
High-Energy Beamline Facility, Prague, Czech Republic

Courtesy of ELI

The Extreme Light Infrastructure: Optics' Next Horizon

Gérard Mourou and Toshiki Tajima

The Extreme Light Infrastructure—a project involving nearly 40 research and academic institutions from 13 EU member countries—will allow researchers to probe laser-matter interaction at unprecedented intensity levels.

For almost as long as the laser has been in existence, researchers have been striving to construct large-scale infrastructures that could demonstrate laser-produced thermonuclear fusion. This scientific pursuit culminated with the construction of the National Ignition Facility (NIF) at Livermore, Calif., U.S.A., and the Laser Megajoule (LMJ) in France. Both facilities deliver megajoule pulses in a few nanoseconds, corresponding to a peak power of 0.5 PW.

A few years ago, the European Strategy Forum for Research Infrastructure proposed a new type of large-scale laser infrastructure—one designed to produce the highest peak power possible in the sub-exawatt regime, or about 1,000 times the NIF or LMJ peak power. These gargantuan powers could be obtained by packing laser energy in extremely short pulses measured in femtoseconds or few optical periods. When this energy is focused to a spot about the size of the laser

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Nuclear Physics Facility
Magurele, Romania

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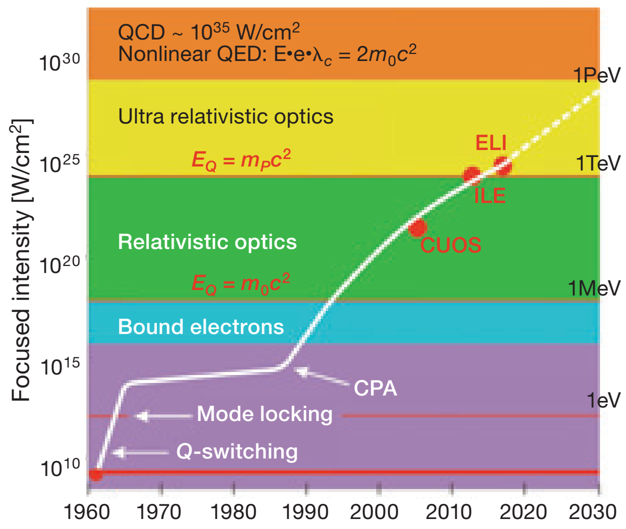
wavelength—i.e., a few micrometers—extraordinarily large intensities will be produced, in the 10^{25} W/cm^2 range.

A laser with ultrarelativistic intensity (>10^{24} W/cm^2) is ELI's quintessence. It leads to:

- the possibility of allowing light to move matter, electrons and ions at relativistic velocities
- the possibility of producing much shorter pulses than the initial one, in the zeptosecond-yoctosecond range
- the generation of coherent or incoherent high-energy radiation, and
- the generation of the highest electromagnetic field.

[Laser intensity and electron quiver energy vs. years]



We have extended our graph to 2020-30 when it could become possible to use the large-scale lasers to produce subzettawatt peak power pulses. In this case, pair production could be directly obtained from vacuum.

These four unique features offer a new set of powerful structural dynamic tools. They define the four "pillars" of the ELI.

ELI will explore ultrafast phenomena in the attosecond-zeptosecond domain, becoming the gateway into the ultrarelativistic regime of laser-matter interaction, which could reach into nonlinear quantum electrodynamics; this would allow elementary particles to be created from vacuum. ELI's scientific mission will be to investigate matter from atoms to vacuum.

At the same time, it will also promote new technologies, such as relativistic microelectronics, with the development of compact laser accelerators that deliver very-high-energy particles and photon sources. Perhaps its greatest societal benefit will be in the field of medicine: ELI may enable the development of new radiography, hadron therapy methods and nuclear medicine. It may also contribute to material science with the possibility of unraveling and slowing down the aging process in nuclear reactors and the environment by offering new ways to treat nuclear waste.

The preparatory phase of ELI began in November 2007. It involved nearly 40 research and academic institutions from 13 EU member countries. In October of 2009, ELI's founders and stakeholders decided to form a pan-European laser facility based on the four pillars mentioned earlier under one governance. The first three infrastructures we describe here are scheduled to deliver their first light in 2015, while the the high-field infrastructure should be ready for experiments in 2017.

Attosecond Light Pulse Source

Szeged, Hungary

The primary mission of the ELI Attosecond Light Pulse Source (ALPS) is to provide the international scientific community with a broad range of ultrafast light sources, especially with coherent XUV and X-ray radiation, including single attosecond

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pulses, to enable temporal investigations of electron dynamics in atoms, molecules, plasmas and solids on femtosecond and attosecond time scales.

