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Proton-driven plasma-wakefield acceleration

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Plasmas excited by laser beams or bunches of relativistic electrons have been used to produce electric fields of 10–100 GV m^{-1}. This has opened up the possibility of building compact particle accelerators at the gigaelectronvolt scale. However, it is not obvious how to scale these approaches to the energy frontier of particle physics—the teraelectronvolt regime. Here, we introduce the possibility of proton-bunch-driven plasma-wakefield acceleration, and demonstrate through numerical simulations that this energy regime could be reached in a single accelerating stage.

We are on the brink of a new era in particle physics with the commissioning of the Large Hadron Collider (LHC) at CERN (European Centre for Particle Physics). The particle physics community has put forward a teraelectronvolt-scale electron–positron collider (the International Linear Collider) as the next large-scale project needed to elucidate the features of the microworld. The point-like nature of the electron is a great asset in extracting the basic physics. However, the loss of energy through radiation means the International Linear Collider must be built as a one-pass linear collider, and will therefore be very expensive. Here, we propose a new scheme for accelerating electrons up to this energy regime—proton-driven plasma-wakefield acceleration. The use of plasmas allows for very high electric fields, and therefore much more compact accelerators. High-energy protons are readily available, and can be used to generate the wakefields in such a way that the energy from a bunch of protons is transferred to a bunch of electrons. After an introduction to plasma-wakefield acceleration, the properties of the wakefields produced by highly relativistic proton bunches propagating through a plasma are described. A set of parameters is chosen and the resulting energy gain of electrons is presented.

It has been known for some time that plasmas can support very large electric fields, and can therefore be used for accelerating particles to relativistic energies[1–3]. Initially, laser-driven plasma-wakefield acceleration was considered in the literature[4], and experimental verification of the ideas followed[5–7]. Detailed simulations of the process are now available, which have indicated the production of electron beams with interesting characteristics. In recent experiments, gradients in the range 10–100 GV m^{-1} have been achieved. These have so far been limited to distances of a few centimetres, but the progress has been very impressive[8]. To accelerate an electron bunch to 1 TeV, these gradients would have to be maintained over distances of tens of metres, or many acceleration stages would have to be combined.

It was later recognized that the plasma could also be excited by an electron bunch[9]. Given an intense enough bunch of electrons, the plasma is both created[10] and excited by the passage of the bunch. Very large electric fields were predicted and later observed[11]. In the linear regime, the maximal achievable gradient can be written[12] as

$$E = 240(\mathrm{MV\,m^{-1}})\left(\frac{N}{4\times10^{10}}\right)\left(\frac{0.6}{\sigma_z(\mathrm{mm})}\right)^2 \qquad (1)$$

where N is the number of particles in the driving bunch and σ_z is the length (r.m.s.) of the bunch assuming a Gaussian beam profile. In the case of electron-driven plasma-wakefield acceleration, a gradient of 50 GV m^{-1} was achieved and sustained at Stanford Linear Accelerator Center for almost 1 m (ref. 13). However, the maximum energy that can be given to a particle in the witness bunch is limited by the transformer ratio,

$$R = \frac{E_{\mathrm{max}}^{\mathrm{witness}}}{E_{\mathrm{max}}^{\mathrm{drive}}} \leq 2 - \frac{N_{\mathrm{witness}}}{N_{\mathrm{drive}}}$$

which is at most two for longitudinally symmetric drive bunches[14]. This upper limit can in principle be overcome by non-symmetric bunches[15], but this could be difficult.

Plasma-wave excitation by a negatively charged driver is now well studied both theoretically[16–20] and experimentally[13,16,21]. In contrast to plasmas driven by electron beams, only limited investigations of the plasma-wave excitation by a positively charged driver exist[12,22–26]. In the linear wakefield regime, the electric field distribution should be the same as that for the negative driver but shifted in phase. However, the path to the nonlinear stage differs significantly as revealed in multi-dimensional particle-in-cell (PIC) simulations[27]. Physically, the negatively charged driver 'blows out' the background plasma electrons, creating a low-density region behind the driver. The nonlinear 'blow out' regime has quite useful properties that make it successful in plasma-based acceleration: it provides the very high accelerating field, which does not depend on the transverse coordinate, whereas the transverse fields are focusing both for the driver and for the witness bunch. The 'blow-out' regime allows a rapid energy transfer from the driver to the witness beam, thus leading to an efficient acceleration of electrons[28].

