Towards exawatt laser power and sub-attosecond pulses

Interview with Gérard Mourou, project coordinator of the Extreme Light Infrastructure (ELI)

What physics could evolve if we neglected all the current technical problems in laser physics? Gérard Mourou and some colleagues started to explore this question more than ten years ago. The result was a broad vision of new laser physics in the ultra high intensity regime. Now the idea has gained momentum with a giant European research collaboration. Andreas Thoss spoke to Gérard Mourou about the initiative's current status.

Optik & Photonik: Professor Mourou, after 28 years in some of America's top Universities, you returned to France. What was the reason?

GÉRARD A. MOUROU: The reason was very simple. When I left in 1978 with my wife, we had already spent years in America. I got a generous offer from the University of Rochester. I told her however, it was going to be for a few years only. But those few years, you know, became 28 years. And then I reached an age where you think about going back home. I had to fulfill my promise to my wife, so we came back.

O&P: But you didn't return just to retire?

G. M.: That's right. My field of research is so rich, I had a full agenda in mind when I returned to France.

O&P: You have started quite a number of research projects in your life. But ELI (the Extreme Light Infrastructure) stands out, even in this impressive list. Could you briefly describe what ELI is?

G. M.: ELI aspires to be the most intense laser in the world. By most intense, I don't mean the biggest. If you look at NIF at Livermore, or The Laser Mégajoule in Bordeaux, you realize that the size of lasers is a function of energy, not a function of power. ELI is the first large scale laser built with peak power and intensity in mind.

From the start it was conceived to produce the highest peak power we could produce today, e.g. exawatt. However the highest peak power is not the real reason. It must be based on a scientific and societal applications rational. Some of the reasons come from the possibility to move from atomic physics where we are now to nuclear physics or quantum vacuum physics. In terms of scientific applications, we want to explore the possibility to accelerate particles to very high energies or to produce coherent X-rays or even gamma-rays. For societal application the work on ELI could lead to new ways to treat cancer or to understand mechanisms controlling the aging processes in materials.

O&P: If we may turn now to the organization, how many institutes are now involved within ELI?

G. M.: Oh it's enormous. We have 13 partnering countries in the EU, each with a number of labs. So, roughly speaking, there are about 50 EU laboratories involved.

O&P: Asides from a number of existing sites, you have some plans to set up completely new sites. When and where?

G. M.: There are four planned sites. They are related to the project's four pillars.

One pillar is for high energy particles and radiation. This will be at a site in Prague. A second pillar is for attosecond studies, intended for Szeged, Hungary. The third pillar is dedicated to nuclear physics, it will be located in Magurele, Romania. The fourth pillar will be in high intensity physics, the location for which will be decided in 2012.

We are now in the preparatory phase. In five years, these projects will be operative. They are the first big scientific projects for the new European Union members from central-eastern Europe. The budget for the three facilities is large, reaching 800 million Euros, with about 280 million Euros for each country.

O&P: What was the biggest challenge in this project?

G. M.: Well, the preparatory phase of three years will end December 31, 2010. It went remarkably smoothly. The countries like the project. They found attractive the mix of science and applications in addition with the possibility to boost high tech, job creation and the economy. The most difficult part was the site location. ELI was supposed to be under one roof and each country wanted to host the entire ELI. Then, we found it would make much more sense to build ELI on three to four sites. One site for each scientific pillar with a common governance.

O&P: You already mentioned vacuum physics as a final goal of the new systems. What other ideas are behind ELI?

THE PERSON

GÉRARD MOUROU

Gérard A. Mourou is the Director of the Institut de la Lumière Extrême at ENSTA – Ecole Polytechnique in Palaiseau (France). He is Professor at the Ecole Polytechnique. In 2005, he moved back to France after 28 years in the USA at the University of Rochester and the University of Michigan (UM). At UM, he was the A. D. Moore Distinguished University Professor of Electrical Engineering and Computer Science. In 1991, he founded and became the director of the NSF Science and Technology Center for Ultrafast Optical Science. Gérard Mourou has been honored with numerous awards including the 2009 Charles Hard Townes Award of the Optical Society of America (OSA). He is initiator and coordinator of the European project Extreme Light Infrastructure ELI.

