LASERIX facility: achievements and prospectives opened by ICAN project.

David ROS, Head of LASERIX facility

david.ros@u-psud.fr

http://www.laserix.u-psud.fr

IZEST Conference, David ROS
Tokyo, 18-20 November, 2013
Outline

1 – From early 90’s studies to the LASERIX facility

2 – Progress and successes on LASERIX facility:
   • Sources
   • Applications

3 – The context of the development of XUV sources using High Power laser facilities:
   LASERIX, ILE-APOLLON, ELI, …

4 – Perspectives of XUV sources development based on ICAN Project
Outline

1 – From early 90’s studies to the LASERIX facility

2 – Progress and successes on LASERIX facility :
   • Sources
   • Applications

3 – The context of the development of XUV sources using High Power laser facilities :
   LASERIX, ILE-APOLLON, ELI, …

4 – Perspectives of XUV sources development based on ICAN Project
1- Principles of *Collisional pumping scheme*

### Fast radiative decay

- **X-ray laser transition**
- **Creation of lasing ions plasma**
- **Heating the free electrons**

### Forbidden radiative decay

#### Principles of Collisional pumping scheme

- **Neon-like**: $1s^22s^22p^6$ transitions $3p - 3s$
  - Zn$^{20+}$: 21.2 nm

- **Nickel-like**: $3s^23p^63d^{10}$ transitions $4d - 4p$
  - Ag$^{19+}$: 13.9 nm

- **Palladium-like**: $4s^24p^64d^{10}$ transitions $5d - 5p$
  - Xe$^{8+}$: 41.8 nm
1- Principles of collisional pumping scheme

Choice of the Target: choice of the $\lambda$ of the X-ray laser source

Intense IR laser on solid target

Hot and dense plasma

Ne, Te

$E_{\text{out}}$, $\Delta T$

Pumping laser (LULI)
6 beams, 1.06 $\mu$m, 600 ps,
0.45 kJ, $10^{13}$ Wcm$^{-2}$

X-ray laser beam

Saturation

Target 2/3 cm
1. Typical laser drivers used for collisional pumping scheme

1) Quasi-steady state (QSS) regime, "standard" Nd-glass, 1TW pump laser

- **XRL**
  - $t \sim 100$ ps, $E \sim 1$ mJ

- **pump:**
  - $P_p + m_p$, $t \sim 500$ ps, $E \sim 0.5$-1 kJ

2) Transient regime, CPA Nd-glass, 100 TW pump laser

**Aim:** Separate ionisation and heating ($T_e \gg T_{\text{ionisation}}$)

- **pump:**
  - $P_p + m_p$, $t \sim 500$ ps + 1 ps, $E \sim 10$-100 J

- **travelling wave**
  - First pulse ($\sim 10^{12}$ W/cm$^2$): creates the plasma
  - Second pulse ($\sim 10^{15}$ W/cm$^2$): heats the free electrons
Typical laser drivers used for collisional pumping scheme

1) Quasi-steady state (QSS) regime, "standard" Nd-glass, 1TW pump laser

XRL
t \sim 100 \text{ ps},
E \sim 1 \text{ mJ}

 Aim: Separate ionisation and heating (T_e >> T_{ionisation})

pump: P_p + m_p,
t \sim 500 \text{ ps},
E \sim 0.5-1 \text{ kJ}

2) Transient regime, CPA Nd-glass, 100 TW pump laser

XRL
t \sim 1-5 \text{ ps},
E \sim 10 \mu\text{J}

First pulse (~10^{12} \text{ W/cm}^2):
creates the plasma

Second pulse (~10^{15} \text{ W/cm}^2):
heats the free electrons

pump: P_p + m_p,
t \sim 500 \text{ ps} + 1 \text{ ps}
E \sim 10-100 \text{ J}

travelling wave

1/2 cavity

Influence of the pumping parameters on the X-ray laser properties
1- … the benefit of the CPA technic

