

Development of a Laser-based Emittance Monitor for Negative Hydrogen Beams

Entwicklung eines Laser-basierten Messgeräts
zur Ermittlung der Emittanz von Negativen
Wasserstoffionenstrahlen

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Abstract

High energy particle accelerators are designed to collide charged particle beams and thus study the collision products. Maximising the collision rate, to generate sufficient statistics for precise measurements of rare processes, is one of the key parameters for optimising the overall collider performance.

The CERN Large Hadron Collider (LHC) Injectors Upgrade (LIU) includes the construction of LINAC4, a completely new machine working as a first linear acceleration stage for the LHC beam. By accelerating a negative hydrogen beam (H^-) instead of protons, it aims to double the beam brightness via a more efficient transfer to the first circular accelerator and subsequently boost the LHC collision rate. To achieve this, a precise knowledge of the transverse beam characteristics in terms of beam emittance is essential.

This thesis work covers the development of a laser-based monitor meant to measure non-destructively the LINAC4 beam transverse profile and emittance. This included the implementation of different prototypes that were successfully tested at various beam energies during the LINAC4 commissioning and the design of the final system to be installed at the LINAC4 top energy.

The laser emittance meter is based on the photo-detachment effect which describes the liberation of an electron from a negative hydrogen ion. By scanning a focused laser-beam through the H^- beam, the profile can be reconstructed by counting the amount of the detached electrons. The transverse emittance can be obtained by separating the H^0 from the H^- beam by a dipole magnet and recording the H^0 profiles downstream the dipole for each laser position.

The thesis work introduces the basic principles of transverse beam dynamics and the techniques typically used to determine the transverse beam characteristics. Hereafter a bibliographic research is presented about the state of the art in the field of beam diagnostics based on photo-detachment.

Then, an extensive simulation campaign of the photo-detachment process led to the conclusion that the laser-system can be based on a low-power laser-source and a fibre-optic transfer of the laser beam to the interaction point with the H^- beam. To distinguish the H^0 created by the laser interaction from background radiation, a fast, sensitive and radiation-hard diamond strip-detector

was implemented. First tests of a prototype were conducted at a 3 MeV and 12 MeV H^- beam and the results were compared with conventional techniques, which resulted to agree within $\pm 3\%$ in terms of emittance.

In the following LINAC4 beam commissioning periods at 50, 80 and 107 MeV a second prototype of the instrument based on monitoring the detached electrons has been validated. The setup, consisting of a laser system with 73 m long fibre-optic transfer line, electron deflector magnet and single-crystal diamond detector, has been fully characterised and the obtained profiles were compared with conventional techniques, where an agreement within $\pm 2\%$ has been found.

All these prototype tests were essential for the design of permanent installations at the LINAC4 top energy of 160 MeV in the transfer-line towards the injection into the successive machine (PS-Booster). The design combines electron and H^0 detection and provides a simultaneous emittance and profile measurement in the horizontal and vertical planes, with an expected resolution of $< 75 \mu\text{m}$ and $< 100 \mu\text{rad}$. The instruments shall be routinely operated for automated on-line monitoring of the transverse beam parameters to optimise the PS-Booster injection and subsequently avoid losses and the consequent activation of the environment. Due to the non-destructive measurement method, the instrument can gather an extensive amount of beam characteristics data without leading to downtimes of the machine.

Zusammenfassung

In Hochenergie-Teilchenbeschleunigern wie dem Large Hadron Collider (LHC) prallen geladene Teilchenstrahlen aufeinander, wodurch eine Analyse der Kollisionsprodukte ermöglicht wird. Um sehr seltene Prozesse mit hinlänglicher statistischer Signifikanz zu beobachten ist die Kollisionsrate des Teilchenbeschleunigers entscheidend.

Im Rahmen von CERNs LHC Injectors Upgrade (LIU) soll der neue Linearbeschleuniger LINAC4 negative Wasserstoff Ionen (H^-) auf 160 MeV beschleunigen. Durch eine effiziente Einspeisung in den nachfolgenden Kreisbeschleuniger soll die Leuchtdichte des Teilchenstrahls verdoppelt werden und somit die Kollisionsrate des LHCs gesteigert werden. Um dies zu erreichen ist die präzise Kenntnis der transversalen Strahlcharakteristik in Sinne der Strahl-Emittanz essenziell.

Die vorliegende Arbeit behandelt die Entwicklung eines laser-basierten Messgeräts zur zerstörungsfreien Erfassung des transversalen Strahlprofils und der transversalen Emittanz. Dafür wurden verschiedene Prototypen bei unterschiedlichen Teilchenstrahl-Energien während der Inbetriebnahme getestet. Anschließend wurde ein finales Messgerät entwickelt welches langfristig im Hochenergiebereich des LINAC4 integriert werden wird.

Die laser-basierte Emittanzmessung beruht auf dem Photo-Detachment Effekt, der die Ablösung eines Elektrons von einem negativen Wasserstoff-Ion beschreibt. Wird ein fokussierter Laserstrahl durch den H^- Strahl gesannt, werden freie Elektronen erzeugt, mithilfe derer das H^- Strahlprofil rekonstruiert werden kann. Die generierten H^0 Teilchen können durch einen Dipol-Magneten vom H^- Hauptstrahl separiert werden. Mittels Messung der H^0 Winkelverteilung kann somit die transversale Emittanz bestimmt werden.

In der Dissertation werden zu Beginn die Grundlagen der transversalen Strahldynamik behandelt und klassische Techniken zur Bestimmung der transversalen Strahlparameter erläutert. Der Stand der Technik für laser-basierte Verfahren zur Strahlprofil- und Emittanz-Messung wird mittels einer Literaturrecherche zusammengefasst.

Daraufhin werden umfassende Simulationen des Photo-Detachment Prozesses beschrieben, die zum Ergebnis führen, dass eine Laserquelle mit vergleichsweise niedriger Puls-Spitzenleistung im Kilowattbereich und ein faseroptischer Strahltransport zum Interaktionspunkt die Systemanforderungen erfüllen. Um die vom Laserstrahl erzeugten H^0 von Hintergrundstrahlung zu unterscheiden, wurde ein schneller, empfindlicher und strahlungsfester Diamant-Detektor implementiert. Erste Prototypentests wurden auf einer H^+ Strahlenergie von 3 MeV und 12 MeV durchgeführt und mit konventionellen Messmethoden verglichen. Die Emittanzmessungen stimmen mit einer Genauigkeit von $\pm 3\%$ überein.

In der darauffolgenden LINAC4 Inbetriebnahmephase mit Strahlenergien von 50, 80 und 107 MeV wurde ein zweiter Prototyp getestet, welcher durch Detektion der freigesetzten Elektronen das Strahlprofil rekonstruierte. Dieser Aufbau bestand aus einem Laser-System, einem 73 m langen faseroptischen Transfer des Laserstrahls, einem Elektron-Ablenkmagneten und einem Einkristall-Diamantdetektor. In der Testkampagne wurden diese Subsysteme eingehend charakterisiert und die erhaltenen Strahlprofile mit konventionellen Messmethoden verglichen. Dabei wurde eine Übereinstimmung von $\pm 2\%$ festgestellt.

Die beschriebenen Prototypentests waren essenziell, um Messsysteme für permanente Installationen im Hochenergie-Bereich (160 MeV) des LINAC4 zu entwickeln. Profil- und Emittanz-Messungen in horizontaler und vertikaler Ebene mit einer Auflösung von $< 75 \mu\text{m}$ und $< 100 \mu\text{rad}$ werden durch kombinierte Detektion von Elektronen und H^0 ermöglicht. Die Messgeräte sollen routinemäßig für automatisierte Messungen der transversalen Strahlparameter eingesetzt werden, um die Einspeisung in den nachfolgenden Beschleuniger PS-Booster zu optimieren und somit Verluste und damit einhergehende Radioaktivität zu vermeiden. Da es sich um eine zerstörungsfreie Methode handelt, können die Geräte permanent Strahlcharakteristik-Daten aufnehmen, ohne Ausfallzeiten des Beschleunigers zu verursachen.

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VIII

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List of Symbols and Abbreviations

Constants

Symbol	Value	Unit	Description
c_0	299792458	m/s	Speed of light in vacuum
ϵ_0	$8.8542 \cdot 10^{-12}$	C/(Vm)	Vacuum permittivity
h	$6.62606957 \cdot 10^{-34}$	J/s	Planck constant
k	$1.3806488 \cdot 10^{-23}$	J/K	Boltzmann constant
m_e	510998.9461	eV/c ²	Electron mass
m_p	938272046	eV/c ²	Proton mass
N_A	$6.022140857 \cdot 10^{23}$	mol ⁻¹	Avogadro's number
r_e	$2.817940 \cdot 10^{-15}$	m	Classical electron radius
e	2.7182818		Euler's number
π	3.1415927		

Symbols

Symbol	Unit	Description
A	m ²	Area
A	u	Atomic mass
$\mathbf{B}(x, y, z)$	Vs/m ²	Magnetic flux density
B	Hz	Bandwidth
B	(π m rad) ⁻²	Beam brightness
C	F	Capacitance
$C_{B,th}$	1	Critical factor
d	m	Distance
$\mathbf{E}(x, y, z)$	V/m	Electric field intensity

Symbol	Unit	Description
E	eV	Energy ¹
E'	eV	Lorentz shifted energy
F	$\text{m}^{-2}\text{s}^{-1}$	Flux
f	m	Focal length
f	Hz	Frequency
g_B	1	Brillouin gain-coefficient
I	W/m^2	Intensity
i	A	Electric current
I_H	A	Beam current
K	Vs/m	Quadrupole gradient
L, l	m	Length
L	$\text{m}^{-2}\text{s}^{-1}$	Luminosity
M^2	1	Beam quality factor
M_λ	$\text{W}/(\text{m}^2 \text{ nm})$	Spectral radiant exitance
N	1	Number of particles
n	1	Refractive index
NA	1	Numerical Aperture
P	W	Power
P	N/m^2	Pressure
$\mathbb{P}$	1	Probability
p	eV/c	Particle momentum
Q, q	C	Charge
q	C	Elementary charge
R, r	m	Radius
$R(E)$	m	Range of an energetic particle
R_{event}	1/s	Event rate
T	K	Temperature
T	s	Period length
t	s	Time
u	m	Amplitude in x/y
u'	rad	Divergence in x/y
U	V	Voltage
V	m^3	Volume

¹ Kinetic energy of particle beam / binding energy of electron to atom etc.

Symbol	Unit	Description
V	1	Normalised frequency
v	m/s	Velocity
v_A	m/s	Acoustic velocity
$W(z)$	m	Laser spot radius
x, y	m	Coordinates perpendicular to beam direction
x_R	m	Rayleigh length
Z	1	Atomic number
z	m	Coordinate in beam direction
$\alpha(z)$	1	Twiss Parameter
$\beta(z)$	m	Twiss Parameter (beta-function)
β_{rel}	1	Relativistic beta
$\epsilon_{x/y}$	π m rad	Transverse emittance
$\epsilon_{x/y}^*$	π m rad	Normalised transverse emittance
η	kg/(m s)	Viscosity
$\gamma(z)$	m^{-1}	Twiss Parameter
γ_{rel}	1	Relativistic gamma
γ_B	1	Fibre-specific Brillouin coefficient
Γ_B	1/s	Bandwidth of angular frequency
λ	m	Wavelength
ω	s^{-1}	Angular frequency
Ω_B	s^{-1}	Brillouin frequency
Φ	m^{-2}	Fluence
ϕ	rad	Phase
ρ	m^{-3}	Density
σ		Beam matrix
σ	m^2	Cross-section
$\sigma_{x/y}$	m	Transverse RMS beam size
σ_z	s	RMS bunch length
τ	s	Duration
Θ	rad	Angle
$\theta_{x,y,z}$	rad	RMS angular/momentum spread
$\varnothing$	m	Diameter

Abbreviations

Abbreviation	Description
ADC	Analogue Digital Converter
AR	Anti Reflective
ASpBS	Amplified Spontaneous Brillouin Scattering
BCT	Beam Current Transformer
Beamlet	Separated fraction of particle beam
Bkg	Background
BPM	Beam Position Monitor
BSM	Bunch Shape Monitor
CCD	Charge Collection Distance
CCD	Charge Coupled Device
CCDTL	Cell Coupled Drift Tube LINAC
CCE	Charge Collection Efficiency
CERN	Conseil Europeen pour la Recherche Nucleaire
CVD	Chemical Vapour Deposition
DAQ	Data Acquisition
DPA	Displacement Per Atom
DTL	Drift Tube LINAC
e^-	Electron
EMT	Electron Multiplier Tube
ENOB	Effective Number Of Bits
FBG	Fibre Bragg Grating
FESA	Front-End Software Architecture
FETS	Front End Test Stand
FODO cell	Combination of focusing and defocusing quadrupoles
GEM	Gas Electron Multiplier
H^-	Negative hydrogen ion
H^0	Neutral hydrogen atom
HL-LHC	High Luminosity LHC
IP	Interaction Point
ISOLDE	Isotope Separator OnLine DEvice
LD	Laser Diode
LEAR	Low Energy Antiproton Ring
LEBT	Low Energy Transfer Line

Abbreviation	Description
LHC	Large Hadron Collider
LINAC	Linear Accelerator
LIU	LHC Injector Upgrade
LMA	Large Mode Area
MCP	Multi Channel Plate
MIP	Minimum Ionising Particle
MM	Multi Mode
MOPA	Master Oscillator Power Amplifier
n^0	Neutron
NIEL	Non Ionising Energy Loss
PCIE	Peripheral Component Interconnect Express
p^+	Proton
pCVD	Poly-crystalline Chemical Vapour Deposition
PIMS	PI Mode Structure
PD	Photo Diode
PM	Polarisation Maintaining
PSB	Proton Synchrotron Booster
PXI	PCI eXtensions for Instrumentation
RD42	Radiation Detector group 42 (diamond detector section)
RFQ	Radio Frequency Quadrupole
RHUL	Royal Holloway University of London
SBS	Stimulated Brillouin Scattering
sCVD	Single-crystalline Chemical Vapour Deposition
SEM	Secondary Emission Monitor
SEY	Secondary Emission Yield
SNR	Signal to Noise Ratio
SM	Single Mode
SpBS	Spontaneous Brillouin Scattering
UHV	Ultra High Vacuum
WS	Wire-Scanner
YDF	Ytterbium Doped Fibre

Introduction

CERN, the Organisation for Nuclear Research of Europe, is one of the world-leading institutes in particle physics. Since its foundation in 1954 it has operated several large-scale accelerators and achieved major contributions to fundamental questions of physics. The current flagship of CERN is the 27 km long Large Hadron Collider (LHC) that, after the discovery of the Higgs-Boson in July 2012 and the consecutive award of the Nobel prize to Peter Higgs in 2013, became a symbol for CERN's leading role in particle physics worldwide. But CERN is not just the LHC, it has a diverse infrastructure of accelerator facilities with about 30 experiments to examine the building blocks of matter.

Fig. 1.1 shows CERN’s accelerator complex with the LHC and its four ex-

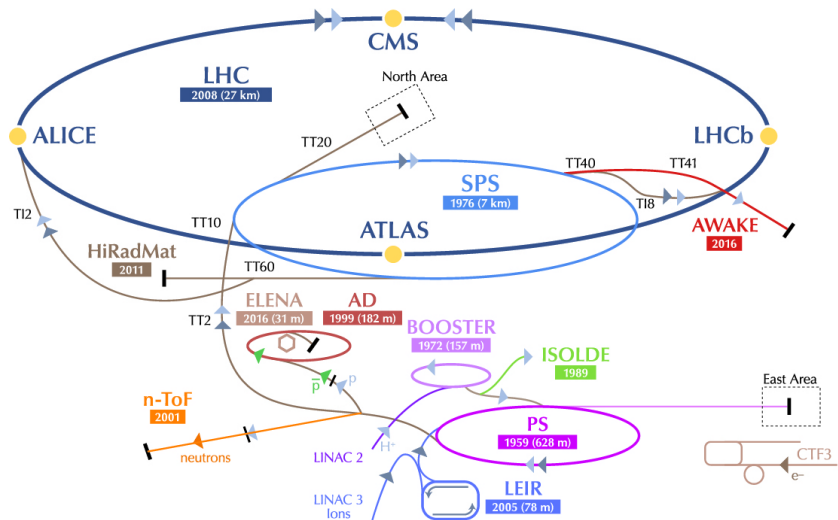


Figure 1.1: CERN’s current accelerator complex. [CER16]

periments ATLAS, CMS, LHCb and ALICE, which analyse head-on particle collisions. Super Proton Synchrotron (SPS), Proton Synchrotron (PS), Booster (PSB) and Low Energy Ion Ring (LEIR) are circular pre-accelerators. They are used to deliver particles for the LHC but also for 19 other experiments, like the Isotope Separator OnLine DEvice (ISOLDE), the Neutrons Time of Flight (n-ToF) and several experiments hosted at the Antiproton Decelerator (AD).

LINAC2 and LINAC3 provide the first acceleration from the particle sources to the downstream accelerators. LINAC3, built in 1994, accelerates lead ions to be used at the LHC and fixed-target experiments. LINAC2 runs already since 1978 and provides proton beams to the whole accelerator complex.

1.1 LHC Injector Upgrade and High-Luminosity LHC

In 2013, delegates from all CERN member states forming the CERN Council decided on an update for the European Strategy for Particle Physics:

"Europe's top priority should be the *exploitation of the full potential of the LHC*, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma." - [Cou13]

This mentioned high-luminosity upgrade of the LHC (HL-LHC) includes the LHC Injectors Upgrade (LIU), which is the framework of this thesis. In Fig. 1.2 one finds the time-line for this project together with the anticipated kinetic energy of the colliding beams and the integrated luminosity.

The luminosity L is a measure for the event rate R_{event} of a reaction with a given cross-section σ_{react} :

$$R_{event} = L \cdot \sigma_{react} \quad (1.1)$$

Considering 2 identical double Gaussian beams colliding, the luminosity is defined as

$$L = N_b^2 \cdot f_b / (4\pi\sigma_x\sigma_y) \quad (1.2)$$

where N_b is the number of particles per bunch, f_b is the bunch frequency and $\sigma_{x/y}$ the transverse beam dimensions [Wil01]. The integrated luminosity $\int L dt$ measured in inverse femtobarn ($fb^{-1} = 10^{43} m^{-2}$) defines the number of collisions per femtobarn of target cross-section. The main goal of LIU and HL-LHC is to maximise this value in order to achieve sufficient statistics for rare processes with low cross-sections.

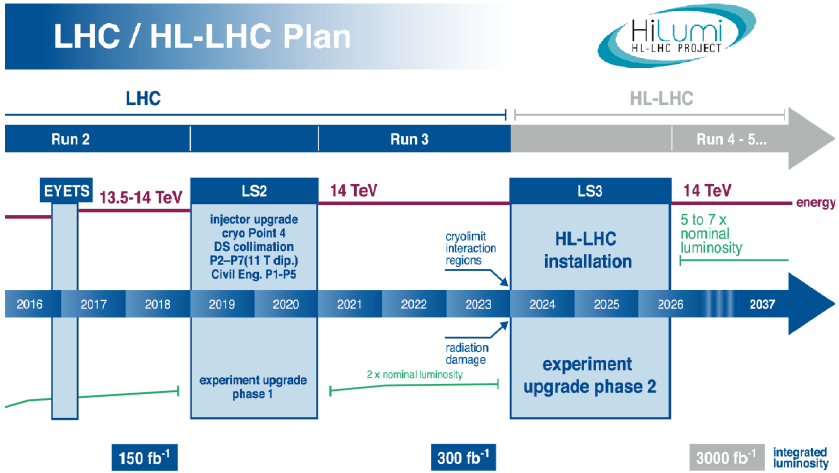


Figure 1.2: Time-line for the LHC and HL-LHC. [CER14a]

To reach this goal, the density of particles in the interaction point is the key-factor. In Fig. 1.3 the envelopes of the colliding proton beams are visualised. At the run in 2012 the beam sizes in x and y were squeezed down to $\sigma = 15 \mu\text{m}$ at ATLAS.

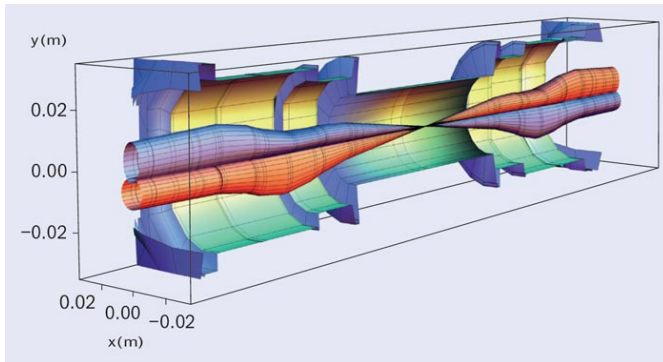


Figure 1.3: Beam envelopes in the interaction region at the ATLAS experiment. [LJ13]

Major contributions of HL-LHC are devoted to make this value as small as possible and increase the luminosity of a factor 10 beyond the LHC's design value. Superconducting magnets with a magnetic field of 13 Tesla and special crab-cavities in proximity of the interaction region are key-elements to

increase the luminosity. But the brightness of the beam exhibits a fundamental limit, which is already defined earlier in the accelerator chain. To create a beam with high brightness and accelerate it without losses to the LHC injection energy, an upgrade of the CERN injector complex is necessary. For this reason CERN launched the LHC injection upgrade (LIU) project, which involves modifications at the SPS, PS and PSB machines but also includes a complete replacement of the elderly LINAC2 by a new machine called LINAC4.

1.2 LINAC4

In 2007, CERN approved to build LINAC4. After the completion of the civil engineering part, the machine is currently in a staged commissioning phase and will be connected to the PSB during the Long-Shutdown 2 (2019/2020). Figure 1.4 shows the LINAC4 source, tunnel, dump and the transfer line to the PSB.

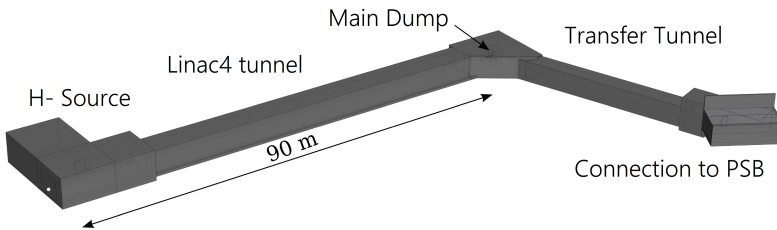


Figure 1.4: General layout of LINAC4 and its transfer-line to the PSB.

In Fig. 1.5 a block diagram of the machine is shown. The commissioning is divided into 5 stages, taking place at 3 MeV, 12 MeV, 50 MeV, 102 MeV and finally 160 MeV. This enables a detailed characterisation of all subsystems and hence ensures a reliable operation of the complete machine.

The main aim for LINAC4 is to reach an increase of beam brightness defined by the ratio of the bunch population N_b and the transverse emittances $\epsilon_x \epsilon_y$,

$$B = \frac{N_b}{\epsilon_x \epsilon_y} \quad (1.3)$$

by a factor of 2 in regard to the LINAC2 beam. Given the relationship between transverse emittances and beam sizes (see Sec. 2.1.3), the higher the brightness the higher the luminosity expressed in Eq. 1.2.

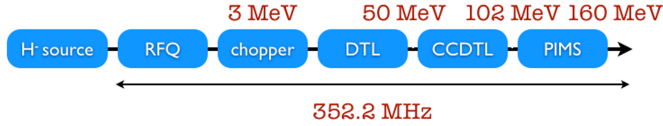


Figure 1.5: Block diagram of LINAC4. After generating the ion beam in a caesiated surface source the radio-frequency quadrupole (RFQ) bunches the beam and simultaneously accelerates it to a kinetic energy of 3 MeV. The chopper selects a temporal slice of the beam for further acceleration. DTL (Drift Tube Linac), CCDTL (Cell-Coupled) and PIMS (Pi-Mode-Structure) accelerate the beam to the final energy of 160 MeV. [CER12]

The increase of beam brightness will be achieved by combining two effects. Firstly the increased top energy of 160 MeV (see Table 1.1) will reduce significantly space charge effects causing emittance blow-up in the PSB, secondly the use of H^- ions instead of protons makes it possible to inject into the PSB via charge exchange scheme, which will be described in the next section.

Table 1.1: Main machine parameters of LINAC2 and LINAC4 [GV⁺06]

Parameter	LINAC2	LINAC4
Particle Type	Protons	H^- ions
LINAC Length [m]	30	80
Top Energy [MeV]	50	160
Bunch Frequency [MHz]	200	352.2
Pulse current [mA]	160	40
Pulse length [μs]	20...150	400
Pulse frequency [Hz]	1	0.83
ϵ_x^* ; ϵ_y^* [π mm mrad] ¹	1.2; 1.2 [RMCB12]	0.34; 0.43 [T^+ 10]

1.2.1 Charge Exchange Injection

The charge exchange injection process, shown on Fig. 1.6, combines a circulating proton beam with an incoming H^- beam in the same transverse phase-space, which is only possible due to the contrary charge of the incoming and the circulating beam. Subsequently the beam brightness can be increased incrementally, unlike the injection method currently used at LINAC2.

¹Normalised RMS emittance in horizontal and vertical plane

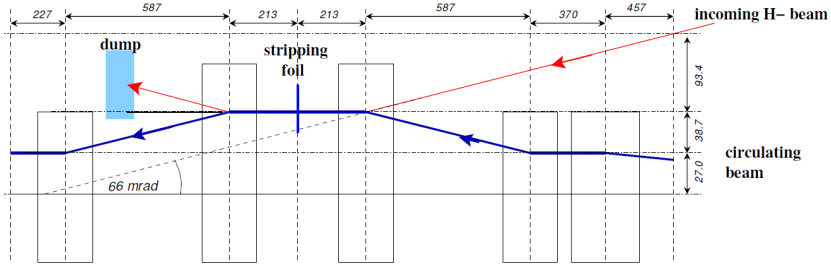


Figure 1.6: Charge exchange scheme. The incoming H^- beam from LINAC4 is bent to the right onto the same trajectory as the circulating proton beam. After stripping the electrons of the H^- ions, the remaining protons stay on the circular trajectory. Unstripped H^- or partially stripped H^0 are expected to be less than 2 % and will hit the dump. [GV⁺06]

The simulated result of this technique can be seen in Fig. 1.7, where the brightness measurements for LINAC2 are compared with the simulated values for LINAC4 as a function of bunch intensity. For more information regarding the techniques for creating the high-brightness beam at LINAC4, the technical design report [GV⁺06] is recommended for further literature.

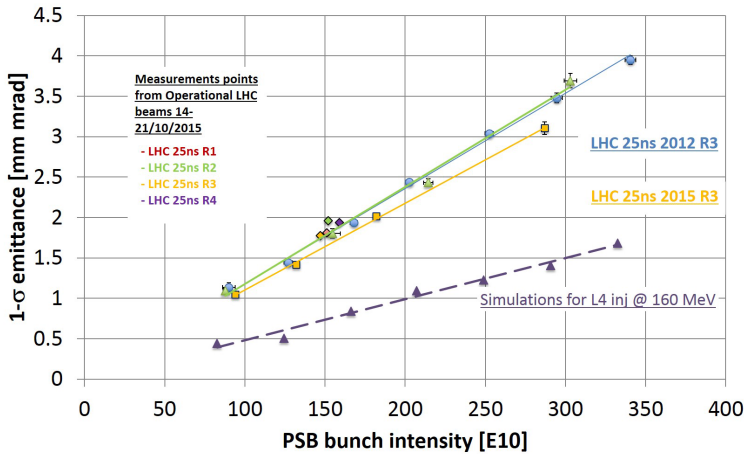


Figure 1.7: Beam brightness measured at PSB, produced by LINAC2 (LHC 25ns 2012/2015 R3) with nominal settings for LHC injection compared with simulated brightness of LINAC4 (purple). [Ste16]

1.2.2 Profile and Emittance Measurements at LINAC4 Top Energy

To avoid beam losses and subsequently a high radiation environment at the injection region into the PSB, the transverse emittance of the LINAC4 beam must be monitored carefully during operation. For this reason, the 3-profile measurement technique (see Sec. 2.2.1) was proposed to be installed at the 160 MeV region of LINAC4 [LLP12]. Figure 1.8 shows this area of LINAC4 where the wire-grids are visualised as purple boxes in the straight line at the bottom. The reason for using 4 wire-grids instead of 3 is to gain flexibility for different beam settings.

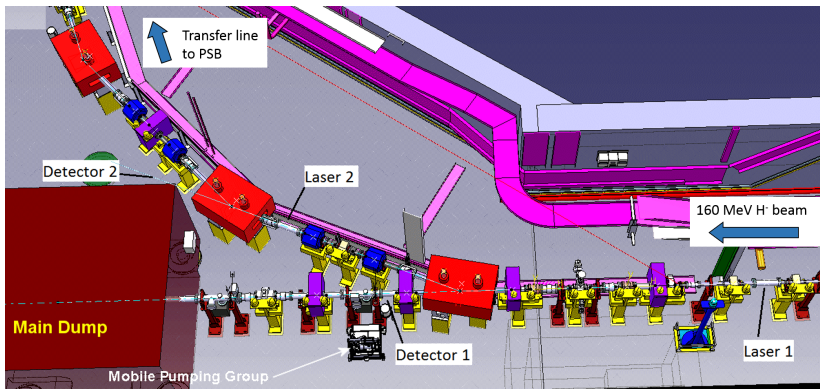


Figure 1.8: Layout of the beam-line from the end of the LINAC4 (right) to the main dump (left) and the transfer line to the PSB (top).

The 3-profile method is a well established and reliable technique for transverse emittance measurements. However this technique has limitations due to the high intensity of the H^+ beam. A special beam setting with reduced current has to be used in order not to damage the wires by overheating. Moreover corrections for the strong space charge forces in this high brightness beam need to be applied which add some uncertainty to the measurement result [LLP12]. Finally, wire grids are partially destructive for the beam (multiple Coulomb scattering between the particles and the wire material generates an emittance increase) and cannot be used while sending the beam to the PSB.

To overcome these limitations, it was proposed to use complementary laser-based instruments to measure the emittance of the H^+ beam non-destructively [Bra09]. A laser shall be used to cross the H^+ beam and strip a small amount (< 1 ppm) of electrons from the H^+ ions. The resulting H^0 atoms drift unperturbed by magnetic fields to a detector system while the liberated electrons can

be collected close to the laser interaction. Figure 1.8 shows the proposed 2 locations of the lasers and the associated H^0 detector systems. The principle of operation of the instrument will be discussed in more detail in Sec. 3.2.2. The naming convention "Detector 1/2" and "Laser 1/2" will be maintained in the following.

1.3 Thesis Contents

The conceptual design, prototype tests and design of a laserwire system to be permanently installed in the LINAC4 160 MeV area are the subject of this thesis.

Chapter 2 describes the principles to accelerate charged particles and the associated behaviour in the transverse plane with a focus on linear accelerators. The definition of emittance in the transverse phase-space is introduced and the instruments most frequently used to measure transverse profile and emittance of ion beams are briefly discussed.

Chapter 3 discusses the photo-detachment effect, which is the underlying physical principle for the laser-based emittance monitor. The concepts for profile measurement via electron collection and emittance measurement via H^0 profiling are introduced and the state of the art in laser-based H^- diagnostics on H^- beams is discussed.

The design guidelines for the instrument are determined in Chapter 4 by modelling the interaction of the laser beam with the H^- beam but also considering perturbations of the measurement by different sources of background. Accordingly the laser system is dimensioned in terms of the laser beam parameters and its fibre-based delivery to the accelerator. The requirements for the H^0 and electron detectors are summarised and potential detector principles are reviewed. The characteristics of the chosen detector types are hereafter described in depth.

First tests with a prototype of the instrument to measure the transverse emittance were carried out at the LINAC4 3 MeV beam. The beam parameters and the corresponding setup of the laserwire emittance scanner are pointed out in chapter 5 and the results of the measurement campaign and the consecutive 12 MeV campaign are discussed.

A strongly modified version of the instrument was used afterwards at the 50, 80 and 107 MeV commissioning stage of LINAC4. The aim of this test-run was to measure the beam profile by collecting the liberated electrons. The corresponding design changes are depicted together with the 50/80/107 MeV

H⁻ beam parameters in Chapter 6. The results are analysed in order to optimise the setup planned to be permanently installed.

In Chapter 7 the H⁻ beam parameters at the interaction points with the 160 MeV beam are summarised and a detailed review of the system design for the final instruments will be given. This includes the laser-delivery, -diagnostics and -interaction setup as well as an exhaustive discussion of the dimensioning of the H⁰ and electron detection systems.

Chapter 8 summarises the developments of laser-based instrumentation for LINAC4 and sketches the anticipated next steps in this domain.

Chapter 2

Particle Beam Parameters and Measurement Techniques

Particle accelerators are drivers of science and technology in each industrialised country. They can be found in every scale starting from old TV-tubes over room-size cyclotrons and synchrotrons up to the 27 km long LHC at CERN. Charged particles or ions are accelerated by electric fields and focused or bent by magnetic fields until they reach the target energy which is necessary for the desired experiment.

To commission and operate such machines one needs to have a sophisticated set of instruments to measure and control all relevant parameters. This chapter shall introduce in accordance with [Wie07] the most important parameters of transverse beam dynamics and illustrate by which means one can measure them.

2.1 Principles of Beam Dynamics

To accelerate charged particles, it is essential to keep them on a stable trajectory in the transverse domain. In this thesis x will be used as the horizontal plane, y as the vertical plane and z as the direction of propagation of the particle beam.

2.1.1 Acceleration Principle

Both acceleration and focusing are based on the interaction of a charged particle beam with electromagnetic fields, which act through the Lorentz force on the beam:

$$\mathbf{F}_L = q\mathbf{E} + q(\mathbf{v} \times \mathbf{B}) \quad (2.1)$$

The electric field $\mathbf{E}$ and the magnetic field $\mathbf{B}$ act hereby on a particle with the charge q moving with velocity $\mathbf{v}$.

Although the focus of this thesis is the measurement of the transverse beam parameters, at least the main principle of the acceleration of charged particles shall be introduced. The acceleration in LINACs is based on energy transfer of radio-frequency waves to the particle beam. Like it can be seen in Fig. 2.1, the particle beam travels through a periodic structure of drift tubes and gaps. By applying a RF wave on the drift tubes, the bunched beam is exposed to an electric field in the gaps. The energy gain ΔE in this region is expressed in Eq. 2.2 with g being the gap length and $\mathbf{E}(x, y, z)$ as the electric field strength caused by the RF-wave:

$$\Delta E = q \int_{-g/2}^{g/2} \mathbf{E}(x, y, z) dz \quad (2.2)$$

While the particle bunch is electrically shielded inside the drift tube, the field changes polarity in order to provide again an accelerating field gradient, when the particle bunch reaches the next gap.

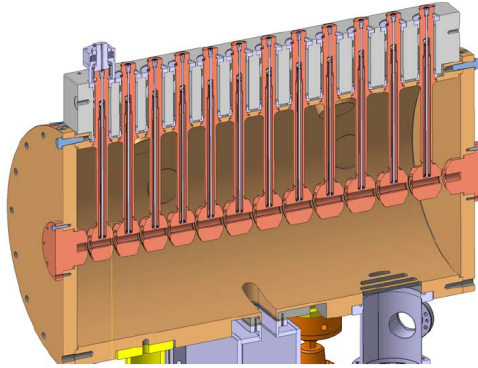


Figure 2.1: Design of a tank of the LINAC4 drift tube linac supplied by an RF-wave of 352.2 MHz. The increasing length of the drift tubes from left to right indicates the usage for a non-relativistic beam. [R⁺08]

2.1.2 Transverse Beam Dynamics

While the acceleration of particles along the beam axis is based on electric fields, deflection in the transverse plane is done using the more powerful magnetic fields. One can illustrate this by applying the Lorentz force to relativistic¹

¹Relativistic beams are predominant in most accelerators. As LINACs are used at the source of accelerator chains, they are an exception in this regard.

particles $v \approx c$. To create an equal Lorentz force using Eq. 2.1 one needs either a magnetic field of $B = 1$ T, perpendicular to the particle movement or an unrealistic high electric field strength of $E \approx 300$ MV/m, which makes clear why magnetic fields are used to deflect the charged particles.

The most commonly used magnet types are dipoles to bend the beam and quadrupole magnets to focus and defocus the beam. As shown in Fig. 2.2 the Lorentz force of a quadrupole magnet is proportional to the position of the particle in x and y as the magnetic field components are increasing respectively.

$$B_x \propto y, \quad B_y \propto x \quad (2.3)$$

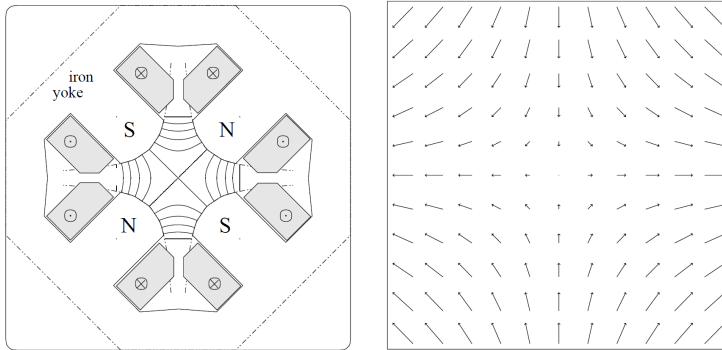


Figure 2.2: Cross-section of quadrupole magnet. Left: Poles of the magnet with coils and resulting magnetic field lines. Right: Lorentz force on charged particles moving into the image plane.

This is in agreement Gauss's law for magnetism $\nabla \cdot \mathbf{B} = 0$ which imposes that particles get focused in the horizontal plane but defocused in the vertical plane and vice-versa for reversed polarity. To keep the beam focused along the accelerator, quadrupoles with alternating polarities separated by drift spaces (O) are used. The naming for focusing (F) and defocusing quadrupoles (D) is always referring to the horizontal plane. A very often used combination of focusing and defocusing sections is called FODO cell.

2.1.2.1 Single Particle Motion

The position of a charged particle travelling along the accelerator can be described by the equation of motion of a harmonic oscillator. Equation 2.4 shows

this differential equation often referred to as Hill's equation. The variable u is hereby representing x or y in the coordinate system introduced in Section 2.1.

$$\frac{d^2u}{dz^2} + K(z)u = 0 \quad (2.4)$$

While for simple harmonic motion $K(z)$ is constant, in an accelerator $K(z)$ depends on the quadrupole strength and varies along z . The solution to the equation can be expressed as in Eq. 2.5. The oscillation amplitude $u(z)$ is dependent on the source parameter ϵ called transverse emittance and the beta-function $\beta(z)$. Moving along the accelerator, one single particle oscillates in the 2-dimensional phase-space (u, u') on an elliptical trajectory. Liouville's theorem states that under the influence of conservative forces the area of this ellipse stays constant. This area is just dependant on the beam emittance.

$$u(z) = \sqrt{\epsilon \beta(z)} \cos(\phi(z) + \phi_0) \quad (2.5)$$

2.1.2.2 Collective Motion of Charged Particles

To describe the collective behaviour of a particle beam the parameters $\alpha(z)$ and $\gamma(z)$ are introduced which are related to the beta-function $\beta(z)$:

$$\alpha(z) = \frac{-\beta(z)^2}{2} \quad (2.6)$$

$$\gamma(z) = \frac{1 + \alpha(z)^2}{\beta(z)} \quad (2.7)$$

The parameters α , β and γ , also known as the Twiss parameters, together with the emittance ϵ define the transverse characteristics of a particle beam at each location along the accelerator. While the emittance is in ideal conditions constant along the accelerator, the Twiss parameters are dependent on the z -position. In transverse phase-space the beam is enclosed by an ellipse as illustrated in Fig. 2.3. The ellipse equation can be expressed by

$$\gamma(z)u(z)^2 + 2\alpha(z)u(z)u(z)' + \beta(z)u(z)'^2 = \epsilon(u) \quad (2.8)$$

As the beam propagates along the accelerator the Twiss parameters change. This transformation is carried out by expressing the accelerator elements in matrix notation:

$$\begin{pmatrix} u(z_2) \\ u(z_2)' \end{pmatrix} = M \cdot \begin{pmatrix} u(z_1) \\ u(z_1)' \end{pmatrix} \quad (2.9)$$

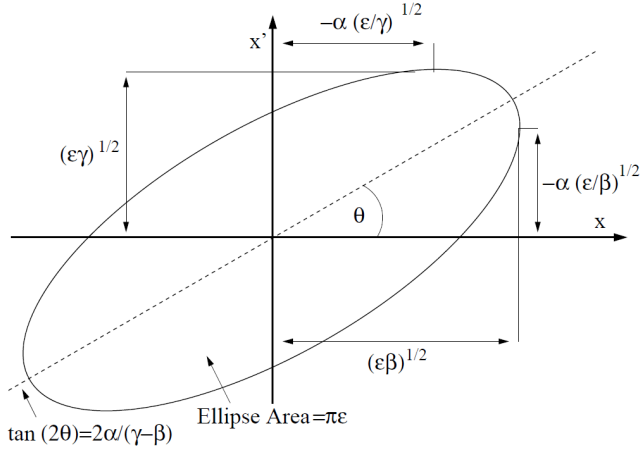


Figure 2.3: Phase-space in the x -plane. One particle moves along an elliptical path in the transverse phase-space while travelling along the accelerator. The collective beam behaviour can be described using the Twiss parameters α , β and γ and the emittance ϵ .

The most relevant elements of an accelerator regarding the transverse beam dynamics are drift spaces, dipoles and quadrupoles. In matrix notation they can be expressed as follows

$$M_{\text{Drift}} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}; \quad (2.10)$$

$$M_{\text{Quad}} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \text{ with } f = \frac{p}{qKL} \quad (2.11)$$

where L is the length of an accelerator element, f is the focal strength of a quadrupole, p the particle momentum, q the charge of the traversing particle and K the quadrupole gradient. A dipole magnet can in first approximation be treated similar to a drift-space as the coordinate system (x, y, z) refers always to the reference orbit which is the average beam centre. It has to be noted, that for quadrupoles Eq. 2.11 is just valid in the thin lens approximation, where L is negligibly short.

Multiplication of the accelerator elements matrices allows to predict the beam parameters along the accelerator. By combining Eq. 2.8 and Eq. 2.9 the Twiss parameters at each position in z can be calculated by

$$\begin{aligned}\beta(z) &= C^2\beta_0 - 2SC\alpha_0 + S^2\gamma_0 \\ \alpha(z) &= -CC'\beta_0 + (S'C + SC')\alpha_0 - SS'\gamma_0 \\ \gamma(z) &= C'^2\beta_0 - 2S'C'\alpha_0 + S'^2\gamma_0.\end{aligned}\quad (2.12)$$

The parameters S , S' , C and C' represent hereby the accelerator lattice as follows:

$$M_{\text{lattice}} = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} \quad (2.13)$$

2.1.3 Transverse Emittance

As shown in Fig. 2.3, an ellipse can be defined to characterise the area in phase-space (u , u') which is populated by the particles. The transverse emittance is a measure of this area and can be expressed in vertical (y , y') or horizontal (x , x') phase-space. To cross the domain of Twiss parameters to the actual beam size and divergence one needs to use another form of the ellipse equation:

$$\mathbf{u}^T \cdot \boldsymbol{\sigma}^{-1} \cdot \mathbf{u} = 1 \quad (2.14)$$

$$\text{with } \boldsymbol{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \quad (2.15)$$

Assuming a Gaussian beam shape, the matrix elements can be described by

$$\begin{aligned}\sigma_{11} &= \langle u^2 \rangle = \epsilon\beta, \\ \sigma_{22} &= \langle u'^2 \rangle = \epsilon\gamma, \\ \sigma_{12} &= \langle uu' \rangle = -\epsilon\alpha.\end{aligned}\quad (2.16)$$

Thus the transverse beam emittance can be expressed by

$$\epsilon_{rms}^2 = \langle u^2 \rangle \langle u'^2 \rangle - \langle uu' \rangle^2 \quad (2.17)$$

This definition is generally used even if the beam-shape varies from a perfect Gaussian shape. This *RMS emittance* describes the part of the beam within one standard deviation in x and y which corresponds to 39% of the particles.

To have a measure which is independent of the beam energy, frequently the normalised form

$$\epsilon_{rms}^* = \beta_{rel} \gamma_{rel} \cdot \epsilon_{rms} \quad (2.18)$$

with the relativistic $\beta_{rel}\gamma_{rel}$ is used to describe the quality of the beam. Although in literature sometimes other emittance definitions (usually multiples of the standard deviation) are cited, in this thesis it is always referred to the RMS emittance.

2.2 Conventional Techniques to Measure the Transverse Emittance and Profile

Measuring the transverse emittance is relevant for any kind of particle accelerator. In accordance with experiences of CERN's profile measurement group and [For13], a versatile instrument has to fulfil various requirements:

Accuracy: As for every kind of instrument, the measurement accuracy is crucial. For emittance measurements, the requirements are usually in the range of $\pm 2...3\%$.

Resolution: The resolution in spatial and divergence domain is a key-parameter of the emittance measurement. It is dependent on the geometric dimensions of the device and the type of measurement - scanning or single shot.

Energy range: In circular machines, the beam is accelerated at each turn. An emittance monitor located in the ring, needs to cover the whole range of energies from injection until the top energy (e.g. LHC: $E_{inject} = 450\text{ GeV}$; $E_{top} = 6.5\text{ TeV}$).

Intensity range: Beam currents range from picoamperes in heavy ion facilities to multiple amperes in spallation sources. The instrument must be adopted to the nominal beam intensity but also be able to cover a certain intensity range which is e.g. essential when used during intensity ramping in a storage ring.

Measurement time: Especially for destructive measurement techniques, the time to measure the emittance is important. One-shot measurements are therefore preferred over time-consuming scanning procedures.

Bandwidth: An ideal instrument would be able to measure the emittance of one bunch with nanosecond length in one shot. To realise this, the instrument's bandwidth is fundamental. For example, the LINAC4 wire grids low bandwidth only allows to measure the average emittance of several bunches.

Non-destructive: This requirement is particularly important, because each time-span where the beam is not destroyed but can be used by following acceleration stages and experiments, contributes to the machine efficiency.

Numerous techniques have been developed in the last decades. As all the listed requirements cannot be fulfilled by a single instrument, each of them has a particular emphasis. In this section, we want to summarise on the most common techniques to measure the transverse profile and emittance of ion beams.

2.2.1 3-Profile and Quadrupole-Scan Method

The transverse emittance is defined in the phase-space of beam size and divergence. While the size can be measured rather simply by a wire grid, the divergence cannot be measured directly. However, if the elements of the lattice are known, profile measurements at 3 different positions can be used to reconstruct the emittance.

In the following we consider P_0 as the position where the emittance will be measured and P_1 , P_2 , and P_3 as the positions of 3 profile monitors. From Eq. 2.12 and Eq. 2.15 the following equation can be deduced:

$$\begin{pmatrix} \sigma_{1,11} \\ \sigma_{2,11} \\ \sigma_{3,11} \end{pmatrix} = \begin{pmatrix} C_1^2 & -2C_1S_1 & S_1^2 \\ C_2^2 & -2C_2S_2 & S_2^2 \\ C_3^2 & -2C_3S_3 & S_3^2 \end{pmatrix} \begin{pmatrix} \sigma_{0,11} \\ \sigma_{0,12} \\ \sigma_{0,22} \end{pmatrix} = M_\sigma \begin{pmatrix} \sigma_{0,11} \\ \sigma_{0,12} \\ \sigma_{0,22} \end{pmatrix} \quad (2.19)$$

Whereas $\sigma_{i,jk}$ are the elements of the beam matrix σ_i at the position P_i while C_i and S_i refer the lattice elements between point P_0 and P_i which form the matrix M_σ . By solving Eq. 2.19, for the beam matrix elements at P_0 , the emittance can be calculated by

$$\begin{pmatrix} \sigma_{0,11} \\ \sigma_{0,12} \\ \sigma_{0,22} \end{pmatrix} = (M_\sigma^T M_\sigma)^{-1} M_\sigma^T \begin{pmatrix} \sigma_{1,11} \\ \sigma_{2,11} \\ \sigma_{3,11} \end{pmatrix} \quad (2.20)$$

$$\epsilon^2 = \sigma_{0,11}\sigma_{0,22} - \sigma_{0,12}^2. \quad (2.21)$$

To record the beam profiles $\sigma_{i,11} = \langle u_i^2 \rangle$ in LINACs, typically instruments like scintillating screens or Secondary Emission wire Monitors (SEM-grid or scanners) are used.

SEM-grids, like the ones used at LINAC4, are shown in Fig. 2.4. The instrument consists of an array of parallel wires which can be moved into the beam path. To obtain the beam profile, the current is recorded which is induced by

the secondary emission of electrons when the beam crosses the wire. Due to this principle, the instrument is not very sensitive as the secondary emission yield (SEY) is typically in the order of $0.5...2 e^-$ per charged particle crossing a wire. Moreover for very intense beams the SEM-grids are limited by heating of the SEM-grid wires.

