General assembly of the Accelerators Department at IJCLAB

19/12/2024

Amplification and characterisation of extreme ultraviolet optical vortices

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Supervisors: Olivier GUILBAUD (main supervisor) and Sophie KAZAMIAS

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

LASERIX

université PARIS-SACLAY | FACULTÉ DES SCIENCES D'ORSAY

ÉCOLE DOCTORALE Ondes et Matière (EDOM)

What are optical vortices?

Light possesses 2 angular momenta:
- Spin angular momentum (polarisation) = rotation
- Orbital angular momentum (OAM) = revolution

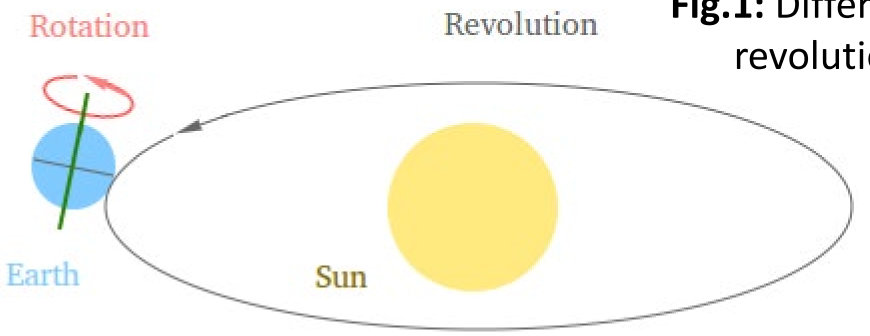


Fig.1: Difference between rotation and revolution in a planetary model

Optical vortex = beam carrying OAM ($\ell \neq 0$)

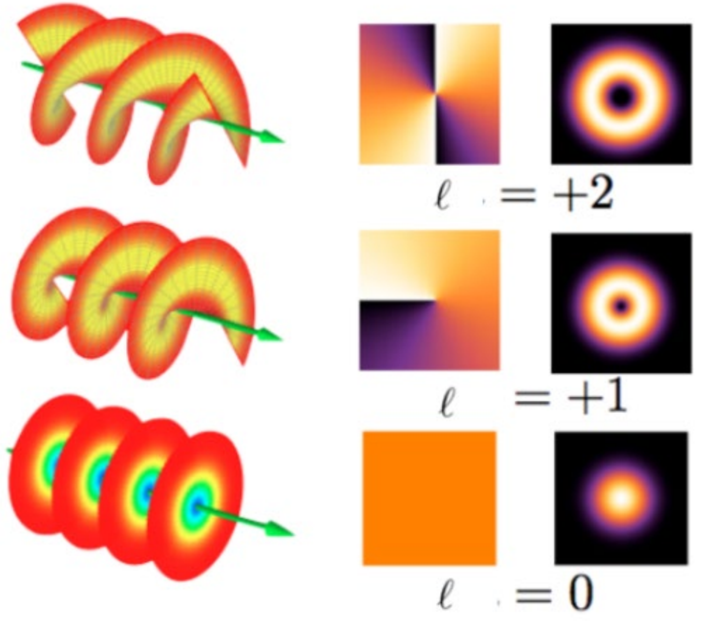
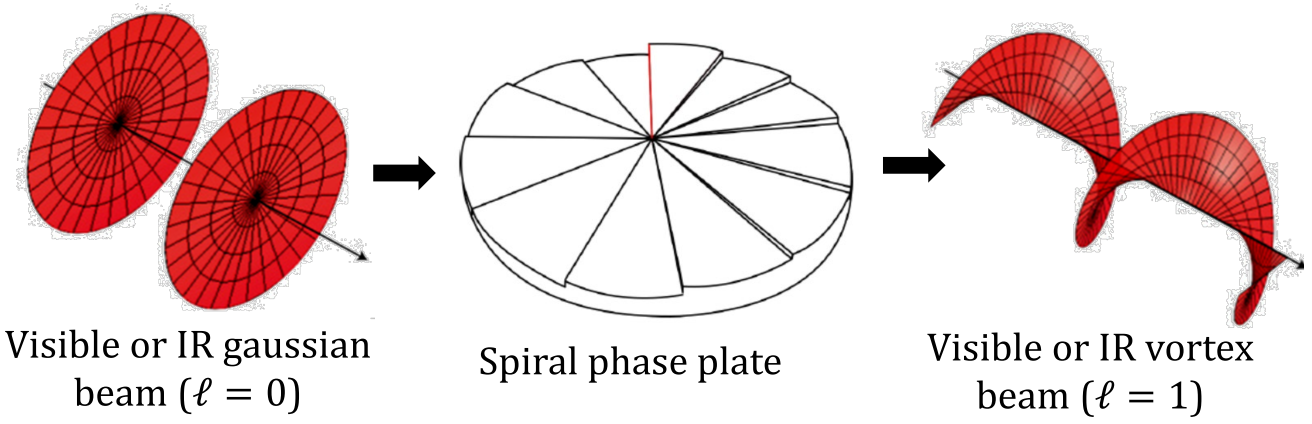


Fig.2: Wavefront, phase and irradiance profiles for vortices with different ℓ[1]

An example of how to generate a vortex beam in the lab:

Fig.3: Using a spiral phase plate to generate a vortex, adapted from [2] [3]



[1] Chris Lee. Twisted light beats quantum light. [EB/OL].
[2] Fabrice Sanson. “Génération et optimisation d’harmoniques d’ordres élevés portant un moment angulaire orbital pour l’injection dans un plasma de laser X-UV”. 2021UPASP026. PhD thesis. 2021.
[3] Alison M. Yao and Miles J. Padgett, “Orbital angular momentum: origins, behavior and applications”, Advances in Optics and Photonics 3, 161-204, 2011

A few applications of optical vortices

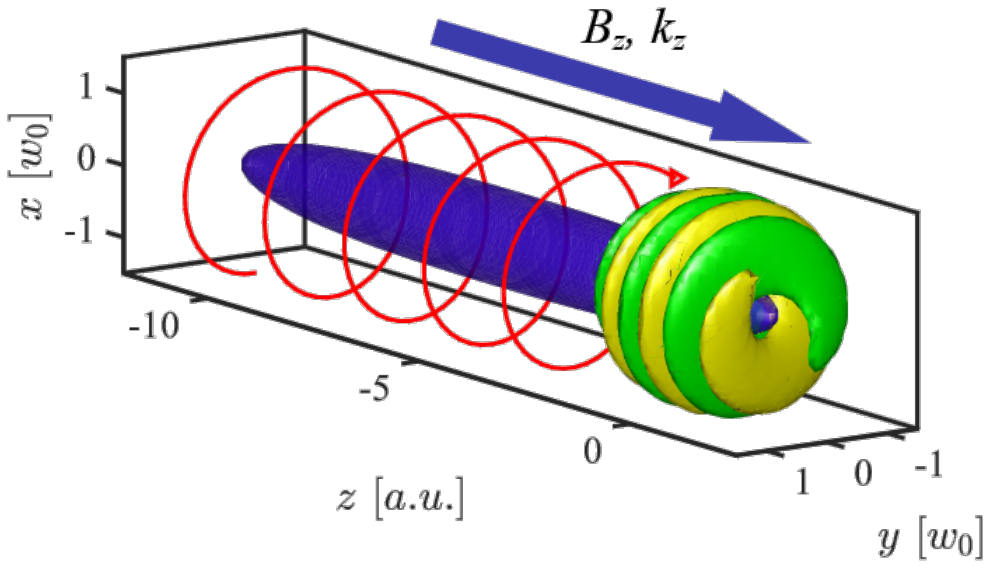
- We can use a driving vortex beam for:

- Enhancing laser wakefield acceleration [4] with hollow electron bunches

- Producing very intense (up to 1kT) axial magnetic fields [5] [6] because of the azimuthal component of the electric current

- Exciting nuclear transitions: γ-rays photons can excite differently specific nuclear transitions whether $\ell = 0$ or $\ell \neq 0$ [7]

Fig.4: Illustration of an IFE driven B-field with a $\ell = 1$[5]



- Our team is specialised in **coherent XUV sources** (~10fs to 1ps, λ~10-100nm scales)
  → I am studying **XUV vortices**

[4] Vieira, J., et J. T. Mendonça. « Nonlinear Laser Driven Donut Wakefields for Positron and Electron Acceleration ». *Physical Review Letters* 112, nº 21 (27 mai 2014): 215001.
[5] Longman, Andrew, et Robert Fedosejevs. « Kilo-Tesla Axial Magnetic Field Generation with High Intensity Spin and Orbital Angular Momentum Beams ». arXiv, 25 novembre 2021.
[6] Ali, S., J. R. Davies, et J. T. Mendonca. « Inverse Faraday Effect with Linearly Polarized Laser Pulses ». *Physical Review Letters* 105, nº 3 (12 juillet 2010): 035001.
[7] Lu, Zhi-Wei, Liang Guo, Zheng-Zheng Li, Mamutjan Ababekri, Fang-Qi Chen, Changbo Fu, Chong Lv, et al. « Manipulation of Giant Multipole Resonances via Vortex $γ$ Photons ». arXiv, 21 juillet 2023.