- 1984 : 4 kJ, 500 ps
- 1993-2002 : 400 J, 600 ps + prepulse
- 1997 : 100 J, 100 ps + prepulse
- 1999 : 5 J, 500 ps + 5 J, 1 ps

<table>
<thead>
<tr>
<th>Driver</th>
<th>Pumping energy</th>
<th>Target length</th>
<th>Ne- like</th>
<th>Ni-like</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 ps</td>
<td>450 J</td>
<td>2 cm</td>
<td>Zn 21.2 nm</td>
<td>5 cm⁻¹ Ag, Sn, Xe</td>
</tr>
<tr>
<td>130 ps + 130 ps</td>
<td>60 J + 60 J</td>
<td>2 cm</td>
<td>Fe 25.5 nm</td>
<td>15 cm⁻¹ + 11 cm⁻¹ Ag 13.9 nm</td>
</tr>
<tr>
<td>450 ps + sub ps</td>
<td>5 J + 5 J</td>
<td>1 cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The genesis of LASERIX facility

IZEST Conference, David ROS
Tokyo, 18-20 November, 2013
1- … following the Japanese example

- OSAKA, Gekko XII, 6 beams 200 J, $\delta t=100$ps, 1997

- small gain $< 1 \text{cm}^{-1}$
- very low rep-rate
- … but waterwindow available

1- … following the Japanese example

- OSAKA, Gekko XII, 6 beams 200 J, $\delta t=100$ps, 1997
  - small gain $< 1$cm$^{-1}$
  - very low rep-rate
  - … but waterwindow available

- Kyoto, APRC, 2004
  - … on the road of applications


Outline

1 – From early 90’s studies to the LASERIX facility

2 – Progress and successes on LASERIX facility:
   • Sources
   • Applications

3 – The context of the development of XUV sources using High Power laser facilities:
   LASERIX, ILE-APOLLON, ELI, ...

4 – Perspectives of XUV sources development based on ICAN Project
2- Progress and successes on LASERIX facility

- Development and Optimisation (reduce pumping energy and increase repetition rate) of Transient Collisional Excitation X-ray lasers between 10 and 40 nm.

- Studies of QSS X-ray lasers, reducing pumping energy.

- Studies of alternative X-ray laser schemes.

- Realisation and development of X-ray laser applications:
  - XUV imaging and interferometry
  - Intense XUV laser-matter interaction.

- CPER 2000-2006 (french minister, County of Essonne, University of Paris-Sud)

- Budget of 4,2 M€
2- Specificities of laser driver of LASERIX

**THALES LASER**
- Oscillator
  - Verdi 5V
  - Femtolaser fs-20
- Dazzler
- Regenerative Amplifier
  - JADE
- 10Hz - 4 Pass Preamplifier

**AMPLITUDE TECHNOLOGIES**
- 10Hz - 4 Pass Cryogenic Power Amplifier

**LIXAM**
- 0.1Hz - 4 Pass Booster Amplifier (100J pump energy)

**Order 0**
- 1 J
  - 50 fs → 1 ps
- 20 J
  - 500 ps

**2.5 J - 10Hz**
- 600 mJ - 10Hz

**mJ – 50 fs**
- auxiliary pulses
  - (probes, HHG...)

**40 J 0.1Hz**
- 10 J
  - 50 fs → 1 ps
- 2.5 J
  - 10Hz
LASERIX Facility for XUV experiments

- XUV wavelengths: 8 nm to 32 nm
- XUV energy: > μJ
- XUV rep. rate: 0.1 Hz & 10 Hz
- Multibeam - optically synchronized (IR fs-ps & HHG)

