Parametric study of plasma wakefield acceleration at CLARA

H. Saberi, J. Zhang, O. Apsimon, S. Boogert, D. Angal-Kalinin,
R. D'Arcy, T. Pacey and G. Xia

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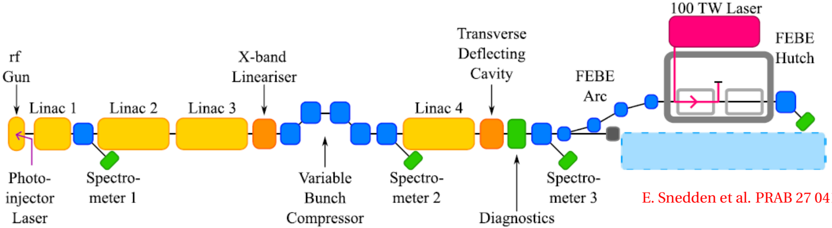
MANCHESTER 1824
The University of Manchester

The Cockcroft Institute
of Accelerator Science and Technology

Unique opportunity of CLARA facility

- CLARA FEBE has a high potential to investigate plasma wakefield acceleration (PWFA) for the first time in the UK.
  - Electron beam with versatile parameters.
  - Advanced mask technology for beam shaping.
  - High power laser alongside the FEBE beamline.
  - Expert scientists and technicians in the field.



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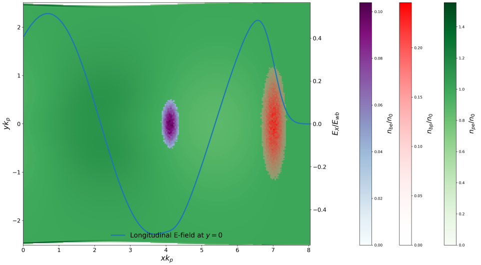
PWFA in a nutshell

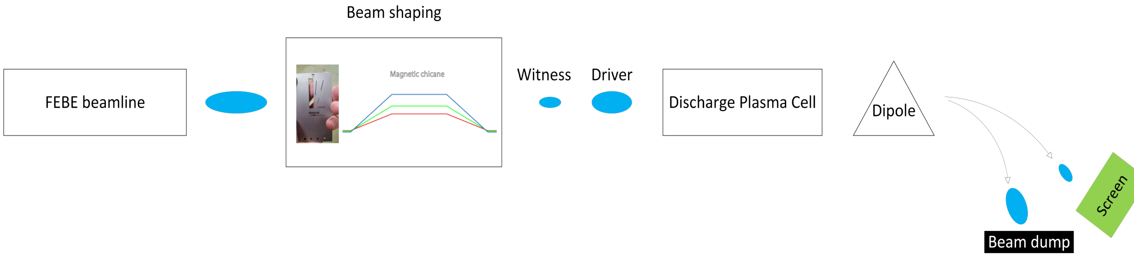
- The driver beam generates a strong accelerating/focusing wakefield inside the plasma.
- A witness beam injected at a proper distance behind the driver can ride the wakefield and accelerate.
- The wakefield could reach 1 GV/m or higher, that leads to a more compact accelerator.



1. Introduction
2. **PWFA @ CLARA - Early research**
   - Baseline parameters (?)
   - Driver's wakefield
   - Witness energy gets doubled
   - Betatron radiation
3. Complementary research
4. Summary

PWFA @ CLARA - A high impact experiment

- We aim at PWFA experiment toward the energy doublings of the witness beam with small energy spread.



Preliminary simulation studies

- Pre-design simulations are needed to investigate the optimum regime of acceleration and the baseline parameters.
- We have conducted particle-in-cell (PIC) simulation studies using
  - QV3D code (Quasistatic 3D code developed by Alexander Pukhov)
  - FBPIC (Cylindrical 2D code developed at Berkeley Lab)

PWFA with feasible parameters (?) at CLARA FEBE

Parameter	Symbol [Unit]	Value
Driver beam		
Energy	$E_{\rm d}$ [MeV]	250
Charge	$Q_{\rm d}$ [pC]	200
Length	$\sigma_{\xi \rm d}$ [μm]	15
Radius	$\sigma_{r \rm d}$ [μm]	50
Energy Spread	$\delta E_{\rm d} [\%]$	1
Normalized Emittance	$\varepsilon_{\rm nr}$ [mm mrad]	2
Witness beam		
Energy	$E_{\rm w}$ [MeV]	250
Charge	$Q_{\rm w}$ [pC]	10
Length	$\sigma_{\xi \rm w}$ [μm]	10
Radius	$\sigma_{r \rm w}$ [μm]	20
Energy Spread	$\delta E_{\rm w} [\%]$	1
Normalized Emittance	$\varepsilon_{\rm nw}$ [mm mrad]	2
Plasma		
Density	n_0 [cm^{-3}]	$5 \times 10^{14} - 10^{17}$
Wavelength	λ_0 [μm]	—
Length	L_0 [cm]	25
Other parameters		
Driver/Witness separation	$\Delta\xi$	$\sim \lambda_0/2$

- Two beams of witness and driver will be generated using the mask already developed at CLARA.
- Here, physically reasonable parameters are selected based on the future developments at CLARA.

