ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST041

PHYSICAL ASPECTS OF COLLINEAR LASER INJECTION AT SLAC FACET-II E-310: TROJAN HORSE EXPERIMENT

M.Yadav[1,2,3]*, B. Naranjo[1], C. Hansel[4], P. Manwani[1], J.B. Rosenzweig[1]
O. Apsimon[2,3], E. Kukstas[2,3], B. Hidding[5] and C. P. Welsch[2,3]
[1]University of California, Los Angeles, CA, USA
[2]University of Liverpool, Liverpool, L69 3BX, United Kingdom,
[3]Cockcroft Institute, Warrington, United Kingdom
[4]University of Colorado Boulder, USA, and
[5]University of Strathclyde, United Kingdom

ABSTRACT

We report on challenges and details of the E-310 experiment which aims to demonstrate low emittance beam production from a plasma photocathode using a collinear injection laser at FACET-II. We performed simulations of planned experiments using the Particle-in-Cell code OSIRIS and examined the mitigation of beam hosing and drive beam depletion. We simulated the generated X-ray betatron radiation and discuss planned radiation diagnostics for the experiment.

INTRODUCTION

The Facility for Advanced Experimental Tests II (FACET-II) [1] is a test facility at SLAC National Accelerator Laboratory primarily dedicated to research and development of advanced acceleration technologies. One of the experiments planned at FACET-II is the E-310, which aims to demonstrate the creation of ultra low emittance electron beams from a plasma photocathode. E-310 builds on the E-210 experiment at the original FACET facility which first demonstrated a plasma photocathode[2]. A Plasma photocathode works by mixing two species of gas inside a vacuum chamber: a low ionisation threshold (LIT) gas and a high ionisation threshold (HIT) gas. We plan to use hydrogen and helium, respectively. A laser pre-ionizes the LIT gas and forms a plasma channel through which the beam propagates, forming a blowout bubble[3]. The second laser is used to locally ionize the HIT gas within the blowout[4], which produces electrons in the bubble which are accelerated by the wake and form the witness beam. The E-210 experiment which demonstrated this principle but did not attempt to produce low emittance beams used to ionise a gas that has HIT. The laser is perpendicular to the beam propagation direction, while the planned E-310 experiment will use a collinear ionization laser. An overview on the underlying principles of the hybrid plasma wakefield acceleration scheme dubbed "Trojan Horse" acceleration is given. The concept of this experiment is based on laser-controlled release of electrons directly into a particle-beam-driven plasma blowout, paving the way for controlled, shapeable electron bunches with ultralow emittance and ultrahigh brightness. In collinear Trojan Horse, it is usually essential to have a delay between the electron beam and the injection laser to achieve a stable witness beam using a plasma photo cathode technique. The generated helium electrons would be affected by the transverse electric field of the drive beam, which imprints a substantial transverse momentum that either prevents trapping altogether, or is detrimental to the emittance. One of the benefits of Trojan horse injection is the ability to adjust the injection position with respect to the wakefields. This allows us to inject at the zero-crossing of the accelerating wakefield in order to minimise interaction with the transverse wakefield.

To achieve the research goals of FACET-II, sophisticated beam diagnostics are required. The utility of betatron radiation diagnostics has already been proven in inverse Compton scattering experiments [5]. The upcoming set of experiments at FACET-II requires simulation models and instruments for recovering single-shot double-differential angular-energy spectra of emitted photons covering a wide energy range, extending from tens of keV through to ten MeV, with an angular resolution on the order of 100 μrad. These spectra provide a unique window into the high field generation, beam-plasma and laser-plasma interactions.

PARTICLE-IN-CELL SIMULATIONS

Using the fully relativistic 3D particle-in-cell (PIC) simulation code OSIRIS [6], we ran simulations of the E-310 experiment. We ran these simulations using the parameters we expect to achieve at FACET-II. These parameters are summarized in Table 1. The HIT ionization laser focus was chosen to be in the bubble at a distance $6k_p^{-1}$ behind the drive beam which is the location of the zero crossing of the longitudinal field E_z. The cell size used was $5\,\mathrm{m} \times 5\,\mathrm{m} \times 2.5\,\mathrm{m}$ and 8 macro-particles per cell were used to model the drive beam and plasma. All simulations use a ponderomotive guiding center (PGC), in which the particles are pushed through the laser ponderomotive force and through the self consistent plasma fields.

