A new approach to linear acceleration: proton-driven plasma wakefield acceleration

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The AWAKE Collaboration proposes to use the proton beam from the CERN SPS to demonstrate proton-driven plasma wakefield acceleration for the first time, which could form the basis of a future high energy lepton collider.

For this proof of principle experiment, we hope to generate average fields of 300 MV/m, with maxima in excess of 1 GV/m.

Using a 10 m long plasma cell, we intend to self-modulate the proton beam (into micro-bunches) to generate high intensity wakefields; inject and capture a low energy (20 MeV) electron beam; accelerate these electrons over 6 m to over 2 GeV; and lastly measure these effects with an array of novel diagnostic techniques.

What are plasma wakefields?

Plasmas are a state of matter in which the molecules have been ionised, leaving the electrons highly mobile, and the heavy ions immobile. Plasma is highly conductive and can support electric fields far greater than is possible in solids.

The wakefield is created as the proton beam is injected into the plasma. This perturbs the electrons away from their equilibrium positions.

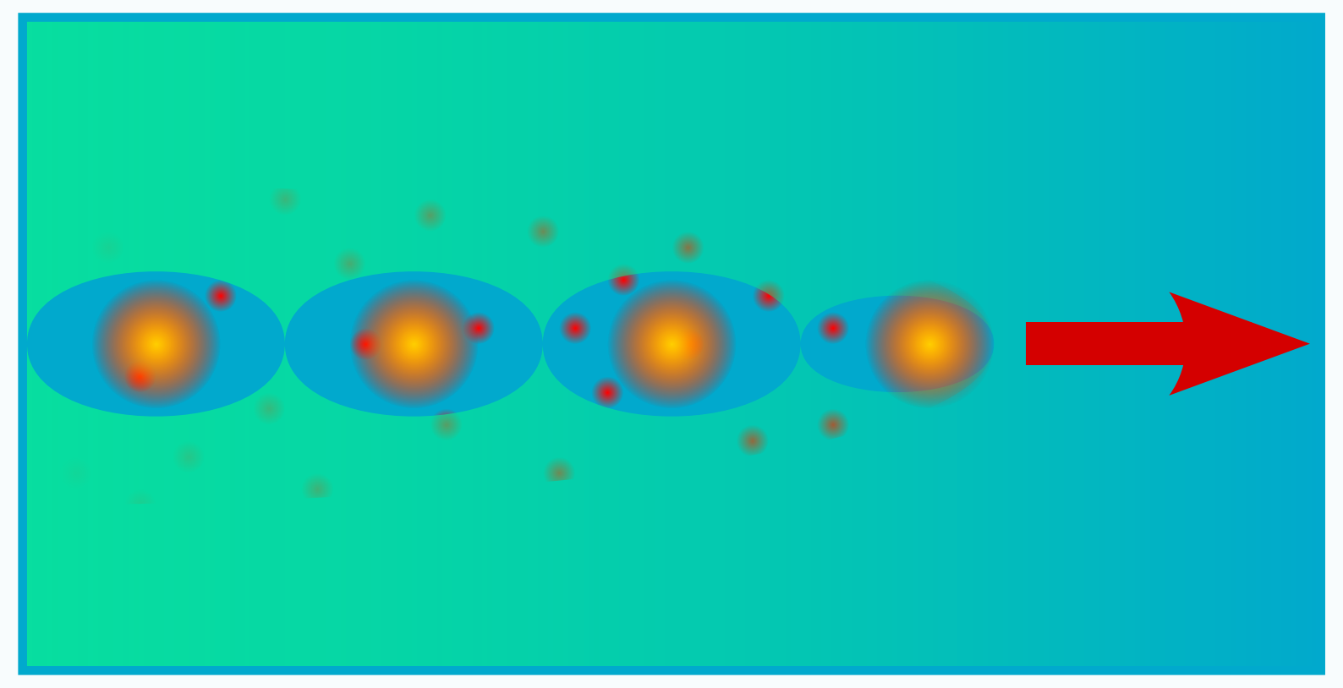


Figure 1: Electrons are shifted from their equilibrium positions by Coloumb interactions with the proton beam, whilst ions remain in place.

Huge forces now exist between the ions & electrons perpendicular to the beam, causing the electrons to oscillate transversely. This is a plasma wakefield.

