LASER-PLASMA ELECTRON INJECTOR DEVELOPMENT FOR THE cSTART STORAGE RING

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Abstract

Laser-plasma accelerators (LPAs) generate ultrashort, high-intensity electron bunches in a compact form factor. At Karlsruhe Institute of Technology (KIT), we are developing an LPA for direct injection into a specifically built storage ring with high momentum acceptance. The compact storage ring for accelerator research and technology (cSTART) can be tuned to energies between 40 – 90 MeV and its lattice is designed to accept electron beams with ±4 % energy spread. Furthermore, the ring lattice can be set up for the storage of ultrashort electron bunches. The LPA electron injector must be readily tunable to match the storage ring parameters. This contribution reports proof-of-concept experiments that demonstrate the generation of high-quality LPA electron beams with parameters that fulfill the cSTART requirements.

INTRODUCTION

The Karlsruhe Institute of Technology is developing cSTART, which will soon enter the construction phase [1]. cSTART is a compact storage ring, which will be able to accept femtosecond electron bunches for investigation of non-equilibrium dynamics, storage of ultrashort electron bunches, compact light sources, and next-generation accelerator technologies [2, 3].

A laser-plasma accelerator will be used as one of the injectors for high-brightness femtosecond electron bunches into cSTART [4]. An LPA is a promising technology for this purpose because the high accelerating gradients produced in a plasma wakefield allow electrons to be accelerated to the target energies over millimeter-scale acceleration distances, which is orders of magnitude smaller than traditional RF-based machines can achieve [5]. The target parameters for the LPA injector for cSTART are listed in Table 1.

Table 1: Target Parameters for cSTART LPA Injector

Parameter (Unit)	**Value**
Charge	1 - 100 pC
Energy Range	40 - 90 MeV
Energy Spread	< 4 %
Bunch Duration	< 30 fs

One challenge of LPAs is designing them to make stable high-quality electron beams at (for LPAs) relatively low energies of < 100 MeV. To test if this can be done for our application, we performed a proof-of-concept experiment at the Deutsches Elektronen-Synchrotron LUX LPA setup [6].

EXPERIMENT

To achieve the required electron energy range for cSTART (40 – 90 MeV), we significantly detuned the LUX LPA system away from the system's standard operating range. The laser parameters were 1.56 J energy, 30 fs pulse width at full-width at half-maximum (FWHM), 22 µm spot size, 1 Hz repetition rate, 800 nm wavelength, resulting in an a_0 of 2.53. From there, we explored the densities and mixtures of gases in the plasma-cell target. A schematic of the LUX electron beamline is shown in Fig. 1 [7].

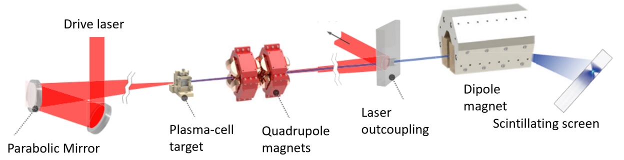

Figure 1: Simplified schematic of the LUX LPA experiment adapted from [7]. The driver laser (red) is focused into a plasma-cell target, where it ionizes argon-doped hydrogen gas creating the laser-plasma electron-accelerating structure. After the plasma-cell target, the electrons (blue) are focused with electromagnetic quadrupoles and the laser is out-coupled leaving the electron beam to travel through a spectrometer comprised of a permanent dipole magnet and a scintillating screen.

The plasma target was a gas-capillary of approximately 500 µm x 5 mm as shown in Fig. 2 [8]. The LPA is based on localized ionization trapping using Ar and H_2 as background gas.

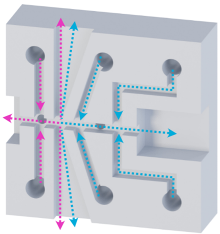

Figure 2: Schematic of the LUX plasma-cell target adapted from [8]. Gas is supplied to the central gas-capillary. A mixture of H_2 and Ar is shown in magenta, and pure H_2 is shown in blue. The laser propagates from left to right.

