

Modelling of Halo and Tail Generation in Electron Beams

Modellierung Halo- und Tailformierender Prozesse in Elektronenstrahlen

DIPLOMARBEIT IM FACH PHYSIK

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Zusammenfassung

Die vorliegende Diplomarbeit beschreibt die Modellierung von halo- und tailformierenden Prozessen. Halo- und Tailteilchen, kurz Haloteilchen, sind Strahlteilchen die einem von der Referenzbahn weit entfernten Orbit folgen. Diese Teilchen können aufgrund des großen Abstands zur Idealbahn leicht verlorengehen, d.h. auf das Strahlrohr oder die umgebende Struktur treffen. Da diese Teilchen meist sehr hochenergetisch sind, kann sich die umgebende Struktur zum Beispiel aufheizen, was unter anderem zum Zusammenbruch des elektromagnetischen Feldes in Magneten und Hochfrequenzmodulen führen kann. Zusätzlich zu dem Effekt der direkten Strahlverluste können Haloteilchen in der Wechselwirkungszone des Beschleunigers wesentlich zum Hintergrund der untersuchten Wechselwirkung der kollidierenden Teilchen beitragen. Deshalb werden die meisten Haloteilchen durch Kollimatoren gestoppt. Durch die Wechselwirkung der Haloteilchen mit dem Material können jedoch sekundäre Teilchen entstehen, die wiederum zum Hintergrund beitragen.

Haloteilchen können folglich das Leistungsvermögen eines Beschleunigers signifikant vermindern, weshalb die Untersuchung bzw. Modellierung der für die Haloentstehung verantwortlichen Prozesse essentiell ist.

Zur Modellierung der haloformierenden Prozesse wurde der Tracking Code PLACET [1] in Kombination mit dem Paket für Halo und Tail Simulationen HTGEN [2] verwendet. Insgesamt wurden Halo- und Tailprozesse für drei Beschleuniger untersucht: den Decelerator des “Compact Linear Collider” (CLIC), die “Test Beam Line” (TBL) der “CLIC Test Facility” (CTF3) und den supraleitende Linearbeschleuniger der vom Forschungszentrum Karlsruhe (FZK) vorgeschlagenen THz Strahlungsquelle “THz Beam Optics for New Experiments” (TBONE).

Der erste der untersuchten Beschleuniger ist der Decelerator von CLIC. CLIC ist eine Studie eines Elektron-Positron Beschleunigers, der die Messungen am Large Hadron Collider (LHC) ergänzen und Präzisionsmessungen ermöglichen soll. Die CLIC Studie [3] strebt eine Design Energie von 3TeV und ein Luminosität von $6.0 \times 10^{34} \text{cm}^2 \text{s}^{-1}$. Die Gesamtlänge von CLIC wird auf 48 km geschätzt, wobei 42 km davon den “Main Linac” bilden. Um Multi-TeV Energien erreichen zu können, wurde eine neue Beschleunigungstechnik entwickelt, die sogenannte “Two Beam Acceleration”, die folgendermaßen

funktioniert: Die Radiofrequenz Leistung für den gesamten Main Linac wird zunächst in einem Elektronenstrahl mit niedriger Energie und hoher Intensität, dem sogenannten "Drive Beam", gespeichert. Der Drive Beam besteht zunächst aus langen Pulsen, die wiederum aus langen Bunchen bestehen. Die Leistung, die in diesen Pulsen gespeichert wurde, wird mit Hilfe von "Power Extraction and Transfer Structures" (PETS) dem Elektronenstrahl entzogen und zu den Beschleunigungsstrukturen des Main Linacs geleitet. Main Beam und Drive Beam laufen in dem Bereich der Energieübertragung parallel zueinander. Wenn die gesamte Leistung für den Main Linac in nur einem Puls gespeichert werden würde, müsste dieser extrem kurz und hochenergetisch sein und eine hohe Ladungsdichte besitzen, was sehr schwer zu produzieren wäre. Deshalb wird der gesamte Main Linac in kleinere Einheiten aufgeteilt, insgesamt 24, in denen jeweils ein Zug des Drive Beams für die Beschleunigung des Main Beams verwendet wird. Die einzelnen Einheiten werden "Decelerator" genannt, da der Drive Beam dort auf bis zu 90% seiner Anfangsenergie abgebremst wird.

Der zweite untersuchte Beschleuniger ist die CTF3 TBL. Da CLIC auf vielen neuen Technologien basiert, die noch nie verwendet wurden und deren Parameter die Grenzen heutiger Technologien übersteigen, wurden verschiedene Testeinrichtungen gebaut, von denen eine die CLIC Test Facility (CTF3) ist. Die TBL ist ein Teil von CTF3, wo das Konzept des Decelerators getestet wird.

Der dritte untersuchte Beschleuniger ist der supraleitende Linearbeschleuniger von TBONE. TBONE ist ein vom FZK vorgeschlagener Beschleuniger zur Produktion von kohärenter Synchrotronstrahlung im THz bis mittleren Infrarot Bereich [4]. Die angestrebte maximale Frequenz der emittierten Strahlung ist 150 THz mit einer maximalen Leistung von bis zu einigen MW. Im Vergleich zu anderen Einrichtungen, die auf THz Strahlung spezialisiert sind, würde TBONE ein größeres Spektrum abdecken kombiniert mit einer höheren Maximalleistung. Anwendungen dieser Strahlung wären z.B. Dynamik von Proteinen in wässrigen Lösungen, Abbildung von bioaktiven Materialien, Zellen und Sensoren, nicht lineare und 2D THz Spektroskopie sowie THz Absorptions Spektroskopie als auch "Photon Echoing". Zusätzlich könnten auch supraleitende "Insertion Devices" dort untersucht werden.

Der TBONE Beschleuniger besteht aus einem supraleitenden Linac, der je nach Endanwendung die Elektronen auf 60 – 100 MeV beschleunigt, gefolgt von einem Bunch Kompressor. Das letzte Element ist eine Folge von Ablenkmagneten, die zur Erzeugung der kohärenten Strahlung dienen. Im Rahmen dieser Arbeit wurden die Strahldynamik im supraleitenden Linac, bestehend aus drei supraleitenden Hochfrequenzmodulen, simuliert. Die Herausforderung war, eine für die anschließende Kompression im Bunch Kompressor geeignete Ladungsverteilung am Ende des Linacs zu finden. Dies wurde erreicht, indem alle drei Hochfrequenzmodule über Transition gefahren wurden. Die Minimierung von Strahlverlusten ist im CLIC Decelerator und im supraleitenden

Linac von TBONE besonders wichtig. Da der CLIC Decelerator die Leistungsquelle des Main Linacs ist und diesen folglich so gleichmäßig wie möglich mit Energie versorgen muss, wären hohe Strahlverluste zusätzlich zu den oben genannten Effekte besonders kritisch. Im Fall von TBONE würden hohe Strahlverluste die Strahlungsleistung senken, da diese mit der Ladung des emittierenden Bunches ansteigt.

Sowohl CLIC als auch TBONE sind Beschleuniger in der Planungsphase, im Gegensatz zu CTF3, welcher schon in Betrieb ist. Daher würde z.B. die CTF3 TBL die Möglichkeit bieten den verwendeten Code PLACET-HTGEN experimentell zu überprüfen. In Rahmen dieser Arbeit wurden keine Messung sondern nur Simulationen durchgeführt, die die Basis für spätere Messungen bilden könnten.

Für die Simulation der Halo- und Tailentstehung oder kurz Haloentstehung wurde der Tracking Code PLACET und das Halosimulationsprogramm HTGEN verwendet, welche durch ein Interface verbunden werden können zu PLACET-HTGEN.

In HTGEN sind folgende Prozesse verantwortlich für Haloentstehung implementiert:

Bremsstrahlung, Mottstreuung, Vielfachstreuung und Streuung an Spoilern.

und in PLACET existieren:

Strahloptische Fehlanpassungen, Kopplung, Dispersion, Nichtlinearitäten, Fehlaufstellung von Elemente, Synchrotron Strahlung, "Beam Loading" und "Wakefields".

Nicht implementiert hingegen:

Compton Streuung, Elektronen- und Ionenwolkeneffekte, Touschek Effekt, Intrabeam Streuung, Raumladungseffekte sowie Rauschen, Vibrationen und dunkle Ströme.

HTGEN war ursprünglich für hohe Energien gedacht und der erste Schritt war daher eine Validierung des Programms in Bezug auf niedrige Strahlenergien. Diese ergab, dass PLACET-HTGEN auch für niedrige Energien anwendbar ist, jedoch bei einigen Prozessen deren Relevanz für jeden Strahl individuell überprüft werden muss.

Die Halo und Tailsimulationen und analytische Abschätzungen für die drei Beschleuniger ergaben:

Die Strahldynamik des CLIC Decelerator wird durch den Effekt der Wakefields dominiert. Diese verursachen eine Abbremsung der Strahlteilchen und einen gleichzeitiges Anwachsen der Emittanz. Weiter müssen für die Gewährleistung der Strahlstabilität die Quadrupole bis auf $2\text{ }\mu\text{m}$ und die PETS bis auf $200\text{ }\mu\text{m}$ ausgerichtet werden [5]. Analytische Abschätzungen zeigen, dass die "Fast-Ion Instability", ein Ionenwolkeneffekt, möglicherweise auftreten könnte. Es sind weitere Simulationen zur Überprüfung der Relevanz dieses Effekts geplant. Touschek Effekt und Intrabeam Streuung sind wahrscheinlich vernachlässigbar aufgrund der relativ großen Strahlgröße, jedoch könnte ihr Effekt durch die Abbremsung der Teilchen verstärkt werden und zu nicht vernachlässigbarem Halo führen. Alle anderen Effekte sind vernachlässigbar.

Auch in der CTF3 TBL sind die Wakefields der dominante Prozess und führen zu einer Abbremsung der Teilchen und einem Anwachsen der Emittanz. Der Effekt der Fehlauf-

stellung von Elementen wird momentan experimentell bei CTF3 untersucht. Auch hier gelten strenge Grenzen für die Positionierung. Strahloptische Fehlanpassung, Kopplung und Nichtlinearitäten wurden im Rahmen dieser Arbeit nicht untersucht. Alle anderen Prozesse sind vernachlässigbar bis auf Touschek Effekt und Intrabeam Streuung die aufgrund der Abbremsung doch relevant sein könnten.

Für TBONE liegen noch keine exakten Berechnungen der Wakefields vor. Da im Main Linac des ILC die gleichen Hochfrequenzmodule zur Beschleunigung verwendet werden wie in TBONE, wurden die Wakefields verursacht durch den TBONE Strahl durch die Wakefield Berechnung für den ILC Main Beam mit veränderten Eingangswerten angenähert. Die Simulationen zeigen keinen signifikanten Zuwachs der Strahlgröße und folglich keine signifikante Haloentstehung aufgrund von Wakefields. Weiterhin sind Compton Streuung, Synchrotron Strahlung, Elektronen und Ioneneffekte, Bremsstrahlung und Mottstreuung als auch Touschek Effekt und Intrabeam Streuung sehr wahrscheinlich vernachlässigbar. Optische Effekte wurden nicht untersucht, jedoch könnte eine Strahlablage bei Injektion in den Linac einen starken Einfluss haben, da der Effekt der Wakefields auf weiter von der Mitte des Elements entfernte Teilchen wesentlich stärker ist als auf Teilchen in der Mitte.

Es konnte gezeigt werden dass das Halo- und Tailsimulationsprogramm PLACET-HTGEN auch für niedrige Strahlenergien anwendbar ist, jedoch muss im Zweifelsfall die Vernachlässigbarkeit des betrachteten Prozesses durch analytische Abschätzungen bestätigt werden. Die analytischen Abschätzungen und Simulationen des CLIC decelerator, der CTF3 TBL und des supraleitenden Linac von TBONE ergaben, dass Halo- und Tailentstehung in diesen drei Beschleunigern eine untergeordnete Rolle spielt.

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Chapter 1

Introduction

Halo and tail particles, or short halo particles, are beam particles which follow an orbit far away from the reference orbit. Due to the large distance from the ideal orbit, these particles are likely to hit the beam pipe or the surrounding structure and are lost. Because beam particles and therefore also halo particles have a high energy, they can increase the heatload in the surrounding structure significantly, which e.g. can lead to electromagnetic breakdown in magnets or cavities. In addition to the direct particle losses, halo particles can be a major source of background which is unwanted by particle physics experiments. Therefore most halo particles are stopped by collimators placed in the interaction region. Due to the interaction of the halo particles with the material of the collimators, secondary particles can be generated, which again contribute to the background.

As a consequence halo and tail studies are needed in order to minimize any potential performance limitations of future accelerators from this source.

For the Modelling of halo and tail generation we used the tracking code PLACET [1] combined with the halo and tail simulation package HTGEN [2]. Three accelerators were studied: the Compact Linear Collider (CLIC) decelerator, the CLIC Test Facility (CTF3) Test Beam Line (TBL) and the superconducting linac of the THz radiation source THz Beam Optics for New Experiments (TBONE) proposed by the Forschungszentrum Karlsruhe (FZK). Because all three accelerator have low or medium energy beams and HTGEN was originally written for high energies, a low energy validation of the package was performed in the framework of this thesis.

The first accelerators under study were the CLIC decelerator and the CTF3 TBL. CLIC is a Multi-TeV electron-positron collider [3], which has the potential for particle physics experiments complementary to the ones at LHC. Furthermore CLIC allows precision measurements. The baseline design of CLIC envisages a collision energy of 3 TeV and a luminosity of $6.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. To reach Multi-TeV energies, the CLIC study follows a novel concept, the so called two beam acceleration. Here the rf power for the main linac is not provided by klystrons, but instead by a high-current low energy electron beam, the

drive beam. All the power required for the acceleration is stored in several drive beams, which are generated in a relatively small drive beam complex. The drive beams are then transported to decelerators, where they run in parallel to the main beam and where almost 90% of the energy is extracted. The energy is then converted to rf power in special Power Extraction and Transfer Structures (PETS) and transferred to the main accelerating structures.

One major program in the CLIC R&D is the CLIC Test Facility (CTF3), which includes a Test Beam Line (TBL) imitating a part of the decelerator and is in general a test facility for the two beam acceleration.

Second and last the superconducting linac of TBONE was studied. TBONE [4] is a new radiation source proposed by the Forschungszentrum Karlsruhe. This new electron machine will deliver coherent radiation with a frequency of maximal 150 THz and a power of up to several MW. Depending on the operation scheme the electron beam is accelerated to 60 – 100 MeV in a superconducting linac, then transferred to the bunch compression system followed by a magnetic structure to generate coherent synchrotron radiation. Compared to other radiation sources optimized for THz radiation, TBONE covers a much larger spectral range combined with a higher peak power, which opens up a wide field of new research possibilities. The most important ones are monitoring of protein and solvation dynamics, imaging of bioactive materials, cells and sensors, non linear THz spectroscopy, 2D-THz spectroscopy and THz absorption spectroscopy as well as photon echoing.

In the CLIC decelerator and the superconducting linac of TBONE it is essential to transport the beam with minimal losses: The decelerator is responsible for the power supply of the main linac and even small beam losses could endanger the required and uniform supply of power for the main accelerating structures. TBONE is a coherent THz radiation source with a high peak power. Significant beam losses would reduce the peak power, which scales quadratically with the number of radiating particles in the case of coherent radiation.

CLIC and TBONE are both future accelerators, contrary to CTF3, which is already existing. Consequently the CTF3 TBL would provide the opportunity to benchmark PLACET-HTGEN. Therefore the halo and tail simulations for this beamline performed in the framework of this thesis are an excellent basis for future experiments.

This thesis is organized as follows:

After a brief introduction in linear accelerators (chapter 2), the three accelerators under study are discussed in detail (chapter 3 and 4). Chapter 5 is devoted to halo and tail generation. Here the tracking and halo and tail simulation code PLACET-HTGEN as well as the low energy validation are described and the simulation results of the three studied

accelerators are presented.

The main conclusions of this thesis are summarized in chapter 6.

Basic Waveguide parameters, fundamental formulas for the description of scattering processes and the CLIC and CTF3 TBL drive beam parameters are given in appendix A, B and C.

Chapter 2

Linear Accelerators

The present particle physics experiments demand high beam energies and luminosity. Circular accelerators are generally more economic than linear accelerators, because the beam circulates many times until it is finally dumped. The disadvantage is that the energy loss due to synchrotron radiation increases considerably with rising beam energy. In linear accelerators this effect is negligible (chapter 2.4). Therefore the only option for future high luminosity accelerators with beam energies above several hundred GeV is the concept of linear acceleration.

In this chapter we will derive the basics of linear accelerators following [6], [7] and [8].

2.1 Layout of Linear e^+e^- - Accelerators

Linear accelerators consist of three basic units, the *source*, the *injector* and the *main accelerator*.

Electrons can be generated by a *thermionic gun*, where a heated cathode of a special material emits electrons, or a *photo cathode*, where a strong laser pulse knocks out electrons of a cathode. Devices where an accelerating rf cavity follows the photo cathode are called *rf guns*.

Positrons are created by colliding a relatively high energy electron beam on a heavy metal target (e.g. Beryllium), where by electromagnetic pair production, positrons are created. The positrons and electrons are then separated by strong electromagnetic fields.

For the particle acceleration, rf fields are commonly used. This type of acceleration requires a specific time structure of the beam, because without it a large fraction of beam particle would be lost. If a photo cathode is used as electron source the time structure can be created by pulsing the laser in the right way. In the case of a thermionic gun, a chopper and a prebuncher must be used. For positrons the desired time structure is provided by giving the generating electron beam the right time structure. As the source already gives the beam its time structure, it builds the basis for the further behaviour of the beam and

has a great influence on the beam dynamics throughout the whole accelerator. A careful choice of the source is therefore essential.

The positron beam produced by the source normally has a too large beam size and beam divergence to be directly accelerated in the main linac. Both are reduced in so called *damping rings*, where the particles simply circulate for some time without being accelerated. The principle of damping rings is, that the particles lose their transverse momenta through the emission of synchrotron radiation photons. To reduce the damping time and achieve the required beam sizes for further acceleration, damping wigglers are used in addition or instead. They consist of alternating dipoles, which force the particles on a sinusoidal trajectory. As the bending radius is very small and the number of bends is high, the particles strongly emit synchrotron radiation and the transverse oscillations are damped fast. Damping rings are also used for electrons if needed. After the damping rings the particles are transferred directly or via a transfer line to the main accelerator. A typical layout of a linear accelerator is the CLIC layout (Fig. 3.0.1)

2.2 Beam Dynamics

In every accelerator the particles are supposed to follow a determinate path. The ideal path of one particle through the beamline is also called *reference path*. For the description of the particle trajectories a specific coordinate system is used, where the coordinates are separated into two different parts, the longitudinal (s) and the transverse direction (x, y) (Fig. 2.2.1).

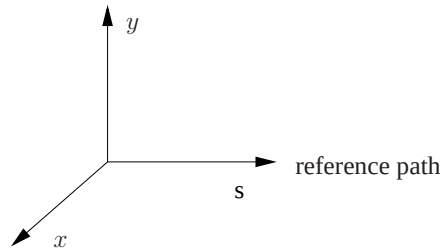


Figure 2.2.1: Coordinate system

To keep the beam close to the ideal path throughout the lattice and accelerate it to the desired energy, electromagnetic fields are used. Their effect on one particle with charge q and velocity $\vec{v}$ is given by the Lorentz force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (2.2.1)$$

For relativistic particles the force from a magnetic field of 1 T is equivalent to the one of an electric field of 3×10^8 V/m. A magnetic field of 1 T can be easily generated, but

an electric field of 3×10^8 V/m adequate for particle guidance is very difficult to reach. Therefore rf fields are used for particle acceleration (chapter 2.2.1) and magnetic fields for particle guidance (chapter 2.2.2).

2.2.1 RF Acceleration

In the very beginning of accelerator physics, the particles were commonly accelerated with electrostatic fields, which is still used in e.g. guns. These were limited by electrical breakdown. In 1925 Ising proposed to accelerate the particles with high frequency alternating fields. Nowadays most accelerators use radio frequency (rf) cavities, which are excited by rf generators like klystrons.

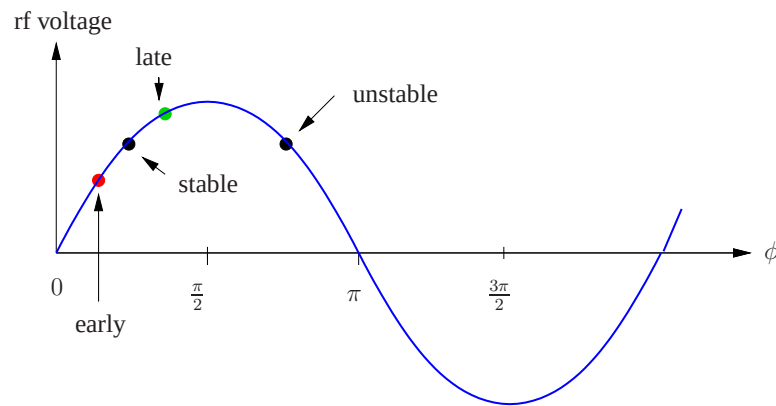


Figure 2.2.2: Schematic drawing of an rf wave: A stable operation requires that $0 < \phi < \pi/2$.

Simplified the electromagnetic field seen by the beam in a cavity has a sinusoidal shape. During the half period, when the field is positive, the particles are accelerated, while during the other half period, the beam must be shielded from the field in order not to be decelerated.

Each cavity is designed to produce a given energy gain per cell. Particles with the correct initial velocity then gain the right amount of energy and maintain synchronism with the accelerating field. There are two phases where the energy gain per cell is equal to the design value. Only the earlier phase, called the *synchronous phase*, leads to a stable orbit. Particles that arrive earlier than the synchronous phase, so particles with too much energy, experience a smaller accelerating field, and particles that arrive later, so particles with too

little energy, will experience a larger field (Fig. 2.2.2). Driven by this mechanism the particles will start to oscillate around the synchronous phase. As the particles approach relativistic energies, the phase oscillations slow down, and the particles maintain an almost constant phase relative to the traveling wave.

2.2.2 Linear Beam Dynamics

For the beam transport through the whole accelerator magnetic fields are used. Because the orbit of the particles usually differs very little from the reference orbit, it is useful to expand the magnetic field around the reference orbit.

$$\begin{aligned}
 \frac{q}{p} B_z(x) &= \frac{q}{p} B_{z0} + \frac{q}{p} \frac{dB_z}{dx} x + \frac{1}{2!} \frac{q}{p} \frac{d^2 B_z}{dx^2} x^2 + \frac{1}{3!} \frac{q}{p} \frac{d^3 B_z}{dx^3} x^3 + \dots \\
 &= \frac{1}{R} + kx + \frac{1}{2!} mx^2 + \frac{1}{3!} ox^3 + \dots \\
 &\quad \text{Dipol} \quad \text{Quadrupol} \quad \text{Sextupol} \quad \text{Oktupol} + \dots
 \end{aligned} \tag{2.2.2}$$

As shown the field can be expressed as a sum of multipoles, where each multipole has a different effect on the particles. Dipoles bend the orbit, quadrupoles focus the beam, sextupoles compensate chromatic effects and octupoles correct the influence of field errors. The part of beam dynamics including only lattices with dipoles and quadrupoles is called *linear beam dynamics*.

Transverse Focusing by Magnetic Quadrupoles

Focusing is needed in a linear accelerator, because the particles are commonly defocused by the rf transverse electric fields. In addition the beam size increases, because the initial beam particles always have finite non zero transverse velocity and are repelled by each other due to the Coulomb forces. Therefore transverse focusing is needed to ensure a stable operation. The most common solution is to include magnetic quadrupole focusing lenses.

A quadrupole is suited for focusing because the field increases linearly from the center and particles with a larger offset to the ideal orbit experience a stronger focusing force than particles with a smaller offset which leads to an overall focusing of the beam. The field pattern of a quadrupole shows that the particles are only focused in one plane and are defocused in the other plane (Fig. 2.2.3). A total focusing of the beam in both transverse planes can be obtained by a combination of quadrupoles. The most common arrangement is a FODO cell (Fig. 2.2.4). FODO stands for the order of the elements: Focusing

quadrupole, drift length, Defocusing quadrupole, drift length. The drift lengths are often substituted by other elements like accelerating structures, beam position monitors etc.

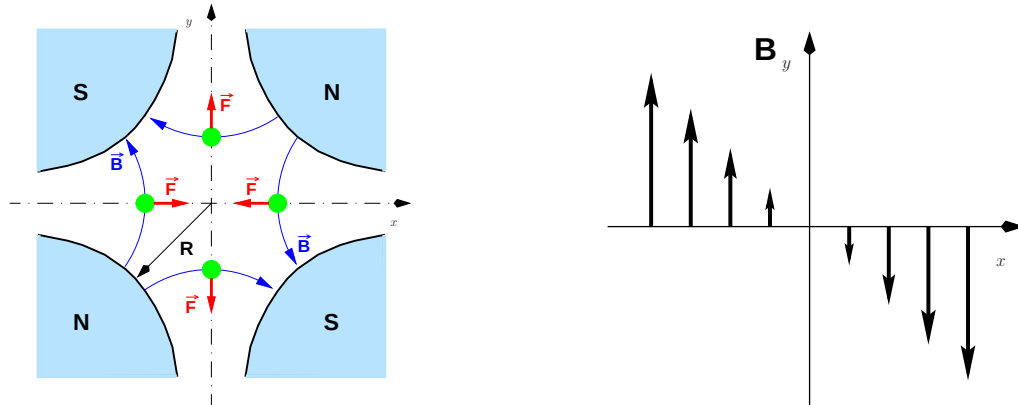


Figure 2.2.3: Field of a magnetic quadrupole: The quadrupole has a focusing effect in the x-plane and a defocusing effect in the y-plane. The field strength increases linearly from the center.

