

Master Thesis

Machine Learning for betatron tune diagnostics and control on the Super Proton Synchrotron at CERN

Niki Gallou

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Matrikelnummer: 6244576

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Supervisor:	Prof. Dr. Hans Rudolf Schmidt, Eberhard Karls Universität Tübingen
Second Referee:	Prof. Dr. Tobias Lachenmaier, Eberhard Karls Universität Tübingen
Supervisor at CERN:	Dr. Michael Schenk, CERN



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Kurzfassung

Der Conseil européen pour la recherche nucléaire (CERN) hat sich verpflichtet, den Automatisierungsgrad seiner Beschleunigeranlagen zu erhöhen. Zu den wichtigsten Zielen gehören die Erhöhung der betrieblichen Effizienz und Maschinenverfügbarkeit, sowie die Verbesserung der Strahlqualität. Die jüngsten Fortschritte im Bereich des maschinellen Lernens spielen dabei eine wichtige Rolle. Insbesondere wurden bestimmte kritische Parameter und Optimierungsverfahren, die bisher manuell durchgeführt wurden, als Hauptkandidaten für die Nutzung dieser technologischen Fortschritte identifiziert. Zu den Parametern gehören die Betatron-Tunes und Chromatizitäten – grundlegende Maschineneinstellungen, die sich direkt auf die Lebensdauer des Strahls auswirken.

In den vergangenen 15 Jahren wurde am Super Proton Synchrotron (SPS) ein Tool namens "Multi-Q" zur Analyse und Optimierung dieser Parameter eingesetzt. Die zugrundeliegende Analysemethode ist jedoch in ihrer Genauigkeit limitiert und erfordert typischerweise eine manuelle Bereinigung der Daten. Das Ziel dieses Projekts bestand darin, dieses Mess- und Korrekturverfahren zu verbessern. Dazu wurde ein Python-Paket namens "ml-for-tune-analysis" entwickelt, welches dank eines neuartigen Ansatzes, der die HarPy-Spektralanalyse mit unüberwachtem maschinellen Lernen kombiniert, deutlich bessere Ergebnisse erzielt. Dies kommt auch der Chromatizitätsmessung zugute.

Die Vorteile der neuen Analysemethode wurden während der Inbetriebnahme des SPS im März 2023 experimentell bestätigt. Die Tests zeigten eine verbesserte Messgenauigkeit und konsistente Identifikation der Tune-Linie über den gesamten Zyklus, ohne manuelle Bereinigung. Infolgedessen wurde eine grafische Benutzeroberfläche (GUI) mit dem Namen "SPS Tune app" unter Verwendung von PyQt5 entwickelt und zur internen Verwendung am CERN bereitgestellt.

Sowohl das Tune- als auch das Chromatizitätstool wurden am SPS unter Verwendung von Maschinenentwicklungsstrahlen (MDs) ausgiebig getestet und lieferten äußerst zufriedenstellende Ergebnisse. Das neue Tune-Analysepaket wird auch bereits von anderen Kollegen eingesetzt.

Abstract

Conseil européen pour la recherche nucléaire (CERN) has made a commitment to enhance the level of automation within its accelerator facilities. The primary objectives include improving operational efficiency, increasing machine availability, and enhancing beam quality. Recent advancements in machine learning play an important role in achieving these goals. Specifically, certain critical parameters and optimization procedures, previously performed manually, have been identified as prime candidates for leveraging these technological advancements. Among these parameters are the betatron tunes and chromaticities, which are fundamental machine settings that directly impact the beam lifetime.

Over the past 15 years, a tool named "Multi-Q" has been used at the Super Proton Synchrotron (SPS) to analyze and adjust these parameters. However, both the tool and the underlying analysis method have limitations in terms of accuracy, often requiring manual intervention to clean up the data. The primary objective of this project was to modernize and enhance the measurement and correction procedures. A Python package named "ml-for-tune-analysis" was developed, compensating for the deficiencies of the previously employed analysis technique. Significantly improved results were achieved through a novel approach that combines HarPy spectral analysis with unsupervised machine learning. The improvements made to the tune analysis also benefited the measurement of chromaticity.

The effectiveness of the new analysis method was experimentally confirmed at the SPS during beam commissioning in March 2023. The testing demonstrated improved measurement accuracy and the ability to consistently identify the tune line throughout the cycle without requiring manual intervention. Consequently, a graphical user interface (GUI) called "SPS Tune app" was developed using PyQt5 and deployed at CERN for internal use.

Extensive testing of both the betatron tune and chromaticity tools was conducted at the SPS using machine development beams (MDs), yielding highly satisfactory results. The tool is now ready for use in SPS operations. The new tune analysis package has also found application in the work of other colleagues as well.

Acknowledgments

I would like to express my heartfelt gratitude to all those who have supported me throughout my journey in conducting my Master's thesis at CERN. Specifically, I would like to extend my gratitude to Dr Michael Schenk and Dr Verena Kain from the Data Science for Beam Operations section at CERN, as well as Prof Dr Hans Rudolf Schmidt and Prof Dr Tobias Lachenmaier from Eberhard-Karls Universität Tübingen for giving me the opportunity to work on this project.

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1 Introduction

Particle accelerators are employed in a wide range of fields ranging from fundamental and material science to medical and security applications [1]. They have been the drivers of discovery in particle physics for several decades, leading to the detection of the W and Z bosons [2, 3], the top quark [4], and the Higgs boson [5, 6], to name only a few. They have also been key instruments in the search for dark matter and beyond standard model physics in general [7].

The *Conseil européen pour la recherche nucléaire*, or *CERN*, has a long history of developing, building, and operating particle accelerators for fundamental research. The production of high-quality proton and ion beams is of paramount importance to the physics experiments to maximize the accuracy and efficiency of their measurements as well as the discovery potential for new physics. The more advanced the experiments become, the more challenging the beam parameter requirements typically are. A key figure of merit of particle accelerators is the beam brightness which depends on the beam intensity and the transverse size. Increasing the intensity and reducing the transverse size results in brighter beams, increasing the event rate in colliders or at fixed-target experiments.

CERN has dedicated entire projects to the upgrade of the existing accelerator complex, regarding both hardware and software, and the investigation of future experimental facilities. Two recent ones are the LHC Injectors Upgrade (LIU) [8] and Physics Beyond Colliders (PBC) [9] projects. Producing the challenging beams for some of the proposed physics experiments also requires thorough optimization of the machines. Given the complexity of particle accelerator systems with thousands of parameters, this task requires automation and a modern approach employing the latest technological advances in control theory and signal analysis. Besides the stricter requirements on the beam quality, machine availability is another essential aspect to be improved upon. This can be achieved by reducing beam commissioning times, requiring focus on automation in beam setting up, as well as improving day-to-day machine operation.

1.1 Motivation

More challenging beam parameters and requirements on the beam quality mean more accurate control of fundamental machine parameters. The push towards higher efficiency and reduction in setting up times can be realized by improving the data analysis and control algorithms. This becomes possible thanks to the great advances in machine learning, as well as in computing power. With the recently approved Efficient Particle Accelerators (EPA) project, CERN has officially committed to using these technological advances to improve machine operation and availability.

Two fundamental parameters that heavily impact beam quality are the betatron tunes and chromaticities. When they are not well set, they can cause a number of beam physics phenomena the most prominent of which are tune resonances and beam instabilities. These in turn will lead to a reduction in beam lifetime or, in other words, increased beam loss. The lost particles will produce radio-activation and may even cause damage to machine equipment. Keeping the betatron tunes constant throughout a beam cycle is paramount to the operation of the CERN Super Proton Synchrotron (SPS). The Base Band Tune Meter (BBQ) is the instrument that records live turn-by-turn beam position data from which the tune signals are deduced. The same device can also be employed to measure chromaticities by introducing slight momentum errors to the beam.

The existing betatron tune and chromaticity measurement tool, called "Multi-Q", has been used for this purpose since 2008. The underlying analysis method is, however, limited in the resolution and accuracy it can provide. Furthermore, the data post-processing typically requires manual input from the user to remove outliers or discard faulty measurements before a correction can be applied in the machine. This results in longer beam commissioning times and limited control of the concerned beam parameters.

1.2 Objectives

The goal of this project is to introduce optimization and automation in the betatron tune measurement and control process. The improvements will equally benefit the measurement and correction of chromaticity. This work is an extension of the aforementioned cumulative effort to bring automation and innovation into the way the accelerator complex is controlled, by exploring possible machine learning applications.

1.2. Objectives

The first goal of this project is to develop a new signal analysis method, which clears the BBQ signal of unnecessary noise and reinforces the reconstruction of the betatron tune lines, without requiring beam excitation. A different analysis algorithm will be used, still based on the Fast Fourier Transform (FFT), but less limited in resolution. The new analysis method should improve the accuracy of the measurement and avoid incorrect readouts overall. This can be challenging, as there is often a linear coupling line in the raw data which can strongly bias the measurement. The tune measurement method will also be reevaluated overall to reduce manual user input to a minimum.

The second goal of the project is to overcome possible challenges and provide an automatic correction. Most possible obstacles are taken into account and are automatically considered by the algorithm when encountered. Such examples are empty or noisy acquisitions, as well as incomplete data originating from beams that were dumped mid-cycle. In case the algorithm still struggles to provide a correct measurement, two options will be offered to overcome these obstacles and obtain the final correction. The first option will be to remove the linear coupling line in the transverse planes. The second option will be to manually limit the allowed tune range to aid the chosen machine learning algorithm in selecting the correct tune line. Lastly, the user will always have the possibility to edit the calculated correction manually to improve details, before sending new settings to the accelerator control system.

Finally, a Graphical User Interface (GUI) will be developed to simplify the utilization of the newly developed analysis method in SPS operations at the CERN Control Center (CCC). The GUI will also be evaluated during machine development sessions to ensure the validity of the algorithm, improvements of analysis, and the proper functionality of the tool.

2 Background

2.1 CERN accelerator complex

CERN is the European organisation that hosts the largest particle physics laboratory in the world. CERN was founded in 1954 by 12 member states (Belgium, Denmark, France, Germany, Greece, Italy, Netherlands, Norway, Sweden, Switzerland, United Kingdom, Yugoslavia) on the French-Swiss border (Meyrin) outside Geneva, Switzerland [10]. Its original purpose was to reduce the brain-drain, emigration of scientists, towards the United States after World War II. The laboratory runs by the motto "Science for Peace" [10]. Today, CERN has 23 member states and 10 associate member states. In 2019, CERN hosted 12400 users from institutions all around the world.

Today CERN hosts the world's largest particle collider, the *Large Hadron Collider (LHC)*, the world's largest particle detector, *ATLAS (A Toroidal LHC Apparatus)*, and holds the record for highest energy particle collisions at 13.6 TeV [10]. The research at CERN focuses mostly on particle and nuclear physics, as well as their medical applications. Research is also conducted on antimatter, at the dedicated Antimatter Factory facilities, new acceleration techniques and technology, detector technology, and data analytics. By colliding high energy particles inside the LHC, scientists manage to simulate the conditions just after the Big Bang, in an attempt to answer some of the fundamental questions of mankind. CERN hosts a large computing facility, where data from experiments are stored and analyzed. The CERN Data Center operates the *Worldwide LHC Computing Grid (WLCG)*, which is a grid-based computer network infrastructure, a global collaboration of around 170 computing centers in more than 40 countries [11]. CERN is also the birthplace of the *World Wide Web (WWW)*, invented by Tim-Berners Lee in 1989 and opened for public use in 1991. The work conducted at CERN has led to many great scientific discoveries and distinctions, with the latest being the discovery of the Higgs boson in 2012, which resulted in Peter Higgs and François Englert winning the Nobel Prize in Physics [5, 6].

2.1.1 Introduction

In 2023, CERN operates an accelerator complex of seven main particle accelerators (LINAC3, LINAC4, PSB, LEIR, PS, SPS, LHC) and two decelerators (AD, ELENA) that provide particle beams to a number of physics experiments (Fig. 2.1). The particle beam begins its journey in a linear accelerator (*LINAC*) and continues in circular accelerators, called *Synchrotrons*, to be accelerated to higher energies. The beam energy rises as it passes through each accelerator in the chain. The beam is then either injected into the next accelerator or directly extracted to fixed-target experiments. Since the particle beam is provided for various experiments, it needs to be adjusted to fulfil the specific requirements (e.g. bunch intensity, number of bunches, beam size, bunch length and spacing, etc.) of each end-user.

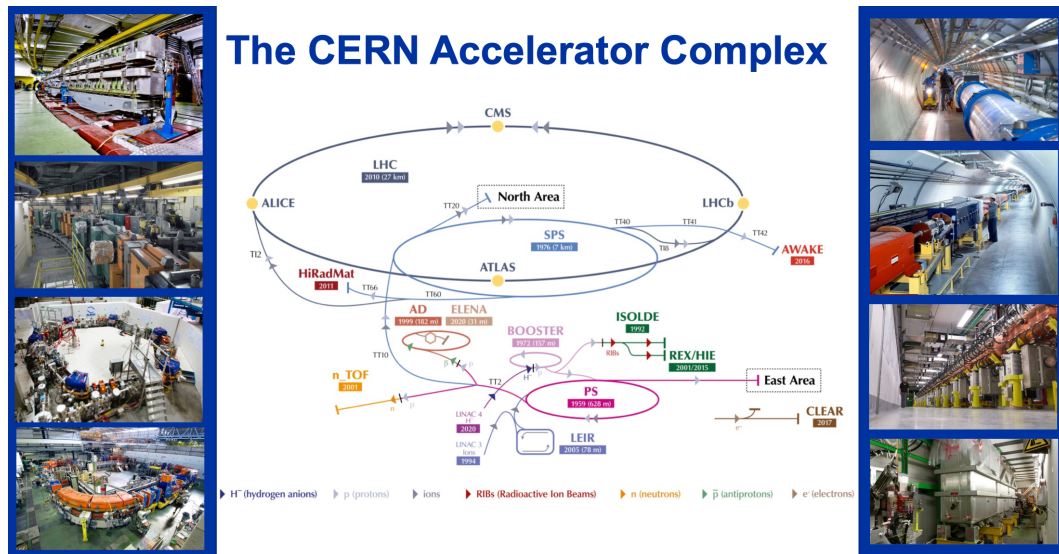


Figure 2.1: CERN accelerator complex.

Photos: PS, PSB, ELENA, LEIR (left, top to bottom), and LHC, SPS, LINAC4, ISOLDE (right, top to bottom) [12].

The main accelerator complex is designed to accelerate two types of beams: proton and ion beams. The proton beam originates from hydrogen gas H_2 . The ion beam consists of ions from either light or heavy elements (e.g. N_2 , O_2 , Pb , Xe , etc.). To prepare the beams for collision at the LHC, protons and ions need to follow slightly different paths. The proton beam starts its journey from a hydrogen bottle. H_2 passes through the ion source [13] where it is converted to H^- and subsequently accelerated by the different stages of LINAC4. After reaching the final energy at the exit of LINAC4, the beam is transferred to the Proton Synchrotron Booster (PS Booster). At

injection, H^- is stripped of its electrons by passing the beam through a stripping foil, such that only protons remain. This process is called charge-exchange injection [14]. In the PS Booster, the proton beam is accelerated in four vertically stacked rings and extracted into the Proton Synchrotron (PS). The PS, besides acceleration, also has the ability to perform bunch splitting, according to specific beam requirements requested by the end-user [15]. PS provides beam for the Super Proton Synchrotron (SPS). After acceleration in the SPS the proton beams are injected into the LHC, sequentially filling the two opposite-rotating beams. The LHC accelerates the two beams to their maximum energy (6.8 TeV) and collides them at the four collision points, around which the large particle detectors are built (ATLAS [16], CMS [17], ALICE [18], LHCb [19]). The LHC filling with protons is illustrated in Fig. 2.2 showing the beam preparation and transfer between different stages of the injector complex. Ions start their journey, already stripped of their electrons, in LINAC3 and are further accelerated in the Low Energy Ion Ring (LEIR), PS, SPS, and eventually collide in the LHC.

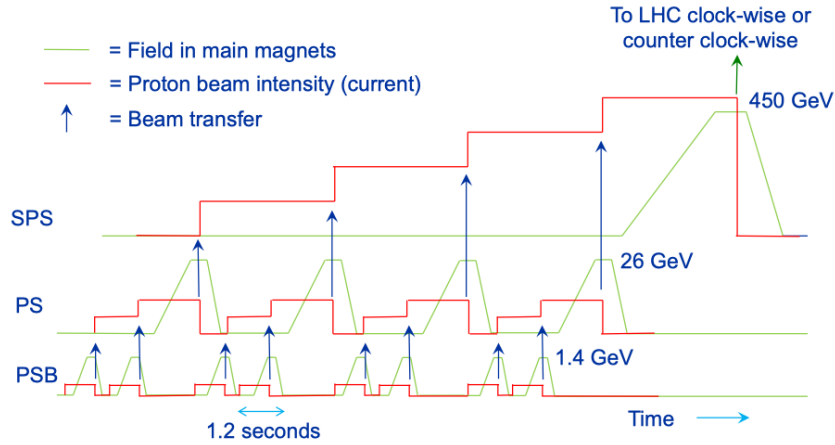


Figure 2.2: Filling the LHC: beam cycles are shorter on lower energy accelerators and get longer as we move to higher energies. This technique is used, among others, to create time slots in order to provide beam for different end-users simultaneously [12].

LINAC4

Linear accelerator 4 or *LINAC4* is the latest linear accelerator in CERN's accelerator complex and started operation during RUN3 in 2022. It is 86 m long and located 12 m below ground. LINAC4 has been designed to accelerate H^- ions to the energy of 160 MeV [20].

H^- ions are produced in a caesiated molybdenum (Cs-Mo) plasma source [21]. There

are two main advantages in using charge-exchange injection from LINAC4 into PS Booster. This method allows for higher proton intensity into the same phase space, avoiding at the same time, a significant increase in beam emittances. This is part of the High-Luminosity LHC injector upgrades [8], to increase luminosity for the LHC experiments. Compared to direct proton injection, safety concerns are reduced thanks to the stripping process' reduced beam losses [20].

Beam matching from the source to the Radio-Frequency Quadrupole (RFQ) is achieved through the Low-Energy Beam Transport (LEBT) line (Fig. 2.3). After the proton beam passes through the ion source and the LEBT, it will be captured, bunched, and focused by the RFQ. Through this process, the beam will reach the energy of 3 MeV. The Medium Energy Beam Transport (MEBT) succeeds the RFQ and encompasses a beam chopping system. It is also known as the "chopper line". MEBT dumps bunches creating distinct spacing for efficient acceleration in the Radio-Frequency (RF) cavities of the PS Booster [20]. At the final stage, the beam passes through RF cavities for further acceleration.

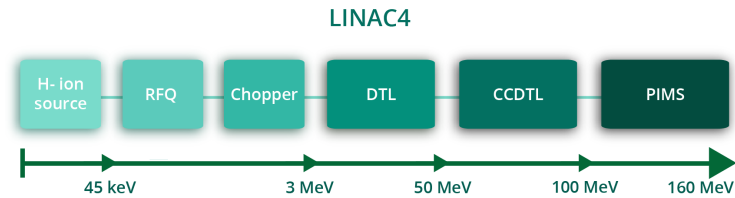


Figure 2.3: LINAC4 diagram [22].

Proton Synchrotron Booster

The *Proton Synchrotron Booster (PSB)* is the first synchrotron in the proton chain of the CERN accelerator complex and contains four superimposed rings with a circumference of 157 m. It first became operational in 1972. PSB receives protons of 160 MeV from LINAC4 and accelerates them further to 2 GeV.

During injection into the PSB, the H^- beam gets stripped of its electrons by passing through a stripping foil, and gets deflected by a dipole into the Booster rings (Fig. 2.4). The ions that do not get deprived of both electrons get deflected onto the beam dump by the same dipole. Each time new bunches arrive from the LINAC4 the existing PSB bunches get filled with more protons to increase beam intensity in the ring. Each ring will inject over multiple turns, using charge exchange injection. The design of four stacked rings allows to reach the intensity of 10^{13} protons per bunch

before injecting into the PS. Since 1992 the On-Line Isotope Mass Separator (ISOLDE) facilities is receiving proton beams directly from the PS Booster.

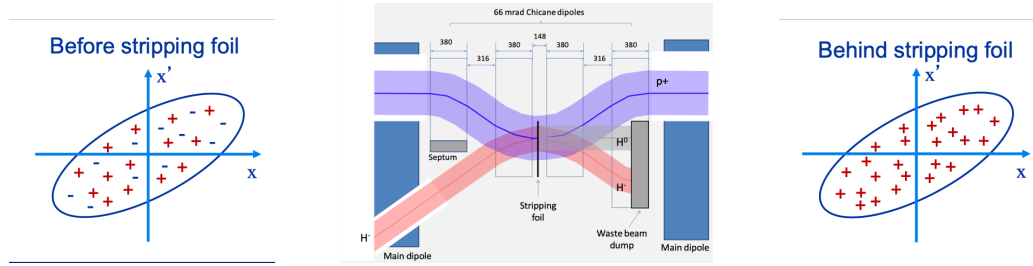


Figure 2.4: Phase space before and after the stripping foil [12].

Low Energy Ion Ring

The *Low Energy Ion Ring (LEIR)* has a circumference of 80 m and became operational in 2005. The predecessor of LEIR was the Low Energy Antiproton Ring (LEAR), which decelerated antiprotons. It is interesting to note that the first creation of anti-hydrogen ($\bar{\text{H}}$) atoms ever, took place in LEAR in January 1996.

Long pulses are injected from LINAC3 into LEIR, which are then split into four short bunches of $2.2 \cdot 10^8$ ions. LEIR accelerates bunches, in groups of two, within 2.5 s from 4.2 MeV/u to 72 MeV/u. It also features an electron cooling system to restrict the bunch spread in the transverse planes and a stochastic cooling system to restrict the bunch spread in the longitudinal plane. Once they reach 72 MeV/u, the ions are sent through the PS, SPS, and eventually into the LHC. It takes around 10 min for LEIR to provide the 592 bunches required for a complete LHC to eventually fill. LEIR also prepares the ion beam for the North Area (NA) fixed-target experiments (SFTION beam).

Proton Synchrotron

The *Proton Synchrotron (PS)* is CERN's first ever built synchrotron and began its operation in 1959, making it the oldest CERN accelerator still in operation today. It has a circumference of 628 m (4x PSB circumference) and can rise the beam energy up to 26 GeV. This is the accelerator, in which transition crossing happens [23] for LHC beams.

The PS has several RF systems, capable of doing RF "gymnastics", to allow further splitting of the bunches (triple splitting, quadruple splitting, see Fig. 2.5) before

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extraction to satisfy the user requirements [15]. Acceleration and bunch manipulation have to be performed avoiding beam instabilities and minimizing beam losses. The PS provides beam further to the SPS, East Experimental Area, and the Antiproton Decelerator.

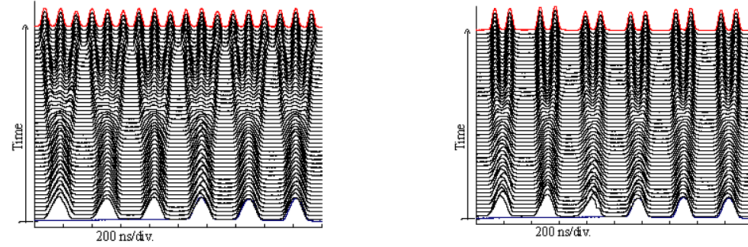


Figure 2.5: Longitudinal beam profiles measured in the PS at triple (left) and quadruple (right) bunch splitting. In the latter case, one bunch is first split into two bunches and later on the two bunches are split into four (not visible here) [15].

Large Hadron Collider

The *Large Hadron Collider (LHC)* is the largest and most powerful particle accelerator in the world. It was commissioned in September 2008 after it had been built inside the tunnel of the former *Large Electron Positron Collider (LEP)* (1989-2000). The LHC holds the record for the highest energy particle collisions ever achieved, at a center of mass energy of 13.6 TeV. The LHC has a circumference of 27 km, it is located 100 m underground and has a beam revolution frequency of 11 kHz. The particles circulating the ring can reach the velocity of 99.9999991% the speed of light. Its magnets and RF cavities are superconducting to achieve magnetic fields of up to 8.33 T. To create the conditions for superconductivity, the whole system is cooled down to 1.8 K using a liquid helium cryogenic system.

The LHC lattice consists mainly of 1232 15 m-long dipole magnets, which bend the beams each by 0.3° , 392 quadrupole magnets, each 5 to 7 m long, to focus the beams, RF cavities, and collimation structures. Inside the accelerator the beams advance in opposite directions in two separate beam pipes (Fig. 2.6), at ultrahigh vacuum conditions. Magnetic triplets focus the beam even further near the collision points to increase the probability of collision. There are four collision points where huge multipurpose detectors are installed to study the outcome of the collisions - ATLAS, CMS, ALICE, and LHCb.

The *CERN Control Centre (CCC)* houses the controls for all accelerators, their technical infrastructure and services in one place. There, the individual machines are very

precisely tuned and synchronized to provide the LHC and all other users with particle beams customized to their needs.

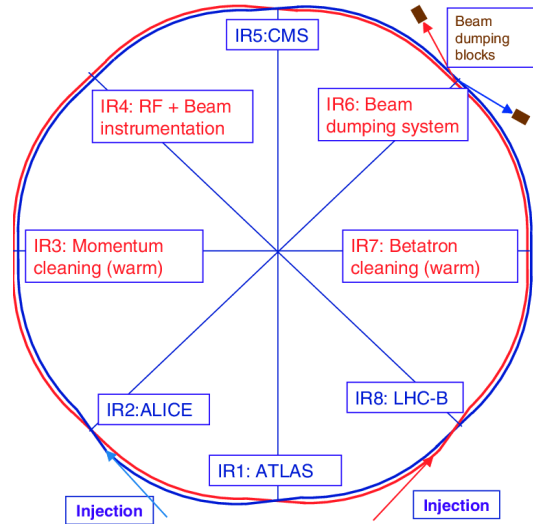


Figure 2.6: LHC schematic layout. Synchrotrons are not perfect rings, but consist of straight and bending sections [24].

