ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST029

FIRST START-TO-END SIMULATIONS OF THE 6 GeV LASER-PLASMA INJECTOR AT DESY

S. A. Antipov*, I. Agapov, R. Brinkmann, Á. Ferran Pousa, M. Jebramcik, A. Martinez de la Ossa, M. Thévenet, Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany

Abstract

DESY is studying the feasibility of a 6 GeV laser-plasma injector for top-up operation of its future flagship synchrotron light source PETRA IV. A potential design of such an injector involves a single plasma stage, a beamline for beam capture and phase space manipulation, and a X-band rf energy compressor. Numerical tracking with realistic beam distributions shows that an energy variation below 0.1%, rms and a transverse emittance about 1 nm-rad, rms can be achieved under realistic timing, energy, and pointing jitters. PETRA IV injection efficiency studies performed with a conservative 5% beta-beating indicate negligible beam losses for the simulated beams during top-up. Provided the necessary progress on high-power lasers and plasma cells, the laser plasma injector could become a competitive alternative to the conventional injector chain.

INTRODUCTION

Using plasma as an accelerating medium has been attracting attention in the accelerator community for years, promising unmatched accelerating gradients and thus compact, energy-efficient acceleration [1]. Laser-plasma acceleration (LPA) in particular has shown significant progress, achieving (although in different setups) GeV energies [2], narrow energy spectrum [3], and low emittance [4]. Recently, the LUX LPA at DESY demonstrated a percent level of energy stability during a 24 hour long operation run [5].

This progress encourages considering an LPA as a possible injector for various applications. In a synchrotron light source, an LPA injector could be used to accumulate charge in the storage ring, significantly lowering the load on the conventional injector chain. The proposed injector is based on an active energy compensation scheme [6], utilizing an X-band rf cavity to compensate potential energy fluctuations of the LPA beam [7]. A low-energy demonstrator of the approach, based on the existing driving laser infrastructure [8] as well as already demonstrated plasma cell performance, is presently being designed at DESY [7].

LPA BEAM FOR TOP-UP INJECTION

PETRA IV is a future 6 GeV fourth generation light source [9]. In its Brightness operation mode it will store 1900 electron bunches of 1 nC each with a ~ 5 h lifetime. In its baseline scenario the machine will use an off-axis accumulation scheme to top up beam intensity as well as for the initial filling. In the off-axis accumulation mode one would have to top up about 100 pC at a 1 Hz repetition rate to compensate for beam losses (e.g. from Touschek effects) and keep the total charge in the ring constant, while also maintaining bunch-to-bunch charge fluctuations within 10%. To achieve an efficient off-axis injection the rms geometric emittance would have to be $\lesssim$ 1 nm and the rms relative energy spread and variation well below 1% [10].

A research on a suitable 6 GeV plasma cell parameters is currently under way at DESY. While it is in its early stage, preliminary numerical simulations show that with a single LPA stage driven by a ~ 20 J laser pulse could generate suitable beams. Figure 1 shows the LPA beam that has been obtained using a bayessian optimization [11] in the FBPIC particle-in-cell (PIC) code [12], taking into account the laser-plasma interaction, wakefields, beam loading, and a plasma density downramp [13]. The electron bunch at the exit of the plasma cell has a charge of 87 pC, a transverse emittance below 1 nm, rms divergence < 0.2 mrad, rms bunch length of 3 µm, and an rms momentum spread of 10^{-2} (Table 1). This LPA beam can then be captured and manipulated by a specially designed beamline.

