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SIMULATION STUDY OF BEAM-DRIVEN PLASMA WAKEFIELD EXPERIMENTS ON CLARA

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Abstract

The Compact Linear Accelerator for Research and Applications (CLARA) is an electron test facility capable of delivering tuneable 250 MeV electron beams with up to 250 pC charge to the Full Energy Beam Exploitation (FEBE) experimental area . In this study, we investigate the feasibility of conducting beam-driven plasma wakefield acceleration (PWFA) experiments using the CLARA beam and experimental area. We present simulations of various potential experiments, considering the baseline and R&D beam parameters expected to be delivered to the FEBE experimental chambers. Our findings highlight the potential for CLARA to support advanced PWFA research, with detailed analysis of beam dynamics and experimental configurations.

INTRODUCTION

Beam-driven plasma wakefield acceleration (PWFA) experiments are ongoing at multiple accelerator facilities worldwide, with developments towards applications of PWFA a key focus of international accelerator physics strategies [1, 2]. Accelerator test facilities have the opportunity to support PWFA projects and related technologies, using beams delivered with parameters matching those required for such applications.

The Compact Linear Accelerator for Research and Applications (CLARA) at Daresbury Laboratory is a 250 MeV electron accelerator, built with the goal of researching accelerator technologies, including novel acceleration techniques, FEL related technologies, and accelerator related topics such as medical and industrial applications [3]. CLARA will deliver electron beams with up to 250 pC charge to the Full-Energy Beam Exploitation (FEBE) hutch, with the facility layout shown in Fig. 1. FEBE is designed to house user experiments, with two experimental chambers and the capability to characterise output beam energies up to 2 GeV [4]. FEBE includes a 100 TW laser for use in novel acceleration experiments alongside the electron beam.

In these proceedings we present simulations of PWFA in FEBE, using start-to-end simulations of the CLARA beamline. We will present a potential experimental layout, using movable permanent quadrupole magnets for transverse beam matching into a plasma target cell. These simulated were performed to evaluate potential PWFA regimes that may be possible for user experiments; so we have considered both linear and non-linear plasma field excitation to provide insights on a wide range of potential experiments. Plasma and beam parameters have been considered in the context of fully depleting the 250 MeV CLARA beam in a 30 mm plasma cell.

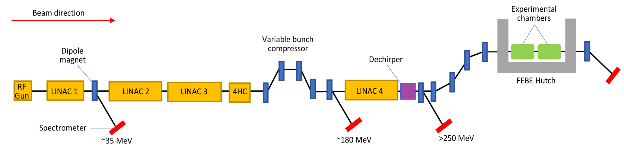

Figure 1: Schematic of the CLARA beamline, including the FEBE hutch which include the 100 TW laser system [4].

CLARA FULL-ENERGY BEAM EXPLOITATION

FEBE is designed for experimental uses of the CLARA beam and contains two experimental chambers (FEC1 and FEC2) [4]. Each chamber is 1.84 m long, allowing for the installation of multiple pieces of experimental equipment in both chambers. It is envisioned that a range of diagnostics will be available for use in the second chamber (FEC2), with options including a permanent magnet spectrometer capable of measuring electron beam energies up to 2 GeV and a passive dielectric wakefield streaker for longitudinal bunch diagnostics [5]. The beam parameters designed to be delivered to FEBE are listed in [4], with baseline parameters expected for first user experiments and R&D parameters requiring machine development.

Simulations of the CLARA beamline have been made using SimFrame, a start-to-end simulation package for CLARA, using ASTRA and Elegant [6]. CLARA simulations end at the start of FEC1, and output beam files are used as inputs for plasma experiment simulations. CLARA simulations have been conducted to optimise sets of beam parameters, it is not possible to achieve the minimum/maximum designed parameters simultaneously. For example, minimising bunch length and beam emittance is achieved at lower bunch charges rather than the 250 pC possible from the gun.