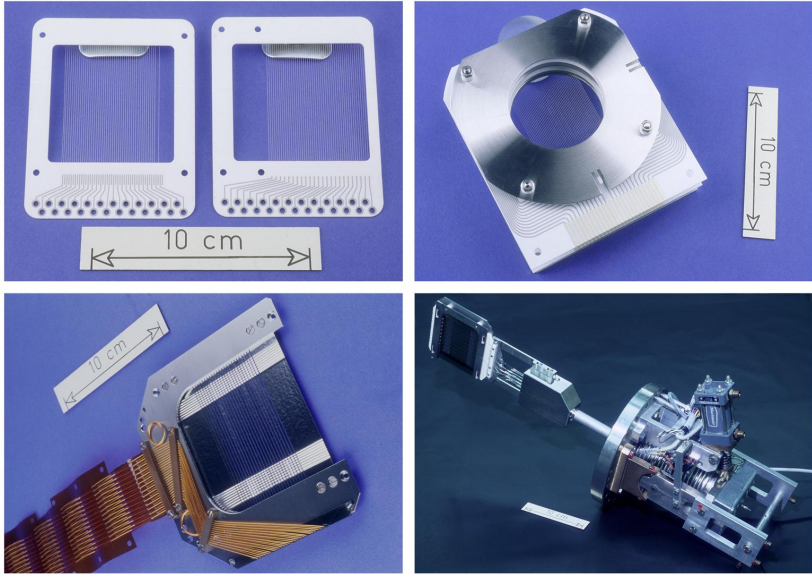


Figure 2.4: Different types of SEM-grids with associated mounting mechanisms or actuator mount (bottom right), used at CERN. [CER02]

As SEM-grids can measure a profile in a single shot, the 3-profile method is considered as a fast method to measure the emittance although the 3 profiles have to be recorded sequentially due to the induced scattering in the wires. In most cases this technique can be considered invasive but not destructive and can be used over a wide range of energies. However, it requires proper modelling of the beam transport and the space charge effects the beam undergoes among the 3 locations along the path, especially for high brightness and/or low energy beams. In [LLP12] an example can be seen of how the 3-profile method is implemented at LINAC4 to characterise the transverse beam emittance.

Similar to this method the emittance can also be measured even with just one SEM-grid. By varying the strength of a quadrupole, Eq. 2.19 can be used to create a set of linear equations. The indices i refer in this case to the different currents applied at a quadrupole situated in between an observer at P_0

and the position of the SEM-grid. It has to be mentioned that this method ensures an acceptable accuracy only if the different quadrupole settings produce a significant change of beam size on the SEM-grid.

2.2.2 Pepper-Pot

The pepper-pot device has its scope of application on low intensity, low energy beams as often present in heavy-ion facilities. It can be used for a fast measurement of both planes in a single shot. It uses a matrix of holes in a plate, which absorbs the ion beam except for the ions travelling via the holes. The concept of the instrument is shown in Fig. 2.5.

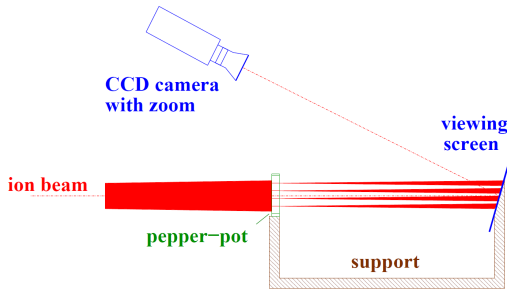


Figure 2.5: Principle of a pepper-pot emittance meter. A plate with a matrix of holes lets pass only the ions travelling through the holes. These propagate onto a scintillator screen. The emitted image is recorded by a camera. [For13]

Assuming linearity of scintillator and camera, the beam emittance can be calculated for the horizontal and vertical plane by applying Eq. 2.17 to the obtained image of the scintillator-screen. The single-shot measurement benefits of being independent of fluctuations from pulse to pulse.

Important design parameters are the distance between plate and screen as well as the hole separation and diameter. It has to be ensured that no overlap of the arriving beamlets¹ at the screen occurs. This on the other hand limits the distance between the holes and therefore the spatial resolution. Because of this, scanning emittance techniques exhibit usually higher resolution than the pepper-pot method. As the ion beam must be almost fully absorbed, the heating of the pepper-pot plate constitutes the upper intensity limit of the device while the lower limit is dependent on the hole diameters.

¹ Beamlet: Transmitted part of particle beam

2.2.3 Slit/Grid

The slit/grid method is a widely used method to measure the transverse emittance of low-energy ion beams with high resolution. Figure 2.6 provides an overview of the working principle and the parts interacting with the particle beam.

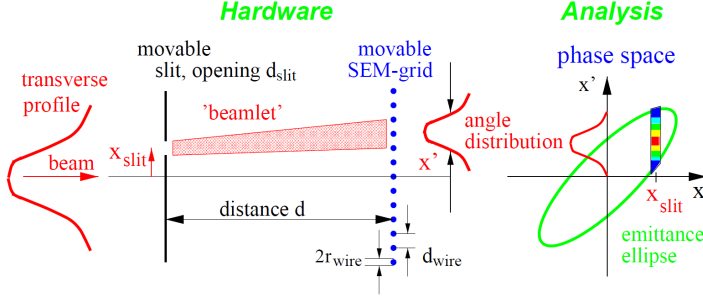


Figure 2.6: Concept of a slit/grid measurement. The slit is scanned in steps through the beam profile. For each step, the angular distribution of the transmitted beamlet is measured by a SEM-grid. By doing a full scan, the emittance ellipse can be reconstructed in the plane perpendicular to the slit direction. [For13]

The energy range is limited, as particles with higher energies perturb thick layers of material¹ and a functional slit design becomes impossible. Also this instrument is fully destructive to the beam, which is the reason why at high beam intensities elaborate cooling techniques must be used to convey the energy deposited by the absorbed particles [Che11].

The spatial resolution of the device is defined by the slit width

$$\Delta x = d_{slit}. \quad (2.22)$$

In practice however also the step-size between two positions of the slit is often the limiting factor as this determines the time for the emittance measurement. The angular resolution is given in approximation for small angles as

$$\Delta x' = (d_{slit} + d_{wire})/d \quad (2.23)$$

but it can be improved by scanning the SEM-grid for each slit position in steps lower than d_{wire} to the maximum resolution of

$$\Delta x' = (d_{slit} + 2r_{wire})/d. \quad (2.24)$$

¹E.g. the range of 100 MeV protons in lead is 14.2 mm.

In [Che11] the design of a slit/grid system to monitor the transverse emittance in the low energy region of LINAC4 is described in detail.

2.2.4 Wire-Scanner

To measure beam profiles rather than the full transverse emittance a big variety of instruments exists. One very frequently used device called wire-scanner shall be discussed, as it has similarities to the laser-based profile monitor.

The principles of the two most common types are shown in Fig 2.7. In both methods thin wires ($\varnothing = 10\text{ }\mu\text{m} \dots 40\text{ }\mu\text{m}$) are moved across the particle beam. Wire materials are usually carbon, SiC or tungsten depending mainly on the beam energy. The rotating type achieves higher wire velocities and therefore is usually used for high beam intensities, to limit the wire heating. The linear type is used for high precision applications as the position of the wire can be recorded more accurately in this configuration. Furthermore the 45° setup allows to mount 2 wires orthogonal to measure vertical and horizontal profile of the beam in a single scan.

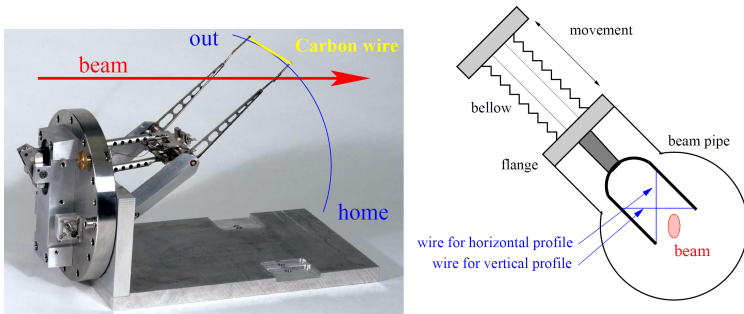


Figure 2.7: Left: Photo of a rotating type wire-scanner used at CERN's synchrotrons. Right: Principle of a linear wire-scanner to measure horizontal and vertical profile. [For13]

To reconstruct the beam profile the information of the number of particles traversing the wire must be recorded. This can be done with two different methods. In case of a conducting wire, a current which is created by secondary emission by the hitting particles can be read out similar to the SEM-grid. The second method is based on the secondary particles released as the beam crosses the wire which can be detected by a scintillator with attached photo-multiplier installed downstream of the wire-scanner. By scanning the wire through the beam, the beam profile can be reconstructed.

In comparison to profile measurements with other techniques as screens or SEM-grids the effort for data acquisition is lower and the accuracy of wire-scanner measurements is typically superior, as the scanning method eliminates any crosstalk or coupling from neighbouring wires or pixels. In terms of resolution, values down to 1 μm have been achieved by deconvoluting the contribution of the wire diameter:

$$\sigma_{beam}^2 = \sigma_{meas}^2 - 4r_{wire}^2 \quad (2.25)$$

As the divergence information is not recorded by a wire-scan, the emittance cannot be reconstructed. In practise¹ however wire-scanners are cross-calibrated with other instruments so that the measured profiles can be used to calculate the emittance by dividing with the beta-function (see Eq. 2.16).

Limitations of this method reveal at high intensity beams with small beam sizes where wire breakage and subsequent vacuum contamination due over-heating of the wire is an issue. Furthermore the measurement requires stable beam conditions by its principle as the profile is not taken at a single shot.

Rating the effect of the measurement on the particle beam, it can be classified as invasive but not destructive as just a small portion of the beam is lost due to the small wire diameter. For further literature on techniques for profile measurements [For13, Str06] can be recommended. An overview, describing how the different measurement techniques are implemented at LINAC4 can be found in [R⁺10].

2.2.5 Summary

This section gave an overview of the various methods for determining the transverse beam emittance. Each method can be accomplished with the use of one or more classes of instruments, depending on the beam parameters (e.g. energy, intensity) and the accelerator type (e.g. Linac or Synchrotron).

Focusing on linear accelerators, for beam energies below few MeV the pepper-pot and the slit/grid systems are often the preferred choice. The slit/grid method offers high accuracy [Che11], whereas, even though it needs a rather sophisticated data processing, the pepper-pot method has the advantage of providing the emittance information in a single beam passage.

At higher energies these two methods are not suitable, since the slit or pepper-pot plates would need to be too thick to select one (slit) or few (pepper-pot) beamlets. The emittance has then to be inferred from profile measurements

¹Routine emittance measurements at CERN's Booster and Proton Synchrotron

(wire-scanners, SEM-grids, scintillating screens) either by using the three-profile method [LLP12] or a quadrupole scan. In this case the main sources of uncertainty are the knowledge of the beam optics (to pass from profiles to emittances) and the modelling of space charge effects, to be considered in the beam transport among profile monitors or between the quadrupole and the monitor. All these methods have in common the disadvantage of being partially or fully interceptive, i.e. during their operation the beam cannot be exploited by other users.

The laser-based technique proposed for LINAC4 overcomes most of the limitations described above. It is practically non-intercepting, it requires a very limited knowledge of the beam optics and does not feature any beam intensity, power or energy limitation.

Chapter 3

Concept of the Instrument

3.1 Photo-Detachment of H⁻ Ions

Laser diagnostics developed for H⁻ ion beams are based on photo-detachment. This effect describes the stripping of electrons from ions by interactions with photons. The interest in this topic dates back to the 1930's and was mainly driven by astrophysics. It was observed that the solar spectrum exhibited reduced spectral power-density continuously for photon energies between 0.75 eV and 4 eV in comparison to the spectrum of a black-body. R. Wildt proposed in 1939, that the photo-detachment effect of H⁻ ions in the photosphere of the sun



can explain this behaviour [Wil39]. The analytical description of this elastic scattering process was subsequently developed by S. Chandrasekhar.¹

Although high-power, narrow-band light-sources were not available at that time, the first measurement proving the continuous absorption spectrum between 400 nm and 900 nm was achieved by L.M. Branscomb et al. in 1954 [BS55] by using an arc lamp and sharp-cut glass filters. These early measurements exhibit just minor differences in the area below 4 eV to the data, used commonly at present (see Fig. 3.1).

The analytical description of the behaviour of the photo-detachment cross-section beyond 10 eV was accomplished by Broad and Reinhard in 1976 [BR76]. The obtained cross-section is shown in Fig. 3.1 and can be divided into three domains. The continuous cross-section rises steeply above the binding energy of the outer electron ($E = 0.75$ eV) and ranges until 10.9 eV. This marks the one-electron excitation regime with the maximum $\sigma_{PD} = 4.0 \cdot 10^{-17} \text{ cm}^2$ at $E_{\text{Photon}} = 1.5$ eV ($\lambda = 830$ nm). The absence of excited bound states and

¹ An overview on Chandrasekhar's work can be found in [Cha58].

therefore resonances in this area was proofed experimentally and also analytically [Hil77].

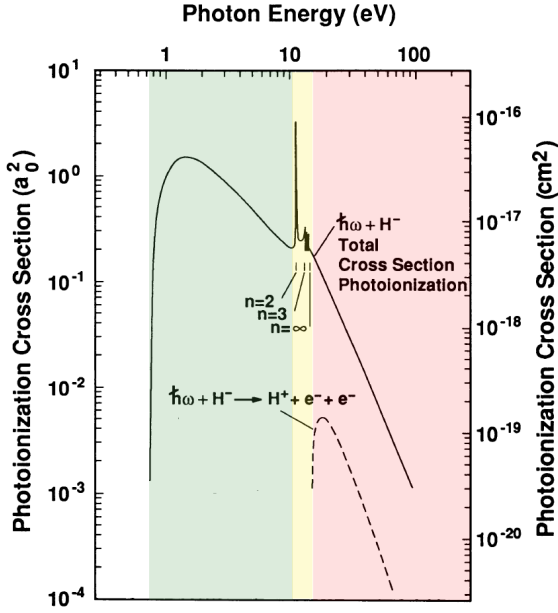


Figure 3.1: Cross-section of H^- for single and double electron photo-detachment with the three different regimes from Eq. 3.2 hatched. [BR76]

The second domain from 10.9 eV until 14.35 eV (threshold for double break-up) is characterised by multiple resonances due to the generation of various excited states of both electrons ($n \geq 2$). This area with the highest cross-section was experimentally studied at Los Alamos by H.C. Bryant [Bry77]. These tests with high energy resolution ($\Delta E = 10 \text{ meV}$) were possible thanks to the use of high power lasers. The investigated energy range up to $E_{max} = 15 \text{ eV}$ ($\lambda = 83 \text{ nm}$) was reached by changing the angle between laser and the 800 MeV H^- beam, thus maximising the Doppler-shift in the rest-frame of the H^- beam (see Section 4.2.1).

In the third domain $E_{\text{photon}} > 14.35 \text{ eV}$ double photo-detachment can be achieved but the continuous cross-section is reduced by more than 2 orders of magnitude in comparison to single electron detachment. All three regimes of

photo-detachment are summarised in Eq. 3.2. A more detailed discussion of the history and recent research on H^- ions can be found in [Rau96].

$$H^- + hf \begin{cases} \rightarrow H^0(1s) + e^-, & | 0.75 \text{ eV} < E_{\text{photon}} < 10.9 \text{ eV} \\ \rightarrow H^0(n \geq 2) + e^-, & | 10.9 \text{ eV} < E_{\text{photon}} < 14.35 \text{ eV} \\ \rightarrow H^+ + 2e^-, & | E_{\text{photon}} > 14.35 \text{ eV} \end{cases} \quad (3.2)$$

Due to the large cross-section over a wide range of wavelengths in the visible and near-infrared, the first regime is the natural choice for the proposed instrument for transverse emittance measurement, based on single electron detachment. In the remaining part of the thesis we will therefore always refer to this regime.

Nevertheless it shall be mentioned that in recent developments, double electron detachment becomes an attractive technique for charge exchange injection (see Fig. 1.6). By replacing the carbon foil commonly used to strip both electrons with a laser, foil degradation and breaking can be avoided and emittance blow-up and beam losses can be almost completely suppressed [C⁺14]. In these H^- double-stripping experiments, the third regime is however avoided due to the low cross-section and subsequently the need of high power lasers. Instead, different methods are used for stripping of both electrons, often combining laser excitation to $n = 2 \dots 4$ with magnetic field stripping (see Section 4.3.4). The group at the Spallation Neutron Source (SNS) in Tennessee, USA aim to implement such a system (see Chapter 8 and [C⁺17]). An overview on the state of the art for single and double electron stripping of H^- ions can be found in [Joh].

3.2 Concepts for Different Instrument Types

As discussed above, laser diagnostics on H^- beams are based on photo-detachment. Measuring the products of the interaction provides information on the properties of the H^- beam. While in this thesis the focus will be on transverse profile and emittance measurements, by using specific setups, different H^- beam parameters like energy spread or longitudinal beam profile can be obtained. In [CDD⁺11] and [LHA13] interested readers can find more information on these topics.

3.2.1 Laser-based Transverse Profile Measurement

Measuring the transverse beam profile is the most frequent application of laser-based instruments on H^- beams. It is often referred as a *laserwire*-scanner be-

cause of the similarity of the laser at the interaction point to a wire-scanner (Sec. 2.2.4).

As it can be seen in Fig. 3.2, the laser is focused on the H^- beam and its waist is such that it is nearly constant (see Sec. 5.2.1.3) while crossing the ion beam. The photo-detachment in the overlap of laser and ion beams occurs in the single electron detachment regime (Eq. 3.2), characterised by the broad cross-section between 0.75 eV and 10.9 eV. Typically Nd-YAG lasers with wavelength at 1064 nm, nanosecond pulse length and peak power in the megawatt range are used to neutralise a small fraction of the H^- beam.

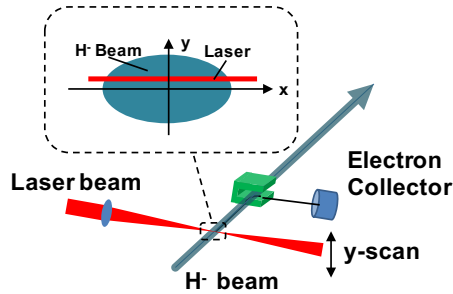


Figure 3.2: Concept for laser-based vertical profile measurements.

The liberated electrons are separated from the H^- beam via a dipole magnet which bends the electrons by 90° but has negligible effect on the H^- beam according to the ratio of the rest masses between H^- and electrons.

The free electrons are detected by an integrating electron collector as e.g. a Faraday cup. By scanning the laser via the H^- beam and recording for each laser position the arriving number of electrons, the beam profile can be reconstructed. The resolution of this technique is limited by the diameter of the laser interacting with the H^- beam. Distortions of the profile can be caused by variations of the laser beam diameter when crossing the H^- beam.

The sketch in Fig. 3.2 refers to the measurement of a vertical profile. To measure the beam profile in the horizontal plane, the laser-beam must be redirected to propagate along the y -axis, while the dipole and electron collector setup can be used without modification.

Due to its non-invasive nature (i.e. the very low number of stripped ions per single beam pass), laser profile monitors are used to replace conventional wire-scanners in high power H^- beam accelerators. In [LAA⁺10] a system is described to measure the transverse beam profile at 9 positions along the 1 GeV LINAC of the Spallation Neutron Source (SNS). The principle for each

profile station is similar as described previously, however the laser beam can be diverted into the vertical plane, to be able to measure also the horizontal H^+ beam profile.

3.2.2 Laser-based Transverse Emittance Measurement

The concept of the laser-based technique to measure the transverse emittance can be seen in analogy to the slit/grid method presented in Section 2.2. The basic principle of the instrument is shown in Fig. 3.3 where the slit gap is replaced by the laser beam.

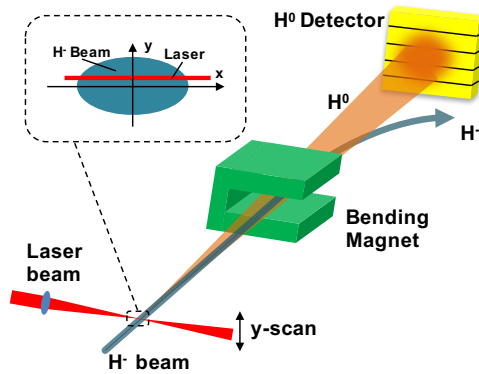


Figure 3.3: Schematic principle of a laserwire emittance scanner. A fraction of the H^+ particle beam collides with photons of a focused laser beam ($\lambda = 1064$ nm). The neutralised H^0 are detected by a downstream detector after being separated from the main beam by a dipole magnet. By measuring the H^0 profile at the detector plane for different laser y -positions, the angular spread and ultimately the transverse phase-space can be sampled. By applying Eq. 2.17 to the obtained data, the transverse emittance can be reconstructed in the vertical plane [HKB⁺15]. For measurement of the horizontal plane, laser beam and H^0 detector must be rotated by 90° .

Compared to the conventional slit/grid, the laser-based concept is not limited to low energy beams. Furthermore no hazard of damage due to high beam intensities is present and subsequently there is also no risk of vacuum degradation. The spatial and angular resolution is equally high as the slit/grid (typ. $\approx 200\text{ }\mu\text{m}$ and $200\text{ }\mu\text{rad}$ - described in Sec. 2.2.3). The unique advantage over all conventional techniques is however, that the laser-based method is considered non-destructive because the number of stripped H^0 atoms is negligible.

As for the slit/grid method, the technique requires multiple ion beam pulses (at each pulse the laserwire position is moved) to complete the emittance phase-space reconstruction. The higher the required resolution in the x (or y) coordinate, the smaller the laser position steps and the longer the measurement time. Of course, the laserwire technique is only applicable to negative ions with small binding energies, as the case of H^- ions. The signal to noise ratio (SNR) and the dynamic range of the instrument depend on the H^0 background, which will be discussed in Section 4.3.

3.3 State of the Art of Laser Based H^- Diagnostics

Laserwire diagnostics for measuring an H^- beam were originally built at Los Alamos National Laboratory [CBC⁺85, CJSY92], and subsequently developed at facilities including the Brookhaven National Laboratory LINAC [Y⁺93], and the Spallation Neutron Source at Oak Ridge National Laboratory [LAA⁺10, LAL⁺12]. More recently the technique has been considered for future applications such as the Front End Test Stand (FETS) at Rutherford Appleton Laboratory, UK [GKM⁺05, G⁺13]. In the following, 2 recent and innovative examples are described, to represent the state of the art in this field of beam instrumentation.

As demonstrated in [CDD⁺11], current developments aim not just to measure the beam profile but are also capable to identify other beam parameters, in this case the energy spread. Figure 3.4 illustrates this particular laserwire setup. The laser interacts with the H^- beam, strips electrons from the atomic core and the free electrons are steered by a dipole into an electron detector. Scanning the laser through the ion beam, the beam profile can be obtained by collecting the stripped electrons in the Faraday cup. The crucial part about this recent setup is the high voltage (HV) grid in front of the Faraday cup. By applying a voltage on this grid ($U_{\text{grid}} \approx E_{\text{kin},e^-}/e$), a fraction of the stripped electrons with $E_{\text{kin},e^-}/e < U_{\text{grid}}$ are repelled. By scanning U_{grid} the energy spread of the H^- beam can be deducted.

In [GKM⁺05] C. Gabor firstly proposed to measure the transverse emittance of H^- beams with a laser-based system. The concept shown in Fig. 3.5 is based on the collection of the neutralised H^0 atoms as the stripped electrons can be deflected easily by parasitic magnetic field components due to their very low rest mass and loose the divergence information of the H^- beam. The setup which is similar to the one proposed in Fig. 3.3 takes into account the H^0 background, produced by collisions of the H^- beam with residual gas molecules. Therefore the interaction with the laser beam takes place inside the dipole magnet,

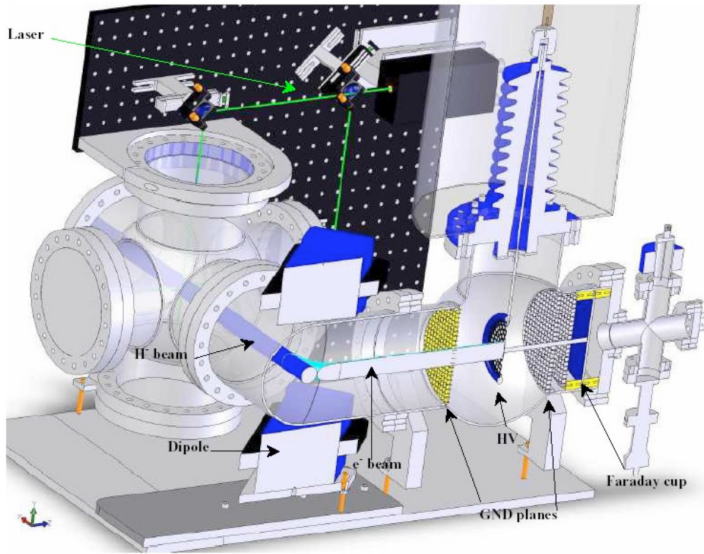


Figure 3.4: Setup of the laser-wire beam-profile and energy-spread monitor installed at the Brookhaven National Laboratory (BNL) LINAC. [CDD⁺11]

which divides the beam into 3 parts: The main H^- beam not affected by the laser is bent the most, the laser-neutralised atoms experience just some deflection occurring upstream of the interaction point (IP) and H^0 produced upstream drift unaffected straight through the dipole. In this way, only the desired H^0 beamlet is recorded by a CCD-camera in high resolution unaffected by the H^0 background. By scanning the laser across the H^- beam, the transverse phase-space can be reconstructed.

In view of the instrument development for LINAC4, the diverse H^0 background contributions have been summarised in Sec. 4.3. It shall be anticipated that the signal to background ratio is sufficient in this setting to design an instrument which does not need the interaction point inside a dipole magnet. This simplifies the instrument design which is described in detail in Chapter 7.

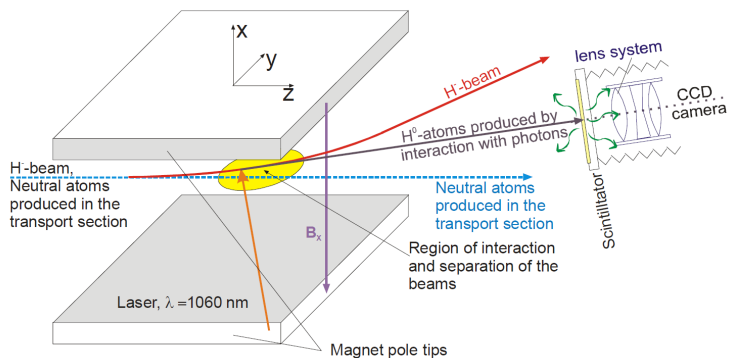


Figure 3.5: Concept of laser-based emittance measurement by laser-interaction inside a dipole magnet. [GKM⁺05]

Chapter 4

Design Considerations

As discussed in Section 3.2, instruments for laser-based emittance and profile measurements can be very different depending on beam parameters and the case-by-case functional specifications. This section shall address the key parameters of the laser and H^0 detector, which, together with the LINAC4 beam characteristics at 160 MeV, allowed completing the design of the final system.

4.1 LINAC4 Beam Parameters at 160 MeV

Among the LINAC4 beam parameters (see Table 1.1), the beam characteristics in the time domain are particularly relevant for the laser emittance meter design. The LINAC4 beam structure as function of time is shown in Fig. 4.1.

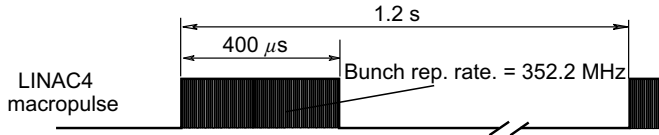


Figure 4.1: Timing diagram of the LINAC4 machine.

The laser must be synchronised to the LINAC4 pulse structure, while the detector and its DAQ system have to feature enough temporal resolution to sample the H^0 signal.

The parameters of the H^- beam at the proposed laser location (see Fig. 1.8) were analysed in detail, starting from the particle tracking simulations carried out in [T⁺10], which were used to plot the transverse ($x, x'; y, y'$) and longitudinal ($z, dp/p$) phase-spaces shown in Fig. 4.2.

The particle density is displayed colour-coded and the RMS emittance ellipse is drawn in blue. The beam size defines the absolute scanning range of the laserwire scanner for covering $\pm 4 \sigma_{x,y}$. To give an example, the scanning

range in the vertical plane is: $y_{scan} = 4 \cdot 2.9 \text{ mm} = \pm 11.6 \text{ mm}$. The divergence information is used for the detector design regarding its distance to the laser, its size, resolution and sensitivity.

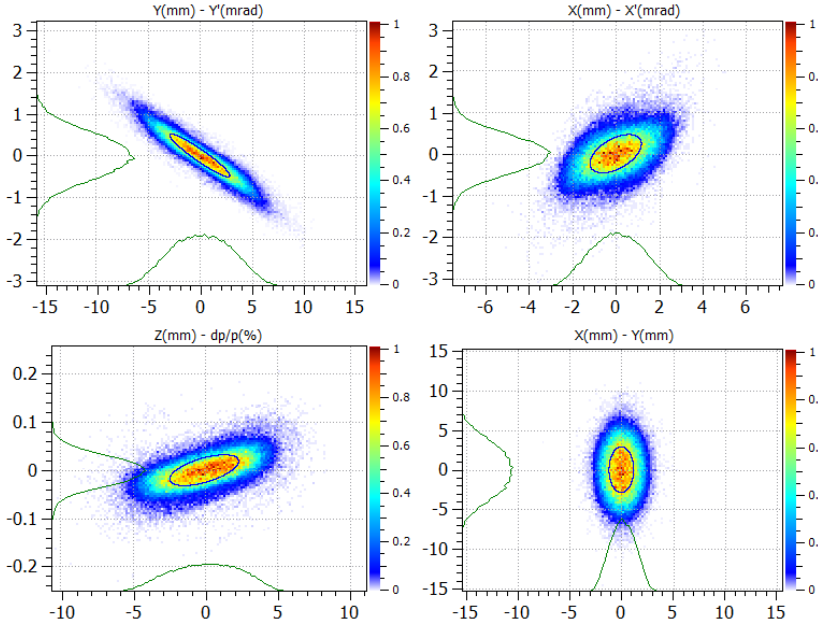


Figure 4.2: Transverse and longitudinal phase-space distributions of the H^- particles at the first laser location (plot titles: horizontal axis - vertical axis).

4.2 Photo-Detachment Model

The prediction of the electron photo-detachment yield during the laser interaction with the H^- ions is fundamental to dimension both, the laser system and the detector systems for stripped electrons and H^0 atoms. In the following sections the interaction is modelled with different complexity levels. At first, the laser- H^- beam interaction is modelled analytically in order to compute the total number of liberated H^0 and electrons. In a second step, numerical tracking simulations are used to calculate the photo-detachment probability of each H^- ion while traversing the laser beam (simulated with its expected flux and transverse dimensions). This is used to then track each electron and H^0 to the respective detectors.

4.2.1 Analytical Description of Yield

To compute, in a first approximation, the amount of expected stripped electrons a simplified model [Gab06] was used, where the Gaussian density distributions of photons and H^- ions were replaced by a constant density. Fig. 4.3 shows the H^- particle beam moving with $v_{H^-} = \beta_{rel} \cdot c$ along the red axis, modelled as a cylinder with radius R_H and constant particle density ρ_H .

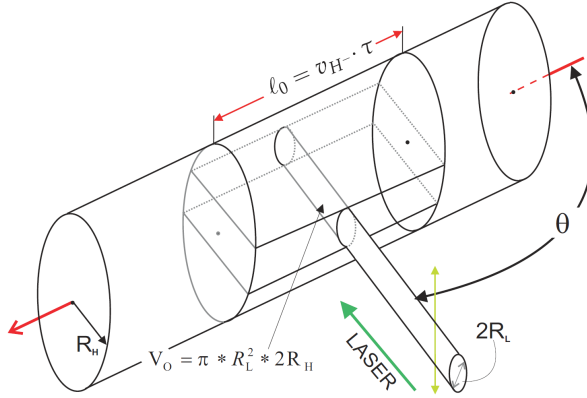


Figure 4.3: Simplified photo-detachment model. [Gab06]

The laser beam with wavelength λ_L is also modelled as a cylinder with constant radius R_L perpendicular to the direction of the H^- beam. The laser-pulses exhibit a constant power P_L along their pulse-length τ . In step with actual practice, the frame-conditions $R_L < R_H$ and the duration of interaction $t_i = 2R_L/v_{H^-} \ll \tau$ being much shorter than the laser pulse-length are defined. With the laser in the centre of the H^- beam the interaction volume can be defined as:

$$V_0 = \pi R_L^2 \cdot 2R_H \quad (4.1)$$

For laser-powers in the kilowatt range the H^- density ρ_H can be treated as constant and the photo-detachment yield can be calculated by the volume integral:

$$N_0(P_L) = \sigma_{PD}(\lambda_L) \Delta v \tau \int \rho_H \rho_L dV \quad (4.2)$$

In this simplified case, the integral can be substituted to

$$N_0(P_L) = \sigma_{PD}(\lambda_L) c \tau \rho_H \rho_L V_0 \quad (4.3)$$

and the relative velocity Δv becomes c for perpendicular interaction. By substituting ρ_L and ρ_H the photo-detachment yield becomes

$$N_0(P_L) = \frac{2I_H \sigma_{PD}(\lambda_L) \tau \lambda_L}{R_H v_H h c e^{-\pi}} \cdot P_L \quad (4.4)$$

with I_H being the beam current and $\sigma_{PD}(\lambda_L)$ the cross-section of the process. It is noteworthy that in this regime $N_0(P_L)$ is independent of the diameter of the laser beam. In Table 4.4 typical parameters for laser interaction with the LINAC4 160 MeV H^- beam are used to calculate the yield and subsequently dimension the laser system.

4.2.2 Single Particle Behaviour

The detailed detector design requires to track the laser beam interaction product trajectories from the interaction point to the detectors. To achieve this, the laser beam has been modelled as

$$W(x) = W_0 \sqrt{1 + \left(x \frac{\lambda_L M^2}{\pi W_0^2} \right)^2} \quad (4.5)$$

where $W(x)$ is the laser beam radius (distance from the centre of the distribution to the position where the intensity drops by a factor e^2), W_0 is the laser radius at its waist, λ_L is the laser wavelength and M^2 is a factor which describes the quality of the real beam compared to an ideal TEM_{00} Gaussian beam (for which $M^2 = 1$) [ME10].

For the H^- beam, the output of a particle tracking simulation (TRAVEL) [PA⁺07] provides a realistic distribution of particles in the plane of the laser interaction, by giving for each particle the x , x' and y , y' coordinates (see Fig. 4.2).

The probability of photo-detachment for a single particle is given by

$$\mathbb{P}_{PD} = 1 - e^{-\sigma_{PD}(\lambda_L) \cdot F_L \cdot t} \quad (4.6)$$

where σ_{PD} is the cross-section, F_L the photon flux and t the time of flight of the particle through the laser light [CJSY92]. Since the photon flux is not constant along the path of the particle (see Fig. 4.4) the total stripping probability $\mathbb{P}_{PD, total}$ is calculated numerically as:

$$\mathbb{P}_{PD, total} = 1 - \prod_{i=1}^n \overline{\mathbb{P}_{PD_i}} \quad (4.7)$$

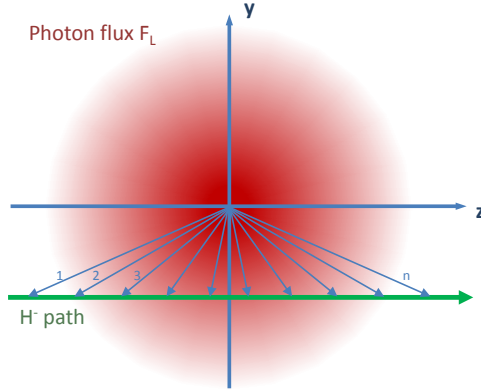


Figure 4.4: Model for laser interaction with single H^- ion. [H⁺13]

To obtain the interaction yield, each particle is weighted with its stripping probability. As the photon energy is typically very low (e.g. 1.2 eV for a laser with $\lambda_L = 1064$ nm), the impulse transfer in the elastic scattering interaction is negligible for high energy beams. Therefore the x' and y' values of the H^- ion can be used without modification to track the interaction products in order to dimension the detector geometry.

4.2.3 Relativistic Doppler Effect

The photo-detachment cross-section σ_{PD} as a function of photon energy E_{pho} is determined from the data of Fig. 3.1. However for relativistic ion beams the photon energy must be Lorentz-transformed into the rest-frame of the moving ion beam to obtain the correct cross-section of the interaction. The Lorentz-shifted photon energy,

$$E'_{pho} = \gamma_{rel}(1 - \beta_{rel} \cos\Theta) E_{pho} \quad (4.8)$$

$$\gamma_{rel} = \frac{1}{\sqrt{1 - \beta_{rel}^2}} \quad (4.9)$$

depends on the Lorentz factor γ_{rel} , the relativistic velocity ratio of the H^- ions β_{rel} , and the angle Θ between the laser and particle beams, as shown in Fig. 4.3. By increasing Θ above 90° , higher photon energies can be reached and E'_{pho} can be fine-tuned. This is well described in [Bry77] (characterisation of the photo-detachment cross-section) and [D⁺03] (recent developments

for laser charge-exchange injection). For beam diagnostics, considering the large cross-section in the visible and near-IR range, it is rare to setup systems with a non-perpendicular laser beam interaction. However this relativistic Doppler effect acts in contrast to the acoustic Doppler effect also for perpendicular interactions with $\Theta = 90^\circ$ [BE15]. For the commonly used Nd-YAG laser ($\lambda_{Nd-YAG} = 1064 \text{ nm}$) this is often beneficial as it down-shifts the laser wavelength for higher ion beam energies towards the maximum of the cross-section. For a 100 MeV ion beam, the Lorentz-shifted wavelength would be $\lambda'_{Nd-YAG} = 962 \text{ nm}$.

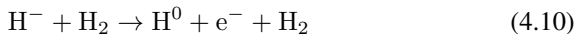
4.3 H⁺ Background Evaluation

Electron detachment of H⁺ ions does not only occur by photo-detachment but also due to other processes that thus constitute a source of disturbing background for the instrument.

For profile measurements, based on the detection of the stripped electrons, the background is negligible, since most of the free electrons created upstream of the laser interaction are lost after passing through the magnetic field of quadrupoles. On the other hand, the neutral H⁰ are not perturbed by any magnetic or electric field, hence they drift on a linear trajectory through the machine and can therefore cause an unwanted H⁰ background. This poses a challenge for the emittance measurement where H⁰ detection is needed. Especially for detector position 1 (see Fig. 1.8) where neutral H⁰ produced in the whole LINAC4 can potentially reach the detector, this can have significant influence on the accuracy of the emittance measurement. It is therefore necessary to quantify the different H⁰ background sources and assess the impact on the system performance.

4.3.1 Residual Gas Stripping

Stripping of electrons of the ion due to collisions with residual gas molecules,



are described in several publications on laser-based H⁺ diagnostics as the dominant background contributor [Gab06, J⁺09]. The probability of ejecting one electron from an H⁺ ion is given by

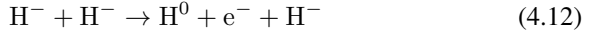
$$\mathbb{P}_{Gas} = 1 - e^{-l/\lambda} \text{ with } \lambda = \frac{kT}{\sigma P}; \quad \sigma \propto \frac{1}{\beta_{rel}^2} \quad (4.11)$$

The stripping probability $\mathbb{P}_{Gas}$ is calculated from the interaction length l , the Boltzmann constant k , the beam pipe temperature T and the pressure P of the residual gas, which consists typically mainly of hydrogen molecules. The cross-section σ , of hydrogen- H^- collisions decreases with beam energy ($\propto 1/\beta_{rel}^2$) [Cho05]. Reference values can be found in literature [HHS76, Gil77].

At the location of the laser emittance monitor (see Sec. 1.2.2), the beam exhibits $E_{kin} = 160$ MeV, the cross-section is $\sigma = 3.76 \cdot 10^{-19} \text{ cm}^2$ and the residual gas pressure is $P = 10^{-7}$ mbar. By applying Eq. 4.11, the stripping probability $\mathbb{P}_{Gas}$ results to be $1.1 \cdot 10^{-7} \text{ m}^{-1}$.

4.3.2 Intra-Beam Stripping

Another source for beam losses is caused by collisions of H^- ions of the same bunch with each other:



This effect was first observed at the Low Energy Antiproton Ring (LEAR) [CGL⁺87] but it was just recently discovered, that in H^- accelerators with ultra-high vacuum ($< 1 \cdot 10^{-9}$ mbar), as present in superconducting LINACs, this can be the dominant source for beam losses [SGA⁺12].

The stripping probability per unit lengths was approximated in [LSO⁺10], by using the maximum cross-section $\sigma_{max} = \max(\sigma(\Delta v)) \approx 4 \cdot 10^{-15} \text{ cm}^2$ referring to the relative velocities of the H^- ions Δv ,

$$\frac{1}{N} \frac{dN}{dz} = \frac{N \sigma_{max} \sqrt{\gamma_{rel}^2 \theta_x^2 + \gamma_{rel}^2 \theta_y^2 + \theta_z^2}}{8\pi^2 \sigma_x \sigma_y \sigma_z \gamma_{rel}^2} \cdot \left(1 + \frac{2 - \sqrt{3}}{\sqrt{3}(\sqrt{3} - 1)} \frac{\gamma_{rel} \theta_x + \gamma_{rel} \theta_y + \theta_z}{\sqrt{\gamma_{rel}^2 \theta_x^2 + \gamma_{rel}^2 \theta_y^2 + \theta_z^2}} \right) \quad (4.13)$$

with N being the number of H^- ions per bunch, γ_{rel} the Lorentz factor, $\theta_{x,y} = \sqrt{\epsilon_{x,y}/\beta_{x,y}}$ the transverse local RMS angular spreads, $\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}}$ the RMS bunch sizes, θ_z the relative RMS momentum spread and σ_z the RMS bunch length.

By using the beam parameters $\beta_{x,y,z}$, $\epsilon_{x,y,z}$ of the LINAC4 H^- beam in the 160 MeV region [T⁺10] and inserting them into Eq. 4.13, the stripping probability $\mathbb{P}_{Intra}$ becomes $1.8 \cdot 10^{-8} \text{ m}^{-1}$.

4.3.3 Black Body Radiation

Similar to the laser photo-detachment, also black-body radiation originating from the beam pipe of the accelerator can cause stripping of electrons. From Planck's law, the spectral radiant exitance,

$$M_\lambda(\lambda, T) dA d\lambda = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1} dA d\lambda \quad (4.14)$$

as a function of temperature T is known. At room temperature ($T < 300$ K) the energy of the thermal photons is below the threshold for photo-detachment of 0.75 eV which equals 1654 nm wavelength, hence the black-body radiation is not causing any significant electron stripping.

However taking into account the Lorentz-shift (see section 4.2.3), the black-body radiation gets blue-shifted and therefore photo-detachment can take place to a minor degree.

Detailed calculations regarding the black-body stripping probability for relativistic H^- ion beams can be found in [BH06, Car07]. The stripping probability per unit length of a 160 MeV H^- beam in a 300 K beampipe was found to be $\mathbb{P}_{BB} = 8.0 \cdot 10^{-13} \text{m}^{-1}$. For the laserwire application this effect is negligible.

4.3.4 Magnetic Field Stripping

When passing a magnetic field, the H^- ion is bent due to its net negative charge. However the electrons experience the Lorentz-force in opposite direction than the proton and this, for high magnetic fields and beam energies, can result in electron detachment.

Indeed, this phenomenon can be used for charge-exchange injection, realised by a combination of laser excitation and magnetic field stripping as currently under development at the SNS accelerator [D^+03 , C^+14 , C^+17].

For LINAC4 though, the magnetic field stripping effect is a non-desired beam loss mechanism which effects the high energy part of the accelerator. Following [Tho87], the magnetic field can be Lorentz-transformed into an electric field in the rest-frame of the H^- beam:

$$\mathbf{E} = c\beta_{rel}\gamma_{rel}\mathbf{B} \quad (4.15)$$

The average lifetime of a H^- ion in the vicinity of electric field,

$$\tau(E) = \frac{7.96 \cdot 10^{-6} \text{Vs/m}}{E} e^{\left(\frac{4.256 \cdot 10^9 \text{V/m}}{E}\right)} \quad (4.16)$$

was found experimentally for electric field strengths near 2 MV/cm [SOM⁺69]. Hence the stripping probability can be calculated by $\mathbb{P}_{Magn} = 1 - \exp(-t/\tau)$.

In the 160 MeV region of LINAC4, the beam is bent by 3 dipole magnets into the transfer line (see Fig. 1.8). Each magnet exhibits a magnetic length of 0.87 m and operates nominally at $B = 0.885$ T [T⁺13]. By inserting this data in Eq. 4.15 and Eq. 4.16, the electric field for the 160 MeV beam results in 1.62 MV/cm and the average lifetime becomes 5.6 ns. By applying the time of flight, the ion needs to traverse the magnet, a stripping probability of $\mathbb{P}_{Magn} = 3.8 \cdot 10^{-7}$ is obtained.

4.3.5 Summary of H^0 Background Sources at LINAC4

The concept for emittance measurements as described in Section 3.2.2 is based on the detection of the laser generated H^0 atoms. The various H^0 background sources were discussed in the previous paragraphs and a summary is given in Table 4.1.

Table 4.1: Processes for H^0 background creation at 160 MeV region of LINAC4

Process for Stripping	$\mathbb{P}_{Strip}$
Residual Gas Collision	$1.1 \cdot 10^{-7} \text{ m}^{-1}$
Intra Beam Collision	$1.8 \cdot 10^{-8} \text{ m}^{-1}$
Black Body Radiation	$8.0 \cdot 10^{-13} \text{ m}^{-1}$
Magnetic Field	$3.8 \cdot 10^{-7}$

As H^0 collisions with residual gas molecules or other H^- ions in the same bunch (intra-beam) are taking place all along the 80 m long LINAC4 accelerator, these effects are the dominating beam-loss mechanisms. To quantify how many of these neutral background particles will reach the H^0 detector, detailed particle tracking simulations must be carried out, taking into account the beam dynamics along the accelerator as well as the H^0 detector geometry. Such simulations will be discussed in the next sub-section.

Table 4.1 also shows that the electron stripping by black body radiation is negligible in comparison to the other effects, in particular because the stripping probability decreases fast for beam energies below 160 MeV.

The electron detachment by magnetic fields was calculated for the most powerful type of magnet at LINAC4, at the start of the transfer line to the Booster (cp. 3 red dipoles in Fig. 1.8). The stripping probability for H^- ions traversing

this magnet is comparably high but also for this type of H^0 background, the H^0 detector position and geometry needs to be taken into account to estimate the relevance for the laser-based instrument.

Regardless of the source of H^0 background, it is advisable to keep the dimensions of the detector as small as possible, needed to monitor the laser-stripped H^0 . Bigger dimensions are just integrating more of the background, which subsequently worsens the ratio between signal and background.

A similar rule is even more relevant in the time domain. The time constant of the detector system should be smaller than the laser pulse-length in order to distinguish the H^0 signal caused by the laser from the permanent H^0 background.

4.3.6 Model for H^0 Background at Detector 1

In the previous section, the analytical models for H^- electron detachment due to different sources were described. In order to dimension the laser power to create significant more laser-stripped H^0 than the background level and to design a detector which is capable to distinguish the laser created H^0 from the background, more detailed tracking simulations were conducted.

The background level at the detector position 1 (see Fig. 1.8) is expected to be the highest as neutral particles from the whole accelerator line drift straight to this location. In order to develop a model for worst-case circumstances the background on detector position 1 was simulated taking into account H^0 background created all along the LINAC4 accelerator.

As shown in Table 4.1, the relevant sources for H^0 background are collisions with residual gas, intra-beam collisions and magnetic field stripping. For the former two sources the contribution from all along the LINAC are relevant while for the magnetic field stripping just the dipole magnet in front of the detector can cause significant H^0 background due to the high field strength and the energy dependence of this process.

To calculate the background contribution of intra-beam and residual gas collisions, the simulation consisted in dividing the LINAC4 into sections of 3 cm length and assigning to each of them the real beam pipe aperture and the theoretical H^- beam parameters ($\alpha_{x,y}$, $\beta_{x,y}$, $\epsilon_{x,y}$, E_{kin}). The gas pressure levels were either measured (LEBT and MEBT) or taken from the vacuum design parameters. With this information the stripping probabilities were calculated using Eq. 4.11 and 4.13.

The transport of the obtained H^0 distributions towards the detector was modelled as a drift space where the apertures along the beam line cut the tails of the H^0 distributions. The detector itself was modelled as a 20 mm $\times$ 20 mm

square in the centre of the beam pipe. The background simulation concept is visualised in Fig. 4.5, showing the LINAC4 sectors and an example of a slice of H^0 background generated in a portion of the LEBT.

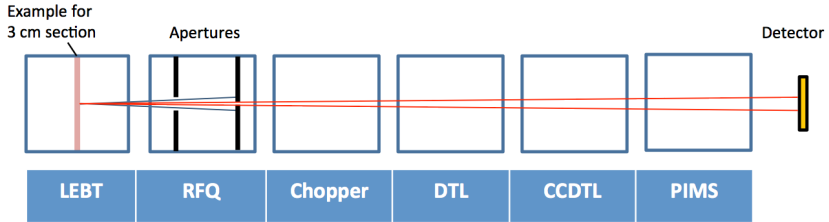


Figure 4.5: Simulation concept of the LINAC4 background level by residual gas stripping and intra-beam stripping with the example of H^0 particles generated in a portion of the LEBT and transported to the detector.