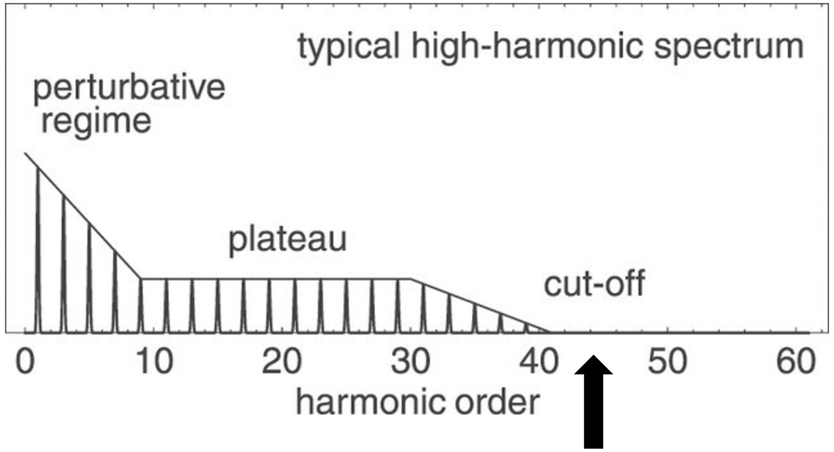
How to get XUV optical vortices?

XUV light : from to 10 to 100nm (12 to 120 eV)

We use non-linear optics : **High Harmonic Generation**

Fig.6: Sketch of an experiment of HHG

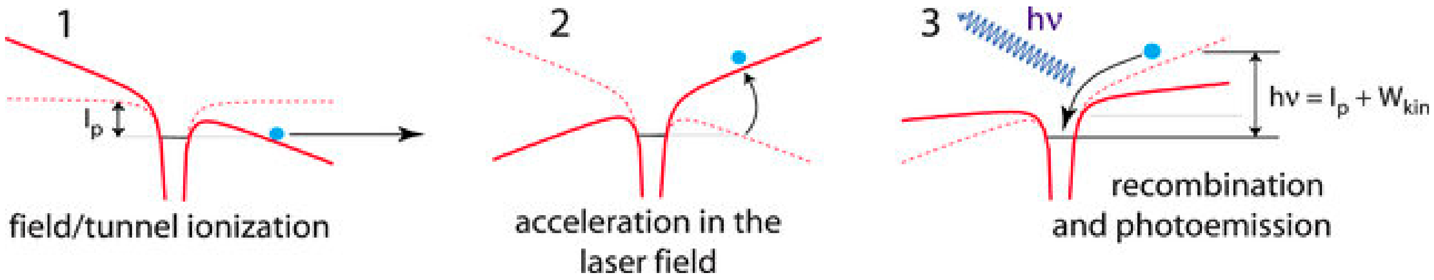
Fig.5: Typical HHG spectrum [8]



Maximum order depends on $|E_{IR}|^2$ and λ

Basic understanding of the process: the 3 step model [9] :

Fig.7: Sketch of the 3 step model[10]



In this PhD, we work on the **25th** harmonic around **32.8nm ($q = 25$).**

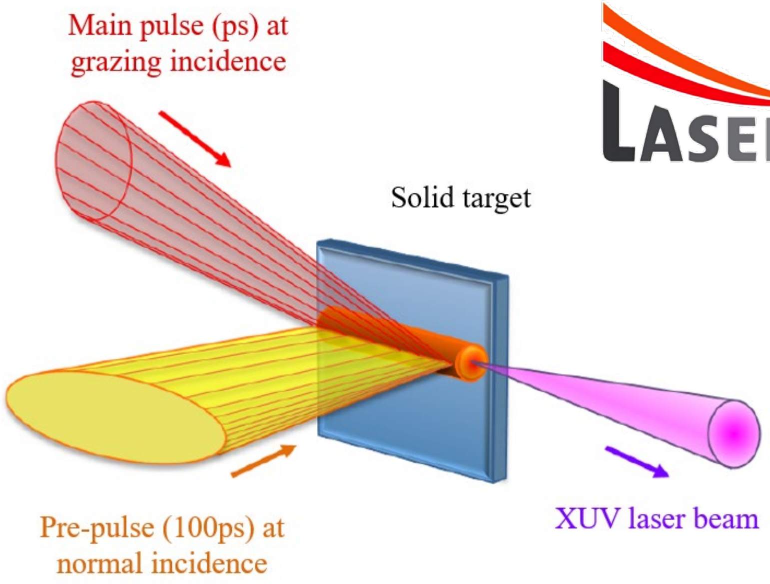
HHG is very inefficient → **amplification with an XUV laser** (transition pumped with electron/ion collisions from a hot plasma)

[8] Carsten Winterfeldt, Christian Spielmann, and Gustav Gerber. “Colloquium: Optimal control of high-harmonic generation”. In: Rev. Mod. Phys. 80 (1 Jan. 2008), pp. 117–140.
[9] P. B. Corkum. “Plasma perspective on strong field multiphoton ionization”. In: Phys. Rev. Lett. 71 (13 Sept. 1993), pp. 1994–1997.
[10] Liran Hareli *et al* 2020 *J. Phys. B: At. Mol. Opt. Phys.* **53** 233001

Amplifying medium: the plasma-based XUV laser

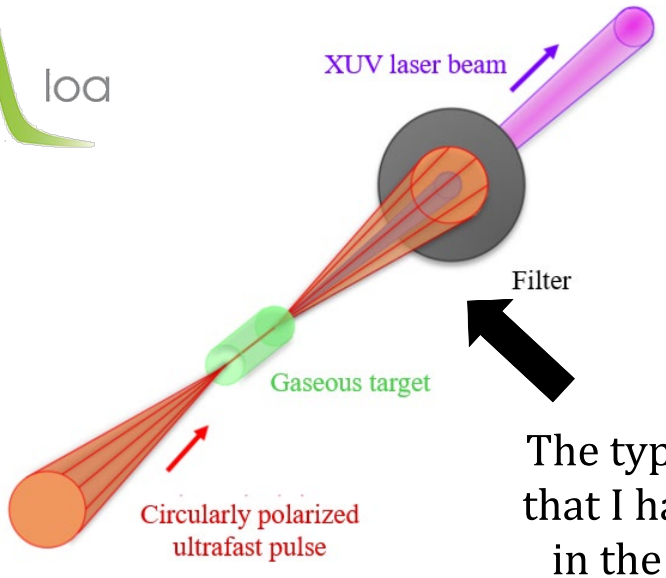
On a solid target (LASERIX platform): the 1st pulse creates the plasma, the 2nd pulse heats the plasma electrons

Fig.8: Sketch of a collisional XUV laser on a solid target [11]



In a gas cell (LOA Salle Jaune): a single ultrafast pulse (~40fs) creates the plasma and heats the electrons

Fig.9: Sketch of a collisional XUV laser in a gas cell [11]



The type of XUV laser that I have used so far in the experiments

XUV laser with poor spatial quality BUT if used as an amplifying medium:

- Energy is multiplied by orders of magnitude
- Both temporal [12] and spatial [13] coherences of the harmonic are preserved → high quality beam
- BUT perfect **spatial** and **spectral synchronisations** of the seed and the XUV laser are mandatory

[11] Fabien Tissandier. “Caractérisation spatio-temporelle d’une chaîne laser à 32. 8 nm par plasma laser et perspectives vers une source ultrabrève et intense”. 2011EPXX0026. PhD thesis. 2011, 1 vol. (244).
[12] O. Guilbaud et al. “Fourier-limited seeded soft x-ray laser pulse”. In: Opt. Lett. 35.9 (May 2010), pp. 1326–1328.
[13] Y. Wang et al. “High-Brightness Injection-Seeded Soft-X-Ray-Laser Amplifier Using a Solid Target”. In: Phys.Rev. Lett. 97 (12 Sept. 2006), p. 123901.

Experimental setup and results: LOA 2023 (1/3)

- Problem:
  - if the infrared laser has $\ell = 1$, the q-th harmonic has $\boldsymbol{\ell_q = q}$
  - for $q = 25$, $\ell_q = 25 \times \ell$ → the XUV vortex is larger than the IR one and 5 times **more divergent**!