PWFA EXPERIMENT SIMULATIONS

CLARA simulations have been conducted with a focal point at the centre of FEC1, where the plasma cell is centred. A limiting factor for minimal beam sizes is the 0.92 m between the start of FEC1 and the centre. To maintain beam quality through a plasma cell, beam divergence should be cancelled by focusing forces within the plasma bubble. For this matching, the beam size should be approximately

$$\sigma_r \simeq \epsilon_n \sqrt{\frac{2\epsilon_0 m_e c^2}{\gamma n_e e^2}}, \quad (1)$$

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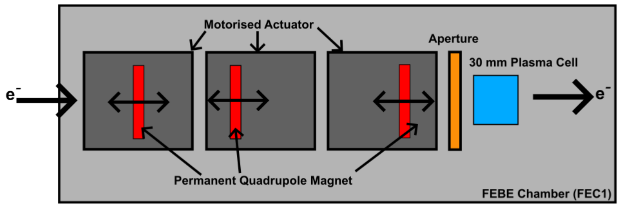

Figure 2: Schematic of the FEC1 chamber for PWFA simulations with a movable permanent quadrupole triplet, aperture, and 30 mm plasma cell.

where ϵ_n is the normalised emittance n_e is the plasma density and γ is the beam Lorentz factor [7]. For typical plasma densities, this results in micron or sub-micron transverse beam size requirements [8]. To achieve micron-scale beam sizes, a series of permanent quadrupole magnets mounted within FEC1 are considered, shown in Fig. 2. With quadrupoles on longitudinal translation stages, the beam optics into the plasma can be optimised. An aperture at the plasma cell entrance can further reduce the beam size if required.

Simulations within the plasma cell are performed with Wake-T, a quasi-static 2D plasma simulation package [9]. In all simulations the plasma cell length is 30 mm. The plasma density increases and decreases over 5 mm at the start/end of the cell, with a minimum plasma density 0.5× the peak density. Given these simulations are intended to demonstrate the feasibility of PWFA simulations, and not intended to give expected results or benchmark experimental results, a quasi-static field solver is considered suitably detailed. Simulated beams after the plasma cell could be reintroduced into SimFrame for complete start-to-end simulated PWFA experiments on CLARA.

Linear Field Excitation

Exciting a linear field requires a drive bunch density lower than the plasma density; using lower plasma densities relaxes the transverse matching requirements, allowing for experiments studying drive beam quality preservation. A CLARA simulation with sub-micron normalised emittance in both transverse planes, and approximate transverse symmetry, was chosen. The simulated bunch/plasma parameters are listed in Table 1. Setting the quadrupole strengths in Fig. 2 to $kl = (0.13, -0.185, 0.17)$ m^{-1} at (0.024, 0.290, 0.688) m

Table 1: Beam Parameters for the Setups Used for Linear and Non-linear Field PWFA Simulations

Parameter	**Maximum Linear Field**	**Non-Linear Field**
Bunch Charge [pC]	20	250
RMS Bunch Length [μm]	2.2	7.2
$\epsilon_{x,n}$ [mm mrad]	0.79	6.31
$\epsilon_{y,n}$ [mm mrad]	0.29	0.77
Plasma Density [cm^{-3}]	2×10^{18}	2.5×10^{17}
$\sigma_{x,y}$, FEC1 Entrance [μm]	(149.7, 37.8)	(525.2, 58.0)

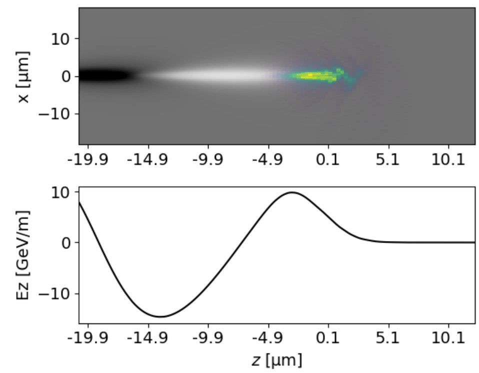

Figure 3: Plasma density (colour = beam density) and longitudinal field for the linear plasma field.

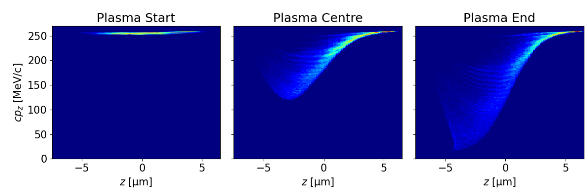

Figure 4: Longitudinal phase space, at the beginning, centre, and end of the plasma cell for the linear plasma field.

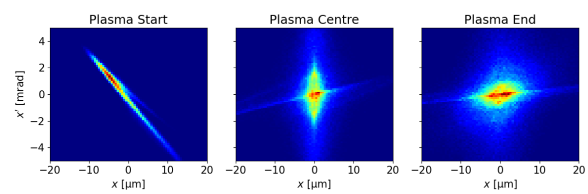

Figure 5: Horizontal phase space, at the beginning, centre, and end of the plasma cell for the linear plasma field.

from the FEC1 entrance, σ_x and σ_y are reduced to 5.06 and 6.14 μm.

