Sources of femtosecond X-rays based on Laser Plasma Accelerators

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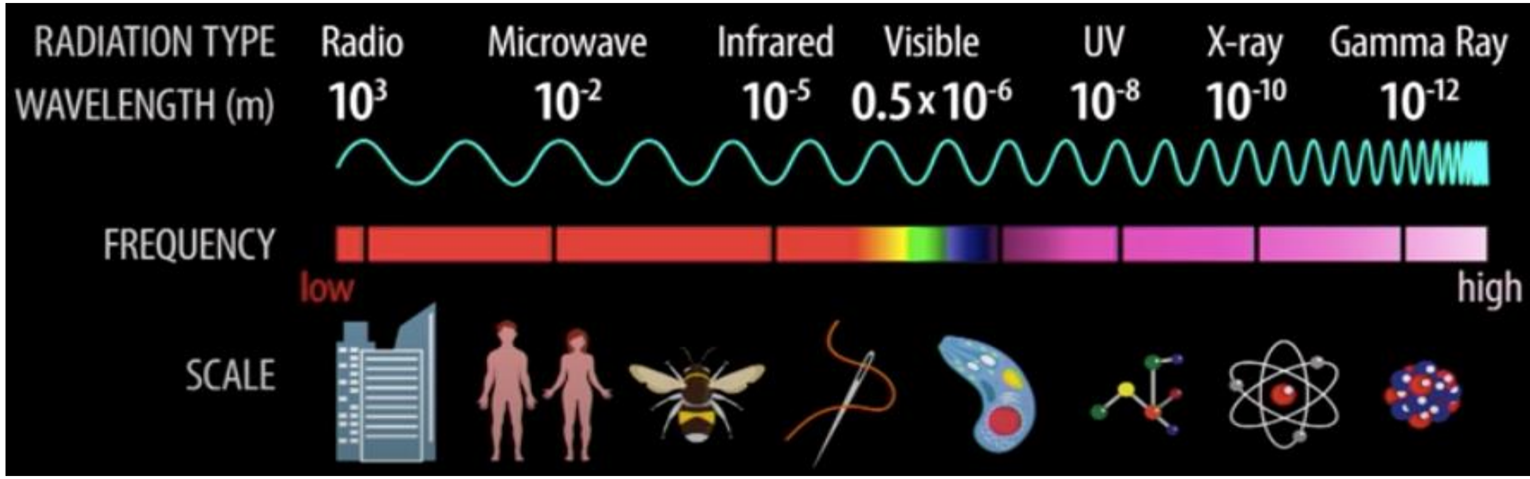
Motivation

X-ray at a "nutshell"

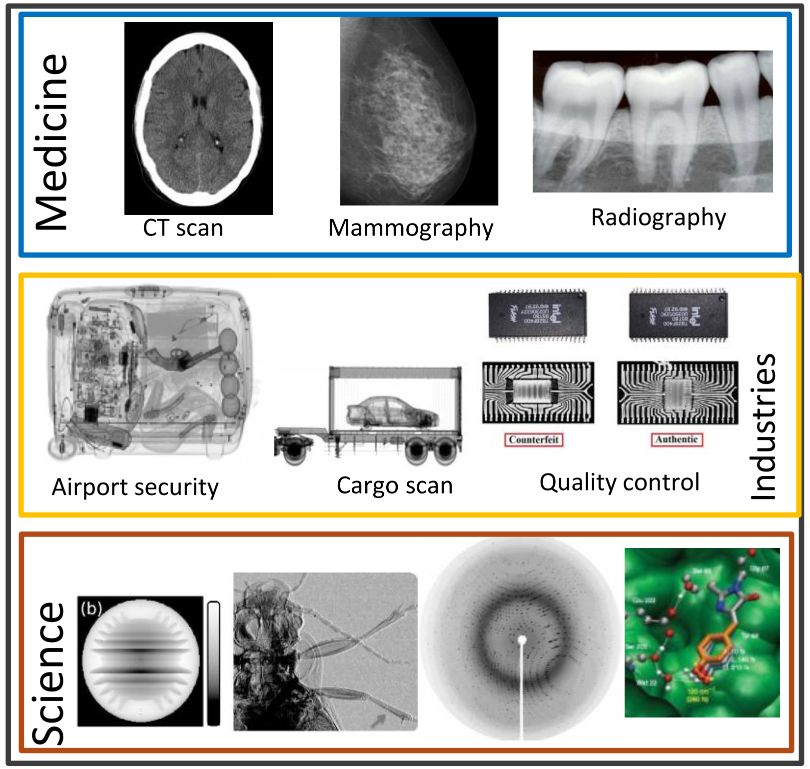


- EM-radiation in above keV range (< 1.3 nm),

  - Wavelength comparable to distance between atoms

- X-rays were discovered in 1895 by **Röntgen.** First medical radiography 1896
- Low absorption: X-ray can propagate through matter
- Widely used in science, industry, & medicine
- Very wide range of applications

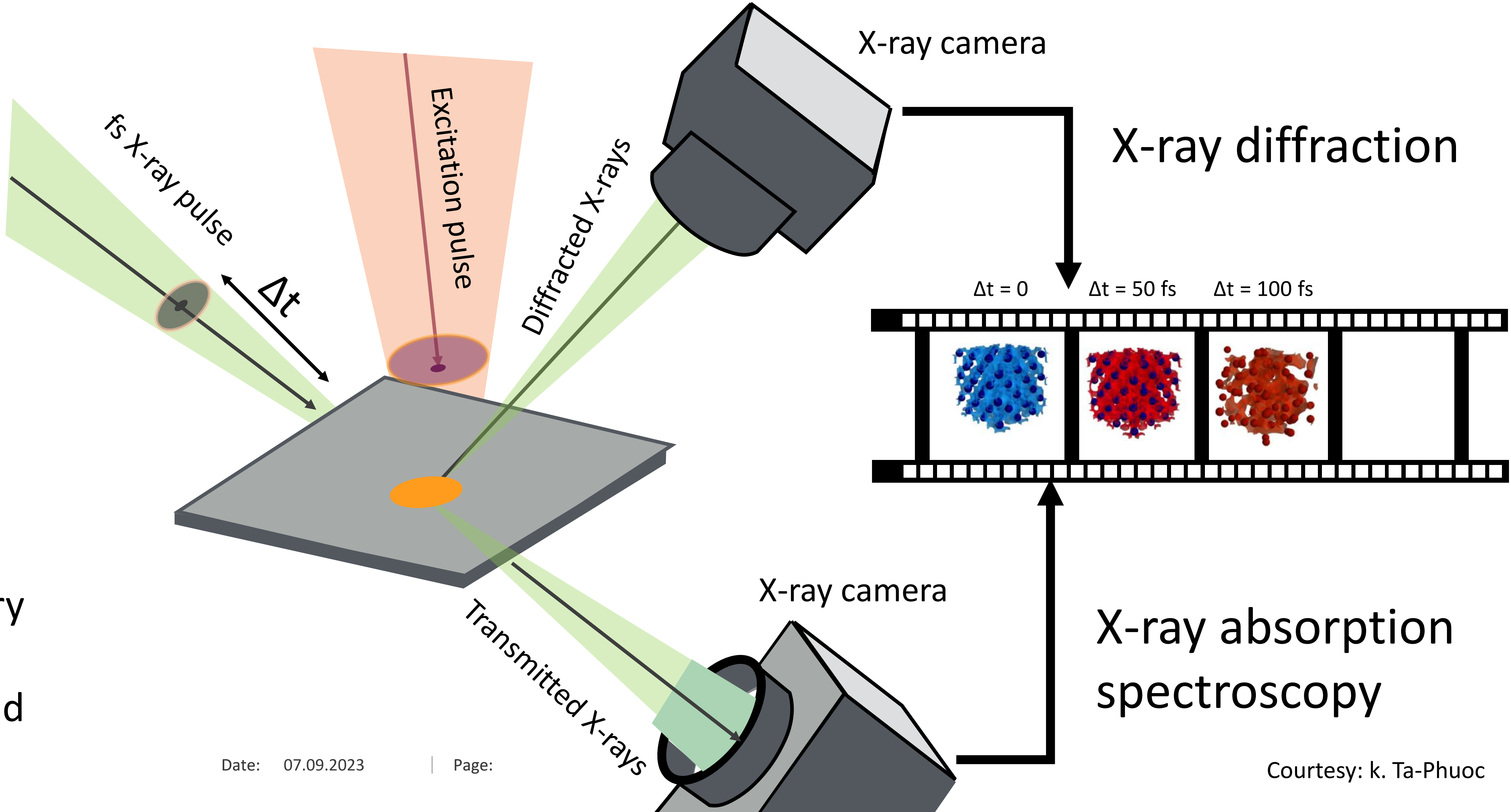
  Most applications rely on absorption properties



With "ultrashort" X-ray source

- Study nature in **smaller spatial** and **shorter time** scales
- **High temporal resolution** in pump-probe experiments

X-rays for fundamental Science: Atomic & electronic structures



Applications:

- Physics
- Chemistry
- Biology
- WDM and more…

Courtesy: k. Ta-Phuoc

Motivation

Needs for short “bright” X-ray pulses

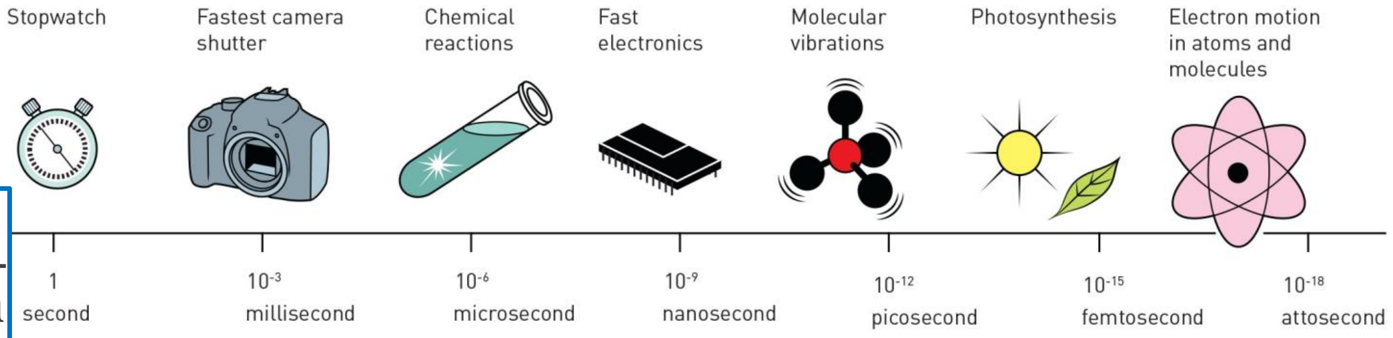
$$\text{Brightness} = \frac{\text{Photons}}{\text{mm}^2 \times \text{mrad}^2 \times \text{s} \times 0.1\%\ \text{bandwidth}}$$

High flux- high SNR or high magnification

Small source size - high resolution lens-less imaging

Look at ultra-fast processes

Important for structural studies (diffraction, scattering)



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Synchrotron (> 10 ps)

X-ray Free electron laser (>10 fs)

- Very bright, large-scale (expensive) and limited access
- Difficult to synchronize with pump laser pulse

Bright source →

- Many photons
- Small bandwidth
- Low divergence
- Small source size
- Short duration

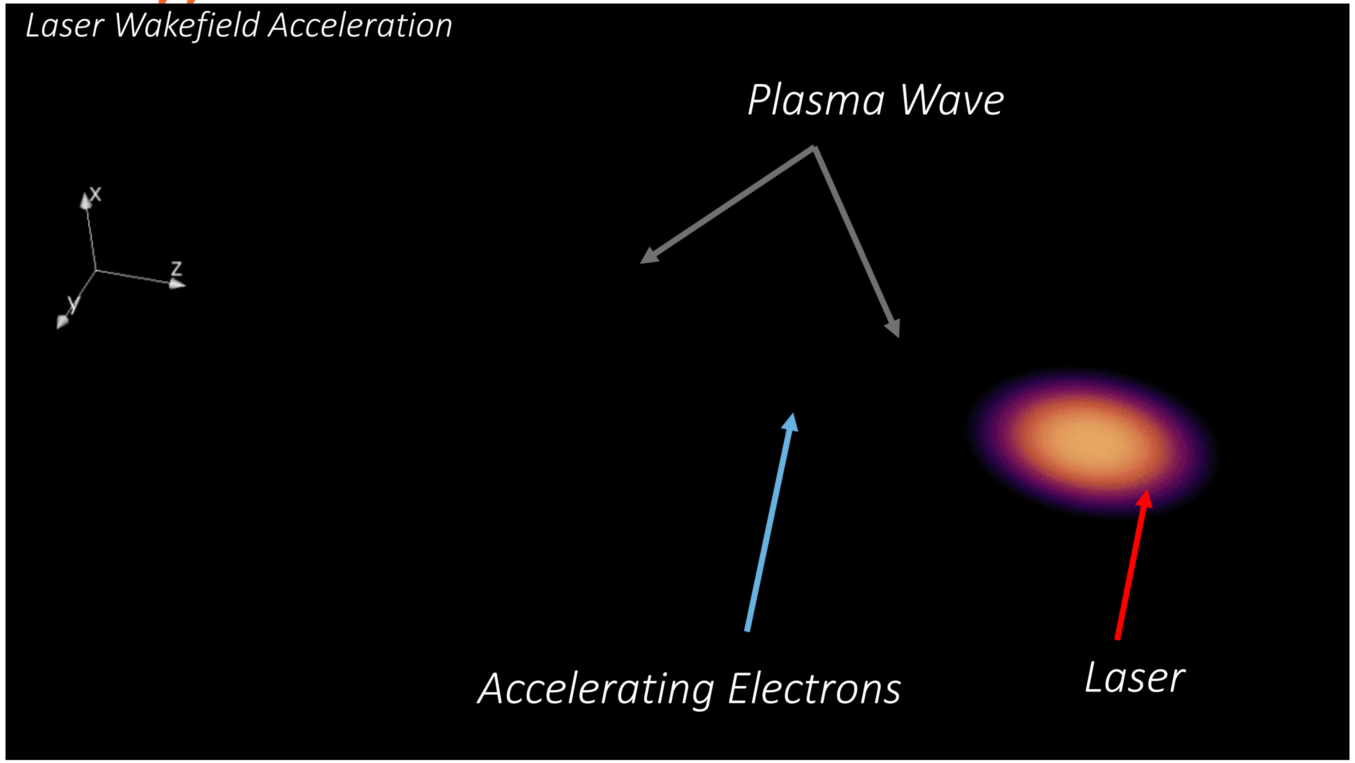
} laser based X-ray sources

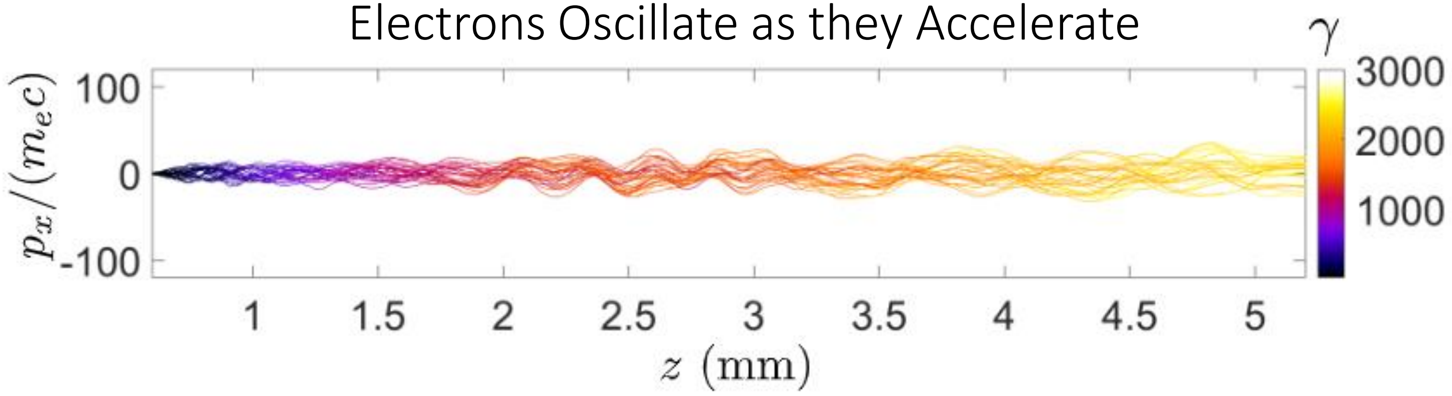
Laser-driven X-ray sources at ELI beamlines facility

- High-order harmonic generation from gas
- Plasma X-ray sources (PXS)
- **Sources based on laser wakefield electron acceleration (LWFA)**
    - Betatron radiation
    - Thomson Scattering/Inverse Compton scattering (ICS)
    - Laser-driven Undulator source (LUIS)

Talk by J. Andreasson

Laser plasma accelerator based Betatron X-ray source





Short laser pulse with relativistic intensity ($I > 10^{18}$ Wcm^{-2}) interacts with underdense plasma

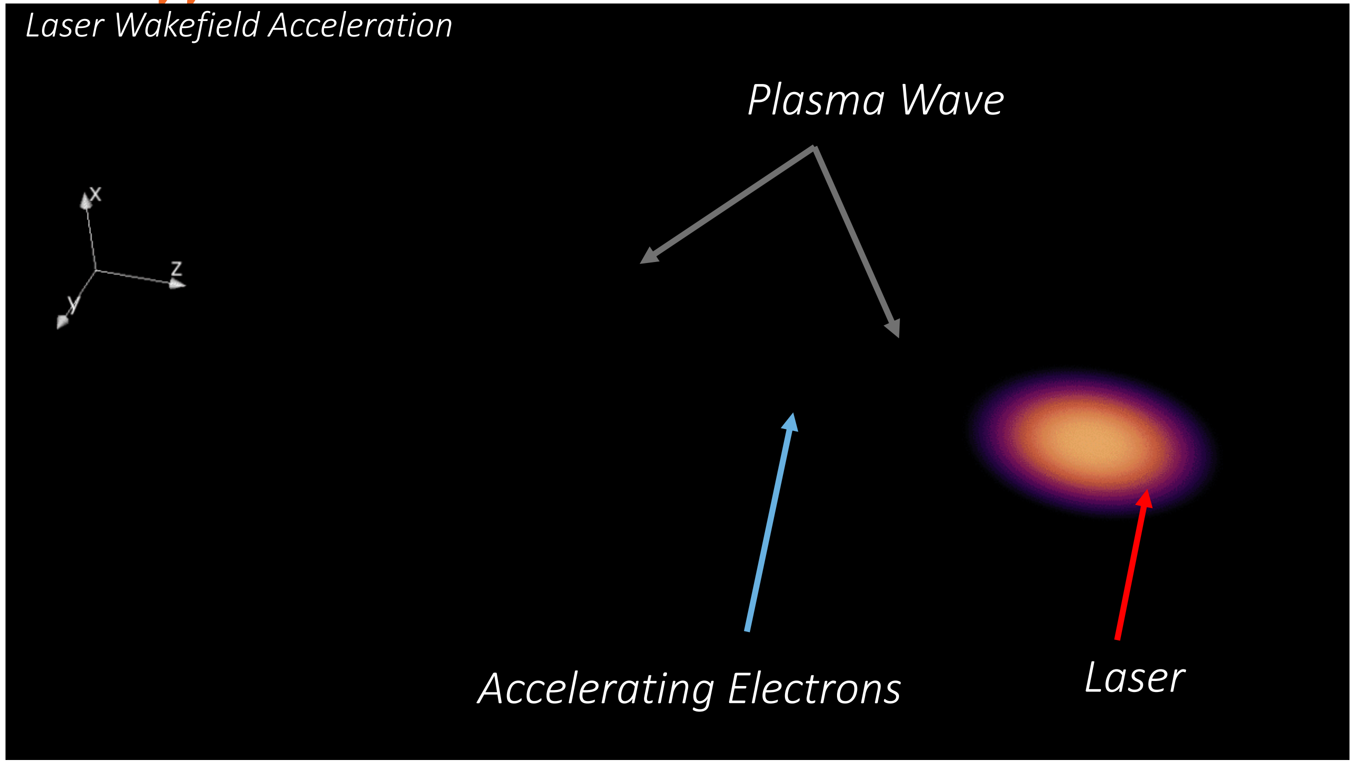
Radiated energy — Velocity — Acceleration — Position

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} e^{i\omega[t-\vec{n}.\vec{r}(t)/c]}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\,.\,\vec{n})^2}dt\right|^2$$

- Acceleration is necessary to produce radiation.
- Transverse acceleration is more efficient
- Radiation is emitted in the direction of the e^- velocity
- Relativistic electrons can produce X-ray radiation even if they are not wiggled at X-ray wavelength.