The forces on these electrons are enormous. The electric fields generated can reach up to *100 GV/m* [1]: one thousand times what is possible in conventional accelerators [2].

The *AWAKE* experiment

By driving a plasma wakefield with a high energy proton beam, it may be possible to construct an accelerator with accelerating gradients of 1 GV/m over a kilometre [3]. If possible, this would open up a new frontier for lepton collider physics, with the ability to investigate the Higgs sector and beyond with extremely high precision.

The AWAKE experiment intends to inject the 450 GeV proton beam from the CERN SPS into a 10m plasma cell. We hope to demonstrate average electric fields of hundreds of over 300 MV/m, peak fields in excess of 1 GV/m, capture and accelerate a low energy 20 MeV electron beam with high capture efficiency, and accelerate them to in excess of 2 GeV.

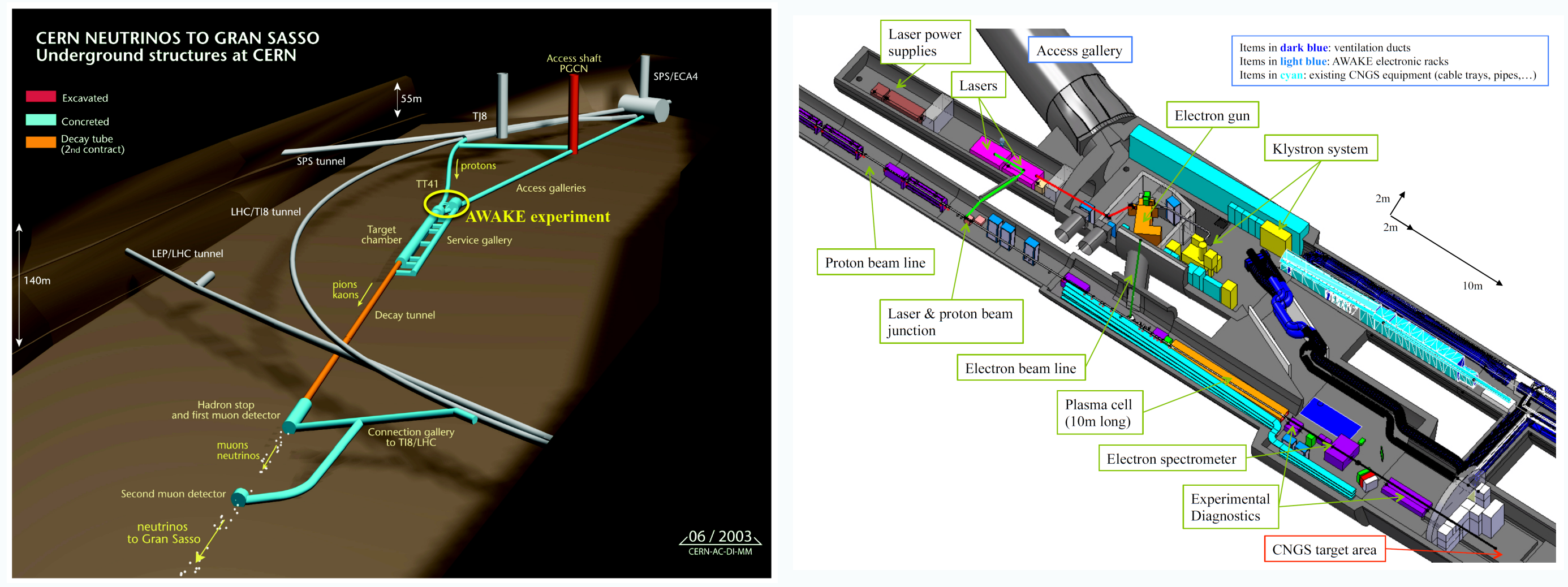


Figure 2: Proposed location of the AWAKE experiment at CERN, and experimental layout.

The SPS proton beam is injected into the plasma cell. A terawatt class laser is fired simultaneously to ionise the plasma. The protons drive the wakefield deep into the plasma where the electrons are side-injected, captured and accelerated by the wakefield.

