FEASIBILITY STUDY OF PLASMA WAKEFIELD ACCELERATION AT THE CLARA FRONT END FACILITY

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Abstract

Plasma wakefield acceleration has been proposed at the CLARA Front End (FE) facility at Daresbury Laboratory. The initial phase of the experiment will acceleration of the tail of a single electron bunch, and the follow-up experiment will study preserving a high quality beam based on a two-bunch acceleration scenario. In this paper, a concept for the initial experiment is outlined and detailed simulation results are presented.

INTRODUCTION

Plasma wakefield acceleration experiments have demonstrated extremely high accelerating gradients, orders of magnitude greater than can be achieved with radio frequency metallic structures [1, 2]. However, a major challenge in developing a practical plasma-based accelerator (either beam-driven or laser-driven) is preserving beam quality. An electron beam driven plasma wakefield accelerator experiment at Daresbury Laboratory has been proposed initially using the CLARA-FE beam with an energy of approximately 45 MeV, with the potential to use a future 250 MeV CLARA [3]. Although the relatively low energy of the beam limits the accelerating gradient that can be achieved over long distances, such an experiment would provide a facility for demonstrating techniques in plasma wakefield acceleration that could be applied to higher energy accelerators in the future.

PROPOSED EXPERIMENT

The initial stage of the proposed experiment will be to demonstrate plasma wakefield acceleration of the tail of the electron bunch using the head of the bunch. This will allow for demonstration of the plasma cell and testing of diagnostics. Figure 1 shows an initial design for the discharge cell. The overall length of the cell is approximately 30 cm including a 10 cm plasma region. Details of the proposed beamline and particle dynamics are available elsewhere in these proceedings [4].

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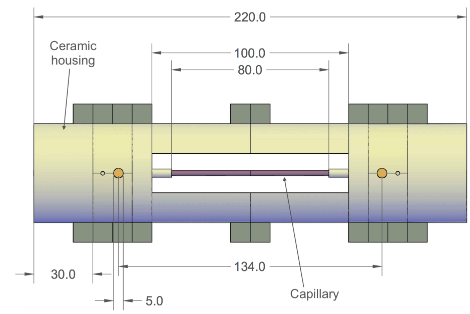

Figure 1: Initial design of a plasma discharge cell for PWFA experiments with CLARA-FE. Dimensions are in mm.

Table 1: Modelled Beam Parameters in VELA User Area 1 with CLARA-FE

Charge Q (pC)	250
Energy E (MeV)	55
Population N (10^6)	1563
RMS bunch length σ_z (µm/ps)	270/0.9
RMS bunch size σ_x (µm)	100
RMS bunch size σ_y (µm)	100
Norm. emittance x/y (µm)	15/6
Peak density n_b (m^{-3})	3.7×10^{19}

EFFECT OF BEAM AND PLASMA PARAMETERS

In order to accelerate the tail of the bunch, the bunch length must be long enough such that the tail is in an accelerating region of the plasma wakefield. This is in contention with the requirement for the bunch to be short compared to the plasma wavelength λ_p to achieve a large amplitude wakefield. A large amplitude response from the plasma requires $k_p\sigma_z \leq 1$, where k_p is the plasma wavenumber, corresponding to $\sigma_z \leq \lambda_p/2\pi$. A bunch length which is approximately one third of the plasma wavelength is a reasonable compromise between accelerating gradient and placing the bunch tail in the accelerating region. For a Gaussian bunch this gives a density in the accelerating region of $\rho(1.5\sigma_z) = 0.1\rho_0$, where ρ_0 is the peak density of the bunch. The beam energy must be high enough that the decelerated particles near the head of the bunch remain highly relativistic, but otherwise dependence of the wakefield on the initial beam energy is not expected [5].

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Two-dimensional PIC simulations were carried out using VSim [6] to investigate the effect of the bunch energy, plasma density and bunch transverse size on the resultant bunch energy distribution. A Gaussian bunch truncated at 5σ with the parameters given in Table 1 [7] was used as the baseline in the simulations. This distribution was then modified as required for parameter scans. The maximum energy was reduced to 45 MeV due to doubts that 55 MeV could be achieved at the experimental station.

