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DYNAMIC APERTURE STUDIES FOR THE TRANSFER LINE FROM FLUTE TO cSTART

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Abstract

The compact STorage ring for Accelerator Research and Technology cSTART project will deliver a new KIT accelerator test facility for the application of novel acceleration techniques and diagnostics. The goal is to demonstrate storing an electron beam of a Laser Plasma Accelerator (LPA) in a compact circular accelerator for the first time. Before installing an LPA, the Far-Infrared Linac and Test Experiment (FLUTE) will serve as a full energy injector for the compact storage ring, providing stable bunches with a length down to a few femtoseconds. The transport of the bunches from FLUTE to the cSTART storage ring requires a transfer line which includes horizontal, vertical and coupled deflections which leads to coupling of the dynamics in the two transverse planes. In order to realize ultra-short bunch lengths at the end of the transport line, it relies on special optics which invokes high and negative dispersion. This contribution presents dynamic aperture studies based on six-dimensional tracking through the lattice of the transfer line.

INTRODUCTION

Making future accelerators more compact and energy efficient is a global goal of general interest. A key technology for achieving this goal are Laser Plasma Accelerators (LPA) [1]. These new accelerator structures promise to be much smaller and come with new characteristic beam properties. Especially the typical short bunch lengths makes them interesting for applications like the generation of coherent synchrotron radiation (CSR). The compact STorage ring for Accelerator Research and Technology cSTART [2] project at KIT will provide the first storage ring for LPA-like bunches. It serves as a test bench for manifold R&D topics e.g. the non-equilibrium evolution of an ultra-short bunch length or the development of dedicated diagnostic devices. The linac-based test experiment, the Far-Infrared Linac and Test Experiment (FLUTE) can produce electron bunches with a wide parameter range, especially the expected bunch length of down to 3 fs allows to mimik an LPA accelerator. This makes FLUTE the first full-energy injector for this project [3]. For injecting the bunches into the storage ring a complex 3D transfer line (TL) is required. As a solution to this problem, a systematic study was proposed on the lattice design with suitable optics to support the injection of ultra-short bunches into the storage ring [4]. A sketch of the geometrical arrangement with best result for the transfer line is shown in Fig. 1. This contribution briefly summarizes the beam dynamics in the transfer line and furthermore presents the dynamic aperture (DA) studies.

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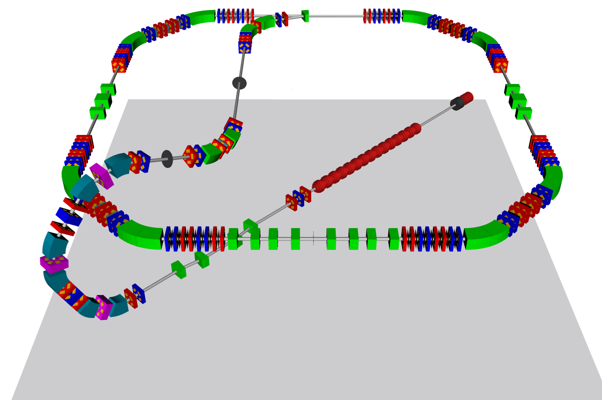

Figure 1: In grey, the footprint of the experimental hall, with FLUTE orientated diagonally, starting in the top right corner on the ground floor. The TL guides the bunches from the end of FLUTE to the injection point of the storage ring, which is horizontally aligned above FLUTE in the first floor. Dipoles are shown in green (h)/turquoise (v), quadrupoles in red (h)/blue (v), combined-function magnets in pink. The FLUTE RF components are also shown in red, the solenoid in grey. Two grey discs in the TL represent rotations of the Frenet-Serret coordinate system.

OPTICS IN THE TRANSFER LINE

FLUTE can create electron bunches with a wide range of parameters. For the design of the TL and the DA studies only one specific parameter set is picked out and referred to as the FLUTE example bunch. The example bunch parameters lead to peak performance in the longitudinal bunch compression with a final RMS bunch length of 3 fs by passing the FLUTE bunch compressor. Table 1 summarizes the beam parameters after the linac to include the optics of the FLUTE bunch compressor into the optics calculations for the TL.

Table 1: Beam Properties of FLUTE Example Bunch

Parameter	value
E	42 MeV
δE	0.25 %
q	1 pC
$\epsilon_{x,y}$ (norm)	193 nm rad
σ_t	173 fs
$\sigma_{x,y}$	1.4 mm

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Longitudinal Bunch Compression

The TL is designed to influence the bunch in the longitudinal phase space exactly such, that the primary long bunch becomes compressed towards the injection point.