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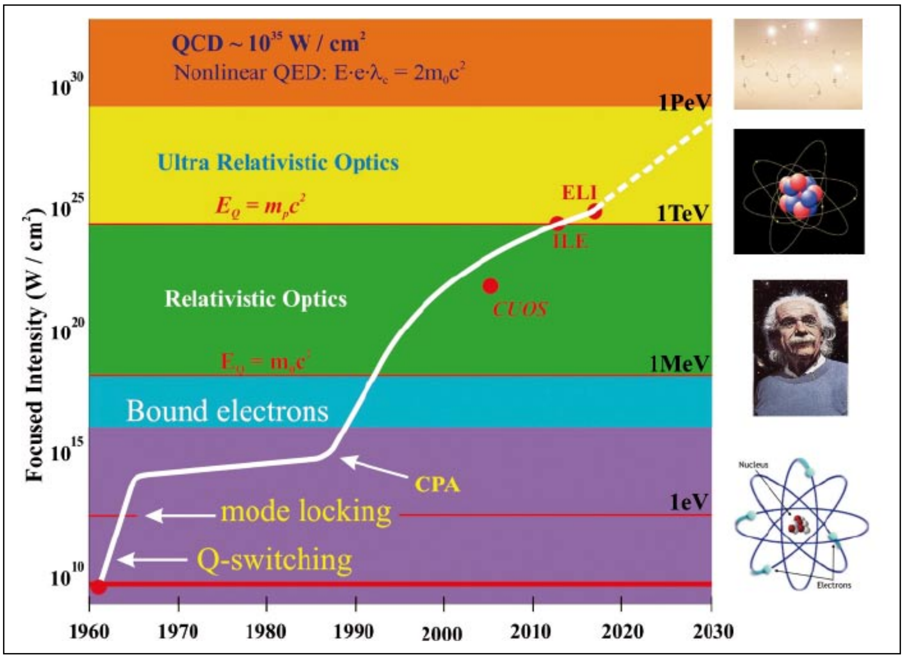

FIG. 1: **Maximum laser intensity as a function of time and fields of research accessible with these intensities.**

G. M.: Of course vacuum physics is the holy grail in terms of high-field research. As I mentioned , the idea to study nuclear physics is also very exciting. Until now the laser was mostly involved in atomic physics – eV physics. If we want to study nuclear reactions we will need ultra short pulses in the attosecond, zeptosecond end even yoctosecond regime of gamma-rays. It turns out, with ELI we are lucky. If we look at pulse duration as a function of time, you will notice that all the progress came whenever we improved the laser peak power and intensity. So there is a strong correlation between power and pulse duration. We call it the Intensity-pulse duration conjecture. Q-switching, dye mode locking, Kerr lens mode locking, SESAME mode-locking, pulse compression techniques, nanosecond, picosecond, femtosecond and attosecond pulses always came after having increased the peak power.

So ELI being the highest intensity laser, will naturally give us access to the shortest pulse duration of attoseconds, zeptoseconds or even yoctoseconds. Of course, these shortest pulses will be associated with the shortest wavelengths. They will be the product of relativistic and ultra relativistic optics (see Figure 1). If we produce extremely short pulses of gamma radiation we can perform photonuclear physics in a new way.

Maybe the most important practical application will be the particle acceleration invented by Toshiki Tajima. It is the result of laser interaction in plasma. In the relativistic intensity regime this process is natural and efficient. I like to see it as optical rectification. We can now with a 100 TW laser produce GeV electrons. The particle can be quasi monoenergetic with a dE/E of < 1 %. You see that 100 GeV accelerators could fit on a football field instead of a 3 km facility like in SLAC (50 GeV). With a high energy, monoenergetic beam we could make compact free electron laser and produce 10 keV, X-ray beams.

Among other applications we also need to think about testing general relativity or studying extra dimensions and producing Hawking radiation.

O&P: Tuning systems to ever higher power is one thing, but what real changes do you expect at those high intensities?

G. M.: Since 1990 after the invention of CPA, we have been in the regime of relativistic optics. The interaction of light with electrons becomes different because we have to include the v x B term now, which really makes the law of optics different. v is the electron velocity and B the light's magnetic field.

In 1990, we showed that we could get intensities to 10^{18} W/cm² and more, where the v x B is not negligible anymore as in classical optics or even in nonlinear optics of the bound electron. In fact, it becomes dominant, pushing the electrons forward and enabling electron acceleration to reach relativistic velocities.