Peak accelerating fields

To excite high intensity electric fields using the SPS proton beam (σ_z = 12 cm), the beam must be modulated into short micro-bunches, due to the inverse square relationship of field strength to bunch length (Eq. 1). This is readily achieved using the self-modulation instability, eliminating the need for SPS bunch-length compression [4]. In this case, the maximum electric field attainable is given by:

$$E_{z(\mathrm{max})} = \frac{q_e}{5ec\sqrt{m_e\varepsilon_0}}\frac{N}{\lambda_p\sigma_z^2} \qquad (1)$$

Equation 1: Maximum attainable electric field. q_e is the electron charge, e is Euler's number, c is the speed of light, m_e is the electron mass, ε_0 is the vacuum permittivity, N is the number of particles per bunch, λ_p is the plasma wavelength, and σ_z is the unmodulated RMS bunch length.

Simulating the injection of the SPS proton beam into a low density plasma (n = 7×10^{14} cm^{-3}), the growth of this electric field due to proton beam self-modulation is evident, yielding peak fields in excess of 1 GV/m (Fig. 3). By implementing a more advanced plasma cell architecture, this field is sustainable over 100 m, clearly scalable for a collider.

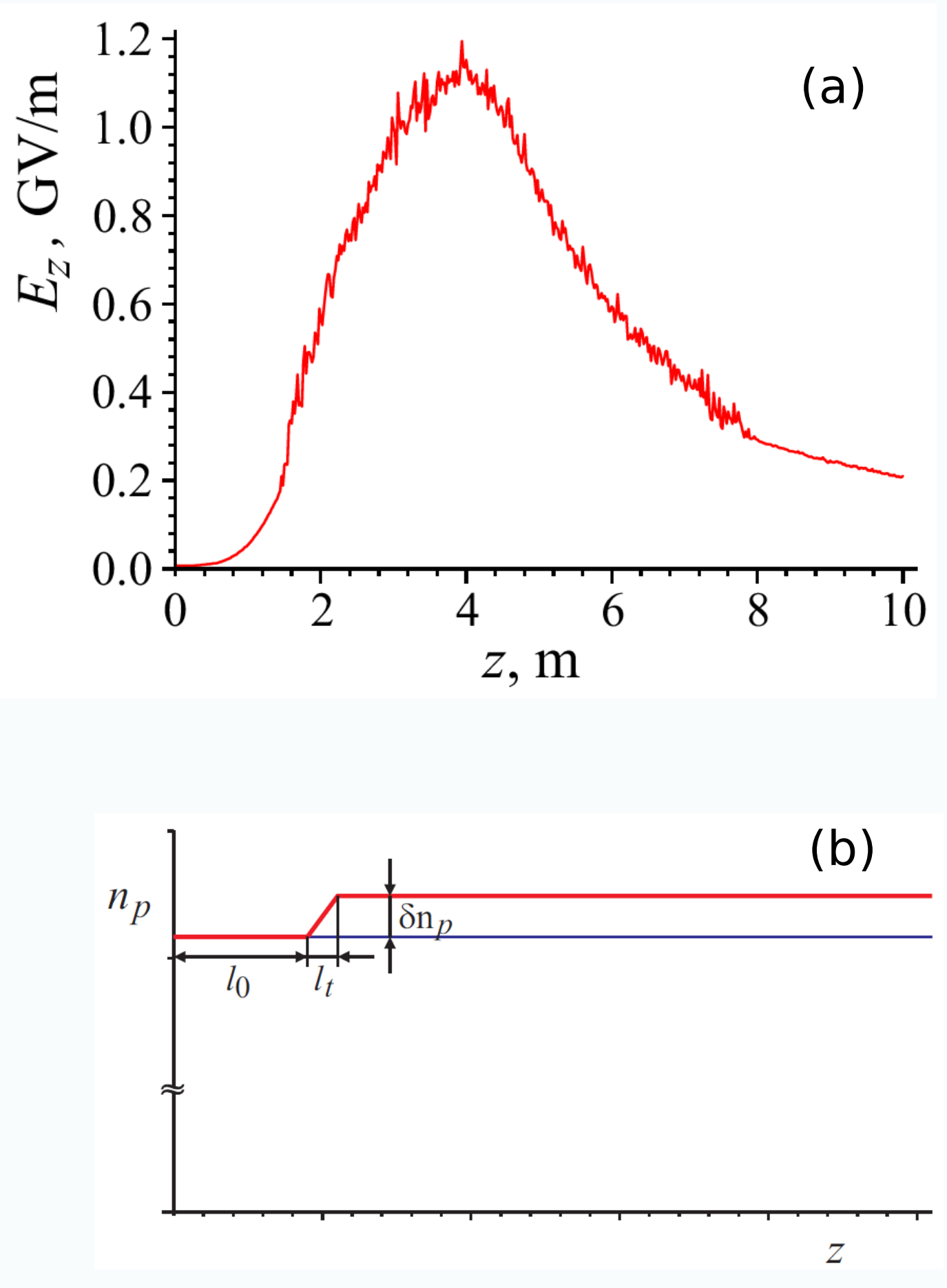
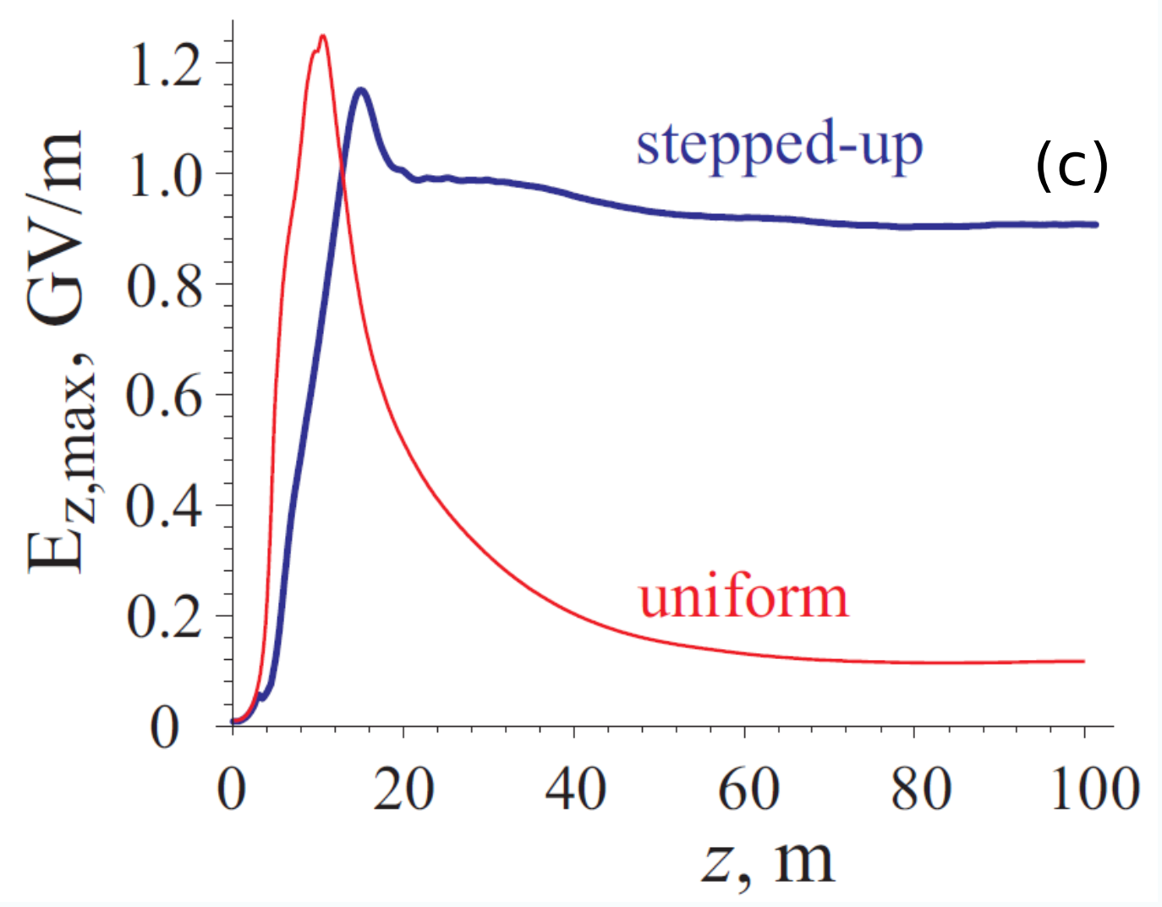


Figure 3: (a) Accelerating electric field versus position with a uniform plasma.
Initially the proton beam undergoes the self-modulation instability to become a train of micro-bunches. This generates the high intensity wakefield peaking at over 1 GV/m.
After 4 m, the micro-bunch train breaks apart, reducing field strength.
(b) By introducing a density ramp, this effect can be mitigated (shown in (c)), where the wakefield is maintained over 100 m.



