FACET shows the way in accelerator research

By addressing key questions for a plasma wakefield accelerator, the Facility for Accelerator Science and Experimental Tests (FACET) at SLAC will help a scientific concept with extraordinary potential to become the accelerator technology of the 21st century.

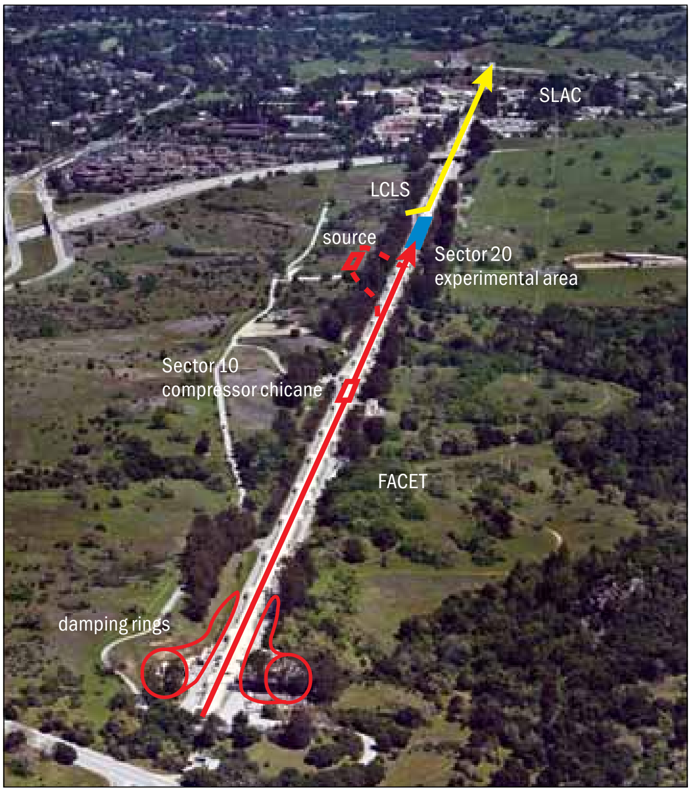

Fig. 1. Aerial view of SLAC showing the location of FACET, which will use the first 2 km of the main linac (red) to deliver high-energy electron and positron beams to a new experimental area (blue). The LCLS X-ray laser (yellow) uses the final kilometre of the SLAC linac. (Image credit: SLAC.)

In their quest to learn more about the fundamental nature of matter, high-energy physicists have developed particle accelerators to reach ever higher energies to allow them to "see" how matter behaved in the extreme conditions that existed in the very early universe. The LHC at CERN has set the latest record for this "energy frontier" in particle physics, but looking beyond the LHC affordable colliders operating at ever larger centre-of-mass energies will call for new – perhaps even radical – approaches to particle acceleration.

In the past decade, the plasma wakefield accelerator (PWFA) has emerged as one such promising approach, thanks to the spectacular experimental progress at the Final Focus Test Beam (FFTB) facility at the SLAC National Accelerator Laboratory. Experiments there have shown that plasma waves or wakes generated by high-energy particle beams can accelerate and focus both high-energy electrons and positrons. Accelerating wakefields in excess of 50 GeV/m – roughly 3000 times the gradient in the SLAC linac – have been sustained in a metre-scale PWFA to give, for the first time using an advanced acceleration scheme, electron energy gains of interest to high-energy physicists (*CERN Courier* June 2007 p28).

To develop the potential of the PWFA and other exploratory advanced concepts for particle acceleration further, the US Department of Energy recently approved the construction of a new high-energy beam facility at SLAC: the Facility for Accelerator Science and Experimental Tests (FACET). It will provide electron and positron beams of high energy density, which are particularly well suited for next-generation experiments on the PWFA (Hogan *et al.* 2010).