T. Tajima, T., & J.M. Dawson, PRL 43(4), 267 (1979)

Laser plasma accelerator based Betatron X-ray source



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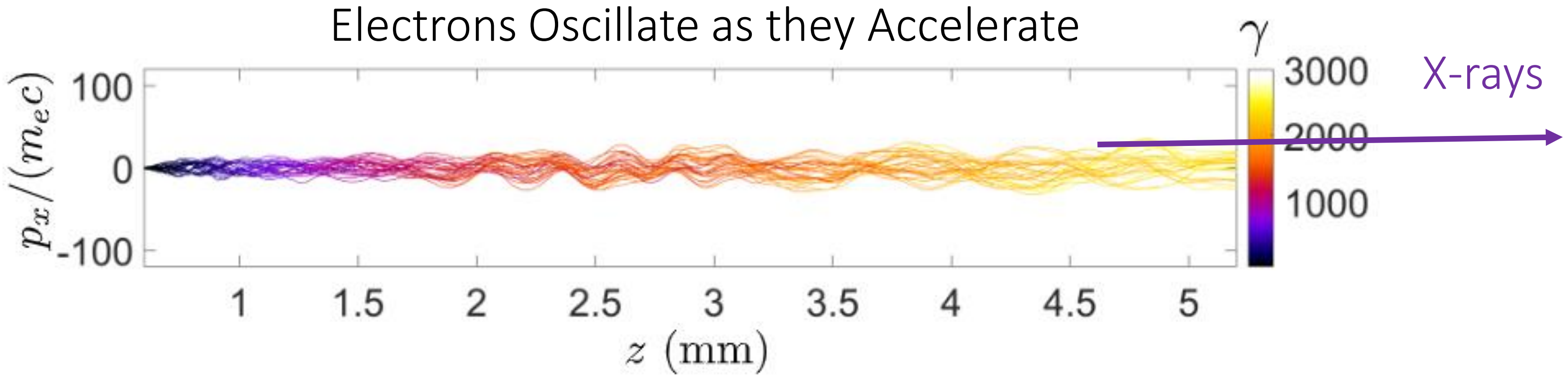
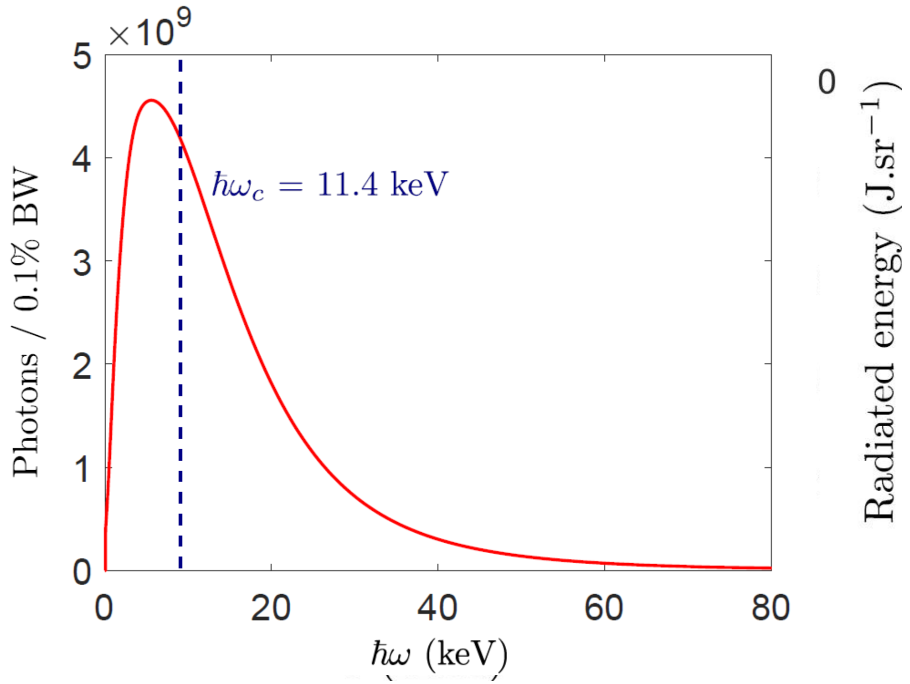
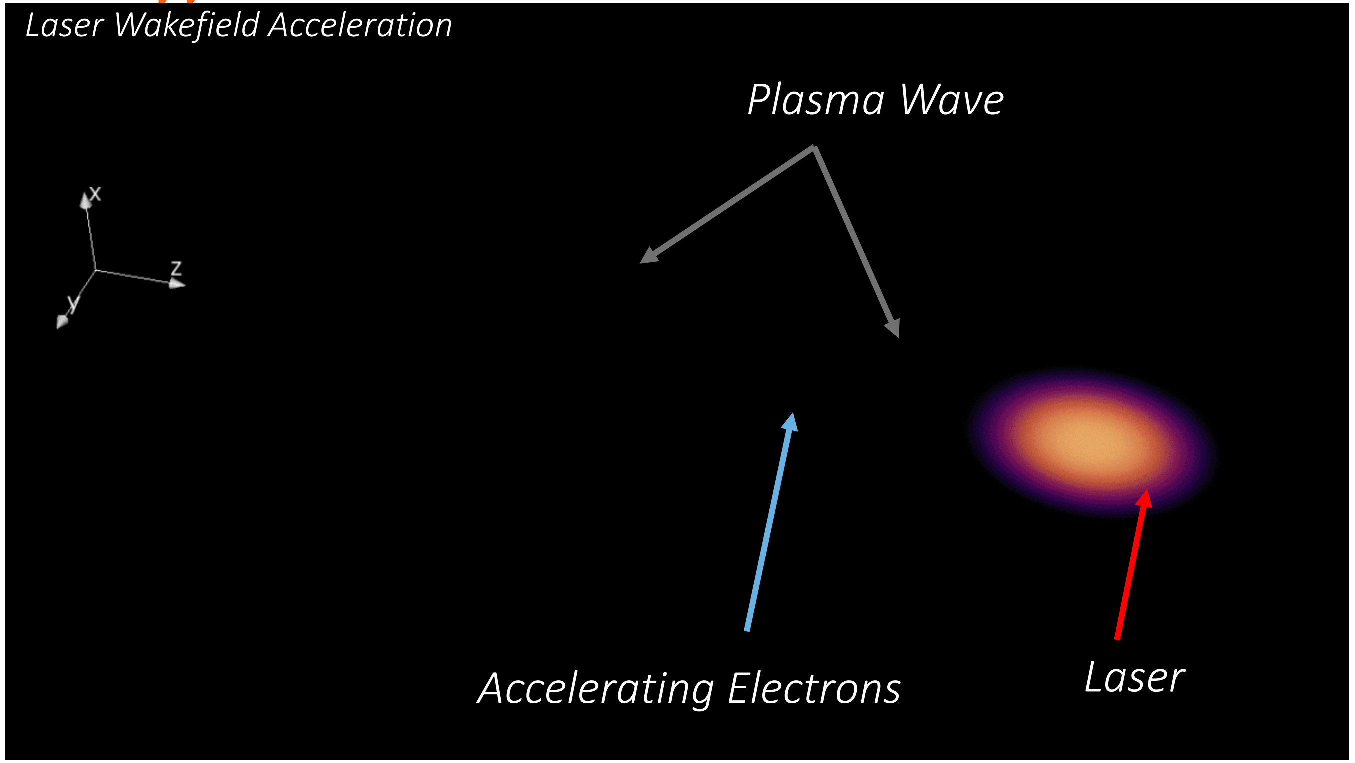
LWFA + transverse oscillations = X-rays





S. Corde et al., RMP, 85, 1 (2013)

Laser plasma accelerator based Betatron X-ray source



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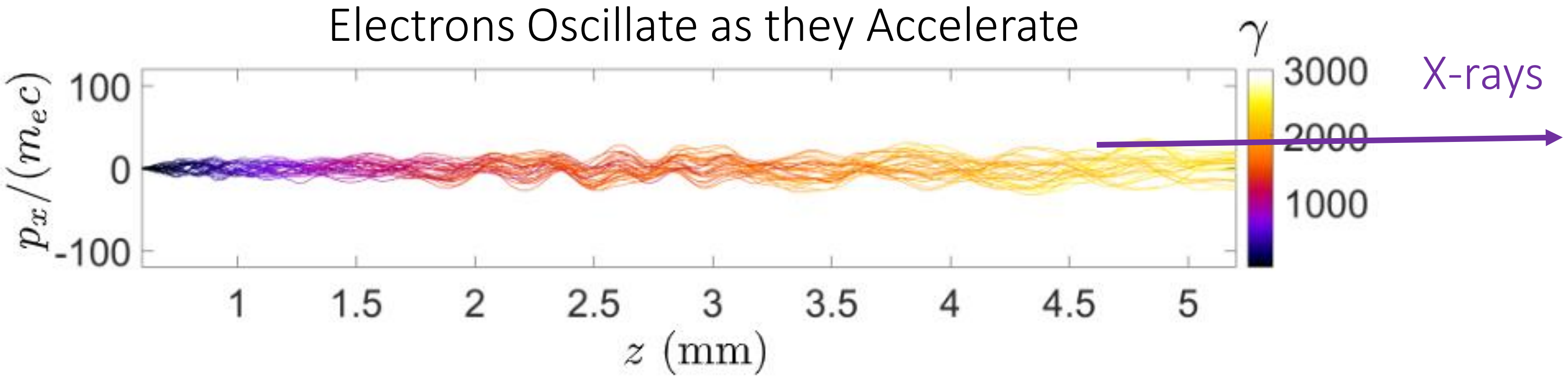

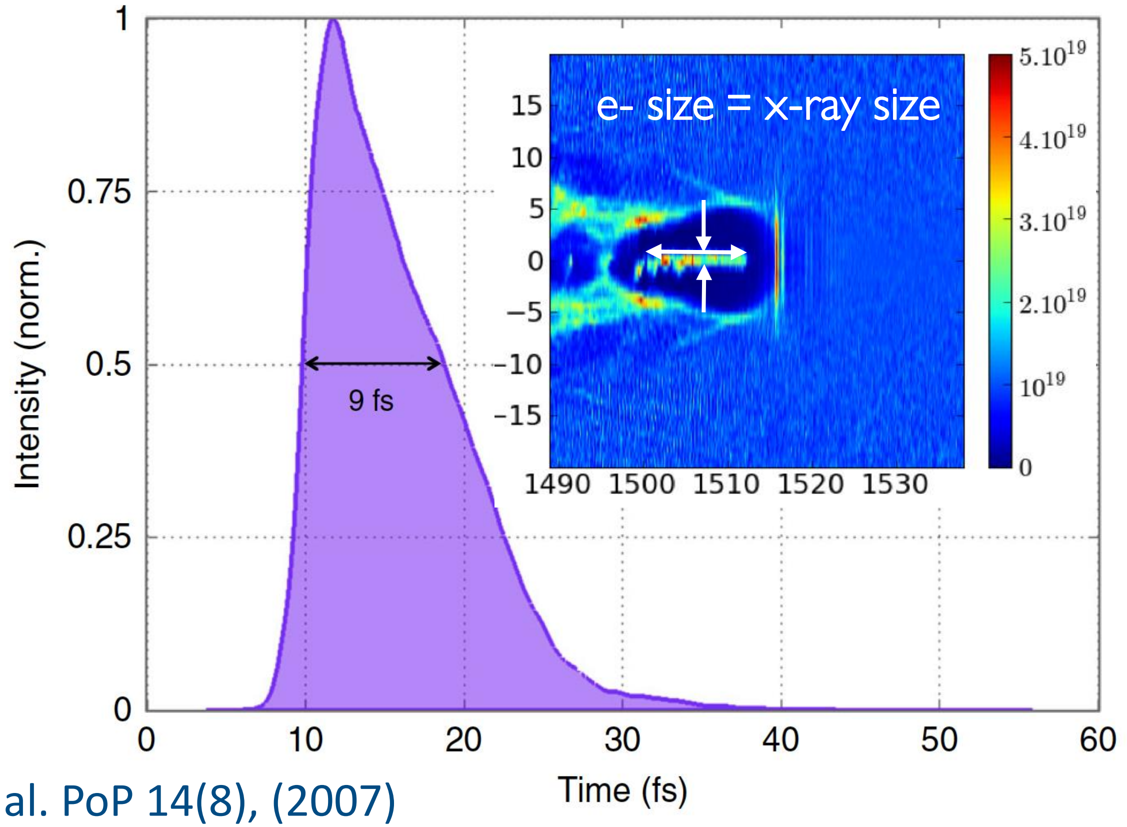

S. Corde et al., RMP, 85, 1 (2013)

K. ta-Phuoc et al. PoP 14(8), (2007)

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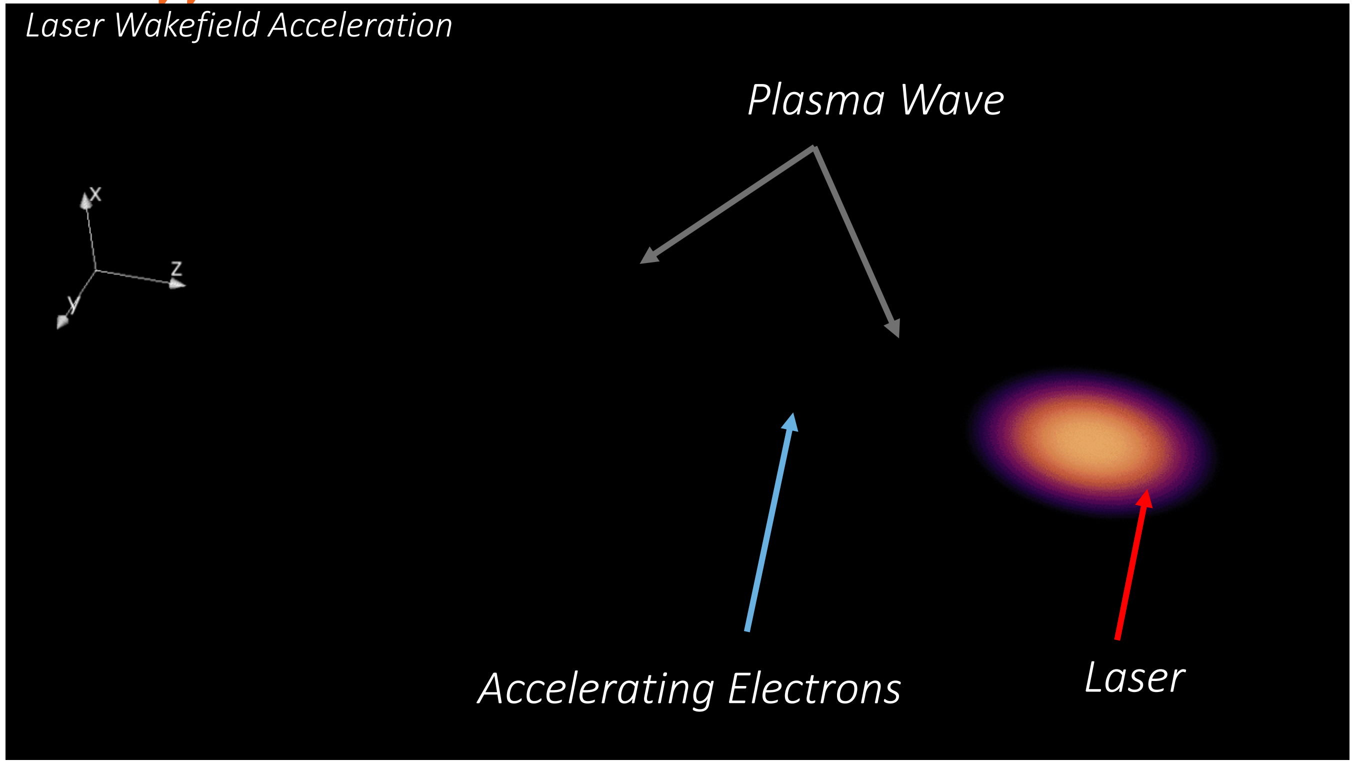
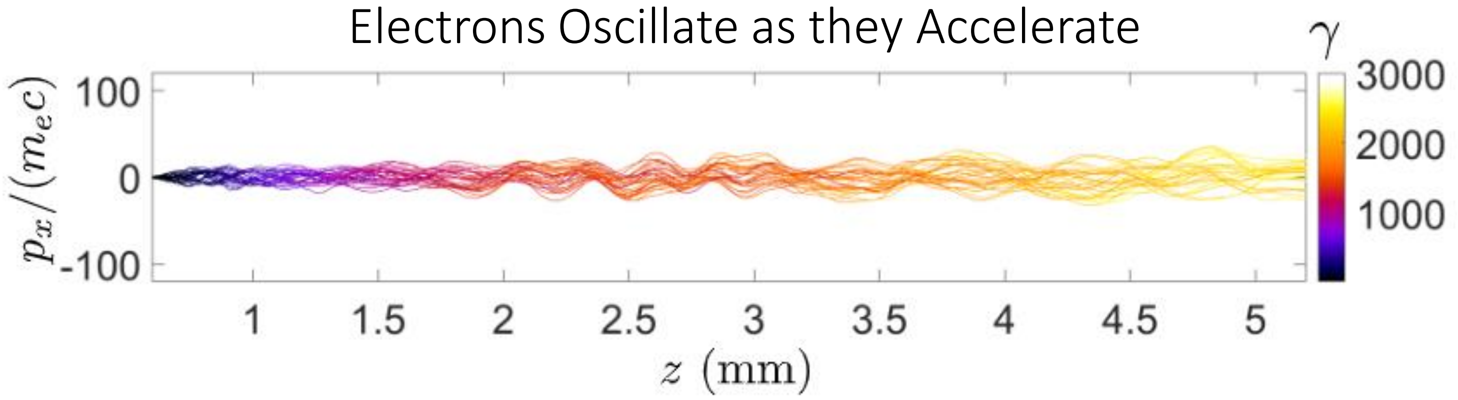




Short laser pulse with relativistic intensity (I >10^{18} Wcm^{-2}) interacts with underdense plasma

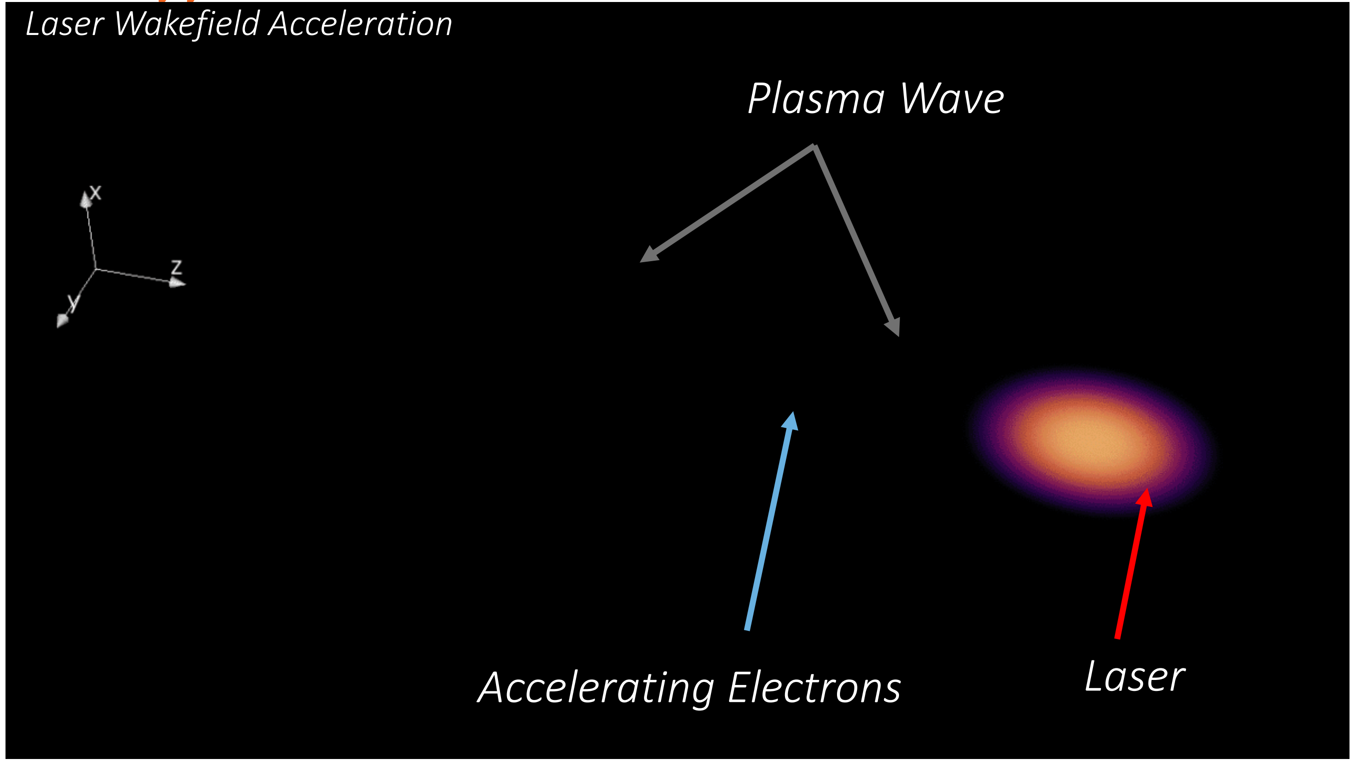
LWFA + transverse oscillations = X-rays

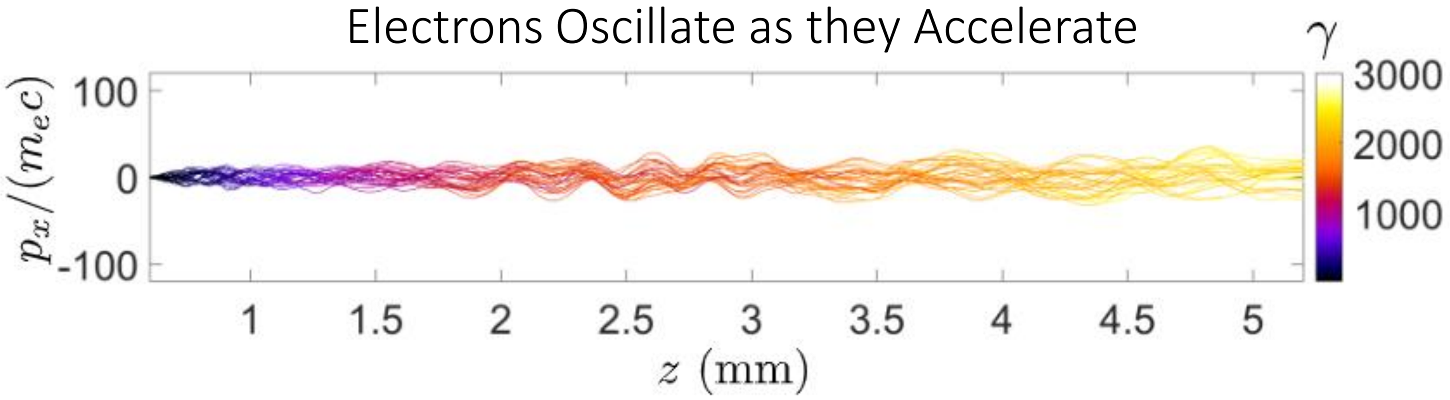
Characteristics of Betatron radiation

- Source size: few µm
- Broadband, crit. energy: 20 - 50 keV
- Number of Photons: 10^9 - 10^{11}/shot
- Beam divergence < 15 mrad
- Pulse duration ~ 10 fs