The secondary purpose is to contribute to the development of 200 PW pulses—which is the ultimate goal of the ELI project. ELI-ALPS will also operate as a user facility and hence it will serve basic and applied research in physical, chemical, material and biomedical sciences as well as industrial applications.

High-Energy Beamline Facility

Prague, Czech Republic

ELI will provide energetic particles (>10 GeV) and radiation beams (up to few MeV) with an ultrashort time structure produced from compact laser plasma accelerators.

The beamline facility will exploit the PFS technology in the front-end up to a few hundred millijoules, and it will use amplification techniques exploiting repetition-rate pumping (especially cryogenic multislab pump systems) to provide ultrashort petawatt-class pulses with up to 50 J of energy at a repetition rate of up to 10 Hz.

Ideally, all the beamlines should run at a 10-Hz repetition rate in order to enable ELI to become a highly competitive source of accelerated electrons or protons for applications.

The contribution of ELI beamlines to the development of the high-intensity facility will consist of two laser blocks, each providing 10 PW. The design options for laser high-intensity systems, as well as the techniques of coherent combination of their pulses, will be prototyped and tested at ELI beamlines.

Nuclear Physics Facility

Magurele, Romania

The ELI-Nuclear Physics (ELI-NP) facility will generate laser and gamma beams with unique characteristics suited to perform frontier laser, nuclear and fundamental research. The core of the facility is a double multi-PW chain laser system. In order to perform cutting-edge photo-nuclear physics experiments, a complementary high-brilliance gamma beam, with very-low-bandwidth energies in the 15 MeV range, will be generated via the laser interaction with a brilliant bunched electron beam.

Thus, ELI-NP will allow either combined experiments using the high-power laser beams and the γ-beam or stand-alone experiments. The design of the facility is modular, reserving space for further extension of the laser system in the future.

The basic objectives of the ELI-NP infrastructure is to:

- precisely diagnose the laser beam interaction with matter using nuclear methods and techniques,
- create photonuclear reactions for nuclear structure studies and applications,
- study exotic nuclear physics and astrophysics, and
- engage in fundamental physics based on high-intensity lasers and very brilliant γ beams.

Courtesy of ELI

Attosecond Light Pulse Source
Szeged, Hungary

The pulse intensity-duration fosters the hope that zeptosecond—and perhaps yoctosecond—pulses could be produced using kJ-MJ systems.

The ELI-NP high-power laser system essentially consists of two 10-PW-class Apollo-type lasers that are coherently added to the high intensity of 10^{23}-10^{24} W/cm^2 or electrical fields of 10^{15} V/m. Higher repetition 100-TW and 1-PW laser pulses will also be available for experiments.

Ultrahigh Field Science

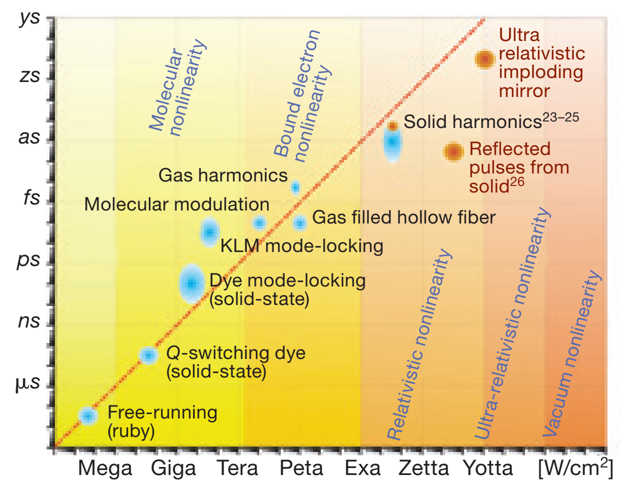
Site to be decided in 2012

In this pillar, ultrahigh intensity will be applied to nonlinear field theory, nonlinear QED, vacuum physics, high-energy particle physics and gravitational physics. The site and ultrahigh-intensity technology will be decided in 2012.

The pulse intensity-duration conjecture

The ELI was founded on our desire to create the highest electromagnetic field, high energy radiation and the shortest pulse duration. It turns out that these three features are intrinsically linked. In order to get the highest peak power and hence intensity, we need to shrink pulse duration. However, the less trivial converse posits that, to get the shortest pulse, we need the highest intensity.

