
ICAN

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The Next Laser Powerhouse

An international team of researchers is looking toward the next frontier of high-energy laser physics: building efficient, high–average-power lasers. With a revolutionary architecture that combines thousands of coherent fibers, the laser being developed under the ICAN project could transform nuclear medicine, detect nuclear waste, and form the basis for the next great particle accelerator.

Illustations by Phil Saunders/spacechannel.org

Today's high-energy lasers can produce superb peak powers in the petawatt regime—a capacity that forms the cornerstone of the large and active area of high-field physics. Over the past decade, researchers at Lawrence Livermore National Lab have been working with some of the world's most powerful lasers in a quest to achieve fusion ignition, for example, while Europe's Extreme Light Infrastructure (ELI) project is planning to produce a laser so powerful that it could actually tear apart the fabric of space.

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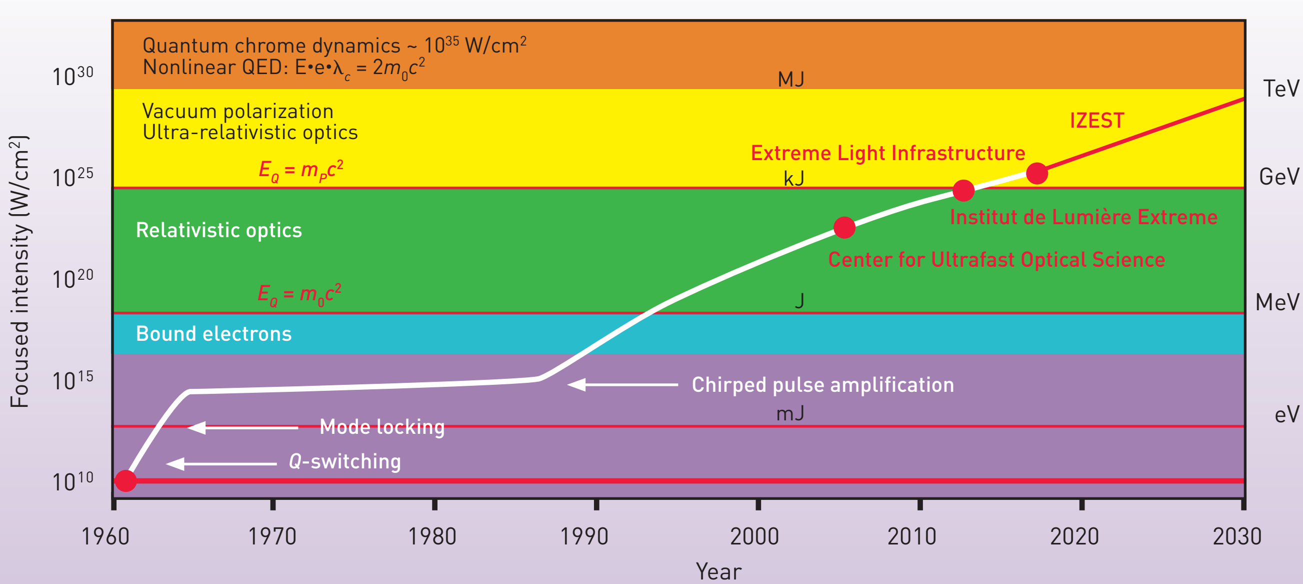
Yet as mighty as these lasers are, the *average* power of current technology is rather pitiful—in the 10-W regime. This has prevented lasers from becoming the basis for particle accelerator technologies such as the Large Hadron Collider, which was key to the recent discovery of the Higgs boson, or "God" particle. In addition, efficiencies are sorely lacking as well, with most lasers at less than 0.1 percent.