2.1.2 Super Proton Synchrotron

The *Super Proton Synchrotron (SPS)* started operation in 1976. It has a circumference of 7 km, is located 40 m underground, and has a beam revolution frequency of 40 kHz. It accelerates protons from 26 GeV to 450 GeV, where they reach velocities up to 99.9998% the speed of light. Over the years, the SPS has been used to accelerate protons and antiprotons, heavy ions, electrons, and positrons.

Today, the SPS is responsible to provide beam to the LHC, *North Experimental Area (NA)* [25], *High-Radiation to Materials (HiRadMat)* [26], and the *Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE)* [27].

To efficiently produce and deliver beam to all users, all the injectors (accelerators in the chain before LHC) are synchronized via supercycles. A supercycle consists of several beam cycles that are bound to different users and can produce different types of beams. Figure 2.7 presents an example of a magnetic supercycle containing two cycles. Beam injection happens where the magnetic field is low. This is followed by the ramping of the magnetic field which translates to beam acceleration. Finally, the beam is extracted at the flat-top region and the magnetic field is restored to a low value for the next cycle to begin.

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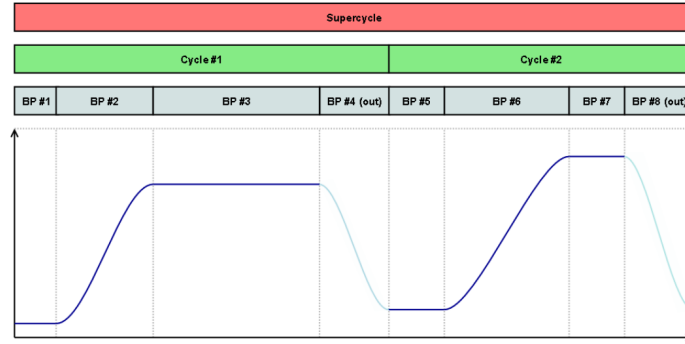


Figure 2.7: Example of a magnetic supercycle composed of two cycles. The first cycle stretches between beam processes (BP) #1 and BP #4 while the second between BP #5 and BP #8. BP #1 is used for injection, BP #2 for acceleration, BP #3 marks flat-top and extraction, and BP #4 the ramp down of magnet currents. The same supercycle is then played repeatedly [28].

Figure 2.8 presents the SPS-Page1, showing the SPS supercycle along with important information about the current state of the machine. The white line represents the current passing through the dipole magnets. It is proportional to the dipole magnetic field and hence to the beam energy. The yellow and blue lines correspond to the beam intensity (number of charges) in the SPS ring. The yellow and blue colors refer to high and low-intensity beams, respectively. The supercycle shown here consists of five cycles in the following order: SFTPRO1 (NA fixed-target proton beam), AWAKE1 (beam destined for the AWAKE experiment - blue line), MD1 (machine development beam - magnetic cycle only - no particle beam is produced or accelerated in this cycle), LHC25NS (beam for LHC), and again MD1. The MD1 cycles are always empty and their purpose is to partially cancel out the magnetic hysteresis effect, caused by the previous cycle, to reduce the impact on the following cycle.

It is interesting to note that the NA fixed-target beam is delivered to the experiments employing a method called *resonant multi-turn extraction*, sometimes referred to as *slow extraction* [29]. This is visible from the linear slope of the SFTPRO1 extraction in Fig. 2.8). To perform slow extraction in the SPS, the RF system is first switched off in order for the beam to debunch, i.e. become continuous longitudinally. The sextupole magnets are simultaneously engaged to drive a horizontal third-order resonance. By bringing the particle tunes close to this resonance, their oscillation amplitudes are slowly increasing over multiple revolutions, and eventually reach a phase-space region to be extracted by a septum magnet. When implemented correctly, the extraction rate remains constant throughout this process [29, 30].

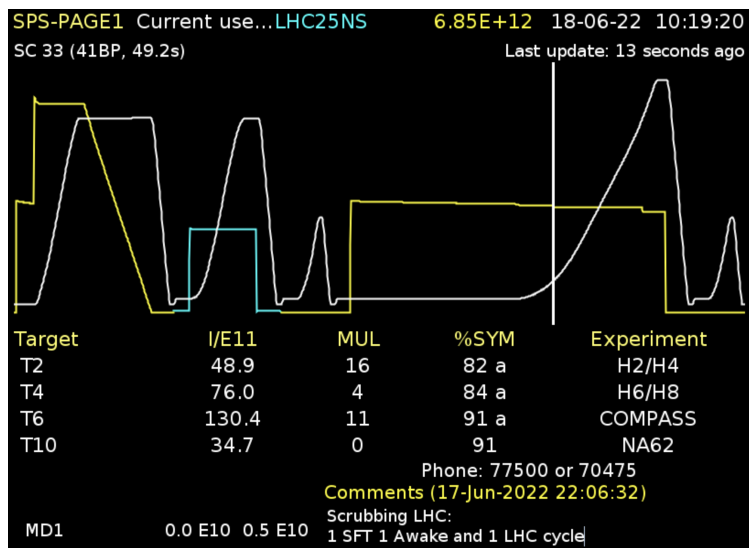


Figure 2.8: Example of the SPS-Page1 showing a supercycle consisting of three beam types and two empty magnetic cycles. The sequence of cycles is SFTPRO1, AWAKE1, MD1, LHC25NS, and MD1.

2.2 Introduction to accelerators

There are three main particle accelerator technologies currently in use: cyclotrons, linear accelerators (linacs), and synchrotrons.

The *cyclotron* is one of the oldest particle accelerator technologies. It consists of two circular metallic plates – electromagnets, that create a homogeneous magnetic field between them, and two hollow metallic D-shaped electrodes are placed in the space between the magnetic plates (see Fig. 2.9, left) [31]. An alternating high voltage at radio frequency is applied to the two D-shaped electrodes, such that the ions, from the central ion source, are accelerated each time they pass between the electrodes. The radius of the ions’ trajectory increases as their energy increases until they are finally ready for extraction.

A *linear accelerator (linac)* is a machine that accelerates charged particles along a straight trajectory. Linacs consist, mostly, of an injection structure (e.g. source, duoplasmatron [32], Radio-Frequency Quadrupole (RFQ), etc.), various acceleration structures (drift tubes, RF cavities), and quadrupole magnets. Acceleration is achieved by applying a time-varying electric field inside the RF cavities, created by an alternating high voltage at radio frequency (see Fig. 2.9, right) [33]. This way, the beam constantly "feels" an attractive force forward when passing through the cavities.

Chapter 2. Background

The field inside the drift tubes is zero, so the beam simply passes through them to enter the next gap to be accelerated further.

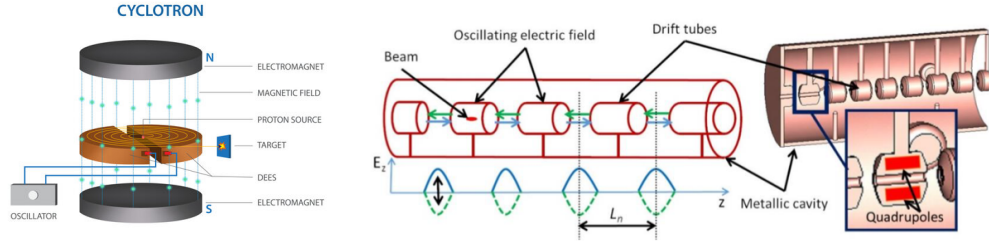


Figure 2.9: *Left*: cyclotron main components. *Right*: Linac structure [33].

2.2.1 Synchrotron

A *synchrotron* is a ring-shaped particle accelerator. Its big advantage is that the beam circulates around the ring thousands of times, passing through the RF cavities once per revolution and acquiring a small energy increase each time. A synchrotron defines a constant orbit during acceleration which is achieved by simultaneously increasing the magnetic dipole field. The revolution frequency ω and the frequency ω_{RF} of the RF cavities also increase as the energy increases. The synchronism condition is described by [34]:

$$\omega_{RF} = h\omega, \quad \frac{C}{v_s} = \frac{2\pi R}{v_s} = hT_{RF}, \quad (2.1)$$

where $h \in \mathbb{N}$ is the harmonic number, i.e. the number of RF cycles per revolution and hence equivalent to the number of RF buckets, v_s the particle velocity, C the particle orbit circumference, R its radius, and $T_{RF} = 2\pi/\omega_{RF}$ the RF period. There is a synchronous RF phase ϕ_s for which the increase of the magnetic field corresponds to the energy gain ΔE per turn required to keep an orbit of constant radius.

$$\Delta E = q\hat{V}_{RF} \sin \phi_s, \quad R = \frac{C}{2\pi}, \quad B\rho = \frac{p}{q}, \quad (2.2)$$

where q is the electric charge of the particle, $\hat{V}_{RF}$ the RF voltage, ρ the bending radius, B the magnetic dipole field, and p the particle momentum. $B\rho$ is also referred to as the beam rigidity.

Synchrotron lattice

In theory, the *synchrotron lattice* shown in Fig. 2.10 (left) is a circular periodic structure that consists mainly of dipoles (Fig. 2.15), quadrupoles (Fig. 2.16) and sextupoles

(Fig. 2.17) placed in a FODO (focusing - drift/dipole - defocusing - drift/dipole) sequence to provide bending and strong focusing in the two transverse planes [35]. In reality, the lattice is not a perfect circle, but consists of several straight and bending sections. The main lattice components are RF cavities (Fig. 2.9, right), dipole magnets, quadrupole magnets, higher-order magnets (up to dodecapoles), and other elements (e.g. septa, kicker magnets, collimators, etc.) (Fig. 2.10, right).

Straight sections are used for injection, extraction, dumping, acceleration, and collimation. Dipole magnets are responsible for steering the beam and are located in the bending sections. Quadrupole magnets are responsible for focusing and stabilizing the beam, keeping the particles from colliding with the pipe walls. Sextupole magnets typically accompany quadrupole magnets and account for chromaticity corrections (see Section 2.4.5).

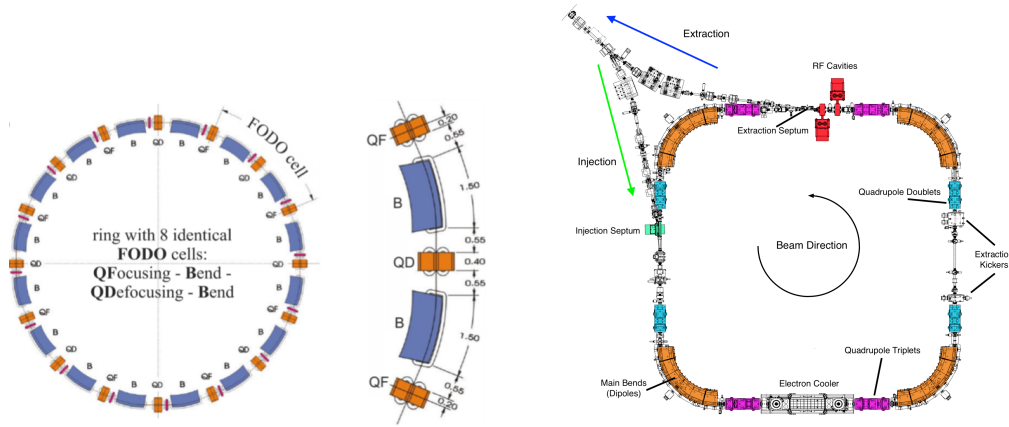


Figure 2.10: *Left*: The synchrotron lattice consists of a periodic structure of dipoles, quadrupoles, and sextupoles [35]. *Right*: Schematic of a real synchrotron (LEIR) including straight sections and other elements [36].

2.3 Longitudinal beam dynamics

The force $\vec{F}$ applied on a particle of electric charge q traveling through an electromagnetic field is equivalent to the Lorentz force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (2.3)$$

where $\vec{v}$ is the particle's velocity.

From this equation, it can be derived that to achieve acceleration, only a longitudinal electric field component E_z should be present in an RF cavity. The magnetic field $\vec{B}$

on the other hand needs to be as small as possible (ideally zero in superconductive conditions LHC), since it always creates a force perpendicular to the direction of motion. The kinetic energy gained from an electric field along the z direction can be calculated as [37]:

$$\Delta E = q \int E_z dz = q\Phi, \quad (2.4)$$

where Φ is the electric potential. The evolution of the particle's velocity depends on its properties and is given by:

$$v = \beta c = c \sqrt{1 - \frac{1}{\gamma^2}}, \quad \text{where} \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}, \quad (2.5)$$

where c is the speed of light in vacuum and γ is the Lorentz factor. In order for the acceleration system to remain synchronized, the radio-frequency ω_{RF} will have to change to match the revolution frequency in a synchrotron.

2.3.1 Radio-frequency cavities

Radio-frequency (RF) cavities are essential components of linacs and synchrotrons. They are the systems responsible for acceleration. Inside an RF cavity, an alternating electric field is created providing the particle with extra energy (Eq. (2.4)). The RF system also creates buckets and focuses the particles longitudinally to group them into bunches (Fig. 2.11) [38]. A very precise technique has been developed for further bunch splitting in a synchrotron, as described in Section 2.1.1. It is based on slowly adding higher-frequency components through the RF system (Fig. 2.5).

The synchronous particle is the particle that maintains a constant, also known as the *synchronous*, phase ϕ_s after each revolution. ϕ_s changes during acceleration:

$$\phi_s = \arcsin\left(2\pi\rho \frac{\dot{B}}{\hat{V}_{RF}}\right). \quad (2.6)$$

This means that ϕ_s depends on the RF voltage and the time-derivative of the magnetic dipole field $\dot{B}$. The RF frequency must follow the variation of the B field according to:

$$\frac{f_{RF}(t)}{h} = \frac{c}{2\pi R} \sqrt{\frac{B(t)^2}{(m_0 c^2 / q c \rho)^2 + B(t)^2}}, \quad (2.7)$$

where m_0 is the particle rest mass.

2.3. Longitudinal beam dynamics

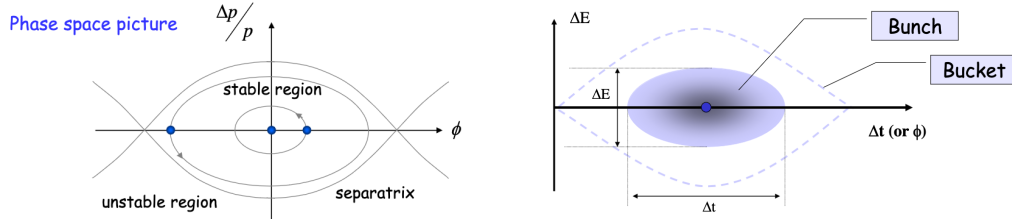


Figure 2.11: Creating stable bunches inside the RF buckets. The areas of stable motion (closed trajectories) in longitudinal phase space are called *buckets*. The number of available buckets is equal to the harmonic number h , which corresponds to the maximum number of bunches in a ring [34].

2.3.2 Longitudinal focusing

For stationary conditions, the phase of the synchronous particle is established as $\phi_0 = 0$. Given the inherent position distribution among particles within an actual beam, the majority of particles are not synchronous. Instead, they exhibit an initial phase either greater than ϕ_0 ($\phi_1 > \phi_0$) or smaller than ϕ_0 ($\phi_2 < \phi_0$) [34], as illustrated in Fig. 2.12, left.

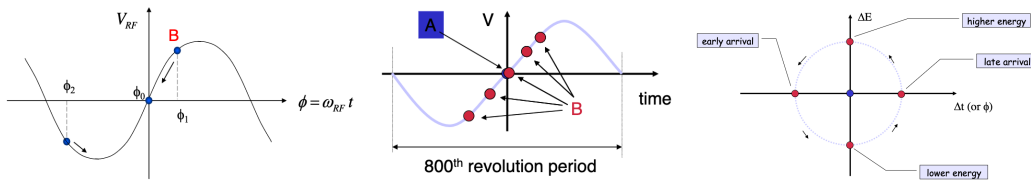


Figure 2.12: *Left*: Particle B has an initial phase $\phi_1 > \phi_0$. *Middle*: Particle B oscillates around ϕ_0 , has a different phase after each revolution. *Right*: Particle B trajectory in the longitudinal phase space [34].

In Fig. 2.12, particle B initially arrives at the RF cavity at phase $\phi_1 > \phi_0$ (left), i.e. "later" than the synchronous one. As a result, it experiences a positive RF voltage and hence gains in kinetic energy (assuming electric charge $q > 0$, and velocity $v \ll c$). The increased velocity leads to a faster revolution frequency and the particle will hence arrive at the RF cavity at a phase $< \phi_1$, thus approaching the synchronous phase. This is illustrated for several revolutions in Fig. 2.12 (middle, right). On the other hand, a particle with an initial phase ϕ_2 would experience deceleration, due to the negative voltage. Due to its reduced velocity, it would hence arrive at the RF cavity at a phase $> \phi_2$ after one revolution and also approach the synchronous phase. This concept is called *longitudinal focusing* and the resulting oscillations are referred to as *synchrotron oscillations* [38, 34]. The amplitude of these oscillations is influenced by the initial phase and energy of the particle. Notably, the oscillation frequency in

this context is considerably slower than the oscillation frequency in the transverse planes. Typically, a large number of revolutions are required for a single complete synchrotron oscillation to occur. The count of such oscillations over one revolution is called the *synchrotron tune*.

2.4 Transverse beam dynamics

An "ideal" particle (or reference particle) is a particle whose trajectory follows the design orbit of the synchrotron. A co-moving coordinate system can be defined along the design orbit, to describe the transverse displacements $x(s)$ and $y(s)$ at any longitudinal position s . This way it is possible to describe the transverse position (x, y) of an individual particle [35].

In a physical synchrotron, x -axis points towards the center of the synchrotron ring, y -axis points upwards and z -axis is tangential to the synchrotron ring, and points towards the anticlockwise motion of the beam [35]. Any change in the transverse displacements can be characterized by the s -position derivatives x' , y' , also called the *angular displacements*. The angles α_x , α_y are the projections of a particle's trajectory on the (x, s) or (y, s) planes (see Fig. 2.13).

$$x' = \frac{dx}{ds} = \frac{dx}{ds} \frac{ds}{dt} = \tan \alpha_x, \quad y' = \frac{dy}{ds} = \frac{dy}{ds} \frac{ds}{dt} = \tan \alpha_y. \quad (2.8)$$

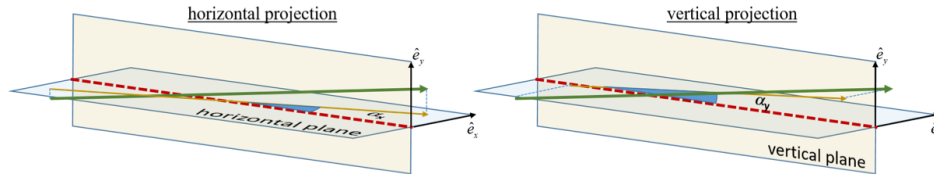


Figure 2.13: Illustration of the transverse planes. *Left* : Horizontal (H) plane in blue. *Right* : Vertical (V) plane in yellow [35].

Each particle's position can be characterized by the following two vectors, including information for position and angle (phase-space):

$$\vec{x} = \begin{pmatrix} x \\ x' \end{pmatrix}, \quad \vec{y} = \begin{pmatrix} y \\ y' \end{pmatrix}. \quad (2.9)$$

2.4.1 Basic lattice elements and optics

The magnetic fields created by multipole magnets of the synchrotron lattice are illustrated in Fig. 2.14. The influence of dipoles, quadrupoles, and sextupoles on the beam trajectory will be presented in the subsections below.

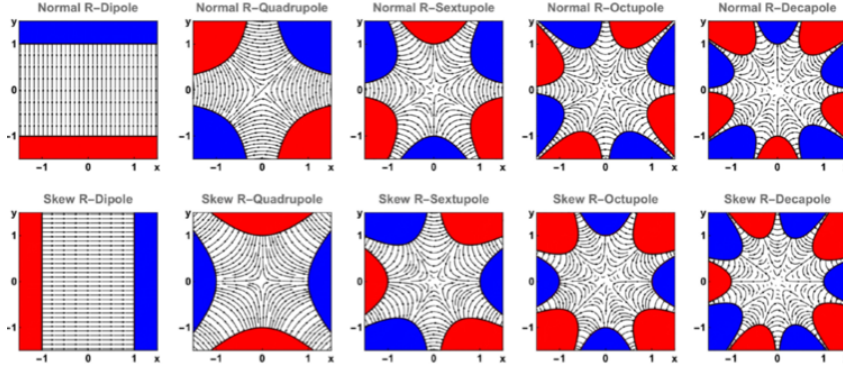


Figure 2.14: Field patterns of different magnetic multipoles, specifically: dipoles, quadrupoles, sextupoles, octupoles and decapoles [35].

Dipole magnets

Dipole magnets are usually ferromagnets creating a homogeneous magnetic field, between the two coils in order to deflect the beam into a certain direction. Dipoles are mainly used to steer the beam around the synchrotron ring and to apply trajectory corrections [35] (see Fig. 2.15).

The dipole magnetic field strength B_0 is provided by the relation:

$$B_0 = \mu_0 \frac{nI}{h}, \quad (2.10)$$

where μ_0 is the magnetic permeability, n the number of coil windings, h the gap height, and I the electric current. The dipole strength κ is equivalent to the curvature of the orbit $1/\rho$, which is the inverse bending radius:

$$\kappa = \frac{1}{\rho} = \frac{q}{p} B_0. \quad (2.11)$$

κ is in units of m^{-1} .

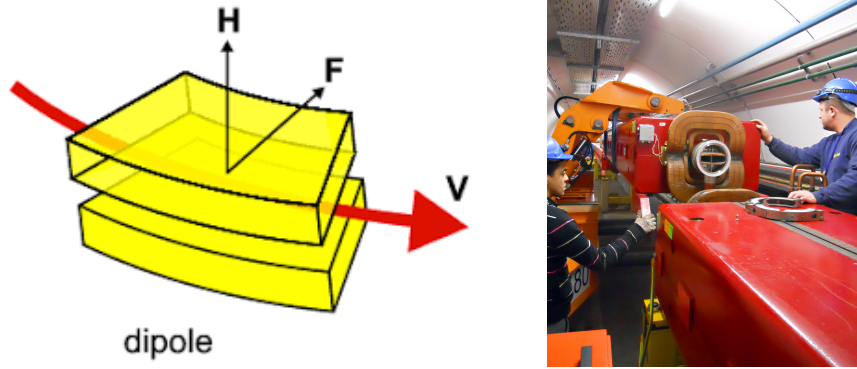


Figure 2.15: *Left*: Negatively charged particle beam passing through a dipole magnet. The Lorentz force points towards the center of the synchrotron ring [39]. *Right*: SPS dipole (Image: CERN).

Quadrupole magnets

Beam focusing can be achieved using the Lorentz force created by a gradient field. It is important that the restoring force has a linear relationship to the distance from the optical center of the focusing device [35]. A quadrupole magnet (Fig. 2.16) is capable of creating a transverse gradient magnetic field, scaling linearly with the transverse offset (x, y) . Focusing in the horizontal plane is accomplished with a vertical field B_y proportional to x , and focusing in the vertical plane is accomplished with a horizontal field B_x proportional to y [35]:

$$B_x = -g \cdot y, \quad B_y = -g \cdot x, \quad \text{where} \quad g = -\frac{\partial B_y}{\partial x} = -\frac{\partial B_x}{\partial y} = \text{const.} \quad (2.12)$$

The Lorentz force applied on a charged particle passing through the gradient field can be described by [35]:

$$\vec{F} = qvg \cdot (x\hat{e}_x - y\hat{e}_y), \quad (2.13)$$

where g is the quadrupole field gradient defined in Eq. 2.12, and $\hat{e}_{x,y}$ are the unit vectors of the horizontal and vertical planes, respectively.

The corresponding potential is described by [35]:

$$\Phi(x, y) = x \cdot y \cdot g. \quad (2.14)$$

The purpose of a quadrupole magnet is to focus in one transverse plane, which automatically defocuses in the other plane. This is dependant on the sign of the field

2.4. Transverse beam dynamics

gradient g and the particle's charge q . The normalized *quadrupole strength* k expresses the focusing strength of a quadrupole and is expressed in units of m^{-2} [35]:

$$k = \frac{q}{p} g. \quad (2.15)$$

$k < 0$ and $k > 0$ provides horizontal and vertical focusing, respectively. From now on, the "thin lens" convention will be used. In this approximation, the *focal length* $f_{x,y}$ is much larger than the length L of the quadrupole magnet. The relation between focal length and quadrupole strength in the two transverse planes can be described by:

$$\frac{1}{f_x} = -kL, \quad \frac{1}{f_y} = kL. \quad (2.16)$$

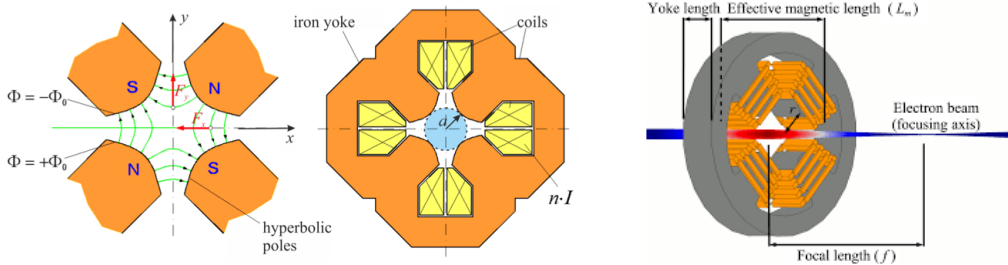


Figure 2.16: *Left*: Quadrupole (illustration of magnetic poles and field) [35]. *Right*: Focusing of an electron beam using a quadrupole [40].