S. Corde et al., RMP, 85, 1 (2013)

Laser plasma accelerator based Betatron X-ray source





S. Corde et al., RMP, 85, 1 (2013)

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X-rays

- Critical energy:

$$E_c = \frac{3}{2} K \gamma^2 \hbar \omega_\beta \quad = 5.24 \text{ x } 10\text{-}21 * \gamma^2 * n_e \text{ [cm}^{-3}\text{] } r_b$$

- Total emitted X-ray radiation:

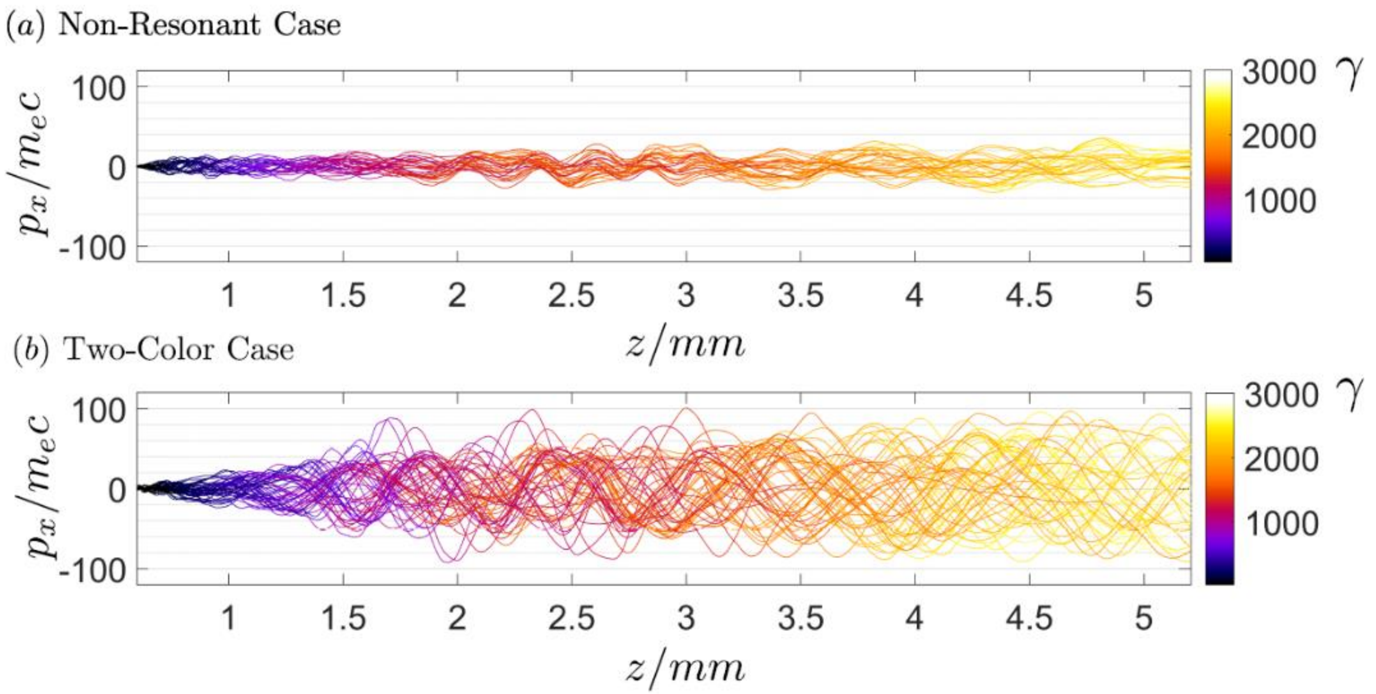
$$W_{tot} \propto N e\, \gamma^{5/2}\, r_b^2$$

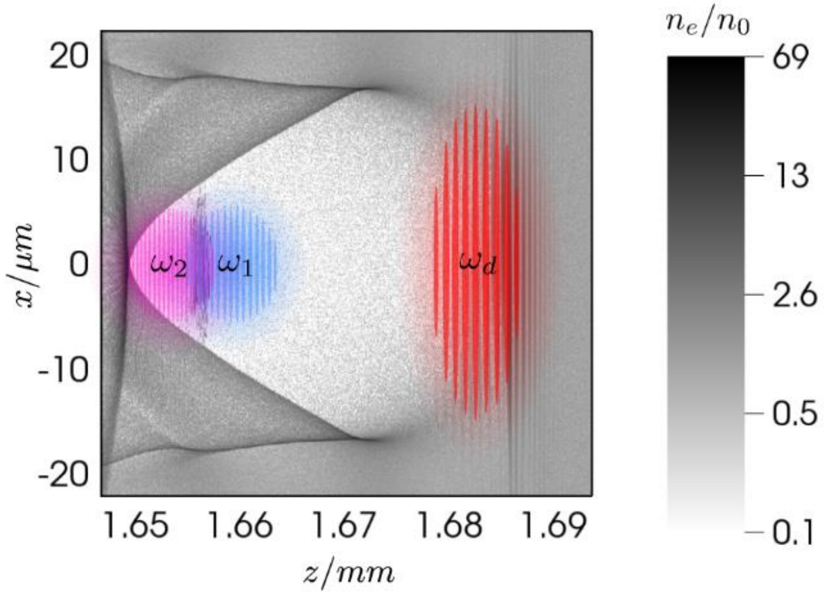
=> Higer energy and brighter radiation for higher γ and r_b

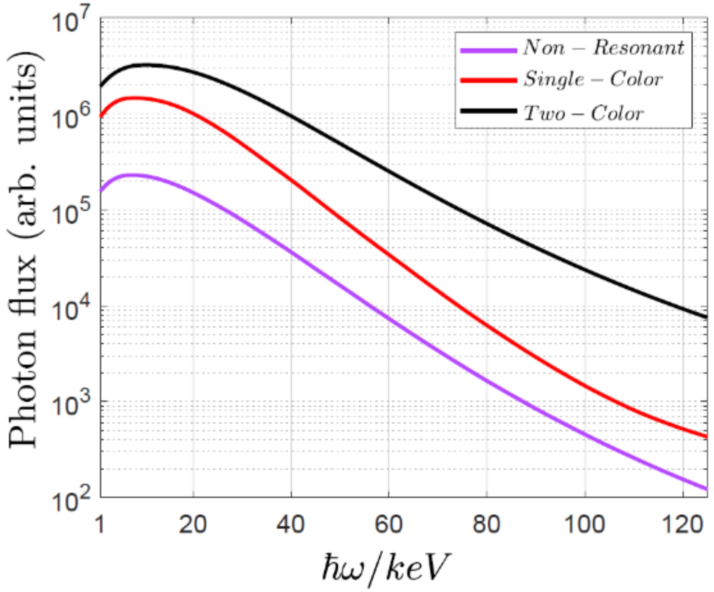
Two-color nonlinear resonances in plasma betatron

Advanced plasma Betatron

- Increase of betatron oscillation amplitudes (undulator parameter K)
- Rel. elecrons resonant with either of the fields and/or combination resonances

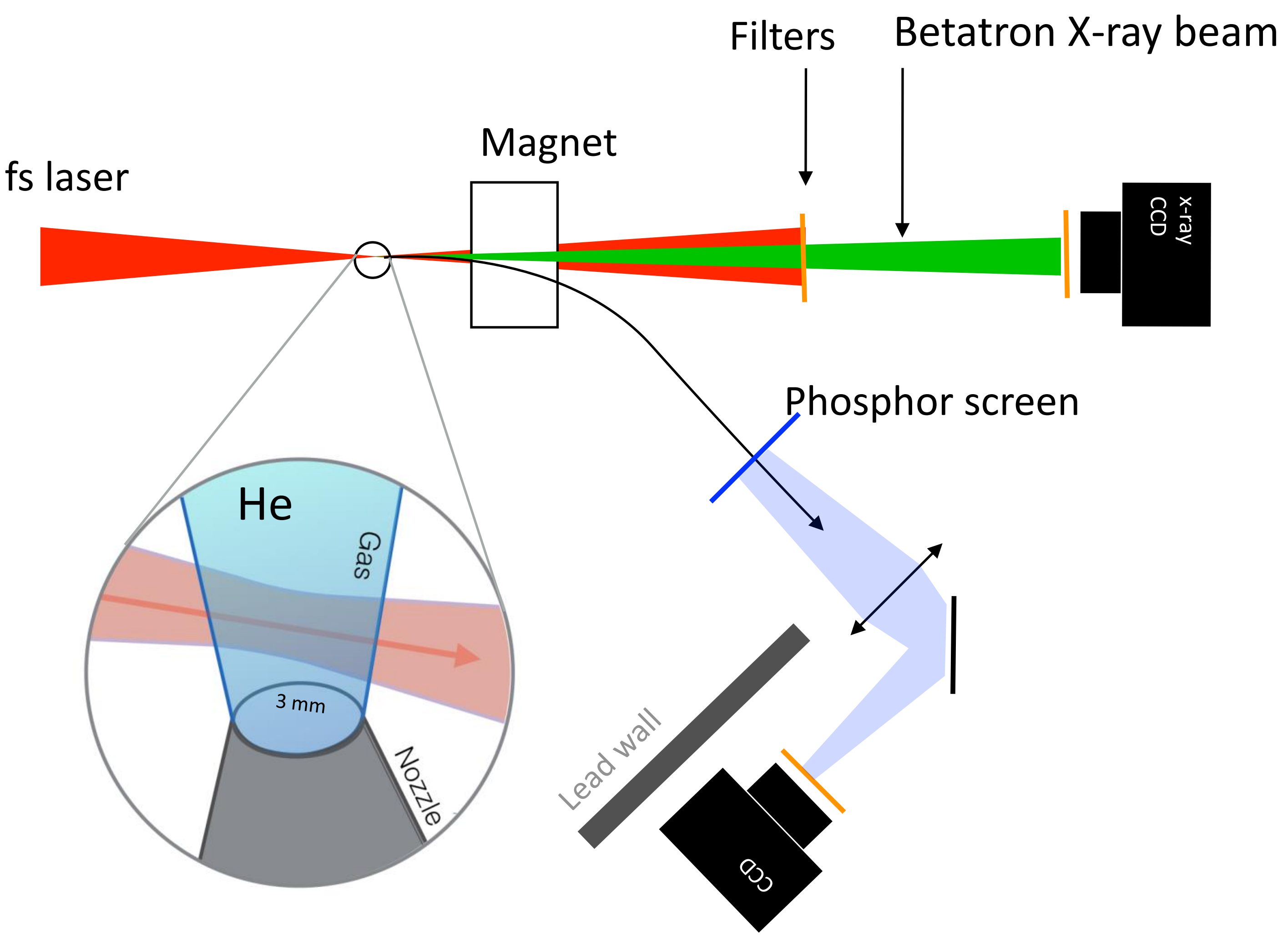






M. Lamač et al., Phys. Rev. Res. 3, 033088 (2021)

Longitudinal up-ramp + sharp transverse density gradient (up ramp + shock)



Advanced plasma Betatron

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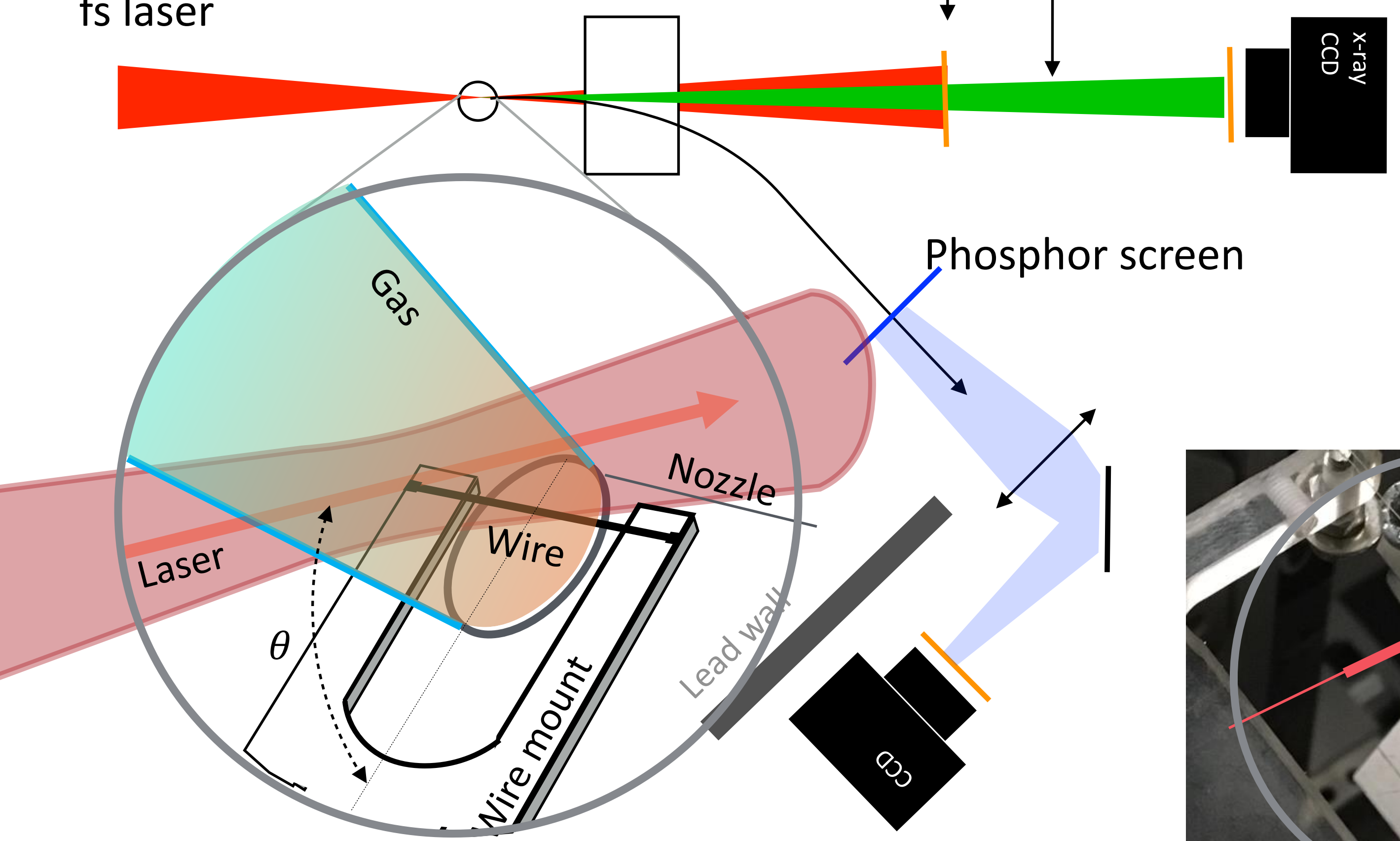
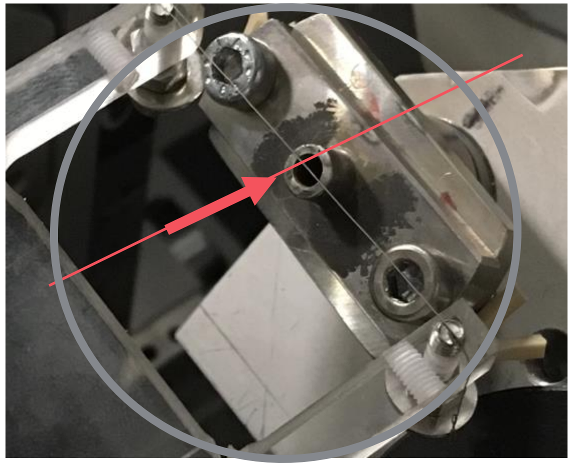
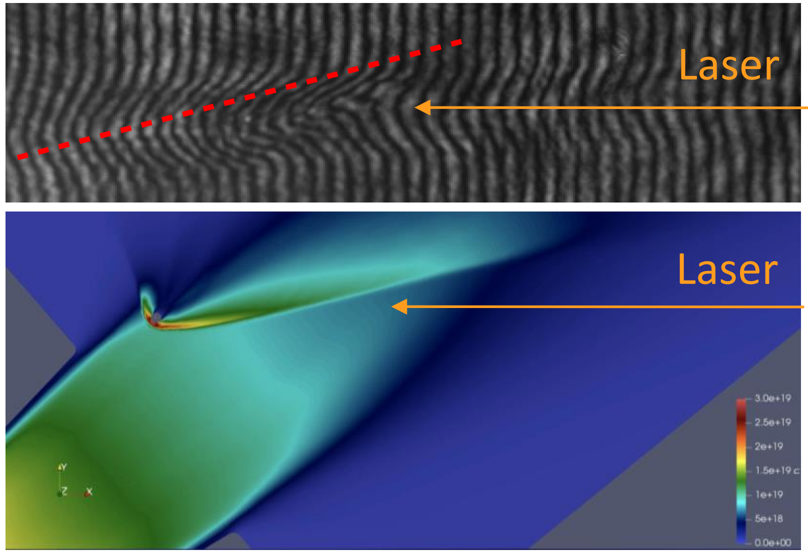


