Extreme (Exawatt) Light Physics

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„Optics Horizon”

This field does not seem to have natural limits, only horizon.
Relativistic

Ultra Relativistic

Relativistic Compression

QCD $\sim 10^{35}$W/cm$^2$
Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$

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

Ultra-Relativistic Optics

$E_Q = m_p c^2$

CUOS

Relativistic Optics

$E_Q = m_0 c^2$

ELI

Bound electrons

$E_Q = m_0 c^2$

CPA

Focused Intensity (W/cm$^2$)

1 PeV

1 TeV

1 MeV

1 eV


Mode locking

Q-switching

NL Optics

Ultra-relativistic intensity is defined with respect to the proton $E_Q = m_p c^2$, intensity $\sim 10^{24}$W/cm$^2$.
The different Epochs of Laser Physics

1960
Coulombic Epoch

\[ E_c = \frac{e}{r_b^2} = \frac{m^2 e^5}{\hbar^4} \]

1990
Relativistic Epoch

\[ E_R = \frac{m_0 c^2}{e \lambda} = \frac{h \nu}{\lambda_c e} \]

2010
ELI Nonlinear QED Epoch

\[ E_S = \frac{2m_0 c^2}{\lambda_c e} \]

\[ Ec = e / r_b^2 = m^2 e^5 / \hbar^4 \]

\[ ER = m_0 c^2 / e \lambda = h \nu / \lambda_c e \]

\[ ES = 2m_0 c^2 / \lambda_c e \]
Ultra high Intensities:

By putting the Extreme Light Infrastructure (ELI), Europe is Pulling all the Stops!!
The Extreme Light Infrastructures, ELI Has Been Selected to be on the ESFRI (European Strategic Forum on Research Infrastructures) Roadmap

- ELI, an Exawatt Laser pursuing science and technology Research at the highest intensity level

ELI has been the first Infrastructure launched by Brussels November 1st 2007. It is in its Preparatory Phase.
ELI to Scale

\[ \tilde{1PW} \]

\~ \textit{highest power laser today}

Most of the Hihest Peak Power Today (50TW) are in the linewidth

\[ 50TW \]
ELI to Scale

\[ \text{2PW, 20cm} \]

\[ \text{iPW, 1mm} \]

\text{~highest power laser today}

\text{Few Facts about ELI}
Peak Power 200PW
Energy per Pulse 2kJ
Pulse duration 10fs
Intensity > \(10^{25} \text{W/cm}^2\)
OPCPA-CPA Ti:sapphire
10 beams
1 shot /mn
First Light 2016
Total cost 400M€
Le projet européen ELI

Les 13 pays de ELI (P):

- Bulgarie
- République tchèque
- France
- Allemagne
- Grèce
- Hongrie
- Italie
- Lithuanie
- Pologne
- Portugal
- Roumanie
- Espagne
- Royaume-Uni
ELI: 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.
Why should we build an Extreme Light Infrastructure?
New Paradigm to Fundamental Physics: Vacuum structure

The vacuum defines:

1) Structures and properties of the laws of Physics
2) It defines the value of fundamental constants
3) Visible matter mass is due to the quark confining properties 10^{-5}s after the Big Bang
4) The idea is to recreate the physical properties akin to those of the early universe over a macroscopic volume
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/cm²

Modelocking, Dye
I=MW/cm²

Mode-Locking KLM
I=GW/cm²

MPI
I>10¹³ W/cm²

Relativistic and Ultra R
Atto, zepto….?
Contents

ELI’s Bricks

a) Relativistic and Ultrarelativistic Optics
b) Relativistic Rectification (wake-field) the key to High energy electron beam
c) Generation of Coherent x and g-ray, by Coherent Thomson, Radiation Reaction, X-Ray laser, …
d) Source of synchronized attosecond photon and particle pulses

ELI’s Science

a) Study of the structure of matter from atoms to vacuum
b) Nonlinear QED, quantum vacuum and vacuum structure

The Laser: Hybrid OPCPA-CPA
Ultra-relativistic intensity is defined with respect to the proton \( E_Q = m_p c^2 \), intensity \( \sim 10^{24} \text{W/cm}^2 \).
Relativistic Optics
Relativistic Optics

$$\vec{F} = q \left( \vec{E} + \left( \frac{\vec{v}}{c} \wedge \vec{B} \right) \right)$$

a) Classical optics $v \ll c$,  b) Relativistic optics $v \sim c$

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

$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0}{mc^2} \lambda$

Electric field  Magnetic field

$\Delta x \sim a_0$  $\Delta z \sim a_0^2$
Relativistic Rectification

(Wake-Field Tajima, Dawson)$\vec{E}_s$

1) $\vec{v} \land \vec{B}$ pushes the electrons.