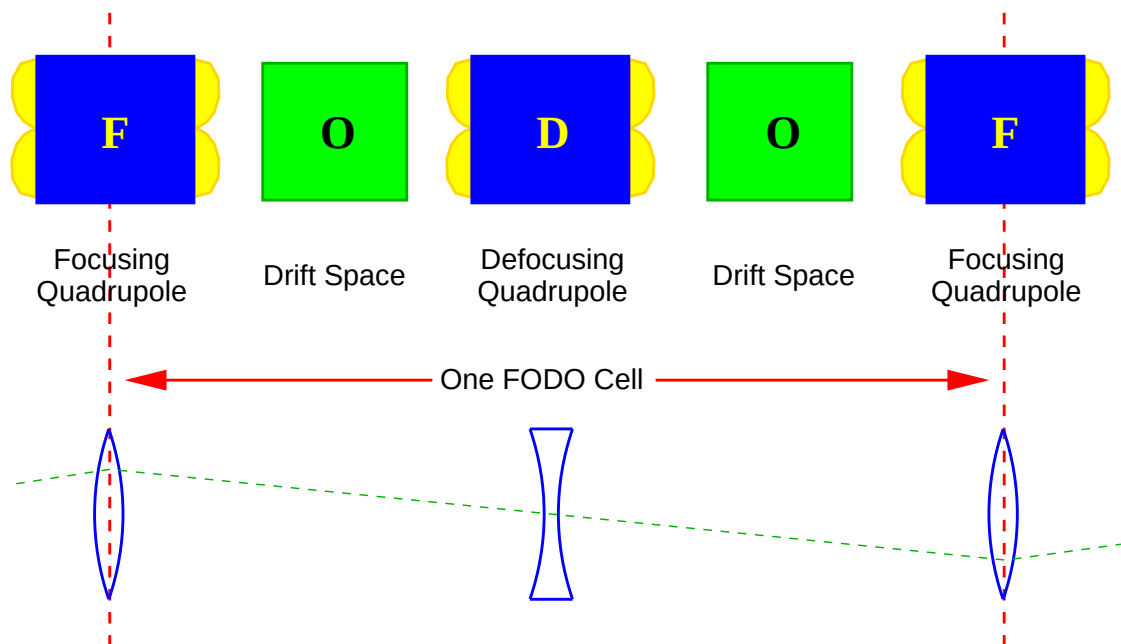


Figure 2.2.4: FODO lattice: The combination of a focusing magnetic quadrupole lens and a following defocusing magnetic quadrupole lens results in an overall focus of the beam particles as known from classical optics. The focusing and defocusing quadrupole have the same focal strength $\frac{1}{f} = kl$ and the distance between two equal lenses is $2f$.

Equation of Motion and Matrix Formalism

In linear beam dynamics the two transverse coordinates are decoupled from each other and it is sufficient to treat them individually. Since in linear accelerators bending magnets are only needed for transfer lines or damping rings and our main interest lies in the linear section like the main accelerator, this chapter will treat only lattices consisting of quadrupoles and drifts.

The particle trajectory in a sequence of quadrupoles is described by the *Hill's equation of motion*:

$$x'' + k(s)x = 0 \quad (2.2.3)$$

where $x'' = \frac{d^2x}{ds^2}$ and $k(s)$ the quadrupole strength defined in Eq. 2.2.2. A quadrupole has a focusing effect if $k > 0$ and a defocusing one if $k < 0$. Because Eq. 2.2.3 is a linear second-order differential equation, its solution can be written in matrix form:

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \quad (2.2.4)$$

where x_0 and x'_0 are the initial displacement and divergence angle and x and x' are the final values. The 2×2 matrix is called *transfer matrix*. The total transfer matrix through a sequence of elements is obtained by forming the product of the individual transfer matrices. If the beam passes the elements 1, 2, 3, $\dots$, n the total transfer matrix is $R = R_n \cdot \dots \cdot R_3 \cdot R_2 \cdot R_1$.

Twiss Parameters

If $k(s)$ is a periodic function of s the solution of Hill's equation has a form similar to that of a harmonic oscillator:

$$x(s) = \sqrt{\epsilon\beta(s)} \cos(\phi(s) + \phi_0) \quad (2.2.5)$$

ϵ and ϕ_0 are constants determined by the initial conditions. $\beta(s)$ and $\phi(s)$ are called amplitude and phase function and are related by:

$$\phi(s) = \int_0^s \frac{1}{\beta(\tilde{s})} d\tilde{s} \quad (2.2.6)$$

It can be shown that x and x' satisfy the equation:

$$\gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2 = \epsilon \quad (2.2.7)$$

where $\gamma\beta - \alpha^2 = 1$. Equation 2.2.7 is the general equation of an ellipse with the center at the origin of the x - x' phase space and area $\pi\epsilon$ (Fig. 2.2.5). The parameters $\gamma(s)$, $\alpha(s)$ and $\beta(s)$ describing the ellipse are called *Twiss parameters* and are all periodic functions

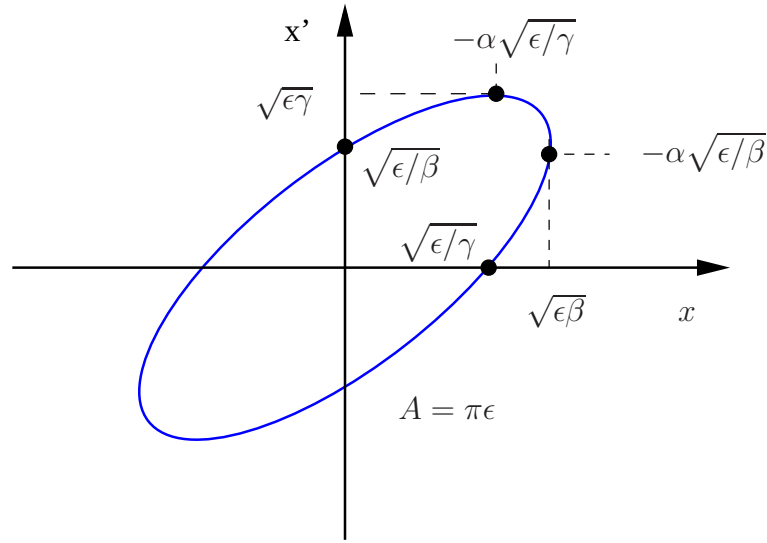


Figure 2.2.5: Phase space ellipse

of s with the same period as $k(s)$. ϵ is called the *Courant-Snyder Invariant* for a single particle and *emittance* for a distribution of many particles.

In this chapter the matrix formalism to transport particle coordinates between two points of the lattice has been introduced. This formalism can be also applied to the beam ellipse. Instead of transforming single particle coordinates, the whole ellipse, defined by the *Twiss matrix*:

$$\sigma_{\text{Twiss}} = \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \quad (2.2.8)$$

is transformed. Equation 2.2.7 is equivalent to the matrix form $X^\top \sigma_{\text{Twiss}}^{-1} X = \epsilon$, where $X = (x_0, x'_0)^\top$ are the phase space coordinates. If R is the transfer matrix between the initial phase space coordinates X_0 and the final phase space coordinates X , then the initial Twiss matrix $\sigma_{\text{Twiss},0}$ transforms like:

$$\sigma_{\text{Twiss}} = R \sigma_{\text{Twiss},0} R^\top \quad (2.2.9)$$

It is important to note, that because all transformations are linear, the beam emittance ϵ stays constant.

Beam Matrix

In linear accelerators the phase space beam distribution has often an elliptical shape. To estimate the transformation of the beam through the lattice, the phase space beam distribution can be enclosed by an ellipse in phase space. The general equation for an ellipse is given by Eq. 2.2.7, which is also used for the description of the beam ellipse. Because particle distributions have no sharp contours, it is useful to work with the rms-values of

the distribution. The ellipse parameters β and γ are defined such that the ellipse projection on the x - x' axes equals the rms values of the distribution. α is defined, so that the rms ellipse coincides with the trajectory ellipse. This definition yields:

$$\begin{aligned}\sigma_x^2 &= \overline{x^2} = \sqrt{\beta\epsilon} \\ \sigma_{x'}^2 &= \overline{x'^2} = \sqrt{\gamma\epsilon} \\ \sigma_{xx'} &= \overline{xx'} = -\alpha\epsilon\end{aligned}\tag{2.2.10}$$

σ_x is called the *beam envelope* and $\sigma_{x'}$ the *beam divergence*. The emittance is then given by:

$$\epsilon = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \sigma_{xx'}^2}\tag{2.2.11}$$

Analogical to the Twiss matrix, the beam matrix is defined by:

$$\sigma_{\text{beam}} = \begin{pmatrix} \sigma_x^2 & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'}^2 \end{pmatrix}\tag{2.2.12}$$

and is related to the Twiss matrix by $\sigma_{\text{beam}} = \epsilon \sigma_{\text{Twiss}}$.

The emittance defined by Eq. 2.2.11 is conserved under two conditions: that Liouville's theorem is satisfied in the six-dimensional phase space and that the forces are uncoupled in the three directions. If acceleration and deceleration of the beam are allowed, the rms emittance doesn't stay constant any more. Applying Liouville's theorem again, one finds that the so called normalized emittance defined by

$$\epsilon_{\text{normalized}} = \beta\gamma\epsilon_{\text{rms}}\tag{2.2.13}$$

is conserved. In this case $\gamma = E/mc^2$ is the relativistic γ -factor and β the velocity in units of the speed of light.

2.2.3 Dispersion

Particle beams are in general not monoenergetic but have a very small finite energy or momentum spread $\Delta p/p$. The effect of the momentum offset on the particle trajectory can be best described with the dispersion function, which is defined as the trajectory of a particle with $\Delta p/p = 1$. The transverse position $x_{\text{tot}}(s)$ of a particle with momentum offset $\Delta p/p$ is then given by [8]:

$$x_{\text{tot}}(s) = x(s) + D(s) \frac{\Delta p}{p}\tag{2.2.14}$$

where $x(s)$ is the trajectory of the reference particle with $\Delta p/p = 0$.

2.3 Basics of RF Cavities

In this chapter we give a short summary of the basics of rf cavities using the example of a cylindrical cavity and focus on the subjects relevant for the CLIC accelerating and decelerating structures as well as for the TESLA cavities. Accelerating structures in general are discussed in [6] and [7]. A list of the characterizing parameters is given in appendix A.

2.3.1 Cylindrical Cavity

Particles are commonly accelerated by high frequency alternating fields (chapter 2.2.1). Free electromagnetic waves do not have a component in the longitudinal direction and are therefore not usable without modification. By introducing the right boundary conditions electromagnetic waves obtain a longitudinal field component, which is given by the Laplace equation [6]:

$$\nabla^2 \vec{E} - \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} \quad (2.3.1)$$

with the solution for the longitudinal component:

$$E_s = E_{0s} e^{i(\omega t - ks)} \quad (2.3.2)$$

A similar equation holds for the azimuthal magnetic field.

For a cylindrical cavity it is more adequate to use cylindrical coordinates. The azimuthal field component varies periodically with the azimuth θ and therefore $\partial^2 / \partial \theta^2 = -n^2$, where n is the periodicity. With this Eq. 2.3.1 yields for the longitudinal component E_s :

$$\frac{\partial^2 E_s}{\partial r^2} + \frac{1}{r} \frac{\partial E_s}{\partial r} + \left(k_c^2 - \frac{n^2}{r^2} \right) \quad (2.3.3)$$

where the cutoff wave number k_c is defined by:

$$k_c^2 = \frac{\omega^2}{c^2} - k^2 \quad (2.3.4)$$

This differential equation can be solved with Bessel functions. The solution depends on the periodicity n , the so called *modes* of the cavity. Transverse magnetic and electric field components can be derived from Eq. 2.3.1 using Maxwell's curl equations and exhibit a similar mode structure.

The modes can be classified into two main groups, the TE modes, with only transverse electric field components and the TM modes, with only transverse magnetic field components. For particle acceleration only the TM modes can be used as they possess a longitudinal electric field component. Each mode is characterized by three indices TM_{npq} , where n is the azimuthal periodicity, p the radial periodicity and q the longitudinal. For

acceleration e.g. the TM_{010} would be adequate as it has a longitudinal field component. In most cases the fundamental mode of the structure is used for acceleration.

In order to obtain a travelling wave and not a decaying one, the wave number k_c^2 must be positive and we assume according to Eq. 2.3.2 $\omega/c > k_c$ and define the cutoff frequency $\omega_c = ck_c$.

Important for particle acceleration are the phase and group velocity of the wave. For a cylindrical cavity the phase velocity v_{ph} is bigger than the speed of light while the group velocity v_g is smaller:

$$v_{ph} = \frac{c}{\sqrt{1 - \omega_c^2/\omega^2}} > c \quad v_g = \frac{c^2}{v_{ph}} < c \quad (2.3.5)$$

2.3.2 Disk Loaded Waveguide

By introducing the right boundary conditions, the plane electromagnetic waves are modified to a wave with a non vanishing longitudinal electric field component, but with a phase velocity bigger than the speed of light. For particle acceleration the phase velocity must be equal to the particle velocity. This can be achieved by inserting metallic structures into the waveguide. The most common shape of these structures are disks, which are placed perpendicular to the waveguide axis. The resulting waveguide is a *disk loaded waveguide*. The inserted disks create a sequence of cavities coupled through the central hole, the *iris*, which in total acts as a band pass filter allowing electromagnetic fields of certain frequencies to propagate. By choosing the right geometry the desired frequency and phase velocity can be adjusted. Structures of this type are for example used in TBONE.

2.4 Synchrotron Radiation

The Maxwell equations and the theory of retarded potentials predict, that every moving charged particle loses energy in form of emitted radiation. This was first observed in 1974 at the 70 MeV synchrotron built at General Electric. Since then the radiation is called synchrotron radiation.

End of last century Lamor calculated the power of the radiation emitted by a nonrelativistic particle ($v \ll c$) with charge e moving with a momentum $\vec{p} = m_0\vec{v}$ [8]:

$$P_s = \frac{e^2}{6\pi\epsilon_0 m_0^2 c^3} \left(\frac{d\vec{p}}{dt} \right)^2 \quad (2.4.1)$$

The angular distribution of the radiation is identical with the one of a Hertzian dipole (Fig. 2.4.1).

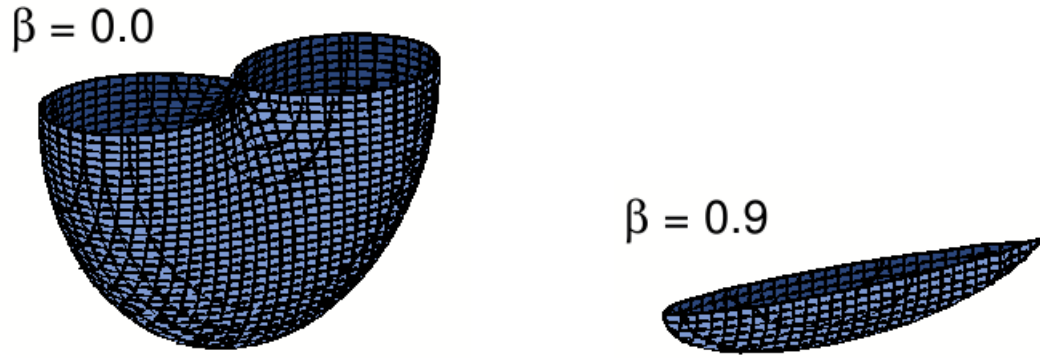


Figure 2.4.1: Angular distribution of Synchrotron radiation: In the rest frame of the electron ($\beta = 0.0$), the angular distribution is equivalent to the one of a Hertzian dipole and has a toroidal shape. In the laboratory system for an electron with ($\beta = 0.9$) it changes to a conical shape due to the Lorentz boost.

In the case of relativistic velocities ($v \approx c$), which is a good approximation for most electron machines, Eq. 2.4.1 changes to:

$$P_s = \frac{e^2 c}{6\pi\epsilon_0(m_0 c^2)^2} \left[\left(\frac{d\vec{p}}{d\tau} \right)^2 - \frac{1}{c^2} \left(\frac{dE}{d\tau} \right)^2 \right] \quad (2.4.2)$$

where τ is the time in the restframe of the electron (Fig. 2.4.1).

The radiation power depends on the direction of motion and acceleration of the particle. In the following the case of longitudinal ($\frac{d\vec{v}}{d\tau} \parallel \vec{v}$) and transverse acceleration ($\frac{d\vec{v}}{d\tau} \perp \vec{v}$) will be treated in more detail .

2.4.1 Longitudinal Acceleration

For linear acceleration Eq. 2.4.2 yields [8]:

$$P_s = \frac{e^2 c}{6\pi\epsilon_0(m_0 c^2)^2} \left(\frac{dp}{dt} \right)^2 \quad (2.4.3)$$

Hence in a linear accelerator the energy loss caused by synchrotron radiation is very small. This can be shown with a simple example. If the energy gain per meter is dE/dx and we assume that the particles are relativistic, then the efficiency - the ratio between the radiated power and the power gained by the acceleration - yields:

$$\frac{P_s}{dE/dt} = \frac{P_s}{v dE/dx} = \frac{e^2}{6\pi\epsilon_0(m_0 c^2)^2} \frac{1}{\beta} \frac{dE}{dx} \quad (2.4.4)$$

For example for an acceleration per meter of $dE/dx = 15 \text{ MeV/m}$, the efficiency is 5.5×10^{-14} and in comparison for TBONE with a higher acceleration per meter $dE/dx =$

30 GeV/m the efficiency is 1.1×10^{-6} , which is in both cases very small.

Also if in a first approximation synchrotron radiation can be neglected for linear accelerators, it has to be taken into account if more accuracy is required. It can become relevant in elements, where the particles follow a bend orbit (e.g. dipoles, quadrupoles and cavities).

2.4.2 Transverse Acceleration

If a particle is following a circular orbit, the emitted radiation is [8]:

$$P_s = \frac{e^2 c \gamma^2}{6\pi \epsilon_0 (m_0 c^2)^2} \left(\frac{dp}{dt} \right)^2 \stackrel{dp/dt = pv/R}{=} \frac{e^2 c}{6\pi \epsilon_0 (m_0 c^2)^4} \frac{E^4}{R^2} \quad (2.4.5)$$

where R is the bending radius of the particle orbit. Accordingly the synchrotron radiation power:

- is larger for particles with a smaller rest mass ($\sim \frac{1}{m_0^4}$).
- increases with the energy of the particle, so becomes more relevant for high beam energies ($P_s \sim E^4$).
- increases with decreasing bending radius ($\sim \frac{1}{R^2}$).

2.4.3 Coherent Synchrotron Radiation (CSR)

A particle bunch always emits coherent as well as incoherent synchrotron radiation. Coherent radiation is only emitted with wavelengths equal to or larger than the bunchlength (Fig. 2.4.2). Commonly the wavelengths are very large and cut off by the beampipe. Therefore the bunchlength has to be very short in order to make the coherent part of the radiation accessible. In linear accelerators the bunches can emit coherently, if the bunch length is very short, which is e.g. used in TBONE.

The characteristic of coherent synchrotron radiation is, that the radiation power increases quadratically with the number of particles per bunch instead of linearly in the case of incoherent radiation.

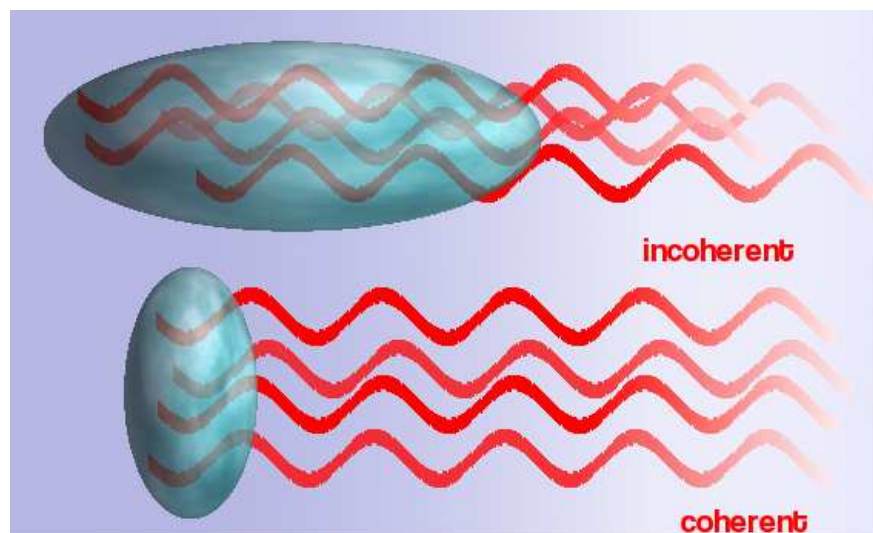


Figure 2.4.2: Coherent and incoherent synchrotron radiation: The radiation is coherent, if the wavelength is equal to or larger than the bunch length.

Chapter 3

CLIC

The large hadron collider (LHC) will be the first accelerator in the multi TeV range. Many open questions in elementary particle physics such as e.g. the existence of a Higgs boson or supersymmetry will be hopefully answered by the experiments at the LHC, but there is a good chance that some of the problems will be left unsolved. Some of them may best be addressed by a lepton-antilepton collider.

As the energy loss per turn due to synchrotron radiation scales with $1/m^4$ and is thus much larger for electrons than for protons, it is not feasible to build a circular electron-positron collider for this energy scale. Therefore, present studies of future lepton-antilepton colliders in the TeV range focus on linear electron-positron accelerators. The Compact Linear Collider (CLIC) is a possible design for a linear electron-positron collider in the TeV range based on the two beam acceleration technique. It has been shown that with this technique center-of-mass energies from 500 GeV up to 5 TeV and a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ or higher could be reached. The physics experiments require a luminosity of at least $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a minimal center-of-mass energy of 1 TeV. The CLIC design study presently concentrates on a center-of-mass energy of 3 TeV and a luminosity of $5.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. A description of CLIC as well as the latest parameters can be found in [3] and [9].

3.1 CLIC RF Power Production and the Two Beam Acceleration Technique

To reach the design energy of 3 TeV within a reasonable accelerator length ($< 40\text{km}$) the accelerating gradient has to be very high (100 MV/m). Because superconducting technology as used for the International Linear Collider (ILC) is limited to lower gradients ($< 50\text{MV/m}$) [10], room temperature travelling wave structures have to be used. The most obvious idea would be to generate the rf pulses with klystrons. Following this idea,

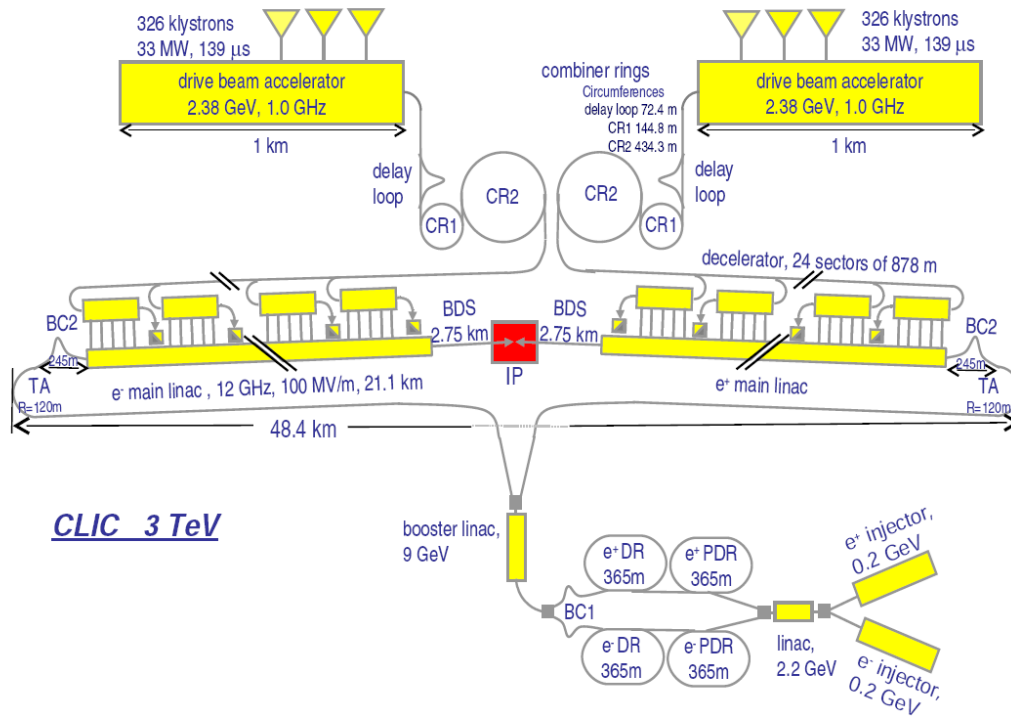


Figure 3.0.1: Schematic layout of CLIC for a design energy of 3 TeV and a frequency of 12 GHz: The bottom half shows the main beam complex, the upper half the drive beam complex, which will act as power source of the main linac. [9]

the together 42 km long main linacs would have to be equipped with X-Band klystrons producing short pulses. This would be of course very costly. Instead a more cost efficient and promising way of producing high accelerating gradients at high frequencies is the two beam acceleration technique [11].

The principle of the two beam acceleration technique is to transform long rf pulses with low frequency, which are easy to produce by standard klystrons, into short rf pulses with high frequency and peak power. The manipulation of the rf pulses is done with the help of a high intensity electron beam, the so called drive beam. The advantage of electron beam manipulation compared to manipulation of rf pulses is that beam pulses can be transported over long distances with very low losses and be highly compressed.

