7th European Advanced Accelerator Conference

EAAC2025

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Physics and Application of the ELI Betatron Radiation Source

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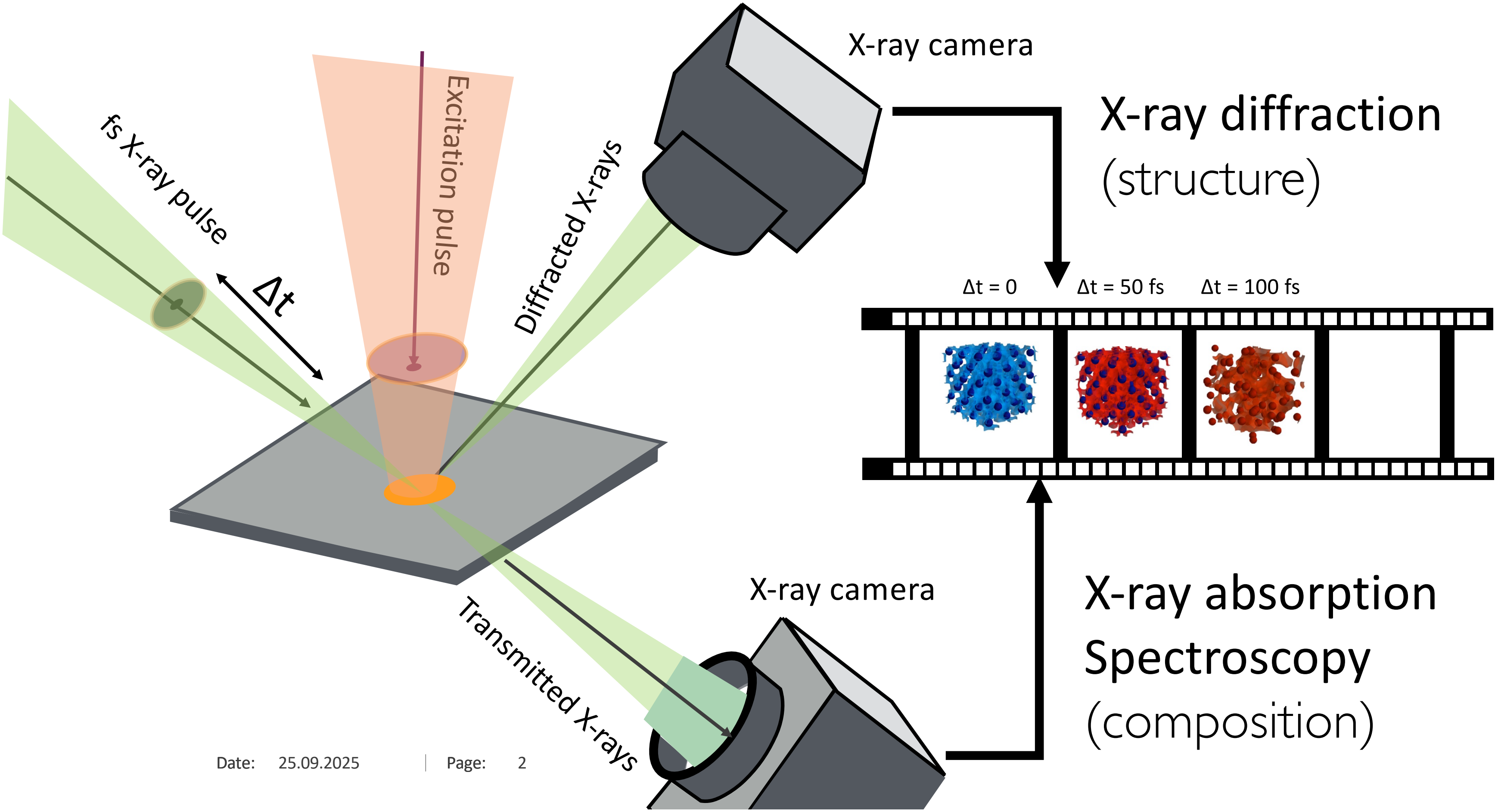
Date: 25.09.2025

Short pulse X-rays for fundamental Science: Atomic & electronic structures



Applications:

- Physics
- Chemistry
- Biology
- WDM and more…

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Needs for short “bright” X-ray pulses

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

- Photons: High flux- high SNR or high magnification
- $\text{mm}^2 \times \text{mrad}^2$: Small source size - high resolution imaging
- s: Look at ultra-fast processes
- 0.1% bandwidth: Important for structural studies (diffraction, scattering)

Bright X-ray sources →

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

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

Low divergence, small source size, short duration → laser based X-ray sources

Synchrotron (> 10 ps)

X-ray Free electron laser (>10 fs)

One of the ELI missions:

Develop and deploy compact alternatives laser-based X-ray sources for scientific and societal application