Table 4.2 summarises the simulation parameters and results, used for the background simulations for H^0 detector 1 situated between the first bending magnet and the main dump. The results show that with no surprise, the background is dominated by H^0 generated in the LINAC part closest to the H^0 detector (PIMS and the drift sector from the PIMS to the detector). The relatively high contribution from the LEBT is due to the high residual gas level in this sector. In conclusion, the background arriving at the $20 \text{ mm} \times 20 \text{ mm}$ big detector is expected to be about $394 H^0 / \text{ns}$ during the $400 \mu\text{s}$ LINAC4 macro-pulse.

Table 4.2: Background simulation: parameters and resulting background contributions

	LEBT	RFQ	Chopper	DTL	CCDTL	PIMS	Transfer
$L_{sector} [\text{m}]$	2.0	3.0	3.7	19.0	25.0	22.9	7.5
$P_{Gas} [10^{-7} \text{ mbar}]$	20	10	1	1	1	1	1
$r_{min} [\text{mm}]$	50	3.54	6.2	10	14	20	21.4
$I_{beam} [\text{mA}]$	80	68	52.5	40	40	40	40
$E_{kin} [\text{MeV}]$	0.045	1.5	3.0	26.5	76	131	160
H^0 / ns	30	0	4	15	33	115	197

The contribution generated by magnetic field stripping arriving on the detector was calculated by considering the bending magnet - detector distance and the detector size. Due to the small detector dimensions, just the H^0 background created in the first 14 mm of the magnet reaches the detector. The stripping probability therefore drops to $\mathbb{P}_{Magn} = 6.2 \cdot 10^{-9}$, which yields to $2.5 H^0 / \text{ns}$

at the detector. This contribution is negligible compared to the background created by intra-beam and residual gas collisions.

The expected H^0 density at the detector plane generated by the two dominant background sources (intra-beam and residual gas collisions) is shown in Fig. 4.6.

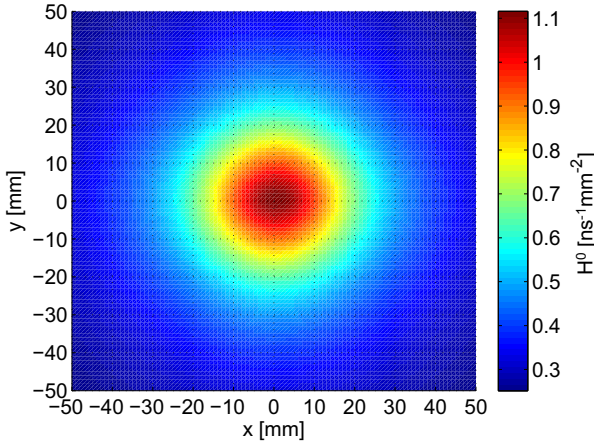


Figure 4.6: H^0 density at the detector 1 plane (160 MeV) created by residual gas and intra-beam stripping.

4.4 Laser System

Existing laser-based systems for profile and emittance measurement typically use lasers with peak powers above the megawatt level and laser beam transport to the IP in free-space [LAA⁺10, CJSY92]. Such laser systems need frequent maintenance, are prone to instabilities and alignment issues and require a high level of safety measures.

Many components in a high-power laser are very sensitive to ionising radiation, therefore attempts to position the laser in the vicinity of the beam pipe result in a very short lifetime of the laser-head. An example for this degradation has been reported at the Brookhaven National Laboratory (BNL) LINAC, which features similar beam parameters as LINAC4 [CDD⁺11]. Thus, a laser transport line is in most cases necessary to avoid installing the laser source in the radiation environment of the accelerator.

To overcome the difficulties of free-space laser transmission, it was decided to study a system based on fibre-transmission, which implies the use of rela-

tively low laser pulse power (i.e. in the kilowatt range). This choice allows designing a relatively compact system, featuring enhanced temporal and spatial laser output stability, practically immune to mechanical vibrations and misalignment. This has been demonstrated in [LHA13], with a picosecond laser pulse used to measure the longitudinal beam profile.

In this section, the key-parameters for a fibre-based laser system shall be determined in order to select a suitable laser source.

4.4.1 Transverse Profile and Beam Quality

As schematically shown in Fig. 3.2, the laser beam is focused on the H beam to achieve a small but approx. constant diameter in the interaction plane. The radius of the laser waist is defined as

$$W_0 = \frac{\lambda_L}{\pi} \frac{f}{r_f} M^2 \quad (4.17)$$

with f being the focal length, r_f the laser beam radius at the focus lens and M^2 the beam quality factor ($M^2 = 1$ for perfect single mode propagation). The laser beam diameter in the vicinity of the focal point, calculated by inserting Eq. 4.17 into Eq. 4.5 and using the laser parameters expected for this application, is shown in Fig. 4.7

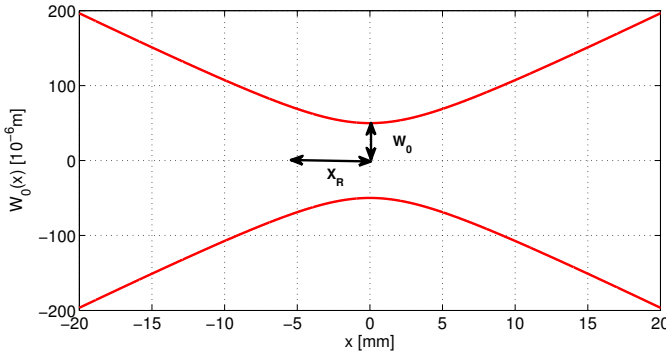


Figure 4.7: Laser beam waist - red lines mark the $1/e^2$ intensity drop w.r.t. the intensity in the centre of the laser beam (see Eq. 4.5).

The Rayleigh length x_R is defined as the distance to the waist where the beam radius becomes $\sqrt{2}W_0$. It can be described as

$$x_R = \frac{\pi W_0^2}{\lambda_L M^2}. \quad (4.18)$$

The inverse proportionality between the Rayleigh length and M^2 is crucial in the laserwire application. As f and r_f must be designed to make the laser waist W_0 an order of magnitude smaller than the H⁻ beam radius, M^2 must be as small as possible to keep the laser diameter approx. constant in the interaction region with the H⁻ beam¹.

In conclusion this means that the laser source and the fibre-based laser transport must be capable to deliver a quasi-Gaussian laser beam ($M^2 \lesssim 2$) to the interaction point.

4.4.2 Fibre-based Laser Transport

The schematic design of the fibre-based laser beam delivery and transport is shown in Fig. 4.8. The laser output is coupled into a Large Mode Area (LMA) transport fibre which is optimised to allow quasi single-mode transmission with biggest possible core diameter to keep the power density in the fibre acceptable. After the transmission to the accelerator tunnel the fibre is mounted at the beam pipe, where the laser beam is focused onto the H⁻ beam. In general, the fibre-based approach implies a limitation on the laser peak power that can be transported. The challenges associated to this approach are discussed in the following sections.

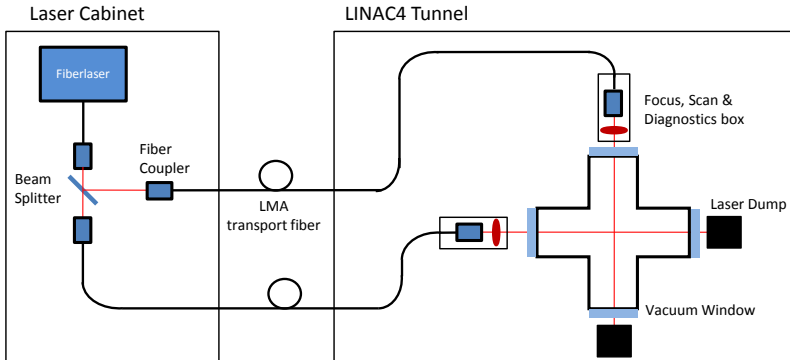


Figure 4.8: Schematic concept of the fibre-based laser transmission to the accelerator tunnel.

¹ Characteristics of H⁻ beam at 160 MeV region, see Fig. 4.2

4.4.2.1 End-facet Damage

The peak power limitation is firstly caused by coupling the laser beam into the transport fibre. As the light shall be focused to a diameter $< 200 \mu\text{m}$, but shall still exhibit a Rayleigh length longer than the size of the H⁺ beam, the laser beam quality must be quasi single-mode (see Sect. 4.4.1). To transport a single-mode laser beam to the beam pipe, the condition:

$$\frac{2\pi \cdot r_{core}}{\lambda} NA < 2.405 \quad (4.19)$$

must be satisfied, with r_{core} being the fibre core radius, λ the wavelength and NA the fibres numerical aperture [ME10].

The NA cannot be arbitrary small in order to avoid high losses in case of fibre bending. Therefore the fibre diameter must be limited to transfer a quasi-Gaussian laser beam to the interaction point.

At the fibre coupler the laser beam is focused down to the dimensions of the fibre core diameter in the micrometre range thus the power densities at the fibre end-facet become very high. Above a threshold power density the end facet is damaged due to thermal effects. Figure 4.9 shows the damage probability versus the fluence on the fibre end-facet. The damage threshold is influenced,

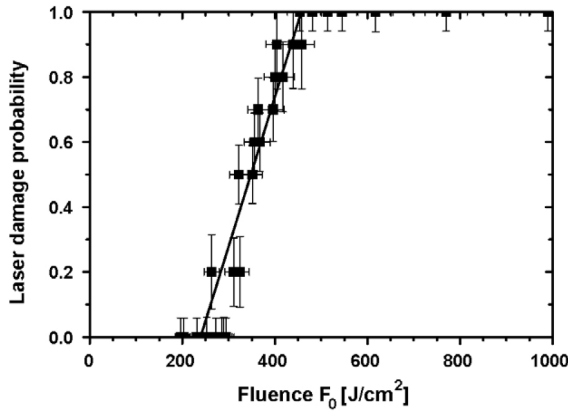


Figure 4.9: Damage probability of a fibre end-facet (1064 nm wavelength, pulse duration $\tau = 15$ ns). [M⁺07]

amongst others factors, by the polishing quality and thermal pre-treatment of the fibre [M⁺07]. Furthermore, the threshold can be scaled with the laser pulse duration $\tau^{0.5}$ as described in [S⁺94]. In conclusion, to achieve reliable laser transmission the peak power must be limited to ensure that the fluence on the fibre end-facet does not exceed the damage threshold.

4.4.2.2 Linear and Non-linear Effects in Optical Fibres

The second limiting factor for the transferable peak power is related to the fibre itself. While linear attenuation effects such as Rayleigh scattering or absorption are negligible for short transmission distances (≈ 1 dB/km at 1064 nm - see Fig.4.10), non-linear effects can cause significant effects, even for fibres several metres long.

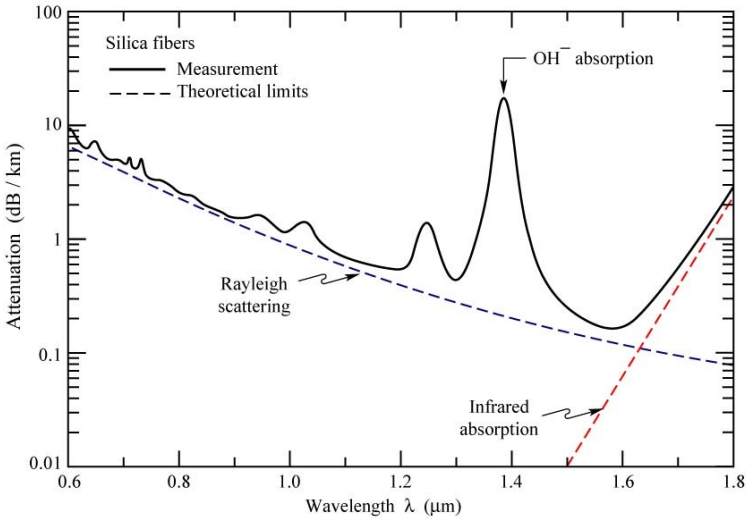


Figure 4.10: Attenuation in optical fibres due to *linear* attenuation effects. [Sch06]

Figure 4.11 provides an overview of the various non-linear effects taking place at high beam intensities in optical fibres. The different kinds of Kerr non-linearities are not relevant for the laserwire application as they do not affect the pulse-energy but the spectral properties of the laser beam. The inelastic scattering processes however can reflect a significant amount of light after the laser power exceeds a specific threshold.

4.4.2.3 Brillouin Scattering

Brillouin scattering is considered the most significant non-linear effect in respect to the laserwire requirements. Thus the basic mechanism shall be described in accordance with [Eng15] and an evaluation shall be given whether this effect can be a limiting criterion for the peak power in the fibre transmission.

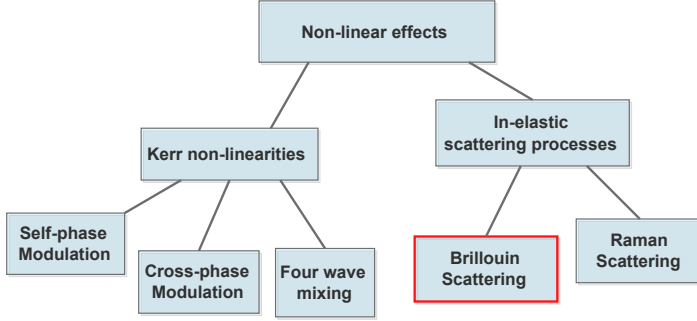


Figure 4.11: Overview on non-linear effects in optical fibres.

Brillouin scattering is caused by acoustic waves modulating the refractive index of the medium. A light-wave with wavelength λ_P can be scattered at the periodic changes of the refractive index, when satisfying Bragg's law

$$\lambda_P = 2n\lambda_A \sin \frac{\Theta}{2} \quad (4.20)$$

where λ_A is the wavelength of the acoustic wave, n is the refractive index of the medium and Θ is the angle between the incident and the scattered light-wave. The frequency shift f_B of the scattered light-wave depends on Θ according to the Doppler effect:

$$f_B(\Theta) = 2n \frac{v_A}{c} f_P \sin \frac{\Theta}{2} \quad (4.21)$$

The angle of back-reflections ($\Theta \approx 180^\circ$), must however satisfy the acceptance criterion of the fibre in order to be guided in opposite direction. The Brillouin gain-coefficient g_B is defined as

$$-\frac{d}{dz} I_S = g_B I_P I_S \quad (4.22)$$

with the laser intensity I_P creating a Stokes shifted back-reflection in negative z direction with intensity I_S . This Brillouin gain is typically 3 orders of magnitude higher than the gain for Raman scattering, thus it is considered the dominating effect in our application [Eng15].

Brillouin scattering can act in different ways as it can be seen in Fig. 4.12. The Spontaneous Brillouin Scattering (SpBS) creates Stokes and Antistokes reflections on thermal excited acoustic waves but due to the omnidirectional

behaviour the scattered light power is very low and therefore it is by itself not relevant.

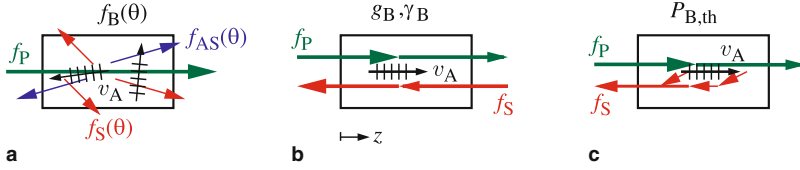


Figure 4.12: Different kinds of Brillouin scattering. **a** Spontaneous Brillouin Scattering (SpBS); **b** Stimulated Brillouin Scattering (SBS); **c** Amplified Spontaneous Brillouin Scattering (ASpBS). [Eng15]

The stimulated type of Brillouin Scattering (SBS) is based on the electrostriction effect, which describes the density modulation of a medium due to the local intensity of an electromagnetic wave. If the frequency shift of 2 counter-propagating light waves $f_P - f_S$ is equal to the Brillouin frequency offset f_B as defined in Eq. 4.21, the pump-wave (with f_P) can amplify the counter-propagating wave (with f_S). This principle is used in Brillouin fibre-lasers which produce very narrow emission spectra.

The significant effect in the laserwire application is shown in Fig. 4.12 c. This type of Brillouin scattering combines both effects described previously. A thermally excited acoustic wave creates a Stokes and Antistokes reflected light-wave according to Eq. 4.20, which is amplified due to the incipient Stimulated Brillouin Scattering. As it can be seen in the example plot in Fig. 4.13, the transmitted power saturates when the threshold power for Brillouin Scattering

$$P_{B,th} = C_{B,th} \frac{1}{\gamma_{B,eff} L_{eff}} \quad (4.23)$$

is reached, where $C_{B,th}$ is the critical factor ($\approx 18^1$ [Eng15, Eng14]), $\gamma_B(f)$ the fibre-specific Brillouin coefficient and L_{eff} the effective fibre length.

4.4.2.4 Brillouin Threshold for laserwire

Figure 4.14 is illustrating the ASpBS effect, potentially taking place in the transport fibre of the laserwire, where the pump-wave represents the laser beam travelling towards the accelerator tunnel.

To calculate the Brillouin threshold $P_{B,th}$ from Eq. 4.23 in our application, at first the fibre-specific gain coefficient must be calculated as

¹ Approximation, dependent on various fibre parameters.

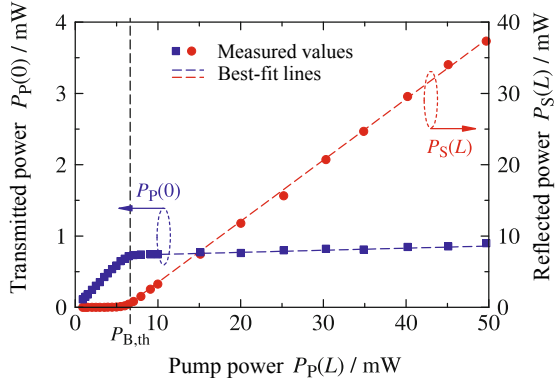


Figure 4.13: Measured transmitted and reflected power caused by ASpBS on a step-index fibre over 40 km. [Eng15]

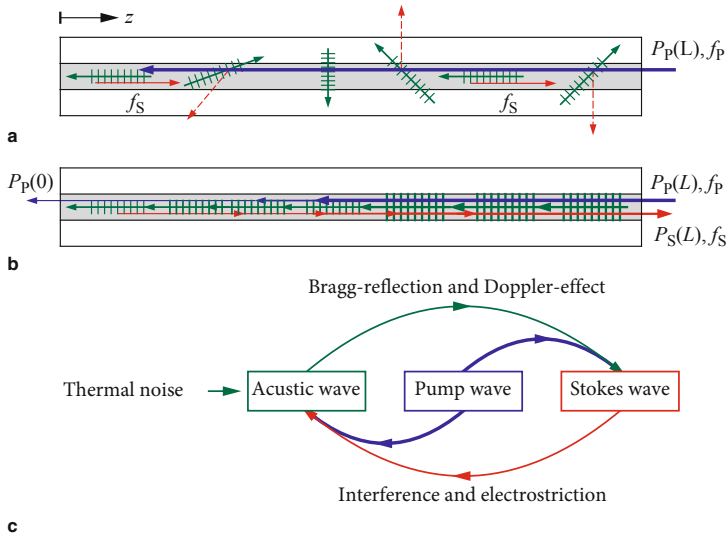


Figure 4.14: Detailed principle of Amplified Spontaneous Brillouin Scattering. **a** A pump-wave ($P_P(L), f_P$) is scattered on thermal excited acoustic waves (SpBS). **b** The stokes-shifted counter-propagating wave ($P_S(L), f_S$) is amplified by SBS thus can reach similar power as the pump-wave. **c** Reciprocal coupling between acoustic-, pump- and stokes-wave. [Eng15]

$$\gamma_B(f) = \frac{g_B(f)}{A_{eff,B}} \quad (4.24)$$

where $g_B(f)$ represents the material specific gain and $A_{eff,B}$ stands for the effective mode area of the light-wave travelling in the optical fibre, which is approximated by the Petermann II mode field radius [HM85],

$$\frac{r_{eff}}{r_{core}} = 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} - (0.016 + 1.561V^{-7}) \quad (4.25)$$

with the use of the normalised frequency,

$$V = NA \frac{2\pi r_{core}}{\lambda}. \quad (4.26)$$

The frequency dependence of the material specific Brillouin gain influences directly the Brillouin threshold and can therefore be used to suppress the unwanted Brillouin scattering. In Fig. 4.15 the characteristic frequency of the specific material Brillouin gain g_B is shown. The maximum gain in the centre of the distribution g_{B0} is purely dependent on the fibre material characteristics:

$$g_{B0} = \frac{\omega_p^2 \gamma_e^2}{c^3 n_{core} \rho_0 v_a \Gamma_B} = \frac{\gamma_e^2}{4c v_A n_{core}^3 \eta} \quad (4.27)$$

with the electro-strictive constant γ_e , the acoustic velocity in the medium v_A and η and ρ_0 represent the viscosity and average density of fused silica. The bandwidth Γ_B of $g_B(f)$ follows from the coupling of the acoustic wave and the pump wave,

$$\Gamma_B = \frac{\eta \Omega_B^2}{\rho_0 v_A^2} \quad (4.28)$$

where Ω_B is the Brillouin frequency ($\omega_P - \omega_S$). For a pump waves at 1064 nm the bandwidth Γ_B is typically in the order of 50 MHz¹.

The effective SBS coefficient $\gamma_{B,eff}$, results from the convolution of the pump light-wave spectrum ($S(f)$) and the gain spectrum of the Brillouin gain,

$$\gamma_{B,eff}(\Delta f) = \gamma_B(\Delta f) * S(\Delta f). \quad (4.29)$$

In the laserwire case, the equation can be simplified, because the bandwidth of the pump is much smaller than the Brillouin gain bandwidth ($B_P \ll B_B$) so it is sufficient to approximate as an indirect proportionality:

$$\gamma_{B,eff} \approx \gamma_{B0} B_B / B_P \quad (4.30)$$

¹In literature typically values around 25 MHz can be found, which correspond to a pump wave at the attenuation minimum of 1550 nm.

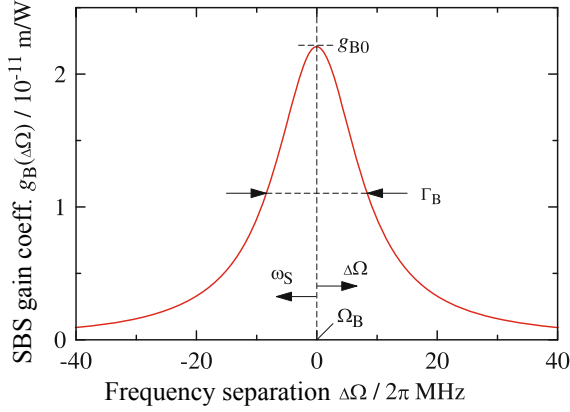


Figure 4.15: Bandwidth of material specific Brillouin gain g_B , calculated for SiO_2 . [Eng15]

The effective fibre length L_{eff} in Eq. 4.23 is typically defined as the equivalent fibre length taking into account the fibre attenuation. In a worst-case approximation this attenuation effect was neglected. However the length where the pump and Stokes-wave interact can be limited by the pulse-length of the pump laser

$$L_p = \frac{c\tau}{n} \quad (4.31)$$

with τ being the laser pulse duration. Thus the effective interaction length of the counter-propagation light-waves is limited either by the laser pulse or the fibre length:

$$L_{eff} = \begin{cases} \frac{L_p}{2}, & | \frac{L_p}{2} < L_{fibre} \\ L_{fibre}, & | \frac{L_p}{2} > L_{fibre} \end{cases} \quad (4.32)$$

This is valid as long as a laser with low pulse frequency in comparison to the fibre length is used, which is the case for the laserwire application.

The framework developed here will be applied in Sec. 5.1.2.3 to determine the Brillouin threshold for the used laser and fibre characteristics.

4.4.3 Laser Pulse Timing

The time structure of the laser is in many ways crucial for the performance of the whole instrument. In the past, many systems were typically using Nd-YAG lasers with 5...10 ns pulse widths and repetition rates limited to approx.

10...100 Hz due to the flash-lamp pumping [CDD⁺11, LAA⁺10, T⁺05]. To maximise the fibre transmission and to cope with the detector system and the accelerator timing these parameters were reviewed.

The detectors need to record the electron and H⁰ pulses created by the laser, so their required bandwidth is directly dependent on the laser pulse duration. Taking into account integrating detectors, longer pulses also result in a higher integrated signal and therefore reduce the requirements regarding their sensitivity. Concerning the fibre transmission, long laser pulses are however more difficult to handle, as the SBS threshold is proportional to the effective length defined in Eq. 4.32 and the thermal load on the end-facet of the fibre increases similarly.

Finally, the laser time structure must be compatible with the fixed accelerator timing as it is shown in black in Fig. 4.16. The laser pulse frequency f_{laser} should be in the kilohertz range to be able to interact multiple times with the 400 μ s LINAC4 pulse. By synchronising the laser frequency with the bunch repetition rate, the laser pulse has always the same phasing with respect to the LINAC4 macro-pulse. Moreover, the amplification of the laser-pulses must start before the LINAC4 macro-pulse in order to take into account the rise time of the amplifier. On the other hand, it is desirable to keep the amplification interval t_{amp} as short as possible to avoid heating of the fibre end-facets. This means that the laser-pulse duration t_{pulse} must be defined according to the laser transmission and detector requirements.

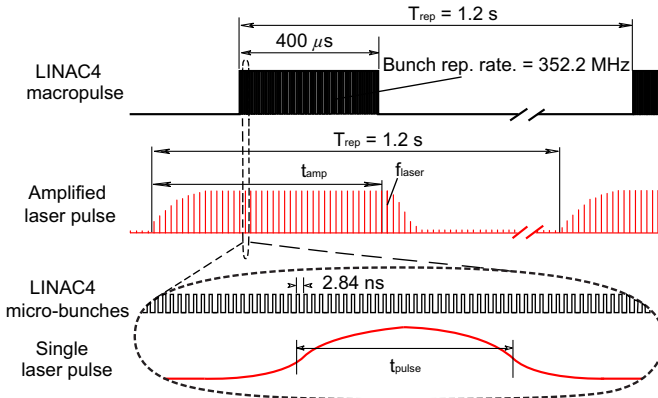


Figure 4.16: LINAC4 timing and laserwire timing compared.

4.4.4 Peak Power

As discussed earlier, the most substantial difference between previous systems and the fibre-based approach presented in this thesis is the laser peak power. To avoid end-facet damage and SBS, the peak power is limited to the kilowatt range in our application.

To check the feasibility of this fibre-based approach, the yield of the laser interaction was compared with the background level to show whether the laser power is sufficient to distinguish the H^0 created by the laser interaction from the background floor.

The background distribution can be inferred from Table 4.2 and Fig. 4.6. The yield of the laser interaction was calculated analytically in Sec. 4.2.1 by using Eq. 4.4 with the parameters listed in Table 4.3 (conservative choice of laser characteristics restricted by the fibre transmission).

Table 4.3: Parameters for Eq. 4.4 - Laser Stripping Yield at 160 MeV

Parameter	Symbol	Value	Units
H ⁻ current	I_H	40	mA
H ⁻ beam radius	R_H	2	mm
Relativistic β	β_H	0.52	
Laser wavelength	λ_L	1064	nm
Cross-section	$\sigma_{PD}(\lambda'_L)^1$	$4.04 \cdot 10^{-17}$	cm ²
Laser pulse-length	τ	100	ns
Laser peak power	P_L	1000	W
H^0 yield	N_0	9424	ns ⁻¹

The comparison between Table 4.2 and Table 4.3 evidences that the signal generated by the laser interaction is significantly higher than the background arriving at the detector. This applies if the detector bandwidth is sufficiently high to distinguish between the continuous background and the pulsed signal of the laser interaction. Sections 5.3.1 and 7.2 contain more detailed simulations to characterise the expected signal to background levels.

¹ λ'_L being the Lorentz shifted wavelength following Eq. 4.8

4.4.5 Summary of Laser Requirements

Table 4.4 gives a summary on the requirements for the laser system as discussed in detail in the previous sections. The wavelength is for our system not very critical, since the cross-section is very broad (see Fig. 3.1). Therefore it was decided to use the emission wavelength of Nd:YAG (1064 nm) where a wide choice of commercial lasers is available.

Table 4.4: Requirements for the laser system [HKB⁺15]

Parameter	Requirement	Units
Wavelength	900 ± 300	nm
Pulse peak power	> 1	kW
Pulse length	10...100	ns
Repetition rate	> 10	kHz
Synchronisation to LINAC4	Required	–
Beam quality factor (M^2)	$\lesssim 2$	–

As already discussed above, the required laser pulse-length follows from a compromise among SBS suppression, the end-facets quality preservation and the need to avoid too short pulses that would put hard requirements for the bandwidth of the H^0 detector and DAQ system.

With a repetition rate above 10 kHz in synchronisation with the LINAC4 timing, the LINAC4 macro-pulse can be sampled multiple times at constant phase. The beam quality factor ensures that the laser beam can be focused to a thin diameter with respect to the H^- beam while exhibiting a nearly constant diameter.

4.5 H^0 Detector

The design of an H^0 detector, to be installed after the laser interaction point and the bending dipole separating H^- from H^0 particles, is driven by the characteristics (time structure, spatial distribution, intensity etc.) of the laser and H^- beams. This section will focus on the candidate detector types, their potential performance, their advantages and disadvantages. More details in terms of simulations and tests will be given in Chapters 5, 6 and 7.

4.5.1 Requirements

As introduced above (see Fig. 3.3), the H^0 detector needs to feature a multi-channel readout (stripes or pixels) in order to measure the divergence profile of the stripped hydrogen atoms for each laser position. Its size and resolution depend on the distance from the laser IP and on the H^- beam divergence. As the relatively low number of stripped H^0 per laser-pulse (as calculated in Section 4.4.4) is spread over many channels, the detector sensitivity is a fundamental design parameter.

The detector time resolution is a key factor in order to distinguish the laser stripped H^0 very short pulses from the permanent H^0 background. For laser-pulses with 10...100 ns length (see Table 4.4) a bandwidth of > 20 MHz is required to record a pulse with negligible distortion [HBB⁺16].

Finally, the detector has to be capable to work in a harsh radiation environment. At the LINAC4 dump, the ambient radiation caused by the activation is expected to be significant, as it can be seen in Fig. 4.17. The plot shows the 1 MeV equivalent neutron fluence, which is a common reference for the radiation damage in semiconductor detectors [Spi05].

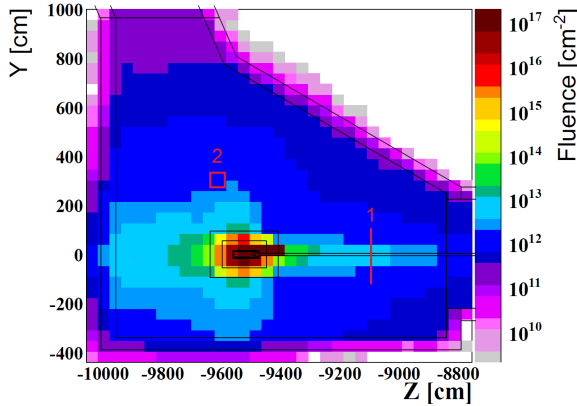


Figure 4.17: Radiation environment in terms of 1 MeV equivalent neutron fluence in the vicinity of main dump cumulated over the lifetime of LINAC4 [BV13]. Positions of H^0 detectors 1 and 2 marked in red.

The radiation damage due the direct H^0 irradiation by laser-stripping and background, as calculated in Sections 4.3 and 4.4 has additional impact on the detector lifetime. However, most of the time the detector will be in its rest position out of the beam pipe to allow the H^- beam to go straight to the main dump. Therefore only during emittance measurements this direct irradi-

ation needs to be considered. At the location of the first H^0 detector a fluence of approx. 10^{15} cm^{-2} is expected to be integrated over the LINAC4 lifetime. The detector damage is strongly related to the detector material and will be discussed in detail in Section 4.5.3.4 and 7.3.3.7.

4.5.2 Review of Potential Detector Systems

After reviewing the different techniques commonly used in beam instrumentation and particle physics experiments for the detection of high energy particles, the short list of potential candidates for the H^0 detectors resulted to be:

- SEM grid
- Scintillator screen
- Multi Channel Plate (MCP)
- Gas Electron Multiplier (GEM)
- Semiconductor detector
- Diamond detector

SEM-grids are widely used in beam instrumentation (see Section 2.2.3) due to their simple setup and their radiation hardness. In the use-case of the laserwire though, the secondary emission of the wire which yields typically approx. $1 e^-$ per incident particle is too low so that the signal cannot be distinguished from thermal noise on the wire.

As described in [GKM⁺05] scintillating screens can potentially be used as detectors in laserwire applications. However organic screens exhibit a very low radiation tolerance and inorganic materials have typically decay times in the millisecond range. Therefore, it would not be possible to distinguish the fast laser-pulses from the continuous H^0 background at LINAC4.

In contrast, MCPs offer nanosecond time response and high sensitivity due to the staged secondary emission process similar to photo-multipliers. However, the critical factor for these kind of detectors is the radiation damage, which causes a loss of sensitivity and response uniformity among the different channels.

GEM detectors widely used in high-energy physics applications are also promising devices to be used in beam instrumentation. In [P⁺11] 2D-profiles of antiproton beams were measured using just a single GEM detector. The drawback of this technique are the organic materials used, which are not compatible with a ultra-high vacuum (UHV) environment. The implementation of

such a device at LINAC4 would require an air gap in the beam line ending at the main dump. Due to heating of the vacuum-windows and scattering of the H^- beam in the air gap, this type of detector is impractical in the LINAC4 setting.

Semiconductor detectors combine high sensitivity, resolution and homogeneous response of all channels due to the advanced manufacturing technology developed in industry. The drawback for our application is the sensitivity to ionising radiation which introduces traps in the material bulk and leads to lower sensitivity and subsequently an inhomogeneous response.

Diamond detectors are used in applications where highest radiation tolerance is needed [Mat08]. As examined in numerous studies, their radiation hardness is significantly superior to silicon. In [dB⁺07] a factor 10 higher radiation tolerance was found for proton beams above 100 MeV. The diamond material offers high sensitivity (approx. $10^4 e^-$ per MIP¹) and a signal response of typically < 10 ns. Artificially grown chemical vapour deposition (CVD) diamond detectors with dimensions > 10 mm x 10 mm are however just available in polycrystalline (pCVD) form, which might exhibit slight inhomogeneities.

4.5.3 Diamond Detector

The choice to use pCVD diamond detectors in our application was driven mainly by the radiation tolerance requirements. In addition the achievable resolution was also a crucial point. Comparing to sCVD material, pCVD diamond can be manufactured in much bigger sizes. As the spatial resolution of the detector is limited by the charge sharing effect (see Section 7.3.3.6), the angular resolution of the instrument can be increased with a longer drift space between laser and detector and subsequently a bigger detector size.

In this section the principle of operation and the relevant detector characteristics will be briefly described. More details can be found in [Spi05] and [Sar14].

4.5.3.1 Energy Deposition by Particles

The energy loss of charged particles traversing a material is described by the Bethe-Bloch theory [O⁺14]. This model can be used also in our application of impinging neutral hydrogen atoms, as the associated electron is detached from the proton in the first atomic layers of the material. Therefore in the following the impinging particle will be considered as a proton.

¹Minimum Ionising Particle

Eq. 4.33 represents the Bethe-Bloch formula. It describes the differential energy loss dE/dx due to the Coulomb interactions between the particle and the electrons in the material.

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right] \quad (4.33)$$

The parameters of the impinging particle are charge ze and relativistic $\beta\gamma$ factor. N_A , Z and A being Avogadro's number, the atomic number and the atomic mass of the detector material, m_e and r_e being the electron mass and its classical radius. T_{max} is the maximum kinetic energy that can be transferred to a free electron in a single collision, I the mean excitation energy and δ a correction coefficient for the shielding of the electric field of the impinging particle by the atomic electrons.

The differential energy loss is plotted in Fig. 4.18 for different materials as a function of the $\beta\gamma$ factor of the impacting particle. For $0.1 < \beta\gamma < 1$ the energy loss falls approx. proportional to β^{-2} , followed by a broad minimum between $\beta\gamma = 3$ to 4 decreasing with Z . Particles with this energy are called Minimum Ionising Particle (MIP) and are often referred in literature of particle detectors. Towards higher particle energies dE/dx rises slowly as the logarithmic term starts to dominate. In case of a proton with $E_{kin} = 160$ MeV, $\beta\gamma$ is equal to 0.61 and dE/dx in carbon becomes $4.7 \text{ MeVg}^{-1}\text{cm}^2$.

4.5.3.2 Charged Particle Detection

Protons crossing a diamond material undergo different kinds of scattering processes and loose kinetic energy along their trajectory. Most of this energy is converted into ionisation. Presuming a high energy particle and a thin slice of diamond where the range of the particle is much bigger than the thickness of the material ($d \ll R(E_{kin})$), the differential energy loss dE/dx can be considered as constant. The carrier-hole pairs, created from one particle crossing the diamond are evenly spread over the thickness and the number of pairs

$$N_{pairs} = \frac{d \cdot dE/dx}{E_{Gen}} \quad (4.34)$$

only depends on the material thickness d and its average energy to generate an carrier-hole pair E_{Gen} . For diamond E_{Gen} equals 13.1 eV [ABS80].

For low-energy particles, loosing all their kinetic energy in the detector material, the number of created carrier-hole pairs is defined by the quotient of kinetic energy and E_{Gen} .

$$N_{pairs} = \frac{E_{kin}}{E_{Gen}} \quad (4.35)$$

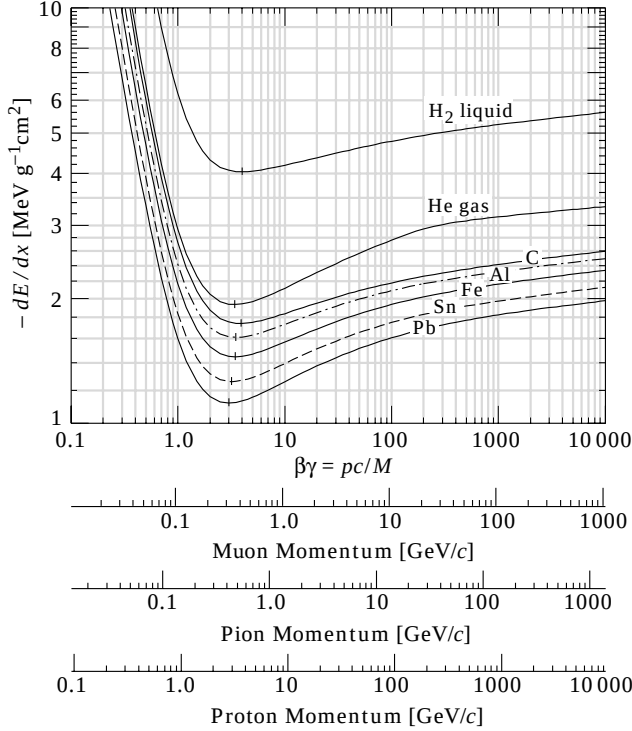


Figure 4.18: Energy loss following Bethe-Bloch theory in different materials. [O⁺14]

To collect the created charge, a diamond detector is typically configured as shown in Fig. 4.19. The electrodes located on one side of the diamond are divided in pixels or strips to determine the position of the impinging particle in one or two dimensions. Between the top and the bottom electrode a bias voltage is applied which creates a uniform electrostatic field $\mathbf{E} = U/d$.

The carrier-hole pairs are accelerated in the electric field and within 1 ps reach a saturated drift velocity $\mathbf{v} = \mu\mathbf{E}$ that is defined by the mobility of the electrons μ_e and holes μ_h in the material [Sus09]. Due to the movement of a carrier, a current is instantaneously induced on an electrode in the vicinity of the carrier. To determine the induced current, the Shockley-Ramo theorem [Ram39, Sho38] is applied:

$$i_{el} = -q \cdot \frac{\mathbf{v}}{d} \quad (4.36)$$

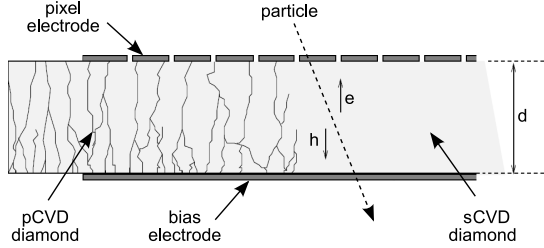


Figure 4.19: Charged particle crossing a diamond detector.

where i_{el} describes the instantaneous change, caused by the movement of a single charge, of the electrostatic flux lines ending on the chosen electrode which is held at unit potential with all other electrodes grounded. For electrode dimensions bigger than the thickness of the diamond bulk d , the current is almost exclusively induced in the electrode next to the impinging particle. However, for a geometry as shown in Fig. 4.19 the current is shared between the electrodes in the vicinity of the carrier-hole pairs. This is known as charge-sharing and will be simulated in detail in Section 7.3.3.6 for the chosen detector geometry.

The macroscopic behaviour of the current created when a high energy particle crosses the detector is defined by the cumulative behaviour of all created carriers,

$$i(t) = \sum_{i=1}^{2N_{pairs}} i_{el}(t) \quad (4.37)$$

where N_{pairs} is the number of created carrier-hole pairs (see Eq. 4.34) and i_{el} is again the current induced by one moving charge. For MIP-like particles the signal shape is triangular as it can be seen in Fig. 4.20 due to the uniform charge distribution created in the diamond bulk. The response time is defined as $t_d = d/v_{Drift}$. The maximal charge at the electrode equals for an ideal detector the number of created carrier hole pairs as the drift distance is always shared between electrons and holes $d_{e^-} + d_{hole} = d$.

$$Q_{Diamond} = N_{pairs} \quad (4.38)$$

The electric equivalent circuit for the detector is in first approximation a current source with a parallel capacitor as shown in Fig. 4.21.

The capacitance C can be calculated as for a plate capacitor $C = \epsilon A/d$ with ϵ being the permittivity and A being the electrode size of the referring channel. The current source representing the ionisation in the material comprises

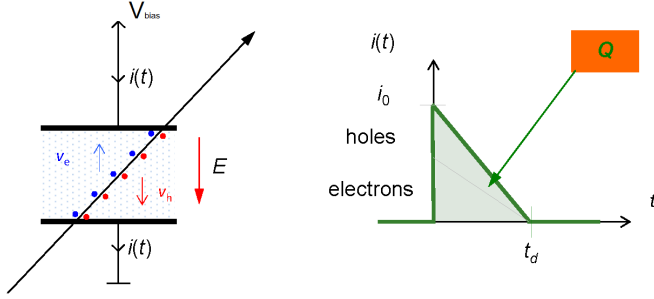


Figure 4.20: Left: Ionisation by one MIP particle; Right: Signal shape for MIP particle crossing diamond. [Gri15b]

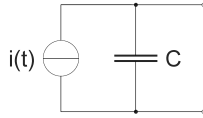


Figure 4.21: Equivalent circuit approximation of diamond detector.

a leakage current typically in the picoampere range, which is negligible in the laserwire application.

4.5.3.3 Charge Collection Efficiency

With respect to the ideal models presented above, real diamond detectors suffer from imperfections due to impurities, grain boundaries (see Fig. 4.22) or dislocated atoms from the lattice due to collisions of impinging particles with atomic cores. These effects cause vacancies in the lattice in which the charge carriers can be trapped. Subsequently less charge is collected on the electrodes Q_C with respect to the generated charge $Q_{Diamond}$ by the Charge Collection Efficiency (CCE) factor.

$$CCE(E) = \frac{Q_C(E)}{Q_{Diamond}} \quad (4.39)$$

The CCE rises with the applied electric field E as the drift velocities increase, but reaches saturation at approx. $1 \text{ V}/\mu\text{m}$ for pCVD diamond detectors respectively $0.4 \text{ V}/\mu\text{m}$ for sCVD devices [Wei14]. Due to trapping in the grain boundaries the CCE of pCVD material typically does not exceed 40% while in contrast sCVD devices can reach above 95% charge collection.

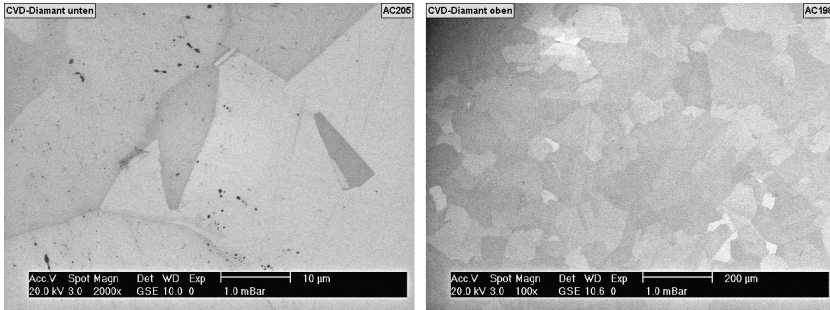


Figure 4.22: SEM¹ images of a polycrystalline (pCVD) diamond detector [Gri15a]. At the distinct grain boundaries charges can be trapped.

A more detailed simulation of how the CCE affects not only the collected charge but also the charge-sharing between different channels of the detectors can be found in Section 7.3.3.6.

4.5.3.4 Radiation Damage in Diamond

As stated earlier, the radiation tolerance was the key factor for the choice of diamond detectors as H^0 monitors. The excellent radiation hardness of diamond is described in numerous publications [Mat08, Sar14], but such a material is still affected by damage due to atomic displacements, when exposed to high energy particles.

The acceptable damage threshold is very application-specific. Since diamond detectors are frequently used for particle counting or tracking, the radiation tolerance is often defined at a much higher level than acceptable for profile measurements where any distortion of the profile is crucial.

The radiation effects in diamond detectors occur in different domains. The damage of the diamond bulk by impinging particles has been already extensively studied (e.g. in [Mül10, dB⁺07, Col08]) and is the dominating effect.

However also other effects can lower the response of the diamond detector: damage of the electrode-diamond interface, polarisation building up inside the diamond due to implanted charges or trapped charge carriers in the bulk material. These effects can result in a shielding of the external applied field and therefore reduce the drift velocity of the charge carriers and subsequently decrease the CCE.

In the following, the bulk damage shall be discussed in detail, comparing different diamond types (sCVD and pCVD) as well as silicon detectors. The

¹ Scanning Electron Microscope

Charge Collection Distance (CCD) (as defined in Eq. 4.40) is usually used to measure the degradation of the diamond material as a function of the impinged particle fluence Φ [Mül10]:

$$CCD(\Phi) = \frac{d}{CCE(\Phi)} = \frac{CCD_0}{1 + k\Phi CCD_0} \quad (4.40)$$

The k-factor depends on the particle type and its kinetic energy. In literature, the radiation damage is often modeled by the Non Ionizing Energy Loss (NIEL) scaling hypothesis, which assumes a damage cross-section proportional to the NIEL in the material [dB⁺07]. However, a new model was recently proposed, which simulates exclusively the Displacements Per Atom (DPA) for impinging particles [Mül10]. This model considers only the interactions that are above the lattice displacement threshold ($E_{th,diamond} = 42$ eV) and is therefore expected to give more accurate results.

Fig. 4.23 shows the DPA in silicon and diamond as function of the kinetic energy of the penetrating particle as simulated with the FLUKA code [Mül10]. It can be seen that the diamond material is clearly more radiation tolerant than silicon. In the high energy range the difference is more than one order of magnitude. For 160 MeV protons, the ratio of radiation tolerance becomes approx. 10.

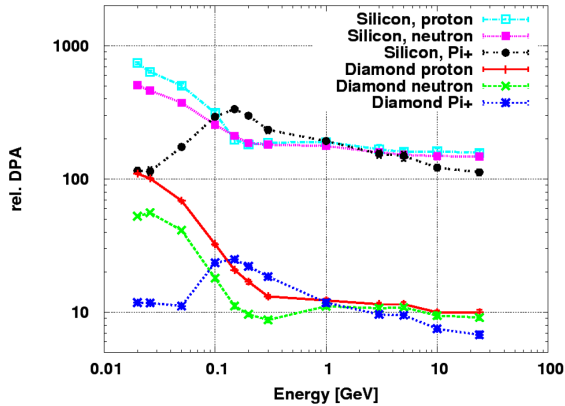


Figure 4.23: Simulation of radiation damage of neutrons and protons in diamond and silicon in terms of relative Displacements Per Atom (DPA). $DPA_{abs} = 1.75 \cdot 10^{-21}$ for 24 GeV proton beam on diamond. [Mül10]

The RD42 group¹ compared experimentally the radiation tolerance of sCVD and pCVD diamond by irradiating diamonds with fluences up to $1.8 \cdot 10^{16} \text{ p}^+/\text{cm}^2$ [Col08]. The results are shown in Fig. 4.24.

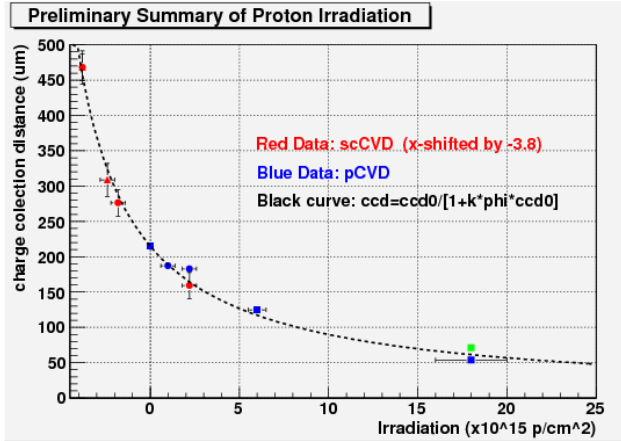


Figure 4.24: Comparison of the radiation damage for irradiation with 24 GeV protons at sCVD and pCVD material. The sCVD data shifted to *negative fluences* to visualise the comparison. [Col08]

The data of the pCVD detector fits very well with a k-factor of $6.2 \cdot 10^{-19} \text{ cm}^2/\mu\text{m}$ (see Eq. 4.40). The sCVD data was shifted by $-3.8 \cdot 10^{15} \text{ p}^+/\text{cm}^2$ to overlap with the pCVD data. It was concluded that the pCVD diamond behaves similarly to the sCVD diamond which has already been irradiated by $3.8 \cdot 10^{15} \text{ p}^+/\text{cm}^2$, as the polycrystalline material naturally exhibits vacancies in its lattice. The results from [Mül10] support this hypothesis.

