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DEVELOPMENT OF A TRANSFER LINE FOR LPA-GENERATED ELECTRON BUNCHES TO A COMPACT STORAGE RING

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Abstract

The injection of LPA-generated beams into a storage ring is considered to be one of the most prominent applications of laser plasma accelerators (LPAs). In a combined endeavor between Karlsruhe Institute of Technology (KIT) and Deutsches Elektronen-Synchrotron (DESY) the key challenges will be addressed with the aim to successfully demonstrate injection of LPA-generated beams into a compact storage ring with large energy acceptance and dynamic aperture. Such a storage ring and the corresponding transfer line are currently being designed within the cSTART project at KIT and will be ideally suited to accept bunches from a 50 MeV LPA prototype developed at DESY. This contribution presents the foreseen layout of the transfer line from the LPA to the injection point of the storage ring and discusses the status of beams optics calculations.

INTRODUCTION

Synchrotron light sources are among the most prominent applications of particle accelerators as they build the foundation for a huge set of user experiments in various scientific fields such as material science, biology, or chemistry. The combination of a short pulse injector with a storage ring would, as long as the short bunch length can be maintained either on a regular basis or at a certain position of the ring, allow the users observations at much shorter time scales with high repetition rate. Laser-plasma accelerators (LPAs) are promising candidates to revolutionize injectors for light sources [1]. They provide ultra-short bunches and easily reach accelerating field strengths orders of magnitude larger than those available from conventional RF-based injectors leading to a compact, lab-scale infrastructure footprint. The LPA community has shown dramatic progress over the past few years: Beam energies up to 8 GeV [2], continuous 30 h operation [3], and few-fs pulse length from a laser-plasma accelerator [4] have been demonstrated bringing LPAs closer to applications.

In order to reach the ambitious goal to demonstrate the very first injection of LPA beams into a storage ring, DESY and KIT formed a collaboration [5]: DESY will design, setup and operate an LPA injector with stable, reproducible high quality electron beams, while KIT will devise the no less challenging transfer line and high acceptance storage ring.

LPA Injection into the cSTART Storage Ring

The aim of the KIT project cSTART is to investigate non-equilibrium beam dynamics of bunches of femto-second length with high repetition rate in a storage ring and provide the first study of LPA injection into a ring-based light source. Therefore, the lattice of the storage ring has been specifically designed to offer large momentum acceptance of $\delta = \pm 5.5\%$ and large dynamic aperture $\Delta x = \pm 15$ mm in the horizontal plane and $\Delta y = \pm 10$ mm in the vertical plane as presented in [6–10]. The storage ring will have a circumference of 43.2 m and is designed for a beam energy of 50 MeV. Two different injectors are foreseen: On the one hand the linac-based test facility FLUTE [11], which provides conventionally accelerated electron bunches, and on the other hand the LPA injector. All three accelerators will be housed in the same experimental hall. FLUTE is located at the ground floor, while the LPA and the cSTART storage ring will be installed at a level of about 3.5 m. Figure 1 shows an artificial view of FLUTE and the cSTART storage ring including the first design of the transfer line that lifts the electron bunches produced by FLUTE up to the height of the storage ring and re-compresses them to ultra-short bunch lengths [8, 12]. The LPA will be driven by a TW laser system installed in a clean room next to the experimental hall. The plasma cell will be positioned such that the LPA electron beam line will intersect the transfer line coming from FLUTE at the end of the long straight section and share the last Double-Bend Achromat (DBA) cell and the injection section as illustrated in Figure 2.

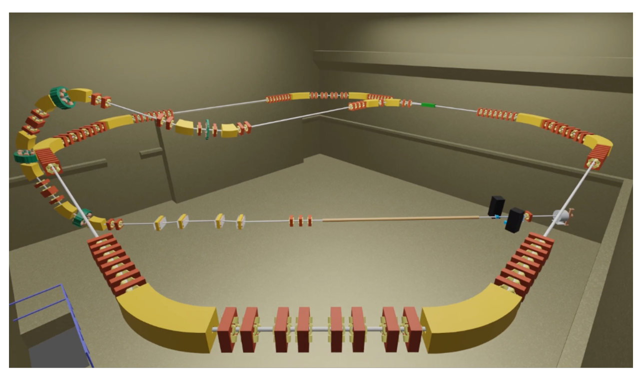

Figure 1: Artificial view of the cSTART storage ring, the injector FLUTE and the transfer line, in which the transfer line coming from the LPA will be incorporated (Courtesy J. Schäfer). The diameter of the storage ring is 12.5 m.