**Laser driver**
- PW class
- Ti:Sa

**HRR**
- 2 J - 10 Hz
- XUV Laser
  - High rep. rate
  - > 10 nm - 1 μJ - 10 Hz

**Compressor**
- 100 mJ - 10 Hz – 40 fs à 10 ps
- HHG: > 20 nm - 10 Hz

**HE**
- 40 J – 0.1 Hz
- XUV Laser
  - High energy
  - > 4-8 nm - 20 μJ – 0.1 Hz

**Compressor**
- 100 mJ - 10 Hz – 40 fs à 10 ps
- HHG: > 20 nm - 10 Hz
2- Present status of LASERIX facility

2003 – 2006: Demonstration of laser system 40 J / 0.1 Hz in a experimental room of the LOA (90 m²)

Since 2007:
- X-ray and HHG sources @ 10 Hz
- Increase reliability
- First applications @ 10 Hz
2 - The LASERIX facility @ 10 Hz

Titanium-Sapphire laser driver
800 nm
10Hz, 3J, 35 fs,
Dazzler
Contrast > 10^9
2 – GRIP scheme available on LASERIX facility

Solid Target

Delayed Compressed laser pulse
(4 ps, 0.7 J)

Plasma column

Stretched laser pulse
(500 ps, 0.5 J)

XUV beam
DGRIP Principle (single beam pumping technique)

Regenerative amplifier → Amplifiers → Compression

Regen cavity selects the propagation direction → the two pulses propagate along the same beam path

Öffner stretcher
2- A LASERIX facility dedicated to users

- **SXRL 0.1 Hz**
- **HHG 0.1 Hz**
- **Comp. 2J - 10Hz**
- **Comp. 40J - 0.1Hz**

**ADONIS laser driver**

IZEST Conference, David ROS
Tokyo, 18-20 November, 2013
2- A LASERIX facility dedicated to users
2- A LASERIX facility dedicated to users
2- A 10Hz facility useful for XUV sources and applications development

X-ray laser source

Wavelengths:
• 18.9 nm (Mo ni-ilke, 4d-4p) and 22.6 nm (4f-4d)
• 13.9 nm (Ag ni-like, 4d-4p)

Repetition rate: 10 Hz
Source size 20 µm x 60 µm
Divergence 5 mrad x 10 mrad
Energy: µJ

Applications

Double-stand breaks in DNA samples induced with LASERIX

Pump – probe experiments
2- Application: Biological effects induced by low X-rays; amplification by nanoparticles

Motivation « Radiation Biology »

Electron microscopy

Double-stranded DNA  Open circular DNA

SSB  SSB

DSB

Linear DNA

DNA Helix

Irradiated Cell

Death

Total restauration

Partial restauration

Alteration

H2O → HO

Indirect effects

DNA Helix

Sage et al, CNRS / Institut Curie

Sage et al, CNRS / Institut Curie

Photon

Direct effects

Double Strand Break

Single Strand Break

Total restauration

Partial restauration

Alteration

Death
2- A dedicated chamber for irradiation

Sample holder

XUV CCD camera

Spherical multilayer mirror

Sample holder

XUV CCD camera

Spherical multilayer mirror
2- LASERIX source

Experimental method

- Accumulation of a XUV dose perfectly known and uniform
- Strand rate estimation by an ex-situ electrophoresis

Experimental irradiation

- Source: Laser X
- Energy: 65 eV
- Dose rate: 600 Gy/min
- Dose: approx. 500 kGy
- Beam focalized and centered on the DNA pellet

- In-vacuum target alignment via cross-hair in target plane and video camera (precision 0.5 mm)
- Spot optimization and characterization
- by back-thinned XUV CCD
2- Time scale involved in “Radiation Biology”

Up to 25000 shots of 300 nJ each in 2 h = \(4,3 \times 10^{14}\) photons

Typical single shot...