4.5.3.5 Radiation tolerance of pCVD diamond to 160 MeV H^0 atoms

The fluence of impinging particles in the laserwire application will be always higher in the central part of the detector, which will cause a degradation gradient over the detector surface. The *relative* damage for the chosen pCVD detectors is however much lower than for sCVD, as it can be seen in Fig. 4.24. To define a limit in terms of particles per cm^2 when the radiation damage is still acceptable, two criteria must be met:

- The average sensitivity of the detector should not drop below approx. 90% of the initial sensitivity to avoid the signal to noise ratio (SNR) being sig-

¹ Collaboration to study the potential of diamond material for particle detectors at CERN.

nificantly degraded by the noise sources of the following electronics and digitization.

- The relative change of sensitivity of each detector channel by radiation damage should be negligible ($< 2\%$) in order not to distort the measured beam profile.

In practise it is very difficult to define a precise radiation limit, as it is dependent on the initial CCD_0 and additional damage at the metal-diamond interface or due to polarisation effects might affect the detector performance [Mül10]. Therefore only a conservative estimation of the radiation tolerance can be given, based on the bulk damage of 160 MeV protons in pCVD diamond. Using the k-factor from Fig. 4.24 and scaling it with the help of Fig. 4.23 for 160 MeV protons, $k_{pCVD,160MeV} = 12 \cdot 10^{-19} \text{ cm}^2/\mu\text{m}$ is obtained, which can be inserted in Eq. 4.40. By defining $CCD(\Phi) = 0.9 \cdot CCD_0$ with $CCD_0 = 200 \mu\text{m}$ (see Fig. C.9), the fluence limit for 10% radiation damage results to be: $\Phi_{10\%} = 4 \cdot 10^{14} \text{ p}^+/\text{cm}^2$.

Chapter 5

Emittance Measurements at 3 MeV and 12 MeV H^- Beam

LINAC4 is commissioned in stages. Starting from the source, the following accelerator section is installed and the beam parameters are characterised and compared to simulations, before installing the next accelerator elements. In this way, misalignment and transmission issues can be located precisely in order that a controlled commissioning of the machine is possible.

The characterisation of the H^- beam along the accelerator took place at four different beam energies before the H^- beam reached its top energy of 160 MeV:

- 3 MeV - Output of Chopper
- 12 MeV - Output of first Drift Tube Linac tank (DTL)
- 50 MeV - Output of last DTL tank
- 107 MeV - Output of first Pi Mode Structure tank (PIMS)

5.1 Experimental Setup

The development of the laser-based profile and emittance monitor has been scheduled also in stages, in parallel with the commissioning of the LINAC4. The commissioning phase at 3 MeV with the H^- beam emerging after the chopper was used to conduct tests of the first prototype design of the instrument.

In this section, the instrument setup at 3 MeV is described. For the 12 MeV measurement campaign a similar setup was used, the few changes in comparison to the 3 MeV setup are presented in the corresponding section 5.4.1.

5.1.1 Diagnostic Test-bench

Due to the tight mechanical tolerances, the RFQ transmission is a very critical parameter. Therefore a full set of instruments was integrated into a diagnostic test-bench, to characterise the 3 MeV beam in various domains. Figure 5.1 shows the layout of this test-bench, which was temporarily installed first at 3 MeV and then at 12 MeV beam.

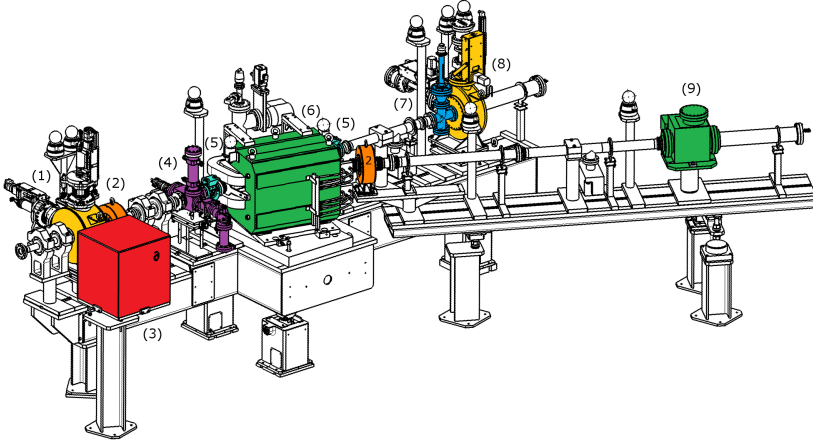


Figure 5.1: Diagnostic test-bench with instruments highlighted: (1) Retractable Slit x and y (part of slit/grid emittance measurement); (2) Beam Current Transformer (BCT) to measure the beam intensity; (3) Laser Focus and Diagnostic box (part of laser-based emittance measurement); (4) Bunch Shape Monitor (BSM) to measure the longitudinal characteristics of the H^+ bunches; (5) Beam Position Monitor (BPM); (6) Dipole magnet to measure the energy spread of the beam; (7) Diamond detector to measure the laser stripped H^0 ; (8) SEM grid (part of slit/grid emittance measurement); (9) SEM grid (part of energy spread measurement).

The subsystems of the laser-based emittance measurement to couple the laser beam into the beam pipe (3) and the H^0 detector (7) are installed in the straight line, separated by 3.35 m. The dipole magnet is essential for the system to split the main H^+ beam from the neutralised hydrogen atoms.

The sampling of the phase-space takes place in the plane of the laser IP with identical z -coordinate as the slit of the reference system (slit/grid) to measure the transverse emittance. This is an important fact as the reconstructed transverse phase-spaces can therefore be directly compared. Further information on the various instruments can be found in [GV⁺06].

5.1.2 Laser System

To develop the laser system, a collaboration between the CERN Beam Instrumentation group and the Front End Test Stand (FETS) beam diagnostics team was established [G⁺13]. This first setup was dedicated to conduct a proof-of-principle experiment by measuring the vertical emittance (i.e. crossing the H⁻ beam with the laser horizontally). The prototype system consisted of 3 sub-systems:

- Laser Source
- Laser Transport System
- Laser Scanning, Diagnostics and Focus Setup

5.1.2.1 Laser Source

For the 3 MeV and 12 MeV prototype a Q-switched, diode pumped, Yb-doped fibre Master Oscillator Power Amplifier (MOPA) was used as laser source. Its principle of operation is shown in Fig. 5.2.

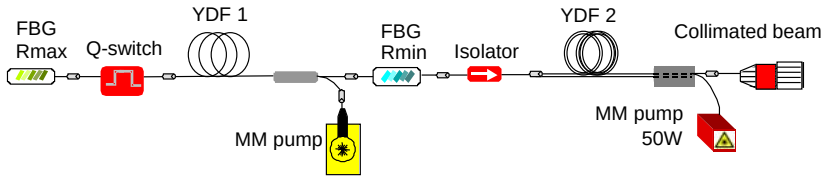


Figure 5.2: Concept of MOPA fibre-laser¹. Ytterbium doped fibre (YDF1) acts as the master oscillator and YDF2 as the power amplifier. [Man11]

A single emitter laser diode injects into the master oscillator, which generates pulses with approximately 100 ns pulse-length and a repetition rate selectable between 30 kHz and 100 kHz. The power amplifier (YDF2) is pumped by a laser diode that can run either in continuous wave (CW) or can be driven by an external signal with a repetition rate of up to 5 kHz and an adjustable duty cycle, which enables the train of amplified pulses to be synchronised to an external source.

The output of the Yd-doped fibre amplifier is a pulse-train at wavelength of 1080 nm. The maximum average power of the laser system is specified with 30 W when pumped in continuous wave (CW) regime and the maximum pulse energy 1 mJ in 30 kHz operation. The exiting laser beam exhibits a nearly Gaussian profile as it can be seen bottom left in Fig. 5.14.

¹Manlight SAS, (Lannion, France), model: ML-30-PL-R-TKS

5.1.2.2 Fibre-based Laser Transport

As discussed in Section 4.4, the laser source must be protected from the radiation environment of the accelerator at 160 MeV and therefore cannot be installed in the accelerator tunnel. This section will focus on the laser transport via optical fibres, which is a novelty for these kind of applications.

At the test campaigns at 3 MeV and 12 MeV, the range of the particles was very low and the radiation environment still tolerable. Therefore it was possible to place the laser source in the accelerator tunnel mounted in a rack approx. 3 m from the beampipe. Next to the laser head, an optical setup for coupling the laser light into the transport fibre was installed, as it can be seen in Fig. 5.3.

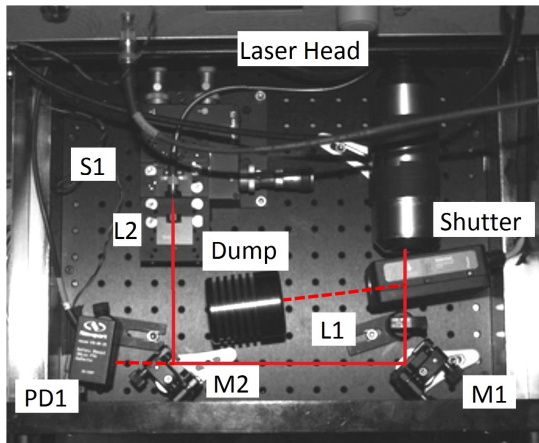


Figure 5.3: Photo of setup for coupling the laser beam into the transport fibre.

The head of the fibre-laser consists of a collimator and an optical isolator assembly. The exiting laser beam traverses a shutter, which can optionally deflect the beam to a dump. Referring to the figure, L1 corrects for the slight divergence of the beam and the mirrors M1/M2 deflect the beam towards the 3D-stage S1 holding the transport fibre. The fast photodiode PD1, installed behind M2, monitors the temporal structure of the laser beam. An aspheric lens L2 with 6.24 mm focal length was used to couple the light into the core of the fibre.

The 3 MeV setup required a 5 m fibre-transmission to the beampipe. Regarding the transport-fibre, a compromise had to be found regarding the core diameter. The smaller the diameter, the lower the probability of coupling to higher order modes worsening the M^2 factor of the laser source, but the higher the risk of end-facet damages and SBS. It was decided to use a commercially

available Large Mode Area (LMA) fibre with 20 μm core and 130 μm cladding diameter and a numerical aperture of 0.08 [Nuf13]. The minimal bending radius is specified as 10 cm for negligible losses.

5.1.2.3 Calculation of Brillouin threshold

As discussed above, Brillouin scattering can limit the transferable laser peak power through the fibre. To estimate the threshold power in the laserwire application, laser and fibre characteristics are summarised in the Tables 5.1, 5.2 and used as input parameters for the set of equations defined in Sec. 4.4.2.2.

Table 5.1: Laser characteristics at working point for 3 MeV and 12 MeV campaigns

Parameter	Value
Pulse length (2σ)	110 ns
Pulse frequency	60 kHz
Wavelength	1080 nm
Linewidth ¹	1 nm

Table 5.2: Fibre parameters used for calculation of SBS threshold

Parameter	Value
Length ²	10 m
Core Diameter	20 μm
Numerical Aperture	0.08
Refractive Index Core	1.448
Electrostrictive Coeff.	0.895
Density SiO_2	2.20 g/cm^3
Acoustic velocity in SiO_2	5900 m/s

A Brillouin threshold of 103 kW was obtained for this application, which is well above the peak power that was used till now and will be used in the future. However it shall be noted, that the calculation holds some uncertainties like the spectral characteristics of the laser which were modelled as a simple continuous Gaussian spectrum. Furthermore the Brillouin threshold equation

¹ As the laser source shown in Fig. 5.2 is pumped by a MM single emitter diode in CW mode, the lasing generated in the master oscillator exhibits a continuous spectrum of approx. 1...3 nm. For the calculation of the Brillouin threshold 1 nm was used as a worst case scenario.

² 10 m for 12 MeV and 5 m for 3 MeV measurements

(Eq. 4.23) was developed for CW light-waves, thus the applied scaling of $P_{B,th}$ by using the effective length (see Eq. 4.32) can introduce an error.

5.1.2.4 Diagnostics, Scanning and Focus System

The transport fibre arrived at the diagnostics test-bench in a light-tight box (see Fig. 5.4) next to the slit tank (see (3) in Fig. 5.1). It consists of an optical line used for interaction with the H^- beam and an optical line to monitor the laser characteristics (dashed path).

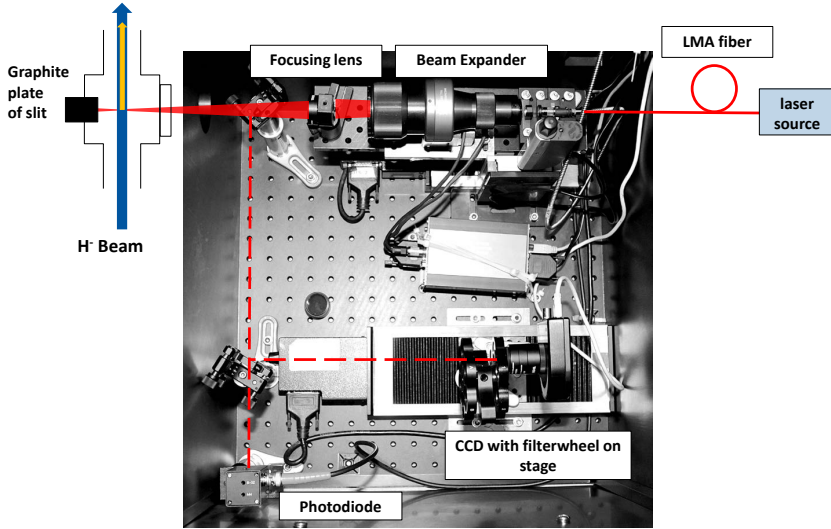


Figure 5.4: Diagnostics, scanning and focus system next to the laser IP with the H^- beam.

The output facet of the fibre together with the focus optics are set on a small plate and mounted on a stack of two automated translation stages with 50 mm range and $\approx 1 \mu\text{m}$ step resolution. One set is used to scan the laser beam vertically (scanning stage or y -stage) and the second one to adjust the laser focusing (longitudinal stage or x -stage). The focus optics consist of a collimation lens with 6.24 mm focal length, a remotely controllable beam expander that has a range of magnification adjustable between 1x and 8x and a focusing lens with focal length of 500 mm. In this optical line the laser beam enters the vacuum chamber via an anti-reflection coated vacuum window, interacts with the H^- beam and gets absorbed by graphite plate, which is part of the slit-setup, mounted 60 mm behind the IP. The characterisation of the laser waist at the IP with the H^- beam as described in Eq. 4.17 can be found in Sec. 5.2.1.

The second optical path is such that, when the y -stage is set at its lowest position, the laser beam is directed via a mirror towards an optical window, which reflects a small portion of light into a CCD camera. This camera is mounted on a translation stage in order to check (on demand) the laser spatial characteristics. The majority of light is transmitted through the optical window and is detected by a photodiode for peak power and pulse duration measurements.

To follow the regulations in terms of laser safety, an interlock system was implemented. If the focus system or the coupling system was opened or the fibre was cut, the laser source would be switched off.

5.1.3 Detector System

As discussed in Sec 4.5, pCVD diamond has been selected as H^0 detector material. During the 3 MeV and 12 MeV measurement campaigns, a prototype detector with reduced resolution was used. The development was carried out in collaboration with CIVIDEC GmbH, to profit from their extensive experience in the domain of particle detection with diamond material.

5.1.3.1 pCVD Diamond Material Properties and Layout

The parameters of the pCVD diamond material are summarised in Table 5.3 and the detector layout is shown in Fig. 5.5.

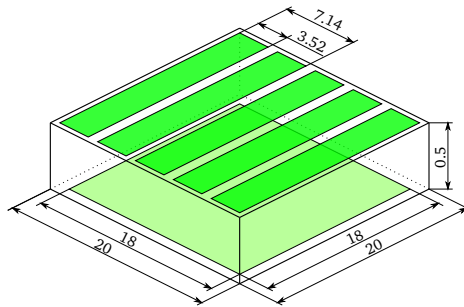


Figure 5.5: Geometry of pCVD diamond slab with strip electrodes - units in millimetre.

The electrode metallisation consists of a 200 nm layer of aluminium. The electrode width of 3.52 mm was chosen to reduce the effort in the DAQ chain for this proof of principle prototype (i.e. minimise the number of read-out channels), although for a precise phase-space sampling they are much too wide.

Table 5.3: Parameters of pCVD diamond material

Parameter	Value	Reference
Charge Collection Efficiency	10%...20%	[Gri13a]
Hole Mobility	$2.5 \cdot 10^3 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$	[Jan13]
Electron Mobility	$1.8 \cdot 10^3 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$	[Jan13]
Pair-creation energy	13.1 eV	[ABS80]
Relative permittivity ϵ_0	5.7	[Spi05]

The capacity of one 3.52 mm x 18 mm channel can be approximated by a plate-capacitor.

$$C = \epsilon \frac{A}{d} = 6.4 \text{ pF} \quad (5.1)$$

The thickness of 500 μm is a standard size for CVD diamond material. A simulation based on Bethe-Bloch theory with the SRIM package [ZZB10, Zie99] showed that 3 MeV / 12 MeV H⁰ atoms are stopped after 48 μm / 539 μm in diamond. This is not optimal for the 3 MeV case but is was accepted taking into account that the final use-case of this detector will be for 160 MeV H⁰ atoms.

For the 3 MeV H⁺ beam the number of carrier hole pair created by one H⁰ particle can be calculated, according to Eq. 4.35, as:

$$N_{pairs,3 \text{ MeV}} = 3 \text{ MeV} / 13.1 \text{ eV} = 2.3 \cdot 10^5, \quad (5.2)$$

since the whole kinetic energy is absorbed inside the diamond. For the 12 MeV beam, a simulation of the ionisation inside the diamond was performed using SRIM. It was found that one H⁰ loses 9.3 MeV when traversing the 500 μm diamond, which results in an significant increase of carrier pairs per H⁰:

$$N_{pairs,12 \text{ MeV}} = 9.3 \text{ MeV} / 13.1 \text{ eV} = 7.1 \cdot 10^5 \quad (5.3)$$

5.1.3.2 PCB Design

As the detector had to comply with a ultra high vacuum environment its components needed to be all made of low-outgasing material. The pCVD diamond slab was fixed on a ceramic PCB with a thermoplastic adhesive film, designed for UHV applications¹. Figure 5.6 shows the detector mounted on the PCB, with the 5 coaxial kapton² cables (30 cm) for the signals of the detector-strips, which add 28 pF capacitance to the signal path.

¹Staystik 571 from Cookson Electronics

²low-outgasing polyimide material

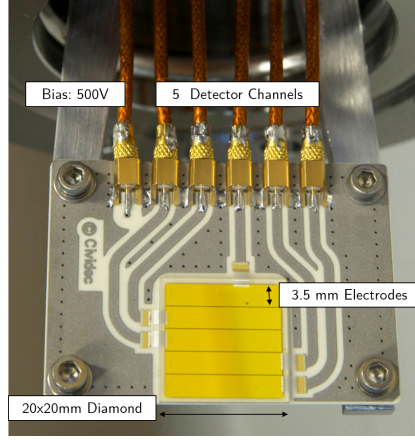


Figure 5.6: Photo of diamond strip-detector mounted on ceramics PCB.

A detector bias, 500 V, generating 1 V/ μm electric field strength, allowed maximising the signal (see Sec. 4.5.3.3) without running into danger to create spark-overs. The bonding of the detector strips to the PCB has been performed at CERN using an aluminium wedge bonding process, where each channel was bonded by 18 aluminium wires with 25 μm diameter.

Appendix B.1 shows the complete schematic of the PCB and displays how the 4 capacitors (3 x 330 nF; 1 x 1 nF, not visible in Fig. 5.6) are connected to the diamond backside where also the bias voltage is fed in via a filter circuit.

The capacitors were dimensioned to allow fast re-charge of the diamond bulk after each laser-pulse. To estimate conservatively the created charge during one laser-pulse, Eq. 4.4 was applied with typical laser parameters (see Table 4.3) and the beam parameters at 3 MeV and 12 MeV (Appendix A.1, A.2). If all created H^0 atoms arrive at the diamond detector, the created charge per laser pulse ($N_0 \cdot N_{\text{pairs}}$) becomes maximal in the 12 MeV case with $Q_{\text{max}} = 5 \cdot 10^{-7} \text{ C}$. This charge needs to be supplied by the capacitors in order to minimise the bias voltage drop. Assuming a tolerable voltage drop of 1% (= 5 V) in Eq. 5.4, the minimal required capacity becomes 100 nF.

$$C = \frac{dQ_{\text{max}}}{dU_{\text{bias}}} \quad (5.4)$$

5.1.3.3 Pre-Amplifiers

The signals of the 5 detector channels were pre-amplified directly after the vacuum feed-through due to an unexpected low sensitivity of the detector. The effect causing this will be discussed quantitatively in Sec. 5.3.2.

In the 3 MeV campaign, AC-coupled linear amplifiers with 46 dB gain and 100 MHz bandwidth were used. The circuit diagram of the pre-amplifiers can be found in Appendix B.2.

5.1.3.4 Integration into Test-Bench

The diamond detector was located in the straight line after the dipole magnet (see Fig. 5.1). As visible in Fig. 5.7, the PCB with the detector was fixed to a fork-shaped support-frame situated inside a 4-way cross chamber. The support was installed on an actuator driven by a stepping motor, allowing a vertical movement of 80 mm in steps of 150 μm . This allowed intercepting all H^0 particles during a laser scan, despite the limited detector acceptance.

A hardware-based interlock system was connected to the actuator, to avoid sending any H^- beam in the straight line when the diamond detector was outside its parking position. Only when the main dipole magnet was powered and the H^- beam was deflected, the detector could be safely moved into the beam pipe. Otherwise the 10^{14} H^- ions present in one full LINAC4 pulse could have seriously damaged or even destroy the detector.

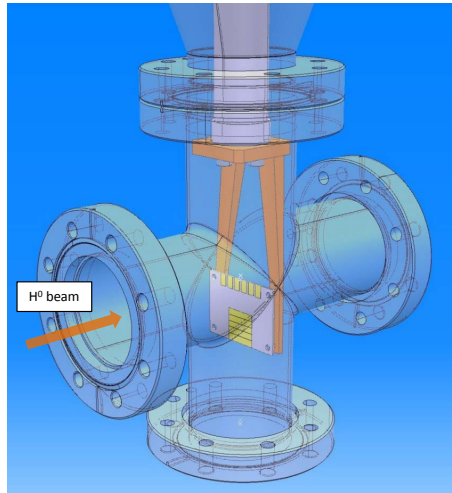


Figure 5.7: Integration of diamond detector in the vacuum chamber at the straight line of the diagnostics test-bench.

5.1.4 DAQ and Controls System

To record the data from the diamond detector and control all devices which are part of the instrument, a modular PXI¹ system was configured. Figure 5.8 illustrates, how the different units were interconnected. A LabVIEW application was designed to supervise, via the PXI computer, all control and read-out tasks. At a lower level, the diamond detector was read-out by a 1GS/s sampling rate oscilloscope².

Moreover the central CERN control system was accessed to operate the diamond actuator and read the data from a beam current transformer (BCT) located after the laser IP (see (2) in Fig. 5.1). The whole system was configured to be remotely controlled by an external PC over Ethernet.

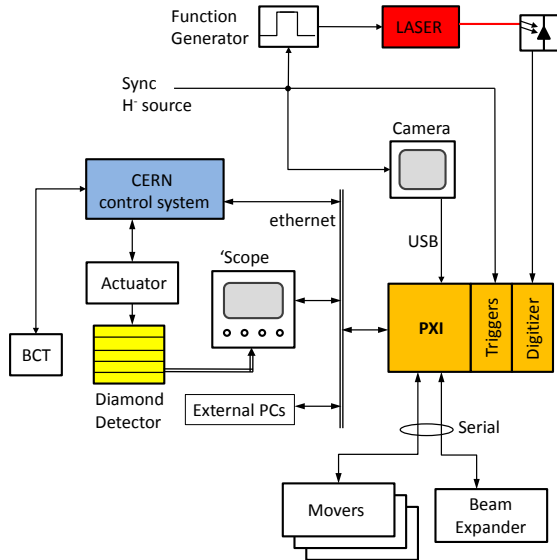


Figure 5.8: DAQ and controls setup based on a PXI system interfacing with the CERN control system.

Due to the low laser duty cycle (≈ 100 ns long pulses at 60 kHz repetition rate), it was decided to record only segments of $1 \mu\text{s}$ length in order not to increase unnecessarily the amount of recorded data. Figure 5.9 shows how the oscilloscope was synchronised to the LINAC4 pulse and the laser timing.

¹PCI eXtensions for Instrumentation

²Lecroy Waverunner 6100A

The reference signal from the H^- source was used to start the laser amplifier and ensure that the laser pulses were at constant amplitude during the LINAC4 macro-pulse. The window for the DAQ trigger was chosen in order to record the 400 μ s LINAC4 pulse including 100 μ s before and after the pulse.

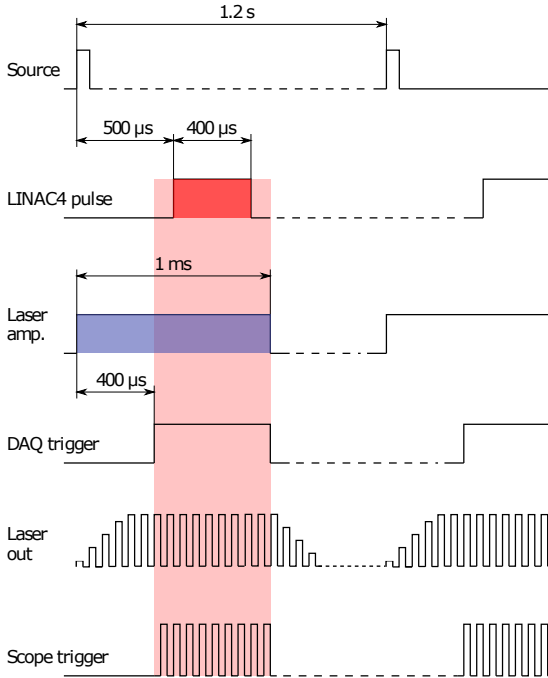


Figure 5.9: Synchronisation of diamond detector acquisition via oscilloscope to LINAC4 and laser timing. [Kru15]

5.2 System Characterisation and Commissioning

Before the 3 MeV measurement campaign, the laser and detector systems were characterised in the laboratory and compared to simulations.

5.2.1 Laser System

The characterisation of the laser head was mainly performed at Royal Holloway, University of London [B⁺13]. The measured laser head parameters,

shown in Table 5.4, are in good agreement with laser factory specifications [Man13] and match the laser emittance meter requirements listed in Table 4.4. It must be noted that, for this setup, the laser power-amplifier was synchronised to the LINAC4 400 μs macro-pulse, but the base-frequency of the single laser pulses (30...100 kHz) could not be synchronised to the LINAC4 bunch frequency (352 MHz) due to the electronics design of the laser source.

Table 5.4: Measured parameters of the laser source used for the 3 MeV and 12 MeV measurement campaigns [B⁺13]

Parameter	Value
Wavelength	1080 nm
Pulse peak power	max. 8 kW
Pulse length (σ)	55 ns
Frequency	30...100 kHz
Synchronisation to LINAC4	Partially
Beam quality factor	$M_x^2 = 1.8; M_y^2 = 1.6$
Amplifier risetime	434 μm

It was important to measure the laser pulse to pulse fluctuations since they obviously had, and always have for this kind of application, a direct impact on the H⁰ particles monitoring accuracy. An example of a laser pulse with the system set for the 3 MeV measurements ($f = 60 \text{ kHz}$; $t_{amp} = 1 \text{ ms}$; $I_{amp} = 35 \text{ A}$) is shown in Fig. 5.10. By recording a high number of pulses, the pulse-length was found to exhibit an RMS variation of $\sigma_{t_{laser}} = 6.3\%$ and the pulse integral of $\sigma_{int} = 7.3\%$ (see Fig. C.2). No long-term drift during operation was observed.

5.2.1.1 Fibre Coupling

The main challenge for setting up the laser transmission was the coupling of the laser into the fibre core. As shown in Fig. 5.3, the mirrors M1 and M2 were used to provide angular adjustment of the laser beam and S1 was used for 3D alignment of the fibre end-facet. After a fine-adjustment with low laser power, the level of the laser amplifier was increased until the working point with $154 \pm 6 \mu\text{J}$ per laser-pulse was reached. This corresponds to a power density of approx. 50 J/cm^2 at the fibre end-facet and is considerably lower than the damage limit of 250 J/cm^2 shown in Fig. 4.9. Nevertheless the end-facet was burned few times (see the right side of Fig. 5.11), thus compromising the coupling. This required the assembly of a new connector the end-facet re-polishing.

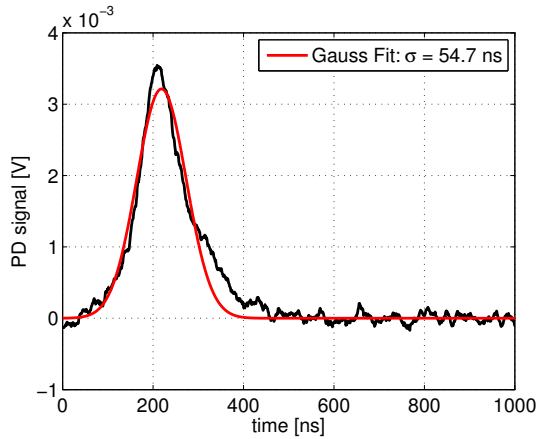


Figure 5.10: Single laser pulse measured with PD1 (see Fig. 5.3) and a 1 GS/s oscilloscope.

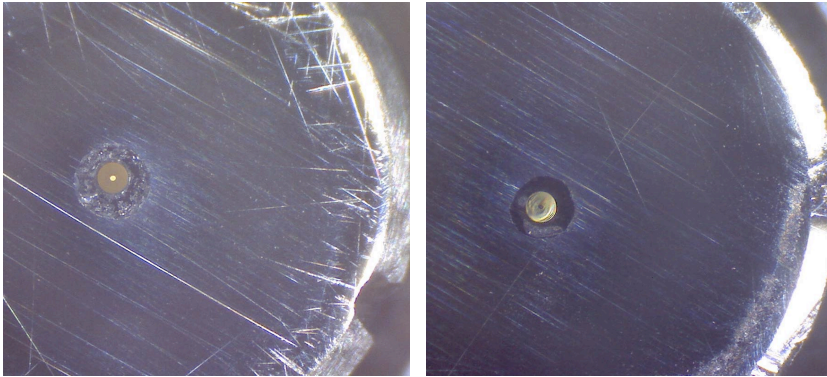


Figure 5.11: Left: Polished end-facet of LMA-fibre with light transmitted through the 20 μm core; Right: End-facet after damage. fibre exhibits inhomogeneous pattern in cladding, no light transmission through core.

Even though the end-facet damage could not be reproduced systematically, the effectiveness of the manual polishing (0.3 μm grain size) and the information available in literature [M⁺07, S⁺94] bring to the conclusion that the damage is related to a sub-micron end-facet deterioration causing excessive heat losses. For the 12 MeV measurements the coupling to the fibre was therefore modified to avoid these problems.

5.2.1.2 Fibre Transmission

The fibre transmission and the energy per laser-pulse were calibrated by using an integrating power meter. For the desired laser working point ($f = 60$ kHz; $t_{amp} = 1$ ms), the average power $\bar{P}$ was measured before and after fibre transmission. The resulting ratio, representing the fibre efficiency is plotted in Fig. 5.12. The transmission drops slightly from 70% to about 65% for high laser power. This effect was attributed to coupling losses rather than to non-linear effects taking place inside the fibre as no pulse distortions could be observed.

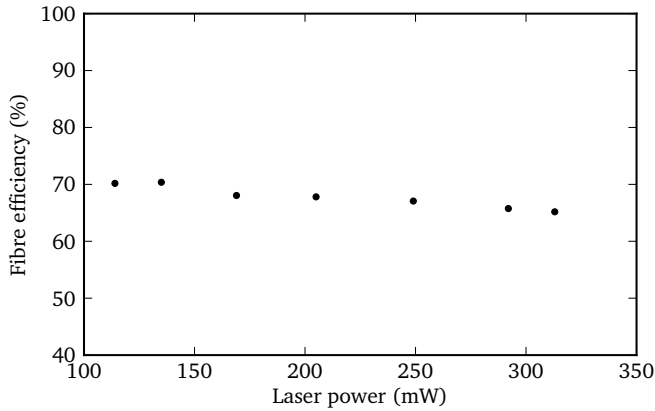


Figure 5.12: Transmission over 5 m LMA fibre as function of the laser average power $\bar{P}$ of the laser head. [Kru15]

The energy per laser pulse was calculated for the laser timing shown in Fig. 4.16. The measured average power $\bar{P}$ was scaled with Eq. 5.5, assuming the energy during the rise and fall time of the amplifier to be equal. The pulse energy E_{pulse} is inferred from the power during the amplified laser burst $\bar{P}_{amp}$ accordingly to Eq. 5.6. Figure 5.13 shows the laser pulse energy as function of the pump diode current, by means of a quadratic fit of the measured data:

$$T_{rep} \cdot \bar{P} = t_{amp} \cdot \bar{P}_{amp} + (T_{rep} - t_{amp}) \cdot \bar{P}_{no\ amp} \quad (5.5)$$

$$E_{pulse} = \bar{P}_{amp} / f_{laser} \quad (5.6)$$

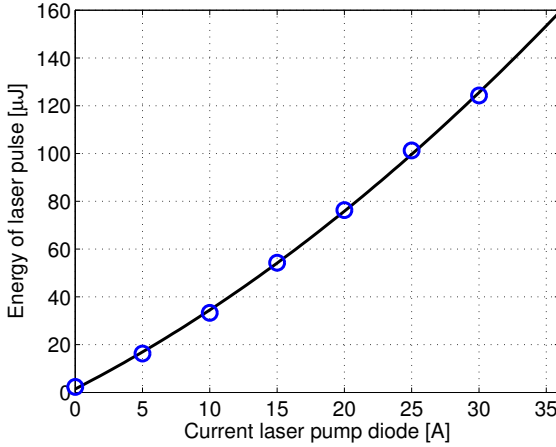


Figure 5.13: Energy of laser-pulse at IP with H^- beam.

5.2.1.3 Transverse Characteristics of Laser Beam at IP

As the interaction of the laser with the H^- beam takes place inside the vacuum vessel, the laser beam cannot be characterised in-situ. By redirecting the laser beam inside the diagnostics setup (see Fig. 5.4), a virtual IP can be produced outside the vacuum vessel. At this location, a CCD sensor combined with a filter-wheel on a movable stage was used to monitor the transverse laser beam parameters.

The size of the laser-waist is primarily crucial in the vertical domain as this defines maximal resolution of the instrument for beam profile measurements (in analogy to the slit size in the traditional slit/grid method). Moreover the Rayleigh length in the vertical plane y_R (see definition in Eq. 4.18) is of interest, for ensuring a nearly constant diameter at the IP. To achieve negligible distortion of profile and emittance measurements the Rayleigh length y_R should be bigger than 3 times σ_x of the H^- beam (at 3 MeV: $\sigma_x = 2.28$ mm; see Fig. A.1).

Figure 5.14 shows a scan of the CCD-sensor to characterise the laser waist. This resulted in a beam quality factor $M_y^2 = 2.0$, a beam radius at the focal plane of the lens $W_{0y} = 75 \mu\text{m}$ (corresponding to a σ_y of $37.5 \mu\text{m}$) and a Rayleigh length $y_R = 8$ mm. The degradation of the M^2 with respect to the one before fibre transmission (see Table 5.4) can be attributed to the generation of higher order modes by imperfections in the fibre-coupling or narrow bends of the fibre. However this effect was not systematically observed, as the M^2

measured for the 12 MeV tests will show. The observable astigmatism can be a result of slightly misaligned or malformed optical elements between the fibre output and the CCD (see Fig. 5.4). As the horizontal plane is not relevant for the performance of the measurement system the effect was not systematically studied in detail.

In conclusion, the laser beam can be approximated as a thin cylinder with constant diameter ($\varnothing = 150 \mu\text{m}$) when traversing the H^- beam.

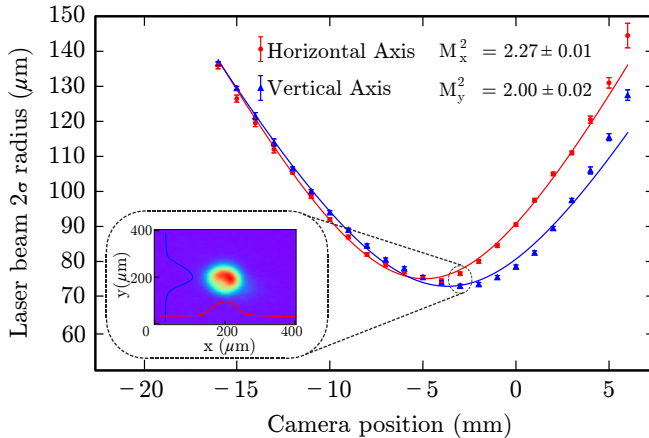


Figure 5.14: Scan of the waist of the laser beam in the virtual IP with the H^- beam. [HKB⁺15]

5.2.2 Detector System

The diamond strip detector, described in Sec. 5.1.3, was tested at PSI¹ in a dedicated proton irradiation facility [BBG12], to check the response to a 160 MeV proton beam.

To qualify the uniformity and the linearity of the pCVD diamond material a faint proton beam with 5 mm diameter was used in order to measure the detector response of single particle hits (proton rate per detector channel $< 2 \cdot 10^5 \text{ p}^+/\text{s}$). The detector surface was scanned with the proton beam and the resulting pulse spectra were acquired for each channel.

The obtained data shows a good uniformity of the material and an additional scan of the proton flux showed a strict linearity of the detector response in this flux range.

¹Paul Scherrer Institute, Villigen, Switzerland

Recent studies confirmed the linearity of polycrystalline diamond material for rates up to 10^9 MIP per impinging bunch [L⁺15, S⁺15]. Other studies on the homogeneity confirm that defects in the diamond lattice are typically small-grained so that the overall sensitivity for surfaces even bigger than $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ is uniform [Cer14b].

5.2.2.1 Test of the Diamond Detector with α -Source

To check the detector response for low energy particles, comparable to the 3 MeV H^0 atoms which get implanted in the diamond material, a test of the diamond detector has been conducted by using a radioactive α -source, by means of the setup shown in Fig. 5.15. The source was placed on top of the pCVD detector (10 mm air gap), which was biased with $\pm 500\text{ V}$. The current of the detector was pre-amplified by a charge sensitive amplifier [Gri13b] and the resulting signal was digitised by a fast oscilloscope.

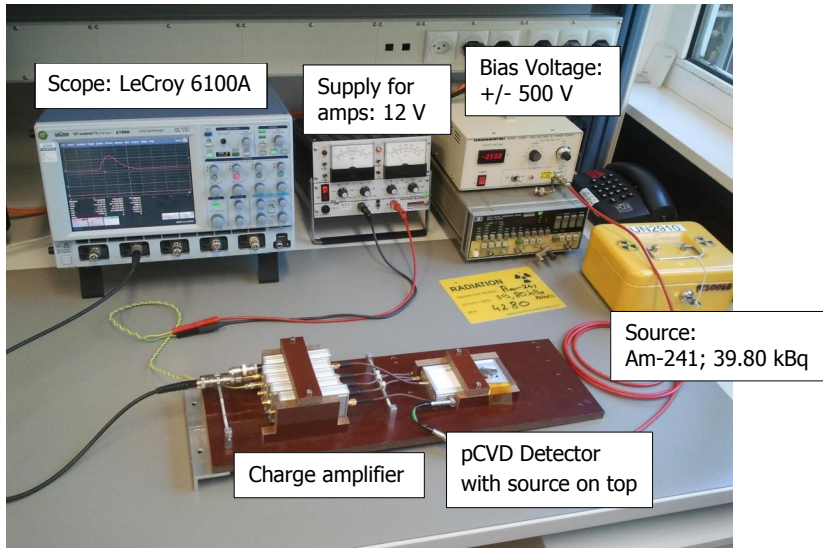


Figure 5.15: Setup for test of diamond detector with low energy α -particles impinging.

By scanning the source over each detector channel, the response of each channel could be recorded. Figure 5.16 shows the overlay of many traces for one detector channel biased with 500 V during an acquisition period of 60 s. The plots for all 5 detector channels exhibited no significant differences.

The amplitude of the pulses varied greatly due to the energy loss of the α -particle in the air gap between α -source and detector. For the shortest path

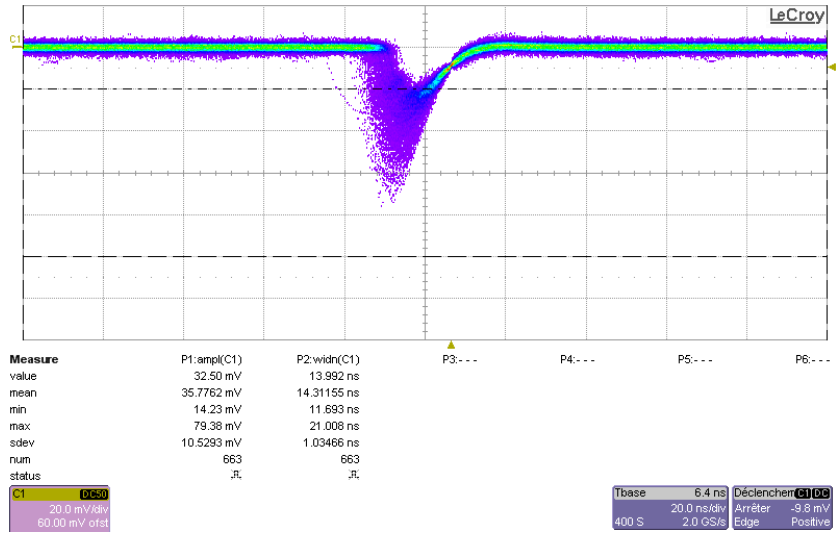


Figure 5.16: Overlay of signal of diamond detector, responding to α -particles.

(10 mm) the particle loses 850 keV^1 , but for particles moving not perpendicular to the detector surface the losses can be much higher. The temporal signal profile resulted from the pulse shaper, included in the charge amplifier as it can be seen in the signal chain scheme in Fig. 5.17.

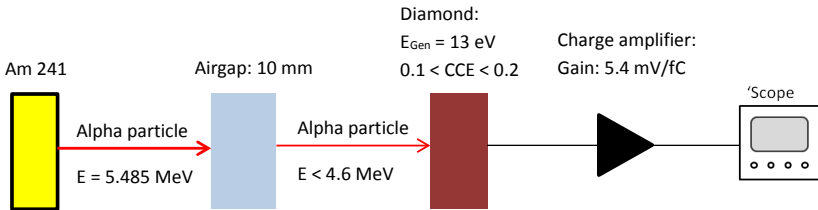


Figure 5.17: Signal chain of diamond detector test.

Comparing the maximum measured signal amplitude (79 mV in Fig. 5.16) to the calculated value from Eq. 5.7, the CCE is in the expected range, which indicates proper function of the charge readout.

$$U_{\text{max}} = \frac{E_{\text{kin},\alpha}}{E_{\text{Gen}}} \cdot \text{CCE}_{\text{max}} \cdot \text{Gain} = 61 \text{ mV} \quad (5.7)$$

¹Calculated with the SRIM package [ZZB10]

A more detailed characterisation of the response of the pCVD diamond strip-detector for higher particle fluence and subsequently operation of the detector in current mode will be described in the analysis of the 12 MeV beam tests (Sec. 5.4.5).

5.3 3 MeV H^- Beam Tests

The 45 keV beam produced at the H^- source was accelerated to 3 MeV by an RFQ and transported through the chopper to the diagnostic test-bench. The macroscopic timing of the pulsed H^- beam at 3 MeV is similar as at 160 MeV shown in Fig. 4.1. Apart from the beam energy, the main difference between the nominal beam parameters (Table 1.1) and what was achieved at 3 MeV was the limited beam current (8.5 mA). The design value for vertical normalised RMS emittance at this position after the chopper $\epsilon_{y,rms}^*$ was simulated to be $0.26 \pi \text{ mm mrad [T}^+10]$.

The prototype of the laser-based instrument installed at the diagnostic test-bench was designed to measure the vertical emittance of the beam. The H^- beam optics (see Appendix A.1) in the chopper and the test-bench were set to optimise the slit/grid emittance measurements accuracy. As the laser was located at the slit location, these settings were also convenient for the laser-diamond measurements.

This section, describing the 3 MeV test campaign, is based on what was published in [HKB⁺15] previously.

5.3.1 Simulation of Laser Interaction and H^0 Background

The interaction of H^- and laser beam was simulated based on the parameters summarised in Table 5.5 in which the laser parameters correspond to the setup of the laser system chosen for the 3 and 12 MeV, which were described in detail in Sec. 5.1.2.

The relativistic Doppler-shift as defined in Eq. 4.8 for a perpendicular interaction of a 3 MeV beam and a 1080 nm laser beam is about 3.4 nm and is therefore negligible. The H^- beam parameters reflect the real conditions of the LINAC4 machine during commissioning described previously.

The distribution of the photo-detached ions at the detector plane 3.35 m downstream the laser IP was calculated. The interaction model has been described in Sec. 4.2.2, where Eq. 4.5 is used to model the laser and Equations 4.6 and 4.7 to determine the stripping probability for each H^- ion passing the laser.

Table 5.5: Parameters of photo-detachment simulation

Parameter	Value	Unit
Laser pulse energy	67	μJ
Laser pulse length (2σ)	106	ns
Laser waist radius (2σ)	76	μm
Ion beam current	8.5	mA
Vertical ion beam size (1σ)	1.01	mm
Distance from the IP to the detector	3.35	m

The simulation of the background distribution in the plane of the H^0 detector was performed using the relevant contributions due to intra-beam stripping and residual gas stripping with the model of the background generation described in Sec. 4.3 (see Table 4.2). At this 3 MeV stage, just the data from LEBT, RFQ and Chopper were used and the mean current in each section was scaled to the real conditions at 3 MeV by the factor $k = 8.5 \text{ mA}/40 \text{ mA}$. The results of the signal and background simulations are summarised in Fig. 5.18.

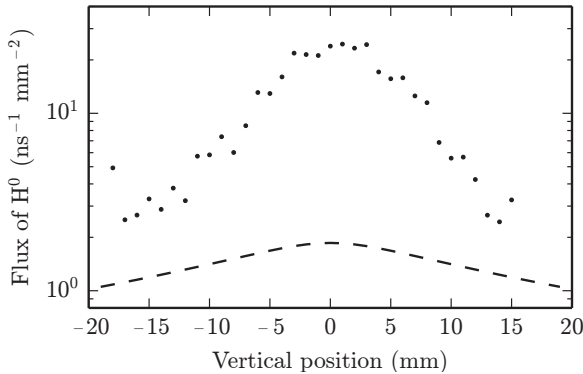


Figure 5.18: Flux of H^0 arriving at the detection plane from laser stripping in the centre of the H^- beam - in average during laser pulse duration - (dots); H^0 flux from the background - permanently during macro-pulse - (dashed line). [HKB⁺15]

The dotted curve shows the average H^0 density (along the laser pulse duration) in the detector plane produced by a laser pulse crossing the 3 MeV H^- beam centre. The dashed curve corresponds to the flux of H^0 produced by residual gas and intra-beam interactions. Since the time structure of the two signals is very different, they can be easily separated in frequency domain. In

fact, the H⁰ signal generated by the laser is correlated to the laser pulse itself (≈ 100 ns). The background is generated all along the LINAC structure and is composed of H⁰ with kinetic energies ranging from 45 keV to 3 MeV. Therefore, it arrives at the detector plane un-bunched and with a duration comparable with the particle macro-pulse (≈ 400 μ s).

The signal, which is expected on the central electrode of the diamond detector, can be calculated in terms of detector charge as:

$$Q_{Diamond} = \int \int \int n_{H^0} dx dy dt \cdot e \cdot N_{pairs}, \quad (5.8)$$

where the 3-fold integral represents the impinging H⁰ over the area of a detector-strip for the length of a laser pulse and N_{pairs} the number of electron-hole pairs per impinging H⁰.

For the given strip-size (3.5 mm x 18 mm), laser pulse length (106 ns) and $N_{pairs} = 2.3 \cdot 10^5$ (see Eq. 4.35) the created charge in the diamond $Q_{Diamond}$ is 5.73 nC.

In reference to Eq. 4.39, the result has to be scaled with the charge collection efficiency (CCE) (CCE = 15%; [Gri13a]) which corresponds to a charge read out from the detector of $Q_C = 0.86$ nC (equals 428 mV peak signal without amplification) [H⁺14].

5.3.2 Diamond Detector Signal Examination

To test the diamond detector response, laser and detector were positioned in order to maximise the signal in one specific channel of the diamond detector.

The upper plot of Fig. 5.19 shows the amplified laser pulses, interacting with the H⁺ beam, recorded with the photodiode in the coupling box. The lower plot shows the signal of an amplified channel of the diamond detector during a H⁺ beam pulse. This signal corresponds to one laser position and one diamond position and each segment represents a 1 μ s time-interval as described in the setup of the DAQ-system (see Sec. 5.1.4).