Date: 07.09.2023



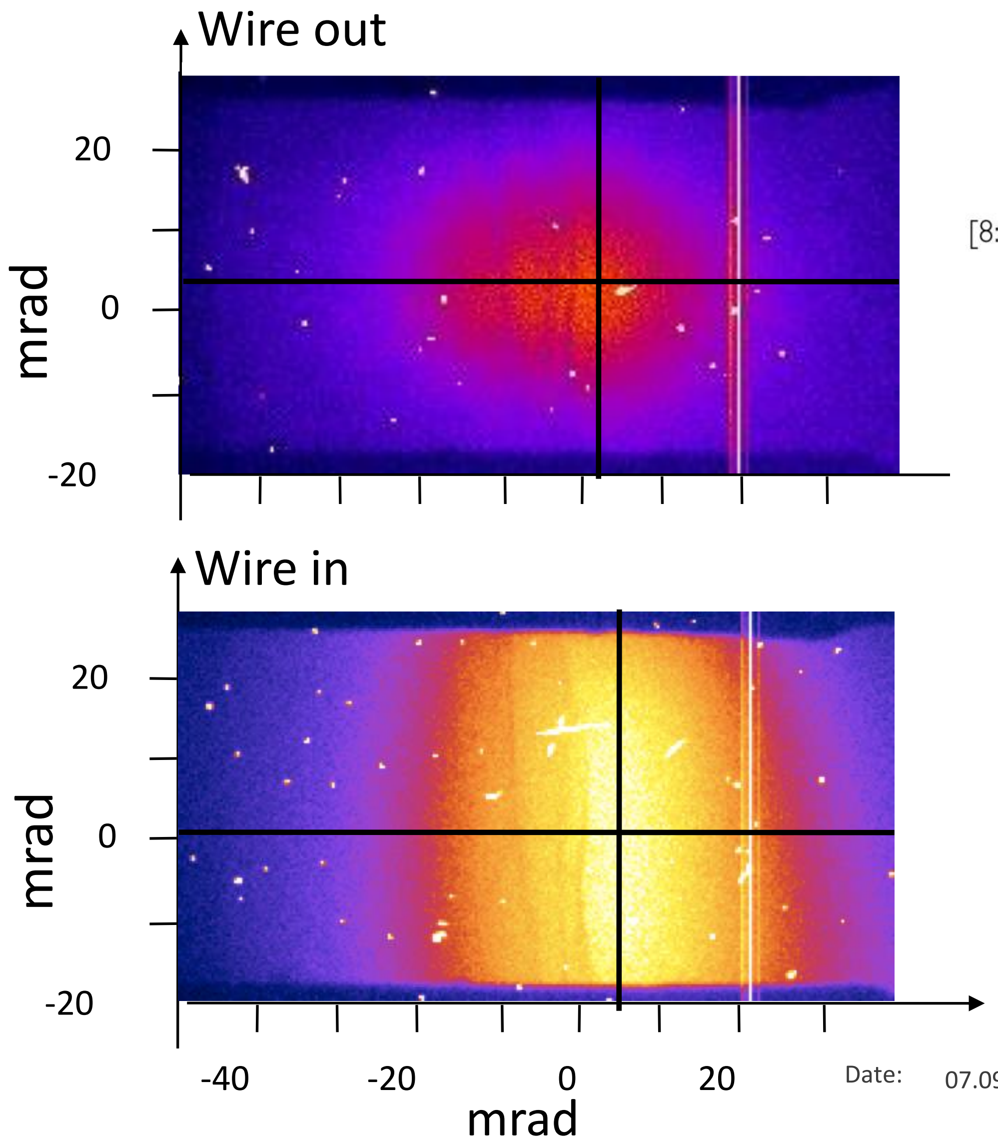


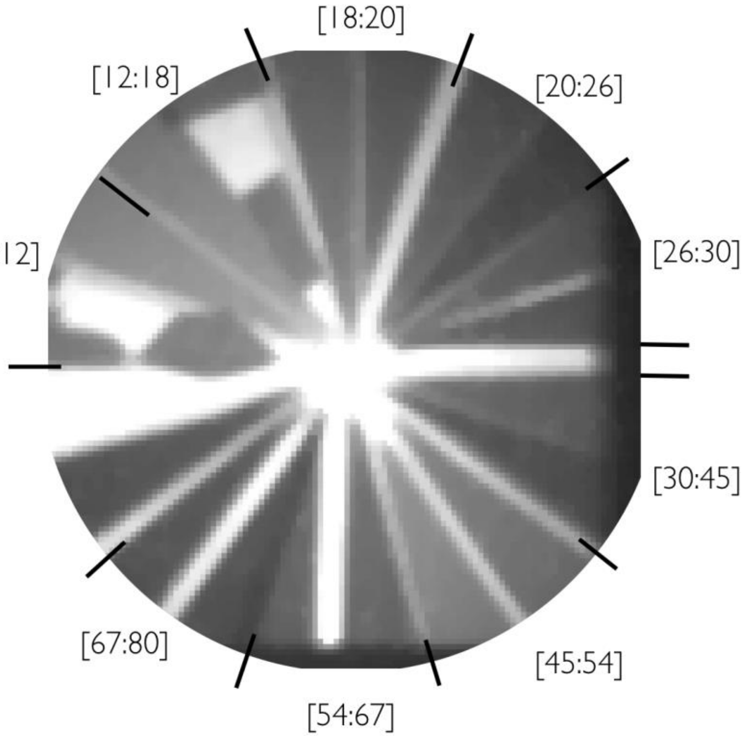
Density profile with wire in the jet

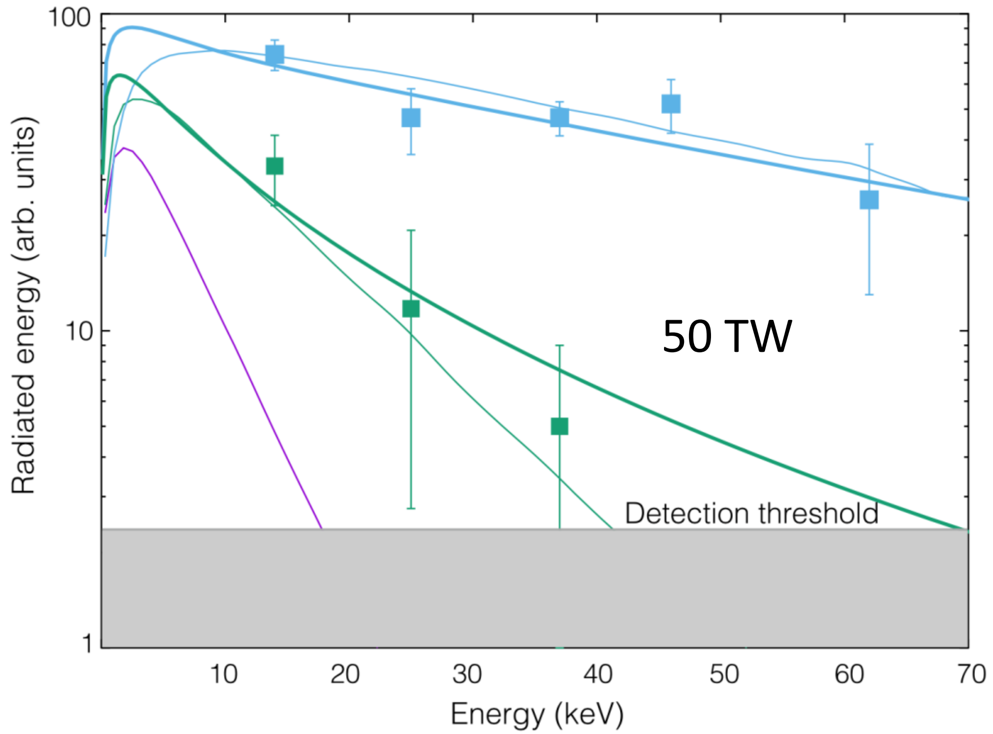
- Electrons remain for longer at the back of the cavity. The energy of the e^- is increased.
- The oscillation amplitude of electrons is increased.
- An increase in the Betatron energy and flux is expected

Advanced plasma Betatron

Longitudinal up-ramp + sharp transverse density gradient (up ramp + shock)







- Increase of the electron energy (x 1.5)
- Increase of the Betatron oscillation amplitude (>2)
- Shift of the spectrum towards higher energies
- Significant increase of critical energy (x 5) & photon flux (x 20)

M. Kozlova et al., Phys. Rev. X 10, 011061 (2020)

Summary of the Betatron source feature

- ✓ 10^6 photons/shot/0.1% BW and 10^{11} photons/shot over the whole spectrum
- ✓ collimated: 10’s mrad
- ✓ ultrashort: ~10’s fs
- ✓ Broadband: 1-100 keV (depends on driving laser)
- ✓ source size: 1- 2 microns
- ✓ 10% flux variation
- ✓ 10% energy variation

Combine unique features for wider applications:

Broad spectrum & fs duration, micron source size

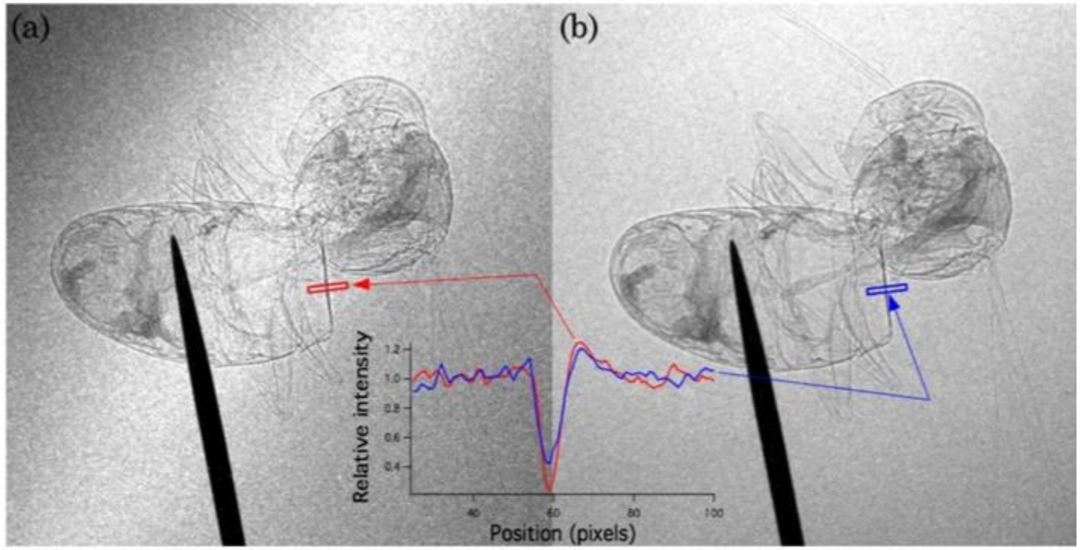
Betatron X-ray source - Applications

I. Absorption contrast, Phase contrast Imaging, and tomography

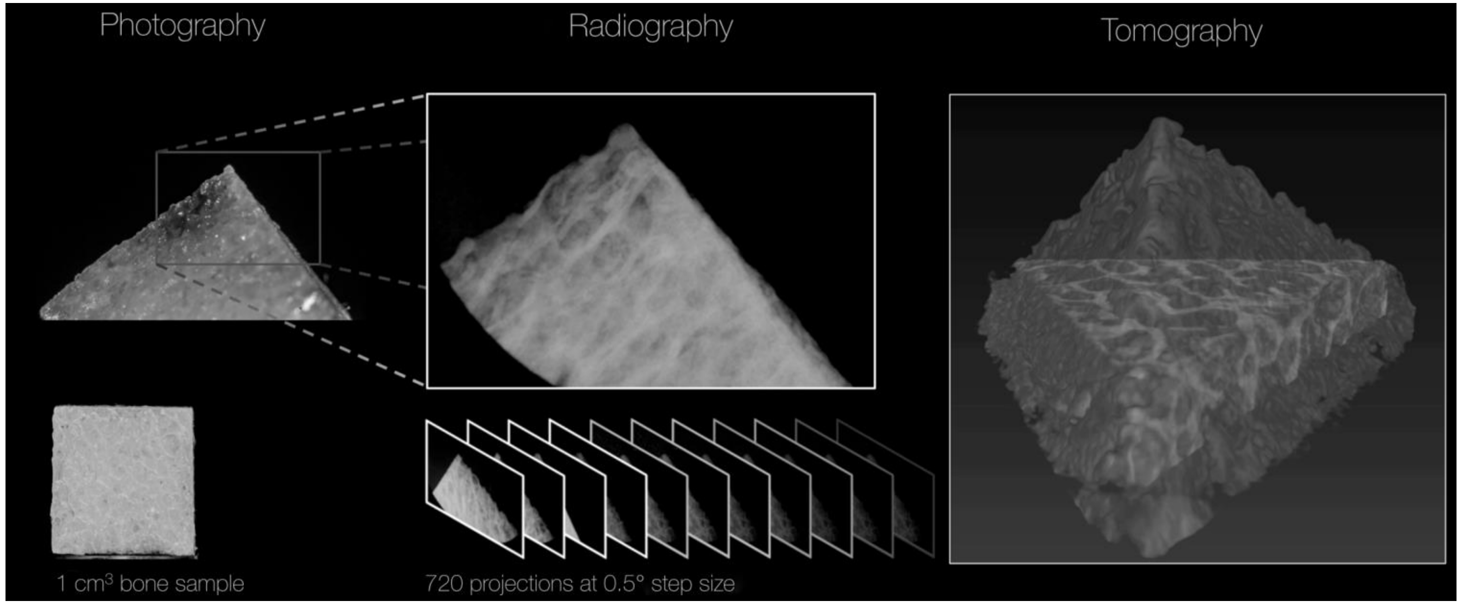
- Small Source (order of mm), high brightness (10^{23} BU, coherence length of ~10 um (for 5 keV)

- High definition, high resolution imaging using phase contrast, images possible in a single shot (30 fs exposure)

J.Cole et al., Sci. Rep. 2015



S. Fourmaux et al., Optics Letters 2011

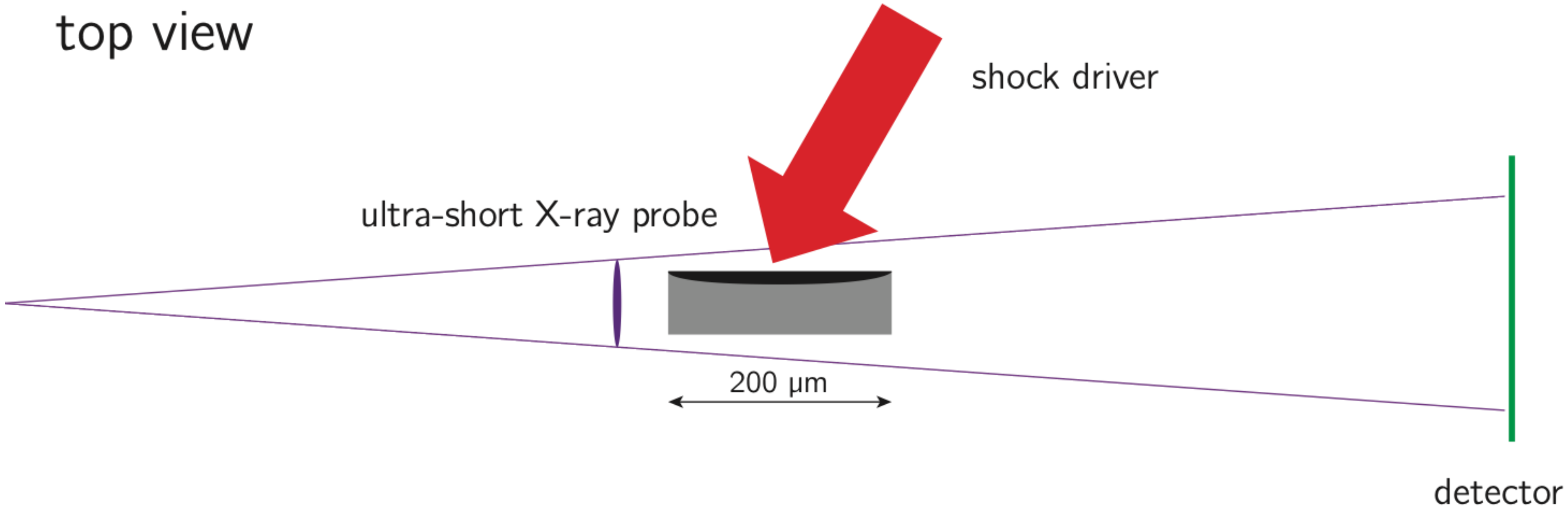


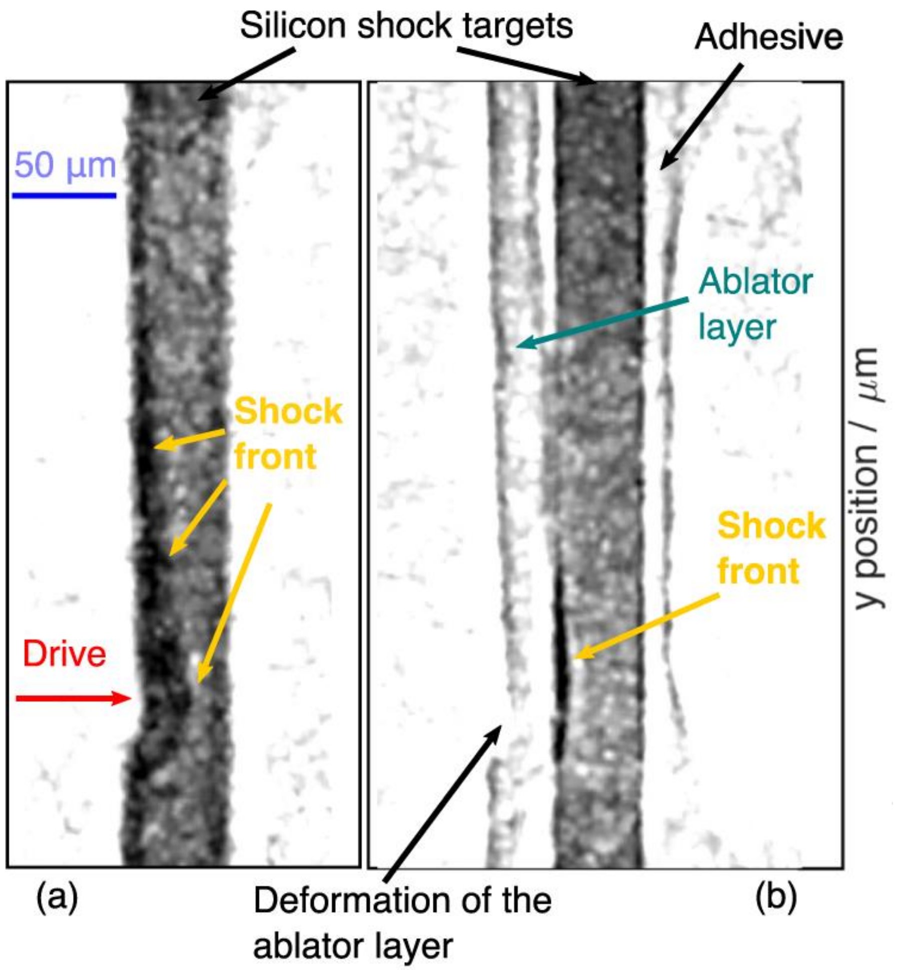
A. Döpp et al., Optica, 5, 199 (2018)

Stable source, tomography at 1 Hz (acquired in 3 min)

Betatron X-ray source - Applications

II. Dynamic imaging



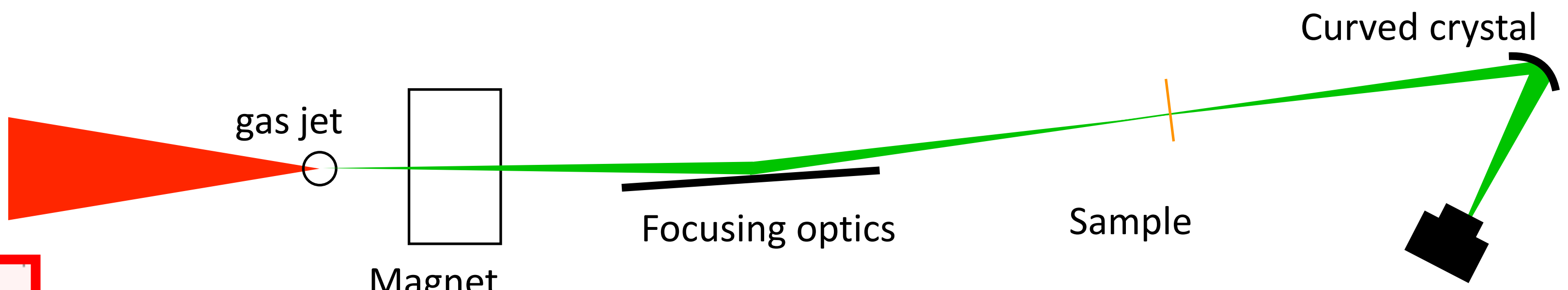


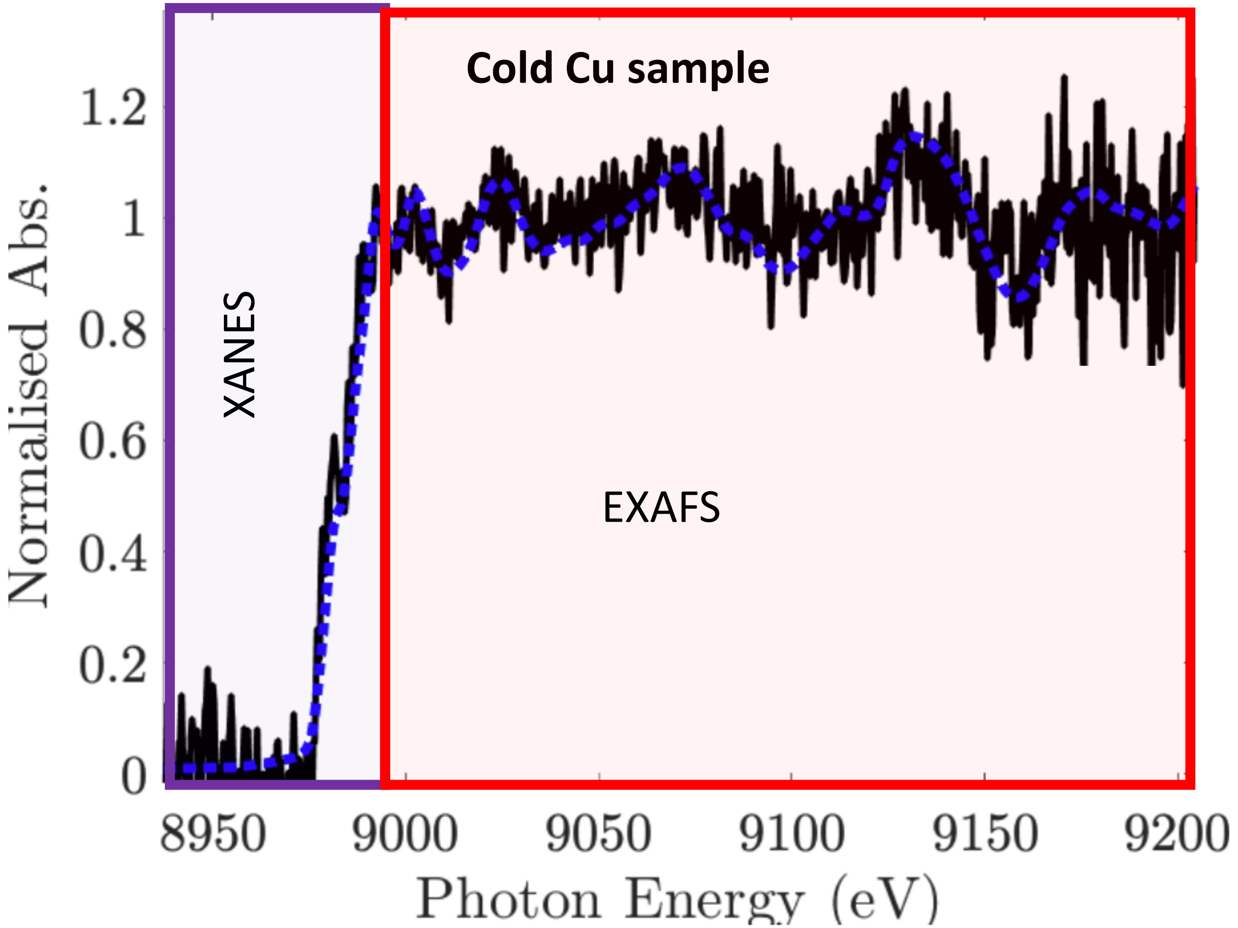
J Wood et al., Sci Rep 8, 11010 (2018)

Small source size of Betatron source enables use to make high-resolution imaging of laser-driven shocks and probe fast-moving shocks without blurring

III. X-ray Absorption Spectroscopy

Betatron X-ray source - Applications





a. X-ray absorption Near Edge Spectroscopy (XANES)

- Near absorption edge: electron distribution function, density of states, temperature

b. Extended X-ray Absorption Fine Structure (EXFAS)

