ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR44

LASER-PLASMA INJECTOR FOR AN ELECTRON STORAGE RING

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Abstract

Laser-plasma accelerators (LPAs) have field gradients that are approximately 3 orders of magnitude higher than current RF-based machines, which allows for very compact accelerators. LPAs have matured from proof-of principle experiments to accelerators that can reproducibly generate ultrashort high-brightness electron bunches. Here we will discuss an LPA design for a first combination of LPAs with an electron storage ring, namely an LPA-based injector for the cSTART ring at the Karlsruhe Institute of Technology (KIT). The cSTART ring is currently in the final design phase. It can be adjusted to energies in a range in the range 50-90 MeV and for each energy setting will have a large momentum acceptance to accommodate the comparably large energy spreads of LPA-generated electron beams. The LPA injector will be required to reproducibly generate electron bunches with few-percent energy spread. To that end, controlled electron injection methods into the plasma accelerating structure in combination with tailored plasma densities are a promising approach that will allow tunability of the electron beam over a wide parameter range.

INTRODUCTION

The high accelerating field gradients of LPAs allows the realization of accelerators with compact dimensions. LPAs routinely generate few hundred MeV electron bunches from millimeter to centimeter-long acceleration distances and have recently demonstrated beams with energies of up to 8 GeV [1]. The generated electron bunches have femtosecond duration and high brightness with parameters that are mostly comparable to those of conventional accelerators [2]. Their compact dimensions also makes LPAs comparably energy efficient. This makes them an attractive option as injectors for electron storage rings and light sources [3]. Over the last decades, the beam quality and stability of LPAs have tremendously improved. However, LPA electron bunches still have a comparably large energy spread of a few percent and require further improvements in stability to operate as injectors for storage rings. First experiments towards LPA injectors for storage rings will be performed at the cSTART storage ring at KIT. The demands on the LPA injector will be to reproducibly generate electron bunches at the energy required by the storage ring with small energy spread and small beam pointing variations. The LPA injector will be tuned for different operation modes ranging from low charge and small energy spread to higher charge bunches with increased energy spread.

To this end, we have performed simulations to investigate the tunability of the LPA injector. The design is based on controlled injection into the so-called ”bubble” plasma accelerating structure using ionization injection to reach a comparably low energy spread and a tailored plasma density profile to obtain the target beam energy.

LASER PLASMA INJECTOR FOR CSTART AT KIT

cSTART Project

The compact STorage ring for Accelerator Research and Technology (cSTART) [4, 5] is designed to be a large energy spread acceptance storage ring at KIT. The 43.2 m circumference ring can be adjusted for beam energies between 50 - 90 MeV. The scientific program of cSTART includes the demonstration of injection of laser-plasma accelerated electron bunches and the investigation of the non-equilibrium dynamics of ultrashort electron bunches [6]. To accommodate the comparably large energy spread of LPAs, the lattice of cSTART is designed for an energy acceptance of $\pm 4\%$ [7]. The dynamic aperture of the ring will be 18 mm horizontal and 14 mm vertical so that the LPA-beam can be stored stably. Additionally, cSTART will have diagnostics to measure the evolution of sub-ps electron bunches. cSTART is reaching the completion of the design phase and construction is expected to begin in 2026.

Laser-Plasma Injector

To reproducibly generate electron bunches with small energy spread, the LPA will use individually controllable injection and acceleration sections. In particular, to control the injected charge, energy, and energy spread we will use ionization injection from a nitrogen-doped hydrogen gas [8]. In ionization injection, a small amount of a gas with higher atomic number, in this case nitrogen, is added to the lower-Z background gas, typically hydrogen. For hydrogen, the intensity at the front edge of a typical LPA laser pulse is already sufficient to fully ionize and generate a plasma. Due to the higher Z, nitrogen atoms are typically ionized to 5+ at the laser front edge while the two inner-shell electrons require a higher intensity for ionization. The laser forms the accelerating ”bubble” plasma structure by interacting with the plasma background electrons from the hydrogen and outer-shell nitrogen. The two remaining inner-shell N^{5+} electron are ionized near the peak laser intensity, closer to the center of the laser pulse envelope. As a result, these electrons are ”born” mostly on-axis and into an accelerating phase of the bubble. The amount and spatial confinement of

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the nitrogen doping to a small section of the gas target leads to defined electron injection with control over the injection position. It also allows us to control the amount and temporal and spatial distribution of the injected charge, which in combination with the accelerating section determines the final phase space distribution of the beam, including beam energy and energy spread [9]. In addition to a spatially defined injection, the mean beam energy and energy spread are largely impacted by the interaction of injected charge and the accelerating field. This includes the suppression of the accelerating field due to the self-field of the injected electron bunch. A matched bunch charge and shape leads to a constant value of accelerating field gradient for the whole bunch. Such an optimized beam loading leads to a decrease in energy spread [10].

