Extreme Light Infrastructure: Attosecond Physics to Relativistic and Ultra-Relativistic Optics

Roumanian Institute of Atomic Physics

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Optics Horizon

This field does not seem to have natural limits, only horizon.
Two large Laser Infrastructures Have Been Selected to be on the ESFRI (European Strategic Forum on Research Infrastructures) Roadmap

"a - HIPER, civilian laser fusion research (using the fast ignition scheme) and all applications of ultra high energy laser
"b - ELI, reaching highest intensities (Exawatt) and applications

ELI has been the first Infrastructure launched by Brussels November 1st 2007.
Why should we build an Extreme Light Infrastructure?
1) Is ours the only universe?
2) What drove cosmic inflation?
3) When and how did the first stars and galaxies form?
4) Where do ultrahigh-energy cosmic rays come from?
5) What powers quasars?
6) What is the nature of black holes?
7) Why is there more matter than antimatter?
8) Does the proton decay?
9) What is the nature of gravity?
10) Why is time different from other dimensions?
11) Are there smaller building blocks than quarks?
12) Are neutrinos their own antiparticles?
13) Is there a unified theory explaining all correlated electron systems?
14) **What is the most powerful laser researchers can build?** Theorists say an intense enough laser field would rip photons into electron-positron pairs, dousing the beam. But no one knows whether it's possible to reach that point.
15) Can researchers make a perfect optical lens?
16) Is it possible to create magnetic semiconductors that work at room temperature?
Contents

• The Peak Power-Pulse Duration conjecture
• Relativistic Optics: A parallel with Bound Electron Nonlinear Optics
• Relativistic Rectification (wake-field) the key to High energy electron beam, proton beam, x-ray and γ-beams
• Source of attosecond photon and electron pulses
• Generation of Coherent x-ray by Coherent Thomson scattering
• A route to the critical (Schwinger) field
• Few examples of applications to High energy Physics
  General Relativity, Hawking Radiation, Extradimensions.

ELI (Extreme Light Infrastructure) An Exawatt laser Infrastructure on the Large Infrastructure Road Map of Europe
Peak Power - Pulse Duration

Conjecture

1) To get high peak power you must decrease the pulse duration.
2) To get short pulses you must increase the intensity
Laser Pulse Duration vs. Intensity

- Q-Switch, Dye: \( I = kW/cm^2 \)
- Modelocking, Dye: \( I = MW/cm^2 \)
- Mode-Locking KLM: \( I = GW/cm^2 \)

MPI: \( I > 10^{13}W/cm^2 \)

Relativistic and Ultra R Atto, zepto & .?
Ultra-relativistic intensity is defined with respect to the proton $E_Q = m_p c^2$, intensity $\sim 10^{24} \text{W/cm}^2$. Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0 c^2$. Ultra-Relativistic Optics.
Small-Scale Self-Focusing

Instabilities grow with a maximum growth rate:

\[ n = n_0 + n_2 I \]

B-integral < 3 for good beam quality:

\[ B = \frac{2p}{l} \int_0^L n_2 I(z) dz \]
Chirped Pulse Amplification
D. Strickland and G. Mourou 1985
Matched Stretcher-Compressor

1000 Times Expansion/Compression of Optical Pulses for Chirped Pulse Amplification

M. Pessot, P. Maine, and G. Mourou, Optics Commun. 62, 419-421 (June 1987)
Bound Electron Nonlinear Optics

\[ \vec{F} = q \vec{E} \quad F \not\propto x \]

The field necessary corresponds to \( \frac{\hbar v}{\lambda^3} \)

"Harmonics"
"Optical Rectification"
"Self-focusing"
Relativistic Optics
Relativistic Optics

a) Classical optics $v \ll c$

$$a_0 \ll 1, \quad a_0 \gg a_0^2$$

b) Relativistic optics $v \sim c$

$$a_0 \gg 1, \quad a_0 \ll a_0^2$$

Delta $\Delta x \sim a_0$

Delta $\Delta z \sim a_0^2$
Relativistic Rectification
(Wake-Field Tajima, Dawson)\(\vec{E}_s\)

1) pushes the electrons.

