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DESIGN SPECIFICATION FOR SUPPORTING AND ALIGNMENT SYSTEMS OF A LINEAR PARTICLE COLLIDER

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Abstract

This thesis describes a design specification for supporting and alignment systems of a linear particle collider. The Compact linear collider study at the European organization for nuclear research carried out by international collaborations aims at showing the feasibility of a multi TeV electron - positron linear collider with an acceleration gradient of 100 MV/m before year 2010. The accelerator units should be aligned within 14 μm at 1σ Furthermore, accelerator requires stabilization to nanometer level above four Hz for some components.
This work aims at setting the baseline for the mechanical design of the complete supporting and alignment systems of the accelerator. The work consist of the background to the project, definition of the demanded requirements and an overview to theories, methodologies and methods of design. Following the selected method of Pahl & Beitz, a design specification was made including both a requirement list and a schematic layout for the supporting and alignment systems. The preliminary tolerance budgets were calculated for the obtained supporting structures.
The accelerator was divided in modules, which should be assembled on the surface and afterwards transported into tunnel for final installation. The obtained tolerances were challenging, being often micron level requirements. Furthermore, a large number of structures constitute a challenge as well. However, this work can be used as a baseline and a platform for the future research and system design.

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HELSINKI UNIVERSITY OF TECHNOLOGY
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Design Specification for Supporting and Alignment Systems of a Linear Particle Collider

Master's Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

Geneva, February 1, 2008

Supervisor: Prof. Matti Juhala

Instructor: Dr. Germana Riddone (CERN, AB-RF)

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ABSTRACT OF THE MASTER'S THESIS

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Keywords: design specification, product specification, supporting system alignment system, tolerance propagation, requirement

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Tässä työssä kehitetään tuotespesifikaatio lineaarisen hiukkaskiihdyttimen tuenta- ja asemointijärjestelmille. Kansainvälisessä Compact Linear Collider -projektissa CERN:ssä pyritään osoittamaan energialtaan usean teraelektronivoltin hiukkastörmäyttimen soveltuvuus ja toteutettavuus ennen vuotta 2010. Kiihdyttimen tarkimmat komponentit tulisi alustavasti asemoida 14 μm tarkkuudella (1σ). Lisäksi, osalle komponenteista tarvitaan värähtelyjen stabilointi 1 nm tasolle.

Tässä työssä pyritään kehittämään konseptitason linjaukset kiihdyttimen tuennalle ja asemoinnille. Työhön sisältyy aluksi taustojen kartoitus, asemoinnin tavoitteiden asettelu ja yleiskatsaus suunnitteluteorioihin, -metodologioihin ja menetelmiin. Tältä pohjalta kehitettiin tuotespesifikaatio valitun menetelmän (Pahl & Beitz) mukaisesti, mikä sisältää vaatimuslistan ja tuennan layoutin. Kehitetyn tuennan komponenteille laskettiin toleranssit.

Kiihdytin jaettiin moduuleihin, jotka kootaan maan pinnalla tunneliin kuljetusta ja viimeistä kokoonpanoa varten. Saavutetut toleranssit olivat tiukkoja, usein mikrometrien suuruusluokkaa. Lisäksi, komponenttien suuri lukumäärä toi haasteita mukanaan. Tätä työtä voi kuitenkin käyttää jatkossa perustana kiihdyttimen kehitykselle ja yksityiskohtaisemmalle suunnittelulle.

Avainsanat: suunnitteluspesifikaatio, tuotespesifikaatio, tuenta asemointi, toleranssien ketjuttaminen

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Geneva, February 1, 2008

Risto Nousiainen

Contents

Notations

f_{FR}	accelerator frequency	[Hz]
Δx	propagated tolerance	[μm]
Δx_{AS}	propagated tolerance of the AS	[μm]
L	luminosity	[$\frac{1}{cm^2 s}$]
μ	nominal position	
n	number of items	
σ	confidence interval	
x_i	tolerance of i	[μm]

Abbreviations

AD	Axiomatic Design Theory
AHP	Analytic Hierarchy Process
AS	Accelerating Structure
BC	Bunch Compressor
BDS	Beam Delivery System
BPM	Beam position Monitor
CCD	Charge Coupled Device
CERN	European organization for nuclear research
CLIC	Compact LInear Collider
CR	Combiner Ring
DB	Drive Beam
D.O.F	Degree of Freedom
EDMS	Engineering Data Management System
GDT	General Design Theory
GFD	Quality Function Deployment
GPS	Global Positioning System
HDS	Hybrid Damped Structure
HLS	Hydrostatic Leveling System

IP	Interaction Point
LHC	Large Hadron Collider
MB	Main Beam
NA	Not Applicable
OFE	Oxygen Free
PETS	Power Extraction Structure
RF	Radio Frequency
PNR	Propagation Network Reference
TA	Turn Around loop
TMS	Tilt Measurement System
TRIZ	Theory of inventive problem
UHV	Ultra High Vacuum
WFM	Wake Field Monitor
WPS	Wire Positioning System

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Chapter 1

Introduction

1.1 Scope of the Thesis

The specification phase is an important part of a product development process. In the following thesis, the specifications for a supporting system of a linear particle collider are presented. The current project has many challenging aspects concerning both traditional and modern engineering. Furthermore, since the number of systems to be integrated is large, the project has a good potential to be used as a platform for product specification studies. The main questions are: firstly, how to manage and produce specifications for a large project, where current technology perhaps cannot provide solutions. Secondly, what can be achieved by improvements of the technology before the execution phase and therefore considered as feasible. Thirdly, how all that can be changed to specifications that serve the designers instead of binding them into overwhelming sequences of documentation update. Therefore, the main purpose of the thesis is to carry out one of the first phases of the design process by making specifications in a clear and convenient format that can later be used as a platform for system design.

The thesis will first introduce the reader in to the Compact LInear Collider (CLIC) project in terms of background and overall perspective. After providing an overview of the project, the main components of the current system are presented. The last part of the introduction gives the reader insight into the discussed systems, i.e. external supporting and alignment systems. Then the current situation of the development of the external supporting and alignment systems of the accelerator is given and the requirements for the supporting system will be presented (Ch. 2). In chapter 3, the specified and most common applicable methods for the first phases of design in product development are presented. The description covers design theories, methodologies and methods as a review. After the introduction to design from the theoretical point of view, the tools and aids for composing a design specification are collected and evaluated against the current need. After discussing the methods, one is chosen for the current project. Essentially, the formulation of the design specification will be described in detail as well as the process which was used during the composition phase of the design specification. Furthermore, the incorporation and exclusion of the topics included in the document will be defined to obtain a framework for the design specification. Chapter 4 gives the requirements for the particle linear collider external support and alignment systems in terms of the applied method. At the end of the thesis, the used method is analyzed and discussed with respect to the obtained results. Also the feasibility of the requirements is discussed and evaluated against the current available technologies.

1.2 Introduction to CLIC Project

The highest priority at CERN (European organization for nuclear research) in the 21st century will be experiments probing beyond the Standard Model [1]. The first exploration of the TeV energy range will be made with the Large Hadron Collider (LHC) [2], where wealth of the new physics in the TeV range can be expected. The nature of physics including Higgs boson, or something else replacing it, is one of the objectives in the LHC as well as in the other accelerator projects having TeV energy range. However, it is impossible to expect that the experiments at the LHC will answer all the questions concerning new physics explored at TeV range. Many of the open questions can be addressed best by a lepton-antilepton (e.g. electron-positron) collider. Therefore, various laboratories are proposing electron-positron colliders with centre-of-mass energies between 0.5 TeV and 1 TeV. The required technology to collide electrons and positrons at energies ranging from 0.2 TeV up to a maximum of approximately 3 TeV (in stages) has been developed within the CLIC study.

The CLIC study at CERN carried by an international collaboration aims at showing the feasibility of a multi TeV electron - positron linear collider with acceleration gradient of 100 MV/m before year 2010. If successful, the CLIC might become the next significant particle physics facility after the LHC [2, 3]. The study of the technology has been going on for several years; in fact the research has started already in 1980s.

The important milestone at 2010 is approaching, therefore, the development of the collider has become more systematic and intensive. The development of an overall and credible concept for the accelerator has become the first priority. Big efforts have already been employed to find methods to fulfill the requirements (e.g. achieve the accelerating gradient) of key systems, those being the bottlenecks for the concept of

CLIC. However, recently a detailed engineering development of the overall system has started.

Like the name CLIC suggests, the accelerator has linear accelerating units. These two 20.85 km long units called accelerators on both sides of the interaction point require space of an overall length of 47.9 km. The aim is to locate these accelerators in a tunnel underneath the surface to avoid radiation effects and have stable conditions for the components. The CLIC accelerator uses a two beam scheme, where the power is supplied into the main accelerator i.e. into the main beam by decelerating an other beam - called drive beam. Therefore, the CLIC has two parallel beams through the whole length of the accelerators. The phenomenon at the energy supplying beam is actually an inverse phenomenon compared to one in the accelerating structures. In brief, the beam power of an electron beam is converted to RF-power and vice versa in the power supply and in the accelerating structures, respectively. However, the one side of accelerator has a positron beam and the other has an electron beam. The acceleration frequency (f_{FR}) of the beam is 12 GHz.

Both beams are focused with quadrupole magnets that are situated along the length of accelerators. The quadrupoles have a significant effect on the final collision intensity, i.e. on the luminosity. Currently the luminosity (L) is $5.9 \times 10^{34} \frac{1}{cm^2 s}$. The present schematic layout of the CLIC collider is presented in Figure 1.1. [4–6]

1.3 CLIC Structures

The CLIC collider has a variety of different structures within an accelerator, where the external supporting and alignment systems will be implemented. To understand the reasons behind the supporting requirements for the accelerator, an introduction of the subsystems is important. Therefore, the main structures and systems of the CLIC are introduced and described more in detail in the following sections.

Before going into details, the key terms concerning accelerator alignment and support are explained for better understanding:

- Interaction point: the point where the two accelerators intersect and the electron beam collides with the positron beam.
- Longitudinal direction: the direction parallel to the tunnel and beam line.
- Transversal direction: the directions showing on the tunnel cross-section transverse to the beam line.
- Tilt of a structure: the tilt over the transversal axes that are perpendicular against beam axis.

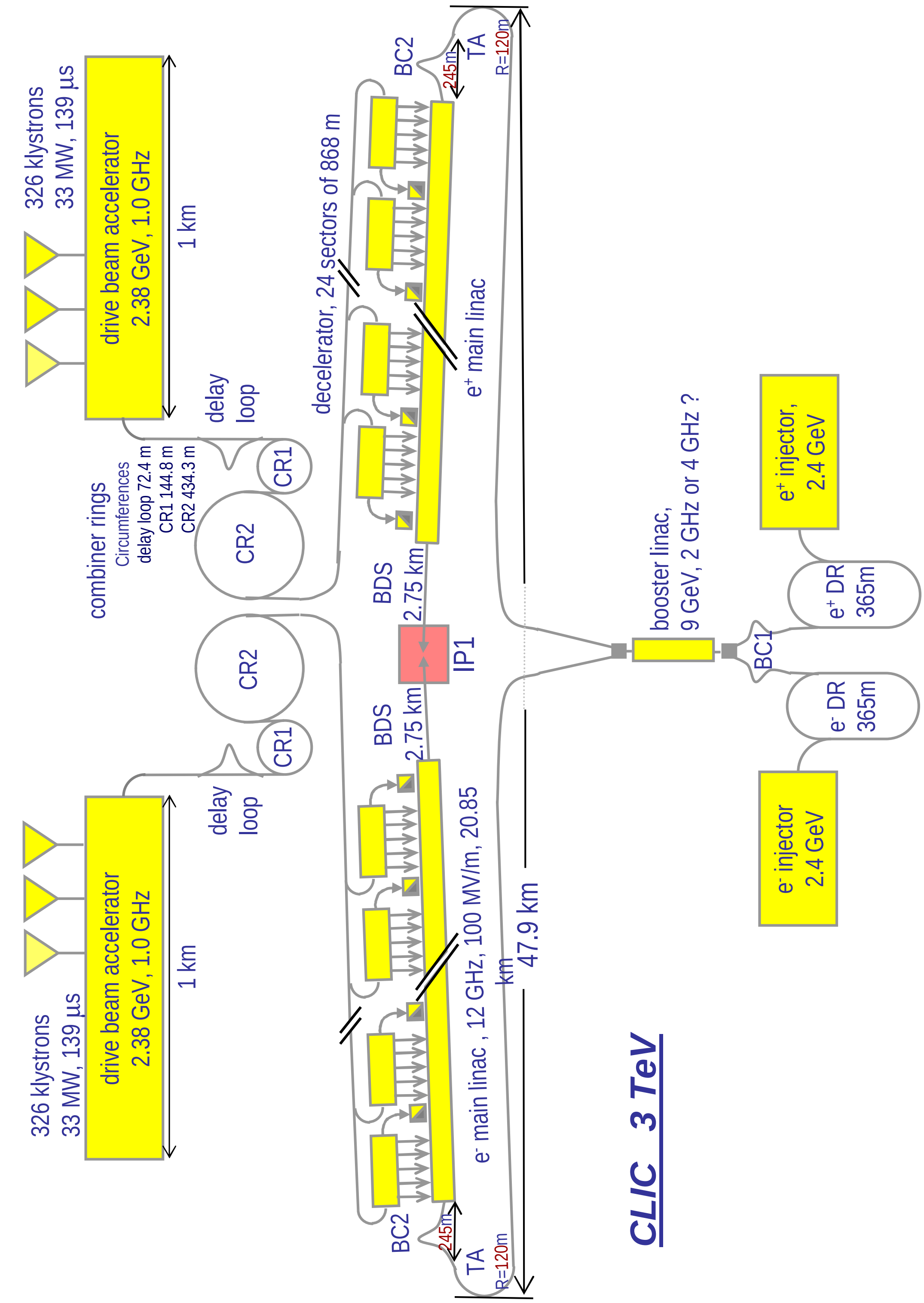

Figure 1.1. CLIC collider layout [3].

