Lumière Extrême
L’ Optique Relativiste
Et ses Applications

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Nonlinear QED: \( E \cdot e \cdot \lambda_c = 2m_0c^2 \)

Zettawatt Laser

Laser Intensity Limit:
\[
I = \frac{hv}{c^2}, \quad \frac{\Delta v_g}{\sigma} = \frac{P_{th}}{\lambda^2}
\]

Relativistic Optics: \( v_{oe} \sim c \)
(large ponderomotive pressures)

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

\( E_Q = m_0c^2 \)

\( E_Q \sim h\nu \)

Electron Characteristic Energy

1PeV
1TeV
1MeV
1eV

Electroweak Era
Quark Era
Positron-Electron Era
Plasma Era
Atomic Era


mode-locking CPA
Q-switching
Chirped Pulse Amplification
D. Strickland and G. Mourou 1985
Progress in Laser Peak Power

10TW

10TW
The Various Epochs of Laser Physics

1960
Coulombic Epoch

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

1990
Relativistic Epoch

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

2000
Nonlinear QED

\[ E_S = \frac{2m_0 c^2}{\kappa_c e} \]
## Sommaire

- L’intensité relativiste
- L’optique relativiste et son parallèle avec l’optique nonlinéaire de l'\( ^7 \)électron lié
- Le redressement optique relativiste: la clé de la production d'\( ^7 \)électrons, protons, rayonX et \( \gamma \) de haute énergie.
- Production d'\( ^7 \)impulsions attosecondes de photons et d'\( ^7 \)électrons
- X-ray cohérent par diffusion Thomson cohérente
- Vers le champ critique(champ de Schwinger)
L’optique relativiste
Bound Electron Nonlinear Optics

\[ \vec{F} = q \vec{E} \quad \vec{F} \propto x \]

The field necessary corresponds to \( hv/\lambda^3 \)

- Harmonics
- Optical Rectification
- Self-focusing
Nonlinear Optics (bound electron)

- Harmonic Generation  
  "Franken 1961"
- Sum and Difference Frequency Generation  
  "Bass et al. 1962"
- Optical Rectification  
  "Bass et al. 1962"
- Parametric Generation and Amplification  
  "Giordmaine et al. 1965"
- Stimulated Raman Scattering  
  "Woodbury and Ng 1962"
- Stimulated Brillouin Scattering  
  "Chiao et al. 1964"
- Two-Photon Absorption  
  "Kaiser et al. 1961"
- Four-wave Mixing  
  "Maker and Terhune 1965"
- Optical Kerr Effect  
  "Gires and Mayer 1964"
- Multiphoton Ionization  
  "Voronov and Delone 1965"
- N. Isenor and S. L. Chin 1969
- Transient Coherent Effects: Photon Echoes  
  "Hartman et al. 1966, Self-Induced Transparencies McCall and Hahn 1967"

- P. Agostini, A. L’ Huillier, C. Manus, G. Mainfray  
  "High Harmonic Generation 1989 "Extreme (bound electron) nonlinear Optics"
**Relativistic Optics**

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

**a) Classical optics** \( v << c \), \( a \ll 1, a_0 \gg a^2 \)

**b) Relativistic optics** \( v \sim c \)

\( a_0 \gg 1, a_0 \ll a_0^2 \)
Relativistic Laser: Helios at LANL

$a_0 \sim 1$, Rep. Rate $\sim \text{mHz}$

Carman et al 1981
Relativistic $\lambda^3$ Laser CUOS
$a_0 \sim 0.6$, Rep. Rate kHz

Seung-Whan Bahk
Relativistic $\lambda^3$ regime


- Spatial focus ($\lambda^2$)
- Temporal focus ($\lambda/c$)
- Relativistic intensity $I=2 \times 10^{18}$ W/cm$^2$ ($a=1$), wavelength $\lambda=0.8\mu$m, 1mJ, 1KHz

"Gérard Nonlinear optics started at 1 photon/pulse" (R. Chen, private communication during a nice party in Korea)
HERCULES
Hercules: $10^{22}$W/cm$^2$

