

Highest intensities, shortest pulses

Towards new physics with the Extreme Light Infrastructure

• The Extreme Light Infrastructure (ELI) [1] will be the first research infrastructure dedicated to the fundamental study of laser-matter interaction in the ultra-relativistic regime. It provides the link between high-field science and ultra-fast science. It further offers a few gigantic steps towards connecting optics, high-energy physics, nuclear physics, medicine and nuclear engineering, only to name a few.

To study laser-matter interaction in a new and unsurpassed regime of laser intensity (see Figure 1), ELI will provide laser light in the ultra-relativistic regime, where even ions become relativistically accelerated by the optical fields. At the center is an exawatt-class laser, 1,000 times more powerful than either the Laser Mégajoule in France or the National Ignition Facility (NIF) in the USA. In contrast to those projects, ELI should attain its extreme power from the shortness of its pulses (femtosecond (10^{-15} s) or attosecond (10^{-18} s)). The infrastructure serves to investigate a new generation of compact accelerators, delivering energetic particle and radiation beams of femtosecond to attosecond duration. Relativistic compression offers the potential of intensities exceeding $I_L \geq 10^{24}$ W/cm², which encroaches on the vacuum critical field as well as provides a new avenue to ultrafast attosecond to zeptosecond (10^{-21} s) studies of laser-matter interaction. ELI should provide wide benefits to society, ranging from improvements of oncological treatment, medical imaging, fast electronics and our understanding of aging of nuclear reactor materials, to the development of new methods of nuclear waste processing. In this article we outline the fundamental scientific rationale for weaving through three (or even four) ELI pillars. Why are the most intense lasers relevant to the shortest possible pulses? What fundamental steps do the ELI pillars provide for the future growth of ultra-relativistic optics? What scientific impacts should we expect on adjacent scientific disciplines

THE AUTHORS

TOSHIKI TAJIMA

Toshiki Tajima is considered as the founder of high field science. Along with J.M. Dawson he invented laser acceleration about 30 years ago. This vision has been experimentally realized in many laboratories in the world. He served as Chair of the International Committee of Ultra Intense Lasers and for the Scientific Advisory Committee of ELI. He is the recipient of the Blaise Pascal Chair (Paris). He served as Jane and Roland Blumberg Professor at the UT Austin and as Director General of the Kansai Photon Science Institute.



•• Toshiki Tajima
Fakultät für Physik
Ludwig-Maximilians-Universität München
Am Coulombwall 1
85748 Garching, Germany
Phone: +49 (0)89 2891 4085
Fax: +49 (0)89 2981 4072
E-mail: Toshiki.Tajima@physik.uni-muenchen.de

DIETRICH HABS

Dietrich Habs is a Professor Emeritus at the Ludwig-Maximilians University of Munich and Max-Planck Fellow of the Max-Planck-Institute of Quantum Optics (Garching). He is active in three fields: Laser particle acceleration, classical acceleration and nuclear spectroscopy. Professor Habs has achieved important results in radiation pressure acceleration, building up the radioactive beam accelerator REX ISOLDE at CERN and has studied super- and hyper-deformed nuclei in the actinide region.



•• Dietrich Habs
Fakultät für Physik
Ludwig-Maximilians-Universität München
Am Coulombwall 1
85748 Garching, Germany
Phone: +49 (0)89 2891 4077
Fax: +49 (0)89 2981 4072
E-mail: Dietrich.Habs@physik.uni-muenchen.de

GÉRARD A. MOUROU

Gérard Mourou is Professor at the Ecole Polytechnique and Director of the Institut de la Lumière Extrême at ENSTA. He is also the A.D. Moore Distinguished University Emeritus Professor of the University of Michigan. He has made important contributions in the field of ultrafast lasers, high-speed electronics, as well as in medicine, where he introduced the field femtosecond ophthalmology. His most important one is certainly the invention of the CPA technique at the University of Rochester (NY). Professor Mourou is Member of the US National Academy of Engineering, foreign member of the Russian Science Academy, Austrian Science Academy and the Lombardy Academy for Sciences and Letters.