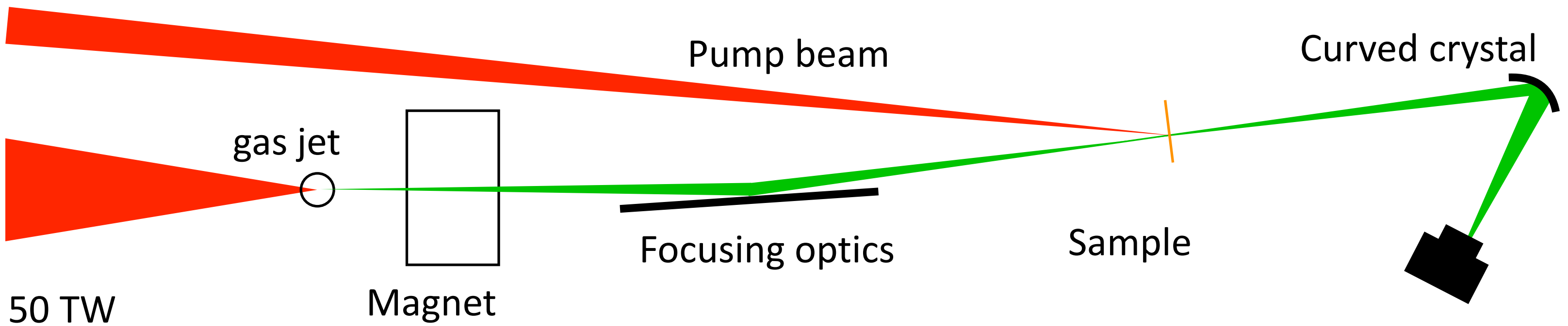
- Ion structure and ion temperature

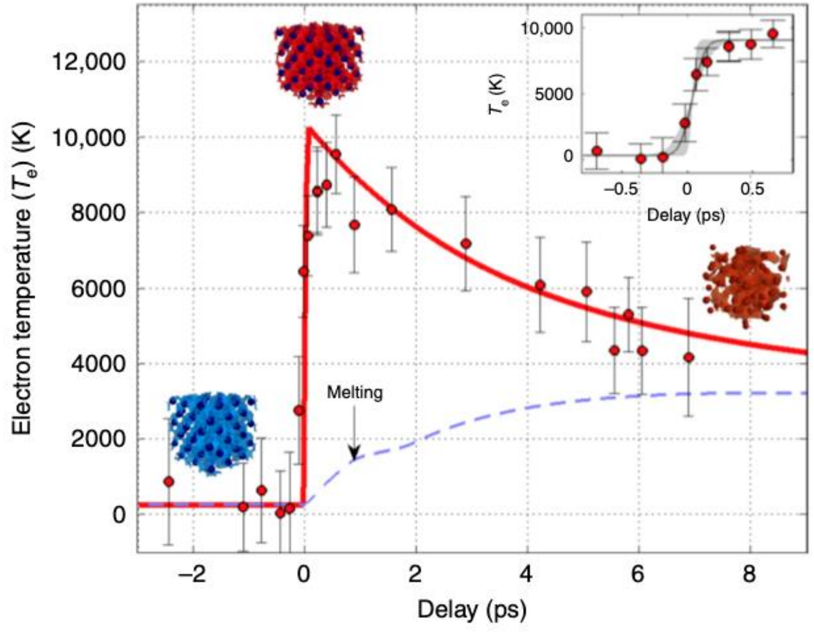
Single shot X-ray absorption spectroscopy

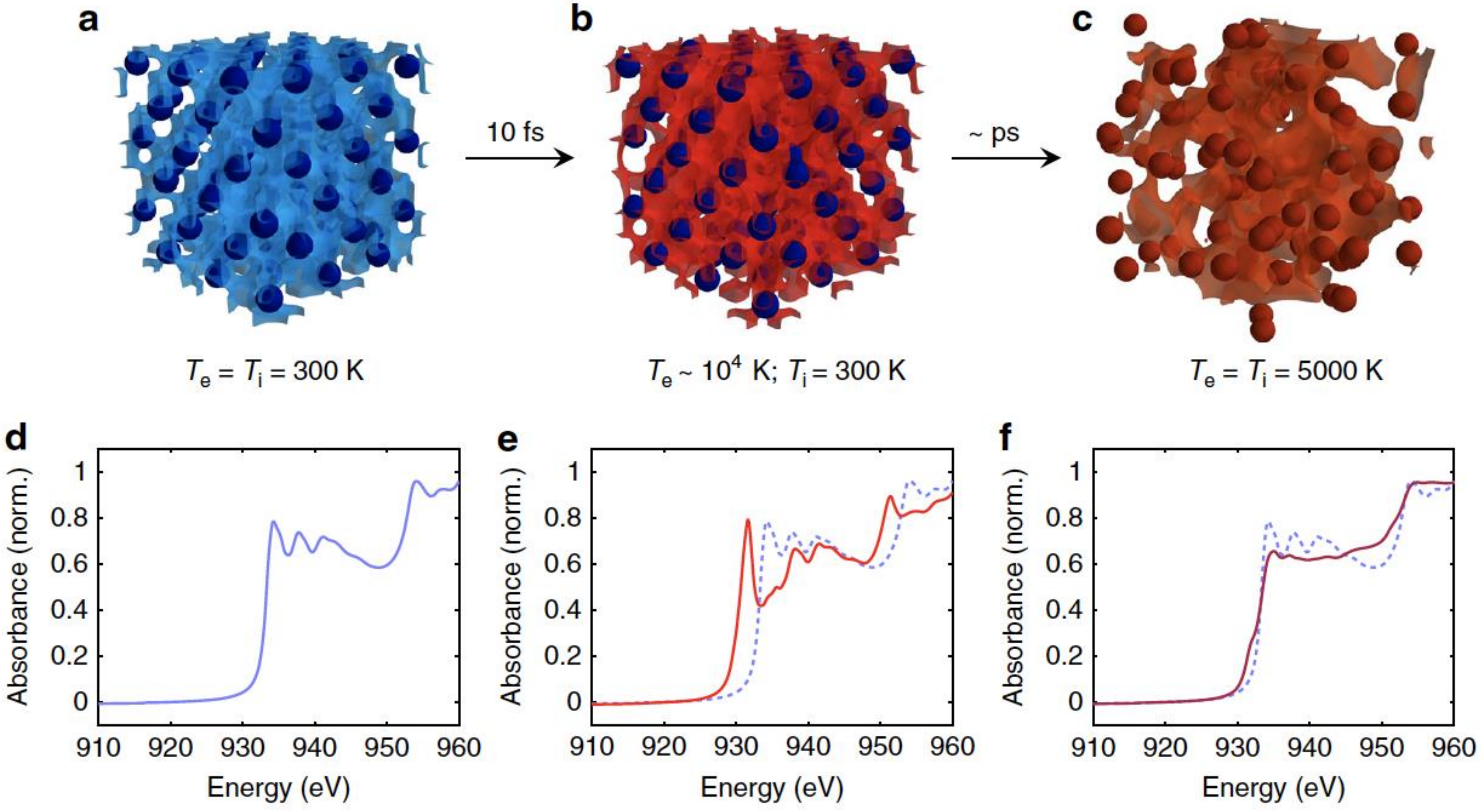
B Kettle et al., PRL, 123, 254801 (2019)
B. Kettle et al. arxiv.2305.10123 (2023)

III. X-ray Absorption Spectroscopy

Betatron X-ray source - Applications





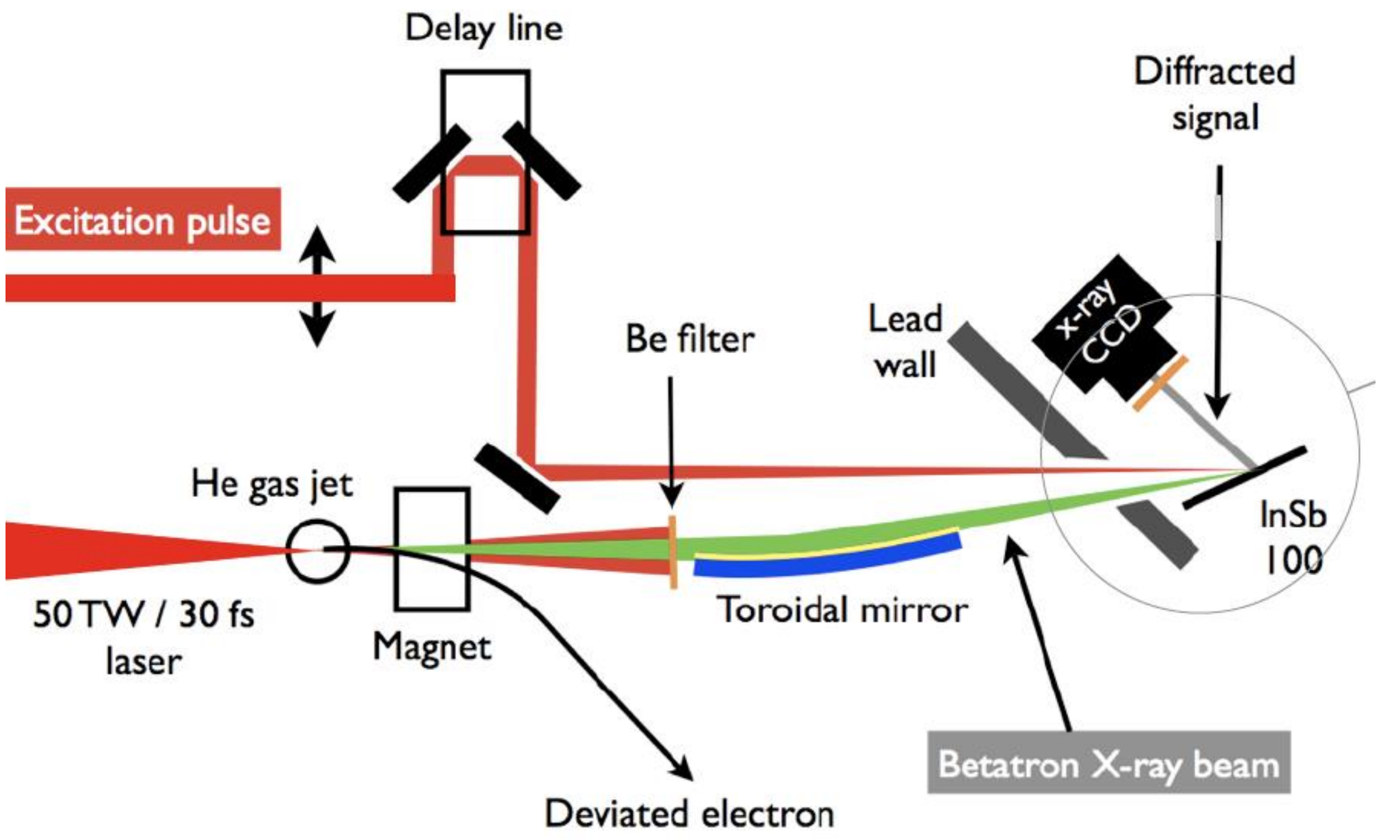


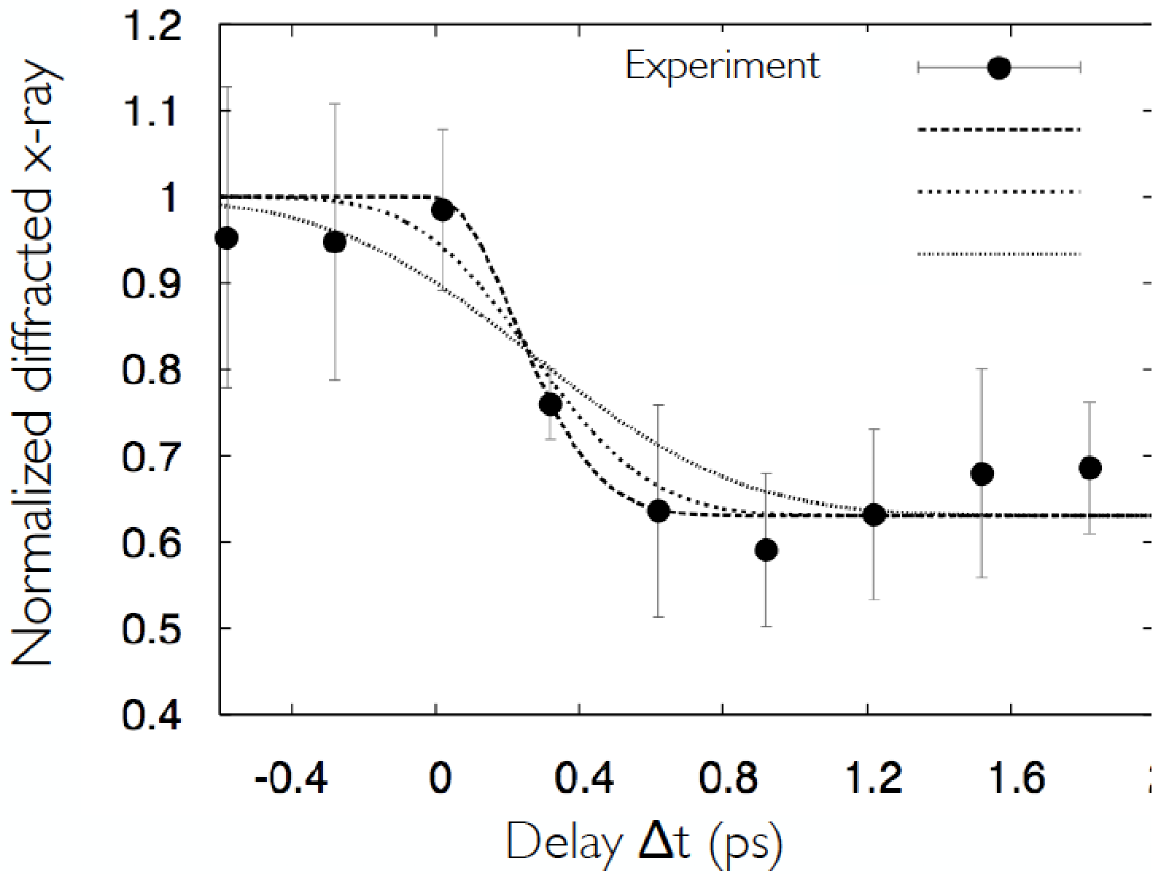
Ultrafast phase transition in a 80 nm Cu sample heated with a fs laser pulse
- observed sub-100 fs electron heating of warm dense copper (L-edge XANES)

B. Mahieu et al., *Nat. Commun.* 9; 3276 (2018)

Betatron X-ray source - Applications

III. Ultrafast X-ray Diffraction





K. ta-Phuoc et al., PoP 14(8), (2007)

Using a Betatron source, ultrafast phase transition can be measured with fs resolution

Laser-driven X-ray sources at ELI beamlines facility

- High-order harmonic generation from gas
- Plasma X-ray sources (PXS)
- **Sources based on laser wakefield electron acceleration (LWFA)**
    - Betatron radiation
    - Thomson Scattering/Inverse Compton scattering (ICS)
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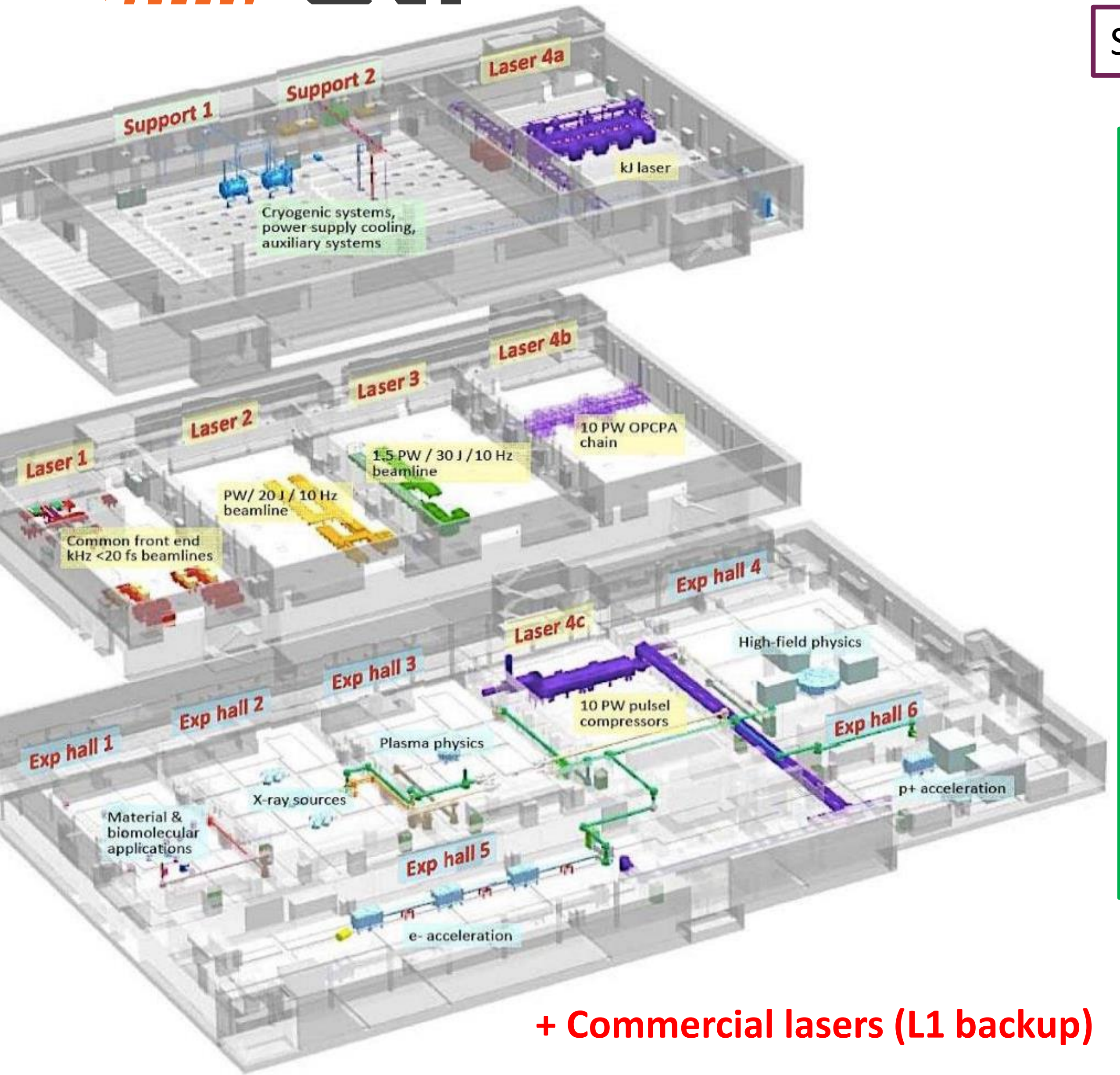
Facility layout and laser drivers for X-ray sources



+ Commercial lasers (L1 backup)

Synchronization within <100 fs by master facility clock

L1 – ALLEGRA

Technology
- OPCPA
- Circular
- Gaussian
- Synchronized probe beam

Parameters

Nominal	Current
100 mJ	55 mJ
1 kHz	1 kHz
15 fs	15 fs

L2 – DUHA

Technology
- OPCPA
- Circular
- Flat-top
- Synchronized mid-IR pulse

Parameters

Nominal	Current
5J	Work
10s Hz	in
<40 fs	Progress

L3 – HAPLS

Technology
- Ti:Sa, DPSSL
- Square (25x25 cm^2)
- Flat-top

Parameters

Nominal	Current
30 J	**14 J**
10 Hz	**3.3 Hz**
30 fs	**30 fs**

L4 – ATON

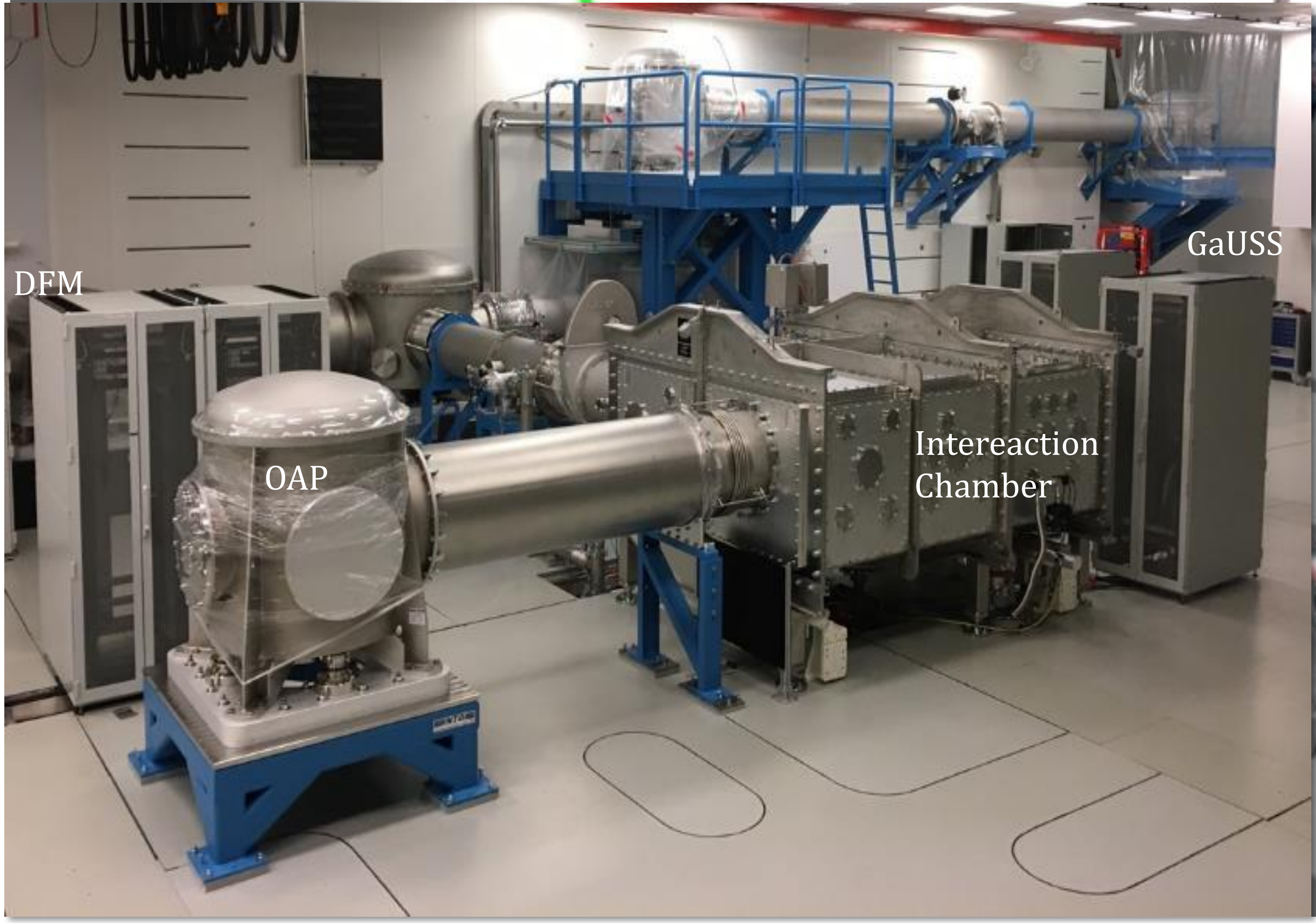
Technology
- Nd:glass
- Square, (55x55 cm^2)
- Flat-top
- Also ns & ps

