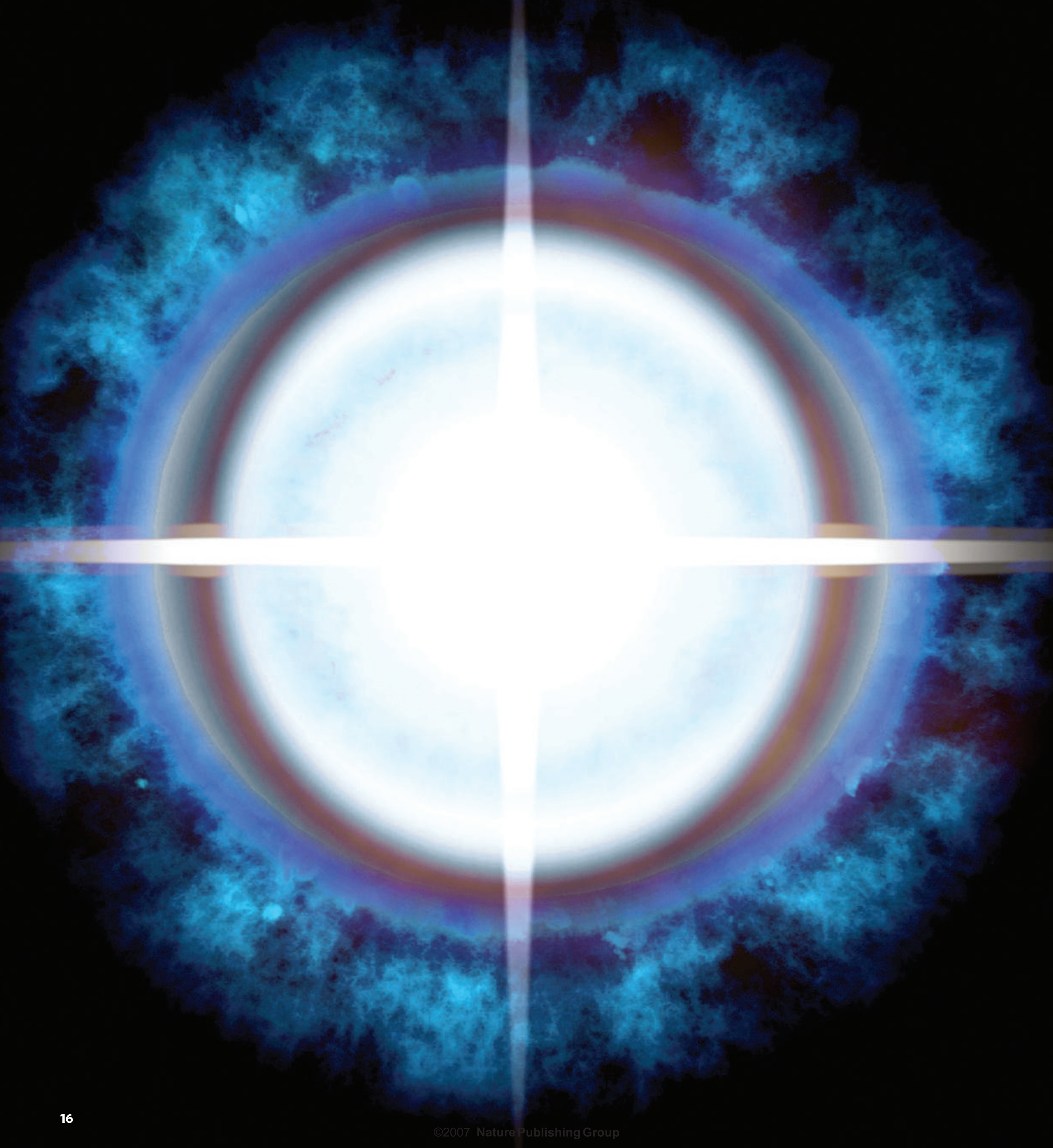
EXTREME LIGHT

Physicists are planning lasers powerful enough to rip apart the fabric of space and time. **Ed Gerstner** is impressed.



C. DARKIN

Almost 100 million times more powerful than its earliest ancestor, the Large Hadron Collider (LHC) is the latest triumph in a century of astounding physics. Officially inaugurated later this year, the €3.7-billion (US$4.9-billion) accelerator at CERN, Europe's particle-physics laboratory, will next year be fully up to speed in its search for exotic phenomena, such as the Higgs boson, that can only be discovered at the extreme energies it makes available. Yet even before it is turned on, the particle-physics community is already looking beyond it, with plans for an even more powerful machine, the International Linear Collider (ILC), which will cost some $6.7 billion.

