# A PROPOSED PLASMA ACCELERATOR RESEARCH STATION AT CLARA FACILITY

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*Abstract*

We propose a Plasma Accelerator Research Station (PARS) based at proposed FEL test facility CLARA (Compact Linear Accelerator for Research and Applications) at Daresbury laboratory. The idea is to use the relativistic electron beam from CLARA, to investigate some key issues in electron beam transport and in the electron beam driven plasma wakefield acceleration, e.g. the high acceleration gradient driven by relativistic electron bunch, two bunch acceleration for CLARA beam energy doubling, high transformer ratio, long bunch self-modulation and the related beam instabilities in plasmas. This paper discusses feasibility studies of electron beam parameters to meet the requirements for beam driven wakefield acceleration and presents the simulation results based on CLARA beam parameters. The possible experiments which can be conducted at the PARS beam line are also discussed.

## INTRODUCTION

Plasma accelerators utilize the breakdown medium “plasma” as the accelerating structure and therefore avoid the further breakdown limit posed by the conventional accelerating structures, e.g. copper or niobium RF cavities. The wavebreaking field can reach 100 GV/m for a plasma with density of $10^{18}$ $cm^{-3}$. It is therefore an ideal medium to sustain a very large electric field for the particle beam acceleration.

Plasma based accelerators have achieved tremendous progress in recent decades [1]. With the advances in laser technology, especially the introduction of the Chirped Pulse Amplification (CPA), the peak power of cutting edge short pulse (tens of femtoseconds) lasers can reach a few hundred Terawatts ($10^{12}$ Watts) or even Petawatts ($10^{15}$ Watts). Employing such a laser pulse as driver, the laser wakefield accelerator (LWFA) nowadays can routinely achieve GeV level electron beam within a few centimeter plasma channel and with the electron energy spread of only a few percent [2]. This will lead to the future compact light source or collider based on LWFA scheme [3]. For the electron beam driven plasma wakefield accelerator (PWFA), experiments conducted by a group of scientists from UCLA/USC/SLAC collaboration at the FFTB at SLAC, have successfully demonstrated energy doubling for the SLC 42 GeV electron beam. The resulting accelerating gradient in the experiment is about three orders of magnitude higher than the accelerating field at the SLC linac [4].

## CLARA FACILITY

The aim of CLARA is to develop a normal conducting test accelerator able to generate longitudinally and transversely bright electron bunches and to use these bunches in the experimental production of stable, synchronized, ultrashort photon pulses of coherent light from a single pass FEL with techniques directly applicable to the future generation of light source facilities [5]. The CLARA facility comprises a photo injector gun, normal conducting cavities, magnetic bunch compressor and radiation undulators. The maximum beam energy is 250 MeV and the maximum bunch charge is about 250 pC. The bunch length is quite flexible which spans from 800 fs to 30 fs depending on user requirements.

For the electron beam driven PWFA experiment at PARS, a dogleg will guide the full energy CLARA beam to a parallel beam line off-set by ~1.5m from CLARA beam axis contained within CLARA shielding area. Figure 1 shows the conceptual layout of the CLARA facility and the PARS beam line. The proposed dogleg beam line design using “–I “ transform between the dipoles using two FODO doublets keeps the transverse beam emittance blow up due to coherent synchrotron radiation within acceptable limits. The PARS beam line which consists of the final focus, plasma cell, energy spectrometer (phosphor screen) and the final beam dump. The final focus is designed to focus the electron beam transversely so as to get a high peak current driver beam and meanwhile to match the electron beam beta function with the plasma beta function. A variable 10-50 cm long plasma cell (a DC discharge plasma source seems feasible) will be built to test the key issues in the PWFA experiment at various beam parameter ranges. An energy spectrometer, together with a phosphor screen will be employed to characterize the energy of electrons exiting the plasma cell. The final beam dump will absorb the energy of electrons exiting the plasma source. Prior to the final focus and plasma cell, a magnetic chicane may be needed to compress the bunch further to an extremely short length. According to the linear theory of PWFA [6], the maximum wakefield amplitude is proportional to the bunch charge (number of electrons per bunch) and inversely proportional to the bunch length squared. Therefore a short drive beam is in principle preferable for a high wakefield excitation. Based on the CLARA beam parameters, a preliminary study has shown that an accelerating gradient of a few GV/m can be excited if a short (therefore high peak current) electron bunch can be achieved.

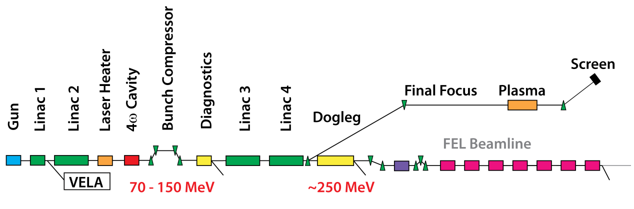


Figure 1: Conceptual layout of the CLARA facility, with the proposed PARS beam line.