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

$$E_s = \frac{c\gamma m_0 \omega_p}{e} = \sqrt{4\pi\gamma m_o c^2 n_e}$$

3) The electrostatic field $E_s \approx E_L$
Relativistic Rectification

*Ultra-high Intensity Laser is associated with extremely large E field.*

\[ E_L^2 = Z_0 * I_L \]

Medium Impedance \quad 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$^2$, $E = 0.6$ PeV/m, it is SLAC (50 GeV, 3 km long) on 10 μm. 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

- Red: protons
- Blue: electrons

Z, μm

Proton energy, MeV
The Dream Beam

J. Faure et al., C. Geddes et al., S. Mangles et al., in Nature 30 septembre 2004
Tunable monoenergetic bunches

Front and back acceleration mechanisms

Peak energy scales as: $E_M \sim (I_L \times \lambda)^{1/2}$
The Ultra relativistic: Relativistic Ions

Non relativistic ions

\[ V_p \sim 0 \]

Relativistic ions \( >10^{24} \)

\[ V_p \sim C \]

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

\[ E_p \sim I \]
High Energy Radiation

- Betatron oscillation
- X-ray laser
- Radiation reaction
Radiation Reaction: Compton-Thomson Cooling

N. Naumova, I. Sokolov

a) Charge separation. E-field Creation

b) e- move backwards, scattered on the incoming field, cooling the e-
Attosecond Generation from Overdense plasma
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

The Gaussian laser pulse $a=a_0 \exp\left[-(t/\tau)^2\right] \cos \omega_0 t$ 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!!!
Multi-keV Harmonics


First coherent, femtosecond, sub-nm source

Courtesy of M. Zepf
Attosecond pulse generation by Relativistic Compression in the $\lambda^3$ Regime

$$\varepsilon = 1 - \frac{\omega_p^2}{\gamma_0 \omega^2}$$  where  $$\gamma_0 = \sqrt{1 + |a_0|^2}$$
2-D PIC simulation
2-D PIC simulation
Scalable Isolated Attosecond Pulses

Duration, \( \tau \) (as)

2D: \( a=3, \ 200\text{as} \)

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

\( n_0 = n/n_{cr} \)

\( \lambda = 10^{19}\text{W/cm}^2 \) (\( \lambda^3 \) laser)

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

1D PIC simulations in boosted frame

\( I = 10^{22}\text{W/cm}^2 \) (Hercules)
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: $E \cdot e \cdot \lambda_c = 2m_0 c^2$
Attosecond Generation
(electron)
Attosecond Electron Bunches

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

N. Naumova, I. Sokolov, J. Nees, A. Maksimchuk, V. Yanovsky, and G. Mourou,
Coherent Thomson Scattering

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

N. Naumova, I. Sokolov, J. Nees, A. Maksimchuk, V. Yanovsky, and G. Mourou,
ELI: A Unique Infrastructure that offers simultaneously

- Ultra high Intensity $\sim 10^{26}$ W/cm$^2$
- High Energy particles $> 100$ GeV
- High Flux of X and $\gamma$ rays
- With femtosecond time structures
- Highly synchronized

(We could possibly get beams equivalent to $10^{36}$ W/cm$^2$)
ELI will be Unique: it will provide Photons and Particles with Short and Synchronized Time Structure in the femtosecond attosecond regime

Particules: Electrons Protons, muons,…

High energy radiation: X, gamma ray
Nonlinear QED
Relativistic Ultra Relativistic Relativistic Compression

Ultra-relativistic intensity is defined with respect to the proton $E_Q = m_p c^2$, intensity $\approx 10^{24}$ W/cm$^2$. 

Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0 c^2$ 

Ultra-Relativistic Optics 

$E_Q = m_p c^2$ 

Relativistic Optics 

$E_Q = m_0 c^2$ 

Bound electrons 

Ultra-relativistic intensity is defined with respect to the proton $E_Q = m_p c^2$, intensity $\approx 10^{24}$ W/cm$^2$. 

NL Optics
According to the theory of general relativity, space is endowed with physical qualities: in this sense there exist an ether.

According to the general relativity space without ether is unthinkable. There would not be any propagation of light possible, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor any space-time intervals in the Physical sense.

But this ether may not be thought of as endowed with the quality, characteristics of ponderable media, as consisting of parts that may be tracked through time. The idea of motion may not be applied to it.

A. Einstein Lorentz Lecture 1920
Testing Quantum Vacuum

The CLASSICAL ("ordinary," or "pneumatic") vacuum on the other hand is defined as the absence of matter: the classical vacuum is empty.

