

LASERIX ++

Recent activities using the LASERIX high power laser facility

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HIGHLIGHTS

LASERIX facility:

X-ray laser:

DELLIGHT:

A brief introduction

Coherent x-ray sources

Deflection of light by light in vacuum

PALLAS :

Laser wakefield acceleration see next talks !

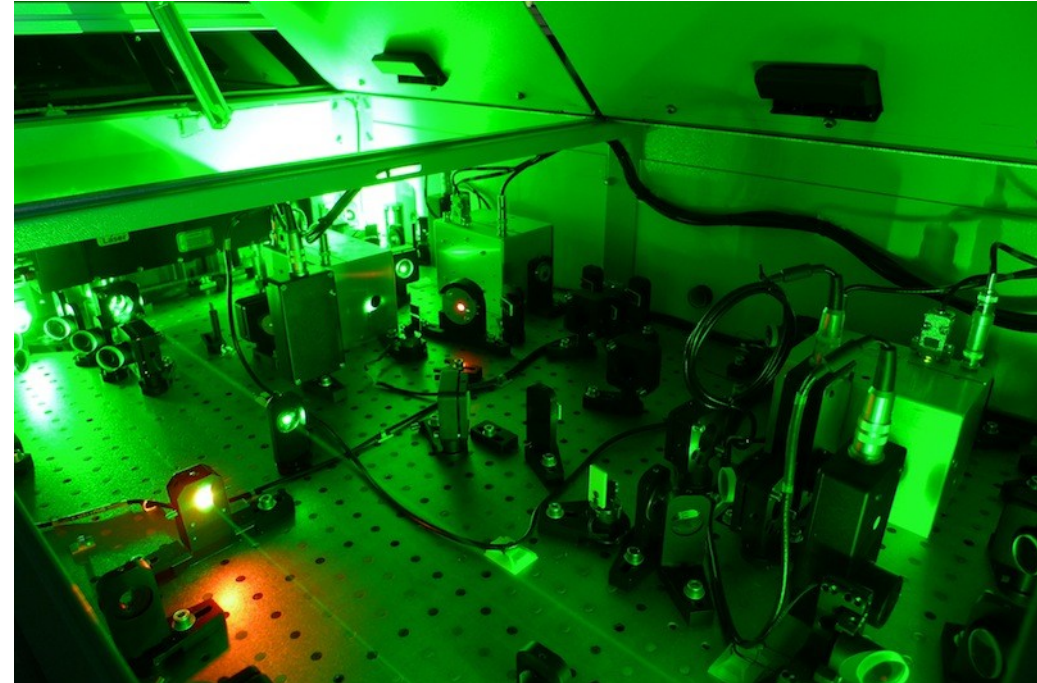
LASERIX In a Nutshell...

A TeraWatt class laser :

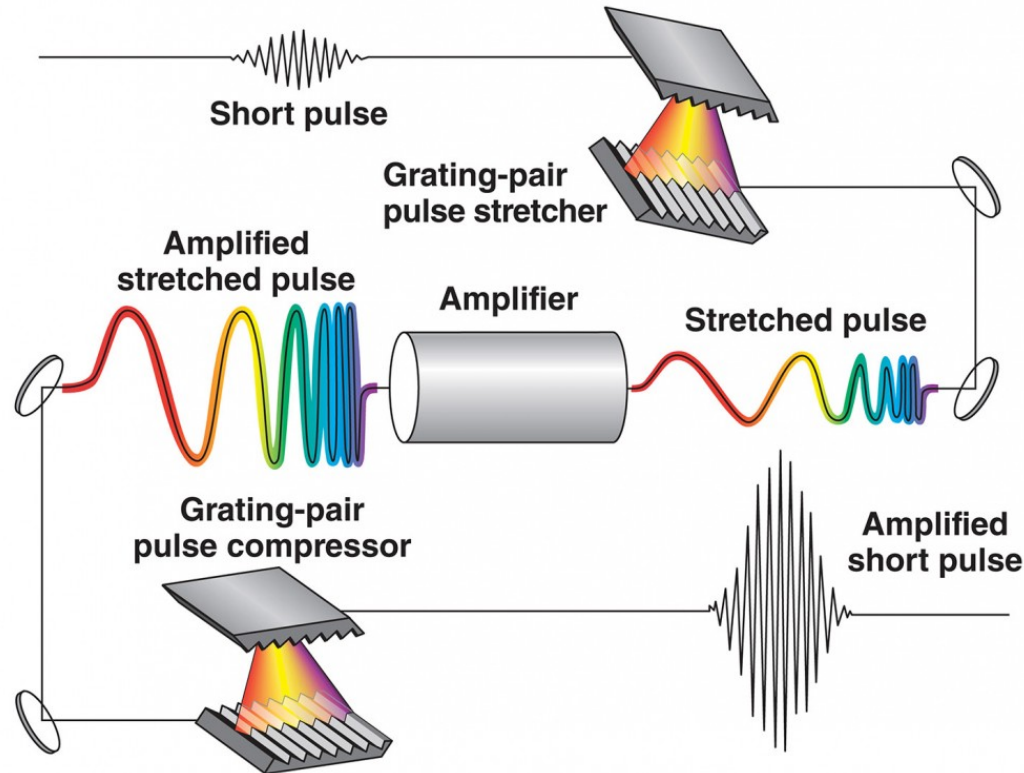
$3 \text{ J in } 30\text{fs} \Rightarrow 3\text{J} / 30\text{fs} = 100 \text{ TW}$