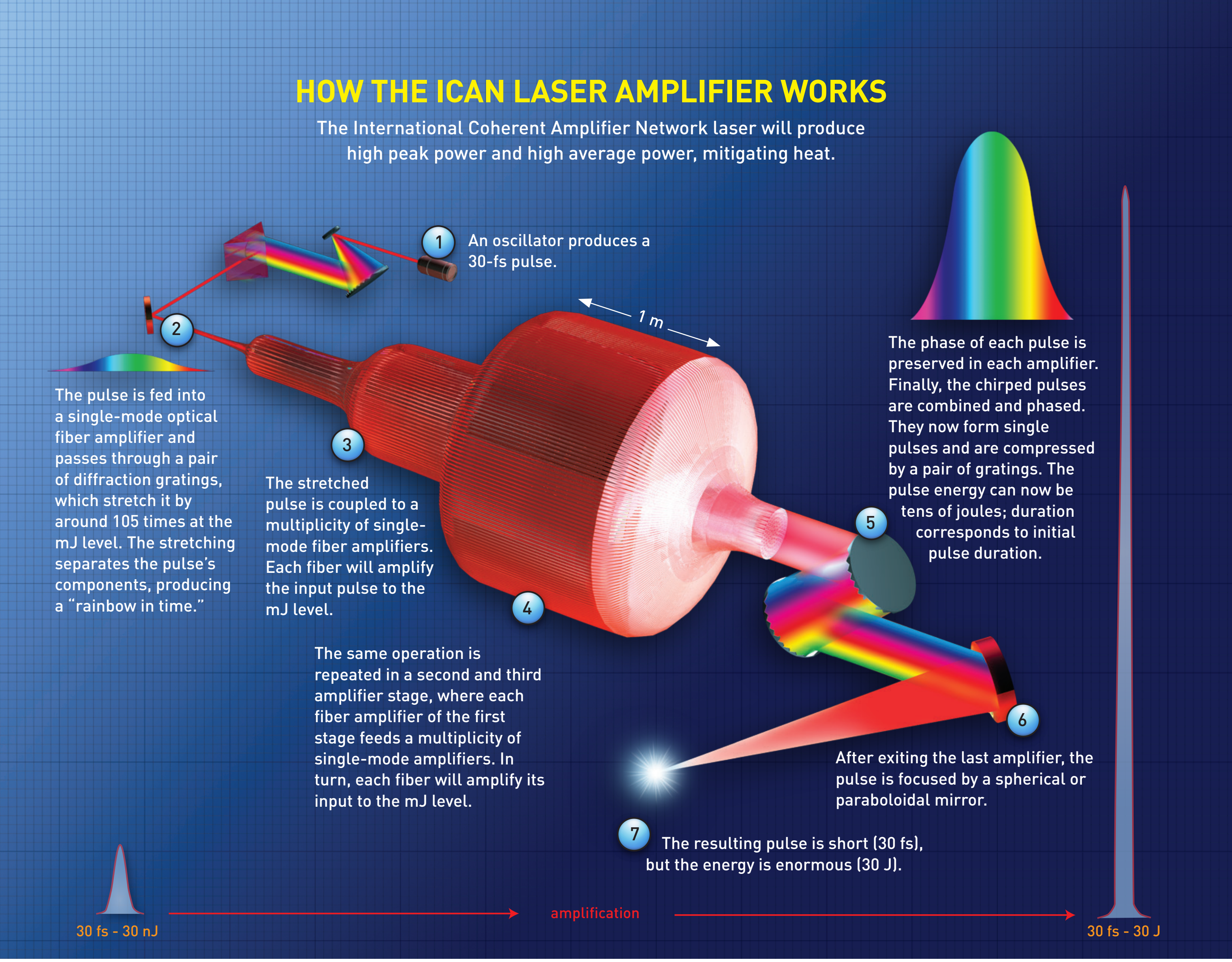
That's a big problem when you consider that particle collider luminosity demands PW peak power on top of MW average power—plus a wall plug efficiency of greater than 30 percent. There are also a number of accelerator applications that require not only high intensity, but also high average power and efficiency, such as laser-driven ion-beam sources, laser-driven proton therapy accelerators, and the X-ray free electron laser driver.

The challenge is that lasers consume too much power, and there is currently no way to remove the excess heat they create—which limits their capacity for the sustained high-energy acceleration needed to produce particle collisions. We are seeking to address these issues through the International Coherent Amplification Network (ICAN), an 18-month laser project conducted by the International Center for Zetta-Exawatt Science and Technology (IZEST) with funding from the European Union. The project was launched last February and is overseen by a consortium

HIGH-INTENSITY LASER ROAD MAP



To go beyond the Large Hadron Collider, a laser-driven collider will require laser intensity of 10^{18} W/cm^2, high average power greater than MW, and efficiency greater than 30 percent. The generation of relativistic protons demands a laser in the $>10^{22}$ W/cm^2 regime.



with four major partnering institutions: Ecole Polytechnique (France), Friedrich Schiller University (Germany), the University of Southampton (United Kingdom) and CERN (Switzerland).