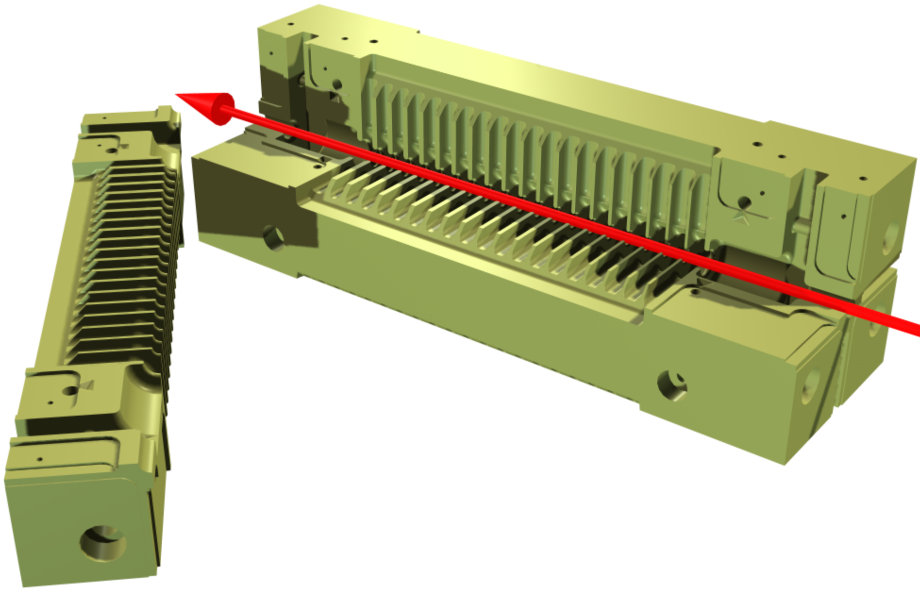

Figure 1.2. Accelerating structure and the path of the beam.

- Particle bunch: the beam consist of bunches of particles traveling in a certain sequence.
- Beam based alignment: alignment system monitors the beam dynamics and the obtained data is used for alignment of the accelerator.

1.3.1 Accelerating Structure

The RF-power is supplied into the accelerating structures, where the actual accelerating cavities are situated. In the present configuration the main accelerator has HDS (hybrid damped structure) accelerating structures (Fig. 1.2) made of oxygen free copper [7]. The HDS structures are built of four quadrants, which form the accelerating cavities for the accelerator. Additionally, there is also development for another type of structure, called as disc structure, which is constructed of discs that are clamped together. Both of these structures are developed in parallel.

With the present parameters and suggested configuration of the CLIC overall layout, one accelerator has an overall accelerating cavity filling factor of 79%, i.e. the accelerating cavities cover 79% [8] of the length of the accelerator. In the thesis the structures are denoted as accelerating structures.

The RF-power is changed in the accelerating structures into an oscillating sinusoidal electric field wave that accelerates the beam bunches. In order to work properly, the sinusoidal wave and the bunches have to be synchronized. Basically, the beam surfs

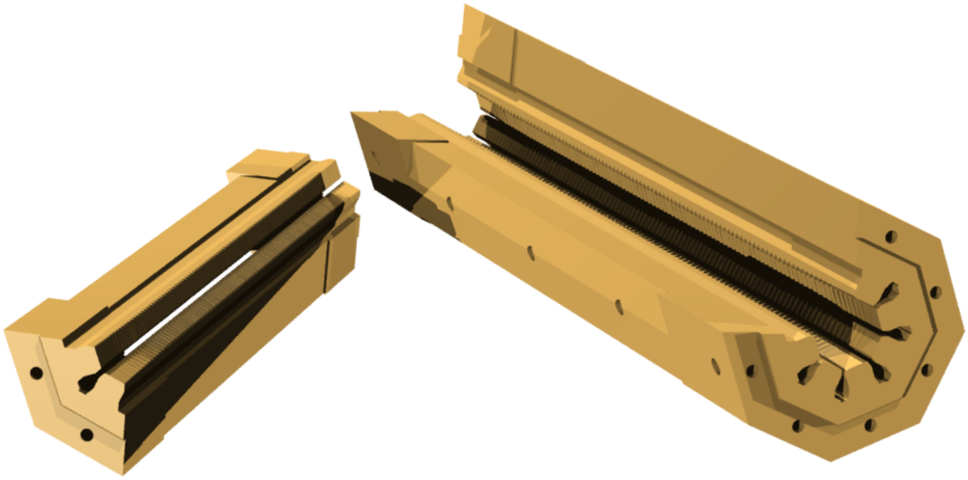

Figure 1.3. Power extraction structure.

on top of the sinusoidal wave, which has the correct electrical charge compared to the bunch charge. For this reason, the accelerating structures have to be aligned within a certain accuracy in the transverse and the longitudinal direction. Furthermore, misalignment causes harmful effects on the beam [9].

1.3.2 Power Extraction Structure

The accelerator has a power supply system parallel to the main accelerator (Fig. 1.1), which has a power supplying beam and decelerators, denoted as drive beam and as the power extraction structure (PETS) (Fig. 1.3). In the present configuration one power extraction structure is assembled of eight octants in copper, where the decelerating cavities are situated on the inner surface of the octagon. To clarify the terms, the parts of power extraction structure are called octants.

The power supply to the structures needs to have a shut down system. The power is shut down in order to avoid damages in the accelerating structures induced by the power effects [9]. At the moment, the power extraction structure includes an on-off mechanism, which cuts down the power chain. From the supporting point of view, the on-off mechanism is included in the power extraction structure.

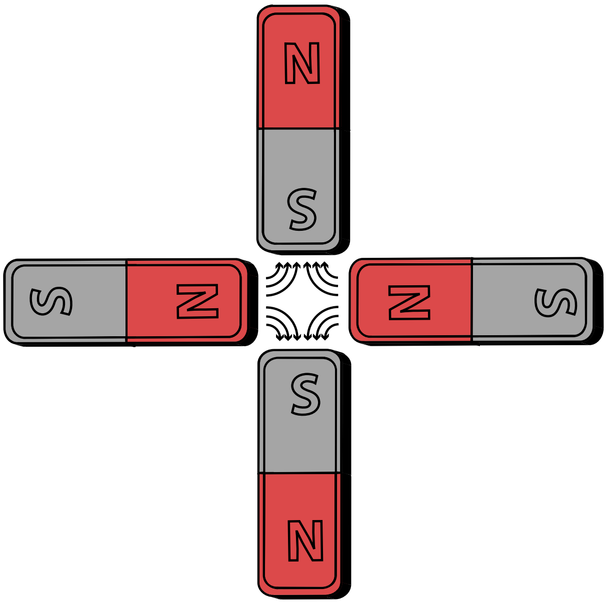

Figure 1.4. Working principle of a quadrupole, where N is a magnetic north pole and S is a magnetic south pole.

1.4 Main Components

1.4.1 Quadrupole

The particle beam consist of compressed bunches of particles that passes through the accelerator. The common charge of the particles in the bunch leads easily up to a growth of the bunch size. Furthermore, the beam has to be focused with a certain precision to the center of the cavities. Quadrupoles are used both for focusing the particle bunches and for keeping the bunches compact. The quadrupole has four pole tips, two opposing magnetic north poles and two opposing magnetic south poles (Fig. 1.4). The electrically charged particles feel a transverse kick if they hit aside from the center of a quadrupole dipoles. The alignment of a particle beam can be controlled with these structures. Due to the present suggestion for the alignment system, the CLIC main and drive beam have quadrupoles in a certain sequence in order to focus the beam. The alignment requirements are based directly on the required beam behavior.

1.4.2 Wake Field Monitor

Wake field monitors (WFM) measure the wake fields induced by the main beam. At the moment WFM is inserted in each accelerating structure. For example, the wake fields are induced if the structure is not at the center with respect to the beam line [9]. The beam travels in trains, i.e. in sequences of bunches, and in case of the previous train has induced wake fields, the next train will be affected by the the wake fields the previous train caused. The phenomenon keeps easily repeating itself and grows stronger. Eventually, the chain of events can harm the efficiency of the accelerator. To avoid the loss in efficiency, the wake fields have to be monitored and by compensating adjustments kept on an acceptable level. This level is measured in terms of the main beam efficiency which should reach the current nominal level of 27.7 % [10]. The present strategy is to adjust the transversal position of structures with respect to the reading of wake field monitors and thus minimize the wake fields. The adjustment strategy is called beam based alignment or feedback loop.

1.4.3 Beam Position Monitor

Beam position monitor (BPM) is used to measure the position of the beam and thereby adjust a quadrupole. The beam position monitor has the same functions as the wake field monitor, but here it has a different name, because of the different design. At the moment, each drive beam and main beam quadrupole has one BPM attached. The main beam and drive beam BPMs are mechanically integrated in the corresponding quadrupoles.

1.5 Main Systems

1.5.1 Vacuum System

The particle beam requires a vacuum for the whole length of the accelerator to avoid fast ion instability [11]. Therefore, vacuum has to be compatible with requirements dictated by fast ion instability. At the moment, the required vacuum is from 10^{-6} Pa to 10^{-8} Pa. The present estimation of the required vacuum is 10^{-6} Pa. In certain structures of the CLIC ultra high vacuum (UHV) can be necessary. The level of UHV begins at 10^{-7} Pa. More detailed definitions of vacuum levels can be found in [12]. In the thesis vacuum system denote components for the vacuum sealing of the accelerating structure and of the power extraction structure. The whole length of the beam pipe should be in vacuum.

1.5.2 Cooling System

The estimated overall input power of the collider is 322 MW [10]. On the other hand the wall plug to main beam efficiency is 8.8 % [10], which shows a significant loss. Most of the lost power is dissipated into heat. For example, in the accelerating structure heat losses are due to the pulsed surface heating introducing a cyclic heat load [13, 14]. At the moment, the nominal dissipated powers to an accelerating structure and to a power extraction structure are $\sim$ 550 W and $\sim$ 110 W [15], respectively. To sustain the heat loading the accelerator requires an efficient cooling system. Currently water cooling is considered for the CLIC accelerator. The cooling has a great effect on the achieved alignment precicion due to the induced thermal dilatations.

1.6 Survey Elements

1.6.1 Geodetic Reference Network

The geodetic reference network is the basis of the alignment system. In the construction phase of the accelerator, the geodetic reference network provides the needed information on opening the tunnel. In fact, there will be two different reference networks, the upper one on the surface and the lower one at the level of the accelerator. The first reference network on the surface can be oriented on the relative accuracy of ± 1 mm with evolved GPS techniques. The lower network - the alignment network - consists of independently aligned platforms located every 50 meters in the tunnel. These platforms, called as metrological plates, will be aligned vertically due to the ground reference at the incoming shafts with specially designed tools. The metrological plates between the shafts will be aligned with respect to the two nearest plates at the shafts. The estimated precision achieved for the lower network is ± 5 mm. Besides the platform alignment the actual accelerator base will be constructed relative to the lower alignment network. The accelerator will have references denoted as standard support references that are aligned with respect to the lower alignment network. The position of a standard support reference can be measured and aligned transversally with respect to the metrological plates. [16]

1.6.2 Propagation Network Reference

At the moment the propagation network reference consist of a Rasnik charge coupled device (CCD) alignment system [16, 17] and of a wire positioning system (WPS). The Rasnik system is used for local alignment of the structures and the wire positioning system is used for the alignment of the local alignment system. The Rasnik system has low cost optical sensors that establish a proximity network for the local alignment [17].

The wire position system utilizes capacitive measurement techniques to measure the position on two transversal perpendicular axes with respect to the beam line. A capacitive sensor measures the position of a stretched wire, which works as a reference. One sensor has an electrode on both sides of the wire along each measured axis. WPS is used to align accelerating structures, main beam quadrupoles, power extraction structures and drive beam quadrupoles. The wire measurement is considered to be done with two parallel wires in 200 meter sections, where the overlap of wires is 100 meter. The wire position system will be installed on the metrological plates. [16, 17]

1.6.3 Hydrostatic Leveling System

The hydrostatic leveling system (HLS) can be used for vertical reference. The system has water vessels which are connected with channels. In order to minimize the interference of the surroundings, the water leveling system is closed from free air except at one point. For the measurement, a capacitive measuring method is used to determine the level of water in each vessel. The vertical reference is obtained from these measurements. Nevertheless, the use of HLS in the CLIC has not been confirmed. [16]

Chapter 2

Alignment Requirements

2.1 Introduction

The CLIC external support includes a supporting system for the accelerators. On the other hand, the alignment system includes the methods and systems which provide the needed accuracy and stabilization for the accelerator. The main components in the accelerator are [16]:

- Accelerating structure and wake field monitor
- Power extraction structure
- Main beam quadrupole and beam position monitor
- Drive beam quadrupole and beam position monitor

In addition, the supporting system has accessories which are necessary for the system and have effects on the external support.

- Vacuum tank for the accelerating structures
- Vacuum tank for the power extraction structures
- Vacuum interconnections
- Active alignment system
- Stabilization system for the main beam quadrupole
- Vacuum pumps
- Cooling system

These structures and accessories should be integrated into the accelerator with a supporting system.

2.2 Description of External Supporting and Alignment Systems

The CLIC structures, the main structures, the main systems and the survey elements are part of the external supporting and alignment systems. External support covers the supporting chain from the tunnel floor up to the active structures in the accelerator. The alignment system is included in the external support, providing the needed installation accuracy, precision and stabilization. The concept external support also includes the assembly, transportation and installation strategies. These become important when considering the limited space in the tunnel (Fig. 2.1). Bad design might lead to an unnecessary large tunnel cross-section and therefore to increasing expenses. Nevertheless, integration of the components into a tunnel having scarce space is costly as well. On the other hand, a proper design in the early phase can save a lot of time and cost.

Installation and transportation of the components from the ground surface into the tunnel has been a time consuming phase in previous collider projects at CERN. During the transportation the surroundings are not clean and due to the fairly long transportation distances, the structures are vulnerable to alignment errors and to contamination. According to the mentioned reasons, the limitations from transportation and surroundings need to be considered in the requirement planning. The estimated cross section (Fig. 2.1) of the CLIC tunnel illustrates the present tunnel model and the surroundings of the accelerator.