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- Two beams of witness and driver will be generated using the mask already developed at CLARA.
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- Both beams have similar energy of 250 MeV.

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- Two beams of witness and driver will be generated using the mask already developed at CLARA.
- Here, physically reasonable parameters are selected based on the future developments at CLARA.
- The CLARA beam is cut close to the tail.

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- Two beams of witness and driver will be generated using the mask already developed at CLARA.
- Here, physically reasonable parameters are selected based on the future developments at CLARA.
- Identical energy spread and emittance are considered.

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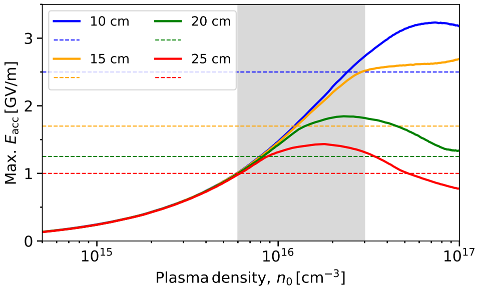
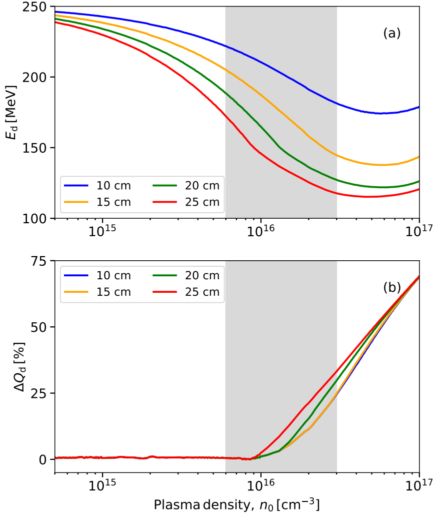
Driver beam moving inside plasma

- Simulations for plasma density scan are conducted using QV3D code.
- Plasma length is 25 cm.

Maximum on-axis accelerating wakefield at positions 10 cm, 15 cm, 20 cm and 25 cm.



Driver energy and charge loss.



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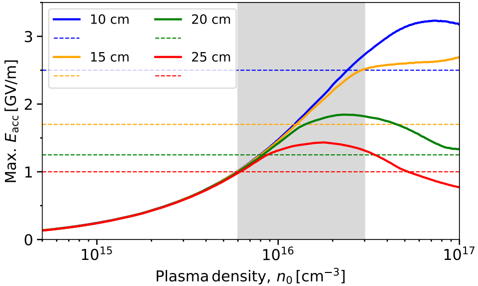
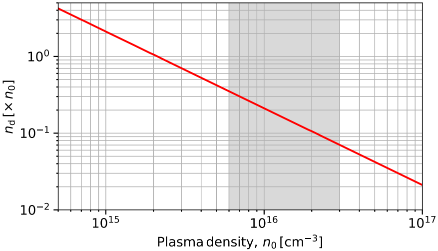
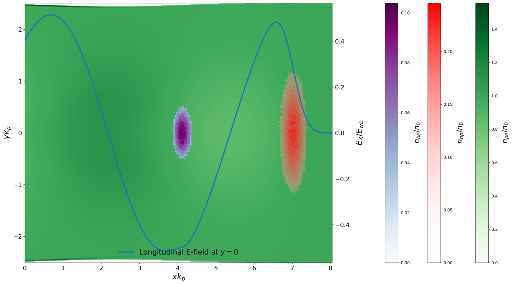




The driver interaction at the optimum density (grey area) will be in the linear regime.

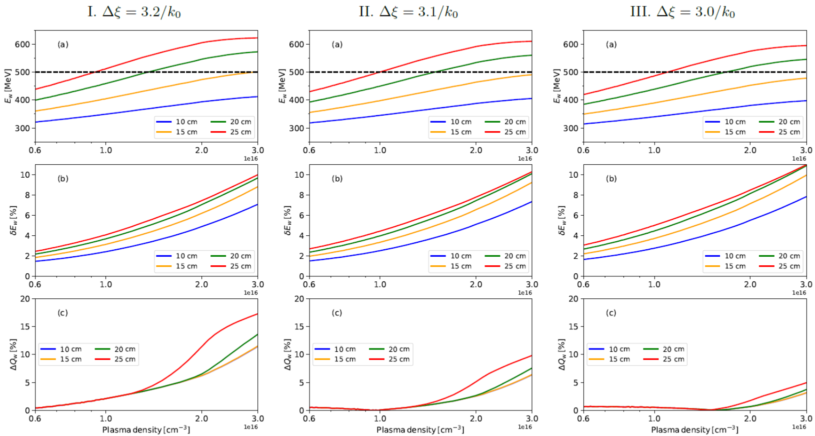
Beam-loading

- Witness needs to be injected at the accelerating and focusing phase, i.e. at a distance of $\lambda_p/2$ from the driver beam.
- The witness current can change the accelerating wakefield, known as beam-loading effect.
- The aim is to benefit beam-loading to flatten wakefield for monoenergetic acceleration of witness beam.