Plots of the pre-ionized (hydrogen) plasma electron density and the density of electrons generated from the plasma photocathode are shown in Fig. 1. The plasma bubble as well as the generated witness beam are both clearly visible. The longitudinal electric field inside the bubble is shown in Fig. 2. This shows the peak accelerating field in the bubble of

* monika.yadav@liverpool.ac.uk

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST041

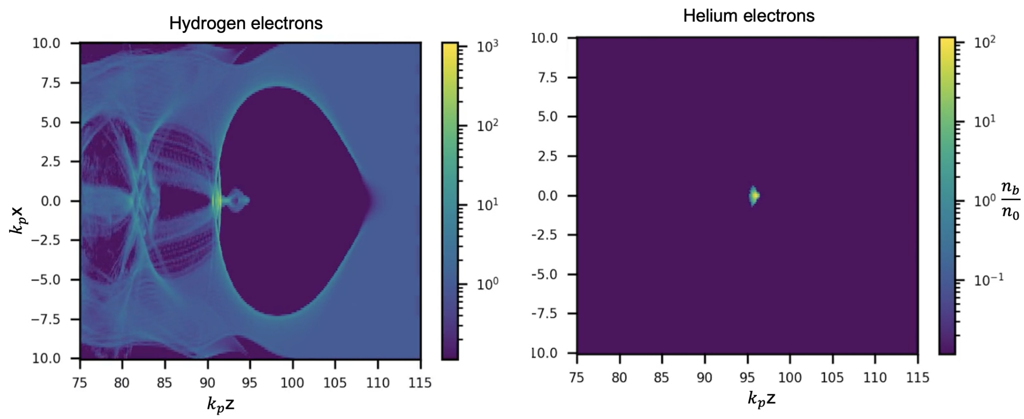


Figure 1: Plots of the pre-ionized (hydrogen) plasma electron density and the density of electrons generated from the plasma photocathode are shown. The laser pulse interacts with the beam radial fields on both sides of the mid-plane. The blowout on one side of the mid-plane are shown here. The generated helium electrons due to ponderomotive guided ionisation(pgc) algorithm is shown in right.

Table 1: Laser and Electron Beam Parameters for the E310 Experiment at FACET-II

Parameter	Value	Unit
Plasma		
LIT Species	H	-
HIT Species	He	-
n_0 (Same for H and He)	1.79×10^{16}	cm^{-3}
Plasma Skin Depth (k_p^{-1})	39.79	m
HIT Ionization Laser		
Vector Potential Amplitude	0.02	$m_e c/e$
Wavelength	800	nm
Pulse length	50	fs
Waist	7	m
Drive Beam		
Energy	10	GeV
Charge	−1.5	nC
Peak Number Density	52	n_0
Normalized Emittance	3.5	m
Spot Size in Plasma	4.5	m
Beam σ_z	12.15	m

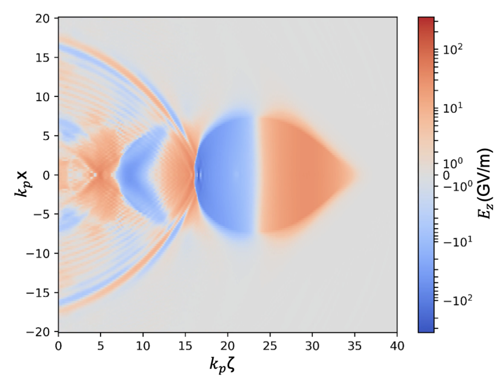


Figure 2: Longitudinal electric field inside the bubble. The peak accelerating field in the bubble is 40 GVm^{-1}. The superposition of the laser fields with the radial fields of the beams causes the electric field to be greater than the ionization potential of the high ionization threshold species and locally ionizes it.

