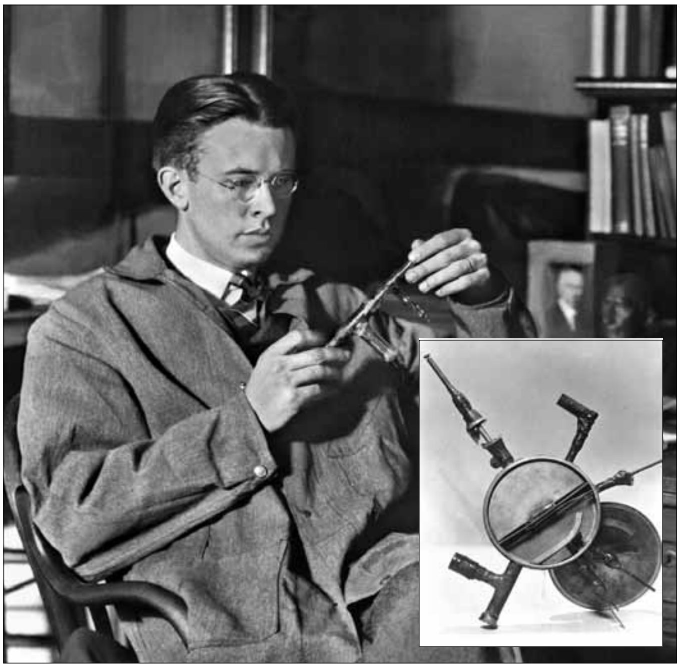

Fig. 1. Left: Ernest Lawrence invented the first circular accelerator in 1930. His cyclotron was 10 cm in diameter and accelerated protons to 80 kV. (Courtesy LBNL.) The first laser was a ruby laser produced by Theodore Maiman in 1960. (Courtesy HRL Laboratories.)

How lasers cast a light on accelerator science

Since their invention, lasers have played important roles in research at particle accelerators. This link is set to continue growing ever closer, as **Chan Joshi** explains.

Particle accelerators, invented during the first half of the 20th century, and lasers, invented during the latter half of the 20th century, are arguably the two most successful tools of scientific discovery ever devised. The first cyclotron, which Ernest Lawrence conceived of in 1930, and the first laser, which Theodore Maiman produced exactly 30 years later, were both palm-size devices (figure 1). Just as the cyclotron was followed by betatrons, synchrotrons and colliders, the ruby laser was followed by other solid-state, liquid, gaseous and semiconductor lasers. Since their inception, both lasers and accelerators have found applications in science, medicine and industry. Today, in contrast to their humble antecedents, the LHC at CERN and the laser of the National Ignition Facility at Lawrence Livermore National Laboratory (LLNL) are indisputably the most complex scientific instruments ever constructed for particle physics and inertial-fusion research, respectively.

The relationship between these two inventions runs deeper than this parallel history. Accelerator-based free-electron lasers (FELs) have over the past three decades been extending the capabilities of coherent light sources (p17). On the flip side, intense, short-pulse lasers are being used to accelerate charged particles at a rate thousands of times greater than is possible using conventional microwave accelerators (*CERN Courier* June 2007 p8). There is little doubt that these two great inventions will continue to be the premier tools of scientific discovery in the foreseeable future.

Laser Compton scattering

Lasers began to play an important role in accelerator-based science not long after their invention. In a head-on collision between photons and electrons the Compton scattered (CS) photons are shifted up in frequency by a double Doppler shift. Within four years of the invention of the laser in 1960, a ruby laser was used to demonstrate Compton scattering of laser photons off a 6 GeV electron beam ▷

at the Cambridge Electron Accelerator (Bemporad *et al.* 1965). This was the first time that photons of a few electron-volts had been frequency up-shifted more than 100 million times to produce gamma-ray photons with energies of more than 100 MeV. Since then, laser CS photons at these energies have been used for nuclear physics. It was not until the late 1990s – when lasers had become sufficiently powerful – that collisions between giga-electron-volt CS photons, off relativistic electrons, and multiple laser photons were able to produce electron–positron pairs in the first demonstration of light-by-light scattering (Burke *et al.* 1997).

These early experiments used head-on collisions between giga-electron-volt electrons and visible laser photons to produce CS photons in the giga-electron-volt range. However, X-ray photons with an energy of a few kilo-electron-volts are needed for many scientific applications, such as to probe structural dynamics in condensed matter. In 1996, using the 50 MeV injector beam of the Advanced Light Source at the Lawrence Berkeley National Laboratory (LBNL), experimenters made a laser pulse collide with the electrons at 90° to produce the first subpicosecond pulses of X-ray photons with a wavelength of 0.04 nm (Schoenlein *et al.* 1996).