Longitudinal dynamics in 1. order To compress the bunch in first order, the transport matrix element R56 of the TL needs to cancel out the initial bunch chirp. To achieve this, the three DBA cells in the return arc section act together. By oversteering the central (main) quadrupoles inside the DBA's, the dispersion between two DBA's is pushed to negative values. The DBA subsection loose the achromatic feature but the arc overall still is achromatic, forming a hexabend achromat HBA. This way, the integrated dispersion and the sections R56 value can be precisely adapted to lower and even negative values. This allows the positive R56 values of the subsequent DBA sections to be compensated and eventually fulfils the full compression condition derived in [4] in first order. The principle is plotted in Fig. 2.

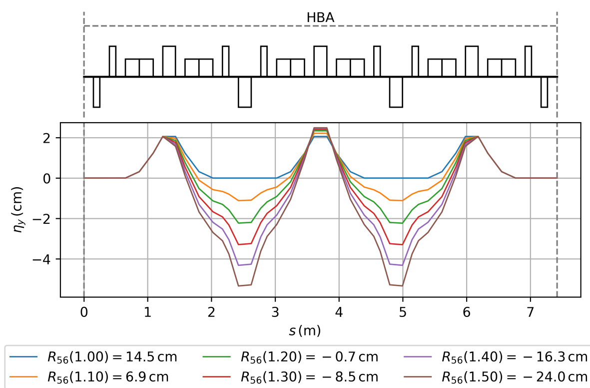

Figure 2: Dispersion function in the TL arc section for increasing the strength of the main quadrupoles stepwise by 10 % with the corresponding R56 value in the legend.

Longitudinal dynamics in 2. order The negative dispersion in the arc section comes with the price of high quadrupole fields within dispersion. This leads to chromatic effects and causes the bunch bend in the longitudinal phase space. To compensate for these second order effects, sextupole fields need to be applied in the three main quadrupoles of the arc. For the simulation it is assumed to build a combined-function magnet (CFM) with quadrupole and sextupole field components.

Transverse Optics Matching

The quadrupoles surrounding the arc and the subsequent DBA sections are not bound to solve the full compression conditions. Their open degrees of freedom are used to control the overall beam size during the transport and finally match the transverse beam parameters at the injection point to the applied optics of the storage ring [5].

Final Compression Performance

In tracking simulation with the matrix tracking code elegant [6] the FLUTE example bunch has been tracked through the TL, considering transport matrices up to third order and different calculation of radiation effects. The bunch was transported with 0 % particle losses and a longitudinal compression down to an RMS bunch length of 18 fs was achieved.

DYNAMIC APERTURE STUDY

Although the example bunch was transported without any particle losses, it is necessary to study the DA for particles with larger or energy offsets. With the asymmetric 3D geometry of the TL, the DA is measured by a dedicated procedure of full-fledged 6D tracking. The tracking simulation of different test bunches reveals particle losses by collisions with the beam pipe during the transport.

FLUTE Inspired Test Bunch with $\delta E = 0\,\%$

To create a test bunch for the tracking simulations the 6D phase space coordinates (x, y, z, x', y', E) need to be defined for every macro particle within the bunch. For the attempt of finding the DA simple rules can be rolled out to find these numbers. The TL simulation starts after the FLUTE linac where the beam parameters shown in Table 1 where read out. At this point the example bunch has a rotation symmetry and is transversely convergent with a clear linear correlation between transverse offset and momentum. The test bunches mimic these properties but are much larger and fill the entire beam pipe.

Coordinate x, y: The transverse plane will be filled uniformly within the radius $\rho = 19$ mm of the round beam pipe. Then the x and y coordinates are distributed evenly within $\sqrt{x^2 + y^2} < \rho$.

Coordinate z: With an energy of even below 50 MeV radiation effects can be neglected for this single pass transport. Suppressing their calculation allows collapsing the longitudinal dimension of the bunch and $z = 0$ can be assigned for every macro particle.

Coordinate x', y': With the slope of the linear correlation m between the x'-x distribution of the example bunch, the transverse momenta follow the rule $x' = x \times m$. As a consequence of to the rotation symmetry this holds also for the vertical plane $y' = y \times m$.

Coordinate E: The remaining parameter is the energy and it will be set to the same value for every particle in a single test bunch. This forms mono-energetic test bunches with a given energy offset δE from the design energy of the TL. Starting with the test bunch with energy offset $\delta E = 0\,\%$, every macro particle has exactly the mean energy of the example bunch that is $E = 42$ MeV.

