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BEAMLINE TO INJECT ULTRASHORT LASER PLASMA ACCELERATED ELECTRONS INTO A QUASI-ISCOCHRONOUS STORAGE RING

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Abstract

Laser plasma accelerators (LPAs) can produce ultrashort high-energy electron bunches from short distances. Coupling LPAs to dedicated storage rings tuned to quasi-isochronous conditions would demonstrate the capture and storage of ultra-short electron bunches in a circular accelerator. LPA electron bunches have a comparably large angular divergence and energy spread. We, therefore, design a flexible beamline that can transport ultrashort bunches with large angular and energy spread to a ring and that compensates for the injection optics inside the ring, such as septum and kicker. We have used the accelerator design program OPA to build up the optical model of a beamline. The line is composed of focusing, dispersion compensating and matching sections. A set of short bending magnets counteracts the dispersion created by injection septum and kicker of the storage ring and provides quasi-isochronous bunch transfer with a flexible value of longitudinal dispersion (R56).

INTRODUCTION

The compact storage ring project for accelerator research and technology (cSTART) is realized at the Institute for Beam Physics and Technology of the Karlsruhe Institute of Technology (KIT) [1-3].

The goals of cSTART include the demonstration of direct injection and circulation of LPA electron bunches [4, 5]. Furthermore, deep variation of momentum compaction factor with simultaneous control of high order terms of alpha would demonstrate the capture and storage of ultra-short electron bunches of electrons in a circular accelerator.

LPAs have been developed over recent decades and can now produce electron bunches with energies well above 1-GeV [6, 7], small normalized emittance of less than 1 µm [8, 9] and as short as few-fs duration [10, 11]. The short bunch duration allows a modest bunch charge, for example around 50 pC, to result in a high peak current > 5 kA.

A concept for an LPA injector operating at 90 MeV has been developed for a laser-driven injector for the cSTART ring [12]. The transverse size of electron beam exiting the plasma cell is expected to be about σ_x=5 µm (rms), and the divergence approximately $\sigma_{x'}$= 2 mr i.e. two times more than at 1 GeV LPA injection line [13].

Parameters of ultra-short electron bunches after LPA plasma cell to be accepted for circulation in the cSTART ring are presented in Table 1 [14-19].

The relative energy spread of the LPA electron bunch (more than 1%) and divergence (around 2 mr) are large compared with conventional sources.

Table 1: Plasma Cell Electron Bunch Parameters

Parameter	Values
Beam energy	90 MeV
Magnetic rigidity of a ring	0.30 T·m
Energy spread σ_p	1.2 % (rms)
Number of particles/pulse	6×10^6 to 6×10^9
Charge per pulse	1 pC to 1 nC
Pulse length / duration	0.3–30µm / 1–100 fs
Rep. rate of laser pulses	1 to 10 s^{-1}
Transverse beam size $\sigma_{h,v}$	5 µm (rms)
Transverse divergence	2 mr (rms)
Beam emittance $\varepsilon_{h,v}$	10 nm (rms)

The initial bunch of LPA electrons after exiting the plasma cell has a geometric emittance of approximately 10 nm (rms) and normalized emittance of 2 µm. In a storage ring, the large energy spread and divergence degrade the bunch properties [18, 19]: for example, leading to associated bunch elongation during circulation [20].

At the same time, the LPA bunch duration is just a few to tens of femtoseconds. Variation of the length of the injected bunch helps to minimize the blow up of momentum spread due to coherent synchrotron radiation (CSR) generated at bending magnets of cSTART ring [21].

To accommodate some of the less favorable bunch properties we propose a dedicated beamline that can transfer and inject electron bunches generated by an LPA into a storage ring.

BEAMLINE CONFIGURATION

The LPA beamline for cSTART is designed to deliver single bunches of low energy (90 MeV) electrons with

- large energy spread particles up to 1.2% (rms)
- large divergence up to 2 mr (rms)
- quasi-isochronous transfer of electron bunches of variable pulse length, in particular ultrashort bunches, without significant bunch elongation for off-momentum particles
- free pass and dump for laser light to avoid scattering of photons on the vacuum chamber walls.

In addition, the LPA injection line is limited in length to fit inside the cSTART ring [4].

The LPA line is split into three sections (Fig. 1).

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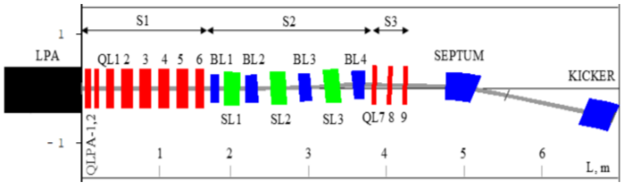

Figure 1: The layout of LPA beam line with elements of injection system of cSTART ring. The focusing section (S1) comprises two permanent magnet quadrupoles and six quadrupoles QL1-QL6. Second section (S2) is composed of four small angle anti-bends BL1 to BL4 to compensate dispersion generated by injection elements of a ring. Third section (S3) comprises three weak quadrupoles QL7-9 to match the beam at the merging point.

