# Breaking the vacuum

Europe is planning to build the world's most powerful laser that will literally rip empty space apart. **Michael Banks** lifts the lid on the Extreme Light Infrastructure

This year is one of celebration for Gérard Mourou – and not just because 2010 marks the 50th anniversary of the invention of the laser. It is also 25 years since the 65-year-old French physicist published details of one of his most coveted contributions to laser science. Going by the rather ungainly name of chirped-pulse amplification (CPA), the technique has enabled physicists to create lasers that are orders of magnitudes more powerful than were achievable without it (see box).

CPA now lies at the heart of most high-powered laser facilities in the world. It was used in the now-decommissioned Nova PW system at the Lawrence Livermore National Laboratory in the US, which generated record-breaking 1.3 PW ($1.3 \times 10^{15}$) pulses, and in the 1 PW Vulcan laser at the UK's Rutherford Appleton Laboratory in the UK, which is in the midst of being upgraded to go beyond the 10 PW level.

But now Mourou is designing a laser facility that will be so powerful that it can rip apart empty space itself. Mourou's parting shot to the laser community, the Extreme Light Infrastructure (ELI) will create very short pulses of light barely 1 femtosecond ($10^{-15}$ s) long with energies of several kilojoules corresponding to petawatts of power. While other lasers such as Vulcan can provide a high-powered pulse every 20 minutes, ELI will be able to deliver one every few minutes.


Hamiltons Architects

**Four for the future** The Extreme Light Infrastructure will consist of four facilities, including this one in the Czech Republic that will use short pulses of light to test accelerating electrons with lasers.

Although ELI will be used for nuclear physics, attosecond physics and studies of laser-based particle acceleration, perhaps its most exciting possibility is to test the properties of the vacuum, or empty space, itself. "This is not just a laser that is about breaking the next record," says Mourou, who is ELI's project coordinator and director of the Institut de la Lumière Extrême at the Ecole Nationale Supérieure de Techniques Avancées in France. "There is a fundamental reason behind building it."

Mourou first proposed ELI five years ago and he has been the driving force behind the project ever since. In 2006 it was chosen as one of 35 projects on a "wish list" of scientific facilities drawn up by the European Strategy Forum on Research Infrastructures that researchers in Europe want to see built within the next decade.

The new laser facility quickly garnered support with laser scientists in Europe, including Wolfgang Sander, director of the Max Born Institute for nonlinear optics and short-pulse spectroscopy in Berlin and the president-elect of the German Physical Society. "ELI offers a factor of 100 more in achievable power than anywhere else in the world," he says. "A lot of new physics could be done with it – it is revolutionary."

A competition to build ELI was begun in 2007. Five countries – the Czech Republic, France, Hungary, Romania and the UK – initially bid to host the project. But after the UK and France pulled out of the running, in October 2009 the ELI steering committee decided to not build one single facility, but four – one in Romania on nuclear physics, another in Hungary on attosecond physics, a third on laser-based particle-beam production in the Czech Republic and a fourth in ultrahigh-powered lasers. The latter's location is still up for grabs.

The €250m needed to build each of the first three of these facilities will be met by the host nation and construction is due to start at the end of the year. Once up and running in 2015, a number of European member states belonging to the European Research Infrastructure Consortium are expected to pay for labs' operational costs.

## Surfing electrons

The Czech facility, which will be built in Prague, will seek to generate for the first time pulses with a few petawatts in power at a frequency of about 100 Hz. These femtosecond laser pulses will be fired into a gas to create an electron–proton plasma that could be used to make a very compact particle

## Shining light in the femtosecond regime

All four sites belonging to the Extreme Light Infrastructure project have one aspect in common: a way of generating very short pulses of light at very high energies. At their heart, the four facilities will use the chirped-pulse amplification (CPA) technique invented 25 years ago by Gérard Mourou, now director of the Institut de la Lumière Extrême at the Ecole Nationale Supérieure de Techniques Avancées in France.

To generate the high-energy beams, a standard off-the-shelf table-top laser source will be used to generate pulses that are a femtosecond in length. These pulses, however, only have a small amount of energy – about a nanojoule. To get a high-powered petawatt beam, the energy needs to be increased by a factor of about $10^{12}$. However, as the energy of a short-pulse laser beam is amplified, the refractive index of the medium it is passing through starts to change; and once the power of the beam goes beyond a few gigawatts, it starts to produce nonlinear effects in the medium. This can lead to so-called self-focusing, where the intensity of the beam increases rapidly damaging the optics in the process.

To keep the intensity of laser pulses below the threshold of nonlinear effects, laser systems had to be very large and expensive, and the peak power of laser pulses was still limited to a few terawatts for very large multibeam facilities. In 1985 Mourou, then at Rochester University, US, and his colleague Donna Strickland, developed CPA to get around the nonlinear effects (*Optics Communications* **56** 219). It works by taking the short pulse and passing it through a pair of gratings that stretch the pulse in time by a factor of a 100 000. The gratings are arranged so that the low-frequency component of the laser pulse travels a shorter path than the high-frequency component does, so the high-frequency component lags behind the low-frequency component and the pulse spreads out in time.

As the pulse is longer, its power is lower and its energy can then easily be increased by passing the pulse through a amplifier such as a titanium–sapphire crystal. The amplified pulse is then passed through a second pair of gratings that reverse the dispersion – forcing the high-frequency component of the laser pulse to travel a shorter path and the low-frequency component to travel a longer path, so the pulse then "recombines" into a short femtosecond pulse.

accelerator. As the laser propagates through the plasma, the electrons are expelled around the laser pulse – just as a boat displaces water around it as it moves forward. As the electrons then rush back in behind the laser pulse, they set up a trailing wave-like structure known as a "wakefield" – like a water wave travelling behind the boat. Other plasma electrons trapped by these waves "surf" on them behind the laser pulse picking up energy and accelerating.