Sextupole magnets

Sextupoles (Fig. 2.17) can both focus and defocus the beam particles depending on their momentum deviation when located in a region with non-zero dispersion (Fig. 2.24). Particles with a positive momentum deviation ($\Delta p/p > 0$) are focused and particles with a negative momentum deviation are defocused ($\Delta p/p < 0$). The magnetic field inside a sextupole magnet can be described by [35]:

$$\vec{B} = \frac{1}{2} g' (x^2 - y^2) \hat{e}_y + g' xy \hat{e}_x, \quad \text{where} \quad g' = \frac{\partial^2 B_y}{\partial x^2} = \text{const.} \quad (2.17)$$

The corresponding potential can be expressed as [35]:

$$\Phi(x, y) = \frac{1}{6} g' (y^3 - 3x^2 y). \quad (2.18)$$

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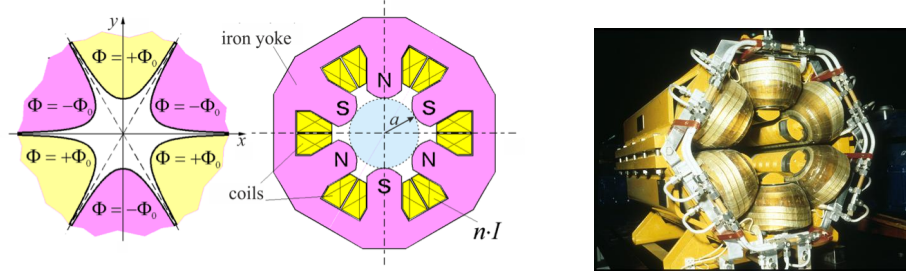


Figure 2.17: *Left*: Sextupole (illustration of magnetic poles) [35]. *Right*: Large Electron Positron collider sextupole (Image: CERN).

Optics

In the lattice simulation below, only the influence of dipoles and quadrupoles on the beam trajectory will be taken into account (linear beam optics). Dipole displacement can be approximated as a drift in free space (see Fig. 2.18) [35] since dipole magnets deflect particles on a circular orbit with radius ρ , independent of their initial transverse position (x_0, y_0) . Inside the drift section, position displacements change linearly in relation to drift length L , whereas the angular displacements remain constant:

$$x = x_0 + Lx', \quad y = y_0 + Ly', \quad x' = x'_0, \quad y' = y'_0. \quad (2.19)$$

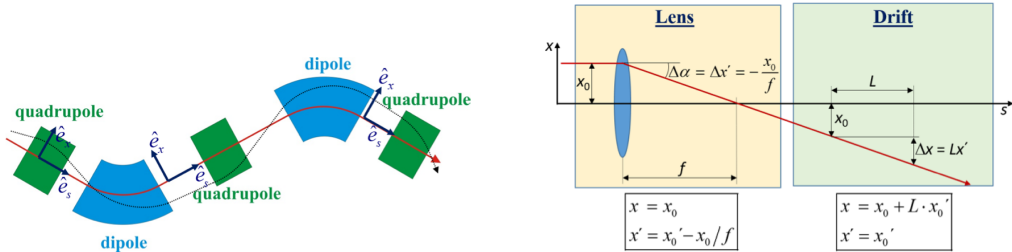


Figure 2.18: *Left*: Top view of a FODO cell element sequence showing the reference path (red), the trajectory of a horizontally displaced particle passing through the FODO cell (dashed) [35]. *Right*: illustration of the change in a particle's angular displacement when passing through a thin focusing lens followed by a drift space [35].

To maintain a stable beam trajectory, a periodic structure called *FODO* (focusing - drift/dipole - defocusing - drift/dipole) is usually used to design the synchrotron lattice. A quadrupole magnet can act on the beam, either as a focusing or as a defocusing element, by rotating it by 90° . Focusing and defocusing the beam allows to constrain its size in the transverse planes and eliminate beam losses.

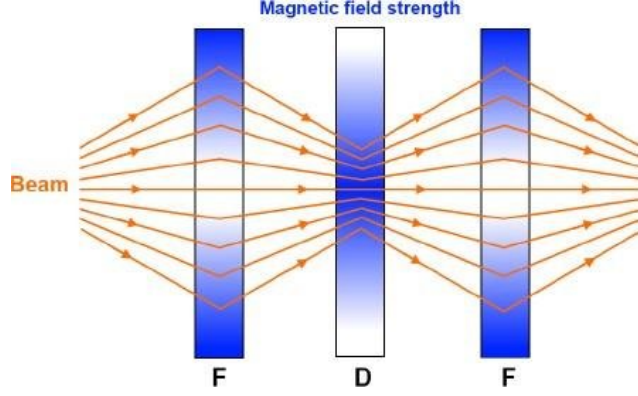


Figure 2.19: Particle beam passing through the FODO lattice [35].

The matrix describing the influence of a dipole (drift) of length L is:

$$M_{drift} = M_{dip,x} = M_{dip,y} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}, \quad (2.20)$$

and the matrices describing the influence of a thin quadrupole are:

$$M_{quad,x} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_x} & 1 \end{pmatrix}, \quad M_{quad,y} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_y} & 1 \end{pmatrix}. \quad (2.21)$$

The *transfer matrix* M describes the effect of a complete beam transfer line, and can be calculated by multiplying the matrices M_i of the individual elements i [35]:

$$M = \prod_{i=a} M_i. \quad (2.22)$$

2.4.2 Equations of motion

Assuming the reference particle ($\Delta p/p = 0$), the equation of motion in the transverse plane is [41]:

$$x''(s) - \left(\frac{1}{\rho^2(s)} - k(s) \right) \cdot x(s) = 0. \quad (2.23)$$

The focusing parameters $k(s)$ are functions of the coordinate s and are periodic $k(s+L) = k(s)$, which leads to *Hill's differential equation* [42]. The solution of Hill's equation can be rewritten following Floquet's theorem [43] in a more general expression [41]:

$$x(s) = \sqrt{\varepsilon \beta_x(s)} \cos[\psi(s) + \phi], \quad x'(s) = -\sqrt{\frac{\varepsilon}{\beta_x(s)}} \sin[\psi(s) + \phi] + \alpha_x(s) \cos[\psi(s) + \phi], \quad (2.24)$$

where $\alpha_x(s)$ and $\beta_x(s)$ are two of the three Twiss, or Courant-Snyder parameters [44], and ε is the particle action (for a beam of particles it would be beam emittances), described in the following subsection. Similarly, the corresponding equations can be derived for $y(s)$, $y'(s)$. In cases where only conservative forces are taken into account, the values of ε and ϕ are constants of the specific trajectory.

In reality, the (longitudinal) momenta of the beam particles follow a distribution of finite width. Every particle j has a certain relative momentum deviation compared to the synchronous particle: $\delta_j = (p_j - p_0)/p_0 = \Delta p/p_0$. The equations of motion for a particle with transverse offset are expressed by [35]:

$$x''(s) + \left(\frac{1}{\rho^2(s)} - k(s) \right) \cdot x(s) = \frac{1}{\rho} \frac{\Delta p}{p_0}, \quad y''(s) + k(s) \cdot y(s) = 0. \quad (2.25)$$

2.4.3 Twiss parameters and beam emittances

The treatment will now again be restricted to monochromatic beams ($\Delta p/p_0 = 0$). Liouville's theorem states that the phase-space distribution function remains invariant when conservative forces are applied [45, 35]. This statement implies that the phase-space area A occupied by any subset of particles remains constant. The integration constant ε can be expressed as:

$$\varepsilon_x = \gamma_x(s) \cdot x^2(s) + 2\alpha_x(s) \cdot x(s) \cdot x'(s) + \beta_x(s) \cdot x'^2(s), \quad (2.26)$$

where $\gamma_x(s)$ is the third Twiss parameter, detailed further below. Here and in the section to follow, the formalism is only noted down for the horizontal plane, but is equally valid for the vertical one.

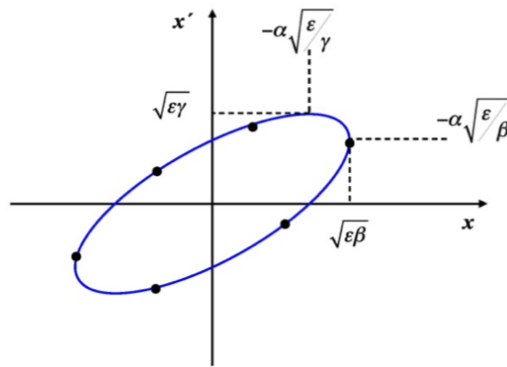


Figure 2.20: Particle action ellipse (phase-space) at a certain position- s in the synchrotron ring [41].

describes an ellipse in $x - x'$ phase-space with parameters $\alpha_x(s)$, $\beta_x(s)$, $\gamma_x(s)$. The phase-space area is equivalent to $A = \pi\epsilon$ [41].

The *Twiss parameters* $\alpha(s)$, $\beta(s)$, $\gamma(s)$ are valid per transverse plane. They are position-dependent and gain physical meaning in relation to beam emittances in Eq. (2.26) [41].

- $\sqrt{\beta(s)}$ expresses the root-mean-square (rms) beam envelope per unit emittance;
- $\sqrt{\gamma(s)}$ expresses the rms beam divergence per unit emittance;
- $\sqrt{\alpha(s)}$ is proportional to the relation of x and x' or y and y' .

The expression for $\alpha(s)$ and $\gamma(s)$ parameters in relation to $\beta(s)$ follows below (Eq. (2.27)). The $\beta(s)$ -function defines the beam envelope and is calculated through simulations of the synchrotron lattice. The beam size does not remain constant throughout the synchrotron ring, it oscillates due to focusing and defocusing effects on the beam (Fig. 2.21). The beam envelope defines the beam size along the ring and it depends strongly on the sequence of the lattice elements (optics).

$$\alpha(s) = -\frac{1}{2}\beta'(s), \quad \gamma(s) = \frac{1 + \alpha^2(s)}{\beta(s)}. \quad (2.27)$$

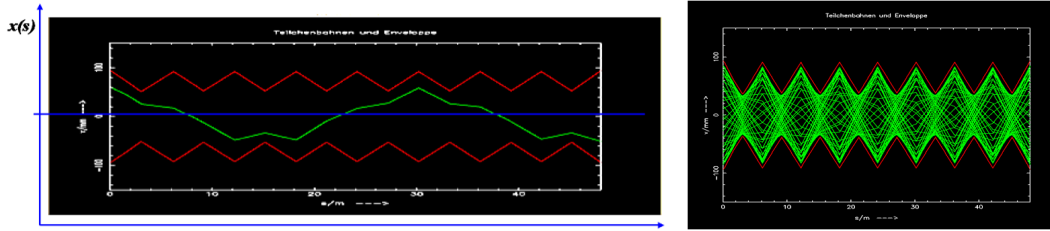


Figure 2.21: *Left*: Single particle trajectory inside the envelope over one revolution [41]. *Right*: Single particle trajectory inside the envelope over multiple revolutions [41].

2.4.4 Betatron tune Q

The *betatron tune* Q , or simply the tune, is defined as the number of oscillations a particle with position deviation in relation to the ideal trajectory, will undergo while completing a full revolution around the synchrotron ring [46]. The tune is an important property of the synchrotron lattice and is related to the strength k of quadrupoles. There are two tune values (Q_x and Q_y), separate for the horizontal and vertical transverse plane. Their values should not be exactly the same, to avoid the coupling resonance.

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The betatron tune Q can be further divided into two components: the integer tune and the fractional tune q . The integer tune represents the number of complete oscillations the beam undergoes over one revolution. The fractional tune defines the fractional difference of the oscillation from one revolution to the next, and is directly related to the phase advance μ . The fractional part q must be measured and controlled with great accuracy, as its value is decisive for the determination of the optimal working point of the machine (see Section 2.4.6).

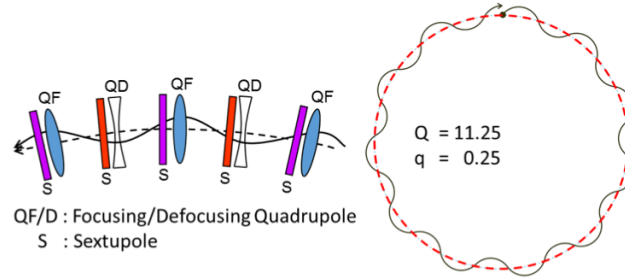


Figure 2.22: The betatron tune describes the transverse oscillation of the beam centroid around the ring and can be divided into an integer part and a fractional part. *Left*: illustration of the transverse oscillations of a particle passing through the optical elements of the lattice. *Right*: Illustration of transverse oscillations of the particle beam around the synchrotron ring [46].

The *betatron phase advance* is defined as the difference in the phase of the oscillation from one point of the synchrotron ring s_0 to the next s . It is given by:

$$\mu_x(s) = \int_{s_0}^s \frac{1}{\beta_x(s)} ds. \quad (2.28)$$

One of the most important control room tasks is to measure and optimize the betatron tune throughout each timing-user cycle. The integer tune is measured by the beam position monitoring system (BPMs), which takes measurements along the global beam orbit. The fractional part of the tune is measured using the base-band tune meter (BBQ) [46], described in Section 2.5.1. This monitor is installed at one location of the synchrotron ring and acquires the beam position once per revolution, separately for the horizontal and vertical planes. The accuracy of the measurement of q is very important, since the derivation of other characteristic parameters, such as chromaticity and (linear) betatron coupling, depends on it.

Tune Correction

To apply a tune correction, the strength of the quadrupole magnets on the lattice needs to be changed. The Twiss matrix for the FODO cell is described by [12]:

$$M_{FODO} = \begin{pmatrix} \cos \mu + \alpha \sin \mu & \beta \sin \mu \\ -\gamma \sin \mu & \cos \mu - \alpha \sin \mu \end{pmatrix}. \quad (2.29)$$

Adding a small QF (focusing quadrupole) to the lattice with strength dk and length ds would add a horizontal focusing (and vertical defocusing) term:

$$\begin{aligned} M' &= \begin{pmatrix} 1 & 0 \\ -dk ds & 1 \end{pmatrix} \begin{pmatrix} \cos \mu + \alpha \sin \mu & \beta \sin \mu \\ -\gamma \sin \mu & \cos \mu - \alpha \sin \mu \end{pmatrix} = \\ &= \begin{pmatrix} \cos \mu + \alpha \sin \mu & \beta \sin \mu \\ -dk ds (\cos \mu + \alpha \sin \mu) - \gamma \sin \mu & -dk ds \sin \mu + \cos \mu - \alpha \sin \mu \end{pmatrix}. \end{aligned} \quad (2.30)$$

Since the new cell is again a FODO cell with a new phase $\mu_1 = \mu + d\mu$ the corresponding Twiss matrix is obtained:

$$M'_{FODO} = \begin{pmatrix} \cos \mu_1 + \alpha \sin \mu_1 & \beta \sin \mu_1 \\ -\gamma \sin \mu_1 & \cos \mu_1 - \alpha \sin \mu_1 \end{pmatrix}. \quad (2.31)$$

This is valid for very small values of $d\mu$, such that the changes in β can be ignored. From Eqs. (2.30) and (2.31) the following relation can be derived:

$$2 \cos \mu_1 = 2 \cos \mu - dk ds \beta \sin \mu. \quad (2.32)$$

By substituting $\mu_1 = \mu + d\mu$ and considering $dQ = d\mu/2\pi$ in Eq. (2.32) a phase difference, and in extend, tune difference can be calculated:

$$d\mu = \frac{1}{2} \beta dk ds, \quad dQ_x = \frac{1}{4\pi} \beta_x dk ds. \quad (2.33)$$

Therefore, the generalised expression is:

$$\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta k(s) ds. \quad (2.34)$$

Eq. 2.34 describes the influence on the betatron tune caused by a distribution of quadrupole errors $dk(s)$, spread along the synchrotron ring. Quadrupole errors dk cause large tune deviations, when they happen to be in locations with large β -functions [35]. Following the same logic as in Eq. (2.33) for both transverse planes,

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considering both focusing (QF) and defocusing (QD) quadrupoles, a tune correction is described by [12]:

$$dQ_y = \frac{1}{4\pi}\beta_y dk_D ds_D - \frac{1}{4\pi}\beta_y dk_F ds_F \quad (2.35)$$

$$dQ_x = -\frac{1}{4\pi}\beta_x dk_D ds_D + \frac{1}{4\pi}\beta_x dk_F ds_F \quad (2.36)$$

2.4.5 Chromaticity Q'

Until now, the assumption of a monochromatic particle beam has been made to simplify the calculations. Momentum or energy deviation of the particles (typically $\sigma_{\Delta p/p_0} \approx 10^{-3}$) also needs to be taken into account, to provide a more realistic picture of the behaviour of the particle beam.

In the main dipoles, particles with non-zero momentum deviation will be deflected with different radii. The horizontal displacement at any location s in the ring is described by the *dispersion function* [12]:

$$x_D(s) = D_x(s) \cdot \frac{\Delta p}{p_0}, \quad (2.37)$$

Normally, there are no vertically deflecting dipoles, apart from small orbit correctors, placed along the ring implying $D_y(s) = 0$. $D_{x,y}(s)$ is expressed in units of m.

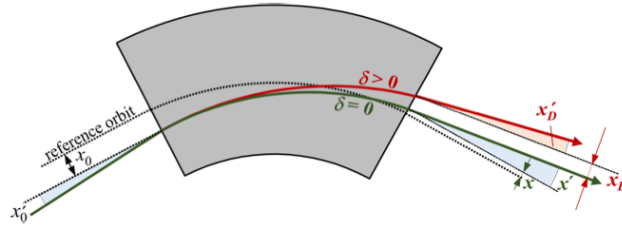


Figure 2.23: Particles with non-zero momentum error experience a deviation in trajectory when passing through a dipole [35].

The focusing strength k of the quadrupoles relates to the beam momentum p [12] as follows:

$$k = \frac{dB_y}{dx} \cdot \frac{1}{B\rho} = \frac{dB_y}{dx} \cdot \frac{1}{3.3356Bp}. \quad (2.38)$$

A spread in k can be caused by a spread in p , and since the tune Q depends on the strength k [12] the resulting relation is:

$$\frac{\Delta k}{k} = -\frac{\Delta p}{p} \Rightarrow \frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}, \quad (2.39)$$

where ξ is a constant called *chromaticity*. Chromaticity quantifies the relationship between the tune spread of the transverse motion and the momentum spread in the beam. It is defined as the ratio of tune spread to the nominal tune caused by a spread in its momentum to the nominal momentum [46]. It is a characteristic property of the lattice and can be fine-tuned by the sextupole magnets.

Figure 2.24, left, shows how particles with $\Delta p/p_0 < 0$ will be deflected stronger by a focusing quadrupole and will hence have a higher betatron tune. Particles with $\Delta p/p_0 > 0$, on the other hand, will be deflected less, and therefore, have a lower betatron tune.

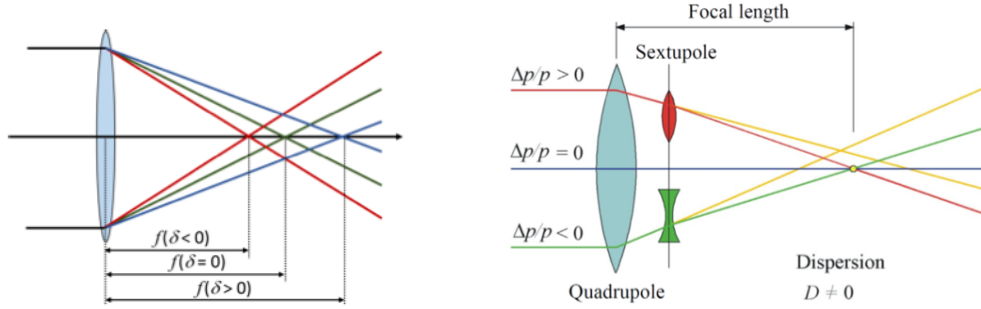


Figure 2.24: Illustration of the behaviour of particles with different momenta passing through magnets. *Left:* dependence of focal length on momentum deviation $\delta = \Delta p/p_0$ without sextupole correction. *Right:* Correction of differences in focal length by means of a sextupole [35].

In order to account for this error in focusing strength, called chromatic aberration, the particles need to be deflected using strengths adjusted to their momentum deviation. This can be achieved with sextupole magnets placed e.g. directly after the quadrupoles and in a region of non-zero dispersion (see Fig. 2.24, right). Inside a sextupole a field $B_y = Cx^2$ is created for $y = 0$. Similarly as in Eq. (2.38):

$$k = \frac{dB_y}{dx} \cdot \frac{1}{B\rho} = 2Cx \cdot \frac{1}{B\rho} \Rightarrow \Delta k = \frac{2C}{B\rho} \Delta x \quad (2.40)$$

Substituting Δx from Eq. (2.37) in Eq. (2.40):

$$\Delta k = dk = 2C \cdot \frac{D(s)}{B\rho} \frac{\Delta p}{p}. \quad (2.41)$$

Chapter 2. Background

From (2.17) it is known that: $C = \frac{1}{2} \frac{\partial^2 B_y}{\partial x^2}$. Combining Eqs. (2.33), (2.41) and (2.39) results in:

$$\frac{\Delta Q}{Q} = \frac{l\beta(s)}{4\pi} \cdot \frac{d^2 B_y}{dx^2} \cdot \frac{D(s)}{B\rho Q} \cdot \frac{\Delta p}{p} \Rightarrow \xi = \frac{l\beta(s)}{4\pi} \cdot \frac{d^2 B_y}{dx^2} \cdot \frac{D(s)}{B\rho Q} \quad (2.42)$$

where l is the sextupole length. The most efficient way to correct chromaticity is to perform a localized correction, i.e. inserting a sextupole after every quadrupole (see Fig. 2.17).

A different expression for chromaticity based on the nonlinear dispersion function can be derived [47]:

$$Q\left(\frac{\Delta p}{p_0}\right) = Q_0 + Q' \frac{\Delta p}{p_0} + \frac{Q''}{2!} \left(\frac{\Delta p}{p_0}\right)^2 + \dots + \frac{Q^n}{n!} \left(\frac{\Delta p}{p_0}\right)^n \quad (2.43)$$

where Q^n are higher-order terms. Note that:

$$\xi = \frac{Q'}{Q_0}. \quad (2.44)$$

2.4.6 Tune resonances

Real accelerators are imperfect machines, so resonances and instabilities on the beam can be created. Some examples are magnet imperfections (undesired higher-order field components in the magnets), machine misalignment (magnets with tilts or offsets), etc. This leads to a reduction in the beam lifetime, which needs to be taken into account and corrected [12].

Assuming an integer tune, a dipole error would lead to a growth in amplitude with each revolution, and the particle would eventually be lost. This is called a 1st order resonance [12]. A quadrupole gradient error at an arbitrary position s_0 , and integrating over all quadrupole perturbations, the following relation can be extracted [35]:

$$\Delta\beta(s) = \frac{\beta(s)}{2\sin(2\pi Q_0)} \oint \delta K(s_0) \beta(s_0) \cos[2(\mu(s) - \mu(s_0) - \pi Q)] ds_0. \quad (2.45)$$

This shows that in the presence of quadrupole gradient errors and for half-integer tunes, the beta function experiences unbounded growth, leading to an infinite increase in the beam size. This phenomenon is a result of the quadrupole kick-induced oscillation intensifying with each revolution, ultimately causing the loss of

particles. This is called a 2nd order resonance [12]. When the betatron tune obtains a half-integer value, any focusing error δk will consistently "kick" a transversely displaced particle, directing it either inward or outward based on the polarity of δk (Fig. 2.25). The cumulative effects of these successive impacts result in an escalation of the betatron oscillation's magnitude. It is also possible to calculate 3rd order resonances caused by sextupoles at integer value, 0.33, and 0.66, as well as 4th-order resonances caused by octupoles at 0.25, 0.5, etc.

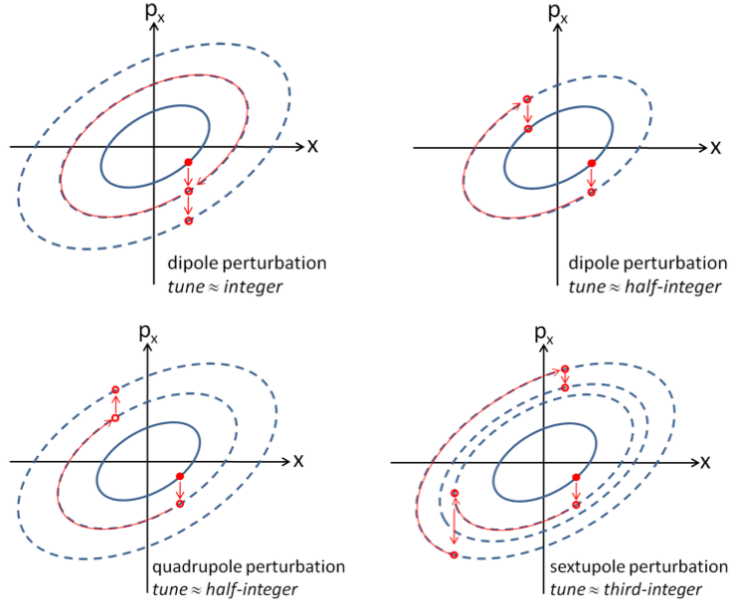


Figure 2.25: Tune resonances in transverse phase space caused by different multipole perturbations [35].

To keep the machine working in a stable state, these resonances need to be taken into consideration. Figure 2.26 shows the transverse resonance diagram. The choice of the working point is between the resonance lines (red dot) and is selected after extensive machine studies. Each beam type may favor a different working point according to its configuration, functionality, and performance requirements. In the SPS, for most cases, the tune needs to remain constant throughout the entire magnetic cycle. In other machines, the tune value can vary over time in a given cycle.

The general resonance condition considering the coupling effect between the horizontal and vertical betatron oscillations can be described by:

$$mQ_x + nQ_y = N. \quad (2.46)$$

where m , n , and N are integers. $|m| + |n|$ represents the order of the resonance.