Titanium-Sapphire laser :

- $\Rightarrow$ Large amplification bandwidth
for short pulse handling
- $\Rightarrow$ High repetition rate 10Hz
(less for PALLAS)



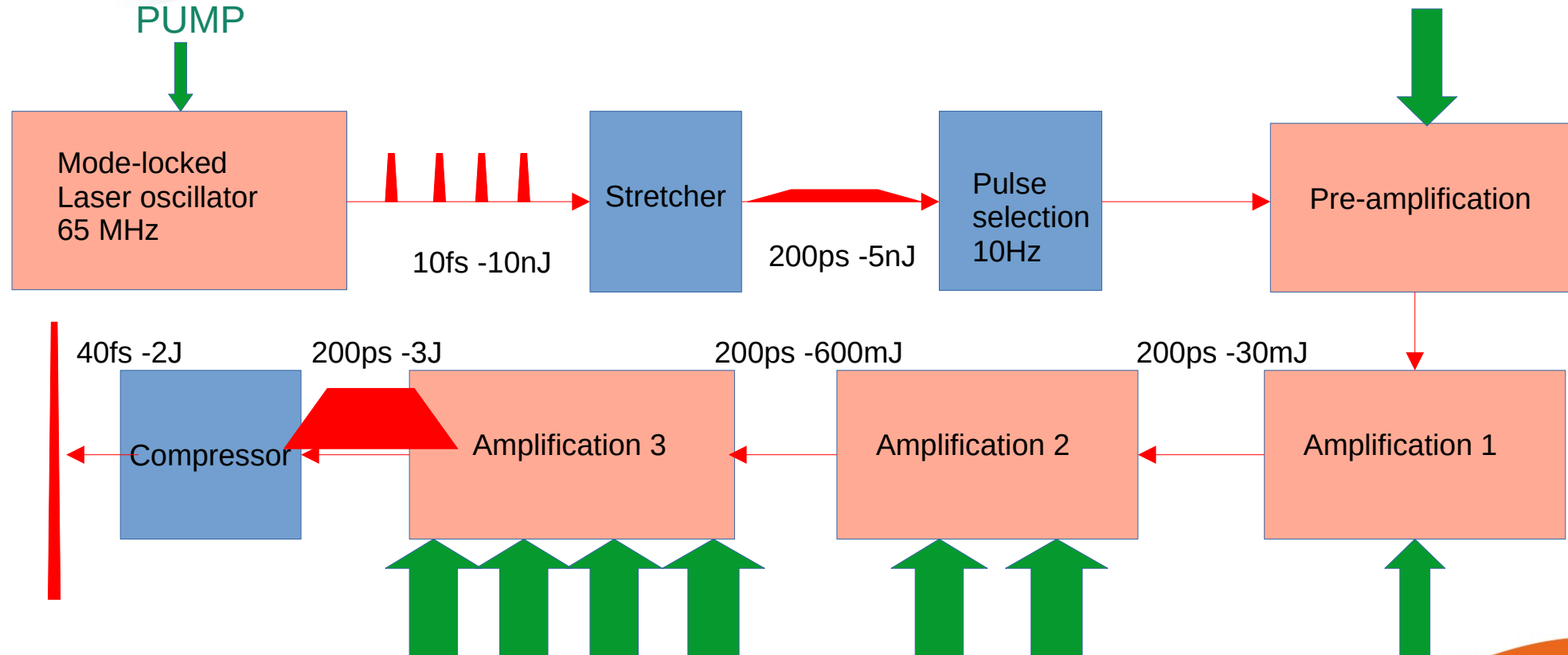
A chirped pulse amplification (CPA) laser chain



Mourou, Strickland Nobel prize 2018

Source : LLE Rochester

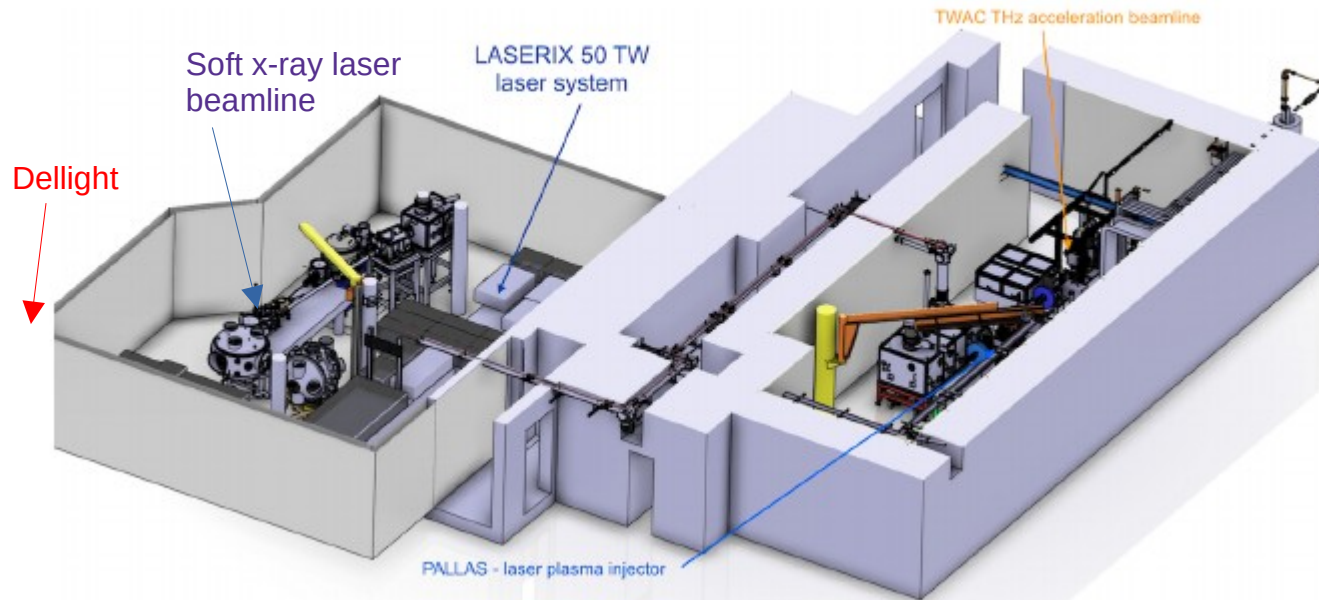
Chirped Pulse Amplification (CPA)