It is much more difficult to reach the blow-out regime with a positively charged driver, such as protons. Instead of 'blowing out' plasma electrons, they 'suck them in' towards the propagation axis. Owing to the radial symmetry, this leads to an electron density enhancement on-axis and effective increase of the local plasma frequency. As a result, the proton driver must be even shorter to excite the plasma wake resonantly. In the highly nonlinear regime, numerical simulations have to be relied on to find the optimal beam–plasma parameters for the resonant wakefield generation.

Given that protons can be accelerated to the teraelectronvolt regime in conventional accelerators, it is conceivable to accelerate electron bunches in the wake of the proton bunch up to several

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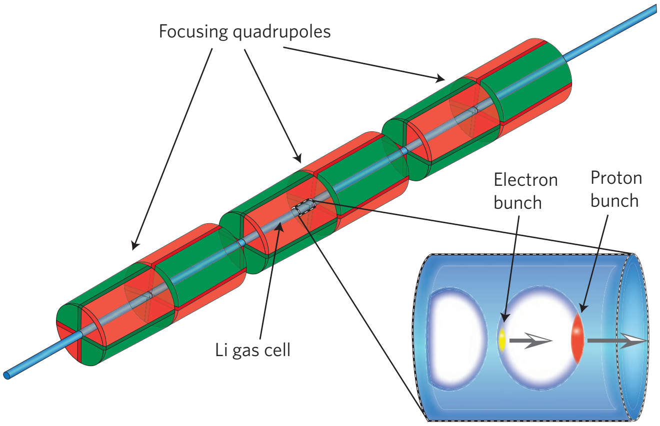

Figure 1 | A schematic description of a section of the plasma-wakefield-accelerating structure. A thin tube containing Li gas is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

teraelectronvolts (for example, in the wake of an LHC proton beam) in one pass through the plasma. Several issues come to mind, such as the possibility of producing a proton bunch with large enough charge density, the possibility of phase slippage as protons slow down, the effect of proton beam divergence and dissipation in the plasma and so on. We will discuss these points below. We then discuss a specific parameter set close to existing proton beams, and show that the production of a TeV electron beam is in principle allowed with a proton-driven plasma-wakefield accelerator.

Initial considerations

The accelerating structure we have studied for proton-driven plasma-wakefield acceleration is shown in Fig. 1. A high-density proton bunch propagates through the plasma and sets the plasma electrons in motion. For a highly relativistic driving bunch, the electric field seen by the plasma electrons is in the transverse direction, and the plasma electrons begin to oscillate around their equilibrium position with frequency ω_p given by

$$\omega_{\mathrm{p}} = \sqrt{\frac{n_{\mathrm{p}} e^2}{\epsilon_0 m}}$$

where n_p is the density of plasma electrons, ϵ_0 is the permittivity of free space and m is the mass of the electron. Given their large mass, the plasma ions are effectively frozen. The oscillating electrons initially move towards the beam axis, then pass through each other, creating a cavity with very strong electric fields. The cavity structure repeats, and the pattern moves with the proton-bunch velocity. An appropriately timed witness bunch can be placed in a region of very strong electric field and accelerated. The plasma also provides a radial force that keeps the witness bunch, as well as the tail of the drive bunch, from expanding radially.

In the linear regime, equation (1) applies to particles of either charge, and can therefore be used to calculate the field produced by a bunch of protons passing through a cold plasma (the nonlinear case will be discussed below). Proton bunches with 10^{11} particles are available today, and the main issue in producing strong electric fields in the plasma is the formation of short bunches. Teraelectronvolt proton beams typically have a relative momentum spread $\sigma_p/p = 10^{-4}$ and a r.m.s. bunch length of 50 cm. Assuming this longitudinal phase space area is preserved and that a technically feasible scheme for a phase rotation will be found, a proton bunch with $\sigma_z = 100\,\mu$m would have a momentum spread of about 50%. This is probably too large. The LHC foresees reaching $\sigma_p/p = 10^{-4}$ for bunches with a r.m.s. length of only 7.55 cm. In this case, $\sigma_z = 100\,\mu$m could in principle be achieved with a momentum spread of about 7.5%, which is much more favourable. We have simulated a 1 TeV proton driver with $\sigma_z = 100\,\mu$m and $\sigma_p/p = 0.1$.