2) The charge separation generates an electrostatic longitudinal field. (Tajima and Dawson: Wake Fields or Snow Plough)

3) The electrostatic field
Relativistic Rectification

_Ultrahigh Intensity Laser is associated with Extremely large E field._

\[ E_L^2 = Z_0 \times I_L \]

Medium Impedance \quad \text{Laser Intensity}

\[ I_L = 10^{18} \, W/cm^2 \quad E_L = 2 \, TV/m \]

\[ I_L = 10^{23} \, W/cm^2 \quad E_L = .6 \, PV/m \quad (0.6 \times 10^{15} V/m) \]
Laser Acceleration:

At $10^{23}$ W/cm$^2$, $E = 0.6$ PV/m, it is SLAC (50 GeV, 3 km long) on 10µm. The size of the Fermi accelerator will only be one meter (PeV accelerator that will go around the globe, based on conventional technology).

Relativistic Microelectronics
5 GeV proton bunch at solid state density

3d PIC simulations, A. Pukhov, Theorie, MPQ,
(a) on-axis particle density, cm$^{-3}$

(b) accelerating field, 100 TeV/m

(c) $10^{12}$ protons from 4 to 5 GeV
The Dream Beam

J. Faure et al., C. Geddes et al., S. Mangles et al., in Nature 30 septembre 2004
Relativistic Protons

Non relativistic

\[ V_p \sim 0 \]

Relativistic protons

\[ V_p \sim C \]

\[ E_p \sim I^{1/2} \]

\[ E_p \sim I \]
The structure of the ion cavity

Longitudinal acceleration

Transverse oscillation: Betatron oscillation
Experiment Setup

A. Rousse et al.

Laser 1.5 J/30 fs  (Salle Jaune)

Helium jet

$n_e \sim 10^{19} \text{ cm}^{-3}$

Permanent magnets

Electrons

X-rays
Simultaneous measurements of X-ray and Electron Beams

X-ray CCD (taper) Roper Scientific
6cm x 6cm CCD area
with 500 µm Be filter

Electron beam
\( n_e = 10^{19} \text{ cm}^{-3} \)

K. Ta Phuoc et al
Attosecond Generation
(photon)
Attosecond by Bond electron Nonlinear Optics


The technique relies on High harmonic Generation and not very efficient.

It is limited to nJ and not scalable to high energy.
HHG and Subfemtosecond Pulses from Surfaces of Overdense Plasmas


S. Gordienko et al PRL 93, 115002 (2004)

N.M. Naumova et.al., PRL 92, 063902 (2004)

Reflected radiation spectra: the slow power-law decay

1D simulation

\[ I \sim \omega^{-8/3} \]


The Gaussian laser pulse \[ a = a_0 \exp\left[-\left(\frac{t}{\tau}\right)^2\right] \cos \omega_0 t \] is incident onto an overdense plasma layer with \( n = 30n_c \).

The color lines correspond to laser amplitudes \( a_0 = 5, 10, 20 \).

The broken line marks the analytical scaling \( I \sim \omega^{8/3} \).

Possibility to produce zeptosecond pulses!!!
VULCAN Experiment: Harmonics down to “Water Window”


\[ I_n \sim n^{-2.5} \]

*Figure 3* Unprocessed high harmonic spectrum recorded with the extreme-ultraviolet spectrometer. *a*, Raw CCD image obtained with the double PM setup (\( E = 70 \text{ J} \) on target, false colours). *b*, A lineout of *a*. Spectral features: (1) first-order carbon K-edge (4.36 nm), (2) second-order carbon K-edge, (3) third-order carbon K-edge, (4) region of resolved harmonics around 200th order.