The relativistic regime starts at 10^{18} W/cm² for 1 micron light and extends up to 10^{24} W/cm². At this point ions themselves become relativistic. We call this regime ultra relativistic. It is characterized by the fact that electrons, ions and photons are all relativistic. So in the interactions, the energy exchange between the pump laser, electrons and ions is more efficient.

And if we go one step further, to 10^{29} W/cm², we get pair generation. ELI is aiming for 10^{25} W/cm² which seems to be far from 10^{29} W/cm² – considered as the canonical threshold. However, this is only partially true because we should produce pairs below the threshold. Also we plan to use some of the laser pulse "by products", gamma-rays or high energy electrons as catalysts.

O&P: So I guess radiation is problematic.

G. M.: Yes in this intensity regime, radiation is a major concern. Handling a laboratory in this intensity regime is like managing a nuclear physics lab. This is what we have to be concerned about.

Remember the laser was invented in 1960. We just celebrated its 50th anniversary this year. CPA started in circa 1990. Until then, lasers were basically utilized for atomic physics where the science is in the electron volts regime. Now, with ELI at 10^{24} W/cm², the quiver energies are in the tens of GeV. We can start to study nuclear physics and as I said previously it is one of ELI's major goals. Here it becomes clear why the combination of intensity plus short pulses is so beautiful.

With ultra-short pulses, we can look at electrons dancing around the nucleus, just as Ferenc Krausz did. If we produce ultrashort pulses in the attosecond regime or even shorter, in the gamma-ray regime, we can study nuclear physics reactions in real time.

THE PROJECT

Extreme Light Infrastructure (ELI)

ELI will be a new scientific infrastructure devoted to scientific research in the field of lasers, dedicated to the investigation and applications of laser-matter interaction at the highest intensity level (more than 6 orders of magnitude higher than today's laser intensities). The ELI project is a collaboration between almost 50 scientific research institutions of 13 European countries. The preparatory phase of the ELI project started in November 2008 and will last until December 2010. It will be followed by a five year construction period called ELI delivery consortium or ELI DC.

www.extreme-light-infrastructure.eu

O&P: If we look at the roots of ELI, you brought nuclear physics experience, and even some particle physics experience, into the laser field, right?

G. M.: That's correct, absolutely. This is particularly true for Romania's pillar that will be constructed on a nuclear laboratory site. ELI really provides the opportunity to explore regimes in nuclear physics that were only accessible with high energy particle accelerators. Now we can do that with lasers.

O&P: What makes ELI different to other European research projects such as XFEL or ITER? What is new about this idea?

G. M.: ELI is not just after one goal, such as ITER for instance. ITER is trying to generate energy by magnetic fusion, a really important project for our society. ELI will have to be compared more to XFEL. With ELI, the range of research is very diversified. It is fundamental research in a new physics domain. We do this differently compared to conventional high energy physics. Usually, they are building a very expensive machine with only a few particular goals in mind, such as generating the Higgs boson, for instance.

With ELI we want to explore an entirely new regime of laser-matter interaction relevant to nuclear physics, general relativity and high energy physics to mention a few.

O&P: Can you tell me more about the top three or four research targets that you are focusing on at the moment?

G. M.: Yes, the first is our research on high-energy particles acceleration. As I said we can accelerate electrons efficiently by the phenomenon known as wake field acceleration. We can certainly build much more compact systems for electron acceleration to produce electrons and positron at the 100 GeV level.

We should also be able to produce relativistic ions, GeV ions. One application will be in proton therapy. Of course, we don't need GeV ions for this application, 500 MeV will suffice. But in order to understand the mechanisms of ion acceleration thoroughly we need to study the process over a wide dynamic range.

Then we have high-energy radiation. Here we would try to build a compact XFEL. Instead of having a km-long accelerator to produce 10 to 15 GeV electrons, we aspire to produce it on a smaller setting, i.e. tens of meters. The electrons need to be monochromatic and with a substantial amount of charges (nC). With a high quality electron source provided by laser acceleration and periodic magnets acting as wiggler we have all the ingredients for a coherent X-ray FEL that would produce coherent X-rays.

The next one is exotic physics. Here I would put nuclear physics, vacuum physics testing nonlinear quantum electrodynamics and nonlinear chromodynamics, extradimension physics, general relativity, etc. To perform this work we will use not only the large field but also the synchronized electrons, ions, X-ray and gamma ray short pulses produced by the laser itself.

