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STATUS REPORT OF THE 50 MeV LPA-BASED INJECTOR AT ATHENA FOR A COMPACT STORAGE RING*

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Abstract

Laser-based plasma accelerators (LPA) have successfully demonstrated their capability to generate high-energy electron beams with intrinsically short bunch lengths and high peak currents at a setup with a small footprint. These properties make them attractive drivers for a broad range of different applications including injectors for RF-driven, ring-based light sources. In close collaboration the Deutsches Elektronen-Synchrotron (DESY), the Karlsruhe Institute of Technology (KIT) and the Helmholtz Institute Jena (HIJ) aim to develop a 50 MeV plasma injector and demonstrate the injection into a compact storage ring. This storage ring will be built within the project cSTART at KIT.

As part of the ATHENA (Accelerator Technology HElmholtz iNfrAstructure) project, DESY will design, setup and operate a 50 MeV plasma injector prototype for this endeavour. This contribution gives a status update of the 50 MeV LPA-based injector and presents a first layout of the prototype design at DESY in Hamburg.

INTRODUCTION

The development and operation of laser plasma accelerators have achieved significant milestones in the last years. The demonstration of generating and accelerating high energy [1], reproducible and stable [2], few-fs short [3] electron beams over several hours raises the hope to drive various applications with LPA-based facilities. In addition, a better understanding of injection processes and plasma effects [4] as well as the implementation of machine learning tools [5] pushes the achievable beam quality beyond well-known limits of this technology.

One innovative application of LPAs will be the usage as next generation of new driver-technology for storage rings and ring-based light sources. Beside a small footprint of the setup, the big potential of LPAs lies in their capability of generating electron beams with short bunch lengths and high peak currents. In particular, these features will allow to increase the current performance of synchrotron light sources. Physics on much shorter time scales can be investigated with the radiated photon beam. Further, the radiation spectrum can be extended far into the THz regime [6].

Three German research institutes, DESY, KIT and HIJ, have started a collaboration for first proof-of-principle studies on an LPA-based plasma injector for the large acceptance, compact storage ring of the cSTART project at KIT. DESY is designing a 50 MeV plasma injector prototype, whose status will be reported in this contribution.

LASER-PLASMA INJECTOR PROJECT

The laser-plasma injector project is part of the ATHENA program [7]. Since 2018, ATHENA supports to build an R&D infrastructure platform in Germany to demonstrate the applicability of plasma-based accelerators in different fields. The application as an injector requires from the LPA a stable, reproducible, high quality electron beam with controlled transverse emittance and energy spread. Consequently, the accelerator design, available diagnostics and active feedback loops must be adapted for this purpose.

The injector prototype will be designed, setup and commissioned at DESY Hamburg. After successful demonstration of electron beams with injector-type quality, the facility will be used for injection into the large-acceptance, compact storage ring of the cSTART project at KIT [8-10]. Foreseen as an R&D facility the special lattice of the ring has been carefully optimized to handle an electron beam injected from an LPA with ultra-short bunch length, relatively large emittance and large energy spread compared to a beam accelerated by an RF system. An injection energy of 50 MeV has been chosen in order to enable the comparison of the performance of two injectors, FLUTE, a 50 MeV linear RF accelerator and the LPA injector [11]. Table 1 lists the key parameters of the storage ring [12].

Table 1: Parameters of the cSTART Lattice

Parameters	cSTART lattice
Circumference	43.2 m
Beam energy	50 MeV
Momentum acceptance	±5.5%
Momentum compaction	$(-1 \text{ to } +2)\cdot 10^{-2}$
Dynamic aperture (horz./vert.)	15 mm/10 mm

The storage ring within the cSTART project is currently in procurement. The latest lattice design of the compact storage ring is displayed in Figure 1 [12].

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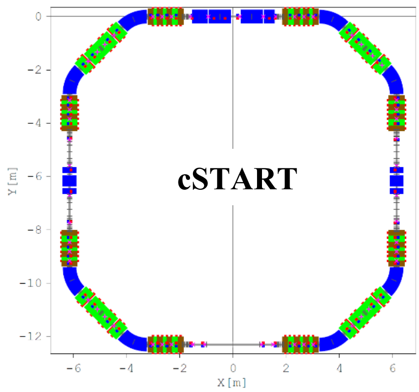

Figure 1: Lattice of the compact storage ring in the cSTART project at KIT (dipoles blue, quadrupoles red, sextupoles green, octupoles brown) [12].

In order to operate the LPA injector in Karlsruhe, KIT provides initially a commercial laser system, which will generate pulses up to 1.5 J and 30 fs long at a repetition rate of up to 10 Hz. KIT is additionally designing the transfer beamline from the plasma injector to the storage ring [13]. The overall goal of the collaboration will be the successful demonstration of the full-energy injection and storage of an LPA-generated electron beam.