The focusing section controls the large divergence of the LPA bunch. Additional quadrupoles provide smooth focus at injection point. The position of focal plane should be adjustable to match the LPA bunch to different ring optics configurations. Due to lack of space the focusing section is composed of six strong quadrupole magnets QL1–QL6.

Parameters of magnetic elements of LPA line, septum and kicker magnets of a ring are presented in Table 2. Anti-bends of LPA line generate negative dispersion to compensate contribution of positive dispersion at injection elements of the ring, namely, at the 15° septum magnet and injection kicker, to bunch elongation.

Table 2: LPA and Injection Section Elements

Parameter	**Values**
Focusing Quadrupoles	QL1 to QL6
Length QL1,6 / QL2-5	0.1 / 0.14 m
Nominal strength	33 m^{-2}
Nominal gradient	10 T/m
Bore radius QL2-5	25 mm
Pole tips field	2.5 kGs
Anti-bends	BL1,2,3,4
Angle BL1,2,3,4	+0.44/-2.5/-1.8/+5°
Length BL1/BL2,3,4	0.1/0.15 m
Matching quadrupoles	QL7,8,9
Length QL7,8,9	0.05 m
Strength QL7,8,9	Variable
Bore radius QL7,8,9	25 mm
Sextupole integr. Strength	Up to 70 m^{-2}
Injection septum angle	+15°
Septum length	0.393 m
Septum radius	1.5 m
Injection kicker angle	1.2°
Injection kicker length	0.4 m

The second section is composed of four small angle anti-bends and provides quasi-isochronous conditions for short bunch transfer. The anti-bends compensate dispersion generated by injection elements of a ring and reduce longitudinal dispersion to almost zero (R_{56}≈0) which corresponds to no change in bunch chirp.

At comparably low relativistic energies, electrons in a bunch may outrun each other due to velocity differences (ballistic lengthening). At 90 MeV an electron bunch of 1% energy spread would ballistically lengthen by $\Delta\beta=\sigma_p/\gamma^2=1$ fs per meter of transport. To minimize effect of velocity difference in a beamline we use sextupole magnets to minimize second order term of longitudinal dispersion (T_{556}).

The third section is composed of three quadrupole magnets of moderate strength QL7,8,9 to match the beam from the second section to the injection point of a ring and to provide flexibility of beam tuning.

BEAMLINE OPTIC

Beta-functions and dispersion of LPA beamline are shown in Fig. 2. The focusing section is matched with a preference for larger values of the beta-functions occurring close to the plasma exit to reduce the resulting beam size throughout the transport. Due to comparably large energy spread of the LPA bunch and the chromaticity of the beam transport, the beam size represented by a given beta-function value will also increase along the beamline. To reduce the beam size at all points, it is preferable to allow larger beta-function values to occur close to the plasma source rather than further downstream. The maximum value of beta-functions is limited to 350 m for vertical and horizontal planes.

The beam envelopes are presented in Fig. 3. The cross-section of large divergent beam of about 11 mm at location of focusing quadrupoles QL4 is smoothly reduced to few mm at focusing point. By collimating beam halo at focusing section one may effectively reduce large divergence of a bunch and this way to control emittance of injected beam.

Reduction of bunch emittance helps to limit the contribution of beam transverse dimensions into the pulse length.

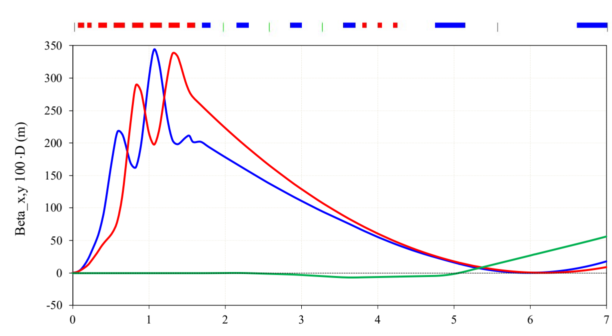

Figure 2: Beta-functions of LPA beamline - vertical beta in red, horizontal - in blue and dispersion in green.

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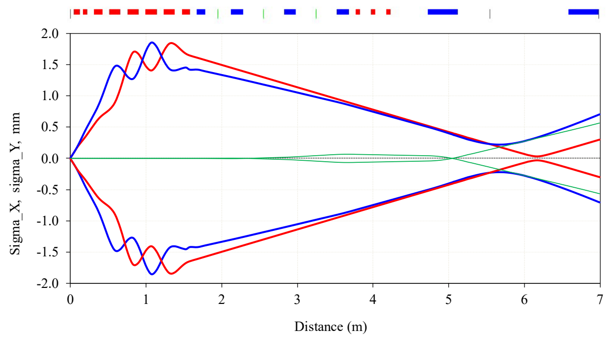
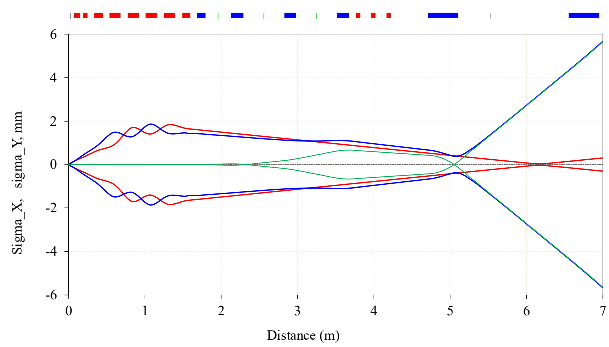