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Tracking and Data Representation

After tracking the first test bunch with $\delta E = 0\,\%$ the particle losses during the transport are evaluated. The initial starting position of the surviving macro particles are drawn in blue in Fig. 3. The black background shows the envelope of the beam pipe wherein the test bunch initially was uniformly distributed. The two plotted white circles represent the FLUTE example bunch beam size. The inner of the two circles shows the 1 RMS bunch size and the outer circle revolves around the absolute envelope of all simulated macro particles of the example bunch. The data shown in the plot means, that particles starting into the TL from within the blue area will survive the transport. The blue surface shows, where the TL is permeable for an electron injected with $\delta E = 0\,\%$. Particles starting from within the black surface will not survive the transport but collide with the beam pipe somewhere during trespassing.

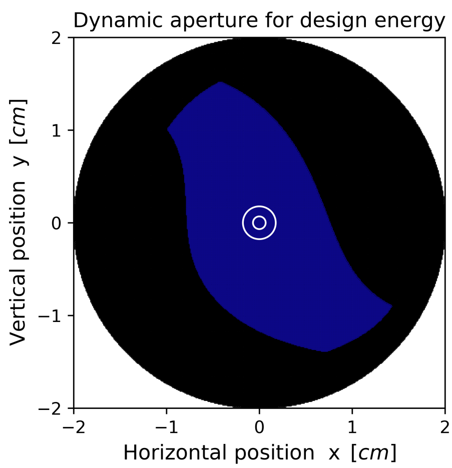

Figure 3: Tracking for $\delta E = 0\,\%$.

Test Bunches with a Finite Energy Offset

To get the full picture, other test bunches with a finite energy offset have been created, tracked and evaluated in the same way. In total 65 mono-energetic test bunches with different energy offsets between −5 % and +5 % have been investigated. The permeability is evaluated for every test bunch individually, it shrinks monotone from 0 % to a negative respectively positive δE value. This allows to stack all results of the test bunches in a single plot according to the sign of the offset. The different test bunches then are represented by applying a color code. The results for a negtive energy offset $\delta E < 0$ are shown in Fig. 4 and for $\delta E > 0$ in Fig. 5.

CONCLUSION

From the stacked color coded plots one can follow the evolution of the permeability with an increase in the energy offset. Three differences occur between the results for negative and positive δE:

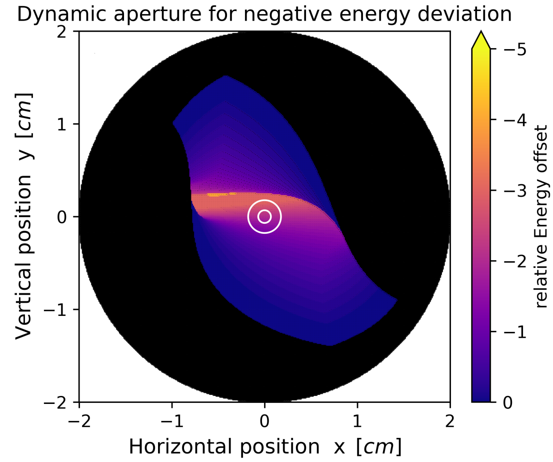

Figure 4: Tracking for $\delta E < 0\,\%$.

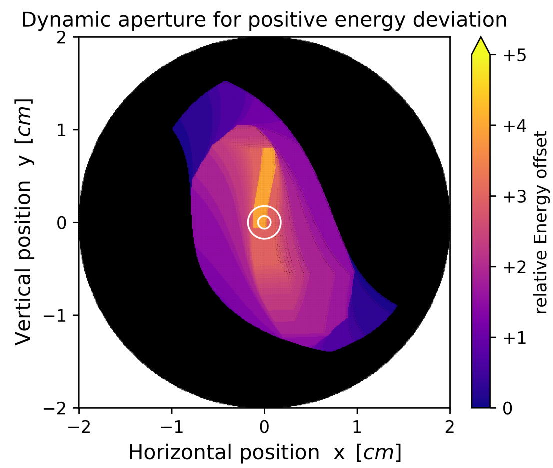

Figure 5: Tracking for $\delta E > 0\,\%$.

- The permeable area rotates counterclockwise for $\delta E < 0$ and clockwise for $\delta E > 0$.
- The rotation angle is larger for $\delta E < 0$ than for $\delta E > 0$.
- The permeable area shrinks faster for $\delta E < 0$ than for $\delta E > 0$.

These differences originate from the rigidity of the electrons that increases with more energy. This study reveals more than sufficient DA for transporting the FLUTE example bunch. From these results one can find a strategy to safely transport a bunch with a very large energy spread: The TL magnets strengths have to be decreased such, that the bunches mean energy already is above the optics design energy. Then more shares of the bunch fall into the regime of a positive energy offset and witness a larger DA.

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