The laser being developed by ICAN uses optical fibers as the gain medium in order to manage the heat generated and allow higher repetition rates. We believe that ICAN will play a critical role in unleashing the full potential of high-energy lasers. It could enable the next-generation of high-energy accelerators, lead to highly sophisticated imaging technology, and possibly help with the disposal of nuclear waste.

How it works

The 1985 demonstration of chirped pulse amplification (CPA) is what enabled researchers to develop ultrahigh-peak-power laser systems. By temporally stretching a short pulse before the amplification stages and then using a set of gratings to recompress it to its original duration, one can produce orders-of-magnitude higher peak powers than would be possible by directly amplifying the pulse. As a result, we can now access laser intensities of greater than 10^{18} W/cm^2, which leads to relativistic electron motion in the laser field. These extremely high laser intensities have spawned a branch of optics called relativistic optics, which has made possible new forms of imaging with hard X-rays and the laser-based particle acceleration that scientists use to probe the dynamics of subatomic interactions.

At laser intensities above 10^{22} W/cm^2, even the motion of ions becomes relativistic. This ultra-high–intensity regime has been the focus of the ELI project. Recent experiments have used plasma wakefields to achieve electron acceleration to energies of GeV over distances of a few centimeters. While the acceleration is impressive, the repetition rates that can be achieved are still orders of magnitude smaller than what is possible using traditional radio frequency accelerators. Even the state-of-the-art petawatt laser of the Berkeley Lab Laser Accelerator (BELLA) has a repetition rate of 1 Hz, resulting in an average power

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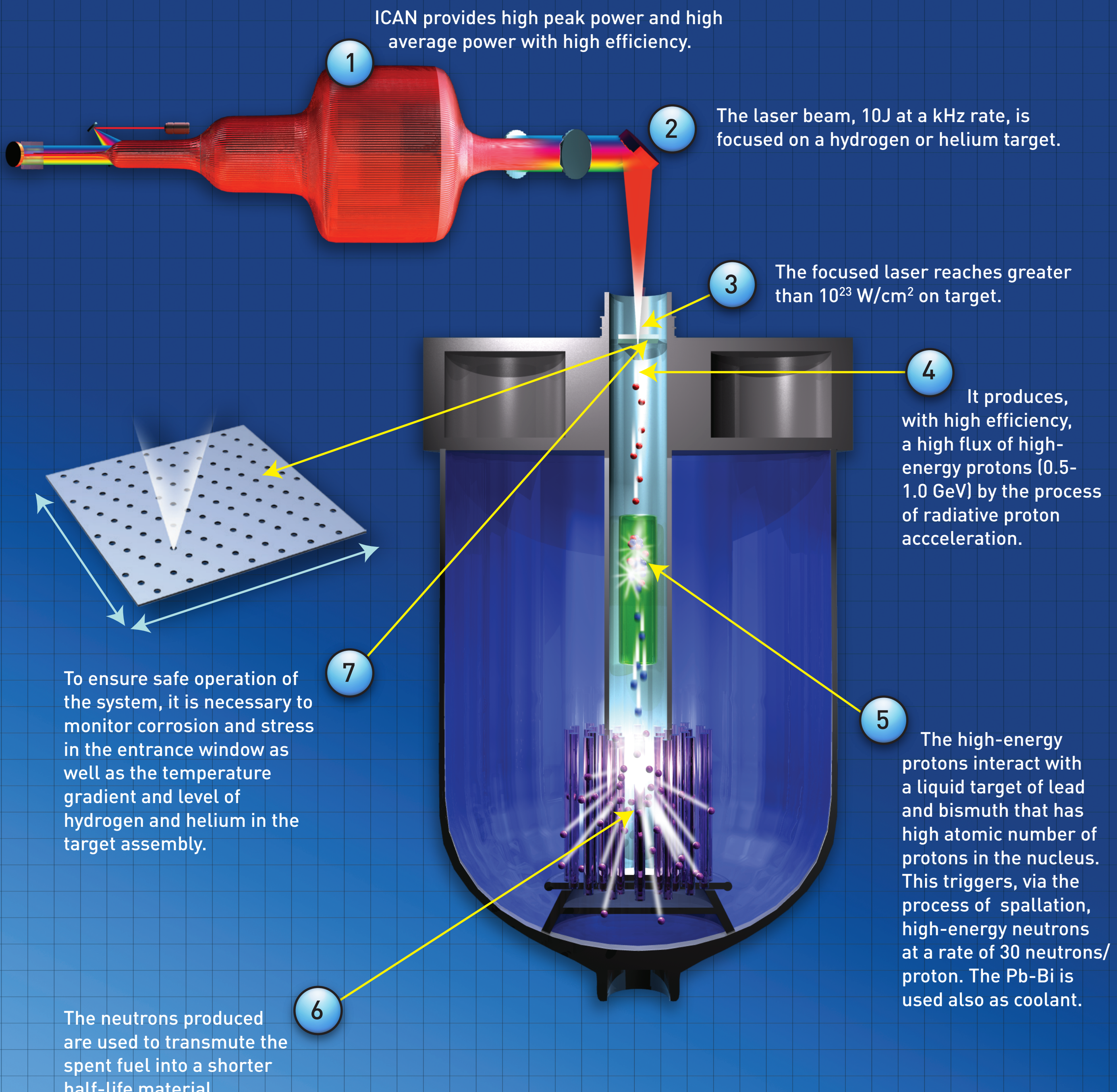
USING A HIGH-POWER LASER TO TREAT NUCLEAR WASTE