Using a single drive beam pulse for the acceleration of the main beam along the total linac length, would require very short pulses of high energy and current. Such pulses would be very challenging to create, accelerate and manipulate. Instead the parallel section (Fig. 3.0.1), where the power is extracted from the drive beam and transferred to the main beam, is divided into 24 smaller units. In each unit one train supplies the power required to accelerate the main beam along the length of one unit.

3.2 Main Beam

The general layout of the main linac consists of the injector complex, the transfer line and the main accelerator (Fig. 3.0.1). All parameters as well as more information can be found in [9].

3.2.1 Injector Complex

CLIC is designed for a polarized electron beam and an unpolarized positron beam. The injector complex consists of a positron and a polarized electron source, an injector linac and pre-damping and damping rings (Fig. 3.2.1).

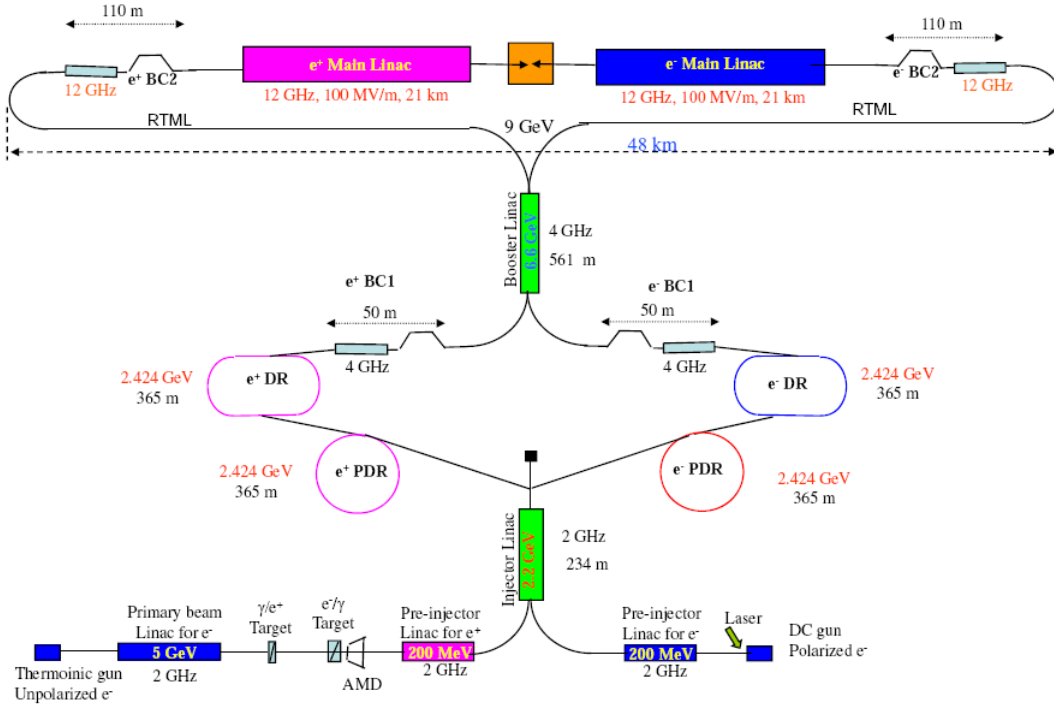


Figure 3.2.1: Main linac injector complex. [9]

Electron Source

The polarized electron beam is produced using a high-voltage DC photo injector. A laser which provides already the final time structure of the beam hits a GaAs cathode situated in a high voltage gun. The gun is designed to deliver 4.4×10^9 electrons with 80 % polarization to the entrance of the pre-damping rings. A 2 GHz L-band linac will accelerate subsequently the polarized electrons to 200 MeV followed by a 2.2 GeV linac at the same

frequency. This injector linac also serves as positron accelerator (Fig. 3.2.1). Because the positron beam has by far the largest transverse emittance, the constraints for the injector linac are set by the positron beam and not the electron beam. With the exception of the peak current the key parameters of this source have been achieved in existing or past polarized electron sources.

Positron Source

For the positron generation a 5 GeV electron beam is sent to a tungsten single crystal target. It produces photons and electron-positron pairs. Electrons, positrons and photons are then separated by a dipole magnet. An Adiabatic Matching Device (AMD) with a magnetic field varying from 7 to 0.5 T is used to prepare the positron beam for the injection into the first accelerating structure [12]. In a large acceptance L-band linac with a different design than the corresponding 200 MeV electron linac, the positrons will be accelerated first to 200 MeV and subsequently to 2.2 GeV by the injector linac shared with the electron beam.

Pre-damping Rings and Damping Rings

In order to reach the design luminosity, the emittance constraints for the main linac are very tight. For the emittance reduction pre-damping and damping rings are used. Due to the different generation of the positron and electron beam, the positron beam will have a considerably larger emittance than the electron beam and is therefore the more challenging beam in respect to beam size reduction.

To decouple the wide aperture requirements for the positron beam from the final emittance requirements of the main linac, the beam is pre-damped in a pre-damping ring with a large dynamic acceptance and a relatively large equilibrium emittance. The pre-damping ring is followed by a damping ring with a racetrack like layout and a total length of 365.2 m (Fig. 3.2.2). The two arcs contain theoretical minimum emittance (TME) cells and the straight sections FODO cells with damping wigglers ending with dispersion suppressors, an injection/extraction region or rf cavities. A pair of sextupoles is responsible for the chromaticity corrections. The beam dynamics of the damping rings are dominated by intrabeam scattering due to the relatively small energy, small beamsizes and high current.

The emittance of the electron beam after the injector would be small enough to do without a pre-damping ring. The reason for the additional pre-damping ring is the reduction of the damping time, so that the electron and positron beam keep synchronised [13].

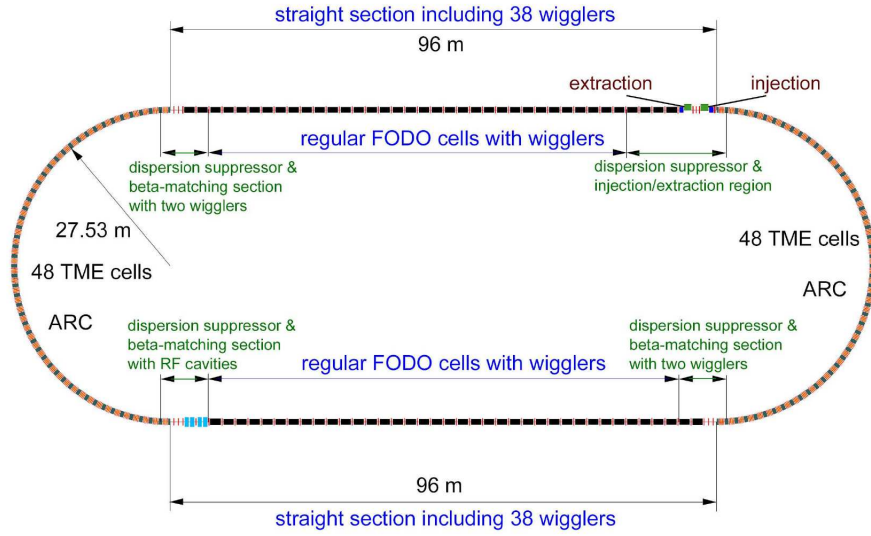


Figure 3.2.2: Schematic layout of the CLIC damping rings. [9]

3.2.2 Booster Linac, Ring To Main Linac (RTML)

The transfer line from the damping rings to the main linacs includes the bunch compression, the acceleration to 9 GeV in the booster linac and the RTML (Fig. 3.2.1). The main challenge is to preserve the beam quality obtained in the damping rings until the end of the transfer line.

The bunch compression is done in two stages: first in front of the Booster linac to shorten the bunch for acceleration and finally at the entrance to the main linac. Each chicane consists of four magnets and compresses the bunches first by a factor nine and finally by a factor four [14]. Rf cavities are placed in front of each bunch compressor to introduce the right energy chirp for the compression. For the 270 degree turn around loop at the beginning of each linac special optics were designed to preserve the emittance taking coherent synchrotron radiation and intrabeam scattering effects into account.

3.2.3 Main Linac

The rf power for the main linac is supplied by the drive beam and transferred from the Power Extraction and Transfer Structures (PETS) (chapter 3.3.2) to the main accelerating structures (chapter 3.1). To facilitate the matching of the optics of the two beamlines the different structures are combined in modules, where each module consists of four PETS. Each PETS provides the power for two accelerating structures (Fig. 3.2.3). The necessary focusing is performed with a conventional FODO lattice. The quadrupoles are part of the modules and replace up to four of the cavities. A beam position monitor is placed in front of each cavity [15].

The beam dynamics of the main beam are strongly influenced by the wakefield effects. Transverse wakefields are mostly responsible for the emittance growth, which is compensated by the quadrupole focusing of the beam. Longitudinal wakefields induced from the head of the bunch are decelerating the tail and introduce an energy spread in each bunch. For this reason the beam is accelerated below transition.

For the acceleration waveguide damped structures are used. To reduce the effect of long-range as well as short-range transverse wakefields on the beam, the accelerating structures were carefully designed and optimized. A description of the present structure design can be found in [9].

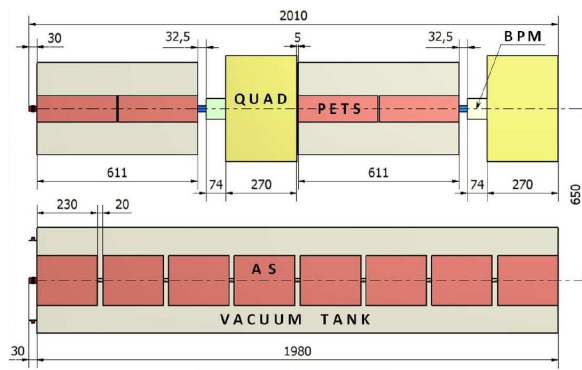


Figure 3.2.3: Schematic layout of one CLIC module. The drive beam is shown on top and the main beam on the bottom. One PETS supplies the power for two accelerating structures. [9]

3.3 Drive Beam

The purpose of the drive beam is to provide the power for the main beam acceleration (chapter 3.1). The general layout of the drive beam complex is shown in Fig. 3.0.1. It consists of the drive beam accelerator, the drive beam manipulation section, the transfer line and the parallel section consisting of 24 decelerators per linac. A summary of the main issues of the decelerator will be given in the following. A more detailed description with emphasis on the beam dynamics can be found in [5].

3.3.1 Drive Beam Generation

After gun and injector the drive beam is a $140 \mu\text{s}$ long electron beam. This beam is then accelerated to approximately 2.4 GeV in a linear accelerator powered by klystrons. The accelerating structures of the linac are fully loaded, so that about 98 % of the rf power are transferred to the beam (Fig. 3.3.1). After the acceleration the beam pulse is composed of 24×24 sub-pulses, each 240ns long. In each sub-pulse the electron bunches occupy

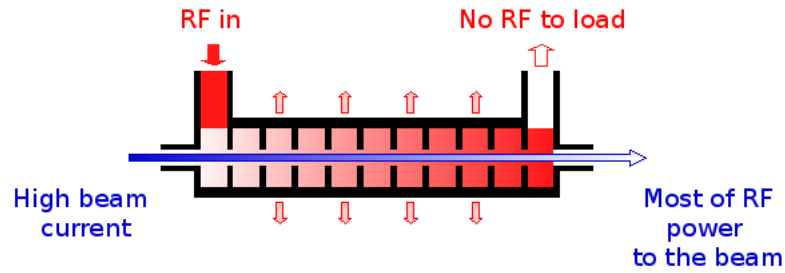


Figure 3.3.1: Fully loaded structure. [9]

alternately only the even or odd buckets of the drive beam accelerator. The long pulse then passes through a delay line, where a rf deflector combines the bunches, so that the delayed bunches are placed between the bunches of the following sub-pulse. After the delay loop the whole pulse consists of 12×24 sub-pulses. The sub-pulses are then combined again by two consecutive combiner rings, first by a factor 3 to 4×24 and then by a factor 4 to obtain the final 24 sub pulses or trains required for the main linac (Fig. 3.3.2). Each final train consists of 2928 bunches with a charge of 8.4 nC/bunch and an energy of 2.4 GeV. The trains are then transported via a common transfer line to the section, where main and

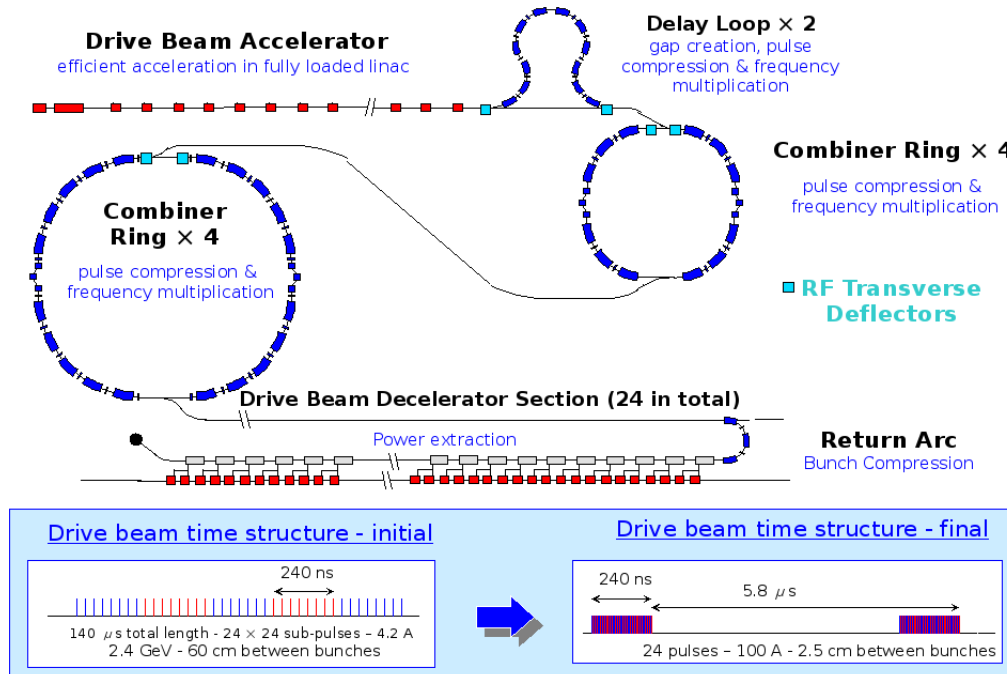


Figure 3.3.2: Schematic layout of one CLIC rf power source complex. [9]

drive beam run parallel to each other. Pulsed magnets deflect each train at the appropriate time into a turn around loop leading to the corresponding decelerator. There the beam

is decelerator in Power Extraction and Transfer Structures (PETS) (chapter 3.2) by 90 % of its initial energy and the output power is transferred to the main beam accelerating structures. At the end of each decelerator the beam is dumped and the next train is used to accelerate the main beam along the next unit.

3.3.2 Power Extraction and Transfer Structures (PETS)

The PETS is basically a travelling wave-structure with a fundamental mode frequency of 12 GHz, where rf power is produced instead of being absorbed (Fig. 3.3.3). The functional principle of the PETS is not fundamentally different from any travelling wave accelerating structure. Simplified, in order to extract power from the beam, the steps in the process of acceleration are taken in reversed order. A charge passing through the PETS excites the fundamental mode and the field of this mode will travel along the PETS trailing behind the charge with a velocity $v_g < c$. At the end of the PETS the field of the excited mode travels out of the structure and is transferred to the main accelerating structure of the main linac.

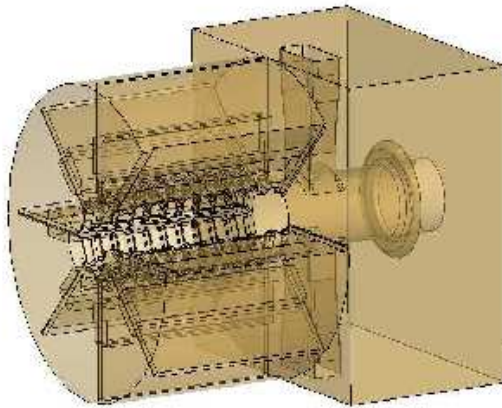


Figure 3.3.3: CLIC module [9]

3.3.3 Decelerator Beam Dynamics

In this chapter we want to give a short summary of the beam dynamics studies for the decelerator, which are documented in [5].

The decelerator beam dynamics are dominated by the effect of the PETS wakefields on the beam. The beam experiences two main effects in the PETS: the desired deceleration caused by the longitudinal wake field of the fundamental mode and the effect of higher order mode wakefields leading to unwanted behaviour of the beam. In [5] the dipole mode

has been studied in detail, but the influence of wake fields from quadrupole or higher order moments have not been inspected in any work.

Deceleration

Beam particles, which pass the PETS excite the fundamental mode and the resulting wakefield decelerates trailing particles. At the end of each PETS the field is then coupled out and transferred to the main linac. A trailing charge therefore sees the sum of the wakefields of all particles ahead of it except the part, which has already left the PETS. This leads to a smaller deceleration of particles in the head and tail of one bunch and a larger deceleration of particles in the center (Fig. 3.3.4 (b)). The second effect is, that the deceleration of the bunches increases along the beam until the “steady state” is reached, where each bunch sees the same decelerating field (Fig. 3.3.4 (a)).

Following the baseline specification the most decelerated particle loses 90% of its energy along the whole decelerator. This stands in contrast to the least decelerated particle, which almost maintains its energy throughout the whole decelerator. This behaviour causes a large asymmetric energy spread in the beam and in one bunch, which is very unusual for common beams and is a characteristic of the drive beam.

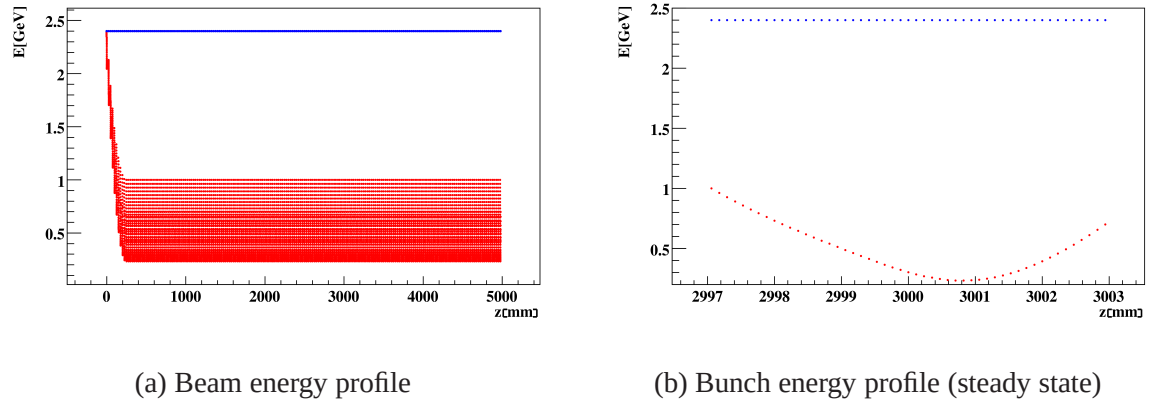


Figure 3.3.4: Beam energy profile at injection, in blue, and at the end of one decelerator, in red. Figure (a) shows the beam profile: The deceleration of the bunches increases along the beam until the “steady state” is reached. Figure (b) shows the bunch profile (steady state): The particles in the head and tail of one bunch are more decelerated than the particles in the center.

Lattice Design and Transverse Focusing

The PETS are designed to supply the power for two accelerating structures. If other elements e.g. quadrupoles for transverse focusing are installed instead of accelerating

structures in the main linac, the corresponding PETS will have to be substituted by drift lengths. This leads to different lengths of the decelerators as in every decelerator the same energy must be extracted from the beam.

While the longitudinal wakefields are responsible for the deceleration, the transverse wakefields cause a transverse deflection of the beam particles resulting in a large emittance growth. To compensate for this effect one FODO cell per module will be installed. Between each quadrupole none, one or two PETS will be placed depending on the number of accelerating structures (Fig. 3.2.3). The quadrupole strength is adjusted, so that the most decelerated particle experiences a constant normalized quadrupole strength along the lattice. It is obvious that only a small fraction of the beam particles will be focused in an optimal way, which implies that a small energy spread is required at injection and a large emittance growth is expected along the decelerator despite the strong focusing.

3.4 CTF3 - CLIC Test Facility

The CLIC technology is based on a number of novel concepts which have never been used before and some parameters are approaching the limit of available technology. One major programme in the CLIC R&D is the CLIC Test Facility (CTF3). The aim of this facility is to demonstrate by the year 2010 [16]:

- The feasibility of the CLIC rf power source: The drive beam generation using the bunch interleaving technique with rf deflectors and generation of 12 GHz rf power with PETS.
- A parallel unit consisting of an accelerating structure fed by one PETS with nominal CLIC parameters of power and accelerating field and acceleration of a probe beam.

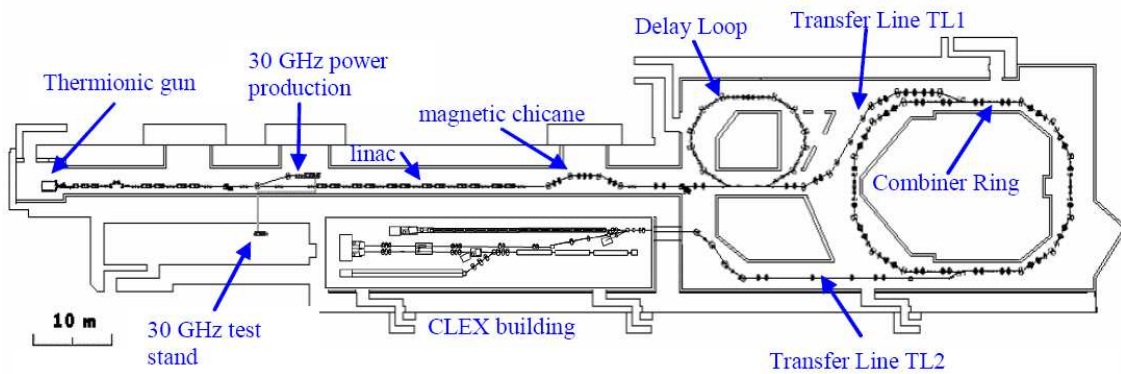


Figure 3.4.1: Layout of CTF3 [16]

The layout of CTF3 is shown in Fig. 3.4.1. The beam is generated with a thermionic gun followed by a system of bunchers and then accelerated in 3 GHz rf linac. During the acceleration in the linac the beam can be extracted to the 30 GHz power production test stand. A magnetic chicane at the end of the linac allows lengthening of the bunches to control coherent synchrotron radiation effects in the following two rings. The bunch train after the linac is $1.4 \mu\text{s}$ long and consists of ten 140 ns long sub-trains. The next elements are the delay loop and the combiner ring, where the sub-pulses are combined first by a factor of 2 and then by a factor of 4. After the combiner ring the beam is compressed in the Transfer Line (TL2) and transported into CLEX (CLIC Experimental Building). CLEX contains several beam lines:

Test Beam Line (TBL) : The beam will be decelerated to about have its energy in up to 16 PETS. The basic lattice cell consists of one PETS and one quadrupole for focusing, which will be on movable supports in order to simulate alignment errors and beam based alignment.

Probe Beam : In a stand alone linac a low current probe beam will be accelerated to 200 MeV. The aim is to demonstrate particle acceleration with CLIC accelerating structures.

The Two Beam Test Stand (TBTS) : This test stand will simulate the CLIC main linac. The probe beam will be accelerated at the nominal CLIC gradient. The beam from CTF3 runs parallel to the main beam and delivers the power for the acceleration of the probe beam. The power is extracted with CLIC-type PETS, which are modified such that the nominal CLIC rf power can be produced with the 30 A beam.

The main CTF3 and CLIC beam parameters are given in Table 3.4.1. Status and commissioning results as well as more detailed information and further references to CTF3 can be found in [16].

	CLIC	CTF3
Drive beam energy	2.4GeV	150MeV
Drive beam current	100 A	28 A
Drive beam rf frequency	999.5 MHz	3 GHz
Train length in linac	$139 \mu\text{s}$	$1.5 \mu\text{s}$

Table 3.4.1: CLIC and CTF3 main parameters

Chapter 4

TBONE - A New Facility for Coherent THz to mid-IR Radiation

High power THz to mid-IR radiation has a wide range of applications in condensed matter science like superconductivity and behaviour of correlated electron systems as well as in biology like protein folding, solvation and biological interfaces. In order to make the investigation of these fields possible or to complement present research programs, the Forschungszentrum Karlsruhe (FZK) proposes a new THz light source called TBONE (THz Beam Optics for New Experiments).

Common sources of THz and IR radiation are short pulse lasers, table top sources like thermal radiators and Free Electron Lasers (FEL). Most FEL and XFEL facilities concentrate on X-ray emission and existing THz FELs have longer pulse lengths compared to TBONE and narrow band operation, i.e. to change the photon energy by reconfiguring the accelerator can take up to several minutes and is inappropriate for spectroscopic applications. In comparison to other facilities optimized for THz radiation like JLab TBONE covers a much larger spectral range and delivers orders of magnitude higher peak power. Therefore the door for new science would be opened by the new intense radiation source TBONE [4],[17].

TBONE aims at a spectral range from about 0.1 to 150 THz with a peak power of several MW. In order to achieve this the effective pulse length must be of the order of 5 fs and the repetition rate around 10 MHz. For the purpose of spectroscopic studies an energy of 60 MeV would suffice, but in order to use TBONE also as a teststand for superconducting insertion devices the option for an energy of 100 MeV is kept. The design parameters of TBONE are given in Table 4.0.1.