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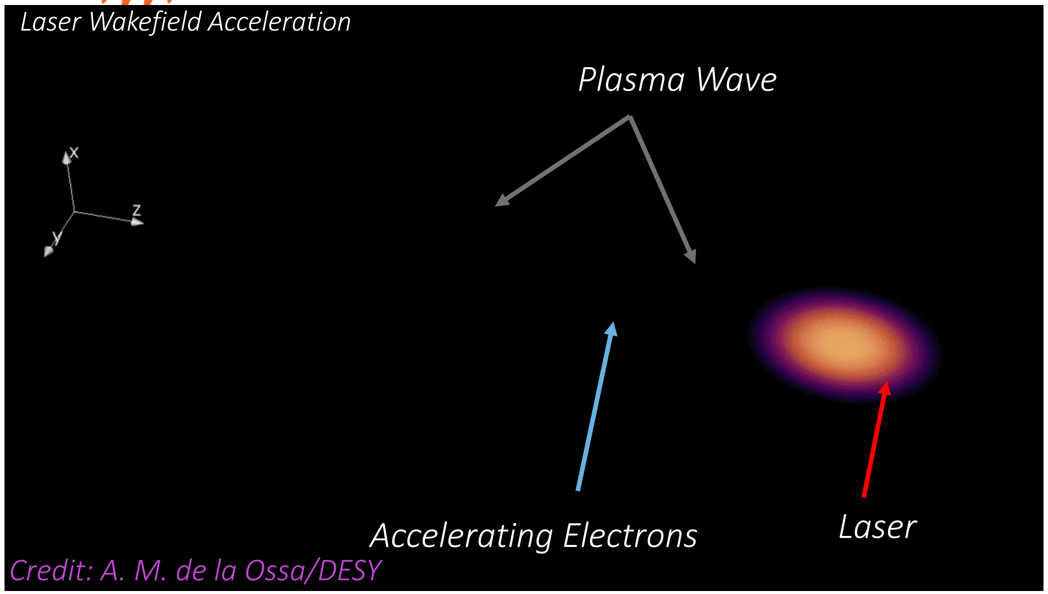
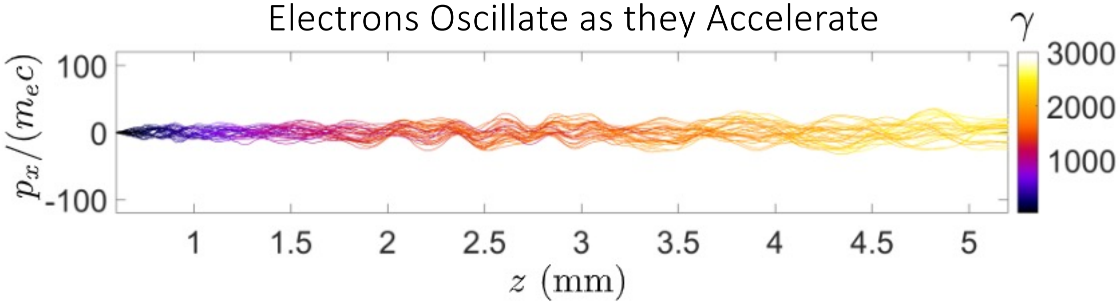
Laser plasma accelerator based Betatron X-ray source





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

Betatron radiation is like Synchrotron radiation. It is a moving charge radiation

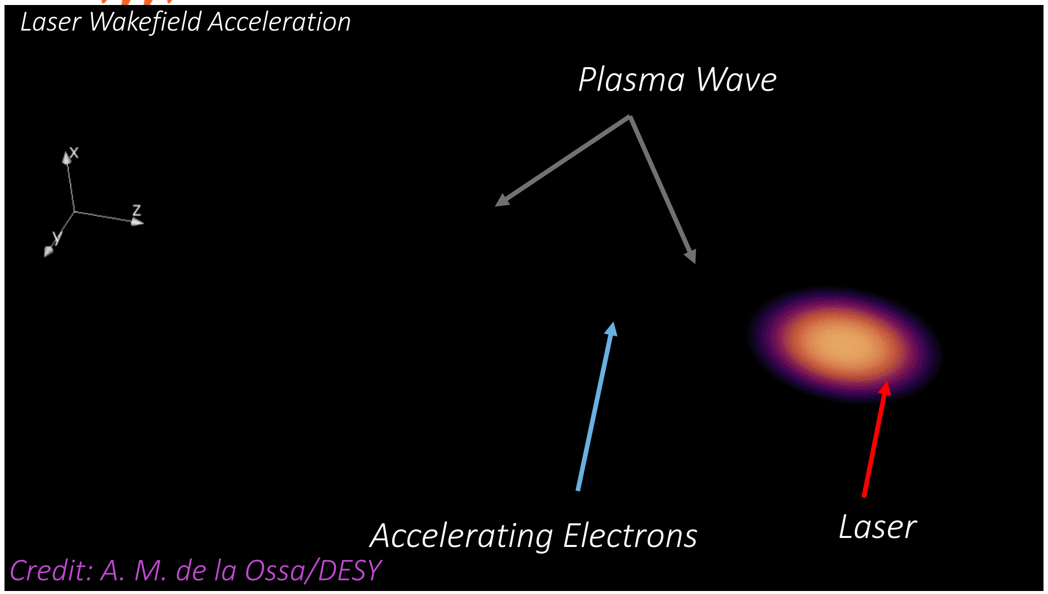
Velocity — Acceleration

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

Radiated energy — Position

- 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.

