Plasma wakefield acceleration at CLARA

(Simulation study for energy doubling)

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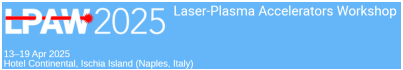
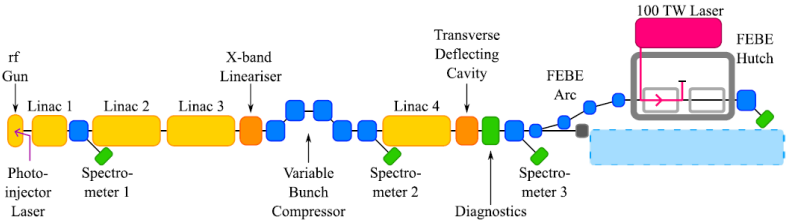


Compact Linear Accelerator for Research and Applications (CLARA)



E. Snedden et al. PRAB 27 041602 (2024)

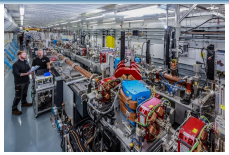


Image courtesy of D. Angal-Kalinin, CLARA User Meeting, 2024

- CLARA is a test facility at STFC Daresbury Laboratory.
- Delivers ultrabright electron bunches up to 250 MeV.
- FEBE beamline provides access to a dedicated shielded experiment area (hutch).
- Access to a high-power (100 TW; 25 fs; 5 Hz) Ti:Sapphire laser.

Mid-energy range facilities at Europe

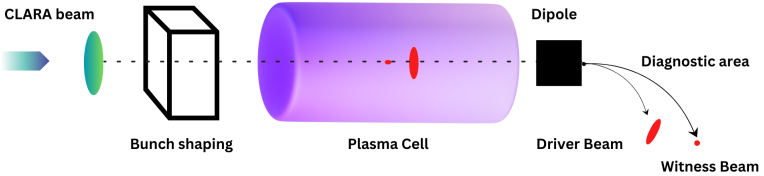
D. Angal-Kalinin D et al., IPAC23

Facility	Maximum Beam Energy [MeV]	Bunch Charge [pC]	Bunch Length	Maximum Repetition Rate [Hz]	Micro-bunches per train	Micro-bunch Spacing
ARES	160	0.003 - 280	0.8 fs - 1 ps[a]	50	1	N/A
CLARA	250	5 - 250	≤ 50 fs - 10 ps	100	1	N/A
CLEAR	230	5 - 3000	100 fs - 10 ps	10	1 - 150	1.5 or 3 GHz
FLUTE	41	1 - 1000	1 fs - 300 fs	10	1	N/A
PITZ	22	0.1 - 5000	100 fs - 60 ps	10	1 - 4500	0.1 - 5 MHz[b]
SPARC_LAB	180	10 - 2000	20 fs - 10 ps	10	1 - 5[c]	N/A

[a] Measured 20 fs as TDS is not fully operational
[b] Besides fixed repetition rate, the selection of individual bunches in the train is also possible
[c] Delay between bunches is 0.5 ps - 20 ns, whilst delays larger than ≈ 360 ps are achieved by injecting the bunches in different RF buckets

CLARA is comparable to CLEAR and SPARC_LAB, with a significant potential for plasma wakefield acceleration (PWFA) research.

Schematic of the PWFA experiment



Research Focus

We investigate driver evolution, wakefield generation and witness acceleration inside plasma in this simulation study.

CLARA Beam parameters

Parameter [Unit]	FEBE (general)	FEBE (for PWFA)
Energy [MeV]	50-250	250
Charge [pC]	5-250	250
Repetition rate [Hz]	100	100
RMS bunch length [fs]	50-10e3	50-100
RMS bunch radius [μm]	50-100	50
RMS energy spread [%]	<5	1
Normalized emittance [mm-mrad]	<5	2

Table 1: Reference for FEBE parameters are E. W. Snedden et al., PRAB (2024) and D. Angal-Kalinin et al., Front. Phys. (2024)

Two-beam parameters for PWFA

Parameter [Unit]	Driver beam	Witness beam
Energy [MeV]	250	250
Charge [pC]	150	10
Electrons per bunch [$\times 10^8$]	9.4	0.6
RMS bunch length [fs]	50	33
RMS bunch radius [μm]	50	10
RMS energy spread [%]	1	1
Normalized emittance [mm-mrad]	2	2

Two-bunch generation

Longitudinal bunch shaping is needed to generate driver and witness from the CLARA beam using the mask technology.