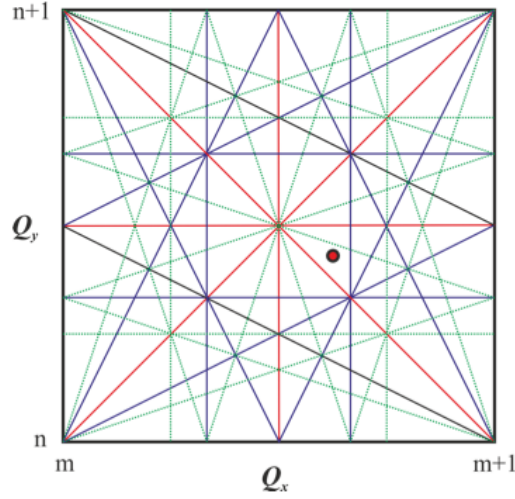


Figure 2.26: All resonance lines up to the 5th order are illustrated in the tune diagram above ($m \leq Q_x \leq m+1$, $n \leq Q_y \leq n+1$). The working point (red dot) should not coincide with a resonance line [35].

2.5 Tune measurement and reconstruction

2.5.1 Base Band Tune (Q) Meter

Since the phases of the particles inside the beam are random, their motion lacks coherence. Instruments designed for beam measurement are only capable of capturing the center of charge and detecting a steady signal that correlates with the overall intensity and mean position. Coherent motion can be accomplished using external excitation methods, such as "kicking" or "chirping" of the beam. As a result, the same phase is imposed on all particles [46].

The *Base Band Tune Meter (BBQ)* is the instrument that measures the transverse position of the beam centroid once per revolution. It consists of two pairs of induction plates, one pair per transverse plane (see Fig. 2.27). In the following, the equations refer to the horizontal plane, but are equally valid for the vertical plane, too. This device detects and measures the electric current induced when the beam passes through and provides information about the beam centroid position using the following basic principle [12]:

$$x = a \cdot \frac{U_{\text{right}} - U_{\text{left}}}{U_{\text{right}} + U_{\text{left}}}, \quad (2.47)$$

where U is the detected potential and a is a constant calibration factor. The signal

provided by the BBQ is amplitude vs revolutions. The typical, theoretical achievable tune resolutions are of the order of $\Delta Q \approx 10^{-3} - 10^{-4}$.

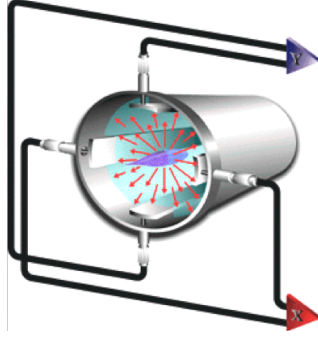


Figure 2.27: Base Band Q Meter illustration. The pick-ups measure the position of the beam centroid in the transverse planes [12].

2.5.2 Fast Fourier Transform

A signal can be converted from the time-amplitude domain to the frequency-amplitude domain by applying a *Fast Fourier Transform (FFT)* [48]. The FFT is basically an instance of the *DFT (Discrete Fourier Transform)*, with the number of input samples N being a power of two ($N = 2^m$). This requirement facilitates expedited calculations of the Fourier transform. However, computational speed aside, both DFT and FFT are essentially the same [48]. For a continuous frequency spectrum the FFT can be described as:

$$\mathcal{F}\{x\}(f) = \int_{-\infty}^{+\infty} x(t) \cdot e^{-j2\pi ft} dt. \quad (2.48)$$

The resulting frequency resolution of an FFT depends on the number of samples N of the time-domain signal through the following relation: $\Delta f = \frac{2f_s}{N}$, where f_s is the sampling frequency. Unambiguous results in the frequency domain can be achieved solely by signals with frequencies below half the sampling frequency. Signals with frequencies higher than $f_s/2$ are incorrectly perceived as mirror frequencies ($f_s - f$), leading to the phenomenon known as *aliasing* [48]. This is the reason why the tune analysis from the BBQ turn-by-turn data can produce values $Q \in [0, 0.5]$ rather than $Q \in [0, 1]$.

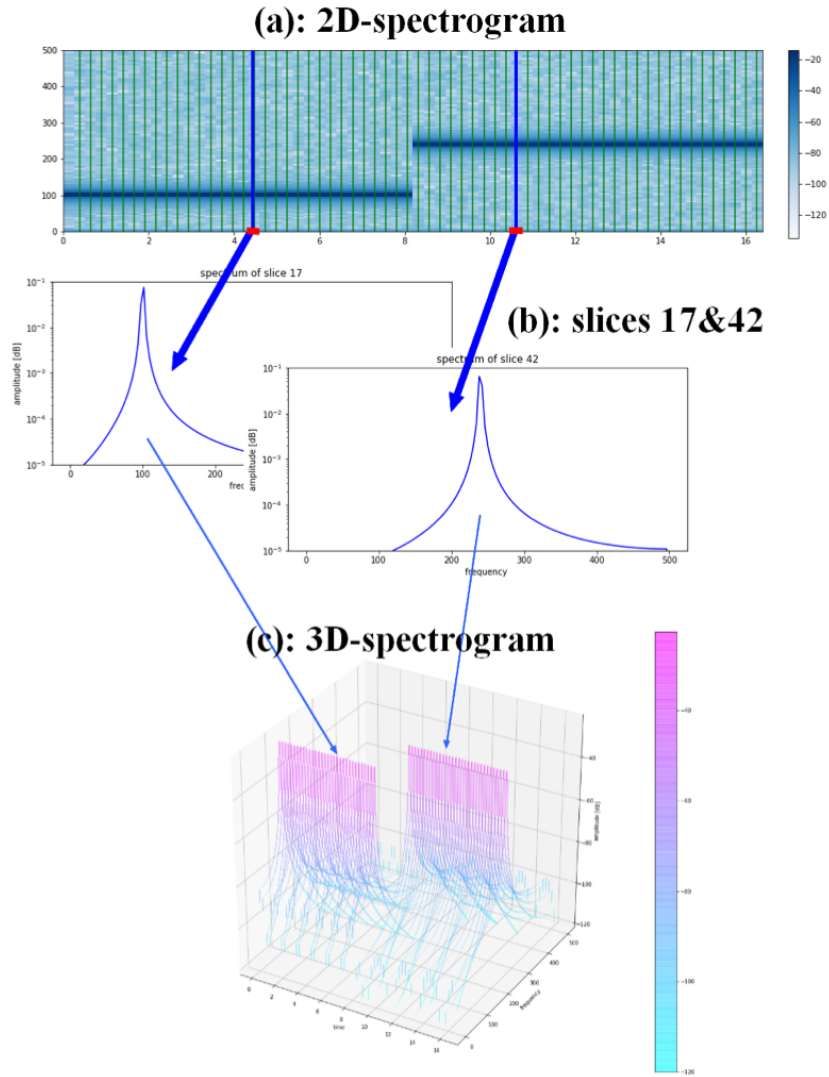


Figure 2.28: a) 2D spectrogram: frequency-time domain. The amplitude information is denoted by colour, dark peaks have higher amplitudes b) 2D slices: amplitude-frequency domain. c) 3D spectrogram: provides all information of the data in one plot – time, frequency and amplitude [48].

2.5.3 Harmonic Analysis - Jacobsen

As many other interpolation algorithms, the Jacobsen algorithm interpolates directly either the complex DFT coefficients, using [49]:

$$Y_k = \sum_{t=0}^{T-1} X_t e^{-i \frac{2\pi k t}{T}}. \quad (2.49)$$

or the real coefficients, by using the periodogram [49]:

$$I(\lambda) = \frac{2}{T} \left| \sum_{t=0}^{T-1} X_t e^{-it\lambda} \right|^2, \quad (2.50)$$

where $I(\lambda)$ is available only at the discrete Fourier frequencies $2\pi jt/T$.

The analysis method used in the HarPy algorithm (Section 3.3.2) is derived by the Jacobsen Algorithm [49]:

$$\hat{\omega}_{Jacobsen} = \lambda^* + \frac{2\pi}{T} \Re \left(\frac{Y_{k-1} - Y_{k+1}}{2Y_k - Y_{k+1} - Y_{k-1}} \right) \quad (2.51)$$

where λ^* denotes the maximising frequency of the periodogram. This algorithm interpolates between the three highest DFT peaks (Fig. 2.29) and provides an estimation of the frequency.

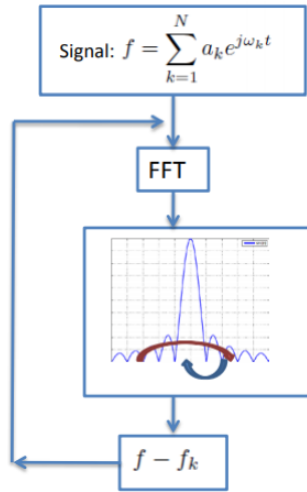


Figure 2.29: FFT estimation and interpolation between the three highest DFT peaks [48].

2.6 Unsupervised Machine Learning

Unsupervised machine learning describes algorithms that detect patterns in unlabeled data. Unlike supervised methods, which map inputs to outputs, unsupervised methods focus on compact data representations for exploration or analysis. These algorithms autonomously cluster unlabeled datasets, revealing hidden patterns, without the need for human intervention. Some unsupervised learning applications are exploratory data analysis, customer segmentation, and image recognition.

2.6.1 Overview on clustering algorithms

Cluster analysis or *clustering* is defined as the action of grouping a set of objects which have a common property. Often a certain metric is used to calculate the distances between the data points to decide whether they belong to the same cluster or not. The user can adjust the clustering process by tuning the hyperparameters of an algorithm. Figure 2.30 provides an overview of different clustering algorithms from the scikit-learn package [50] illustrating their performance on various datasets.

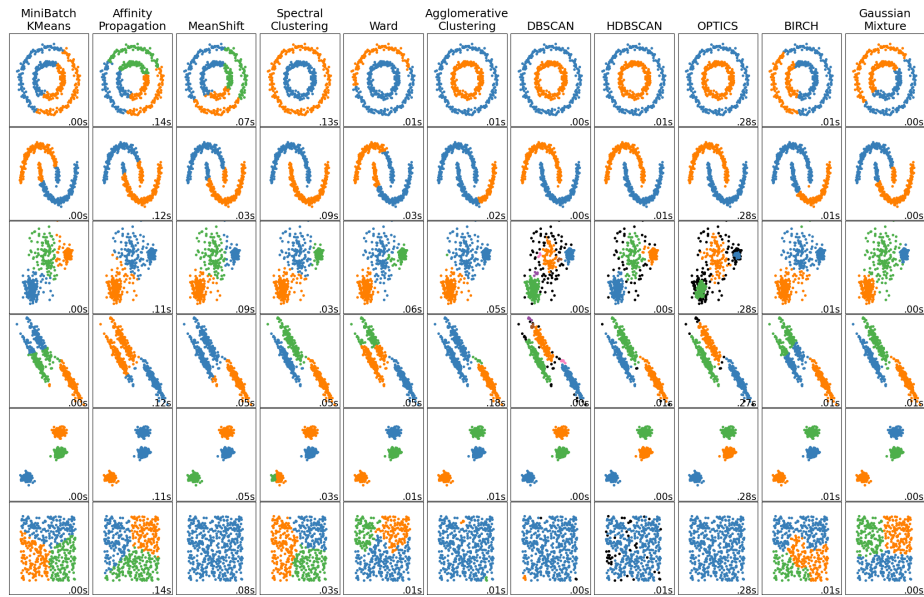


Figure 2.30: Comparison of clustering algorithms available in scikit-learn [50].

After comparing their clustering abilities and looking into their various use cases, DBSCAN and HDBSCAN were considered promising for tune analysis in particle accelerators. These algorithms are particularly efficient for applications with noise and are hence described in more detail in the following subsections. The table in Fig. 2.31 summarizes descriptions of the individual algorithms, their hyperparameters, scalability, use-cases, and geometry.

Method name	Parameters	Scalability	Usecase	Geometry (metric used)
K-Means	number of clusters	Very large <code>n_samples</code> , medium <code>n_clusters</code> with MiniBatch code	General-purpose, even cluster size, flat geometry, not too many clusters, inductive	Distances between points
Affinity propagation	damping, sample preference	Not scalable with <code>n_samples</code>	Many clusters, uneven cluster size, non-flat geometry, inductive	Graph distance (e.g. nearest-neighbor graph)
Mean-shift	bandwidth	Not scalable with <code>n_samples</code>	Many clusters, uneven cluster size, non-flat geometry, inductive	Distances between points
Spectral clustering	number of clusters	Medium <code>n_samples</code> , small <code>n_clusters</code>	Few clusters, even cluster size, non-flat geometry, transductive	Graph distance (e.g. nearest-neighbor graph)
Ward hierarchical clustering	number of clusters or distance threshold	Large <code>n_samples</code> and <code>n_clusters</code>	Many clusters, possibly connectivity constraints, transductive	Distances between points
Agglomerative clustering	number of clusters or distance threshold, linkage type, distance	Large <code>n_samples</code> and <code>n_clusters</code>	Many clusters, possibly connectivity constraints, non Euclidean distances, transductive	Any pairwise distance
DBSCAN	neighborhood size	Very large <code>n_samples</code> , medium <code>n_clusters</code>	Non-flat geometry, uneven cluster sizes, outlier removal, transductive	Distances between nearest points
HDBSCAN	minimum cluster membership, minimum point neighbors	large <code>n_samples</code> , medium <code>n_clusters</code>	Non-flat geometry, uneven cluster sizes, outlier removal, transductive, hierarchical, variable cluster density	Distances between nearest points
OPTICS	minimum cluster membership	Very large <code>n_samples</code> , large <code>n_clusters</code>	Non-flat geometry, uneven cluster sizes, variable cluster density, outlier removal, transductive	Distances between points
Gaussian mixtures	many	Not scalable	Flat geometry, good for density estimation, inductive	Mahalanobis distances to centers
BIRCH	branching factor, threshold, optional global clusterer.	Large <code>n_clusters</code> and <code>n_samples</code>	Large dataset, outlier removal, data reduction, inductive	Euclidean distance between points
Bisecting K-Means	number of clusters	Very large <code>n_samples</code> , medium <code>n_clusters</code>	General-purpose, even cluster size, flat geometry, no empty clusters, inductive, hierarchical	Distances between points

Figure 2.31: Clustering algorithms: parameters, scalability, use case, and geometry [50].

2.6.2 Density Based Spatial Clustering of Applications with Noise

The *Density Based Spatial Clustering of Applications with Noise* or DBSCAN algorithm clusters the input data with regard to their density in normalized units [50]. According to this algorithm, a cluster consists of a group of core samples (core points), within reaching distance from each other, and non-core samples (border points), within reaching distance to a core sample (without being core samples themselves) (see Fig. 2.33, left). The algorithm has two hyperparameters, *min_samples* and *eps*, which define the density of the clustered points [50]. Clusters defined by DBSCAN are not restricted in shape, unlike clusters resulting from other algorithms.

A core point is defined as the point in the dataset, around which *min_samples* other points can be found within *eps* distance. A cluster is a set of core samples accompanied by the corresponding border points. Any point at a distance greater than *eps* from any core sample is labelled as a noise point (outlier) by the algorithm and is marked to belong to cluster -1 [50].

The *min_samples* parameter defines the algorithm's sensitivity to noise. The parameter

eps must be chosen appropriately for the specific dataset and distance function. When the parameter eps is chosen too small, the majority of data points will not belong to any cluster. In the case that eps is chosen too large, neighbouring clusters will be joined into one larger cluster. One of the methods to define the parameter eps , customized on a dataset, is to calculate the nearest neighbor distances plot and decide for the maximum point of curvature using the knee locator [50]. This is described in Section 3.3.2.

In Fig. 2.33 (right), each color indicates one DBSCAN cluster. Smaller colorful circles represent neighbouring points. Black points mark outliers.

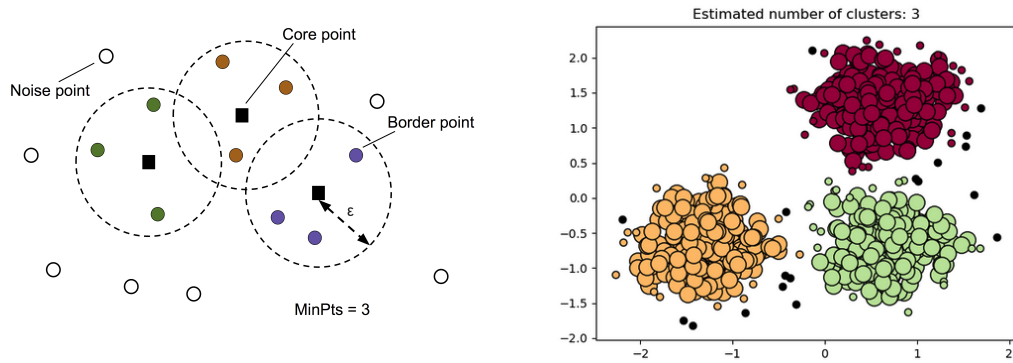


Figure 2.32: *Left*: DBSCAN working principle [51]. *Right*: Example of DBSCAN clustering on a dataset [50].

2.6.3 Hierarchical Density Based Spatial Clustering of Applications with Noise

Hierarchical Density Based Spatial Clustering of Applications with Noise or *HDBSCAN* is an algorithm which functions in a similar manner as DBSCAN and OPTICS. Their main difference is the fact that, DBSCAN is oblivious to the density property of clusters in the dataset and considers it globally homogeneous, whereas HDBSCAN is capable of investigating all possible density values. It then creates an alternative representation of the clustering problem [50].

HDBSCAN basically performs DBSCAN clustering across all eps values. For optimal efficiency, HDBSCAN initially derives a minimum spanning tree (MST) from the fully-connected mutual reachability graph. Subsequently, it removes the edges with the highest weights. Consequently, HDBSCAN has the ability to systematically extract all potential values, DBSCAN would also achieve given a constant $min_samples$ value. The main difference is that HDBSCAN does this in a hierarchical manner

2.6. Unsupervised Machine Learning

and decides for the optimum value automatically. This unique approach enables HDBSCAN to conduct clustering across various densities, making the input of an additional hyperparameter unnecessary. Its functioning now hinges solely on the *min_samples* parameter selection [50].

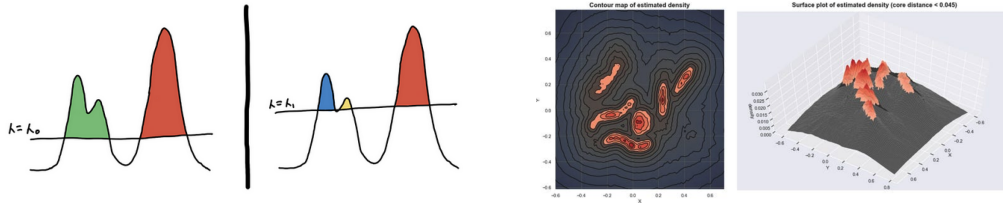


Figure 2.33: HDBSCAN working principles: *Left*: illustration of how clustering is achieved in a hierarchical manner, the number of clusters created depends on the decided value *Right*: 3D illustration of HBDSCAN application on a dataset [52].

3 Method

In the following chapter, the work conducted during this project will be presented. There is a short introduction to the LHC Software Architecture (LSA) and the make-rules hierarchy. This is the software framework which translates higher-level parameter changes into changes directly applicable to accelerator hardware. Then, the existing tool for betatron tune and chromaticity measurement and correction, called "Multi-Q", will be introduced. This is followed by a detailed explanation of the new tool, called "SPS Tune app", along with its newly developed analysis software "ml-for-tune-analysis". Finally, in Chapter 4, a comparison of the two methods will be conducted to underline the advantages of the SPS Tune app in accelerator control.

3.1 LHC Software Architecture

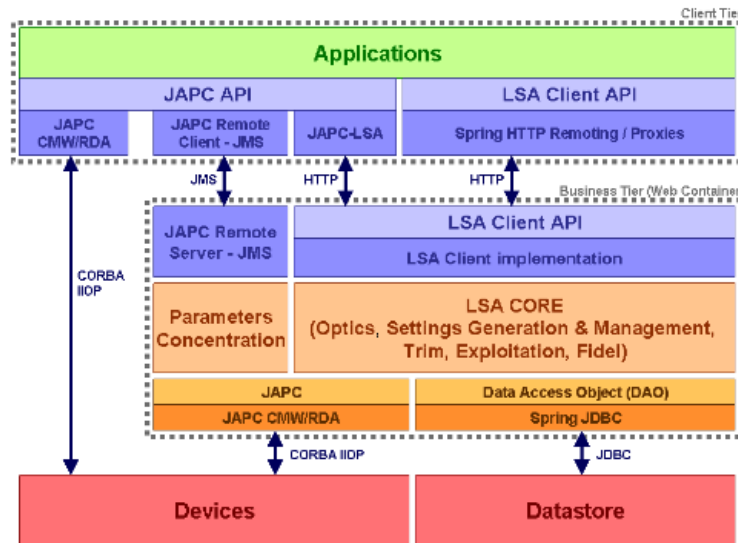


Figure 3.1: LHC Software Architecture [53].

The *LHC Software Architecture (LSA)* has been designed to offer a unified controls framework for the efficient operation of most of the CERN accelerator complex,

including the SPS accelerator, SPS beam transfer lines, and the LHC [53]. The LSA framework contains essential components of accelerator controls. This includes optics, value generation and settings management (functions derived from optics), trim hierarchies and history (adjustments of settings, interpretation of physics parameters to hardware parameters). It also encompasses the utilization of hardware and operational aspects (apparatus control, measurements), and facilitates beam-based measurements. A key objective of the LSA is to establish a standardized and versatile API accessible to all operational applications, ensuring a streamlined and consistent approach to core functionality [53].

Parameters within the LSA are organized in hierarchical structures, where the top levels usually consist of physics-oriented, high-level parameters like tune, chromaticity, and momentum. As the hierarchy descends, hardware parameters are encountered, such as voltages or currents. Each hierarchy establishes relationships between different parameters, meaning that any modification to one parameter invariably impacts all its dependent parameters [53]. In Fig. 3.2 the tune hierarchy is illustrated as an example.

Machine operators typically interact with the top-level parameters. Consequently, LSA automatically calculates the corresponding adjustments in the propagated parameters. Every parameter has a specific value type, which can either be a function, representing changes over time, or a specific type, which encompasses scalar values. This structured approach allows for efficient, safe management and manipulation of parameters within the LSA [53].

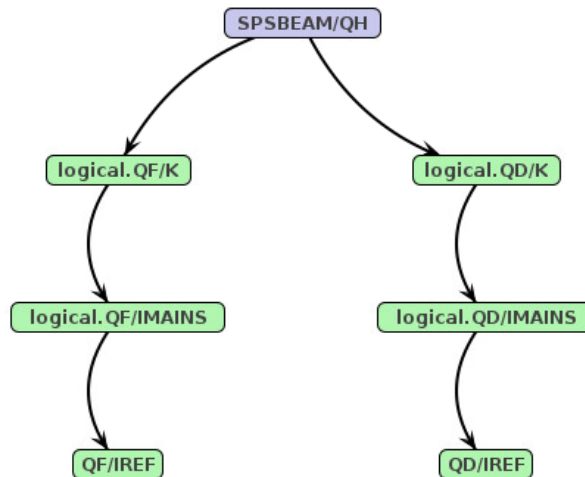


Figure 3.2: LSA parameters hierarchy for the horizontal tune (QH) function.

In the LSA, a *context* refers to a defined time span during which a parameter holds a specific value. The system incorporates three distinct types of contexts: the *super cycle*, the *cycle*, and the *beam process*. A super cycle consists of multiple cycles responsible for generating various types of beams for timing-users. Super cycles are executed in repetition in cycling machines. On the other hand, a beam process pertains to a particular process of a beam. Such examples are injection, acceleration, extraction, applicable to a specific accelerator or transfer line [53].

A setting denotes the allocated value of a parameter within a specified context. Whenever a setting is fine-tuned ("trimmed") for a specific parameter, the adjustment is extended to all interconnected parameters within the hierarchy. Once a trim is executed at a certain level, it is automatically propagated to the dependent parameter settings using what are known as "make rules", and all altered hardware settings are promptly transmitted to the relevant hardware when appropriate. This ensures a streamlined and automated process of applying changes throughout the system [53].

3.1.1 Settings management (LSA Trim Editor)

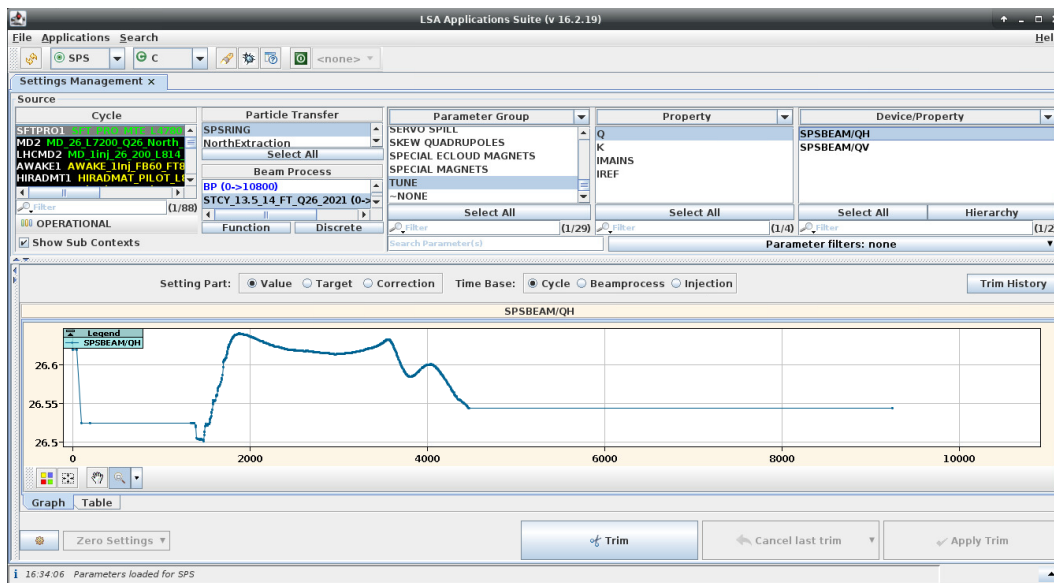


Figure 3.3: LSA Trim Manager: graphical user interface. Example of horizontal betatron tune settings for the SFTPRO1 timing user (SPSBEAM/QH).