Laser plasma accelerator based Betatron X-ray source



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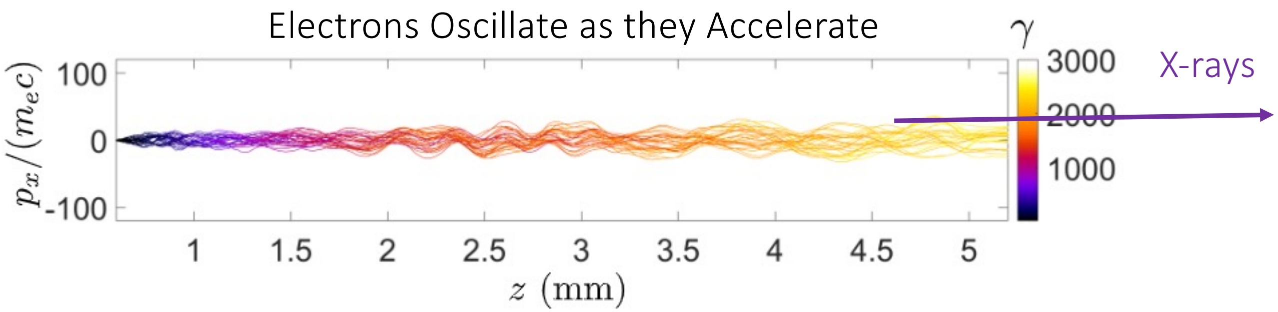
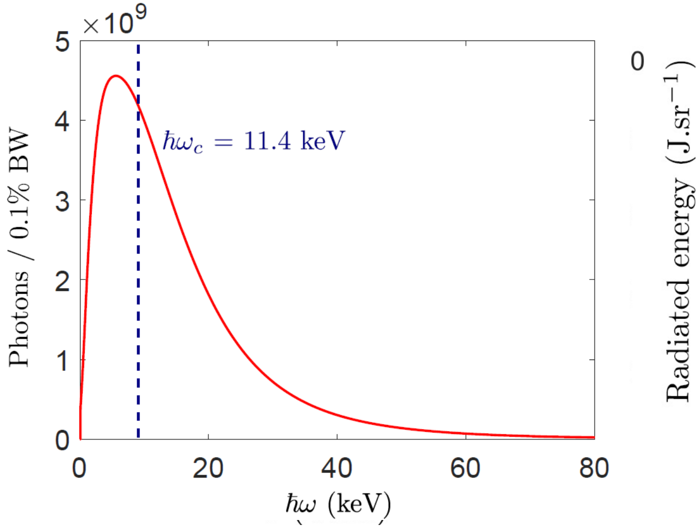
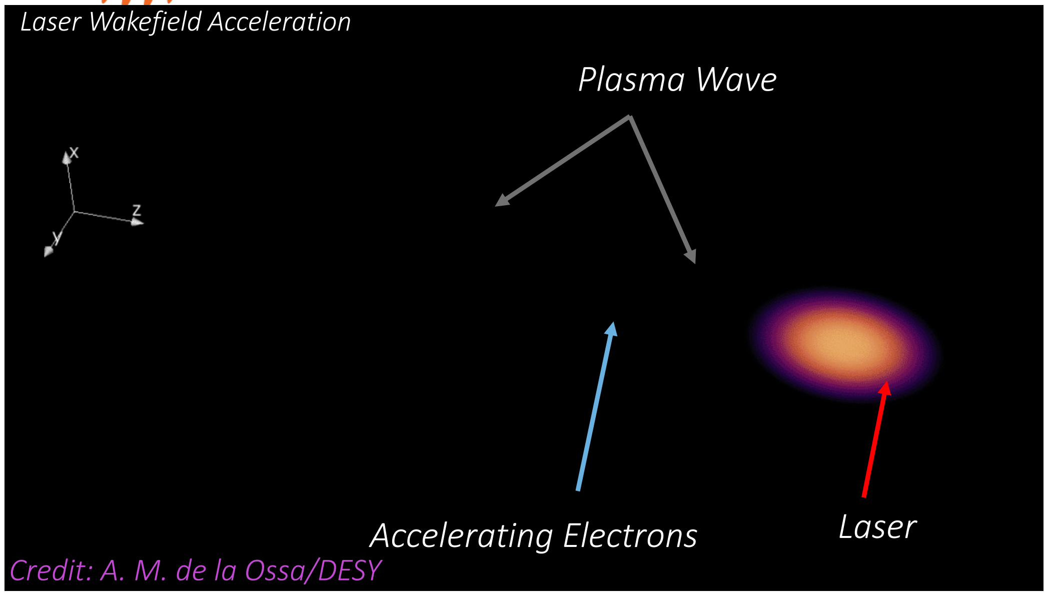
LWFA + transverse oscillations = X-rays





Laser plasma accelerator based Betatron X-ray source



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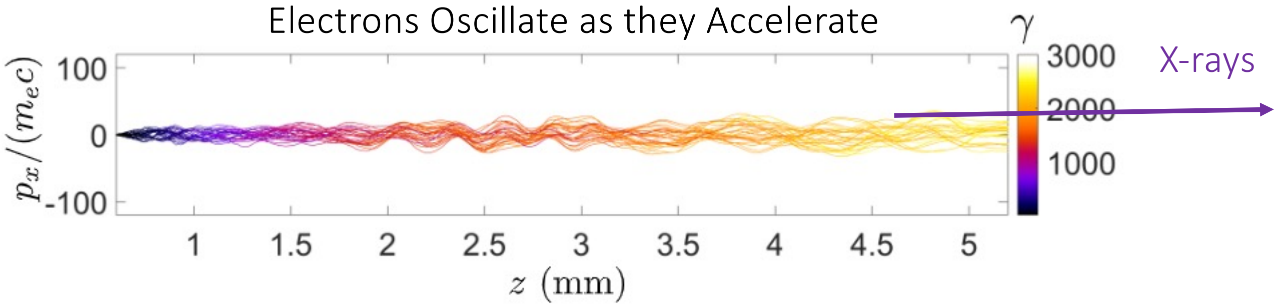