The presented design parameters i.e. the duty cycle for the chosen current can only be achieved with a superconducting electron linac. The proposed layout of the facility is shown in Fig. 4.0.1. As electron source two options are considered: a DC photo emission gun [18] or and SRF photo injector [19]. The injection system is followed by a booster

Frequency range	0.1 – 150 THz
Peak power	up to several MW
Pulse length	down to 5 fs
Repetition rate	10 MHz
Linac energy	60 – 100 MeV
Bunch charge	10 – 100 THz

Table 4.0.1: TBONE design parameters

and the superconducting linac, which consists of 3 superconducting 9-cell TESLA cavities [20]. After the linac an insertion device test stand can be installed followed by the bunch compression system. In order to obtain a frequency of 150 THz the charge distribution after the bunch compression needs to have a 5 fs peak, but does not have to be necessarily gaussian. One option for the bunch compression in TBONE would be a 4-dipole magnetic chicane [21]. To limit the divergence of the beam after the extreme compression a so-called “Missing Bend FODO” lattice [22] is proposed for the magnetic lattice responsible for the generation of coherent radiation [17].

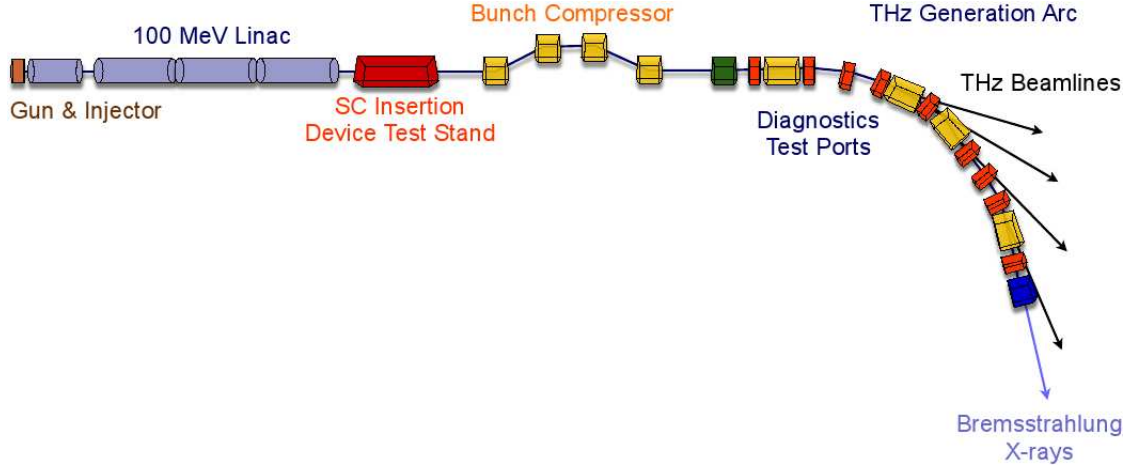


Figure 4.0.1: Lattice layout of TBONE: The lattice consists of injector, linac, insertion device test stand, bunch compressor and magnetic lattice for the generation of coherent radiation.

4.1 Injector System

Our aim is to study the beam dynamics in the superconducting linac. In order to obtain realistic simulation results the beam distribution at injection in the linac, so at the exit of the injector, is needed. The choice and following simulations of the injector system for

TBONE are not yet finished. As a substitute we chose the ALICE injector design as presented in [18], because this design has final beam parameters similar to the ones required for TBONE. The ALICE injector layout is shown in Fig. 4.1.1.

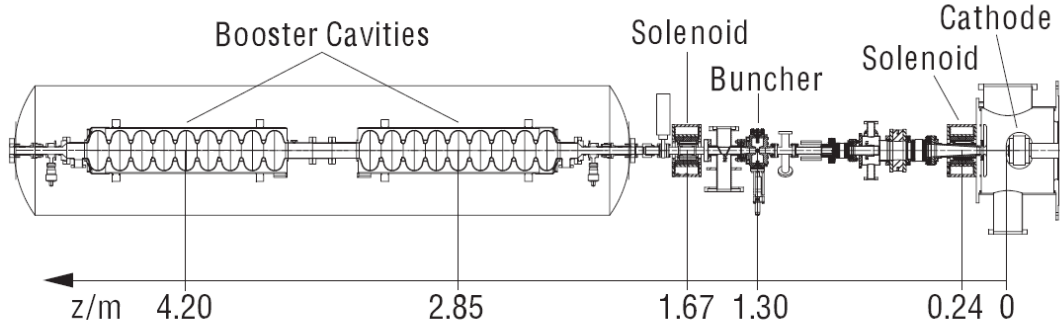


Figure 4.1.1: ALICE injector design [18]

The DC photocathode gun consists of a GaAs photocathode which is illuminated by a laser beam from a Nd : YVO₄ laser. At the end of the gun the emitted electrons have an energy of 350 keV. The gun is followed by a solenoid for focusing, a single-cell normal conducting buncher cavity operated at the fundamental linac frequency of 1.3 GHz and a second solenoid for further focusing. The Booster consists of two 9-cell superconducting cavities operated at 1.3 GHz, where the electrons are accelerated to an energy of 8.35 MeV. At the entrance of the first booster cavity the electrons have not yet reached relativistic velocities and are therefore slightly decelerated in the first cell of the cavity. In the second cavity the beam is relativistic and the chosen cavity phase does not influence the bunchlength any more, but can induce an energy chirp in the beam. The beam parameters at the end of the ALICE injector taken from [18] are summarized in Table 4.1.1. For TBONE the beam distribution at the end of the ALICE injector has a by a factor of 2 too long bunch length and $\alpha \neq 0$. A shorter bunch length is required in order to reach the design pulse length of 5 fs after the bunch compressor. Since in the present TBONE layout no further focusing is done, a non-zero α would lead to an increase of the beam size. By a different operation mode of the first booster cavity and a better adaption of the laser, a shorter bunch length at the exit of the booster could probably be obtained. Another option would be to use the second proposed injector used at ELBE [19], which delivers the required bunch length but has an upper limit to the bunch charge of 77 pC. We therefore assume a beam distribution similar to the one after the ALICE injector, but adapted to TBONE. The modified parameters are summarized in Table 4.1.1 and the beam distribution at the exit of the injector system shown in Fig. 4.1.2.

Parameter [unit]	Symbol	ALICE	TBONE (assumed)
norm. transverse emittance [μm]	$\epsilon_{x,y}$	1.40	1.40
alpha function	$\alpha_{x,y}$	-2	0
beta function [m]	β_x	15.0	15.19
beta function [m]	β_y	15.0	15.30
bunch length [mm]	σ_z	1.20	0.62
bunch length [ps]	σ_z	4.0	2.06
Beam energy [MeV]	E	8.35	8.35
Bunch charge [pC]	Q_{bunch}	80.0	83.86
numb. of part. per bunch [10^9]	N_{bunch}	0.50	0.52

Table 4.1.1: Beam parameters and assumed beam parameters after the injector for ALICE and TBONE

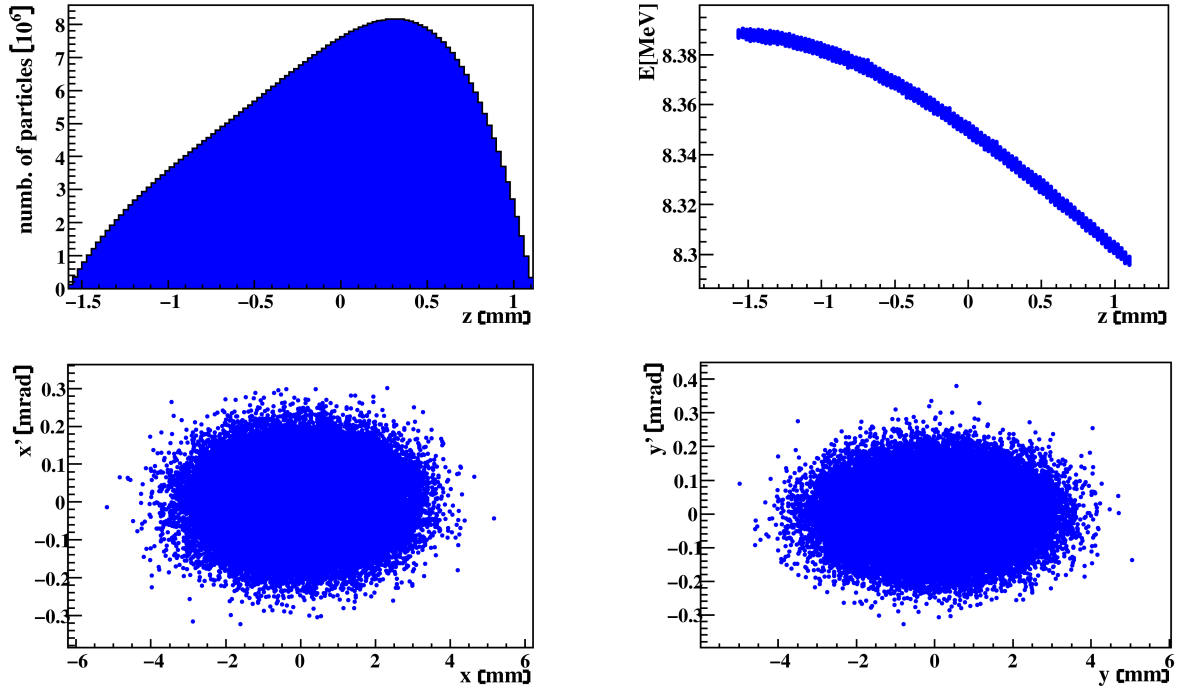


Figure 4.1.2: Assumed beam distribution after the injector system of TBONE

In detail we have performed the following modifications of the bunch distribution: For the generation of the bunch distribution we wrote a script in Octave, which fits a polynomial on the charge and kinetic energy spread distribution at the end of the ALICE injector and shortens both by a factor of 2.1 to obtain the required bunch length. A simulation of all 10^8 beam particles is not possible as the simulation would just take too long. Therefore we sliced the beam into 101 slices and reduced the number of particles to 101000. The

transverse distribution of every slices is based on the Twiss parameters of ALICE. In order to obtain $\alpha = 0$ we afterwards rotated the transverse phase space distribution. The final distribution was then used as input for the simulations of the beam dynamics in the superconducting linac (chapter 4.2).

4.2 Superconducting Linac

The superconducting linac consists of three superconducting 9-cell TESLA cavities operated at a fundamental frequency of 1.3 GHz (Fig. 4.2.1).

The beam dynamics of the superconducting linac were simulated with PLACET [1],



Figure 4.2.1: Superconducting 9-cell TESLA cavity

which includes the simulation of the rf and wakefield kick (chapter 5.3.7) in the cavities. The simulation method is described in [23]. The wakefields in the superconducting linac have not yet been computed, but an exact calculation of the wakefields would be out of scope of this thesis. Since the ILC main linac is composed of the same type of superconducting linac modules, we used as a first approximation the wakefield calculation for the ILC main linac but with the bunch length and charge of TBONE as input parameters.

For the bunch compression a very large energy chirp in the beam is needed. By operating all three cavities above transition with rising phase of the cavity, some particles are decelerated and a large energy spread can be induced. For the first cavity we chose a phase of 5.3° , for the second 40.3° and for the third also 40.3° . The distribution at the end of the linac is shown in Fig. 4.2.2 and the final beam parameters given in Table 4.2.1.

With the performed simulations it was possible to show, that by running all three cavities above transition a final distribution suitable for the later bunch compression could be obtained.

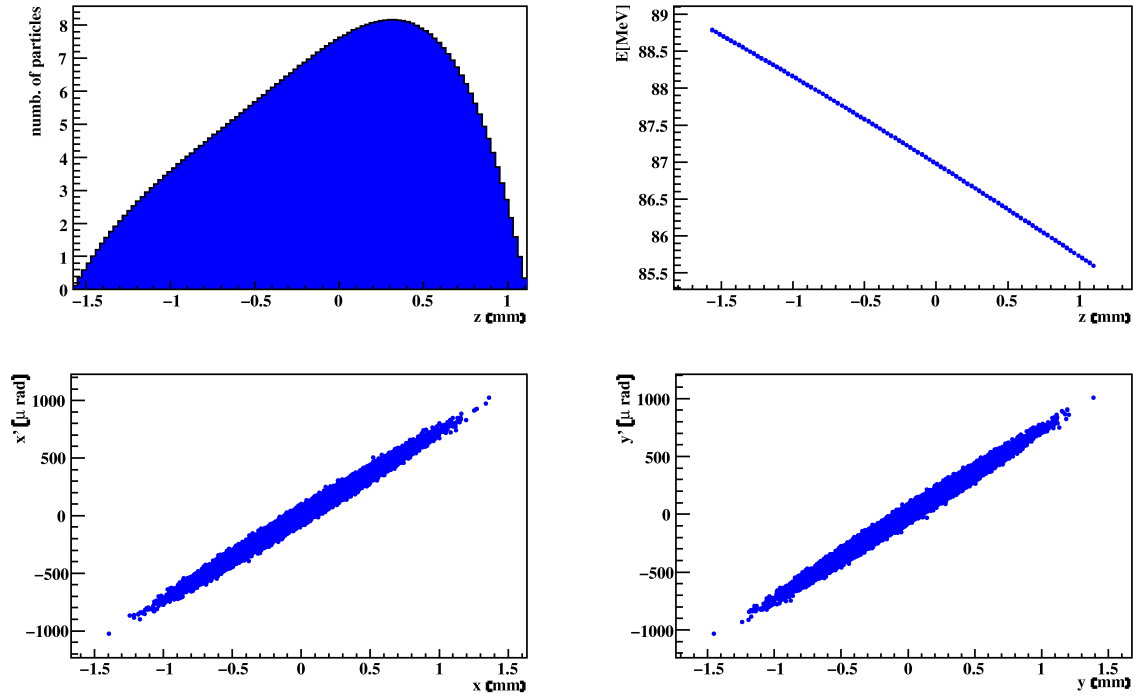


Figure 4.2.2: Beam distribution after the superconducting linac of TBONE

Parameter [unit]	Symbol	Value
norm. transverse emittance [μm]	ϵ_x	1.40
norm. transverse emittance [μm]	ϵ_y	1.40
alpha function	α_x	-8.44
alpha function	α_y	-8.50
beta function [m]	β_x	11.56
beta function [m]	β_y	11.64
bunch length [mm]	σ_z	0.62
bunch length [ps]	σ_z	2.06
Beam energy [MeV]	E	87.02
Bunch charge [pC]	Q_{bunch}	83.86
numb. of part. per bunch [10^9]	N_{bunch}	0.52

Table 4.2.1: Beam parameters after the superconducting linac of TBONE

4.3 Bunch Compression

For the studies of the bunch compressor the simulated distribution after the superconducting linac was used as input. The initial bunch distribution is shown in Fig. 4.3.1 and the

final one in Fig. 4.3.2. The bunch compression is described in detail in [21], where it is shown that a bunch length of 5 fs can indeed be reached.

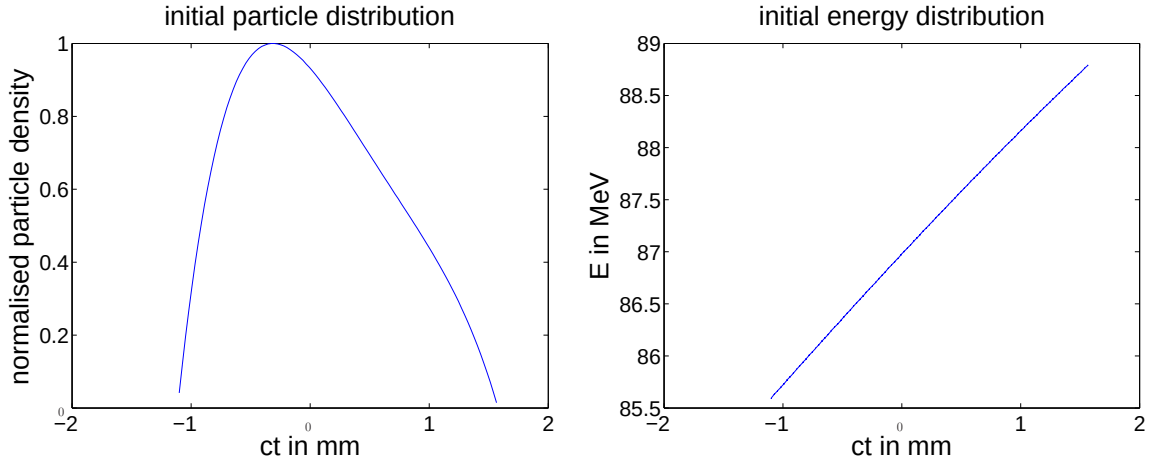


Figure 4.3.1: Longitudinal bunch and energy distribution at injection in the bunch compressor [21].

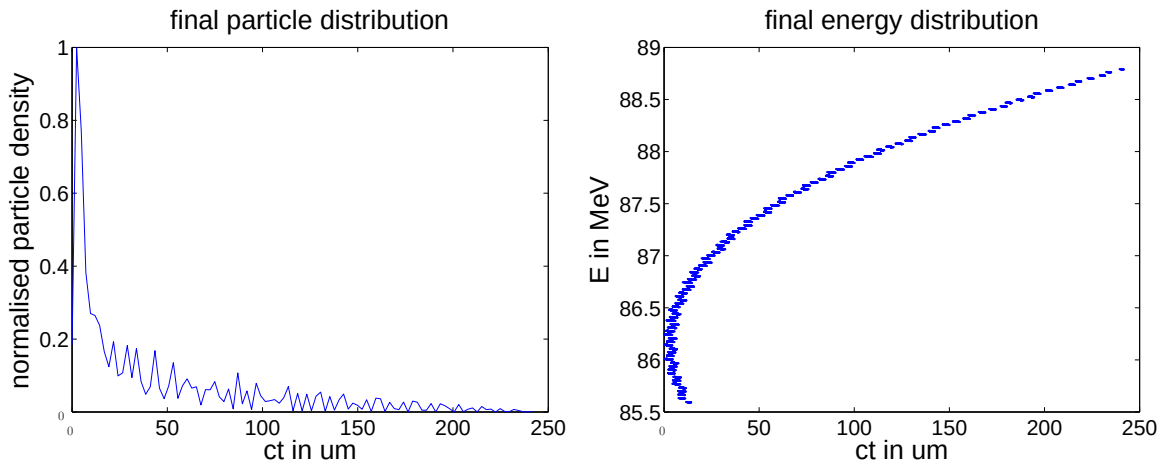


Figure 4.3.2: Longitudinal bunch and energy distribution after the compression [21].

Chapter 5

Halo and Tail Generation

Halo and tail particles are beam particles, which follow an orbit far away from the reference orbit (Fig. 5.0.1). The motivation behind halo and tail studies is, that halo particles



Figure 5.0.1: Beam and halo

can cause a growth of the beam size and though a loss in luminosity and can contribute significantly to the background of particle interactions and to the emitted radiation. The background can be reduced by placing collimators in the interaction region, which stop most of the halo particles. But by interacting with the material of the collimators, the stopped halo particles can still produce an unwanted background of secondary particles. Beside the unwanted generation of background and radiation, halo particles can lead to beam losses in all parts of an accelerator.

5.1 Candidate Processes of Halo and Tail Generation

The increase of the amplitude of a beam particle and the associated generation of a halo particle can be caused by the following effects:

Particle Processes:

- **Beam Gas Scattering and Multiple Scattering:**

Beam particles perform elastic scattering (Mott scattering) or inelastic scattering (bremsstrahlung) with the residual gas molecules. Multiple scattering can occur i.e. when beam particles hit a spoiler or any other dense material.

- **Spoiler Scattering:**

Spoilers made of some dense material are often installed in front of Collimators to protect latter from e.g. overheating. Beam or Halo particles hitting the spoilers are stopped or perform multiple scattering.

- **Scattering of Thermal Photons (Inverse Compton Scattering):**

Inverse Compton scattering is the inelastic scattering process between an electron and a photon.

- **Synchrotron Radiation:**

Synchrotron radiation photons are emitted by relativistic charged particles traveling in a magnetic field.

- **Electron and Ion Cloud Effects:**

Electrons or Ions can be accumulated near the beam and start interacting with the beam. This can cause serious instabilities.

- **Touschek Effect and Intrabeam Scattering:**

The Touschek effect is a single scattering effect, where the small transverse momentum of two beam particles is transferred into a large longitudinal momentum. Both particles are lost, one with too much and one with too little energy. Intrabeam scattering is a multiple scattering effect with small scattering angles between beam particles. It leads to diffusion in all three dimensions and causes mainly a blow up of the whole beam instead of the direct loss of single particles.

- **Space Charge Effect:**

The space charge effect is the effect of the electromagnetic self field of the beam on itself.

- **Beamloading and Wakefields:**

The electromagnetic field of the bunch induces surface charges and currents in the

conducting walls of the surrounding structure. These fields can then act back on the beam particles.

Optics Related Effects:

- **Mismatch:**

If the beam density contours do not coincide with the ellipse corresponding to the particle trajectories, the beam is mismatched. In this case the amplitude of some beam particles can increase significantly.

- **Coupling:**

The movement of the particles in the horizontal and the vertical plane can be coupled. This is for example the case in sextupoles.

- **Dispersion:**

The deflection of off momentum particles in any electric or magnetic field differs from the one of the reference particle. Dispersion is the beam dynamics effect of the momentum offset.

- **Nonlinearities:**

The equation of motion becomes nonlinear, if a lattice includes elements with non-linear electromagnetic fields, e.g sextupoles. Also magnetic field errors can be the source of nonlinearities.

- **Misalignment**

If an element is misaligned, the beam particles experience a slightly other field depending on the extent of the misalignment. The error in the field experienced by the beam particles can cause an unwanted additional deflection.

Other Sources:

- **Noise and Vibrations:**

Noise and vibrations of all different kinds can be transferred to the beam and lead to oscillations and emittance growth. For example rf noise can cause the generation of tails as well as the loss of particles, which are situated close to the separatrix but still in the stable region. Vibrations of elements e.g. quadrupoles can induce oscillations of the beam particles and emittance growth.

- **Dark Currents:**

The walls of a structure can emit electrons. For example in a rf cavity these electrons are accelerated, which leads to a in most cases negligible current conduction.

A more detailed description of most of the sources of halo and tail generation will be given in chapter 5.3 in the context of the low energy validation of PLACET-HTGEN.

5.2 Halo and Tail Simulation with PLACET-HTGEN

For the simulation of halo and tail generation we have used PLACET-HTGEN. The tracking code PLACET [1] allows to simulate the beam dynamics of the main accelerating or decelerating part of CLIC and partly of the ILC [24]. HTGEN [2] is a generic halo and tail generation package providing an interface to PLACET. An overview of the sources of halo and tail generation included in the simulation is given in Table 5.2.1.

HTGEN was written for high beam energies. To be able to apply it also to medium and

Optics related effects:

Mismatch (P)

Coupling (P)

Dispersion (P)

Nonlinearities (P)

Misalignment (P)

Other Sources:

Noise and Vibrations

Dark Currents

Particle processes:

Beam Gas Scattering and Multiple Scattering (H)

Spoiler Scattering (H)

Compton Scattering

Synchrotron Radiation (P)

Electron and Ion Cloud Effects

Touschek Effect and Intrabeam Scattering

Space Charge Effect

Beam Loading and Wakefields (P)

Table 5.2.1: ■ Included in PLACET (P) ■ Included in HTGEN (H)

low energies, a critical review and low energy validation was carried out (chapter 5.3).

A description of the simulation technique and the used beam models is given in chapter 5.2.1 and chapter 5.2.2, while the particular motivation and challenges of the simulations performed are described in chapter 5.4 together with the results obtained.

5.2.1 Beam Models

Particle Beam Model

A particle beam consists of several bunches and each bunch of many particles, which are represented by a position in phase space $(x_i, x'_i, y_i, y'_i, E_i, z_i)$. To reduce the runtime of the simulation program the number of beam particles is normally scaled down. For halo simulation a particle beam model is more adequate as halo particles are generated by scattering of individual beam particles.

Sliced Beam Model

For high intensity beams it is better to use a sliced beam model, because the simulation of e.g. wakefield effects becomes easier and considerably faster. In the sliced beam model

the beam consists of several bunches. Each bunch is cut into longitudinal slices. Each slice consists of one or several macroparticles, which are represented by the position of the centroid in the phase space $(x_i, x'_i, y_i, y'_i, E_i, z_i)$, the weight w_i and the sigma matrix σ_i defined by Eq. 2.2.12. The weight of one macroparticle is proportional to the number of particles it represents. The weights together with the position of the slices therefore define the longitudinal distribution of the beam (Fig. 5.2.1). The exact definition of the weights can vary. In PLACET the sum over all weights must be equal to one ($\sum_i w_i = 1$). The sigma matrix which belongs to each macroparticle gives information about the particle distribution, normally a gaussian distribution, it represents.