The Settings module in the LSA, shown in Fig. 3.3, is responsible for managing the storage and retrieval of settings, parameters, and trims. It facilitates the modification of settings, and each adjustment is recorded as a trim. This module also handles

various contexts, offering essential functionalities to access settings categorized by cycle or super cycle, considering that settings are stored per beam process. Consequently, obtaining the setting of a cycle typically requires assembling several settings from multiple beam processes [53].

A trim represents a modification made to one or more parameters. Adjusting physics parameters' settings through trimming is the preferred method for customizing the generated settings to match specific conditions of a given accelerator. Typically, hardware parameters are derived from the settings of physics parameters. Trims are archived, enabling the possibility to revert to previous configurations if needed. Each parameter gives the possibility to edit three LSA functions: *Values*, *Target* and *Correction*. They are connected with the following relation: $Values = Target + Correction$.

3.2 Existing method for betatron tune analysis in the SPS

The *Multi-Q* is the application used in the CERN Control Center (CCC) for tune and chromaticity measurements on the SPS since 2008. It is a complete tool, which includes tune measurement and trim, decoupling option for the linear coefficient, injection tune configuration, chromaticity measurement and trim. The tool also provides multiple viewing options for the data, such as raw turn-by-turn beam position, 1D and 2D FFT, etc.), so the user can study the acquisition in depth and gets multiple perspectives for cross-checks.

3.2.1 Multi Q app

The existing betatron tune analysis method works as follows. The user first defines the measurement configuration by editing the acquisition start and stop times in the cycle, setting the FFT accuracy through the window length (number of turns) and shape (Fig. 3.4, left). The window length can be set between 256 and 32000 turns and the windowing options are: rectangular, Hann, Blackman, Nuttall, flat_top.

After an acquisition is taken, the BBQ raw data is fed to a sliding-window FFT analysis. This outputs a spectrogram showing cycle time vs tune value, and colouring the amplitude dimension (see Fig. 3.4 right). The tune line appears yellow in this case, because the signal is weak. The horizontal tune line is also visible in the vertical plane as a result of linear coupling.

3.2. Existing method for betatron tune analysis in the SPS

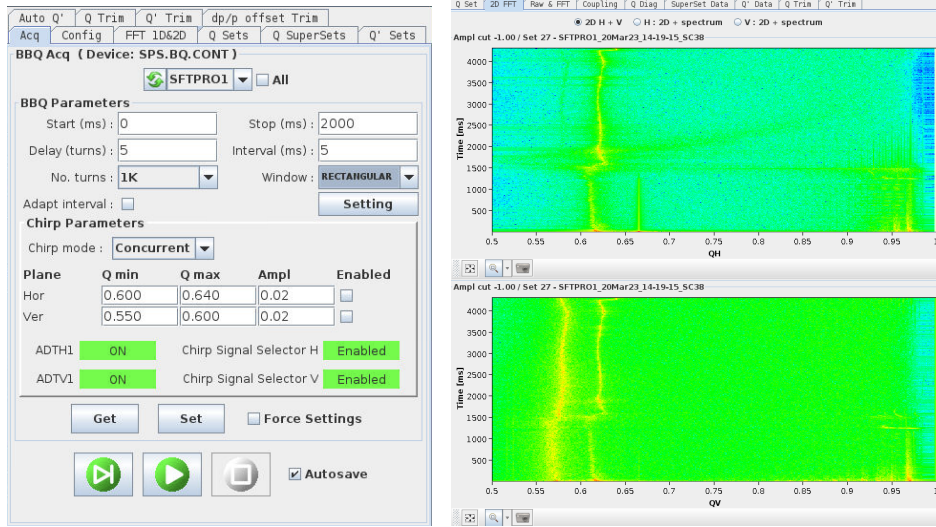


Figure 3.4: Multi-Q app. *Left*: acquisition parameters. *Right*: horizontal (above) and vertical (below) betatron tune analysis

In order to enhance the measurement accuracy, the user has the option to employ the chirp excitation technique, which generates a more robust tune signal. The chirp excitation involves applying small, precise perturbations to the particle beam. During a chirp sweep, the excitation frequency is systematically varied within a predefined range. As the frequency intersects with the tune resonance, the transverse beam oscillation intensifies, producing a stronger tune signal (Fig. 3.5 red line). This process is reiterated at consistent intervals, yielding one measurement per sweep.

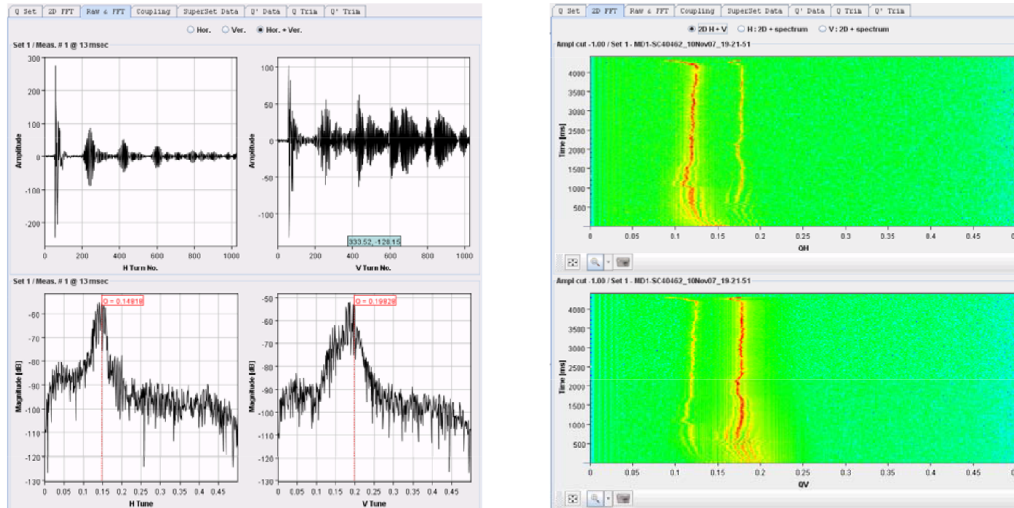


Figure 3.5: *Left*: raw BBQ Data using chirp and FFT peak. *Right*: FFT tune readout using chirp.

Chapter 3. Method

The tune value information is directly extracted as the highest peak in a certain user-defined tune window. There is the possibility to set the tune window depending on the beam. There are three tune window settings available: FT (Fixed-Target) Beam (H: 0.55 - 0.70, V: 0.52 - 0.62), LHC Beam (H: 0.05 - 0.20, V: 0.10 - 0.30) and LHC Ion Beam (H: 0.27 - 0.33, V: 0.22 - 0.28) (Fig. 3.6).

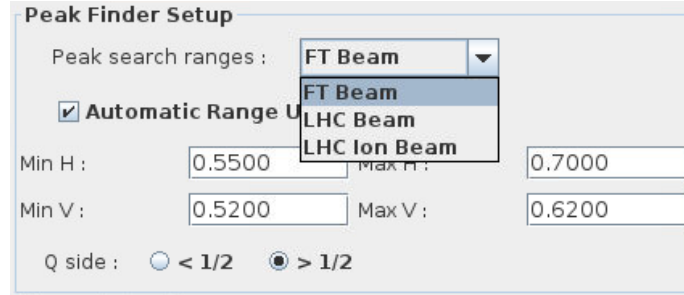


Figure 3.6: Multi-Q app: tune window settings.

In Fig. 3.7 (left) the result of the peak finder inside the tune window is presented for the horizontal and vertical planes. On the right, the corresponding LSA function is calculated, which after editing can be sent as a trim to LSA. Manual editing by the user is usually necessary. After sending the function to LSA, another acquisition should be taken to check its influence on the beam tunes. The final correction is usually achieved after taking several acquisitions and sending several corrections.

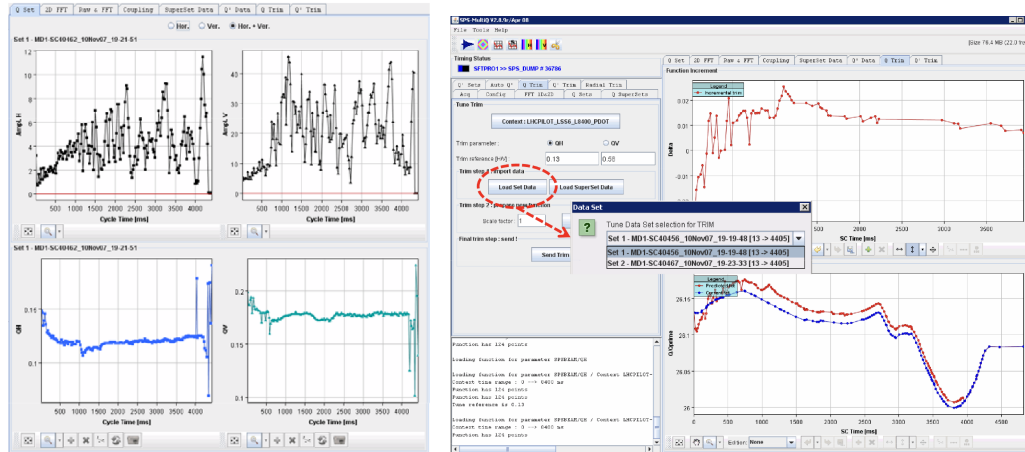


Figure 3.7: Multi-Q app. *Left*: extracted tune values. *Right*: LSA function after editing.

The app also provides the possibility to measure chromaticity as shown in Fig. 3.8 and to send corrections. The user can move through all available timestamps by dragging

3.2. Existing method for betatron tune analysis in the SPS

the arrow above the top plot (Q'/Q vs cycle time). This way, the corresponding measurements for Q vs dp/p and a fit line are presented in the plot below. The user also has the possibility to change the fit polynomial degree and apply manual corrections before sending a new LSA function.

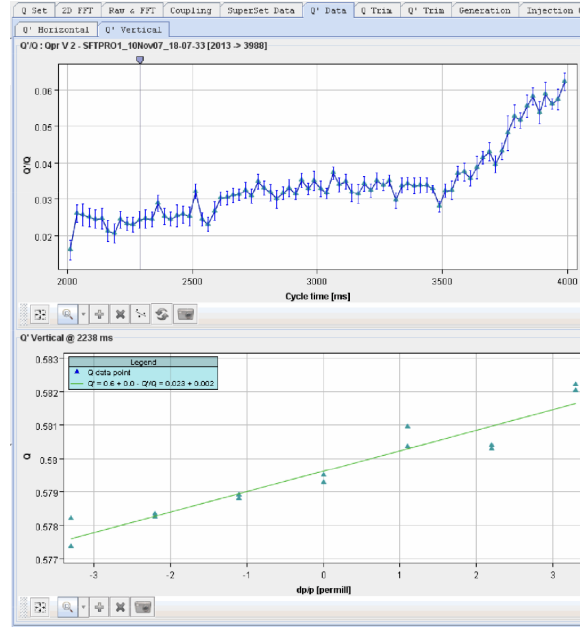


Figure 3.8: Multi-Q app: chromaticity measurement plots.

3.2.2 Shortcomings

The advantage of Multi-Q is that it provides a tune estimation within a few seconds, depending on the FFT configuration. Unfortunately, there are several disadvantages to this method, which created the need for the development of a new optimized and automated tool.

One of the disadvantages is the tune measurement technique. By applying FFT analysis, the output signal-to-noise ratio (S/N) is often not high enough as illustrated in Fig 3.4. In order to get a strong enough signal for readout, the user needs to continually either kick or chirp the beam, see Fig. 3.5. The resolution of the output is constrained by the FFT, both in turns and tune. The maximum turns resolution is 256 turns and the maximum tunes resolution can be calculated $4 \cdot 10^{-3}$.

Another disadvantage is that the result often needs manual cleaning by the user before sending a correction to LSA. The peak finder searches only inside a narrow tune window around the expected tune line. This means that the algorithm is unable

to identify the tune line if it is outside this window. It also often gets stuck on noise peaks or on coupling lines. Such an example can be seen in Fig. 3.7. For cycle times ≥ 4000 ms the algorithm selects peaks that are unrelated to the tune line. Instead, they are probably the result of strong noise or coupling lines. These points need to be removed manually by the user before sending the correction.

Several acquisitions need to be taken and several corrections need to be sent before achieving a satisfactory result. When it comes to chromaticity measurements, some of the tune measurements are incorrect, due to the issues mentioned above, and need to be removed by hand. It is almost impossible to remove all incorrect tune measurements for all the timestamps. This can heavily impact the accuracy of the chromaticity measurement.

3.3 Development of new analysis procedure and software

The goal of this project is to develop a novel approach to tune and chromaticity measurements, providing an improved tune readout and correction automatically. This means that there should be as little input as possible needed by the user. If the readout can be achieved with more accuracy, a more accurate correction can be sent over one (worst case few) acquisition and significantly speed up the tune set-up process.

By developing a new analysis method, it is no longer necessary to chirp the beam. The BBQ signal can be analysed and denoised with much higher accuracy, both in the time and frequency domains. A decoupling mode has been added in the tool, to overall omit manual intervention due to incorrect peak selection. The final tune estimation is given by amplitude-weighted averages.

For this project the following tools were developed: a Python package called *ml-for-tune-analysis* and a new *SPS Tune app*. *ml-for-tune-analysis* encompasses the newly developed tune analysis method from low-level functions to higher-level ones. *SPS Tune app* is the Graphical User Interface (GUI) developed to apply the *ml-for-tune-analysis* package in a user-friendly environment, and, therefore, simplify the tool's utilization in the operation of the accelerator. *SPS Tune app* is the place, where data is acquired live, tune and chromaticity calculations are performed, and corrections are calculated and sent to LSA.

3.3.1 Python package: ml-for-tune-analysis

ml-for-tune-analysis is the Python (3.9) package, developed to encompass all functions necessary for the tune analysis from raw data to tune estimation, as well as, chromaticity calculation.

The package contains five files: `harmonic_analysis.py`, `data_processing.py`, `complex_functions.py`, `plotting.py` and `params.py`. The `params.py` file contains parameters to run the analysis in a timing-user-specific manner. The `plotting.py` file contains possible plots that accompany tune analysis. This file is not directly used in the tool developed for SPS operations, but is necessary for the completeness of the package, for possible use by other colleagues. The `data_processing.py` file contains all functions used from processing the signal, to smoothing, and extraction of chromaticity. The `complex_functions.py` file combine the functions of `data_processing.py`, `plotting.py` and `params.py` into high-level analysis functions.

The package has been released internally and is available CERN wide. It provides a higher accuracy and overall better performance in tune measurement than the existing tool. It is already used by other colleagues in their studies and tool development.

3.3.2 Working principles of the algorithm - Analysis method

The signal processing method included in the *ml-for-tune-analysis* package, is called *Harmonic Analysis* or *HarPy* for short. HarPy uses the Jacobsen algorithm, described in Section 2.5.3, as its core analysis method and applies it as follows.

HarPy takes as input a slice of turn-by-turn raw beam oscillation data of a specific transverse plane from the BBQ (Base Band Tune Meter) - from the time-amplitude domain, the number of harmonics (N) and the range of the tune/frequency window (this can also be set to None, meaning $\{0,1\}$). It uses the Jacobsen algorithm to analyse the signal and returns N highest frequency peaks found in this time-slice of data. The algorithm outputs three properties: time, which is in turns (revolutions in the accelerator), frequency, which is the decimal part of the betatron tune value in the interval $\{0, 0.5\}$ and amplitude, which indicates the signal strength. Normally, the tune values would be expected in $\{0, 1\}$ range, but due to aliasing, the values of $\{0.5, 1\}$ are mirrored to $\{0, 0.5\}$, so the output of HarPy is eventually in $\{0, 0.5\}$. The reason the measurement only includes the decimal part is the fact that the BBQ measures the betatron tune only once per revolution. The BBQ stores data for the horizontal (H) and vertical (V) transverse planes separately, and the analysis needs

Chapter 3. Method

to be applied twice. On the plots only the turns vs tunes information is displayed. The amplitude information is considered later on for the final tune estimation.

In order to minimize the loss of information and to gain accuracy, the signal processing function uses a sliding window, to provide HarPy with slices of data. The window size is 2000 turns and the step is 125 turns. The range of the frequency window is by default $\{0.1, 0.9\}$, to eliminate noise that is usually present below 0.1 (or above 0.9, which due to aliasing appears below 0.1). In Fig. 3.9 the output of HarPy on sample data for the AWAKE1 timing user is presented.

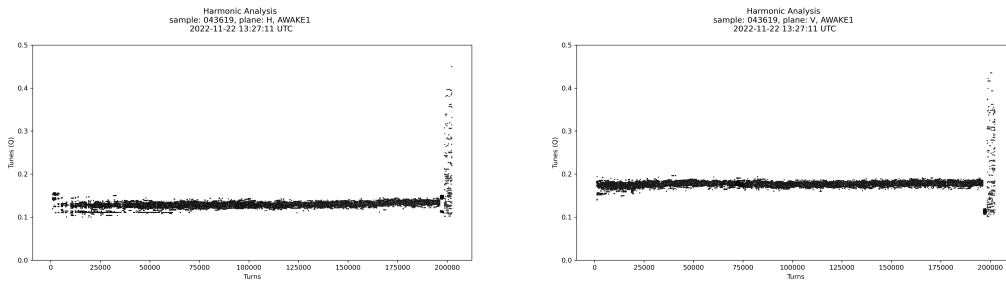


Figure 3.9: HarPy output on an AWAKE1 sample dataset. *Left:* Horizontal plane. *Right:* Vertical plane.

A dictionary containing timing-user-specific parameters has been created in a separate file (params.py), in order to adjust the analysis for optimal timing-user-specific results. The parameters included in the dictionary are: number of harmonics (num_harmonics), lowest tune value (q_cut_low), highest tune value (q_cut_high), initial turns value (turns_i), and final turns value (turns_f). As an example, the dictionary values for the SFTPRO1 timing user (NA fixed-target proton beam) are presented below:

```
1 "SFTPRO1": {  
2   "num_harmonics": 25,  
3   "q_cut_low": 0.1,  
4   "q_cut_high": 0.9,  
5   "turns_i": 0,  
6   "turns_f": 183000,  
7 }
```

The number of harmonics has been chosen such that the reconstruction of the signal is satisfactory, by keeping only the prominent peaks, and, at the same time, suppressing the noise. A higher number of harmonics can reconstruct unnecessary noise. In Fig. 3.10, STFPRO1 datasets are reconstructed, using a different number of harmonics. The num_harmonics parameter is set to 100 (left) and 25 (right), respectively. It is

3.3. Development of new analysis procedure and software

obvious that by using a higher number of harmonics the tune line can be enhanced, but, at the same time, the noise signal becomes more prominent as well.

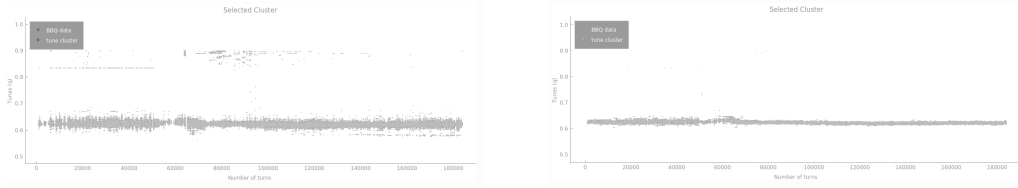


Figure 3.10: SFTPRO1 datasets reconstructed *Left*: num_harmonics = 100. *Right*: num_harmonics = 25.

In order to exclude any noise lines below 0.1, the algorithm has been programmed to make 100 attempts for one slice of data, to find N peaks inside the range $\{0.1, 0.9\}$. When this number is reached the algorithm will move to the next turns window, regardless of whether the required number of peaks were found. This is to avoid extensive or even infinite loops and to make the algorithm faster, by slightly compromising on its accuracy. This is the reason why in some cases there may be gaps in the signal reconstruction. Having a gap in the tune line means that the noise signal below 0.1 is much more prominent than the tune line signal itself. In Fig. 3.11, it is visible that there is a strong noise signal between tunes 0.1 and 0.2, which results in a gap of in the tune line around 0.4.

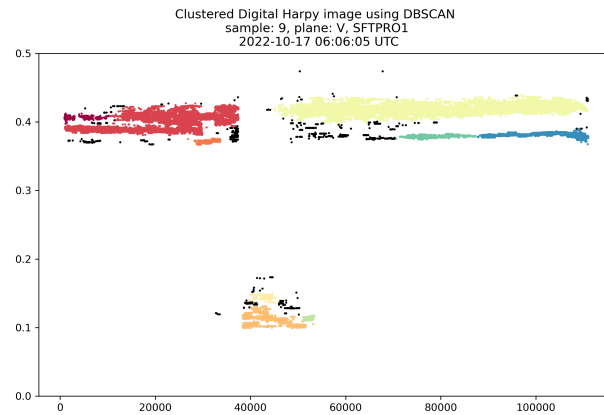


Figure 3.11: Output of DBSCAN clustering using HarPy on SFTPRO1 dataset for the vertical plane. Different colours are used for the different clusters found by DBSCAN. The strong noise signal between 35000 and 60000 turns creates a gap in the reconstructed tune line.

Unsupervised learning is used in this algorithm to achieve an automatic selection of the tune cluster and deprive the tune line of unnecessary points. This way the

tune estimation can be conducted without manual cleaning and a more accurate estimation can be extracted. The clustering algorithm DBSCAN was chosen over HDBSCAN, because it provides more consistent results. The main difference between DBSCAN and HDBSCAN, is that HDBSCAN takes into account a cluster density factor. While this can be beneficial for some applications, it can result in incorrect cluster selection when employing this method for tune analysis. This is because the reconstruction of BBQ data often results in inconsistent point densities in the time-frequency domain. Figure 3.12 shows an example of HDBSCAN vs DBSCAN applied to a sample on the MD3 timing user.

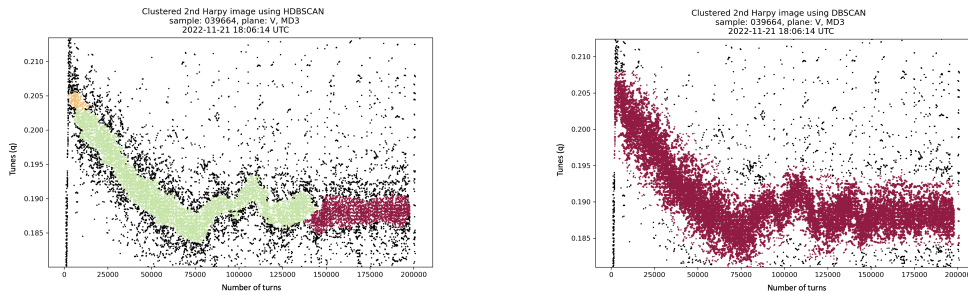


Figure 3.12: Vertical tune reconstruction on the same MD3 dataset using two different clustering algorithms. While HDBSCAN (*left*) fails to cluster the entire tune line since it "sees" different densities inside the tune line, DBSCAN (*right*) produces a perfect result.