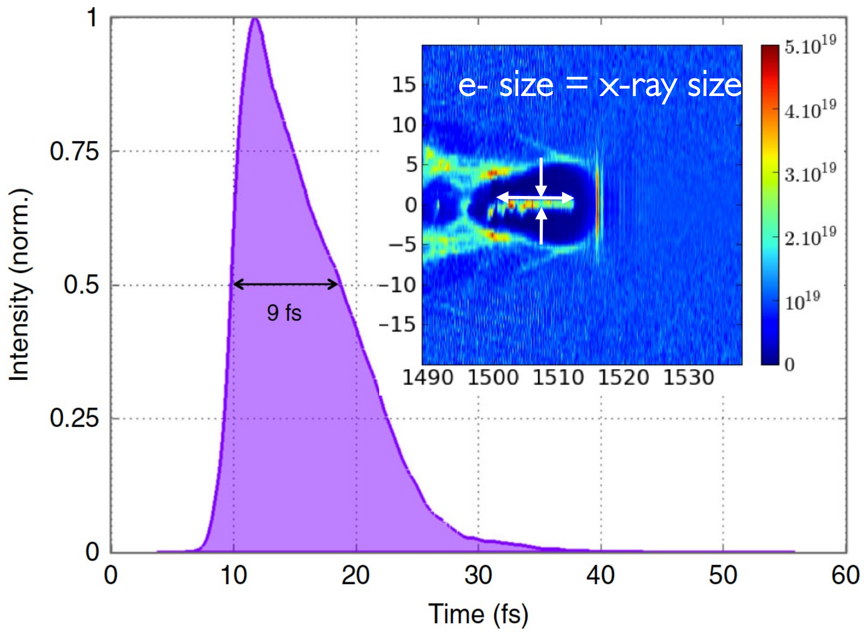

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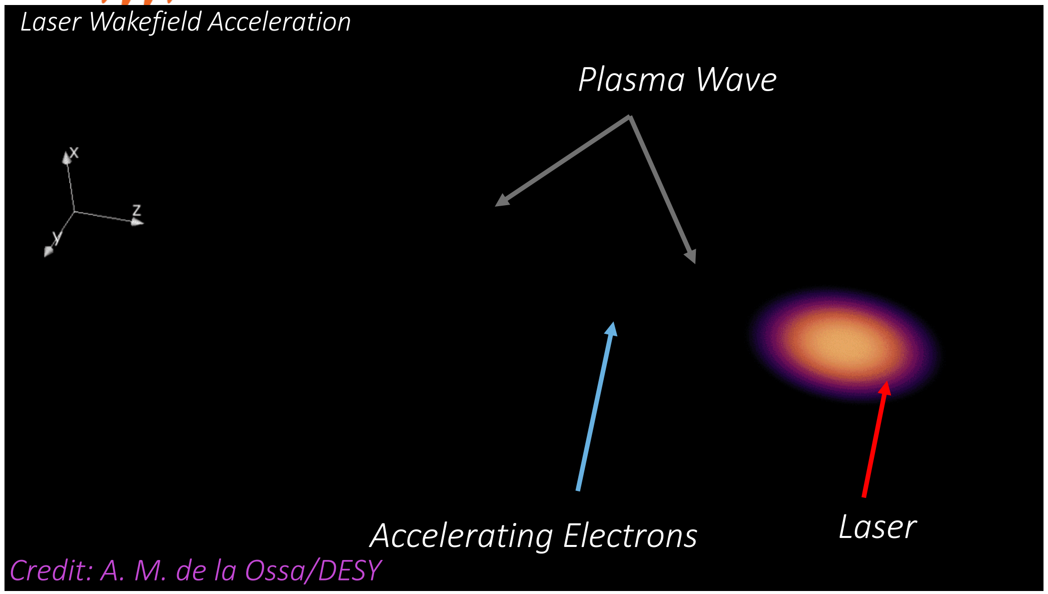
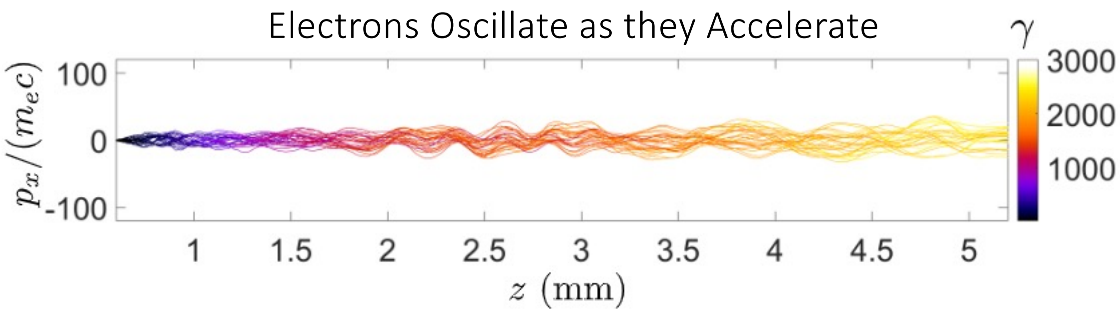
Laser plasma accelerator based Betatron X-ray source





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

LWFA + transverse oscillations = X-rays

X-rays →

- Critical energy:

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

- Total emitted X-ray radiation:

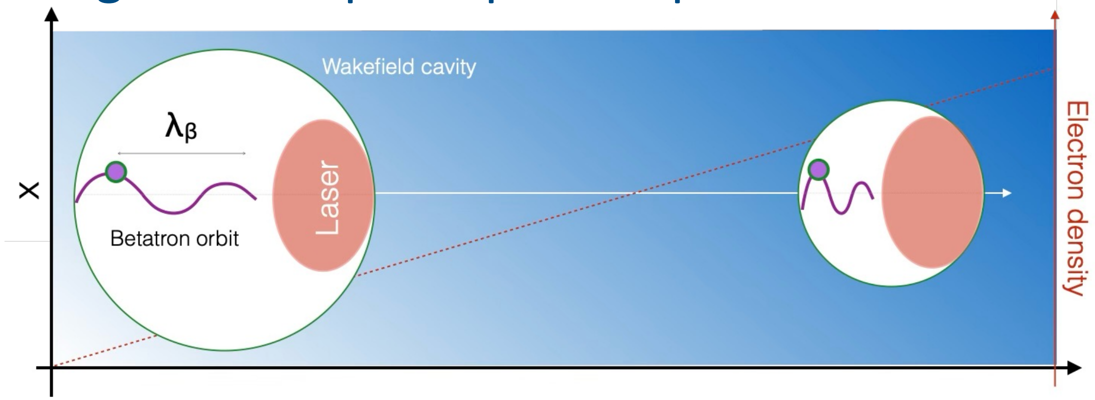
$$W_{tot} \propto Ne\, \gamma^{5/2}\, r_b^2$$