As the proton bunch propagates, the momentum spread will induce a lengthening of the bunch. This can be evaluated for vacuum propagation as follows:

$$d \approx \frac{L}{2\Delta\gamma^2} \approx \left(\frac{\sigma_{\mathrm{p}}}{p}\right)\frac{M_{\mathrm{p}}^2 c^4}{p^2 c^2} L$$

where d is the spatial spread of the particles in the bunch induced by the momentum spread, L is the distance travelled, M_P is the proton mass, p is the proton momentum, γ is the Lorentz factor and c is the speed of light. Given a 1 TeV proton beam, 10% momentum spread leads to a growth of about $0.1\,\mu\mathrm{m\,m^{-1}}$. Large relative momentum spreads will still allow for long plasma-acceleration stages provided the drive beam is relativistic.

As mentioned above, the plasma has a strong focusing effect on the tail of the drive bunch, as well as on the witness bunch. However, the head of the drive bunch will tend to fly apart unless quadrupole focusing is applied. We therefore foresee an arrangement with strong focusing of the proton drive bunch along the length of the plasma channel. A possibility for these quadrupoles are small-diameter permanent magnets, such as those described in ref. 29, producing gradients of order $1\,\mathrm{T\,mm^{-1}}$.

Another issue is phase slippage between the proton driving bunch and the electron witness bunch. As the proton bunch travels through the plasma, it will slow down and the phase relation with the light electron bunch will begin to change. The phase change is given by[14]

$$\delta \approx \frac{\pi L}{\lambda_{\mathrm{p}}}\left[\frac{1}{\gamma_f \gamma_i}\right] \approx \frac{\pi L}{\lambda_{\mathrm{p}}}\left[\frac{M_{\mathrm{p}}^2 c^4}{p_f p_i c^2}\right]$$

where λ_p is the plasma wavelength and $p_{i,f}$ are the initial and final momenta of the protons in the driving bunch. To maximize the gradient (equation (1)), the plasma wavelength should have a definite relation to the length of the driving bunch:

$$\lambda_{\mathrm{p}} = \sqrt{2}\pi\sigma_z$$

Requiring a phase slippage of only a fraction of the plasma wavelength implies that the driving beam energy cannot change appreciably, and this could be a severe limitation on acceleration by a proton bunch. However, with an initial proton energy of 1 TeV and a final energy of 0.5 TeV, it should still be possible to have plasma lengths of many metres. In addition, it is possible to control the plasma wavelength by adjusting the density of the plasma[30], in part or fully compensating for the phase slippage.

Proton interactions in the plasma are not expected to be a big issue. The plasma density and plasma wavelength are related by

$$\lambda_{\mathrm{p}} \approx 1\,\mathrm{mm}\sqrt{\frac{10^{15}\,\mathrm{cm}^{-3}}{n_{\mathrm{p}}}}$$

Typical values of n_p will be in the range 10^{14}–$10^{17}\,\mathrm{cm}^{-3}$, and the mean free path for inelastic reactions of high-energy protons with the gas are orders of magnitude larger than the expected plasma cell length. A GEANT4 (ref. 31) simulation for a 1 TeV proton beam in Li vapour of density 1×10^{15} atoms cm^{-3} gives a transverse

Table 1 | Table of parameters for the simulation.

Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$T\,m^{-1}$
Magnet length		0.7	m

growth rate of the proton beam of less than 0.01 µm m^{-1} owing to multiple scattering, which is small compared with the size of the proton bunch.

Plasma-wave excitation by relativistic protons

We have simulated the wakefield-acceleration process assuming a pipe containing Li gas inserted in a region of alternating vertically focusing and defocusing quadrupole fields. The parameters of the simulation are listed in Table 1. It was assumed that the gas was fully ionized.

We have used the three-dimensional fully electromagnetic relativistic PIC code VLPL (ref. 32) as well as the quasi-static PIC code LCODE (refs 33, 34) to simulate the beam–plasma interaction. The three-dimensional PIC simulation gives a very detailed shape of the plasma wave and cross-checks the radially symmetric results of the quasi-static code. On the other hand, the computationally efficient quasi-static code allows the simulation of electron acceleration up to teraelectronvolt energies over hundreds of metres of plasma.