*Figure 4* Relative intensity of harmonics normalized to the 238th harmonic (at the carbon K-edge). The lines are fits to the data with the exponent \( p \) as a fitting parameter such that \( I(n) / I(238) = n^{-p} / 238^{-p} \). The best fit (red line) corresponds to a value of \( p = 2.5 \) confirming harmonic production in the relativistic limit. The error
Relativistic Self-focusing:

\[ \varepsilon = 1 - \frac{w_p^2}{g_0 \nu^2} \]

where \( g_0 = \sqrt{1 + |a_0|^2} \)

Single Mode Relativistic optics in Reflection

Under the action of the light pressure the critical surface will be pushed (curved) at relativistic speed at twice the laser frequency ($\omega$).

If the laser is focused on $1\lambda$, it will act as a perfect single mode mirror, leading to well behaved reflection and deflection.

The restoration force is a function of the plasma density
Moving plasma profile deflecting the isolated attosecond pulses at the instants of their generation

Relativistic electrons create the Doppler compression

3-D PIC simulation

Electromagnetic energy density

attosecond pulse

Electron density

P-plane    S-plane
2-D PIC simulation

- most intense attosecond impulse

- 200 as impulse

- beam divergence

- direction of pulse maximum
2-D PIC simulation
Scalable Isolated Attosecond Pulses

Duration, $\tau$ (as)

2D: $a=3$, 200 as

$\lambda=10^{19} \Omega/\chi \mu^2$ ($\lambda^3$ laser)

$\tau(\text{as})=600/a_0$

1D PIC simulations in boosted frame

optimal ratio: $a_0/n_0=2$, or exponential gradient due to $\omega_{cr} = \omega_0 a^{-1/2}$

$I=10^{22} \text{W/cm}^2$ (Hercules)

$n_0 = n/n_{cr}$
Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$

Zettawatt Laser

Laser Intensity Limit: $I = \frac{hv^3}{c^2} \cdot \frac{\Delta \nu_g}{\sigma} = \frac{P_{th}}{\lambda^2}$

Relativistic Optics: $v_{osc} \sim c$

(Electronic Oscillations, large ponderomotive pressures)

$E_q = m_0c^2$

Bound Electrons: $E = \frac{e^2}{a_0}$

$E_q \sim h\nu$

Electron Characteristic Energy

Electroweak Era

Quark Era

Positron-Electron Era

Plasma Era

Atomic Era

Focused Intensity (W/cm$^2$)


10$^{10}$ 10$^{12}$ 10$^{14}$ 10$^{15}$ 10$^{16}$ 10$^{18}$ 10$^{20}$ 10$^{22}$ 10$^{24}$
Laser-Induced Nonlinear QED


Vacuum can be considered like a dielectric

Schwinger Field

\[ E_s = 1.3 \times 10^{16} \text{ V/cm} \]

Vacuum Tunneling

\[ I_s = 10^{30} \text{W/cm}^2 \]
Towards the Critical Field

For $I=10^{22}\text{W/cm}^2$ $a_0^2 = 10^4$

The pulse duration $\tau = 600/a_0 \sim 6\text{as}$

The wavelength $\sim \lambda/1000$

The Focal volume decreases $\sim 10^{-8}$

The Efficiency $\sim 10\%$

Intensity $I=10^{22}\text{W/cm}^2$ $\rightarrow I=10^{28}\text{W/cm}^2$
Isolated Attosecond Pulse Generation by Relativistic Compression and Deflection in the $\lambda^3$

- Optimum use of the energy
- Provides pulse isolation
- Predicted to be efficient ($10^{-1}$-$10^{-2}$)
- Single mode and short pulse suppress the unstabilities, that is very good beam quality expected.
- It relies on relativistic plasma therefore scalable to any pulse energy (kJ)
- The higher the intensity the shorter the pulse
Attosecond Generation
(electron)
Attosecond Electron Bunches

\( a_0 = 10, \tau = 15\text{fs}, f/1, n_0 = 25n_{\text{cr}} \)