•• Gérard A. Mourou
Institut Lumière Extrême ENSTA
Chemin de la Hunière
91761 Palaiseau, France
Phone: +33 1 69 31 9708
Fax: +33 1 69 31 9742
E-mail: gerard.mourou@ensta.fr

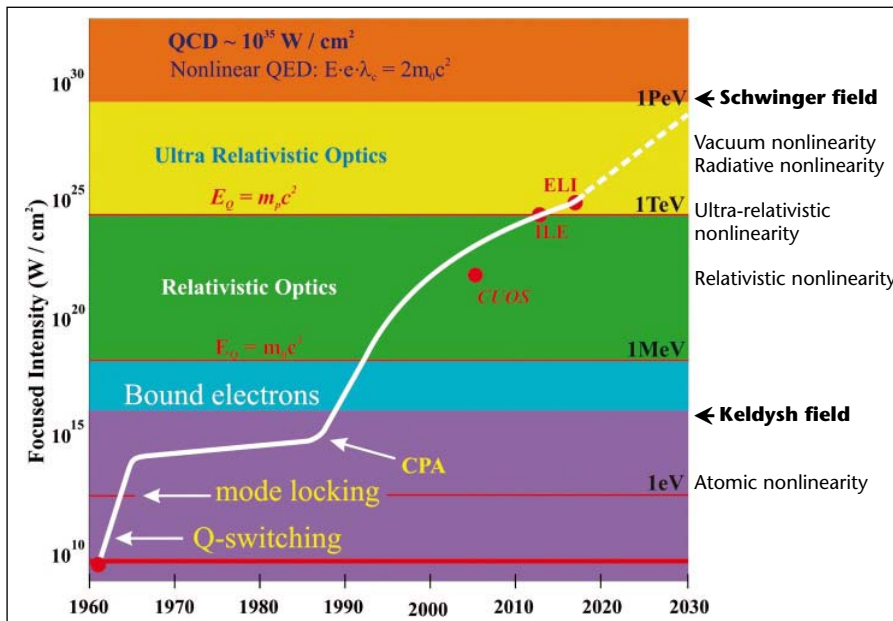


FIG. 1: Development of maximum intensity in laser science and the relation to respective fields of research.

such as high-energy physics, nuclear physics etc.?

Launched in November 2007, the Preparatory Phase of ELI within the EU 7th Framework programme has involved nearly 40 research and academic institutions from 13 EU Member Countries. It has led to the decision that this pan-European laser facility will form an integrated infrastructure, based on three to four sites. The facility should be operational in 2015 for the three first pillars and 2017 for the highest intensity one. ELI will be the first large-scale infrastructure based in the eastern part of the European Community. It is an investment in laser science and applications of an unprecedented amount, exceeding 800 million Euro. The project will run under a centralized management, presiding over this integrated infrastructure to promote research, knowledge sharing, training, and technology transfer.

Extremely High Intensity

Since the first demonstration of the laser principle in 1960, we have seen a relentless pursuit towards large-scale laser infrastructures, designed to fuse nuclei on earth for the production of energy. The most advanced are the National Ignition Facility (NIF) at Livermore and the Laser Mégajoule project in France. The NIF for instance delivers 1 MJ of laser energy in a few nanoseconds, corresponding to a peak power of 0.5 PW. ELI's output power will exceed this a 1,000 times, producing a kilo-joule over 10 fs.

To get into the ultra-relativistic regime, we need to boost the pulse power and intensity by 12 orders of magnitude, while

maintaining the pulse duration. To reach this objective, we use amplification techniques based on chirped-pulse amplification (CPA). First we stretch the pulse produced from a short-pulse oscillator before amplification by typically 10^3 – 10^4 times. CPA offers the possibility to use superior energy storage materials like Nd:Glass, Ti:Sapphire, etc., reducing the size of the amplifier by the same amount. CPA prevents the spatial and temporal beam degradation due to nonlinear effects during amplification. The reduced size of the amplifier entails a superior cooling and hence a greater laser average power. This technique led to an improvement of 10^3 in average power of a femtosecond oscillator, with a pulse duration of the order of 10–100 fs. Today CPA is being used on small micro-joule fiber lasers all the way up to large-scale kilo-joule systems.

In an elegant variant of CPA, known as OPCPA, the conventional laser amplifier is substituted by an optical parametric amplifier (OPA), composed of nonlinear optical crystals. The OPA will produce an idler wave with reverse frequency chirp. Since the first proof-of-principle experiments in 1992, OPCPA became recognized as a rapidly developing amplification technology for high-power femtosecond pulse generation. It is widely used either separately or in conjunction with laser amplifiers.