The final beam energy can be mainly controlled via the acceleration length, the plasma density and beam loading. To reproducibly reach the same beam energy with low energy spread, the plasma density should be terminated near the dephasing length, i.e., when the electron bunch reaches the center of the bubble and transitions from an accelerating to a decelerating phase. As the target beam energy of 50-90 MeV is comparably low for LPAs, we introduced a slowly decreasing plasma density profile. The negative density slope leads to a continuous elongation of the bubble length as it propagates and a decrease in the plasma wave phase velocity. This allows the injected electrons to reach the dephasing length sooner and it can be ejected from the plasma at the required comparably low electron beam energy.

Here, we show particle-in cell (PIC) simulations of an LPA that can generate electron bunches with suitable energy and energy spread. In particular, we show tunability of the electron beam properties as a function of nitrogen doping. The control over these parameters with nitrogen-doping allows us to generate electron bunches with different properties and investigate the nonlinear phase-space dynamics for a wide range of initial parameters.

LASER-PLASMA SIMULATIONS

We demonstrate a design for an LPA injector and investigate its tunability by modeling the interaction in FBPIC. FBPIC is a quasi-3D particle-in-cell (PIC) simulation code that solves for fields in spectral space using a quasi-cylindrical grid [11]. The simulations use an 800 nm laser pulse with an energy of 1.14 J, 29.6 fs FWHM pulse duration, a beam waist of 16 µm, resulting in a normalized laser intensity of $a_0 = 2$, where $a_0 \simeq \lambda[\mu\mathrm{m}](I_0[\mathrm{W/cm^2}]/1.4 \times 10^{18})^{1/2}$, with the laser wavelength λ and laser intensity I_0.

In the simulations we have optimized the LPA to generate electron bunches with properties that match the acceptance parameters of cSTART. We show that we can tune the charge, beam energy, and energy spread by varying a single parameter, namely the density of the nitrogen dopant in the ionization injection section. The simulations use the plasma density profile shown in Fig. 1. The phase-space densities for a typical bunch at the exit of the plasma density

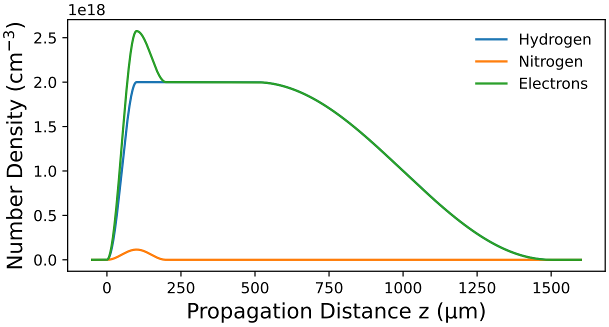

Figure 1: Gas and plasma density profiles showing hydrogen density (blue), the nitrogen density (yellow) and the plasma density (green) for a nitrogen doping density of $8{\times}10^{16}$ cm^{-3}.

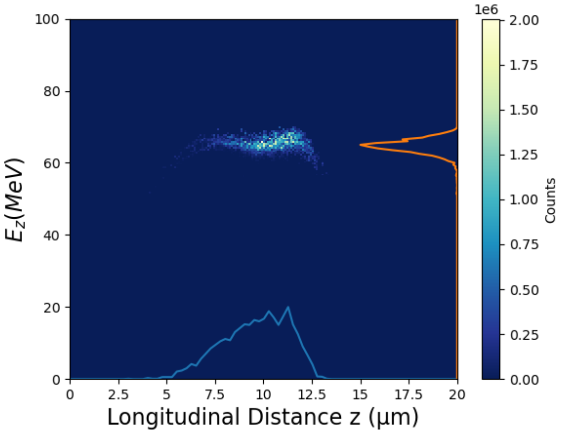

Figure 2: Phase-space density of an electron bunch generated by the density profile with a nitrogen dopant density of $12{\times}10^{16}$ cm^{-3}. The orange curve shows the temporally integrated spectrum and the blue curve the energy-integrated temporal profile of the bunch.

Figure 3: Injected charge vs nitrogen doping density.

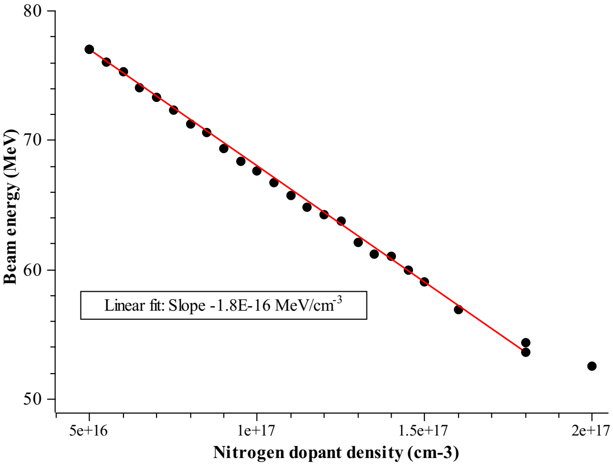

Figure 4: Electron beam energy vs nitrogen density. The linear fit does not include the highest two density data points.