In 2006 the FFTB facility was decommissioned to accommodate the construction of the Linac Coherent Light Source (LCLS) – the world's first hard X-ray free-electron laser (*CERN Courier* December 2010 p17). The new FACET facility is located upstream of the injector for the LCLS (figure 1). It uses the first 2 km of the SLAC linac to deliver 23 GeV electron and positron beams to a new experimental area at Sector 20 in the existing linac tunnel. By installing a new focusing system and compressor chicane at Sector 20, the electron beam can be focused to 10 μm and compressed to less than 50 fs – dimensions appropriate for research on a high-gradient PWFA. Comparable positron beams will be provided with the addition of an upstream positron bunch-compressor in Sector 10. Peak intensities greater than 10^{21} W/cm^2 at a pulse repetition rate of 30 Hz will be routinely available at the final focus of FACET. Electron and positron beams of such high energy-density are not available to researchers anywhere else in the world.

The construction phase of the FACET project started in July ▷

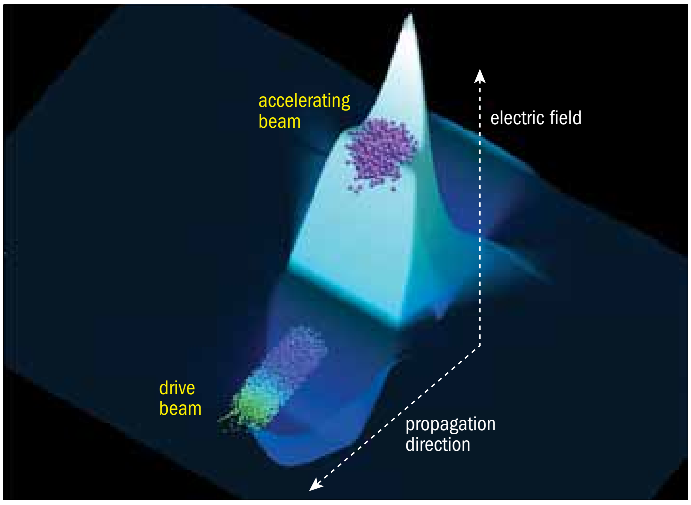

Fig. 2. The principle of plasma wakefield acceleration. The propagation of a short but intense electron drive-beam through a plasma produces a wake. The beam particles in the drive beam lose energy in exciting the wake, whereas the particles at the back – the accelerating beam – gain energy as the longitudinal electric field reverses its sign. (Image credit: F Tsung/UCLA.)

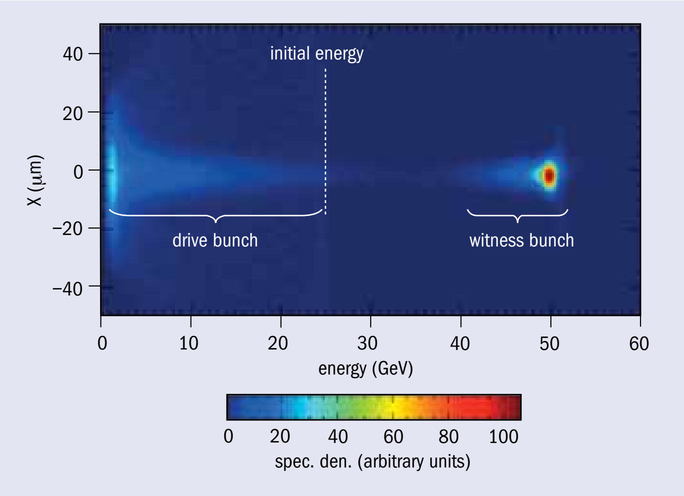

Fig. 3. Computer simulations of the change in energy experienced by drive and trailing beams, initially of 23 GeV, as they propagate through a metre-scale plasma. The drive beam loses nearly all of its energy in exciting the wake, whereas the trailing beam doubles its energy to nearly 50 GeV while maintaining a narrow energy spread (Hogan et al. *2010).*

2010 and should finish in April this year. Beam commissioning will follow and the first experiments are expected to begin in the summer. A recently completed shielding wall at the end of Sector 20 allows simultaneous operation of FACET and the LCLS.