The supporting and alignment concept has been under development by the Technical Support department at CERN. The study has been focusing on the alignment system [17]. According to current supporting strategy the accelerator consist of own supporting systems for the accelerating structure, the power extraction structure and the main beam quadrupole. Each subsystem has its own requirements for stability, for tolerances and for maneuvering. Each of the three subsystems requires independent movement with respect to each other. For example, the accelerating structure should be adjustable with respect to the power extraction structure and main beam quadrupole. At the moment, the accelerating structures are the most sensitive from the alignment point of view. The main beam quadrupole is the second most sensitive and then follows the power extraction structure which has the loosest tolerances of the main components. Currently, the accelerating structure and the power extraction structure should be aligned with respect to three degrees of freedom and the main beam quadrupole with respect to five degrees of freedom [16]. As accelerating structures, power extraction structures and main beam quadrupoles are aligned separately, the connections and

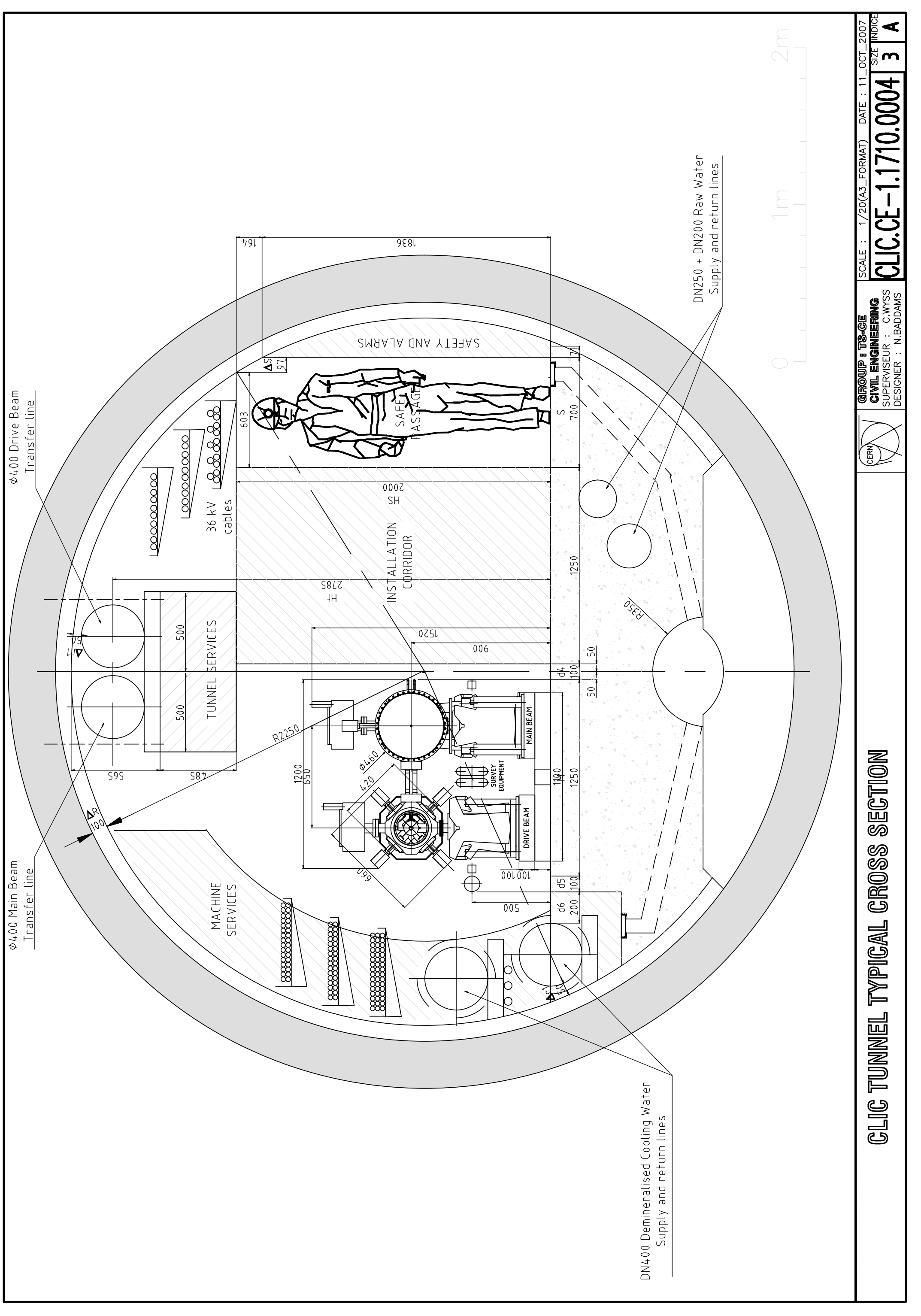

Figure 2.1. CLIC tunnel cross section [18].

linkages between them need to be flexible. However, the vacuum should be uniform over all the structures.

According to the developed supporting scheme [17] a set of accelerating structures is mounted on a girder. The structures are aligned with respect to each other on the girder, which forms a subsystem for the active alignment system. Then these subsystems are mounted in series, where the girders are aligned with respect to the beam. Here the term beam based alignment is also used. Currently the girders are estimated to be aligned with respect to three degrees of freedom [16]. The degrees of freedom are the transversal translations and the tilt over the beam axis. The key issue is that the girders are linked together - therefore forming a continuous system. At the moment the external support for a girder is the following [17]: One end of a girder is attached directly to supporting structure and the second end of the girder is coupled with the adjacent girder. In other words, one supporting structure is coupled with one girder and at that point the girder is coupled with an adjacent girder. In practice, this requires a kinematic linkage between adjacent girders but on the other hand only one support for each girder.

The same supporting scheme is also used for the power extraction structure [16]. The power extraction structures are assembled on the girder which form subsystems for the alignment system. Furthermore, there are two power extraction structures and two drive beam quadrupoles installed on one girder. Consequently, one power extraction structure supplies the power for two accelerating structures.

Currently, the main beam quadrupole has four configurations according to the needed steering energy for the beam. In the beginning of the accelerator the main beam quadrupole is shorter than at the end of accelerator. At the vicinity of the interaction point the needed length for a quadrupole is four times longer. Furthermore, due to the current requirement, the main beam quadrupole should be aligned with respect to five degrees of freedom [16]. The alignment should involve all degrees of freedom except the longitudinal translation. To define the orientation of the component also a tilt measurement system has been introduced [16]. The main beam quadrupoles also require a stabilization system. The requirements for the stabilization are given in the following section.

At the moment, the accelerator consist of structures which form sequences. The consistency is due to the girder strategy which have already been developed [16]. Therefore, the accelerator has been divided into modules. Currently, the length of a module is roughly two meters. Essentially, the module will be a supporting and alignment platform for the accelerating structures, the main beam quadrupoles, the power extraction structures and the needed components as well as for the needed survey equipment.

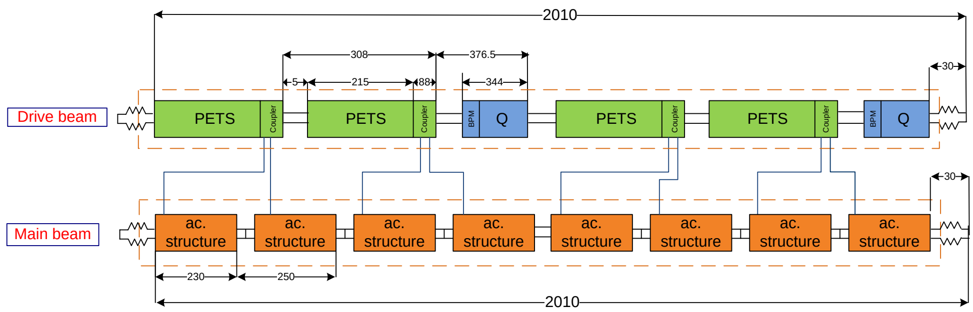

Figure 2.2. CLIC standard module [20].

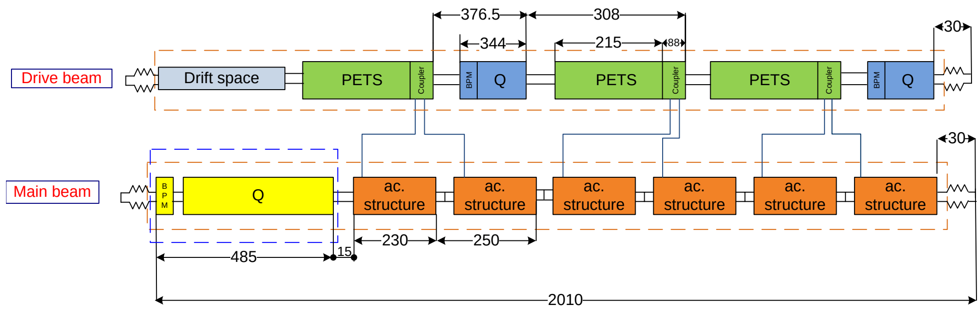

Figure 2.3. CLIC module, type 1 [20].

The accelerator will have main beam quadrupoles installed in a certain sequence along the accelerator. The main beam quadrupoles will replace accelerating structures at the point where the quadrupole is installed. Currently there is no exact information on where the quadrupoles need to be installed. Moreover, there will be a need for installation of four different types of quadrupoles. Despite the lack of information for installation and the four of types of quadrupoles, the module should fulfill the demand on working as a common platform for the quadrupoles. Consequently, the base line has been developed, which involves five different type of modules (Fig. 2.2, 2.3, 2.4, 2.5, 2.6) in the accelerator. These five modules should fulfill the installation requirements of the accelerator. The standard module (Fig. 2.7) has only accelerating structures. In the special modules pairs of accelerating structures are removed and replaced with a main beam quadrupole. The modular approach brings flexibility to the design [19].

2.3 Alignment Requirements for the Accelerator

The alignment of the accelerator has been divided in two stages. The first phase is pre-alignment, which consist of mechanical alignment of the components with respect

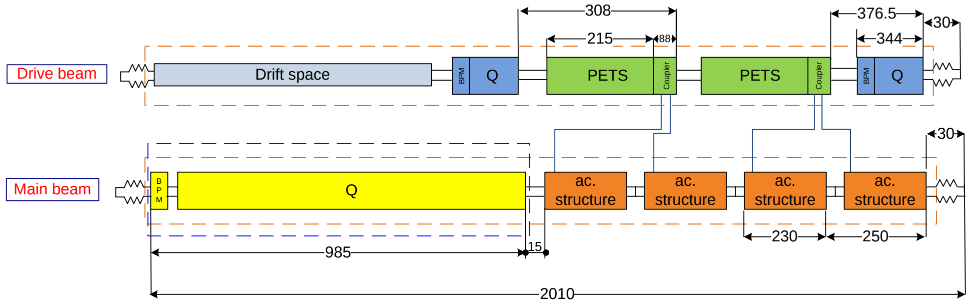

Figure 2.4. CLIC module, type 2 [20].

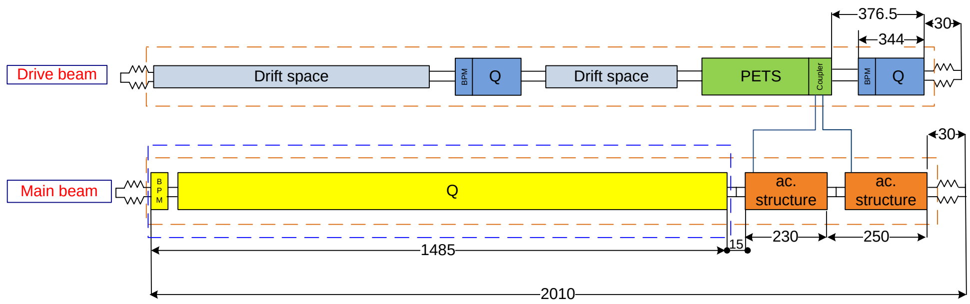

Figure 2.5. CLIC module, type 3 [20].

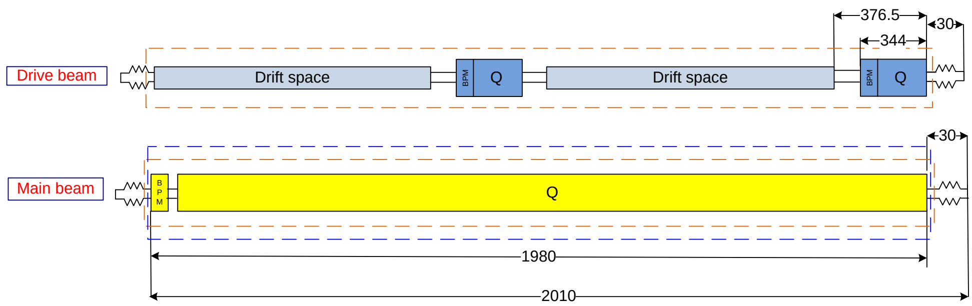

Figure 2.6. CLIC module, type 4 [20].

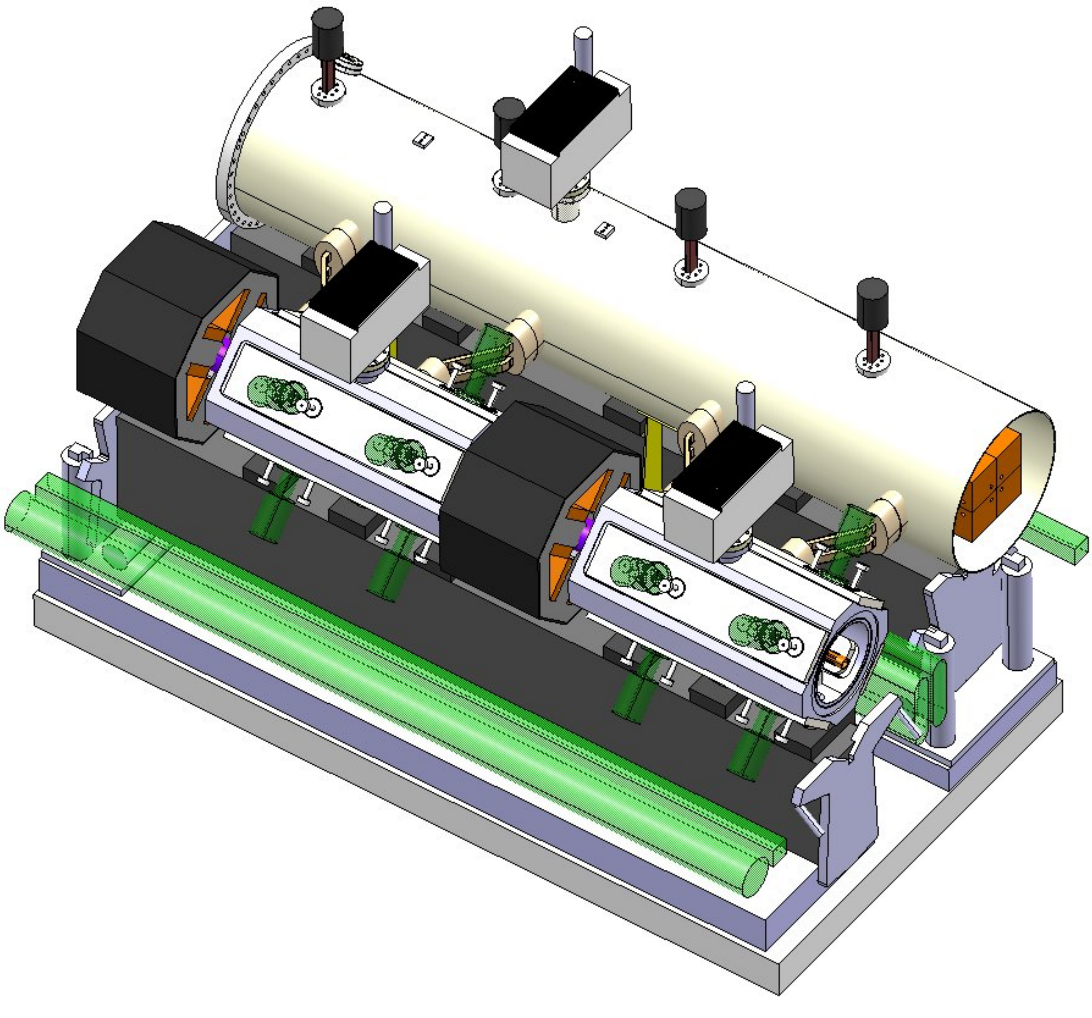

Figure 2.7. Layout of a standard module [20].