Two-beam parameters for PWFA

Parameter [Unit]	Driver beam	Witness beam
Energy [MeV]	250	250
Charge [pC]	150	10
Electrons per bunch [$\times 10^8$]	9.4	0.6
RMS bunch length [fs]	50	33
RMS bunch radius [μm]	50	10
RMS energy spread [%]	1	1
Normalized emittance [mm-mrad]	2	2
Bunch population [$\times 10^8$]	9.4	0.62
Peak density [cm^{-3}]	1.6×10^{15}	4.0×10^{15}

Simulation experiment

- QV3D code.
- Computing resources provided by STFC Scientific Computing Departments SCARF cluster.
- Simulation approach
  - Simulate driver beam
  - Study witness acceleration
  - Study betatron radiation

Simulation parameters	
Simulation window	
(x, y, z) Dimension $[k_p^{-1}]$	(7, 12, 12)
(x, y, z) Resolution $[k_p^{-1}]$	(0.1, 0.01, 0.01)
Time step $[\omega_p^{-1}]$	5
Macroparticles per cell	
Plasma	4
Driver	16
Witness	16
Other	
W/D delay	$\lambda_p/2$

Plasma cell and its assumptions

- The length of plasma cell is 25 cm.
- Pre-ionized plasma is considered.
- Uniform plasma density.
- Density scan over $10^{15} - 5 \times 10^{16}\,\mathrm{cm}^{-3}$.

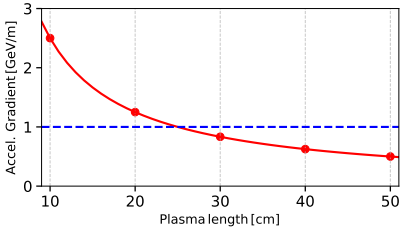
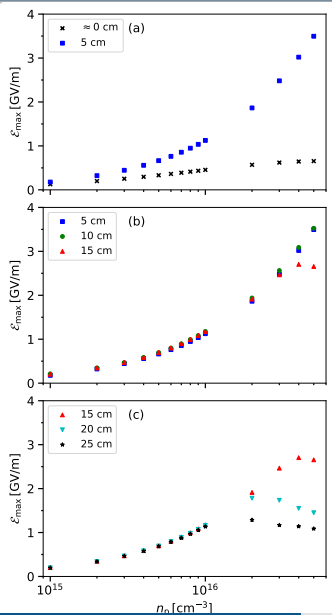
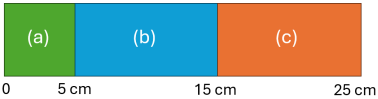
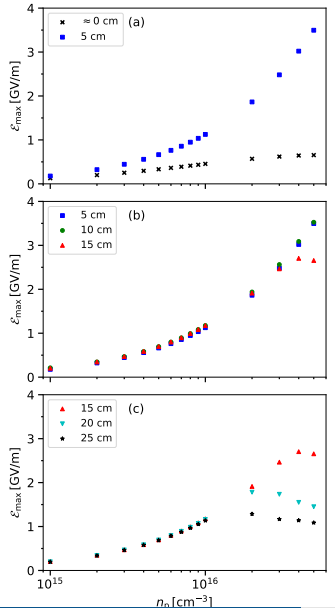
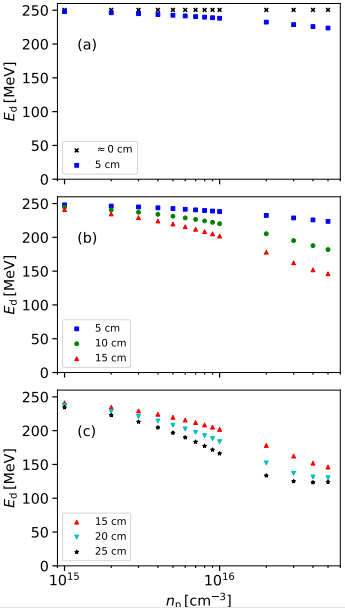


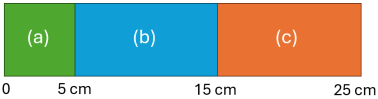
Figure 1: Acceleration gradient that is needed for energy doubling (final energy of 500 MeV) over any specific distance.