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

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

Advanced plasma Betatron

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

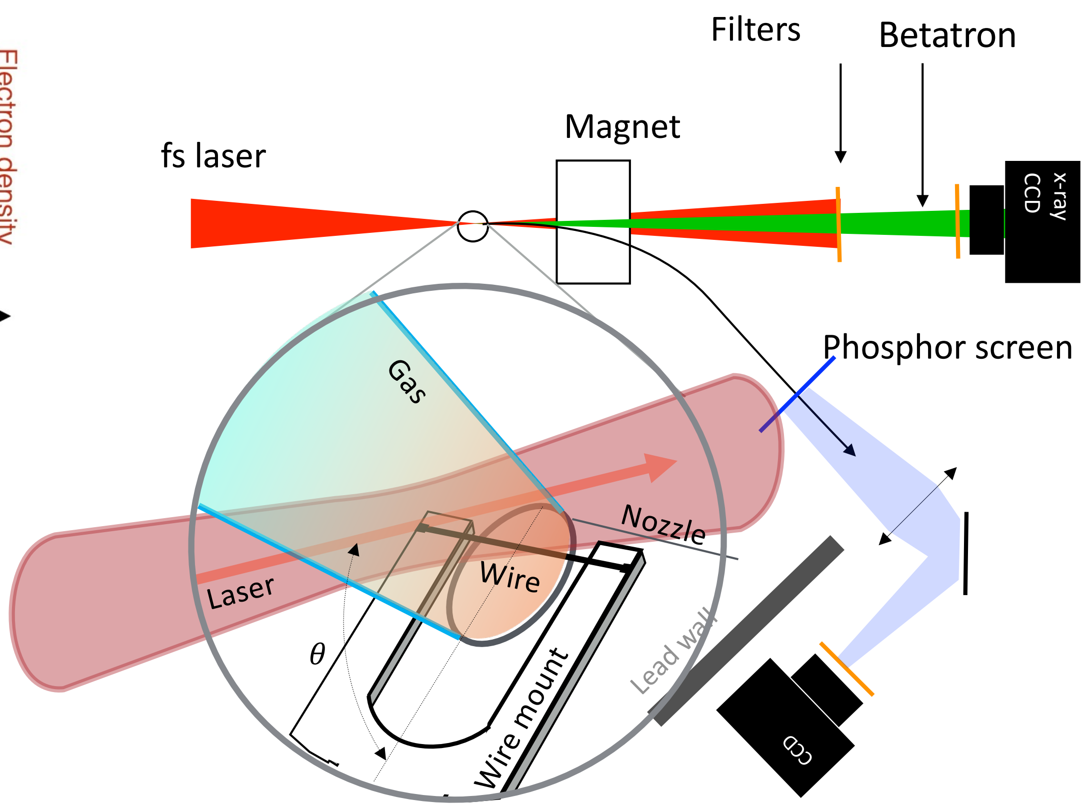


Up- ramp (tilt)

- Electrons remain for longer at the back of the cavity. The energy of the e^- is increased.
- The oscillation periods of electrons is reduced.

Inclusion of wire (shock)

- Shock formation causing strong increase of the transverse oscillation amplitude



Kozlova et al. PRX 10, 011061 (2020)

Advanced plasma Betatron

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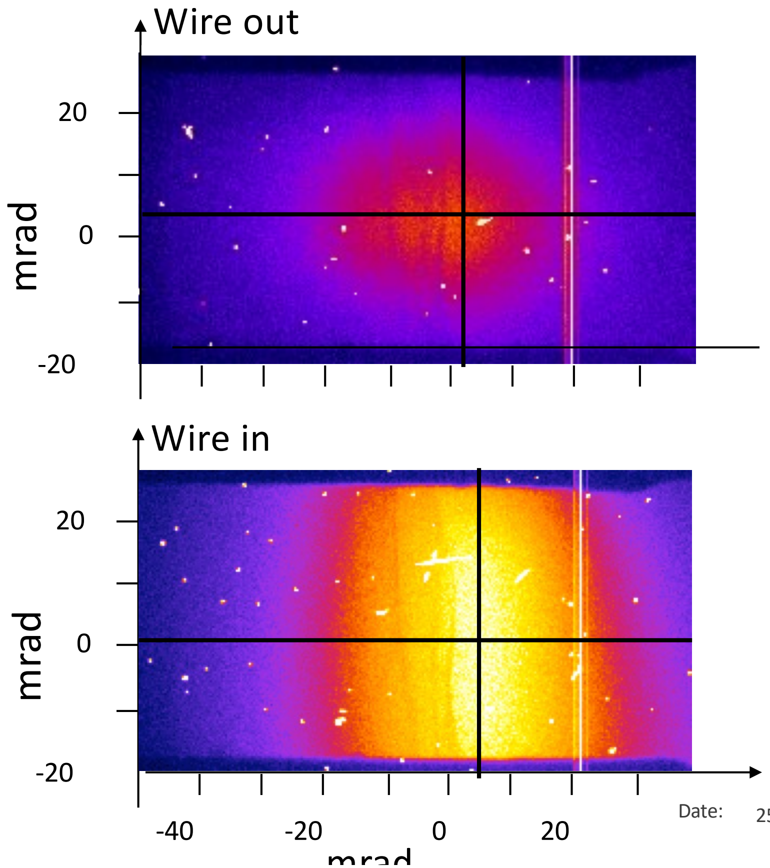
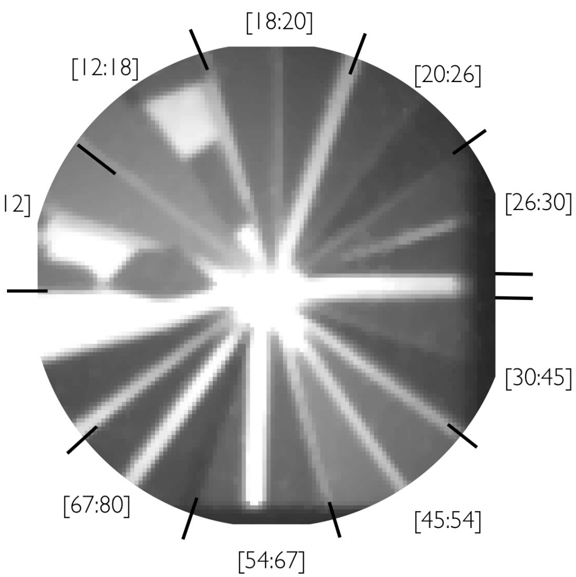
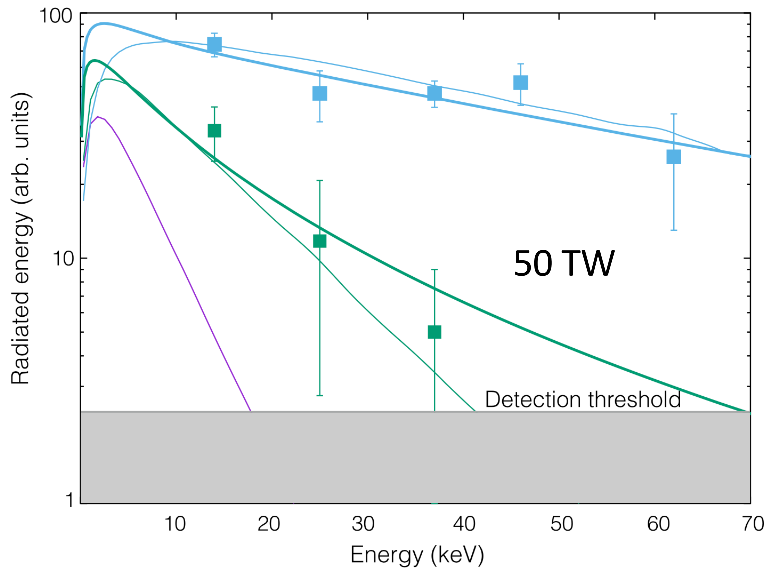