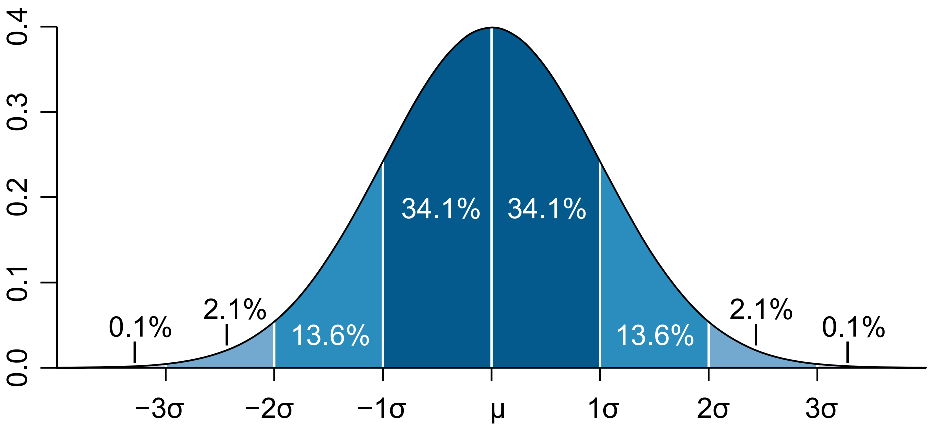

Figure 2.8. Illustration of six sigma tolerances for a normal distribution.

to mechanical references. Pre-alignment takes place before an actual pilot beam. The pilot beam is a low energy beam which is used for the second phase of alignment, the beam based alignment [21]. During operation, beam based alignment is used with the high energy beam. Even if the accelerator is called linear, from the beam dynamics point of view the accelerator is not linear. For example, in the main beam quadrupole, the beam is sensitive to adjustments of $\sim$ 10 nm [21]. Therefore, the aim is not at reaching the optimum linearity (straightness of the accelerator), because the beam can be destroyed anyway due to the harmful effects induced by the beam itself [22]. Instead, the aim is at finding acceptable trajectory for the beam through the accelerator, where the harmful effects are minimized [21]. As a result, the alignment requirements have two types of requirements: first, the pre-alignment requirements and second, the beam based alignment requirements.

The required alignment tolerances for the CLIC structures are presented by means of the statistical tolerances [23]. The method is based on standard deviation and on confidence intervals 1σ and 3σ (Fig. 2.8). The achieved tolerances for a set of structures is assumed to follow normal distribution (Fig. 2.8). Thus, when considering structures with tolerances at 1σ, roughly 68 % of the produced stuctures are within the one standard deviation, i.e. withing 1σ. For tolerances at 3σ the corresponding value is 99.7 %.

The pre-alignment requirements for the accelerator are defined statistically at 1σ (Table 2.1) [10, 20]. The tolerances are position tolerances in three degrees of freedom. The errors in alignment have a severe effect on the efficiency of the accelerator. The misalignment of the components also cause harmful dynamic effects to the beam [9, 22].

Table 2.1. Alignment requirements for the linear accelerator.

Structure	Tolerance (1σ)	Unit
AS	14	[μm]
PETS	31	[μm]
MB Quadrupole	17	[μm]
MB Quadrupole BPM	14	[μm]
AS - WFM	5	[μm]
Structure - BPM	10	[μm]

The, tolerances denoted as "AS - WFM" and "MB quadrupole - BPM" (Table 2.1) are relative tolerances for the beam based alignment. The reason why the relative tolerances have been introduced is that the relative position of the structures is the foundation of the beam based alignment strategy. The harmful effects induced in the beam can be minimized with respect to the reading of the wake field monitors and beam position monitors if they are positioned accurately enough according to the corresponding accelerating structures and the quadrupoles, respectively. At the moment, these are the tolerances of the CLIC structures and components, which the supporting and alignment systems has to achieve.

Furthermore, the stabilization of the main beam quadrupole is important for the performance of the accelerator. At the moment, the main beam quadrupole needs to be stabilized to 1 nm level above 1 Hz in vertical and to 5 nm level above 1 Hz in horizontal direction [21, 24].

According to these alignment and stabilization requirements, a design specification and a detailed supporting concept as well as a supporting strategy should be defined. An elaborate document should be composed, which can be then used as a basic reference for the future design. Therefore, we need to take a look at the methods that could be used for definition and evaluation of requirements.

Chapter 3

Methods and Design Specification Development

3.1 Related Work

3.1.1 Product Specification and Product Concept

The terms product specification and product concept are widely known. However, it is useful to clarify their given definitions. In fact, the definitions are fairly complex in their genuine forms. One specification includes a metric and a value [25]. The metric points out the holder of the value whereas the value gives the labeled information with the appropriate unit [25]. Furthermore, (by mistake) the terms requirement and specification have often the same meaning in literature. Compared to a specification, a requirement can appear in a different format. A requirement can have a descriptive nature, describing a demand with a free format, instead of having only the metric and value like a specification. Therefore, they are not the same. According to literature, a product specification can be defined as:

- *Collection of requirements that drive a design process and against which resulting designs are evaluated* [26].
- *Accurate specification of the performance required of a design solution* [27].
- *Precise description of what the product has to do* [25].

According to the given definitions a product specification sets the boundaries for the product in terms of requirements and specifications as well as the aim for required performance of the final product. To clarify the issue with the definitions, in this thesis requirements and specifications will be called requirements.

On the other hand, a design specification is the document including the specifications and requirements. The design specification is defined in a following way by Yoshikawa [28]:

- *Designates the functions of the required entity by using abstract concepts.* [29]

Over the whole design process at any stage, the design specification is the basic reference [30]. Further, the nature of design specification is not static but dynamic, which means that the individual requirements evolve during the development [31]. According to that, the clarity of the design specification is essential for the project. The requirements for each detail should be clearly and easily available for the designers, which requires a good structure of the design specification. Furthermore, putting the design specification into a clear format, the needed changes for the requirements can be applied quickly. Therefore, a design specification should consist of definite statements and the structure should be clear. There is also an other aspect to be considered: the clarity of the document both reduces the number of misinterpretations and mistakes during the project and decreases the tendency of the designer to neglect some requirements [32].

In addition, the level of details in the design specification should be considered. Having a design specification at too high level of generality makes unacceptable results possible, whereas a too specific design specification reduce the solution alternatives [25]. In the extreme case some acceptable solutions will not meet the specifications and are dropped out from the solution alternatives.

Product concept describes how the product fulfills the designed operations. In literature, the following definitions are given for a product concept [33]:

- *Product concept is an approximate description of the technology, working principles, and form of the product. It is a concise description of how the product will satisfy customer needs* [25].
- *Product concept is a brief statement that explains the product a manufacturer intends to make and describes the product attribute, benefit and value to customer. It takes a free format* [34].
- *Product concept has a well-defined form, including both a written and visual description that includes its primary features and customer benefits combined with a broad understanding of the technology needed* [35].

Conceptual design is defined as follows:

- *Early phase of the design process, where suitable solution principles for the task are searched, concepts generated and further evaluated* [36].

Following the given definitions, a deeper and more rigorous nature of the product concept aims at showing how the requirements in the design specification can be met.

Furthermore, a suggestion is that the product concept pursues the technologies and aids which will define the product functionality and layout in terms of overview. Having no detailed design at the conceptual design phase restricts the product concept but an inevitable requirement is that a product concept has to appear credible enough to show the feasibility of a solution alternative.

3.1.2 Background to Design Theory, Design Methodology and Design Method

Design theory is the foundation of design methodologies. From the basis of design theory the questions concerning the theoretical definition of design can be enlightened and answered. Each design theory has its own way to describe how and what do change given inputs to desired results. This descriptive level of theory often focuses on the overall functions instead of a specific operation [28].

Design methodology follows the guidelines set by a design theory. The methodology itself is a collection of procedures, tools and methods for designing [28]. The nature of methodology is prescriptive. Therefore, it should be widely applicable, independent of discipline and not require wide technical knowledge from the user [37].

Design methods can be described as a set of specific tools and procedures that form a way of designing. Consequently, the performed design activities, techniques, aids or tools can be defined to be a design method [27]. From the design process point of view the utilized methods shape the framework for design [36]. The anticipated outcome from the utilization of methods is to ensure the quality of a product and the overall success of the process.

The given descriptions of design theory, methodology and method are supplemented with the following more detailed definitions, which aim at showing the nature of each entity.

> **Design theory**: *Collection of principles that are useful for explaining the design process and providing a foundation for the basic understanding required to propose useful methodologies. Design theory is descriptive as it indicates what design is or what is being done when designing* [28].
>
> **Design methodology**: *Collection of procedures, tools and techniques for designers to use when designing. Design methodology is prescriptive as it indicates how to design* [28].
>
> **Design method**: *Way of working, within the context of designing, can be considered to be a design method* [27].

In order to understand design theories better, it is important to perceive the overlapping of single theories. One design theory is not an empiric entity but instead a qualitative and descriptive. Therefore, an existing design theory contributes to a specific entity that may incorporate both certain methodologies and methods. Similarly the specific entity can share the same methods with another theory or methodology. The entities that can be considered to be design theories [28] are the general design theory (GDT) by Yoshikawa [28, 38], axiomatic design theory (AD) by Suh [28, 38, 39], the abstract design theory (ADT) [28], the theory of Hubka [28, 37], the theory of Bahl & Beitz [37] and the theory of inventive problem (TRIZ) [28, 39]. These design theories are partly contributing to the framework of design at its theoretical level.

3.1.3 Methods for the Early Phases of Design

The term "early phases of design" can be characterized with respect to the stage of design process and the nature of design work [36]. In literature, different authors have their own interpretations on the stages of design process, that are included in the "early phases of design" [36]. Furthermore, the naming of the phases of design at the "early phases of design" is by no means coherent between authors [36]. As a consequence, the obscurity of the definition is due to the unclear framing of the "early phases of design". Here the phases of a design process are being defined following the approach by Pahl & Beitz [37], where design process is being divided into four stages: 1. Planning and clarification, 2. conceptual design, 3. embodiment design and 4. detail design. The two first stages can be considered to be included in early phases of design [36]. The two latter phases of design are not included into the early phases of design. Therefore, those phases of design are not discussed in the thesis.

For planning and clarification of the task the following methods can be utilized: Objective tree [37], paired comparisons [37] and quality function deployment (GFD) [27]. However, these are only methods for certain phases of planning and clarification of the task. In addition, the distinction between the phases "planning and clarifying the task" and "conceptual design" is not clear. The phase "planning and clarifying" tends to involve assumptions about the concept, hence accompanying a dependency between the two stages.

For supporting conceptual design the following methods have been presented [40]: Pugh's evaluation method [30], Concept rating methods by Pahl & Beitz and analytic hierarchy process (AHP) by Thomas L. Saaty [41]. Pugh's evaluation method is also described by Ulrich and Eppinger. [25]. However, often the methods focus on comparing the solution alternatives, instead of the actual concept creation.

3.2 Specification Methods - Review and Selection

In order to produce an elaborate design specification for the current project, specification methods were studied and reviewed. Specification methods were collected from literature concerning product design. The books concerning product design were the only acceptable sources for the methods. Main reason for this decision was to ensure that the chosen method would be universally accepted among the field of engineering design. The main methods discussed in literature were evaluated against the current need and one method was chosen for the project.

The considered product specification procedures are illustrated by Pahl & Beitz [37], by Cross [27], by Ulrich and Eppinger [25] and by Pugh [30]. The procedures have similarities and the pursued outcomes are almost the same. However, each of them has some own specific approaches concerning definitions, structuring and documentation.

In the current project the amount of requirements is substantially high. Furthermore, the competition between products can be neglected, since the pursue is to develop something that does not yet exist and the development is for scientific purposes.

According to section 3.1.1, a design specification should define the product in terms of requirements. However, from the nature of requirements follows that the individual requirements are not necessarily equally important. Therefore, there should be a way to distinguish more and less important requirements. One way to categorize the requirements is to divide them into demands and wishes, where demands should be met under any condition and wishes should be considered whenever possible [37]. The categorization of requirements to demands and wishes was considered effective and clear. Hence, the approach was adapted to the current project.

The method by Eppinger and Ulrich [25] having a target specification introduces a numbered importance from one to ten for each requirement. According to the earlier decision to divide the requirements in demands and wishes, the method by Eppinger and Ulrich was omitted. On the other hand the method by Pugh [30] focuses more on the rivalry aspects where the product is compared against other products. However, the current project has a scientific nature where the rivalry aspects are not the highest of importance, because the rivalry products do not exist. Therefore, method by Pugh was excluded as well. Dropping the two methods out leaves only the Pahl & Beitz and the Cross approaches available. Both methods include the characterization of the requirements to demands and wishes. On one hand, the method of Pahl & Beitz has been generally considered as a standard guideline for developing specifications, providing well described tools to produce design specification in a clear format. On the other hand, the method by Cross has an extremely similar approach compared to

Pahl & Beitz. However, the method of Pahl & Beitz was more appropriate, because the description of the method was found more complete. Therefore, the method by Cross was dropped out and the method by Pahl & Beitz was chosen for establishing a product specification for the project.