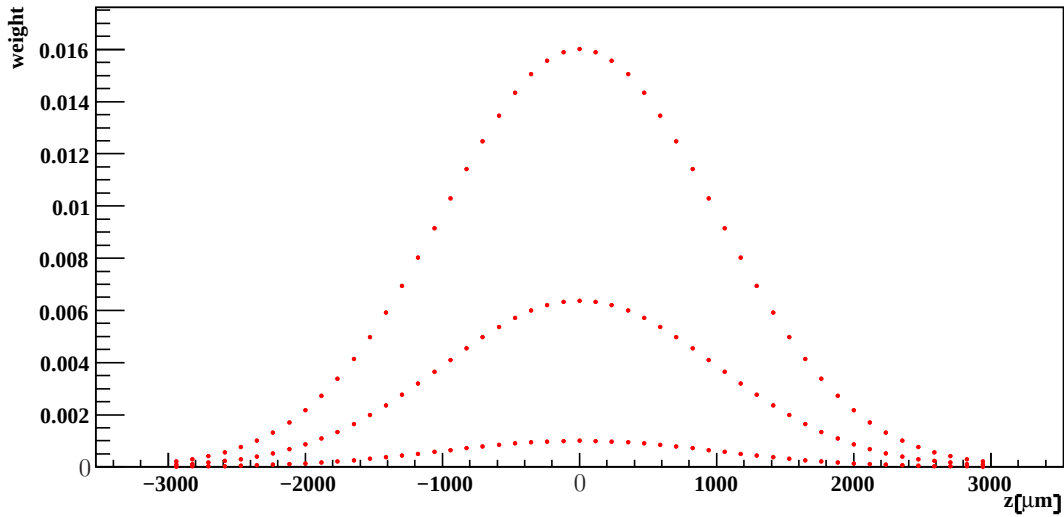


Figure 5.2.1: Example of a sliced beam: One bunch of the CLIC drive beam with 51 slices and 5 macroparticles per slice

5.2.2 Simulation Technique

We first give a general description of PLACET-HTGEN and then describe in more detail the implementation of the halo tracking in cavities and PETS and the implementation of the effect of misalignment on the halo.

General Description

HTGEN simulates the deflection of beam particles due to beam gas scattering and multiple scattering. In the case of beam gas scattering only single scattering is simulated, which is a good assumption as the probability for double scattering is very small in materials of smaller density. PLACET performs the tracking through the different elements including the simulation of several other halo sources (Table 5.2.1). It is possible to define an initial

halo, but for simplicity we assume, that there is no halo in the beginning of the beamline. First the beam is tracked through the first element. Then HTGEN computes the number of scattered halo particles N_{scatt} given by:

$$N_{\text{scatt}} = P l N \quad (5.2.1)$$

where P is the scattering probability (Eq. B.0.2) of the specific process (Mott scattering, bremsstrahlung or multiple scattering), l the length of the element and N the number of beam particles. After the calculation of the number of scattered particles, the individual particles are picked randomly out of the beam and scattered according to the scattering angle distribution of the process. After scattering, beam and halo are tracked through the next element. At the end of the element the N_{scatt} halo particles generated in this element are added to the existing halo and beam and halo and beam are again tracked through the next element. This is repeated until the end of the beamline.

Halo Tracking in Cavities and PETS

In most elements it is sufficient to track the halo as a second independent beam through the beamline and neglect the influence of the beam on the halo. However, in elements where collective effects like wakefields play a role the halo must be tracked together with the beam in order to obtain a realistic halo tracking. As the particle density of the halo is very small compared to the particle density of the beam, the halo does not effect the beam but the beam can effect considerably the halo. For the three accelerators studied, the affected elements are cavities and PETS, where the effect of wakefields can not be neglected.

For the tracking in cavities and PETS a sliced beam model of the beam is more adequate in order to provide an acceptable running time. Using this model all macroparticles of one slice experience the same wakefield and rf kick. For the halo particles a pure particle model was used originally. To be able to apply the same wakefield and rf kick to the halo and beam particles with a z-position in the same slice, a slicing of the halo beam was required. Therefore we have binned or sliced the halo beam but have not adapted the model of macroparticles as it is not suited for the simulation of the halo. Using this beam model for the halo, we have implemented the halo tracking in cavities and PETS, so that the halo and beam particles in the same slice experience the same rf and wakefield kick. A description of the simulation technique for the tracking of the beam and implicitly for the halo in cavities and PETS can be found in the manual [23].

Misalignment

The misalignment tolerances for CLIC are very tight (they lie in the μm range). Therefore the simulation of misalignment effects on the beam is rather essential and is implemented

in PLACET.

In the simulation the beam is translated or rotated depending on the type of misalignment at the beginning and end of each misaligned element. This is after the principle of relativity equal to giving the elements themselves an offset. We have extended the simulation of misalignment by rotating or translating also the halo beam, so that the halo particles experience the same translation or rotation as the beam particles in misaligned elements.

5.2.3 Benchmarking

A correct halo tracking requires, that halo and beam particles with the same initial coordinates in the 6d phase space follow exactly the same path and that the halo particles do not influence the beam particles. A good picture of the halo and beam tracking in PLACET is to think of the halo as a second beam, which has no influence on the beam, but is itself influenced by the beam.

To benchmark the halo tracking a new routine has been written, which works in the following way: First an arbitrary beam is defined and an exact copy of it is defined as initial halo beam or rather test beam. Test beam and beam are then tracked through the beamline, which consists of elements to be tested.

If the coordinates of the beam particles match exactly with the coordinates of the corresponding test beam particles at the end of the beamline, the halo particles are tracked the same way as the beam particles, which proves the correct implementation of the halo tracking.

All elements used in the performed simulations (cavities, PETS, quadrupoles and drift lengths) have been benchmarked in this way and show a correct halo tracking.

5.3 Low Energy Validation of PLACET-HTGEN

TBONE, the CTF3 TBL and the CLIC drive beam are medium or rather low energy beams. Because HTGEN was written for high beam energies, we have performed a low energy validation of the simulation package.

5.3.1 Beam Gas Scattering

Beam particles can perform elastic (Mott scattering) or inelastic (bremsstrahlung) scattering with the molecules of the residual gas (Fig. 5.3.1 and 5.3.2).

The molecule density n_{gas} , pressure p and temperature T are connected by the ideal gas equation:

$$p = n_{\text{gas}} k_B T \quad (5.3.1)$$

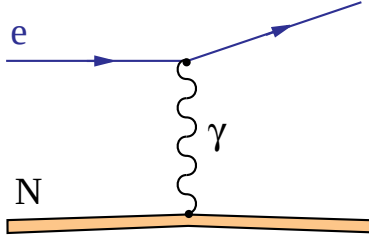


Figure 5.3.1: Mott scattering

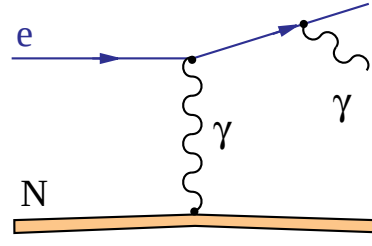


Figure 5.3.2: Bremsstrahlung

where k_B is the Boltzmann constant.

Elastic Beam Gas Scattering - Mott Scattering

The Mott scattering differential cross section is given by [25]:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \left(\frac{Zr_e}{2\gamma\beta^2 \sin^2 \frac{\theta}{2}}\right)^2 \left(1 - \beta^2 \sin^2 \frac{\theta}{2}\right) \quad (5.3.2)$$

The first term is the Rutherford cross section, which is multiplied by a second term in order to respect helicity conservation. The total Mott cross section would be divergent for $\theta = 0$. In order to avoid this divergence a minimal deflection angle $\theta_{\min}$ is introduced:

$$\sigma_{\text{Mott}}(\theta_{\min}) = \pi \left(\frac{Zr_e}{\gamma\beta^2}\right)^2 \left(\frac{1 + \cos \theta_{\min}}{1 - \cos \theta_{\min}} + \beta^2 \ln \left(\frac{1 - \cos \theta_{\min}}{2}\right)\right) \quad (5.3.3)$$

In the limit of highly relativistic electrons and small scattering angles ($\beta \approx 1$, $\theta_{\min} < 0.05$), the terms except $(1 + \cos \theta_{\min})/(1 - \cos \theta_{\min})$ can be neglected.

$$\sigma_{\text{Mott}}(\theta_{\min}) = \pi \left(\frac{Zr_e}{\gamma}\right)^2 \left(\frac{1 + \cos \theta_{\min}}{1 - \cos \theta_{\min}}\right) \overset{\cos \theta_{\min} \approx 1}{\approx} 2\pi \left(\frac{Zr_e}{\gamma}\right)^2 \left(\frac{1}{1 - \cos \theta_{\min}}\right) \quad (5.3.4)$$

For very small angles $\theta_{\min} < 10^{-6}$ the term $1/(1 - \cos \theta_{\min})$ can lead to numerical instabilities and it is better to use the Taylor expansion of $(1 - \cos \theta_{\min}) \approx \theta^2/2$:

$$\sigma_{\text{Mott}}(\theta_{\min}) \approx \frac{4\pi Z^2 r_e^2}{\gamma^2 \theta_{\min}^2} \quad (5.3.5)$$

Relevant for halo production are scattering angles which exceed the beam divergence, or roughly:

$$\theta_{\min} = \sqrt{\epsilon/(\gamma\beta_y)} \quad (5.3.6)$$

where ϵ is the normalized emittance and β_y the local vertical beta function.

Eq. 5.3.4 and 5.3.5 are implemented in HTGEN.

Validity of HTGEN

The Mott scattering cross section scales with $1/\gamma^2$ and therefore becomes more relevant for small energies (Eq. 5.3.4). The approximation of $\beta \approx 1$ and $\theta_{\min} < 0.05$ is still a good approximation for electron beams in the 10 MeV range, so also for TBONE and the CLIC and CTF3 TBL drive beam. The minimal scattering angles given by Eq. 5.3.6 lie in the μrad to mrad and well below 0.05. We can conclude that the implementation of Mott scattering is still valid for low energies.

Inelastic Beam Gas Scattering - Bremsstrahlung

In the bremsstrahlung process the electron interacts with the field of one individual residual gas molecule and radiates a photon (Fig. 5.3.2).

The first quantummechanical calculations of the bremsstrahlung/pair production cross section were published by H. Bethe and W. Heitler in 1934 [26]. Bethe and Heitler used the Born approximation and assumed, that the nucleus is infinitely heavy, pointlike and spinless, and its Coulomb field screened by the atomic electrons. In general the Born approximation becomes worse as the atomic number of the target increases, the initial electron energy decreases and the photon energy approaches the high frequency region. The theory also doesn't model the screening effects properly, which become more relevant for very low electron energies and for targets with high atomic numbers. Between 1954 and 1959 the Bethe-Heitler theory was extended by Davies, Bethe, Maximom, Olsen and Wergeland (DBMOW theory) [27], [28], [29], [30]. They substituted the plane-wave functions used in the Born approximation by the better relativistic Coulomb wave function, known as Coulomb correction, and included screening in the formfactor calculation. These two corrections are nearly independent and additive at high energies [29]. The DBMOW theory is applicable for energies higher than 50 MeV, and tends to fail in the high frequency limit of the bremsstrahlung spectrum. In 1964 Drell and Walecka generalized the results of Bethe and Heitler to targets of arbitrary mass, spin and form factors and arbitrary final states [31] and made it possible to generalize the theory of bremsstrahlung. In 1974 Y. Tsai published a review of the DBMOW theory, where he uses the Thomas-Fermi form factor model [32]. HTGEN is based on the Tsai formulas.

Cross Section after Tsai

At very high energies and excluding the high-energy tip of the bremsstrahlung spectrum, the bremsstrahlung cross section can be approximated in the complete screening case by [32]:

$$\frac{d\sigma}{dk} = 4\alpha r_e^2 \frac{1}{k} \left[\left(\frac{4}{3} - \frac{4}{3}y + y^2 \right) (Z^2(L_{\text{rad}} - f) + ZL'_{\text{rad}}) + \frac{1}{9}(1 - y)(Z^2 + Z) \right] \quad (5.3.7)$$

where k is the photon energy, $y = k/E$ the photon energy in units of the beam energy, α the fine structure constant and r_e the classical electron radius. L_{rad} is derived from the elastic form factor, L'_{rad} from the inelastic form factor and f is the Coulomb correction. In particle physics the bremsstrahlung cross section is often expressed in terms of the radiation length:

$$\frac{1}{X_0} = \frac{4\alpha r_e^2 N_A}{A} (Z^2(L_{\text{rad}} - f) + ZL'_{\text{rad}}) \quad (5.3.8)$$

and ignoring the term $(1-y)(Z^2 + Z)$ in Eq. 5.3.7 the cross section becomes proportional to the radiation length. Subsequent multiplication by E yields:

$$\frac{d\sigma}{dy} = \frac{A}{N_A X_0} \frac{1}{y} \left(\frac{4}{3} - \frac{4}{3}y + y^2 \right) \quad (5.3.9)$$

In the infrared limit the ignored term is approximately 2.5%.

The total cross section is obtained by integration of Eq. 5.3.9 over y from $y = y_{\text{min}}$ to $y = 1$:

$$\sigma_{\text{brem}} = \frac{A}{N_A X_0} \left(-\frac{4}{3} \ln y_{\text{min}} - \frac{5}{6} + \frac{4}{3}y_{\text{min}} - \frac{y_{\text{min}}^2}{2} \right) \quad (5.3.10)$$

A good value for y_{min} is 0.01.

Radiation Length after Tsai

The radiation length X_0 of elements from $Z = 1$ to $Z = 92$ after Tsai is defined by:

$$\frac{1}{X_0} = \frac{4\alpha r_e^2 N_A}{A} (Z^2(L_{\text{rad}} - f) + ZL'_{\text{rad}}) \quad (5.3.11)$$

where r_e is the classical electron radius, N_A the Avogadro constant and α the fine structure constant. L_{rad} and L'_{rad} are given in Table 5.3.1. For elements with $Z \geq 5$ Tsai uses the Thomas-Fermi-Molière approximation. The Coulomb correction $f(Z)$ for elements up to $Z = 92$ can be represented to 4-place accuracy by

$$f(Z) = z^2 ((1 + z^2)^{-1} + 0.20206 - 0.0369z^2 + 0.0083z^4 - 0.002z^6) \quad (5.3.12)$$

where $z = \alpha Z$.

Element	Z	L_{rad}	L'_{rad}
H	1	5.31	6.144
He	2	4.79	5.621
Li	3	4.74	5.805
Be	4	4.71	5.924
Others	≤ 4	$\ln(184.15Z^{-1/3})$	$\ln(1194Z^{-2/3})$

Table 5.3.1: Tsai's L_{rad} and L'_{rad}

A compact fit after Dahl of Tsai's formula provides an easy to implement formula and gives values better than 2.5% accuracy for all elements except Helium, where the result is 5% to low [33].

$$X_0 = \frac{A}{4\alpha r_e^2 N_A Z(Z+1) \ln(287/\sqrt{Z})} = \frac{716.408 A}{Z(Z+1) \ln(287/\sqrt{Z})} \quad [\text{g cm}^{-2}] \quad (5.3.13)$$

Often the residual gas consists of different gas molecules. In this case neglecting the effect of molecular bindings the radiation length can be approximated by:

$$\frac{1}{X_0} = \sum f_i \frac{1}{X_i} \quad (5.3.14)$$

where f_i are the fractions by weight of elements i given by:

$$f_i = \frac{A_i}{\sum_{i=1}^N A_i} \quad (5.3.15)$$

where a_i is the number of atoms of the i th element of the molecule.

Accuracy of Tsai's theory

The formulas derived in the DBMOW and consequently also in Tsai's theory are estimated to have an accuracy of the order of $(Z/137)^2(\ln E/E)$ [34], so get less reliable for small energies, which corresponds approximately to an uncertainty of 3% for energies above 50 MeV. This was also experimentally confirmed [35]. In the intermediate energy region between 2 MeV and 50 MeV the high energy approximations tend to fail and the formulas become more cumbersome, if at all assignable. Only very few measurements have been made in this energy region. There have been attempts of numerical calculation e.g. by Tseng and Pratt [36] and e.g. GEANT4 uses the Tsai formula down to 1 GeV and for lower energies a fit to the EEDL data set [37] with an estimated relative error of $\Delta\sigma/\sigma = 4 - 5\%$ for energies bigger than 1 MeV [38].

Landau Pomeranchuk Migdal (LPM) effect

The LPM effect is the suppression of photon production due to the multiple scattering of the electron. As the density of the atoms in the residual gas is very small multiple scattering becomes very unlikely and with it also the LPM effect.

Molecular Bindings

The various theories apply only to a gas of free atoms. The effect of molecular bindings are very small, except for energies below 1 keV [39], but are significant in crystals, which is shown e.g. in [40].

Angular distribution

The angular distribution is of the form [41]:

$$f(\theta)d\theta = \frac{\theta}{(\theta^2 + \gamma^{-2})^2} \quad (5.3.16)$$

where θ is the angle between the initial electron and the emitted photon. The average angle is of the order $\theta \approx 1/\gamma$, which is e.g. for a beam energy of 100 MeV in the mrad range.

Validity of HTGEN

In HTGEN Eq. 5.3.13 and Eq. 5.3.10 are implemented. This is a good approximation for energies bigger than 50 MeV, but tends to be less reliable for smaller energies. The assumption of complete screening might not be adequate for very low electron energies. The LPM effect can be neglected. As the energy decreases Mott scattering becomes more and more the dominating process and the exact calculation of bremsstrahlung less important. As a consequence HTGEN is in most cases also still valid for energies smaller than 50 MeV.

5.3.2 Scattering of Thermal Photons - Inverse Compton Scattering

Inverse Compton scattering is the inelastic scattering process of a photon with an electron resulting in an energy gain of the photon.

Thermal Photons

Most of the photons originate from the black body radiation of the beampipe respectively the surrounding structure. Consequently the density and energy distribution is given by the Planck formula [42]:

$$dn_p = \frac{\epsilon^2 d\epsilon}{\pi^2 c^3 \hbar^3 (e^{\epsilon/k_B T} - 1)} \quad (5.3.17)$$

where ϵ is the photon energy, c the speed of light, $\hbar$ the Boltzmann constant and T the absolute temperature of the black body in Kelvin.

The total number of photons per cm^3 is:

$$n_p = \frac{2.4(kT)^3}{\pi^2 c^3 \hbar^3} = 20.2 T^3 \text{ cm}^{-3} \quad (5.3.18)$$

and the average energy of the photons is:

$$\langle \epsilon \rangle = 2.7 k_B T \quad (5.3.19)$$

Kinematics of Compton Scattering

The total Compton cross section is [43],[42]:

$$\sigma_{\text{Compton}} = 2\pi r_e^2 \frac{1}{x} \left(\left(1 - \frac{4}{x} - \frac{8}{x^2} \right) \ln(1+x) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(1+x)^2} \right) \quad (5.3.20)$$

where r_e is the classical electron radius and x the dimensionless parameter:

$$x = \frac{4E\epsilon}{m^2 c^4} \cos^2 \frac{\alpha_0}{2} \quad (5.3.21)$$

E the initial electron, ϵ the initial photon energy in the laboratory system and α_0 the collision angle (Fig. 5.3.3).

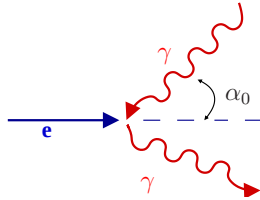


Figure 5.3.3: Kinematics of Compton scattering

In the nonrelativistic limit $x \ll 1$ the Compton cross section can be approximated by:

$$\sigma_{\text{Compton}} = \frac{8\pi r_e^2}{3} (1 - x) \quad (5.3.22)$$

where the first term is the Thomson cross section $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$. and in the ultrarelativistic limit $x \gg 1$ by:

$$\sigma_{\text{Compton}} = 2\pi r_e^2 \frac{1}{x} \left(\ln x + \frac{1}{2} \right) \quad (5.3.23)$$

The cross section and the mean free path length are normally small even for room temperature and therefore the deflection of the electrons by Compton scattering negligible [44]. Beside the deflection the electron also loses energy in the scattering process, which can cause an energy spread leading to noticeable beam losses. The maximum energy loss of the scattered electron caused by Compton scattering is [42]:

$$\frac{\Delta E}{E} = \frac{\epsilon_{\text{max}}}{E} = \frac{x}{x+1} \quad (5.3.24)$$

The maximum energy loss of the scattered electron is an upper limit for the energy spread due to Compton scattering. An example for the significance of Compton scattering is LEP [44].

Validity of HTGEN

The simulation of Compton scattering is not included in PLACET-HTGEN, but the effect can be analytically estimated with the above formulas. Compton scattering becomes more relevant for high beam energies and is in most cases negligible for small energies.

5.3.3 Synchrotron Radiation

A relativistic particle following a curved trajectory loses energy due to synchrotron radiation. This can lead to an energy spread in the beam resulting in a generation of halo particles. In a quadrupole for example, particles further away from the center of the quadrupole are focused more towards the center, so the orbit has a stronger curvature than the orbit of a particle closer to the center. A smaller bending radius implies a higher emitted synchrotron radiation power and with it a larger energy loss.

Validity of HTGEN

The simulation of synchrotron radiation is implemented in PLACET. However, the effect of synchrotron radiation is normally negligible in linear accelerators and decreases with decreasing beam energy, therefore is less relevant for low energies.

5.3.4 Residual Gas Ionization, Electron and Ion Cloud Effects

Electron Cloud Effects

Free electrons in the beampipe can be generated by the ionization of the residual gas or by synchrotron radiation photons, which hit the beampipe and knock out photo-electrons. If the beam particles are positively charged, the electrons are accelerated in the beam field and hit the wall of the beampipe. The wall then emits more electrons due to secondary emission. The electrons are again accelerated in the field of the beam and knock out more and more electrons of the wall. Hence in a circular accelerator, every time the beam passes, new electrons are generated and a significant number of electrons can be accumulated. These electrons can interact with the beam particles, which is known as electron cloud effect. Because new electrons are generated with each passage of the beam, the electron cloud effect is more relevant in storage rings than in linacs. In addition in a storage ring the number of photo electrons is much higher than in a linear accelerator due to the high number of synchrotron radiation photons hitting the beampipe.

Beams with negatively charged particles repel the electrons in the beampipe, so they are not accumulated around the orbit and usually don't interact with the beam particles.

Validity of HTGEN

In summary electron cloud effects mostly occur in storage rings with a positively charged circulating beam and not in electron accelerators.

Ionization of the Residual Gas

Electron beams ionize the residual gas in the beam pipe. The ionization cross section is given by [45]:

$$\sigma_{\text{ion}} = 4\pi \left(\frac{\hbar}{m_e c} \right)^2 \beta^2 [C_1 + C_2(2 \ln(\beta\gamma) - 1)] \quad (5.3.25)$$

where C_1 and C_2 are characteristics of the molecules. Table 5.3.2 gives a list of values of C_1 and C_2 for different molecules together with the atomic number Z and the mass number A . Referring to [46] Eq. 5.3.25 is valid for relativistic velocities larger than 10 keV and has been experimentally proved by F. Rieke and W. Prepejchal for electrons of kinetic energies in the 1 MeV range [47].

Molecule	C_1	C_2	Z	A
H ₂	8.1	0.5	2	2
N ₂	34.8	3.7	14	28
CO	35.1	3.7	14	28
O ₂	38.8	4.2	16	32
H ₂ O	32.3	3.2	10	18
CO ₂	55.9	5.75	22	44

Table 5.3.2: C_1 and C_2 for different molecules

Each electron ionizes $n_{\text{gas}}\sigma_{\text{ion}}$ ions per unit length [48], hence the number of ions per unit length at the end of one bunch is:

$$\lambda_{\text{ion}} = N n_{\text{gas}} \sigma_{\text{ion}} \quad (5.3.26)$$

and respectively at the end of one train:

$$\lambda_{\text{ion}} = n N n_{\text{gas}} \sigma_{\text{ion}} \quad (5.3.27)$$

where n is the number of bunches per train, N the number of electrons per bunch and n_{gas} the residual gas density.

To get an estimate for the ionization of the residual gas, the line density as seen by the beam is compared with the maximal longitudinal ion density at the end of one train. The line density as seen by the beam is given by:

$$\lambda_{\text{gas}} = A_{\text{beam}} n_{\text{gas}} \quad (5.3.28)$$

where A_{beam} is the beam cross section. The beam cross section is given by the area of the beam ellipse $\pi a_x a_y$ (Fig. 5.3.4). The semiaxis of the ellipse are related to the rms beam sizes by $a_{x,y} = \sqrt{5}\sigma_{x,y}$. If the residual gas consists of different molecules, the total

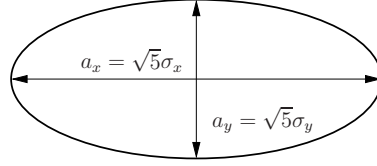


Figure 5.3.4: Beam cross section

longitudinal density is given by the sum of the longitudinal density of the residual gas constituents λ_i . The same holds for the number of ions per unit length at the end of one train/bunch.

$$\lambda_{\text{gas/ion}} = \sum_i \lambda_{i,\text{gas/ion}} \quad (5.3.29)$$

We define the residual gas ionization by the ratio of the number of ions per unit length to the line density:

$$\text{Ionization} = \frac{\lambda_{\text{ion}}}{\lambda_{\text{gas}}} \quad (5.3.30)$$

Validity of HTGEN

In the present treatment, the residual gas is assumed to be neutral. A considerable ionization would imply changes in the halo generation, but for low energies the residual gas ionization is in most cases irrelevant as the cross section increases with the beam energy (Eq. 5.3.25). To assure the validity of HTGEN a rough estimate has to be obtained for each case under study.

Ion Cloud Effects - Conventional Ion Instability and Fast Ion Instability

Conventional Ion Instability:

The ion cloud effect mainly occurs in electron accelerators because a positively charged beam typically pushes the ions to the wall of the vacuum chamber before they can do a significant damage to the beam. In the case of an electron beam the ions can be either lost between two bunches or they are not sufficiently accelerated, so that they don't reach the wall before the next bunch arrives and are trapped. In the latter case the number of ions around the beam increases linearly with the number of bunches passing.

In circular machines when the gap between two bunches is not large enough to clear the ions from the chamber, the ions are trapped and the number of ions increases rapidly. This is known as the conventional ion instability. To avoid the ion trapping, a gap is introduced between the bunches/trains or clearing electrodes are used (Fig. 5.3.5 and 5.3.6).