Date: 25.09.2025

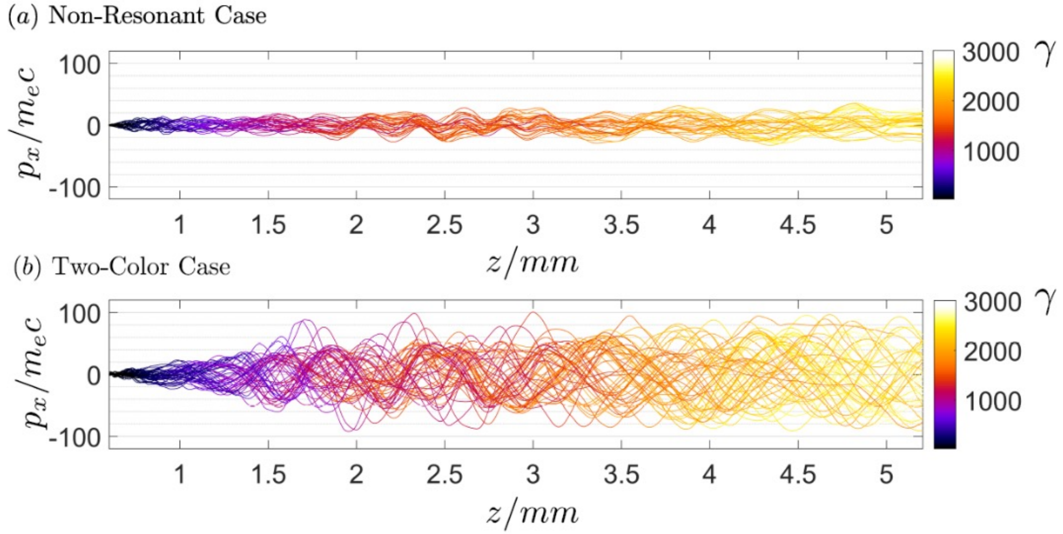
- Increase of the electron energy (x 1.5)
- Increase of the Betatron oscillation amplitude (>2)
- Shift of the spectrum towards higher energies
- Significant increase of critical energy (x 5) & photon flux (x 20)

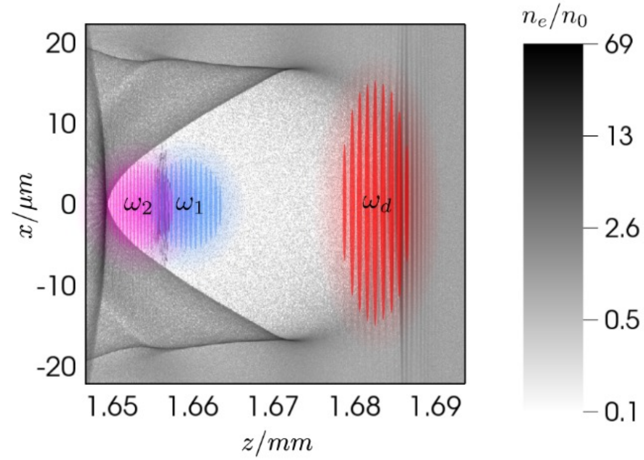
Kozlova et al. PRX 10, 011061 (2020)

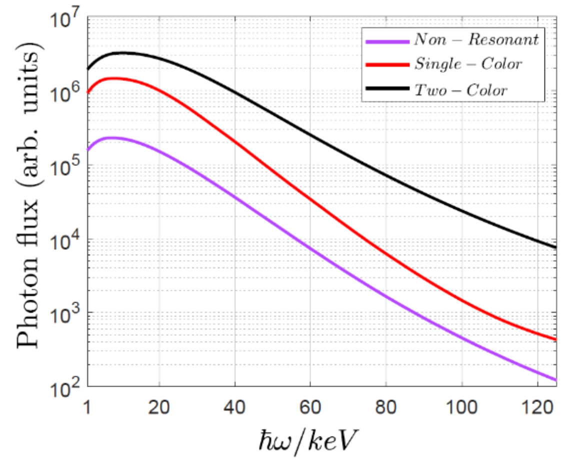
Two-color nonlinear resonances in plasma betatron