Figure 2 shows the dependence on initial beam energy of the average accelerating gradient over the 10 cm plasma seen by particles in the tail of the bunch. The gradient is reduced for low initial energies, as the part of the bunch in the decelerating region lose energy. Figure 3a shows the longitudinal phase space for a low energy bunch. The centre of the bunch (pink region) has been decelerated to non-highly-relativistic speed and has been overtaken by the tail of the bunch, which is then decelerated in turn. This limits the energy gain of the bunch tail even though the initial accelerating gradient is similar to the higher energy cases. For a higher energy bunch (Fig. 3b), the centre of the bunch loses energy to the tail but retains its near-c velocity.

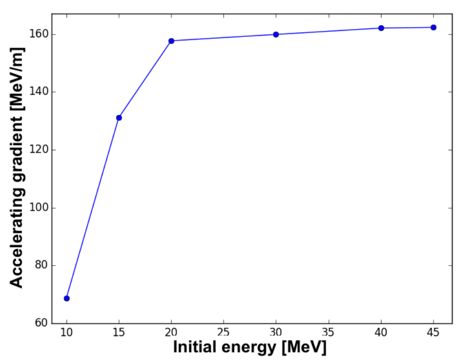
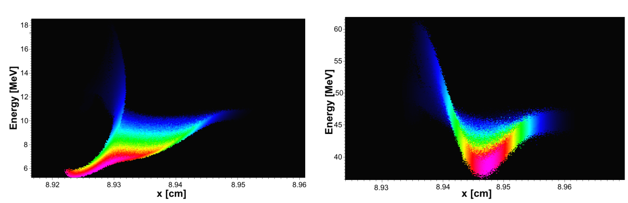


Figure 2: Dependence of average accelerating gradient for particles in the tail of the bunch on initial bunch energy.



(a) 10 MeV (b) 45 MeV

Figure 3: 2D histogram of the longitudinal phase space after 9 cm for bunches with initial energies of 10 MeV and 45 MeV. The colour scale corresponds to the sum of the weights of the macroparticles in the histogram bin.

Figure 4 shows the effect of plasma density on the accelerating gradient seen by the tail of the bunch. The accelerating gradient seen by particles in the tail of the bunch was found to increase linearly as the plasma density was reduced. As the plasma density decreases $k_p\sigma_z$ reduces towards 1 and hence the accelerating field increases. However, if the plasma density is too low the peak accelerating region will be too far behind the bunch centre and little charge will be present. An intermediate plasma density is preferable to accelerate a significant quantity of charge at a reasonable gradient.

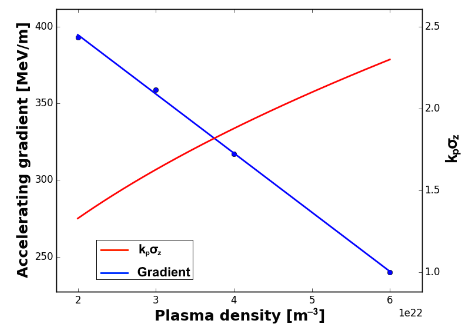


Figure 4: Dependence of average accelerating gradient for particles in the tail of the bunch on plasma density, for a bunch radius of 50 μm. The variation of the product $k_p\sigma_z$ is also shown, and the gradient plot includes a least-squares fit to a linear function.

Figure 5 shows the effect on the accelerating gradient of the bunch radius and thus density. Much higher accelerating gradients can be achieved with higher density bunches even while the length remains constant. This gives a motivation in further refinement of the design to optimize for bunch radius in preference to bunch length for the purposes of this experiment. However, future experiments are likely to benefit from shorter bunches so flexible bunch parameters would be most desirable.

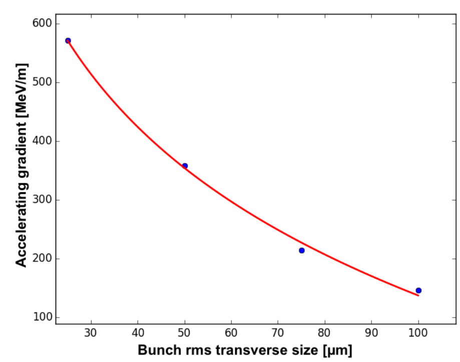
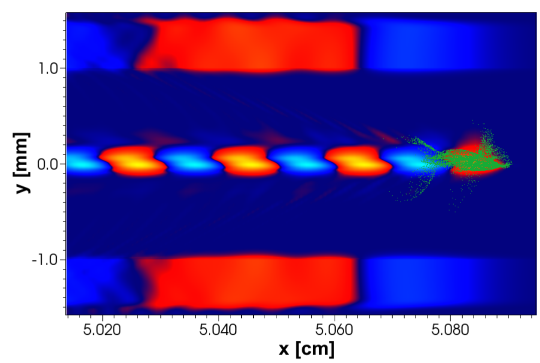


