Progress on laser-driven XUV lasers at LOA

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Optical field ionization XUV lasers: principle

Ultrashort IR pulse (a few 10TW)

Gas target

Soft X-ray emission

Electron heating:
circular polarization

Tunnel ionization:

- Laser intensity (W/cm²)
- Time (fs)

- Ar^8⁺
  - 2s0 2p⁶ to 1s0 2p⁵3d
  - 280 eV
  - 46.9 nm

- Kr^8⁺
  - 1s0 3d⁹4f to 1s0 3d⁹4p
  - 145 eV
  - 32.8 nm

- Xe^8⁺
  - 1s0 4d⁹5f to 1s0 4d⁹5p
  - 106 eV
  - 41.8 nm

Laser intensity stages:
Seeded OFI SXRL architecture

- IR pump beam: 0.5 J, 30 fs
- ASE laser: 32.8 nm
- Al filter
- Kr cell
- λ/4 plate
Seeded OFI SXRL architecture

0.5J, 30 fs IR pump beam

$\lambda/4$ plate

ASE laser 32.8nm

Kr cell

Al filter

Amplifier
Seeded OFI SXRL architecture

- Seeded 32.8 nm laser
- 0.5 J, 30 fs IR pump beam
- Seeded 32.8 nm laser
- 10 mJ, 30 fs IR beam
- Delay line
- HHG source
- Lens
- Toroidal mirror
- Ar cell
- λ/4 plate
- Al filter
- Kr cell
- Amplifier
- Source harmonique
- Lame λ/4
Evidence of strong laser amplification at 32.8nm
Polarization control of the SXRL: setup

Plasma suitable to amplify a circularly-polarized field
Polarization control of the SXRL: setup

16 mJ, 350 fs
IR beam
1.36 J, 30 fs
IR pump beam

Delay line
Lens
Gas cell (argon)

Polarizer
Plasma amplifier
X-ray camera

Rotating analyzer
Al filter
Soft x-ray laser beam

X-ray camera
Shot-to-shot reference

1.36 J, 30 fs
IR pump beam

Polarizer transmission 1%

Circular HH
Linear HH
Gas cell
Lens
λ/2 waveplate
IR laser
Amplification preserves the initial polarization

Linear seed:

Circular seed:

Strong amplification compensates for polarizer losses

$10^{10}$ photons/pulse
Single-shot duration measurement of the pulse duration

30 fs laser

Traveling wave Plasma line

Spherical mirror

Soft X-rays

X-ray CCD

$\int_{-\infty}^{\cos \theta}$ $\varphi(t) \, dt$
Single-shot duration measurement of the pulse duration

Spherical mirror

Soft X-rays

X-ray CCD
Single-shot duration measurement of the pulse duration

- Ref
- Shot

30 fs laser
Spherical mirror
Soft X-rays
Spherical mirror
X-ray CCD
Single-shot duration measurement of the pulse duration

- The XUV beam transverse profile is the envelope of the integrated signal.
- The lack of shot-to-shot reference makes the envelope retrieval harder.
- Noisy CCD signal makes fitting mandatory: we assume a skewed Gaussian temporal profile.

F. Tissandier et al., submitted
Single-shot duration measurement of the pulse duration

Calculated gain

Measured gain dynamic

Measured pulse profile

Good agreement with the expected gain duration
How to shorten the pulse duration?

➢ Extension of the CPA schema to the XUV range:


➢ Gain gating in OFI amplifiers:

T. Mocek et al., PRL 95, 2005.
Gain gating in high-density OFI amplifiers

\[ n_e = 6 \times 10^{18} \, \text{cm}^{-3} \]
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\[ \Delta t_{\text{gain}} \approx 350 \text{ fs} \]

\[ n_e = 4 \times 10^{20} \text{ cm}^{-3} \]
\[ \Delta t_{\text{gain}} \approx 150 \text{ fs} \]
When the electron density is increased:

- Gain and saturation intensity are increased
- The gain lifetime is shortened due to strong collisional ionisation
- The pump beam hardly propagates into the plasma

Gain gating in high-density OFI amplifiers

Gain (cm⁻¹) vs. t (s) and K_r⁸⁺

Electron density (cm⁻³) vs. Saturation intensity (W/cm²)

Peak gain (cm⁻¹) vs. Electron density (cm⁻³)

Code OFIKinRad, G. Maynard, LPGP
Optically-preformed plasma waveguide

Ignitor pulse 150mJ, 30fs

Heater pulse 750mJ, 0.6ns

High-density plasma amplifier
Evolution of the plasma channel

$\Delta t = 1.55 \text{ ns}$

$n_e = 2.9 \times 10^{19} \text{ cm}^{-3}$

(in the channel)

Electron density at nominal lasing conditions

Plasma channel 1.55 ns after the ignitor

Plasma amplifier when the driving beam is guided

$<n_e> = 2.9 \times 10^{19} \text{ cm}^{-3}$

$<n_e> = \text{a few } 10^{20} \text{ cm}^{-3}$
Far-field patterns of the ASE radiation VS plasma length
High-density HH-seeded plasma amplifier

16 mJ, 350 fs! IR beam!