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

Advanced plasma Betatron





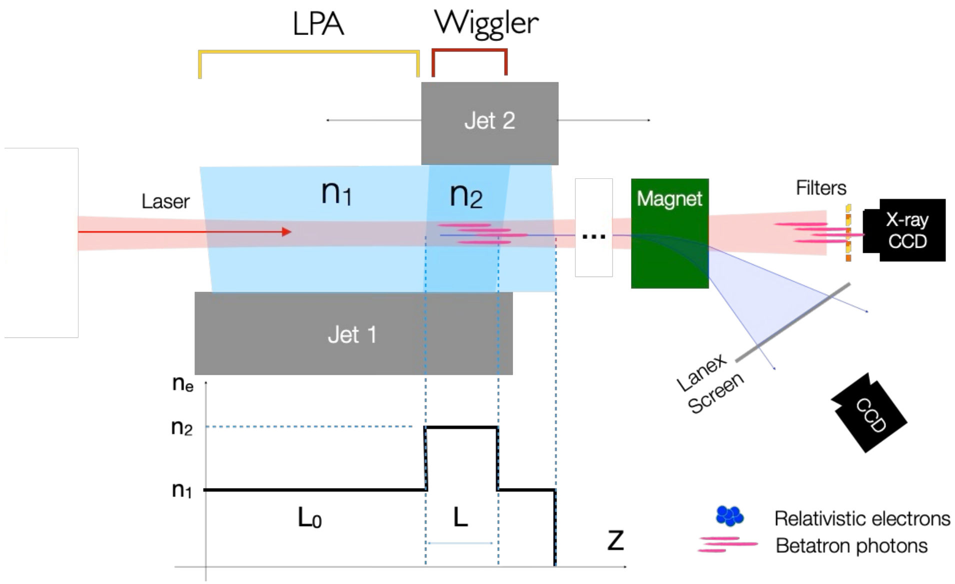


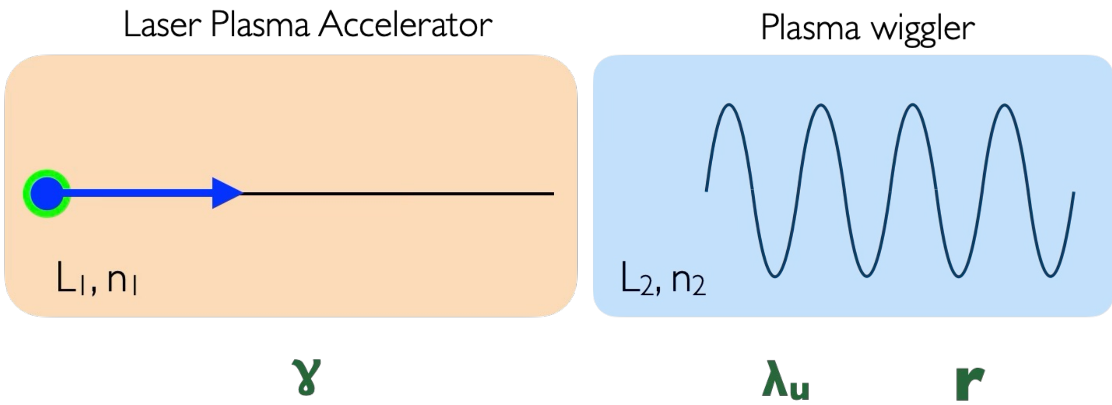
Lamač et al., PRR. 3, 033088 (2021)

Decoupling Acceleration and wiggling

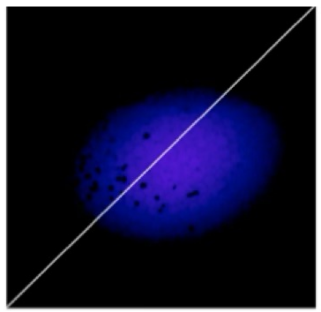
Advanced plasma Betatron

- This would offer allows us to optimize independently acceleration and wiggling.
- Control of the Betatron radiation properties

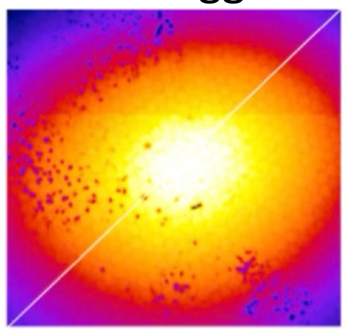




First stage : optimized Laser Plasma Accelerator
Second stage : optimize Plasma Wiggler



One Jet



Double Jets

Ferri et al. PRL, 120.25 (2018), Zhu et al., Sci. Adv. 6,7.240 (2020), Gautier et al. PoP, 32.8 (2025)