... next shot
2- Time scale involved in “Radiation Biology”

Up to 25000 shots of 300 nJ each in 2 h = $4.3 \times 10^{14}$ photons

Typical single shot... Integration over 10 shots

... next shot Integration over 100 shots (with stronger filters)
2- Time scale involved in “Radiation Biology”

Up to 25000 shots of 300 nJ each in 2 h = 4,3*10^{14} photons

Typical single shot... Integration over 10 shots

... next shot Integration over 100 shots (with stronger filters)

Fresh target surface every 200 shots

50 mm
2- Time scale involved in “Radiation Biology”

Up to 25000 shots of 300 nJ each in 2 h = 4.3*10^{14} photons

- Multilayer mirror photocurrent recorded during sample irradiation.
- System stops when the desired number of shot or integrated signal is reached.
2- Time scale involved in “Radiation Biology”

Up to 25000 shots of 300 nJ each in 2 h = $4.3 \times 10^{14}$ photons

X-ray laser stability

Source very stable during more than 20000 shots
2- Analysis by gel electrophoresis

Control after lyophilisation, in vacuum: not degraded

DNA linear (double strand break)

DNA super coiled

DNA linear (double strand break)

DNA circular (simple strand break)
2- Results: accumulated dose per sample (loaded with platinum)

Simple damage

<table>
<thead>
<tr>
<th></th>
<th>ADN</th>
<th>ADN+PtTC</th>
<th>ADN+NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSBs per plasmid</td>
<td>0.00</td>
<td>+105%</td>
<td>+104%</td>
</tr>
</tbody>
</table>

Complex damage

<table>
<thead>
<tr>
<th></th>
<th>ADN</th>
<th>ADN+PtTC</th>
<th>ADN+NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSBs per plasmid</td>
<td>0.00</td>
<td>+76%</td>
<td>+102%</td>
</tr>
</tbody>
</table>

**Perspectives**

- **dose-response curve**
  - Variation of dose and XRL wavelength to find respective DNA damage thresholds
  - Increase length of homogeneity of line foci to increase number of XRL photons

- **Lower energies** (below DNA resonance < 10 eV)

- **effect of the dose rate**
Outline

1 – From early 90’s studies to the LASERIX facility

2 – Progress and successes on LASERIX facility:
   • Sources
   • Applications

3 – The context of the development of XUV sources using High Power laser facilities:
   LASERIX, ILE-APOLLON, ELI, …

4 – Perspectives of XUV sources development based on ICAN Project
3- Regimes accessible with LASERIX, ILE APOLLON and ELI Laser

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

- 10 PW Class
- 100 PW Class
- PW Class

Focused Intensity (W/cm²)

10³⁰
10²⁵
10²⁰
10¹⁵
10¹⁰
10⁵


ULTRA-RELATIVISTIC OPTICS

RELATIVISTIC OPTICS

BOUND ELECTRONS

E₀ = m₀c²

CPA

mode locking

Q-switching
3- Specificities of laser driver of ILE APOLON

Single 10 – 20 PW laser beamline set-up

FRONT END

- Early Front End
- Front End

POWER AMPLIFIERS

- Ampli1
- Ampli2
- Ampli3

- 10 mJ <10fs 1KHz
- 100 mJ <10fs 10Hz
- 2J 15fs 10Hz
- 30J 15fs 0.1-1Hz
- 300J 15fs 1shot/mn
- 10TW 10^{21} W/cm^2
- 150TW 10^{22} W/cm^2
- 2PW 10^{23} W/cm^2
- 20PW 10^{24} W/cm^2

LASERIX
3- Specificities of laser driver of ELI

Targeted performances for ELI multiple laser beamlines

Synergy ILE/ELI:
ELI → 10 times ILE
3- The investigations using ELI

High <P> laser techno.
- 100TW
- 1J < 10fs
- 1KHz
- diode-pumped amplis

Power amplifiers
- 4PW
- 60J, 15fs
- 10Hz
- diode-pumped amplis

Plasma physics acceleration
- 12x300J
- 15 fs
- 3'