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Over a period of approximately 4 hours, we collected 1304 shots. The consecutive electron spectra are shown in Fig. 3. To characterize the energy spread, a Mean-Absolute Deviation (MAD) was calculated for each shot, which for a dataset x, is defined as:

$$MAD = \sum_{i=1}^{n} \frac{|x_i - \bar{x}|}{n},$$

with the median $\bar{x}$ and the number of elements n.

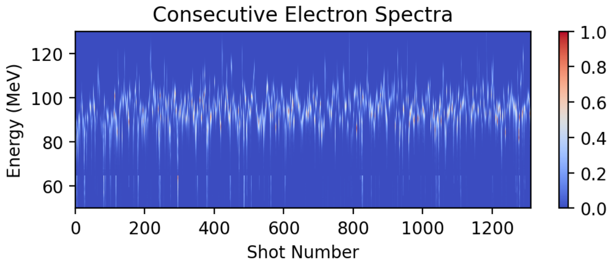

Figure 3: Consecutive spectra series. Electrons are vertically dispersed by the permanent dipole magnet spectrometer and detected by a scintillating screen. The series of spectra for 1304 shots are shown. The intensity corresponds to the charge density at a given energy. A measurement artifact can be seen below 70 MeV due to a crossover between two scintillating screens.

For the whole dataset, the averages for median energy, relative energy spread, charge, and spectral density were 92.4 MeV, 4.4 %, 19.6 pC, and 7.8 pC per 1 % energy spread, respectively. Selected single shot energy spectra near the desired energy of 90 MeV are shown in Fig. 4. These electron beams had median energies in the range of 40 – 90 MeV MeV with < 4 % energy spread. Beams with these characteristics are suitable for direct injection into cSTART as nearly all of the charge would have been accepted into the storage ring.

However, significant shot-to-shot variations in median energy and energy spread (dE) can be seen in Fig. 3. Ordering the data by MAD energy spread shows a relation between mean energy and energy spread (Fig. 5). The increased energy spread is likely due to an unmatched beam loading of the wakefield [9, 10]. The comparably large variations arise from operating at laser and beam energies that are substantially below the LUX experiment's designed parameters [11]. This includes the length of the gas target that was not optimized for such low beam energies as well as the electron beam optics. At such a significant de-tuning, significant parameter variations are expected. Despite this, the data from this experiment already shows that a large fraction of shots have parameters that are suitable for cSTART. A substantial improvement in reproducibility is expected from an optimized gas density profile [12].

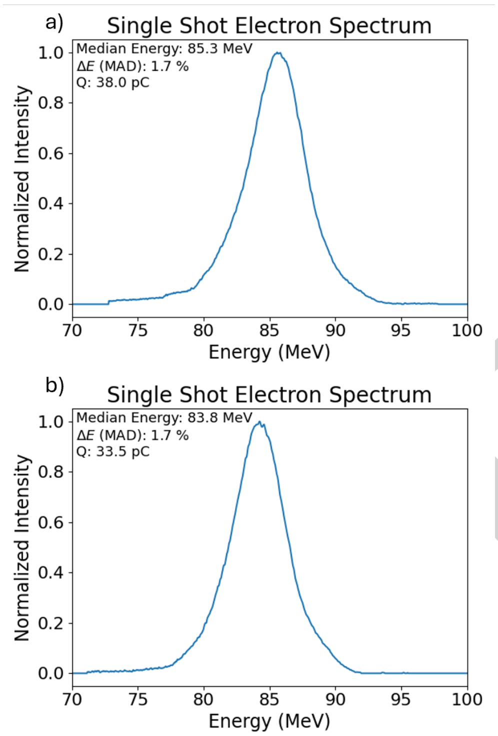

Figure 4: Single shot energy spectra. Energy, energy spread, charge, spectral density: a) 85.3 MeV, 1.7 %, 38.0 pC, 22.5 pC/(1 % energy spread), b) 83.8 MeV, 1.7 %, 33.5 pC, 19.6 pC/(1 % energy spread).