The phase for design specification is incorporated into *product planning and clarifying the task* [37], which comprises product planning by collecting information about requirements and by developing initial product ideas. The outcome of this phase is to draw up an elaborate requirement list, i.e. a design specification. The methods and tools for requirement definition in the current project are illustrated later after the detailed description of the used specification method.

3.3 Design Specification for CLIC

The categorization of the requirements into demands and wishes is essential for the design specification [37]. On the other hand, the final requirements concerning the external supporting and alignment systems in the current project had to be regularly updated due to developing accelerator parameters. Therefore, the nature of requirements was dynamic. In order to keep the developing requirements up to date the emphasis concerning the design specification was on having a well formed structure being able to adapt to emerging changes instead of determining the final value for each requirement.

The alignment system has been already studied and developed. The earlier work [16] has focused on the main challenges concerning the alignment system (Ch. 2) in terms of the alignment concept and its feasibility for the accelerator. In fact, a solution principle already exist for the alignment system [16, 17]. The existing partial concept has been accepted for the project [18]. Therefore, the currently available solutions for the alignment system were included in to the design specification. The concept of the existing solution principle was further developed to cover the whole supporting system. As a consequence, the conceptual design of the supporting and alignment system was developed in parallel to the design specification. Furthermore, the modular architecture of the accelerator was included to the design specification by setting the requirements for one module. Hence, the requirements are valid for each module type with one remark: the requirements for the main beam quadrupole are valid only for the special modules (Fig. 2.3, 2.4, 2.5, 2.6).

To define alignment requirements for the whole alignment and supporting system, the supporting chain had to be defined in terms of supporting structures for the whole system. Furthermore, to determine the conceptual design for the supporting and the alignment system the installation strategy and the rough transportation strategy of the accelerator had to be specified. These initial decisions made the definition of the the alignment requirements and the tolerances possible for each structure. The first objective was to specify tolerances in such a manner that the alignment requirements (ch. 2) were met for the CLIC structures. The elaborate budgets for the tolerances were established, evaluated and included in the design specification. The second objective was to make the integration of components and systems possible. At that stage only the support integration was taken into account. The system integration had a lower priority. These objectives were pursued by paying attention to the design of the supporting chain in terms of modularity, alignment references and adjustments. Here the term alignment reference is used for the definition of a supporting reference and of an outer reference, such as propagation network reference. Other main design objectives were to enhance compatibility for transportation and facilitate the installation in the tunnel. In short, the main design attributes for the design specification were assembly, alignment, integration, transportation and installation.

The arrangement of the requirements includes two main tasks [37]. First, *define the objectives and the main characteristics*. Second, *split into identifiable sub-systems, functions, assemblies etc.* Therefore, a following structure was established for the design specification: The design specification includes a requirement list (fig. 3.1) and a schematic lay out (fig. 3.2).

In order to enhance clarity, the design specification follows a certain structure. Each item in the design specification was defined with a name and an index. Further, each item was described according to a check list. Corresponding items are illustrated in the schematic lay out (fig. 3.2). Moreover, each item in the requirement list and in the schematic layout has an index, which is coherent with respect to each other. Thus, the reader can look at the elements in the schematic layout and find the detailed specifications for the element from the requirement list according to the indexation. Each item has its own page in the requirement list. Similarly, a new item begins at the top of a clear page, if the previous item requires more than one page of space.

However, few functional items were added to the schematic layout without numbering to improve the clarity of the conceptual design. Moreover, the requirements for the vacuum systems were added to the requirement list but the corresponding items were omitted from the schematic layout. The items were dropped, because the schematics of the vacuum systems do not give much extra value for the layout of the supporting and alignment system.

The sequence of headings in the requirement list was used to define the main aspects of the supporting and alignment system. Six headings were defined for each

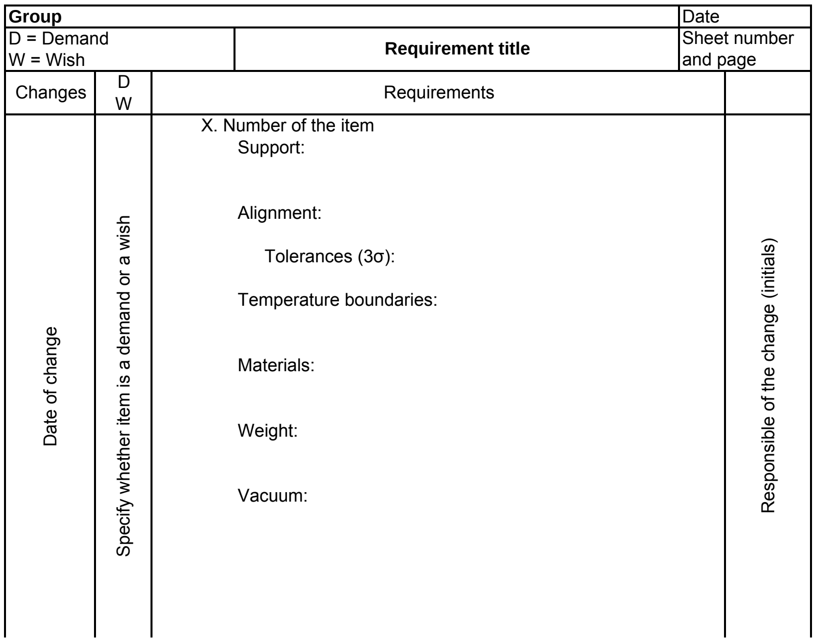

Figure 3.1. Layout of the requirement list of the design specification.

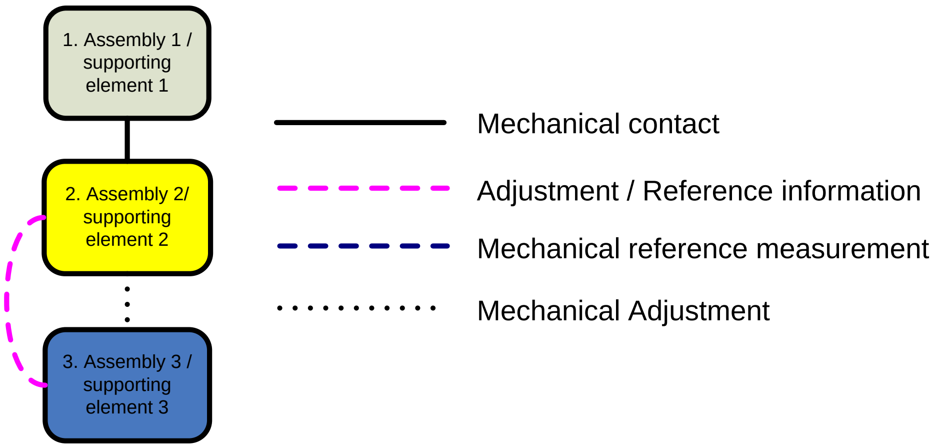

Figure 3.2. Illustration of the structure of the schematic lay out.

item: “support”, “alignment”, “temperature boundaries”, “materials”, “weight” and “vacuum”.

3.4 Description of the Structure of the Requirement List

Under the first heading “support” the supporting structure for an item was defined. Similarly, detailed requirements concerning element support were stated under ”support”. The second heading “alignment” incorporates the concrete alignment reference and the tolerances with respect to the reference. The heading “alignment” has a subheading “tolerances”, where transversal and longitudinal tolerances were specified. The tolerances for the items were given at 3σ (Ch. 2). If the element had a passive or an active alignment system, the range of adjustment with the denoted direction was defined as well. The third heading is “temperature boundaries” which includes the possible requirements for the temperature. The fourth heading “materials” comprises the boundaries for the material selection. Under the fifth heading “weight” the requirements concerning weight were defined. The last heading of the sequence is “vacuum”, where the vacuum requirements were defined.

The described features were considered in the design specification. When needed, additional requirements were added under the main sequence. Furthermore, if the additional requirements formed an entity, an extra heading was added for providing clarity. To have a framework for this work, some limitations were defined and topics were eliminated from the design specification. The design specification did not consider directly geometry, energy, signals, safety, ergonomics, recycling, costs or schedules. Nevertheless, some of the topics were partly incorporated into the conceptual design. The detailed requirements for the control electronics were also excluded from the design specification. At this early phase of design, the level of detail was reduced to minimum. However, these excluded issues are important and should be addressed later on during the design.

3.5 Tolerance Budgets

To ensure, that the required tolerances (Table 2.1) for the structure are met, the elaborate tolerance budgets should be defined for each component in the supporting and alignment chain. However, defining tolerances in conservative manner, regarding the worst case for each tolerance in a large stack of components easily leads to overly pessimistic tolerances. For a linear accelerator, where the number of components is extremely large, statistical phenomena can be considered valid [20]. Therefore, a tolerance stacking method was used [42] for obtaining the tolerances for each item in the supporting chain. The key idea was to consider the corresponding alignment requirement (Table 2.1) of the structure as the propagation (Eq. 3.1) of the uncertainties, i.e. the tolerances, of the individual supporting structures.

$$\Delta x = \sqrt{\Sigma_{i=1}^{n}(x_i)^2} \tag{3.1}$$

The n is the number of items in the supporting chain and the x_i is the tolerance of the item i (Eq. 3.1). Δx is the propagated uncertainty (i.e. the tolerance) corresponding the alignment requirement (Table 2.1).

The tolerance budgets were calculated for the structures (Table 2.1) that have definitions for the alignment requirements. The tolerances for the items in the supporting chain were incorporated from the earlier studies and development [20] and developed further to meet the current conceptual design. The tolerances definitions were composed not only to the requirement list of the design specification but also to tables which define the supporting system from the corresponding alignment reference to the structure, including the inherent accuracies of the alignment references and the structures. The inherent accuracy of the active structures (i.e. accelerating structure and power extraction structure) include the fabrication and assembly tolerances which are not discussed in this thesis, because these challenges will be addressed during detailed design.

Furthermore, the kinematic linkage between adjacent girders were considered for main beam and drive beam supports. Namely, due to the current kinematic linkage, the precision at the other end of the girder is reduced by the uncertainty of the coupling. The supporting reference was defined according to the schematic layout and the alignment strategy.

The composed budget tables consist of four columns: legend (1), items (2) and tolerances at 1σ (3) as well as 3σ (4). The overall uncertainty, i.e the tolerance for the structure was also included in the tolerance budgets. In the first column legend the interface between components was defined. To enhance clarity, the second column items includes the corresponding indexes in the design specification.

3.6 The Definition Process of the Requirements in CLIC

The definition of the requirements for the CLIC was divided into three phases. First phase was the “establishment phase” where the requirements were composed in written form in the design specification. The second phase was the “preliminary publication”, where the design specification was spread to the group of specialists for attaining updates on the specific requirements as well on the structure of the design specification. The third phase was the "continuous improving" which was done by the collaboration in parallel during the project after the first two phases.

During the first phase the published papers were the basis for requirements. In the CLIC study a number of publications have been published [43] concerning the components. Therefore, dozens of documents were available for this study. The main sources of information were the CLIC technical notes [43] and the CERN Engineering Data Management Service (EDMS) documents. However, the EDMS is partly restricted from public. Other sources of written information were the workshop presentations, weekly meeting presentations and meeting minutes.

The second source was the private communication. Discussions with the individual group members contributed greatly to the requirement definition. The experts in the corresponding topics could give extremely valuable insight for better understanding and also set concrete requirements concerning the systems they were involved. Furthermore, collaborative meetings between study groups, where the main challenges were discussed gave good insight into overall understanding of the supporting requirements. Therefore, part of the requirements were obtained by private discussions.

The first step to establish a design specification was to build a structure for a preliminary requirement list and a schematic layout for the supporting and alignment system. The requirement list and the schematic layout were developed according to the described requirements, objectives and aims (Ch. 1, 2). The documents were developed in collaboration with the local supervisor who gave guidelines for the development. The work also consisted of iterations to incorporate the previous work into the documents. For example, the representatives from the department, being responsible of the alignment system were working collaboratively to establish a common baseline for the supporting and alignment system. When the drafts of the two documents were established, the structure of the design specification was checked by the supervisor. After obtaining the first finalized version of the design specification, the results were viewed at a collaborative meeting [18] and the design specification was published for a team of specialists through the EDMS application. The specialists to whom the design specification was sent are the developers of the CLIC structures, components and survey elements. Enclosed with the design specification there was a notification for each member to give comments before a set deadline on the requirements concerning their own field of expertise. The time for giving feedback was three weeks. Eventually, according to obtained feedback the design specification was updated and published again for the team.

During the third phase of definition the emerging improvements were adapted to the design specification. This part of the definition process is still going on until the possible construction of the collider.

Chapter 4

Results - Design Specification

4.1 General Layout for the Supporting Systems

To accomplish with the assembly, integration, transportation and installation of the components, different options for the construction were defined. Three options were considered for this project (Table 4.1). The option three was chosen for this project, where the operations are done at the surface as much as possible.

The first decision having influence on the conceptual design was the decision to assemble modules at the surface and transport them to the tunnel for final installation. At the moment, the strategy was to transport one module at a time. Therefore, the layout was divided into three entities: 1. tunnel support, 2. accelerator module and 3. main beam quadrupole module. The two latter entities were decided to be assembled at the surface level and delivered to the tunnel for the final installation. The distinction of the entities follow an other rule as well. The high precision components were separated from each other and also from the low precision components. This gave the possibility to align main beam (accelerating structures) and drive beam (power extraction structures) separately. These structures require connection for the wave guides, which supply the RF power from the main beam to drive beam. Choke mode flanges were used for the connection that provide a small movement in three degrees of freedom, allowing maximum misalignment of 0.5 mm for the structures [44]. The main beam support, the drive beam support (accelerator module) and the quadrupole module form each an own supporting and alignment system. The vacuum systems were kinematically decoupled from the structures they seal. Overall, the layout for supporting and alignment systems has 20 indexed items, that are specified according to the check list (S. 3.3, Fig. 3.1) in the requirement list (App. A). Furthermore, the layout has 11 additional items without indexation. These items were added either to improve clarity or to define conceptual

Table 4.1. The considered construction options of the accelerator. Surface = action done on the ground level; tunnel = action done in the tunnel; assembly = assembly of components; integration = assembly and pre-alignment of module; installation = interconnection of modules.