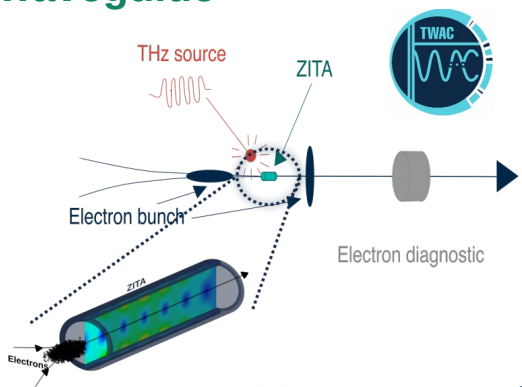
Chirped Pulse Amplification (CPA)



A versatile tool, hosting 4 main projects



THz electron acceleration in a dielectric coated waveguide



Laser Plasma Wakefield Acceleration

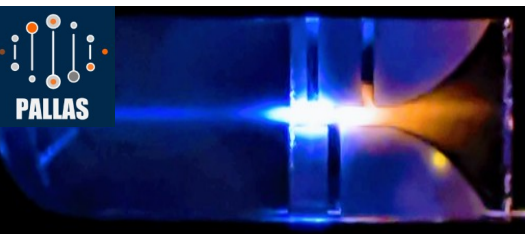


Photo Injector
electron source

RF timing

LASERIX

Practicals

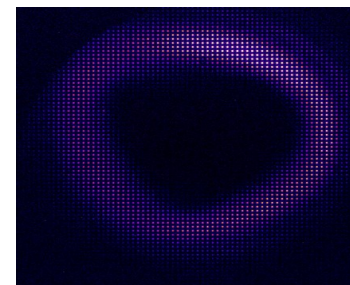
M2 Grands Instruments
Erasmus Mundus LASCALA

QED fundamental test

Deflection of light by light
(DELLIGHT)

Coherent EUV sources

Structured HHG in gas
Plasma-based x-ray laser



HIGHLIGHTS

LASERIX facility:

X-ray laser:

DELLIGHT:

A brief introduction

Coherent x-ray sources

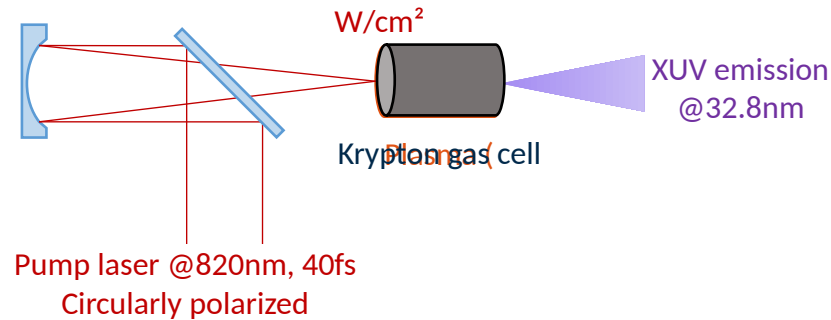
Deflection of light by light in vacuum



What is a plasma-based XUV laser?

Optical Field Ionization (OFI)^[9] in Krypton (Salle Jaune, LOA).

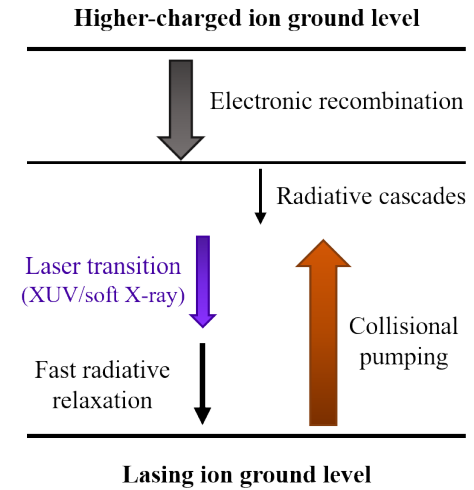
Fig.1: Set-up for generating a Ni-like XUV laser^[10]



Transition at pumped with the electron/ion **collisions** of the plasma

Lasing ion Kr^{8+}

Fig.2: Schematic of the collisional pumping



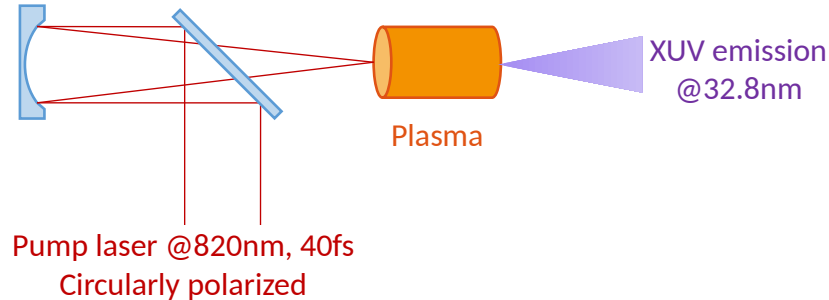
[9] Sebban et al., Phys. Rev. Lett. 86 (2001), pp. 3004–3007. [10] Faivre et al., Nature 431.7007 (2004), pp. 426–429.