At about the time that the LHC hopes to be homing in on the Higgs, construction of a much less feted multibillion-dollar physics research facility, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in California, will be reaching completion. At a cost of about US$4 billion, NIF is an assembly of 192 lasers that, for a billionth of a second at a time, can pump out energy at more than 50 times the rate that it is generated in all of Earth's power stations put together. Its aim is to ignite a fusion reaction that turns a tiny pellet of hydrogen at the lasers' focus into helium.

Science at NIF will bring astrophysics into the laboratory by aping stars in microcosm, and it could conceivably provide the basis for future energy generation. But the main rationale for NIF, and the reason it has been able to command the budget that it has, is to help the United States assure the operability and safety of its nuclear arsenal. Similar motivations lie behind the French Laser MegaJoule (LMJ) facility, which is expected to achieve ignition a few years after NIF.

The lasers of the LMJ and NIF don't come close to an accelerator such as the LHC in terms of generating excitement among physicists. At least, not yet. But laser beams even more intense than NIF's — and far cheaper to generate — might in the next decades begin to take over from particle accelerators in exploring the outermost frontiers of the physical world. The world may never see conventional particle accelerators much more powerful than the LHC and ILC. But lasers a million times more intense than NIF are already to be found in the presentations of physicists looking for funding.

Let there be light

The guiding inspiration for extreme lasers lies in the way light interacts with the vacuum. Quantum field theory sees the vacuum as a strange sea of possibilities, where pairs of 'virtual' particles and antiparticles ceaselessly pop in and out of existence. When light is bright enough, the electromagnetic fields it is composed of begin to interact with that sea in unusual ways. The vacuum no longer behaves as a simple, predictable medium — it becomes something altogether more exotic, unpredictable and nonlinear.

Pump in enough energy, and the paired virtual particles become real, separated at birth by the extraordinarily strong fields involved. This energy level, currently thought to require fields of a little more than 8×10^{18} volts per metre, is known as the Schwinger limit, and it is the point at which the vacuum sea begins to boil.

"When I give talks to general audiences, that's the thing that they really seem to get drawn in by," says Tom Katsouleas, an extreme-laser enthusiast at the University of Southern California in Los Angeles. The problem is that the Schwinger limit is a long way away. For fields of 8×10^{18} V m^{-1} you need a laser with an intensity of more than 10^{30} W cm^{-2} — a thousand trillion times more intense than NIF. Given NIF's multibillion-dollar pricetag, that seems an overly ambitious target.

But a team led by Gérard Mourou, director of the Laboratory of Applied Optics near Paris, believes it can meet this target for a relatively moderate price. And the researchers predict all manner of wonders on the way to their eventual goal. Throughout their history, lasers have excited physicists by opening up new possibilities with light. In the 1960s, the fact that early lasers were powerful enough to change the refractive index of the medium through which they travelled opened up fresh vistas in 'nonlinear' optics. Today the frontier buzzword is 'relativistic optics' — systems in which the fields associated with the laser light can accelerate every electron in the medium the light is passing through close to the speed of light.

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> — William Unruh

Need for speed

Mourou's proposal — the Extreme Light Infrastructure (ELI) — would up the ante further, moving into 'ultrarelativistic systems' in which not only electrons but also the ions from which they have been stripped move close to the speed of light. Mourou notes that the nonlinear effects of lasers revealed in the 1960s far exceeded expectations. "Only the tip of the iceberg was predicted," he says. He is similarly optimistic about what the new energies available at the ELI could deliver.

On 15 February, the French government announced that it had bought into the vision enough to pay for a new laser beamline at the Laboratory of Applied Optics to show that the ELI could work. If it goes ahead, the full facility would provide unprecedented opportunities for scientists to pursue fundamental, curiosity-driven science, says Mourou. Perhaps more importantly, it would be relatively cheap, costing €138 million to build and €6 million per year to run — considerably less than the £380-million (US$746-million) Diamond synchrotron X-ray source recently opened in Britain, for example.

High-power lasers achieve their awesome intensities by squeezing moderate amounts of energy into very short-lived bursts, thus driving up the power — which is energy divided by time. So although the power of NIF's lasers sounds incredible, they actually use relatively small amounts of energy. A single pulse contains just 2,000 kilojoules — roughly half a kilowatt hour. It's just that all that energy is delivered in a few billionths of a second.