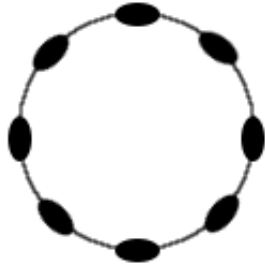


Figure 5.3.5: Filling pattern in a ring, where conventional ion trapping can occur. Note, that there is no gap in the e^- -beam. In the case of ion trapping, the ion lifetime $\gg 1$ turn

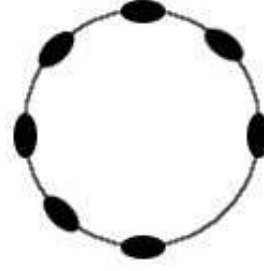


Figure 5.3.6: Filling pattern in a ring, where only the fast ion instability can occur. Note the gap in the e^- -beam. The ions are not trapped and the ion lifetime < 1 turn

Fast Ion Instability:

Even if the ion lifetime is smaller than one turn, the ions can still cause an instability, the fast ion instability. The fast ion instability is a head-tail effect, where the trains/bunches in the head built up an ion cloud, which then interacts with the bunches/trains in the tail while the ones in the head are not affected (Fig. 5.3.7). Therefore it can arise in circular machines as well as in linacs. In the following we will shortly introduce the relevant parameters necessary for our rough estimates.

The electrons from the ionized molecules are repelled by the negatively charged bunch

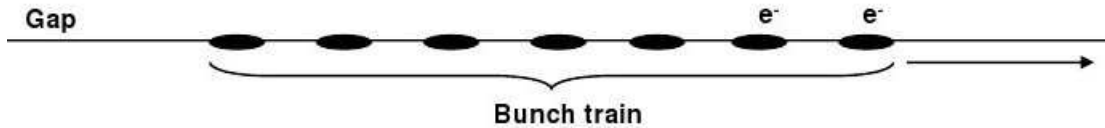


Figure 5.3.7: Filling pattern in a linear accelerator. Only the fast beam ion instability can occur. If this is the case the bunches in the head effect the ones in the tail.

and gain high enough velocities to reach the wall before the next bunch arrives. Because the ions are heavier than the electrons their transverse velocity can be so small, that they move less than the transverse beams size before the next bunch arrives. In this case the produced ions affect the following bunch(es). The resulting vertical motion of the beam particles and the ions is a mutually driven oscillation. The ions can be trapped between bunches/trains if their coherent transverse frequency f_i is smaller than the frequency of the arriving bunches/trains [49]:

$$4f_i < \frac{c}{\Delta z} \quad (5.3.31)$$

where Δz is the distance between two bunches/trains. This trapping condition is derived from the assumption that the ions only move very little between the passage of consecutive bunches. There exist different trapping conditions, but all have the form of $\text{const} \cdot f_i <$

$c/\Delta z$, where the constant const lies between 3 and 4 [49], [50].

The oscillation frequency f_i is given by [50]:

$$f_i \approx \frac{c}{\pi} \sqrt{\frac{Q_i \tilde{n} r_p}{3\sigma_y(\sigma_x + \sigma_y) \Delta z A}} \quad (5.3.32)$$

r_p is the classical proton radius, A the atomic weight, $\sigma_{x/y}$ the horizontal/vertical rms beam size, Q_i the ion charge and $\tilde{n}$ the number of particles per bunch ($\tilde{n} = N$ for trapping between bunches or in the case of trapping between trains $\tilde{n} = nN$). With this expression of the oscillation frequency (Eq. 5.3.32), the inequality 5.3.31 can also be written as a lower limit to the mass number A :

$$A > A_{\text{trap}} = \frac{16Q_i r_p \tilde{n} \Delta z}{3\pi^2(\sigma_x + \sigma_y)\sigma_y} \quad (5.3.33)$$

Ions with a mass number smaller than A_{trap} are therefore not trapped, while ions with a higher mass number are trapped.

For the three studied accelerators only trapping between bunches can occur and we will assume from now on, that the ions are only trapped between bunches and not between trains. If the coherent oscillation of the ions is small compared to the beam size, the force acting on the beam can be assumed to be linear. Otherwise the decay of the force at large distances would have to be considered. Under this condition an initial vertical perturbation $\hat{y}$ would increase purely exponentially [49]

$$y_b \sim e^{\sqrt{t/\tau_e}} \quad (5.3.34)$$

with an e-folding risetime of [51]:

$$\frac{1}{\tau_e} = \frac{\lambda_{\text{ion}} r_e c}{\sqrt{18} a \sqrt{Q_i} \left(\sqrt{\epsilon_y \epsilon_x \beta_x / \beta_y} + \epsilon_y \right)} \quad (5.3.35)$$

where f_i is the coherent ion oscillation frequency given by Eq. 5.3.32. The parameter a is the peak-to-peak ion frequency variation. It takes into account the variation of the ion frequency along the beam line as well as the ion decoherence, e.g. caused by the dependence of the vertical ion oscillation frequency on the horizontal position. For a FODO lattice $a \approx 0.1$. In [52] it is shown that Eq. 5.3.35 underestimates the risetime by a factor 2-3.

Another important parameter is the number of risetimes n_{rt} :

$$n_{rt} = L / (c\tau_e) \quad (5.3.36)$$

the beam needs to pass the beamline of a length L as well as the coherent and incoherent tune shift $\Delta\nu_{x,y,\text{coh},\text{incoh}}$:

$$\begin{aligned} \Delta\nu_{x,y,\text{incoh}} &= \frac{\beta_{x,y} r_e Q_i \lambda_{\text{ion}} L}{4\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)} \\ \Delta\nu_{x,y,\text{coh}} &= 2\Delta\nu_{x,y,\text{incoh}} \end{aligned} \quad (5.3.37)$$

induced by the fast ion instability [53]. The tune shift in a linac can be defined as the shift in the phase advance per period. To avoid an instability the caused tune shift and the number of risetimes must stay below 1.

Validity of HTGEN

The fast ion instability can not yet be simulated by PLACET, but it is planed to include the fast ion instability simulation code FASTION [54] into PLACET. As the ionization cross section Eq. 5.3.25 increases with the energy, the ion cloud effects are less relevant for low energy beams.

5.3.5 Touschek Effect and Intrabeam Scattering

The typically small transverse momentum of two beam particle can be transformed into a large longitudinal momentum by Coulomb scattering. Both scattered particles are lost, one with too much and one with too little momentum. This effect is known as Touschek effect. Intrabeam Scattering is the multiple Coulomb scattering effect and leads to diffusion in all three directions and a change in the beam dimensions. Both effects are only relevant for low energy beams with a very small beam size. The particle beams we studied have all a relatively large beam size and we don't expect any halo and tail generation due to intrabeam scattering or Touschek effect. Analytical estimates can be obtained e.g. by the formulas derived by Piwinski [55].

Validity of HTGEN

For small beam energies and small beam sizes Touschek effect and intrabeam scattering become relevant and HTGEN has to be extended. The Touschek effect could be implemented in a straight forward way. One possibility is shown in [56], but in the case of HTGEN it is probably easier to implement the cross section and angle distribution analogical to Mott scattering and bremsstrahlung.

5.3.6 Space Charge Effect

The particle motion depends not only on the external fields, but also on the fields from the Coulomb interactions between the particles themselves. The effect of the Coulomb forces can be separated into two contributions. First the space charge field, which is the smoothed field resulting from the combination of the fields of all particles. Second the short range fields from binary Coulomb collisions. According to [6] the short range fields are very small compared to the average space charge field and can be neglected.

The electric and magnetic self field of the beam can be calculated using the Maxwell equation and depend on the beam distribution. These fields exert a force on a test particle with charge q and coordinates x , y and z given by the Lorentz force:

$$\vec{F} = q \left(\vec{E} + \vec{v} \times \vec{B} \right) \quad (5.3.38)$$

As shown in [6] the transverse electric force acts repulsive on the particles while the transverse magnetic force has an attractive effect and tends to compensate for the defocusing electric force with increasing beam velocity. When the velocity approaches the speed of light the electric and magnetic self field in the transverse plane tend to cancel. The longitudinal motion is only affected by the electric self field and scales with $1/\gamma^3$. In linear accelerators the longitudinal electric self field always has a defocusing effect, while in circular accelerators it is defocusing below transition and focusing above.

For a three dimensional uniform ellipsoidal beam the electric field is given by [6]:

$$\begin{aligned} E_{sx} &= \frac{3qN(1-f)}{4\pi\epsilon_0(a_x+a_y)a_z} \frac{x}{a_x}, & E_{sy} &= \frac{3qN(1-f)}{4\pi\epsilon_0(a_x+a_y)a_z} \frac{y}{a_y} \\ E_{sz} &= \frac{3qN(1-f)}{4\pi\epsilon_0 a_x a_y} \frac{z}{a_z} \end{aligned} \quad (5.3.39)$$

where a_x , a_y and a_z are the semiaxes of the ellipsoid in the laboratory frame, N the number of particles per bunch and q the charge of one particle. The semiaxes are related with the rms beam sizes by $a_{x,y,z} = \sqrt{5}\sigma_{x,y,z}$. x , y and z are the coordinates of the test particle relative to the bunch centroid. The quantity f is an ellipsoidal form factor and is a function of the parameter $p = \gamma a_z / \sqrt{a_x a_y}$ with $f(0) = 0$. For a nearly spherical bunch, where $0.8 < p < 5$, a useful approximation is $f(p) = 1/3p$. The exact values of $f(p)$ can be found in [6].

In the transverse plane the equation of motion without space charge effects is given by the Hill's equation (Eq. 2.2.3). The effect of space charge is included in the equation of motion by adding a space charge term F_s , which includes the self electric as well as the self magnetic forces [6]:

$$x'' + k(s)x - \tilde{F}_{sc} = 0 \quad (5.3.40)$$

$\tilde{F}_s$ is the space charge force term and is related to the electric field by

$$\tilde{F}_{sc} = \frac{qE_s}{\gamma^3\beta^2 m_0 c^2} \quad (5.3.41)$$

where γ and β are the relativistic γ and β factor, m_0 the rest mass of one beam particle and c the speed of light. In general the space charge term is not linear in x , but in the case of an elliptical bunched beam the electric field is linear in all three directions and Eq. 5.3.40 can be simplified:

$$x'' + (k(s) - F_{sc})x = 0 \quad (5.3.42)$$

where $F_{sc} = \tilde{F}_{sc}/x > 0$. In the case of a FODO lattice $k(s)$ is the quadrupole focusing strength, which can be approximated by the average β -function:

$$k(s) = \frac{1}{\langle \beta \rangle^2} \quad (5.3.43)$$

According to Eq. 5.3.42 the focusing strength of the quadrupole is reduced by the effect of the space charge force.

Longitudinal Beam Dynamics with Space Charge

An estimate of the longitudinal space charge effects could be obtained by comparing the longitudinal space charge field with e.g. the longitudinal field in the cavities in the case of TBONE or in the PETS in the case of the CLIC decelerator. However, these kind of estimates are not straight forward and out of scope of this thesis.

Validity of HTGEN

Space charge effects are not included in PLACET-HTGEN, but are normally only relevant for electron beams in the keV range or for very high peak currents. For an estimate of the relevance of space charge effects the equations presented above can be used.

5.3.7 Beam Loading and Wakefields

Only for very low energies in the keV range electrons can't be treated anymore as relativistic particles. Even in low energy accelerators, the beam energy lies in the MeV range and we can assume that the beam particles are relativistic and move approximately with the speed of light.

A free relativistic charged particle emits radiation perpendicular to its direction of motion with a narrow angular spread of $1/\gamma$ and the longitudinal electric field approaches zero. This is still the case for a relativistic particle moving in a perfectly conducting pipe. When the fields traveling along with the relativistic particle encounter geometric variations such as rf cavities, kickers, diagnostic components etc., they are reflected on the structure and can act back on the beam. As the velocity of the particles is close to the speed of light the principle of causality prohibits that the radiation catches up with the source particles or particles in front, but it can act back on trailing particles. Therefore the scattered radiation carried along with every beam particle is called the wakefield of the particle.

For short bunches the strength of the wakefield tends to increase. For low energies the wakefield effect is normally much smaller than the direct space charge effect. As a consequence wakefields are negligible for very low energies.

In general Wakefields are damped electromagnetic waves, which can be described as a

sum of all resonant modes excited in the structure. The wakefield effect of the main accelerating mode is also called beamloading and is commonly stronger than the effect of the higher order modes. Modes with frequencies higher than the cut off frequency of the structure propagate away along the beam pipe and do not stay localized, while modes with frequencies below the cutoff frequency remain localized in the structure and may effect trailing bunches.

One distinguishes between short-range and long-range wakefields. The short-range wakefields, which are generated by the particles in the head of the bunch, affect trailing particles in the same bunch, leading to energy loss and a transverse deflection of off-axis particles. The long-range wakefields influence trailing bunches. The high-Q transverse modes of the long-range fields have the strongest effect and cause time varying transverse deflection of trailing bunches.

Validity of HTGEN

For the CLIC PETS in combination with the drive beam and the TESLA cavities in combination with the ILC main beam the wakefields have been calculated with GdFidl and/or other tools and are included in PLACET. For other beams and elements the simulation code would have to be extended. For electron beams in the MeV to GeV range wakefields can have a considerable effect on the beam dynamics as seen on the example of the TBL drive beam and have to be taken into account.

5.3.8 Optics Related Effects

The relevance of optics related effects depends more on the beam size and energy spread than the average beam energy. Therefore they are not more or less relevant for low energy beams.

5.3.9 Other Sources

Dark currents, noise and vibrations are not energy dependent and have to be included if a considerable effect on the beam is expected.

5.4 Analytical Estimates and Simulation Results

We have performed halo and tail generation studies for three accelerators: the CLIC decelerator, the CTF3 TBL and TBONE. All input parameters for the CLIC decelerator and CTF3 TBL are summarized for a better overview in appendix C. Parameters of importance for scattering processes are defined in appendix B.

5.4.1 CLIC Drive Beam Decelerator

The CLIC drive beam decelerator is the rf power source of the main linacs (chapter 3.1). To ensure a uniform supply of power, it is essential to transport the drive beam with very few losses until the end of the decelerator. In addition to the direct effect on the rf power production, lost beam or halo particles or emitted radiation could considerably increase the heat load of the PETS and cause rf breakdown. The results of the halo and tail generation studies for the decelerator have been published in [57].

Analytical Estimates and Simulation Results

All decelerators have a slightly different length depending on the corresponding lattice of the main linac. We expect the largest halo generation for the longest decelerator, for which we performed the simulations. As a model we used the baseline specification of the decelerator, which includes the effect of misalignment, longitudinal and transverse wakefield effects as well as an initial beam offset. We chose a sliced beam model with 200 bunches per train, 51 slices and 1 macroparticle per slice.

The residual gas in the decelerator consists of 40% H₂O, 40% H₂ and the remaining 20% shared among CO, N₂, CO₂ with a total pressure of 10 nTorr and a temperature of 300 K, which we also used for the analytical estimates. In order to simplify the simulation input we used a gas equivalent of pure N₂ gas.

The basic parameters of the CLIC drive beam decelerator are given in Table 5.4.1 and 5.4.2. The input parameters of the different halo sources are listed in the corresponding sections. All input parameters are given together with the CTF3 TBL input parameters in appendix C.

pressure [nTorr]	10
temperature [K]	300
molecule density [m ⁻³]	3.22×10^{14}

Table 5.4.1: CLIC vacuum specifications

Wakefields:

The PETS dipole mode transverse wakefields and fundamental mode longitudinal wakefields are included in the simulation and the results are presented in [5]. A summary of the results is given in chapter 3.3.3.

Misalignment and Beam Offset:

The effect of misalignment of quadrupoles and PETS is described in detail in [58].

As the strength of the dipole wake of the PETS is proportional to the offset of the source

DB station length [m]	1053.23
number of trains	1
Bunches per train	2928
Bunch separation [m]	0.025
Bunch length [mm]	1
number of particles per bunch [10^9]	52.5
E_{initial} [GeV]	2.4
E_{final} [GeV]	0.4

Table 5.4.2: Beam and lattice parameters of the CLIC drive beam decelerator

particle, the resulting transverse kicks will grow linearly with the transverse misalignment. A small error in the angle of the orientation of the PETS has the same effect as a position offset and can therefore be simulated accordingly. In order to avoid large kicks and a resulting envelope growth, the PETS misalignment must be kept below an rms offset of $200 \mu\text{m}$. In the simulation discussed the misalignment error is set to the maximum value of $200 \mu\text{m}$.

A quadrupole offset adds a dipole component in the lattice, resulting in transverse kicks. The quadrupoles and BPMs (Beam Position Monitors) can be pre-aligned at best to an accuracy of $20 \mu\text{m}$. An offset of this magnitude would increase the beam envelope by an acceptable amount. The misalignment of the quadrupoles can be compensated by correction schemes like DFS (Dispersion Free Steering) [5]. We haven't included the correction of dispersion free steering in the simulation and therefore used a reduced misalignment of the quadrupoles of $2 \mu\text{m}$.

In principle an offset of the beam has the same effect as a misalignment of the first element of the beamline. For the simulations we have assumed an initial beam offset equal to the corresponding rms beam size. The beam sizes and beam divergences are given in Table 5.4.3.

Initial rms beam size in x [mm]	0.14
Initial rms beam size in y [mm]	0.33
Initial beam divergence in x' [mrad]	0.23
Initial beam divergence in y' [mrad]	0.10

Table 5.4.3: Beam size parameters of the CLIC drive beam

Dispersion:

In the definition of the dispersion function a small momentum spread of the beam is assumed (chapter 2.2.3). This assumption doesn't hold any more for the decelerator as the particle energy can differ significantly from the reference energy. In general we could

extend the definition and define the dispersion function over the Taylor expansion of the particle trajectory $x(s, p + \Delta p)$ with a sufficiently large Δp . A better approach taken in [5] is to inspect the behaviour of an energy dependent beta function $\beta(s, E(s))$.

Beam Gas Scattering:

The total number of N_{halo} halo particles due to beam gas scattering at the end of the decelerator is given by the integrated scattering fraction multiplied by the total number of beam particles (appendix B, Eq. B.0.5):

$$N_{\text{halo}} = n N S_{\text{int}} = n N \sum_{i=1}^{N_{\text{elem}}} P_i l_i \quad (5.4.1)$$

where N_{elem} is the total number of elements, N the number of particles per bunch, n the number of bunches per train, P_i the scattering probability in the element i and l_i the length of the element. As the residual gas consists of different constituents (40% H₂O,

	$\rho_{\text{gas}} [\text{m}^{-3}]$
H ₂ O	1.29×10^{14}
H ₂	1.29×10^{14}
N ₂ , CO, CO ₂	6.44×10^{13}

Table 5.4.4: Molecule density of residual gas constituents

40% H₂ and the remaining 20% shared equally among CO, N₂, CO₂, so 20/3% each, the scattering probability P_i is the sum over the scattering probabilities of the constituents j with a density n_j (Table 5.4.4):

$$P_i = P_{i,\text{brem}} + P_{i,\text{Mott}} = \sum_{j=1}^{N_{\text{res}}} n_j (\sigma_{i,j,\text{brem}} + \sigma_{i,j,\text{Mott}}) \quad (5.4.2)$$

where N_{res} is the number of residual gas constituents, $\sigma_{i,j,\text{Mott/brem}}$ the Mott respectively bremsstrahlung cross section of the constituent j in the element i given by Eq. 5.3.4, 5.3.10 and 5.3.13. The Mott scattering cross section depends on the particle energy and the minimal scattering angle, which we approximated by the beam energy defined as the energy of the central slice and the beam divergence in the element given by Eq. 5.3.6. The Twiss parameters and emittance in each element were taken from the beam dynamics simulations and correspond to the beam size definitions. The bremsstrahlung cross section only depends on the minimal photon energy, which we set to a fixed value of $k_{\text{min}} = 0.01$. Using these input parameters, we obtain for the integrated scattering fraction and the total number of halo particles the values listed in Table 5.4.5. The total integrated scattering fraction S_{tot} is very small and we therefore expect a very small halo generation due to beam gas scattering.

$S_{\text{Mott,tot}}$	7.69×10^{-9}
$S_{\text{brem,tot}}$	1.17×10^{-10}
S_{tot}	7.81×10^{-9}
N_{halo}	1.20×10^6

Table 5.4.5: Integrated scattering fraction along the decelerator for Mott scattering $S_{\text{Mott,tot}}$ and bremsstrahlung $S_{\text{brem,tot}}$ as well as the total integrated scattering fraction S_{tot} and the total number of halo particles N_{halo}

Even if we don't expect a significant halo generation, we want to analyze the tracking results obtained to point out some characteristics of halo and tail generation.

A comparison of the scattering fraction of bremsstrahlung and Mott scattering shows, that Mott scattering is the dominant process. As the Mott scattering cross section increases with decreasing energy, the halo generation due to Mott scattering is stronger in the end of the decelerator than at injection, which is underlined by the initial and final scattering probability (Table 5.4.6). The bremsstrahlung cross section and therefore the scattering probability is energy independent and stays constant along the whole beamline (Table 5.4.6). The analytical estimates enable the computation of the total number of halo

$P_{\text{Mott,initial}} \text{ m}^{-1}$	7.85×10^{-12}
$P_{\text{Mott,final}} \text{ m}^{-1}$	4.19×10^{-11}
$P_{\text{brem,initial}} \text{ m}^{-1}$	1.11×10^{-13}
$P_{\text{brem,final}} \text{ m}^{-1}$	1.11×10^{-13}

Table 5.4.6: Initial and final scattering probability for Mott scattering and bremsstrahlung. The effect of Mott scattering increases along the decelerator while bremsstrahlung stays constant.

particles, but not the halo distribution and the number of lost particles as well as their characteristics, which we therefore simulated with PLACET-HTGEN. For simplicity we used a gas equivalent of N_2 instead of the exact residual gas constitution, a constant scattering angle equal to the minimal beam divergence of $97.58 \mu\text{rad}$ along the decelerator and a constant minimal photon energy of $k_{\text{min}} = 0.01$. In Fig. 5.4.1 and Fig. 5.4.2 the trajectory of beam and halo particles along the whole decelerator and for closer inspection for an extract of the decelerator is shown. Halo particles, which are scattered far outside the beam core follow a trajectory far away from the beam core and finally are lost, when the trajectory increases too much.

The beam and halo distributions at the end of the decelerator are shown in Fig. 5.4.3.

Especially interesting in the decelerator is the energy distribution of the lost halo particles. Most halo particles are lost at the end of the decelerator and have mainly a low

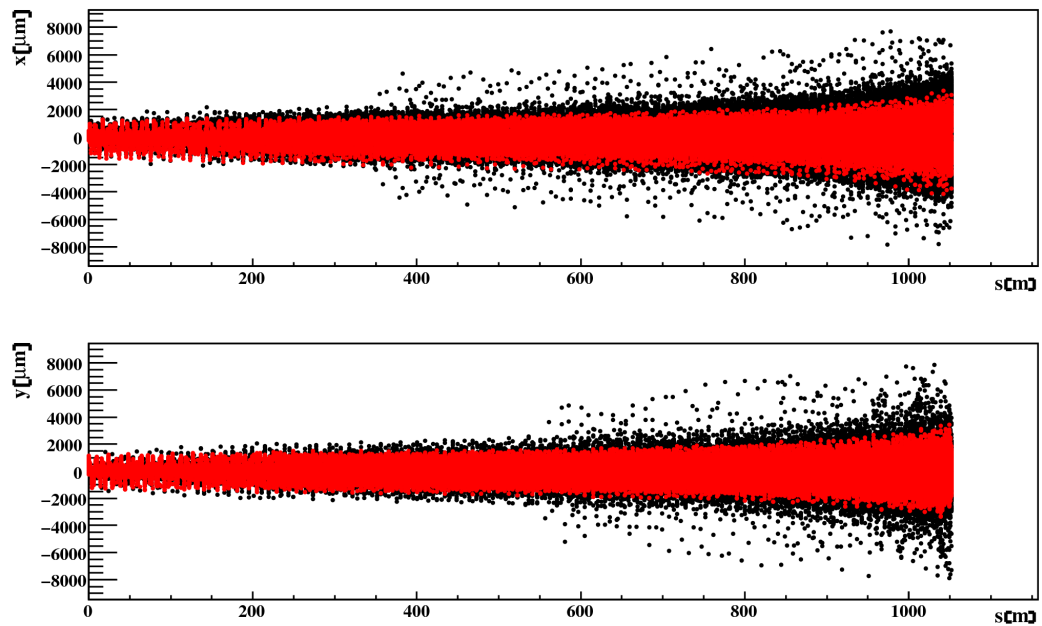


Figure 5.4.1: Tracking of halo and beam along the longest CLIC decelerator: The beam emittance increases along the whole decelerator due to the deceleration .