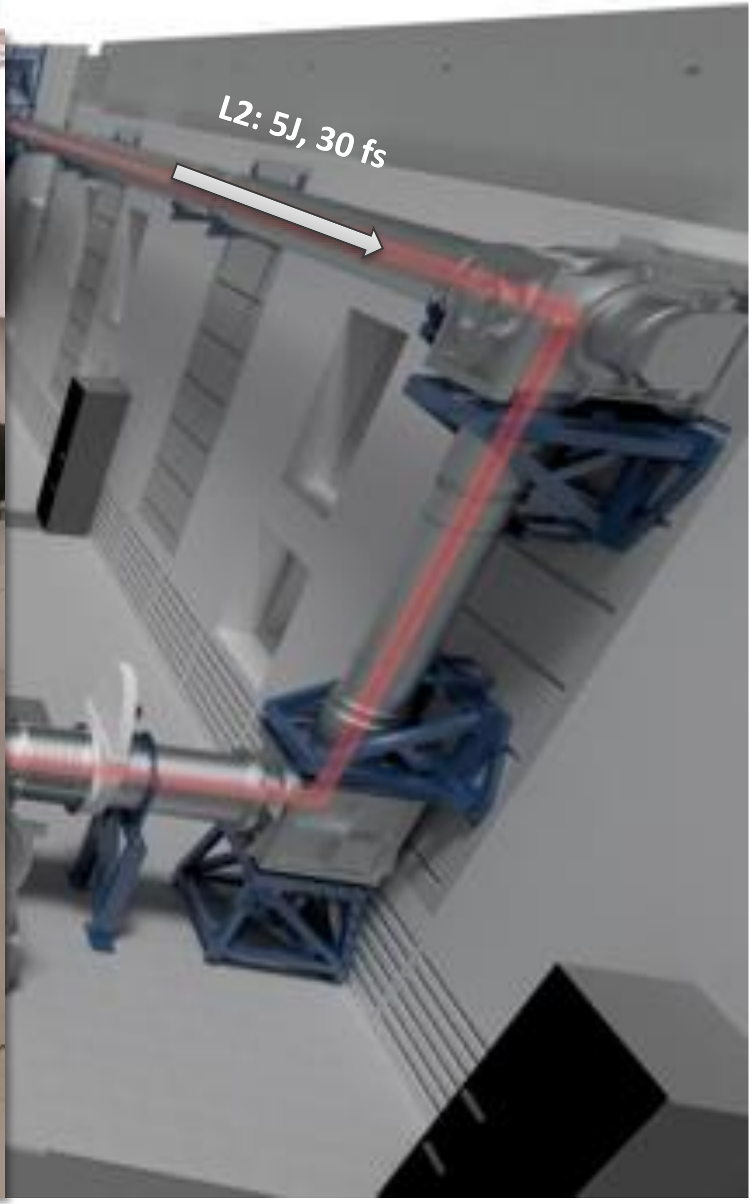
Parameters

Nominal	Current
1.5 kJ	**600 J**
1/min	**1/min**
150 fs	**1 ns**

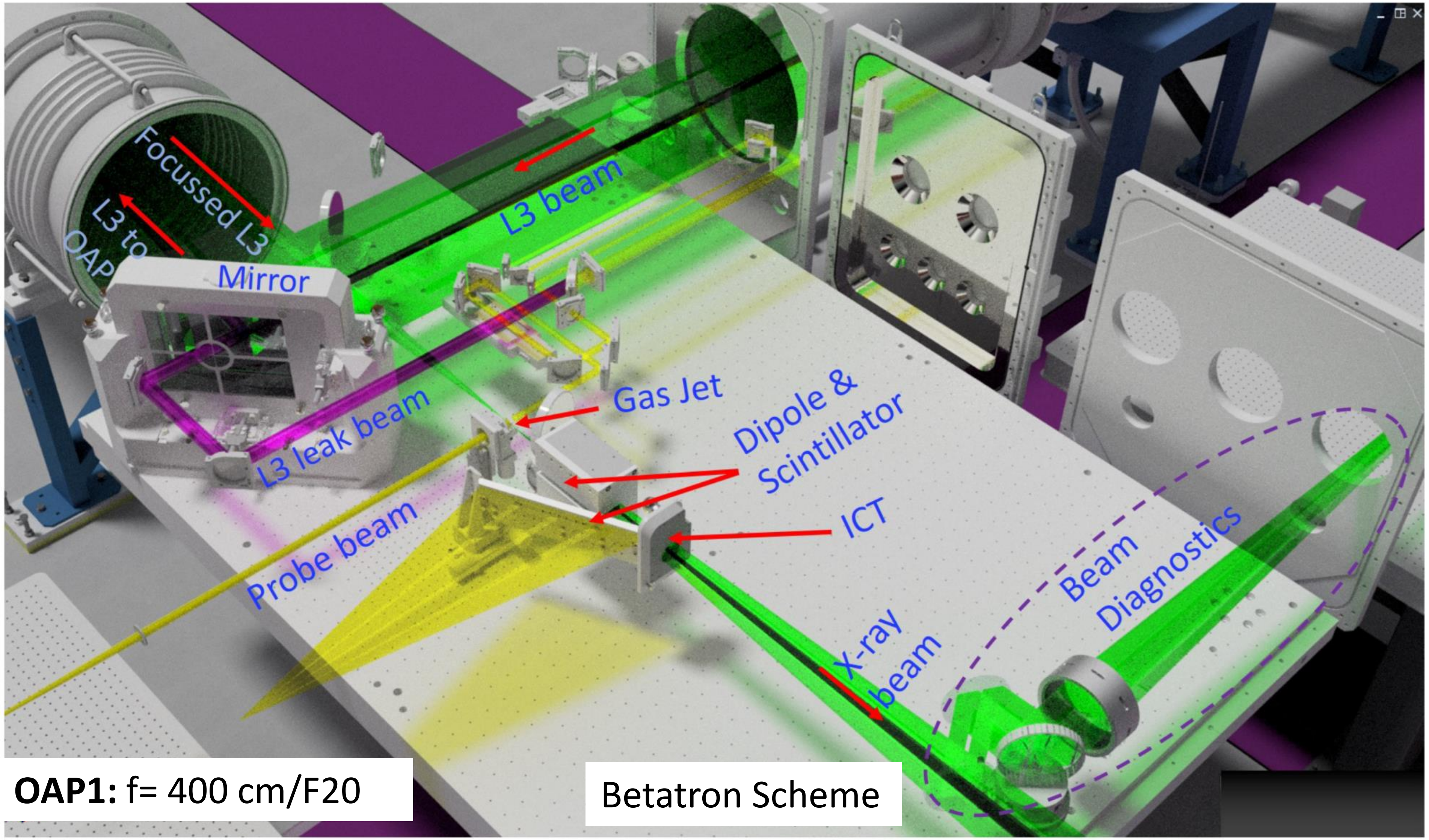
- Coherent LEGEND Elite DUO: 1kHz, 12 mJ @ 35 fs
- Coherent Astrella: 1 kHz, 2x6 mJ @ 45 fs
- Coherent Hidra: 10 Hz, 100 mJ @ 40 fs

ELI Gammatron Beamline



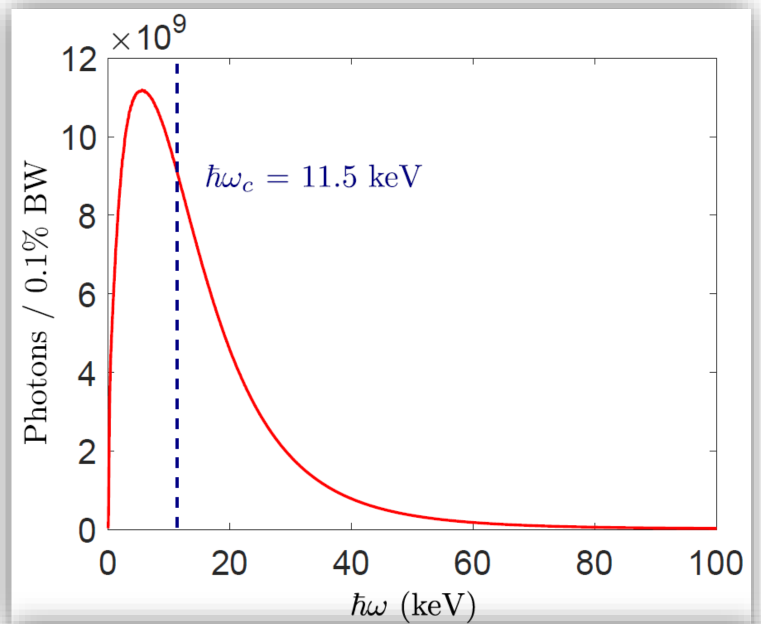


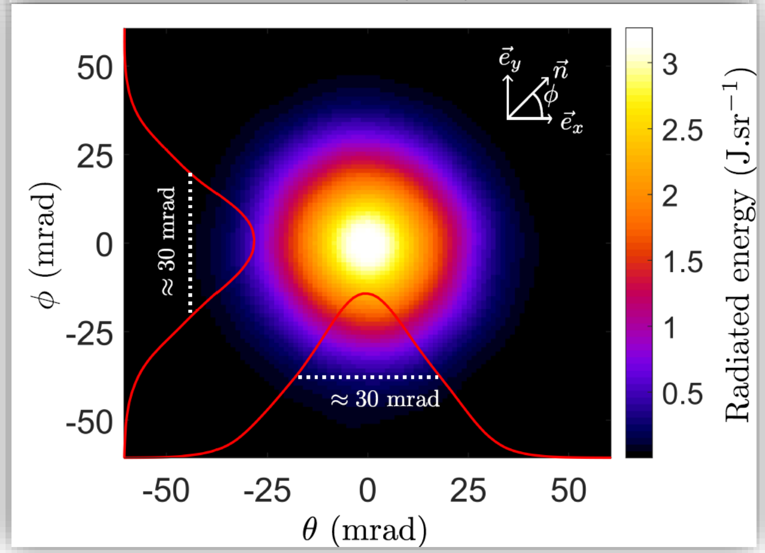
ELI Gammatron Beamline



OAP1: f= 400 cm/F20

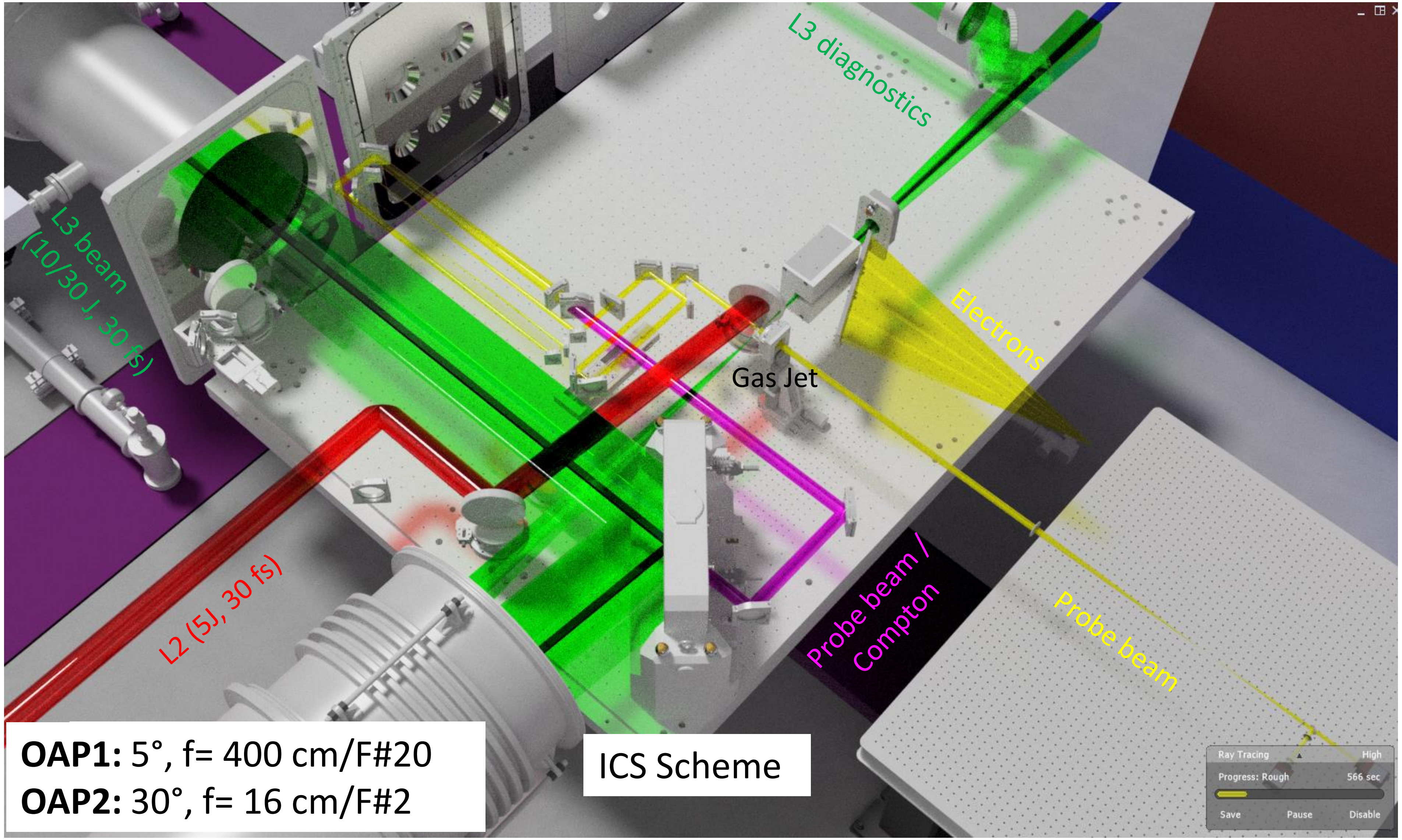
Betatron Scheme





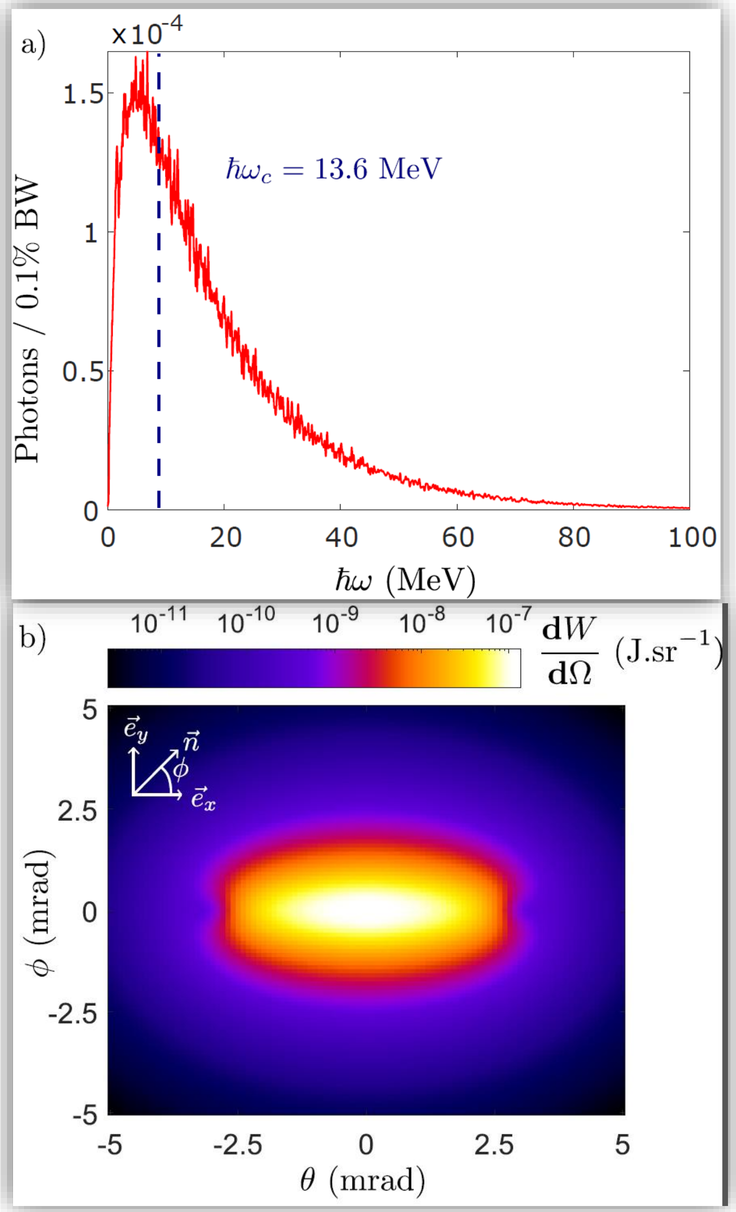
Chaulagain et al., Photonics 2022, 9(11), 853 (2022); Raclavský et al., Photonics 8, 579 (2021)

ELI Gammatron Beamline



OAP1: 5°, f= 400 cm/F#20
OAP2: 30°, f= 16 cm/F#2

ICS Scheme



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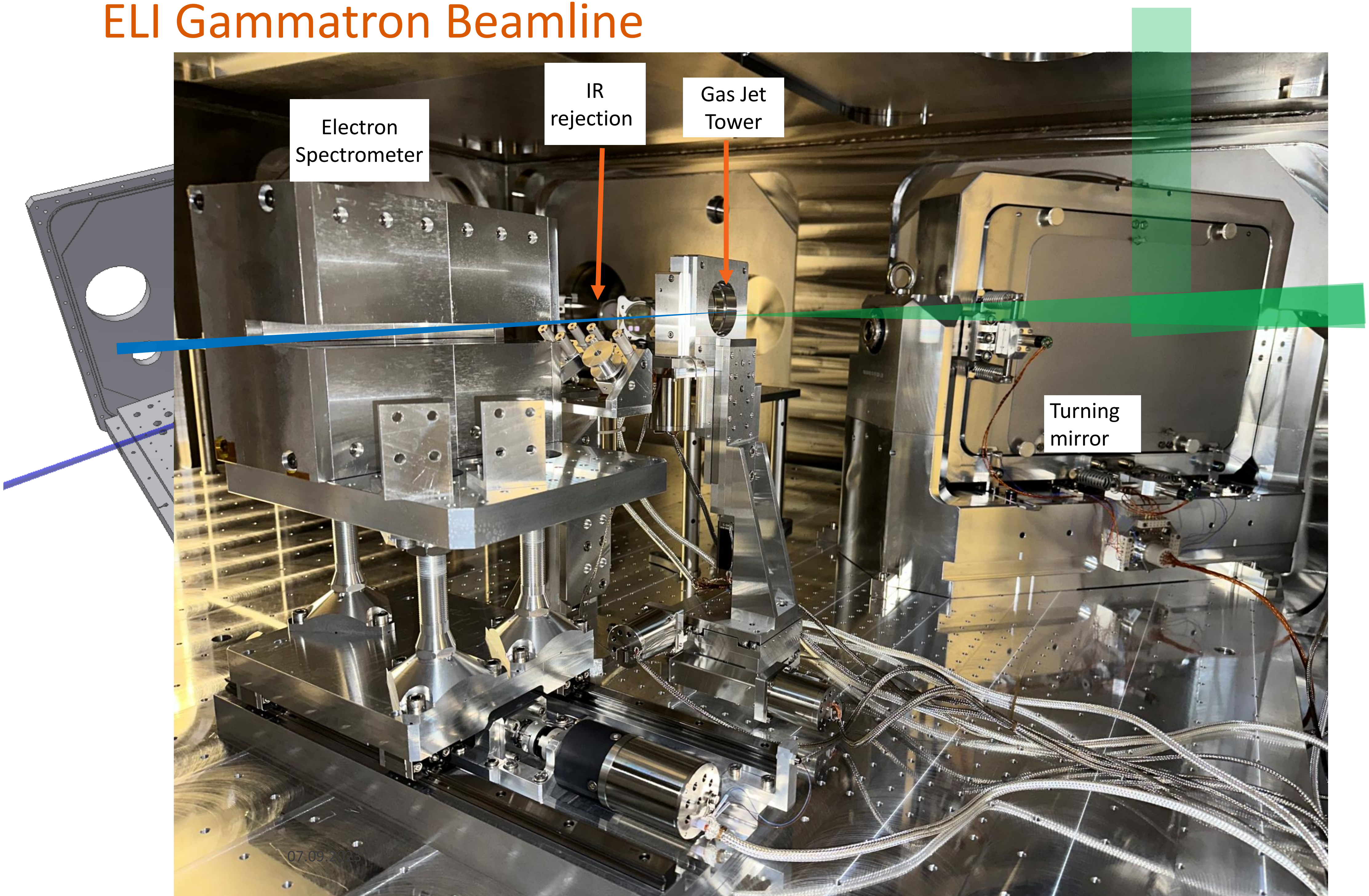