Comparing the continuous laser pulses with the signal on the diamond detector, one finds a clear correlation just between the segments 4 and 24 where the 400 μ s long H⁺ macro-pulse can interact with the laser pulses. In this time frame the H⁰ created by the laser interaction form sharp peaks in the diamond signal. Furthermore the H⁰ background originating by collisions with the residual gas molecules cause an offset on the diamond.

Figure 5.20 shows a zoom of one of the pulses where the diamond signal (solid) and the laser pulse (dashed) overlap. The clear agreement in the signals

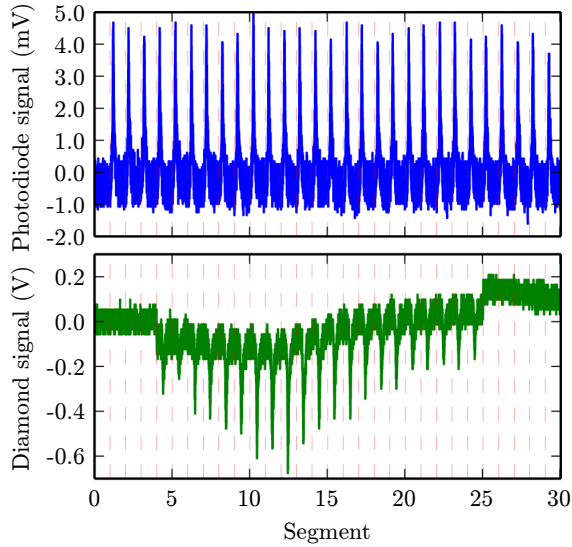


Figure 5.19: Comparison of laser pulses recorded with photodiode PD1 from Fig. 5.3 and the amplified signal of one channel of the diamond detector.

shape demonstrates the linear relation between the laser-power and the output signal of the diamond detector.

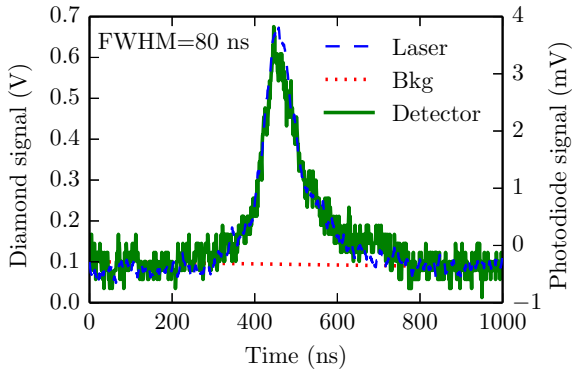


Figure 5.20: Zoom on one of the diamond signals of Fig. 5.19 (solid - inverted), compared to the corresponding laser pulse (dashed). Dotted trace – linear fit of the background.

To characterise further the detector response, a comparison was done between the H⁺ beam current recorded shortly behind the laser interaction (with first BCT in Fig. 5.1) and the *unamplified* diamond detector raw signal, as shown in Fig. 5.21. The ratio between the signal peaks and the continuous background is fairly constant (between 10 and 11) in the detector signal. Given the uncertainties of the simulation input (e.g. gas pressure, detector time response etc...), this value compares well to the simulations (see Fig. 5.18). In addition, the time response of the diamond signal was compared with the BCT all along the LINAC4 macro-pulse. Even though in some cases the signal from the diamond reproduced well the beam current evolution [RH⁺14], in most cases, as presented here, the agreement was poor in the second part of the beam pulse.

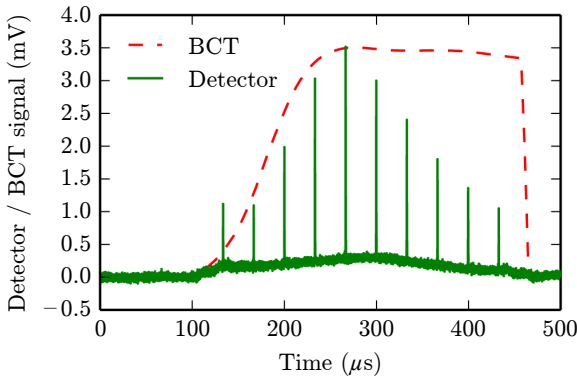


Figure 5.21: Unamplified signal from a diamond detector channel sampling the H⁰ particles for a given laser position ($E_{pulse} = 67 \mu\text{m}$; $f_{pulse} = 30 \text{ kHz}$), as function of time along the 3 MeV H⁺ beam pulse. This is compared to the beam current measured with a beam current transformer (BCT) downstream the laser station.

This effect, obviously affecting the overall measurement accuracy, was related to the implantation of 3 MeV protons into the diamond bulk, after $48 \mu\text{m}$ of detector material. It was simulated that more than 10^7 protons are implanted by the background for one LINAC-pulse. The variation of the electrostatic field inside the diamond could thus lead to a decreased CCE during the LINAC macro-pulse. This might also explain the signal amplitude of just a few millivolts, which is two orders of magnitude lower than expected by calculations not considering the effects of the proton implantation (see simulation in Sec. 5.3.1). This disturbance is supposed to be negligible for beam energies $E_{kin} > 11.5 \text{ MeV}$ for which the protons have high probability to traverse

and escape the 500 μm diamond bulk without being stopped. The measurement results at the 12 MeV in Sec 5.4.5 will confirm this hypothesis.

5.3.3 Data Analysis Method

To reconstruct the transverse phase-space and subsequently extract the transverse emittance value from the raw data, a dedicated analysis routine was developed. The first action is to define the segments with useful data in the digitised signal (e.g. Seg. 6-23 in Fig. 5.19). Hereafter, each segment is treated individually. At first a finite impulse response (FIR) low-pass filter (3 dB cut-off at 22 MHz) is used to suppress high-frequency noise. Now a time-interval is defined, which separates the laser pulse from the background (see Fig. 5.20, e.g. 300...700 ns). By fitting linearly the data outside of this window, a subtraction of the diamond signal from the background can be conducted. Finally the data in the time-interval of the laser pulse can be integrated.

To get the mean emittance value along the duration of the LINAC4 macro-pulse, the integrated values for the selected segments are averaged. The resulting value corresponds to one sample in the transverse phase-space.

The normalised transverse emittance can finally be calculated by using these samples as in the following:

$$\epsilon_{y,rms}^* = \beta_{rel}\gamma_{rel}\sqrt{\langle y^2 \rangle \langle y'^2 \rangle - \langle yy' \rangle^2} \quad (5.9)$$

The relativistic factors β_{rel} and γ_{rel} serve for the conversion from the geometric to the normalised emittance. To extract the vertical beam profile from this data, the values at different y' positions can be integrated for each y coordinate.

5.3.4 Results

This first commissioning phase was affected by various issues in both the laser and detector systems. An example is the fibre end-facet damage, discussed in Sec. 5.2.1.1 and several issues with the movement of the diamond detector. The very low signal level discussed above represented a challenge for the readout electronics.

Nevertheless, over a time-frame of 3 month, several sets of data were recorded. The last set of measurement with optimised setup shall be presented here, where the slit/grid system was used as reference for comparison.

5.3.4.1 Profile and Emittance Reconstruction and Comparison with Slit/Grid

To measure the vertical H^- beam emittance the laserwire was moved vertically across the ion beam with variable step size (0.5 mm at the tails and 0.25 mm around the peak) in order to accurately sample the shape of the distribution.

At each laser position, the diamond detector was scanned across the H^0 beamlets with steps of 1.8 mm, firstly because the DAQ-system could in this stage just record 3 detector channels but also in order to increase the angular resolution. Each detector scan, corresponding to a fixed laser position, was stored in a separate data file. The data were then analysed offline according to the method described above. The resulting integrated and averaged signal was used to plot the phase-space distribution.

The results were compared to the conventional slit/grid emittance meter. The slit, installed at the same point as the laser IP (see Fig. 5.1) was scanned across the ion beam in the vertical direction. At each vertical position, well defined with respect to the ion beam centre, the slit selects a narrow slice of the ion beam. The distribution of the particles transmitted through the slit was measured after 3.4 m drift space by two wire grids [Z⁺14]. As in case of the laserwire, by scanning the slit vertically across the ion beam and measuring the profiles of particle beamlets passed through the slit, the whole phase-space was reconstructed. The vertical phase-space, as measured at 3 MeV by the laser/diamond and slit/grid systems is shown in Fig. 5.22.

Despite the lower angular resolution of the laser-diamond during this first test, the ellipse size and orientation is well in agreement with the slit/grid. The difference in the measured average divergence (y') can be attributed to an inaccurate alignment of the vertical laser beam position w.r.t. the H^- beam axis.

Table 5.6 compares the two systems in terms of normalised RMS emittance and Twiss parameters. Also in this domain a satisfying agreement can be seen. The sources for the residual difference, that can be assumed systematic, will be discussed in the next section.

Table 5.6: Comparison of normalised emittance and Twiss parameters obtained with both methods

	Slit-Grid	Laser-Diamond
Norm. RMS emittance [π mm mrad]	0.242	0.215
Beta [m]	0.906	0.848
Gamma [m^{-1}]	1.16	1.328
Alpha	-0.225	-0.348

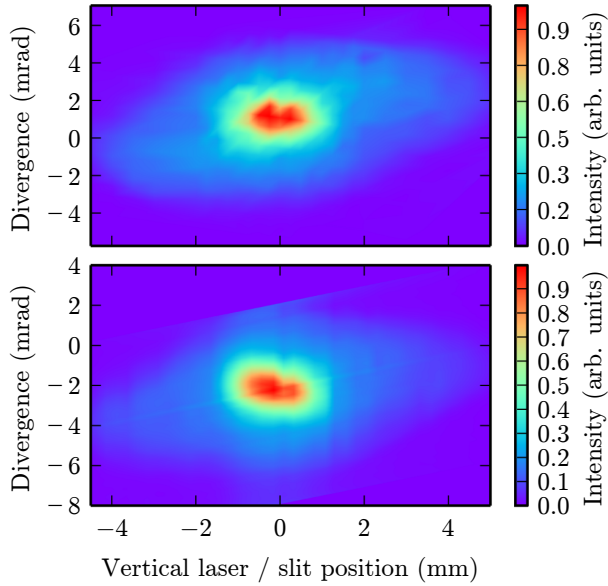


Figure 5.22: Vertical transverse phase-space (interpolated) of the 3 MeV H^- beam measured by laser/diamond (top) and slit/grid method (bottom).

Vertical profiles, inferred from the phase-space projections, were also compared in Fig. 5.23. Differences are only evident on the profile tails outside

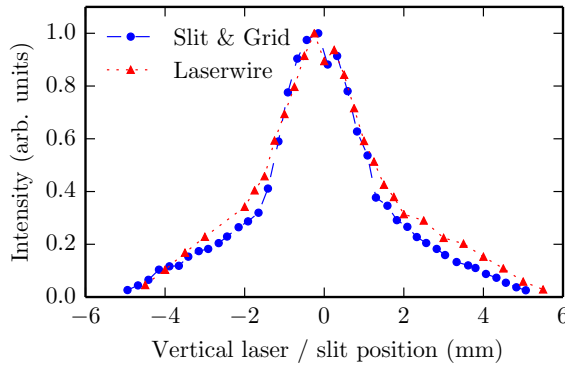


Figure 5.23: Vertical profile of the H^- beam measured by laserwire (red; dotted) and slit/grid (blue; dashed) methods.

the Gaussian core. Both systems exhibit non-Gaussian tails, slightly larger for laser-diamond monitor. The non-Gaussian shape regardless of the measurement methods indicates that such shape is caused by the processes of beam generation at the source rather than a measurement error.

5.3.4.2 Error Sources and Resolution Limitations

At this stage, the most perturbing error sources were identified and summarised together with the effect on the measurement in Table 5.7.

Table 5.7: Dominant error sources for profile and emittance measurement

Error source	Effect on measurement
H^- pulse current instability	$\pm 2\%$
Laser pulse energy instability	$\pm 7\%$
Time jitter between laser and H^- pulse	$< \pm 5\%$
H^0 background	-
Laser diameter not constant	spatial and angular blur
Strip size diamond detector	angular blur

The pulse-to-pulse fluctuations of laser and H^- beams represented the major error sources. The 1σ uncertainty for each interaction is 2% for the H^- pulse and 7% for the laser pulse. The graphs in the appendix (Fig. C.2, Fig. C.3) show the deviations for a high number of pulses.

To reduce the uncertainty of the diamond data in the future, it is therefore considered to normalise each pulse by the according H^- beam current and laser-pulse energy, which can be recorded permanently by a beam current transformer and a photodiode sampling the laser beam.

The synchronisation between laser and LINAC4 was at this stage just accomplished in a macro-level, which means that the laser power-amplifier was powered in synchronisation with the LINAC4 macro-pulse. However the laser pulse frequency (60 kHz) was free-running, which induced a $16.7\ \mu\text{s}$ jitter of the laser-pulses with respect to the start of the H^- macro-pulse. Especially in the first $100\ \mu\text{s}$ during the rising edge of the H^- pulse (see Fig. C.3) the induced error is significant, so the data along this part of the pulse were discarded. Due to the slight undulation of the H^- beam current also in its flat-top, an error of up to 5% is induced to the signal.

The H^0 background, dominated by residual gas stripping (see Sec. 4.3), explains the baseline signal evident in Fig. 5.21. By means of the linear background fit and subtraction, this effect can be largely suppressed.

In summary, each sample in the phase-space area is proportional to the number of stripped particles N , described by Eq. 4.4. The uncertainty can be determined by

$$\sigma_N = \sqrt{\sum_{i=1}^n \sigma_i^2} \quad (5.10)$$

where σ_i are the associated errors of multipliers in Eq. 4.4 as summarised in Table 5.7. Applying the errors sources listed above, σ_N becomes 9%. With 60 kHz laser frequency, the H^- macro-pulse is sampled 15 times, thus the confidence interval becomes

$$\frac{\sigma_N}{\sqrt{15}} = \pm 2.3\% \quad (5.11)$$

As already discussed above, the diameter of the laser in the interaction point does not affect the measurement accuracy. However, it limits in first approximation the spatial and angular resolution. In analogy to the slit/grid system, the spatial resolution of the instrument follows from Eq. 2.22:

$$\Delta y = 2\sigma_{y,laser} = 75 \mu\text{m} \quad (5.12)$$

Taking into account the variation of the laser diameter due to the infinite Rayleigh length, a slight distortion in phase-space has to be considered. This effect was investigated by misaligning the focus of the laser beam horizontally with reference to the centre of the H^- beam. Even for a misalignment of ± 25 mm no measurable distortion in phase-space was observed, thus this effect is considered negligible.

The angular resolution is dependent on Δy , the detector resolution as well as the drift length between laser and detector. For the current geometry of the laserwire instrument, the angular blurring induced by the strip size of the diamond detector becomes the dominant term. According to Eq. 2.23, the angular resolution $\Delta y'$ becomes

$$\Delta y' = (2\sigma_{y,laser} + d_{strip})/d = 1.1 \text{ mrad} \quad (5.13)$$

with d being the distance from the laser to diamond. This is clearly too low for proper phase-space sampling, however was accepted for this prototype in order to limit the DAQ requirements. In the final configuration this resolution will be significantly enhanced.

An additional systematic error might be introduced due to non-linear effects as result of proton implantation in the diamond bulk, which could not be characterised quantitatively. Furthermore, for the quadrupole settings used, a

small percentage ($< 8\%$) of particles have missed the diamond detector, as it is smaller than the wire-grid. Finally, the noise suppression algorithm excluded all values in phase-space which are below a certain threshold corresponding to a percentage of the maximum amplitude. Some dependency on the applied threshold also has an influence on the results shown in Table 5.6. The influence of this effect will be discussed quantitatively in see Sec. 5.4.6.3.

5.4 12 MeV H⁻ Beam Tests

At the end 2014, 9 months after the completion of the 3 MeV beam commissioning, the first DTL tank was installed (see Fig. 2.1) and the H⁻ beam reached the kinetic energy of 12 MeV. The setup of the diagnostic bench remained the same as the one described in Sec. 5.1.1, the time between the two commissioning phases was used to refine the instrument design. In the following section the setup changes will be described and the re-characterisation of the instrument will be briefly outlined.

The data recorded at 3 MeV already confirmed the functional principle of the instrument, thus the test campaign at 12 MeV was dedicated to characterise the properties of the instrument more in detail. This included the behaviour of the diamond detector, taking into account that no proton implantation was expected at 12 MeV, as it will be for the final instrument at 160 MeV. The results presented in this chapter are based on what was already published in [HBB⁺16].

5.4.1 Instrument Setup Changes

The most significant setup change was related to the fibre-transmission of the laser light to the accelerator. As the distance from the laser-head to the interaction point with the H⁻ beam changed from 5 m at 3 MeV to 10 m at 12 MeV due to the additional installed DTL-tank, the fibre was exchanged and the occasion was used to make the coupling of the laser into the end-facet of the fibre more reliable.

As described in Sec. 5.2.1.1, the high power density of the focal spot at the input facet of the transport-fibre regularly caused problems. Figure 4.9 shows that the probability of damage is rising fast after a certain threshold of power density. It was therefore decided to increase the laser beam diameter at the air-fibre transition, where highest losses take place. Figure 5.24 illustrates the end-cap which was inserted into the ferrule of the connector.

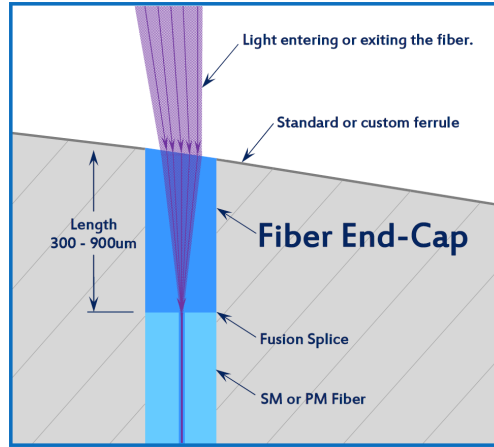


Figure 5.24: Principle of the end-cap used for coupling of a high-power laser into an optical fibre to minimise the risk of end-facet damage. [Con14]

By inserting a $330\text{ }\mu\text{m}$ long end-cap, featuring the same refractive index as the fibre core but having the diameter of the fibre cladding, the power density can be decreased by a factor

$$k = \frac{r_{las}^2}{r_{core}^2}. \quad (5.14)$$

The radius of the laser at the end-cap entry r_{las} can be calculated with the NA of the fibre and trigonometric considerations and results in factor $k = 7$ of power density reduction.

The laser setup has been further modified by replacing the silicon photodiodes monitoring the laser pulse-shape before and after fibre transmission by InGaAs based detectors. Especially at the coupling side (see PD1 in Fig. 5.3), the higher sensitivity of InGaAs at 1080 nm is highly beneficial, as the transmission via the AR-coated mirror is very low.

Furthermore, the cause for the low signal amplitude recorded at the 3 MeV beam with the diamond detector (Sec. 5.3.2) was not fully understood before the 12 MeV campaign. Several different pre-amplifier configurations were designed in order to be prepared for a wide range of signal strengths. Figure C.4 in the Appendix shows an example test result of an amplifier with integrated frequency separating filter [Gri15a]. It shall however be anticipated that the final results recorded at 12 MeV were recorded *without* any pre-amplifier as the signal amplitude was significantly higher than at 3 MeV as predicted by theory and simulations (see Sec. 5.4.4).

The data acquisition system shown in Fig. 5.8 was improved by exchanging the oscilloscope which records the signals of the diamond detector by 2 ADC-cards¹ integrated over the PCI-bus of the PXI-system. Delays caused by the Ethernet based data transfer could thus be eliminated and consequently the overall speed of the phase-space scan be increased.

5.4.2 Instrument Re-characterisation

Before the 12 MeV beam period, the instrument was again fully characterised to ensure its performance. As the setup was changed just in a few domains, most of the system characteristics stayed similar as for the 3 MeV beam tests. Thus in this section only the differences shall be presented.

5.4.2.1 Laser System

The re-characterisation of the laser system focused mainly on the fibre transmission with the new 10 m long fibre equipped with an end-cap as well as the transverse laser characteristics at the IP.

The transmission of the laser beam was extensively tested up to 3 kW laser peak power. In comparison to the transmission for the 3 MeV campaign basically no differences could be observed. This is coherent with the calculations of the SBS-threshold in Sec. 5.1.2.3, where it was predicted that just above 103 kW peak power back-reflections caused by SBS are expected. An optical inspection of the end-facet (similar to Fig. 5.11) showed no changes in the end-cap.

The measurement of the beam quality (M^2) shown in Fig. 5.25 indicates improved performance, especially in the y -plane, where the M^2 is very close to the characteristics provided by the laser source (Table 5.4).

5.4.2.2 Detector System

The pCVD diamond detector was tested in order to check any damage caused by the 3 MeV beam. To compare the results with the ones carried out before the 3 MeV irradiation (see Sec. 5.2.2.1), the same setup has been used (Fig. 5.15) to record the detector response to α -particles. Particular care was taken to set all relevant test parameters as bias voltage, trigger threshold and the position of the α -source equal as in the test prior to the 3 MeV measurements. Recording for 60 s each detector channel while being radiated with α -particles, the mean value $\bar{A}$ and the standard deviation σ of the signal amplitude (statistics figures at bottom of Fig. 5.16) were calculated. The results from the diamond detector before and after the 3 MeV beam campaign are summarised in Table 5.8.

¹NI PXI-5152

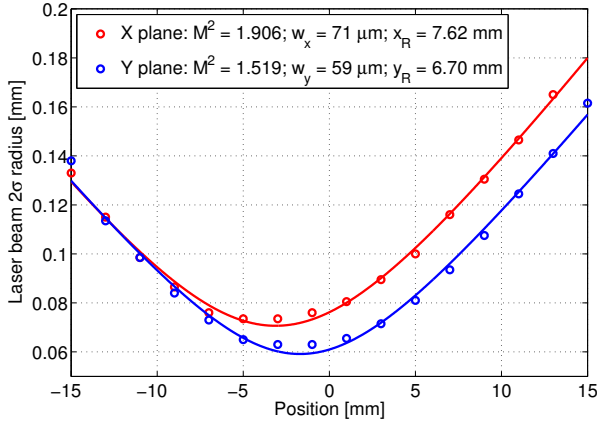


Figure 5.25: M^2 of laser beam after transmission to IP with H^- beam.

Table 5.8: Response of the diamond detector stripes to α -particles before and after the 3 MeV measurement campaign

Channel	Before 3 MeV		After 3 MeV	
	$\bar{A}$ [mV]	σ [mV]	$\bar{A}$ [mV]	σ [mV]
1	33.5	9.43	23.0	5.25
2	35.1	10.88	24.9	7.36
3	35.8	10.53	23.7	5.71
4	35.2	10.35	21.8	5.10
5	35.8	10.03	24.8	5.30

The mean values recorded before and after the 3 MeV beam tests show a clear decrease of approx. 30% for all channels. The standard deviation is even more decreased by almost 50%. Both effects indicated the degraded detector sensitivity. Due to the degraded charge collection efficiency, the lower mean value becomes obvious. The change of the standard deviation follows from the effect, that with lower CCE, fewer particles surpass the trigger level (always kept at -10 mV), the lower end of the distribution is clipped and the standard deviation shrinks.

In summary, the degradation of the detector material has been clearly shown. However no quantitative statement to the radiation damage can be given, as the number of H^0 , which were hitting the detector during the 3 MeV test-run is not

known. Furthermore it shall be noted that at the final location of the instrument at 160 MeV, the damage will be less significant as the stopping power at higher energy is significantly reduced (see Eq. 4.33, Fig. 4.18) and no implantation of protons will take place.

5.4.3 H^- Beam Parameters

The macroscopic pulse structure of the 12 MeV H^- beam was equal as shown in Fig. 4.1. The beam current at 12 MeV ranged from 6 mA to 8 mA and the pulse to pulse fluctuations were comparable with what was observed at 3 MeV (see Sec. 5.3.4.2, Fig. C.3).

The simulated transverse beam parameters in the plane of the laser interaction are summarised in Fig. A.2 in the Appendix. The vertical normalised RMS emittance was simulated to be $\epsilon_{y,rms}^* = 0.26 \pi \text{ mm mrad } [T^+10]$.

5.4.4 Simulation of Diamond Detector Signal

The background level arriving in the H^0 detector was simulated according to the model developed in Sec. 4.3.6. It was found that, with nominal beam parameters, $69 H^0/\text{ns}$ were expected at the central strip of the diamond detector, due to intra-beam and residual gas stripping. This has to be compared to the $408 H^0/\text{ns}$ of expected at the central channel due to photo-detachment [H^+14]. The ratio between signal and background thus becomes approx. 6, which is lower compared to the situation at 3 MeV.

The charge created in the diamond bulk can be calculated with Eq. 5.8. For scaling this with the charge collection efficiency according to Eq. 4.39, a value of $CCE_{12\text{MeV}} = 10\%$ was used to take into account the degradation of the diamond material described in Sec. 5.4.2.2. The charge that could be read out of the detector becomes finally $Q_C = 1.3 \text{ nC}$.

5.4.5 System Characterisation on H^- Beam

5.4.5.1 Signal Amplitude at Diamond Detector

The signals received from the diamond detector were compared to the predictions to verify that the laser and detector systems worked as expected. The plot of Fig. 5.26 shows the signal from the diamond detector caused by one laser pulse. The background level is again due to residual gas and intra-beam stripping. To determine the charge created by the laser interaction, this background was subtracted and the resulting distribution was then integrated (see Fig. 5.26).

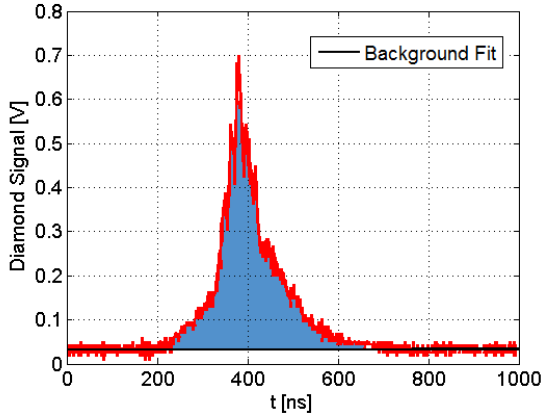


Figure 5.26: Red: Signal on diamond in response to one laser pulse and constant H^0 background; Blue: integrated charge.

Values up to 1.2 nC have been measured, depending on the laser and detector position with respect to the H^- beam. This is slightly less than expected, but taking into account the uncertainties in the simulation due to the uncertain CCE value of the detector, the agreement is adequate.

5.4.5.2 Signal Linearity along Beam Pulse

In order to determine the linearity of the diamond detector response during the ion beam pulse, a comparison with a beam current transformer (BCT) was performed. Special attention was paid to this test, since the previous results using the 3 MeV beam (see Fig. 5.21) showed non-linear behaviour.

The signal from the BCT situated immediately after the laser interaction point was measured for the duration of the phase-space scan. The signal from the diamond detector was recorded as shown in Fig. 5.27.

A whole phase-space scan was made for each detector channel. The phase-space was then integrated for comparison with the averaged BCT signal during the scan period, as shown in Fig. 5.28. The plot shows that the behaviour of each of the three diamond detector channels is very similar. The agreement between each channel and the averaged BCT signal is within 10% for each sample of the pulse. This is a significant improvement over the 3 MeV measurements, for which the diamond signal dropped dramatically in the second half of the beam pulse, which was caused by the pile-up of implanted H^- ions in the diamond bulk material.

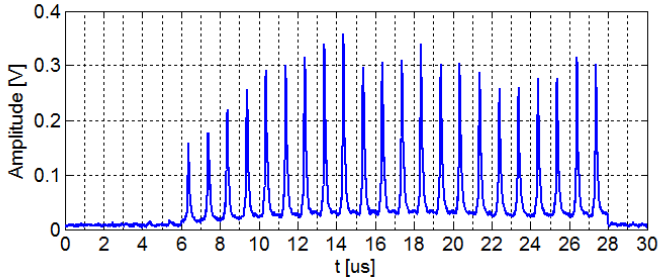


Figure 5.27: Diamond signal segments during the $400\ \mu\text{s}$ H^- ion pulse. The laser was pulsed at 60 kHz and creates 24 signal peaks in the signal of the diamond detector. For each peak, a $1\ \mu\text{s}$ time interval was recorded. The plot shows these signal intervals stitched together for the duration of the ion pulse.

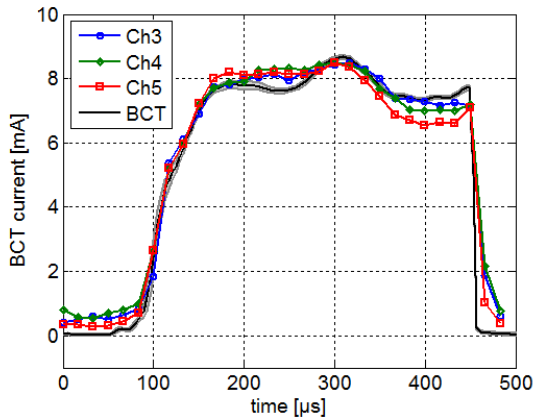


Figure 5.28: Comparison of the averaged beam current with the signals of 3 channels of the diamond detector. The diamond signals were normalised to compare with the BCT signal.

5.4.5.3 Homogeneity of Diamond Detector

The signals from each of the diamond channels were compared to check the homogeneity of the polycrystalline diamond material. Since the DAQ system was still in development, the system was only capable of recording the signals from 3 out of the 5 detector channels. The focused laser beam was kept at a fixed position, and the detector was moved to record each detector channel at the same position in phase-space. The curves in Fig. 5.29 correspond to

the integrated charge per laser pulse in each segment. The difference between channels is approx. $\pm 2\%$, which is within their error bars corresponding to the standard deviation (SD) of successive recordings. The increase in error during the rising and falling edge is due to the missing synchronization of the 60 kHz laser with the ion beam, which introduced a $16.7 \mu\text{s}$ jitter on the signal from the diamond detector, as described in Sec. 5.3.4.2.

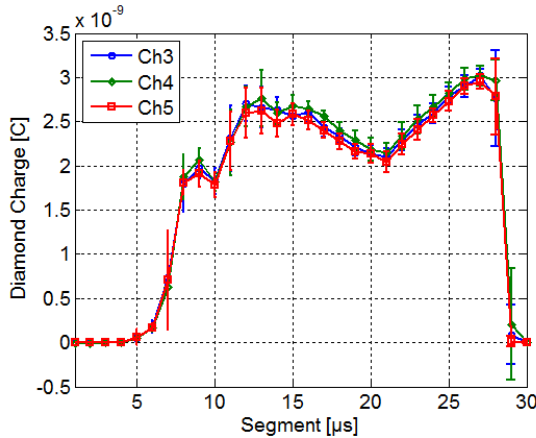


Figure 5.29: Signal charge of 3 detector channels, which were recorded with laser beam at fixed position and each detector channel moved to the same location.

5.4.5.4 Signal Linearity versus Laser Pulse Energy

A key aspect in determining the beam profile and the emittance is the linearity of the diamond detector with respect to the impinging particles. It is difficult to change the LINAC4 ion beam current without changing the beam divergence and size, therefore a different approach was chosen. Assuming a linear relation between the laser pulse energy and the number of stripped H^- ions, the linearity of the diamond detector can be determined by varying the laser power.

The laser pulse energy at the end of the fibre was measured and the laserwire was positioned at the centre of the H^- beam. The results with the detector at a fixed position are shown in Fig. 5.30. The values of the slopes are different due to the different positions of the detector channels. However, the linear fit indicates that the signal distortion due to non-linearities is within the error bars of the signal (see $\tilde{\chi}^2$ values).

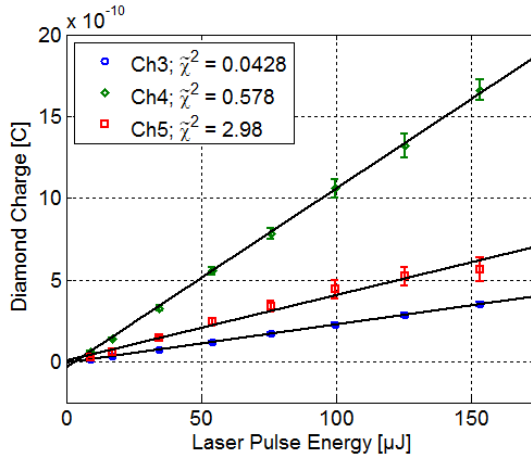


Figure 5.30: Integrated charge recorded by the diamond detector channels as a function of the laser pulse energy. Solid lines: Linear fit for each channel.

5.4.6 Data Analysis and Results

5.4.6.1 Temporal Beam Properties

The measurement campaign was mainly focused on sampling the phase-space and then reconstructing the transverse beam emittance and profile. However, by using a high bandwidth detection system (no pre-amplifier, 2.5 GHz ADC), temporal beam properties could also be measured. Figure 5.31 shows the laser pulse recorded before delivery to the beam pipe and the signal from the diamond detector. The similarity of the shapes shows clearly that the signal from the diamond detector originates from H^0 atoms created by the laser pulse. The delay of the 2 signals of 194 ns (SD, 4 ns) has three contributions:

- time of the laser delivery to the IP with the particle beam (51 ns);
- time-of-flight (TOF) of the particle from IP to the diamond detector (71 ns);
- cable delay from the diamond detector to the DAQ system (72 ns).

Even though this system cannot replace a dedicated system for TOF-measurement, it can be used to estimate the energy of the H^- ions.

Additional information could be inferred from the Fourier-Transform of the diamond detector signal. The spectra of the signals shown in Fig. 5.31 are plotted in Fig. 5.32. The frequency components with high amplitude in the lower frequency range are very similar when comparing the laser pulses recorded at the PD and the diamond. In the high-frequency range a clear signal from the

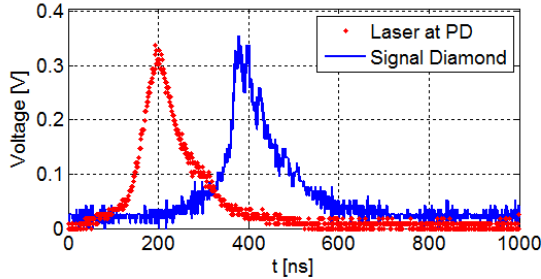


Figure 5.31: Laser pulse recorded with fast photodiode (PD) and signal of diamond detector.

diamond is recorded at 352 MHz, the bunch frequency of the LINAC4. This illustrates the potential of the diamond detector regarding measurements with highest time resolution. The absence of the 352 MHz peak in the background signal is also well understood. The H^0 particles in the background are generated by collisions with residual gas atoms or H^- ions all along the accelerator, each with different kinetic energy thus the arriving particles are expected to be completely de-bunched.

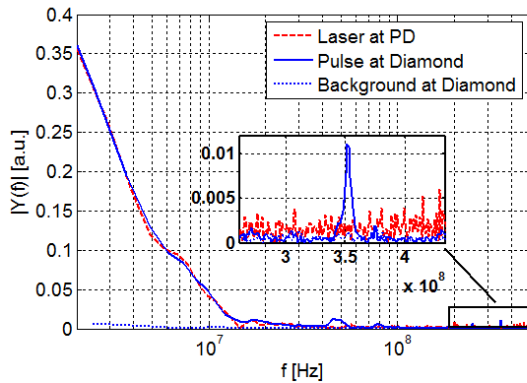


Figure 5.32: Fourier transformation of the laser pulse at the PD, the pulse at the diamond detector and the constant background arriving at the diamond detector. Zoom: Peak at 352 MHz bunch freq.

5.4.6.2 Transverse Phase-Space and Beam Profile

As for the 3 MeV case, a system for sampling only the *vertical* phase-space was developed for the 12 MeV experiments. Just before the set of emittance

measurements started, a fault in the LINAC4 machine interlock system allowed a full H^- pulse to hit the diamond detector. The resulting radiation damage left only one diamond channel surviving with sufficient CCE. Consequently, to complete each emittance scan, it was necessary to scan the surviving channel (in steps of 1.8 mm) across the all H^0 beamlet for each laser position (in steps of 0.5 mm).

The raw data (of the kind shown in Fig. 5.27) was analysed in three steps. The detector signal was first low-pass filtered to remove high frequency noise. Then a linear fit to the background level was made (see Fig. 5.31) and subtracted from the signal, before summing the charge of the resulting signal. The obtained values in vertical phase-space are shown in Fig. 5.33 where they are compared with the results of the conventional slit/grid instrument measured with same H^- beam parameters, to evaluate the precision of the novel laserwire instrument.

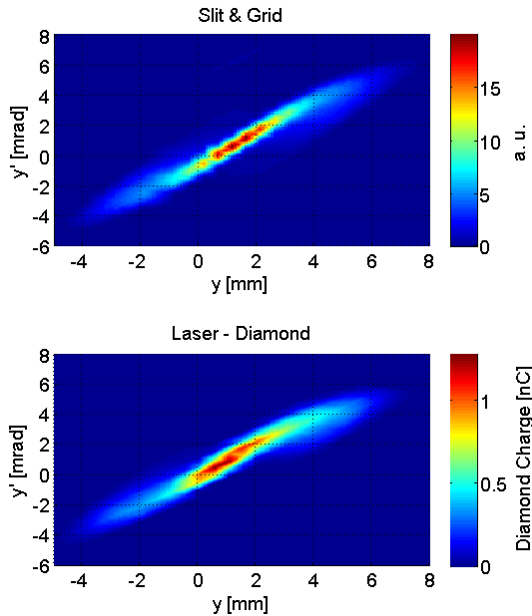


Figure 5.33: Phase-space sampled with the slit/grid method (upper plot) and with the laser/diamond system (lower plot).

The two phase-space distributions exhibit a remarkable overall agreement. Minor differences are mainly present in the angular distribution. The measure-

ment using the laserwire exhibits a slightly broadened angular profile, which is caused by the lower spatial resolution of the diamond detector.

Integrating the phase-space in the divergence domain, the resulting beam profile is plotted for both instruments in Fig. 5.34. The disagreement in terms of profile shape and therefore extracted beam size is well below 2%. The error bars, calculated as the signal's amplitude variation in time along the LINAC4 pulse, are in the same range for both the laser/diamond and slit/grid systems.

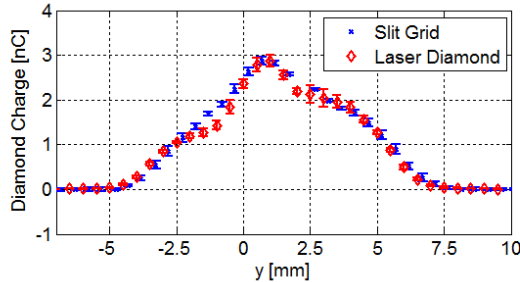


Figure 5.34: Comparison of the measured beam profiles: signal of the slit/grid signal normalised to the charge measured with the diamond detector.

5.4.6.3 Emittance Reconstruction

The value of the normalised emittance has been defined in Eq. 5.9. The measurement depends strongly on the sampled phase-space area due to the constant noise level of a real instrument. To suppress the noise a simple method is commonly used to exclude all values in phase-space which are below a certain amplitude threshold, corresponding to a percentage of the maximum amplitude [C⁺11, B⁺12]. Figure 5.35 shows the resulting emittance values, measured with the laser/diamond instrument and the slit/grid reference system as a function of the applied threshold. The characteristic kink in this curve marks the spot where the noise is largely suppressed and the sampled signal starts to originate from impinging particles. For the laserwire system this point is quite distinct at $1 \pm 0.1\%$. The equivalent position for the slit/grid is not so clearly defined but is in the same region (see hatching in Fig. 5.35). Assuming the same threshold of 1% for both systems the resulting emittance values are summarised in Table 5.9, including the uncertainty due to the choice of a reasonable threshold (between 0.9% and 1.1%) and the standard deviation (SD) of measurements during the LINAC4 pulse.

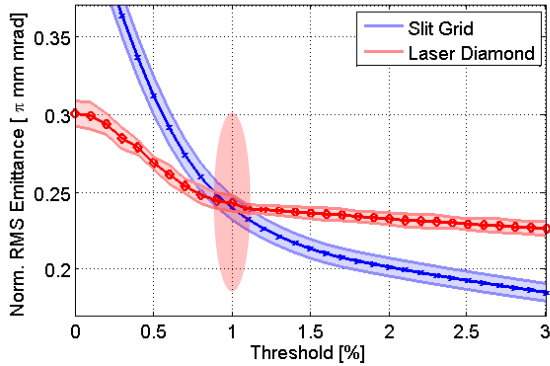


Figure 5.35: Normalised emittance value resulting from both instruments. Dependence on used threshold for noise suppression.

Table 5.9: Comparison of emittance result values

	Slit/Grid	Laser/Diamond
Norm. RMS emittance [π mm mrad]	0.240	0.243
Threshold dependence	± 0.0084	± 0.0024
SD during LINAC4 pulse	± 0.0070	± 0.0026

5.5 Summary

The considerations from Chapter 4 have been applied to build a first prototype of the laserwire emittance monitor. In this regard an optics setup has been developed to couple the laser light into the transport fibre, characterise the laser beam and the subsequently focus the light onto the H^- beam. A strip-detector for H^0 detection based on pCVD diamond has been designed and tested and the associated DAQ and control system was implemented.

Challenges during the first beam tests at 3 MeV have been encountered due to the high power densities at the fibre end-facets and the proton implantation in the diamond material and subsequent low signal amplitudes (see Sec. 5.2.1.1 and 5.3.2).

The recorded signal of the diamond detector has been analysed and compared with the laser pulses and the H^- beam current recorded downstream of the laser IP. Scans of the laser via the H^- beam allowed to reconstruct the vertical emittance and compare the results with the slit/grid system installed in

the same plane. Finally the dominant error sources for the 3 MeV emittance measurements were identified in Sec. 5.3.4.2.

During the 12 MeV commissioning the instrument was improved w.r.t. the 3 MeV design and its performance was characterised in depth. The amplitude of the diamond detector signal was compared to simulations and a good agreement ($\pm 10\%$) was found. The linearity of the detector was characterised in the time domain along the LINAC4 pulse and also in comparison to the number of impinging particles. In both domains the response of the detector is linear. The homogeneity of the different detector channels also proved to be satisfactory ($\pm 2\%$). Overall the diamond detector system exhibits a significantly improved performance due to the higher range of the impinging particles compared with the previous 3 MeV tests.

The most noteworthy changes in comparison to the 3 MeV setup is the insertion of a fibre-endcap and the extension of the fibre delivery of the laser beam to the IP to 10 m. Even for pulses with peak power above 2 kW the endcap managed to protect reliably the end-facet of the fibre. The transported laser pulses did not show any distortion and the transmission efficiency stayed constantly at 70%.

The diamond strip-detector showed about 30% signal degradation caused by the 3 MeV H^0 irradiation. Even though an interlock failure allowed several full H^- pulses to hit the diamond, causing significant damage, the detector was still able to measure the emittance with reduced sensitivity.

Analysing the measurements with the laserwire system allowed determining temporal beam parameters as the time-of-flight or the bunch structure but the main focus of the measurements remained the profile and emittance reconstruction. The results of the emittance measurements with the laserwire system were compared with the well-established slit/grid method. Vertical phase-space plots and beam profile projections agree very well, however the resulting RMS emittance value is dependent on the threshold for noise suppression. Given a reasonable choice of threshold, the emittance results of the two systems agree within 3%.

Chapter 6

Profile Measurements at 50 MeV, 80 MeV and 107 MeV H^- Beam

After finishing the commissioning phase at 12 MeV, the last 2 DTL tanks were installed in order to accelerate the H^- beam to 50 MeV. This milestone was particularly important as 50 MeV is equal to the current top energy of the ageing LINAC2. In case of a sudden failure of LINAC2, LINAC4 is supposed to supply the downstream accelerator complex temporarily with a 50 MeV proton beam in order to exclude unforeseen down-times most notably for the LHC.

In this chapter the experimental setup for commissioning at 50 MeV, 80 MeV and 107 MeV will be outlined, which is fundamentally different from the previous measurement campaigns. Hereafter the design of the instrument for measurement of vertical beam profiles by detecting the stripped electrons will be described and the measurement results at all 3 beam energies will be presented in accordance with [RRH16, H⁺15].

6.1 Experimental Setup

The commissioning of the 50/80/107 MeV H^- beams was accomplished with a different diagnostic test-bench, which was not equipped with a dipole magnet. Thus it was not possible to separate H^0 and H^- ions and subsequently measure the distribution of stripped H^0 after the laser interaction. In this regard the instrument setup was modified to collect the stripped electrons rather than the H^0 atoms and measure only the beam profile without divergence information in accordance to Fig. 3.2.

6.1.1 Diagnostic Test-bench with Laser Profile Monitor

Fig. 6.1 illustrates the test-bench characterising the beam, emerging after the last DTL cavity (50 MeV) and the first PIMS cavity (80 MeV and 107 MeV).

It consists of wire-scanners and SEM-grids for transverse profile measurements and emittance measurements via the *3-profile method* as described in Sec. 2.2.1. The two beam position monitors (BPM) which are typically used to determine the mean transverse beam position were also used to determine the beam energy by measuring the time of flight between both BPMs. The beam intensity was measured with the BCT and the longitudinal bunch profile could be recorded with the bunch shape monitor (BSM).

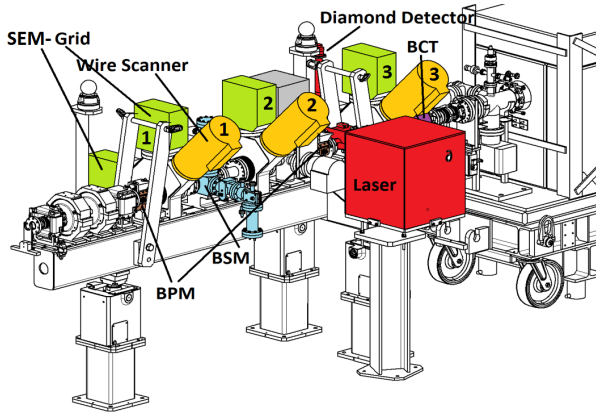


Figure 6.1: Diagnostic test-bench used for beam commissioning at 50 MeV, 80 MeV and 107 MeV H^- beam. [RRH16]

The section marked in red represents the instrument for laser-based profile measurement. The corresponding photograph in Fig. 6.2 shows the design of the vacuum-chamber dedicated to host the laser IP and the downstream electron detection setup. It consists of a system for laser delivery and diagnostics similar to the one used for the measurements at 3 MeV and 12 MeV (see Fig. 5.4), a steerer magnet to deflect the stripped electrons and a sCVD diamond detector mounted on a vertical actuator to monitor the electrons.

6.1.2 Laser System

In view of the upcoming permanent installation of the instrument at 160 MeV, the laser system for the 50/80/107 MeV measurements, was designed in order to reuse major parts for the final system.

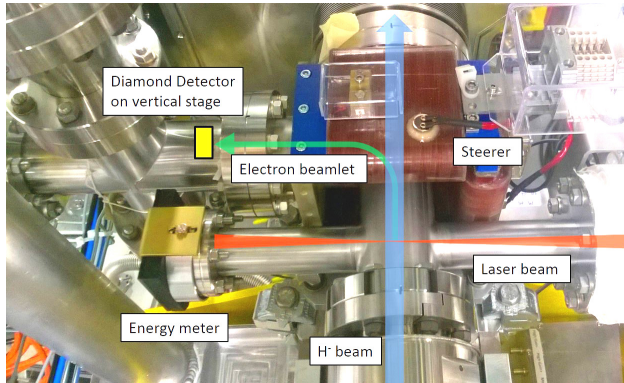


Figure 6.2: Photo of vacuum-chamber for laser interaction with associated steerer magnet to deflect electron beamlet towards the diamond detector.

6.1.2.1 Laser Source and Transport System

The most noticeable installation was the laser cabinet which was built to host the new laser-source and the coupling of the laser beam into the transport fibre in the klystron gallery as shown in Fig. 6.3. This container satisfies all regulations to host a Class 4 laser source and due to its location, the laser-source is not exposed to any ionising radiation. In comparison to the very small drawer used for coupling in the 3 MeV and 12 MeV setup (see Fig. 5.3) this 2 m x 2 m large space is sufficiently big to host future extensions needed for the final installation at 160 MeV.

The optical table inside the laser cabinet in Fig. 6.4 includes the laser-source and the setup to couple the beam into the transport fibre. As this configuration is very similar to the one used in the 3/12 MeV setup, the reader can refer to Sec. 5.1.2.2 for the functional description.

The laser-source in the upper left corner of Fig. 6.4 is however different from the one used previously at 3/12 MeV as this was a temporary loan in the framework of the collaboration between CERN and the FETS group.

For the 50/80/107 MeV beam tests a new collaboration between the Royal Holloway, University of London and CERN was established and a new laser source was conjointly purchased. The principle of the new laser¹ is represented in Fig. 6.5. It comprises a Master Oscillator Power Amplifier (MOPA) configuration with a laser diode (LD) based optical seed pulse oscillator followed by a dual-stage fibre amplifier system that is pumped by multi-mode laser diodes.

¹ V-Gen VPFL-ISP-1-40-50



Figure 6.3: Laser cabinet (marked in red) situated above 160 MeV area of the LINAC4 tunnel and next to klystrons which supply the RF-cavities in the accelerator tunnel below this hall. [1] refers to the rack where the DAQ and control system is located.