O&P: Looking at the first points, it appears that a major goal of the project is to develop smaller, more stable laser systems with higher output performance.

G. M.: Yes, if I want to produce GeV electrons today, I will use SLAC which produces 50 GeV electrons over three kilometers. If we reduce the size to a football field then it is a superb achievement that I think is doable over 5 years.

We know also that in about 15 years, high-energy physics will have a problem to go beyond several TeV at a low cost. Laser acceleration could be the replacement technology that we were all looking for – if we can produce 1 GeV acceleration on a scale of just a few centimeters. We could envision a TeV accelerator with decent size and costs. This is one of ELI's main objectives.

O&P: For most applications the repetition rate of today's laser facilities is too small. What's your opinion about that?

G. M.: Indeed, we can produce the highest peak power on earth. But we are not good in producing decent average power. For instance, with a terawatt system, we may have 100 pulses per second corresponding to an average power of about ten watts. It is vital for the field to improve the repetition rate. People working on laser fusion have the same problem. They are going to show the principle on a single shot per day basis. But for real life they will need to make it at a few tens of Hz. So my next project is to go to the kilowatt or even the megawatt level.

FIG. 2: **Gérard Mourou is initiator and coordinator of the ELI project.**

O&P: On average power?

G. M.: Yes, especially for laser accelerators in high energy physics. If we want to replace existing high energy accelerator systems with lasers, then we have to produce kilojoules per pulse at 10 kHz, which means more than 10 megawatts. That is six orders of magnitudes above what we have. On top of that, we need to do it very efficiently, i.e. 30 % to 50 % efficiency and not 1 % like the high peak power laser today. We don't want to produce 10 megawatts with a one percent efficiency. That would be unimaginable for applications. You see the challenge!

We are working on a new concept based on fibers, called CAN. It is the abbreviation of Coherent Amplification Network. We are forming a consortium with the likes of Andreas Tünnermann (Jena) and David Payne (Southampton). This type of laser would give us simultaneously peak power, average power, and efficiency.

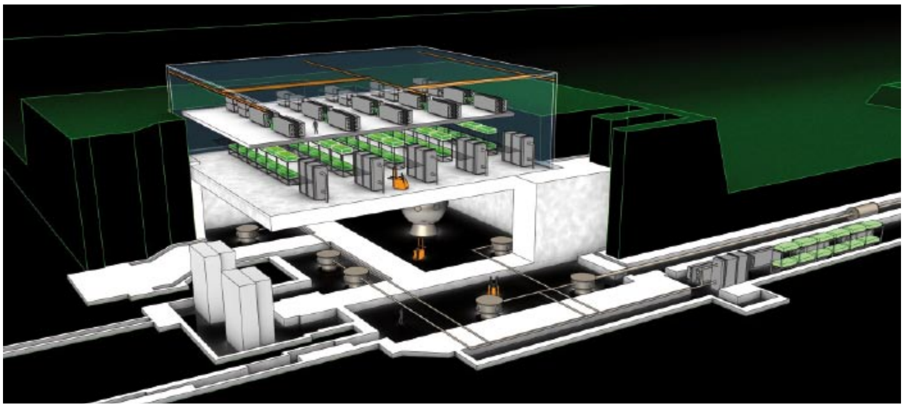

FIG. 3: **ILE laser facility, housed in the former Accelerateur Linéaire de Saclay infrastructure. APOLLON laser is on the bottom right. ELI laser could be composed of 10 phased APOLLONs, if France were selected as the 4th ELI's pillar.**

Fiber lasers offer some attractive features: they are very efficient. They are diode pumped – and diodes are again very efficient. The problem is, we have to use a lot of them and we have to couple them coherently, because we can only produce around one millijoule per fiber even if we want to produce say, 10 joule per stage.

The nice thing about fiber technology is that we can take advantage of the tremendous work the telecom community has done already.

We have sent a proposal to Brussels on the study of an efficient laser driver based on this principle. The goal is to demonstrate 30 % to 50 % efficiency. If we can do that, then we can talk about applications.

O&P: What other applications can you imagine?