40 GVm^{-1}. The magnitude of the radial fields are dependent on the beam and are highly sensitive to betatron oscillations and current fluctuations. Injection of the witness beam using the radial fields produced by the drive beam without an ionization laser would therefore not be easily controlled. The electric fields at the wake vertex and drive should be less than the ionization threshold of the HIT gas to ensure that there is no uncontrolled injection which can degrade the beam quality. A plot of the longitudinal phase space of the injected witness beam is shown in Fig. 3.

BETATRON RADIATION ANALYSIS

Betatron radiation will be used to provide diagnostics for this experiment, as well as other plasma acceleration experiments at FACET-II. At highly relativistic energies the betatron radiation is highly collimated and emitted within a cone of angle $\theta \approx K/\gamma$ in the direction of motion. Betatron radiation schemes are highly attractive since it is easy to produce and control betatron oscillations by releasing the HIT electrons off axis. The stability and quality of the witness beam generated depends on the plasma channel width, which in our case is 400 m.The longitudinal phase space of the witness beam is shown in Fig. 3.

Because the wavelength of the betatron radiation is much smaller than the scale of the PIC simulation, it is not possible to simulate the generation of this radiation in the PIC code, thus the radiation was computed in post-processing. After running the PIC simulations we saved the particle trajectories and imported them into the Liénard–Wiechert code discussed in [7, 8]. Rather than computing radiation from every particle trajectory output by OSIRIS, a subset of those trajectories was randomly sampled and the result was scaled

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST041

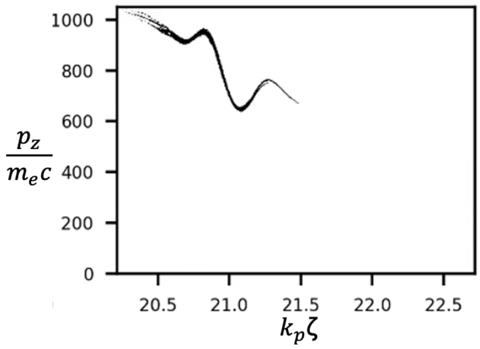


Figure 3: Longitudinal phase space of the injected witness beam. Final witness beam phase space with $z = 21$ representing the witness beam location.

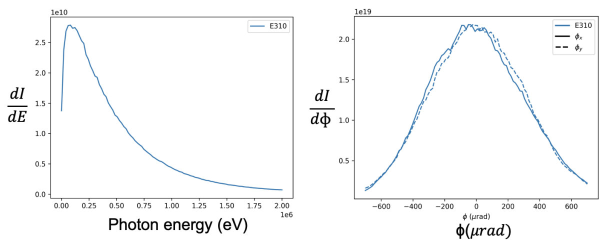


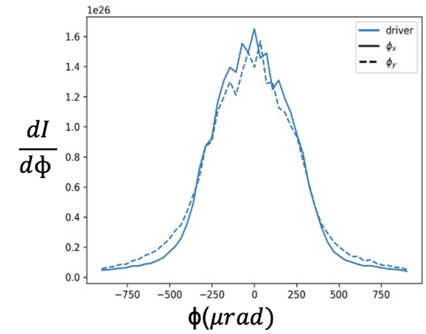
Figure 4: Left: Betatron radiation spectrum computed using Liénard–Wiechert and QuickPIC code. Right: 1D distribution of E310 experiment at FACET-II.

to the number of physical particles. This was done properly to ensure correctness despite particles in OSIRIS having different weights.