Electron capture & acceleration

The ultimate aim is to demonstrate useful capture and acceleration of a low energy electrons, with electric fields much greater than that of a conventional accelerator, scaleable for use as the basis of a future linear collider.

The AWAKE collaboration is designing an electron gun to inject bunchs of 6×10^9 electrons (1 nC), of energies within the range of 10-20 MeV, to be injected at angles of 0-20 mrad. A spectrometer is also being designed to measure energies.

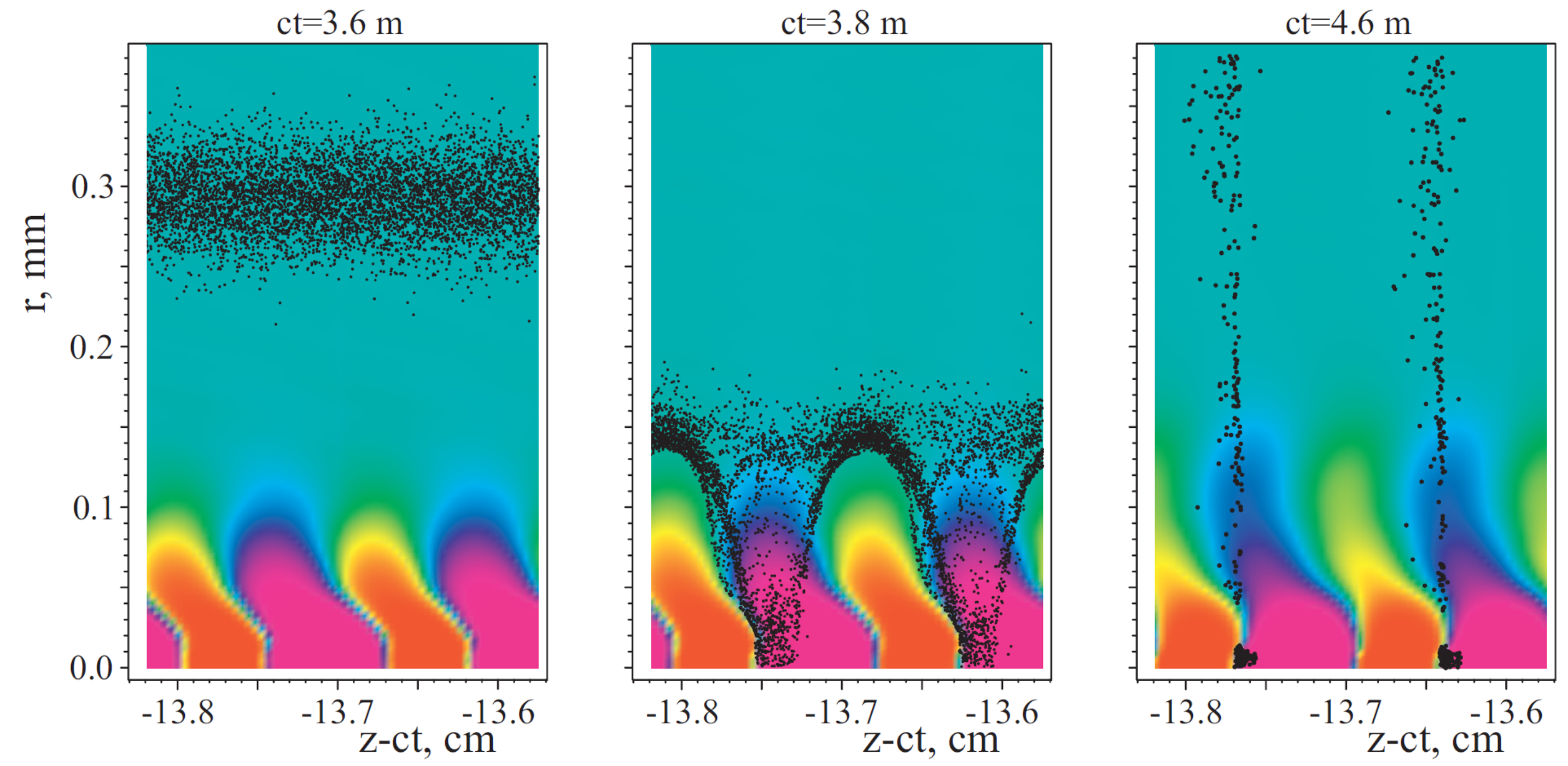


Figure 4: Example of the electron capture process. A long & narrow bunch of electrons (in black) are injected at a shallow angle (5-20 mrad) to the proton beam