The FACET beam will offer new scientific opportunities not only in plasma wakefield acceleration but also in dielectric wakefield acceleration, investigation of material properties under extreme conditions and novel radiation sources. To get a head start on the research opportunities, university researchers and SLAC physicists met at SLAC in March 2010 for the first FACET Users Workshop. This was the first opportunity for SLAC to unveil details about FACET's capabilities and for the visiting scientists to outline their research needs. Beam time will be allocated using an annual, peer-reviewed proposal process.

The plasma wakefield technique

In the PWFA a short but dense bunch of highly relativistic charged particles produces a space-charge density wave or a wake as it propagates through a plasma. As figure 2 shows, the head of the single bunch ionizes a column of gas – lithium vapour – to create the electrically neutral plasma and then expels the plasma electrons to set up the wakefield. As the plasma electrons rush outward, they create a longitudinally decelerating electric field that extracts energy from the head of the bunch. The plasma ions that are left behind create a restoring force that draws the plasma electrons back to the beam axis. When the electrons rush inwards, they create a longitudinally accelerating field in the back half of the wake, which returns energy to the particles in the back of the same bunch or alternately to a distinct second accelerating bunch. The plasma thus acts as an energy transformer.

The FFTB plasma wakefield experiments used a single 20 kA electron drive bunch to excite 50 GeV/m wakes in plasma of density 2.7×10^{17} e^-/cm^3. Energy was transferred from the particles in the front of the bunch to the particles in the tail of the same bunch via the wakefield. These experiments verified that the accelerating gradient scales inversely with the square of the bunch length and demonstrated that these large fields can be sustained over distances of a metre, leading to doubling of the energy of the initially 42 GeV electrons in the trailing part of the drive bunch.

Plasma wakefield acceleration will be a major area of research at FACET. Simply put, this research will strive to answer most of the outstanding physics issues for high-gradient plasma acceleration of both electrons and positrons, so that the potential for a PWFA as a technology for a future collider can be realistically assessed. The main goal of these future experiments is to demonstrate that plasma wakefield acceleration can not only provide an energy gain of giga-electron-volts for electron and positron bunches in a single, compact plasma stage, but can also accelerate a significant charge while preserving the emittance and energy spread of the beam.

The plasma wakefield experiments on FACET will need two distinct bunches, each about 100 fs long separated by about 300 fs. The first contains about 10 kA of peak current both to produce a uniform, metre-long column of plasma and then to drive the wake. The second bunch, which extracts energy from the wake, has a variable peak current. The sub-100 fs bunches needed for plasma wakefield acceleration are generated at FACET through a three-stage compression process that continually manipulates the longitudinal phase space so as to exchange correlated energy spread for bunch length, in a process called "chirped pulse compression". There will be an additional collimation system within the final compression stage at FACET and the collimation in the transverse plane will result in structures in the temporal distribution of the final compressed bunch(es).

In this way FACET will produce two co-propagating bunches. By adjusting the charge and duration of the witness bunch, FACET will be able to pass from the regime of negligible beam-loading that has been studied so far to beam acceleration with strong wakeloading. By loading down or flattening the accelerating wakefield, FACET will accelerate the witness bunch with a narrow, well defined, energy spread as the simulation in figure 3 shows.

Key beam properties

High-energy physics applications require not only high energies but also high beam power to deliver sufficient luminosity. For a linear collider with an energy of tera-electron-volts in the centre-of-mass this translates to nearly 20 MW of beam power for a luminosity of $10^{34}\,\text{cm}^{-2}\text{s}^{-1}$. When combined with the efficiencies of other subsystems (wall-plug to klystron to drive beam), maximizing the efficiency of the plasma interaction will be a crucial element in keeping down the overall costs of the facility. For example, a recent conceptual design for a PWFA-based linear collider (PWFA-LC) used a drive-beam-to-witness-beam coupling of 60% to achieve an overall efficiency of 15% (Seryi *et al*. 2009). Theoretical models and computer simulations have estimated the efficiency of the plasma interaction to be on the order of 60% for Gaussian beams and approaching 90% for specifically tailored current profiles (Tzoufras *et al*. 2008).