The ICAN system could provide energies intense enough to generate neutrons by spallation, a process in which fragments of material (spall) are ejected from a body due to impact or stress. Spallation neutrons can be used in accelerator-driven systems that reduce the volume and hazard of nuclear waste by the process of transmutation, or converting one chemical element or isotope into another. Here’s how it works.



of a few tens of watts and a wall plug efficiency on the order of 10^{-4}.

ICAN is a project based on fiber lasers, which have an active medium confined within the core of an optical fiber and which are pumped using semiconductor laser diodes. Over the past decade, these lasers have seen unprecedented increases in both average power and efficiency. In 2004, researchers demonstrated continuous-wave fiber lasers with average powers in the kW regime; such devices have since become commonplace with high efficiencies.

> **Over the past decade, these fiber lasers have seen unprecedented increases in both average power and efficiency.**

Semiconductor diode lasers can provide very high average powers and efficiencies (50 to 60 percent) at very low costs (projected to be as low as $5/W), but their beam quality is poor. Fiber lasers, on the other hand, act as effective brightness converters, taking poor quality diode beams and using them to generate coherent light with very high efficiency: The optical-to-optical conversion efficiency can be nearly 90 percent at kW powers. The fiber laser geometry and material are ideal for high average power handling. For this reason, these lasers have become the tool of choice in many industrial situations where high–average-power laser radiation is required together with the ability to manufacture reliable lasers in large quantities.

Unfortunately, though, fiber lasers don't do a good job of delivering high peak power. When produced in pulses, light with high peak powers propagates nonlinearly, resulting in pulse distortion and lengthening. In fact, the generation of high-energy ultrafast pulses in fibers is limited by the very core geometry that makes high average powers possible. In bulk gain media, the beam can be expanded, reducing peak power; in fiber, however, an increase in beam size is limited because it compromises single mode light guidance. Moreover, large core fibers start to lose the thermal and geometric advantages of the fiber medium.

CPA provides a way to help resolve these issues. It can be used to mitigate nonlinear effects, and researchers have been able to demonstrate in-fiber generation of 2.2-mJ pulses with peak powers of roughly 38 GW. While meeting the key requirement of the combination of high pulse energy and high average power does demand some design compromise, we are encouraged by the potential of CPA; so far, the best combination of the two has produced 1-mJ pulses at an average power of 300 W.

Pulse lengths available from fiber-based systems are longer than those from bulk ultrafast lasers, because the gain bandwidth of a typical fiber host, Yb^{3+} in silica glass, is significantly smaller than that of the most common bulk host, Ti^{3+} in sapphire. However, pulse lengths down to 250 fs are certainly achievable in Yb-doped fiber CPA systems, and further reduction should be feasible as well.