Option 1		Option 2		Option 3	
Surface	Tunnel	Surface	Tunnel	Surface	Tunnel
	Assembly	Assembly	Integration	Assembly	Installation
	Integration		Installation	Integration	
	Installation				

alignment layout (Fig. 4.1).

The first entity tunnel support constructs of the supports built in the tunnel before the accelerator modules (2) and the quadrupole modules (3) are brought for the final installation. The main components are the survey elements (S. 1.6) and the foundation of the supporting structures. The modular interface for the tunnel support (1) was defined at the item 5, called cradle, for the accelerating structure and at the item 9 quadrupole support (Fig. 4.1) for main beam quadrupole. The base (Fig. 4.1) is basically the tunnel floor under the accelerator. The common adjustable base is aligned by measuring the position of the standard support reference with respect to the two adjacent metrological plates (Fig. 4.1, S. 1.6). The designed layout makes possible the installation of survey elements into the tunnel before the final accelerator module (2) -installation.

The accelerator module (2) consist of the main beam girder assembly (Fig. 4.1), of the drive beam girder assembly (Fig. 4.1) and of the main beam as well as of the drive beam vacuum systems (S. 1.5). The support for vacuum systems will be decoupled from the supports for girder assemblies. At the moment the structures above girder will be aligned trusting on the fabrication tolerances, which means that there will be no mechanical adjustments. Instead, the whole girders will be adjusted with the active alignment system (Fig. 4.1). To make the supporting system continuous, the adjacent girders will be coupled with a kinematic joint together. The accelerator module (2) was designed to be assembled and its structures aligned at the surface level with respect to a external reference. Consequently, when the assembly and alignment of the structures of the accelerator module (2) is done, the positions of the structures are know with respect to the external references (S. 1.6). Moreover, the sensors (S. 1.6) denoted as "S" (Fig. 4.1) are attached to the main beam cradle and their position is measured

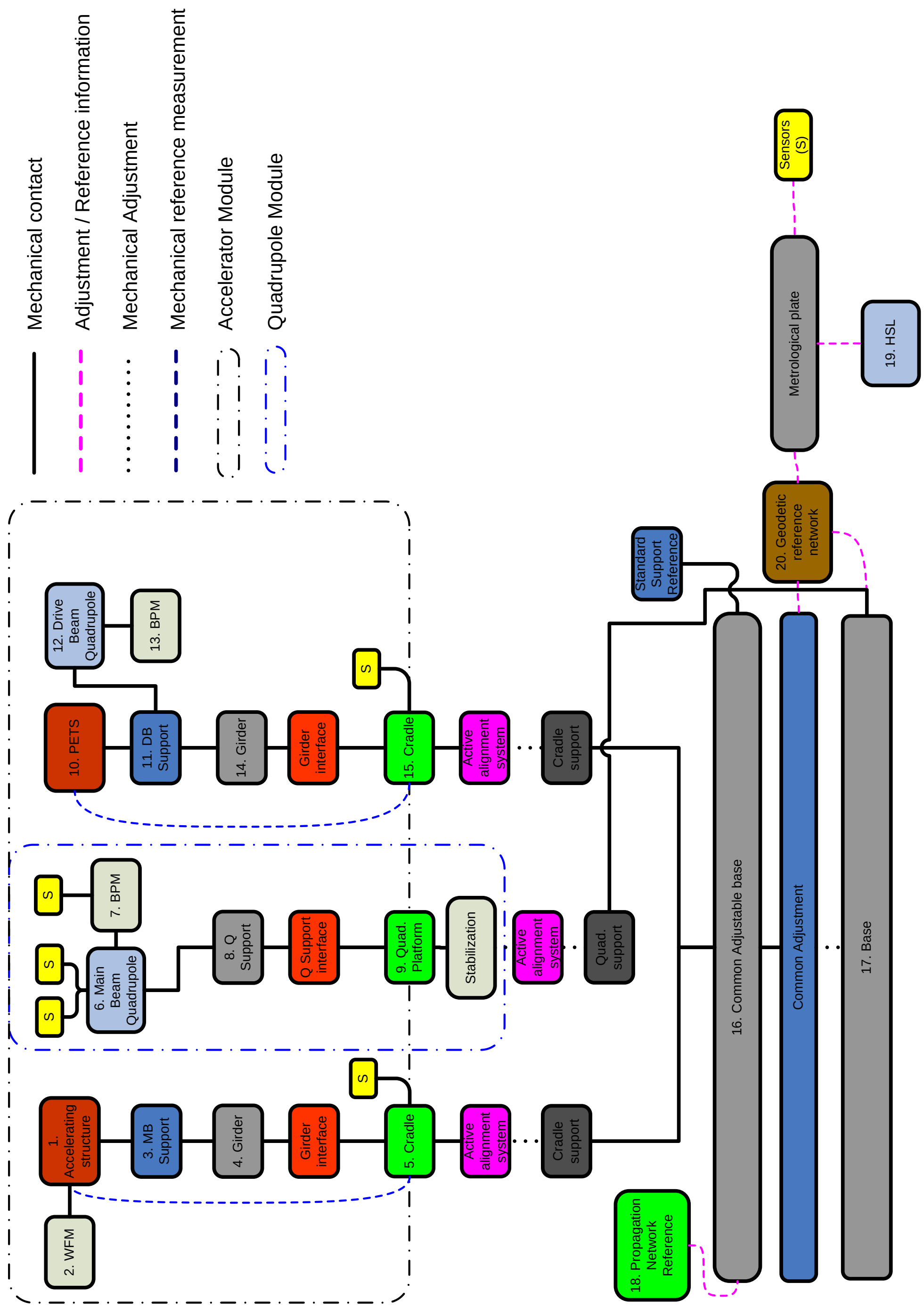

Figure 4.1. Schematic layout of the supporting system, where S = sensor and Q = quadrupole.

with respect to the external reference. As a result the positions of the structures are know with respect to the position of the sensor.

The main beam quadrupole module (3) has a quadrupole for focusing the beam and a beam position monitor for the alignment of the corresponding quadrupole. The quadrupole module (3) will have four configurations depending on the module type (S. 2.2). The layout consist of the active alignment in five degrees of freedom and of the stabilization for the structures with required interconnections (Fig. 4.1) for the support. The sensors (S. 1.6), which are partially used for the alignment, are installed directly on to the main beam quadrupole. The quadrupoles need to be stabilized (Ch. 2), hence, a stabilization system was included in the layout of the quadrupole module (3). The quadrupole module (3) support was designed to be decoupled from the accelerator module (2) support. Therefore, the quadrupole module (3) support was specified to be directly supported on the base.

The requirement list (App. A) follows the indexation of the schematic layout for the supporting and alignment systems. The first five items define the main beam supporting and alignment systems. Then the items between six and nine describe the main beam quadrupole module (3). The items between 10 and 15 specify the drive beam supporting and alignment systems. The items from 16 to 20 define the tunnel support (1). The mentioned first and third set of items construct the accelerator module (2). In addition, the requirement list has requirements for three items which are left out from the schematic layout (Fig. 4.1). These items are: The main beam vacuum tank, the drive beam vacuum tanks and the transportation unit for the accelerator module (2). The vacuum tanks are kinematically separate from other structures, i.e. they do not have a supporting function for the high precision components. The vacuum system was defined to be supported on the common adjustable base (App. A). The transportation unit is used as an additional support while the accelerator module with the vacuum system is being transported to the tunnel. The transportation unit should sustain the alignment precision achieved at the ground surface.

4.2 Conceptual Design for Main Beam Support

The accelerating structures were supported with main beam support, which consist of the structure mounted on the main beam girder. The item 3 (Fig. 4.1) called main beam support does not include mechanical adjustments but the precision is achieved with fabrication and installation precision. V-shaped structures were preferred for the accelerating structure support, since these were used in the previous experiment [16]. However, to sustain the freedom of design the V-shaped structures are not necessarily required for the resulting design. Each support also has an interface for the vacuum system, which provides the flexibility between vacuum system and accelerator module. The components under vacuum were considered to be made of AISI 316LN stainless steel. The main beam cradle, the main beam girder, main beam supports and accelerating structures form an entity which has to meet the pre-alignment precision of 14 μm at 1σ for accelerating structures. However, due to the high thermal power dissipation to the accelerating structures (S. 1.5), the main beam support requires thermo-mechanical alignment compensation to meet the requirements. For details, see Appendix A.

4.3 Conceptual Design for Drive Beam Support

The power extraction structures were supported with the item 11 called drive beam support (Fig. 4.1). The support consist of drive beam support which is mounted on the drive beam girder. Currently, the support did not require adjustments. The drive beam quadrupoles are also mounted on the drive beam support, i.e. being supported on the girder as well. The defined materials for the drive beam support are different types of stainless steel. The conceptual design of the power extraction structure design includes power extraction structures, drive beam quadrupoles, drive beam support, the drive beam girder and the drive beam cradle. This entity should fulfill the pre-alignment requirement of 32 μm at 1σ for the power extraction structure. For details, see Appendix A.

4.4 Conceptual Design for Main Beam Quadrupole Support

The main beam quadrupole was mounted on the quadrupole support. Assembly of the beam position monitor, the main beam quadrupole, the main beam quadrupole support and the main beam quadrupole platform form the fist entity in the supporting chain. This entity should fulfill the pre-alignment requirement of 17 μm at 1σ for the main beam quadrupole. This first entity is supported on the active alignment and stabilization systems. These systems are directly supported on the base (Fig. 4.1). The considered material for the supporting structure was stainless steel. For details, see Appendix A.

4.5 Tolerance Budgets

The tolerance budgets were calculated according to propagation of uncertainty (Eq. 3.1) for the accelerating structure (Table 4.2), for the power extraction structure (Table 4.3), for the main beam quadrupole (Table 4.4) and for the main beam quadrupole beam position monitor (Table 4.5). The obtained total uncertainties (S. 3.5) of the accelerating structure, the power extraction structure, the main beam quadrupole and the main beam quadrupole beam position monitor correspond to the values of the alignment requirements (Table 2.1). The tolerances for the items in the supporting chain were defined to fulfill the alignment requirement in terms of propagated uncertainty.

The tolerance budget of each structure follows the supporting chain of the schematic layout (Fig. 4.1) and the indexation in the requirement list (App. A). For the accelerating structure and the power extraction structure the coupling between adjacent girder were included in the propagation of uncertainty.

For the accelerating structure, the propagated uncertainty (Eq. 4.1, 3.1) was calculated at 1σ according to the defined tolerances of the items in the supporting chain (Table 4.2) as follows:

$$\Delta x_{AS} = \sqrt{5^2 + 3^2 + 3^2 + 5^2 + 5^2 + 5^2 + 9^2}\mu m \approx 14\mu m \qquad (4.1)$$

Where Δx_{AS} is the propagated uncertainty defining the alignment tolerance. The tolerances for the power extraction structure, for the main beam quadrupole and for the main beam quadrupole beam position monitor were defined according to the same procedure.

Table 4.2. Tolerance budget for the accelerating structure.

Legend	Index	1σ [μm]	3σ [μm]
Inherent accuracy of AS	1	5	15
AS - MB support	1 - 3	3	9
MB support - MB girder	3 - 4	3	9
MB girder - MB cradle	4 - 5	5	15
MB cradle - PNR	5 - 18	5	15
Inherent accuracy of PNR	18	5	15
MB girder - MB girder	4 - 4	9	27
Total uncertainty		**14**	**42**

Table 4.3. Tolerance budget for the power extraction structure.

Legend	Index	1σ [μm]	3σ [μm]
Inherent accuracy of PETS	10	20	60
PETS - DB support	10 - 11	6	18
DB support - DB girder	11 - 14	6	18
DB girder - DB cradle	14 - 15	5	15
DB cradle - PNR	15 - 18	20	60
Inherent accuracy of PNR	18	5	15
DB girder - DB girder	4 - 4	10	30
Total uncertainty		**32**	**96**

Table 4.4. Tolerance budget for the main beam quadrupole.

Legend	Index	1σ [μm]	3σ [μm]
Inherent accuracy of MB quadrupole	6	10	30
MB quadrupole - PNR	6 - 18	8	24
Inherent accuracy of PNR	18	10	30
Total uncertainty		**17**	**51**

Table 4.5. Tolerance budget for the main beam quadrupole BPM.

Legend	Index	1σ [μm]	3σ [μm]
MB BPM - MB quadrupole	7 - 6	5	15
MB quadrupole - PNR	6 - 18	8	24
Inherent accuracy of PNR	18	10	30
Total uncertainty		**14**	**42**

Chapter 5

Discussion

5.1 Analysis of the Results

The different construction methods were analyzed according to main factors (Table 5.1) contributing to the design. The most suitable method was selected for the project according to the evaluation. The selected option was proposed and confirmed in a collaboration meeting [18].

The requirements for the alignment and for the installation had the greatest value in

Table 5.1. Evaluation of the construction options. Assembly = assessment of the conditions for high precision assembly (e.g. cleanliness); integration = efficiency of the assembly of the module; installation = efficiency of the final installation in the tunnel; transportation = efficiency of the transportation; organization at the surface = efficiency of work at ground level; organization in tunnel = efficiency of work in the tunnel; cost = assessment of the overall cost.

Aspect	Option 1	Option 2	Option 3
Assembly	-	+	+
Integration	-	-	+
Installation	-	+	+
Transportation	-	+	+
Organization at the surface	+	+	+
Organization in tunnel	-	-	+
Cost	-	-	+

the conceptual design. At the same time, integration of the adjacent components was not the most important issue, because that could be tackled better later during the design. Instead, the strategy was to have one subassembly with the minimum number of components, that contains all the high precision components and the measurement references. In parallel, the installation in the tunnel became more convenient; development which was considered to reduce the installation time and cost. The trade-off between cost, precision and time in the installation phase accompanied uncertainty for transportation. As a result, it is an extreme challenge to transport the accelerator modules (2) and the main beam quadrupole modules (3) and sustain the alignment precision of few microns for the components.

The main beam quadrupole was the only component which consisted of both active alignment (currently 5 degrees of freedom) and stabilization features (App. A). However, the conceptual solution for the alignment of the main beam quadrupole module (3) became more straight forward compared to the accelerator module (2), since the alignment sensors were attached directly to the quadrupole making the alignment chain shorter. Furthermore, the main beam quadrupole and the beam position monitor formed a clear entity.