axis, into the potential wells of the plasma wakefield. The beams are designed to intersect after 4 m of propagation, but electrons are "pulled-in" earlier. After a metre of co-propagation, the majority of electrons are focused into a train of micro-bunches.

Simulations show we should be able to capture a signficant fraction of these electrons (5-40%), and accelerate them to in excess of 2 GeV over 6 m with narrow energy spread (Fig. 5).

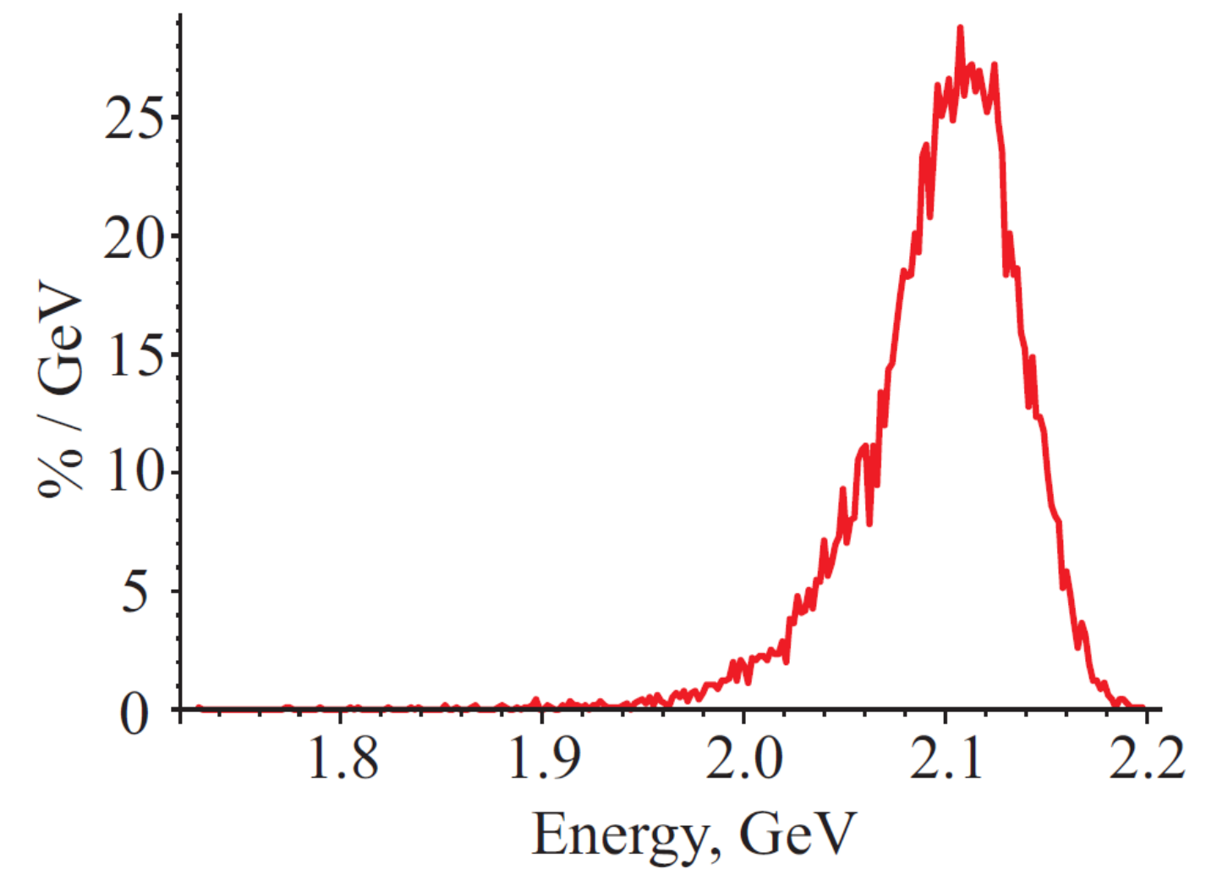


Figure 5: Histogram of the energy spectrum of the captured and accelerated electron beam. A 16 MeV electron beam is injected into a uniform plasma at 4 m, accelerated to over 2 GeV over 6 m, exhibiting a narrow energy spread.