BEAMLINE DESIGN

The injector beam line is based solely on proven conventional technology and pursues three main objectives: (a) capture the LPA electron beam with minimum chromatic emittance degradation; (b) improve its energy spread and stability to a sub-permille level; (c) match the optics functions to those at the injection point of PETRA IV (Table 1). Figure 2 (top) depicts a schematic view of the beamline and its linear lattice functions (bottom). First, the LPA beam is captured by a triplet of strong quadrupole mag-

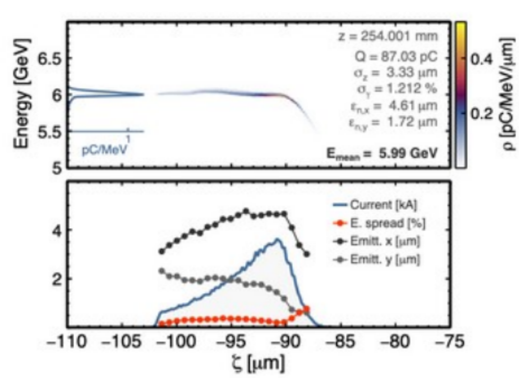

Figure 1: Estimated parameters of a potential LPA beam. Top – a longitudinal distribution of bunch energy spread; bottom – bunch current and normalized slice emittances. Results of an FBPIC [12] simulation; head is on the right.

* Sergey.Antipov@desy.de

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST029

Table 1: Beam Parameters at the Entrance and at the Exit of the Beamline, Charge Transmission and the Final Energy Spread were Computed for a Realistic LPA Beam Distribution

Parameter	Plasma cell exit	Final
Twiss α (x,y)	-2.6, -2.1	0, 0
Twiss β (x,y)	6.4, 5.7 cm	46, 6.8 m
Norm. ϵ (x,y)	4.6, 1.7 μm	5.3, 2.0 μm
Bunch charge	87 pC	84 pC
Energy spread, rms	1.2×10^{-2}	5×10^{-5}

nets[1], followed by drift space for laser beam removal and diagnostics. Afterwards, an S-chicane with well separated β-functions and four sextupoles corrects the chromatic emittance increase in the horizontal plane. This weak chicane with $R_{56} = 5$ mm also serves as a pre-stretcher, increasing the rms bunch length from ~ 3 to ~ 50 µm in order to mitigate coherent synchrotron radiation (CSR) effects in the main chicane that follows. The main chicane is composed of four strong dipoles with a collimator in the middle. The large horizontal dispersion allows an efficient momentum collimation at ±3%. The R_{56} of the chicane is 10 cm, i.e. it creates an energy-position correlation (chirp) of 60 MeV/mm. Then an X-band RF dechirper corrects energy deviation. Using an active dechirper one compensates both the beam energy spread and the jitter of its central energy. Table 2 lists key parameters of the beamline components.

The total required RF voltage is about 250 MV, or 5% of what be needed for a conventional linac to accelerate the particles to 6 GeV. Given the high gradients achievable in state-of-the-art X-Band structures, the total length of the RF section could be within 5 m. A suitable X-band cavity design is being developed in the scope of the CompactLight project [14], where a set of four cavities powered by a 50 MW RF station would be capable of providing accelerating voltages above 200 MV. Given the relatively large length of the RF bucket laser-to-RF synchronization can be done with all-RF technology. A similar system at FLASH offers timing stability at a 100 fs level.

The total length of the beamline is 37 m, which together with ~ 10 m required for the laser beam focusing would bring the total length of the LPA injector to ~ 50 m.

Table 2: Parameters of Key Beamline Elements

Element	Length	Strength
Capture quads	50 cm	$G \leq 82$ T/m
S-chicane dip.	70 cm	$B = 1$ T
Chromatic sextupoles	30 cm	$S \leq 550$ T/m^2
Main chicane dip.	175 cm	$B = 1.45$ T
12 GHz dechirper	500 cm	$V = 250$ MV

[1] We assume magnets with a field gradient up to 100 T/m, a length of 50 cm, and a bore radius of 12.5 mm, similar to Ref. [15]

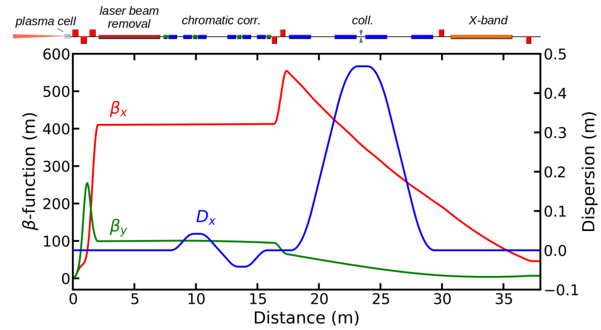

Figure 2: Beamline optics functions from the plasma cell to the PETRA IV injection magnet. Dipoles are shown in blue, quadrupoles in red, sextupoles in green, and the X-Band RF in orange.