This technique allows laser light to accelerate electrons over a much smaller distance than conventional particle accelerators, which can be tens of kilometres long. "Typically, we think we can achieve electron energies of about 10–20 GeV," says Mourou. "So instead of building a 1 km linear accelerator, we can instead use something that is only 1 m long."

Mourou says that the Prague ELI centre, which could also accelerate protons for use in hadron therapy, will complement, rather than replace, other facilities that generate short pulses of X-rays, such as the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory. But while LCLS, which is an X-ray free-electron laser, can only produce monochromatic radiation with pulse durations of the order of 100 fs, ELI could produce polychromatic radiation of the order of a femtosecond or less, making it possible to take images of chemical reactions in real time.

"ELI is pushing the boundaries in terms of testing this technology to provide a range of applications," says John Collier, head of the high-power-lasers division at the Central Laser Facility at the Rutherford lab.

## Ripping atoms

ELI's nuclear-physics facility in Romania is set to be built in Magurele, 20 km south of Bucharest. The facility will produce 10 PW beams that are shone directly onto a nucleus to study how the pulse affects nuclear energy levels. Researchers expect that the laser pulse should be able to deposit about 1–10 keV on the nucleus – enough to modify energy levels and forcing it to release a gamma ray. Detecting this radiation would be proof that researchers have affected the nucleus directly with laser light, thus allowing them to study nuclear transitions in more detail.

As for the Hungarian "attosecond" facility, it will use a 5 fs pulse with a laser beam of a few joules to generate powers of the order of a petawatt. The facility, to be built in Szeged, 100 km south of Budapest, will generate pulses every 1 ms that will be used to take snap-shots on the attosecond scale ($10^{-18}$ s) of electron dynamics in atoms, plasmas and solids. It will do this by shooting a femtosecond pulse of light at a dense plasma target. In a process known as "relativistic harmonic generation", the ionized plasma then gives off so-called phase-locked radiation in the ultraviolet and soft X-ray regime at multiples of the frequency of the original femtosecond pulse. Researchers at ELI will then select the pulses that are generated in the attosecond regime with a filter and send them to experimental stations to study materials on the atomic scale.

CNRS Photothèque/Alexis Chezière

**Particle test-bed** The LASERIX laser at the Université Paris-Sud II has been testing whether lasers can produce X-rays, as the Czech ELI facility hopes to do.

## Boiling the vacuum

The host for what is dubbed the "heart" of ELI – the "ultrahigh peak power" facility – will not be known until 2012, after some initial testing of technology for the three main facilities is carried out. With an expected completion date of 2018, the facility will attempt to generate a 100–200 PW beam and use mirrors to focus it onto an area of 1 $\mu$m$^2$ in the hope of ripping open the fabric of the vacuum to produce particle and antiparticle pairs. "The vacuum is not something empty, but is full of activity of particles being created and destroyed," says Mourou. "It defines all the constants of physics."

Quantum field theory states these "virtual particles" continually pop in and out of existence. It is predicted that paired virtual particles could become real as they are torn apart by the pulse's extremely strong electromagnetic fields. However, this happens too quickly to leave a trace and requires light with an intensity of about $10^{29}$ W cm$^{-2}$. Known as the "Schwinger limit", it is seven orders of magnitude larger than any current laser can achieve.

In its current design, ELI's high-intensity facility will only be able to reach $10^{25}$ W cm$^{2}$; however, Mannuel Hegelich, project leader of short-pulse experiments and lasers at the Los Alamos National Laboratory in New Mexico, says there are some new theories being proposed that could bring the Schwinger limit within ELI's reach. "The vacuum has energy levels and it would be great if we could somehow manage to modify them," says Hegelich. Mourou also say the Schwinger limit could be matched by colliding electron beams created by two lasers.

One of the technical challenges of the ultrahigh-peak-power facility will be producing the vacuum itself. "Even ultrahigh-vacuum environments produced by highly efficient pumps still have a few atoms floating around," says Hegelich. One method would be to first shoot a laser pulse into the high-vacuum environment that would expel all the particles and then quickly follow that up with a second high-powered pulse. "Technically, there is nothing that can't be overcome with the ultrahigh-peak-power facility," says Hegelich. "It is more an engineering challenge that a physics one."

One phenomenon that ELI should be able to detect, which is predicted to happen at about $10^{23}$ W cm$^{-2}$, is the vacuum becoming polarized and exhibiting optical phenomenon such as birefringence. Some theorists are already proposing experiments for the ultrahigh-peak-power facility such as a "matterless" double-slit experiment where the photons generated from electron and positron pairs annihilating form a double-slit diffraction pattern (*Nature Physics* **4** 92).

As well as being a revolutionary physics project that will test fundamental theories and show how lasers could become the next particle accelerator or collider, ELI is also tipping the scales of Europe's portfolio of major infrastructures slightly more eastwards. The presence of three major facilities in the Czech Republic, Hungary and Romania will allow these nations to attract researchers from abroad, as well as inspiring future generations of researchers.

"ELI will create new scientific communities and it will be a magnet for hi-tech companies," says Sander, who notes that for every euro spent on a large infrastructure, €4 is given back to the economy. Yet for most physicists, it is ELI's ultrahigh-power facility, which will provide laser power far beyond any existing today, that is the most exciting and eagerly awaited. "Within the next decade," says Mourou, "we will be entering a new paradigm in physics."

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