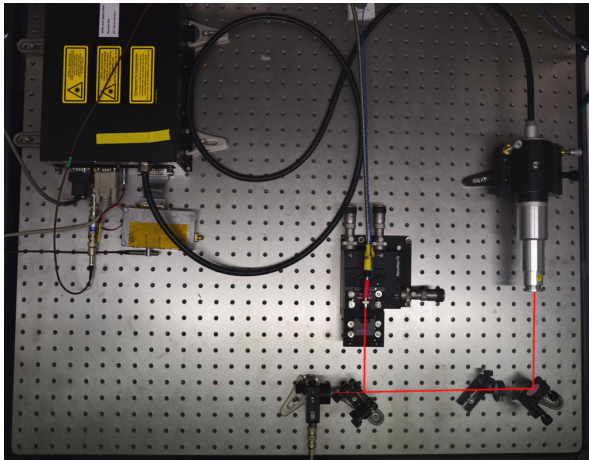


Figure 6.4: Laser source (left) and coupling of laser beam into transport fibre on optical table in laser cabinet.

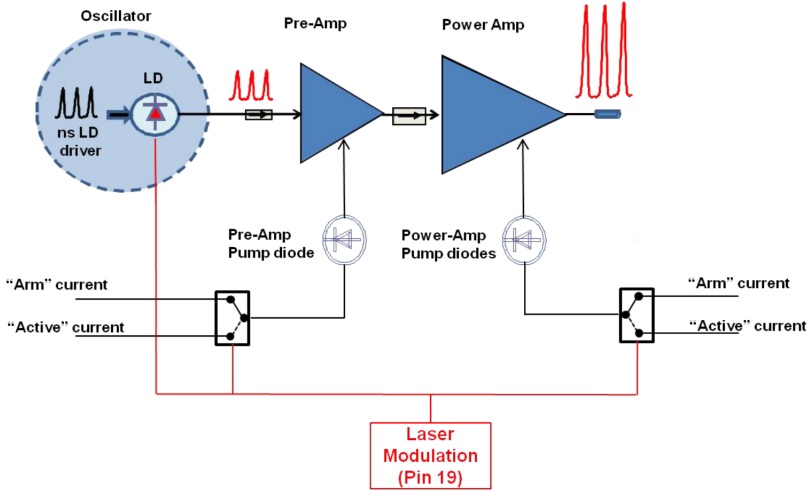


Figure 6.5: Schematic design of fibre-laser used in 50/80/107 MeV setup. [VG13]

Table 6.1 summarises the most relevant laser parameters. With maximal 40 kW peak power the system is able to supply several laserwire interaction points and the adjustable pulse length gives an additional degree of freedom, which can be adopted to requirements of the accelerator timing and the detector systems. The pulse rate up to 500 kHz can be used for high-frequency sampling of the H^- macropulse but even more important: it is externally controllable so that it can be synchronised to the accelerator RF-system and thus avoid errors due to time jitter between laser and H^- pulse as shown in Table 5.7. The beam quality factor of 1.3 ensures a narrow beam diameter and long Rayleigh range in the IP with the H^- beam (see Eq. 4.17, 4.18).

Table 6.1: Characteristics of laser-source for 50/80/107 MeV measurements

Parameter	Value
Wavelength	1064 nm
Peak power	max. 40 kW
Pulse length	1 ns...300 ns
Pulse frequency	35 kHz...500 kHz
Line-width	1 nm...5 nm
M^2	1.3

The transport of the laser beam to the beampipe was done by the type of LMA-fibre used previously [Nuf13]. The end-caps introduced for the 12 MeV setup as described in Sec. 5.4.1 were used similarly for the coupling into the transport fibre. The fibre length however had to be significantly increased to 73 m as the distance from the laser cabinet to the 50 MeV area in the accelerator tunnel had now to be bridged.

In regard to potential Brillouin scattering taking place in the transport fibre, the adjustable pulse-width and the line-width of $\lambda_L > 1$ nm are favourable. In reference to the framework developed in Sec. 4.4.2.4, the Brillouin threshold becomes 115 kW for a 100 ns long pulse with 1 nm line-width transported over 73 m. Therefore also in this setup no perturbations from non-linear effects inside the transport fibre are expected.

6.1.2.2 Laser System at IP

The overall setup to focus the laser beam into the vacuum vessel and scan it across the H^- beam was similar to the one used at the 12 MeV measurement campaign. The interior of laser delivery system to the accelerator beampipe shown in the red cube in Fig. 6.1 has therefore already been described in Sec. 5.1.2.4.

However the vacuum vessel for interaction with the H^- beam, as shown in Fig. 6.2, hosted exclusively the laserwire. Thus after the IP, an energy meter¹ could be installed to survey and simultaneously also dump the laser beam in a controlled manner. The characteristics of the pyroelectric energy meter are summarised in Table 6.2.

Table 6.2: Energy meter characteristics

Parameter	Value
Dimensions active area	50 mm x 50 mm
Absorption coeff.	83% ²
Surface inhomogeneity	< 0.5%
Noise level	10 μ J
Saturation level	15 J
Integration window	4 ms
Repetition rate	max. 200 Hz
Calibration uncertainty	$\pm 3\%$

¹Gentec QE50ELP-S-MB-DO-4ms-5m

²for $\lambda = 1064$ nm

Due to its large active area the energy meter can be used online over the whole scan range. The calibrated detector works in integrating mode such that it sums up a whole train of amplified laser-pulses which interact with one LINAC4 macropulse (see Fig. 4.16) to record its absolute energy value. The single laser-pulse energy can be calculated by combining the data with the laser-burst envelope recorded with a photodiode. For typical laser-bursts energies of 1...50 mJ the dynamic range is exploited just to a very little extent. However the signal to noise level is sufficient for this application and could just be increased by a smaller active area of the detector.

The reflected part of the incident beam exhibits an lambertian radiation pattern. Due to geometrical considerations no effect of this residual stray light on the H^- beam is expected.

A further modification was implemented for the 80 MeV and 107 MeV beam campaign, to monitor the laser pulse shape online just before interaction with the H^- beam. The photodiode mounted previously in the diagnostic line of the laser system (see Fig. 5.4) was replaced by a photodiode attached to the stage which scans the laser through the H^- beam as shown in Fig. 6.6.

In this way the photodiode data can be used to normalise the signal of the downstream electron-detector and thus reduce the measurement error caused by the laser pulse-to-pulse fluctuations (see Table 5.7).

6.1.3 Electron Detection

The setup for electron collection is the heart of the instrument used at 50/80/107 MeV beam energy. In this section, the dimensioning of a steerer magnet to deflect the liberated electrons and a sCVD diamond detector to record the electron signal shall be presented, in accordance with [H⁺15].

6.1.3.1 Electron Deflector

To dimension a suitable steerer magnet for electron deflection, the deflection angle was chosen to be 90° , in order to minimise the needed space along the accelerator z-axis. The required integrated field for this deflection can be calculated by applying the Lorentz force,

$$B \frac{l}{\alpha} = \frac{p}{e} \quad (6.1)$$

with B being the magnetic field strength, l the arc length, α the deflection angle and p the particle momentum. To calculate the maximum required integrated field $\int B \, dz$, the electron momentum was based on 160 MeV H^- beam energy for the permanent installation, resulting in $\int B \, dz = 1.6 \text{ mTm}$.

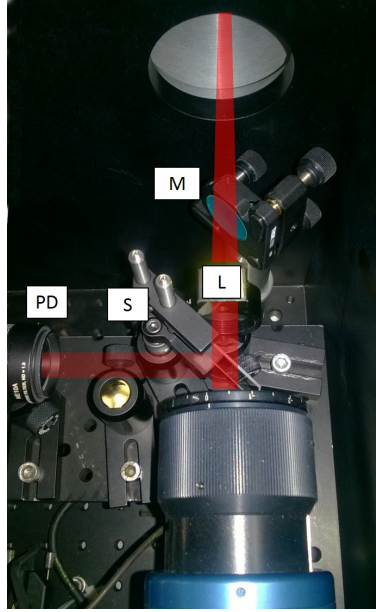


Figure 6.6: Focusing optics towards IP at 80 MeV setup. The laser beam exiting the beam expander is passing the single side AR-coated beam sampler (S) and the 500 mm lens (L) towards the IP with the H^- beam. The photodiode records the reflection of the beam sampler. In lowest position of the stage the laser beam is deflected by a mirror (M) towards a camera for measuring the M^2 of the laser beam.

Steerer magnets used routinely at LINAC4 to correct for angular misalignments in both planes can provide an integrated field of up to 3.5 mTm [C⁺12]. We therefore decided to modify one of these steerer magnets as a simple and cost-effective solution.

Fig. 6.7 shows a modified version of the LINAC4 steerer magnet. The upper and lower coils, which can be used for vertical deflection are not used in the electron deflector application. The left coil was replaced by a support frame to host the T-shaped beampipe where the stripped electrons are separated from the main H^- beam. The vertical B-field is thus generated by powering just the right coil, so that the composition acts as in a C-shaped magnet configuration.

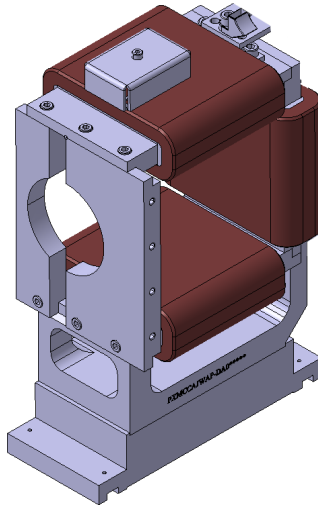


Figure 6.7: 3D model of modified steerer magnet for electron deflection.

6.1.3.2 Electron Tracking Simulation

The trajectory of the electrons in the magnetic field was simulated to verify, that the dimensions of the vacuum chamber are sufficiently large and to determine the spot size of the electrons in the plane of the diamond detector.

In the following it shall be assumed that the field strength can be linearly scaled with the coil current such that the simulation will be described just for the 50 MeV H^- beam scenario. In this case the electron kinetic energy is only 27 keV, as can be derived from the 50 MeV H^- energy and the proton to electron mass ratio. These low energy electrons can be deflected by 90° with an integrated field of only 0.9 mTm.

To predict the electron trajectories in the modified steerer field, a magnetic field-map was simulated with just one coil powered. In Fig. 6.8 the B-field in the y -plane is plotted. The trajectories for the stripped electrons were simulated using as input the beam dynamics data in the plane of the laser interaction ($x=0$ mm; $z=-83$ mm - see Appendix A.3) and the magnetic vector-field. In addition to the Lorentz force, space charge effect of the main H^- beam and synchrotron radiation was taken into account but had no significant effects on the path of the electrons.

The black curve in Fig. 6.8 represents the 6-sigma envelope of the electron trajectory when powering the magnet coil with a current of 4.7 A. The dark blue bar at $z=-60$ mm represents a shielding which surrounds the beampipe

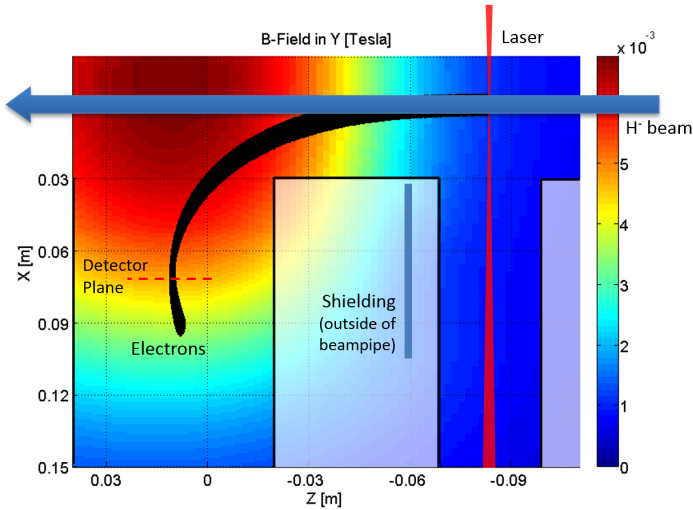


Figure 6.8: Magnetic field-map (in tesla) and electron trajectories (black) from the laser interaction point to the diamond detector. White areas are outside of beampipe.

between laser IP and steerer magnet. This shielding was designed to modify the magnetic field lines in order to avoid electrons being deflected too early after the stripping process and subsequently hitting the wall of the beampipe before reaching the extraction channel towards the electron monitor.

Fig. 6.9 visualises an overlay of electron distributions, generated during the laser scan process, arriving at $x = 72$ mm. It represents the superposition of the stripped electrons at multiple laser positions during the vertical laser-scan. For one laser position, the electron beamlet size in the detector plane would be $\sigma_z = 230 \pm 30 \mu\text{m}$ and $\sigma_y = 110 \pm 15 \mu\text{m}$. The detector position $x = 72$ mm was chosen, as this is the focal point generated by the weak focusing of the dipole.

6.1.3.3 Diamond Detector and DAQ System

The detector was dimensioned to be able to detect the electron signal of the 50 MeV H^- beam, which generates the lowest signal amplitude as compared to the 80 MeV, 107 MeV and 160 MeV beams. Thus in the following the 50 MeV use-case design will be discussed.

A laser pulse with $100 \mu\text{J}$ pulse-energy and 100 ns pulse-length is expected to detach approx. $5 \cdot 10^5$ electrons from the H^- ions. To sense these low energy

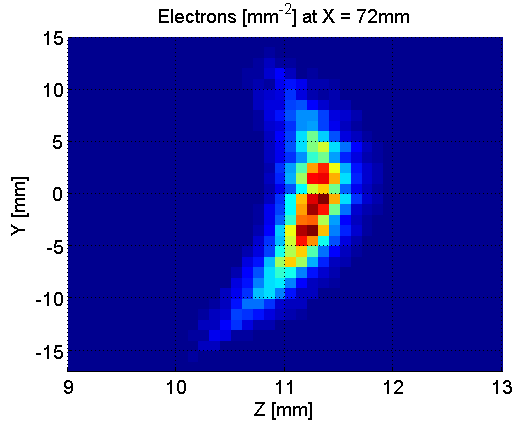


Figure 6.9: Expected electrons distribution at the detector plane, accounting for all laser positions during a scan.

electrons ($E_{kin} = 27 \text{ keV}$), a detector design with high sensitivity and high bandwidth (to cope with the short laser pulses) is required.

After considering various options, it was decided to use a single-crystal chemical vapour deposition (sCVD) diamond detector, capable of providing a fast response, high sensitivity and radiation hardness. The detailed specifications of the sCVD material can be found in the Appendix in Fig. C.9. The ultra-compact detector design, which allowed movement in the beampipe ($\varnothing = 60 \text{ mm}$) has been developed in collaboration with CIVIDEC GmbH. A picture of the detector that was recently installed in the laser profile meter tank assembly is shown in Fig. 6.10.

The front electrode of the detector facing the electron beamlet is bonded to ground potential all around its perimeter to avoid electro-magnetic disturbance from the main H^- beam passing just 72 mm away from the detector.

Special attention has been given to the layer composition of this front electrode as the low range of the 27 keV electrons ($6 \mu\text{m}$ in diamond) requires it to be as thin as possible to minimise energy loss. Table 6.3 lists the front electrode layer materials and associated energy loss. In summary for the scenario with lowest beam energy at 50 MeV, 3.2 keV of the electron energy is absorbed in the electrode layers while 23.8 keV is left to create a signal in the diamond bulk.

The electron signal generation and read out is sketched in Fig. 6.11. The 23.8 keV energy deposition creates electron hole pairs, each requiring 13 eV (see Eq. 4.34). This means that a charge of $1.5 \cdot 10^{-10} \text{ C}$ is created from the

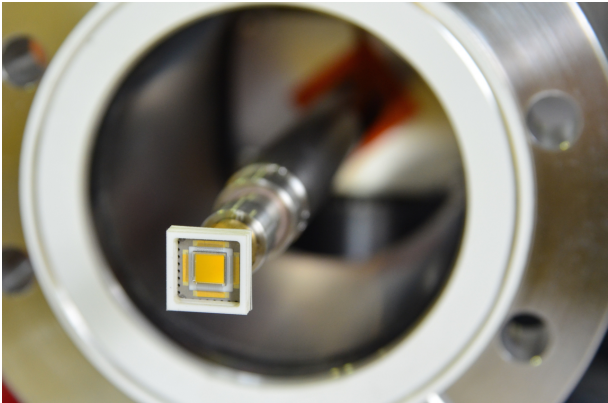


Figure 6.10: sCVD diamond detector [Gri15a] mounted on the actuator that is part of the laser monitor assembly for the 50/80/107 MeV measurement campaigns.

Table 6.3: Diamond detector layer composition and energy loss for 50 MeV scenario

Layer	Thickness	Energy Loss of e^-
Gold	250 nm	2.3 keV
Platinum	120 nm	0.7 keV
Titanium	100 nm	0.2 keV
Diamond	500 μm	23.8 keV

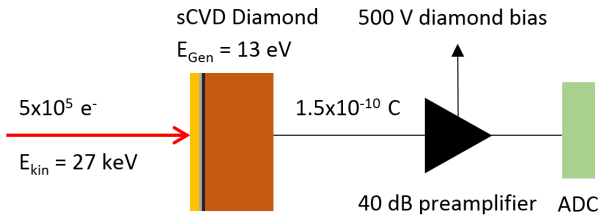


Figure 6.11: Signal creation and readout of the diamond detector.

$5 \cdot 10^{-5}$ electrons generated by each laser pulse, which can then be read out via the applied bias of 500 V. The single crystal diamond material provides hereby almost full charge collection efficiency ($> 95\%$ - see Fig. C.9). The charge is then amplified and converted to a voltage signal that can be digitised by a

1 GS/s Analogue-to-Digital-converter. The general layout and timing of the DAQ and controls system stayed similar to the setup at the 3 MeV and 12 MeV beam tests described in Sec. 5.1.4.

In order to minimise electromagnetic coupling and integration of background due to residual gas stripping (see Sec. 4.3), it was decided to produce a detector with a relatively small surface (4 mm x 4 mm). In this way also parasitic capacitances were avoided and thus the detector bandwidth maximised.

To ensure the collection of all electrons during a scan (see Fig. 6.9) with such a small detector, the diamond is mounted on an actuator that is moved in synchronism with the laser. As the laser beam diameter is approx. 150 μm , the electron beamlet will be spread out less than one millimetre in the y -plane of the detector. Therefore no electrons missing the diamond detector are expected.

6.2 System Characterisation

In this section, the verification of the most relevant system characteristics shall be described. Regarding the laser system, the light-transmission over the 73 m long transport fibre was measured and the laser beam parameters (M^2 , pulse to pulse fluctuations, peak power) were characterised at the IP with the H⁻ beam, as this is most crucial for the system performance.

The novel sCVD diamond detector was characterised with a radioactive source to verify its specifications regarding its response to single particles.

6.2.1 Laser Characteristics at IP

The transmission characteristics of the laser beam to the beampipe was verified experimentally prior to the measurement campaign, to make sure that the end-caps reliably protect the fibre end-facets and the transmitted laser pulses are not degraded by SBS.

In the desired working point ($t_{pulse} = 100 \text{ ns}$; $f_{laser} = 60 \text{ kHz}$; $t_{amp} = 3 \text{ ms}$; $T_{rep} = 1.2 \text{ s}$ - see Fig. 4.16) the laser was coupled into the 73 m long transport fibre as discussed in Sec. 6.1.2.1. With the usage of a calibrated energy meter the total energy of the amplified laser-burst before and after the fibre was recorded while the transient behaviour of the laser pulses was monitored with fast photodiodes.

By normalising the photodiode signal by the burst-energy, the absolute laser power for the single laser pulses was obtained as shown in Fig. 6.12. The pulses after transmission are clearly delayed by 375 ns, which corresponds to

the light propagation along 73 m. Distortions in pulse shape and pulse width cannot be observed even for peak powers above 2 kW.

The plot in Fig. 6.13 shows a transmission $>75\%$ below 1 kW peak power and slightly lower transmission for higher pulse peak powers. Measurements with 5 ns, 10 ns and 30 ns pulse lengths showed similar behaviour. As no transmission dependence on the pulse length and no sudden drop at a certain power level was observed, no influence of SBS on the fibre transmission is expected and the slight drop of transmission is attributed rather to increasing coupling losses.

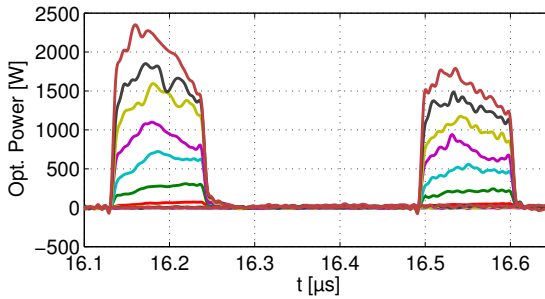


Figure 6.12: Laser pulses with different energies before (left) and after fibre (right).

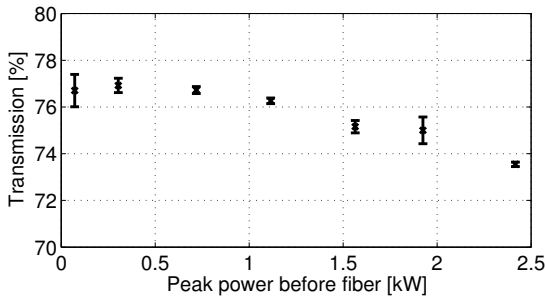


Figure 6.13: Transmission of laser over 73 m LMA fibre. [H^+ 15]

To verify the resolution of the instrument, the spatial properties of the laser beam at the IP were measured with the setup described in Sec. 5.1.2.4. The result is plotted in Fig. 6.14 and shows improved performance as compared to the laser characteristics at the 3/12 MeV measurement campaigns. Due to the lower M^2 factor, the Rayleigh length is longer in both planes and the waist is slightly thinner. The observed astigmatism is not perturbing the resolution of the instrument as only the vertical plane is relevant.

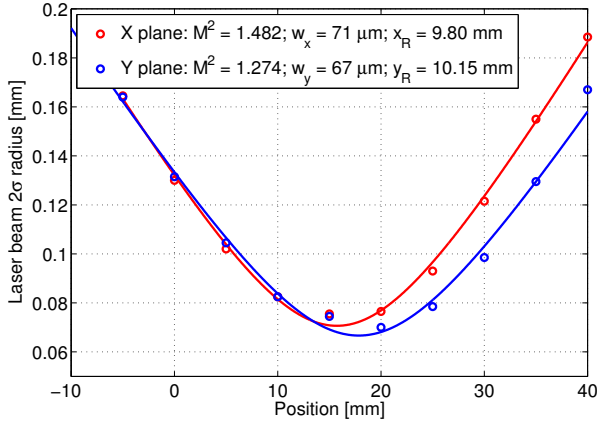


Figure 6.14: Spatial characteristics of laser beam in IP with H beam.

Pulse-to-pulse fluctuations in the laser power are a significant error source of the instrument as it has been shown in Table 5.7. The new laser-source has been therefore characterised recording a high number of pulses and summarising them in a histogram (Appendix: Fig. C.1). It showed an RMS pulse stability of 3% after propagation through the 73 m fibre. To eliminate this introduced error, the signal of the diamond detector shall be normalised by the photodiode signal recorded just before the IP (see Fig. 6.6).

6.2.2 Response of sCVD Diamond Detector

The novel sCVD diamond detector was tested with an α -source prior to the installation in the vacuum vessel. The focus was to test its proper operation rather than a detailed characterisation of its parameters. A laboratory setting similar to the one used previously (see Fig. 5.15) was established for the new detector. However in this setup the α -source could be placed directly above the diamond surface (gap < 1 mm) so that the energy loss of the α -particle in the airgap could be neglected. The detector readout was accomplished as sketched in Fig. 6.11.

Fig. 6.15 shows the result of a 60 s recording with a bias voltage of +500V applied on the diamond. To check roughly the CCE of the material, the charge for 100% CCE, scaled with amplifier gain (40 dB) was calculated:

$$\int I dt = \frac{E_{kin,\alpha}}{E_{Gen}} \cdot CCE \cdot Gain = 6.7 \text{ pC} \quad (6.2)$$

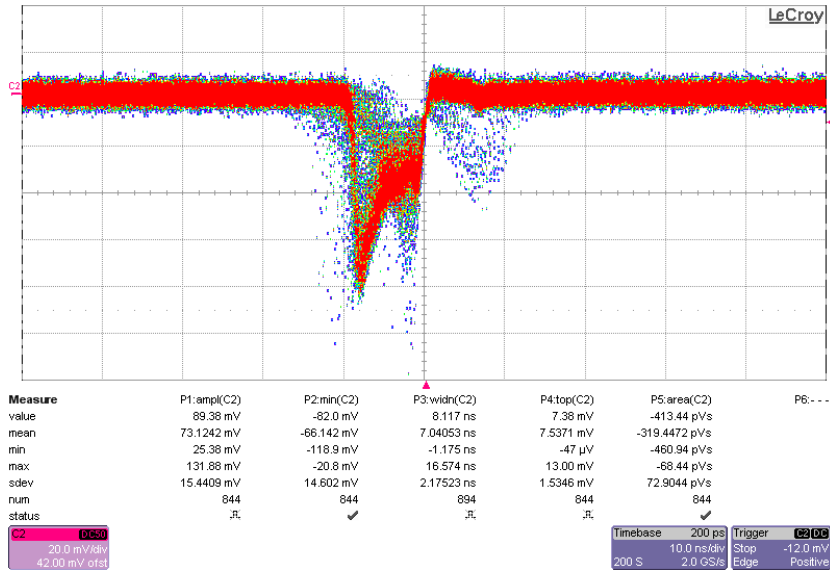


Figure 6.15: Result plot of detector test with α -source - Multiple traces of single α -particle impacting on the diamond.

Comparing this with the measured signal (see P5:area in Fig. 6.15), scaled with the oscilloscope impedance shows a good agreement with the predicted charge for CCE = 100%:

$$Q_{meas} = \frac{3.2 \cdot 10^{-10} \text{ Vs}}{50 \Omega} = 6.4 \text{ pC} \quad (6.3)$$

As in this setup a linear amplifier was used, the signal shape follows directly from the charge-carrier movement inside the detector bulk. Shown in Fig. 6.16, the induced current of an α -particle exhibits a sharp spike at the start due to the short drift length of the generated holes to the lower electrode followed by a rectangular current pulse created by the drifting electrons to the upper electrode. This behaviour can also be observed in Fig. 6.15 although the peak is broadened by the parasitic capacities.

For the measurements with the H^- beam this behaviour will not be visible anymore as the high number of particles, hitting the diamond simultaneously will add up to a single 100 ns long pulse. In these conditions the detector will be characterised in more detail (see Sec. 6.3.2).

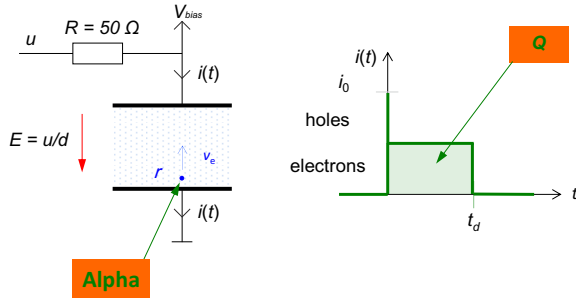


Figure 6.16: Signal created by low-energy particle like α (or also low energy electrons) being absorbed close to the impinging surface. [Gri15b]

6.3 H^- Beam Measurements

In this section, the 3 measurement campaigns at 50 MeV, 80 MeV and 107 MeV shall be summarised.

Comparing the setup, targets and results of all measurements campaigns, very little differences have been found. Therefore it was decided to merge the results and comment on differences where necessary in order not to be repetitive.

6.3.1 H^- Beam Parameters

The H^- beam parameters at these measurement campaigns were manifold as different quadrupole settings were tested. Therefore only ranges can be stated here for the relevant parameters. As simulations demonstrate, typical beam sizes in terms of $\sigma_{x,y}$ do not exceed 2.5 mm in both planes [T⁺10]. The RMS divergence is also similar in both planes between 1 mrad and 2 mrad.

In terms of beam intensity, the source delivered an average pulse current between 8 mA and 20 mA depending on the performance of source and transmission through the previous accelerator structures. Due to the permanent use of the chopper, the beam macropulse was reduced from 400 μ s to 100 μ s (compare Fig. 4.16).

The different beam energies (50 MeV, 80 MeV and 107 MeV) were influencing mainly the setting of the steerer magnet current in order to generate a magnetic field to deflect the electrons always by 90°. At the diamond detector, the signal amplitude rises with beam energy as the ionisation inside the diamond is proportional to the kinetic energy of the impinging electron (see Eq. 4.35).

The photo-detachment yield is also influenced by the relativistic Doppler shift as described in Sec. 4.2.3. Minor changes of the process cross-section

σ_{PD} have been summarised in Table 6.4, together with the laser wavelength λ' in the rest-frame of the H^- beam for the relevant beam energies.

Table 6.4: Change of photo-detachment cross-section due to relativistic Doppler-effect

E_{kin} [MeV]	λ' [nm]	$\sigma_{PD}[10^{-17}\text{cm}^2]$
0	1064	3.68
50	1010	3.86
80	980	3.94
107	957	3.98

6.3.2 System Characterisation on H^- Beam

Before the first measurements of the vertical profile of the H^- beam were accomplished, the instrument itself was characterised regarding its performance. After describing the working point of the instrument, the analysis method to calculate the pulse integral for each electron pulse arriving at the diamond detector will be described. This will be used to characterise the linearity of the instrument and the size of the arriving beamlet at the diamond detector. Eventually the means to minimise the error for each laser-position will be described.

6.3.2.1 Working point of instrument

The parameters of the laser have been already summarised in Table 6.1. For interaction with the H^- beam a laser pulse-length of 100 ns was chosen and the pulse frequency was set to 86 kHz (synchronous to the LINAC4 bunch frequency of 352.2 MHz). Each truncated LINAC4 macropulse was therefore interacting with 9 laser-pulses. The laser pulse-power could be set to a comparably low value of approx. 100 W, as signals in the range of hundreds of millivolt were already obtained with this setting and the output voltage range of the pre-amplifier was limited to ± 1 V.

6.3.2.2 Analysis of raw signal

Fig. 6.17 shows the signal of the diamond detector recorded on a 80 MeV H^- beam with average beam current of 14 mA. Each segment corresponds to a $1.5\mu\text{s}$ long time-frame sampled at 1 GS/s, recorded synchronous to the 86 kHz laser frequency. The 9 pulses are respectively the signals of the liberated electrons by the laser-pulses.

In Fig. 6.18 one of the segments is plot versus time. In comparison to the H^0 signal recorded at the 3 MeV and 12 MeV measurement campaigns no back-

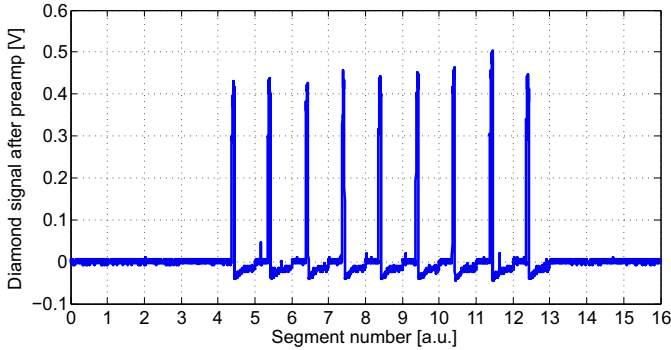


Figure 6.17: Diamond signal recorded in segments.

ground floor is visible as the electrons are bend by 90° before they hit the detector. Therefore no background subtraction is needed to determine the integral of laser-liberated electrons. As it is marked in red, the integral limits were defined coarsely and the integration was accomplished just over the positive values (yellow surface) in order to exclude the re-charging of the AC-coupled detector. By repeating this procedure for all segments and averaging the results, the mean photo-detachment yield is gained.

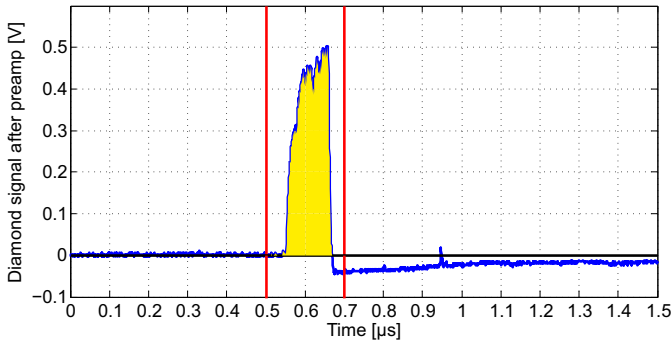


Figure 6.18: Single segment of diamond signal.

It shall be mentioned, that in certain circumstances the raw signal of the diamond detector was not as clear as shown in Fig. 6.18. Especially for sub-optimal quadrupole settings with high losses or if the beam is intercepted upstream of the laser-station by a wire (SEM-grid, wire-scanner or BSM), scattered particles are arriving at the diamond detector. While in normal beam settings this is very rare (see single hit at $0.95\mu\text{s}$ in Fig. 6.18), can become a main error source as shown in Fig. 6.19. It is assumed, that the spikes originate

from proton, H^0 or H^- hits on the detector, which cause much more ionisation inside the diamond material than the photo-detached electrons according to their mass-ratio (see Sec. 4.5.3). It was therefore avoided to work with different instruments in parallel for the characterisation of the H^- beam.

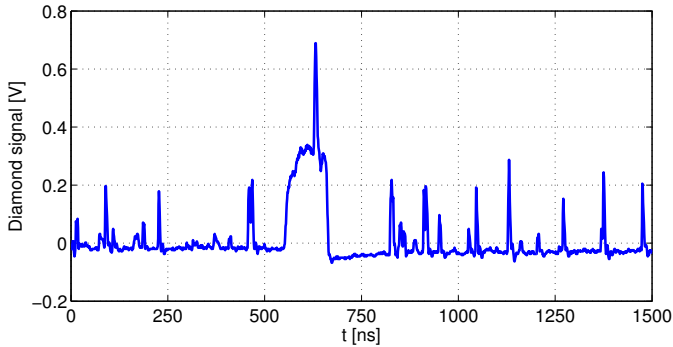


Figure 6.19: Raw signal of diamond detector; Photo-detached electron pulse and single particle hits.

6.3.2.3 Linearity of Diamond Detector Response

To determine the linearity of the diamond detector, a scan of the laser pulse energy was used similar to Sec. 5.4.5.4 to generate different electron fluences.

Using the integration method, described previously, Fig. 6.20 shows the integrated charge read out from the diamond detector versus the signal of the photodiode previous to the IP (see Fig. 6.6).

In this way energy-fluctuations of the laser-pulse do not perturb the measurement as the corresponding signal from the diamond detector can be assigned pulse to pulse. It can be seen from the plot, that the response of the diamond detector follows very linearly the photodiode signal ($\chi^2 = 0.08$). The small offset of the diamond integral was caused by the proton background present at this measurement at 50 MeV H^- beam energy as shown in Fig. 6.19.

Similar measurements have been accomplished at 80 MeV and 107 MeV beam energy. Although the gradient of the curves differ due to the increased kinetic energy of the impinging electrons, the linearity of the detector response is similarly good.

The energy meter installed after the IP (see Fig. 6.2) could be used independently to check the linearity with the advantage to have even an absolute reading of the laser pulse energy. The result of this measurement can be found

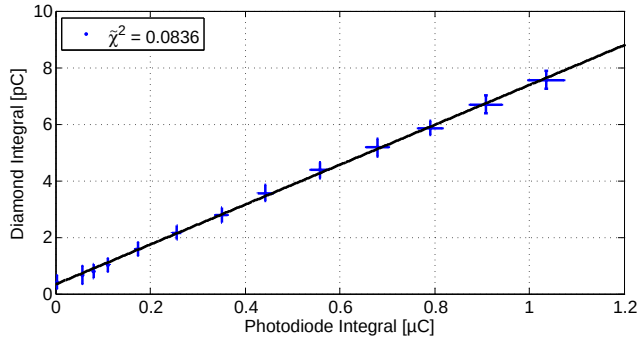


Figure 6.20: Integral of pulse recorded with diamond detector versus integral of pulse recorded with photodiode before the IP with the 50 MeV *H* beam (see Fig. 6.6).

in the Appendix in Fig. C.5. It shows similar good linearity as the measurement with the photodiode.

6.3.2.4 Measurement of Beamlet Size

In Sec. 6.1.3.2 the liberated electron beamlet was tracked after the laser interaction via the steerer-field towards the diamond detector. Due to the small beamlet sizes expected (Fig. 6.9), a very compact detector with just 4 mm x 4 mm cross-section was designed.

The following measurements carried out at 80 MeV beam energy were characterising the beamlet size in the detector plane experimentally. Keeping the laser at constant position, a scan of the *y*-plane¹ was carried out with the diamond detector. The scan in the horizontal plane (*z*-coordinate) was performed by varying the current of the steerer magnet and hereby moving the beamlet position in the *z*-plane.

The signals arriving at the diamond detector were processed according to the analysis method described in Sec. 6.3.2.2. Hereafter the integrated charge was plotted in the *y*-*z*-plane of the diamond detector as shown in Fig. 6.21, whereas the horizontal axis was derived by simulating the beamlet position as a function of different magnet currents.

To deduce the size of the beamlet arriving at the detector from the acquired data in Fig. 6.21, the derivative in the *y*- and *z*-plane needs to be calculated. As it can be seen already qualitatively from Fig. 6.21, the beamlet size is approx. constant for different *y*- and *z*-positions. In Fig. 6.22 the projection along the

¹Coordinate orientation as in Fig. 6.8 and 6.9.

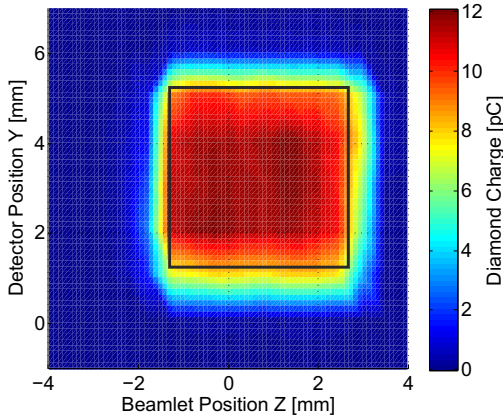


Figure 6.21: Signal of diamond detector for different detector positions in y and different beamlet positions in z ; Black frame as comparison to 4 mm x 4 mm surface of diamond detector.

y -axis shows, how the beamlet size is obtained. Summarising many measurements, the beamlet has a size of $\sigma_z = 0.4 \pm 0.1$ mm and $\sigma_y = 0.45 \pm 0.1$ mm.

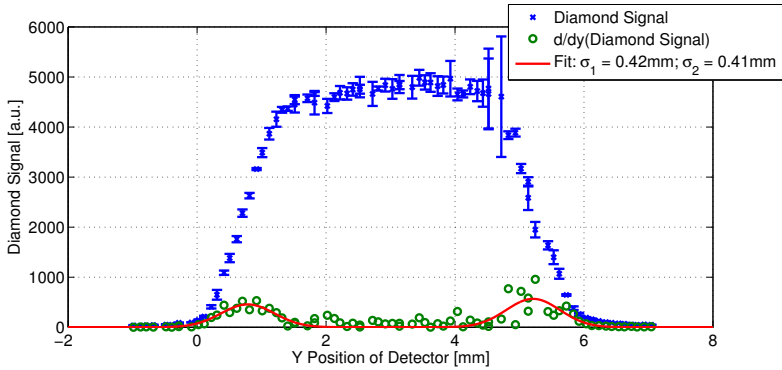


Figure 6.22: Fine scan of vertical detector position. Derivative of signal corresponds to the vertical size of the beamlet arriving at the diamond detector.

Comparing the results with the simulated beamlet sizes from Sec. 6.1.3.2 shows an increase of the measured beamlet size by a factor 2 in the z -plane and 4 in the y -plane. The observed broadening can be attributed to stray fields of the magnetic field, deflecting the electrons slightly in the z - and y -plane. The most significant result is however that the detector surface is clearly sufficiently big to collect all arriving electrons per beamlet, this is also visible through

the uniform signal plateau in Fig. 6.21. Similar results have been observed at 50 MeV beam energy.

6.3.2.5 *Error Minimisation*

The last part of the characterisation of the instrument concerns its precision. In Table 5.7, the dominant error sources of the 3/12 MeV measurement campaigns have been summarised. To minimise these errors, a number of improvements have been implemented and the effect of them on measurements at 107 MeV beam energy shall be described in the following.

With the new laser source used for the measurements, which is described in Sec. 6.1.2.1, it was for the first time possible to synchronise the laser frequency to the H⁻ macropulse. This eliminates completely the time jitter of $1/f_{laser}$ and subsequently the associated error. As can be seen in the macropulse shape in Fig. C.3, the H⁻ beam current is typically rippled but the shape stays constant for many pulses. Especially for a scanning type of instrument it is thus essential to establish a constant phase relation for the laser-pulses and the H⁻ macropulse.

To compensate for the pulse to pulse fluctuations of laser and H⁻ beam, both have been recorded in order to normalise the results. The H⁻ beam current was recorded with the BCT at the end of the test-bench (see Fig. 6.1) and the laser was sampled with a photodiode just before the IP with the H⁻ beam (see Fig. 6.6).

In a test run electrons created by interaction of laser-pulses with 320 LINAC4 macropulses were recorded with the diamond detector at constant laser position. For each laserpulse recorded with diamond and photodiode, the integral was built. For the BCT signal the average over a whole macropulse was calculated.

Fig. 6.23 compares for each macropulse the recorded beam current and the mean integral at the diamond detector. A correlation between both signals can be observed although especially at the beginning and the end it is also visible that the H⁻ beam current is not the only effect influencing the signal of the diamond detector.

Fig. 6.24 visualises the correlation between the signals of the diamond detector and the photodiode. By normalising the signal of the diamond detector with both, photodiode and BCT signals, the RMS-error of the diamond detector could be reduced from 4.6% to 2.5%. Comparing this value with the error for one sample in phase-space in the 3 MeV campaign (9%), it can be concluded that the provisions described earlier could improve significantly the precision of the instrument.

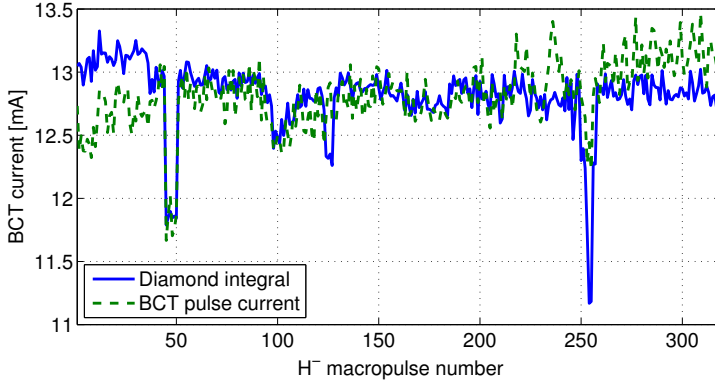


Figure 6.23: Comparison of mean H^- pulse current with signal from diamond detector.

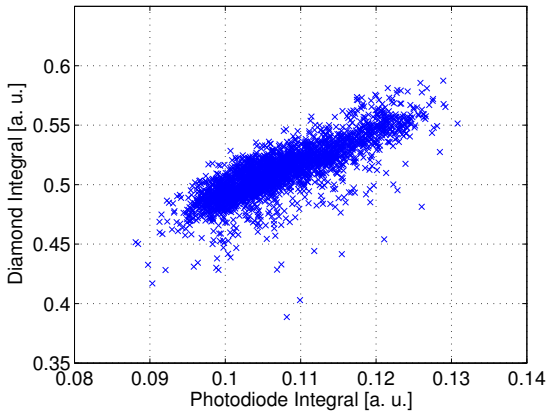


Figure 6.24: Correlation between integrals of diamond detector and photodiode for all laser-pulses in the test run.

6.3.3 H^- Beam Profile Measurements

The measurement of the vertical size of the H^- beam with the laserwire instrument has been performed for all beam energies (50 MeV, 80 MeV and 107 MeV) in a similar manner. In the following the procedure shall be described on the basis of a data-set recorded at 50 MeV.

Fig. 6.25 shows the result of scans of the laser and diamond detector both in the vertical plane. The diamond charge for each position has been deter-

mined as described in Sec. 6.3.2.2 and averaged over the number of recorded laserpulses. This 2D-scan procedure was used for profile measurements as the divergence of the beam is not known in advance and therefore for each laser-position the position of the arriving beamlet needs to be determined by scanning the diamond detector.

The data resemble a vertical phase-space measurement (compare Fig. 5.34), so an extraction of the vertical emittance value by calculating the beamlet size for each laser position as shown in Sec. 6.3.2.4 seemed to be conceivable. In practise however the resulting emittance values were significantly higher than expected by simulations. This discrepancy is a clear effect of the magnetic field components in the z - and x -plane, which can easily deflect the light electrons in the y -plane, which shows that the emittance measurement by H^0 detection is definitely favourable.

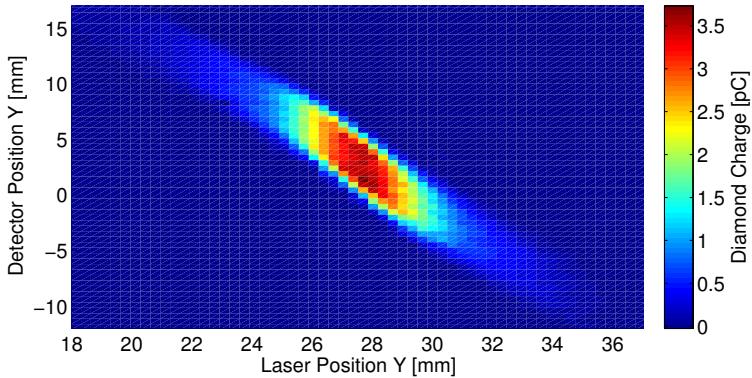


Figure 6.25: Diamond signal for different laser and detector positions.

To extract the vertical beam profile from the 2D-data, the maximum value was used for each laser position to plot the profile as can be seen in Fig. 6.26.

6.3.4 Comparison of Results with SEM-grids and Wire-scanners

To verify the accuracy of the H^- beam profile obtained with the laserwire instrument, a comparison with other instruments was foreseen similar to the 3/12 MeV campaign. Given that in the current setup no instrument was located in the same plane of the laser, the SEM-grids and wire-scanners¹ closest to the

¹In the following abbreviated SEM and WS; functionality see Fig. 2.4 and right in Fig. 2.7

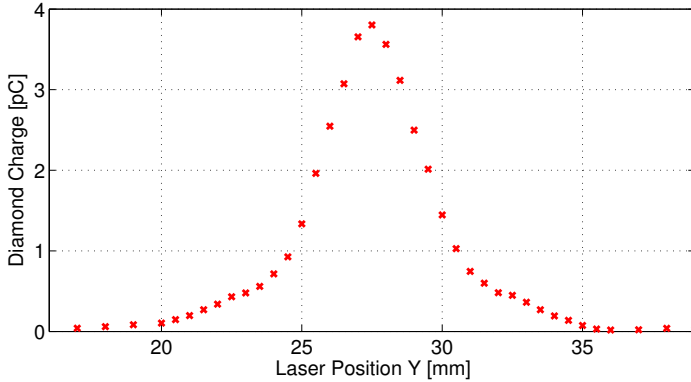


Figure 6.26: Beam profile of 50 MeV beam, measured with laserwire instrument.

laser-position (see Fig. 6.1) were used as reference. In the following the combined wire-scanner and SEM-grid station upstream of the laser is referenced with the index 2 while the station downstream is indexed 3.

In Fig. 6.27 data-sets recorded at 107 MeV beam energy with different devices are compared along the time of a LINAC4 macropulse. In each recorded time-slot a profile was calculated and the σ of its Gaussian profile is plotted. The size of the errorbars, being the result of multiple profile measurements, clearly indicate the start and the end of the 100 μ s long macropulse¹. The grey bars indicate the limits for the calculating the averaged beam profile. As between 390 μ s and 430 μ s a beam instability can be observed, these values were excluded.

To check the accuracy of the recorded profiles with the laserwire system, the results from the SEM-grids and wire-scanners were scaled to the position of the laserwire. Given that no quadrupole magnet is situated between SEM2/WS2 and SEM3/WS3, the beam size and respectively the recorded profiles could be interpolated linearly in between. Figure 6.28 shows the scaled profiles of all 5 recorded instruments averaged over the time-frame limited by grey bars in Fig. 6.27 and errorbars corresponding to measurements at multiple macropulses.

The discrepancy of the profile recorded with the laserwire instrument with respect to the linear interpolation between the SEM/WS profiles have been monitored for multiple measurements at different beam energies and differ-

¹The small errorbars of both wire-scanners between 350 μ s and 390 μ s are the result of scattered particles of the second wire and therefore not relevant in this measurement.

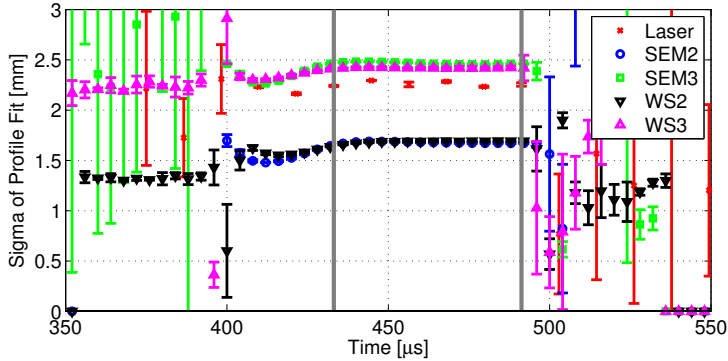


Figure 6.27: Comparison of profile sigma along the LINAC4 macropulse (390 μ s...490 μ s), measured with different devices.