The ELI laser will be a hybrid OPCPA-CPA system, capitalizing on the best properties of both concepts. For instance, OPCPA can provide a large amplification over a short distance, while maintaining even the gain bandwidth. It will be used consequently at

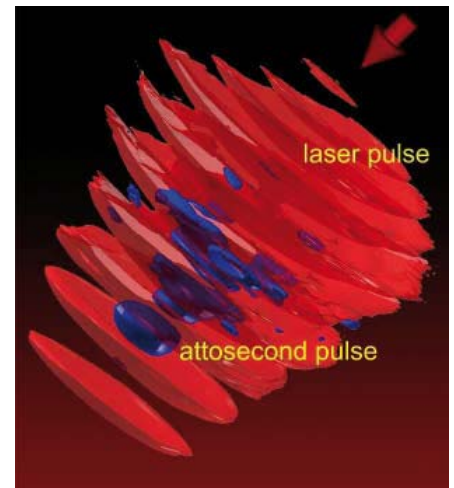


FIG. 2: Three-dimensional computer simulation of a solid target interaction, predicting the generation of attosecond pulses.

(Source: S. Rykovanov, C. Hackenberger)

the front-end to amplify the pulse from the nano-joule to the joule level, i.e. over nine orders of magnitude. On the other hand, Ti:Sapphire-CPA alone will have the tendency to reduce the laser bandwidth, but offers a better efficiency and demands a less complicated pump laser. So it will be used at the system duty-end, where the energy is important. It will boost the pulse energy efficiently from the joule to the kilo-joule regime, a gain of three orders, small enough to maintain the laser bandwidth.

Ultrafast Science with Large-Energy Lasers

ELI is supposed to offer short pulses in the range of attoseconds (10^{-18} s), which is the timescale of atomic events. For comparison, in Niels Bohr's model of a hydrogen atom, an electron completes a revolution around the proton in about 150 as. The latest advances in ultrafast science came about a decade ago, when physicists used intense femtosecond laser pulses to ionize a noble gas and found that new electromagnetic waves were generated in form of "high-order harmonics" at odd multiples of the original optical pulse frequency. It is the interplay between constructive and destructive interference in the superposition of these monochromatic light waves of equally spaced frequencies that gives rise to temporal beating, the underpinning process of attosecond pulse generation (see Figure 2).

Further innovations in short pulse laser technology gave rise to the generation of even single attosecond XUV bursts, which was promptly followed by an upsurge of

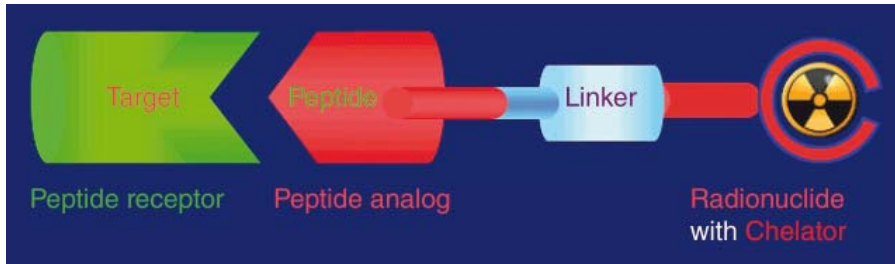


FIG. 3: Schematic picture explaining how a specific radionuclide can be transported to a specific peptide receptor.

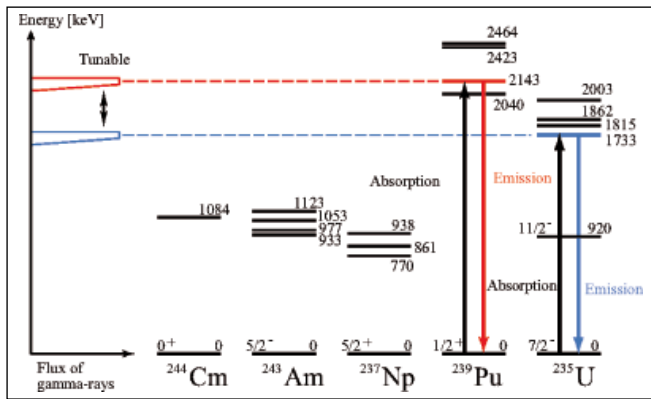


FIG. 4: Nuclear resonance fluorescence of several actinides. The small width of the spectra on the energy axis demonstrates the high sensitivity of the method [3].