Improving accelerator performance using spatially and temporally shaped pulses is one of the forefronts of research in beam physics that can be explored at FACET. Tailoring the current profile of the drive beam allows the plasma to extract energy at a uniform rate along the bunch so as to maximize the overall efficiency. Figure 4 shows an example of such a tailored current profile for FACET and the accompanying simulated plasma wake. Bunch shaping has the added benefit of increasing the transformer ratio – that is, the ratio of the peak accelerating field divided by the peak decelerating field. A larger transformer ratio will lead to more energy gain per plasma stage. Finally, tailoring the profile of the witness beam loads the accelerating wakefield to produce the ▷

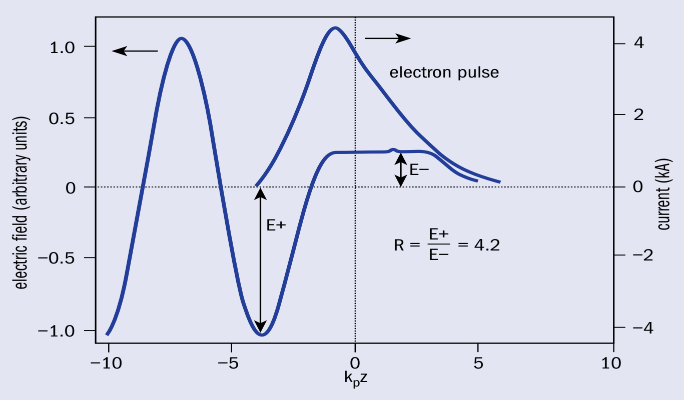

Fig. 4. Shaped electron bunches – with a long rise time and a shorter fall time – can be generated at FACET. Such bunches can produce wakes that have a transformer ratio, R > 4.

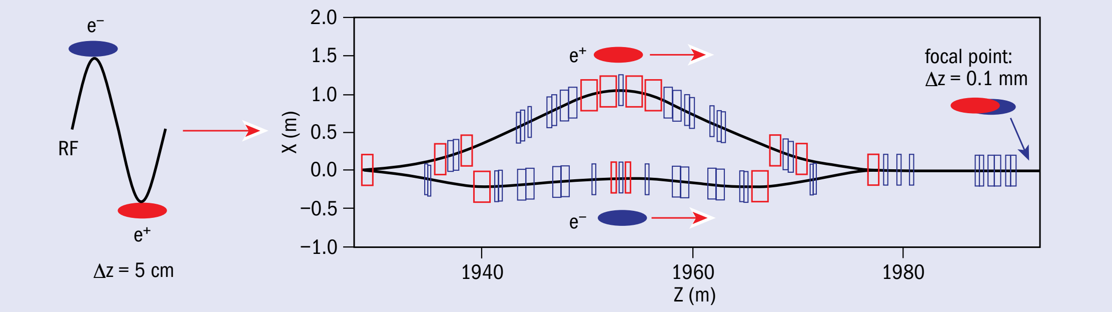

Fig. 5. A possible upgrade to the FACET beamline will add a second (top) chicane to the existing (bottom) chicane, allowing precise positioning of a positron bunch behind an electron bunch or vice versa.

desired narrow energy spread.

In addition to high beam power, the luminosity needed to do physics at the energy frontier will require state-of-the-art emittance with final beam sizes in the nanometre range. The ion column left in the wake of the drive beam provides a focusing channel with strong focusing gradients (MT/m for 10^{17} e$^-$/cm^3) that are linear in radius and constant along the bunch. This ion column allows a trailing witness bunch to propagate over many betatron wavelengths in a region free of geometric aberrations and emittance growth. There are however other sources of emittance growth in the PWFA. For instance, hosing instability (in which any transverse displacement of the beam slices grows as the beam propagates) between the beam and the wake, motion of the plasma ions in response to the dense beam, synchrotron radiation and multiple-Coulomb scattering can all lead to emittance growth. For a plasma accelerator at a few tera-electron-volts, the latter two effects have been shown to be negligible for appropriately injected beams. Experiments at FACET will determine the influence of the electron hose instability and the ion motion on emittance growth.