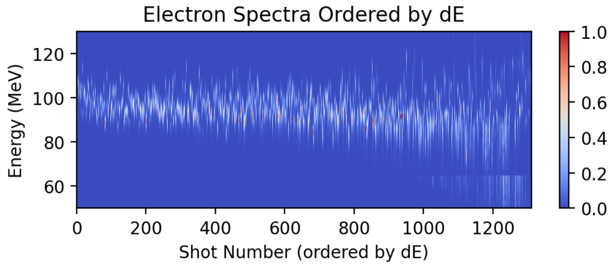

Figure 5: Shot spectra series ordered by MAD energy spread (dE). A trend is observable between decreasing median energy and increasing energy spread.

The properties of the generated electron beams are shown in more detail in Fig. 6, which graphs the dependence of the energy spread as a function of the median energy and charge. It can be seen that the electron energy is tuneable across a range of mean energies (88 – 105 MeV) while staying below 4 % energy spread and without sacrificing spectral density, which is a desirable feature for the variable-energy cSTART ring.

The median energy as a function of charge shows an inverse correlation over a wide range of parameters (Fig. 7). This is due to beam loading, where the electric field of a high-charge electron bunch reduces the accelerating field gradient in the plasma bubble resulting in electron beams with higher charge but lower energy. Defined beam loading and control of the trapped charge by adjusting the gas dopant density has been shown as a potential method for an energy tuning mechanism for LPAs [12].

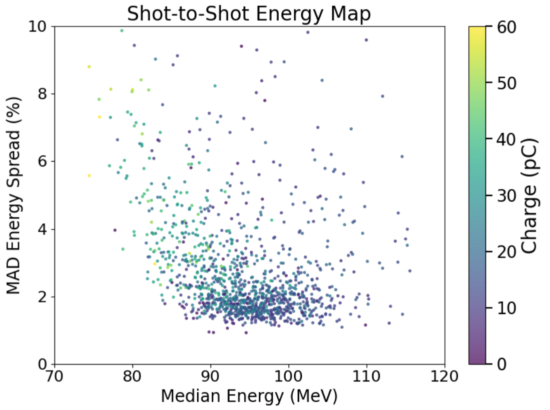

Figure 6: Energy spread as a function of median beam energy. Color coded is the beam charge. A large fraction of the shots already fulfill the < 4 % energy spread requirements of cSTART. The near-zero covariance for a large fraction shows the tunability of the beam energy over a wide energy range.

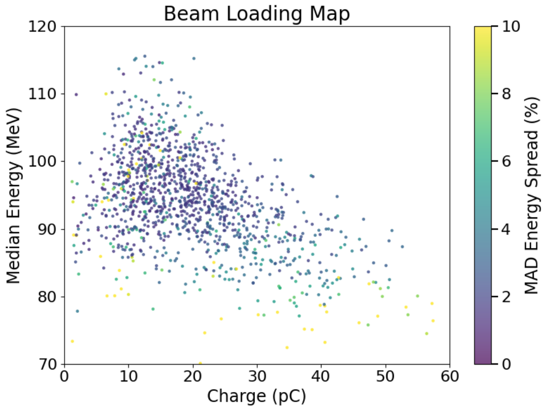

Figure 7: Median energy as a function of beam charge. The negative covariance over a wide range shows tunability of the beam energy via injected charge.

CONCLUSION

Our proof-of-concept experiment shows that LPAs can generate electron beams with the energy and momentum spread required for direct injection into the cSTART ring, albeit with comparable large parameter fluctuations due to experimental conditions that were not optimal for the beam energies. We expect that optimization of a purpose-built LPA for the target energy will substantially reduce the shot-to-shot variation, resulting in a reliable and compact electron source. This includes not only optimizing the parameter space for single ideal shots but also taking into account experimental shot-to-shot fluctuations, such as laser or plasma parameters. To find a suitable parameter-space landscape that can reliably generate the desired beams for a cSTART LPA injector, we are conducting simulations using Bayesian optimization [13].

In 2026, we will begin construction of the cSTART storage ring with a purpose-built LPA to follow.

ACKNOWLEDGEMENTS

This project was fully supported by the Helmholtz Association under program Matter and Technology, topic Accelerator Research and Development. A.Y.S., D.S, J.N. and N.R. acknowledge partial support by the Doctoral School ”Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology” (KSETA).

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