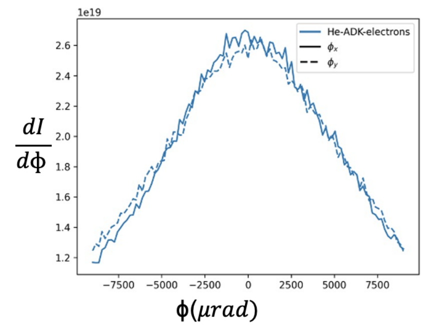
The spectrum of radiation produced by the drive beam is shown in Fig. 4. A key aim is to optimize bunch compactness, charge, and emittance, while the energy spread of the electron bunch driver remains almost negligible. The 1D angular distributions of the drive beam is shown in Fig. 5a and for witness beams in Fig. 5b. Here the angular divergence of the witness beam radiation is much larger than that of the drive beam radiation as the angle of the radiation cone scales as $\theta \sim \gamma^{-1/2}$. We also notice that the centroid in Fig. 5c of the drive beam which is initially on the axis begins to oscillate due to the hosing instability. The drive beam energy reduces from 10 GeV to 8.4 GeV in the 10 cm of propagation length in the plasma. The final emittance and energy of the generated beam are 2 mm − rad and 500 MeV respectively.

CONCLUSION

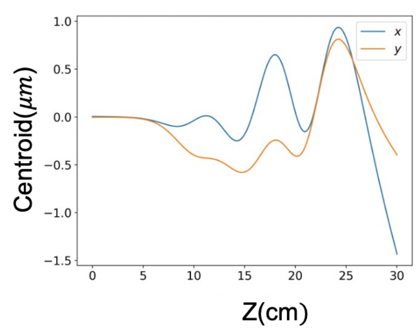
Above we have discussed betatron radiation diagnostics modeling for FACET-II Trojan Horse experiment and generation of witness beam using photocathode. We described the design of a PIC+LW code for betatron radiation modeling. We presented simulations of the betatron radiation for FACET-II relevant parameters including E-310. Further exploration and optimization of the parameter space would require more intensive simulations with much higher



(a)



(b)



(c)

Figure 5: Betatron radiation 1d distribution computed using Osiris and Liénard– Wiechert PIC code for **(a):** driver beam and **(b):** witness beam, **(c):** centroid of drive beam.

resolution and the numerical effects introduced by the asymmetrical nature of the grids need to be further characterized.

ACKNOWLEDGEMENT

This work was performed with support of the US Department of Energy, Division of High Energy Physics, under Contract No. DE-SC0009914. This work was performed with support the STFC Liverpool Centre for Doctoral Training on Data Intensive Science (LIV.DAT) under grant agreement ST/P006752/1.

REFERENCES

[1] C. Joshi *et al.*, "Plasma wakefield acceleration experiments at FACET II," *Plasma Physics and Controlled Fusion*, vol. 60, no. 3, p. 034 001, 2018, doi:10.1088/1361-6587/aaa2e3

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST041

[2] A. Deng *et al.*, "Generation and acceleration of electron bunches from a plasma photocathode," *Nature Physics*, vol. 15, no. 11, pp. 1156–1160, 2019, doi:10.1038/s41567-019-0610-9

[3] J. B. Rosenzweig, B. Breizman, T. Katsouleas, and J. J. Su, "Acceleration and focusing of electrons in two-dimensional nonlinear plasma wake fields," *Phys. Rev. A*, vol. 44, R6189–R6192, 10 1991, doi:10.1103/PhysRevA.44.R6189

[4] A. Habib *et al.*, "Ultrahigh brightness beams from plasma photoguns," English, WorkingPaper, 2021.

[5] Y. Sakai *et al.*, "Single shot, double differential spectral measurements of inverse compton scattering in the nonlinear regime," *Phys. Rev. Accel. Beams*, vol. 20, p. 060 701, 6 2017, doi:10.1103/PhysRevAccelBeams.20.060701

[6] R. A. Fonseca *et al.*, "Osiris: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators," in *Computational Science — ICCS 2002*, 2002, pp. 342–351.

[7] M. Yadav *et al.*, *Modeling betatron radiation diagnostics for e-310 – trojan horse*, 2021, doi:10.48550/ARXIV.2107.00483

[8] M. Yadav *et al.*, "Liénard-Wiechert Numerical Radiation Modeling for Plasma Acceleration Experiments at FACET-II," in *Proc. IPAC'21*, Campinas, SP, Brazil, 2021, paper MOPAB148, pp. 517–520, doi:10.18429/JACoW-IPAC2021-MOPAB148