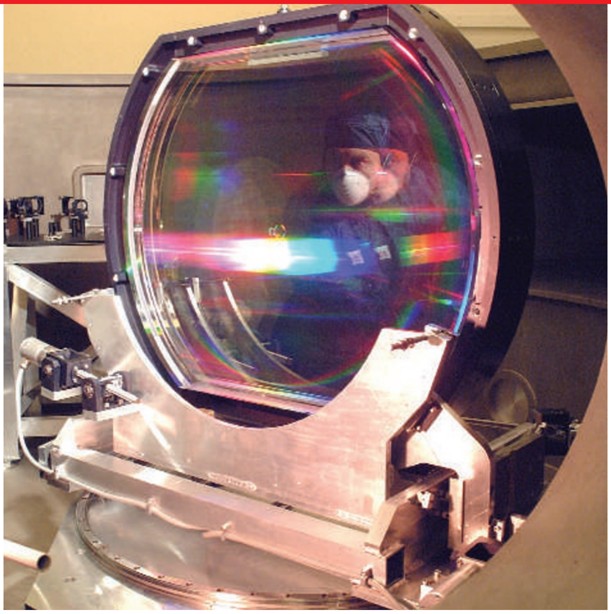
Power trip

The ELI takes the same principle further. By generating pulses a million times shorter than those of NIF — five femtoseconds — the ELI should fairly quickly be able to generate peak powers of more than a petawatt (10^{15} watts) from just a few joules of energy. This radically reduced need for energy makes things much easier than they are at NIF. By shortening the pulse lengths by a factor of a hundred more, down to tens of attoseconds (10^{-18} seconds), the ELI's proponents hope to reach peak intensities of more than 100 petawatts.

The ELI's extraordinarily short pulses will be made possible by a technique called chirped-pulse amplification (CPA), which Mourou developed at the University of Rochester, New York, in the mid-1980s. CPA works by decomposing the light in a laser pulse using a diffraction grating known as a stretcher, which acts like a prism. Having been stretched, the pulse's components, now spread out in space and time, are fed individually through an optical amplifier, before a similar grating designed for the opposite effect — a 'compressor' — reunites them into a pulse far shorter and more intense than the original.

These stretchers and compressors are currently used on almost all of the world's most powerful lasers except those, such as NIF and the LMJ, that need pulses that are relatively long (of the order of nanoseconds). Osaka University and the Central Laser Facility at Rutherford Appleton Laboratory in Didcot, UK, both have CPA lasers that can generate a petawatt, and the University of Rochester is also building one, as are other institutions. Mourou and others feel that the technique has, as yet, no obvious limitations; pulses can go on getting shorter and shorter.

In 2006, the ELI was one of 35 projects short-listed for consideration under the European Roadmap for Research Infrastructures, a programme that will provide money to help develop proposals for international projects. Also on the shortlist is another, costlier project that plans to use a CPA-enabled laser. A consortium led by the Central Laser Facility wants to build HiPER — the High Power Laser Energy Research facility — as a civilian equivalent to NIF and the LMJ, but pursuing a subtly different path to fusion. Whereas NIF



A researcher examines one of the two diffraction gratings used by petawatt lasers to achieve their extreme power.

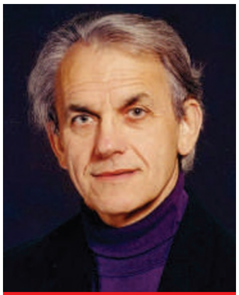
CCLRC RUTHERFORD APPLETON LAB.

and the LMJ use megajoule beams to crush their targets into fusion, the €855-million HiPER would compress the target comparatively gently and then ignite it with a much shorter high-power pulse.

One advantage of this approach is that the laser could be fired far more frequently than NIF. With more pulses, and freed from the demands of weapons research, HiPER should offer physicists far greater scope for non-fusion research — NIF's non-fusion work is effectively limited to about one pulse a week. And the power would be greater. With further developments of CPA, Mike Dunne, director of the Central Laser Facility, predicts that amalgamating HiPER's beams could push the machine's limits beyond petawatts to exawatts (10^{18} watts). "If — and it's a big if — such beamlines could be coherently combined," Dunne says, "then we believe that a beam of up to 2 exawatts is feasible. Although horribly difficult in practice."