ASE soft x-ray laser

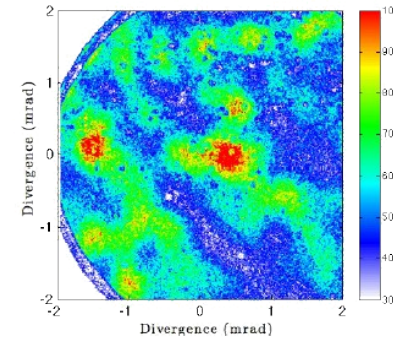
- But gain lifetime ps + low mirror reflectivity @32.8nm **no cavity**
- Works on **Amplified Spontaneous Emission**^[11] (**ASE**) : **poor spatial coherence**

Fig.1: Set-up for generating a Ni-like XUV laser^[10]



Far field = random **speckle-like** grains^[12]

Fig.3: Far field profile of a basic XUV laser beam



From Fabien Tissandier's PhD thesis

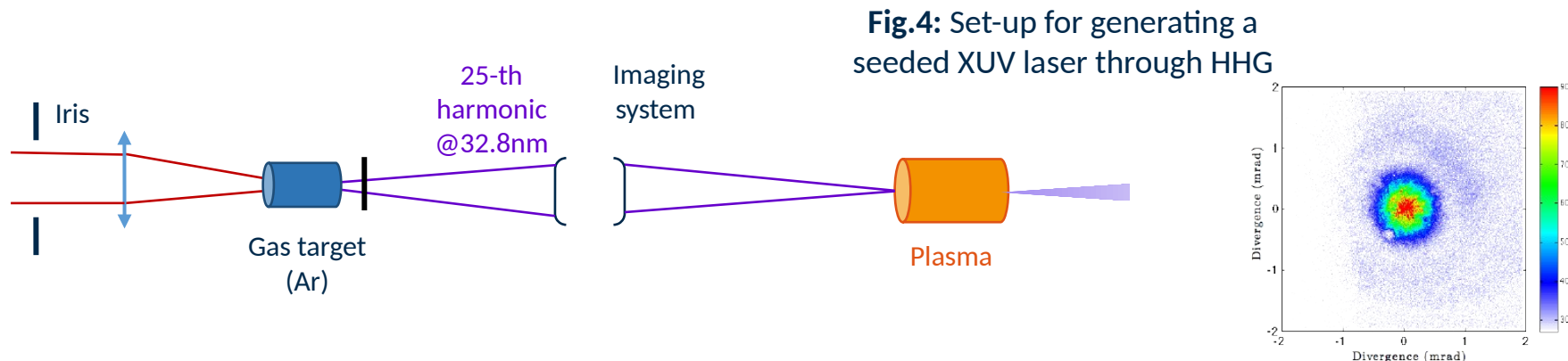
How to increase the spatial coherence?

[11] Tommasini et al., Journal of the Optical Society of America B 17 (2000), pp. 1665–1670. [12] Guilbaud et al., X-Ray Lasers 2006. Springer Netherlands, 2007, pp. 61–68.



Higher spatial coherence via the seeded regime

To increase spatial coherence: the XUV laser seeded with a Laser **High Order Harmonic beam**



- Collimated beam, **even wavefront**^[13,14], **amplification** by orders of magnitude
- **Preservation** of the seed **polarization** also demonstrated^[15]

From Fabien Tissandier's PhD thesis

Seeded XUV laser = coherent, high-energy beam

[10] Faivre et al., Nature 431.7007 (2004), pp. 426–429. [13] Jean-Philippe Goddet. “Etude et développement de sources laser XUV par injection d’harmoniques d’ordre élevé”. [14] Fabien Tissandier. “Caractérisation spatio-temporelle d’une chaîne laser à 32.8 nm par plasma laser et perspectives vers une source ultrabrève et intense”. [15] Depresseux et al., Phys. Rev. Lett. 115 (2015), p. 083901.

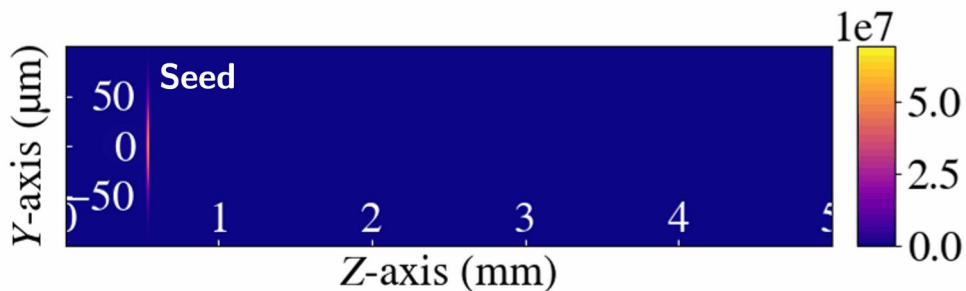


Non-adiabatic regime

Seed amplification **more complex** than usual lasers:

- Characteristic times of the medium (**500fs**) seed duration (**30fs**) **non-adiabatic amplification**
- The seed is not amplified, it triggers a coherent **wake**, modulated by **Rabi oscillations**^[16,17,18].