- Idea: **focusing** the harmonic seed as much as possible

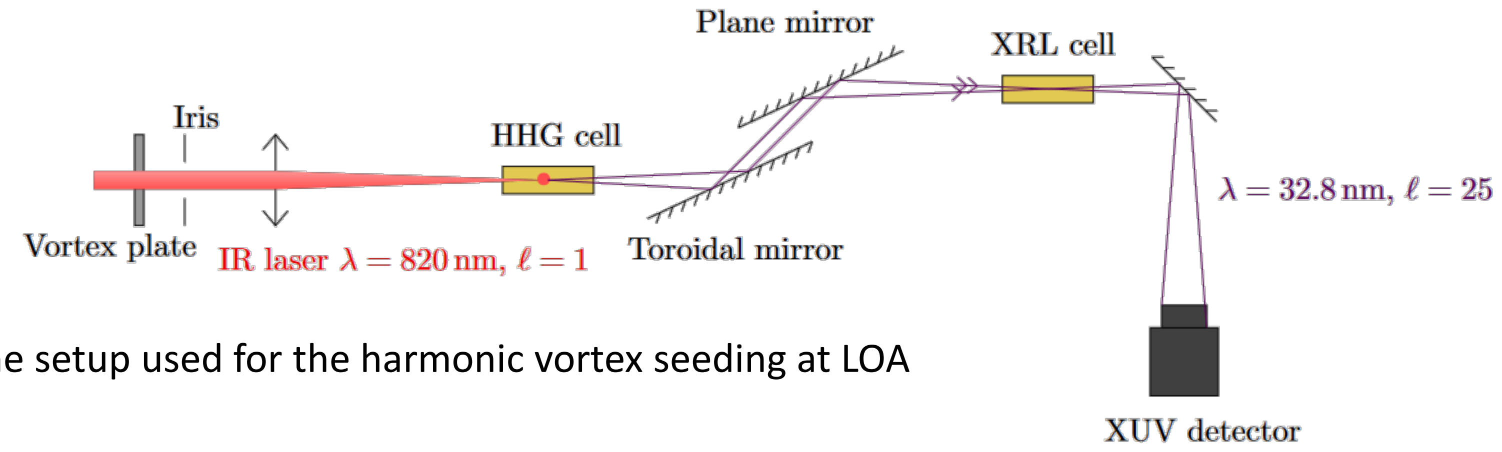


Fig.10: Sketch of the setup used for the harmonic vortex seeding at LOA

Main result:

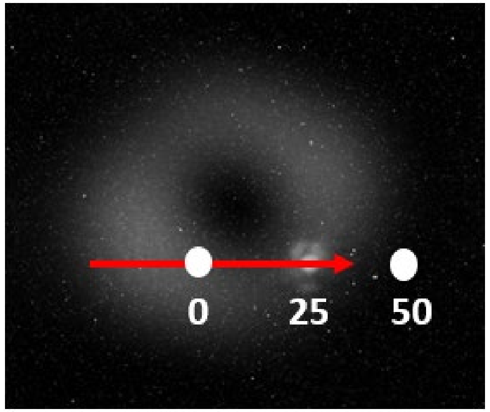
- XUV laser diameter: $\Phi_{\mathrm{XRL}} \sim 60\mu m$
- XUV vortex diameter: $\Phi_{\mathrm{Vortex\ XUV}} \sim 150\mu m$

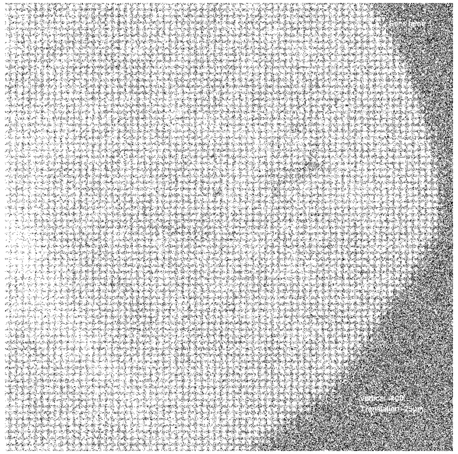
$$\Phi_{\mathrm{Vortex\ XUV}} \approx 3 \times \Phi_{\mathrm{XRL}}$$

→ **Partial seeding**

Experimental setup and results: LOA 2023 (2/3)

- Not at the center (horizontal scan):



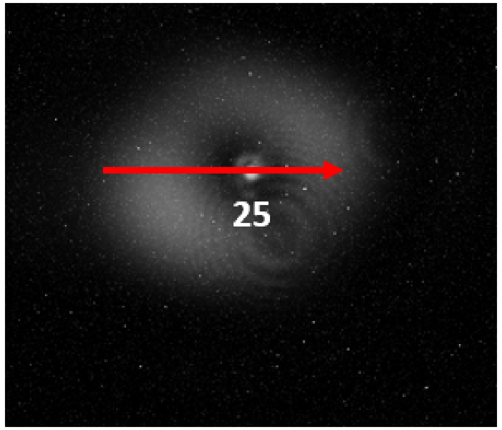


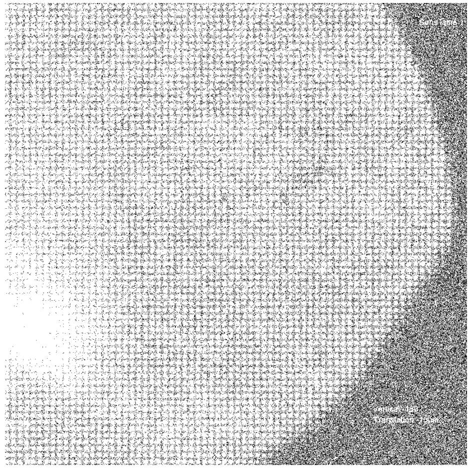
Clear evolution

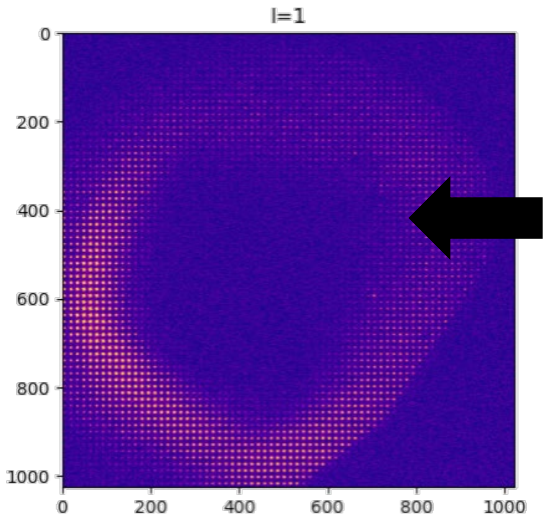
$$\Phi_{\text{Vortex XUV}} \approx 3 \times \Phi_{\text{XRL}}$$

→ Partial seeding

- At the center (horizontal scan):







Follows the shape of the input harmonic

Experimental setup and results: LOA 2023 (3/3)

Is it consistent with theory?

→ DAGON[14] code, collaboration with Eduardo Oliva Gonzalo, Universidad Politécnica de Madrid