Coherent Thomson Scattering

$a_0=10$, $\tau=15\text{fs}$, $f/1$, $n_0=25n_{cr}$

Electron bunches of ~100 as duration would produce backward Coherent Thomson scattering efficiency

- Cross-section for the backward Thomson scattering:
  \[ \sim N + N(N-1) \exp(-2(k'd')^2) \]
depends on the factor in the exponent:
  \[ k'd' = kd(1 + V/c)^2 \gamma^2 \].
- The resulting backward Thomson cross-section:
  \[ \sigma_T N^2 \exp(-8(kd)^2 \gamma^4) \sim 10^{-4} \exp(-8(kd)^2 \gamma^4) \text{ cm}^2 \]
is far above the channel cross-section \( \sigma_{ch} = 10^{-8} \text{ cm}^2 \).
- Limitation for \( d \) and \( \gamma \):
  \[ kd < \gamma^2 (-0.125 \ln(\sigma_{ch}/\sigma_T N^2)^{1/2} ) \]
- Attosecond bunches with width
  \[ d \sim 1/k\gamma^2 \sim (100 \text{ as}) \cdot c \]

\[ \gamma_{\text{photon}} = \frac{l}{4g^2} \text{ for } g = 100 \]
\[ g_{\text{photon}} = 40 \text{ keV} \]
For \( g = 10^3 \), \( g_{\text{photon}} = 6 \text{ MeV} \)

\[ \eta \sim 1 \text{ efficiency} \]

Control & 4D imaging of valence & core electrons with sub-atomic resolution

- petawatt field synthesizer
- attosecond xuv / srx pulse
- sub-fs electron bunch 0.1-1 GeV
- 5-10 MeV
- sub-fs x-ray pulse

Excitation

Friedrich-Schiller-Universität Jena, Germany
Ultra-high Intensity

General Relativity

and Black Holes
Laboratory Black Hole

T. Tajima and G. Mourou  Review of Modern Physics

Equivalent to be near a Black Hole of Dimension? Temperature?
**Is Optics in General Relativity?**

Using the gravitational shift near a black hole:

\[ kT = \frac{\hbar a_e}{2pc} \]

As we increase \( a_0 \) the Swartzschild radius can become equal to the Compton wavelength.
In order to have Hawking radiation, you need the gravitational field strong enough to break pairs.
Finite Horizon and extra-dimensions

The distance to finite horizon is

N. Arkani-Hamed et al. (1999)

Up to $n=4$ extra-dimensions could be tested.

T. Tajima phone # 81 90 34 96 64 21
Moving from the Atomic Structure to the Quark Structure of Matter
Conclusion

Atomic Physics

Nuclear Physics

High Energy Physics

Astrophysics

PeV

Cosmology

eV

Atomic Physics

Nuclear Physics

High Energy Physics

Astrophysics

PeV

Cosmology
Extreme Light Infrastructure

ELI

Extreme by its pulse duration
Extreme by its intensity
Extreme by the energy of its radiations and particles

On the Map of the Very Large Scale European Infrastructures

ELI Proposal
http://loa.ensta.fr
Ultra-relativistic intensity is defined with respect to the proton $E_Q = m_p c^2$, intensity $\sim 10^{24}$ W/cm$^2$. 

Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0 c^2$
ELI Scientific Program: Based on an Exawatt Class Laser

Three Scientific Pillars

• **Ultra high Field Science**: access to the ultra-relativistic regime, ELI will afford new investigations in particle physics, nuclear physics, gravitational physics, nonlinear field theory, ultrahigh-pressure physics, astrophysics and cosmology.

• **Attosecond science**: snap-shots in the attosecond scale of the electron dynamics in atoms, molecules, plasmas and solids.

