PLASMA WAKEFIELD ACCELERATION AT CLARA PARS

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Abstract

PARS is a proposed Plasma Accelerator Research Station using the planned CLARA (Compact Linear Accelerator for Research and Applications) electron linear accelerator at Daresbury Laboratory in the UK. In this paper, two-dimensional particle-in-cell simulations based on realistic CLARA beam parameters are presented. The results show that an accelerating gradient of 2.0 GV/m can be achieved over an accelerating length of at least 13 cm. Preliminary simulation results for a two bunch scheme show an energy gain of 70% over a length of 13 cm, giving an average accelerating gradient of 1.2 GeV/m.

INTRODUCTION

Conventional particle accelerators based on radio frequency (RF) technology are approaching the limits of practicality due to the enormous size and cost of higher energy machines. Plasma wakefield accelerators (PWFAs) offer a potential solution to this problem, as the higher accelerating gradient achievable using a plasma allows an accelerator to be much smaller and hence lower in capital cost than an RF accelerator of equivalent energy.

PARS (Plasma Accelerator Research Station) is a proposed experiment that will take advantage of the properties of the CLARA free electron laser (FEL) test beam at Daresbury Laboratory in the UK to study PWFA using a highly relativistic electron beam [1]. This paper presents results of initial particle-in-cell (PIC) simulations of the plasma wakefield that can be driven by the CLARA beam that were carried out using the PIC simulation package VSim from Tech-X Corporation [2].

CLARA BEAM PROPERTIES

As a test facility for FEL technology, the properties of the CLARA beam will also make it an ideal accelerator for PWFA research. The linear theory of PWFA predicts that the amplitude of the wakefield driven by a particle bunch will be proportional to the bunch charge, and to the inverse of the square of the bunch length [3]. These requirements for a high accelerating gradient in PWFA are also desirable properties for an FEL particle beam. The key parameters in terms of PWFA for two of the different CLARA operating modes are shown in Table 1 [1,4]. The appropriate mode to use for PWFA depends on the accelerating field that can be achieved and the plasma parameters that would be required. If the accelerating field is too high, the bunch will lose its energy over a shorter plasma length than is desirable.

Table 1: CLARA Beam Parameters for Two Operating Modes

Mode	**Short**	**Ultra-short**
Energy E (MeV)	250	250
Charge Q (pC)	250	20-100
Population N (10^8)	16	1.25-6.25
RMS Length σ_z (µm)	75	< 7.5
RMS Radius σ_r (µm)	20	20-100
Density n_b (cm^{-3})	3.3×10^{15}	$2.7\text{-}13 \times 10^{15}$
Peak current (A)	400	~1000

LINEAR THEORY PREDICTIONS

The linear theory of plasma wakefield acceleration can be derived by considering the response of a cold plasma to a point charge moving at relativistic speed, and integrating the result over the charge distribution of interest, in this case a symmetric Gaussian distribution [5]. The linear theory is only valid for regimes in which particle trajectories do not cross [3]. However, if the drive bunch density n_b is in excess of the plasma density n_p, the plasma electrons will be completely expelled from the axis of the beam, and particle trajectories will cross as the electrons return to the axis. This is known as the blowout regime and has a number of desirable characteristics [6]. The nonlinear regime also applies to PWFA driven by a positively charged species, as in such a case electrons are initially sucked into the axis by the space charge force. Simulations have shown that while not strictly valid for $n_b > n_p$, the predictions of the linear theory hold reasonably well up to $n_b/n_p \approx 10$ [3]. A result of the linear theory is the engineering formula [3] (equation 1) for the maximum accelerating field due to a Gaussian charge distribution with a population of N particles of charge q, where e is the elementary charge:

$$E = (236\,\mathrm{MV/m})\,\frac{q}{e}\left(\frac{N}{4\times10^{10}}\right)\times\left(\frac{600\,\mu\mathrm{m}}{\sigma_z}\right)^2\times L \quad (1)$$

where L is a logarithmic term given by:

$$L = \ln\left(\sqrt{\frac{10^{16}\,\mathrm{cm}^{-3}}{n_b}}\,\frac{50\,\mu\mathrm{m}}{\sigma_r}\right) \quad (2)$$

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The logarithmic dependence on bunch radius and the additional square root dependence on bunch density, mean that the overall dependence of the wakefield on these factors is very weak. For PARS, the value of L is approximately 1.5. For the ultra-short pulse mode (see Table 1), the linear theory predicts a maximum accelerating field of 18.5 GV/m for the 100 pC bunch charge case. Such an accelerating gradient would exhaust the 250 MeV CLARA beam in 1.3 cm. Another choice is to use the short pulse mode, which the linear theory predicts would produce an accelerating field of 890 MV/m, leading to an accelerating length of approximately 0.3 m.