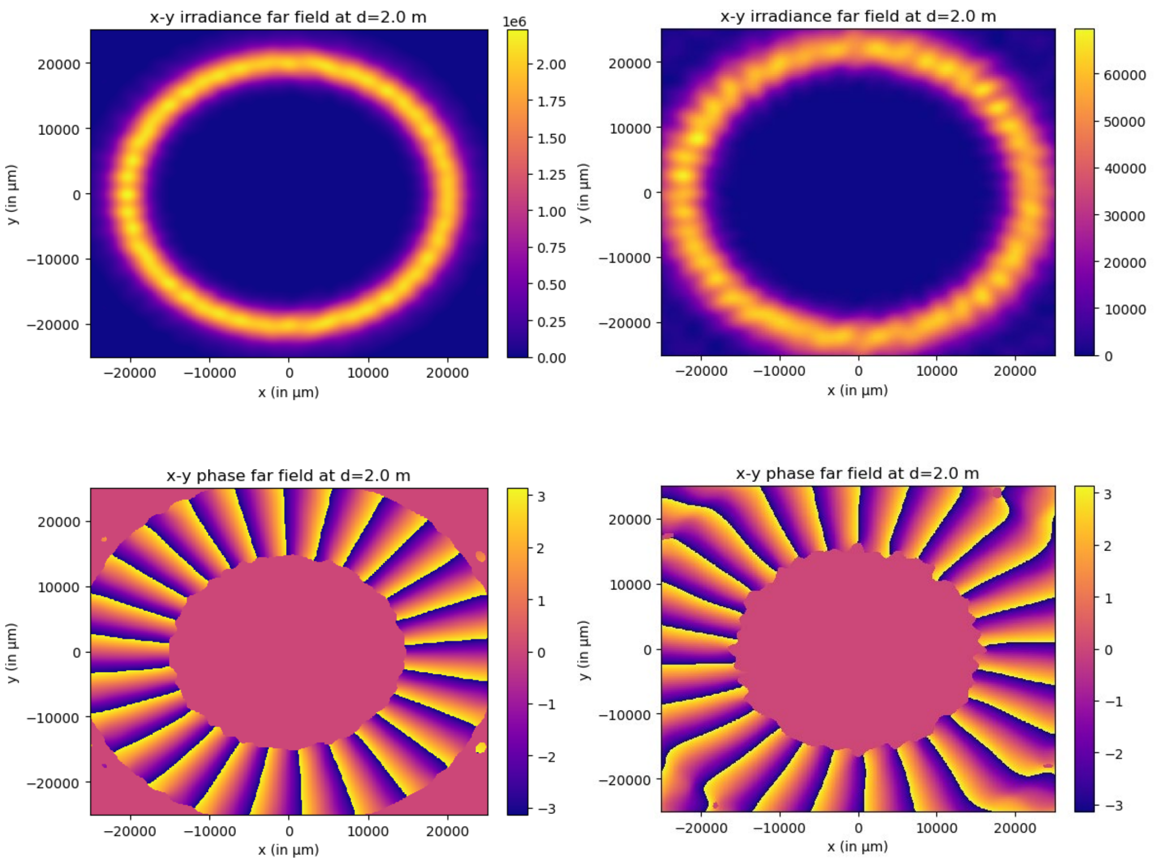


Fig.11: left: perfect vortex before seeding, right: perfectly seeded vortex

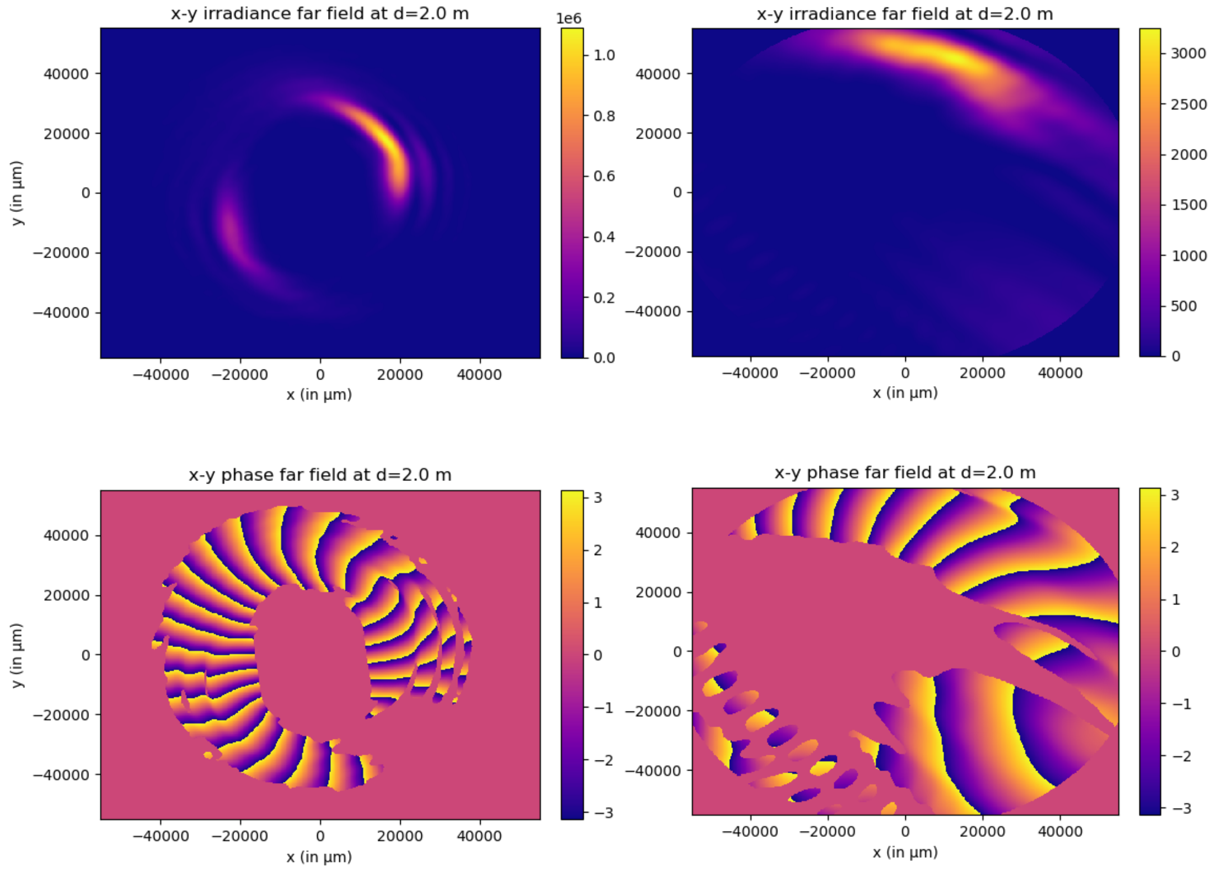


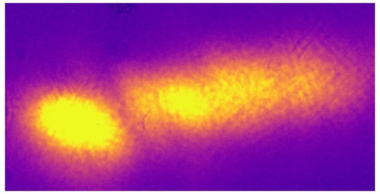
Fig.12: left: realistic vortex before seeding, right: partially seeded realistic vortex

[14] Eduardo Oliva, Manuel Cotelo, Juan Carlos Escudero, Agustín González-Fernández, Alberto Sanchís, Javier Vera, Sergio Vicéns, and Pedro Velarde "DAGON: a 3D Maxwell-Bloch code", Proc. SPIE 10243, X-ray Lasers and Coherent X-ray Sources: Development and Applications, 1024303 (16 June 2017);

Experiments and simulations: LASERIX + LOA 2024 (1/2)

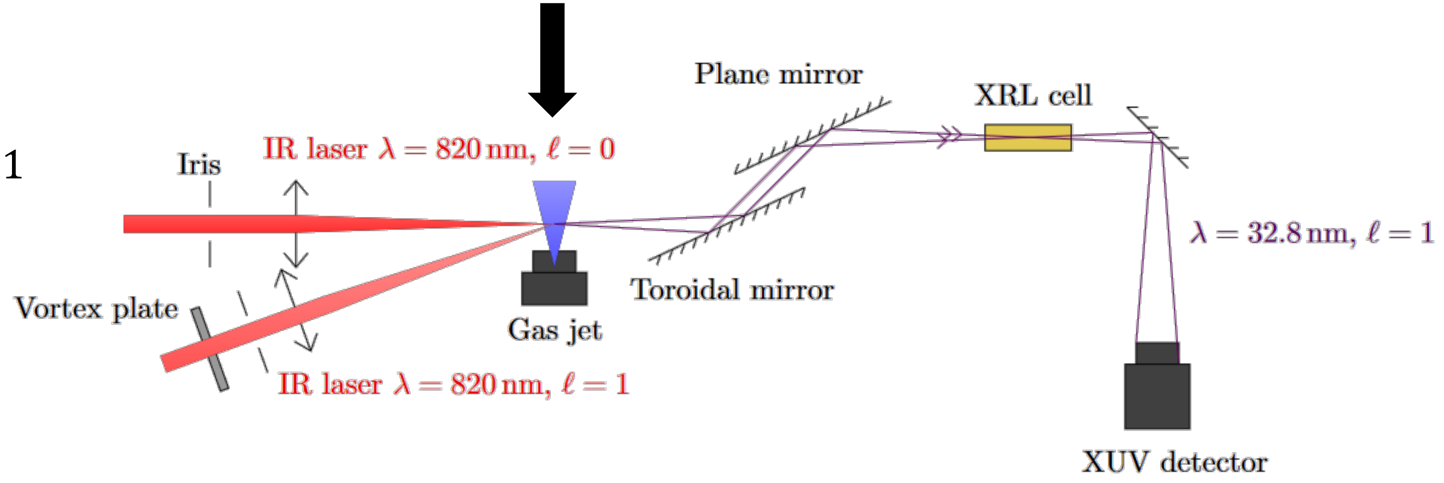
- Idea: vortex divergence doesn't depend on q but on $\sqrt{\ell}$ → we want ℓ=1 in the XUV
- Solution: **two non-colinear beams HHG**:

Fig.14: Sketch of the setup used for the 2 beams HHG seeding at LOA



Signature of 2 beams HHG
(studied on LASERIX)