According to the linear wakefield formula, the optimal plasma density for the chosen beam parameters should be around 5×10^{15} cm^{-3}. However, our simulations have revealed that owing to the 'suck-in' effect, the proton beam excites a very poor plasma wave at this 'linearly predicted' density. Scanning over a range of plasma densities, we found that the optimal wake is produced at the plasma density roughly ten times lower, $n_p = 6\times10^{14}$ cm^{-3}.

The proton beam transverse size and angular spread also needed optimization. As expected, the plasma wave focuses and guides the tail of the bunch. However, the plasma field was too low to guide the head of the bunch. Without extra focusing, the proton bunch head would diffract over a distance of a few metres, whereas for teraelectronvolt acceleration hundreds of metres of propagation are needed. To overcome the natural beam diffraction, we simulated a magnetic quadrupole guiding system. The field strength of the quadrupole limits the allowed initial proton bunch angular spread, and this in turn sets a lower limit on the r.m.s. radius of the proton bunch (given a fixed transverse emittance 0.01 mm-mrad) of about 0.43 mm. This driver radius is not matched with the plasma density. Thus, the tail of the driver is subject to transverse betatron oscillations at the beginning of acceleration. Yet, after a few betatron periods it reaches dynamic equilibrium and becomes matched, while its head is guided by the quadrupoles.

The plasma wave generated by the proton driver is shown in Fig. 2. The rightmost region of high electron density in Fig. 2b, d results from plasma electrons being 'sucked in' by the proton bunch. The electrons then continue to move across the beam axis and create a depletion region very similar to the blow-out region seen

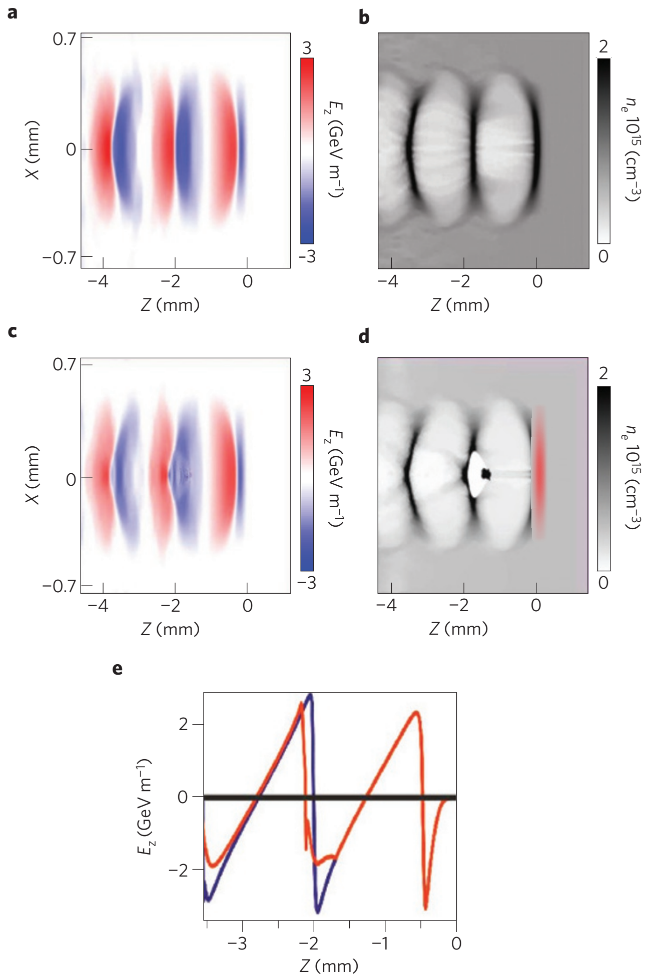

Figure 2 | The electric field strength and the electron density in the plasma. a–d, Simulation results for the unloaded (no witness bunch) case (**a**,**b**) and in the presence of a witness bunch (**c**,**d**). The witness bunch is seen as the black spot in the first wave bucket in **d**. **d** also shows the driving proton bunch at the wavefront (red). **e**, The on-axis accelerating field of the plasma wave for the unloaded (blue curve) and loaded (red curve) cases.

