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NON-LINEAR FEATURES OF THE cSTART PROJECT

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Abstract

The compact storage ring for accelerator research and technology (cSTART) is being designed and will be realized at the Institute for Beam Physics and Technology (IBPT) of the Karlsruhe Institute of Technology (KIT). One important goal of the project is to demonstrate injection and storage of a laser wakefield accelerator (LWFA) beam in a storage ring. As a first stage the compact linear accelerator FLUTE will serve as an injector of 50 MeV bunches to test the ring's performance. A highly non-linear lattice of DBA-FDF type was studied extensively. The specific features of ring optics are reported. A special transfer line from FLUTE to cSTART including bunch compressor and non-linear elements is presented that maintains the ultra-short bunch length of FLUTE.

INTRODUCTION

R&D on laser plasma acceleration is pursued with the aim to clear up key issues on the feasibility of a new generation of very compact, cost-effective accelerators and sources of synchrotron radiation [1]. Laser wakefield accelerators (LWFA) feature short bunch lengths and high peak currents, combined with a small facility footprint. This makes them attractive as injectors for synchrotron light sources. For wavelengths longer than the length of the emitting electron bunch, the photon emission becomes coherent [1]. Thus, the intensity of terahertz (THz) to infrared radiation increases dramatically. However, the repetition rate, typically in the order of 1 Hz, is very low compared to conventional sources. Therefore, the combination of a storage ring and a laser wakefield accelerator might be a basis for a new generation of compact light sources advancing user facilities to different commercial applications including multi-user medical applications etc. Meanwhile, the post-LWFA beam is not directly suitable for injection and storage in conventional light source facilities because their lattice cannot handle the high energy spread and divergence [2]. Extensive studies of possible configurations of a very large acceptance compact storage ring have been done within the cSTART project at KIT to provide "proof–of-principles".

LATTICE AND DYNAMIC APERTURE

cSTART is designed to be a very compact test facility located in the FLUTE experimental hall with a maximum extend of 14×15 m operating at an energy 50 MeV [3, 4]. In order to be able to handle beam produced by an LWFA, following requirements have been defined: the momentum acceptance should be more than $\delta = \pm 6\,\%$. For stable storage of the beam a dynamic aperture of at least ±15 mm in both planes is aimed. In addition, the dispersion function

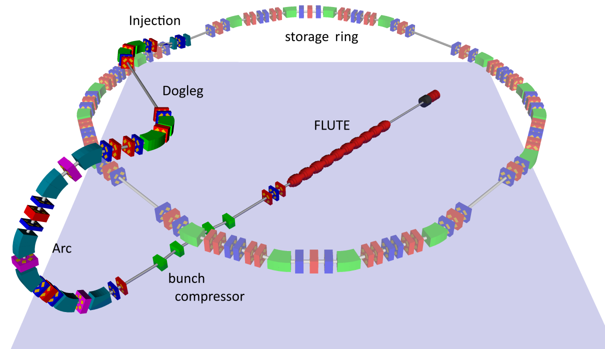

Figure 1: Artistic view of the cSTART facility in the first stage. The FLUTE test facility is installed on the ground floor, the compact storage ring with large momentum acceptance is installed at a height of about 3 m.

should not exceed 25 cm to prevent dispersive dilution in the bending sections, which would require a large vacuum chamber.

These requirements compromise a series of challenges: the compact size requires bends with large bending angle while the dispersion has to stay small. In addition, strong quadrupoles are needed because of the short focusing distance. In combination with the small dispersion this leads to very strong sextupoles. On the one hand these sextupoles are needed to compensate the high negative chromaticity, on the other hand they limit the dynamic aperture and momentum acceptance which are essential to store LWFA beams.

Various versions for the compact storage ring have been analyzed so far. Due to the specific requirements of small value of the dispersion function and lack of free space the double bend achromat cell with focus-defocus-focus quadrupoles in the main dispersive part was chosen for further detailed study. Parameters of the ring are listed in Table 1. The current lattice is composed of four equal achromatic sections. Two double bend achromats with mirror symmetry form one cell with total bending angle of 90° (Fig. 2). The bending magnets have an effective length of 0.5 m and serve a bending angle of 22.5°, which results in a bending radius of 1.3 m. They include a quadrupole component contributing to horizontal focussing. Split quadrupole triplets are located in the dispersive parts of DBA. In-between, a sextupole magnet is installed in addition to the sextupole components that are already included in the quadrupoles.

A proper choice of the ring lattice, in particular splitting of strong quadrupoles in the dispersion sections of the ring, allowed to reduce their strength from 40 down to $<16\,\mathrm{m}^{-2}$.