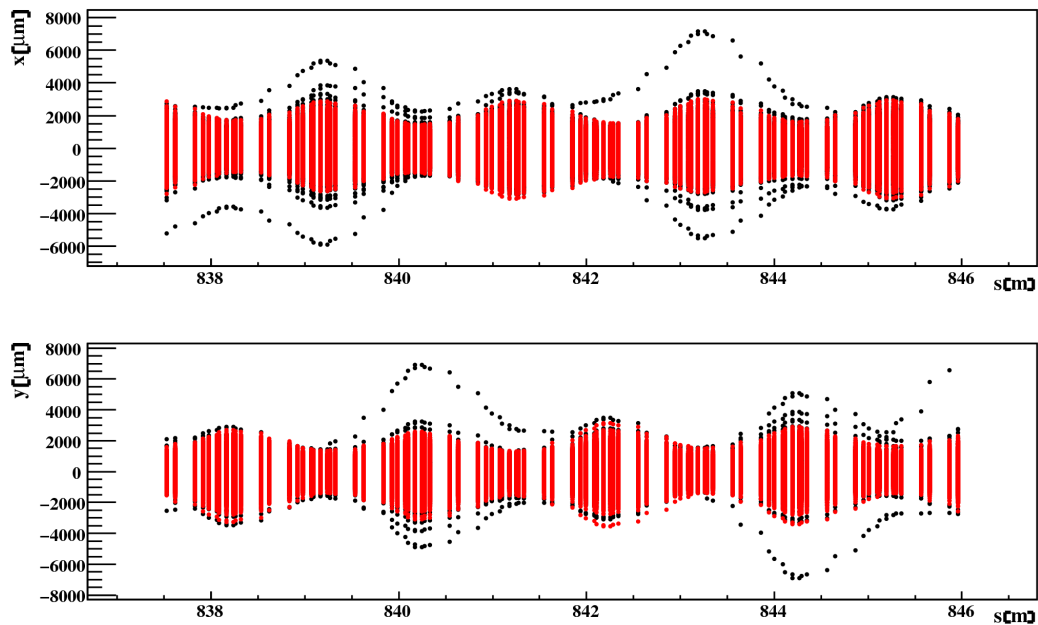


Figure 5.4.2: Tracking of halo and beam along and extract of the longest CLIC decelerator: The amplitude of some halo particles have increased significantly and the particle will soon be lost due to overfocusing in a quadrupole.

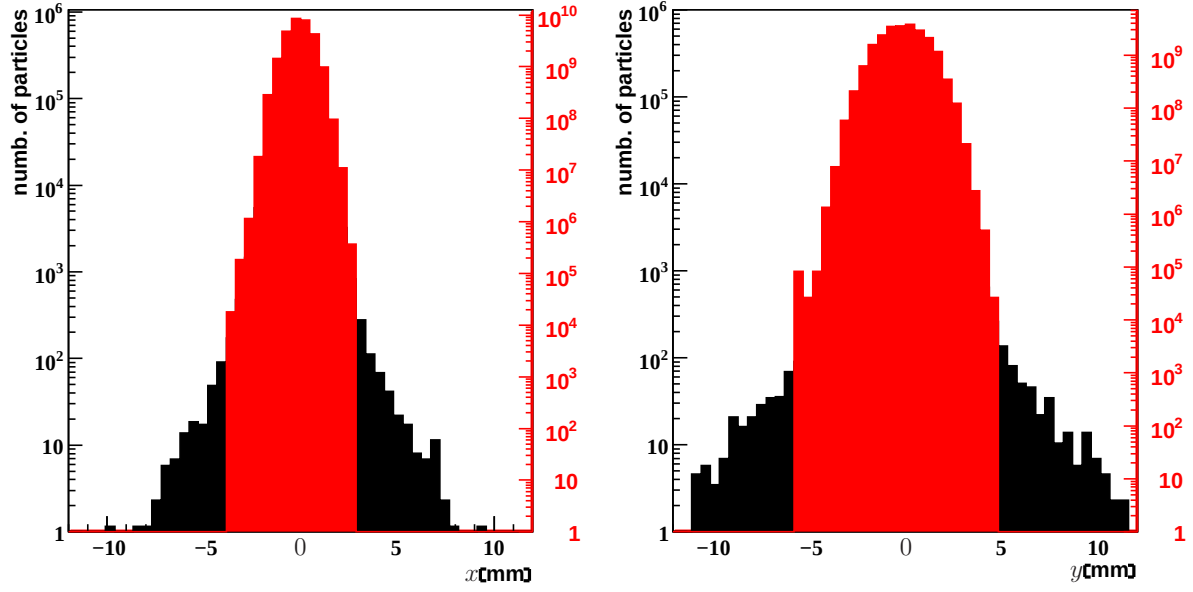


Figure 5.4.3: Beam and halo distribution at the end of the decelerator.

energy (Fig. 5.4.4). This agrees with the results obtained in [5], where especially the most decelerated particles are responsible for the envelope growth in the decelerator.

Typically halo particles with a large initial scattering angle are lost. This effect can also be seen in the decelerator (Fig. 5.4.5). The smallest initial scattering angle of all lost particles is $927.7 \mu\text{rad}$.

In total a fraction (the ratio between the number of lost particles and the total number of beam particles) of 2.35×10^{-6} are lost. Hence the losses due to beam gas scattering in the decelerator are very small and not of importance.

Discussion and Analytical Estimates of Halo and Tail Generation Sources not Included in the Simulation

Ionization of the Residual Gas:

To estimate the ionization of the residual gas, we used a residual gas constitution of 40% H_2O , 40% H_2 and the remaining 20% shared equally among CO , N_2 , CO_2 , so 20/3% each. As the ionization cross section increases with the beam energy, an upper limit for the residual gas ionization is the ionization at the end of the drive beam, which is equivalent to the end of one train as the drive beam consists of only one train, and the maximal beam energy, which is the initial beam energy of 2.4 GeV. For the calculation we used Eq. 5.3.25, 5.3.27, 5.3.28 and 5.3.30. The residual gas densities and beam sizes are given in Table 5.4.2, 5.4.4, 5.4.7 and 5.4.8 and the results in Table 5.4.9. For CO_2 the ionization is largest but is still very small with 6.1%. The total ionization of the residual gas is with

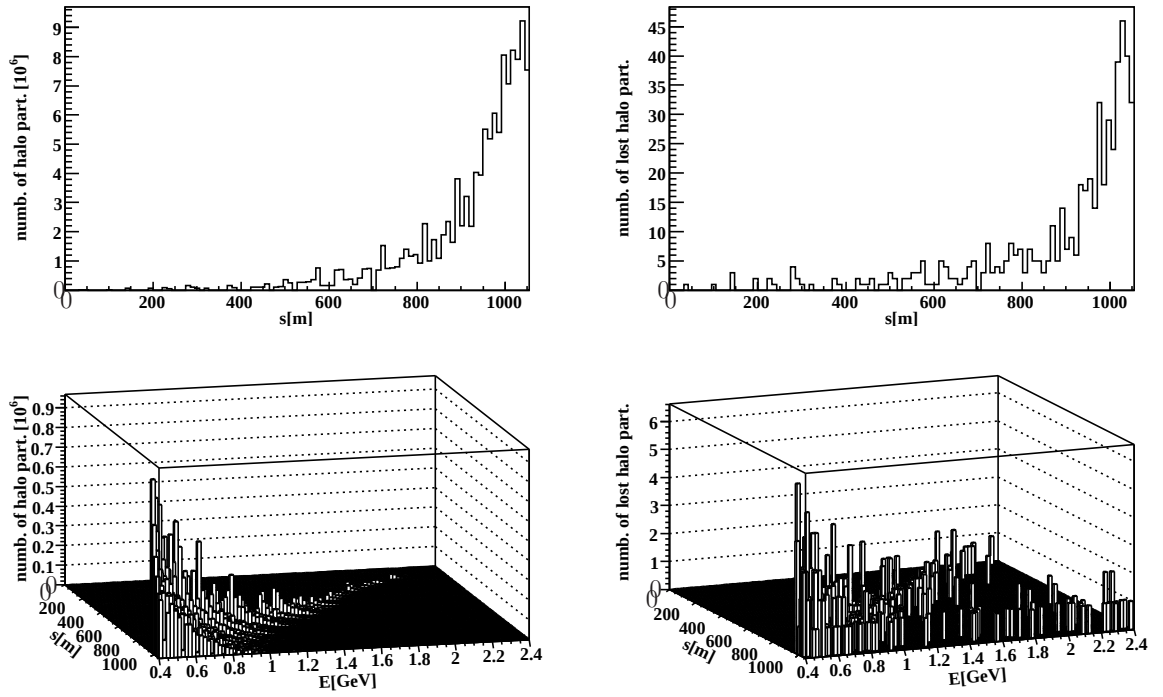


Figure 5.4.4: Top left: Number of halo particles along the decelerator. Top right: Number of lost particles along the decelerator. Most halo particles are lost at the end of the decelerator. Bottom left: Energy distribution of the halo particles along the decelerator. The energy spread increases along the decelerator. Bottom right: Energy distribution of the lost halo particles along the decelerator. Most lost halo particles are low energy particles.

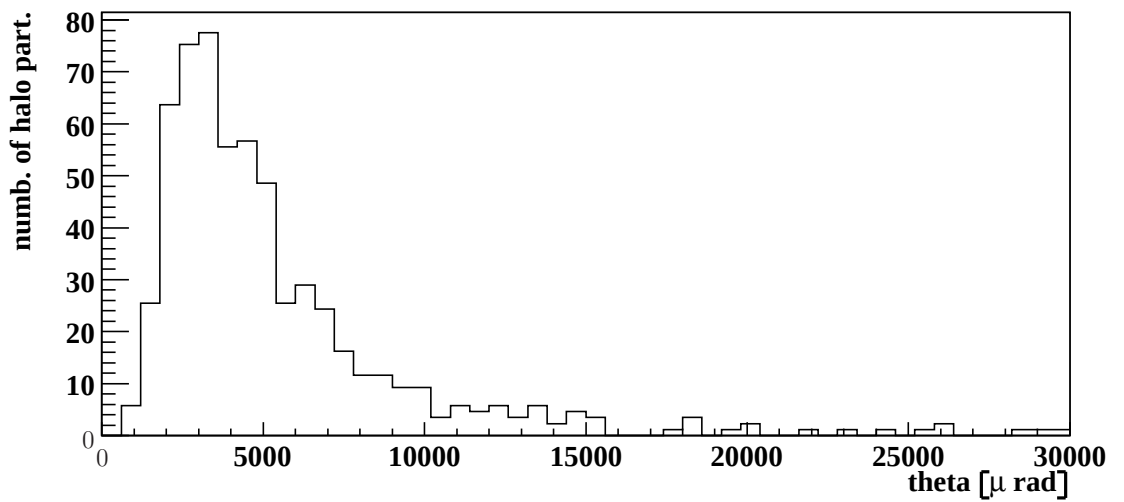


Figure 5.4.5: Initial scattering angle of lost halo particles

1.8% also very small and does not have any influence on the halo and tail generation.

$\sigma_{x,\text{initial}}$ [mm]	0.14
$\sigma_{y,\text{initial}}$ [mm]	0.33
$\sigma_{x',\text{initial}}$ [mrad]	0.23
$\sigma_{y',\text{initial}}$ [mrad]	0.10
$\sigma_{z,\text{initial}}$ [mm]	1.0

Table 5.4.7: Initial rms beam sizes of the CLIC drive beam

$\sigma_{x,\text{final}}$ [mm]	1.50
$\sigma_{y,\text{final}}$ [mm]	1.71
$\sigma_{x',\text{final}}$ [mrad]	0.30
$\sigma_{y',\text{final}}$ [mrad]	0.25
$\sigma_{z,\text{final}}$ [mm]	1.0

Table 5.4.8: Final rms beam sizes of the CLIC drive beam

	σ_{ion} [barn]	λ_{ion} [m ⁻¹]	λ_{gas} [m ⁻¹]	gas ionization [%]
H ₂ O	1.56×10^6	3.09×10^6	1.62×10^8	3.4
H ₂	3.01×10^5	5.96×10^5	1.62×10^8	0.7
CO	1.76×10^6	1.74×10^6	8.10×10^7	3.9
N ₂	1.76×10^6	1.74×10^6	8.10×10^7	3.9
CO ₂	2.77×10^6	2.74×10^6	8.10×10^7	6.1
total	-	5.76×10^6	3.15×10^9	1.8

Table 5.4.9: Residual gas ionization in the CLIC decelerator: A constant beam energy of 2.4 GeV is assumed. The table refers to the values at the end of one train.

Compton Scattering:

Assuming a temperature of 300 K and using Eq. 5.3.18 and 5.3.19 we obtain a photon density of $5.45 \times 10^{14} \text{ m}^{-3}$ and an average photon energy of 0.07 eV. As the dimensionless parameter x defined in Eq. 5.3.21 stays below 10^{-3} , we used Eq. 5.3.22 for the calculation of the Compton cross section. The integrated scattering probability then yields 3.82×10^{-11} , which is very small compared to Mott scattering with an integrated scattering probability of 7.69×10^{-9} . Therefore the effect of transverse deflection by Compton scattering can be neglected. The maximum energy spread caused by Compton scattering is given by Eq. 5.3.24 and lies between 0.04% at the end of the decelerator and 0.26% at injection. This is negligible compared to the energy spread induced by the transverse wakefields.

Synchrotron Radiation:

In the decelerator the energy loss due to synchrotron radiation is very small as the decelerator is a linear accelerator and the only significant energy loss due to synchrotron radiation could occur in the quadrupoles. In addition the small deceleration of the beam

particles caused by the emission of synchrotron radiation photons is negligible compared to the deceleration experienced in the PETS.

Electron Cloud Effects:

As described in chapter 5.3.4 electron cloud effects are not relevant in our case since the drive beam is an electron beam and the decelerator a linear beamline.

Ion Cloud Effects:

According to chapter 5.3.4 the conventional ion instability can not occur in the decelerator, because the decelerator is a linear beamline. A simulation of a possible fast ion instability in the decelerator is planned but the implementation of the FASTION code [54] into PLACET is not yet completed. For an analytical estimate we follow the approach taken in chapter 5.3.4 which was also taken for the long transfer line of CLIC [59].

The number of rise times and the tune shift depend on the beam energy and the Twiss parameters, which change considerably along the decelerator. To estimate the relevance of the fast-ion instability we calculated the critical parameters for the initial beam energy and Twiss parameters as well as for the final ones.

As the drive beam consists of only one train, we can exclude trapping between trains.

Initial norm. emittance in x [μm]	150.0
Initial norm. emittance in y [μm]	150.0
Final norm. emittance in x [μm]	351.4
Final norm. emittance in y [μm]	340.0
Initial β -function in x [m]	0.579
Initial β -function in y [m]	3.354
Final β -function in x [m]	5.029
Final β -function in y [m]	6.778

Table 5.4.10: Initial and final emittance and β -function of the central slice.

The Twiss parameters were obtained from the beam dynamics simulations. All input parameters are listed in Table 5.4.2, 5.4.9, 5.4.7, 5.4.8 and 5.4.10. With an ion charge of $Q_i = 1$ we obtain a critical mass number defined by Eq. 5.3.33 of $A_{\text{trap}} = 7.18 \times 10^{-3}$ for the initial values and $A_{\text{trap}} = 1.97 \times 10^{-4}$ for the final values. Only ions with a mass number bigger than the critical mass number are trapped, which are all ions in our case. The number of risetimes n_{rt} and the incoherent tune shift $\Delta\nu$ given by Eq. 5.3.36 and 5.3.28 yields the values listed in Table 5.4.11 and 5.4.12. The tune shift stays below 1 but the number of rise times is bigger than 1 which indicates a possible occurrence of the fast-ion instability. The foreseen simulations will show, if an occurrence of the fast ion

$\Delta\nu_{x,\text{initial}}$	5.3×10^{-3}
$\Delta\nu_{y,\text{initial}}$	1.3×10^{-2}
$\Delta\nu_{x,\text{final}}$	1.6×10^{-2}
$\Delta\nu_{y,\text{final}}$	3.7×10^{-3}

Table 5.4.11: Incoherent tune shift due to the fast ion instability

$[n_{rt,\text{initial}}, 3n_{rt,\text{initial}}]$	$[1.89, 5.69]$
$[n_{rt,\text{final}}, 3n_{rt,\text{final}}]$	$[0.54, 1.64]$

Table 5.4.12: Number of rise times of the fast ion instability

instability is likely.

Touschek Effect and Intrabeam Scattering:

We would expect that intrabeam scattering and Touschek effect are not relevant in the decelerator as the beam size is quite large and the energy still relatively high. On the other hand Touschek effect and intrabeam scattering could be more important in the CLIC *decelerator* than in comparable linear *accelerators* without decelerating sections as beam particles, which have lost longitudinal momentum due to Coulomb interaction, could lose almost all their longitudinal momentum during the deceleration and are lost [56], [60]. Both effects are not implemented in the simulation. Only a full simulation can show, that a particle loss due to Touschek effect combined with the deceleration can occur.

Space Charge Effect:

From the optics point of view the decelerator is a sequence of FODO cells, where the strength of the quadrupoles can vary according to the beam energy. For a rough estimate we followed chapter 5.3.6 to obtain the ratio between the space charge force F_{sc} and the focusing strength k . The necessary input parameters are listed in Table 5.4.2, 5.4.7, 5.4.8 and 5.4.13.

$\langle\beta_{x,\text{initial}}\rangle$ m	1.97
$\langle\beta_{y,\text{initial}}\rangle$ [m]	1.97
$\langle\beta_{x,\text{final}}\rangle$ [m]	2.26
$\langle\beta_{y,\text{final}}\rangle$ [m]	2.25

Table 5.4.13: Initial and final average β -function over one period

The quadrupole focusing strength k can be approximated by the β function $k = 1/\langle\beta\rangle^2$, where $\langle\beta\rangle$ is the average β function over one oscillation period. As the decelerator is from the optics point of view a FODO lattice, one period corresponds to 2 quadrupoles.

We approximated $\langle\beta\rangle$ by the average over β in the first/last two quadrupoles and β by the average β function over all slices (Table 5.4.7 and 5.4.8). The ratios between the space charge force and the quadrupole strength stay below 0.1% (Table 5.4.14), which is very small and we conclude, that the effect of the transverse space charge is negligible.

$F_{sc,x,\text{initial}}/k_{x,\text{initial}} [\%]$	2.35×10^{-5}
$F_{sc,y,\text{initial}}/k_{y,\text{initial}} [\%]$	4.89×10^{-5}
$F_{sc,x,\text{final}}/k_{x,\text{final}} [\%]$	8.71×10^{-5}
$F_{sc,y,\text{final}}/k_{y,\text{final}} [\%]$	3.78×10^{-4}

Table 5.4.14: Ratio between the space charge force F_{sc} and the focusing strength k

Mismatch:

Studies have shown, that a mismatch of even a few percent does not have an effect on the beam envelope. Therefore if the beam is not heavily mismatched, we don't expect an additional halo generation from this source [61].

Coupling:

For quadrupoles and PETS it is a good assumption that the motion in the transverse plane is uncoupled. The effect of coupling due to misalignment has been studied in [58] and shows that a rotation of the quadrupoles by less than 1 mrad changes the beam envelope only insignificantly. Therefore under the condition of an quadrupole role of less than 1 mrad coupling can be neglected.

Nonlinearities:

As in the PETS simulation only the dipole wake is included, our simulations are purely linear. The error from higher order modes of the PETS has not yet been studied. Small field errors of the quadrupoles are unlikely to lead to a significantly different behaviour of the beam [61].

5.4.2 CTF3 TBL Drive Beam

The CTF3 TBL is the test stand for the drive beam decelerator and provides the opportunity to benchmark the simulation performed with PLACET-HTGEN.

Analytical Estimates and Simulation Results

The CTF3 TBL lattice consists of 16 PETS with quadrupoles placed between the PETS. The quadrupoles follow a FODO lattice with a focal strength adjusted to the beam energy. The main lattice and beam parameters are given in Table 5.4.15, the vacuum specification

in Table 5.4.16. In the simulations with PLACET we have included the effect of a beam offset, misalignment and longitudinal as well as transverse wakefield effects. We chose a sliced beam model with 800 bunches per train, 51 slices and 1 macroparticle per slice. As vacuum specification we assumed the same parameters as for the CLIC decelerator, namely 40% H₂O, 40% H₂ and the remaining 20% shared among CO, N₂, CO₂ with a total pressure of 10 nTorr and a temperature of 300 K. For the simulations we used for simplicity a gas equivalent of pure N₂ gas.

DB station length [m]	22.4
number of trains	1
Bunches per train	1683
Bunch separation [m]	0.025
Bunch length [mm]	1
number of particles per bunch [10^9]	14.6
E_{initial} [MeV]	150.0
E_{final} [MeV]	65.8

Table 5.4.15: Beam and lattice parameters of the CTF3 TBL drive beam

pressure [nTorr]	10
temperature [K]	300
molecule density [m^{-3}]	3.22×10^{14}

Table 5.4.16: CTF3 TBL vacuum specifications

Wakefields, Misalignment and Beam Offset

The PETS dipole mode transverse wakefields and fundamental mode longitudinal wake field are included in the simulation. They cause an emittance growth and deceleration similar to the one described for the CLIC drive beam (chapter 3.3.3). The results of the wakefield studies for CTF3 are presented in [5].

The TBL is equipped with special movers for quadrupoles and PETS to study the effect of misalignment and the correction schemes of beam based alignment and dispersion free steering. For our simulation we have assumed an offset of the quadrupoles in y of $2 \mu\text{m}$ and of the PETS also in y of $100 \mu\text{m}$.

Further an initial beam offset equal to half the corresponding rms beam size was introduced. The beam sizes and beam divergences are given in Table 5.4.17.

Dispersion:

It is possible to define a dispersion function, but a better way is to study the behaviour of

Initial rms beam size in x [mm]	0.65
Initial rms beam size in y [mm]	1.55
Final rms beam size in x [mm]	1.43
Final rms beam size in y [mm]	2.42
Initial beam divergence in x' [mrad]	0.79
Initial beam divergence in y' [mrad]	0.33
Final beam divergence in x' [mrad]	0.89
Final beam divergence in y' [mrad]	0.52

Table 5.4.17: Beam size parameters of the CTF3 TBL drive beam

an energy dependent beta function. This was done for the CLIC drive beam decelerator but could be transferred to the CTF3 TBL drive beam [5].

Beam Gas Scattering:

In the following we only present the results of halo and tail generation due to beam gas scattering as the whole procedure (chapter 5.4.1) is the same for CTF3 TBL as for the CLIC decelerator only with different input parameters.

We approximated the minimal scattering angle and the beam energy needed as input for Mott scattering by the values obtained in the simulations and set the minimal photon energy, needed as input for the simulations of bremsstrahlung, to 0.01. Using these input parameters, we obtain for the integrated scattering fraction and the total number of halo particles the values listed in Table 5.4.18. The total integrated scattering fraction S_{tot} is very small and we therefore expect a very small halo generation due to beam gas scattering. A comparison of the scattering fraction of bremsstrahlung and Mott scattering shows,

$S_{\text{Mott,tot}}$	3.43×10^{-9}
$S_{\text{brem,tot}}$	2.48×10^{-12}
S_{tot}	8.47×10^{-9}
N_{halo}	9.88×10^4

Table 5.4.18: Integrated scattering fraction along the CTF3 TBL for Mott scattering $S_{\text{Mott,tot}}$ and bremsstrahlung $S_{\text{brem,tot}}$. The total scattering fraction S_{tot} and total number of halo particles N_{halo} is very small and can be neglected.

that Mott scattering is the dominant process.

The simulations of beam gas scattering were performed with PLACET-HTGEN. For simplicity we used again a gas equivalent of N_2 , a constant scattering angle equal to the minimal beam divergence of $330.59 \mu\text{rad}$ along the CTF3 TBL and a constant minimal photon energy of $k_{\text{min}} = 0.01$. In total a fraction of 5.64×10^{-5} particles are lost. The number

of lost particles due to beam gas scattering are therefore negligible, but high enough for measurements, so that a benchmarking of the PLACET-HTGEN would be possible.

Discussion and Analytical Estimates of Halo and Tail Generation Sources not Included in the Simulation

Ionization of the Residual Gas:

Ionization of the residual gas is only a problem for high energy beams since the ionization cross section increases with the energy. The CTF3 TBL is a low energy beam and we can neglect the ionization. Analytical estimates analog to the ones performed for the CLIC decelerator (chapter 5.4.1) yield a maximum ionization of 0.01% assuming a constant beam energy equal to the maximum beam energy (initial beam energy), which confirms our assumption.

Compton Scattering:

Assuming a temperature of 300 K the photon density is $5.45 \times 10^{14} \text{ m}^{-3}$ and the average photon energy 0.07 eV. We used Eq. 5.3.22 for the calculation of the Compton cross section as the dimensionless parameter x stays below 10^{-3} . The integrated scattering probability then yields 8.18×10^{-13} , which is very small compared to Mott scattering with an integrated scattering probability of 3.43×10^{-9} . The maximum energy spread caused by Compton scattering stays below 0.016%. The deflection of the particles due to Compton scattering as well as the caused energy spread are therefore very small and can be neglected.

Synchrotron Radiation:

We don't expect any halo and tail generation from synchrotron radiation effect, because the CTF3 TBL is a linear beamline and has a low energy beam. In addition the energy spread caused by synchrotron radiation would be anyway small compared to the one caused by the deceleration.

Electron and Ion Cloud Effects:

The CTF3 TBL is a linear beamline transporting a negatively charged low energy beam, which makes the occurrence of electron cloud effects very improbable. Ion cloud effects i.e. only the fast ion instability would be more probable. We performed the same analytical estimated for the TBL as for the CLIC drive beam decelerator. The number of risetimes is lower than 0.015 and the tune shift smaller than 10^{-4} . Both value are below one and consequently confirm, that the fast ion instability is not relevant.

Touschek Effect and Intrabeam Scattering:

Touschek Effect and Intrabeam Scattering are more relevant in the CTF3 TBL than in the CLIC decelerator due to the lower beam energy of the CTF3 TBL beam. Analog to the CLIC *decelerator* both effects could be more relevant than in a comparable linear *accelerator* due to the strong deceleration. On the other hand the beam size is still quite large, which makes Touschek and intrabeam scattering improbable. A study of this effect would be very interesting, but the implementation in PLACET-HTGEN is time-consuming and out of scope of this thesis.