LPA INJECTOR PROTOTYPE AT DESY

The prototype of the 50 MeV plasma injector will be built at DESY in the upcoming months and years. Hereby, the focus will be to generate and characterize electron beams with the acceptance parameters of the compact storage ring of cSTART. KALDERA, a next-generation, 100 TW LPA drive laser, which shall reach in final stages a repetition rate of 1 kHz, will be used to operate the prototype at DESY.

The first operation phase of KALDERA will provide similar laser parameters as the drive laser at KIT, although the focus of the KALDERA laser operation will be more on an enhanced stability.

Started in 2020, the plasma injector project at DESY is currently in the design phase. In a first step, a capillary type plasma source filled with a nitrogen-hydrogen gas mixture, was designed [14]. Simulations with the particle-in-cell code FBPIC [15] have successfully demonstrated the acceptance parameters for electron beam injection, which are mainly defined by the design and the boundary conditions of the cSTART storage ring as well as the available drive laser at KIT. Beam parameters obtained in FBPIC simulation results are listed in Table 2.

Table 2: Electron Beam Simulation Results of the Current Target Design Displayed at the Target Exit

Parameters	simulation results
Energy	50 MeV
Repetition Rate	10 Hz
Bunch charge	(20 ± 5) pC
Rel. energy spread	2 to 3%
Norm. emittance	µm range
RMS divergence	1 to 2 mrad

The minimum achievable relative energy spread at the plasma injector is limited by the relatively small target energy of 50 MeV. While the rms energy spread is minimized by optimized beam injection mechanism and relying on beam loading [4], the simulations with our laser and target parameters results in an increased relative energy spread of the 50 MeV beam above 2%. The significant relative energy spread itself has an impact on the chromatic fraction of the transverse emittance added during beam transport after the target. Controlling the emittance in the transverse plane by focusing elements close to the target exit is mandatory.

The plasma injector facility will be setup at SINBAD, the former DORIS tunnel at DESY [16]. Therefore, the infrastructure in the tunnel and the rack rooms is currently prepared for the injector installation planned in 2023. After commissioning and the demonstration of the required injection parameters during operation, the LPA-based injector is forseen to be transferred to the test facility site at KIT beginning of 2025.

Plasma Injector Layout

The plasma injector setup at DESY will consist of a vacuum chamber with the focusing optics, laser diagnostics and the plasma source with alignment. The vacuum chamber is followed by an electron beamline providing optics and diagnostics for beam manipulation and characterization. The first layout design of the total plasma injector beamline is shown in Figure 2.

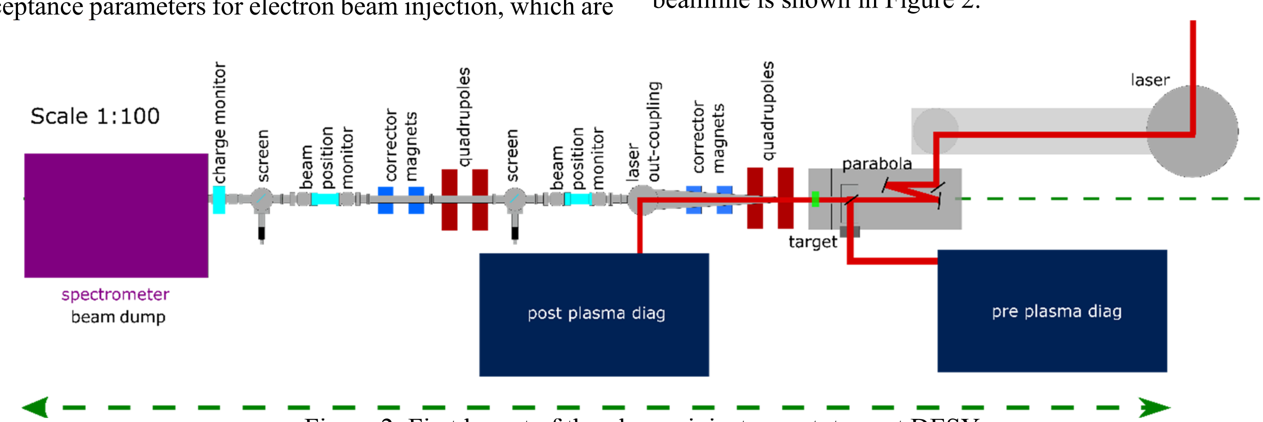

Figure 2: First layout of the plasma injector prototype at DESY.

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Target Chamber Design

The design of the target chamber is ongoing. Figure 3 presents a first sketch of the rectangular vacuum chamber. One mirror will guide the KALDERA laser to the parabola, which will focus the 60 mm beam along a focal length of 900 mm into the plasma target. The leakage beam of the last folding mirror before the target will be used for online diagnostics of the laser. Further, the laser can be de-coupled to an additional diagnostics station that allows to optimize the laser beam properties in the focus position (plasma target). The target chamber is split into two sections by a wall, each section pumped by a separate turbo pump. This system allows differential pumping between the laser focusing and the target area and supports the usage of continuous flow plasma targets.