PARTICLE TRACKING

We tracked the LPA beam through the beamline using the Ocelot tracking code [16], taking into account linear optics, RF, collimation, and CSR effects. Under ideal conditions nearly all charge from the LPA, 84 pC reaches the end of the beamline. The beam is stretched in the transfer line to 0.7 mm rms, its rms energy spread reduces to 5×10^{-5}, and the transverse emittances are preserved at a level of 0.5, 0.2 nm (hor., vert.).

In a real world, the mean energy and chirp of the LPA beam will vary, for example, due to variations of the bunch charge resulting in different levels of beam loading. Recent experiments at LUX [5, 11] give confidence that, with moderate improvements to the laser stability, a central energy stability of 1% rms can be expected. In order to assess the injector's performance under such conditions, we performed a series of tracking simulations varying the central energy of the bunch, while keeping the remaining parameters constant. We assumed a normal distribution of the central energies with an rms spread of 1%. Thus, the average electron energy at the exit of the LPA was 6003 ± 78 MeV. On top of that, we also assumed a Gaussian timing jitter between the LPA drive laser and the rf of $\sigma_t^{\mathrm{tj}} = 100$ fs rms. After passing through the active dechirper the energy spread decreased, as expected. The average value and variation are 6000 ± 5 MeV, which corresponds to a relative stability at the 8×10^{-4} level (Fig. 3). The particles that do not fit into the ±3% acceptance are stopped by the collimator. This results in a slight shot-to-shot variation of the bunch charge: 83 ± 4 pC.

On top of energy and timing jitters one should expect an LPA pointing jitter of the magnitude of beam divergence at the exit of the plasma cell. Our analysis shows that this jitter is likely to dominate the final projected emittances at the end of the transfer line. To quantify the effect we performed an additional scan, randomly adding a Gaussian pointing error with a standard deviation of one rms beam divergence to both transverse planes (0.2 and 0.1 mrad respectively). The results are depicted in Fig. 4; the average final transverse emittance is ~ 1 nm in both planes.

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST029

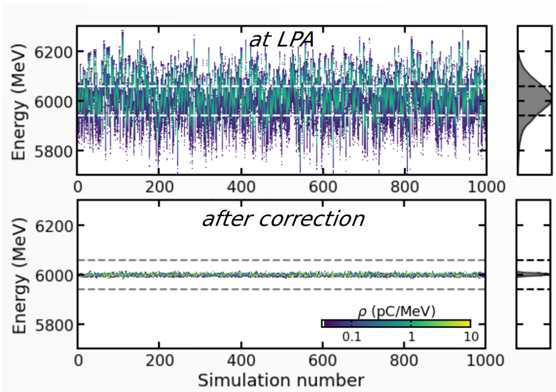

Figure 3: Simulated electron beam spectra at the exit of the plasma target (top) and after the X-band cavity (bottom).

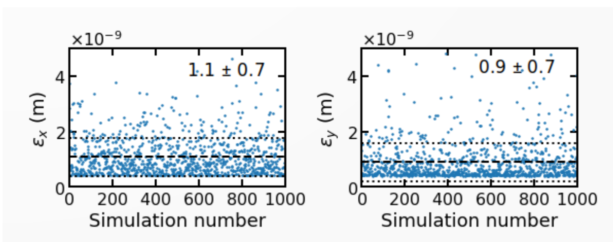

Figure 4: Horizontal (left) and vertical (right) emittances at the beamline exit for a 1 σ LPA pointing angle jitter.