The commercial laser system has been delivered to the ready-to-use clean room at KIT. Plasma cell and target cham-

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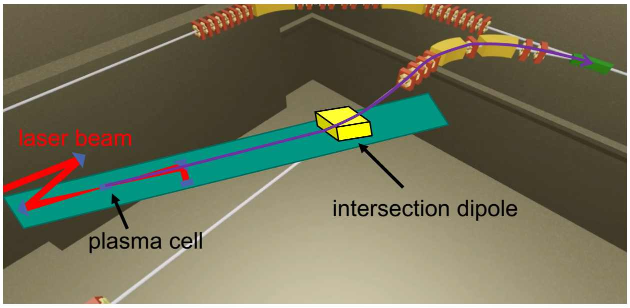

Figure 2: Illustration of the foreseen placement of the LPA in reference to the FLUTE-cSTART transfer line. An intersection dipole will be used to connect the LPA electron beamline with the injection section.

ber are in the final design stage by DESY [13] and the cSTART storage ring is currently in procurement.

TRANSFER LINE LAYOUT AND DIAGNOSTICS

The objectives of the transfer line from the LPA to the injection point of the cSTART storage ring are to collimate the electron beam directly behind the plasma cell, provide diagnostics for characterization of the electron beam, and match the optics functions to their respective values at the injection point. The optics shall offer flexibility to act on variations of initial beam parameters both for dedicated studies of the LPA beam and the case of differences between simulations and real experiment.

In the first section right after the plasma cell a quadrupole doublet is used for beam collimation followed by horizontal and vertical steerer magnets. At a distance of about 1 m behind the plasma cell the laser beam will be extracted [13]. The following diagnostics section foresees a cavity beam position monitor (BPM), an integrated current transformer and a screen station to have two complementary diagnostics devices for both beam position and bunch charge. An additional XY-steerer pair will allow tuning of both position and trajectory angle at the entrance of the subsequent spectrometer. In the spectrometer arm a cavity BPM and a screen station are foreseen before the beam is dumped in a Faraday cup. In forward direction a second quadrupole doublet and a second doublet of steerer pairs will allow to control position, angle and focusing of the electron beam before it reaches the intersection dipole and is deflected towards the injection point. The distance between spectrometer and the second quadrupole doublet is defined by the spectrometer's deflection angle and the transverse size of the quadrupoles and has to be laid out carefully to avoid overlap. Currently a distance of 0.7 m is provided that for a deflection angle of 30° allows a maximum quadrupole diameter of 0.7 m. It is still under discussion whether the intersection dipole chamber will have a Y- or an X-shape. The latter option is the baseline as it allows to install additional diagnostics behind the dipole that could also be used for the bunches produced by FLUTE. More importantly, a beam dump can be installed in forward direction, which would facilitate the commissioning of the LPA by allowing it to operate without direct injection into the storage ring.

In the further course of the transfer line, a DBA module is used to deflect the electron beam by 72°. This DBA cell consists of two quadrupoles in front of the first dipole, one between the two dipoles and two quadrupoles behind the second dipole. In-between the two dipoles a sextupole magnet is foreseen in addition to allow for chromatic corrections. Between intersection dipole and DBA module two additional quadrupoles and a second sextupole will be installed for optics tuning. In front and behind the DBA cell a diagnostics package is foreseen consisting of a cavity BPM, a screen, and a steerer doublet. Just behind the intersection dipole an electro-optical diagnostics station like at KARA [14] is proposed to measure the longitudinal bunch profile using the electro-optical spectral decoding method. In addition, movable collimators will be installed for studies of the beam energy spread and to safely dump electrons with momentum offset larger than the acceptance before injection into the storage ring. Since the final positions of the additional quadrupoles are still being optimized, the arrangement of the diagnostics devices is still to be defined. The quadrupoles of the DBA cell will be equipped with stripline BPMs in order to allow monitoring of beam positions for precise on-orbit injection. The injection scheme consists of a 17° septum and two stripline kickers with small angles of 8 mrad and 10 mrad, respectively. Sufficient space for a vacuum system that delivers a vacuum quality better than 10^{-10} mbar is taken into account in order not to spoil the vacuum of the storage ring.

STATUS OF OPTICS CALCULATIONS

The initial electron beam created in the plasma cell has been simulated with the particle-in-cell code FBPIC [15] and features a beam energy of 50 MeV with an RMS energy spread of 2 % to 3 % and a bunch charge of about 20 pC [5]. The beam has been collimated using the quadrupole doublet and tracked with ASTRA [16] up until a distance of 2 m behind the plasma cell [13].

A model of the remaining transfer line has been implemented in MAD-X [17] according to the layout discussed above. The simulations include the quadrupole doublet in front of the intersection dipole, a second quadrupole doublet behind it, the DBA structure comprising two bending magnets and five quadrupoles, and the injection section of the ring (septum and kicker magnets). The end of the second kicker magnet marks the injection point at which the values of the optics functions have to match the ones in the ring.