G. M.: As I said ion therapy could be one. We could also use high peak power lasers to transmute elements for nuclear waste processing. Sauerbrey did some very nice demonstrations doing just that. But of course efficiency is necessary. We can not envision this application with one percent laser efficiency.

O&P: After an impressive scientific career in Michigan, you have just started one of the biggest laser projects in Europe. What are the next steps?

G. M.: It is true, this is the biggest optics project in the world – in the civilian arena. So the next step is to build it. But to do that we need project managers, not scientists. Engineers must replace the scientists.

The preparatory phase is now ending at the end of December 2010. The program will be transferred to the implementation team, we call it the delivery consortium.

My role will be to keep the scientific community together. I will be also active here in France with the Apollon Project which is the ELI one-beam prototype of the ultrahigh intensity laser of the fourth pillar.

O&P: You spent more than half of your scientific life in the USA. What are the differences in the scientific system in comparison to European research (and education)?

G. M.: Regarding Europe, I can only speak about the French system. In the American system, as a faculty you have to do three things: research, teaching and services to the department. What I discovered is that in the US, research and teaching are closely intertwined. You need to do research and teaching. Also you cannot teach just your favorite topics. You have to teach as many different courses as possible. For instance, I was in optics but I had to teach transistors. If you want to learn about a topic you need to teach it. This mix is very powerful and healthy. It forces you to learn other topics. In France it is different, basically the CNRS does the research and the university the teaching.

Another point where the US universities are doing well is technology transfer. In the States, universities are autonomous, independent. Only the professors are paid on what we call “hard money”. Also a big difference, the research is being performed in the professors laboratories by students and post docs. In few cases by professional researchers. However, everybody else is on “soft” money, that is from a “research contract”. The professor is paid for his teaching, not for his research. He needs to find research contracts for that. So if a researcher in the course of his research stumbles on something exciting, it is logical for him to think about starting a business. They do not have the commitments of running a lab, teaching students, advising students, etc.

From my laboratory we started six very successful companies. One in femtosecond ophthalmology, Intralase Inc, two in photonics, Picometrix Inc., and Medox Electrooptics Inc., one in laser, Clarck-MXR, and one in applications in femtosecond micromachining, Translume. All these companies did perform very well. They were all started by researchers, not professors. I found it exciting to see the process, starting from the idea to become a billion dollars company like Intralase.

O&P: Isn’t that a threat to those trained in science, those passionate about pure science?

G. M.: Of course, students, post docs and researchers do not all start a company, they can go to industry. And those who like research they can apply for a faculty position in the large number of universities. However they have to produce good research if they want to be selected in one of the top universities. The universities like to maintain or improve their ranking.

O&P: Professor Mourou, thank you for this interview.

GLOSSARY

CPA Chirped Pulse Amplification is a technique for amplifying an ultrashort laser pulse up to the petawatt level with the laser pulse being stretched out temporally and spectrally prior to amplification. CPA for lasers was invented by Gérard Mourou and Donna Strickland at the University of Rochester in 1985.

ITER The International Thermonuclear Experimental Reactor is an international research and engineering project which is currently building the world’s largest and most advanced experimental Tokamak nuclear fusion reactor, at Cadarache, France

XFEL European X-ray Free-Electron Laser is a 3.4-kilometre-long facility in Hamburg and Schenefeld (Germany). XFEL is a special electron accelerator that will generate X-ray radiation with properties similar to those of laser light.

NIF The National Ignition Facility is a laser-based inertial confinement fusion research device located at the Lawrence Livermore National Laboratory in Livermore, California. NIF uses lasers to heat and compress a small amount of hydrogen fuel to the point where nuclear fusion reactions take place.

SLAC The SLAC National Accelerator Laboratory, originally named Stanford Linear Accelerator Center, is operated by Stanford University under the direction of the U.S. Department of Energy’s Office of Science. SLAC’s research centers on elementary particle physics using electron beams and a broad program of research in physics, chemistry, biology, and medicine using synchrotron radiation.

Some units

EW	exawatt 10^{18} watt	ps	picosecond 10^{-12} seconds
PW	petawatt 10^{15} watt	fs	femtosecond 10^{-15} seconds
TW	terawatt 10^{12} watt	as	attosecond 10^{-18} seconds
GW	gigawatt 10^{9} watt	zs	zeptosecond 10^{-21} seconds
MW	megawatt 10^{6} watt	ys	yoctosecond 10^{-24} seconds