[The pulse intensity-duration conjecture]



There is an inverse linear dependence between the pulse duration of coherent light emission and the intensity of the laser driver in the generation volume over 18 orders of magnitude. These entries encompass different underlying physical regimes with nonlinearities that are molecular, bound atomic electron, relativistic plasma, and ultra-relativistic, and eventually vacuum in nature. The blue patches are from the experiments, while the red are from the simulation or theory.

From Mourou and Tajima, Science (2011).

This conjecture is the linchpin of ELI. Researchers have established the quantitative relationship between the pulse duration and intensity of lasers (or derived coherent radiation bursts) over more than 18 orders of magnitude, from millisecond to zeptosecond. This leads to a surprising conclusion that the shortest energy radiation/particle bursts are to be produced by the highest power laser—in other words, the most energetic and largest laser.

This result leads to the counterintuitive conclusion that the shortest coherent pulse should come from the largest sized lasers, which include the ones produced by ELI, NIF or LMJ. In addition, these short pulses will be necessarily in the X-ray and γ-ray regimes, opening a route to time-resolved nuclear, vacuum nonlinearities and nonlinear explorations in quantum electrodynamics. For example, we can now quantitatively explore vacuum nonlinearities and compare these with atomic ones.

How far are we from exploiting vacuum nonlinearity?

We have learned that matter exhibits nonlinearities when a strong enough laser is irradiated. Manifested nonlinearities vary depending on the strength of the "bending" field (and thus the intensity). The stronger we bend the constituent matter, the more rigid the bending force we need to exert—and the more rigid the force is, the higher the restoring frequency (or the shorter the time scale).

While the nonlinearities of matter may vary, this response is universal, ranging over nonlinearities that are molecular, atomic, plasma electronic and ionic, and even the stiffest of all—vacuum. Thus, we have witnessed a direct correlation between the pulse shortness and the intensity of its driving laser over the widest intensity range that our laboratory has to offer.

For example, we know that the laser self-focuses above the critical power of GW with χ_3 nonlinearity, while it is around 10^{15} $(\lambda/\lambda_{1\mu})^2$ GW with vacuum nonlinearity. This difference of 15 orders of magnitude is the same as the ratio of the Schwinger intensity to the Keldysh intensity, where at the former intensity vacuum breaks down, while at the latter an atom does.

This turns out to be the (negative) sixth power of the fine structure constant α. We know that the Keldysh field is the field needed to create the potential energy of Rydberg energy W_R over the Bohr radius a_B. On the other hand, the Schwinger field is used to create the potential energy of $2mc^2 = \alpha^{-2}W_R$ over the distance of the Compton length αa_B. We find that the physics of atoms and the physics of vacuums have a lot of parallelisms, and we can learn vacuum physics from atomic physics.

When we inject an XUV photon to an atom to ionize it, and we apply an intense enough CEP laser to accelerate the ejected electron, we can make attosecond resolution streaking by the time-of-flight detection of the electron. An equivalent process in vacuum is the Nikishov/Ritus process, in which a gamma photon is injected into a vacuum while a strong enough laser (or XUV) EM fields are applied.

Nikishov et al. showed that the Schwinger vacuum breakdown is many orders of magnitude reduced. This method should be able to yield a zeptosecond streaking method of vacuum under QED (α^2 times the shortest time scale in the attosecond streaking). It would take an ELI-class laser to achieve this. Another example is vacuum self-focusing. Since the XUV (say, 3keV) coherent photons need 10^7 times less power for the vacuum self-focus at 1 μm, a laser of 0.1-ZW laser can make the vacuum self-focus power.

Courtesy of Lou Giesen and Gerard Mourou

Conclusions

In conclusion, researchers have accumulated evidence over more than 18 orders of magnitude of the pulse intensity-duration conjecture experimentally and with simulation. Our work shows that the pulse duration varies inversely with the intensity from the millisecond to the attosecond and zeptosecond, using values from experiments and simulations. Most notably, it predicts that the shortest coherent pulse in the zeptosecond-yoctosecond regime should be produced by the largest laser, like ELI or NIF and LMJ, if they are reconfigurated in femtosecond pulse systems.

The pulse intensity-duration conjecture may provide an invaluable guide for future ultraintense and short-pulse experiments. It fosters the hope that zeptosecond—and perhaps yoctosecond—pulses could be produced using kJ-MJ systems. It also opens the possibility that we could take snapshots of nuclear reactions or peek into the nuclear interior in the same way that Zewail examined chemical reactions or Corkum and Krausz probed atoms. Finally, it may enable us to study the nonlinear optical properties of vacuums and tie together three distinct disciplines of science—ultrafast science, high-field science and large-energy laser science—with a single stroke.

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