## PARS BEAM PARAMETERS

We have defined the parameter settings for the PWFA experiment at PARS facility. Table 1 summarizes the different working regimes of the beam parameters; with each parameter setting can study some important aspects on beam-plasmas interactions and test the scaling laws of PWFA. In principle three operating regimes, i.e, long pulse, short pulse and ultra-short pulse can be achieved at CLARA facility for the PWFA experimental research [7].

Table 1: Three Operation Regimes for PWFA Experiment at CLARA (PARS) Facility

| *Operating modes* | *Long pulse* | *Short pulse* | *Ultrashort pulse* |
|---|---|---|---|
| Beam energy (MeV) | 250 | 250 | 250 |
| Bunch charge (pC) | 250 | 250 | 20-100 |
| Electron per bunch | 1.56e9 | 1.56e9 | 1.25e8-6.25e8 |
| Bunch length (fs) | 250-800 | 250 | 30 |
| Bunch length (μm) | 75-240 | 75 | 9 |
| Bunch radius (μm) | 30 | 20 | 20 |
| Normalized emittance (mm.mrad) | 1 | 1 | 1 |
| Energy spread | 0.1% | 0.1% | 0.1% |

## PARTICLE-IN-CELL SIMULATION

To gain a full understanding of the wakefield excitation by using the CLARA relativistic electron beam as drive beam, one has to rely on detailed simulations. VORPAL is a fully explicit particle-in-cell (PIC) code developed by Tech-X Corporation at Colorado USA. We use it to simulate the interactions between the electron beams and the plasmas. Figure 2 shows a 2D simulation of a typical accelerating and decelerating wakefield structure in the plasma. Here $x$ denotes the longitudinal beam propagation direction, $y$ is the transverse coordinate as used in VORPAL convention. The parameters used in this simulation are as follows: the beam energy is 250 MeV, bunch length of 30 μm, transverse beam size of 100 μm, bunch charge of 250 pC, plasma density of $5\times10^{16}$ cm$^{-3}$. The maximum longitudinal accelerating and decelerating wakefield is about 600 MV/m, an order of magnitude higher than the conventional RF structures, as shown in Figure 3.

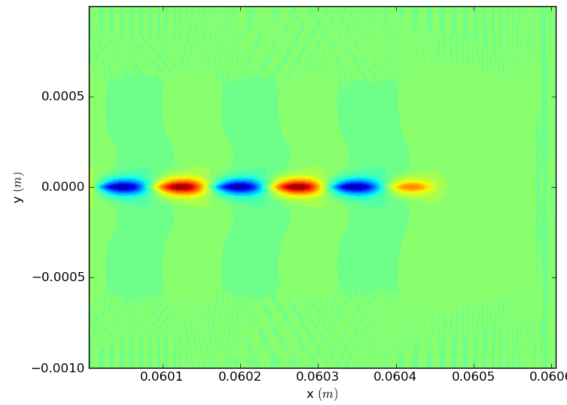


Figure 2: The slice showing the accelerating and decelerating wakefield structure (blue and red regions) driven by a typical CLARA beam.

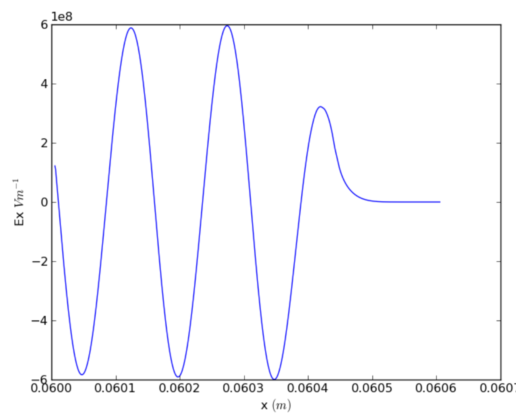


Figure 3: The longitudinal accelerating and decelerating wakefield driven by CLARA beam in plasma.

## STRONGLY FOCUSED BEAM AS DRIVER

If the electron beam is subject to strong transverse focusing (by final focus), one expects a high-density drive bunch can be achieved (the bunch density is $n_b = N_b/\left[(2\pi)^{3/2}\sigma_r^2\sigma_z\right]$ for a Gaussian distribution, it is proportional to the bunch intensity $N_b$, inversely proportional to the bunch length $\sigma_z$ and transverse rms size $\sigma_r$ squared) for a higher amplitude wakefield excitation. Figures 4-6 show the simulation results based on a strongly focused CLARA beam driven wakefield. In this simulation, the electron beam energy is 250 MeV, the transverse beam size is 20 μm, the bunch length is 75 μm, the bunch charge is 250 pC and the normalized emittance is 1 mm.mrad. The plasma density is $3\times10^{15}$ cm$^{-3}$. Figure 4 shows the delicate accelerating and decelerating structures driven by CLARA beam. The longitudinal wakefield amplitude is shown in Figure 5. One can see that in this case, the maximum accelerating field is approaching 1.2 GV/m.