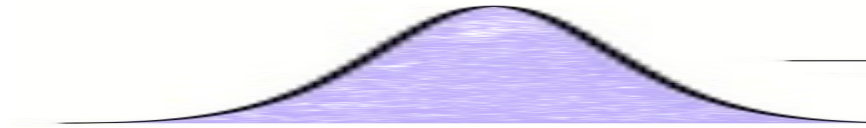
Fig.5a: Non-adiabatic amplification of a Gaussian seed for



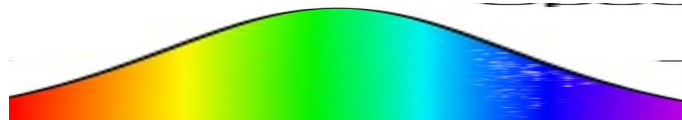
[16] Al'miev et al., Phys. Rev. Lett. 99 (2007), p. 123902. [17] Kim et al., Phys. Rev. A 80 (2009), p. 053811. [18] Oliva et al., Phys.Rev. A 84 (2011), p. 013811.

How to synthesize a very short pulse ?

1. Start with a long quasi monochromatic pulse



2. Apply a time varying phase with frequency modulation

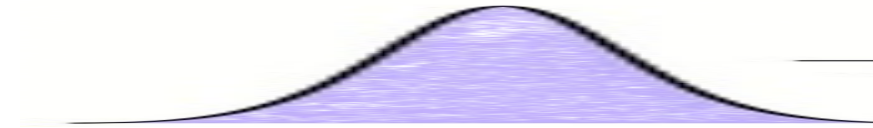


3. Send the pulse in the correct dispersive device

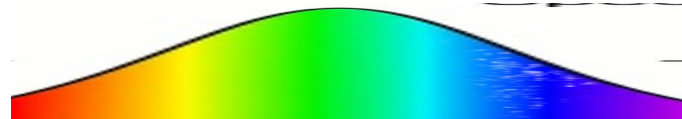


How to synthesize a very short soft x-ray pulse ?

1. Start with a long quasi monochromatic pulse



2. Apply a time varying phase with frequency modulation



3. Send the pulse in the correct dispersive device

**Seeded PLASMA BASED X-RAY
LASER**

**Laser AC Stark shift on ionic
transition**

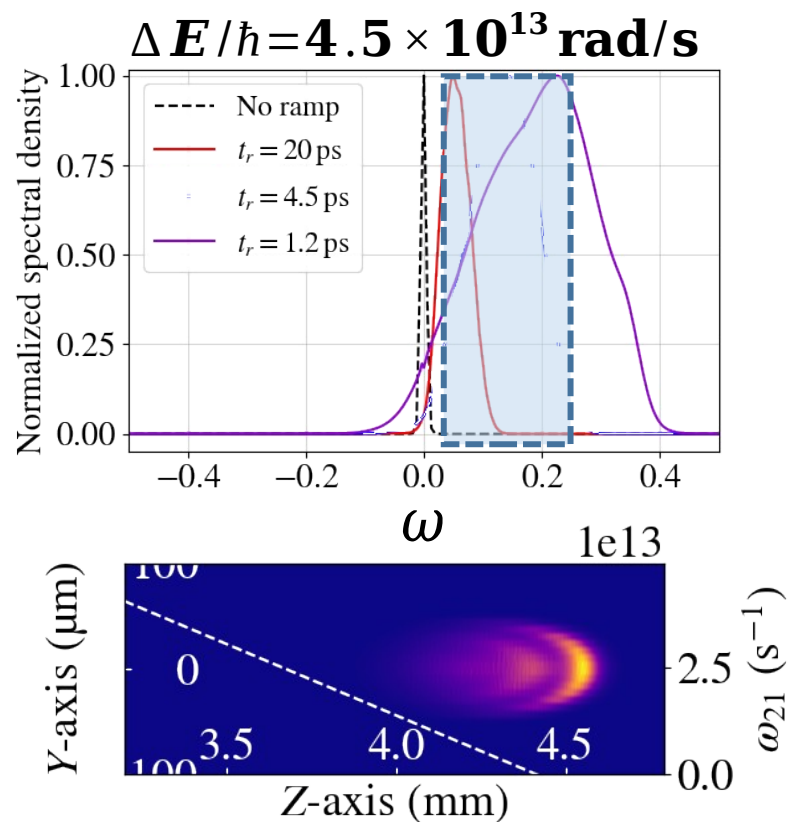


Soft x-ray diffraction gratings



Stark postcompression

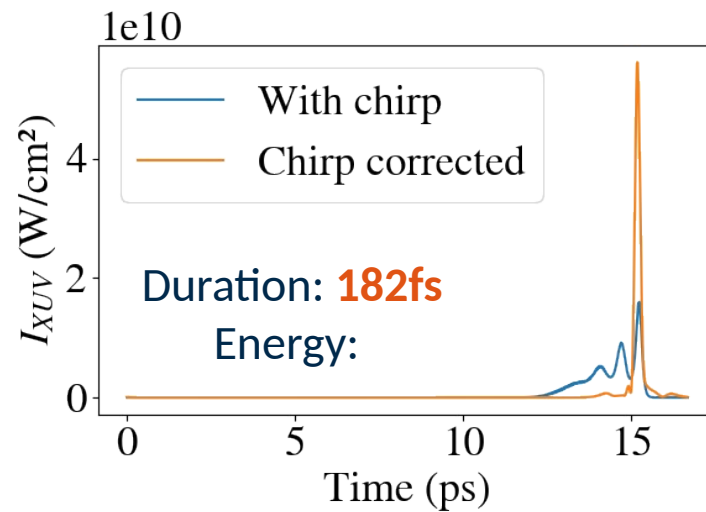
Fig.34: Perturbation with an intermediate ramp