Positron acceleration

Although plasma wakefield acceleration may find applications in areas other than high-energy physics, such as compact X-FELs, collider applications will require plasmas to accelerate not only electrons, but also positrons. Studies have already shown that relatively long positron bunches can create wakefields analogous to the electron case, which can be used to accelerate particles over distances of a metre or so with energy gains approaching 100 MeV (Blue *et al*. 2003). The response of the plasma to the incoming positron beam is different than for an electron beam. In the positron case, the plasma electrons are drawn in towards the beam core. This leads to fields that vary nonlinearly in radius and position along the bunch, resulting in halo formation and emittance growth (Hogan *et al*. 2003 and Muggli *et al*. 2008). FACET will be the first facility in the world to deliver compressed positron bunches suitable for studying positron acceleration with gradients of giga-electron-volts per metre in high-density plasmas.

Recent studies have shown that there may be an advantage in accelerating positrons in the correct phase of the periodic wakes produced by an electron drive beam. A simple yet elegant study of this concept will be done at FACET by placing a converter target at the entrance of the plasma cell and allowing the trailing witness beam to create an e$^-$/e$^+$ shower. The positrons born at the correct phase will ride the wake of multi-giga-electron-volts/metre through the plasma and emerge from the downstream end with a potentially narrow energy spread and emittance (Wang *et al*. 2008). In the longer term, FACET has been designed to allow an upgrade to the Sector 20 beam line, called a "sailboat chicane", which will allow electron and positron bunches from the SLAC linac to be delivered simultaneously to the plasma entrance with varying separation in time (figure 5). By switching the bunch order and delivering the compressed positron beam to the plasma first, FACET can also study the physics of proton-driven plasma wakefield acceleration (*CERN Courier* March 2010 p7). The combination of high energy, and high peak-current electron and positron beams will make FACET the premier facility in the world for studying advanced accelerator concepts and lead the way in turning plasma wakefield acceleration into a future accelerator technology.

● Work supported by the US Department of Energy under contract numbers DE-AC02-76SF00515 and DE-FG02-92ER40727.

● Further reading

M Hogan *et al.* 2010 *NJP* **12** 055030.
A Seryi *et al.* 2009 *Proc. Particle Accelerator Conf.* (Vancouver, BC, 4–8 May 2009).
M Tzoufras *et al.* 2008 *Phys. Rev. Lett.* **101** 145002.
B Blue *et al.* 2003 *Phys. Rev. Lett.* **90** 214801.
M Hogan *et al.* 2003 *Phys. Rev. Lett.* **90** 205002.
P Muggli *et al.* 2008 *Phys. Rev. Lett.* **101** 055001.
X Wang *et al.* 2008 *Phys. Rev. Lett.* **101** 124801.

Résumé

FACET : à la pointe de la recherche sur les accélérateurs

Durant la dernière décennie, la technique d'accélération par champ de sillage plasma (PWFA) est apparue comme une voie prometteuse pour atteindre des énergies dépassant les limites actuelles de la technologie des collisionneurs. Afin de développer le potentiel de ce mode d'accélération, ainsi que d'autres concepts d'avant-garde pour l'accélération des particules, le ministère de l'Énergie des États-Unis a récemment approuvé la construction d'une nouvelle installation pour faisceau de haute énergie au SLAC National Accelerator Laboratory. FACET (Installation pour la science des accélérateurs et les essais expérimentaux) fournira des faisceaux d'électrons et de positons à haute densité d'énergie, qui seront particulièrement adaptés aux expériences de la prochaine génération sur l'accélération par champ de sillage plasma.

Mark Hogan, SLAC, **Chan Joshi**, University of California Los Angeles, and **Patric Muggli**, University of Southern California.