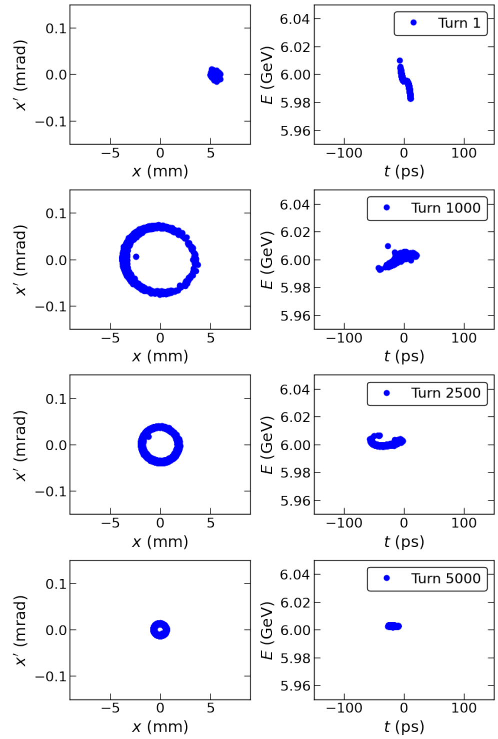

Figure 5: Damping of injection oscillations in the LPA beam. Left – horizontal, right – longitudinal phase space.

INJECTION EFFICIENCY SIMULATION

In order to complete the picture we studied the efficiency of injection of the LPA beam into the PETRA IV light source using element-by-element tracking in Elegant [17] with a realistic aperture model and optics errors. We assumed a conservative 5% rms β-beating with 20 error seeds. On top of that, we assumed a 100 fs timing and 1σ (0.2 mrad) pointing angle jitter of the LPA beam. The initial injected beam offset was 5.5 mm, corresponding to an off-axis accumulation injection. The beam was represented by 10^4 macroparticles and tracked for 5000 turns (1.5 synchrotron damping times). In all cases injected bunch oscillation rapidly decayed with no losses (Fig. 5), except for one macroparticle in one error seed. This encourages expecting a 99.99% top-up injection efficiency in a real machine.

COMPARISON TO THE CONVENTIONAL INJECTOR CHAIN

The conventional injector chain of PETRA IV consists of an L-band linac followed by a booster synchrotron DESY IV [18]. When operating in a top-up accumulation mode the chain will deliver bunches with 19 nm horizontal and 2 nm vertical emittance, 20 mm rms bunch length and 2.6×10^{-3} rms energy spread. To accumulate this beam in PETRA IV a bunch rotation in the transfer line or an aperture sharing injection scheme is required [10]. Given that large bunch charges are not necessary for accumulation, an LPA injector could deliver beams of similar or better quality for the top up, removing the need for aperture sharing or bunch rotation. It is also expected to be significantly more power efficient, although this is beyond the scope of this article.

CONCLUSION

Using an X-band active energy compensation scheme one can achieve sub-permille levels of energy variation in LPA beams. The proposed design of a 6 GeV injector offers competitive beam parameters for a top-up operation, promising ~ 80 pC per shot in ~ 1 nm emittance under realistic jitters and pointing angle tolerances. For the PETRA IV ring such beam parameters translate into injection losses below 100 ppm in the injected beam, as confirmed by a realistic tracking study with conservative optics errors.

Compared to the conventional injector chain, the LPA injector is compact, requiring only about 50 m of space, while at the same time capable of delivering beams of similar of higher quality for the accumulation. The relatively small beam transverse emittance also removes the need to perform bunch rotation or aperture sharing in order to achieve high injection efficiency.