extraordinary applications. Unfortunately, the number of photons per unit time limits the scope of applications of this attosecond pulse generation technique. In particular, most of the envisaged measurements are based on the pump-probe method: the attosecond pulse is split into two and one pulse triggers the system into motion or kick-starts a reaction, and the second one probes it after a controlled delay. But this approach is not possible with attosecond pulses from atomic harmonics: they are just too weak. The next goal is to induce "high-order harmonics" generation in another non-linear medium, exhibiting higher efficiencies at higher laser intensities. The relativistic interaction of an intense laser pulse with an overdense plasma constitutes a very promising approach towards this objective. The main advantage over the process of harmonic generation in rarefied gases is that the plasma medium allows the use of higher laser intensities. The front end of the laser system envisioned for ELI is perfectly suited for this purpose. With projected specifications of few Joules energy output in few-cycle pulses, focused intensities of 10^{21} W/cm² at few hundreds Hz repetition rates appear feasible. It will

thus constitute the ideal driver to a source of intense attosecond pulses. At these intensities, estimates of the number of photons emitted in a given spectral range and of the corresponding XUV pulse duration based on PIC simulations show that indeed such a source would have extraordinary properties. Without a doubt, the availability of an attosecond source with enough photons for pump-probe experiments will open the road to investigations with unparalleled temporal resolution for a multitude of new phenomena.

Applications

Besides the high-power laser backbone, the ELI-Nuclear Physics project in Bucharest (ELI-NP) is going to have a second source. This will be a γ -beam facility, to be developed and provided by the group of Chris Barty at the Lawrence Livermore National Laboratory (LLNL). Here brilliant, intense, and energetic photon beams will be generated via Compton backscattering of laser photons from a high-quality electron beam. With the γ -beam of ELI-NP several new applications can be developed. Many of the applications, e.g. in medicine or radioac-

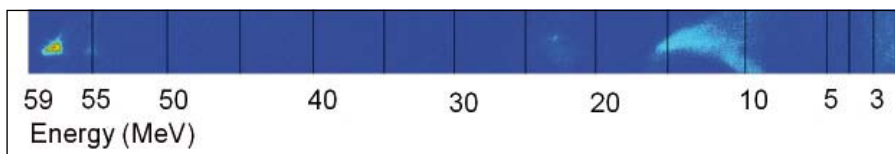


FIG. 6: Electron wake field acceleration. (Credit: L. Veisz)

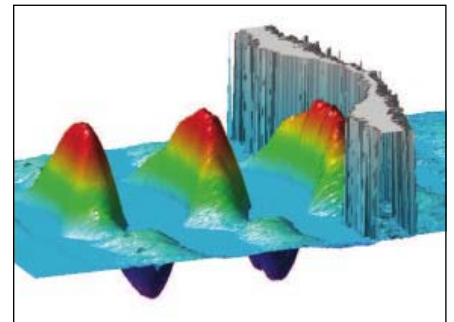


FIG. 5: Shown is the transverse electric field component E_y of a circularly polarized laser pulse incident onto a 5 nm thin, solid-density plasma. Like a light sail, the over-dense plasma is pushed in forward direction by the radiation. The image is based on a 2D PIC simulation.

tive materials and radioactive waste management, open up new perspectives in a socio-economical context.

Medical diagnostics and therapy

With the new γ -beams many new medical radioisotopes can be produced with better specific and absolute activity compared to present production schemes. This is of particular interest for medical diagnostics and therapeutic purposes. With the narrow-bandwidth γ -beams, we can increase production cross sections by two to three orders of magnitude compared to the existing average cross sections [2], rendering them even more interesting for large-scale industrial applications. Here we shall focus on one of the most interesting isotopes, ^{195m}Pt, to give a flavor of the new possibilities.

In chemotherapy of tumors most often platinum cytotoxic compounds like cisplatin or carbonplatin are used. We want to label these compounds with ^{195m}Pt for pharmacokinetic studies like tumor uptake and want to exclude "nonresponding" patients from unnecessary chemotherapy, while optimizing the dose of all chemotherapy treatments. Here the 99 keV γ -transition of ^{195m}Pt is used in single-photon emission computer tomography (SPECT). For such type of diagnostics a large-scale market can be foreseen, but it would also save many people from painful, but useless treatments. It is estimated in [2] that several hundred patient-specific uptake doses could be produced with a γ -beam facility per day. However, this probably can be increased to 10^5 , if optimum gateway states can be identified by scanning the isomer production with high γ -beam energy resolution.

On the other hand, ^{195m}Pt may be used in cancer therapy if transported to the tumor by specific bioconjugates. Special antibody-

ies may be used in radio-immunotherapy (RIT) or peptides in peptide receptor radionuclide therapy (PRRT). Linked to the radioactive isotope, they can guide it to the tumor. In Figure 3 we show how a radionuclide like $^{195\text{m}}\text{Pt}$ is transported to the specific peptide receptor.