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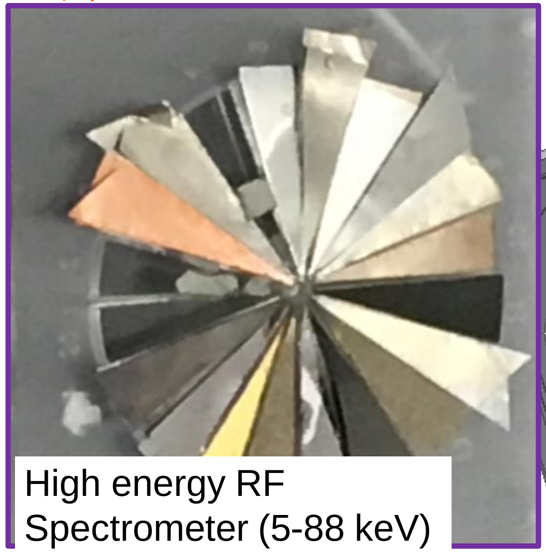
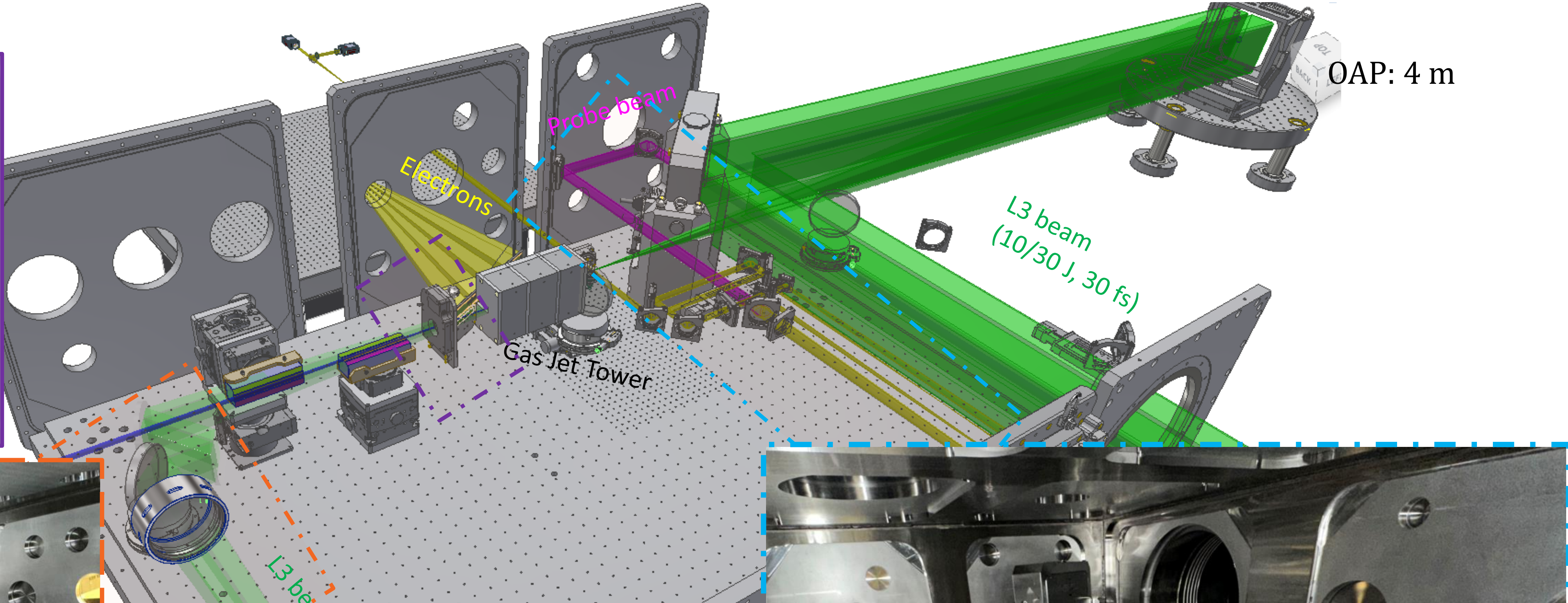
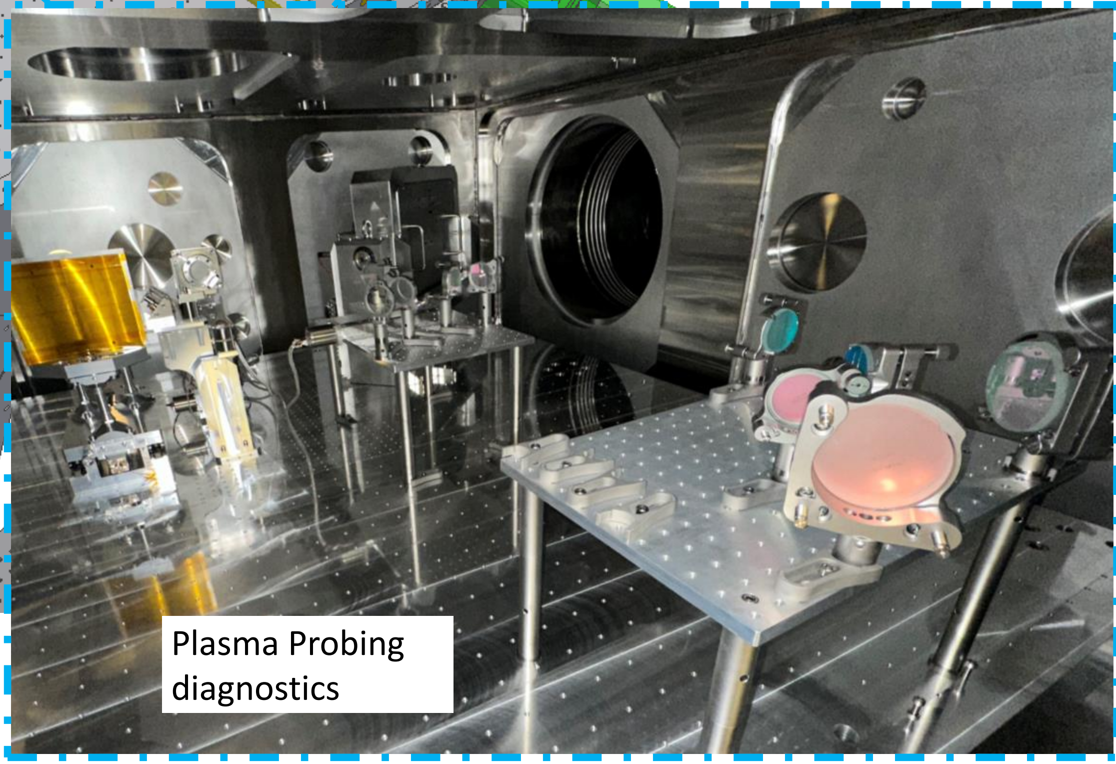
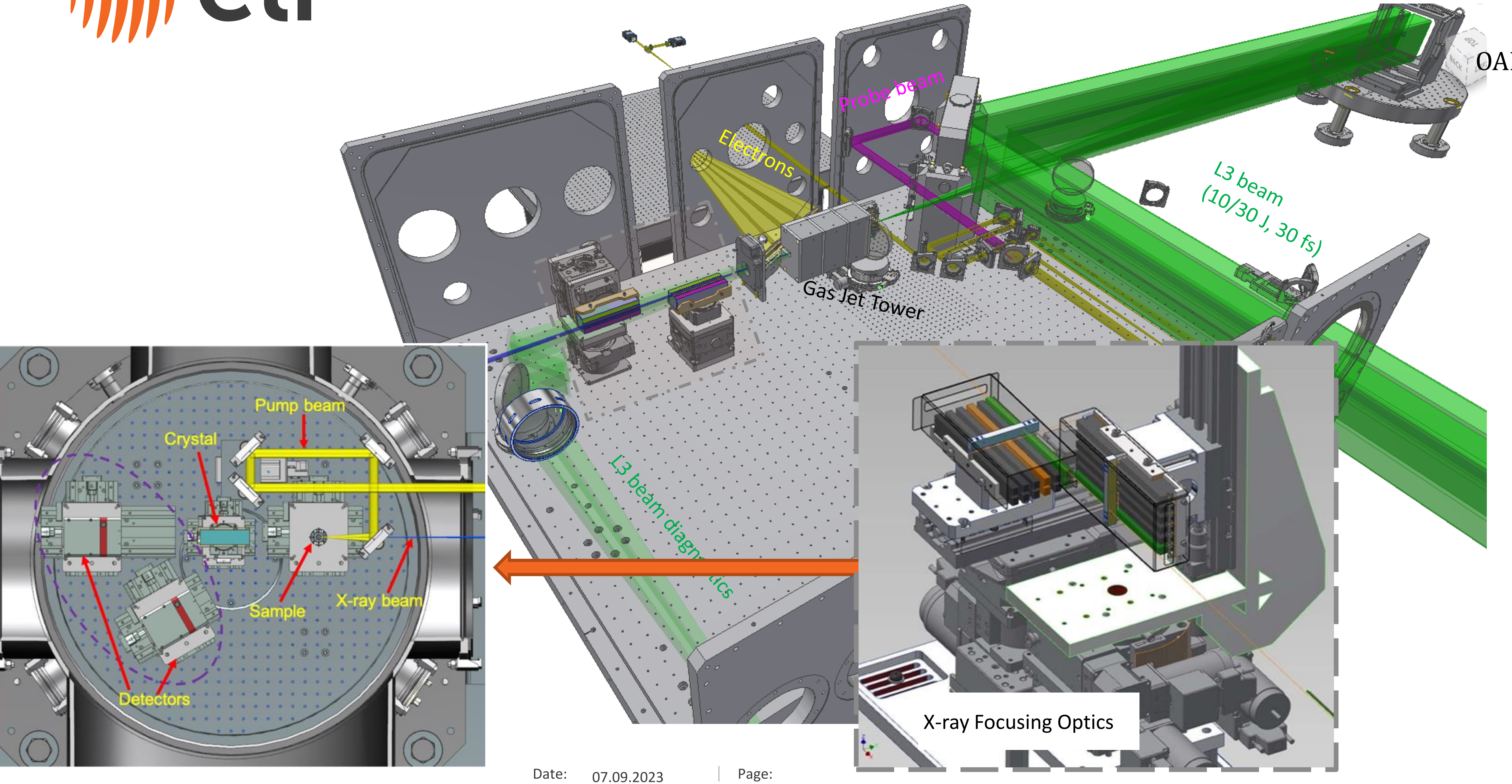

High energy RF Spectrometer (5-88 keV)



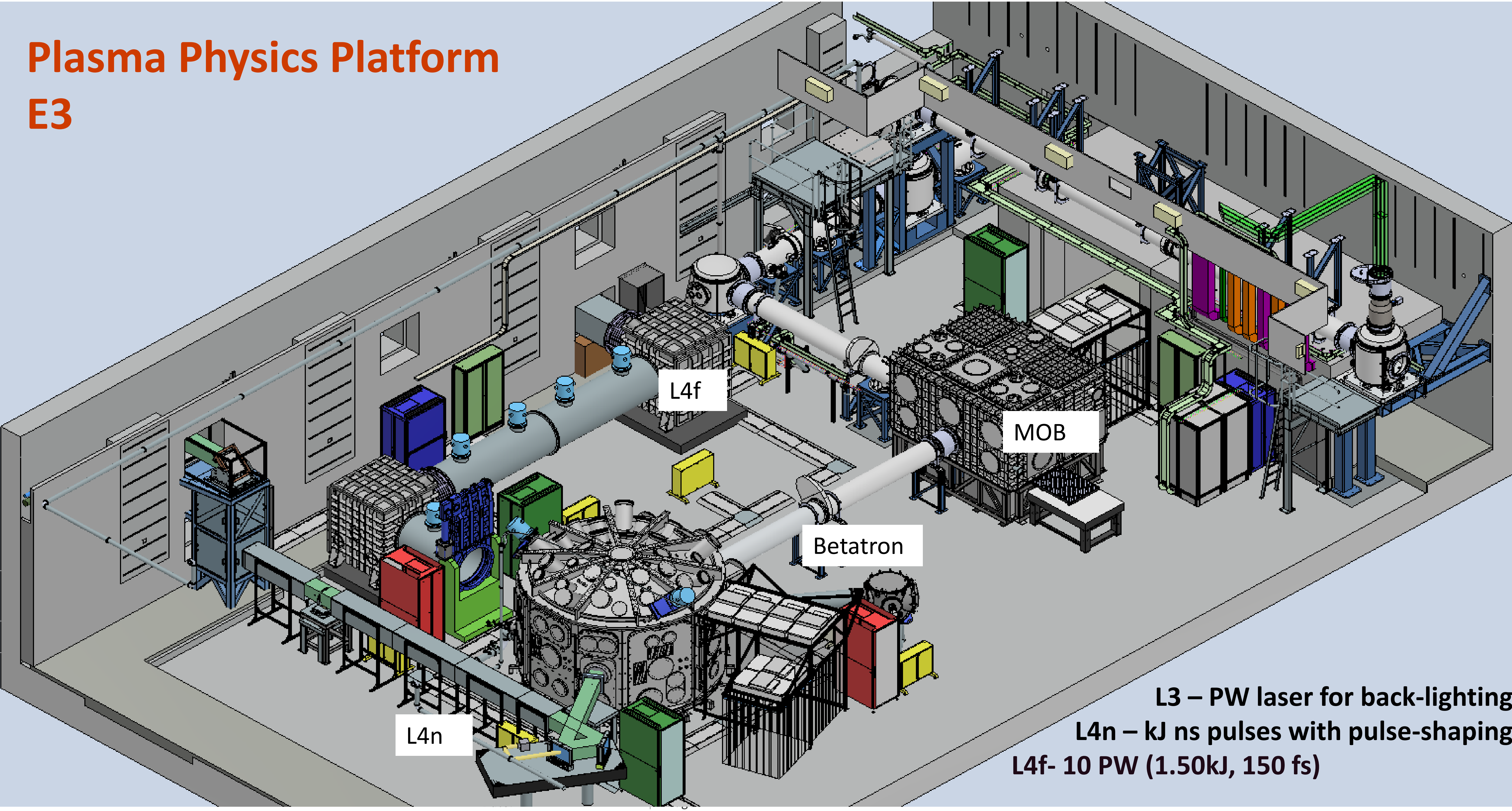

High power beam Diagnostics


Plasma Probing diagnostics

ELI Gammatron Beamline



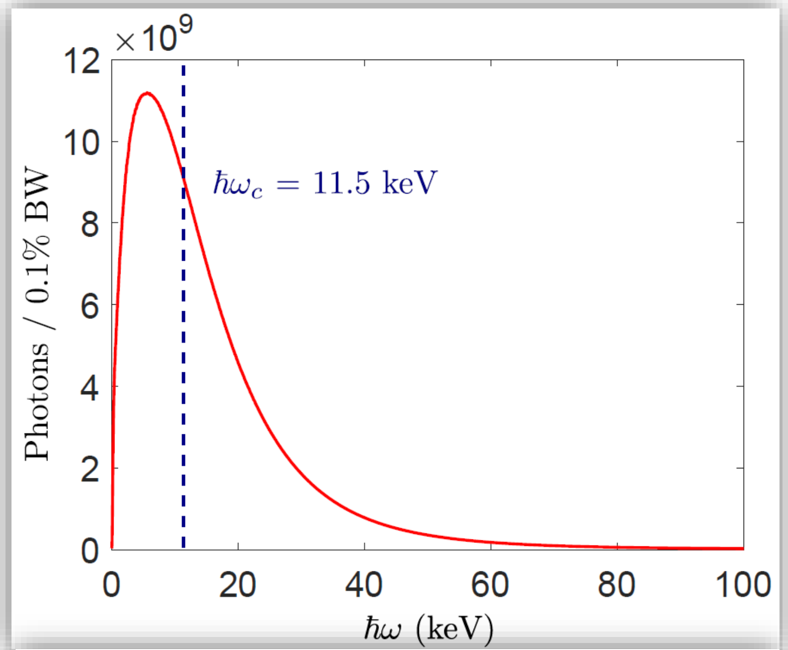
Plasma Physics Platform
E3

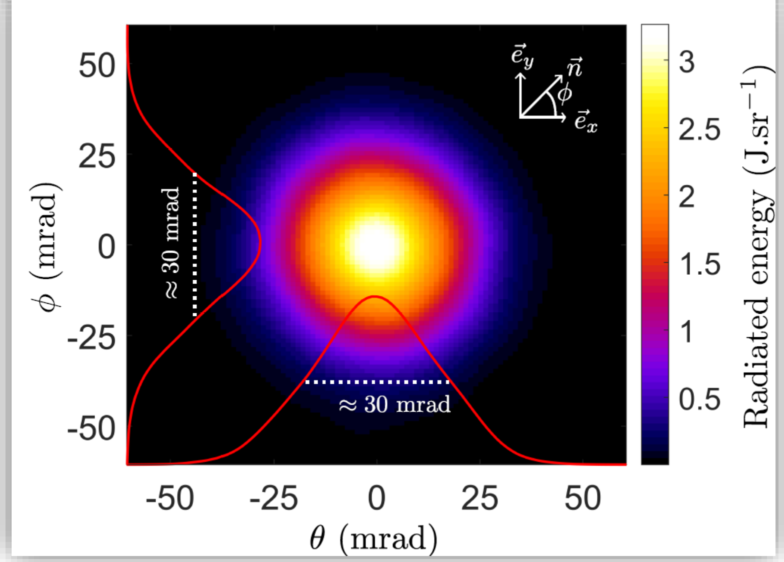


L3 – PW laser for back-lighting
L4n – kJ ns pulses with pulse-shaping
L4f- 10 PW (1.50kJ, 150 fs)

S. Weber et. al, MRE 2, no. 4 (2017): 149-176., N. Jourdain et. al, MRE,6, no. 1 (2021): 015401.

Betatron Source at Plasma Physics Platform





First Light (Q1 2022)

Source commissioning (Q2 2024)

User call (Q3 2024)

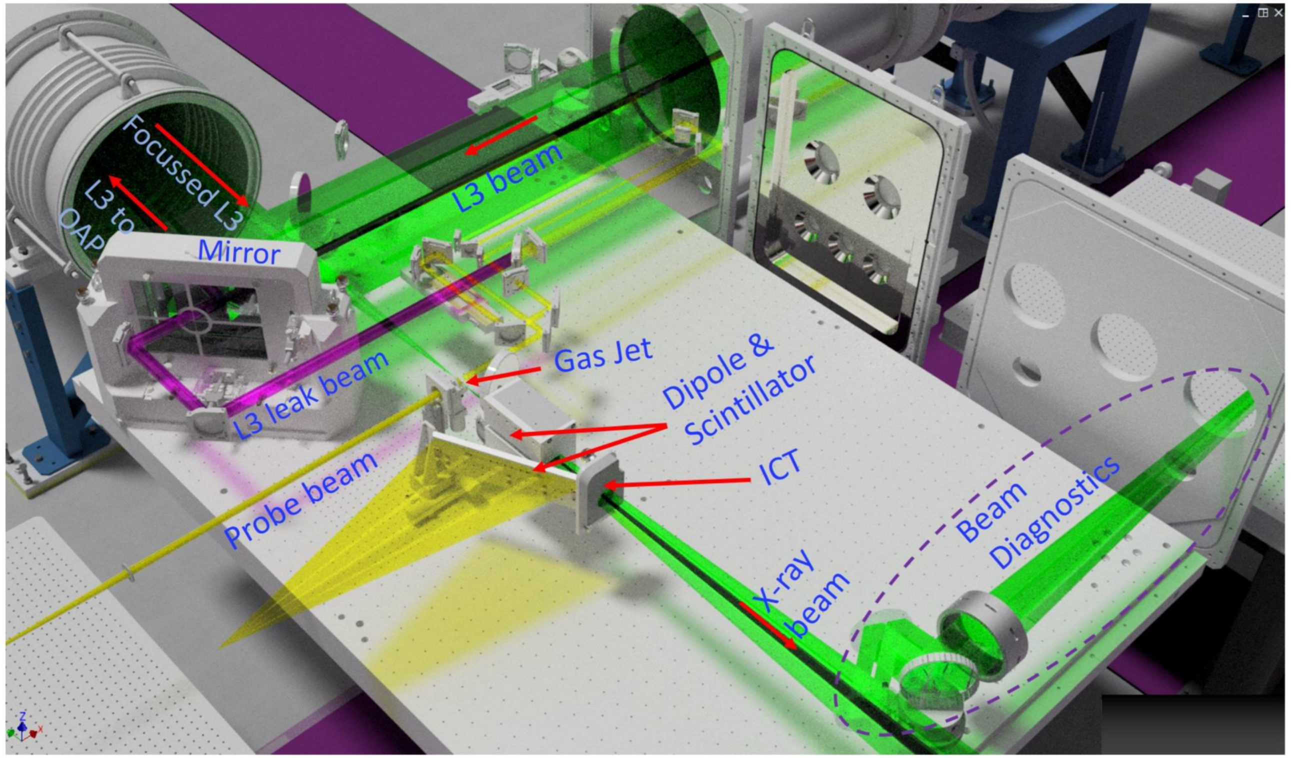
Date: 07.09.2023

N. Jourdain et al., MRE 6.1 (2021): 015401, U. Chaulagain et al., SPIE (2020)

Betatron/Compton beamline in E2/E3

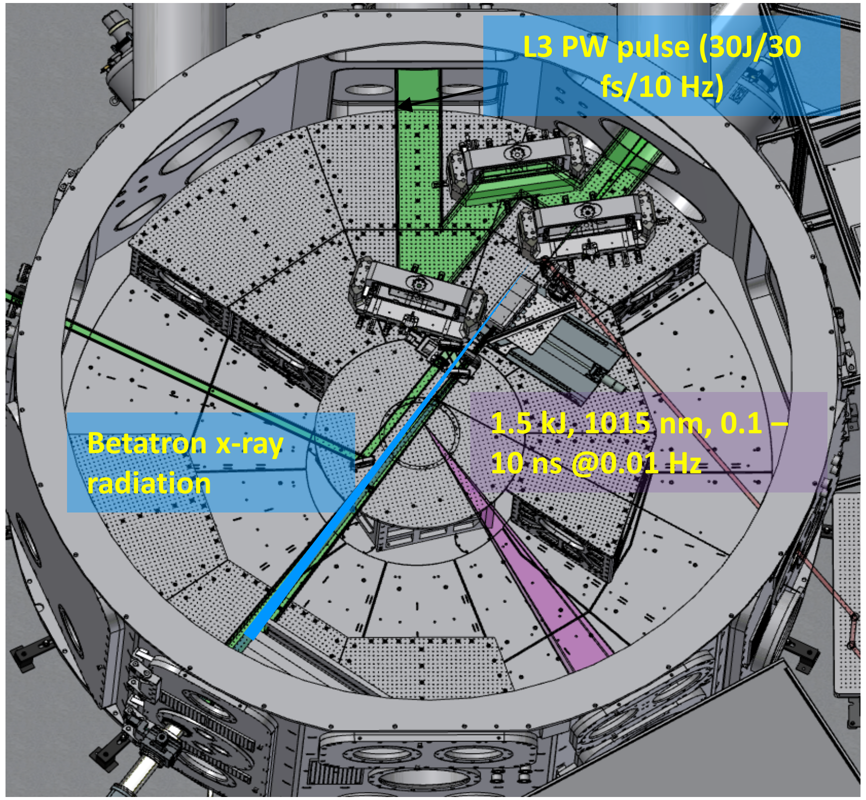
E2: ultrafast X-ray science

- Focusing by OAP (F# = 20)
- Designed for high rep. rate (10 Hz)
- Time-resolved XAS & XES, radiography, Phase contrast imaging, Diffraction etc.
- Operational from Q1 2024