1.36 J, 30 fs! IR pump beam!

HHG seed!

Spherical mirror!

Quarter waveplate!

HHG cell!

Toroidal mirror!

Axicon lens!

Gas jet!

Al. filter!

SXR ampliﬁer!

Waveguiding sequence!

600 ps! time!

Laser!

Heater!

Ignitor!

 SXRL beam!
Far-field pattern of the seeded 32.8nm laser

L=5 mm, \( n_e = 10^{20} \) cm\(^{-3} \)

\( \lambda = 32.8 \) nm

≈ Up to 4 \( \mu \)J per shot

\( \sigma_{\text{RMS}} = 7 \% \)

\( \sigma_{\text{RMS}} = 12 \% \)

\(< \lambda/10 \) RMS

Gain dynamics for different electron densities
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Gain dynamics for different electron densities

Group velocity mismatch between pump and XUV

\[ \beta_g^\lambda = \frac{v_g}{c} = \sqrt{1 - \frac{n_e}{n_c^\lambda}} \]

For \( n_e = 10^{20} \text{ cm}^{-3} \):
- XUV seed propagates at \( c \)
- IR pump pulse propagates at \( 0.9c \)

For \( n_e = 10^{20} \text{ cm}^{-3} \) (gain duration of 500fs), the seed will meet the gain window along 3mm
Controlling the light velocity of the driving laser

Pulse front curvature (PFC) of the driving pulse:

PFC corresponds to longitudinal chromatism at focus

By adjusting the pulse chirp, the effective velocity in focus can be controlled


Courtesy of F. Quéré
PFC effect on 1 cm-long seeded amplifiers

Gain duration

Without PFC

With PFC

a few ps

< 1ps
Far-field patterns of the seeded SXRL VS chirp

2000 fs$^2$

1000 fs$^2$

0

-1000 fs$^2$

-2000 fs$^2$

-3000 fs$^2$

-4000 fs$^2$

-5000 fs$^2$

-6000 fs$^2$

-7000 fs$^2$
Significant enhancement of the XUV intensity

⇒ About 3 orders of magnitude enhancement of the XUV intensity
Single-shot CDI on binary samples – near periodic objects

32nm multilayer spherical mirror

Soft X-rays

32nm multilayer spherical mirror

CCD

3µm
Single-shot CDI on binary samples – near periodic objects

- NA = 0.24
- Transmission geometry
- Up to $4.5 \times 10^4$ counts per shot
- → one shot measurement (lucky shots!)
- Abbe Limit: ~70 nm
- Object size: ~3 μm
Ptychographic reconstruction

- Spiral scan map
- 90% overlap
- Up to $3 \times 10^4$ counts/shot
- NA=0.24
- Imaging of periodic structures
Conclusion

32.8 nm diffraction-limited multi µJ 100’s fs laser operation

Efficient guiding at $n_e = 10^{20}\text{cm}^{-3}$

Full control of the polarization from linear to circular

Source adapted for single shot CDI experiments (narrow bandwidth, high coherence, Fourier limited)

Prospect for 10’s fs multi 10’s µJ operation

**Future challenges:** improve the seeding extraction
Measure the pulse duration with 100 fs time resolution
3D calculations of the XUV amplification

ASE:

Harmonic-seeded:
Modeling the amplification of circular polarization

1D time dependent Maxwell-Bloch code taking into account the interaction of the seed polarization with the different sub-levels

Over 5mm, depolarization is very weak (1.5%) for a circular seed:
Ionization-induced refraction limits propagation

$\rho = 1 - \frac{1}{2} \frac{n_e}{n_c}$

Higher electron density on-axis

- Refraction of the IR pulse
Modeling of the hydrodynamic expansion of the channel

Expansion velocity between 6.5 \( \mu \mathrm{m} / \mathrm{ns} \) and 10 \( \mu \mathrm{m} / \mathrm{ns} \)

- Expansion velocity and the general radial profile well modeled

- Density is overestimated by a factor of two.

This is due to the fact that our code uses local thermodynamical equilibrium (LTE) tables to compute the ionization.

ARWEN: 2D radiative hydrodynamics code with adaptive mesh refinement (AMR)
Measurement of the waveguide transmission

LASER IN:
\[ I_0 = 3 \times 10^{18} \text{ W/cm}^2 \]

LASER OUT:

![Images showing laser output at different gas jet lengths (L=5mm, L=10mm, L=20mm, L=30mm)]

Graph showing IR transmission vs. gas jet length (mm):
Amplifier efficiency VS waveguide transmission
Amplifier efficiency VS laser chirp

« Red » in the pulse Leading edge

« Blue » in the pulse Leading edge

Pump beam duration (fs)
Gain dynamics for different electron densities

Ptychography: back-propagation to the HH-seeded source

Phase curvature
Comparison to peak brightness of other sources