Here $^{195\text{m}}\text{Pt}$ is of high interest, because the emitted conversion electrons and Auger electrons have a rather small range of 1.5–200 μm and allow to kill locally small tumor clusters, while the dose given to normal tissue is rather low. Many new therapeutic radioisotopes with this small range and high linear energy transfer (LET) can be produced by γ -beams.

Nuclear material inspection

The non-destructive detection of materials hidden by heavy shields such as iron with a thickness of several centimeters is difficult. Such inspection of clandestine materials is of importance, e. g., for applications in nuclear engineering. The management of nuclear materials produced by nuclear power plants, the detection of nuclear fissile material in the recycling process, and the detection of explosive materials hidden in packages or cargo containers are just some examples. A non-destructive assay method [3] has been proposed with the extremely high-flux laser Compton scattering (LCS) γ -source. The elemental and isotopic composition is measured using nuclear resonance fluorescence (NRF) with LCS γ -rays. Figure 4 illustrates how characteristic resonances of these elements can be identified.

One has to stress the political importance of this project. Measuring remotely and precisely isotopes like ^{239}Pu , ^{235}U or dominant fission products is very important for radioactive waste management. The handling of radioactive waste and its long-term storage are partially unsolved problems not only in Europe, but worldwide, as exemplified by the strong interest and encouragement by the IAEA on this development.

Electron beams

Excellent secondary beams can be produced by laser acceleration. One example is the new light pressure acceleration [4]. Here an increase of the ion energy roughly proportional to the laser intensity is predicted. This process is illustrated in Figure 5. Recently also the wake field acceleration of electrons with a very sharp electron energy and very little background electrons was observed [5]. In Figure 6 an electron spectrum is shown, where a laser with 8 fs duration, $3 \times 10^{18} \text{ W/cm}^2$ and 80 mJ was injected into an electron density of $2 \times 10^{19} \text{ /cm}^3$. For the high repetition rates of 1 kHz available

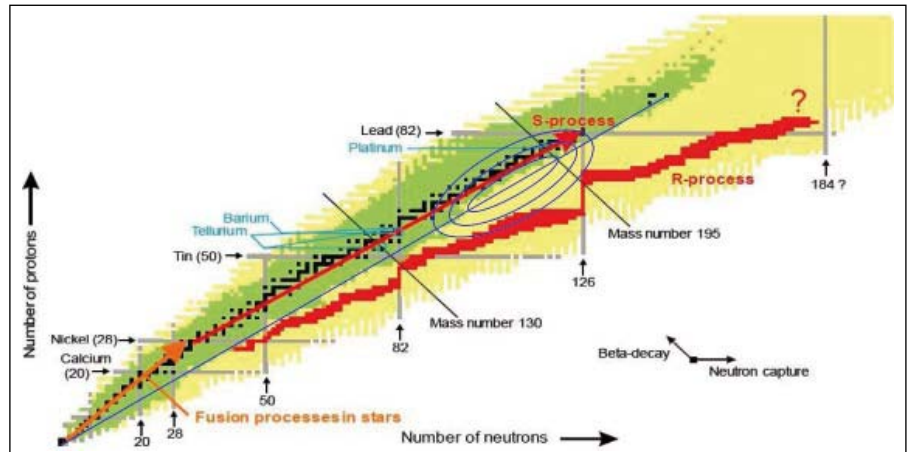


FIG. 7: Nuclidic chart, showing the different nucleosynthesis processes like the r- and the s-processes (red) together with contour lines of the new fission-fusion process (blue) for producing very neutron-rich nuclei close to the $N=126$ waiting point of the r-process.

in the Prague pillar of ELI, feedback systems can lead to even more stable beams. Scaling the present results to the much higher laser energy of 5 Joule and repetition rates of 1 kHz as envisaged for the ELI Beamlines Facility in Prague, many interesting applications can be foreseen. These include laser-driven ions in hadron tumor therapy, or using X-rays originating from electrons passing through undulators for diagnostics in life science or material science.

Nuclear Physics and Astrophysics

The origin of the heaviest elements (e. g. gold, platinum, thorium, uranium) remains one of the 11 greatest unanswered questions of modern physics, according to a recent report by the US National Research Council of the National Academy of Science. Dense, laser-accelerated ion beams open up new access to very neutron-rich nuclei, relevant to heavy element production [6]. A new 'fission-fusion' nuclear reaction process allows to produce the decisive neutron-rich nuclei in the range of the astrophysical r-process (the rapid neutron-capture process) around $N=126$. This is achieved by fissioning a dense, laser-accelerated thorium ion bunch in a thorium target, where the light fission fragments of the beam fuse with the light fission fragments of the target. So far the known isotopes are about 15 neutrons away from astrophysically relevant isotopes, the nuclear properties of which are unknown (see Figure 7).