ACKNOWLEDGEMENTS

We thank W. Leemans and J. Osterhoff for motivating this research, M. Kirchen, S. Jalas, and A. Maier for supporting the numerical simulations and the design of the LPA stage, W. Wuensch and A. Grudiev (CERN) for a fruitful discussion on X-band cavity design, and H. Schlarb for the advice on laser-to-RF synchronization.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST029

REFERENCES

[1] T. Tajima and J. M. Dawson, "Laser electron accelerator," *Phys. Rev. Lett.*, vol. 43, pp. 267–270, 1979. doi:10.1103/PhysRevLett.43.267

[2] A. J. Gonsalves *et al.*, "Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide," *Phys. Rev. Lett.*, vol. 122, no. 8, p. 084801, 2019. doi:10.1103/PhysRevLett.122.084801

[3] C. G. R. Geddes *et al.*, "High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding," *Nature*, vol. 431, pp. 538–541, 2004. doi:10.1038/nature02900

[4] E. Brunetti *et al.*, "Low Emittance, High Brilliance Relativistic Electron Beams from a Laser-Plasma Accelerator," *Phys. Rev. Lett.*, vol. 105, p. 215007, 2010. doi:10.1103/PhysRevLett.105.215007

[5] A. R. Maier *et al.*, "Decoding Sources of Energy Variability in a Laser-Plasma Accelerator," *Phys. Rev. X*, vol. 10, no. 3, p. 031039, 2020. doi:10.1103/PhysRevX.10.031039

[6] A. Ferran Pousa *et al.*, "Energy Compression and Stabilization of Laser-Plasma Accelerators", submitted for publication. doi:10.48550/arXiv.2106.04177

[7] S. A. Antipov *et al.*, "Design of a prototype laser-plasma injector for an electron synchrotron," *Phys. Rev. Accel. Beams*, vol. 24, no. 11, p. 111301, 2021. doi:10.1103/PhysRevAccelBeams.24.111301

[8] N. Delbos *et al.*, "Lux – A laser–plasma driven undulator beamline," *Nucl. Instrum. Meth. A*, vol. 909, pp. 318–322, 2018. doi:10.1016/j.nima.2018.01.082

[9] C. G. Schroer *et al.*, "PETRA IV: the ultralow-emittance source project at DESY", *Journal of Synchrotron Radiation*, vol. 25 no. 5, pp. 1277–1290, 2018. doi:10.1107/S1600577518008858

[10] M. A. Jebramcik *et al.*, "Injection Design Options for the Low-Emittance PETRA IV Storage Ring", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper THPOPT043, this conference.

[11] S. Jalas *et al.*, "Bayesian Optimization of a Laser-Plasma Accelerator," *Phys. Rev. Lett.*, vol. 126, no. 10, p. 104801, 2021. doi:10.1103/PhysRevLett.126.104801

[12] R. Lehe, M. Kirchen, I. A. Andriyash, B. B. Godfrey, and J.-L. Vay, "A spectral, quasi-cylindrical and dispersion-free Particle-In-Cell algorithm," *Computer Physics Communications*, vol. 203, pp. 66–82, 2016. doi:10.1016/j.cpc.2016.02.007

[13] M. Kirchen *et al.* "Optimal Beam Loading in a Laser-Plasma Accelerator," *Phys. Rev. Lett.*, vol. 126, no. 17, p. 174801, 2021. doi:10.1103/PhysRevLett.126.174801

[14] W. Wuensch *et al.*, "XLS Deliverables D4.2:Design reportof the optimized RF units", XLS Deliverables, Mar. 2021.

[15] G. Le Bec *et al.*, "High gradient quadrupoles for low emittance storage rings," *Phys. Rev. Accel. Beams*, vol. 19, no. 5, p. 052401, 2016. doi:10.1103/PhysRevAccelBeams.19.052401

[16] I. Agapov, G. Geloni, S. Tomin, and I. Zagorodnov, "OCELOT: A software framework for synchrotron light source and FEL studies," *Nucl. Instrum. Meth. A*, vol. 768, pp. 151–156, 2014. doi:10.1016/j.nima.2014.09.057

[17] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source, IL, USA, LS-287, Sep. 2000.

[18] H. C. Chao, I. V. Agapov, and S. A. Antipov, "Design Considerations of a High Intensity Booster for PETRA IV", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1386–1389. doi:10.18429/JACoW-IPAC2021-TUPAB023