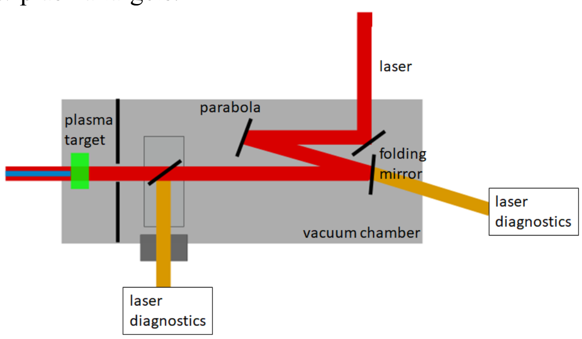

Figure 3: First sketch of the target vacuum chamber.

Electron Beamline

The plasma injector setup at DESY also foresees an electron beamline for beam manipulation and characterization purposes, which follows the target chamber. A quadrupole doublet is planned to catch the divergent electron beam, which will exit the plasma target. In order to control the chromatic emittance growth of the beam, the two quadrupoles will be installed as close as possible to the electron source. Since the strongly divergent drive laser is co-propagating to the electron beam the yoke design of a standard DESY quadrupole has been adapted for the laser to pass.

Multi-objective optimization and simulations with the particle tracking code ASTRA [17] were performed to find best settings for the beam optics to generate a focused or collimated beam at defined positions. Figure 4 shows the beam size and transverse emittance evolution of an LPA beam collimated by a quadrupole doublet. The results are promising as they show that the strong growth of the divergent beam of 2 mrad is captured to x_{rms}= 0.25 mm and y_{rms}= 0.91 mm. The emittance is almost constant after the quadrupoles along the beamline with $\varepsilon_{x,rms}$= 1.9 mm mrad and $\varepsilon_{y,rms}$= 6.0 mm mrad. The asymmetry in the transverse plane as well as the still existing divergence in the x-plane results from the fact that a quadrupole doublet instead of a triplet is used. At KIT the shown beam distribution was used to simulate the transport of the beam through the transfer line and the injection into the cSTART storage ring. All optics were matched and the injection of the 50 MeV beam met all requirements [13].

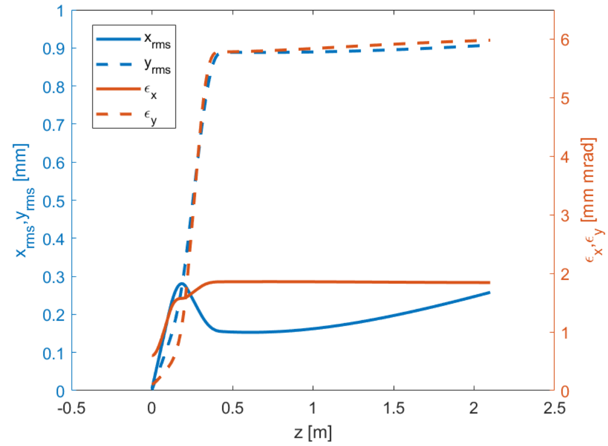

Figure 4: Transverse beam size and normalized rms emittance evolution of the collimated beam. Plasma target exit at z=0 m, quadrupole duplet at z=0.16 m and 0.36 m.

Finally, the drive laser is coupled out of the beamline and can be further investigated by output diagnostics. The collimated electron beam is sent to a short diagnostics section including beam position monitor, profile screen and spectrometer, which enables to measure and optimize the electron beam quality in terms of charge, beam size, transverse emittance, energy and energy spread. A second quadrupole doublet in the beamline allows to create a round electron focus of 0.29 mm at the electron spectrometer roughly 4.6 m after the plasma target. Simulation results are displayed in Fig. 5.

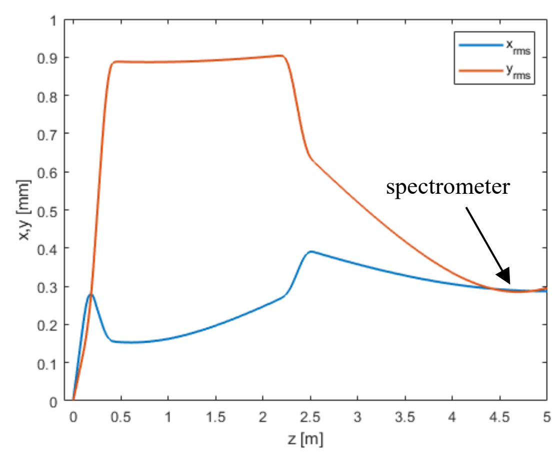

Figure 5: Focus of the symmetric electron beam at the spectrometer at 4.6 m. Second quadrupole doublet at z=2.26 m and 2.46 m.

SUMMARY

This contribution presents the status of the 50 MeV LPA-based injector project at DESY for the injection into the storage ring of cSTART at KIT. The layout of the prototype including the design of the target chamber is introduced. Simulations with ASTRA have been successfully demonstrated that the electron beam can be collimated by the first quadrupole doublet and match the injection requirements. A fully operational and optimized laser-driven plasma injector is expected at KIT during the year 2025.

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