A dramatic contrast with respect to ordinary radioactive beam facilities, where low-density radioactive beams of one ion species are merged with stable targets is the following. The novel fission-fusion process draws on the fusion between high-density, neutron-rich, short-lived, light fission fragments both from beam and target.

Using a high-intensity laser with 300 J and 32 fs pulse length, as, e. g., envisaged for ELI-NP, estimates promise a fusion yield of about 10^3 ions per laser pulse in the mass range of $A=180$ – 190 , enabling to approach the r-process waiting point at $N=126$. The produced nuclei from the fission-fusion process will be injected into a Penning trap to measure their nuclear binding energy with high accuracy [6]. This information will help in understanding the heavy element production by neutron capture.

INFO

Heavy nuclei synthesis

Using laser radiation pressure acceleration (RPA) for hole-boring [4], bunches of ^{232}Th with solid-state density can be generated very efficiently. As production target a thorium layer (approx. 0.5 μm thick), placed on a deuterated diamond-like carbon foil $[\text{CD}_2]_n$ (with approx. 0.5 μm thickness), is used. Laser-accelerated Th ions with about 7 MeV/u will pass through a thin $[\text{CD}_2]_n$ layer in front of a thicker second Th foil (both forming the reaction target) closely behind the production target. Here they disintegrate into light and heavy fission fragments. In addition, light ions (d,c) from the $[\text{CD}_2]_n$ backing of the production target will be accelerated as well, inducing ^{232}Th fission also in the second Th layer. The laser-accelerated ion bunches with near solid-state density are about 10^{14} times more dense than usual ion bunches. This gives rise to a high fusion probability of the generated fission products when the fragments from the thorium beam strike the thorium layer of the reaction target.

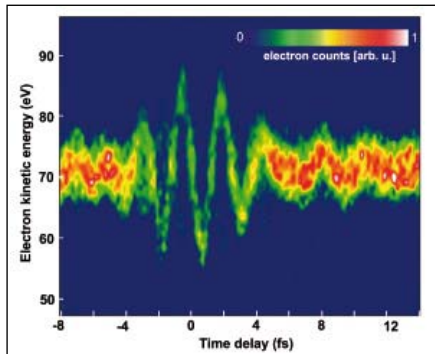


FIG. 8: The waveform of a few-cycle pulse (5 fs) is entirely mapped out by a single 250 as XUV flash from atomic harmonics.

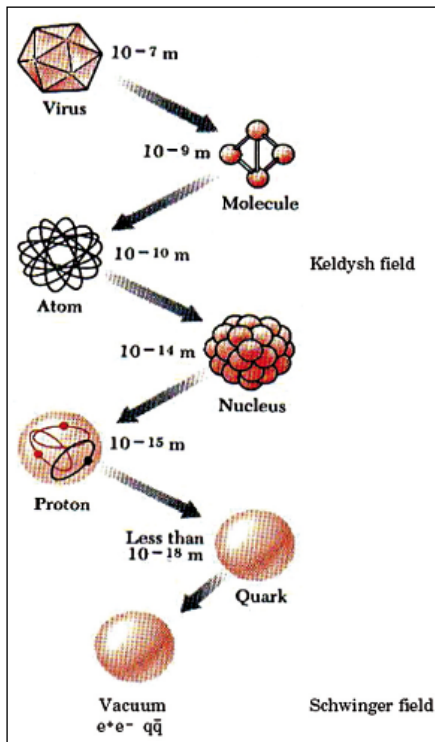


FIG. 9: Hierarchy of nature. While the Keldysh field is used to describe the ionization of atoms, the Schwinger field in an equivalent way describes the pair creation from vacuum.

The more Intense, the Shorter

The scientific motivation of this push towards this extreme power [7] was first to explore the high-field frontier and the related high-energy frontier, enabled by high-intensity physics. However, it is also realized that the prospect to produce exceedingly short bursts of energetic radiation and particles can come from intense lasers. In fact shortest pulses can only come from the most intense lasers. This is because of the following relationship between the pulse shortness and the intensity of laser that drives it [8]. It may be called the Pulse Intensity-Duration Conjecture – in order to shorten the pulse duration, we need to in-

crease the intensity. The reverse is, that the increase of laser intensity I may be achieved by shortening of the pulse length T – as simple as the equation $I=E/T$, where E is the laser energy per unit area. This is obvious, but the Conjecture $T=E/I$ is not.