Based on the linear theory of PWFA, the maximum wakefield amplitude is given by [6]

$$E_{acc}\left[\mathrm{MeV/m}\right] = 244\frac{N_b}{2\times10^{10}}\left(\frac{600\mu m}{\sigma_z}\right) \quad (1)$$




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It gives maximum wakefield amplitude about 1.2 GV/m by using the strongly focused beam parameters, which agrees well with the simulation results as shown in Fig. 5.

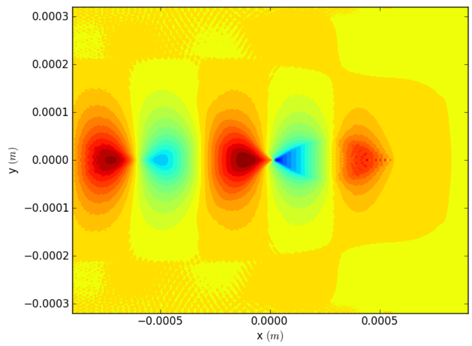


Figure 4: The accelerating and decelerating wakefield structure driven by a strongly focused CLARA beam.

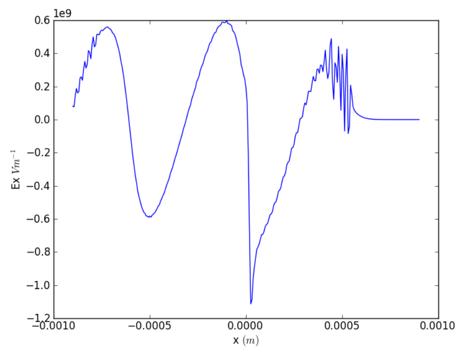


Figure 5: The longitudinal wakefield driven by CLARA strongly focused beam.

Meanwhile, one can also examine the particle acceleration effect from the CLARA beam driven plasma wakefield. Figure 6 shows the beam energy distribution after propagating through a 20 cm long plasma cell for a strongly focused CLARA drive beam. It shows that most of the beam particles have their original energy ($\gamma v = 1.46\times10^{11}$, here $\gamma$ is the gamma factor of beam energy and is $250/0.511 \approx 489$, $v$ is the beam velocity and is given by $v = \beta c$, here $\beta$ is relativistic velocity and $c$ is the speed of light). It indicates clearly that some electrons lose energy while some electrons gain energy from the plasma (spanning over to $\gamma v = 1.60\times10^{11}$).

## OTHER RESEARCH TOPICS AT PARS

There are many interesting topics which can be explored using the CLARA beam driven PWFA. For example, a two-bunch acceleration experiment (one bunch for driving wakefield, another bunch for sampling the wakefield) can be studied at PARS facility. Based on the latest simulations, one could double the energy of CLARA beam with a 10 cm preformed plasma cell. The FEL seeded from the wakefield accelerated beam will enable short wavelength photon production for the scientific research and industrial users.

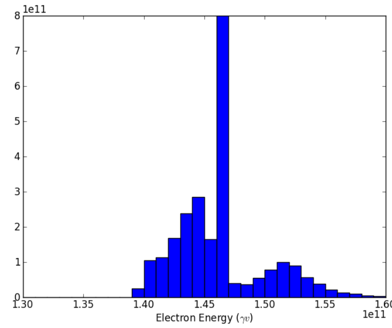


Figure 6: The beam energy distribution after propagating through a 20 cm long plasma cell for a strongly focused CLARA drive beam.

In additional the plasma can act as an undulator to produce a high brightness beam of keV to MeV photons through betatron radiation [8]. The mechanism of the radiation production can be extensively investigated at PARS facility.

Furthermore it is possible to study the self-modulation instability (SMI) of a long electron beam in a high-density plasma. The AWAKE collaboration at CERN will investigate self-modulated SPS proton bunch-driven wakefield acceleration [9]. The CLARA beam has the same gamma factor as the SPS beam, and it is relatively easier to handle than the SPS beam, therefore the experimental results from CLARA can give some inputs to the CERN AWAKE experiment.

Except for the above-mentioned plasma wakefield acceleration experiments, the dedicated beam line at PARS enable us to test some advanced beam dynamics issues, e.g. coherent synchrotron radiation and its countermeasures, microbunching instability, emittance exchange and some novel FEL schemes. The ultrashort PARS beam is also an ideal test bench for beam instrumentation R&D, e.g. the coherent Smith-Purcell radiation, coherent edge radiation and electron-optical sampling (EOS) etc.

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