The plasma density and longitudinal field excited are shown in Fig. 3. A linear plasma field is observed, with maximum decelerating and accelerating fields of 9.8 GV/m and 14.6 GV/m respectively. The longitudinal phase space (LPS) and horizontal phase space (HPS) are shown at the start (after the aperture), centre (after 15 mm of propagation), and exit of the plasma cell in Figs. 4 and 5. The tail of the bunch is fully depleted at the end of the 30 mm plasma. From the HPS, we can see the region of the beam within the plasma bubble remains contained and focused. Using a beam region defining 90% of the beam (i.e. excluding the visible halo), geometric emittance is maintained within 5%.

Non-Linear Field Excitation

Non-linear plasma fields require a beam density much greater than the plasma density. Using shorter bunches and higher plasma densities, the matched transverse beams sizes are too small to be feasible at FEBE. As such, a longer bunch and lower plasma density has been chosen, with

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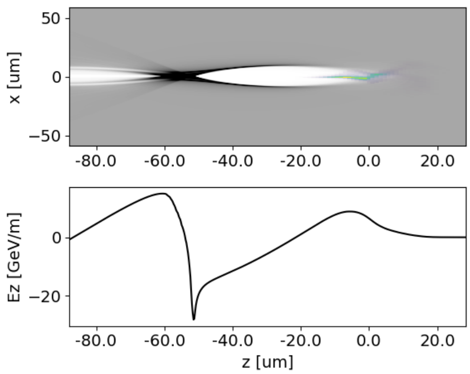

Figure 6: Plasma density (colour = beam density) and longitudinal field for the non-linear plasma field.

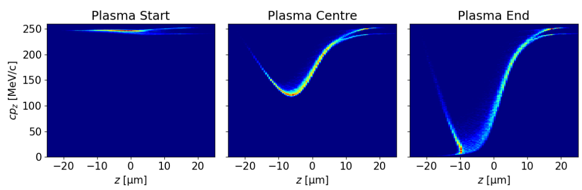

Figure 7: Longitudinal phase space, at the beginning, centre, and end of the plasma cell for the non-linear plasma field.

bunch/plasma parameters listed in Table 1. With these parameters, the transverse matching requirement (from Eqn. 1) is ~1 μm. Using a quadrupole triplet it is not possible to achieve this in both transverse planes; it is instead better to target a larger symmetrical beam size and then use an aperture. Using the setup in Fig. 2, quadrupoles with $kl = (0.38, -0.24, 0.14)$ m^{-1} at (0.03, 0.40, 0.63) m from the FEC1 entrance, σ_x and σ_y at the plasma cell are 3.73 and 13.63 μm respectively. A 12 μm diameter aperture reduces these to 2.79 and 3.31 μm, with 88 pC transported.

The plasma density and longitudinal field are shown in Fig. 6. A non-linear field is excited but the plasma electron density is non-zero in the bubble (i.e no blowout). The LPS and HPS are shown in Figs. 7 and 8, with each displayed at the entrance, centre, and exit of the plasma cell. The bunch tail is depleted, with a small amount of the tail then re-accelerated after falling into the accelerating field. The looser transverse matching requirements—given the lower plasma density compared to the linear field case—result in a smaller beam halo developing, as less of the beam is outside the plasma bubble. Using a simulated beam before the tail is depleted (plasma centre after 15 mm propagation), the geometric emittance is preserved within 5%.

Blow-Out Plasma Bubble

As discussed above, it was not possible to produce a blown-out plasma bubble using beams simulated to FEBE. However, using a 6D Gaussian bunch with parameters given by statistical measurements of the same simulated bunch does produce a blow-out plasma bubble. A 88 pC bunch with those parameters (6D Gaussian with RMS $\sigma_{x,y,z}$ =

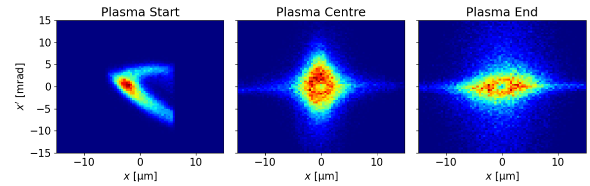

Figure 8: Horizontal phase space, at the beginning, centre, and end of the plasma cell for the non-linear plasma field case.