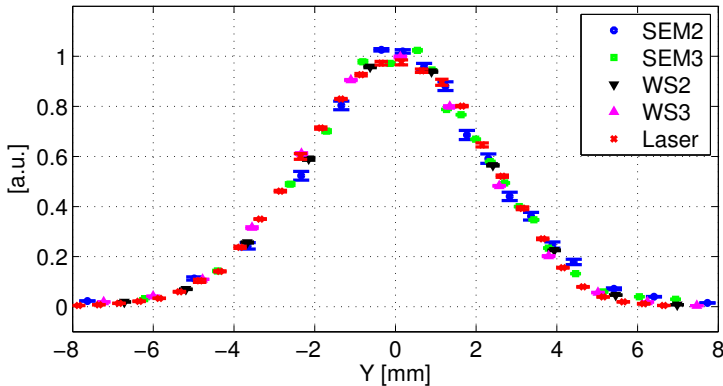


Figure 6.28: Overlay of profiles, recorded at 107 MeV energy with different devices.

ent beam settings. The error has been consistently below $\pm 2\%$ regarding the sigma of the beam. This is similar to the discrepancy observed between wire-scanner and SEM-grid profiles recorded at the same position. In terms of the errorbars for single samples in the profile, the laserwire system showed similar performance as the WS and SEM profiles although operating on much lower sampling rate¹ along the LINAC4 macropulse (see Fig. 6.27).

Further profile plots for 50 MeV and 80 MeV beam energy and their comparison with SEM-grids can be found in the Appendix (Fig. C.6, C.7).

¹Corresponding to 86 kHz laser frequency.

6.4 Summary

For the measurement campaigns at 50/80/107 MeV the instrument setup has been fundamentally changed as it was aimed to measure the vertical beam profile by sensing the detached electrons.

In this regard, a new detector has been designed on basis of sCVD diamond material and a LINAC4 steerer magnet could be adopted to act as an electron deflector. The trajectory of the electrons, after being stripped from the H^- ions, through the magnetic field of the steerer was tracked. Hereafter the interaction of the electrons with the diamond detector was simulated. A comparison of the simulation with the obtained data from the beam measurements showed good agreement.

In view of the upcoming permanent installation of laserwire systems at 160 MeV, a laser cabinet has been installed to host a new laser source and the setup to couple the beam into the transport fibre. The fibre transmission over up to 73 m to the accelerator tunnel has been successfully commissioned and the laser beam has been characterised in the IP with the H^- beam. Due to the new laser source the beam quality at the IP could be significantly improved ($M^2 < 1.5$). The laser setup at the IP was adopted from the 3/12 MeV measurements with minor enhancements.

The measurements on the H^- beam were carried out at many different beam settings and energies. The instrument was characterised in terms of the electron detector's linearity and the size of the beamlet in the detector plane. The beamlet size proved to be much smaller than the detector dimensions as simulated previously and the results for the detector linearity proved to be adequate as well ($\tilde{\chi}^2 = 0.08$). Finally the provisions to reduce the measurement errors were verified, showing that the errors were reduced by more than a factor of 3 with respect to the 3/12 MeV setup.

The H^- beam vertical profile measurements have been performed at all 3 commissioning steps (50 MeV, 80 MeV and 107 MeV). Detailed analysis of the results has been carried out and a comparison with wire-scanners and SEM-grids installed in the vicinity of the laserwire instrument has been conducted. In all investigated beam settings a distinct agreement in beam-shape and an accordance within $\pm 2\%$ in terms of beam-width between all instruments has been measured.

Chapter 7

Design of Combined Emittance and Profile Meter for 160 MeV H^- Beam

It was mentioned already in the introduction of this thesis (Sec. 1.2.2) that the final destination of this novel type of instrument shall be the LINAC4 160 MeV region to monitor periodically the transverse beam parameters in x - and y -domain prior to injection of the H^- beam into the PS-Booster.

In this chapter the design and setup of 2 stations to measure transverse profiles and emittances shall be comprehensively described.

7.1 LINAC4 160 MeV Region

In Fig. 1.8 the 160 MeV region after the end of the PIMS-cavities has been shown. It was decided to install 2 laserwire stations in this area to be able to compare the results from independent instruments as both locations for laser interaction have pros and cons.

In the first location much H^0 background created by residual gas collisions along the LINAC perturbs the measurement of the laser-stripped H^0 beamlet (as simulated in Sec. 4.3.6). Furthermore the measurements can just take place when it is ensured that no LINAC4 pulse is going straight to the main dump in the upcoming time-frame for an emittance measurement (≈ 30 s). This restricts the usage scenarios for the instrument as the direction of a macropulse is often changed from pulse to pulse depending on the final destination in the CERN accelerator complex.

In the second location the H^0 background is much lower and the magnet is interlocked such that no full LINAC4 macropulse can go straight through the magnet, so the H^0 detector can be used all the time. However, at this location between the 2 main bending magnets the H^- beam is not dispersion-free. This

means that the horizontal beam distribution is perturbed by the momentum-spread of the particle distribution.

7.1.1 160 MeV H⁻ Beam Parameters

During the machine operation for injection into the PS-Booster the parameters of the H⁻ beam are stable and very well defined. It has been agreed with the operations team of LINAC4, that the laserwire will be used primarily on these nominal H⁻ beam parameters. They are summarised in Table 7.1¹, which have implications for the H⁰ detector design regarding its position, size and resolution.

Table 7.1: H⁻ beam characteristics summary on both IP with the laser

Parameter	IP 1	IP 2
RMS beam size [mm]	$\sigma_x = 1.2; \sigma_y = 2.9$	$\sigma_x = 2.1; \sigma_y = 2.5$
RMS divergence [mrad]	$\sigma_{x'} = 0.46; \sigma_{y'} = 0.51$	$\sigma_{x'} = 0.83; \sigma_{y'} = 0.31$
Dispersion [mm]	0	1270
Beam current [mA]	64.5 ²	64.5

The influence of dispersion is purely on the horizontal plane, where the dipole enlarges the beam size due to the energy spread of the particle beam. Eq. 2.16 needs thus to be adapted to

$$\sigma_x = \sqrt{\epsilon\beta + \left(D(z) \cdot \frac{\Delta p}{p}\right)^2} \quad (7.1)$$

with $D(z)$ the dispersion function and $\Delta p/p$ being the RMS energy spread of the H⁻ distribution (see Fig. A.4). Reconstructing the horizontal emittance, this has to be taken into account in the second laser location.

Fig. 7.1 shows the dispersion function at the bending magnets. As the second laser had to be placed in a high dispersive region (at red line), it is even more important that the first laser is in the straight line (upstream of the plot), to cross-check their results.

¹More detailed beam characteristics have been visualised in Fig 4.2 and Fig A.4

²40 mA beam average current as specified in [GV⁺06] scaled with 1/0.62 chopping ratio.

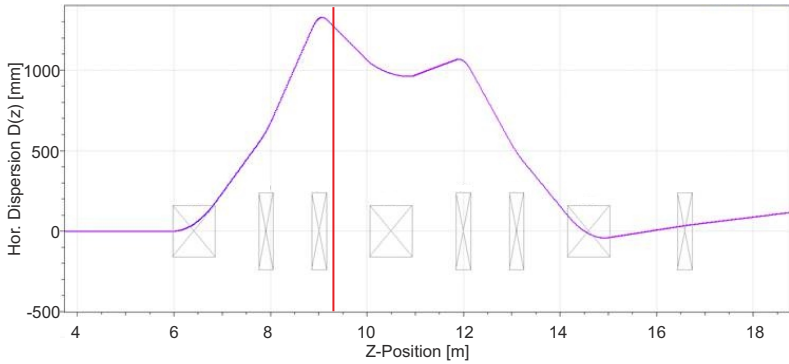


Figure 7.1: Dispersion function at 3 main bends (gray squares). The red line marks the location of laser station 2.

7.2 Photo-Detachment Simulation

The photo-detachment process has been described on a single particle level in Sec. 4.2.2. This approach shall now be applied to the H^- particle distributions in both positions to calculate the yield of the interactions. Furthermore the size of the H^0 beamlets arriving at the detector will be simulated. The obtained results will be used to dimension the detector geometrically and estimate its signal output.

7.2.1 Interaction Yield

For the yield calculation, the laser parameters are assumed to be the same in all 4 interaction points as summarised in Table 7.2. Using the H^- beam parameters described in Table 7.1, the yield for laser interaction with the centre of the H^- beam can be simulated. The number of created H^0 in the 4 IPs are listed in Table 7.3.

Table 7.2: Laser parameters used for yield calculation

Parameter	Value
Laser pulse length [ns]	100
Laser peak power [W]	1000
Laser waist radius [μm]	70

Table 7.3: Photo-detachment yield for laser in centre of H^- beam

Scan direction	Vertical	Horizontal
Position 1	$6.9 \cdot 10^5$	$1.8 \cdot 10^6$
Position 2	$7.9 \cdot 10^5$	$1.0 \cdot 10^6$

Due to the similar H^- beam size in all planes, the results are in the same order of magnitude. In Sec. 7.3 these values will be used to dimension the electron- and H^0 -detectors.

7.2.2 H^0 Beamlets

The angular resolution of the emittance measurement is strongly dependent on the size of the arriving beamlet at the detector and therefore the distance between laser IP and H^0 detector. In an iterative process where many geometrical restrictions were taken into account a distance from laser-IP to the H^0 detector of 7.16 m in position 1 and 4.46 m in position 2 was defined.

The laser stripping simulation was accomplished in all 4 interaction planes. Detailed results shall be presented however just exemplary for a vertical laser-scan in position 2, followed by a summary for the simulations in all IP's.

By using the laser and H^- beam characteristics defined in Table 7.1 and Table 7.2, the laser interaction can be conducted on a single particle level. Scanning the laser through the H^- beam and propagating the stripped H^0 towards the detector, the beamlet distribution can be visualised. Figure 7.2 shows an overlay of 5 beamlets created by the laser-scan and arriving in the detector plane. The parameters of the H^0 distributions were extracted and plotted separately in Fig. 7.3.

In Table 7.4 the mean σ of the beamlets in the detector plane are summarised for all IP's. This data is most relevant to dimension the size and resolution of the H^0 strip-detectors.

Table 7.4: Simulation results for the H^0 beamlets created by horizontal and vertical laser scans in both instruments

Scan direction	Position 1		Position 2	
	Horizontal	Vertical	Horizontal	Vertical
$\bar{\sigma}_x$ [mm]	2.6	4.15	1.1	1.94
$\bar{\sigma}_y$ [mm]	1.4	1.2	4.3	0.9

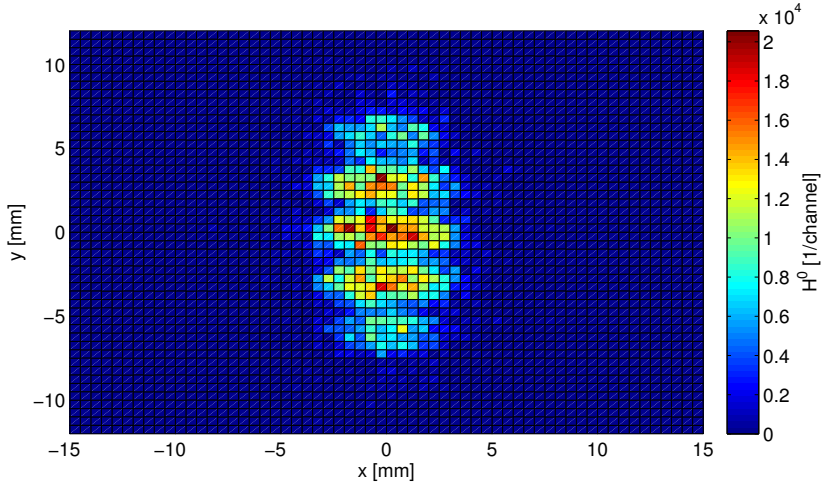


Figure 7.2: Vertical laser scan at second laser IP; Overlay of 5 arriving beamlets in the detector plane.

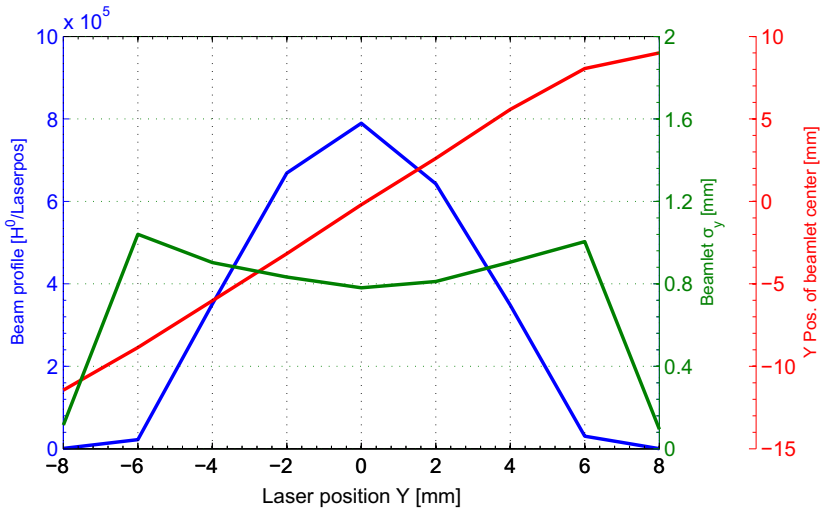


Figure 7.3: Simulated laser scan. For each laser position the number of stripped H^0 (blue), the width σ_y of the H^0 beamlet (green) and the vertical position of the arriving beamlet (red) at the detector is shown.

7.2.3 H⁰ Background

The sources for H⁰ background arriving at the detectors were already comprehensively discussed in Sec. 4.3, where also a detailed simulation of the background arriving in the first detector position was carried out.

In the measurement campaigns at 3 MeV and 12 MeV this background was found very uniform so that it could be subtracted from the laser-stripped signal by a linear fit. In this respect no further simulations were conducted for the second detector location, especially as much lower H⁰ background is expected due to the location behind the first main dipole magnet.

7.3 Instrument Design

In the previous measurement campaigns many valuable insights have been gained, which all contribute to a reliable instrument design to measure permanently the transverse beam parameters at 160 MeV beam energy. Moreover the simulation results presented previously take into account the specific beam parameters in the 2 proposed locations. The focus of the design has been laid on a robust setup, which is capable to withstand the radiation dose accumulated over the 30 years life-time of LINAC4. As the setup at position 2 is nearly a copy of the position 1 setup, only the differences will be described, where appropriate.

7.3.1 Laser System

The new laser system shall deliver laser beams with similar parameters as in the previous prototype tests to the 4 interaction points, each including a scanning mechanism and laser diagnostics.

The laser cabinet hosting the laser-source and its coupling optics used for the last beam campaign (see Fig. 6.4) can be re-used to supply all 4 IPs with sufficient laser power. Figure 7.4 shows a design sketch of the fibre-optic distribution of the laser beam. After the laser-source¹ the beam is split into 4 fibre-couplers by using 3 beam splitters with increasing reflectivity to obtain equal laser-power in each fibre. The fibre-transmission is realised with the LMA-fibre [Nuf13] used in the previous tests, equipped with an end-cap at the coupling side. By using fibres with different lengths (75 m vs. 20 m) the laser-pulses arrive in the LINAC4 tunnel with a time difference of 267 ns. This

¹ V-Gen VPFL-ISP-1-40-50

allows to inject the 100 ns long laser-pulses in both planes almost simultaneously but still being able to distinguish the resulting electron and H^0 pulses.

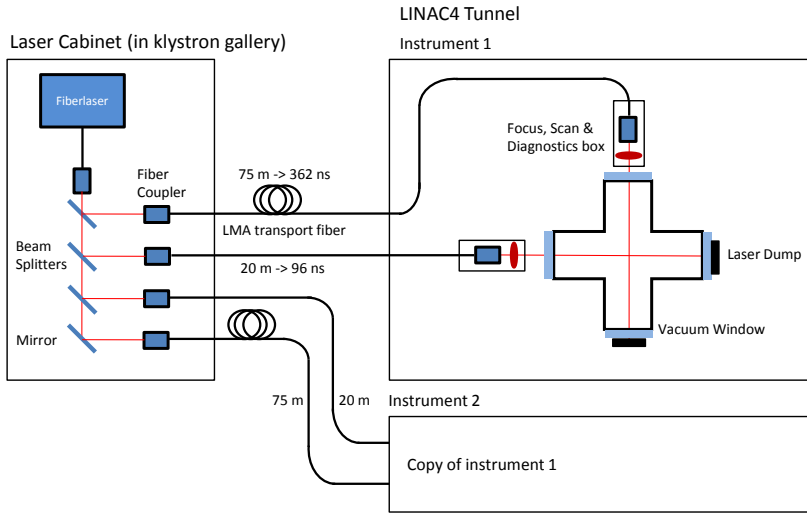


Figure 7.4: Scheme for fibre-based supply of both instruments with laser beam.

The simultaneous laser injection horizontally and vertically into the vacuum vessel demanded a major design change of the optical setup. Figure 7.5 shows the breadboard, which is mounted vertically, below the beampipe. The fibres are mounted on the scanning stages (Sg1/Sg2) where the laser beam emerges with constant diameter (≈ 3.5 mm) due to the attached collimation lens and is subsequently focused by a single lens (L1/L2; $f = 250$ mm) into the vacuum vessel. This simplified setup can be mounted much closer to the beampipe while conserving a similar laser waist ($w_0 = 63 \mu\text{m}$; $x_R = 9.0$ mm; see Sec. 4.4.1) for the interaction with the H^- beam. To monitor the laser-pulses online, a small fraction of the beam is sampled (S1/S2) and directed to fast photodiodes (PD1/PD2), while the absolute energy of a laser-burst is recorded with the energy meters (EM1/EM2) mounted behind the vacuum vessel. Moving the stages (Sg1/Sg2) beyond the range for scanning the H^- beam, mirrors (M1/M2) deflect the laser towards a beam-splitter, which sends 50% of both beams towards a CCD, measuring the transverse profile and the beam quality (M^2) of the laser beam.

Dispensable components like the beam-expander and stages for moving the fibre-holder in direction of the beampipe were removed with reference to the

setup used for the previous measurement campaigns (Fig. 5.4). Therefore the new setup can host the optics for measuring both planes in a significantly reduced volume.

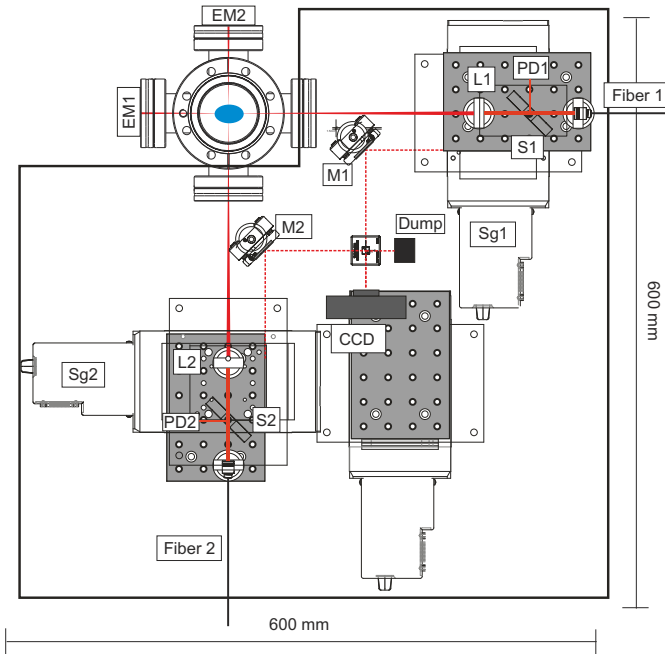


Figure 7.5: Optical setup for horizontal and vertical laser injection into the beampipe.

The integration of the optical setup in the beamline is illustrated in Fig. 7.6. The station consists of a light-tight housing which hosts the laser injection setup, a steerer magnet to deflect the electrons and the associated electron detector.

7.3.1.1 Laser Synchronisation to Chopper Pattern

To inject the LINAC4 beam into the RF-buckets of the PS-Booster, parts of the beam are already removed in the 3 MeV region by the chopper. The resulting beam structure arriving in the 160 MeV region is shown in Fig. 7.7 and compared with the laser timing where the horizontal and vertical pulses arrive separated due to the different fibre lengths. To make sure that both laser pulses hit exclusively full beam bunches, a precise synchronisation between chopper and laser frequency has to be added to the time structure of the laser shown previously in Fig. 4.16.

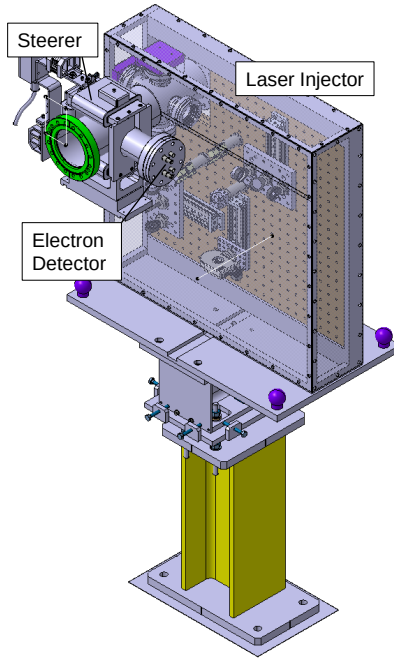


Figure 7.6: Assembly of laser interaction station.

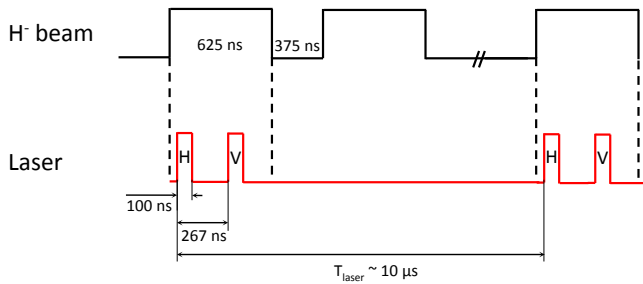


Figure 7.7: H^- beam structure - 625 ns burst corresponds to one PS-Booster bucket - compared with laser pulses for horizontal (H) and vertical (V) interaction.

7.3.2 Electron Detection

The instruments measuring the H^- beam at 160 MeV will record the neutralised H^0 beamlets but also the stripped electrons as tested during the 50/80/107 MeV

beam campaigns. In this section the refined setup to deflect and monitor the electron beamlets shall be presented

7.3.2.1 Dipole Magnet

As described in Sec. 6.1.3, the dipole magnet to deflect the electrons in the 50/80/107 MeV setup consisted in a modified steerer magnet (see Fig. 6.7), where one coil was removed and replaced by a support frame. This simple solution provided sufficient vertical B -field to deflect the electrons by 90° but it was accompanied with stray-field components in the x - and z -plane, which caused defocusing of the beamlets in the vertical plane (compare results in Sec. 6.3.2.4).

The yoke of the steerer was re-designed in order to reduce this defocusing effect, enabling subsequently to mount the electron detector at fixed position in the 160 MeV setup. By introducing a gradient for the horizontal field component $B_x \propto y$, it was aimed to induce a focusing force in the vertical plane similar as a quadrupole magnet (see Sec. 2.1.2). Figure 7.8 shows the final yoke design and the corresponding vector-field in the xy -plane for a coil current of 6 A as the outcome of several design iterations. It can be seen that the main field-component is still in the y -plane, causing the 90° deflection towards the detector. However the field-lines are slightly bent in the space between the beam axis in the centre of the magnet and the detector aperture on the left. This is the result of the sloped geometry of the upper and lower yoke and induces the focusing force in the vertical plane.

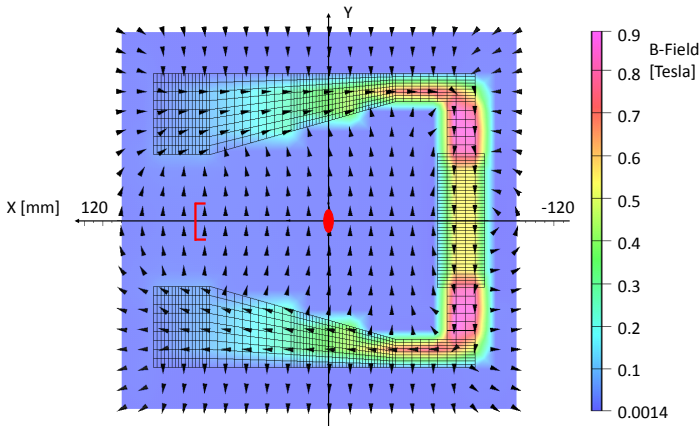


Figure 7.8: Magnetic vector-field in xy -plane for re-designed yoke of steerer. Schematic beam envelope and electron detector aperture marked in red.

It shall be mentioned that this design does not affect the stray-fields in z -direction due to the convex bowing of field-lines at the entrance of the magnet, which still evoke a contrary - defocusing in y - deflection.

To verify the effect of the modified yoke an electron tracking simulation has been performed for the 2 instrument locations likewise as shown previously in Sec. 6.1.3.2. Complete electron stripping of the whole H^- beam was assumed and the electron distribution was tracked towards the detector. The resulting distribution corresponds to an overlay of all possible laser positions (in x - and y -plane).

Fig. 7.9 shows the evolution of the electron beam size along its trajectory to the detector for both instruments (Pos1/2). The dimensions in the horizontal plane (z) are generally very small due to the weak focusing effect of the magnet (see Sec. 6.1.3.2).

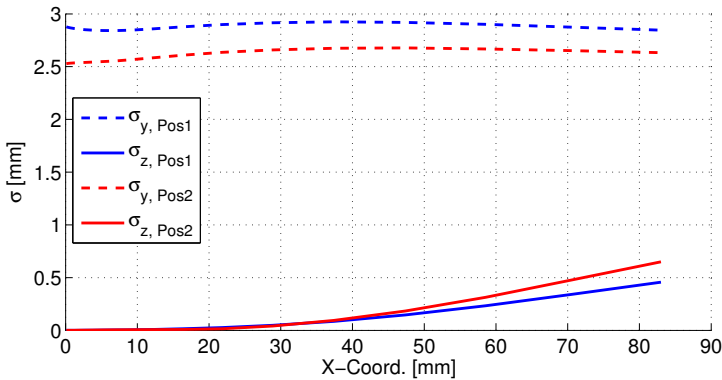


Figure 7.9: Widths of the electron distributions in y - and z -plane¹ for laser stripping of the whole H^- beam at $x = 0$ and the detector located at $x = 60...80$ mm.

In the vertical plane the dimensions are similar to the H^- beam at $x = 0$ due to the whole beam stripping. On the way to the detector at $x = 60...80$ mm the defocusing caused by the z -field component and the focusing caused by the x -field component neutralise such that σ_y stays approx. constant. This is particularly important as it defines the minimal required aperture of the electron detector.

7.3.2.2 Electron Detector

The electron detection method was reviewed, based on the experience during the 50/80/107 MeV run. Although the 4 x 4 mm sCVD diamond detector

¹Coordinate system as in Fig. 7.8 and Fig. 6.8

provided very clear and linear signal response in most beam conditions, the proton background (see Fig. 6.19) was worsening the signal quality for certain H^- beam settings. Furthermore the 2D-scanning procedure of laser and detector was slowing down the beam profile measurements significantly. It was thus decided to change to a Electron Multiplier Tube (EMT), which exhibits a large input aperture to avoid the detector-scan and which is independent of the rest-mass of the impinging particles to suppress the proton background in order to establish reliable operation in all beam conditions.

The EMT detector principle is shown in Fig. 7.10. The negative bias ($-1\text{ kV} \dots -3\text{ kV}$) is split linearly over a cascade of dynodes (right in Fig. 7.10). Each dynode consists of a coarse mesh based on copper with a beryllium oxide (BeO) coating¹. When photo-detached electrons hit the first dynode (DY1), the BeO coating emits electrons, which are directed towards the second dynode due to the applied bias. Assuming a secondary emission yield (SEY) > 1 , an electron avalanche builds up which provides amplification of up to 10^7 electrons per impinging particle.

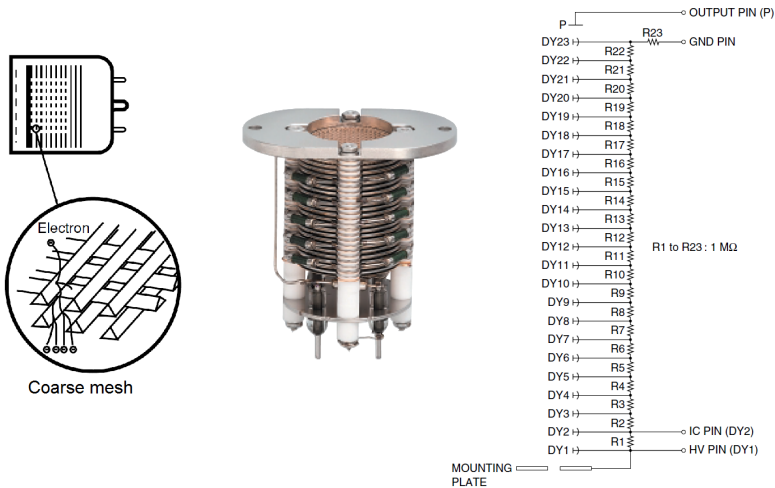


Figure 7.10: Electron Multiplier Tube (EMT). Left: Principle of coarse mesh type EMT; Centre: Photo of EMT selected for 160 MeV electron detection²; Right: Schematic of selected EMT. [Pho15, Pho06]

¹ EMTs are available in a big variety of dynode types. Here only the selected EMT for the laserwire instrument is described in detail. For further studies [Pho15, Pho06] shall be recommended.

² Hamamatsu R2362

In Table 7.5 the characteristics of the EMT model to be used for the laserwire are summarised. Coarse mesh type dynodes are chosen as they provide superior homogeneity over its surface in reference to other dynode types [Pho06]. With its large diameter (20 mm) the EMT is able to detect the particles resulting from all laser positions without the need of vertical detector movement ($\sigma_y < 3$ mm - see Fig. 7.9).

Table 7.5: Characteristics of the Hamamatsu R2362 EMT [Pho15, Pho06]

Parameter	Value
EMT Type	Coarse Mesh
Number of dynodes	23
Dynode material	Cu-BeO
Dynode capacitance	23 pF
Input aperture	$\varnothing = 20$ mm
Bias voltage typ.	-2700 V
Gain typ.	10^6
Rise time	3.5 ns
Dark current	5 pA

Due to the proximity of the dynodes to each other a comparably big capacitance (23 pF) is obtained, which can be used to recharge them and achieve a high saturation current. A further extension of the saturation limit has been obtained by placing additional capacitors (0.1 μ F) in parallel to the last 5 dynodes (DY19...23) where the currents will be highest.

With -2700 V bias voltage the nominal gain of 10^6 is reached, however a wide range of amplification can be accessed for different bias settings (see Appendix Fig. C.8). The rise time of 3.5 ns allows to detect the electrons created by 100 ns long laser-pulses basically without distortion. The dark current of 5 pA is not relevant for the laserwire application as, due to the high number of photo-detached electrons, no signal to noise problem is anticipated.

The detector is typically used to detect positive ions, which are attracted by the negative bias on the first dynode. In our application the bias will slow down the photo-detached electrons but due to their high kinetic energy of 87 keV no change in their spatial profile is expected.

The SEY of BeO is well studied in the low energy range, which will be the case from DY2 to DY23 in our application ($E_{e^-} = U_{bias}/23 = 117$ eV). For the first dynode where the electrons hit with 87 keV a model presented in

[Caz05] can be used to extrapolate the SEY also for higher electron energies. Figure 7.11 shows the measurement data and its extrapolation.

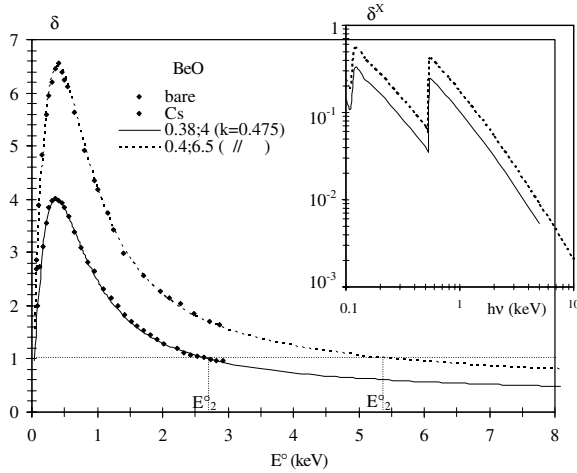


Figure 7.11: BeO secondary emission yield δ as function of kinetic energy of the impinging electrons (solid line - bare BeO, as in selected EMT; δ^X = X-ray-induced SEY) [Caz05].

Using this model an SEY ≈ 3 is expected for DY2 to DY23, while SEY > 0.4 is expected for DY1. Given the high number of impinging electrons the sensitivity of the detector should therefore be more than adequate. In addition, first positive experiences using EMT's to detect high energy electrons ($E_{kin} = 10$ keV) have been gained at LINAC4 during the development of the Bunch Shape Monitor (see [GV⁺06]).

7.3.3 H⁰ Detection

The H⁰ detection with pCVD diamond strip detectors was extensively tested in the 3 MeV and 12 MeV measurement campaigns. Due to its positive outcome this detector type was chosen to be used also for the final system. Further development was focused on the enhancement of the detector resolution and the dimensioning of its corresponding DAQ chain.

7.3.3.1 Concept

To realise simultaneous measurements in the horizontal and vertical planes, it is foreseen to insert two diamond strip-detectors one after another in the vacuum vessel. Figure 7.12 shows the assembly of the detector station, where

the detectors for the x - and y -plane are mounted on actuators, which provide the movement perpendicular to the strip-direction of the referring detector.

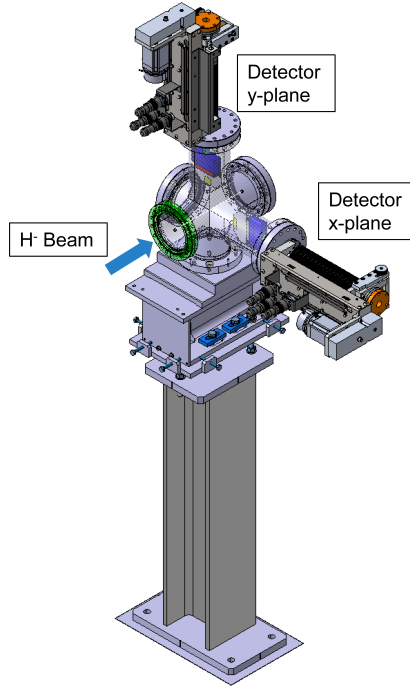


Figure 7.12: H^0 Detector station with 2 pCVD diamond strip-detectors (yellow) for horizontal and vertical emittance measurement.

As both detectors are in the beampipe at the same time, multiple Coulomb scattering takes place when the particles pass the detectors. In this regard the effect on the measurement resolution for the downstream detector shall be calculated. The RMS scattering angle is defined as,

$$\sigma_{\Theta} = \frac{13.6 \text{ MeV}}{\beta_{rel} c p} z \sqrt{\frac{x}{X_0}} \cdot \left(1 + 0.038 \ln \left(\frac{x}{X_0} \right) \right) \quad (7.2)$$

with the relativistic β_{rel} , the particle momentum p , the charge number of the incident particle z , the material thickness x and the radiation length X_0 ¹ [O⁺14]. For a detector composed of a 0.5 mm thick diamond disc and a 0.8 mm thick ceramic (Al_2O_3) PCB the combined RMS scattering angle becomes 4.7 mrad.

¹Distance where particle loses 1/e of its energy due to Coulomb interactions.

Given a distance of 8 mm between the detectors a blur of $75\text{ }\mu\text{m}$ will be induced for the horizontal emittance measurement (downstream detector) which can be seen as a lower limit for the detector strip-pitch.

7.3.3.2 Calibration

The instrument's purpose is to sample the transverse phase-space, which implies that the detector homogeneity and linearity are crucial. Both characteristics have been tested during the commissioning campaign at 12 MeV, where the pCVD diamond material showed satisfying results. However in a long term installation, the sensitivity and thus also the homogeneity of the material can be affected by radiation damage. Although pCVD diamond material has been chosen due to its superior radiation resistance an automated calibration process shall be implemented to verify its performance regularly and re-normalise changes of sensitivity at different detector strips.

To conduct the calibration in same conditions as the emittance measurements, we propose to use the stable LINAC4 beam for this purpose. The laser will be kept in the centre of the H^- beam and the detector is moved perpendicular to the laser direction with step size equal to the detector strip-pitch. In this regard each detector channel records the whole beamlet. Assuming a stable H^- beam for the duration of a detector scan ($< 60\text{ s}$), each channel can be re-normalised, which compensates the effects due to detector inhomogeneities caused by radiation damage.

7.3.3.3 Detector Dimension and Resolution

To dimension the size and the resolution of the required 4 H^0 strip-detectors it has been agreed to refer to the nominal H^- beam parameters in the 2 IPs [Lal]. In this regard the following requirements were defined in step with actual practice:

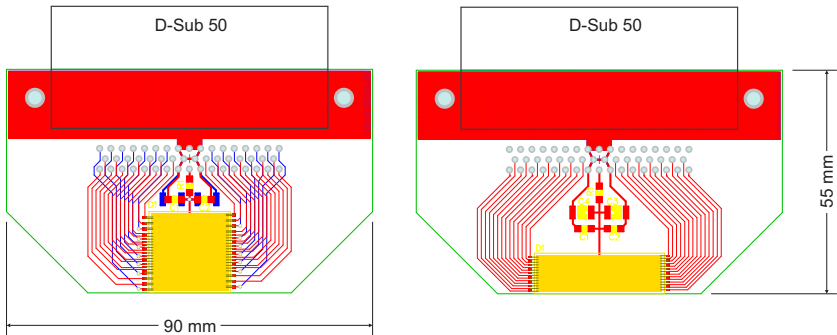
- Detector size: Min. 8 times σ of the beamlet
- Resolution: Min. 2 samples / σ [BP95]
- No. Channels: Constant for all detectors

By using the simulation results from Table 7.4 and applying the defined requirements, the minimal dimensions and resolutions for all 4 H^0 detectors were determined. After minor adaptation to practical dimensions the final detector dimensions are summarised in Table 7.6. It shall be noted that the vertical detector in position 2 and the horizontal detector in position 1 are based on the same detector design with only modified readout (see Fig. B.3). In this way the 4 detectors can be build with just 2 different types of hardware.

Table 7.6: Summary of detector dimensions and resolutions

Resolution	Position 1		Position 2	
	Horizontal	Vertical	Horizontal	Vertical
X Size [mm]	20	32	10	20
Y Size [mm]	20	10	32	10
Resolution r [μm]	680	323	323	340
No channels	28	28	28	28
Samples / σ	3.8	3.7	3.4	2.65

In Fig. 7.13 the design of the 2 detector types is shown with the yellow surface being the 500 μm thick pCVD diamond disc and the green frame being the ceramic PCB. The channel readout, bias supply and mechanical support is realised via a D-Sub connector. The schematics of both detectors can be found in Fig B.3 and Fig. B.4 in the Appendix.

**Figure 7.13:** 2 different detector setups to be used for the 4 strip-detectors. [Gri15a]

7.3.3.4 Detector Material

The pCVD diamond material has been favoured prior to the 3 and 12 MeV beam tests mainly due to its superior radiation hardness (see Sec. 4.5.3.4) and the possibility to manufacture comparably big active surfaces ($> 10 \times 10 \text{ mm}$). Following the encouraging test results from the 3 and 12 MeV commissioning periods the decision has been taken to continue with pCVD material. The selected 500 μm thick pCVD material is specified to reach a charge collection efficiency of 36% and exhibit no inhomogeneities bigger than 200 μm diameter. More detailed specifications can be found in the appendix C.9.

7.3.3.5 Detector Output

To calculate the signal of the central detector channel while the laser is interacting with the centre of the H⁺ beam, the yield data (N_{yield}) from Table 7.3 can be used. The width $\sigma_{x/y}$ of the distribution arriving at the detector in the scanning direction is summarised in Table 7.4. By using the detector resolution r as defined in Table 7.6 the number of H⁰ arriving at the central channel N_{ch} can be calculated with the help of the Gaussian cumulative distribution function Φ :

$$N_{ch} = N_{yield} \cdot \left[\Phi \left(\frac{r/2}{\sigma_{x/y}} \right) - \Phi \left(\frac{-r/2}{\sigma_{x/y}} \right) \right] \quad (7.3)$$

Table 7.7 summarises the results for all H⁰ detectors. The voltage output was calculated by simulating the created ionisation inside the 500 μm thick diamond bulk with the SRIM package based on the Bethe-Bloch equation (Eq. 4.33) resulting in $E_{loss} = 820 \text{ keV/H}^0$. Following Sec. 4.5.3 the readout charge is obtained for a pCVD diamond material with CCE = 36% and subsequently converted to a voltage over 50 Ω impedance.

Table 7.7: Maximum expected signals from H⁰ detectors in 4 positions

Resolution	Position 1		Position 2	
	Horizontal	Vertical	Horizontal	Vertical
H ⁰ in central channel	$1.5 \cdot 10^5$	$0.89 \cdot 10^5$	$1.1 \cdot 10^5$	$1.2 \cdot 10^5$
Detector output [V]	0.28	0.16	0.20	0.22

Signals for different laser and detector positions can be obtained by scaling the results with the corresponding normal distribution of the H⁺ beam (for laser off-centred) and respectively H⁰ beamlet (for channel off-centred) in the detector plane.

7.3.3.6 Charge Sharing

Due to the charge-sharing effect, the resolution of a diamond strip-detector is not only defined by the strip-pitch of the metallisation. As this is crucial with respect to the angular resolution of the instrument, comprehensive simulations were carried out and shall be discussed in the following.

In Sec. 4.5.3.2 the mechanism for signal generation in the diamond bulk was discussed. A moving charge couples to the surrounding electrodes and induces an instantaneous charge. To obtain a quantitative measure of the charge induced to one strip k , the weighting field Φ needs to be calculated by setting all electrodes to 0 V potential while raising an electrode k to 1 V [Ram39]. The

resulting field distribution in the diamond bulk has been simulated with the SUPERFISH package [HH76] and is shown in Fig. 7.14.

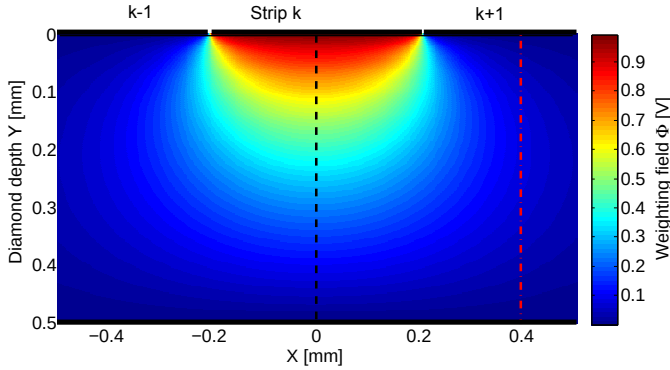


Figure 7.14: Weighting field in diamond bulk for a 400 μm wide strip electrode k .

Supposing a H^0 atom traverses the diamond material along the dashed black line (centred below strip k), it creates carrier hole pairs along its path. Each of them induces a charge Q_k

$$Q_k = e [\Phi_k(\text{Start}) - \Phi_k(\text{End})] \quad (7.4)$$

on the strip electrode k while drifting through the E-Field [Spi05]. Figure 7.15 shows the current

$$I_k(t) = \frac{d}{dy} \Phi_k \quad (7.5)$$

induced to strip k for 2 carrier hole pairs created at different positions (see red and black line Fig. 7.14). The integral defines the net-charge induced, which becomes 0 for charges moving to neighbouring strips (red) as $\Phi_k(\text{Start}) = \Phi_k(\text{End}) = 0 \text{ V}$. If the charge collection distance (CCD) is however shorter than the thickness of the detector, the carriers move just through a fraction of the detector and thus a charge can also be obtained from particles traversing neighbouring strips. This effect called charge-sharing is strongly dependent on the average CCD and also its gradient inside the diamond as well as the pitch of the strip-electrodes.

To determine the impact of charge-sharing quantitatively, a homogeneous distribution of particles impinging at the detector surface was simulated to traverse the bulk material. Figure 7.16 shows the dependence on the width of the strip-electrode for a constant CCE of 36%¹, where the charge sharing is defined

¹Corresponding to the specifications for the pCVD material for the 160 MeV H^0 detector system

as ratio between charge induced by particles traversing the strip k and charge created by particles not traversing strip k .

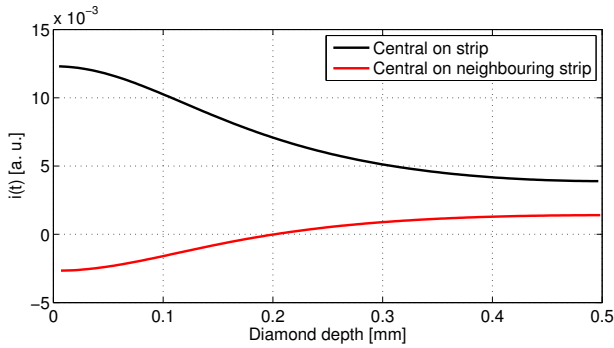


Figure 7.15: Current induced to strip k by a particle impinging central on strip k and at a neighbouring strip of the diamond detector.

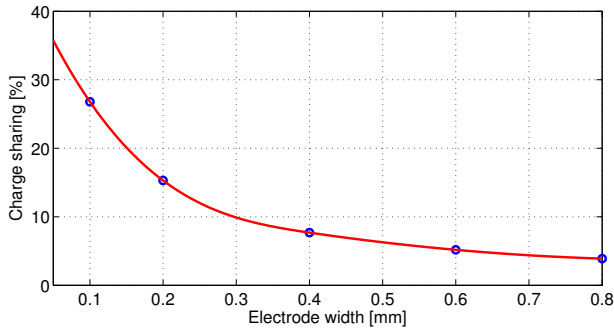


Figure 7.16: Charge Sharing effect for different strip widths.

It shows clearly that strip widths below 300 μm are strongly influenced by charge-sharing while above 300 μm below 10% of the collected charge is shared.

A similar test has been conducted for different gap sizes between the strip electrodes, where just a very weak dependence has been found.

Fig. 7.17 shows the result for detector materials with varying CCE for a metallisation pattern with 400 μm strip width. The plot confirms that for full charge collection (CCE = 1), the charge sharing effects goes towards zero although for the chosen simulation resolution it is not entirely reached.

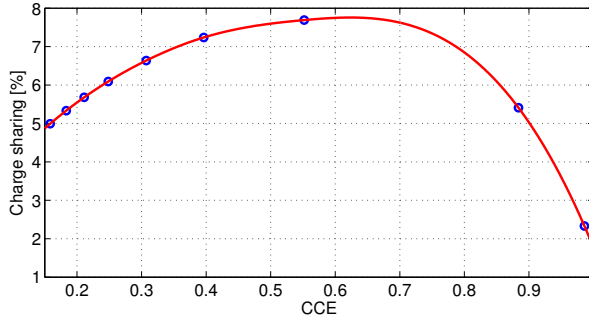


Figure 7.17: Charge sharing effect of different CCE of the detector material.

The pCVD diamond material typically exhibits a gradient in CCE due to the polycrystalline growth process with more grain boundaries respectively lower CCE on the substrate side (see Fig. 4.19), thus a simulation with CCE gradient was conducted. As the CCE gradient for the chosen pCVD material is unknown, no quantitative factor for the change in charge sharing with respect to constant CCE conditions as in Fig. 7.16 could be determined. However the result showed that for the same average CCE the charge-sharing is lower when the particles impinge at the side with higher CCE, so it was decided to apply the strip metallisation facing the H^0 beamlets on the growth side of the pCVD diamond.

7.3.3.7 Radiation Damage

To estimate the life-time of the H^0 diamond detector, the different radiation sources were summarised and their effect on pCVD diamond material assessed. The highest radiation level is expected to be present in the central square millimetre of the first H^0 detector. Table 7.8 summarises the different radiation sources extracted from preceding simulations, whereas the direct H^0 radiation is given in 160 MeV H^0 per 400 μ s LINAC4 macropulse while the ambient radiation is given in 1 MeV neutrons per day (see Fig. 4.17). From NIEL-scaling hypothesis it is however known that both types of radiation cause similar damage in semiconductor material [VL00].

To determine the time when the sensitivity is reduced by 10% in the central mm^2 of the detector, a scenario based on a realistic usage (1 emittance scan / hour of beam) of the instrument was setup. It results in $4 \cdot 10^{11} H^0 / (\text{year} \cdot \text{mm}^2)$ direct H^0 radiation due to the emittance measurements and another $3 \cdot 10^9 n^0 / (\text{year} \cdot \text{mm}^2)$ from the ambient radiation. Comparing

Table 7.8: Fluences in central square millimetre of H^0 detector 1

Radiation type	Value	Unit
Laser stripped H^0	$2.9 \cdot 10^6$	$(H^0 / L4 \text{ macropulse} \cdot \text{mm}^2)$
Direct H^0 background	$4.4 \cdot 10^5$	$(H^0 / L4 \text{ macropulse} \cdot \text{mm}^2)$
Ambient radiation	$9.1 \cdot 10^6$	$n^0 / (\text{day} \cdot \text{mm}^2)$

these values to the radiation hardness of the pCVD material ($4 \cdot 10^{12} \text{ p}^+ / \text{mm}^2$ - from Sec. 4.5.3.4) a life-time of 9 years is obtained.