As quantitatively shown [8], we witnessed the inverse proportionality between the duration and intensity over 15 orders of magnitude. In this range, we have encompassed the exploitation of nonlinearities of molecular, atomic, plasma electronic and relativistic origins. Encouraged by this Conjecture, a more recent theoretical projection [8] has been suggested to reach shorter pulses. It employs the compressed super-solid density as an ultra-relativistic flying mirror to reach another three orders of magnitude coverage of the Conjecture. In order to reach the shortest possible pulse length, we not only generate higher frequency coherent photons, but also compress them, which takes higher intensity. Employing the converse of the Conjecture, this means that we need to increase the laser energy as well.

We have learned that matter exhibits nonlinearities, when irradiated by a strong enough laser. Manifested nonlinearities vary depending on the strength of the “bending” field (and thus the intensity). The stronger we “distort” the constituent matter, the more rigid is the “distorting restoring” force we need to exert. The more rigid the force is, the higher is the restoring frequency. The nonlinearities of matter may vary, but this response is universal, ranging over molecular, atomic, plasma electronic and ionic, and even the stiffest of all nonlinearities in the vacuum. Thus we have witnessed nature’s display of the universal correlation between the pulse shortness and the intensity of its driving laser over the widest intensity range our laboratory has to offer.

Since the pulse duration goes inversely with the intensity from the millisecond to the attosecond regime, we can expect to look for even shorter pulses of zeptosecond duration. Such shortest coherent pulses in the zeptosecond-yoctosecond regime should be produced by the largest lasers, like ELI or NIF and the Mégajoule laser, with a proper reconfiguration into femtosecond pulse systems.

High-energy and vacuum physics

The introduction of kilo-joule and mega-joule lasers will bring in the unprecedented opportunity to enter into the science of high fields, but also into the ultra-fast science going beyond atomic motions as needed for the study of atomic nuclei. We can learn from the example of the electron streaking by lasers that was carried out in

INFO

Yoctosecond pulse generation

The shortest possible experimental pulse is based on the laser irradiation of a solid, which acts as an oscillating relativistic mirror. This yields X-rays by a few 1,000th of harmonic generation from the solid surface. In order to go beyond this, it takes a density beyond the solid density. A way to do so may be to compress the solid shell by laser implosion. In this ions have to be relativistically flying and compressed, which requires orders of magnitude more energy. A combination of this relativistically flying mirror with the implosion of it, such that its density may be enhanced by ten times in each dimension, results in a thousand-fold compression of its density. We surmise that this may be achieved by a large energy pulse (around a mega-joule) at the ultra-relativistic intensity of 10^{24} W/cm² on a partial shell of a concave spherical target. This ultra-relativistic flying mirror with the imploding shell is capable of coherently backscattering a 10 keV coherent X-ray pulse, producing coherent gamma rays of 100 yoctosecond duration.

an atom (see Figure 8). If we can generate a 100 ys coherent gamma pulse at an energy of 0.3 GeV, it will lead to a significant excitation of protons or neutrons, producing pions. Thus we expect a strong pion production. The high acceleration fields then allow to produce brilliant pion, muon or neutrino beams, opening the door to hadron physics. We are assuming an original mirror of $3 \mu\text{m} \times 3 \mu\text{m}$, compressed to a $0.3 \mu\text{m} \times 0.3 \mu\text{m}$ concave pancake scattering back the gamma beam. If the geometry is preserved, this can act to focus the gamma pulse further.

We now find ourselves in a situation where the field intensity exceeds the Schwinger value (above which electron-positron pair creation is possible), but does not break down the vacuum. This is formally analogous to the regime of a large Keldysh parameter, where tunnel ionization of atoms is suppressed. Thus, super-Schwinger fields can probe the vacuum without contaminating the vacuum itself. We therefore can explore, for example, the dielectric permittivity of vacuum under strong fields by phase-contrast imaging. This will provide an excellent chance to prove properties of nonlinear QED, QCD, and other fields.

When we explore the vacuum with high fields, we encounter the reincarnation of atomic physics in a wrapped-up fashion in

vacuum (see also Figure 9). Let us explain what this is. Take an example of self-focusing in an atomic gas vs. the self-focus in vacuum [7]. The critical power for self-focusing in vacuum is directly related to the critical power for self-focusing in an atomic gas. The ratio of these two is simply α^6 , where $\alpha \approx 1/137$ is the fine structure constant. It is also the case that the ratio of the Schwinger intensity to the Keldysh intensity is α^6 . When we try to explore the structure of nature via many entities deeper and deeper from the atom to the vacuum, we are now back to the square 1, when we enter the vacuum. The above re-encounter of the Keldysh parameter is telling.