$\Phi = 0.8\mu m$

$\alpha_0^2 = 10^4$

Redressement Optique Relativiste
(Wake Field Acceleration)
Relativistic Optics

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

\(a)\) Classical optics \(v \ll c\), \(a_0 < \ll 1, a_0 > a_0^2\)

\(b)\) Relativistic optics \(v \approx c\), \(a_0 > \gg 1, a_0 < \ll a_0^2\)

\[ a_0 = \frac{eA_0}{mc^2} = \frac{eE_0}{mc^2} \lambda \]
Relativistic Rectification  
(Wake-Field  Tajima, Dawson)

- $\vec{F}_{Bz} = q\left(\frac{\vec{v}}{c} \wedge \vec{B}\right)$ pushes the electrons.
- The charge separation generates an electrostatic longitudinal field. (Tajima and Dawson: Wake Fields or Snow Plough) $E_s = \frac{c\gamma m_o \omega_p}{e} = \sqrt{4\pi \gamma m_o c^2 n_e}$
- The electrostatic field $E_s \approx E_L$
Relativistic Rectification

-Ultrahigh Intensity Laser is associated with Extremely large E field.

\[ E_L^2 = Z_0 * I_L \]

Medium Impedance \quad Laser Intensity

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

\[ I_L = 10^{23} W / cm^2 \quad E_L = .6 \quad PV / m \quad (0.6 \times 10^{15} V / m) \]
The Relativistic Rectification: Total Serendipity

In the relativistic regime the laser transverse field becomes:

1) Totally rectified
2) Longitudinal
3) As large as the transverse laser field
4) The plasma can not be broken down.

Relativistic rectification could give access to TeV/m to PeV/m.

Million times higher fields than conventional technology.

Accelerator million times more compact.
Laser Acceleration:

At $10^{23} \text{W/cm}^2$, $E = 0.6 \text{PV/m}$, it is SLAC (50GeV, 3km long) on 10$\mu$m. 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
The Dream Beam

J. Faure et al., C. Geddes et al., S. Mangles et al., in Nature 30 septembre 2004
Recent results on electrons acceleration - Setup

LOA – 100 TW

Laser  Nozzle  Magnets  Lanex  ICT

He gas

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

J. Faure et al, Nature 2004
Recent results on electrons acceleration


Divergence < 6 mrad
Application: high resolution $\gamma$-radiography
Advantages: low divergence, point-like electron source

In collaboration with L. Le-Dain, S. Darbon from CEA Mourainvilier and DAM
Higher resolution: of the order of 400 µm

In collaboration with L. Le-Dain, S. Darbon from CEA Mourainvilier and DAM
Secondary effects of electron acceleration: X-ray Beam
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

Magnets

X-ray beam

$E_X > 3$ keV

$20 \text{ mrad}$

e$ = 10^{19} \text{ cm}^{-3}$

Electron beam

K. Ta Phuoc et al
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

5 cm

Behind the target – “straight through” direction

5 cm

5 cm

5 cm

No. of Protons per MeV

10^12
10^11
10^10
10^9
10^8
10^7
10^6

Proton Kinetic Energy (MeV)

10
15
20
25
30
35
Proton Beam Characteristics

Energy

- Aluminum Target
- Plastic Target

Collimation

In collaboration with K. Ledingham and P. Mc Kenna
Attosecond Generation (photon)

Talks at this meeting by T. Tajima, S.V. Bulanov et al., Y.U. Mikhailova et al.
**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.
Relativistic self-focusing

- Previously, relativistic self-focusing has been studied only in the *refractive* regime.

\[
\varepsilon = 1 - \frac{\omega_p^2}{\gamma_0 \omega^2}
\]

where

\[
\gamma_0 = \sqrt{1 + |a_0|^2}
\]

Single Mode Relativistic optics in Reflection

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

Under the action of the light pressure the critical surface will be pushed (curved) at relativistic speed at twice the laser frequency (2\(\omega\)).