Fork pattern at the focus:
diffraction grating



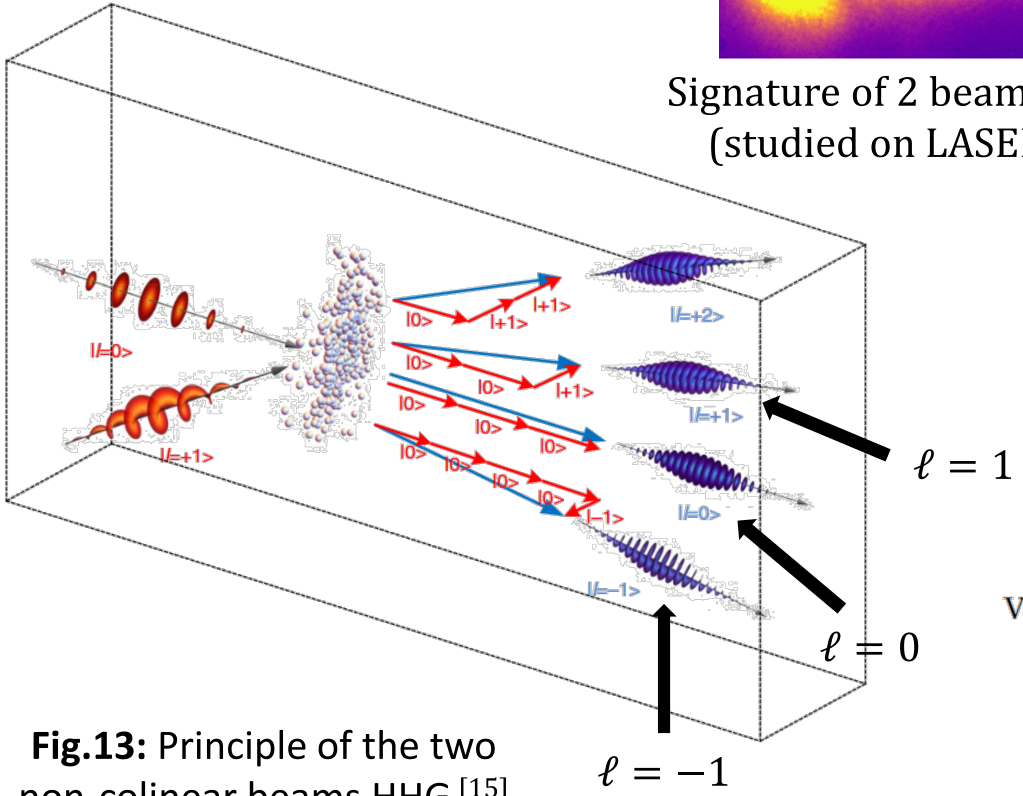


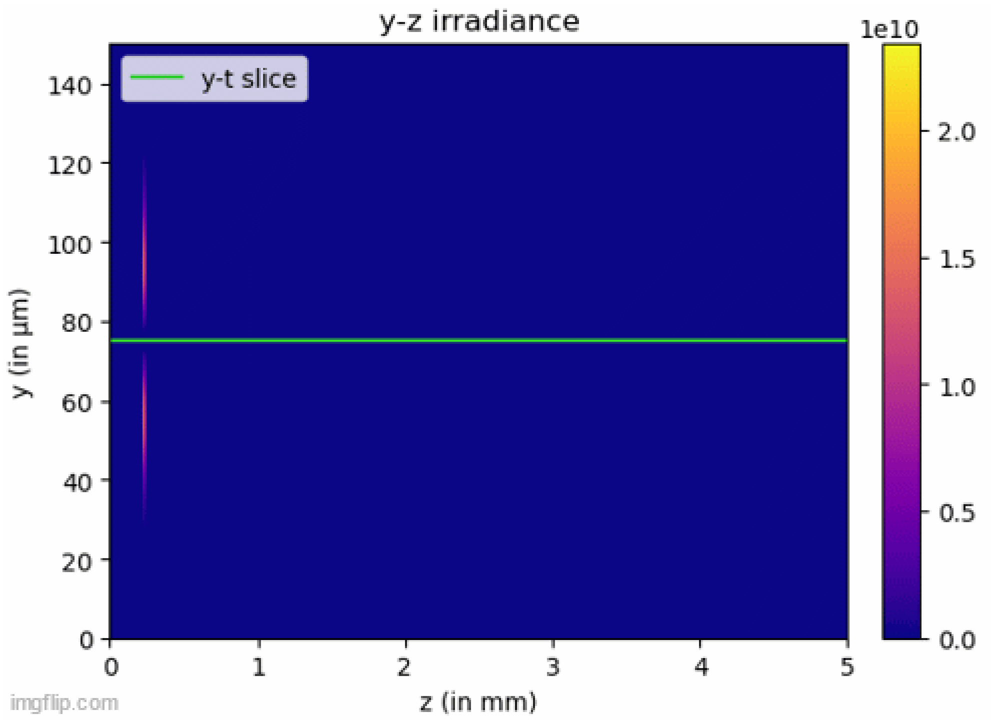
Fig.13: Principle of the two non-colinear beams HHG [15]

[15] Kong, F. et al (2017). Controlling the orbital angular momentum of high harmonic vortices. Nature Communications, 8(1). .

Experiments and simulations: LASERIX + LOA 2024 (2/2)

What is expected from this experiment?

We are working in a very specific regime: the harmonic is **not amplified** but triggers a **wake** [16] with **Rabi's oscillations** [17]



[16] I. R. Al'miev et al. , "Dynamical Description of Transient X-Ray Lasers Seeded with High-Order Harmonic Radiation through Maxwell-Bloch Numerical Simulations", Phys. Rev. Lett. 99, 123902 – Published 21 September, 2007

[17] Olivier Larroche, Limin Meng, Andréa Le Marec, and Annie Klisnick, "Inversion density threshold for Rabi oscillations and modified small-signal gain in extreme-ultraviolet lasers," Opt. Lett. 38, 2505-2508 (2013)

Experiments and simulations: LASERIX + LOA 2024 (2/2)

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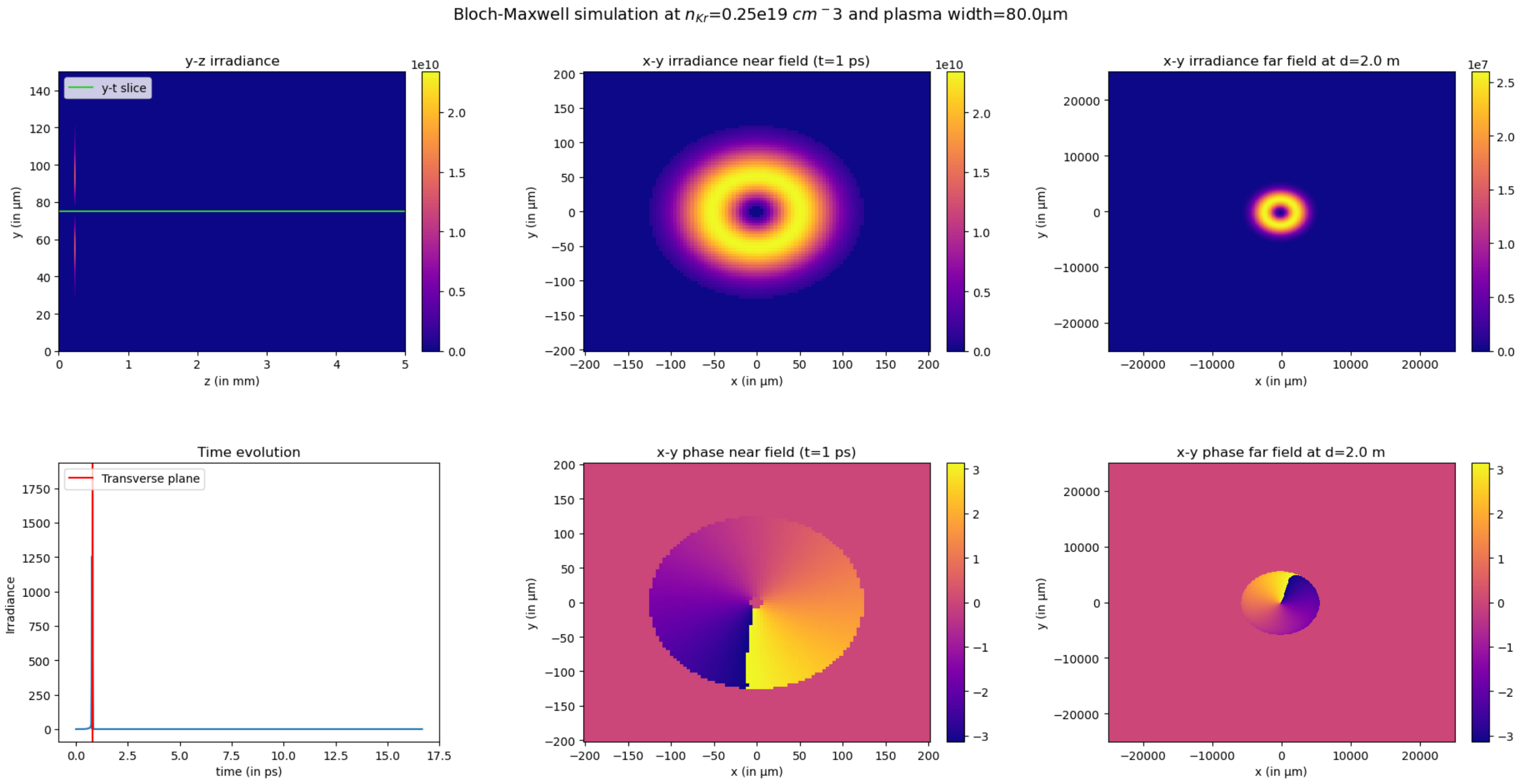

Fig.15: Simulation of the seeding of a perfect vortex with $\ell = 1$ (before amplification)

[16] I. R. Al'miev et al. , "Dynamical Description of Transient X-Ray Lasers Seeded with High-Order Harmonic Radiation through Maxwell-Bloch Numerical Simulations", Phys. Rev. Lett. 99, 123902 – Published 21 September, 2007

[17] Olivier Larroche, Limin Meng, Andréa Le Marec, and Annie Klisnick, "Inversion density threshold for Rabi oscillations and modified small-signal gain in extreme-ultraviolet lasers," Opt. Lett. 38, 2505-2508 (2013)