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Table 1: Parameters of the cSTART Lattice

Parameter	3Q-split lattice
Circumference, m	44,112
Momentum compaction	6.03×10^{-3}
SR losses/turn, eV	<1
Damping time τ_x / τ_y / τ_l, s	24 / 34 / 21
RF frequency (MHz) / h_{RF}	3000 / 440
Injection energy	50 MeV
Inj. energy spread	$\delta = 2 \times 10^{-2}$
Nat. emittance, nm rad	0.18
Nat. energy spread	4×10^{-5}
Betatron tunes	5.844 / 8.461
Nat. chromaticity	$\xi_{x,y} = -16/-21$
Dyn. aperture hor/vert, mm	(-14/+18)
Mom. acceptance	±6-8 %

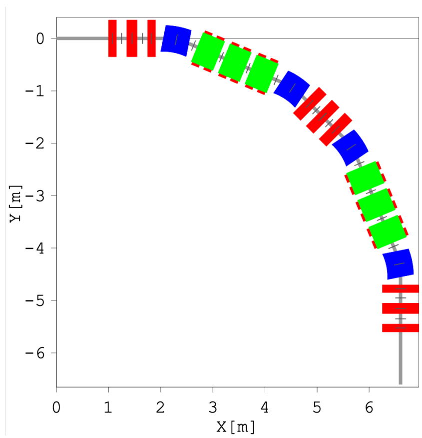
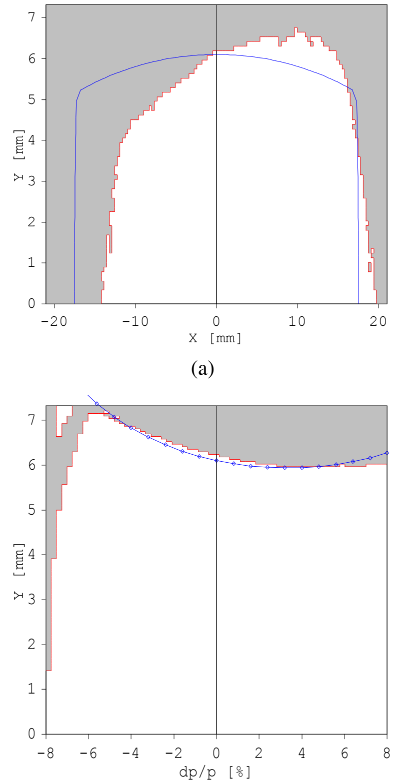


Figure 2: cSTART lattice (one cell is shown). Gradient bends (blue) add to vertical focusing, quadrupoles (red) in dispersive sections are splitted in doublets, families of main chromatic sextupoles (green) are splitted in triplets. Central sextupole of each triplet is flanked between quads.

The phase advance between sextupoles was adjusted to fulfill the "$-I$" condition. Locating the horizontal chromatic sextupoles at mirror symmetry position and at local maxima horizontal betafunction and dispersion helps to reduce integrated strength of sextupoles from 35 m^{-2} to <12 m^{-2}. The phase advance per cell was adjusted to quarter integer values in order to minimize leading resonance-driving terms.

The dynamic aperture of the optimized lattice with split quadrupoles and relaxed parameters was opened to a range from −14 mm to 20 mm in order to fit the wide momentum-spread beam (Fig. 3(a)). Harmonic sextupoles expand the momentum acceptance of the ring to ±6 % in the horizontal plane and to ±8 % in the vertical plane (Fig. 3(b)).

Strength of octupoles should be limited to preserve ring acceptance. Tight tolerances on misalignments, roll-offs, field errors etc. lead to a design of solid magnetic blocks similar to MAX-IV 3 GeV ring magnets [5]. The effect of coherent synchrotron radiation on the longitudinal bunch profile is currently under investigation. However, the evolution of the bunch profile seems to be dominated by the diffluence due to the energy spread.



(a)

(b)

Figure 3: Dynamic aperture of the cSTART lattice in the middle of the straight section: (a) on-momentum particles ($\delta = 0$); (b) harmonic sextupoles expand the momentum acceptance ±8 %.

TRANSFER LINE

As a first stage, the Ferninfrarot Linac- und Test-Experiment (FLUTE) [6–8] will be used as an injector, which is installed in the same experimental hall as cSTART will be (see Fig. 1). FLUTE is a short-pulse facility, the main components are a photo injector, a 3 GHz linac and a four-dipole bunch compressor. It delivers 41 MeV electron pulses with a bunch length of 1-300 fs and is therefore the perfect source for beam commissioning at cSTART. The transfer line is currently being designed with the aim to transport ultra-short electron bunches from FLUTE to the injection point in cSTART without significant lengthening and a certain flexibility for matching to the optics of the storage ring. As FLUTE occupies the ground floor, cSTART will be installed in about 3 m height. The transfer line therefore needs to deflect the beam both in horizontal and vertical direction. The first part, later called the "Arc", lifts the beam up vertically and turns it towards the centre of the experimental hall. In the second part, later referred to as the "Dogleg", the beam is deflected in horizontal direction towards the injection point as illustrated in Fig. 1.