Space Charge Effect:

Space charge effects become more relevant with decreasing energy. The CLIC decelerator and the CTF3 TBL do basically not differ in the lattice (only the lattice length), but the beam energies are different. The increase of space charge effects can be seen by comparing Table 5.4.19 and 5.4.14. Although the space charge effect is stronger for the CTF3 TBL than for the decelerator, it is still negligible ($F_{sc} < 1\%$). The computation of

$F_{sc,x,\text{initial}}/k_{x,\text{initial}} [\%]$	2.30×10^{-3}
$F_{sc,y,\text{initial}}/k_{y,\text{initial}} [\%]$	9.69×10^{-4}
$F_{sc,x,\text{final}}/k_{x,\text{final}} [\%]$	7.20×10^{-3}
$F_{sc,y,\text{final}}/k_{y,\text{final}} [\%]$	4.25×10^{-3}

Table 5.4.19: Ratio between the space charge force F_{sc} and the focusing strength k

F_{sc} follows the computation for the decelerator (chapter 5.4.1). The input parameters are given in Table 5.4.17, 5.4.15 and 5.4.20 and the results in Table 5.4.19.

$\langle \beta_{x,\text{initial}} \rangle \text{ m}$	2.76
$\langle \beta_{y,\text{initial}} \rangle [\text{m}]$	2.75
$\langle \beta_{x,\text{final}} \rangle [\text{m}]$	2.77
$\langle \beta_{y,\text{final}} \rangle [\text{m}]$	2.77

Table 5.4.20: Initial and final average β -function over all slices

Mismatch, Coupling and Nonlinearities:

Mismatch, Coupling and Nonlinearities have not been studied for the CTF3 TBL. To neglect coupling is a good approximation for ideally aligned quadrupoles and PETS, but for example a misalignment of these elements would induce coupling.

Only the dipole wake is included in the simulations and the quadrupoles are treated as ideal magnets without field errors etc., hence all fields are linear. Nonlinearities in the equation of particle motion could be e.g. caused by field errors or higher order modes of

the PETS. Both are expected to be small.

The model of the PETS has been tested at CTF3 and agrees well with the measurements, which confirms the developed model of the PETS.

5.4.3 TBONE

We have studied halo and tail generation only for the superconducting linac of TBONE, where the beam is accelerated to an energy of 87 MeV. The simulations for TBONE have just started and therefore many effects are not yet implemented and the tracking is not totally adapted to the special case of TBONE. However the simulation and analytical estimates performed give a rough estimate of the halo and tail generation in TBONE. As TBONE is supposed to deliver high power coherent THz radiation, the beam has to be transported with minimal losses in order to assure the required radiation power. Therefore an estimate of losses due to halo and tail generation is needed.

Analytical Estimates and Simulation Results

For the simulation and analytical estimates we assumed that the residual gas consists to 100 % of H_2 with a total pressure of 0.07 nTorr and a temperature of 2 K. We have simulated the beam dynamics with PLACET, which is described in chapter 4.2. The beam parameters and vacuum specification are given in Table 5.4.21 and 5.4.22.

pressure [nTorr]	0.075
temperature [K]	2
molecule density [m^{-3}]	3.62×10^{14}

Table 5.4.21: TBONE vacuum specifications

superconducting linac length [m]	3.11
number of bunches	1
number of particles per bunch [10^9]	0.52
Bunch length [mm]	0.62
E_{initial} [MeV]	8.35
E_{final} [MeV]	87.02

Table 5.4.22: Beam and lattice parameters of TBONE

Wakefields:

In PLACET the wakefields are stored in form of a table, which contains the wakefield

kick of each slice. For the computation of this wakefield table we used the routine written for the ILC main linac with adjusted bunch length and charge. Taking the created table as input, the longitudinal short and long range wakefields and the transverse dipole mode wakefield could be simulated with PLACET [62]. In the case of TBONE the long range wakefields are not relevant because the beam only consists of one bunch. As the wakefields mainly depend on the geometry of the structure, the bunch charge, energy and length, the simulations give only an estimate of the wakefield effects. The results of the simulations are shown in chapter 4.2.

Beam Gas Scattering:

The method of beam gas scattering simulations is described in detail in chapter 5.4.1 and we therefore only present the results obtained. As emittance, β -function and beam energy we used the values obtained by the simulation with PLACET. The integrated scattering fraction and total number of halo particles are given in Table 5.4.23. The integrated scattering fraction for bremsstrahlung is very small and we don't expect any halo generation from this source. For Mott scattering the integrated scattering fraction is comparable to the one obtained in the case of the CLIC drive beam decelerator, but as the superconducting linac of TBONE is a very short accelerator, the halo generation due to beam gas scattering is totally negligible.

$S_{\text{Mott,tot}}$	3.66×10^{-9}
$S_{\text{brem,tot}}$	3.14×10^{-14}
S_{tot}	3.66×10^{-9}
N_{halo}	1.91

Table 5.4.23: Integrated scattering fraction along the superconducting linac for Mott scattering $S_{\text{Mott,tot}}$ and bremsstrahlung $S_{\text{brem,tot}}$

Discussion and Analytical Estimates of Halo and Tail Generation Sources not Included in the Simulation

Ionization of the Residual Gas:

The ionization cross section increases with rising beam energy. As the beam energy of TBONE is small we therefore don't expect any significant ionization of residual gas.

Compton Scattering:

The average energy and density of the photons emitted by the surrounding structure decrease with falling temperature. Because the temperature in TBONE is very low (2 K),

we can neglect the halo generation due to Compton scattering and also the energy spread caused by Compton scattering.

Synchrotron Radiation:

The superconducting linac does not include any bending or focusing magnets, where synchrotron radiation could become relevant.

Electron Cloud Effects:

As described in chapter 5.3.4 the electron cloud effect is not relevant in our case as TBONE is a linear electron beam accelerator.

Ion Cloud Effects:

The conventional ion instability only arises in circular accelerators and the fast ion instability normally only in long linear beamlines. In short linear accelerators an occurrence of an ion instability is therefore very unlikely.

Touschek Effect and Intrabeam Scattering:

If the beam size is very small, beam particles could become halo particles due to Touschek or intrabeam scattering. TBONE is first of all a linear accelerator, where intrabeam scattering has hardly any effect, and in addition the beam has a relatively large beam size. Therefore both effects are probably negligible.

Space Charge Effect:

Space charge effects are normally only relevant for electron beams with beam energies in the keV range or lower. Therefore we haven't performed any estimates of space charge effects.

Optics Related Effects

We haven't studied any effects resulting from mismatch, coupling or any dispersive effects, which could be the topic of further studies for TBONE. Nonlinearities are not included either, because only the dipole wakes are simulated and no higher magnetic multipoles are included in the lattice.

Beam Offset

Wakefields are often very small for particles, which pass the structure in the center, but can become quite large for particles with an offset. The effect of a beam offset has not yet been inspected, but it could influence the beam dynamics significantly due to the wakefield effects.

In general more information about TBONE is needed, before more specific results can be obtained.

Chapter 6

Conclusion

The halo and tail generation in three medium to low energy linear accelerators, the CLIC and CTF3 TBL drive beam and the superconducting linac of TBONE, was studied. For the simulations of the beam dynamics the tracking code PLACET and for the halo and tail generation the package HTGEN were used. Both can be combined to the tracking and halo and tail simulation code PLACET-HTGEN. As HTGEN was originally written for high energies, a low energy validation of the code was performed in this work with the following results:

- The implementation of Mott scattering in HTGEN is still valid for low energies and of bremsstrahlung down to 50 MeV. Below 50 MeV the implemented approximation tends to become less reliable.
 - Compton Scattering is more relevant for high energies and can in most cases be neglected.
 - The effect of synchrotron radiation can be simulated with PLACET in the relevant elements. It can be neglected in most linear low energy accelerators.
 - Electron cloud effects are usually not relevant for electron beams and especially for linear accelerators. As the ionization of the residual gas is less for lower than for higher beam energies ion cloud effects become less important. Despite the low energy, an occurrence of the fast ion instability is still possible especially in long beamlines.
 - For low energies and small beamsizes Touschek effect and intrabeam scattering can be the driving force of halo and tail generation, but can be usually neglected for normal beamsizes.
 - Space charge effects are usually only relevant for beam energy up to a few hundred keV. For verification this should be checked for every beam with analytical estimates, especially for beams with very short bunches.
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- The simulation of wakefield effects are implemented, where their influence is expected to be large. For low energies the wakefield effects become negligible compared to the space charge effects.
- Mismatch, coupling, dispersive effects, nonlinearities and misalignment can be simulated with PLACET.
- Noise and Vibrations as well as dark currents are not included in the simulations.

The losses due to halo and tail generation can only be obtained by simulations. For an estimate of the number of lost particles a realistic halo tracking is needed. Therefore the halo tracking in cavities and PETS as well as the effect of misalignment on the halo was implemented in the framework of this thesis.

After this preparatory work we performed the simulations and analytical estimates for the CLIC decelerator, the CTF3 TBL and the superconducting linac of TBONE.

For the CLIC decelerator the wakefields in the PETS are the dominating effect. They drive the beam dynamics in the decelerator and cause a significant emittance growth and deceleration. The simulation of misalignment shows, that the tolerances for misalignment are tight [5]. From all other effects a significant halo and tail generation in the decelerator is not expected. The simulations of beam gas scattering yield, that the losses due to this process are very small and can be neglected. From the analytical estimates of the fast ion instability the occurrence of the instability can not be excluded. There are further simulations planned to investigate this effect. Intrabeam scattering and Touschek effect are usually only relevant for small beam sizes, so not for the drive beam, but the effect of the deceleration can enforce both effects. Because of the relatively large beam size of the drive beam we do not expect a significant halo generation due to this source. The effect from all other sources is estimated to be small and can be neglected.

The CTF3 TBL is a presently operating machine and gives the opportunity of comparing the simulation results and analytical estimates with measurements. In this thesis the simulation part was covered. Just as in the decelerator the driving force of the beam dynamics are the wakefields responsible for the emittance growth and deceleration. Not all effects have been studied, but the not examined ones are expected to be small. The simulation of beam gas scattering shows, that only very few particles are lost due to this effect. Compton Scattering, electron and ion cloud effects as well as space charge effects can be neglected, but the effect of intrabeam scattering and Touschek effect could become relevant because of the deceleration.

For the superconducting linac of TBONE the beam dynamics and the halo and tail generation were simulated. By running all three cavities above transition the for the bunch compression demanded energy chirp could be introduced. In the simulation the effect of wakefields was included. As an approximation the wakefields for the ILC main beam

were used, since they have not yet been calculated for TBONE. Beam gas scattering, Compton scattering, synchrotron radiation, electron and ion cloud effects are expected to be small. Intrabeam scattering and Touschek effect as well as space charge effects and optics related effects could be relevant, but were not studied in the framework of this thesis.

Bibliography

- [1] “The tracking code PLACET.” <https://savannah.cern.ch/projects/placet/>.
- [2] “Halo and tail generation package HTGEN.” <http://hbu.home.cern.ch/hbu/HTGEN.html>.
- [3] T. C. Study Team, “A 3 TeV e^+e^- linear collider based on CLIC technology.” Summary, 2000.
- [4] A.-S. Müller, E. Bründemann, S. Casalbuoni, B. Gasharova, M. Havenith, Y.-L. Mathis, A. Plech, and K. Sonnad, “TBONE: Ultra-fast high-power coherent THz to mid-IR radiation facility.” Proposal.
- [5] E. Adli, *A Study of the Beam Physics in the CLIC Drive Beam Decelerator*. PhD thesis, University of Oslo, August 2009.
- [6] T. P. Wangler, *RF Linear Accelerators*. Wiley-VCH, 2nd ed., 2008.
- [7] H. Wiedemann, *Particle Accelerator Physics - Basic Principles and Linear Beam Dynamics*. Springer Verlag, 1993.
- [8] K. Wille, *The Physics of Particle Accelerators*. Oxford University Press, 2000.
- [9] H. Braun, R. Corsini, J.-P. Delahaye, A. De Roeck, S. Doebert, G. Geschonke, A. Grudiev, C. Hauviller, B. Jeanneret, E. Jensen, T. Lefevre, Y. Papaphilippou, G. Riddone, L. Rinolfi, W.-D. Schlatter, H. Schmickler, D. Schulte, I. Syratchev, M. Taborelli, F. Tecker, R. Toms, S. Weisz, W. Wunsch, and A. Ferrari, “CLIC 2008 Parameters,” tech. rep., CERN - AB Department, 2008.
- [10] D. Proch, *Handbook of Accelerator Physics and Engineering*, ch. 7.3.10, p. 576. World Scientific Publishing Co. Pte. Ltd, 3 ed., 2006.
- [11] A. M. Sessler, “The FEL as a power source for a high gradient accelerating structure,” *AIP Conf. Proc.* 91, p. 154, 1982.
- [12] L. Rinolfi and T. Kamitani, “The CLIC positron production scheme,” *LINAC2002*, 2002.

-
- [13] F. Antoniou and Y. Papaphilippou, “Optics design considerations for the CLIC pre-damping rings,” *PAC’09*, 2009.
- [14] T. E. d’Amico, G. Guignard, and T. Raubenheimer, “The CLIC main linac bunch compressor,” *EPAC’98*, 1998.
- [15] D. Schulte, “Emittance preservation in the main linac of CLIC,” *EPAC’98*, 1998.
- [16] G. Geschonke and for the CLIC/CTF3 collaboration, “Results from the CLIC test facility CTF3 and update on the CLIC design.” CLIC-Note-742.
- [17] A.-S. Müller, T. Baumbach, E. Bründemann, S. Casalbuoni, B. Gasharova, M. Hagelstein, M. Havenith, S. Hillenbrand, E. Huttel, Y.-L. Mathis, D. A. Moss, A. Plech, R. Rossmanith, and K. Sonnad, “TBONE: Ultra-fast high-power coherent THz to mid-IR radiation facility,” *PAC’09*, 2009.
- [18] C. Gerth and F. E. Hannon, “Injector design for the 4GLS energy recovery linac prototype,” *EPAC’04*, 2004.
- [19] J. Teichert, A. Büchner, P. Evtushenko, F. Gabriel, U. Lehnert, P. Michel, and J. Voigtländer, “Results of beam parameter measurement of the ELBE electron accelerator after commissioning,” *Nuclear Instruments and Methods in Physics Research A*, vol. 507, pp. 354–356, 2003.
- [20] D. J. Holder, N. Bliss, A. R. Goulden, P. A. McIntosh, and P. L. Smith, “The status of ALICE, the daresbury energy recovery linac prototype,” *EPAC’08*, 2008.
- [21] S. Hillenbrand, “Studien von magnetoptiken zur erzeugung ultra-kurzer elektronenpakete für TBONE.” Diplomarbeit and der Universität Karlsruhe, October 2009.
- [22] B. Autin, C. Carli, T. E. D’Amico, O. Gröbner, M. Michel, E. Wildner, and et al., “Beam optics: a program for analytical beam optics.” CERN Yellow Report, 1998.
- [23] D. Schulte, E. Adli, B. Burkhardt, Helmut Dalena, P. Eliasson, and A. Latina, “The tracking code PLACET.” Manual.
- [24] E. D’Amico, G. Guignard, and D. Schulte, “Simulation package based on PLACET,” *CERN/PS 2001-028 (AE)*, 2001.
- [25] B. Povh, K. Rith, C. Scholz, and F. Zetsche, *Particles and Nuclei*. Springer, 4 ed., 1999.
- [26] H. Bethe and W. Heitler, “On the stopping of fast particles and on the creation of positive electrons,” *Proc. Roy. Soc.A*, vol. 146, p. 83, 1934.
- [27] H. Bethe and L. Maximom, “Theory of bremsstrahlung and pair production. i. differential cross section,” *Phys. Rev.*, vol. 93, p. 768, 1954.
-

-
- [28] H. Olsen, "Outgoing and ingoing waves in final states and bremsstrahlung," *Phys. Rev.*, vol. 99, p. 1335, 1955.
- [29] H. Olsen, L. Maximon, and H. Wergeland, "Theory of high energy bremsstrahlung and pair production in a screened field," *Phys. Rev.*, vol. 106, p. 27, 1957.
- [30] H. Olsen and L. Maximon, "Photon and electron polarization in high-energy bremsstrahlung and pair production with screening," *Phys. Rev.*, vol. 114, p. 887, 1959.
- [31] S. D. Drell and J. Walecka, "Electrodynamic processes with nuclear targets," *Annals of Physics*, vol. 28, pp. 18–33, 1964.
- [32] Y.-S. Tsai, "Pair production and bremsstrahlung of charged leptons," *Review of Modern Physics*, vol. 46, pp. 815–851, October 1974.
- [33] P. D. Group, "Passage of particles through matter," *Review of Particle Physics*, 2008.
- [34] H. W. Koch and J. Motz, "Bremsstrahlung cross-section formulas and related data," *Review of Modern Physics*, vol. 31, p. 920, October 1959.
- [35] S. M. Seltzer and M. J. Berger, "Bremsstrahlung spectra from electron interactions with screened atomic nuclei and orbital electrons," *Nucl. Inst. and Meth.*, vol. B12, p. 95, 1985.
- [36] H. K. Tseng and R. H. Pratt, "Comments on the calculation of relativistic bremsstrahlung cross sections," *Phys. Rev. A*, vol. 1, pp. 528–531, Feb 1970.
- [37] S. Perkins, D. Cullen, and S. Seltzer, "Eedl," *UCRL-50400*, vol. 31, 1991.
- [38] *Physics Reference Manual*.
p. 120-134, December 2008.
- [39] E. Borie, L. C. Maximon, and H. Olsen, "Molecular coherence effects in radiation processes: Bremsstrahlung," *Phys. Rev. A*, vol. 2, pp. 1443–1449, Oct 1970.
- [40] G. D. Palazzi, "High-energy bremsstrahlung and electron pair production in thin crystals," *Rev. Mod. Phys.*, vol. 40, pp. 611–631, Jul 1968.
- [41] W. Heitler, *The Quantum Theory of Radiation*.
Oxford University Press, 3 ed., 1954.
- [42] V. Telnov, "Scattering of electrons on thermal radiation photons in electron-positron storage rings," *Nuclear Instruments and Methods*, vol. A260, pp. 304–308, 1987.
- [43] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, and V. I. Telnov, "Colliding ge and gg beams based on the single-pass $e^{\pm}e^{\mp}$ colliders (vlepp type)," *Nuclear Instruments and Methods*, vol. 205, pp. 47–68, 1983.
- [44] I. Reichel, *Study of the Transverse Beam Tails at LEP*.
PhD thesis, University of Aachen, 1998.
-

-
- [45] Y. Baconnier, “Neutralization of accelerator beams by ionization of the residual gas,” *CERN/PS/PSR*, 1984.
- [46] M. Inokuti, “Inelastic collisions of fast charged particles with atoms and molecules - the bethe theory revisited,” *Rev. Mod. Phys.*, vol. 43, July 1971.
- [47] F. F. Rieke and W. Prepejchal, “Cross sections of gaseous atoms and molecules for high-energy electrons and positrons,” *Phys. Rev. A*, vol. 6, October 1972.
- [48] G. Rumolo, “Fast ion instability.” Summary.
- [49] F. Zimmermann, J. Byrdy, A. Chao, S. Heifets, M. Minty, T. Raubenheimer, J. Seeman, G. Stupakov, and J. Thomson, “Experiments on the fast beam-ion instability at the ALS,” *SLAC-PUB*, October 1997.
- [50] T. Raubenheimer and F. Zimmermann, “Fast beam-ion instability,” *Physical Review E*, vol. 52, pp. 5487–5504, November 1995.
- [51] J.-B. Jeanneret, E. Adli, A. Latina, G. Rumolo, D. Schulte, and R. Toms, “Beam dynamics issues in the CLIC long transfer line,” *EPAC’08*.
- [52] T. Raubenheimer, F. Zimmermann, and G. Stupakov, “A fast beam-ion instability,” *PAC95*, 1995.
- [53] F. Zimmermann, *Accelerator Physics and Engineering*, ch. Ion Instability, p. 131. World Scientific, 2002.
- [54] G. Rumolo and D. Schulte, “Fast ion instability in the CLIC transfer line and main linac,” *EPAC’08*, 2008.
- [55] A. Piwinski, “The Touschek effect in strong focusing storage rings,” *DESY*, no. 98-179, 1998.
- [56] G. H. Hoffstaetter, M. P. Ehrlichman, and A. B. Temnykh, “Intra beam scattering in linear accelerators, especially ERLS,” *EPAC’08*, 2008.
- [57] M. Fitterer, E. Adli, I. Ahmed, H. Burkhardt, B. Dalena, A. Latina, A.-S. Müller, G. Rumolo, and D. Schulte, “Halo and tail simulations with application to the CLIC drive beam,” *PAC’09*, 2009.
- [58] E. Adli and D. Schulte, “Alignment tolerances for the CLIC decelerator,” *CLIC-Note-773*, 2008.
- [59] J. B. Jeanneret, E. Adli, G. Rumolo, D. Schulte, and R. Tomas, “Beam dynamics issues in the CLIC long transfer line,” *EPAC’08*, 2008.
- [60] A. B. Temnykh, M. P. Ehrlichman, and G. H. Hoffstaetter, “Beam losses due to intra-beam and residual gas scattering for Cornell’s energy recovery linac,” *EPAC’08*, 2008.
-

-
- [61] E. Adli, “Private communication.”
 - [62] K. L. F. Bane, “Short range dipole wakefields in accelerating structures for the NLC,” *SLAC-PUB*, no. 9663, 2003.
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Appendix

Appendix A

Basic Waveguide Parameters

For the specification and description of the accelerating and decelerating structures of a LINAC the definition and interpretation of a few characteristic parameters is necessary. Characteristic of accelerating structures in general are discussed in [6].

Quality factor:

The quality factor characterizes the energy losses in the cavity

$$Q = \frac{\text{stored energy per unit length}}{\text{ohmic losses per unit length per radian of the field oscillation}} = \frac{W \cdot \omega_{rf}}{P} \quad (\text{A.0.1})$$

where W is the stored energy per unit length, P the ohmic losses per unit length and ω_{rf} the fundamental (accelerating) mode angular frequency.

Shunt-impedance per unit length:

The shunt-impedance per unit length measures the effectiveness of producing an axial electric field for a given power dissipated and is independent of the excitation level of the cavity.

$$Z = \frac{(\text{axial electric field})^2}{\text{ohmic losses per unit length}} = \frac{E^2}{P} \quad (\text{A.0.2})$$

where E is the axial electric field and P the ohmic losses per unit length.

Appendix B

Scattering Formulas

N is the number of particles per bunch, n_{gas} the particle density in the vacuum, σ the cross-section of the process, l the accelerator length.

mean free path length:

$$\lambda_{\text{int}} = \frac{1}{n_{\text{gas}} \sigma} \quad (\text{B.0.1})$$

scattering probability:

$$P = n_{\text{gas}} \sigma \quad (\text{B.0.2})$$

scattering per bunch:

$$P_{\text{bunch}} = P N l \quad (\text{B.0.3})$$

scattering fraction:

$$S = P l \quad (\text{B.0.4})$$

integrated scattering probability:

$$S_{\text{int}} = \sum_{i=1}^{N_{\text{elem}}} P_i l_i \quad (\text{B.0.5})$$

where N_{elem} is the total number of elements of the beamline.

Appendix C

Parameter List for the CLIC decelerator and CTF3 TBL

Parameter	Symbol	CTF3	CLIC
pressure [nTorr]	p	10	10
temperature [K]	T	300	300
molecule density [m^{-3}]	n_{gas}	$3.22 \cdot 10^{14}$	3.22×10^{14}
photon density [m^{-3}]	n_p	$5.45 \cdot 10^{14}$	5.45×10^{14}
average photon energy [eV]	$\langle \epsilon \rangle$	0.07	0.07

Table C.0.1: CLIC/CTF3 vacuum specifications

Parameter	Symbol	CTF3	CLIC
DB station length [m]	L	22.4	1053.23
PETS misalignment in x/y [μm]		100	200
Quadrupoles misalignment in x/y [μm]		2	2
number of trains		1	1
Bunches per train	n	1683	2928
Bunch separation [m]	Δz_b	0.025	0.025
number of particles per bunch [10^9]	N	14.6	52.5
initial beam energy [Gev]	E_{initial}	0.150	2.4
final beam energy [Gev]	E_{final}	0.066	0.4

Table C.0.2: Lattice and beam parameters of the CLIC and CTF3 TBL drive beam

Parameter	Symbol	CTF3	CLIC
initial norm. emittance in x [μm]	$\epsilon_{x,\text{initial}}$	150	150.0
initial norm. emittance in y [μm]	$\epsilon_{y,\text{initial}}$	150	150.0
final norm. emittance in x [μm]	$\epsilon_{x,\text{final}}$	162.4	351.4
final norm. emittance in y [μm]	$\epsilon_{y,\text{final}}$	160.5	340.0
initial β -function in x [m]	$\beta_{x,\text{initial}}$	0.83	0.58
initial β -function in y [m]	$\beta_{y,\text{initial}}$	4.72	3.35
final β -function in x [m]	$\beta_{x,\text{final}}$	1.61	5.029
final β -function in y [m]	$\beta_{y,\text{final}}$	4.68	6.778
initial rms beam size in x [mm]	$\sigma_{x,\text{initial}}$	0.65	0.14
initial rms beam size in y [mm]	$\sigma_{y,\text{initial}}$	1.55	0.33
final rms beam size in x [mm]	$\sigma_{x,\text{final}}$	1.43	1.50
final rms beam size in y [mm]	$\sigma_{y,\text{final}}$	2.42	1.71
initial beam divergence in x' [mrad]	$\sigma_{x',\text{initial}}$	0.78	0.23
initial beam divergence in y' [mrad]	$\sigma_{y',\text{initial}}$	0.33	0.10
final beam divergence in x' [mrad]	$\sigma_{x',\text{final}}$	0.89	0.30
final beam divergence in y' [mrad]	$\sigma_{y',\text{final}}$	0.52	0.25

Table C.0.3: Twiss and beam size parameters of the CLIC and CTF3 TBL drive beam