E3: Plasma Physics platform (P3)

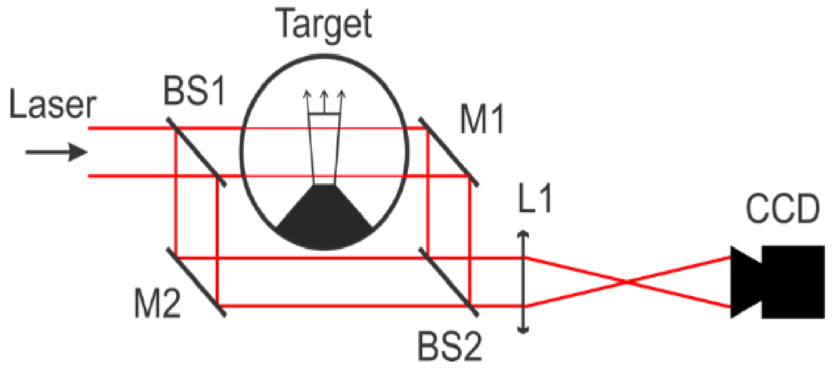
- Focusing by a spherical mirror (F# = 24)
- Betatron source for plasma and WDM diagnostics
- Operational from Q3 2024

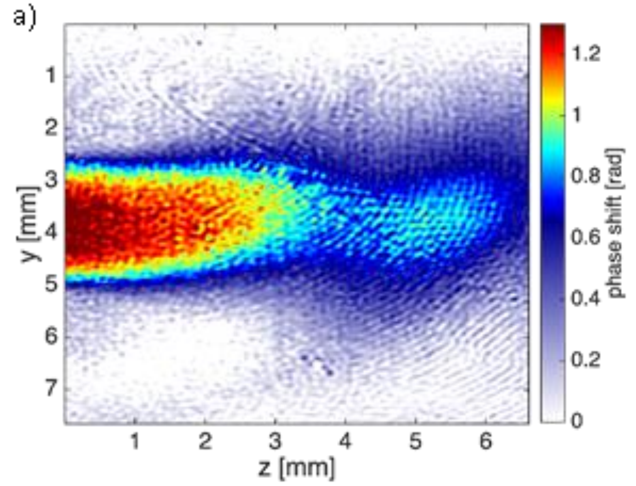


Gas jet characterization (with improved sensitivity)

Traditionally Mach-Zehnder or Nomarski int. (or WF sensor)

- Single pass
- Imaging on the detector (L1)

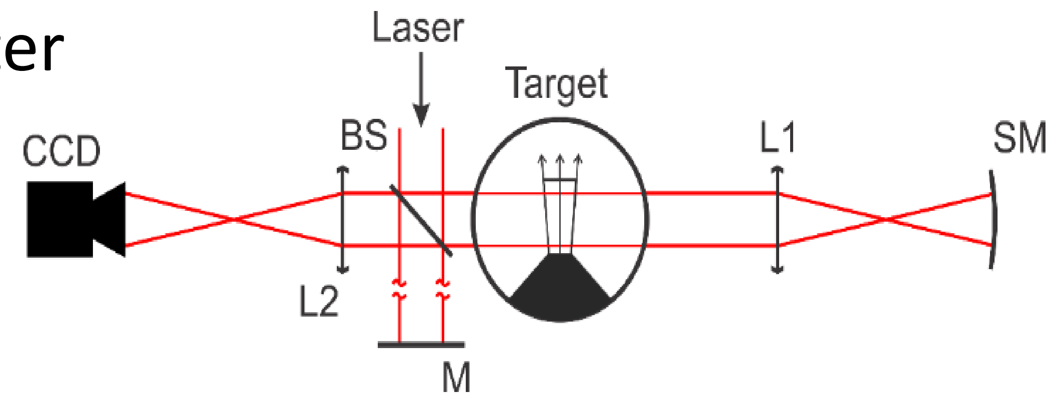


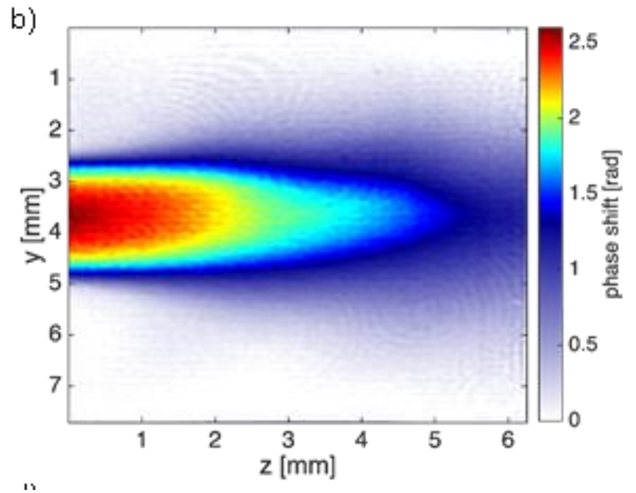


Imaging Michelson interferometer

- Double pass
- **Relay-imaging of the jet**

  (L1+SM) and imaging on the detector (L2)

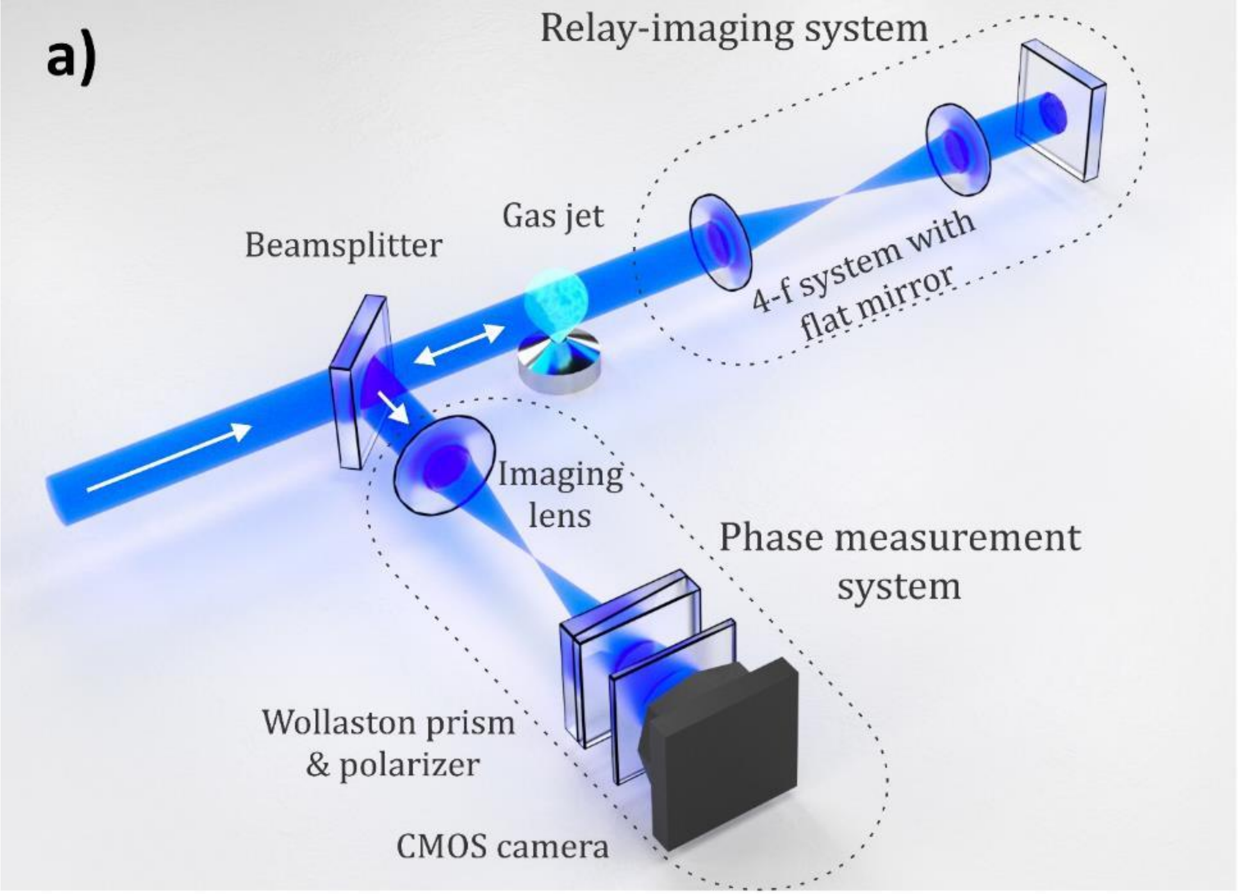




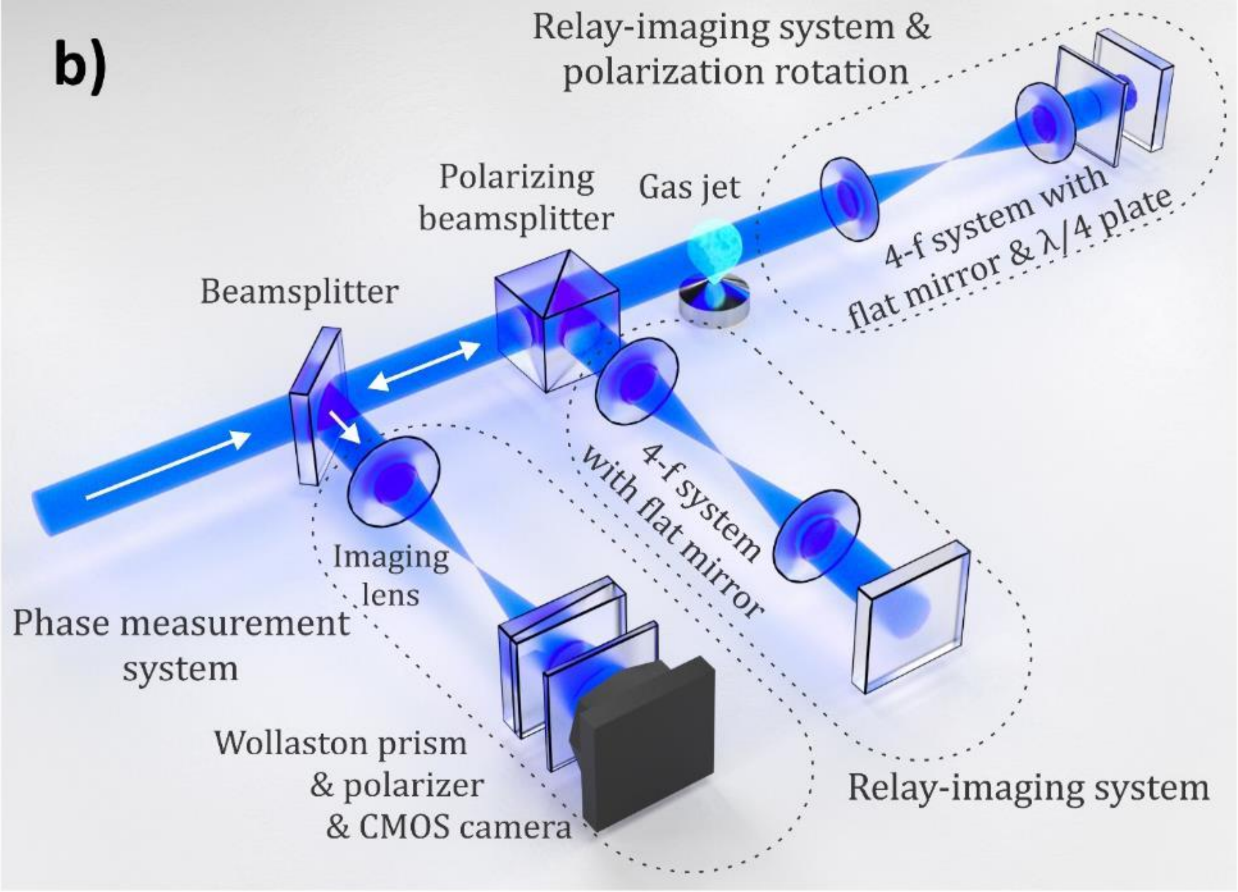
J. Nejdl et al., Rev. Sci. Instr. 90, 065107 (2019)

Gas jet characterization (with improved sensitivity)

Double-pass configuration and four-pass configuration employing polarization switching



two pass

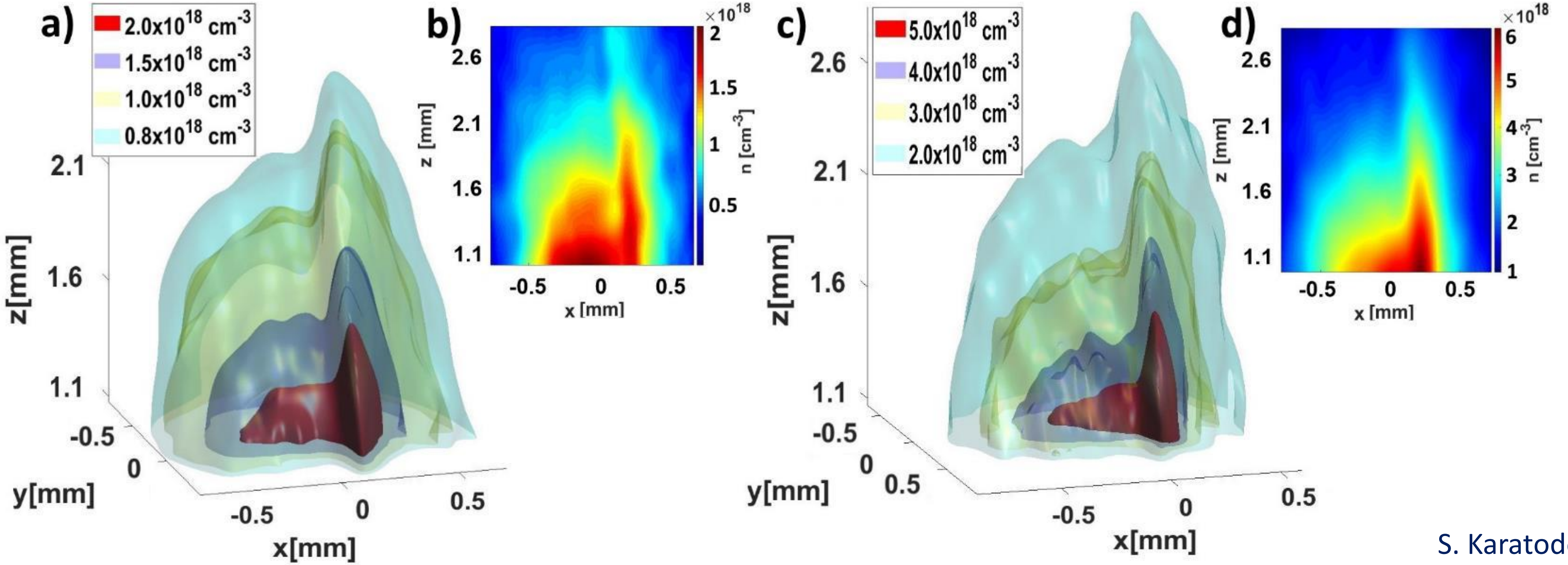


four pass

S. Karatodorov et al. Sci. Rep. 11, 15072 (2021)

Gas jet characterization (with improved sensitivity)

Four-pass configuration employed for tomography of low density gas jets



S. Karatodorov et al. Sci. Rep. 11, 15072 (2021)

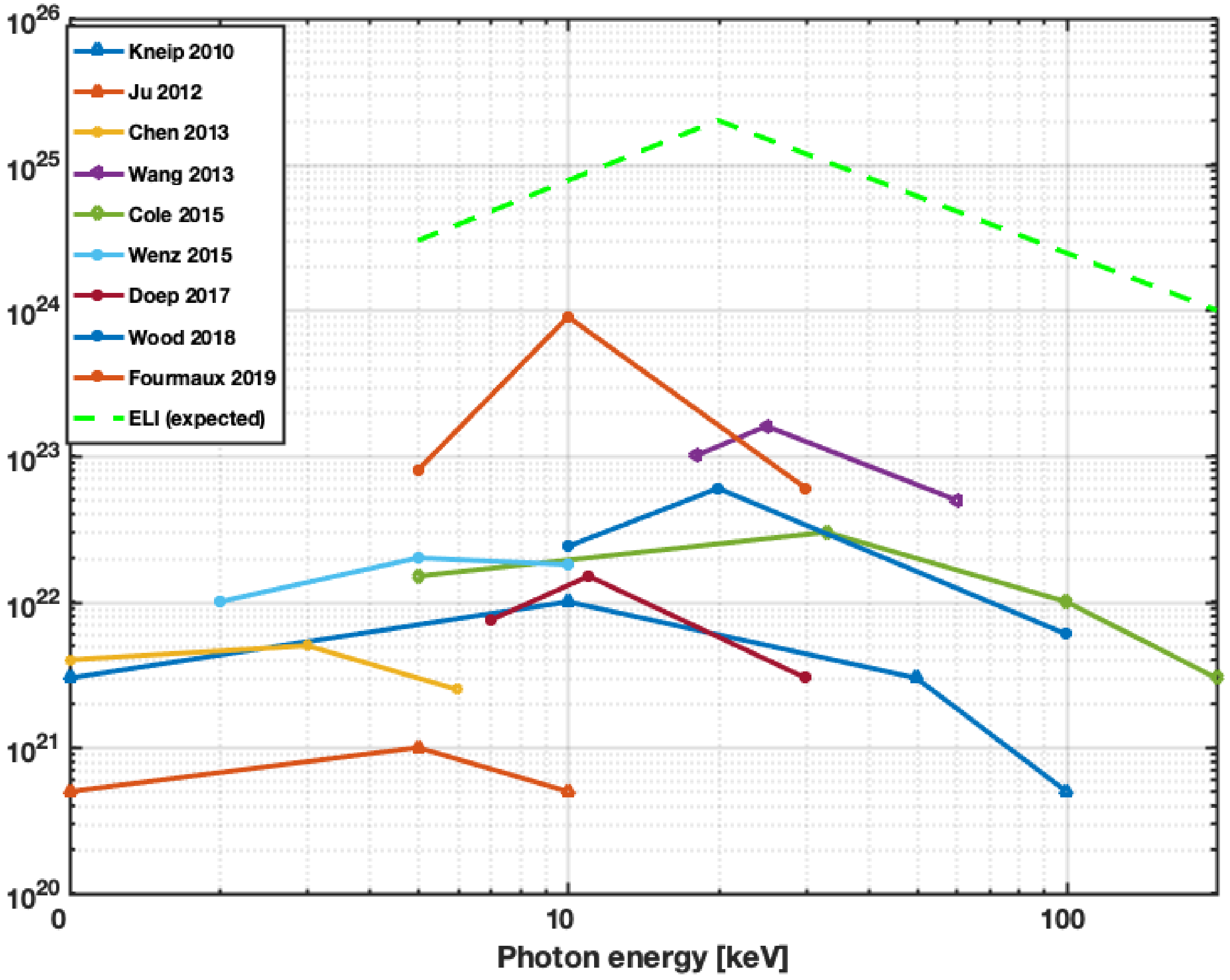
Density isosurfaces of gas jets from 1 mm in diam. supersonic nozzle with a razor blade

A fourfold increase in the SNR and a factor of 4 improvement of the sensitivity of the gas jet density measurements

Automated station for tomography with unprecedented sensitivity

Summary

- ✓ LPA-based X-rays are **maturing**
- ✓ Energy tunable X-ray source with fs duration and jitter-free synchrotron with the driving laser
- ✓ Wide range of applications
  - Imaging/Tomography
  - Time-resolved X-ray Absorption/emission spectroscopy
  - X-ray diffraction
  - and more..



Chaulagain et al. Photonics 2022, 9(11), 853 (2022)

ELI Gammatron beamline hopes to provide some milestones along the way, along with exploiting their wide spectrum of applications

Thank you for your attention!

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