Compton scattering can also occur when an electron beam passes through a periodically varying magnetic field, such as in a magnetic wiggler or an undulator. Here, the static magnetic field looks like an electromagnetic wave in the frame of the relativistic electrons: the electrons Compton scatter these photons, which in classical terms is just synchrotron radiation. In an FEL, Compton scattering provides the noise photons (spontaneous emission) that are subsequently amplified by the FEL instability (stimulated emission). The subpicosecond photon-pulse facility (SPPS) at SLAC – a precursor of the Linac Coherent Light Source (LCLS) – showed that sub-100 fs X-ray pulses could be obtained via an undulator-based CS source of photons in the 10 kV range (Cornacchia *et al.* 2001).

It is extremely difficult for an electronic transition to provide laser action at such short wavelengths because the pumping density – required to achieve gain – scales as the frequency of the photons to the fourth power. Therefore, it is likely that above a photon energy of 1 kV, FELs are the only way to generate high-power, coherent radiation. In an FEL, the electron beam must be bunched on the scale of the photon wavelength so that the phases of the emitted photons all add coherently. This places a stringent requirement on the normalized emittance (ε_N) of the electron beam. However, the recent success of the LCLS has shown that accelerators are capable of producing beams of the necessary brightness (I/ε^2_N, where I is peak current) to produce tunable coherent photon beams in the 1–10 kV range (figure 2).

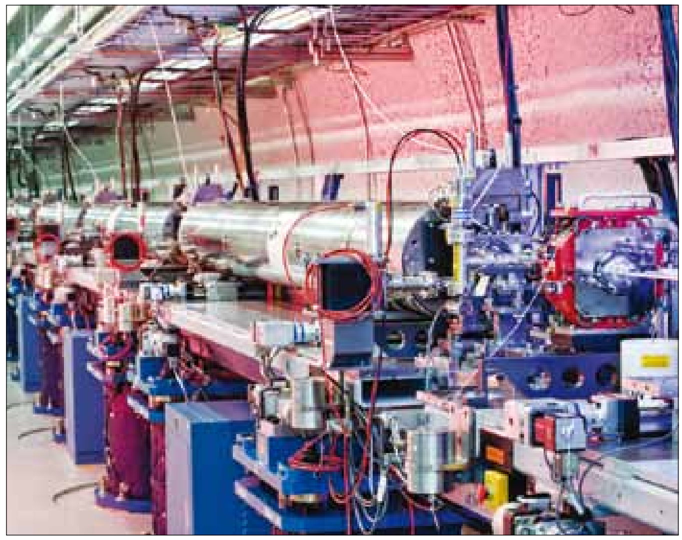

Fig. 2. Inside view of the undulator hall of the LCLS. The world's shortest wavelength laser is based on conventional accelerator technology. (Courtesy Brad Plummer/SLAC.)

Lasers at light sources and accelerators

Synchrotron-radiation facilities such as the European Synchrotron Radiation Facility, France, the Advanced Photon Source, US, and Spring-8, Japan, are now being used by thousands of scientists in virtually every field. The key innovation that led to orders of magnitude increase in the brilliance of the emitted radiation was the introduction of insertion devices, i.e. magnetic wigglers and undulators. Many "pump-probe" experiments on these machines use undulator-produced X-ray photons to pump or induce change/damage in atoms/molecules, electronic and biological samples, together with a time-delayed laser pulse to probe the induced change, or vice versa. These pump-probe experiments on ultrafast phenomena using accelerator-based light sources will continue to push the boundaries of experimental science in the coming years.

How are the high-brightness electron beams needed for X-ray FELs and for future colliders for high-energy particle physics produced? Here, again, lasers have played a critical role. Until the mid-1980s, thermionic cathodes embedded in RF cavities were used to produce electron bunches. It was realized that the emittance of beams from these RF guns could be greatly improved by replacing the thermionic cathode (LaB_6 for instance) by a photocathode (Cu, Mg or alkali cathode). Richard Sheffield and colleagues at Los Alamos National Laboratory carried out pioneering work on the first photo-injector gun with a Cs_3Sb cathode (Sheffield *et al.* 1996). By illuminating the photocathode with a short laser pulse of photons with an energy just greater than the work function of the cathode material and by operating the gun at high gradients, very high currents of electron bunches with emittances less than 1 mm mrad have been produced (Akre *et al.* 2008). For FELs, the short duration combined with low emittance implies a beam of high brightness that can be readily bunched by the FEL instability on the wavelength scale of the emitted radiation. Almost all recent FELs, including FLASH at DESY (p21), the high-gain harmonic-generation (HGHG) FEL at Brookhaven National Laboratory and the LCLS at SLAC, use photo-injector guns as the source of electrons.