It shall be noted that due to the dominance of direct H^0 radiation during emit-tance scans, possible changes in the usage scenario or the laser setup (peak-power, pulse length, pulse frequency...) can have a significant impact on this life-time. Thus, the response of the diamond detectors shall be monitored during operation with the proposed calibration process and if needed the laser parameters can be adapted to reduce the damage.

7.3.3.8 Signal to Background Ratio

The ratio of laser stripped H^0 to the continuous H^0 background (see Sec. 4.3) arriving at the detector has been simulated, taking into account the detector geometry determined in Table 7.6.

Position 1 was chosen as simulation example, because the background level is expected highest at this location. In Fig. 7.18 the number of H^0 arriving during one 100 ns long laser-pulse at the $0.323 \text{ mm} \times 32 \text{ mm}$ stripes of the detector

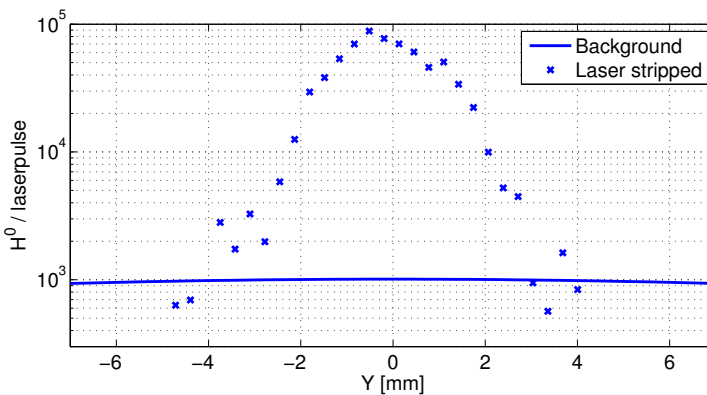


Figure 7.18: Signal comparison of diamond strip detector at position 1 (resolution in y) for horizontal laser beam interacting with centre of H^- beam.

is shown. The ratio varies between 100 in the centre of the beamlet and parity at approx. 3σ (± 3.6 mm). Due to the subtraction of the background applied in the DAQ system, it will not have significant influence on the acquired signal integrals, even in the tails of the distribution.

7.3.4 DAQ and Control System

During the prototype tests, similar types of DAQ systems as described in Sec. 5.1.4 have been used to record the data of the diamond detectors and control all involved sub-systems. The DAQ-system for the 2 instruments at 160 MeV need to combine the acquisition system for electron- and H^0 detection and scale it for the significant increased number of detector channels. Figure 7.19 gives an overview on the system architecture. The control system will be based on a PXI platform and will host a FESA-server¹, a control module for all integral parts of the laserwire system (laser, actuators...) and a DAQ module on FPGA basis to digitise the detector signals. The FESA-server will communicate with other relevant instruments and provide the data to a client, which runs the user interface.

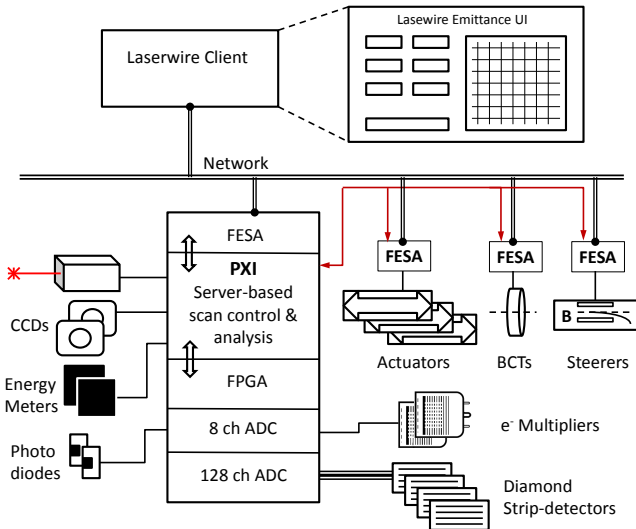


Figure 7.19: DAQ and control system to be used for both instruments at 160 MeV.

¹FESA is a comprehensive software framework used at CERN as a standard for DAQ and control of different instruments.

7.3.4.1 Data Acquisition System Overview

A summary of all devices, which need to be recorded is given in Table 7.9. Energy meters, CCD cameras and BCTs deliver digital data at low data-rate (0.8 Hz), which put no stringent requirements on the DAQ system. In contrast, the photodiodes and the high number of detector channels deliver fast analogue signals so that the DAQ chain needs to be designed carefully in order to identify a DAQ system within budget, which matches all the functional requirements.

Table 7.9: Overview of devices within the 2 instruments, which deliver data to be acquired

No.	Device	data type
128	H^0 detector channels ¹	analogue
2	Electron detectors	analogue
5	Photodiodes	analogue
5	Energy meters	digital (USB)
2	CCD cameras	digital (USB)
2	BCT	digital (FESA)

7.3.4.2 H^0 Detector Pre-amplifiers

While the gain of the electron detectors can be increased over a wide range by raising the bias voltage of the electron multipliers (see Fig C.8), the pCVD diamond detectors are typically operated at constant bias of 1 V/ μm . Therefore a pre-amplifier with variable gain of 0 dB to 20 dB has been designed to boost the signals (see Table 7.7) to the 1 V_{pp} input range of the ADC. Furthermore it matches the output impedance of the detector of 50 Ω to the 100 Ω impedance of the 30 m long differential signal transmission and the ADC input. The schematic of the design can be found in the Appendix B.5 for reference.

7.3.4.3 Requirements for DAQ of Analogue Signals

To determine the needs for the DAQ system, the general timing of LINAC4 and laser in Fig. 4.16 shall be recalled. In order to simplify the DAQ timing it was decided to record all analogue signals continuously during 600 μs (400 μs LINAC4 macropulse plus 100 μs before and after the pulse). The 1199.4 ms between the DAQ intervals can be used to process the acquired data for a real-time visualisation of the phase-space building up.

¹ Four H^0 detectors with each 28 diamond channels and 4 reference channels

With respect to the required sampling rate of the ADC, an electron detector signal from the 107 MeV beam similar to Fig. 6.17 was recorded with a 10 GHz oscilloscope. By applying a Fast Fourier Transformation (FFT) the frequency contents of the photodiode and the diamond detector were visualised in Fig. 7.20.

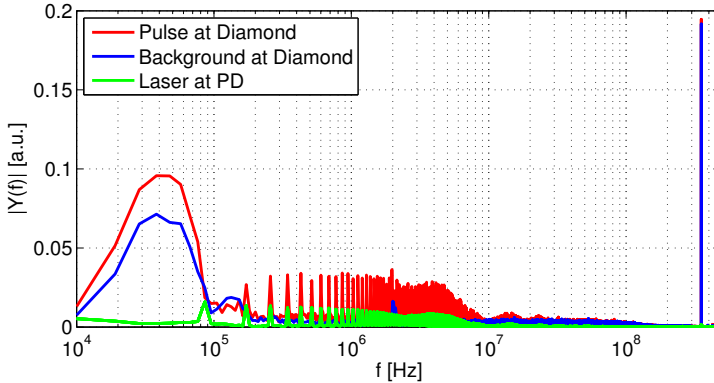


Figure 7.20: FFT of a series of electron pulses (red) and background floor (blue) at sCVD diamond detector recorded at 107 MeV H^- beam with 10 GS/s compared with the signal of the laser-pulses recorded with a photodiode.

Comparing the pulse signals at the diamond detector and a similar recording of just background floor, clear differences can be found in the frequency range between 100 kHz and 10 MHz. These differences correlate very clearly with the signal of the laser-pulses recorded with a photodiode. It can be concluded that the DAQ system needs to cover the indicated frequency range in order to record the desired signal components.

The strong peak at 352.2 MHz is similarly present at the diamond pulse and background signal and represents undesired coupling from the accelerators RF-system. The signal of an H^0 detector is expected to exhibit a similar frequency spectrum, differing just in the very low frequency range (< 1 kHz), where additional components due to the residual gas stripped H^0 background are expected.

7.3.4.4 Design of DAQ System

To record the 28 channels of each H^0 detector the ADC module NI-5752 has been chosen. It consists of 32 12-bit channels, each sampling simultaneously with an external clock of up to 50 MS/s. The effective number of bits (ENOB) is 10.7, equating to a resolution of about 0.6 mV at a full-scale range of 1 Vpp. The ADC channels are AC-coupled with a 16 kHz high-pass filter and anti-alias

filter of selectable corner frequency of up to 14 MHz. The channel response has been measured and is shown Fig. 7.21, using the NI-5752 default gain and filter settings. The response is flat from about 50 kHz to several MHz.

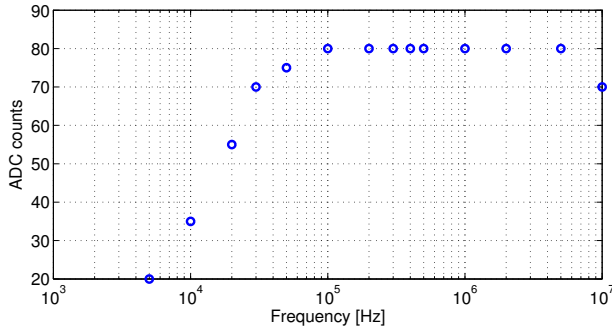


Figure 7.21: NI-5752 frequency response (input: $V_{pp} = 140\text{mV}$; DC coupled).

The gain and offset of each of the 32 channels is individually setttable: the gain ranges from -5 dB to +31 dB in steps of 0.125 dB; the offset is a digital value subtracted from the output when the acquisition completes.

Each H^0 detector channel generates 30 kS, equating to 60 kB due to the 12 bit ADC per LINAC4 macropulse. If all 112 detector channels are read simultaneously 6.7 MB of data is generated. To avoid a very large amount of data being transferred across a network the data shall be pre-processed. Therefore the ADC card was used as a front-end adaptor for FPGA-based Flex-RIO card which allows parallel processing of the detector channels to begin as soon as the detector output starts to be digitised. In Fig. 7.22 the analysis for each channel being executed in the Flex-RIO FPGA card is outlined.

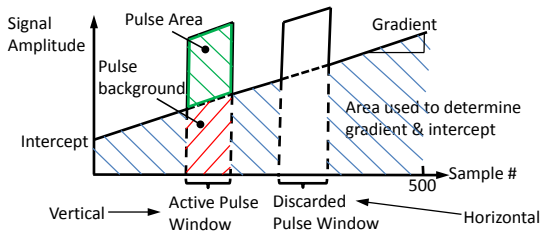


Figure 7.22: Analysis for each channel of H^0 detector. Two pulses (horizontal and vertical laser) arrive separated in time at the diamond detector. A linear fit of the H^0 background is used to determine gradient and intercept and finally integrate the integrated signal of the desired pulse.

The complete architecture of the DAQ-system is shown in Fig. 7.23. Besides the 4 NI-5257 modules it includes an ADC module for electron detectors and photodiodes. The increased sampling rate of this module was chosen to feature an additional degree of freedom for future tests or extensions. The external trigger for the laser and the DAQ-system will be obtained from the chopper system in order to synchronise according to Fig. 7.7.

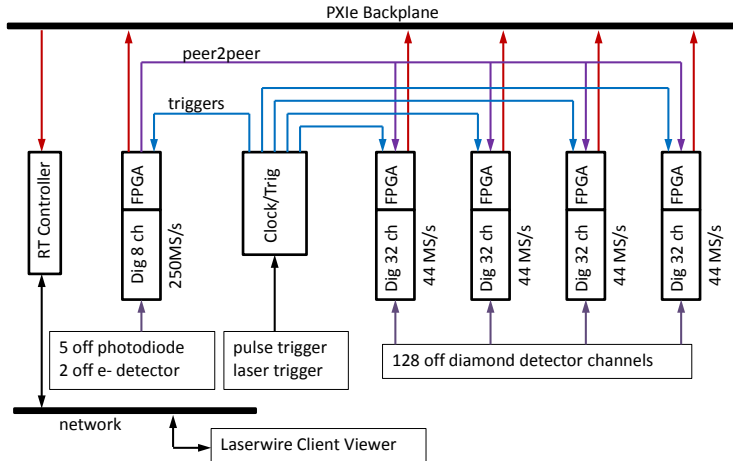


Figure 7.23: Design of DAQ front-end for analogue signal processing.

7.3.4.5 Control System

The control system for both instruments runs on an embedded PXI controller (PXIe-8105), which is housed together with the DAQ system in a common chassis, which hosts the communication between DAQ- and control-system via its PCIe backplane. At LINAC4 the system is situated in a radiation free-zone close to the laser cabinet (see [1] in Fig. 6.3).

In Table 7.10 the devices which shall be operated by the PXI controller are summarised. The actuators and the dipoles can be accessed over CERN's Ethernet infrastructure via their FESA interfaces, while the laser will be directly connected to the PXI-controller via RS232.

The control and data analysis code for operating the laserwire system is written in LabVIEW. Due to the FPGA-based pre-processing, the system is dimensioned to analyse the acquired data in real-time and deliver for each laser position the resulting phase-space to the user interface, which enables the user to abort a scan and re-adjust the instrument parameters in case of a sub-optimal

Table 7.10: Summary of devices within the 2 instruments, which need to be controlled from the PXI controller

No.	Device	interface
1	Laser	RS232
6	Linear actuators (Laser injector)	FESA
2	Dipoles (Electron deflector)	FESA
4	Linear actuators (Diamond detector)	FESA

result. A transverse phase-space scan in both planes (x , y) shall be accomplished within an integer multiple of the LINAC4 period-length. E.g. a scan with 30 laser positions should be finished after $30 \cdot 1.2 \text{ s} = 36 \text{ s}$.

The software design follows an object oriented approach, such that devices can be replaced with just minor software changes. During the different prototype commissioning periods virtual instruments for most devices have been developed such that the development efforts for the final system are limited. For a more detailed description of the software design it shall be referred to [Boo16].

7.4 Status and Next Steps

The status of the laser system and its different subsystems at the moment of writing (May 2017) and plan for the project completion can be summarized as in the following:

- **Mechanics:** The CAD-design of all systems are completed and production drawings have been created. Fig. 7.24 shows the new equipment integrated in the LINAC4 machine. In a first installation phase the vacuum chambers and associated supports will be installed in the LINAC4 tunnel. The actuators for the diamond detectors (see Fig. 7.12), the housings for the laser injectors (see Fig. 7.6) and the special steerer magnets (see Sec. 7.3.2.1) are currently in fabrication and will be installed in July 2017.
- **Laser optics:** The fibre-optic lines between laser cabinet and accelerator tunnel are currently being installed. Tests of the new setup to scan the laser and focus it into the vacuum vessel (see Fig. 7.5) are ongoing in order to characterise the laser-beam waist in the IP. The next tasks will be to assemble all components on the final breadboards and to align the laser injector with respect to the H^- beam axis.

- H^0 and electron detectors: The diamond strip-detectors for H^0 detection (see Fig. 7.13) have been fully assembled and validated for usage in UHV environment. They are currently undergoing a functional test with a β -source to ensure proper operation of all channels. The electron multiplier (see Fig. 7.10) has been purchased and is ready for installation. Both devices will be installed in July 2017 and then extensively characterised with the H^- beam, as described in Sec. 5.4.5.
- Electronics: The design of the pre-amplifiers for the diamond detector channels has been finished, prototypes have been manufactured and were tested. The production of a large batch for the 112 detector channels is ongoing. In addition, several interface-PCBs were designed and assembled. All cables to be installed in the accelerator tunnel were defined and are currently being installed. The configuration of the PXI system is finished and its procurement is in preparation. After all components are installed a system test in the accelerator environment will be carried out.
- Software: Thanks to modular programming style used in the prototype phase, much of the code is already available. The module for FPGA-processing of the diamond channels is finished in its first version. A server-module for data logging, connection to other devices and providing a user interface which can be centrally accessed is currently under development. The next step is to test the code running on the real hardware. After the commissioning of the instrument will be finished, separate applications for expert users and operators will be developed.

It is foreseen to install all the hardware components by the end of July 2017. The commissioning of the instrument with H^- beam is scheduled during the following 6 months. In Sec. 8.2 several ideas for long-term upgrades of the system are presented.

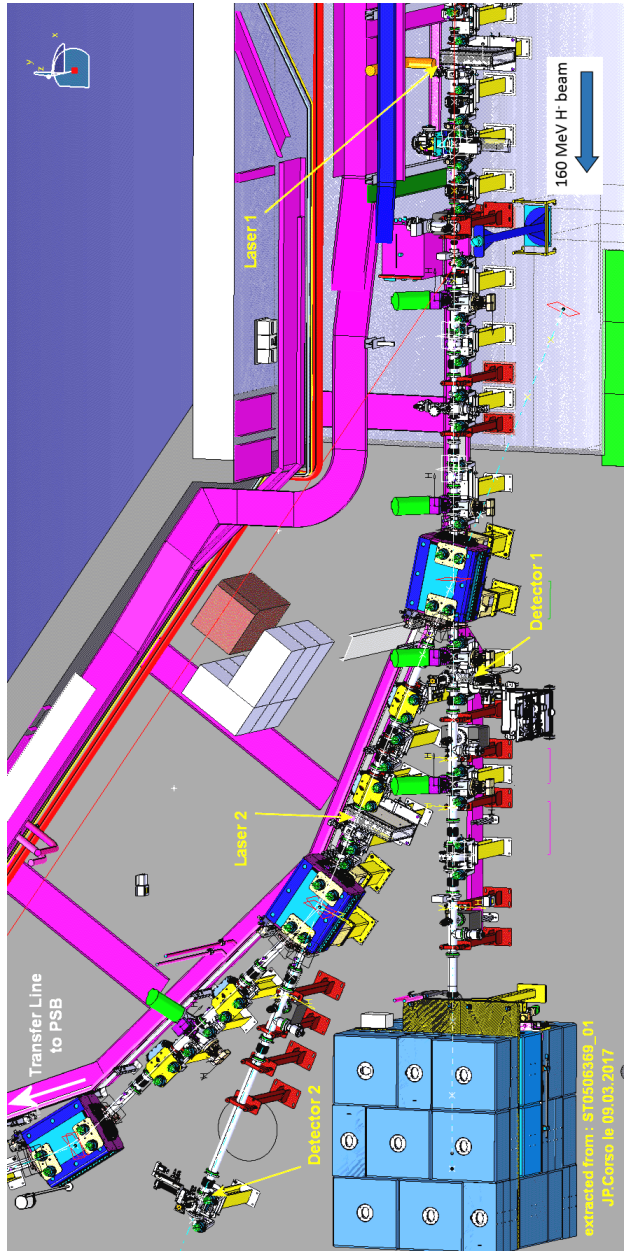


Figure 7.24: Integration of laser- and detector-stations in 160 MeV beam-line.

Chapter 8

Summary and Outlook

8.1 Summary

The aim of this thesis work was the development, test and characterisation of a laser-based instrument to measure the transverse profile and emittance at the CERN's new LINAC4. The motivation to develop this novel type of instrument was driven by its non-destructive principle with no mechanical parts in the main beam which subsequently makes it a well suited instrument for automated periodical measurements, without perturbation of the main H^- beam and no danger of vacuum contamination.

Conventional techniques as well as laser-based concepts for emittance measurements were reviewed in order to evidence their key characteristics and limitations. The transfer of the laser beam to the interaction point with the particle beam was identified as a weak aspect of existing laser-based systems, due to their complex optical free-space transfer lines which degrade the instruments reliability and accuracy.

Simulations of the photo-detachment process $H^- + hf \rightarrow H^0 + e^-$ were conducted and the dominant sources for H^0 background along the LINAC4 accelerator were determined. The results showed that a laser with a relatively low peak-power (1 kW) can neutralise an H^0 beamlet which is significantly higher than the background level. For detection of the H^0 pulses, polycrystalline diamond detectors were identified to provide the required sensitivity, fast response and, most important, high radiation hardness.

In a collaboration with a research group from the Royal Holloway University of London, a prototype of the instrument for laser based emittance measurement has been designed and tested at the 3 MeV and 12 MeV commissioning periods of LINAC4. During these beam-test phases, key features as the fibre-optic laser transmission line and the H^0 detection with the diamond strip-detector could be successfully tested and characterised. The measured phase-

space reconstruction was compared with the conventional slit/grid technique and an agreement within $\pm 3\%$ has been found.

During the following beam commissioning periods at 50, 80 and 107 MeV beam a modified setup, dedicated to reconstruct the vertical beam profile by extracting and counting the stripped electrons, was successfully validated. This achievement implied the design and implementation of a dedicated steering magnet after an extensive set of electron tracking simulations, of an ultra-compact sCVD diamond detector for electron detection and of a new laser system with a 73 m long fibre-optic transfer line. All sub-systems were characterised and the obtained H^- beam profiles were compared with conventional diagnostics as wire-scanners and SEM-grids. In terms of the shape of the profile, no discrepancies could be observed and in terms of reconstructed RMS beam size the agreement was found to be within $\pm 2\%$, for measurements at all beam energies.

The prototypes test results were essential to design the two instruments for emittance and profile measurements that will be installed permanently for measurements at the LINAC4 top energy of 160 MeV (see Fig. 7.24). Both instruments will be equipped with the electron and H^0 detection sub-systems. A new comprehensive set of simulations allowed dimensioning high resolution diamond strip-detectors for H^0 measurements and the associated DAQ chain. A large-aperture electron-multiplier is foreseen to monitor the liberated electrons, as it is less susceptible to undesired background radiation. Finally, the laser-setup has been fully re-designed to allow simultaneous emittance and profile measurement in the horizontal and vertical planes with a resolution of $< 75 \mu\text{m}$ and $< 100 \mu\text{rad}$ in a time-frame of less than 60 s.

8.2 Outlook

At LINAC4 the two final instruments shall be installed, commissioned and characterised at 160 MeV in 2017. During the long shutdown 2 of CERN's accelerator complex (see LS2 in Fig. 1.2) LINAC4 will be connected to the PS-Booster and the instruments shall be used in a fully automated manner to measure and store the phase-space of the H^- beam periodically in order to optimise the PS-Booster injection.

Depending on the needs of the machine operators, different possibilities for instrument upgrades are feasible. As discussed in Sec. 3.3, the energy spread of the H^- beam could be measured by inserting a HV-grid in front of the electron detector. Also beam halo measurements are feasible as demonstrated in [L⁺15], where diamond detectors have been used to measure electron beam

profiles and their corresponding halo with and dynamic range of 10^6 . By modifying the DAQ chain of the system at LINAC4, similar halo measurements could be done.

Concerning fast laser profile systems in general, recent developments at J-Parc [M⁺16] show promising results. In their concept shown in Fig. 8.1, confocal mirrors are used to reflect a laser-pulse multiple times, creating waists ($c_0, c_1, c_2 \dots c_n$) at different positions in reference to a particle beam moving into the image plane. With this approach, a beam profile can be obtained within several hundred nanoseconds with a fully static setup.

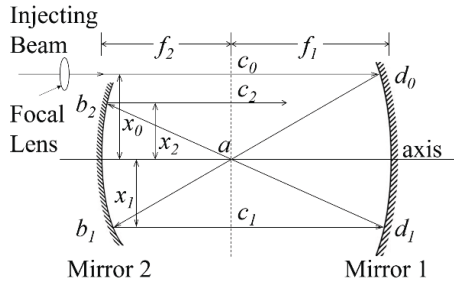


Figure 8.1: Principle for fast laser-based beam profiling using an asymmetrical confocal cavity. [M⁺16]

Another field of application for laser-based H⁻ beam diagnostics is related to longitudinal profile measurements. Bunch-lengths which are typically tenth of picoseconds at H⁻ LINACs can be sampled by ultra-short ($\sim$ ps) laser-pulses. The bunch shape can be reconstructed by scanning the phase of the laser with respect to the bunch-phase and recording the signal of the stripped electrons as demonstrated in [LHA13]. It has been recently proposed to implement such a system at the Front End Test Stand (FETS) at Rutherford Appleton Laboratory, UK.

In the long-term future also laser assisted injection into the PS-Booster as proposed in [D⁺03] can be an option. Recent results from SNS [Cou16] show the feasibility of a system based on the principle described in Fig. 8.2. In this scheme the first electron is detached by magnetic field stripping, followed by a resonant laser excitation of the neutral H⁰ and finally another magnetic field stripping stage to detach the second electron.

In comparison to conventional stripping techniques with carbon foils, the risk of foil breakage and the emittance blow-up by multi-scattering inside the foil are eliminated. However the high laser power is challenging to manage

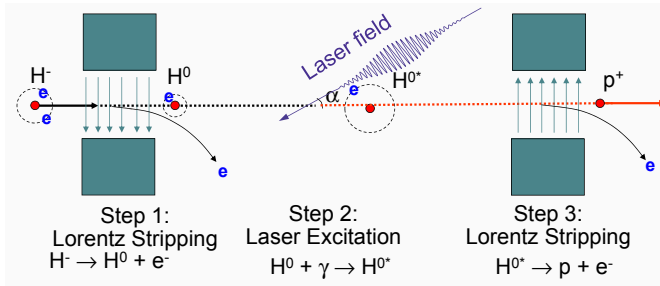


Figure 8.2: Scheme for laser-assisted double electron stripping for charge exchange injection. [Cou16]

and the emittance is slightly increased in the angular domain due to the staged Lorentz stripping.

In conclusion, laser-based beam diagnostics has become a mature technique which is an elegant alternative to conventional, invasive instruments. Although the involved high-power lasers are challenging to handle, new applications are emerging in several fields which attract the attention of a growing international community.

Appendix A

Beam Dynamics

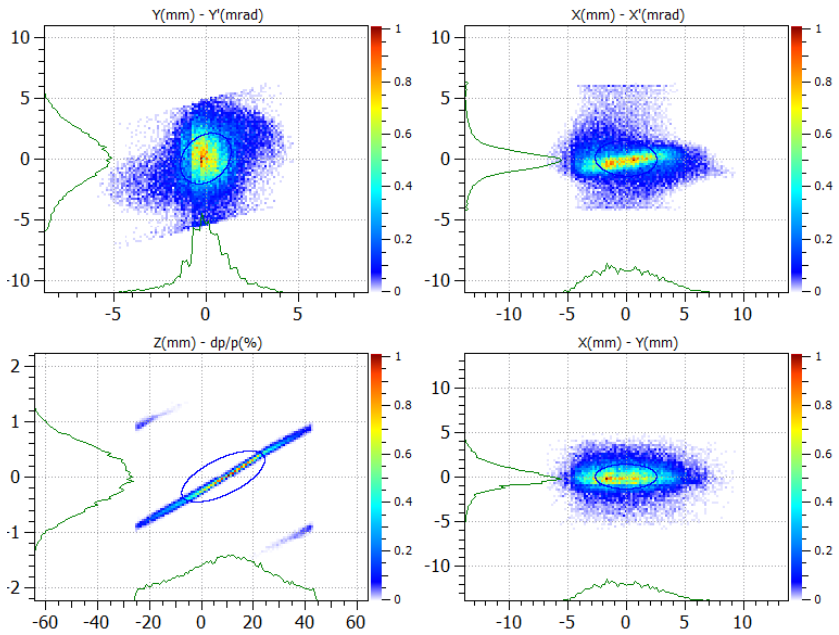


Figure A.1: Beam dynamics of the H beam at the 3 MeV slit and laser IP location of the diagnostic testbench (plot titles: horizontal axis - vertical axis).

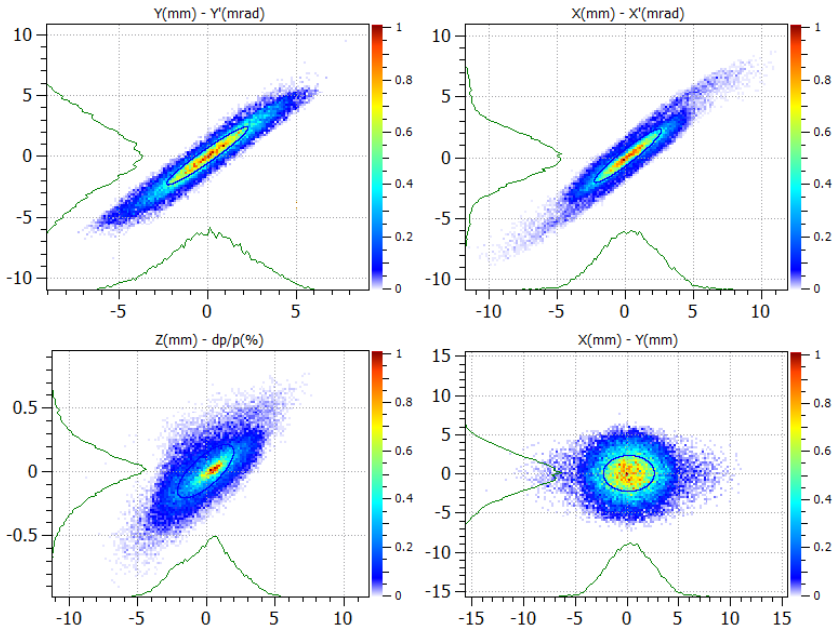


Figure A.2: Beam dynamics of the H beam at the 12 MeV slit and laser IP location of the diagnostic testbench (plot titles: horizontal axis - vertical axis).

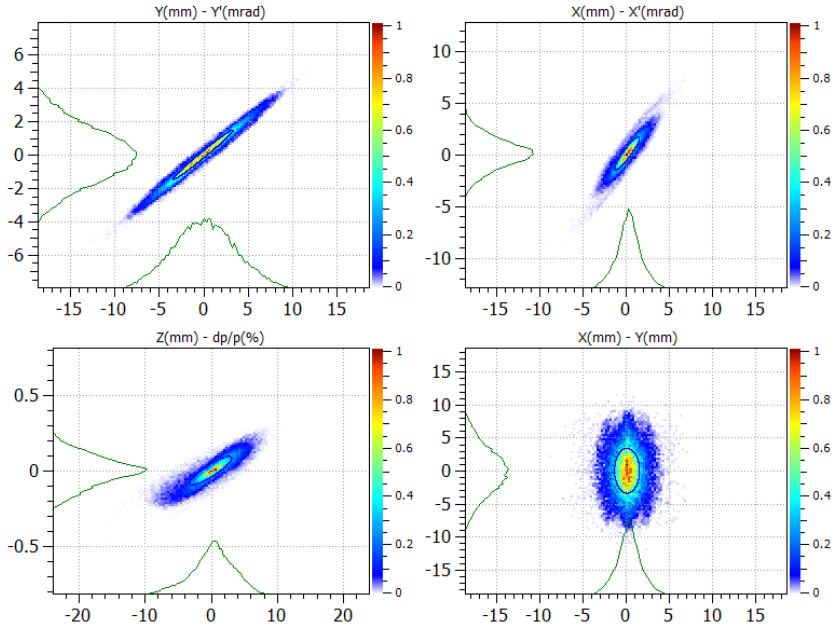


Figure A.3: Beam dynamics at the IP of the 50 MeV H^- beam with the laser (plot titles: horizontal axis - vertical axis).

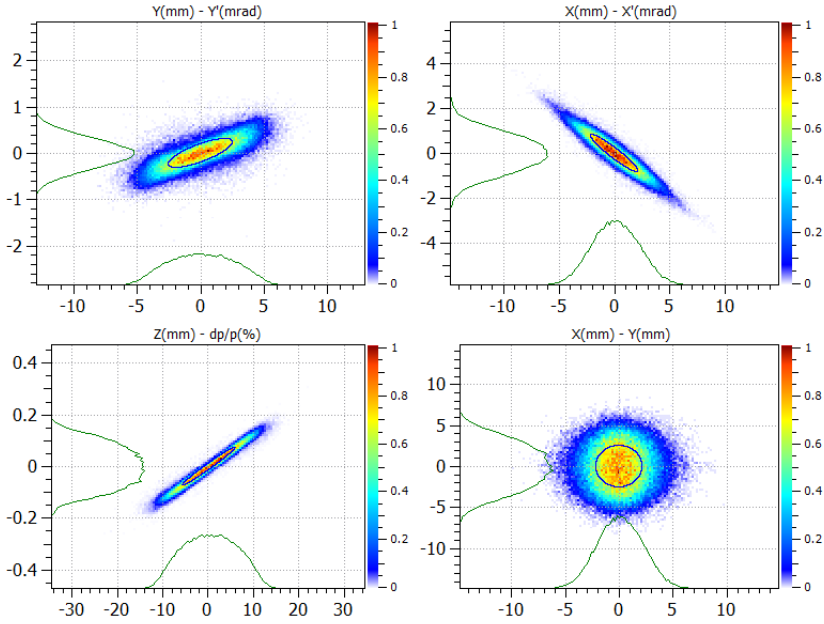


Figure A.4: Beam dynamics at the second laser location at 160 MeV (plot titles: horizontal axis - vertical axis).

Appendix B

Schematics

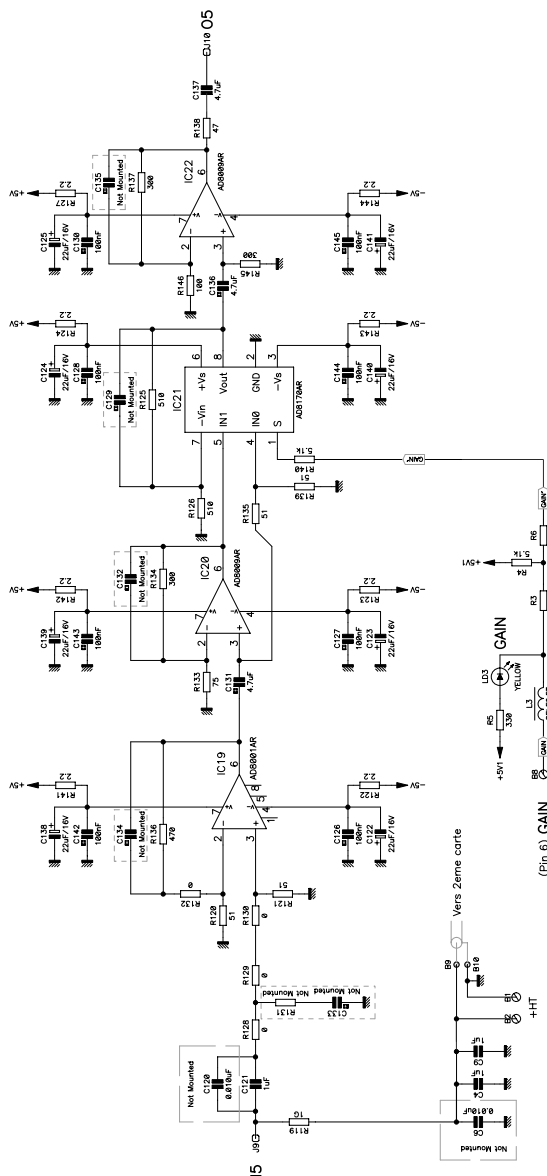
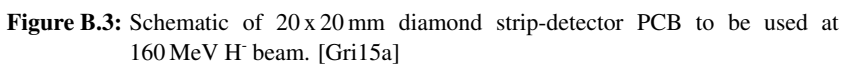


Figure B.2: Schematic of linear pre-amplifier used for signal of diamond detector at 3 MeV test phase.



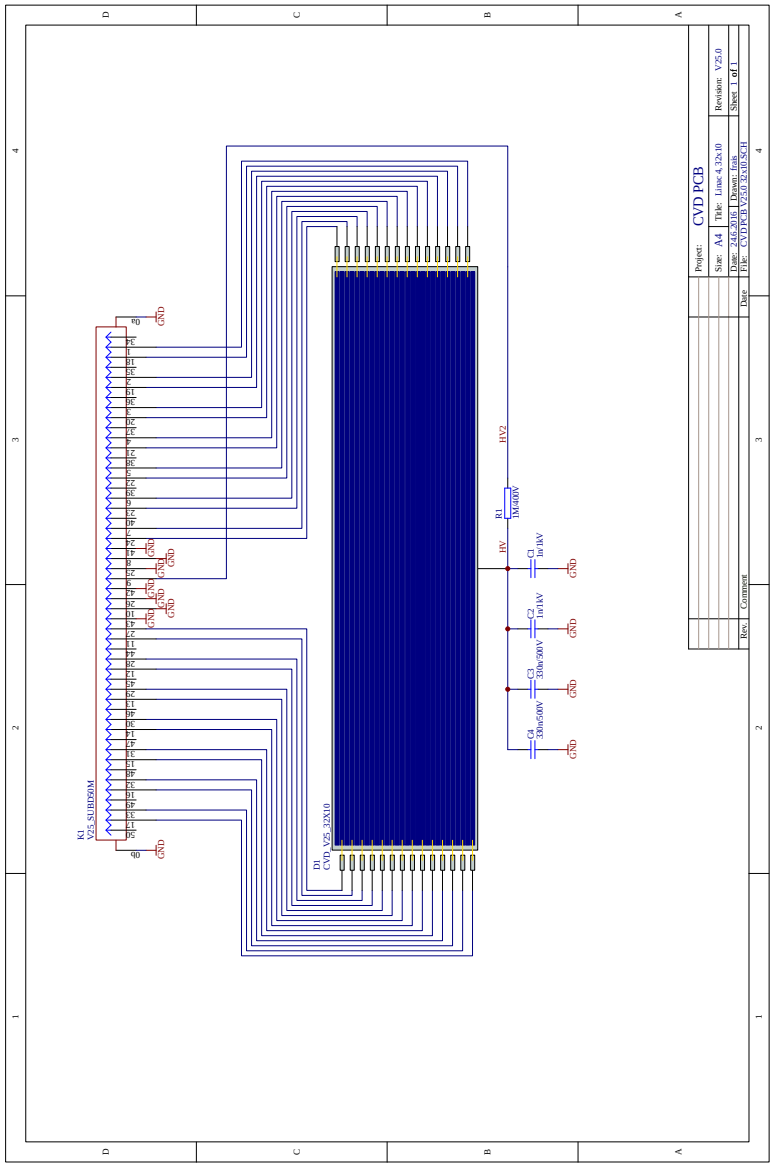


Figure B.4: Schematic of 32 x 10 mm diamond strip-detector PCB to be used at 160 MeV H⁻ beam. [Gri15a]

Appendix C

Supplementary Plots

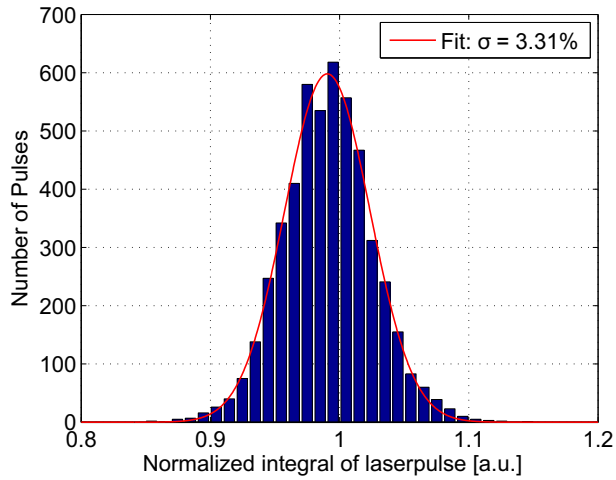


Figure C.1: Pulse energy histogram of the V-Gen Ltd. laser after fibre transmission to the accelerator.

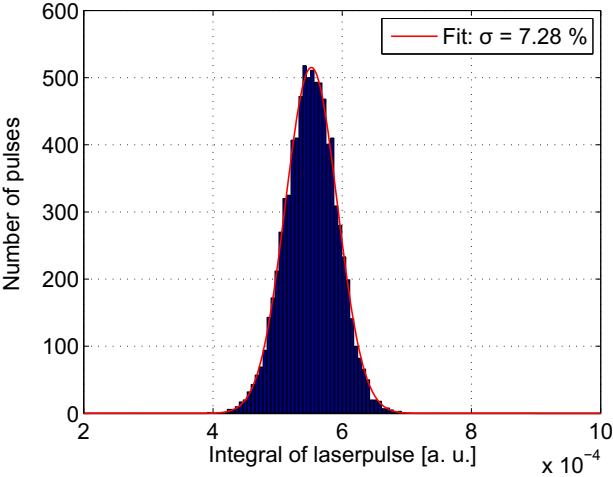


Figure C.2: Pulse energy histogram of the Manlight SAS laser.

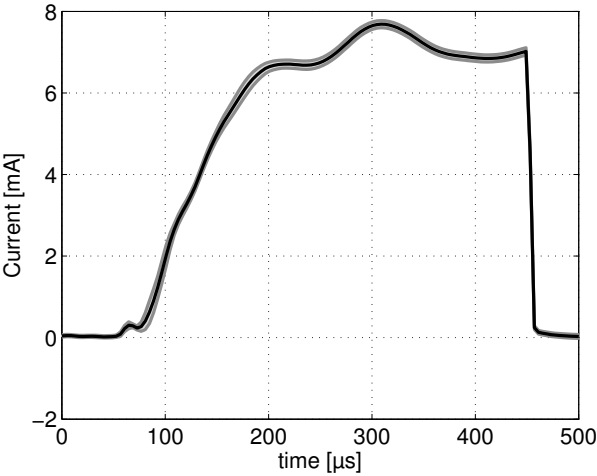


Figure C.3: H⁻ macropulse with pulse to pulse fluctuations (1σ) shaded - measured at 3 MeV beam energy with BCT.

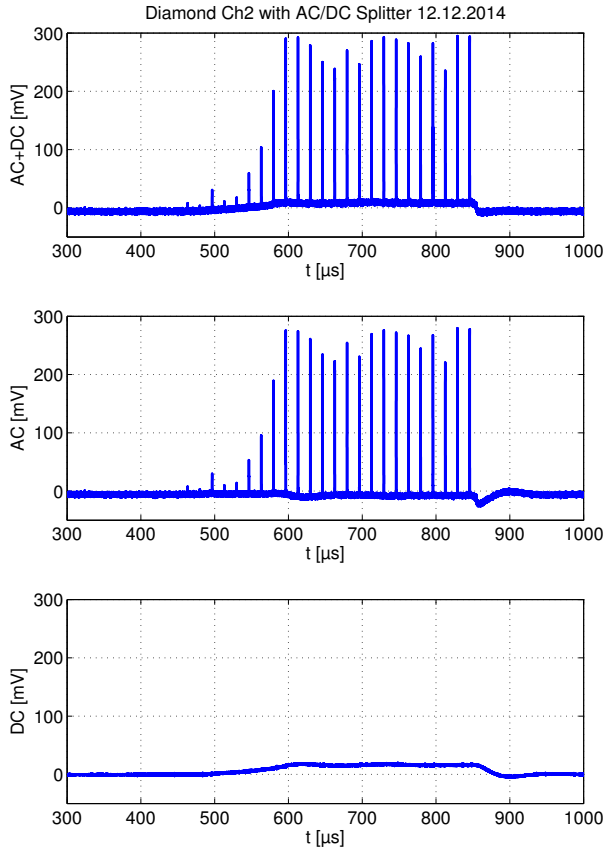


Figure C.4: Recording of channel 2 of the pCVD diamond detector, irradiated with 12 MeV hydrogen atoms. The AC path filters the signal produced from the laser interaction while over the DC path, the H^0 background due to residual gas collisions is separated.

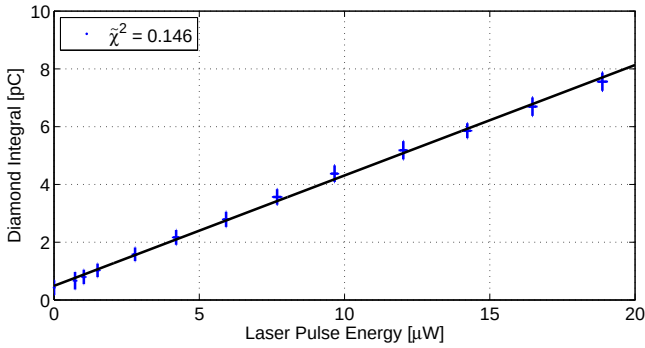


Figure C.5: Integral of pulse recorded with diamond detector for different laser pulse energies - measured with the energy meter after the IP with the H⁻ beam.

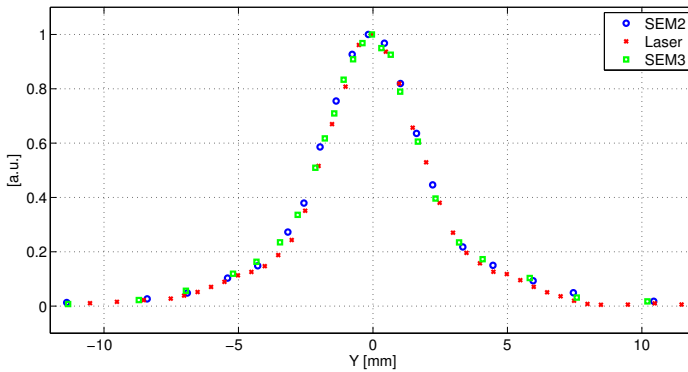


Figure C.6: Overlay of SEM-grid and laserwire profiles, recorded at 50 MeV beam energy.

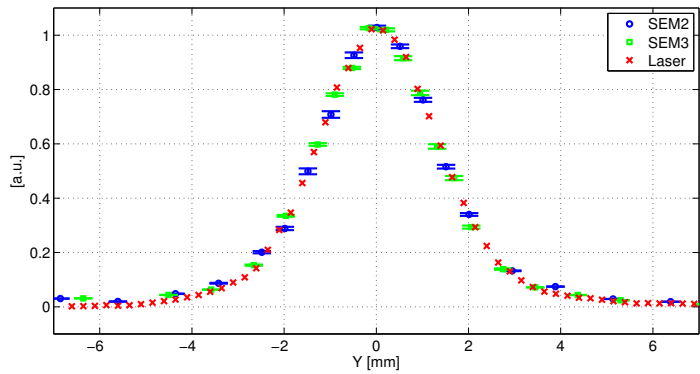


Figure C.7: Overlay of SEM-grid and laserwire profiles, recorded at 80 MeV beam energy.

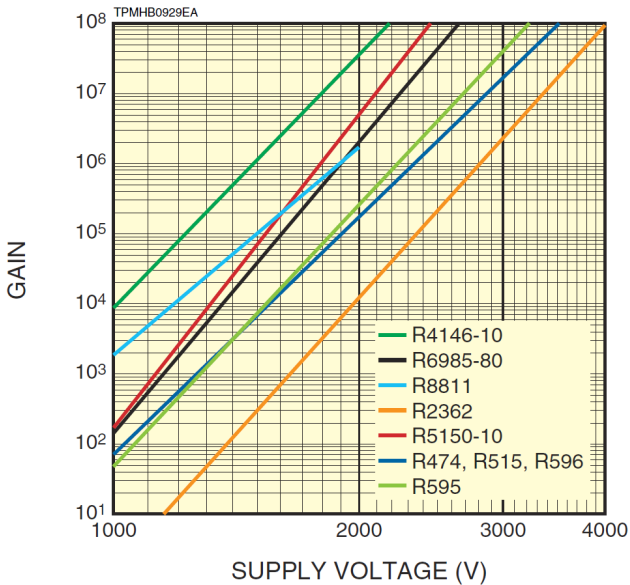


Figure C.8: Gain of different EMTs for different supply voltages. EMT foreseen for 160 MeV setup: R2362. [Pho15]

PROPERTIES	SINGLE CRYSTAL	POLYCRYSTALLINE	COMMENTS
ELECTRONIC			
Hole mobility (cm ² V ⁻¹ s ⁻¹)	>2000	1000	
Electron mobility (cm ² V ⁻¹ s ⁻¹)	>2000	1800	
Carrier lifetime (ns)	~2000	~ 1 - 10	
Charge collection distance	*Typically >475µm	†Typically >180µm	*At 0.5 V µm ⁻¹ applied field, for 500 µm plate † At 1V um ⁻¹ applied field, for 500 µm plate
Charge Collection Efficiency	Typically >95%	Typically >36%	for 500 µm plate
Bandgap (eV)	5.47	5.47	
Electron saturation velocity (cms ⁻¹) x 10 ⁷	2	2	
Radiation Hardness cm ⁻² 24 GeV protons		>10 ¹⁵	With <25% signal drop
Breakdown Voltage (MV cm ⁻¹)	1 - 2		Experimental value. Threshold current 10 µA 4 x 4 mm x 20 µm contact area 0.71 mm ²
IMPURITIES			
[N] _s (ppb)	<5 (typically 0.1 -1)	<50	Measured by EPR
[B] (ppb)	<1	<1	Measured by SIMS
THERMAL PROPERTIES			
Thermal conductivity (W m ⁻¹ K ⁻¹)	>2000	> 1900	
Expansion Coefficient (ppm K ⁻¹) at 300 K	1.0 ± 0.1	1.0 ± 0.1	
Expansion Coefficient (ppm K ⁻¹) at 1000 K	4.4 ± 0.1	4.4 ± 0.1	
DIMENSIONS			
Standard Sizes (mm)	2x2, 3x3, 4.5x4.5	5.5, 10x10, 20x20	Tolerance ± 0.05 mm Polycrystalline available up to Ø110mm
Standard thickness (mm)	0.3 & 0.5	0.3 & 0.5	Tolerance ± 0.05 mm
Laser kerf	3°	3°	
Edge Features (mm)	< 0.2	< 0.2	
Crystallographic Orientation (face / edge)	{100} ± 3° <110>		
PROCESSED			
Surface finish side 1 Ra (nm)	<0.5	Ra <20	Single crystal polished on {100} face
Surface finish side 2 Ra (nm)	<0.5	Ra <20	Single crystal polished on {100} face

Figure C.9: Specifications for sCVD and pCVD detector material used for the electron detector at 50, 80 and 107 MeV and for the H⁰ detectors at 160 MeV. [Tec15]

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