➡

If chirp corrected

Fig.35: Pulse profile after broadening with and without chirp



HIGHLIGHTS

LASERIX facility:

X-ray laser:

DELLIGHT:

A brief introduction

Coherent x-ray sources

Deflection of light by light in vacuum

➤ **The classical electromagnetic vacuum** is described as a linear and unalterable optical medium:

- ✓ Maxwell's equations are linear

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} \end{cases} \quad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

- ✓ c , ε_0 et μ_0 are universal constants, unaffected by any perturbation or external fields
- ✓ Interaction between two different e.m. fields is impossible in classical vacuum

➤ **Heisenberg & Euler (1936), Schwinger (QED, 1951)** : Nonlinearity in vacuum induced by the coupling of the e.m. fields with the e^+/e^- virtual pairs in vacuum

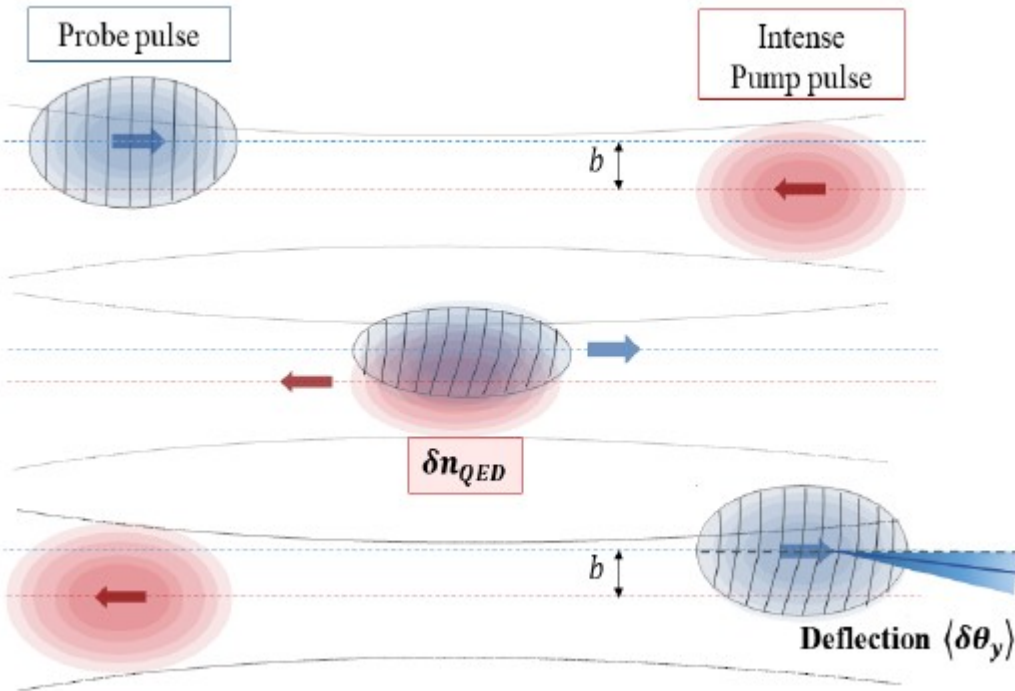
- ✓ Interaction between two different e.m. fields becomes possible
- ✓ Maxwell's equations are not linear anymore

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}(E^2, B^2) \\ \mathbf{B} = \mu_0 \mathbf{H} + \mathbf{M}(E^2, B^2) \end{cases} \quad \text{with} \quad \begin{cases} \mathbf{P} = \xi \varepsilon_0^2 [(E^2 - c^2 B^2) \mathbf{E} + 7c^2 (\mathbf{E} \cdot \mathbf{B}) \mathbf{B}] \\ \mathbf{M} = -\xi \varepsilon_0^2 c^2 [(E^2 - c^2 B^2) \mathbf{B} - 7(\mathbf{E} \cdot \mathbf{B}) \mathbf{E}] \end{cases}$$

$$\xi^{-1} = \frac{45 m_e^4 c^5}{2 \alpha^2 \hbar^3} \approx 3 \cdot 10^{29} \text{ J/m}^3$$

➡ ***In specific conditions, c can be modified by an EM field***

DeLLight Experiment : Deflection of light by light



LASERIX Pump specifications

- ✓ Energy ≈ 2.5 Joules
- ✓ Duration ≈ 50 fs
- ✓ Waist @ focus $\approx 5 \mu\text{m}$