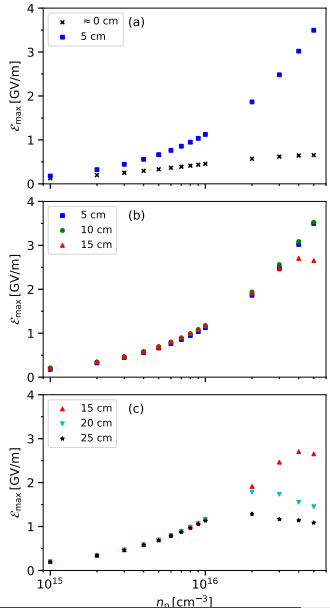

≈ 0 cm
5 cm
(a)
5 cm
10 cm
15 cm
(b)
15 cm
20 cm
25 cm
(c)
$\mathcal{E}_{max}$ [GV/m]
n_0 [cm^{-3}]
10^{15}
10^{16}

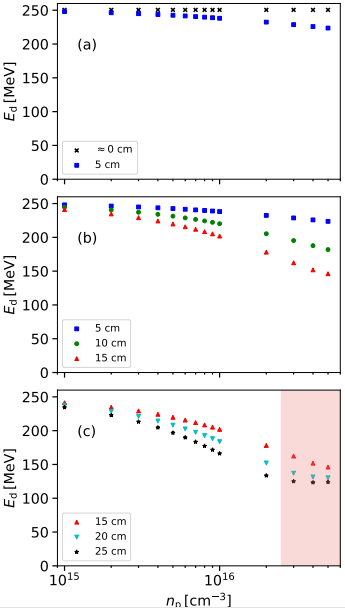

(a)
(b)
(c)
0
5 cm
15 cm
25 cm

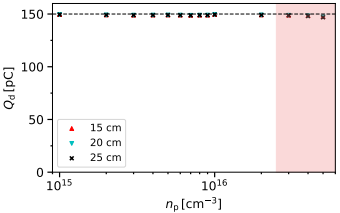

(a)
≈ 0 cm
5 cm
(b)
5 cm
10 cm
15 cm
(c)
15 cm
20 cm
25 cm
$\mathcal{E}_{max}$ [GV/m]
n_0 [cm^{-3}]


(a)
≈ 0 cm
5 cm
(b)
5 cm
10 cm
15 cm
(c)
15 cm
20 cm
25 cm
E_d [MeV]
n_0 [cm^{-3}]

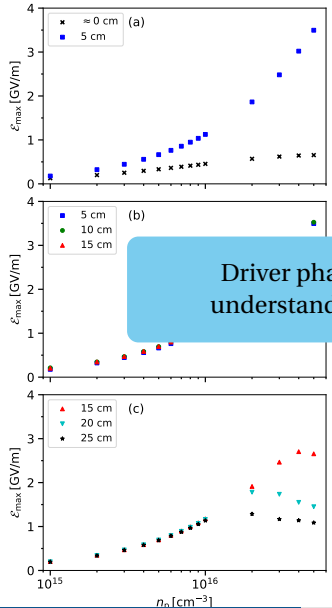

(a)
(b)
(c)
0
5 cm
15 cm
25 cm

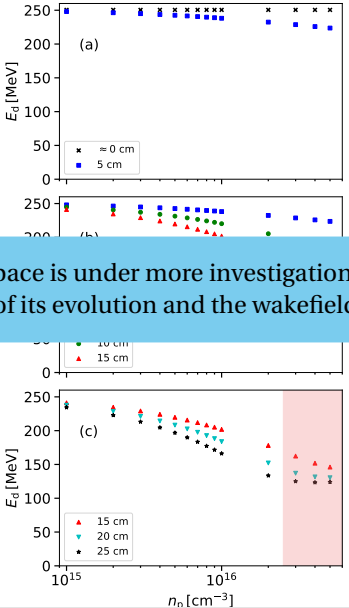


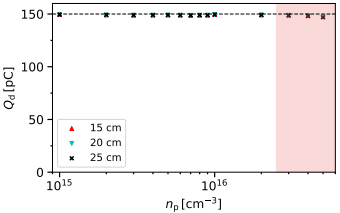




In this range of densities, the beam loses charge so the mean energy is quite constant at the end.







Driver phase space is under more investigation for a better understanding of its evolution and the wakefield generation.