in the case of the electron driver. The electron witness bunch is placed on the left edge of the first bubble, where the longitudinal fields are strongest. The maximum accelerating field of the wave is about 3 GeV m^{-1}, as shown in Fig. 2e. The transverse electric fields in this region are also strong and act to focus the witness bunch. The accelerating gradient increases as the left edge of the bubble is approached, allowing for a low energy spread of the witness bunch. Taking advantage of this feature requires that the wave is properly loaded. The loading of the wakefield results in a lower maximum accelerating field than that seen in the unloaded wave. An appropriate witness bunch is also required for an efficient transfer of energy from the driver to the witness bunch. The electric field and electron density from the loaded plasma wave are shown in Fig. 2c, d. The maximum accelerating field is about 1.7 GeV m^{-1} and is nearly constant over the witness bunch. The transformer ratio is thus less than one, which results in the relatively low efficiency of proton-driven plasma-wakefield acceleration.

The acceleration over hundreds of metres of plasma has been simulated using the quasi-static code LCODE. Figure 3a–d shows snapshots of the particle phase space (energy versus distance from the front of the proton bunch) at several distances along the plasma. The proton bunch is initially distributed around 1 TeV, whereas the electron bunch has a fixed energy of 10 GeV. Further down the

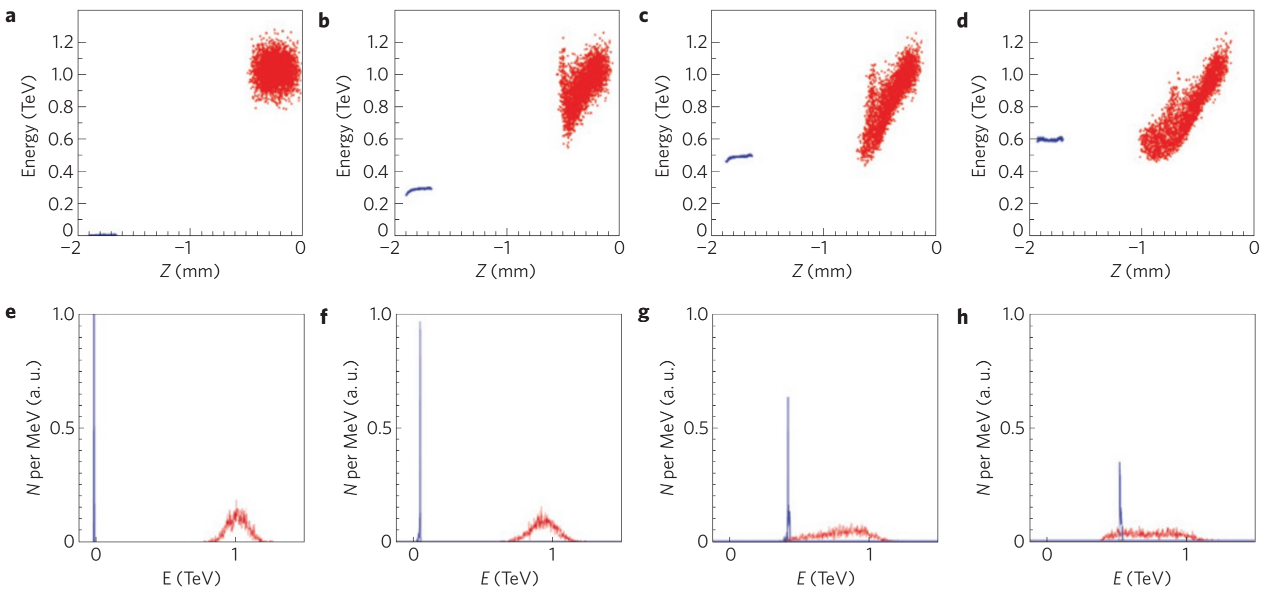

Figure 3 | Evolution of the proton bunch and electron bunch in the plasma. a–h, Snapshots of the combined longitudinal phase space of the driver and the witness bunches (energy versus coordinate) (**a–d**) and corresponding energy spectra (**e–h**). The snapshots are taken at acceleration distances $L = 0, 150, 300, 450$ m. The electrons are shown as blue points and the protons are depicted as red points.

channel, it is seen that the tail of the proton bunch loses significant amounts of energy, while the electron bunch picks up energy. Figure 3e–h shows the energy spectra of the driver and of the witness bunches at the chosen locations along the plasma channel.