On a broad scale, the ICAN project aims to harness the efficiency, controllability and high power capability of fiber lasers to produce high-energy,

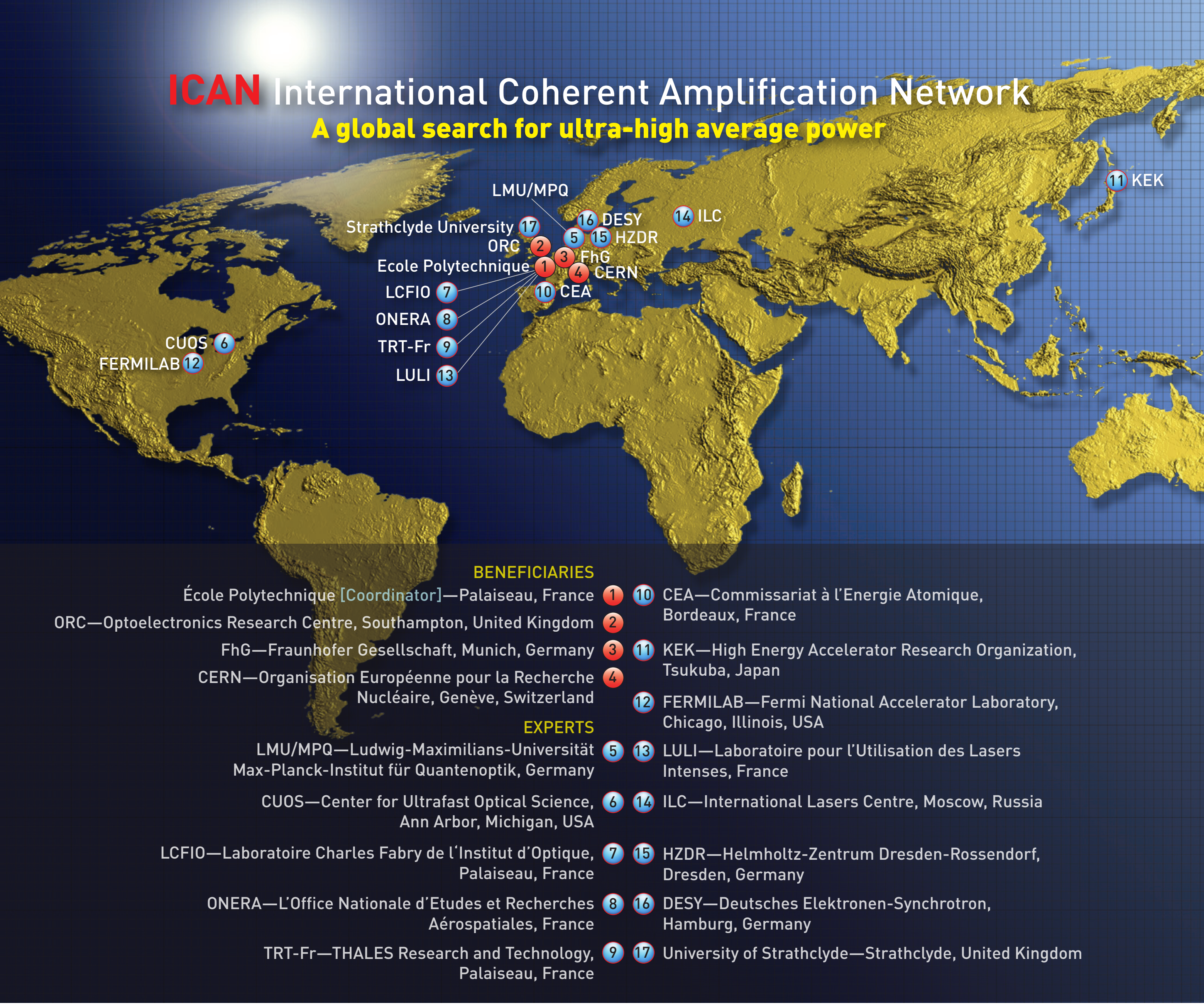
IZEST

International Zeta-Exawatt Science Technology

In September 2011, the French Atomic Energy Commission and the École Polytechnique launched the International Center on Zetta-Exawatt Science and Technology (IZEST)—the first international laser center designed to explore fundamental physics at the highest-intensity frontiers. Its goals are to:

- Design and construct the first large-scale exawatt-based facility.
- Create colliding high-energy particle beams that enable compact accelerators.
- Provide high-energy particles that will enable the search for low-mass particles signaling dark energy and dark matter.
- Accelerate ions to multi-TeV and laser-driven ion bunches, inducing wakefields for multi-TeV electron acceleration.
- Create new technology, transfer technology and create corporate spin-offs in medical, energy and industry applications.