The start values of the optical functions have been calculated from the particle distribution resulting from the ASTRA simulation. The target values at the interaction point are known from optics calculations of the storage ring. Both start and target values are summarized in Table 1. The quadrupole strengths have been matched with MAD-X to obtain the target values of the optics functions at the injection

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Table 1: Start values of the optical functions 2 m behind the plasma cell and target values at the injection point used for the MAD-X optics calculation.

parameter	unit	start value	target value
β_x	m	3.66	2.01
β_y	m	8.11	3.90
α_x		1.86	0.76
α_y		0.29	0.28
D_x	m	0.00	0.00
D'_x		0.00	0.00

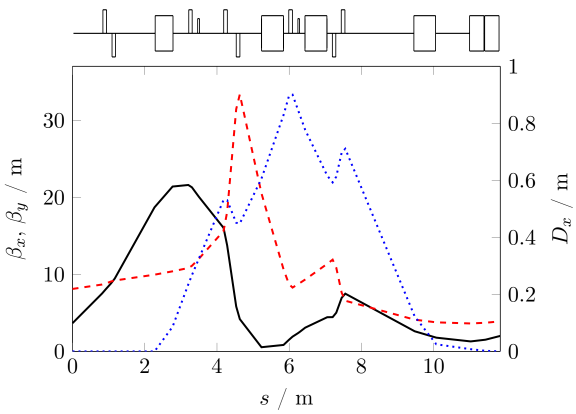

Figure 3: Horizontal and vertical beta functions (solid black and dashed red lines) and dispersion function (dotted blue line) in the LPA transfer line starting 2 m behind the plasma cell with previously collimated electron beam.

point. It turned out that the quadrupoles between intersection dipole and first bending magnet of the DBA structure have not been in optimum position. Therefore, position and number of quadrupoles have been varied with the goal to minimize the overall maximum values of the beta functions. Figure 3 shows the status of the optics optimizations. The achromatic optics used for the DBA cell in case of transfer of FLUTE bunches cannot be kept since in case of the LPA bunches the intersection dipole already creates dispersion. Positions for the quadrupoles between intersection dipole and DBA bends have been found that reduced maximum values of the β functions to about 34 m in the vertical plane and 22 m in the horizontal plane. In this case, only three quadrupoles have been used instead of the available four. This arrangement fulfills the key objectives of the transfer line: LPA bunches can be transported to the injection point of the storage ring obtaining the required values of the optics functions. In addition, positions for two sextupoles for chromatic corrections have been identified: $s = 3.51$ m with $D_x = 0.33$ m, $\beta_x = 20.03$ m, and $\beta_y = 12.06$ m, and $s = 5.84$ m with $D_x = 0.83$ m, $\beta_x = 0.84$ m, and $\beta_y = 10.66$ m.

Currently, the impact of the start values is under investigation. For example, if the divergence of the horizontal beam size could be reduced by stronger focusing in the quadrupoles

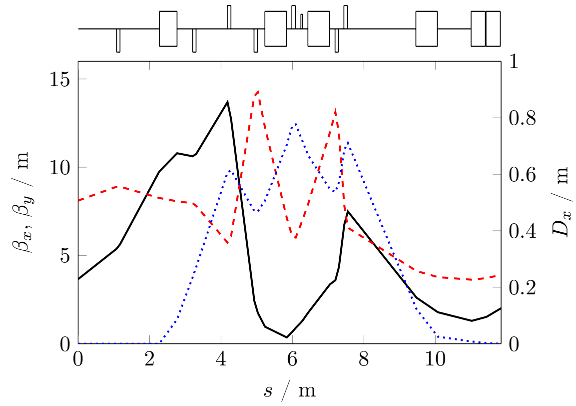

Figure 4: Horizontal and vertical beta functions (solid black and dashed red lines) and dispersion function (dotted blue line) in the LPA transfer line starting 2 m behind the plasma cell with reduced divergence in the horizontal plane at the beginning ($\alpha_x = 0.6$).

doublet directly after the plasma cell, the maximum value of the beta functions could be reduced. Figure 4 shows an optics with a start value of $\alpha_x = 0.6$. In this case only one of the two quadrupoles in front of the intersection dipole has been used. The position of the quadrupole directly in front of the first DBA dipole has been moved, which underlines the importance of these studies for the final design.

The angle of the intersection dipole had been restricted to 20° in order to limit the increase of the dispersion function. For smaller maximum values of dispersion options with smaller intersection angles have to be investigated. A second objective of further optimization is to increase the low minimum value of the horizontal β function, which is only $\beta_x = 0.54$ m at $s = 5.32$ m.

Finally, tracking studies to measure dynamic aperture, momentum acceptance and alignment tolerances will round up the design of this transfer line.

SUMMARY AND OUTLOOK

KIT and DESY formed a collaboration in order to demonstrate the first injection of LPA-generated electron beams into a storage ring. A transfer line from the LPA to the injection point of the cSTART storage ring at KIT is under development. A diagnostics layout has been proposed and optics calculations are in progress. The matching of the optics functions from initial to the target values at the injection point was successful, optimization is in progress. Positions for sextupoles and collimators to control chromaticity and energy spread have been identified in dispersive sections.

Next steps in the development of the transfer line are to reduce the maximum value of the dispersion function, to further investigate the impact of the start values of the optical function followed by tracking calculations, which are the prerequisite for detailed studies of the non-equilibrium beam dynamics in the storage ring.

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