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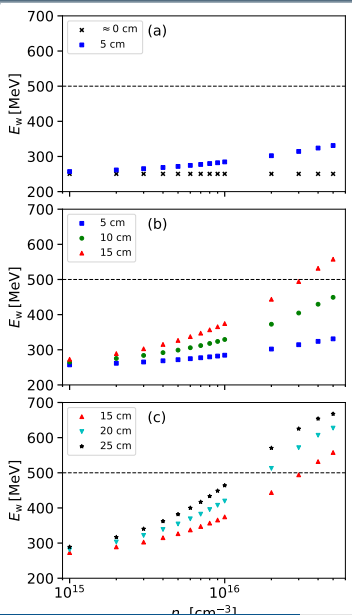
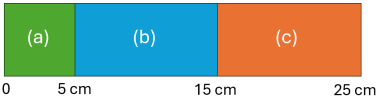
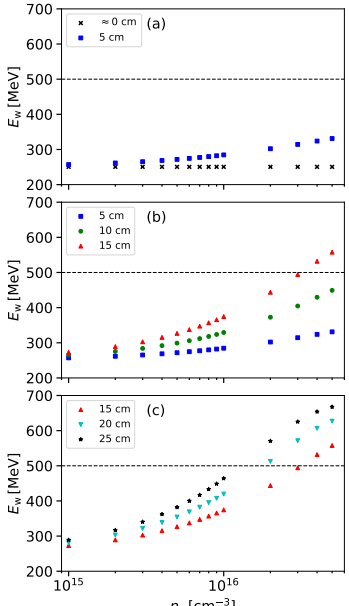
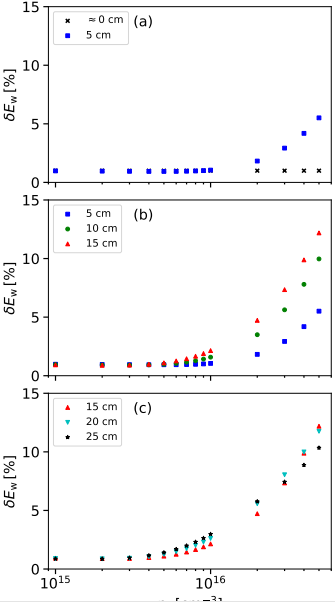
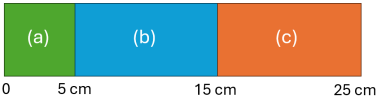
constant at the end.

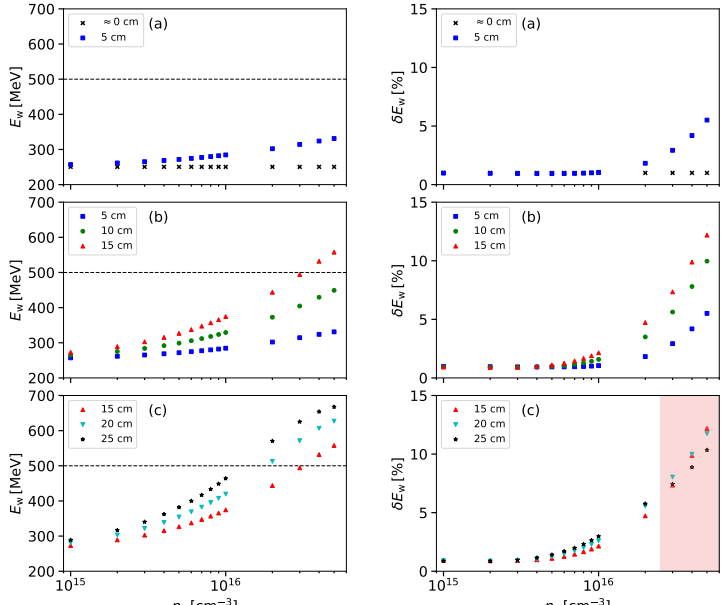

(a)
≈ 0 cm
5 cm
(b)
5 cm
10 cm
15 cm
(c)
15 cm
20 cm
25 cm
E_w [MeV]
700
600
500
400
300
200
10^{15}
10^{16}
n_e [cm^{-3}]

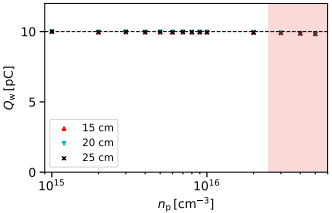

(a)
(b)
(c)
0
5 cm
15 cm
25 cm


(a)
≈ 0 cm
5 cm
(b)
5 cm
10 cm
15 cm
(c)
15 cm
20 cm
25 cm
E_w [MeV]
n [cm^{-3}]