(a)



(b)

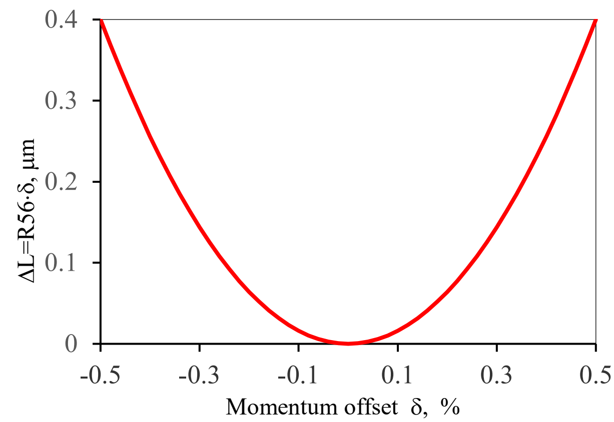
Figure 3: Beam envelope of LPA injection line: (a) small energy spread σ_p=0.1 % (rms); (b) large energy spread σ_p=1% (rms). Vertical envelope in red, horizontal envelope in blue, contribution of dispersion in green.

At the same time, towards the end of focusing section one would require a "stay clear" area for the diverged laser pulse of about 96 mm in diameter to remove the spreading laser light from line axes by a 45° mirror. To solve this potential issue we are planning to install laser mirror between QL3 and QL4 quadrupoles at a reduced laser spot size of 70 mm. Thus, the location and dimensions of slits must be carefully estimated.

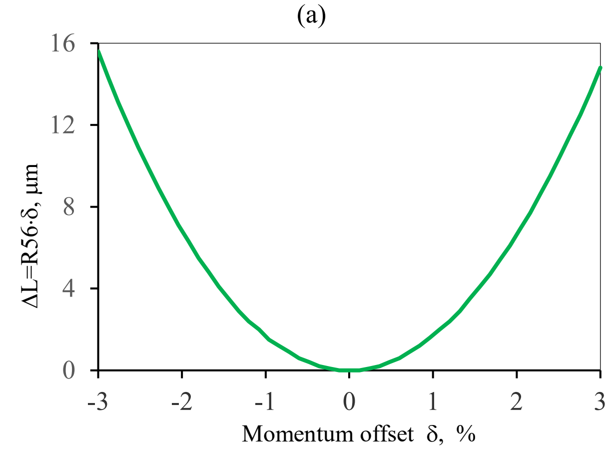
At this specific example we focus the beam at position of injection septum where the full size of beam spot ($\pm3\sigma_p$) is less than 2.5 mm in vertical plane. At septum entrance the beam size in horizontal plane is varied from 2.4 mm for small energy spread beam of about 0.1 % (rms) (Fig. 3a) to approximately 4 mm at large momentum spread of 1% (rms) (Fig. 3b).

At the matching point, the beam size in the horizontal plane is dominated by contribution of growing dispersion from the injection line elements.

The bunch elongation for off-momentum particles in the LPA line is presented in Fig. 4. At a small energy spread the trajectory lengthening for off-momentum electrons might be safely ignored. The length deviation does not exceed 0.4 μm (1.2 fs) for particles with full energy spread of $\pm3\sigma_p$=±0.3% (Fig. 4a). The bunch core elongation of a wide momentum spread beam grows to 16 μm (48 fs) for electrons on periphery of energy distribution where energy offset is about 3% (Fig. 4b).



(a)



(b)

Figure 4: Bunch elongation for off-momentum particles at LPA line. Sextupoles are adjusted to reduce curvature of orbit lengthening (T556): a) Deviation of orbit length does not exceed 0.4 μm (1.2 fs) for low energy spread beam with full energy deviation of $\pm3\sigma_p$=±0.3%; (b) length of particle trajectory for off-momentum particles is increased at 16 μm (48 fs) at large energy spread with σ_p=1% (rms).

CONCLUSION

The design of a LPA injection line for the cSTART ring is under development at Institute of Beam Physics and Technology of Karlsruhe Institute of Technology. Direct injection of ultrashort bunches into quasi-isochronous ring optics would demonstrate storage of ultrashort bunches in a circular accelerator. Also experiments with ultra-short LPA bunches, circulation of wide momentum spread beams, accelerator research and development experiments with low energy electron bunches at non-equilibrium conditions would be available. The flexible ring lattice with variable momentum compaction factor and a variety of electron injection technologies will greatly benefit the research program at cSTART.

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