• **High Energy beam facility**: ELI will provide ultra-short energetic particle (>10 GeV) and radiation (up to few MeV) beams produced from compact laser plasma accelerators.
**Exawatt laser scheme**

**MPQ Garching**

**PW OPCPA Front end**
- 5 Joules
- 5 fs
- 100-1000Hz
- P~1PW

**Duty end, CPA Ti: sapphire Power amplifier(s)**
- 40-70 PW
- 1sh/mn-1sh/sec

**Single Beamline**
- 0.4/0.7 EW

**Multiple Beamlines**
- 0.4/0.7 EW

**Power**
- 1 EW = 1000 PW = $10^{18}$ W
- 0.1 EW = 100 PW = $10^{17}$ W

**Energy**
- $10$ KJ in $10$ fs
- $1$ KJ in $10$ fs
Pumping of a Ø20cm crystal

\[ [\text{Ti}^{3+}] = 1.2 \times 10^{19} \text{ ions/cm}^3 \]

Stack of low absorbing disks

\[ [\text{Ti}^{3+}] = 6.6 \times 10^{18} \text{ ions/cm}^3 \]

NO parasitic effects in crystals
Participating Countries

- France
- Germany
- United-Kindom
- Spain
- Italy
- Greece
- Lithuania
- Austria

- Romania
- Bulgaria
- Hungary
- Belgium
- Poland
- Portugal
Partner Laboratories

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Programme ILE

ELI

10 faisceaux
10 faisceaux

ILE

Un faisceau

Construction Batiment

Bat. Fini Laser commence

Décision site Etude Batiment et APD commencent

ELI PP commence

Salle Jaune épaisseur du trait
Thank you

Become an ELI enthusiast
You can register @

WWW.eli-laser.eu
Eli@eli-laser.eu
One of the big Challenges in Physics would be to build a laser powerful enough to breakdown vacuum.

Survey by Science 2005
Towards the Exawatt Laser: Relativistic and Ultra-Relativistic Optics

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CLEO Europe 2007
Recent results on electrons acceleration - Setup

LOA – 100 TW
Laser
Nozzle
Magnets
He gas
$n_e \sim 10^{19} \text{ cm}^{-3}$

J. Faure et al, Nature 2004
Quasi-monochromatic beam with $E_{\text{max}} = 160$ MeV at $n_e = 2.10^{19} \text{ cm}^{-3}$

![Graph showing the energy distribution of the beam with a peak at 190 MeV and a spread of ±15 MeV.](image)
Tunable monoenergetic bunches
V. Malka and J. Faure

$Z_{\text{inj}}=225 \, \mu m$

$Z_{\text{inj}}=125 \, \mu m$

$Z_{\text{inj}}=25 \, \mu m$

$Z_{\text{inj}}=-75 \, \mu m$

$Z_{\text{inj}}=-175 \, \mu m$

$Z_{\text{inj}}=-275 \, \mu m$

$Z_{\text{inj}}=-375 \, \mu m$

Energy (MeV)
T. Tajima and J. M. Dawson,
Laser electron accelerator,
Secondary effects of electron acceleration:

Proton Acceleration
Front and back acceleration mechanisms

Peak energy scales as: \( E_M \sim (I_L \times \lambda)^{1/2} \)
Large Laser results : Vulcan laser
50J:1ps & 1shot/20min.

- In front of target – “blow-off” direction
- Behind the target – “straight through” direction
Secondary effects of electron acceleration:

X-ray Beam
5 GeV proton bunch at solid state density

3d PIC simulations, A. Pukhov, Theorie, MPQ,

$10^{23}$ W/cm$^2$

50 µm

1 kJ, 15 fs long laser pulse focused down to 10 µm spot on a plasma with $n=10^{22}$ cc$^{-1}$
Pions have 20ns lifetime (6m). They can only be accelerated up to 100MeV during this time with conventional technology. Their mass is \(\sim 200\text{MeV}\), to increase their lifetime 100times, to 2\(\mu\)s, we need to increase their energy by 100 to 20GeV. This can be achieved with laser technology over only 20\(\mu\)m.