The requirements for stabilization of the main beam quadrupole was entailed to the supporting design. In addition, item stabilization was added to the schematic layout without an index. The purpose of including item stabilization in the schematic layout was to clarify the need of the stabilization for the main beam quadrupole (Fig. 4.1). The inner layout for the alignment and stabilization systems was left open in order to sustain the freedom of design. The challenge with the supporting design of the main beam quadrupole is not only due to the tight requirements of the alignment and stabilization, but also due to the limited space available for the supporting system (Fig. 2.1).

The strategy was to keep the alignment requirements for the vacuum sealing as loose as possible. The vacuum system was intented to have no or minimum contribution to the support of the high precision components. Consequently, the vacuum system should be supported on the common adjustable base. The two main reasons for that are: first, vacuum system follows the main structures during the pre-alignment, having the same support as the accelerator module (2). Secondly, vacuum system does not require adjustments. However, defining the vacuum system rigid, the interconnections need to be flexible between decoupled components.

In Chapter 3, the main objectives were defined as assembly, alignment, integration, transportation and installation. As a result, the most important objectives were the alignment, transportation and installation. The integration and assembly finally ended up being secondary design objectives. The best precision for the pre-alignment was considered (Ch. 3) to be achieved with the current strategy, where assembling and integration of the accelerator module (2) and the main beam quadrupole module (3) is done at surface level (Table 4.1). This decision lead to the increased importance of transportation and final installation.

Tolerance budgets were only the first level estimations for the required tolerances. The defined tolerances for the items need to be divided into more specific tolerances during the system design. The developed tolerance budgets only consider the transversal tolerances with respect to the beam line. Furthermore, the tolerance budgets rely on the statistical stacking method (Ch. 3), not considering the worst case. Therefore, these tolerances do not give hands on feeling of the achieved precision. Moreover, the inherent accuracy of the propagation network reference is not rigorous, because it involves many uncertainties (e.g. precision of the sensor, alignment of the reference).

Furthermore, because the supporting chain for the accelerating structure and the power extraction structure (accelerator module) supports had more items between the reference and the corresponding structure, tighter tolerances were required (Table 4.2, 4.3). However, for the power extraction unit, the required tolerance was significantly looser compared to the accelerating structure. For the main beam quadrupole and for the beam position monitor the obtained supporting chains were short and therefore the required tolerances for the supporting items were less tight (Table 4.4, 4.5).

5.2 The Design Specification

The design specification focused on the requirements of alignment, supporting system and stabilization. However, the systems, aids and tools to achieve these requirements were not rigorously defined neither in the requirement list nor in the schematic layout. Only the requirements tightly involved with either support, alignment, or stabilization were defined in the requirement list. The supporting concept did not give the solution principle of an individual item. It only gave the solution principle of the supporting systems of the whole system. The design specification serves as the first attempt to establish the full scale concept for the compact linear accelerator supporting and alignment systems. Therefore, the design specification did not consider detailed components or subsystems rigorously, e.g. girder interconnections, accelerating structures, vacuum sealing, propagation network reference etc.

The previous work served as a baseline for the conducted work. Mainly the previous work gave the solution principles for the pre-alignment and active alignment. However, the achieved results took for the first time the whole accelerator support into consideration, providing the first estimation of the required tolerances for the items in supporting system for each main structure: accelerating structure, power extraction structure and main beam quadrupole.

According to the achieved results, both meeting the tight tolerances of the subsystems and the integration of the subsystems will be a challenge. Tolerances were often at micron level, which is definitely not a trivial requirement. The tolerances are on the very edge of being feasible. However, the achieved results can be used to organize future work efficiently and tackle the incoming challenges, i.e. divide the work into smaller studies of individual systems. Then again, future development of technologies will facilitate the meeting of the aims. Indeed, the results also showed clearly, that the requirements were not complete and require iteration during the following design process. This was evident already due to the changing accelerator parameters but also due to the developing supporting design itself.

The method of Pahl & Beitz gave the platform to make a well structured design specification. The systematic approach contributed to the clarity of the document as well as facilitated the composition of the document, because the the requirements were set according to the same structure for each component. The results have the same structure for all the components in the supporting and alignment systems. However, if the layout of the supporting systems changes, the composed structure cannot be changed easily to fulfill the requirements of the new layout. This is due to the inclusion of the solution principle in the design specification.

It was clarified that the design specification should be designed and composed to give freedom for the design of subsystems. One challenge of the project should not be considered as a bottleneck for the whole progress of research. Therefore, the freedom for the design specification was given by defining the challenges as individual problems which were included in the project as an entity. According the definition of the task (Ch. 1) as well as the elimination process later (Ch. 3) during the project, the definition of main challenges became the most important task, e.g. alignment strategy, division of the supporting chain, tolerance budgets and installation strategy. As a result, this modular design facilitated the freedom of design.

The question concerning the improvements of the technology during the development was taken into account in this project but the approach was fairly pessimistic. Mainly, because the considered strategies were developed according to the current technological solutions and restrictions. The approach was to have a baseline design as simple and straightforward as possible. Challenges (e.g. alignment requirements, integration etc.) will surely emerge in the detailed design of the components. For example, the integration of the support, stabilization and alignment features into the main beam quadrupole was considered to require new techniques and pioneering technology.

The question of the usability of the design specification was tackled via making the document accessible for the developers of the subsystems. The strategy was to design the layout and concept on upper level, and the individual requirements of item will be developed in collaboration with the corresponding designer of each subsystem. In short, part of the responsibility of the individual system requirements was given to the corresponding experts. However, the only way to avoid overlapping work was to enhance the clarity of the design specification, namely divide the requirement list into indexes clearly having both functional and mechanical value (App. A).

In future, the design specification should be refined in parallel with the evolving design of the supporting and alignment systems of the accelerator. Furthermore, the contribution obtained from the conceptual design i.e. layout for the supporting systems, can be used as the basis for sharing the work between collaborations. The work can be divided into detailed studies which focus on a specific entity, e.g. girder interconnection, main beam quadrupole module, accelerator module etc.

Chapter 6

Conclusions

This work started from the data collection concerning the previous research done for the accelerator support and alignment. At that moment the work focused on the definition of supporting and alignment requirements. The previous work (Ch. 2) was further developed to incorporate completely the supporting and alignment systems of the accelerator into this design. This work defined the conceptual solution principle of the supporting and alignment systems, including the required structures from the tunnel floor up to the active structures.

The design specification was composed following the method of Pahl & Beitz. The composed design specification included both the requirement list (App. A) and the schematic layout (Fig. 4.1) of the alignment and supporting systems. The design specification included requirements for support, alignment and stabilization. The conceptual design collected the previous information on both the survey elements and modular design. This work integrated them into one entity. The alignment references were defined and the first estimation for the needed structures and their required tolerances in the supporting chain was given. The individual tolerances for the items were defined by using a tolerance stacking method, where the achieved tolerance of the top end component is a propagated uncertainty of the tolerances of the items in the supporting chain. As a result, tolerances of the accelerating structure, the power extraction structure, the main beam quadrupole and the main beam quadrupole beam position monitor were met according to the required statistical pre-alignment and beam based alignment tolerances (1σ & 3σ) of the accelerator. The required tolerances for the supporting items of the accelerating structure, the power extraction structure, the main beam quadrupole and the main beam quadrupole beam position monitor were summarized in the tolerance budgets (Table 4.2, 4.3, 4.4, 4.5). The same tolerances were also included in the requirement list of the design specification.

This work can be used as the basis for future system design and research of the supporting systems of the accelerator. Following the structuring of the design specification the work can be divided into separate studies that will tackle the issue efficiently, e.g. the accelerating structure support, power extraction structure support, the main beam quadrupole support, girder interconnection etc. Namely, the schematic layout gives the conceptual structure that can be divided into smaller entities and the requirement list gives the requirements for them. Moreover, the understanding of the overall system can be improved by having the developed design specification at hand, because the design specification includes the illustrative layout. As a result, this work indicates the detailed design is required for the systems being integrated into the CLIC accelerator. This work has been done to facilitate the addressing of the future work and to support the feasibility of the CLIC collider project.

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Appendix A

Attachment

A.1 Requirement List for the Supporting and Alignment Systems

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 1

Changes	D W	Requirements	
		1. Accelerating structure (4 quadrants)	
		Support:	
	W	Inserted on V - shaped blocks	
	D	AS-support (Between AS and Girder)	
	W	AS supported from the outer surface	
		Alignment:	
	D	Tolerances with respect to AS support	
		Tolerances (3σ):	
	D	± 0.009 mm in transversal direction	
	D	± 0.015 mm in longitudinal direction	
		Temperature boundaries:	
	W	Allowed internal radial temperature variation set to 3 K for a one quadrant.	
		Materials:	
	D	Copper OFE	
		Weight:	
	D	Less than 25 Kg	
	D	Vacuum 1E-6 Pa	
	D	Only vacuum compatible materials allowed	

CLIC MODULE WORKING GROUP		10.1.2008
D = Demand W = Wish	**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 2

Changes	D W	Requirements	
		2. Main Beam WFM (Mechanically included in 1)	
		Support	
	D	Directly on accelerating structure	
		Alignment	
	D	Aligned with respect to accelerating structure	
		Tolerances (3σ):	
	D	± 0.015 mm in transversal direction	
	D	± 0.06 mm in longitudinal direction	
		Temperature boundaries:	
	D	Has to sustain temperatures occurring in the AS	
		Materials:	
	D	Coaxial cables	
		Weight:	
	D	Less than 1 Kg	
		Vacuum:	
	D	Vacuum 1E-6 Pa	
	D	Only vacuum compatible materials allowed	
		Time resolution	
	D	10 ns	
		Resolution of BPM (Absolute)	
	D	1 μm	
		Precision of BPM (Absolute)	
	D	10 μm	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 3

Changes	D W	Requirements	
		3. Main Beam support (Between girder and AS)	
		Support:	
	D	On girder	
	W	Other side of the girder works as transversal reference	
		Alignment:	
	D	Alignment with respect to the girder	
		Tolerances (3σ):	
	D	± 0.009 mm in transversal direction	
	D	± 0.015 mm in longitudinal direction	
	W	± 0.009 mm in longitudinal direction	
		Temperature boundaries:	
	W	Temperature stabilization	
		Materials:	
		Material inside vacuum:	
	W	Stainless steel AISI 316 LN	
		Weight:	
	D	Less than 10 kg	
	W	Less than 5 kg	
		Vacuum:	
	D	Flexible interface for the vacuum tank	
	D	Vacuum compatible materials	
	W	Feed throughs with bellows	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 4

Changes	D W	Requirements	
		4. Main Beam Girder	
		Support:	
	D	Supported from the ends of the girder	
	D	On one end contact for the cradle interface	
	D	On the other end contact for the intergirder connection	
	D	Enables movement in 3 degrees of freedom	
	D	Travel for transversal directions	
	D	Tilt over the beam axis	
	W	Independent movements for each D.o.F	
	W	The imaginary pivot point of joint lies on the beam axis	
		Alignment:	
	D	Alignment with respect to cradle interfaces	
	D	Passive Longitudinal alignment:	
	D	Resolution 0.001 mm (absolute)	
	D	Range of the travel ± 1 mm	
		Tolerances (3σ):	
	D	± 0.015 mm in transversal direction	
	W	± 0.003 mm in longitudinal direction	
		Temperature boundaries:	
	D	Room temperature	
		Material	
		Silicon carbide	
		Weight:	
	W	Max 65 kg	
		Vacuum:	
		NA	
	D	Contacts for the transportation unit	
	D	Supports only accelerating structures and WFMs	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 5

Changes	D W	Requirements	
		5. Main Beam Cradle	
		Support:	
	D	Inserted on top of the common adjustable base	
		Alignment:	
	D	Gets the positioning information from PNR (Item 18)	
	D	Alignment sensor installed on the cradle	
	D	Active alignment satisfies 3 D.o.F's	
	D	Resolution of travel 0.001 mm	
	W	Resolution of tilt 0.5 mRad	
	D	Active alignment in transversal directions	
	D	Active alignment for the tilt over beam axis	
	W	Designed to work with 3 micro movers	
	D	Tolerances are with respect to the sensor and the measurement reference	
	D	The achieved precision is due to mechanical accuracy of the sensor alignment	
	D	Adjustments range ± 3 mm	
		Tolerances (For the active alignment) (absolute):	
	D	± 0.001 mm in transversal direction	
	D	± 0.002 deg of tilt over the beam axis	
		Tolerances for the sensor - cradle reference (3σ):	
	D	± 0.015 mm in transversal direction	
		Temperature boundaries:	
	D	Room temperature	
		Material:	
	W	Steel AISI 304	
		Weight:	
	D	Less than 20 Kg	
	W	Less than 10 Kg	
		Vacuum:	
		NA	
	D	Alignment system constructed before CLIC modules	
	W	Measuring references inserted for module alignment	
	W	Movers work as an installation interface	

Changes	D W	Requirements	
		6. Main Beam Quadrupoles (Includes 7)	
		Support:	
	D	Main beam quadrupole support	
		Alignment:	
	D	With respect the main beam quadrupole support	
		Tolerances (with respect to support) (3σ):	
	D	± 0.1 mm in transversal direction	
	D	± 0.1 mm in longitudinal direction	
		Tolerances (with respect to sensors) (3σ):	
	D	± 0.024 mm in transversal direction	
	D	± 0.06 mm in longitudinal direction	
		Temperature boundaries:	
	D	Highest allowed operational temperature 350 K	
		Material:	
	W	Steel AISI 316 LN	
	D	Only vacuum compatible materials allowed	
		Weight:	
	D	Less than 90 Kg	
	W	Less than 75 Kg	
		Vacuum:	
	D	Vacuum inside 1E-6 Pa	
	D	Stands in open air	
	D	Accuracy initiates from the mechanical accuracy between sensor and Quad.	
	D	2 sensors (PNR, item 18) / Quadrupole	
	D	Beam based alignment	

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D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 7

Changes	D W	Requirements	
		7. Main Beam BPM	
		Support:	
	D	Main Beam Quad Support	
		Alignment:	
	D	Main Beam Quadrupole works as a reference	
		Tolerances (with respect to support) (3σ):	
	D	± 0.1 mm in transversal direction	
	D	± 0.1 mm in longitudinal direction	
		Tolerances (with respect to 6) (3σ):	
		± 0.015 mm in transversal direction	
		Temperature boundaries:	

		Materials:	
	W	Steel AISI 316 LN	
	D	Only vacuum compatible materials allowed	
		Weight:	
	D	Less than 5 Kg	
		Vacuum:	
	W	Vacuum 1E-6 Pa	
		Time resolution	
	D	10 ns	
		Resolution of BPM (absolute)	
	D	100 nm	
		Precision of BPM (absolute)	
	D	10 μm	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 8