High field physics
- 10^{25} W/cm^2

Electrons ions
- XRL

Booster amplifiers
- 1PW
- 4 exp. 15J, 15fs
- rooms 10Hz

Advanced diode pumped
- Front end's
- 60 mJ
- 10fs
- 1kHz
- 2 exp. rooms

as science (gas/solid HHG)

XRL - XFEL
incoh. X - electrons - ions

High field physics

- 12x300J
- 15 fs
- 3'

3 exp. rooms

- 4x300J
- 15fs
- 3'

TOFU

 Izest Conference, David ROS
Tokyo, 18-20 November, 2013
3- Prospects of *research investigations on ILE and ELI*

**Collisional scheme: shorter wavelengths**

- **QSS**: experiments: QSS
- **TCE**: experiments: TCE
- **GRIP**: experiments: GRIP
- **RADEX theoretical predictions**: GRIP

**Extension of the transient x-ray lasers using more pumping energy**

- **λ (U Ni-like): 2.2 nm**

**Graph:**
- Total pump energy vs. X-ray laser wavelength
- Data points and lines indicating different experimental results and predictions.
3- Prospects of research investigations on ILE and ELI

**Collisional scheme: shorter wavelengths**

- **QSS**
- **TCE**
- **GRIP**

**Experiments:**
- **QSS**
- **TCE**
- **GRIP**
- **RADEX theoretical predictions: GRIP**

**Extension of the transient x-ray lasers using more pumping energy**

- **TCE**
  - 500 J, $\Delta t \sim 500$ ps + 1 kJ, $\Delta t \sim 1$ ps  $\rightarrow$ Ni-like U : 2.2 nm
- **QSS**
  - 1.5 kJ, $\Delta t \sim 100$ ps  $\rightarrow$ Ni-like Au : 3.6 nm

**Parameters:**
- $\lambda$ (U Ni-like) : 2.2 nm
Outline

1 – From early 90’s studies to the LASERIX facility

2 – Progress and successes on LASERIX facility:
   • Sources
   • Applications

3 – The context of the development of XUV sources using High Power laser facilities:
   LASERIX, ILE-APOLLON, ELI, …

4 – Perspectives of XUV sources development based on ICAN Project
ICAN Project will give « real » advantage to X-ray lasers for Applications
4- Prospectives and Dreams with ICAN Project : 1

By strongly increasing repetition rate

ICAN Project will give « real » advantage to X-ray lasers for Applications
ICAN Project will give « real » advantage to X-ray lasers for Applications

- By strongly increasing repetition rate
- By achieving a very high stability of the pumping laser shot by shot

IZEST Conference, David ROS
Tokyo, 18-20 November, 2013
ICAN Project will open a « real » highway applications for the X-ray source lasers
ICAN Project will open a «real» highway applications for the X-ray source lasers

Due to the possibility from the same oscillator
To generate different laser beams
Usefull for multi pump-probe experiments
Due to the possibility from the same oscillator
To generate different laser beams
Useful for multi pump-probe experiments

ICAN Project will open a « real » highway applications for the X-ray source lasers

Due to the possibility to easily investigate
Several synchronised multi-successive amplifier XUV sources: lasers, electrons, ions, …
ICAN Project to produce « real » X-ray lasers

Shorter wavelengths lasers than never obtained : < nm range

How:
1) « Water window » real access
2) investigate new schemes
   - inner-shell of heavy ions
   - transitions in nuclear transitions
Thanks to …

O. Guilbaud, S. Kazamias, K. Cassou (LAL), M. Pittman, O. Delmas, J. Demailly, O. Neveu

and COLLABORATORS:

Ph. Zeitoun and al. (LOA)
G. Mourou, (Ecole Polytechnique),
E. Oliva, B. Cros, G. Maynard (LPGP),
S. Lacombe and al. (ISMO)
T. Kühl and B. Zielbauer (GSI)

Contact: david.ros@u-psud.fr
http://laserix.u-psud.fr