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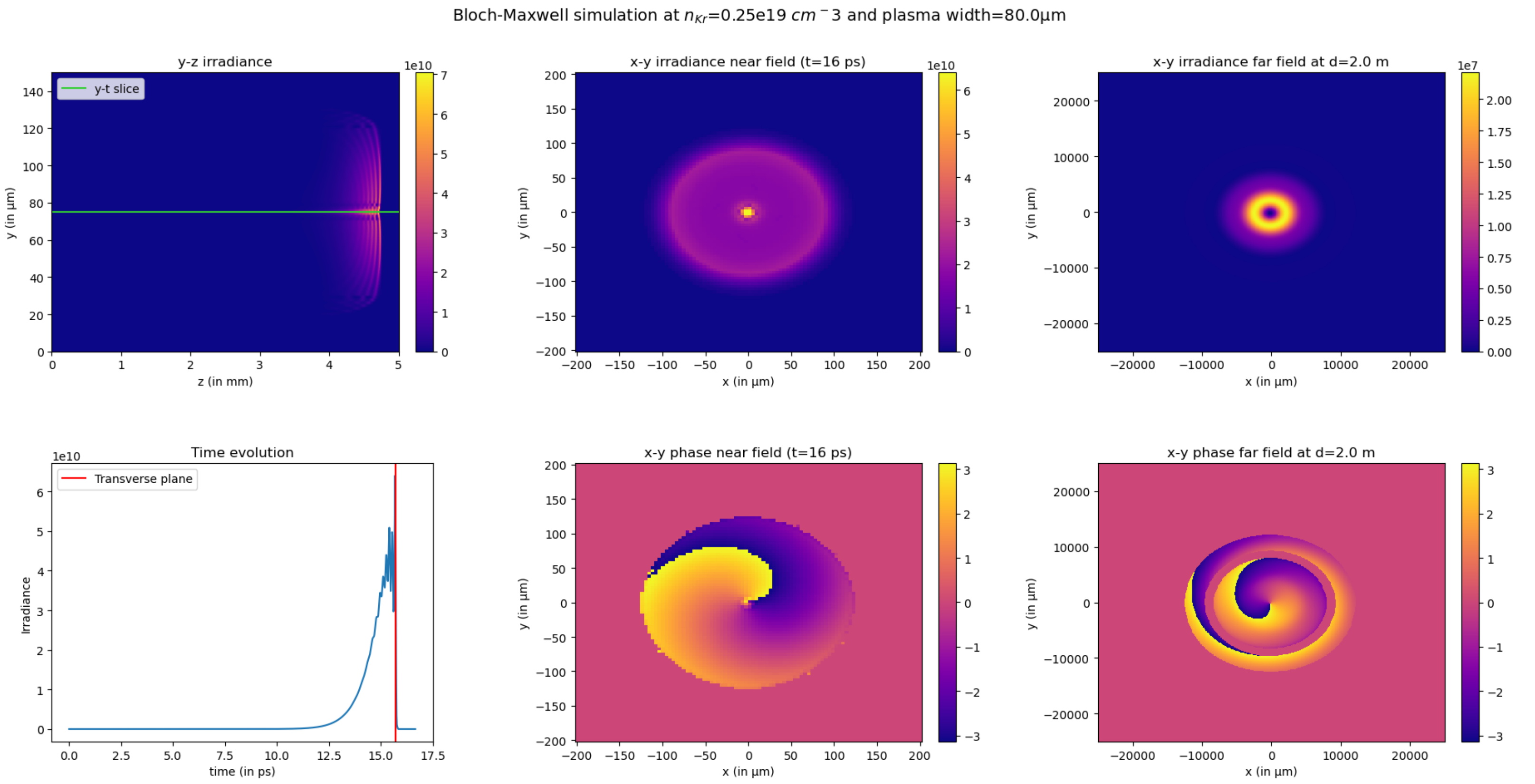


Fig.16: Simulation of the seeding of a perfect vortex with $\ell = 1$ (after amplification)

[16] I. R. Al'miev et al. , "Dynamical Description of Transient X-Ray Lasers Seeded with High-Order Harmonic Radiation through Maxwell-Bloch Numerical Simulations", Phys. Rev. Lett. 99, 123902 – Published 21 September, 2007

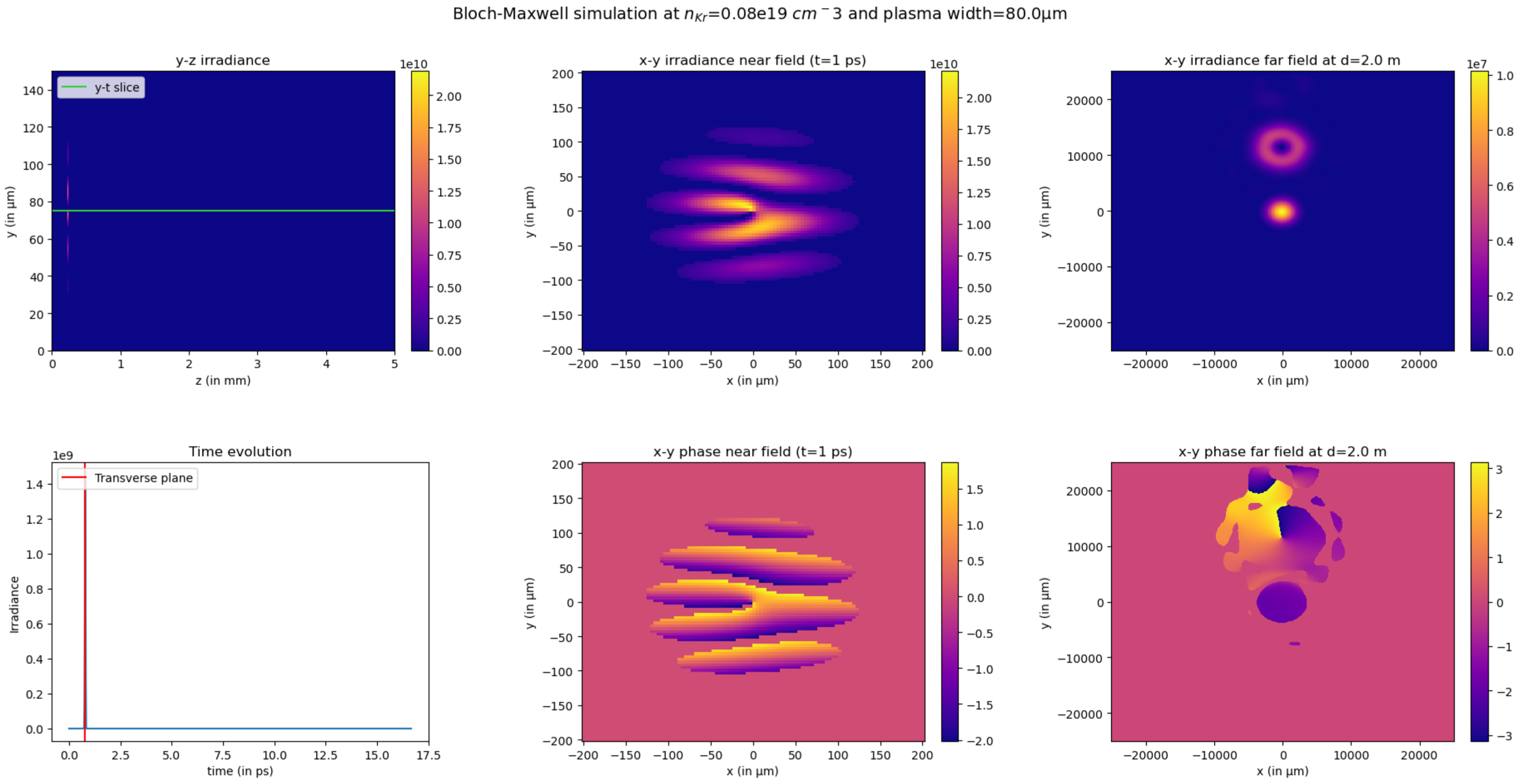
[17] Olivier Larroche, Limin Meng, Andréa Le Marec, and Annie Klisnick, "Inversion density threshold for Rabi oscillations and modified small-signal gain in extreme-ultraviolet lasers," Opt. Lett. 38, 2505-2508 (2013)

Experiments and simulations: LASERIX + LOA 2024 (2/2)

What is expected from this experiment?

We can also seed a more complex pattern:

Fig.17: Simulation of the seeding of a fork pattern (before amplification)