Lasers are also routinely used for alignment and diagnostics in particle accelerators. A "laser wire" is a type of beam-profile monitor used to sample nondestructively the transverse profile of intense electron or positron beams that would ordinarily destroy a thin metallic wire. The local density of the beam is sampled through collisions with a tightly focused laser pulse that has a spot size smaller than the particle beam. The relative CS yield provides a measure of the beam profile.

Future linear colliders for particle physics will bring nanometre-sized beams of electrons and positrons into head-on collision, maximizing the luminosity. Conventional techniques for measuring the

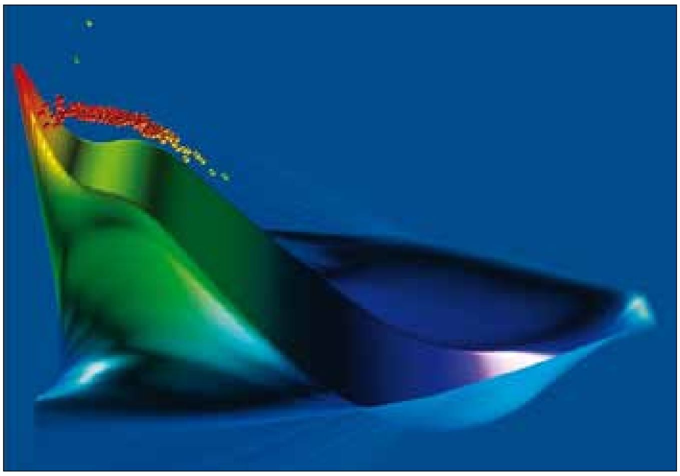

Fig. 3. Computer simulation of electrons (dots) being accelerated by the longitudinal electric field of a wake produced by a laser pulse in plasma. Laser wakefield acceleration has produced the world's highest gradient (100 GeV/m) accelerator. (Courtesy C Huang, Los Alamos National Laboratory, and F Tsung, UCLA.)

size of the beam spot, such as the laser-wire scanning described above, are not suitable for measuring submicron spots. Instead, laser photon CS at 90° has been used as a noninvasive diagnostic technique for measuring ultrasmall beam sizes (Shintake 1992). Two counter-propagating laser beams produce a standing-wave interference pattern. As the focused electron bunch is scanned across this interference pattern (using a weak steering magnet) the gamma-ray yield is modulated and the depth of modulation of the CS gamma-ray flux gives the spot size. This technique has been used at the Final Focus Test Beam Facility at SLAC to measure a 47 GeV beam with a transverse size as small as 60 nm. A modified version of this technique using a propagating beat-wave interference pattern can be used as a bunch-length monitor.

Measurement of the width of highly relativistic electron bunches shorter than 100 fs poses a serious challenge. Fortunately, the transverse electric field of such bunches can itself be used to induce a change in the polarization of a synchronized laser pulse in an electro-optic crystal that is placed in the vicinity of the beam (Cavalieri *et al.* 2005). The duration of the photons that are affected by the polarization change can then be measured to give the pulse width of the electrons.

Accelerating with lasers

Lasers are now being used directly to produce medium-energy (100 MeV–1 GeV) electron beams (Leemans and Esarey 2009). Indeed, laser particle acceleration has grown into a distinct subfield of research since the first Laser Acceleration of Particles Workshop at Los Alamos in 1982. A short but intense laser pulse propagating through plasma can excite a wave in space-charge density, also called a wake, behind the pulse. The longitudinal electric field of this wake can be tens of giga-volts per metre, which is large enough to capture some of the plasma electrons and accelerate them (figure 3). However, the wake propagates at a phase velocity that is equal to the group velocity of the laser pulse in the plasma. Since the group velocity of a photon packet in a medium is always less than the speed of light, the accelerating electrons continuously dephase with respect to the wake. A combination of beam loading and dephasing leads to a quasi-monoenergetic beam of electrons whose energy increases as the plasma density is decreased. The transverse spread of the electrons can be a few microns and the emittance less than 1 mm mrad. Several groups are embarking on research programmes to demonstrate the coherent amplification of undulator radiation, with the eventual goal of demonstrating a tabletop, extreme-ultraviolet FEL based on a laser-wakefield accelerator (LWFA).