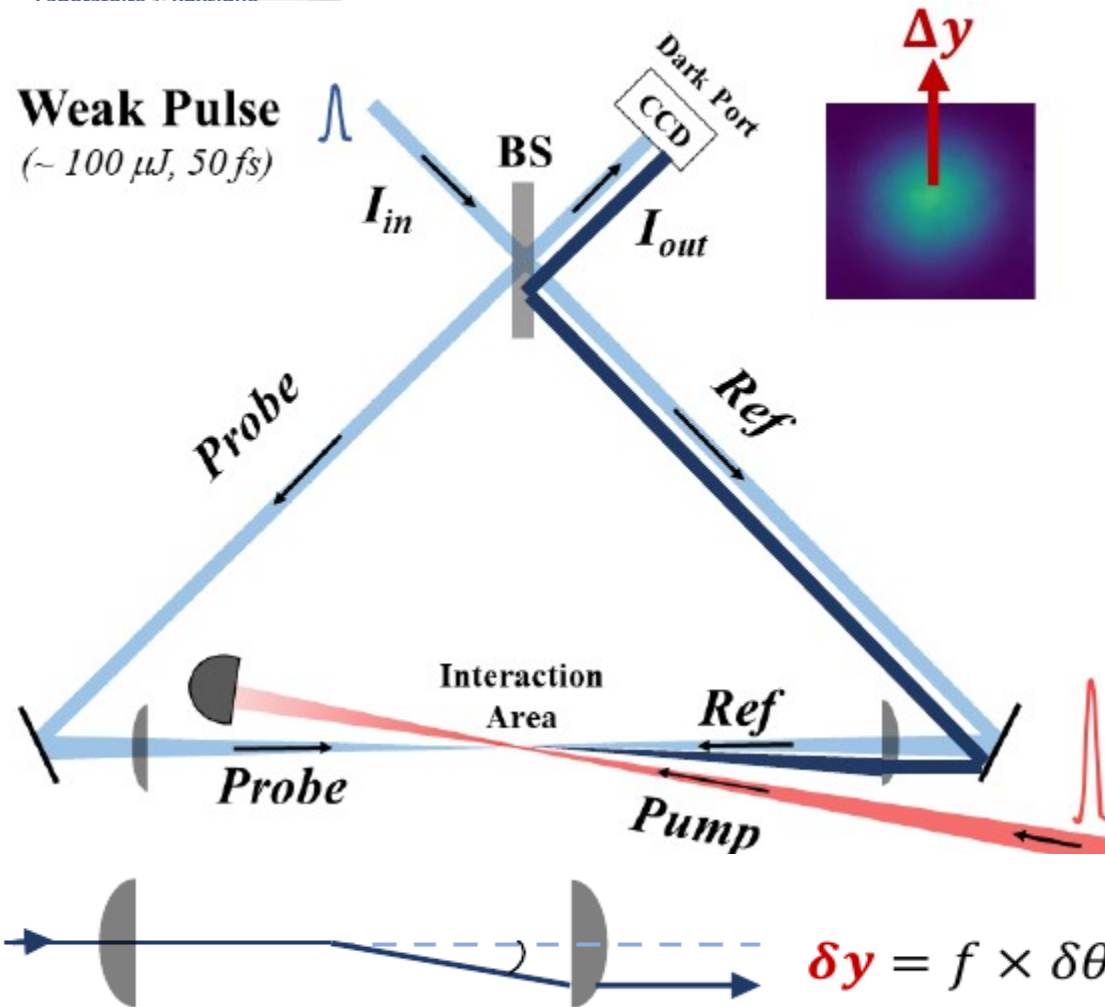
$$\Rightarrow B \sim 10^5 \text{ T} \quad E \sim 3 \times 10^{13} \text{ V/m}$$


 $\delta n \sim 3 \times 10^{-13}$
 $\delta\theta \sim 0.1 \text{ prad}$

E.B terms : Kerr-like effect in pump probe configuration

$$n_2 = n_{2,\text{max}} r_{\text{pol}} \cos^4\left(\frac{\theta_{\text{ilt}}}{2}\right). \quad n_{2,\text{max}} = n_{2,\text{QED}} = \frac{56}{45} \alpha^2 \frac{\hbar^3}{m_e^4 c^6} = 1.55 \times 10^{-33} \text{ cm}^2/\text{W},$$

Refraction measured with a Sagnac interferometer



- δy = Direct vertical shift of the probe inside the Sagnac
- Δy = Vertical shift of the interference intensity profile is **amplified** in the dark output (*Weak Value Amplification*)

$$\Rightarrow \Delta y = \mathcal{A} \times \delta y$$

- Amplification factor $\mathcal{A} = \pm \frac{1}{2\sqrt{\mathcal{F}}}$

$$\mathcal{F} = \frac{I_{out}}{I_{in}} = \text{Extinction Factor}$$

- « UP-DOWN » measurements @ 5 Hz

DeLLight Experiment : Expected sensitivity

Expected signal:

$$\Delta y_{QED} = 3 \times 10^{-12} \times \frac{E(\text{Joule}) \times f(m)}{(w_0^2 + W_0^2 (\mu\text{m}))^{3/2} \times \sqrt{\mathcal{F}/10^{-5}}} \quad (\text{with } \theta_{\text{tilt}} \sim 15^\circ)$$

- ✓ Energy $E = 2.5 \text{ J}$ @ **LASERIX** (10 Hz repetition)
- ✓ Extinction $\mathcal{F} = 10^{-5}$ ($\mathcal{A} = 100$) (Achieved with prototype)
- ✓ Waist at focus $w_0 = W_0 = 5 \mu\text{m}$



$$\Delta y(\text{Up} - \text{Down}) = 2 \times \Delta y_{QED} \sim 10 \text{ pm}$$

- ✓ Spatial resolution $\sigma_y = 15 \text{ nm}$ (CCD shot noise resolution)