THE QUANTUM VACUUM virtual particle-antiparticle pairs are continuously created and annihilated: the quantum vacuum is full of activity.
Testing Quantum Vacuum

The idea is to come with a laser intense enough to breakdown vacuum
Laser-Induced Nonlinear QED

Vacuum can be considered like a dielectric

Schwinger Field

\[ E_s = \frac{2m_0c^2}{e\lambda_c} \quad \text{with} \quad \lambda_c = \frac{\hbar}{m_0c^2} \]

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

Vacuum Tunneling

\[ W \propto \exp \left( -\frac{\pi E_s}{E} \right) \]

\[ I_s = 10^{30} \text{ W/cm}^2 \]
Reaching the highest Intensity: Moving to a Spherical wave

**focal radius** \[ R = \frac{\lambda}{2\pi \Delta} \sim \lambda \text{ for } \Delta \sim 0.16 \]

\[ \Delta \geq 1? \]


Diffraction limit is taken into account automatically.

\( \Delta = 0.16 \)

\( \Delta = 0.4 \)

\( \Delta = 0.7 \)

Effectively, \( \Delta \sim 1 \) corresponds to a contracting wave geometry or to collision of several tightly focused beams.
Laser-induced Nonlinear QED


\[ e^- + \omega \rightarrow e^- + e^+ e^- \]

You can enhance the laser field by the electron $\gamma$ factor for $\sim 1 \sim \text{GeV}$. Intensity $\sim 10^{36} \text{W/cm}^2$ (QCD)
Laser-induced Nonlinear QED


\[ \gamma + \omega \rightarrow e^+ + e^- \]

\[ \hbar \omega_m = \frac{x}{x + 1} E_0 \]
\[ x \approx \frac{4E_0 \hbar \omega_0}{m^2 c^4} \]

for \( E_0 = 10 \text{GeV} \) and \( \hbar \omega_0 = 1.5 \text{eV} \) \( x = 0.24 \)
and \( \hbar \omega_m = 7 \text{GeV} \)
Laser-induced Nonlinear QED


\[ \gamma + \omega \rightarrow e^+ + e^- \]

\[ \hbar \omega_m = \frac{x}{x + 1} E_0 \]

\[ x \approx \frac{4 E_0 \hbar \omega_0}{m^2 c^4} \]

for \( E_0 = 10\, GeV \) and \( \hbar \omega_0 = 1.5\, eV \), \( x = 0.24 \)

and \( \hbar \omega_m = 7.\, GeV \)
With ELI we may witness a Paradigm shift in Fundamental Physics. Could one day Lasers Replace Accelerators?
Ultra-high Intensity
General Relativity
and Black Holes
Laboratory Black Hole


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

Using the gravitational shift near a black hole:

\[
\frac{GM}{R_s c^2} = 1
\]

BH radius \( R_s = \frac{1}{a_0} \frac{\lambda_{laser}}{2\pi} \)

\( kT = \frac{\hbar a_e}{2\pi c} \)

\( a_0 = 1 \to R_s = \lambda_{laser} = 1\mu m \)

\( a_0 = 10^6 \to R_s = .01A \sim \lambda_c \)

As we increase \( a_0 \) the Swartzschild radius can become equal to the Compton wavelength.
Optics and General Relativity: Hawking Radiation

In order to have Hawking radiation, you need the gravitational field strong enough to break pairs.

\[ g m_0 \lambda_c = 2m_0 c^2 \]
\[ R_s = \lambda_c \]
\[ R_s = \frac{\lambda}{2\pi a_0} = \lambda_c \rightarrow a_0 = 10^6 \]
\[ I = 10^{30} W / cm^2 \]
Finite Horizon and extra-dimensions

The distance to finite horizon is

\[ d = \frac{c^2}{a_e} \approx \frac{\lambda}{2\pi a_0} \frac{1}{a_0} \]

4 + nD Gauss Law

for Planck distance

\[ M_{P_4}^2 \sim (r_n)^n M_{P_{4+n}}^{n+2} \]

\[ r_n \sim 10^{\frac{30}{n} - 17} \text{ cm} \]

N. Arkani-Hamed et al. (1999)

Up to \( n=4 \) extra-dimensions could be tested.

T. Tajima phone # 81 90 34 96 64 21
ELI: from the Atomic Structure to the Vacuum Structure
The Extreme Light Infrastructure
Exawatt laser scheme

MPQ Garching

PW
OPCPA
Front end

Duty end, CPA
Ti: sapphire
Power amplifier(s)

Single
Beamline

40-70 PW
1sh/mn-
1sh/sec

multiple
Beamlines
0.4/0.7 EW

5 Joules
5 fs
100-1000Hz
P~ 1PW

1 EW = 1000 PW = 10^{18} W
10 KJ in 10 fs

0.1 EW = 100 PW = 10^{17} W
1 KJ in 10 fs
Partner Laboratories

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Thank you

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You can register @

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