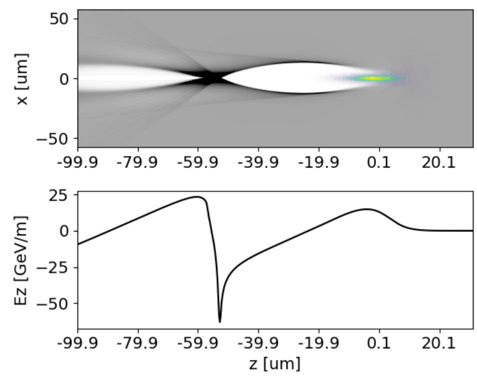

Figure 9: Plasma density (colour = beam density) and longitudinal field for the blow-out regime case.

$(2.8, 3.31, 7.2)$ μm and normalised x, y emittances 6.3 and 0.71 mm mrad), the plasma field excited is shown in Fig. 9. A plasma blow-out is observed with a field double that seen using the CLARA simulated beam. The difference between these results and those with the CLARA simulated beam demonstrate the need to consider the detailed bunch properties if considering experiments that require a plasma blow-out, rather than relying on statistical measurements such as RMS bunch sizes. Conclusions on whether experiments requiring a blow-out regime are feasible will require a full characterisation of the possible beam properties in FEBE, during beam commissioning, and comparison with simulations. Such experiments may require machine development and the delivery of the R&D parameters in [4].

CONCLUSIONS

Through simulations of CLARA into the FEBE experimental chambers, we have shown that it is feasible to excite linear and non-linear plasma fields using a permanent magnet triplet that would fit in the FEBE chamber before a plasma cell. We have shown that the tight transverse matching requirements of such schemes requires consideration of feasible beam setups and an accurate start-to-end simulation package for the accelerator. By using such setups, it is possible to design experiments with realistic expectations of the machine in mind, allowing for more complicated and detailed experiments of PWFA schemes.

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REFERENCES

[1] C. Adolphsen, D. Angal-Kalinin, T. Arndt, *et. al.*, "European Strategy for Particle Physics - Accelerator R&D Roadmap", *CERN Yellow Rep. Monogr.*, vol. 1, p. 1–270, 2022. doi:10.23731/CYRM-2022-001

[2] S. Gourlay, T. Raubenheimer, V. Shiltsev, *et. al.*, "Snowmass'21 Accelerator Frontier Report", *Contribution to Snowmass'21*, 2022. doi:10.48550/arXiv.2209.14136

[3] D. Angal-Kalinin, A.R. Bainbridge, A.D. Brynes, *et. al.*, "Design, specifications, and first beam measurements of the compact linear accelerator for research and applications front end", *Phys. Rev. Acc. Beams*, vol. 23, p. 044801, 2020. doi:10.1103/PhysRevAccelBeams.23.044801

[4] E.W. Snedden, D. Angal-Kalinin, A.R. Bainbridge, *et. al.*, "Specification and Design for Full Energy Beam Exploitation of the Compact Linear Accelerator for Research and Applications", *Phys. Rev. Acc. Beams*, vol. 27, p. 041602, 2024. doi:10.1103/PhysRevAccelBeams.27.041602

[5] T.H. Pacey, D. Angal-Kalinin, A.R. Bainbridge, *et. al.*, "Development of a 6D Electron Beam Diagnostics Suite for Novel Acceleration Experiments at FEBE on CLARA", in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 1–5. doi:10.18429/JACoW-IBIC2022-MO1C3

[6] D.J. Dunning and H.M. Castañeda Cortés, J.K. Jones, and N. Thompson, "Multi-Objective FEL Design Optimisation Using Genetic Algorithms", *In Proc. FEL'19*, Hamburg, Germany, pp. 711–714, 2019. doi:10.18429/JACoW-FEL2019-THP065

[7] E. Esarey, P. Sprangle, J. Krall and A. Ting, "Overview of plasma-based accelerator concepts", *IEEE Trans. Plasma Science*, vol. 24, 2, pp. 252–288, 1996. doi:10.1109/27.509991

[8] C. A. Lindstrøm, S. Corde, *et. al.*, "Beam-driven plasma wakefield acceleration", *arXiv:2504.05558, 2025*. doi:10.48550/arXiv:2504.05558

[9] A. Ferran Pousa, R. Assmann, and A. Martinez de la Ossa, "Wake-T: a fast particle tracking code for plasma-based accelerators", *J. Phys.: Conf. Ser.*, vol. 1350, p. 012056, 2019. doi:10.1088/1742-6596/1350/1/012056