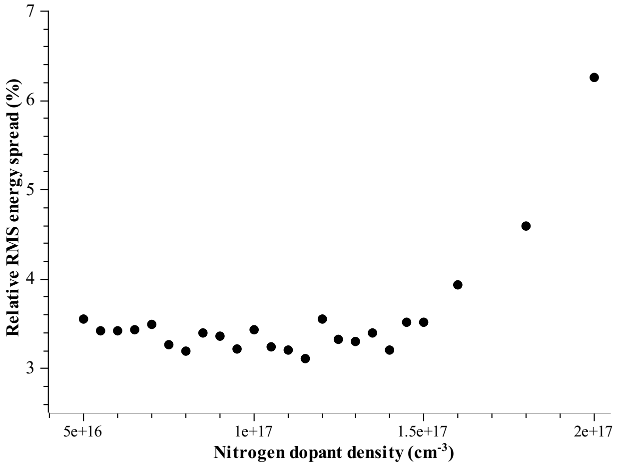

Figure 5: Relative RMS energy spread vs nitrogen density.

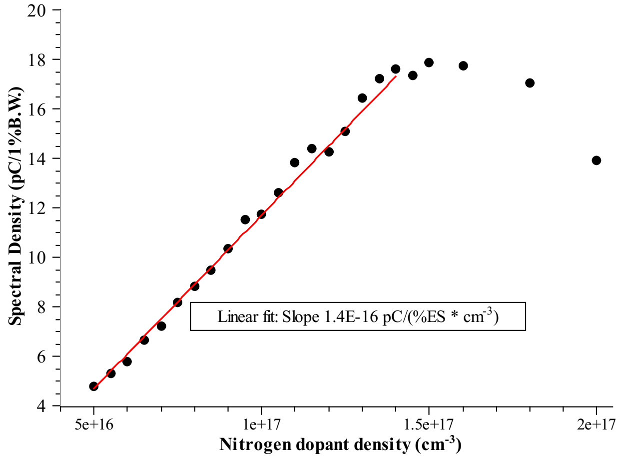

Figure 6: Spectral density vs nitrogen density. The fit only considers data points up to 14×10^{16} cm^{-3} nitrogen density.

is shown in 2. The phase-space distribution was fitted using a Gaussian distribution.

It can be seen that the injected charge scales linearly with the nitrogen dopant density over a large density range and can be varied between 18 - 85 pC, while still fulfilling the cSTART acceptance requirements (see Fig. 3). The final beam energy decreases linearly with nitrogen density (see Fig. 4). This is due to beam loading, where the fields of the increased injected charge lead to a decrease of the effective accelerating field gradients. At higher dopant densities, the energy begins to plateau - the beginnings of which can be seen in highest density data point. The decrease in mean beam energy can in principle be compensated by also adjusting other parameters, such as the laser focusing and the hydrogen plasma density, which we have not considered here. Using this tailored plasma density design allows us to keep the relative RMS energy spread well below 4% over a comparably large parameter space (see Fig. 5). For a dopant density higher than approximately 1.7×10^{17} cm^{-3}, the energy spread increases as the injected charge becomes too high and beam loading is not optimal anymore. The increased injected charge for higher nitrogen dopant density and comparably constant relative energy spread leads to an increase in spectral charge density (see Fig. 6). The spectral charge density begins to drop off as the energy spread increases. Operating the LPA at an increased spectral charge density will, for example, enable an operation mode with spectral filtering before injection to study the effects of energy spread on the electron beam dynamics.

CONCLUSION

This contribution introduced a concept of an LPA-based electron injector operating between 50-90 MeV for the cSTART storage ring project at KIT. To match the momentum acceptance and for reproducible operation, the LPA uses a combination of a nitrogen-doped ionization-injection section and a tailored plasma density profile. The properties of the electron beam, including the beam energy and charge, can be adjusted over a wide range by changing only a single parameter, namely the density of the nitrogen doping, while still generating beams with energy spreads that are compatible with the cSTART ring. This will allow us to use the LPA as injector for investigating the non-equilibrium phase-space dynamics of ultrashort bunches in different parameter regimes. A prototype of this LPA is expected to be operational by early 2025 with cSTART to begin construction in 2026.

ACKNOWLEDGEMENTS

We gratefully acknowledge financial support by the German Bundesministerium für Bildung und Forschung (BMBF) and the state of Baden-Württemberg. N.R., D.S., A.Y.S and J.N. acknowledge the support by the DFG-funded Doctoral School ”Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology” (KSETA)

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