DBSCAN takes as input two hyperparameters: epsilon (eps) and minimum samples (MinPts). As explained in detail in Section 2.6.2, eps is the circle radius (distance) from a core-point, in which MinPts number of neighbouring points must be included, so they can be clustered together. The eps value is automatically selected, individually for each dataset, to achieve optimal results. This addition is described in the code below and is not included in the DBSCAN algorithm. The algorithm considers the HarPy output and calculates normalized Euclidean distances between all the points, ignoring the amplitude dimension. Then, a polynomial line is fitted to the calculated distances and the point of maximum curvature on the fit line is selected as the eps value (see code [54] and Fig. 3.13 below).

```
1 def opt_epsilon(X: np.ndarray, MinPts: int = 25) -> float:
2
3     from sklearn.neighbors import NearestNeighbors
4
5     nearest_neighbors = NearestNeighbors(n_neighbors=MinPts)
6     neighbors = nearest_neighbors.fit(X)
7     distances, indices = neighbors.kneighbors(X)
8     distances = np.sort(distances[:, MinPts - 1], axis=0)
```

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```
9
10 i = np.arange(len(distances))
11 knee = KneLocator(
12     i,
13     distances,
14     S=1,
15     curve="convex",
16     direction="increasing",
17     interp_method="polynomial",
18 )
19 eps = distances[knee.knee]
20
21 return float(eps)
```

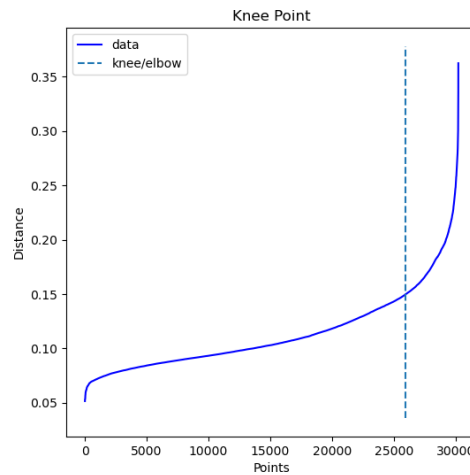


Figure 3.13: The epsilon (ϵ) value corresponds to the distance of the point of maximum curvature in this graph. In this case, $\epsilon \approx 0.15$.

This means that the only hyperparameter that needs to be defined is MinPts. After researching into how parameter optimizers, such as Ray Tune [55], work, it was decided that their use in this case of unsupervised learning was inelegant and would not make that much of a difference. After conducting multiple trials on different datasets for different timing users the value MinPts = 90 was found to be optimal, and hence remains a constant parameter in the algorithm, for both the clustering and denoising stages.

DBSCAN takes as inputs turns and tunes and outputs cluster labels. A label is assigned to each point of the HarPy output. Points belonging to the same cluster

share the same label. Points that do not belong to any cluster are considered noise and are labeled with -1. Different colours were used for better illustration of the different clusters the algorithm found. Examples are shown in Figs. 3.11 and 3.12. Noise points are coloured black. Once DBSCAN has labeled all the points in the HarPy image, the cluster containing the maximum number of points is selected as the main cluster and its values are output (turns, tunes, and amplitudes). In case the user decides to restrict the analysis strictly to a certain range of tunes, and no cluster containing $\text{MinPts} = 90$ can be found, the algorithm will iterate the clustering process while reducing MinPts by 10 until there is an acceptable result.

The next step of the algorithm is to check the selected cluster width in the tunes dimension. If the cluster width is larger than 0.1 along the tune axis, the dataset is rejected and skipped. This happens to omit further analysis of empty shots, which coincidentally gave a stronger signal, or beams that were dumped mid-cycle. An empty shot is obvious to the eye of the user from the HarPy picture, since it contains only noise and no distinct tune line.

After selecting the main cluster, the algorithm searches for its minimum and maximum tune value. Then, the previous steps (HarPy and clustering) are repeated once more, this time in a restricted tune range. This second iteration of harmonic analysis often provides a much better reconstruction of the signal, increases the accuracy and corrects mistakes from the previous cluster selection. In Fig. 3.14 the tune cluster was only partially selected after the first reconstruction. Because the minimum and maximum values of the tune cluster are included in the partially selected tune line, the rest of the tune line was reconstructed more accurately on the right plot and DBSCAN was able to cluster it without gaps.

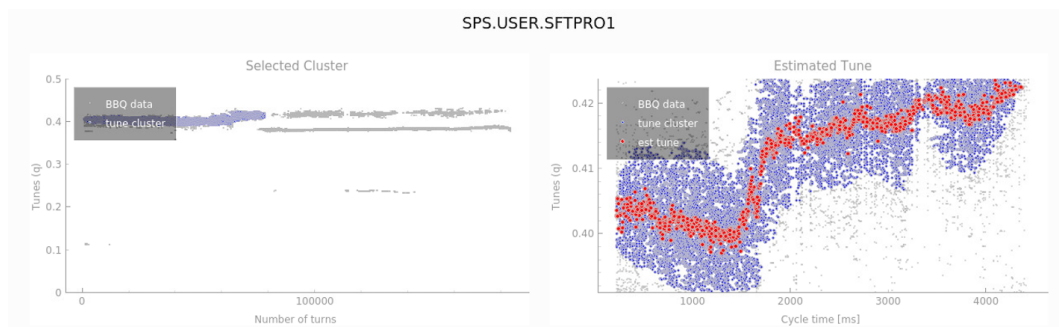


Figure 3.14: Example of successful reconstruction of the vertical tune for the SFTPRO1 timing user. The linear coupling line can be seen at $q = 0.38$.

Now that the tune line is correctly selected and denoised, the amplitude information

3.3. Development of new analysis procedure and software

is taken into account to provide the final tune estimation. A weighted-average value is calculated for each time-slice, by considering only the selected points, and is plotted on top of the selected cluster as red points (see Fig. 3.14 right). The turns information is converted into cycle time, measured in units of ms, for further use.

3.3.3 Decoupling transverse planes

Often there is a coupling line in the reconstructed signal, or part thereof, originating from one plane and displayed on the other. This phenomenon appears because, the beam oscillation in one plane is not perfectly aligned to this plane, but is shared between the horizontal and vertical planes. The case in which part of the horizontal plane signal is displayed on the vertical plane is observed more frequently than the opposite and has to do with beam injection into the SPS. Examples of this phenomenon can be found in Figs. 3.14 and 3.15.

In case the signal of the coupling line is more prominent than the signal of the correct tune line, the algorithm would select the coupling line as the main tune line. To correct that the user has the possibility to run the algorithm in one of the following decoupling modes: `H_from_V` or `V_from_H`. `H_from_V` means decoupling the horizontal line from the vertical plane and `V_from_H` means decoupling the vertical line from the horizontal plane. The case `H_from_V` will be used as an example to explain how decoupling works. The algorithm first fully calculates the horizontal tune and keeps in memory the points corresponding to the selected cluster. Then, it runs HarPy for the vertical plane and searches for remnants of the horizontal tune cluster in memory. A small tolerance around the points is allowed, since HarPy does not necessarily reproduce exactly the same points. The selected horizontal tune points found in the vertical plane are then abstracted from the data input given to DBSCAN for clustering. The result is that DBSCAN is now oblivious to the horizontal tune points, and will hence select the correct vertical tune line. This process is hidden from the user. The only change the user sees is that this time a different line was selected. The same process happens for `V_from_H`, running the vertical plane first and abstracting its points from the horizontal plane data.

This method provides a great improvement compared to the algorithm that has been used for tune analysis until now. This is illustrated in Fig. 3.15 based on data from a HIRADMT1 beam. Without decoupling, the algorithm incorrectly selects the horizontal coupling line over the correct vertical tune line when analysing vertical plane data (left). Instead, when using the decoupling mode `H_from_V`, the algorithm selects the correct tune cluster for further analysis (right).

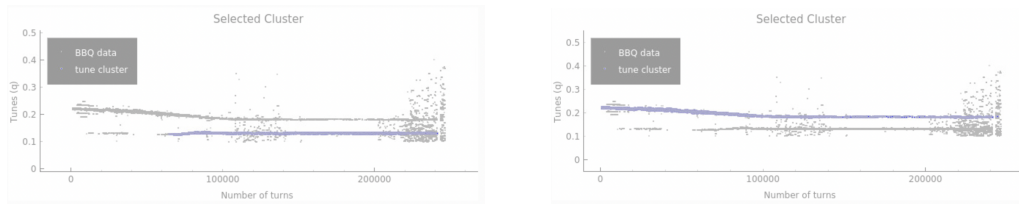


Figure 3.15: Vertical tune analysis for the HIRADMT1 timing user (Left:) without, and (Right:) with decoupling mode `H_from_V`.

3.3.4 Performance improvements

The computations executed on the raw data by HarPy are heavy and slow. Therefore, there was need to use parallel processing, to speed up the process and avoid compromising the accuracy. Originally, the Python library `concurrent.futures.ProcessPoolExecutor` was used to parallelize the process. While this gave a significant speed up, the algorithm would occasionally crash unexpectedly as one of the worker processes died.

To resolve this issue, `loky.get_reusable_executor` was implemented instead. The reusable executor is a strategy used to omit recreating a complete executor pool every time. By employing a singleton executor instance it becomes possible to reuse it for successive calls, thereby reducing the overhead of spawning and shutting down workers. Moreover, the worker processes are capable of automatic shutdown after a customizable period of idling to ensure efficient utilization of system resources [56].

HarPy was parallelized as described in the code below. An instance of *HarmonicAnalysis* is created through the `create_and_run_harpy` function. Each worker instance is provided with a chunk of data - corresponding to a specific range of turns, a number of harmonics, lowest and highest tune values. The results of each executor are appended in the futures array. After all results are returned, they are retrieved from futures. In case of a `TimeoutError` the specific result of that worker is ignored and the entire process continues, instead of crashing.

```

1 def create_and_run_harpy(
2     data_chunk: np.ndarray,
3     num_harmonics: int,
4     q_cut_low: float,
5     q_cut_high: float,
6 ) -> tuple[np.ndarray, np.ndarray]:
7     harm = HarmonicAnalysis(data_chunk)
8     return harm.laskar_method(num_harmonics, q_cut_low, q_cut_high)
9 
```

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```
10
11 def sliding_window_harpy_par(
12     data: np.ndarray,
13     win_size: int = 2000,
14     step: int = 125,
15     num_harmonics: int = 25,
16     turns_i: Optional[int] = None,
17     turns_f: Optional[int] = None,
18     q_cut_low: float = 0.1,
19     q_cut_high: float = 0.9,
20 ) -> tuple[np.ndarray, np.ndarray, np.ndarray]:
21
22     turns = []
23     tunes = []
24     ampls = []
25
26     if (turns_i is not None) and (turns_f is not None):
27         start = turns_i
28         end = turns_f
29     else:
30         start = 0
31         end = len(data)
32
33     from loky import get_reusable_executor
34
35     executor_ = get_reusable_executor(timeout=1)
36     with executor_ as executor:
37         futures = []
38         turn_range = range(start, end, step)
39         for i in turn_range:
40             turn_init = i
41             turn_fin = i + win_size
42
43             futures.append(
44                 executor.submit(
45                     create_and_run_harpy,
46                     data[turn_init:turn_fin],
47                     num_harmonics,
48                     q_cut_low=q_cut_low,
49                     q_cut_high=q_cut_high,
50                 )
51             )
52
53             if (len(data) - turn_fin) < step:
54                 break
55
56     for i, future in zip(turn_range, futures):
```

```

57         try:
58             tune, ampl = future.result(timeout=5)
59             tune = np.array(tune)
60             msk_above_0p5 = tune > 0.5
61             tune[msk_above_0p5] = 1 - tune[msk_above_0p5]
62
63             turn = np.array([i + win_size / 2.0] * num_harmonics)
64             turns.append(turn)
65
66             ampls.append(np.abs(ampl))
67             tunes.append(tune)
68         except FuturesTimeoutError:
69             print("Timed out ...")
70             continue
71
72     ampls = np.array(ampls)
73     turns = np.array(turns)
74     tunes = np.array(tunes)
75
76     return turns, tunes, ampls

```

3.3.5 Perona-Malik Partial Differential Equation

When the tune analysis is finished a tune estimation is provided and a correction is calculated. First, the old tune VALUES function is retrieved from LSA, and a correction is calculated using the estimated tune values and added on top of the old LSA Values, to create the new LSA Values function. The new values are propagated through the make-rules hierarchy to the main quadrupole magnets. Unfortunately, the new function contains a high frequency statistical noise resulting from the tune analysis and is not suitable for the magnet power converters (see Fig. 3.16 red line) and a smoothing filter is hence needed.

After investigating a number of smoothing filters, the Perona-Malik filter was selected for this use-case [57]. The filter solves the Perona-Malik Partial Differential Equation (3.1), and is specifically designed to apply a time series smoothing, while preserving the given function edges very well.

$$u_t = \nabla(c(|\nabla u|^2)\nabla u), \quad \frac{\partial u}{\partial n} = 0, \quad u(x, 0) = u_0(x). \quad (3.1)$$

The user can define the "strength" of the smoothing by changing the `t_end` parameter (time length). Large `t_end` values create a stronger smoothing effect on the time series, therefore, more information is lost.

3.3. Development of new analysis procedure and software

After the corrected part of LSA Values is calculated according to the tune measurement, it passes through the smoothing filter. The parameters for the `perona_malik_smooth` function were decided as follows: $\alpha = 10.0$, $k = 0.05$, $t_{\text{end}} = 5.0$. An example of an LSA Values function before and after smoothing is given in Fig. 3.16.

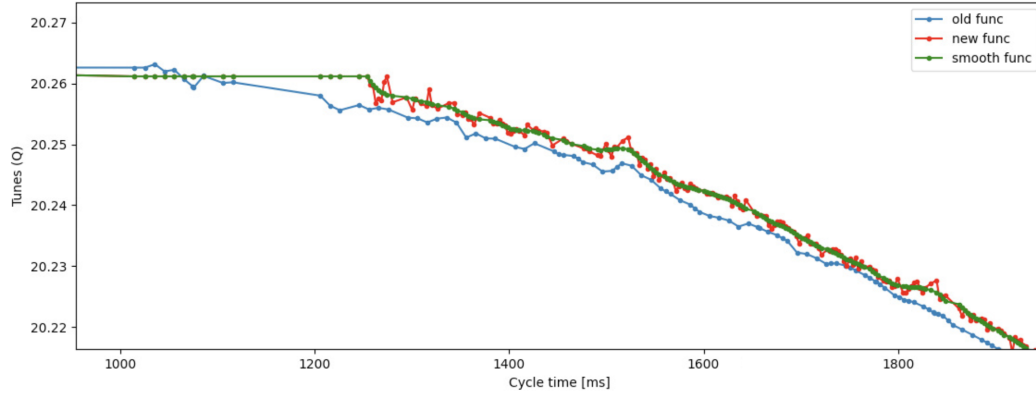


Figure 3.16: New LSA tune VALUES function before (red) and after smoothing (green). The old LSA Values function is also plotted (blue).

3.3.6 Ramer-Douglas-Peucker algorithm

To prepare the function for propagation to the magnets another step must be added to remove unnecessary points from the function. The algorithm responsible for this task is the *Ramer-Douglas-Peucker algorithm*, or *rdp* for short [58].

The *rdp* accepts two input parameters: a dataset to be simplified, and a variable called *epsilon*, which serves as a threshold. The process begins by connecting the first and last points of the original line with a "baseline." Subsequently, the function identifies the point that is farthest from this baseline. If the distance of this point from the baseline exceeds *epsilon*, it will be retained, and the function will recursively split the line into two segments and repeat the process. On the other hand, if the distance of the point from the baseline is less than or equal to *epsilon*, all the points along the baseline are deemed insignificant and can be discarded. The final output will be an array containing only those points that have been marked as retained.

For this use-case *epsilon* is set to 10^{-5} . Figure 3.17 illustrates the effect of *rdp* on the spacing of the points of the function.

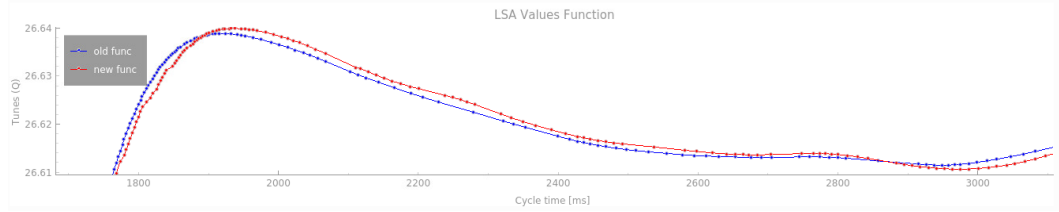


Figure 3.17: Final form of the LSA Values function after passing through the Perona-Malik and rdp filters. The effect of rdp is obvious in the spacing of the points.

3.4 Development of Graphical User Interface

Testing the *ml-methods-for-tune-analysis* package on the SFTPRO1 timing user during the SPS beam commissioning in March 2023 (described in sec. 4.10) proved the novel method a notable improvement in comparison to the existing one. This created the need for a *Graphical User Interface* or *GUI*, to simplify the utilization of the novel algorithms. The PyQt5 Python library [59] and Qt Designer application [60] were used for the development of the GUI.

The purpose of this GUI is to improve the control of the SPS and to be used by the machine operators in the CERN Control Center. Its main purpose is to provide accurate tune measurement and correction, as well as, a chromaticity measurement. After taking into consideration the existing application, I developed this GUI applying the new tune measurement method, while keeping some of the old features that are still relevant in the design. The colour scheme for the plots has been decided after taking into account colour blindness cases.

The *SPS Tune app*, shown in Fig. 3.18, has been designed in tabs, discriminating its functionalities as follows: betatron tune, Laslett shift, and chromaticity¹. At the top of the app there is a live timing-bar which illustrates the current SPS supercycle and highlights the selected timing user (cycle). On the top-right there is a green button which allows the user to login, and, depending on the users status, gain the rights to propagate a correction to the accelerator through the rbac system [61]. On the bottom of the app there is the log console, where logging information, errors and warnings are printed. Some of these widgets are available through CERN's Acc-Py distribution.

¹The Laslett tune shift tab is not part of this work and will be added by the responsible at a later stage, for the completeness of the tool

3.4.1 GUI frontend: Betatron Tune

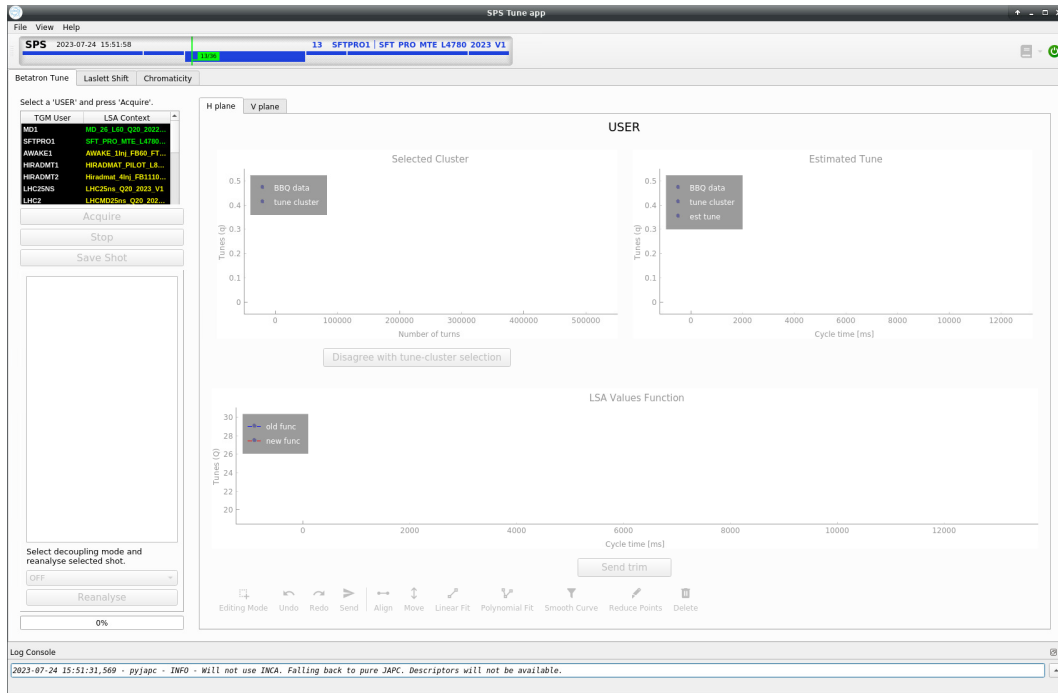


Figure 3.18: SPS Tune app: Betatron Tune design.

Figure 3.18 shows the design of the Betatron Tune tool. On the left hand side, there is a list of the timing users, with the currently active, i.e. played, cycles coloured green. The user has to select one of the green cycles and press the "Acquire" button right below the timing user list, to start the tune measurement. There is a "Stop" button to interrupt the analysis at any stage, and give the user the possibility to reacquire. After an acquisition has been taken, the "Save Shot" button is activated, which allows to save the data of the current acquisition in a list below, for further processing at a later point. In the left-bottom corner there is a progress bar showing the current stage of the analysis.

Included in the Betatron Tune tab are two tabs called "H plane" and "V plane", displaying the output of the analysis for each plane separately. They both look identical in terms of design. In Figs. 3.18 and 3.19 an example of the horizontal plane tab is presented. There are three plots displaying information about the analysed tune signal. The first plot entitled "Selected Cluster" visualizes the output of the BBQ data in gray colour and the selected tune cluster (blue) decided by the clustering algorithm. At this stage the user can check that the tune line has been identified correctly. The second plot entitled "Estimated Tune" visualizes the tune line reconstruction (gray),

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as described in sec. 3.3.2, the denoised tune cluster (blue), and the estimated tunes (red) over the entire cycle.

The third plot below named "LSA Values Function" presents the active LSA Tune VALUES function (blue) and the suggested LSA Tune VALUES function including a correction according to the current measurement (red). This last plot is interactive. The user can perform manual corrections on the red points by selecting them and using buttons from the toolbar below. Examples of manual corrections are: changing the y-position by dragging the selected points up or down, aligning them to a specific y-value, fitting them with a polynomial of varying degree, or reducing/deleting points. Once the user is satisfied with the new LSA Values Function, they can send it to LSA, for propagation to the quadrupole magnet power converters, by clicking the "Send Trim" button.



Figure 3.19: SPS Tune app: Betatron Tune analysis for the HIRADMT1 timing user for the horizontal plane.

In case the coupling line has been selected instead of the correct tune line (Fig. 3.15), the user can click the "Save Shot" button, select the dataset from the list, find the desired decoupling mode from the combo-box below (left-bottom) and click the "Reanalyse" button. The decoupling modes are: OFF, H_from_V, V_from_H, corresponding to the decoupling options described in Section 3.3.3 . The analysis

3.4. Development of Graphical User Interface

should then be able to decouple the horizontal and vertical planes and provide optimal results. In case this approach is not successful, it is recommended to make a new acquisition.

Should there be an issue with the cluster selection not related to linear coupling, there is the possibility to window the analysis to aid the clustering algorithm in identifying the correct tune cluster. To achieve that, the user needs to click on the "Disagree with tune-cluster selection" button. A window appears as shown in Fig. 3.20 to input the turns and tunes range that should be used for the analysis. Should this fail, it is recommended that the user acquires anew.

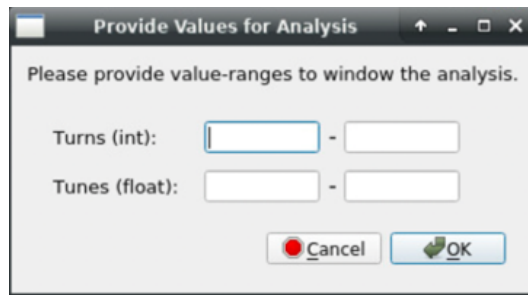


Figure 3.20: SPS Tune app: Values Window

3.4.2 GUI backend: Betatron Tune

The Betatron Tune analysis is designed to run by the click of one button. The user simply needs to select the desired timing user and press "Acquire".

When the "Acquire" button is pressed, a thread is created, which contains the entire analysis. The use of a separate thread for the data acquisition and processing is necessary to avoid blocking the app. A subscription to the BBQ data is created and signal is awaited to acquire data. Once the data is acquired, the *Beam Current Transformer (BCT)* signal is checked before the analysis begins. The beam intensity must reach beyond the threshold of $4 \cdot 10^{10}$ p. This is to ensure beam presence. If the threshold is not reached, another acquisition will be taken automatically, until there is a satisfactory event.

When the beam intensity criterion is fulfilled, the acquisition is analysed consecutively, running the horizontal and vertical planes sequentially. The corresponding plots are displayed as soon as the respective stages of analysis are complete, and the relative buttons are activated. All the plots offer features to zoom and drag. If the user decides to restrict the analysis to a certain range of turns and tune values using

the "Disagree with tune-cluster selection" button, part of the analysis will be rerun in a separate thread for the concerned plane taking into consideration the input values. The second and third plots will get updated, while the first plot remains the same.

When the "Stop" button is pressed, it takes a few seconds to close the thread and reset, such that another acquisition can be taken. When the "Send Trim" button is clicked, the algorithm checks that there were no trims sent between the time of creating the new LSA function and clicking the button. If a trim was sent in the meantime by someone else, the user gets the warning shown in Fig. 3.21). This is to prevent the user from falsely making tune corrections based on an outdated acquisition.



Figure 3.21: SPS Tune app: Warning Window

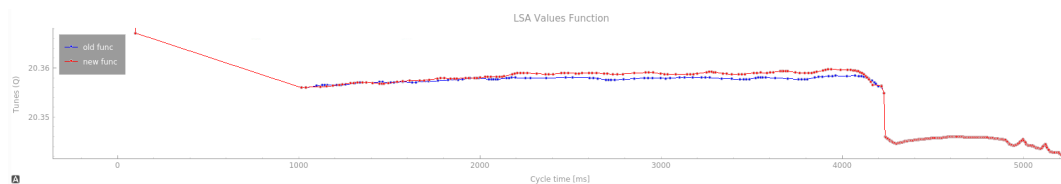


Figure 3.22: SPS Tune app: LSA Value Function for the MD3 timing user.

The new tune LSA Values function is calculated as follows. The LSA Target function is the tune function that should be achieved by applying a correction. To calculate the VALUES function, the Target function needs to be imported. The difference between the tune estimation, deducted from the tune measurement, and the Target function is the correction that needs to be applied. After calculation, the correction passes through the Perona-Malik and rdp filters. The result is added to the old VALUES function for the time period, in which the tune measurement was taken. The new VALUES function consists of the same values, as the old VALUES function, before and after the tune measurement, and of the updated values. Figure 3.22 shows the

3.4. Development of Graphical User Interface

old (blue) and new (red) tune functions. They only differ for the time period during which a tune measurement is available (here: between 1038 ms and 4231 ms).

3.4.3 GUI frontend: Chromaticity

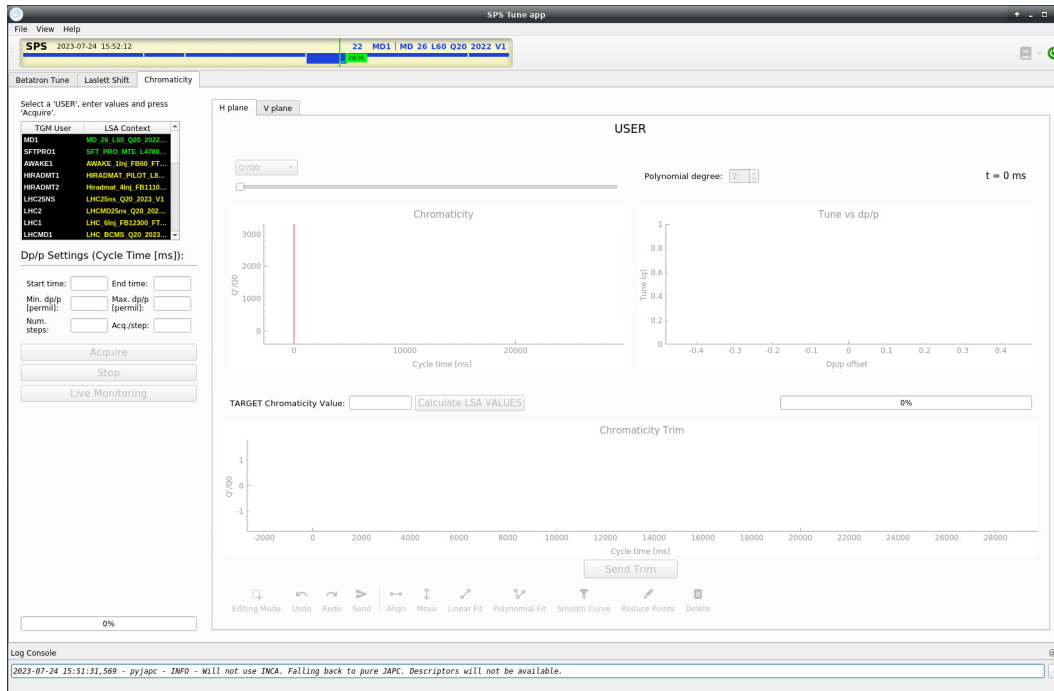


Figure 3.23: SPS Tune app: Chromaticity tab design

Figure 3.23 shows the design of the Chromaticity tool. Identical to the tune tool, on the left side, there is a list of the timing users, with the currently played cycles marked in green. The user has to select one of the green cycles, input the "Dp/p Settings" and press the "Acquire" button right below the timing users list, to start the measurement. Once the user selects a timing user (cycle), a predefined set of "Dp/p settings" appears as a suggestion. The input parameters are: start time [ms], end time [ms], minimum dp/p value [permil], maximum dp/p value [permil], number of steps, and number of acquisitions per step - that need to be taken for each dp/p offset value. The number of steps defines the dp/p offset values between minimum and maximum input value. The minimum acceptable number of steps is 3. For example, if "min dp/p" = -0.003, "max dp/p" = 0.003 and "num. steps" = 3, then the dp/p offset values that will be sent to LSA are: -0.003, 0.000, 0.003 . For each of these dp/p settings, "Acq./step" valid acquisition must be taken. On the left-bottom corner of the app

there is a progress bar, showing the analysis stage. The chromaticity measurement takes several minutes, depending on the number of acquisitions the user requests.