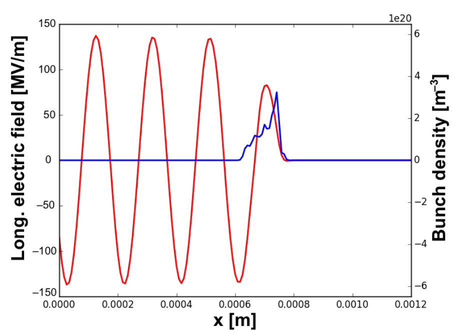
Figure 5: Dependence of average accelerating gradient for particles in the tail of the bunch on bunch radius, for a plasma density of 3×10^{22} m^{-3}. The red line shows a least-squares fit to $\log(\text{const.}/\sigma_r)$, the expected relation from the linear theory for a cigar-shaped bunch [8]

SIMULATIONS WITH REALISTIC NON-GAUSSIAN BUNCH

In order to obtain a more accurate prediction of the performance of the proposed experiment, PIC simulations were also carried out using a bunch distribution generated by tracking the bunch through the proposed beamline using ASTRA [9]. Compared to the Gaussian bunch, the simulated bunch is closer to a pancake than a cigar shape, and is radially asymmetric. It also has a substantial energy chirp, which while it is not expected to have any impact on the plasma wakefield it would have to be taken into account in measurements of the final beam energy especially if the plasma is short and the energy gain correspondingly small.



(a) Pseudocolour plot of longitudinal electric field (red/blue) and bunch macroparticles (green).



(b) Lineout along x-axis of bunch density (blue) and longitudinal electric field (red).

Figure 6: Plots showing electric field and bunch for a realistic CLARA-FE bunch projected into 2D, after a propagation distance of 5.08 cm. The direction of propagation is to the right for both sub-figures.

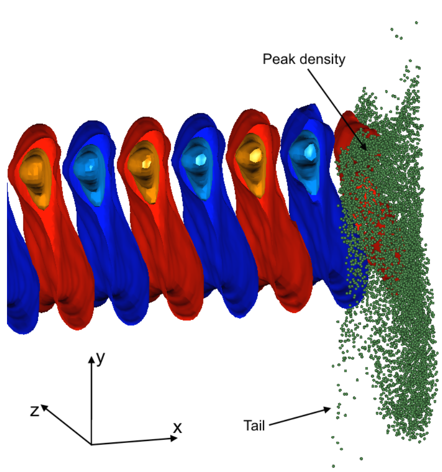


Figure 7: Isosurface plot of longitudinal electric field and bunch macroparticles for 3D simulation of a realistic CLARA-FE bunch. The isosurfaces are clipped in the x-y plane for visibility. The longitudinal coordinate is x.

For 2D simulations, the 3D bunch distribution from ASTRA was projected to 2D. The total number of macroparticles was 10000, and the macroparticle weight was scaled by a factor of $\sqrt{2\pi}\,\sigma_r$ in the 2D case to obtain the correct charge density. The reliability of 2D simulations is limited due to the asymmetric shape of the bunches produced by particle tracking, so 3D simulations were carried out to validate the 2D results. Figure 6 shows the longitudinal electric field and macroparticle distribution for a realistic bunch in 2D. Figure 7 shows a similar plot in 3D, with isosurfaces for the electric field. The difference in the bunch distribution is apparent, notably that in 3D the tail of the bunch is not directly behind the region of highest density, and that the transverse shape of the wakefield isosurfaces is different to the equivalent contours in 2D. The energy gain of the bunch tail in 2D corresponds to a gradient of 105 MV/m whereas in 3D the gradient is 147 MV/m.

CONCLUSION AND OUTLOOK

Simulations show that plasma wakefield acceleration showing a significant energy gain over a 10 cm plasma length is viable using the beam from the CLARA Front End accelerator. 2D and 3D PIC simulations show that a moderate accelerating gradient of more than 100 MV/m can be achieved, and are in reasonable agreement with each other. Further 3D simulations will be required to obtain reliable results as the bunch parameters at the experimental station are refined. Initial experiments would aim to demonstrate acceleration of the tail of a single bunch with an energy gain of approximately 10 MeV over 10 cm. In the longer term experiments will be planned to demonstrate two-bunch acceleration and will aim to use the facility to obtain a high quality beam from a plasma accelerator.

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