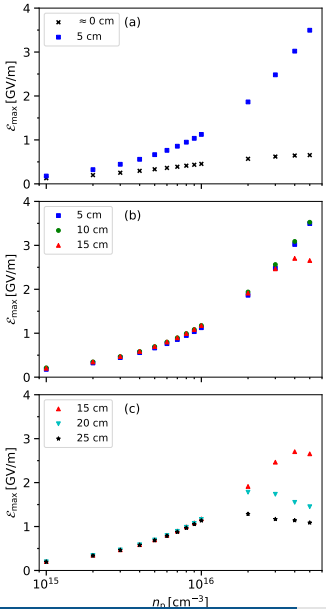

(a)
≈ 0 cm
5 cm
(b)
5 cm
10 cm
15 cm
(c)
15 cm
20 cm
25 cm
δE_w [%]
n [cm^{-3}]

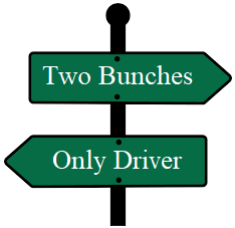

(a)
(b)
(c)
0
5 cm
15 cm
25 cm



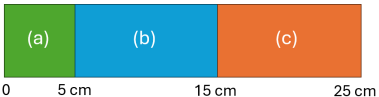


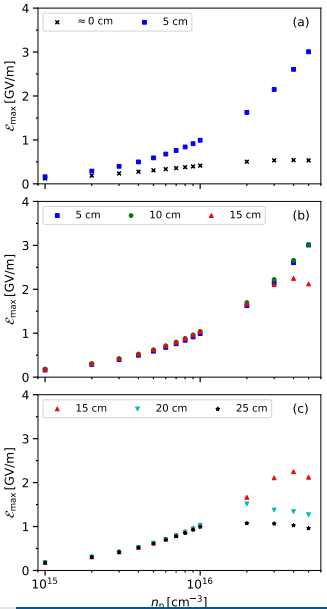
In this range of densities, the beam loses charge so the energy spread reduces.





The beam-loading effect is evident in the maximum wakefield, as the witness field suppresses the driver wakefield.



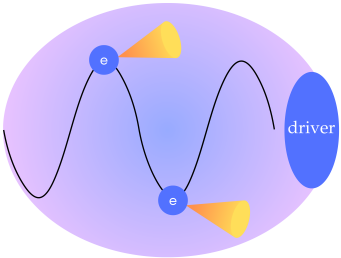


Optimum plasma parameters

- According to current simulations, a plasma cell of length 15-25 centimeter is needed to achieve witness energy doubling.
- We may consider two set of parameters as the optimum plasma
  - Set I. A plasma cell of length 15 centimeter and density of $3 \times 10^{16}\,\mathrm{cm}^{-3}$.
  - Set II. A plasma cell of length 20 centimeter and density of $2 \times 10^{16}\,\mathrm{cm}^{-3}$.
- In the following slides, we investigate betatron radiation in the PWFA within the plasma of Set II.

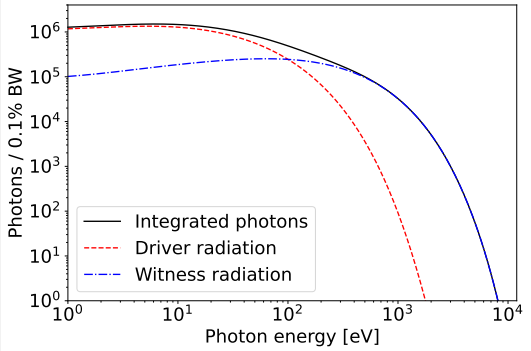
Betatron radiation

- Betatron radiation is a byproduct of plasma accelerators.
- The integrated radiation over 25-centimeter plasma is calculated.
- The proportion of driver and witness radiation is determined.

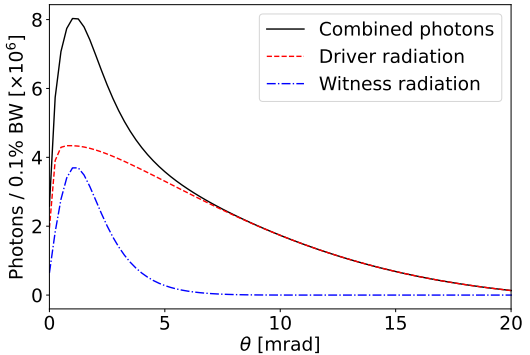


Radiation properties

Radiation spectrum



Radiation divergence



Summary and Conclusion

- Simulations indicate the witness beam energy doubling in a two-bunch PWFA at CLARA facility.
- Optimum parameters for the witness/driver beams and plasma were investigated.
- Betatron radiation in the experiment is mainly in the range of the low energy photons to UV.
- Further simulation and design studies will be conducted for this experiment in the future.

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