Although a laser-based plasma accelerator operating at the energy frontier is at this stage far into the future, the US Department of Energy (DoE) has funded the construction of a research facility called BELLA at LBNL whose goal is to demonstrate a 1 m-scale 10 GeV LWFA that can then be staged multiple times to give high energies (*CERN Courier* January/February 2010 p8).

An alternative approach is to use a laser pulse to produce an accelerating electromagnetic mode directly in a miniature photonic band-gap structure or a slow wave structure in a plasma medium. It is too early to say what the eventual architecture of a high-energy accelerator based on these concepts would look like but the research is fascinating in its own right.

A bright future

In the future we are likely to see even greater merging of lasers and accelerators. Laser CS has been proposed as a method for generating polarized positrons for a future e^+e^- collider using a high-finesse laser cavity in conjunction with an electron storage ring operating at a few giga-electron-volts. In this proposal the electron micro-bunches collide with (the circularly polarized) laser photons circulating in the cavity to produce the CS photons. These polarized multimega-electron-volt photons then collide with a target of high atomic number (Z) to produce a copious number of polarized positrons via pair production (Araki *et al.* 2005).

A CS-based gamma–gamma collider would be a natural second interaction region for any future e^+e^- collider because cross-sections for some reactions are larger for gamma–gamma collisions than for e^+e^- collisions (Telnov 1990). With a proper choice of laser wavelength and intensity, much of the electron energy can be converted into the gamma-ray photon and, with a net yield of about one photon per electron, the final luminosity of a gamma-gamma collider can be comparable to that of an e^+e^- collider (Kim and Sessler 1996). While the peak power (1 TW) and the pulse width (1 ps) required for the laser used in a gamma–gamma collider are easily obtained today, the repetition rate of such lasers is still a couple of orders of magnitude lower than in state-of-the-art lasers. There is reason for optimism, however, because diode-pumped solid-state lasers appear promising for achieving the high average powers needed.

Other possible uses of laser CS photons are for nuclear spectroscopy, where the transition energies are in the multimega-electron-volt range, as mentioned above, and for the detection of hidden fissionable materials via the observation of nuclear resonance fluorescence (NRF). If the line-width of the CS photons can be made to be less than that of nuclear transitions, then such a source could revolutionize nuclear spectroscopy much in the same way that tunable lasers have transformed atomic spectroscopy. An example of an ambitious CS source is MEGa-ray (mono-energetic gamma-ray), now under development at LLNL. It uses a state-of-the-art 250 MeV, X-band accelerator to generate an extremely ▷

bright beam of electrons at an effective repetition rate of 1 kHz, together with a high average power, picosecond laser to generate high fluxes of narrow-bandwidth mega-electron-volt photons for NRF (Gibson *et al.* 2010). A kilo-joule-class nanosecond laser end-station is proposed at the LCLS facility to generate matter of high energy-density that will then be probed by the highly directional X-rays from the FEL. Laser cooling normally conjures up images of cooling atoms of low thermal energy.

However, at a number of places, laser cooling has already been demonstrated on high-energy beams. For example, experiments at GSI, Darmstadt, have used laser cooling on C^{3+} ions at around 1.5 GeV, leading to an unprecedented momentum spread of 10^{-7}. Laser cooling has been proposed as a method for achieving beams of ultra-low emittance for future e^+e^- linear colliders (Telnov 2000).

There is no doubt that lasers will play an ever increasing role in accelerators, and vice versa.

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Résumé

Les lasers pour éclairer la science fondée sur les accélérateurs

Depuis leur invention, il y a 50 ans, les lasers jouent un rôle important dans la recherche menée auprès des accélérateurs de particules. Ainsi, la diffusion Compton entre des photons laser et un faisceau d'électrons de haute énergie a été rapidement utilisée pour produire des rayons gamma destiné à des recherches en physique nucléaire. Il est certain que l'apport des lasers va rester très important et se développer. Les lasers pourront à terme non seulement être utilisés pour le diagnostic de faisceau et servir de source de particules, mais aussi permettre d'accélérer des particules, en utilisant le champ de sillage créé par une impulsion laser intense.

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