The lattice of the transfer line is based on a modified DBA structure. The Arc consists of three cells. Spacial constraints

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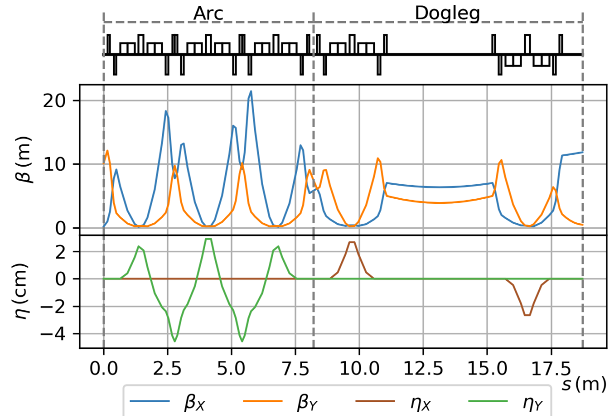

Figure 4: Optics along the transfer line from FLUTE to cSTART. A negative contribution to the dispersion integral is created in the Arc to compensate the R56 of the Dogleg.

require to share the quadrupoles between two adjacent cells. The centre quadrupoles of each cell are equipped with a sextupole component to allow for the correction of non-linear effects. The Dogleg consists of two DBA cells with a long drift space in-between, that could be equipped with an additional bunch compressor chicane if needed.

Isochronous conditions (equivalent to low compaction factor in storage rings) should be applied to the beamline optics in order to maintain the short bunch length. This means, the transfer matrix coefficient R_{56}, responsible for first order longitudinal bunch elongation with momentum offset $\delta p/p_0$, is close to zero. Optics calculations of the transfer line were performed with `elegant` [9]. By increasing the strength of the centre quadrupoles in each DBA cell, the optics is tuned such that the dispersion function becomes negative in the Arc as displayed in Fig. 4. This allows to create a negative value for R_{56} which compensates the positive value of the Dogleg. The shortest bunch length achieved with the FLUTE bunch compressor is $\sigma_t = 5$ fs. However, if FLUTE is used as an injector for cSTART, the bunch compressor is not used to compress the bunches but to de-compress them instead. This has two reasons: first CSR would blow up the bunch length immediately when the bunch reaches the Arc and second operation with opposite energy chirp and decompression is as well creating a negative value for R_{56} and thus relaxing the requirements for the quadrupole strengths in the Arc.

In order to reproduce the longitudinal bunch profile along the transfer line 10^4 particles with 1 pC charge were tracked from the end of the FLUTE linac to the injection point of the storage ring. The longitudinal particle distribution used was calculated with ASTRA [10] and is approximately Gaussian. The longitudinal phase space resulting from the tracking calculations are shown in Fig. 5. Starting with an rms bunch length of $\sigma_t = 255$ fs the bunch is decompressed in the FLUTE bunch compressor reaching a length of $\sigma_t = 462.4$ fs. In the Arc the bunch length is further increased up to a value of $\sigma_t = 1.3$ ps. The final compression is then performed by the Dogleg reaching a minimum value

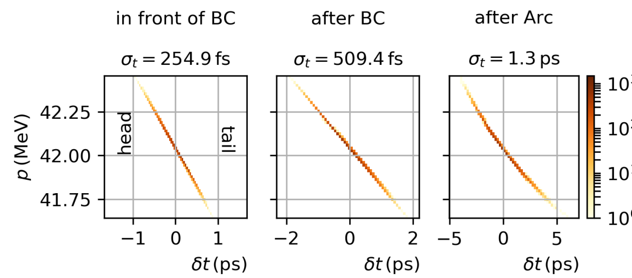

Figure 5: Longitudinal phase space of the tracked particle distribution in front of the FLUTE bunch compressor (left), after the FLUTE bunch compressor (centre) and at the end of the Arc section (right).

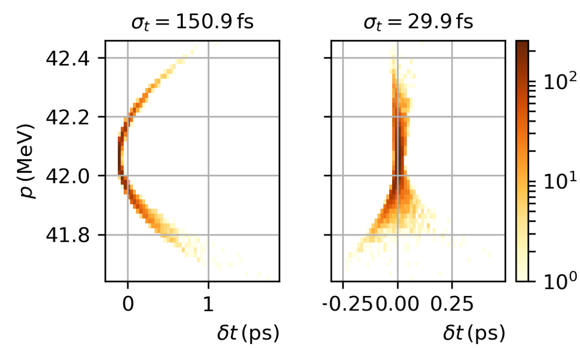

Figure 6: Longitudinal phase space at the injection point showing the final bunch compression without (left) and with sextupoles (right) in the Arc.

of $\sigma_t = 180.5$ fs, which is significantly larger than the bunch length achieved by the FLUTE bunch compressor without transport (5 fs). However, only linear optics are used in the transfer line so far and the phase space of the bunch has a strongly curved shape as shown in Fig. 6. Using the sextupoles that are integrated in the centre quadrupoles of the DBA cells in the Arc allows to linearize the particle ditribution in phase space. The shortest bunch length achieved so far is $\sigma_t = 29.9$ fs at the injection point after the Dogleg.

SUMMARY

cSTART is being designed as an accelerator test facility with the goals to inject beam from a LWFA into a storage ring and also to store femtosecond-short bunches injected by the FLUTE linear accelerator. Preliminary studies on the transfer line between FLUTE and the cSTART storage ring have been presented. The realization of the cSTART project would provide a series of "proof of principles" and is therefore a first step towards a new-genereation multi-user synchrotron light source with short pulses and high repetition rate based on a laser wakefield accelerator as an injector.

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