The mean energy of the electron bunch as a function of the distance along the channel is shown in Fig. 4. After 450 m of acceleration, the electron bunch reaches a mean energy of 0.62 TeV per electron. The spread in the electron energy is also shown in Fig. 4, and is about 1% at the highest energies. This value could probably be improved with optimization of the witness bunch shape. The overall energy conversion from the driver bunch to the witness bunch after this distance was nearly 10% with nearly 100% of injected electrons present in the accelerated bunch. As can be clearly seen in Fig. 3a–d, the proton-bunch phase space changes considerably over the length of the channel, and the acceleration of the electron bunch decreases significantly after about 400 m. The proton bunch acquires a large spread in both momentum and position. After 450 m propagation, the proton bunch length grows so much that it leaves the resonance condition and the plasma-wave excitation becomes inefficient.

Simulations indicate that the normalized transverse emittance of the electron bunch is not significantly affected by the plasma acceleration (see also ref. 35). However, it should be noted that the scattering of electrons on plasma ions was not included in the PIC simulations. A separate simulation using GEANT4 indicates that the growth in emittance from this effect will be less than 0.02 nm-rad after 500 m of propagation in the plasma.

Outlook

The simulation results indicate that a proton bunch could indeed be used to accelerate a bunch of electrons to high energies. Further tuning of parameters would probably lead to improvements in simulation results. The key issue for the future applicability of proton-driven plasma-wakefield acceleration will be the ability to phase rotate a high-energy bunch of protons in such a way that the bunch is very short, of order 100 μm or less. Clearly, advances in longitudinal proton beam cooling would make this task much simpler.

The acceleration of positrons has not been addressed here, and could be considerably more difficult than the acceleration of electrons[36]. Initial investigations indicate that the electric field configurations do not have the broad equilibrium region seen for electron bunches, such that achieving a low energy spread will be

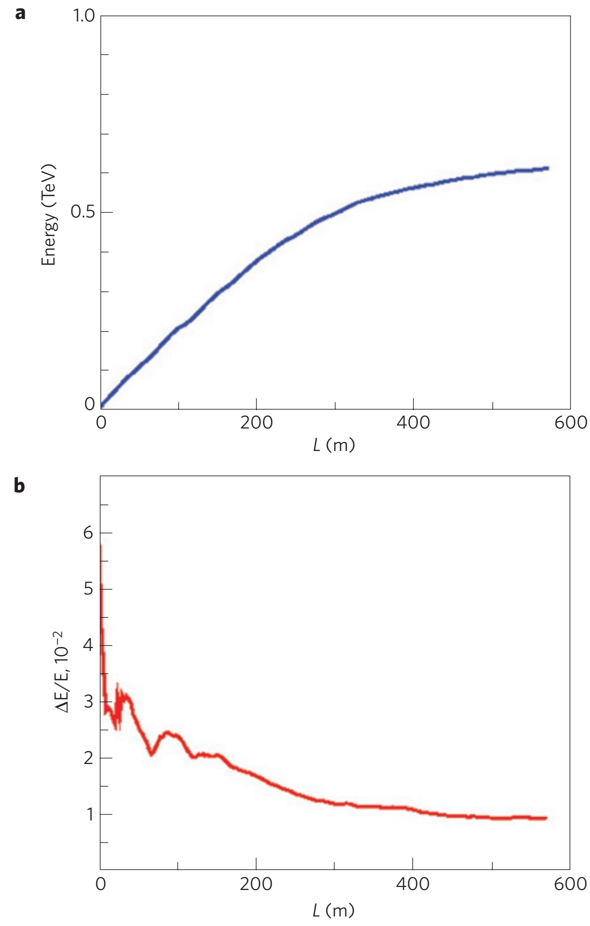

Figure 4 | Electron energy versus distance. a,**b**, The mean electron energy in TeV (**a**) and the r.m.s. variation of the energy in the bunch as a percentage (**b**) as a function of the distance travelled in the plasma.

challenging. Providing sufficient luminosities for an e^+e^- collider would require a high repetition rate of high-energy proton bunches, as well as strong focusing of the high-energy electron and positron bunches. Other issues that will need further study are the potential hosing instability and the proper shaping of the witness beam.

There are clearly many challenges to the development of a proton-driven plasma-wakefield accelerator. Given the potential of proton-driven plasma-wakefield acceleration demonstrated here, these challenges should be taken up and hopefully resolved.

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