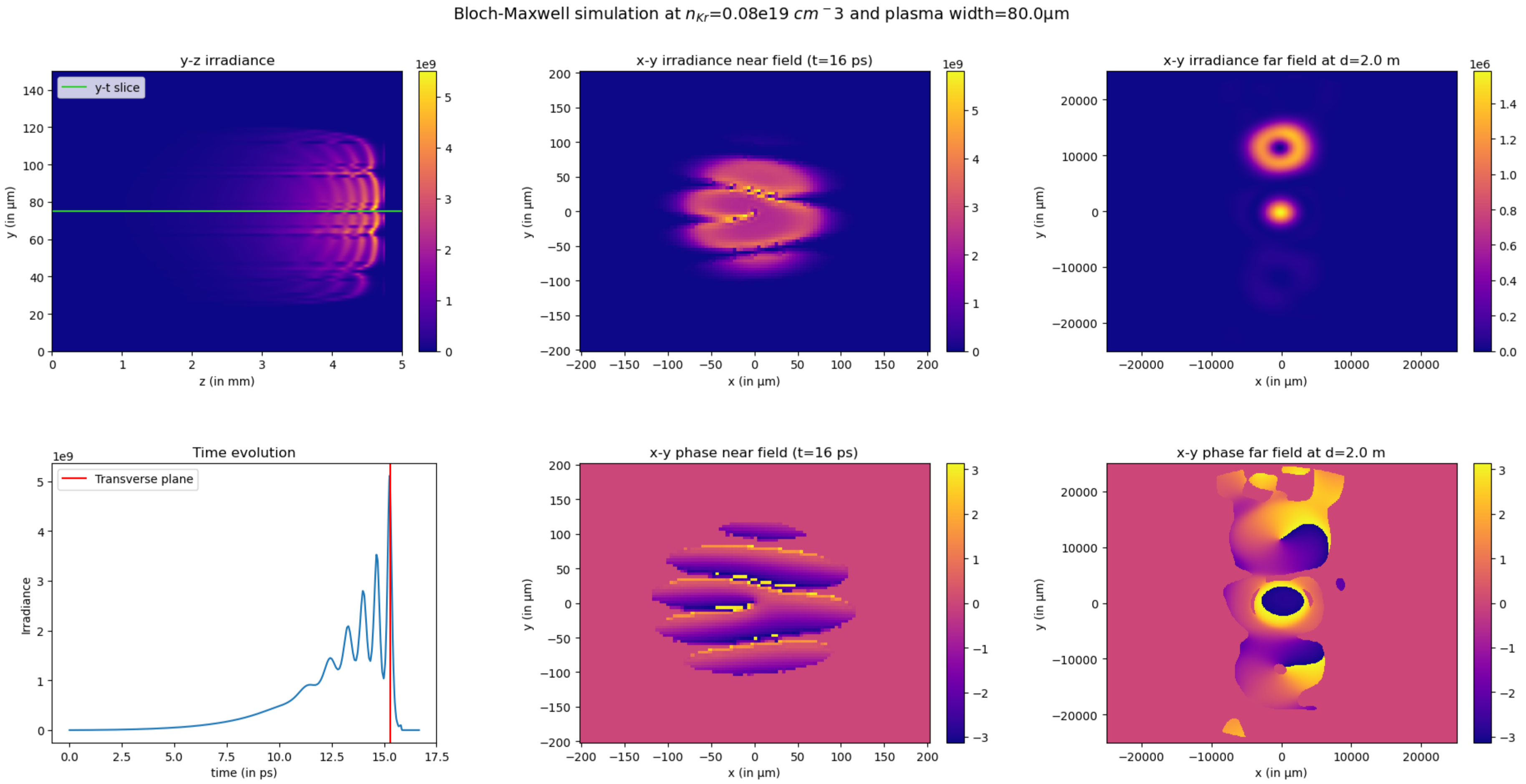


Experiments and simulations: LASERIX + LOA 2024 (2/2)

What is expected from this experiment?

We can also seed a more complex pattern:

Fig.18: Simulation of the seeding of a fork pattern (after amplification)



Summary and next steps

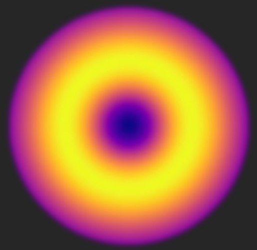
To summarise:

- Only partial amplification achieved with a single focused driving beam, consistent with simulations ?????? À tester)
- Set-up for 2-beams HHG built and tested extensively
- Bloch-Maxwell simulations can be performed with any kind of input using homemade Python scripts
- Seeding and amplification of structured beams are not trivial

To be done during this academic year:

- Seeding with 2-beams HHG on LASERIX
- Deeper investigation of pattern preservation by the XUV laser using DAGON

SUPPLEMENTARY MATERIALS

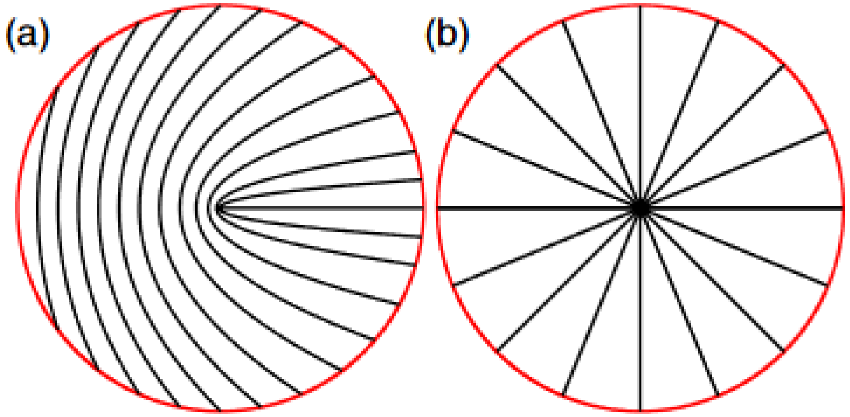


Other ways to generate IR optical vortices

- Spiral Zone Plate: add OAM and focuses the beam at the same time using diffraction around the opaque zones. Diffracted light then interferes constructively at focus.

- q-plate: for a circularly polarized beam, it applies an OAM of $\ell = 2q$ using the transfer of spin and OAM to matter in a both inhomogeneous and anistropic medium

Spiral Zone Plate pattern for $\ell = 1$[i]

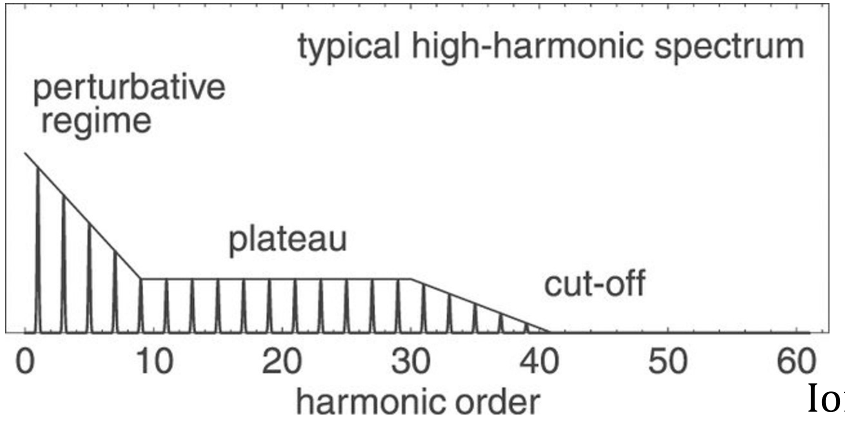


q-plates for (a): $q = \frac{1}{2}$ and (b): $q = 1$ [ii]

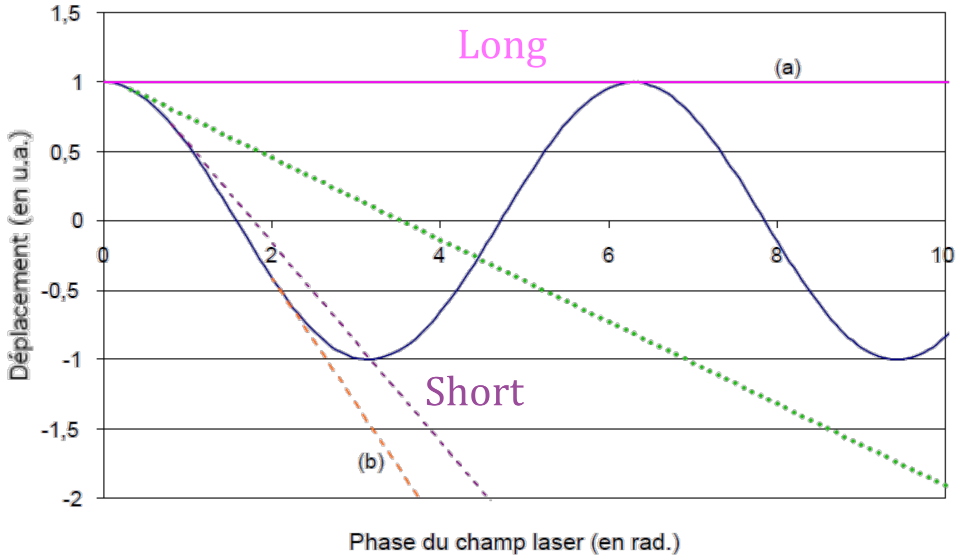
[i] N. R. Heckenberg et al. “Generation of optical phase singularities by computer-generated holograms”. In: Opt.Lett. 17.3 (Feb. 1992), pp. 221–223. abstract.cfm?URI=ol-17-3-221.
[ii] L. Marrucci, C. Manzo, and D. Paparo. “Optical Spin-to-Orbital Angular Momentum Conversion in Inhomogeneous Anisotropic Media”. In: Phys. Rev. Lett. 96 (16 Apr. 2006), p. 163905.