Changes	D W	Requirements	
		8. Main Beam. Quad. Support	
		Support:	
	D	On a separate support from AS and vacuum tank	
	D	Supported on main beam quadrupole platform	
		Alignment:	
	D	Aligned with respect to the quadrupole platform	
		Tolerances (3σ):	
	D	± 0.3 mm in transversal direction	
	D	± 0.3 mm in longitudinal direction	
		Temperature boundaries:	
	D	Room temperature	
		Materials:	
	W	Steel AISI 316 LN	
	D	Only vacuum compatible materials allowed	
		Weight:	
	D	Less than 20 kg	
	W	Less than 10 kg	
		Vacuum:	
		NA	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 9

Changes	D W	Requirements	
		9. Main Beam Quadrupole Platform	
		Support:	
	D	On a separate support from AS and vacuum tank	
	D	Support directly on the base	
	W	Pre-alignment travel 0.5 mm over the CLIC lifetime	
		Alignment:	
		Aligned with respect to PNR (Item 18)	
	D	Active alignment in 5 degrees of freedom (all except longitudinal adjustment)	
	D	Beam based alignment	
	D	Alignment response time above 50 Hz	
	D	Range of the adjustment ± 2 mm	
		Tolerances (For the active alignment) (absolute):	
	D	± 0.003 mm in transversal direction	
	W	± 0.005 mm in longitudinal direction	
		Tolerances (for the construction) (3σ):	
	D	± 0.3 mm in transversal direction	
	W	± 0.3 mm in longitudinal direction	
		Temperature boundaries:	
	D	Highest operational temperature 350 K	
		Materials:	
	W	Steel AISI 316 LN	
	D	Only vacuum compatible materials allowed	
		Weight:	
	D	Less than 50 Kg	
		Vacuum:	
		NA	
	D	Has an installation interface for MB. Q. support	
		Stabilization (absolute):	
		Quadrupoles need to be stabilized to:	
	D	1 nm level in vertical direction above 1 Hz	
	D	5 nm level in horizontal direction above 1 Hz	
	D	Stabilization does not have to work at the same time with alignment	
	W	Main beam quadrupole assembly is brought separately to the tunnel, not with the accelerator module	
	D	Active alignment system assembled into the tunnel before the installation of the accelerator module	

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D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 10
Changes	D W	Requirements	
		10. PETS Structure	
		Support:	
	D	PETS Support (Structure on top of the girder)	
		Alignment:	
	D	No adjustments	
		Alignment with respect to the item 11	
	D	Tolerances (3σ):	
	D	± 0.018 mm in transversal direction	
	D	± 0.15 mm in longitudinal direction	
		Temperature boundaries:	
	W	Internal radial temperature variation below 3 K	
		Materials:	
	W	Copper OFE	
	D	Only vacuum compatible materials allowed	
		Weight:	
		30 Kg	
		Vacuum:	
	D	Vacuum 1E-6 Pa	

CLIC MODULE WORKING GROUP		10.1.2008
D = Demand W = Wish	**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 11

Changes	D W	Requirements	
		11. Drive Beam Support	
		Support:	
	D	Supported on the drive beam girder	
		Alignment:	
	D	No adjustments	
	W	Other side of the girder works as a reference	
	D	Tolerances with respect to girder	
		Tolerances (3σ):	
	D	± 0.18 mm in transversal direction	
	D	± 0.06 mm in longitudinal direction	
		Temperature boundaries:	
	W	Stabilization for temperature	
		Materials:	
	W	Stainless Steel AISI 316 LN in vacuum	
	W	Aisi 304 L otherwise	
		Weight:	
	D	Less than 80 Kg	
	W	Less than 50 Kg	
		Vacuum:	
	D	Vacuum - air sealing interface is introduced here	
	D	Flexible interconnection	
	W	With bellows	
	D	Vacuum 1E-6 Pa	
	D	Only vacuum compatible materials allowed	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 12
Changes	D W	Requirements	
		12. Drive Beam Quadrupole	
		Support:	
	D	Common support with PETS structures i.e. PETS support	
		Alignment	
	D	Tolerances with respect to item 11	
		Tolerances (3σ):	
	D	± 0.03 mm in transversal direction	
	D	± 0.15 mm in longitudinal direction	
		Temperature boundaries:	
	D	Highest allowed operational temperature 350 K	
		Materials:	
	W	AISI 316 LN, Aisi 304 L, Copper OFE	
		Weight:	
	D	Less than 200 kg	
	W	180 Kg	
		Vacuum:	
	D	Vacuum 1E-6 Pa	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 13
Changes	D W	Requirements	
		13. Drive Beam BPM (mechanically included in 12)	
		Support:	
	D	Common support with PETS structures i.e. PETS support	
		Alignment:	
	D	Alignment reference is the drive beam support	
		Tolerances (with respect to 12) (3σ):	
	D	± 0.015 mm in transversal direction	
	D	± 0.3 mm in longitudinal direction	
		Temperature boundaries:	

		Materials:	
	W	Coaxial cables	
		Weight:	
	D	Less than 1 Kg	
		Vacuum:	
	D	Vacuum 1E-6 Pa	
		Time resolution	
	D	10 ns	
		Resolution of BPM (absolute)	
	D	1 μm	
		Precision of BPM (absolute)	
	D	10 μm	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 14

Changes	D W	Requirements	
		14. Drive Beam Girder	
		Support:	
	D	Supported from the ends of the drive beam girder	
	D	On one end contact for the cradle interface	
	W	On the other end contact for the intergirder connection	
	D	Enables movement in 3 degrees of freedom	
	D	Transversal directions travel	
	D	Beam axis tilt	
	W	Independent travel for each degree of freedom	
	D	Inserted on Drive Beam Cradle	
	D	Contacts for the transportation unit	
		Alignment:	
	D	Alignment with respect to the reference on the cradle interface	
		Tolerances (3σ):	
	D	± 0.015 mm in transversal direction	
	D	± 0.15 mm in longitudinal direction	
		Temperature boundaries:	
	D	Room Temperature	
		Materials:	
	D	Silicon carbide	
		Weight:	
	D	Less than 70 Kg	
	W	60 kg	
		Vacuum:	
		NA	
	D	Works as a platform for the PETS and for the main beam quadrupoles	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 15

Changes	D W	Requirements	
		15. Drive Beam Cradle	
		Support:	
	D	Inserted on top of common adjustable base	
		Alignment:	
	D	Gets the positioning information from PNR (Item 18)	
	D	Alignment sensor installed on the cradle	
	D	Measuring references inserted on cradle for module alignment	
	D	Active alignment satisfies 3 D.o.F's	
	D	Resolution of travel 0.005 mm	
	W	Resolution of tilt 0.05 degree	
	D	Transversal directions	
	D	Tilt over beam axis	
	W	Alignment with micro movers	
	D	Tolerances are with respect to the sensor and cradle interfaces	
	D	The achieved precision is due to mechanical accuracy of the sensor alignment	
20071029	D	Adjustments range ± 5 mm	
		Tolerances (3σ) (For the active alignment):	
	D	± 0.03 mm in transversal direction	
	D	± 0.06 in longitudinal direction	
	D	± 0.012 deg of tilt over the beam axis	
		Tolerances for the sensor - cradle reference (3σ):	
	D	± 0.06 mm in transversal direction	
		Temperature boundaries:	
	D	Room temperature	
		Material	
	W	Steel AISI 304	
		Weight:	
	D	Less than 20 Kg	
	W	Less than 10 Kg	
		Vacuum:	
		NA	
	D	Has an interface for girder support	
	D	Alignment system built to the tunnel before the installation of accelerator modules	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 16

Changes	D W	Requirements	
		16. Common Adjustable Base	
		Support	
	D	Concrete base	
		Alignment:	
	W	Alignment due the geodetic network / PNR	
	D	Passive alignment in 2 D.o.F's	
	D	Transversal travel	
		Resolution	
20071029	D	0.05mm	
		Range:	
20071029	D	± 20 mm	
	D	Lockable adjustments	
	D	Common adjustment for the AS and for the PETS	
		Tolerances (3σ):	
	D	± 0.1mm in transversal direction	
	D	± 0.1mm in longitudinal direction	
		Temperature boundaries:	
	D	Room temperature	
		Material:	
	W	For adjustment structures - Steel AISI 304L	
		Weight:	
	D	Less than 100 kg	
	W	70 kg	
		Vacuum:	
		NA	
	D	PNR installation	
	D	Installation of standard support reference	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 17

Changes	D W	Requirements	
		17. Concrete Base	
		Support	
	D	Tunnel ground	
		Alignment:	
	D	Due to the geodetic alignment network	
		Tolerances (3σ):	
20071029	D	± 5 mm in transversal direction	
	D	± 2 mm in longitudinal direction	
		Temperature boundaries:	
	D	Room temperature	
		Material:	
	D	Concrete, Stainless steel is used for the structure interfaces	
		Weight:	
		No limitations	
		Vacuum:	
		NA	
	D	Has to be a good damper against vibrations	
	D	HLS monitor installation	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 18

Changes	D W	Requirements	
		18. Propagation Network Reference (PNR)	
		Support:	
	D	Common adjustable base and the metrological plate	
		(The support depends on the component)	
		Alignment:	
	D	Due to geodetic reference network	
	D	Adjustments in transversal directions	
		(Included in survey elements)	
		Tolerances (3σ):	
20071029	D	± 0.015 mm in transversal direction	
	D	± 1 mm in longitudinal direction	
		Temperature boundaries:	
	D	Temperature compensation	
		Materials:	
	D	AISI 304 for supports	
		Weight:	
		Less than 5 kg (Concerns sensors)	
		Vacuum:	
		NA	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 19

Changes	D W	Requirements	
		19. HLS	
		Support:	
	D	Base \ tunnel ground \ metrological plate	
		Alignment:	
	D	Due to geodetic reference network	
	D	Adjustment in vertical direction	
		(Included in survey elements)	
		Tolerances (3σ):	
	D	± 1 mm in vertical direction (construction tolerance)	
	D	± 1 mm in longitudinal direction (construction)	
20071029	D	± 0.005 mm in vertical direction at the measuring point	
		Temperature boundaries:	
	D	Room temperature	
		Materials:	
	D	AISI 304 for supports	
		Weight:	
		No limitations	
		Vacuum:	
		NA	
	D	System has access to open air only from one point.	

Changes	D W	Requirements	
		20. Geodetic reference network	
		Support:	

		Alignment:	
	D	Due to geodetic reference network at surface	
		Tolerances (3σ):	
	D	± 1 mm in vertical direction [at the exit shaft]	
	D	± 1 mm in longitudinal direction [at the exit shaft]	
		Temperature boundaries:	
	D	Room temperature	
		Materials:	
	D	AISI 304 for supports	
		Weight:	
		No limitations	
		Vacuum:	
		NA	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 21

Changes	D W	Requirements	
		21. Main Beam Vacuum tank	
		Support:	
	D	On a separate support from the girder	
	D	Does not carry external loads	
	D	Has an support interface for the transportation unit	
	D	Supported directly on the common adjustable base	
		Alignment:	
	D	Alignment with respect to the common adjustable base	
	D	No adjustments	
	D	Tolerances (3σ):	
	W	± 0.5 mm in transversal directions	
	W	± 0.5 mm in longitudinal direction	
		Temperature boundaries:	
	D	Room temperature	
		Materials:	
	D	AISI 316L, AISI 304L	
		Weight:	
	D	Maximum weight 200 kilos/module	
	W	Maximum weight 150 kilos/module	
		Vacuum:	
	D	Vacuum up to 1E-6 Pa	
	D	Feed throughs for waveguides and electronics	
	W	With bellows	
	D	Vacuum tank compatible with the CLIC module concept	
	D	Interconnection for Quadrupole sealing	
	W	Main beam supports machinable after the assembly of accelerator module and the installation of the tank	

CLIC MODULE WORKING GROUP			10.1.2008
D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 22
Changes	D W	Requirements	
		22. Drive Beam Vacuum tank	
		Support	
	D	Has a separate support from the PETS	
	D	Does not carry external loads	
	W	Supports directly on the common adjustable base	
	D	Has an support interface for the transportation unit	
		Alignment:	
	D	Alignment with respect to the common adjustable base	
	D	No adjustments	
	D	Tolerances (3σ):	
	D	± 0.5 mm in transversal directions	
	D	± 0.5 mm in longitudinal direction	
		Temperature boundaries:	
	D	Room temperature	
		Materials:	
	D	AISI 316L, AISI 304L	
		Weight:	
	D	Maximum weight 250 kilos/module	
	W	Maximum weight 200 kilos/module	
		Vacuum:	
	D	Vacuum up to 1E-6 Pa	
	D	Feed throughs for waveguides and electronics	
	W	With bellows	
	D	Vacuum tank compatible with the CLIC module concept	

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D = Demand W = Wish		**Requirements for the CLIC supporting system, listing from RF-structures downwards**	Sheet 1, Page 23

Changes	D W	Requirements	
		23. Transportation unit	
		Support (Supported systems):	
		Cradles:	
	D	Drive beam girder	
	D	Main beam girder	
		Common adjustable base:	
	D	Vacuum tanks	
		Alignment:	
		Due to PNR / geodetic reference network	
		Tolerances for the construction (3σ):	
	D	± 0.1 mm in transversal direction	
	D	± 0.3 mm in longitudinal direction	
		Temperature boundaries:	
	D	Temperature variation after PETS/AS installation has to be kept under 10 K	
		Materials:	
		NA	
		Weight:	
	D	Maximum weight 1500 kg	
	W	Maximum weight 1000 kg	
		Vacuum:	
	D	Structures have closed vacuum connections during transport	
	D	Is a compatible transportation unit for transferring the accelerator module to the tunnel, which is rigid enough to satisfy following tolerances [keeps the component within following tolerances]:	
	D	Main beam girder: ±0.08mm	
	D	Main beam vacuum tank: ±0.5mm	
	D	Drive beam girder: ±0.08mm	
	D	Drive beam vacuum tank: ±0.5mm	
	D	Main beam quadrupoles are brought separately into the tunnel	
	D	Alignment process for PETS and AS is done before the final installation at the surface level.	
	D	Transportation unit can be transported to the tunnel as one package	
	D	Main Beam Quadrupoles are assembled during second phase of installation	