Laser-driven X-ray sources: realization and future trends

Patrick Audebert, Julien Gautier, Fabien Quéré, Rodrigo Lopez-Martens, Le Thi Thu Thuy, Philippe Martin, Hamed Merdji, Pascal Monot, Eduardo Oliva, David Ros, Antoine Rousse, Stéphane Sebban, Kim Ta Phuoc, Sophia Chen and Philippe Zeitoun
Panorama of available laser-driven X-ray sources

- High harmonics with solid plasma
- High harmonics with gas plasma
- Non-linear Thomson scattering
- Kα radiation
- Betatron radiation
- Compton scattering

Energy (E) in eV:
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$

Wavelength (λ) in nm:
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$

FERMI, FLASH
LCLS, SACLA

ELI-NP Experimental program workshop, Bucharest 2012
Why X-ray sources for ELI-Nuclear Physics?

Nuclear resonance spectroscopy of the 31-yr isomer of Hf-178

C.B. Collins, 1,2+ N.C. Zaita, 1 F. Davanloo, 1 Y. Yoda, 2 T. Uruga, 2 J.M. Pouvezle, 3 and I.I. Popescu 4

The idea of generating X-ray lasers dates back to the 1970s, when scientists realized that laser beams amplified with X-rays with a higher frequency and a shorter wave length would carry energies in the Million electron volts (MeV) range.

Proposal for a Nuclear Gamma-Ray Laser of Optical Range

E. V. Tkalya  
Institute of Nuclear Physics, Moscow State University, Moscow, Russia

\[ 229_{\text{Th}} \]

\[ \begin{align*}
E, \text{eV} & \quad J^\pi \\
7.6 & \quad 3/2^+ \\
0 & \quad 5/2^+
\end{align*} \]

\[ \text{M1} \]

\[ \text{R, G, B} \]
CILEX is situated in the scientific environment of :

1) French research projects:
   • ANR I-nano-X
   • ANR FEMTO-X-MAG
   • ANR COKKER and ROLEX
   • ANR ASOURIX

2) French pre-industrial projects
   • ASTRE 2011

3) European projects
   • SFINX and INREX « Joint Research Activities » in LASERLAB2 and 3
X-rays may be either developed on short and long focal areas.

**Short focal area**
- allows performing most proposed experiments,
- reduces the cost by sharing equipment
- and enables pump-probe experiments in radio-protected area.
The Betatron source

- Main pulse
- Plasma mirrors and beam diagnostics
- Catwalk for chamber access
- ~0.5 m
- Switch out for circular polarization

20 TW laser

- Energy (keV) vs Photon intensity graph for 20 TW laser
- Rousse et al, 2005

100 TW laser

- Photon energy (eV) vs Photon intensity graph for 100 TW laser
- S. Fourmeau et al, NJP2010

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Energy shifting

*Nature Photonics* spoke to Kim Ta Phuoc about an extremely bright and compact X-ray and gamma-ray source that exploits laser plasma acceleration and Compton scattering simultaneously.
\(\gamma\)-ray Compton scattering

Electron beam
Laser pulse
Thin foil
Plasma mirror
Reflected laser pulse
Oscillating electrons
X-rays

Main pulse
Switch out for circular polarization

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All-optical Compton gamma-ray source

K. Ta Phuoc\textsuperscript{1,\*}, S. Corde\textsuperscript{1,\*}, C. Thaury\textsuperscript{1}, V. Malka\textsuperscript{1}, A. Tafzi\textsuperscript{1}, J. P. Goddet\textsuperscript{1}, R. C. Shah\textsuperscript{2}, S. Sebban\textsuperscript{1} and A. Rousse\textsuperscript{1}

NATURE PHOTONICS | VOL 6 | MAY 2012 | www.nature.com/naturephotonics 309
Attosecond control of collective electron motion in plasmas

Antonin Borot¹, Arnaud Malvache¹*, Xiaowei Chen¹, Aurélie Jullien¹, Jean-Paul Geindre², Patrick Audebert³, Gérard Mourou³, Fabien Quéré⁴ and Rodrigo Lopez-Martens¹
High harmonics on solid

Attoseconde emission

detector

IR pulse

Main pulse

Switch out for circular polarization

Photon energy (eV)

Relative CEP

Frequency (in $\omega_L$)

F. Quéré et al, to be published


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Single attosecond pulse with high harmonics on solid

Rotating wave front

Tilted wave front

Spatially separated attosecond pulses

$\lambda^3$ regime

10 as @ $10^{22}$ Wcm$^{-2}$

The “flying mirror”

The Flying Mirror: future brightest X-ray and γ-ray source

T. Zh. Esirkepov, S. V. Bulanov, M. Kando, A. S. Pirozhkov and A. G. Zhidkov
\[ i\hbar \frac{\partial \rho}{\partial t} = [H, \rho] \]

\[ \Delta E - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} - \frac{\omega_{pe}^2}{c^2} E = \frac{1}{\epsilon_0 c^2} \frac{\partial^2 F}{\partial t^2} \]

\[ E(x, y) = \mathcal{F}[E(u, v)] \]
High harmonics on gas + plasma based-soft X-ray laser

Plasma mirrors and diagnostics

HHG: 5 µJ, 20 fs
Seeded XRL: 30 µJ, 80 fs
Amplified seed coherent <1 µJ

ASE incoherent ~ 5 mJ

Time-resolved laser emission @ 25.1 nm
Amplification of femtosecond vs picosecond soft x-ray seeds
X-ray Chirped Pulse Amplification

- High Gain (transient scheme)
- Low Gain, High E (QSS)
- 10 J 100 J
- 1 mJ ~ 150 fs
- 2 mJ ~ 200 ps

- \( \gamma \)-X ray spectroscopy
- pump-probe experiments
- \( \gamma \) excitation/x-ray imaging

O. Oliva et al, to be published Nat Phot.
Pushing gamma-rays to higher energies

$10^8$ to $10^{11}$ highly monochromatic, fully coherent soft x-ray photons/pulse
Thank you for your attention
**Requirement for nano-imaging (static or dynamic)**

- **Femto-magnetism**
  - \[10^5 \text{ shots} \rightarrow 0.1 \text{mJ}\]
  - IR laser

- **Biological femto-imaging**
  - Mancuso et al, New Jour. Phys, 12, 035003 (2010)