Diagnostics

Novel diagnostics are under development. E.g., the novel new transverse coherent transition radiation diagnostic will enable orthogonal measurement of proton bunch modulation, and beam pointing instability [5]. A schematic is shown in Fig. 6.

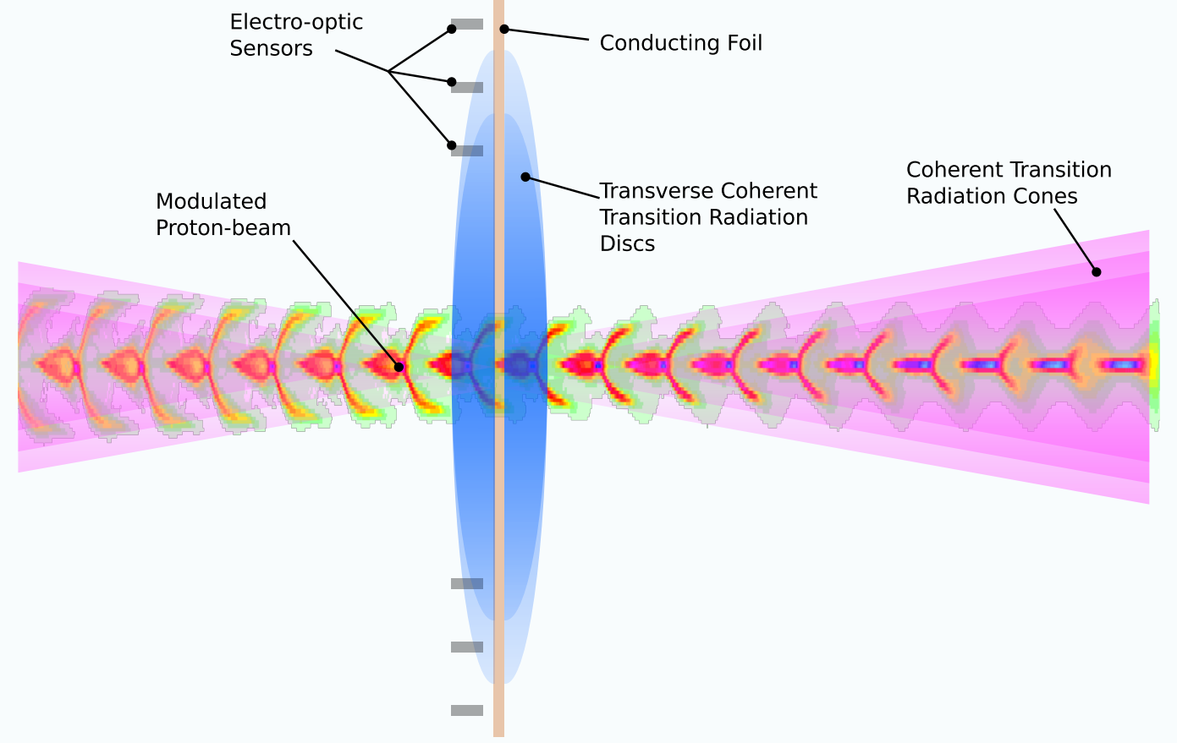


Figure 6: Schematic of the transverse coherent transition radiation diagnostic. The periodic radial beam profile generates symmetric dipole radiation upon traversing a conducting foil. A beam pointing instability will generate anti-symmetric radiation, measurable using electro-optics.

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[1]: Leemans et al. (2006, Oct.) Nature Physics vol. 2, pp. 696–699.
[2]: Guignard et al. (2000) CERN-2000-008.
[3]: Caldwell, Lotov, Pukhov, Simon, (2009, May) Nature Physics vol. 5, pp. 363–367.
[4]: Lotov (2011) Physics of Plasmas vol. 18, 024501.
[5]: Pukhov, Tückmantel (2012) Phys. Rev. ST Accel. Beams vol. 15, 111301.

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