The "Stop" button allows to interrupt the process at any stage and gives the user the possibility to reacquire. Below the "Stop" button there is the "Live Monitoring" button. Once clicked a window with three plots pops up, shown in Fig. 3.24. On the first plot entitled "Dp/p Offset", the current dp/p Offset function is displayed. On the second and third plot, with title "Selected Tune Cluster", the reconstructed data and selected tune lines for the horizontal and vertical planes are displayed, respectively. The user can also monitor the current acquisition progress in the top-right corner of each plot.

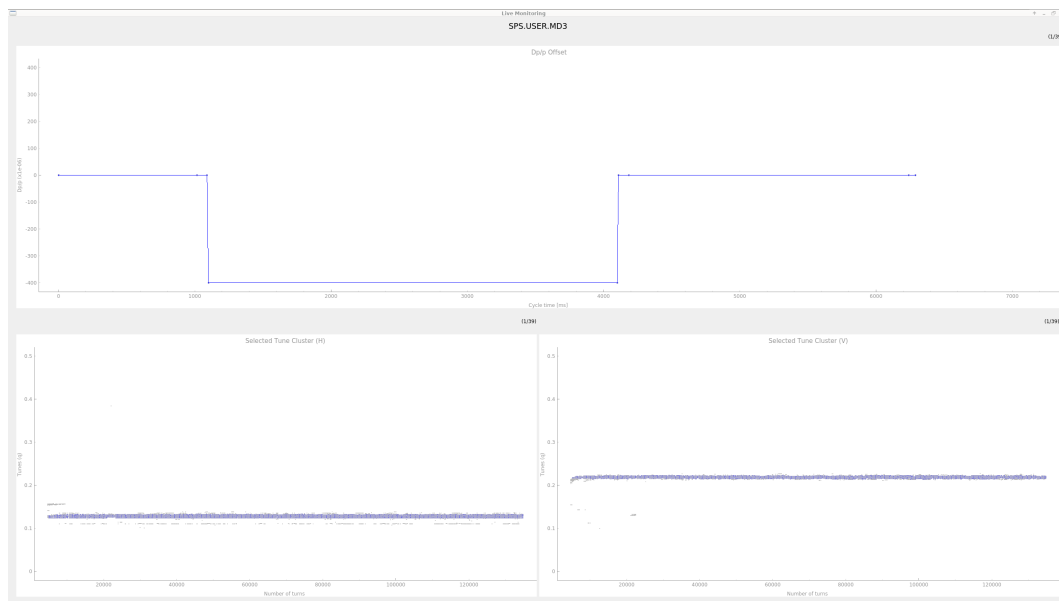


Figure 3.24: SPS Tune app: Chromaticity, Live Monitoring window for the MD3 timing user.

Included in the Chromaticity tab, there are again two tabs "H plane" and "V plane", each displaying the output of the analysis for the two transverse planes separately. Both tabs look identical in terms of design. Figures 3.23 and 3.25 show an example for the horizontal plane. Each plane contains three plots. After all the acquisitions have been taken, the chromaticity is calculated automatically, as a 2nd degree polynomial fit to the data, and the first two plots are displayed.

The first plot with title "Chromaticity" displays the calculated values of Q'/Q_0 versus cycle time. Above the first plot, there is a combo-box and a sliding bar. The combo-box gives the user the possibility to visualize other orders of chromaticity (Q_1 , Q_2 , Q_3 ,

3.4. Development of Graphical User Interface

...), by changing the displayed data on the plot. The second plot with title "Tune vs dp/p" shows the tune measurement of a specific time stamp with regard to relative momentum offset settings and a fitted line (red) on the data. Above this plot, there is a spinbox, where the user can change the degree of polynomial fit, and in extend, the values of chromaticity in the first plot. At the top-right corner of the second plot, the time stamp is displayed in units of [ms]. By dragging the sliding bar, the user can see the time stamp change along with the displayed data on the second plot.

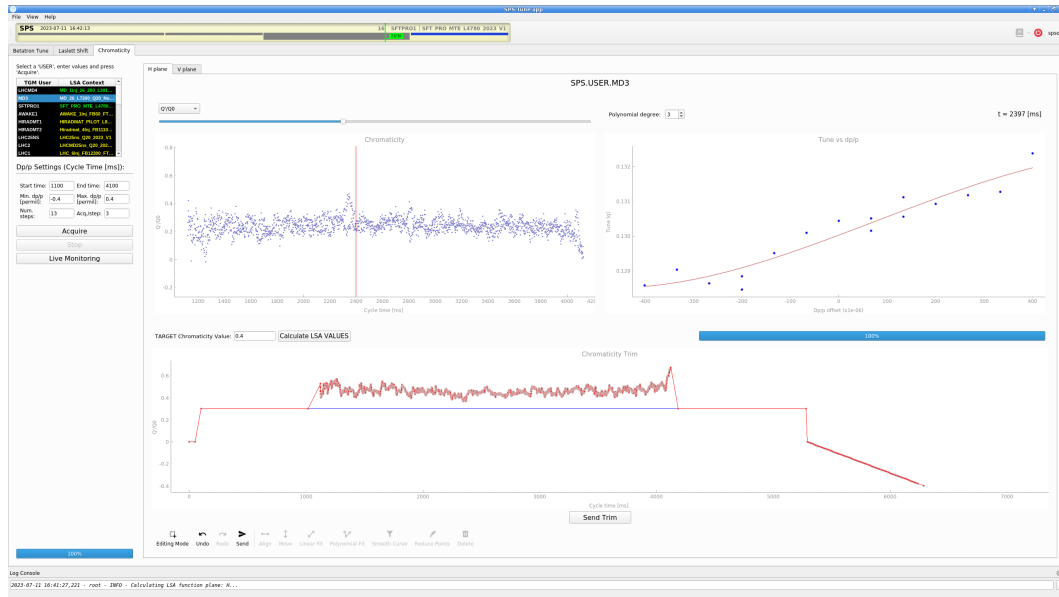


Figure 3.25: SPS Tune app: Chromaticity measurement for the MD3 timing user.

Above the third plot there is an empty box for the user to input a Target Chromaticity Value. After the user inputs the desired Target value and presses the "Calculate LSA Values" button, a chromaticity correction is calculated and a new VALUES function is provided for the measured time window. The third plot is displayed.

The third plot called "Chromaticity Trim" displays the active chromaticity LSA Values function (blue) and the suggested new VALUES function (red). The suggestion is based on the measurement, calculated on the Target value the user wants to apply. The y-axis is in Q/Q_0 units and the x-axis is in cycle time [ms]. This plot is calculated depending on the measurement displayed on the first plot. If the degree of polynomial fit changes, the third plot is automatically cleared, and needs to be recalculated. Same as for the LSA tune plot, this plot is interactive. The user can perform manual corrections on the red points by selecting them and using buttons from the toolbar below. Once the user is satisfied with the result, the trim can be sent to LSA, by

clicking the "Send Trim" button.

3.4.4 GUI backend: Chromaticity

The Chromaticity tool is designed to run as follows. The user simply needs to select the desired timing user, check if the suggested dp/p settings are acceptable, otherwise change them, and press "Acquire".

When the "Acquire" button is pressed, a thread is created that contains the entire analysis. As an example the input values of Fig. 3.25 will be used. The dp/p offset function is originally trimmed to the minimum input value (e.g. -0.4 as in Fig. 3.24, top plot), for the input cycle time period (e.g. from 1100 ms to 4100 ms). After the input number of acquisitions per step is taken and analysed, the dp/p offset function will be trimmed again to move to the next dp/p setting. This process will be repeated until reaching the maximum dp/p value specified by the user.

Same as for the tune measurement, once the data is acquired, the BCT signal is checked for beam presence first before the analysis begins. The tune analysis runs by default in decoupling mode H_from_V, in the same manner it runs for betatron tune measurement. The selected tune cluster plot is included in the live monitoring window as well, as illustrated in Fig. 3.24 (bottom plots). One plot is shown per plane, such that the user can quickly check if the tune analysis is running properly. In the top-right corner of each plot there is a label showing which acquisition the currently displayed plot refers to and what the progress is. In case the selected tune cluster has a tune range larger than 0.1, the measurement is disregarded, as it is possibly an empty shot, noise, or an overall bad measurement. It will hence not be used for the chromaticity calculation.

The tune estimation of each valid acquisition is stored in a dictionary along with the corresponding dp/p value and timestamp. Once the scan is completed, a 2nd degree polynomial line is fitted to the tune vs dp/p data by default. This is done for each timestamp containing at least three valid measurements. The Q' value is extracted from the polynomial fit as the first order polynomial coefficient (e.g. $p(x) = p_0 + p_1 \cdot x + p_2 \cdot x^2$, $Q' = p_1$, $Q'' = Q_2 = 2! \cdot p_2$, etc.). This is in agreement with Eq. (2.43). The Q_0 value is extracted either through interpolation or extrapolation of the fit line. The fraction Q'/Q_0 along with the higher-order chromaticities (Q_2, Q_3 , etc.), are extracted for display on the first plot.

The sliding bar above the "Chromaticity" plot is synchronized with the red vertical line that moves along the time axis, and jumps between the measured timestamps.

3.4. Development of Graphical User Interface

Using the sliding bar, changes the displayed plot on "Tune vs dp/p ", and the timestamp value.

By changing the polynomial degree value above the second plot, Q'/Q_0 is recalculated using the new polynomial fit, also displayed on the plot. This changes automatically the highest chromaticity order available in the combo-box. Note that this will also change the timestamps. The higher the polynomial degree the fewer measurements are available. This is due to the condition $n \geq deg + 1$, the minimum number of points n in a plot, to fit a polynomial line, is $deg + 1$. The maximum degree of the polynomial is hence conditioned by the number of steps: $deg \leq steps - 1$.

To extract the LSA Values function for chromaticity, the user needs to input a Target Chromaticity Value. After clicking on the "Calculate LSA Values" button, a Target function is created, using the input value. A correction is then calculated between the Target function and the chromaticity measurement. In the SPS, correction of higher-order chromaticities are not allowed. Q' is directly corrected through the use of sextupole magnets (as described in Section 2.4.5). Using the same method used for tune, the new Values function consists of points of the current Values function plus a correction on the time period of the measurement (see Fig. 3.25 bottom plot). When the user presses the "Send Trim" button, the algorithm checks if a trim has been sent by another user in the meantime, and if this is the case, a warning window pops up, similar to Fig. 3.21.

4 Results

4.1 Evaluation of method and software upon beam commissioning

The new algorithm was first tested using a script upon beam commissioning of the North Area fixed-target beams (timing user: SFTPRO1) in March 2023. The goal of this test was to observe the algorithm's real-time behavior on the actual beam, to explore its abilities, and gain feedback for improvements.

To conduct the tests, the tune function for the SFTPRO1 timing user was set back to the settings from before the Year-End Technical Stop (YETS) 2022. Figures 4.1 and 4.2 show the readout and corrections for the horizontal and vertical planes, respectively. The top row of plots shows the tune readout of the old settings. The top-right corner plot, entitled "LSA Values Function", shows the tune function currently stored in LSA (blue) along with the suggested correction (red). The bottom row of plots shows the tune measurement after applying the suggested correction. The tune value now seems to remain constant throughout the cycle (note the difference in scale for the vertical axis), and the proposed correction at the second iteration is almost identical to the function currently stored in LSA. No significant correction suggests that the tune has been well set in a single iteration.

Setting up the betatron tunes for the different SPS beams using the existing tool, took a significant amount of time and several iterations. This is because the previous method required a lot of manual interventions on the processed tune values (outlier and noise removal, smoothing, linear coupling peak removal, etc.). The novel approach, on the other hand, automatically identifies the correct tune lines without manual intervention, and makes single-shot corrections possible, resulting in setting the tune more accurately in significantly less time.

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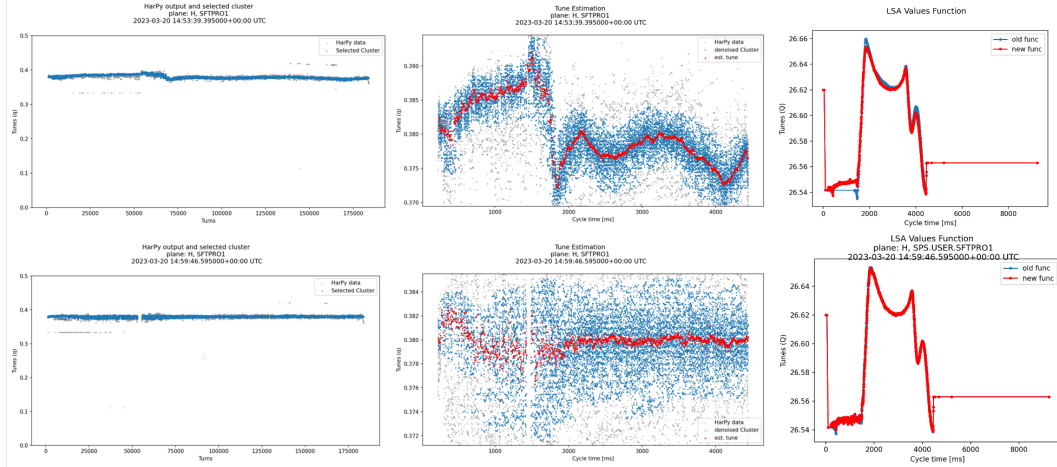


Figure 4.1: Single-shot correction of the horizontal tunes during beam commissioning of the low-intensity North Area fixed-target beam (timing user: SFTPRO1). The top and bottom row plots show the identified tune cluster (*left*), weighted average (*middle*), and LSA functions (*right*) over the cycle, for the first and second iterations, respectively.

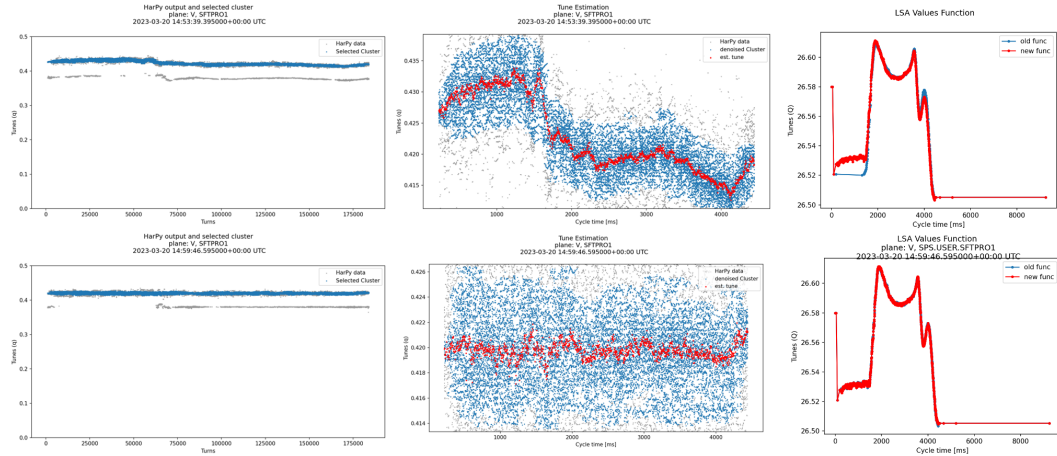


Figure 4.2: Single-shot correction of the vertical tunes during beam commissioning of the low-intensity North Area fixed-target beam (timing user: SFTPRO1). The top and bottom row plots show the identified tune cluster (*left*), weighted average (*middle*), and LSA functions (*right*) over the cycle, for the first and second iterations, respectively.

Second, the ability of the algorithm to identify tune deviations was tested. For this test, an unexpected tune offset was manually inserted into the LSA function using the Settings Manager (see Fig. 4.3).

4.1. Evaluation of method and software upon beam commissioning

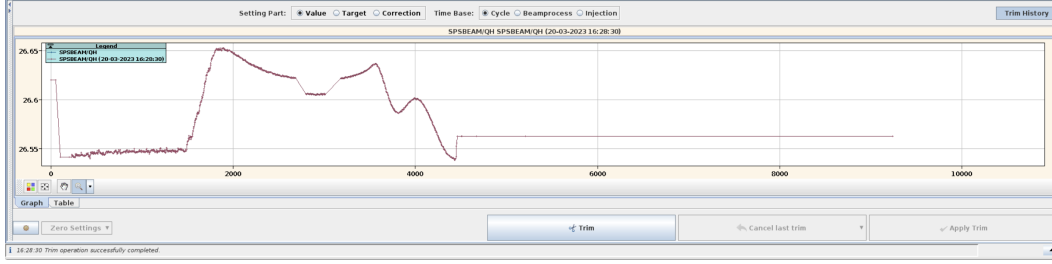
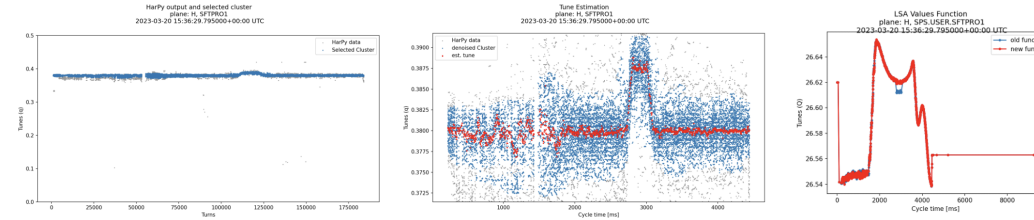


Figure 4.3: Introducing a horizontal tune offset in the LSA tune function.

The algorithm was indeed able to identify both small and more significant tune offsets and corrected them to the desired values within one iteration (see Fig. 4.4). Note that the tune offset appears to be positive on the readout due to the aliasing effect for $q \in [0.5, 1.]$ (the SFTPRO1 horizontal tune value is approximately 26.62). The real offset should be negative according to the changes made in Fig. 4.3. To avoid confusion, this aliasing effect for the fixed-target beams has been taken into account and is corrected in the plots of the GUI.

- Small offset - After 1 iteration



- Large offset - After 1 iteration

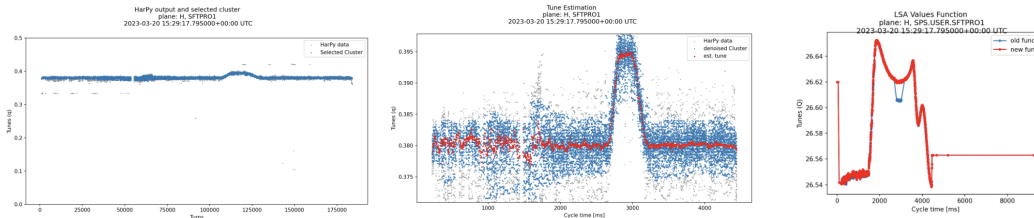


Figure 4.4: Correction of horizontal tune offsets. The top and bottom rows show the identified tune cluster (*left*), weighted average (*middle*), and LSA functions (*right*) for the correction of small ($\Delta q_x = -0.0075$) and a larger ($\Delta q_x = -0.015$) tune offsets, respectively.

The accuracy of the tune measurement is assessed quantitatively and compared to the accuracy of the existing method (Fig. 4.5). An example of tune measurement with an intentionally added small offset on SFTPRO1 (horizontal plane) has been selected. The tune measurement, using the new method, for the time intervals where the tune should remain constant ($220\text{ms} < t < 2715\text{ms}$ and $3094\text{ms} < t < 4440\text{ms}$) is

$q = 0.6202 \pm 0.0007$. This is consistent with the horizontal set tune for the SFTPRO1 timing user and is a result of the initially performed tune correction. The tune measurement of the offset is $q = 0.6124 \pm 0.0004$, so the height of the offset is $\Delta q = -0.0078 \pm 0.0008$. Using the existing method on the same dataset gave the following results: $q = 0.6201 \pm 0.0017$ (constant region), $q = 0.6123 \pm 0.0006$ (offset), and $\Delta q = 0.0078 \pm 0.0018$.

The analysis demonstrates that the new method provides results consistent with the existing approach, however, with a reduction in the uncertainty. In the constant tune region, the error of the measurement has been improved by 2.43 times. In the offset region the error has been improved by 1.50 times, due to the short time range, and on the offset measurement Δq the error has been improved by 2.25 times. This result is presented in the following method comparison plot (Fig. 4.5), where variations in the measurement using the existing method are visibly larger. The first large variation ($t < 220$ ms), present for the pure FFT-based approach (blue), has been excluded from the calculations.

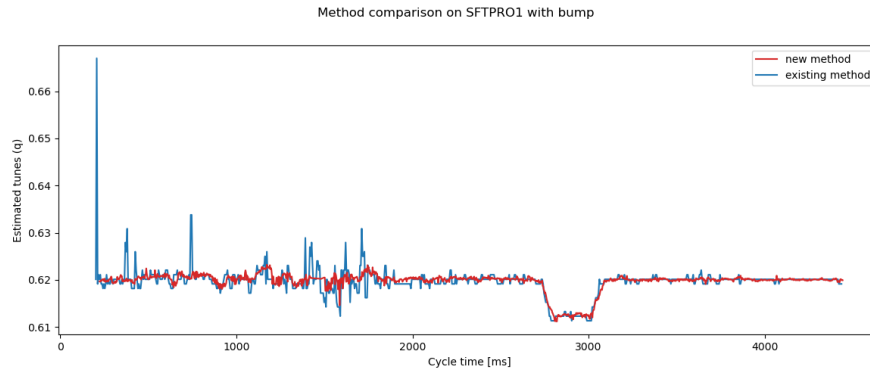


Figure 4.5: Tune measurement method comparison on the SFTPRO1 timing user for the horizontal plane. Here the tune values are reverted to account for aliasing.

4.2 Machine development studies

A number of tests were conducted using Machine Development Beams (MDs) to check the algorithm's ability to read harmonic tune modulations and ensure its usability in the work of other colleagues. The harmonic tune modulation readout is an important use case for single-shot chromaticity measurements and cannot be covered by the existing tune analysis method. A detailed chromaticity scan normally takes about one hour, depending on the required measurement accuracy. By using a harmonic tune modulation, i.e., sinusoidally modulating the momentum error

dp/p over the cycle, a quick, but less accurate, chromaticity scan can be conducted in a single acquisition. This is because the measured tune value will be modulated according to dp/p through chromaticity. By correlating the measured tunes with the given dp/p at each time in the cycle, chromaticity can be deduced [46]. An example modulation function for dp/p is shown in Fig. 4.6.

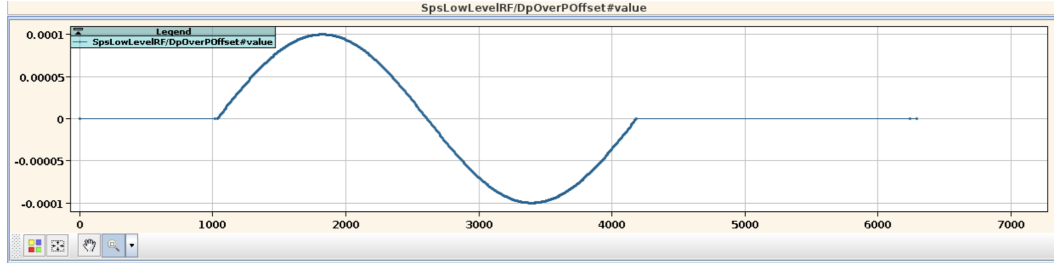


Figure 4.6: Inserting a harmonic modulation into the dp/p function for timing user MD3.

Figure 4.7 shows the measurement of the tune modulation provoked by the dp/p modulation shown in Fig. 4.6 for the horizontal and vertical planes, respectively.

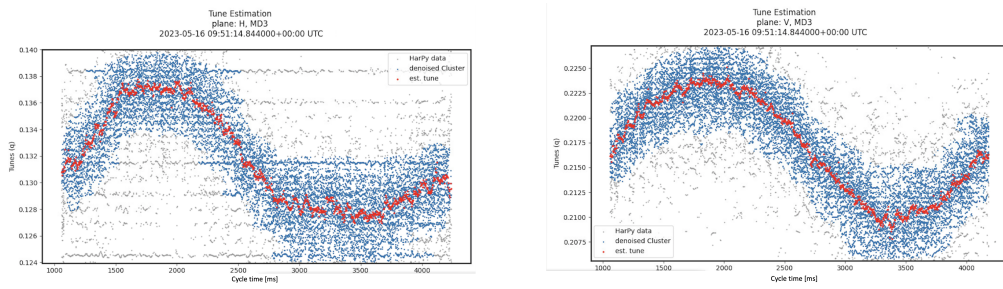


Figure 4.7: Horizontal (left) and vertical (right) tune readout for the low-frequency harmonic modulation of dp/p shown in Fig. 4.6 for timing user MD3.