Curiouser and curiouser

In fundamental physics terms, energies at the exawatt level would offer some intriguing possibilities for producing strangeness from the vacuum, and so could allow physicists to study phenomena unreachable any other way, such as those found at the edges of black holes. In the 1970s, Stephen Hawking predicted that when a virtual particle–antiparticle pair is created just 'outside' a black hole, the warping of the local vacuum by the hole's gravity will be strong enough to tear the pair asunder, with one disappearing into the black hole and the other surviving as matter outside it.



"We're going to change the index of refraction of the vacuum, and produce new particles."
— Gérard Mourou

The effect is analogous to the production of electron–positron pairs by electric fields at the Schwinger limit. "The vacuum really doesn't care if it's an electric field, a magnetic field, a gravitational field, or even if it's a weak nuclear field or a strong nuclear field," says Bob Bingham of the Rutherford Appleton Laboratory. "If you can pack enough energy in, you can excite particles out of the vacuum." The attraction of Hawking radiation is that its dependence on a gravitational field means that its subtleties will depend on interactions between quantum field theory and general relativity, the sort of thing that could throw light on quantum theories of gravity.

The laser-builders don't want to create black holes with which to look for Hawking radiation — but they don't have to. General relativity's equivalence principle means that to something experiencing one of them, a gravitational field and an acceleration are indistinguishable. So, as theorist William Unruh pointed out in the 1970s, when a particle is accelerated at a sufficient rate, it should see and be affected by Hawking-like radiation in its own frame of reference — if, that is, certain assumptions about the curvature and structure of space-time are correct.

The accelerations involved in Unruh radiation are far too extreme for a traditional particle accelerator, but perhaps not for lasers on the scale of the ELI. "Nothing generates fields even close to those produced by an ultra-high-intensity laser — except perhaps a black hole," says Bingham. "Some of the lasers at the Rutherford Appleton Laboratory will produce a field of about 3 trillion volts per centimetre. Nothing else comes close to that!"

Using their lasers to accelerate electrons fast enough to feel Unruh effects could be a tantalizing problem for the ELI, HiPER or other extreme lasers to tackle. "It seems to me to be a very hard experiment — creating such strong and short intense pulses," says Unruh, now at the University of British Columbia in Vancouver. "But I am always astonished at what experimentalists can actually do if they put their minds to it."

This is not the only way in which lasers could beat accelerators at their own game — or help them to greater heights. By definition, relativistic optics requires that electrons be accelerated close to the speed of light. Get them very close and researchers might be able to do particle physics beyond the reach of the LHC and ILC. One approach to this would build on the idea of a 'wakefield' accelerator, in which electrons hitch a ride on the wake left behind by an intense pulse of laser light blasting through a plasma.

"If you look at the progress that has gone on in laser wakefield accelerators," says Katsouleas, "and extrapolate that to the kinds of powers that people are talking about for the ELI, then it becomes possible to think about accelerating particles to [ILC energies] in just a short section of plasma." But even if the vast engineering challenges of such an accelerator could be met, it would hardly be a replacement for what the current and planned accelerators do, because the average power would be far lower: big accelerators store large amounts of energy in their beams.

"To get the luminosity one needs for doing high-energy physics," says Katsouleas, "and for events to be detectable on a reasonable timescale, the average power of the laser isn't sufficient. It's about three orders of magnitude away. But there are already many ways you could think about doing this."

Follow the light

Barry Barish, director of the global design effort for the ILC, is intrigued by the possibility of using lasers to accelerate particles, and agrees that it might be one of the future technologies that keeps the field going. "It's certainly a very promising avenue to pursue, because up front there doesn't seem to be any obvious limitation to it, and it could be that it will help in the long term," he says. But he doesn't see it as the only game in town, or as a sure thing. "It's just hard to know where the show-stoppers will be. But at the level where it won't require enormous resources, this is the sort of thing that needs to be pursued."

Mourou, on this as on much else, is bullish. "Probably within 20 years!" he says of laser-driven follow-ons to the ILC, before backpedalling, at least a little. "The time constant to design it and to build it is ten years. And you always build these things with the previous technology. So I have to be very careful when I say 20 years. But in 10 to 20 years we will have this technology, and then it would take another 10 years to build." Beyond that, he and his colleagues say, there are even more remarkable technologies: gamma–gamma colliders that can reach energies millions of times higher than today's accelerators; and 'relativistic mirrors' that can push light to the Schwinger limit and beyond.

"We're going to change the index of refraction of the vacuum," enthuses Mourou, evoking the ultimate fulfilment of the laser's original promise. "And we're going to produce new particles — the vacuum is the mother of all particles. And I'm sure we're going to discover more." ■

Ed Gerstner is a senior editor on *Nature Physics*.