To learn more, visit www.izest.polytechnique.edu.



high-repetition-rate pulse sources. This will be achieved by coherently combining pulses from thousands of fiber laser systems on very large scales, leveraging the control and mass production capabilities developed by the fiber laser community in the telecom arena. A consortium of experts from the fields of high–average-power fiber lasers, high–pulse-energy fiber lasers, and beam combination technologies are working with industry experts to explore the concept of this system, which would provide tens of joules of energy at rates above 1 kHz.

The prospect of having a large number of independent fibers also raises the possibility for digitally controlling the beam parameters, spot size and temporal shape—which would make ICAN the first truly digital laser.

ICAN applications

The ICAN system could provide intensities high enough to produce relativistic protons with close-to-unity efficiency. Such a system could have important applications in medicine, energy, environmental science and materials manufacturing. One of the most promising possibilities is that it could be used to aid in the clean-up of nuclear waste. Typically, one relativistic proton (1 GeV) can produce 20–30 neutrons. With that kind of source, an ICAN system could generate neutrons by spallation, a process in which fragments of material (spall) are ejected from a body due to impact or stress. Spallation neutrons could be used in accelerator-driven systems (ADS) that treat nuclear waste by the process of transmutation, or converting one chemical element or isotope into another.

At present, ADS relies on conventional accelerators with a size that may exceed that of nuclear reactors. ICAN offers a path toward more compact, efficient and affordable proton accelerators. We call this technology LDT, for laser-driven transmutator. It could make ADS commercially relevant.

Our laser can also drive an energy-specific beam of gamma photons via Compton scattering, which would have important implications for nuclear medicine. In addition, the MeV-range gamma beams would be useful for nuclear physics and nuclear engineering. For example, these photons can trigger nuclear resonance fluorescence reactions that would allow researchers to determine the presence of a particular nucleus—a capability that could be used to detect nuclear materials from a remote location. This could be important for both security applications and nuclear waste reprocessing.

To use a relevant current example, ICAN has the potential to help track down the exposed melt-down fuel from the Fukushima nuclear disaster that followed Japan's 2011 earthquake and tsunami. Once identified, this material could be disposed of safely.

ICAN also provides a realistic route toward laser-based high-energy electron accelerators and colliders. To meet the parameter of a 10-GeV acceleration stage, we would need to shoot for laser pulse energies of 32 J, at 13 kHz, with 240 TW peak power. For a 1-TeV collider, 100 of these stages would be necessary. Using a single stage requires adding the pulses from between 1,000 and 10,000 fiber lasers. It is also possible to convert electrons into gamma photons via Compton scattering. We then also have a gamma-gamma collider, which may be a useful Higgs factory. An estimated cost for a TeV, 1-nC electron collider that is 1 km long at 10 kHz, with a projected diode cost of 5€/W, would be around 2.5B€.

Although the ICAN project is very ambitious, we are on a mission and determined to succeed. To reach our goal to develop the laser, we are planning to enlarge the ICAN consortium of professionals from industry and academia. An important meeting has been scheduled for late April at CERN, where we will present our results and plan for the next steps. (The meeting had not yet happened at press time.) It will include a detailed plan to build a prototype within 5 to 10 years that will demonstrate PW power at a 10-kHz repetition rate and greater-than-30 percent efficiency. In parallel, we will work with ELI and other high-energy laser labs to validate at a few Hz what will be demonstrated with ICAN at 10 kHz.

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With ICAN's energy efficiency, compactness, high repetition rate and large flux, there's no telling how many areas of our lives it could touch. Its potential for compact relativistic ion sources, neutron sources, gamma beams and more may transform imaging, nuclear medicine and the way we explore fundamental physics—making ICAN one can-do laser. OPN

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