Conclusions

ELI is an important and giant step towards the integration of high-field science, ultra-fast science and large-energy laser science. It is also expected to closer integrate traditionally distinct fields of science, such as high-energy physics, nuclear physics, the research in nuclear energy and medical imaging. The more intense a laser is, the more capable it will be to generate shorter coherent bursts

of radiation and particle beams. This dictum guides us how to proceed with ultra-relativistic optics to explore high field science and ultra-fast science in the future. We also open up a possibility to look at nuclei through γ -rays and perhaps in the future even with coherent γ -rays, just as we have done to study atoms with coherent optical beams (laser) since 1960. ELI could reveal the secrets of the vacuum, by doing so we can reach out to new ways to explore nuclear physics and high energy physics with most intense lasers. We also lay down a few stepping stones towards utilizing even larger energy lasers, such as NIF and LMJ. We conclude that ELI could provide a significant gift not only to the 21st century science, but equally to medical and nuclear energy applications.

References

- [1] Extreme Light Infrastructure: www.extreme-light-infrastructure.eu
- [2] D. Habs, U. Köster: "Production of Medical Radioisotopes with High Specific Activity in Photonuclear Reactions with γ Beams of High Intensity and Large Brilliance", *Appl. Phys. B.* (2010), doi:10.1007/s00340-010-4278-1
- [3] T. Hayakawa et al.: "Nondestructive assay of plutonium and minor actinide in spent fuel using nuclear resonance fluorescence with laser Compton scattering γ -rays", *Nucl. Instr. Meth. A* 621, 695 (2010)
- [4] A. Henig et al.: "Radiation-Pressure Acceleration of Ion Beams Driven by Circularly Polarized Laser Pulses", *Phys. Rev. Lett.* 103, 245003 (2009)
- [5] K. Schmidt et al.: "Few-Cycle Laser-Driven Electron Acceleration", *Phys. Rev. Lett.* 102, 124801 (2009)
- [6] D. Habs et al.: "Introducing the Fission-Fusion Reaction Process: Using a Laser-Accelerated Th Beam to produce Neutron-Rich Nuclei towards the N=126 Waiting Point of the r-Process", *Phys. B* (2010), doi:10.1007/s00340-010-4261-x
- [7] G. Mourou, T. Tajima, S.V. Bulanov: "Optics in the relativistic regime", *Rev. Mod. Phys.* 78, 309 (2006)
- [8] G. Mourou and T. Tajima, to be published (2010)

No small Matter

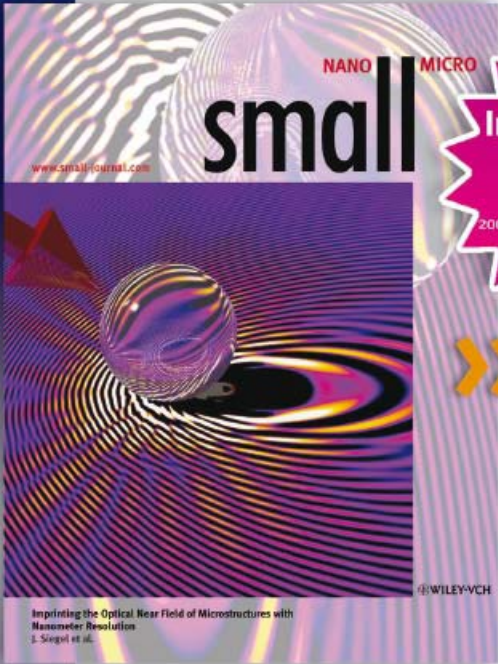
Micro and Nano:

For subscription details please contact Wiley Customer Service:

- » cs-journals@wiley.com
(Americas, Europe, Middle East and Africa, Asia Pacific)
- » service@wiley-vch.de
(Germany/Austria/Switzerland)
- » cs-japan@wiley.com
(Japan)

WILEY

WILEY-VCH



Imprinting the Optical Near Field of Microstructures with Nanometer Resolution
J. Siegel et al.

Impact Factor

6.171

2009 Journal Citation Reports®
(Thomson Reuters, 2010)

» provides the very best forum for experimental and theoretical studies of fundamental and applied interdisciplinary research at the micro- and nanoscales

2010. Volume 6, 24 issues.
Print ISSN 1613-6810 / Online ISSN 1613-6829

For more information please visit

www.small-journal.com

or contact us at small@wiley-vch.de

600601000_bu