More information about High Harmonic Generation

Typical HHG spectrum [iii]



For each harmonic, 2 different trajectories (short & long):



Electronic trajectories at different ionisation times regarding the laser oscillation [iv]

Ionisation potential

Cut-off: ordre harmonique maximal $q_{max} = (I_p + 3.17U_p)/\hbar\omega$

Ponderomotive potential $\propto I\lambda^2$

- For a thin medium (short gas jet), « **thin slab** » model can be used:

  Harmonic electric field q : $E_q^{s,l} \propto E_{IR}^{q_{eff}}\, e^{iq\Phi_{IR}} e^{-i\alpha_q^{s,l} I_{IR}}$

  $\alpha_q^{s,l}$: atomic phase coefficient for the short and long trajectories, q_{eff}~4 effective order

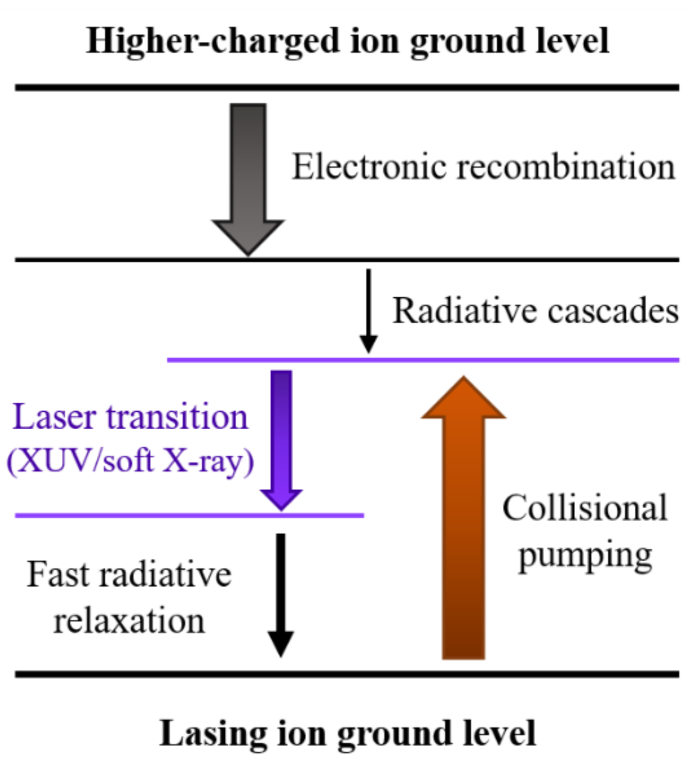
- For a thick medium, phase matching needed (depends on gas pressure, beam shape, iris aperture, focus of the lens)

[iii] Carsten Winterfeldt, Christian Spielmann, and Gustav Gerber. “Colloquium: Optimal control of high-harmonic generation”. In: Rev. Mod. Phys. 80 (1 Jan. 2008), pp. 117–140.
[iv] Sophie Kazamias-Moucan. Optimisation d'une source d'harmoniques d'ordres élevés pour l'optique non-linéaire dans l'extrême UV. Physique Atomique [physics.atom-ph]. Ecole Polytechnique X, 2003. Français. ⟨NNT : ⟩. ⟨tel-00008285⟩

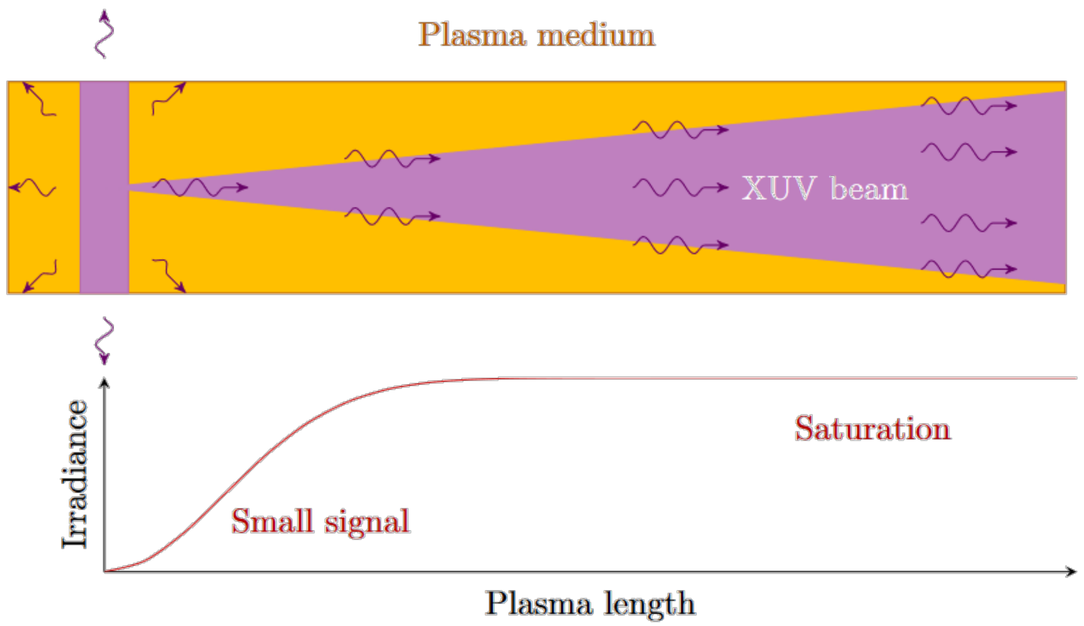
Basic understanding of plasma-based XUV lasers

Idea: creating a plasma so that its electron will pump a transition in the XUV range (collisional XUV laser)

Sketch of the pumped XUV lasing transition in the collisional scheme



XUV low reflectivity and very short gain duration → **no-cavity laser**



Principle of the Amplified Spontaneous Emission (ASE)

Spontaneous emission amplified by stimulated emission until saturation after a few mm of plasma

→ Poor spatial coherence (poor beam quality)

DAGON: a 3D Maxwell-Bloch code

P: polarisation

- $$\frac{\partial P}{\partial t} = -\frac{P}{T_2} - i\omega D E + \Gamma$$ ← Γ: spontaneous emission

T_2: dipole dephasing time, mainly due to collisions

D: population inversion density

- $$\frac{\partial D}{\partial t} = -\frac{D - D_0}{T_1} - \frac{d^2}{\hbar^2 \omega} Re(iPE^*)$$

T_1: population recovering time

ω_p: plasma frequency

- $$\frac{\partial E}{\partial t} + c\frac{\partial E}{\partial z} = i\frac{c^2}{2\omega}\nabla_\perp E + \frac{i\omega}{2}\left(\mu_0 c^2 P - \left(\frac{\omega_p}{\omega}\right)^2 E\right)$$

+ atomic physics data

+ collisional radiative data with OfiKinRad or EHYBRID codes (plasma density and temperature, temporal gain profile, population rates etc…)

POLITÉCNICA

INDUSTRIALES
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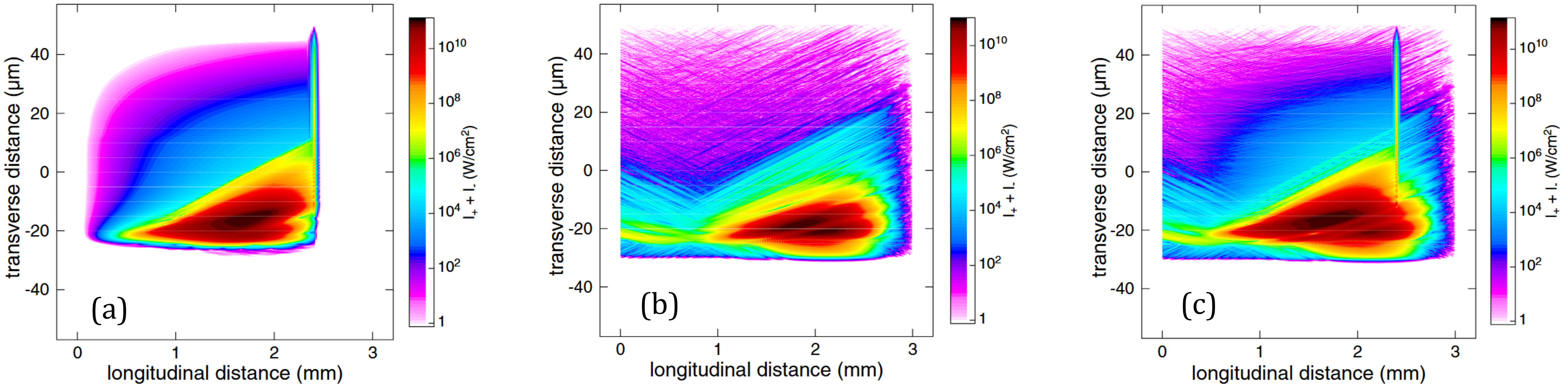
Rabi's oscillations in the non-adiabatic regime

We are working in a very specific regime: the harmonic is **not amplified** but triggers a **wake** [v] with **Rabi's oscillations** [vi]
This the **non-adiabatic regime**[vi] : the population inversion is not reduced immediately when the electric field is applied.

Condition to be in this regime:

Asymptotic Rabi's frequency (for a fully-inverted population) → $$\Omega_O \geq \frac{1}{T_2}$$ ← Dipole dephasing time (from Maxwell-Bloch simulations)

2D map of local XRL intensity[v] : (a) with a seed but no ASE, (b) with ASE but no seed, (c) with both ASE and seed



[v]I. R. Al'miev et al. , "Dynamical Description of Transient X-Ray Lasers Seeded with High-Order Harmonic Radiation through Maxwell-Bloch Numerical Simulations", Phys. Rev. Lett. 99, 123902 – Published 21 September, 2007
[vi] Olivier Larroche, Limin Meng, Andréa Le Marec, and Annie Klisnick, "Inversion density threshold for Rabi oscillations and modified small-signal gain in extreme-ultraviolet lasers," Opt. Lett. 38, 2505-2508 (2013)