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
3-D PIC simulation

Electromagnetic energy density

attosecond pulse

Electron density

P-plane  S-plane
2-D PIC simulation
Relativistic deflection of light observed in experiment

Experimental parameters:
\[ \lambda = 0.8\mu m, \tau = 30\text{ fs}, d = 1.2\mu m, \]
\[ I \approx 1.5 \cdot 10^{18} \text{Wcm}^{-2} \]

Results:
- Splitting of reflected beam into two lobes
- Divergence of the beam: 35°, 45° (input 40°)

Simulation: \(a_0 = 1\), 20fs, f/1, plasma gradient 0.1\(\lambda\)

Erik Power, APS DPP meeting, 2004
2-D PIC simulation
Relativistic Temporal Compression
Scalable Isolated Attosecond Pulses

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

$n_0 = n/n_{cr}$

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

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

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

1D PIC simulations in boosted frame

$\tau = 200$ as

$\lambda = 10^{19} \Omega/\chi \mu^2$ ($\lambda^3$ laser)
Isolated Attosecond Pulse Generation by Relativistic Compression and Deflection

- It should be efficient
- Scalable
- Because it is a relativistic plasma, the higher the intensity, the shorter and the better.
Attosecond Generation
(electron)
2-D PIC simulation Attosecond electron bunch generation:

Intensity: $2 \times 10^{21}$ W/cm$^2$ ($a=30$)

Pulse duration: 10fs

Wavelength: $\lambda=0.8\mu\mu$

Polarization: linear

Focus spot: $1\lambda$

Plasma density: $6.3 \times 10^{22}$ cm$^{-3}$ ($36n_{cr}$)

Channel diameter: $1.4\lambda$
Attosecond Pulse of electrons
Attosecond Pulse of electrons
Attosecond Pulse of electrons
Attosecond Electron Bunches

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

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
  \[ d \sim 1/k\gamma^2 \sim (100 \text{ as}) \cdot c \]

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

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

Nonlinear QED: $E \cdot e \cdot \lambda_c = 2m_0c^2$

Zettawatt Laser

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

Relativistic Optics: $v_{oe} \sim c$
(large ponderomotive pressures)

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

Characteristic Energy:
- $E_\text{Q} = m_0c^2$
- $E_\text{Q} \sim \hbar \nu$

Electron Characteristic Energy

Electroweak Era
Quark Era
Positron-Electron Era
Plasma Era
Atomic Era

Electro-Optic Laser Era

Focused Intensity (W/cm$^2$)

- $10^{10}$
- $10^{15}$
- $10^{20}$
- $10^{25}$
- $10^{29}$

- 1960
- 1970
- 1980
- 1990
- 2000
- 2010

mode-locking
CPA
Q-switching
Laser-Induced Nonlinear QED  

Vacuum can be considered like a dielectric

Schwinger Field \[ E_s = \frac{2m_0c^2}{e\lambda_c} \] with \[ \lambda_c = \frac{\hbar}{m_0c^2} \]

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

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

\[ I_s = 10^{30} \text{W/cm}^2 \]

Talks of N.B. Narozni et al, C. H. Keitel
Towards the Critical Field

The pulse duration and the wavelength scale as:

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 $I = 10^{22} \text{W/cm}^2 \rightarrow I = 10^{28} \text{W/cm}^2$
Ultra-high Intensity

General Relativity

and Black Holes
Laboratory Black Hole

Equivalent to be near a Black Hole of Dimension? Temperature?
Moving from the Atomic Structure to the Quark Structure of Matter
Conclusion

The possibility to generate “Relativistic Intensities” with compact lasers is producing a revolution in the field of laser optics similar to the one we experienced since the 1960’s.

Using the laser itself or “marrying” it with high energy particle accelerators it suddenly extends the realm of optics from the eV to the GeV regime to include Nuclear, High Energy Physics, General Relativity, Cosmology.

It also brings back to the University Laboratory, Science that has been traditionally done on large instruments.