Careful witness injection is necessary

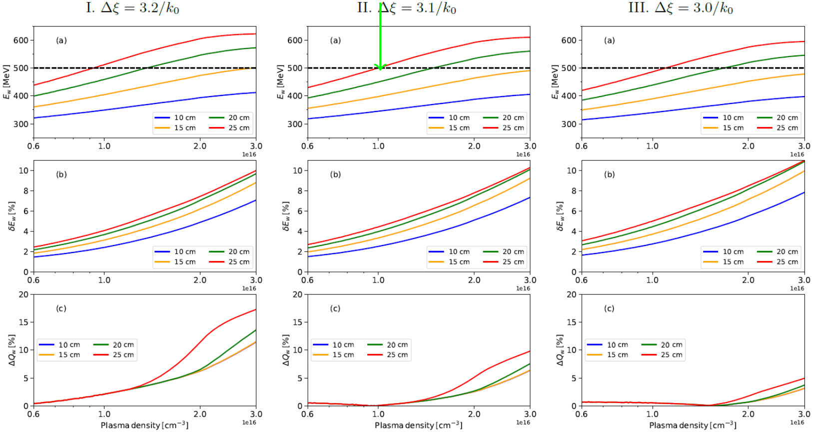
Simulation of witness position at the proximity of $\lambda_p/2$ shows the importance of witness injection at right phase.



High quality witness beam with double energy

Energy doubling with low energy spread and without charge loss occurs at plasma density of $1 \times 10^{16} \mathrm{cm}^{-3}$.

I. $\Delta\xi = 3.2/k_0$ II. $\Delta\xi = 3.1/k_0$ III. $\Delta\xi = 3.0/k_0$



Case study using FBPIC code

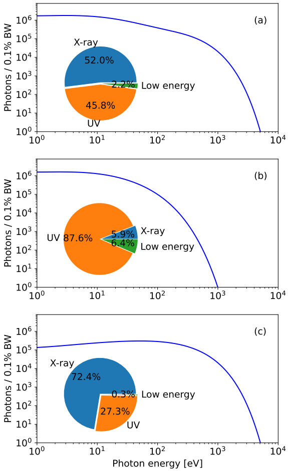
Parameters		Values
Plasma	Density	5.0×10^{16} cm^{-3}
	Length	12 cm
	Wavelength (λ_p)	149.3 μm
	Ions	He^{+}
Driver beam	Density	2.38×10^{15} cm^{-3}
	Charge	150 pC
	Energy	250 MeV
	Bunch length	10 μm
	Bunch radius	50 μm
	Energy spread	1%
	Emittance	5.0 mm mrad

Parameters		Values
Witness beam	Density	3.96×10^{16} cm^{-3}
	Charge	10 pC
	Energy	250 MeV
	Bunch length	10 μm
	Bunch radius	10 μm
	Energy spread	1%
	Emittance	5.0 mm mrad
	Distance from driver	$0.50\lambda_p$ (75 μm)

Click to play the video

Betatron radiation in PWFA

- QV3D calculates the integrated photons.
- Here, the radiation has been calculated for the optimum density and phase lag.
- About radiation spectrum:
  - Plot (a): The combined radiation spans from UV to X-ray.
  - Plot (b): Driver beam mainly emit low-energy photons to UV.
  - Plot (c): Witness beam emit X-ray as the dominant photons.



What else can we explore?

X-ray source

- Betatron radiation
- Synchrotron-like broadband X-ray source

Betatron Radiation diagnostics

- Betatron spectroscopy can works as a novel non-invasive diagnostics

Plasma Beam Dump (PBD) and Energy Recovery

- Active PBD.
- Passive PBD.
- Energy recovery from plasma

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- Plasma Wakefield Acceleration at CLARA FEBE will make this facility the first in the UK to achieve energy doubling.
- This project will foster both national and international collaborations.
- Early studies using PIC codes of QV3D and FBPIC demonstrate that PWFA aiming at energy doubling is feasible at CLARA FEBE.
- The focus is on the PWFA experiment, but there are certainly related topics we can explore alongside this experiment
    - X-ray source based on PWFA
    - Betatron diagnostics
    - Plasma beam dump and energy recovery