The transformer ratio R is defined as the ratio of the maximum accelerating field to the decelerating field, and determines the maximum energy gain for a witness bunch. The limit $R \leq 2$ applies for a symmetric bunch [7], while it can be exceeded for specially shaped bunches.

PARTICLE-IN-CELL SIMULATIONS

The commercial PIC simulation package VSim, incorporating the Vorpal simulation engine was used to carry out 2D PIC simulations of the CLARA beam propagating through a plasma. Smoothing of the beam and plasma currents using a 1-2-1 moving average digital filter was implemented, improving the stability of the simulation from a few cm propagation through the plasma up to around 13 cm. This was sufficient to demonstrate the generation and maintenance of a large amplitude wakefield. In order to demonstrate energy doubling of the CLARA beam at a gradient of 890 MV/m, stability would be required up to 28 cm.

Vorpal initially loads the particle bunch onto a regular grid as an even distribution of variable-weight macroparticles. This "quiet start" can help to eliminate numerical instabilities arising from fluctuations in density [8]. An electrostatic solve in the bunch rest frame is performed, and the resulting electric field is transformed to the "lab" or plasma rest frame to provide the bunch's initial electromagnetic field. Electromagnetic fields are then updated in a finite-difference time domain (FDTD) scheme using the Yee algorithm, with particles moved using a relativistic Boris push. The bunch is allowed to propagate forward into a cosine-flattop plasma density distribution, and the simulation runs for a specified number of time steps, with data dumped periodically to HDF5 files.

2D simulations of the CLARA short pulse mode bunch ($\sigma_z = 75$ µm, $\sigma_r = 20$ µm) propagating into a uniform plasma channel of density $1 \times 10^{15}\text{cm}^{-3}$ were carried out. A moving window of extent 1.2 mm longitudinally and 0.64 mm transversely was used. The grid resolution was 1.25 µm in both the longitudinal and transverse directions.

RESULTS OF PIC SIMULATIONS

An accelerating gradient of 2.0 GV/m was maintained over the 13 cm for which the results could be considered reliable. This contrasts with the linear theory prediction for these parameters of 890 MV/m. Figure 1 shows a pseudocolour plot of the longitudinal (x) component of the electric field. The longitudinal field is dominated by the contribution from the plasma, with the field due to the beam ~10^2 times smaller. A periodic wakefield structure can be seen, which was observed to have a phase velocity very close to the velocity of the moving window, c.

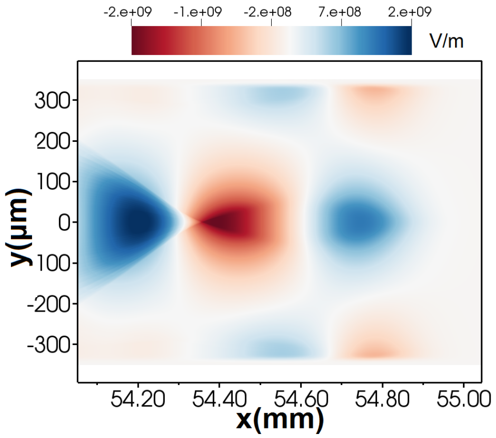

Figure 1: Longitudinal (x) component of the electric field after 5.5 cm propagation for the short pulse mode.

Figure 2 shows the longitudinal electric field on the x-axis. The non-sinusoidal nature of the wakefield indicates that the wakefield is somewhat nonlinear. The decelerating field at the drive bunch is 1.1 GV/m. In this case, the transformer ratio $R = \frac{2.0\text{ GV/m}}{1.1\text{ GV/m}} = 1.8$. The result $R \leq 2$ is as expected for a symmetric Gaussian bunch. A higher transformer ratio could be achieved using an asymmetric drive bunch [7], for example a saw-tooth shape or a sharp-cut half Gaussian.

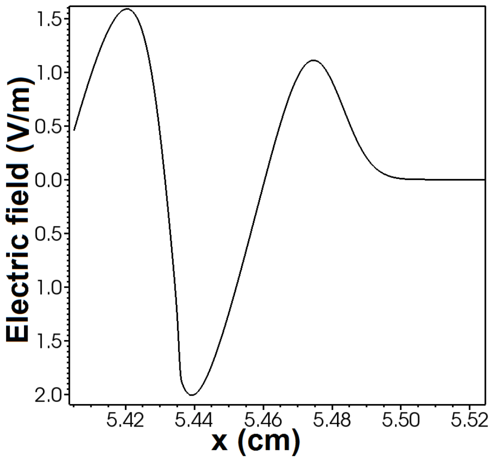

Figure 2: Longitudinal electric field on the x-axis after 5.5 cm propagation for the short pulse mode.