1 sigma sensitivity within ~ **5 days** with **LASERIX**



$$\frac{1}{\sqrt{N}}$$

- ✓ With **KALDERA** laser (under development @ DESY): 3 J @ 1 kHz

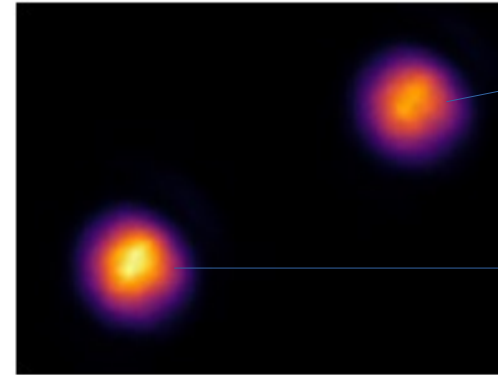
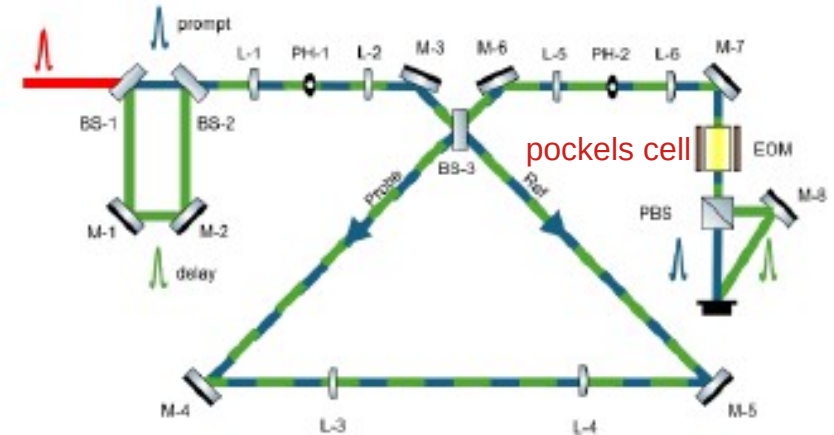


1 sigma sensitivity within ~ **1 hour** with **KALDERA**

$$T_{\text{obs}} \propto \frac{1}{E^2 \times f_{\text{rep}}}$$

Suppression of the interferometric phase noise

Beam pointing fluctuations and interferometric phase noise are suppressed by measuring simultaneously (200MHz) the interferometric signal of a delayed 5ns pulse, used as reference

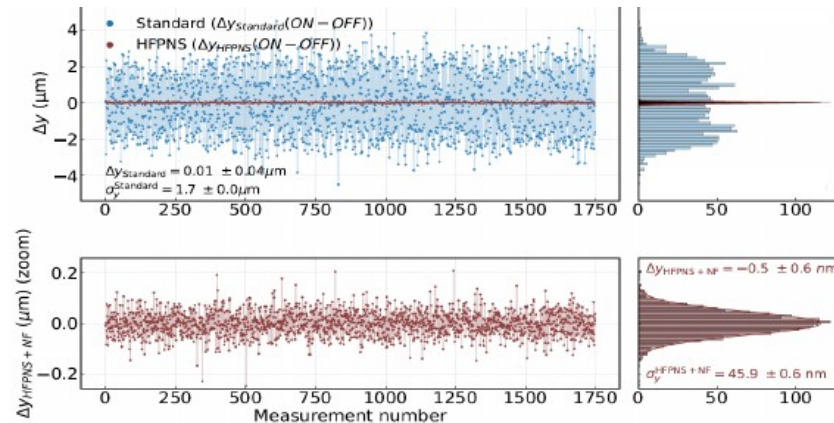


Prompt

Delayed

Motion correlated

Post correction of
signal



Without correction: $\sigma_y \approx 2 \mu\text{m}$

After HFPNS correction: $\sigma_y \approx 46 \text{ nm}$
Expected Quantum Noise: $\sigma_y = 38 \text{ nm}$

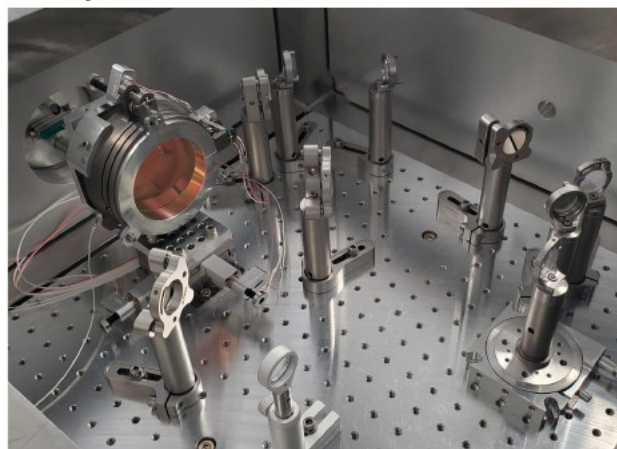
arXiv:2602.10896

End 2024: Proof of concept by measuring Kerr effect in air at $E_{\text{pump}} \sim \mu\text{J}$

A. Kraych et al, Physical Review A 109.5 (2024)

Mid 2025: High Frequency Phase Noise suppression demonstration (A Aras PhD Thesis) *arXiv:2602.10896*

End 2026: commissioning of setup with intense pulse in vacuum



2027: Beam focussing and overlap

2028: Dedicated runs for background measurement

2029: Delight QED measurements

CONCLUSION

- Laserix : a versatile tool, covering a large variety of topics
- A strong effort on diagnostics, laser metrology and stabilisation (including machine learning)
- Synergie with emerging projects (eupraxia, LAPLACE, Attolab...)

THANK YOU !

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