Increasing the modulation frequency in dp/p is interesting to obtain a better time resolution in the chromaticity measurement over the cycle. The algorithm was hence tested for different frequencies of harmonic modulations and was able to capture most cases accurately. Figure 4.8 displays an example of processed horizontal (left) and vertical (right) tune values for a high-frequency dp/p modulation. The analysis shows that for a certain cycle time period (horizontally: 1600 ms to 2900 ms, vertically: 3200 ms to 4100 ms), the tune oscillation amplitudes are increased. This is due to a change in chromaticity within the given periods meant to test the time resolution of this method. The low-frequency modulation given in Fig. 4.7 could not reveal this change in chromaticity.

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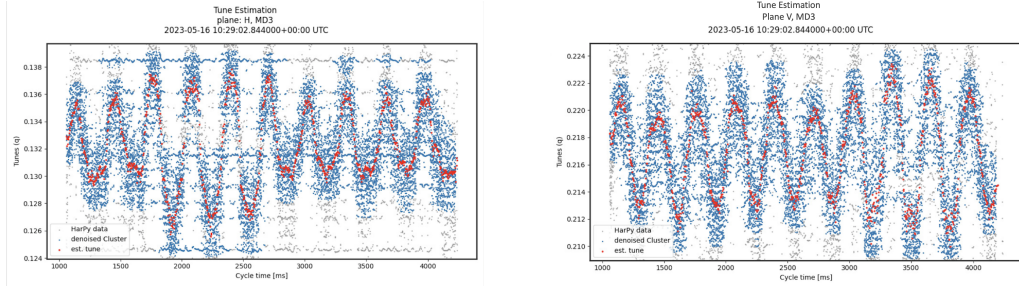


Figure 4.8: Horizontal (*left*) and vertical (*right*) tune readout for a high-frequency harmonic modulation of dp/p for timing user MD3. In this case, the oscillation amplitude appears magnified for certain time periods, resulting from increased chromaticity values.

The tests showed that overall the algorithm was indeed able to read the harmonic tune modulations either automatically or through windowing, i.e. limiting the accepted tune range. The latter was sometimes needed when working with high-frequency modulations.

Chromaticity Measurement

MD beams were also used to test the chromaticity measurement where dp/p is shifted by a constant value for the entire cycle, scanning the amount of the shift over many acquisitions. Two different beam optics, called Q20 and Q26 [62], with an integer tune of 20 and 26, respectively, were used to test the chromaticity tool's abilities. The results for the two optics look very similar, hence only the performance on Q26 optics will be discussed here.

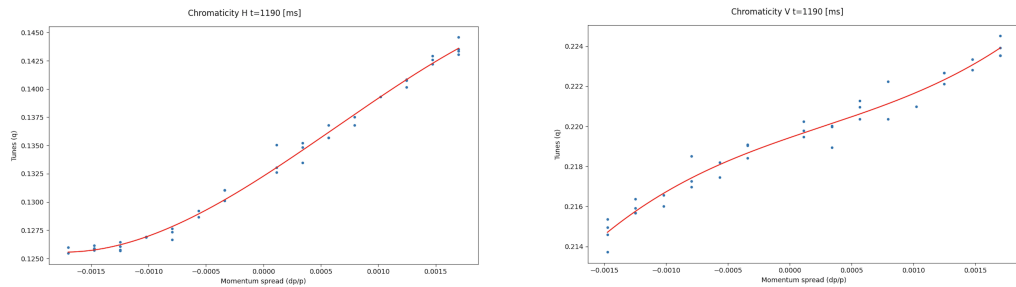


Figure 4.9: Tune vs dp/p measurement and 3rd-order polynomial fit. *Left*: Horizontal plane. *Right*: Vertical plane.

To test the chromaticity measurement, the dp/p offset values were varied between -0.002 and 0.002, in 17 steps. Four acquisitions were taken for each step. Figure 4.9

shows an example tune measurement vs dp/p at the cycle time $t = 1190$ ms together with a least squares third-order polynomial fit (red line). There are no outliers on these measurements. The chromaticity value is extracted from the fit line as described in Section 3.4.4. The final measurement of chromaticity for the horizontal (green) and vertical (red) planes is presented in Fig. 4.10.

In most cycles, the chromaticity is expected to remain constant over the cycle time, in good agreement with the measurement in Fig. 4.10. The outliers indicate inaccurate measurements for specific times in the cycle, usually caused by a lack of reliable tune measurements, and would eventually be excluded when calculating the correction to be applied in the machine.

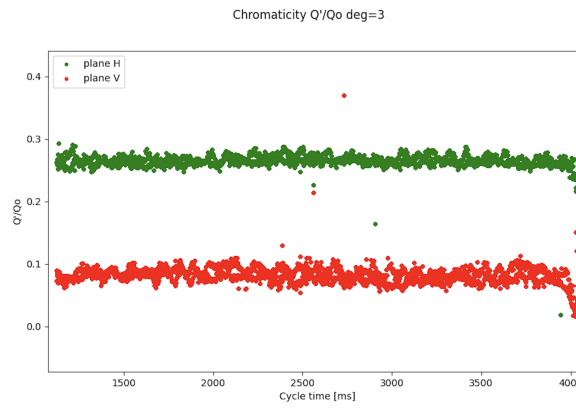


Figure 4.10: Chromaticity measurement for the horizontal (green) and vertical (red) planes for timing user MD3.

To understand how the new tune analysis method compares to the existing one, measurements were taken for the same beam types using the "Multi Q" application. Figure 4.11 illustrates the challenges faced with the old method. Here, for example, for some of the dp/p values, the vertical tune is incorrectly identified and therefore the fit to the Q vs dp/p plot is distorted. The user needs to manually exclude these points for each cycle timestamp to correct the fit (Fig. 4.11, bottom), and therefore the chromaticity measurement. This is very impractical to do for all timestamps, and hence the measurement remains eventually inaccurate.

Chapter 4. Results

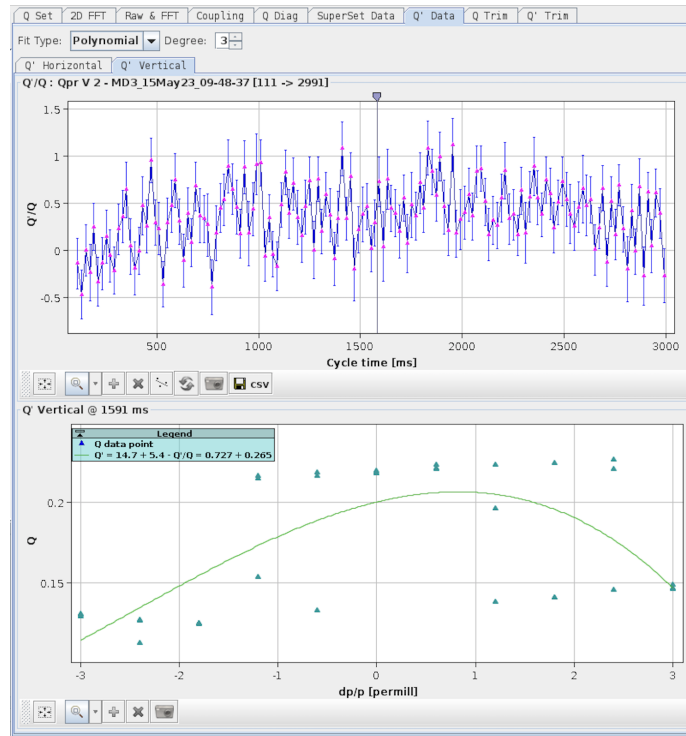


Figure 4.11: "Multi Q" application: chromaticity measurement for timing user MD3 for the vertical plane. The tune readout is incorrect due to the linear coupling line. This results in a false chromaticity measurement indicated by the 3rd-order polynomial fit.

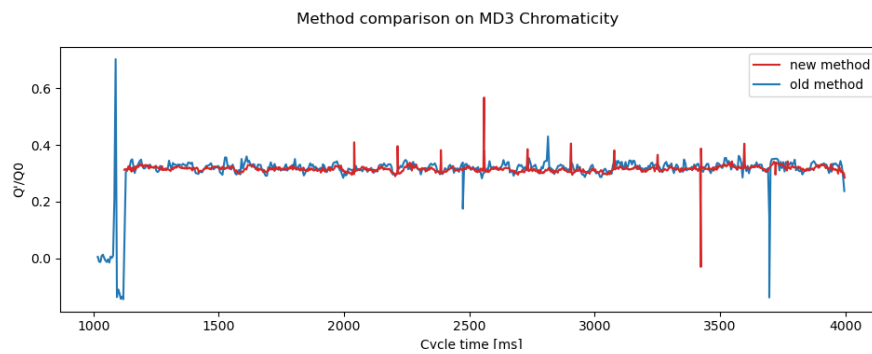


Figure 4.12: Chromaticity measurement method comparison on the MD3 timing user for the horizontal plane.

The accuracy of the chromaticity measurement has been quantitatively assessed on an MD3 (horizontal plane) dataset. To extract this measurement the algorithm has a tolerance of 0.5 around the measurement's mean value to exclude outliers. This is applied to both methods for this comparison. To obtain this measurement,

4.2. Machine development studies

the dp/p offset was varied between -0.003 and 0.003 in 11 steps. Only one acquisition is taken per step. Using the new method, the chromaticity measurement is $Q'/Q_0 = 0.316 \pm 0.014$. Using the existing method on the same dataset gives $Q'/Q_0 = 0.310 \pm 0.068$. Both methods yield consistent results. The new method, however, improves the measurement error 4.96 times. The comparison of the measurement methods is presented in Fig. 4.12, where the variance of the existing method is clearly larger.

To check the algorithm's measurement accuracy and time resolution abilities, chromaticity offsets were inserted in the machine for different cycle time periods. Figures 4.13 and 4.14 show the LSA functions including offsets for the horizontal and vertical planes, respectively.

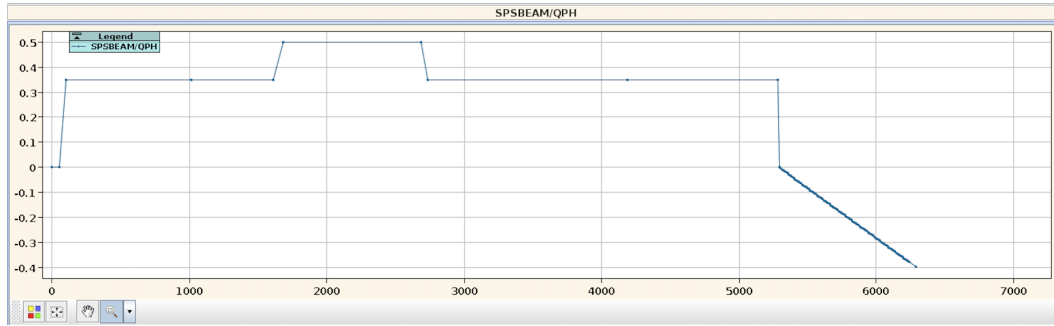


Figure 4.13: Programmed horizontal chromaticity offset of $\Delta\xi_x = 0.15$ for timing user MD3.

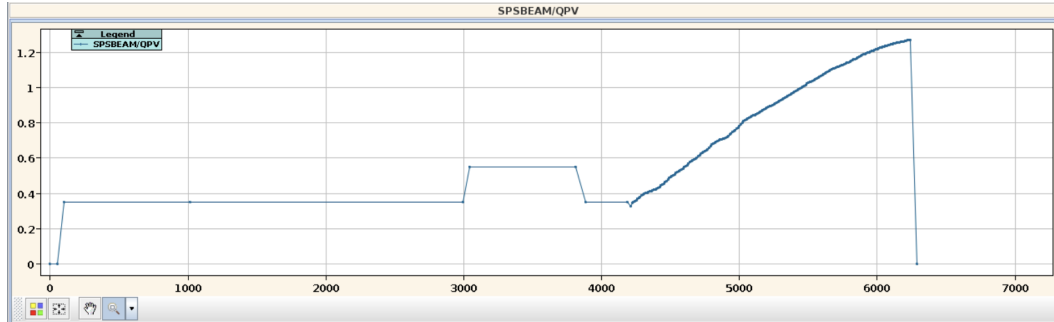


Figure 4.14: Programmed vertical chromaticity offset of $\Delta\xi_y = 0.2$ for timing user MD3.

The algorithm was indeed able to identify the offsets and measure them correctly. In Fig. 4.15 the measurement of these offsets is presented, for the horizontal (green) and vertical (red) planes.

Chapter 4. Results

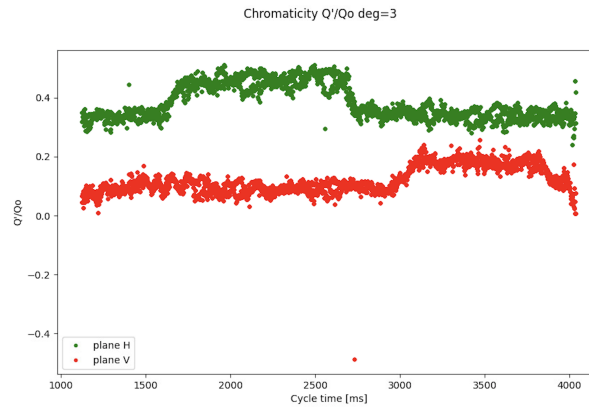


Figure 4.15: Chromaticity measurements after applying the functions shown in Figs. 4.13 and 4.14 for timing user MD3. Horizontal (green) and vertical (red) first-order chromaticities are shown.

Figure 4.16 shows the measurement for the same programmed chromaticity functions, but using the "Multi Q" app. It can identify the chromaticity offsets, using a 3rd-order polynomial fit, and gives an acceptable, but less detailed result with a much higher variance.

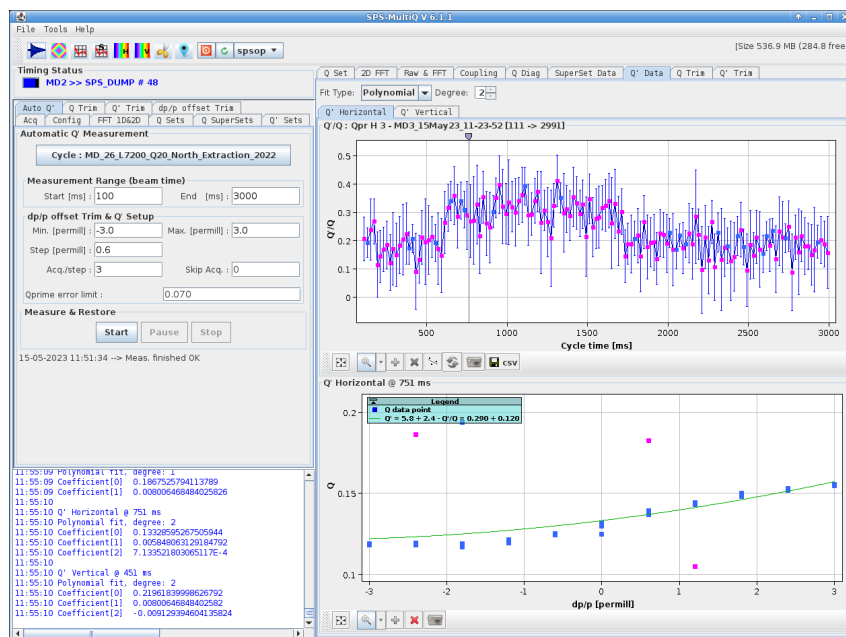


Figure 4.16: Vertical chromaticity measurement after applying the function shown in Fig. 4.14 for timing user MD3, using the former "Multi Q" application.

4.2.1 GUI testing on Machine Development beams

Finally, MDs were planned and carried out to test the functionality of the GUI. All buttons and functions were tested, one by one. Some examples of tested functions for the tune tool are tune measurement, displaying plots correctly, reversing tune values for SFT timing users, sending trims to LSA, running windowed analysis, running in decoupling mode, closing threads, and resetting the acquisition by using the "Stop" button. These tests revealed minor bugs that were fixed for the final version.

For the chromaticity tool, it was important to check whether the dp/p trims are sent correctly to LSA, and if the reaction of the beam to these trims are as expected. Another important check was to see whether the input parameters, such as the number of steps and acquisitions per step, are handled correctly. The GUI's reaction to changing the degree of polynomial through the spin-box was also important to be tested. All plots were indeed cleared and new plots were displayed, as described in Section 3.4.4. The sliding bar works properly, it is connected to the vertical red line on the first plot, the timestamp label above the second plot and the displayed values of the second plot. It was also essential to check that all GUI elements designed to impact one transverse plane, do not influence anything on the other transverse plane.

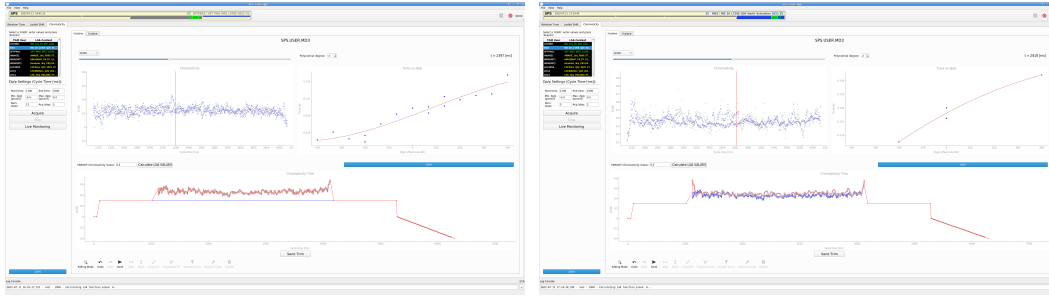


Figure 4.17: Horizontal chromaticity measurement and correction with the new SPS Tune app for timing user MD3. *Left*: initial measurement and correction to target value of $\xi_x = 0.4$. *Right*: Validation measurement after applying the correction.

Figure 4.17, left, shows a chromaticity measurement taken for the horizontal plane. The chromaticity value was measured at $\xi_x = 0.2$. The user then requested a correction with a target value of $\xi_x = 0.4$ (third plot on the GUI). The correction was sent to LSA and a new measurement was taken, shown in Fig. 4.17, right. The new measurement confirms that the chromaticity value has indeed changed to 0.4. Another correction with a target value of 0.4 was calculated afterwards (plot "Chromaticity Trim"). It revealed that on average, the applied correction was right, but the high-frequency

variations of the correction line are not reproducible. The same test is applied in the vertical plane (Fig. 4.18) giving similar results. The post-processing of the chromaticity function has been changed to using a larger time window for the smoothing and larger rdp margin. This avoids small variations in the correction as seen before, it provides a smoother and more uniform correction. Real measurements have not been conducted since there was no time available on the machine.

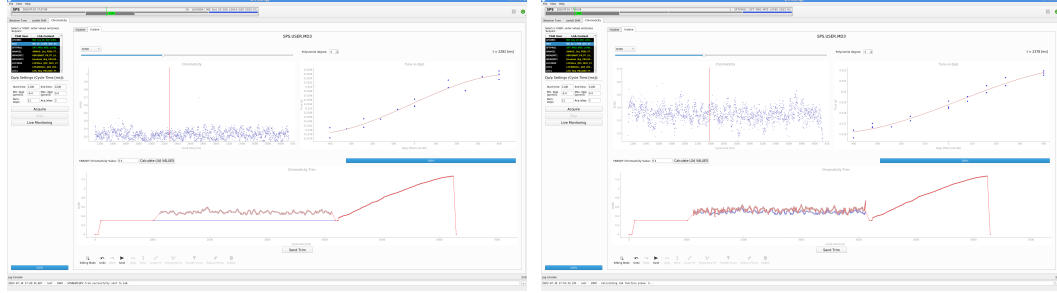


Figure 4.18: Vertical chromaticity measurement and correction with the new SPS Tune app for timing user MD3. *Left*: initial measurement and correction to target value of $\xi_y = 0.4$. *Right*: Validation measurement after applying the correction.

4.3 Comparison to the original analysis method

The "SPS Tune" and "Multi-Q" applications were compared during MD time to evaluate their abilities to analyze the betatron tunes and measure chromaticities. The results of this comparison are presented below.

4.3.1 Tune analysis advantages

Using HarPy in the new analysis method leads to a much higher tune resolution as there is no direct limitation due to discretization compared to a standard FFT approach. This is achieved thanks to an iterative approach and the interpolation of the major FFT peaks for each harmonic line [49]. In addition, the resolution is higher in the cycle time domain as well, since a sliding window of 2000 turns with a step size of 125 turns is used. This makes the method more accurate for abrupt tune changes at specific times in the cycle. In comparison, the highest time resolution "Multi Q" can provide is 256 turns and the tune resolution is limited to $4 \cdot 10^{-3}$. Thanks to HarPy, the signal is also automatically denoised by choosing an appropriate number of harmonics for the analysis.

In terms of tune estimation, "Multi-Q" searches for the highest peak inside a given

4.3. Comparison to the original analysis method

tune window of the FFT output. This window needs to be typically chosen manually by the user and may be limiting the analysis particularly when the tunes feature large excursions over the cycle time. It also may provide incorrect results as the algorithm often selects noise or the linear coupling line. The new algorithm, on the other hand, first selects a connected tune line through clustering. The amplitude information is ignored at this first stage. Once the main tune line is reconstructed and denoised, the amplitude information is considered to provide a tune estimation through amplitude-weighted averages. This method ensures the exclusion or decreased influence of irrelevant points and provides a more accurate and consistent estimation of the tunes over the entire cycle.

Due to the approach explained above, using the "Multi-Q" application requires consistent manual cleaning by the user. With the "SPS Tune" application there is, normally, no need for manual cleaning of the processed tune signals. There is the possibility to do that, nevertheless. Testing the new algorithm for different beam types demonstrated that with a single iteration, the tune values can be corrected to stay almost completely constant throughout a cycle.

In terms of computing time, the new analysis normally takes about one to two minutes to process an acquisition, depending on the cycle length. This has been achieved by using parallel processing. It is, however, still slower than running an FFT. Due to its overall performance, i.e. delivering a high granularity in both tunes and cycle time as well as a clean reconstruction of the tune signals over the entire cycle without manual intervention, the user saves much more time eventually.

Finally, the "Multi-Q" application presents the processed tunes in cycle time vs tune. In "SPS Tune", the axes on the HarPy plot are inverted, i.e. tune vs cycle time, to improve (by eye) the readability of the tune values over the cycle.

4.3.2 Chromaticity analysis advantages

The chromaticity measurement is indirectly optimized thanks to the improvements made to the tune analysis described previously. In addition, by running the tune measurements in decoupling mode, incorrect measurements due to linear coupling have essentially disappeared. In case a faulty measurement is detected, there is a mechanism to ignore the collected data and move on automatically to the next acquisition. Again, there is a higher resolution in the obtained chromaticity value thanks to the increased resolution of the tune measurement. Normally, there is no need for manual cleaning.

Chapter 4. Results

The GUI has been designed to be simple and intuitive for the user. Important characteristics from the original tool have been kept, such as the UI for chromaticity scan configuration, the choice of polynomial degree, as well as the sliding bar to inspect the fits for different cycle times.

5 Conclusions

CERN has committed to enhancing the degree of automation of its accelerator facilities. The goals are to boost operational efficiency, increase machine availability, and improve the beam quality. Recent progress in machine learning is crucial for this process. Certain key parameters and optimization procedures previously done by hand have been identified to best profit from these advances. Among them are the betatron tunes and chromaticities which are fundamental machine settings affecting the beam lifetime. For the past 15 years, a tool called "Multi-Q" has been used at the SPS to analyze and adjust these parameters. However, the tool and the underlying analysis method have limitations in accuracy often requiring manual intervention for data cleaning. This project had the objective to modernize and improve the measurement and correction procedures through various developments.

First, a Python package called "ml-for-tune-analysis" was developed to compensate for the insufficiencies of the previously employed analysis technique. Significant improvements were achieved thanks to a new method combining a HarPy spectral analysis with the DBSCAN clustering algorithm. In most cases, the correct tune line is now automatically identified with a single acquisition and is reconstructed more accurately compared to the previous method. Another key difference is that the new algorithm provides a tune estimation through amplitude-weighted averages, whereas the previous tool identified the highest FFT peak in a user-specified interval. Parallel processing is employed to speed up the heavy HarPy computations without compromising the accuracy of the results. The chromaticity measurement equally benefits from the improvements made to the tune analysis.

Testing the new analysis method at the SPS upon beam commissioning of the North Area fixed-target beams in March 2023 experimentally confirmed the improvement in the measurement accuracy and the ability to consistently identify the tune line along the cycle without the need for manual intervention. This promising outcome motivated the development of a GUI to facilitate the use of the new method during day-to-day operation. A GUI called "SPS Tune" was hence implemented based on PyQt5 and deployed on CERN's Common Consoles Manager (CCM) for internal

use.

The "SPS Tune" application is a comprehensive tool for betatron tune and chromaticity measurements and corrections. It has been designed to require as little manual input as possible from the user side. It offers the possibility to acquire live beam data, displays plots with information about the analysis, and an editable plot to verify and adjust the correction to be sent to the machine. The application also allows saving shots for reanalysis using a decoupling mode which is a very useful new feature. In case of issues in the clustering step, it also provides the option to limit the analysis both in terms of tunes and turns, to aid DBSCAN in identifying the correct tune line. The chromaticity measurement tool provides default settings for every timing user and lets the user observe the changes in momentum deviation and the tune readout progress. It also contains plots with the most important results, a sliding bar updating the Q vs dp/p plot, and the possibility to change the degree of the Q vs dp/p polynomial fit. There is an editable plot in case the user wants to make corrections before sending the calculated function to the accelerator control system.

Both the betatron tune and chromaticity tools were tested extensively on the SPS using machine development beams. All the functionalities of the GUI were validated as well as the ability of the algorithm to correctly identify the tune lines, with and without offsets and modulations. The results were very satisfactory and the tool is ready to be used by SPS operations. The new tune analysis package also found application in the work of other colleagues already as well.

To conclude, using the newly developed tune analysis method, there is a significant improvement in the accuracy of the betatron tune measurements, and a significant reduction of beam setting-up time. This is the result of optimization and automation of the procedure, possible thanks to machine learning techniques.

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