There is a large discrepancy between the predictions of the linear theory and the results obtained from simulation. This appears to be due to the transverse bunch compression that occurs when the bunch enters the plasma. Figure 3 shows the transverse electric field and the bunch charge density after the bunch has travelled 6 mm. The focusing

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field and the effect on the bunch can be seen. The decrease in bunch radius and increase in density cannot, however, account for the simulation result within the linear theory. The dependence of the wakefield on σ_r and n_b is given by equation 2. As n_b is proportional to $1/{\sigma_r}^2$, the change in n_b and σ_r cancel each other out. The mismatch between simulation and theory is instead likely down to the increase in n_b compared to n_p, going beyond the limit $n_b/n_p \approx 10$ for which the predictions of the linear theory are expected to be followed.

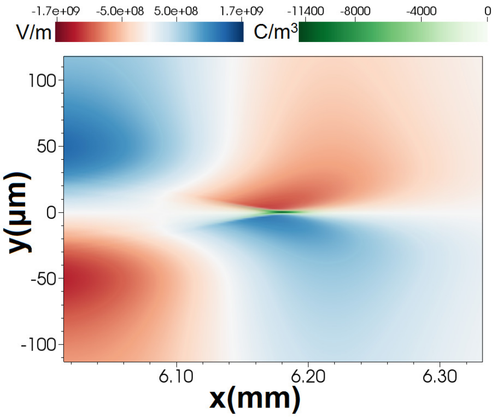

Figure 3: Overlay of the bunch charge density on to the transverse electric field after 6 mm propagation for the short pulse mode.

Preliminary simulations were carried out for a two-bunch scheme, in which the bunch distribution was modified to a bi-Gaussian. The drive bunch was the same as used in the single-bunch simulations. The witness bunch was placed at half the plasma wavelength behind the drive bunch and had a charge of 125 pC, half that of the drive bunch. The witness bunch had otherwise the same dimensions as the drive bunch. These simulations showed some particles in the witness bunch increased in energy by 70%, giving an average accelerating gradient of 1.2 GV/m. Figure 4 shows the energy spectrum of the drive/witness bunch combination and particle weighting after 13 cm. If the simulation were allowed to proceed further, it would be expected that some particles would double their energy in approximately 20 cm.

CONCLUSION AND OUTLOOK

CLARA and PARS provide an opportunity to study plasma wakefield acceleration using a highly relativistic electron drive beam. The properties and flexibility of CLARA make it an ideal accelerator to provide a drive beam for such an experiment.

Particle-in-cell simulations of the response of a plasma of density somewhat lower than that of the CLARA beam demonstrated that a wakefield of 2.0 GV/m is feasible, and can be maintained over a plasma length of at least 13 cm. Transverse compression of the bunch by the transverse wakefield led to an increase in the bunch density, which resulted in a wakefield which did not match the predictions of the linear theory of plasma wakefield acceleration. Preliminary two-bunch simulations showed an energy gain of 70% over 13 cm, and that energy doubling in less than 20 cm is possible with the bunch parameters used.

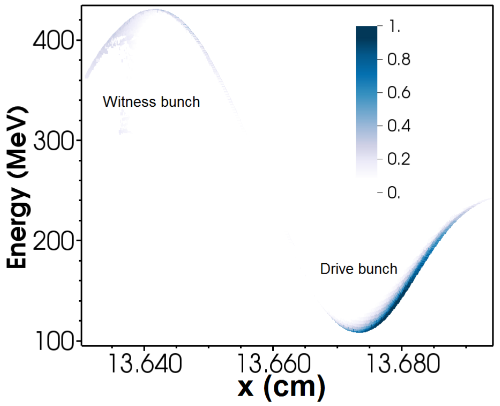

Figure 4: Energy spectrum of a drive and witness combination after 13.7 cm propagation. The colour scale indicates macro particle weighting, with the lowest weight particles coloured white.

Future simulation work will further investigate the potential for PARS to study two-bunch acceleration schemes, initially by using more realistic drive and witness bunch parameters. It is planned to implement an input file in which the drive and witness bunches are treated as two different species, allowing easier analysis of the behaviour of each bunch. Simulations using shaped bunch profiles to achieve transformer ratios greater than 2 will also be carried out. Simulations over a short plasma, such as might be produced from a laser-ionized gas jet, will be used investigate the plasma lens effect.

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REFERENCES

[1] G. Xia et al., Nucl. Instrum. Meth. A 740, 165 (2014).
[2] Tech-X Corporation, www.txcorp.com/home/vsim/vsim-pa
[3] W. Lu et al., Phys. Plasmas 12, 063101 (2005).
[4] J. Clarke et al., STFC (2013).
[5] T. Katsouleas et al., Part. Accel. 22, 81 (1987).
[6] J.B Rosenzweig et al., Phys. Rev. A 44, R6189 (1991).
[7] K.L.F. Bane et al. IEEE Trans. Nuc. Sci. NS-32, 3524 (1985).
[8] C.K. Birdsall, A.B. Langdon, Plasma Physics via Computer Simulation, ISBN: 0-07-005371-5, McGraw-Hill (1985).