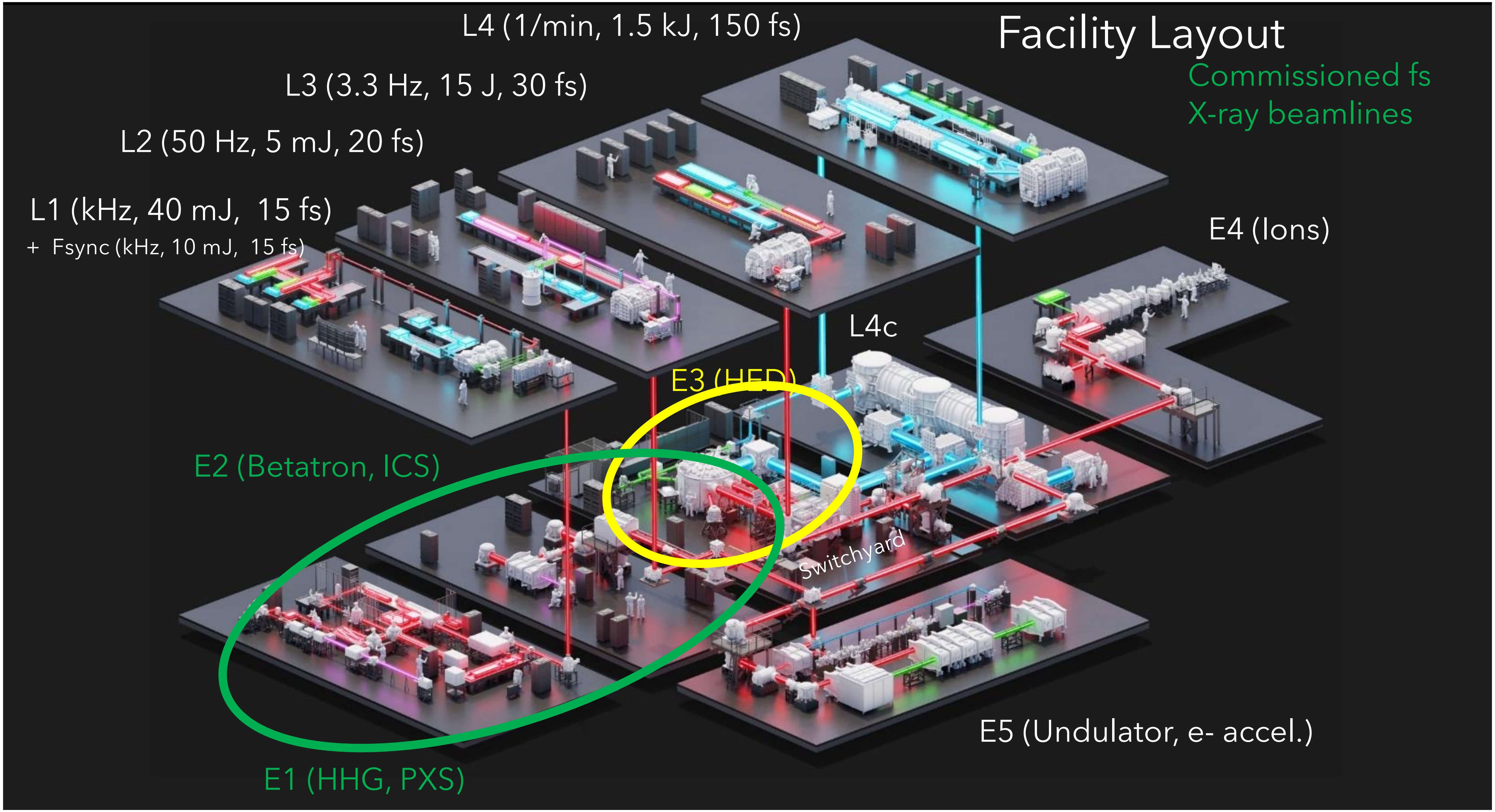
Betatron X-ray source

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's keV (depends on driving laser)
- ✓ source size: 1- 2 microns
- ✓ 10% flux variation
- ✓ 10% energy variation
- ✓ Polarisation tunable (!)

Combine unique features for wider applications:

Broad spectrum & fs duration, micron source size


Facility Layout
Commissioned fs X-ray beamlines
L4 (1/min, 1.5 kJ, 150 fs)
L3 (3.3 Hz, 15 J, 30 fs)
L2 (50 Hz, 5 mJ, 20 fs)
L1 (kHz, 40 mJ, 15 fs)
+ Fsync (kHz, 10 mJ, 15 fs)
E4 (Ions)
L4c
E3 (HED)
E2 (Betatron, ICS)
Switchyard
E5 (Undulator, e- accel.)
E1 (HHG, PXS)

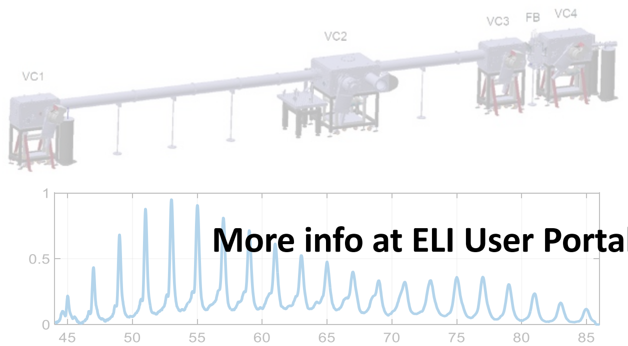
Laser driven X-ray sources: several approaches

E1

L1 driver
1 kHz, 100 mJ, 20 fs

Ti:sapphire backup
1 kHz, 12 mJ, 35 fs
& 10 Hz, 100 mJ, 40 fs

High-order harmonic beamline



More info at ELI User Portal: https://up.eli-laser.eu

	Legend: 10 mJ, 35 fs	L1 Allegra: >20 mJ, ~15fs
Wavelength	10 -120 nm	5 -120 nm
Photons/shot	10^7 to 10^9	few 10^9 -10^{12}
Duration	< 20 fs	< 10 fs
Polarization	Linear	Lin./Circ./Eliptic

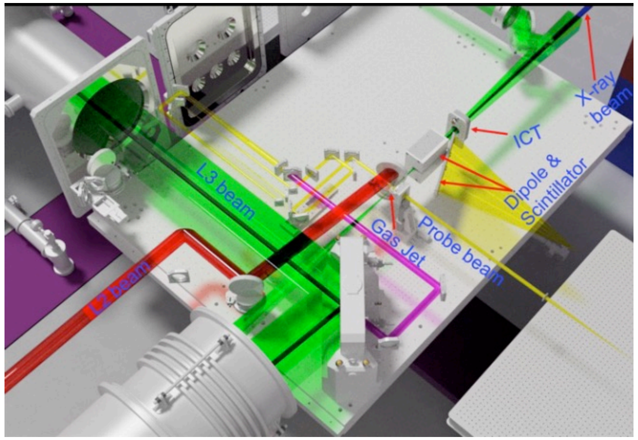
Plasma X-ray source

	10 mJ, 35 fs	20 mJ, 15 fs
photon energy	3 - 40 keV	3 – 80 keV
Kα photons /shot/(4π sr)	> 10^8	> 10^9
Source size	30 μm	30 μm
pulse duration	< 300 fs	<300 fs

E2/E3

L3 driver
10 Hz, 30 J, 30 fs

Betatron / inverse Compton



	Betatron	ICS
photon energy	10- 100 keV	50 – 5000 keV
photons/shot	> 10^9	> 10^8
Source size	< 5 μm	< 5 μm
pulse duration	~30 fs	< 30 fs

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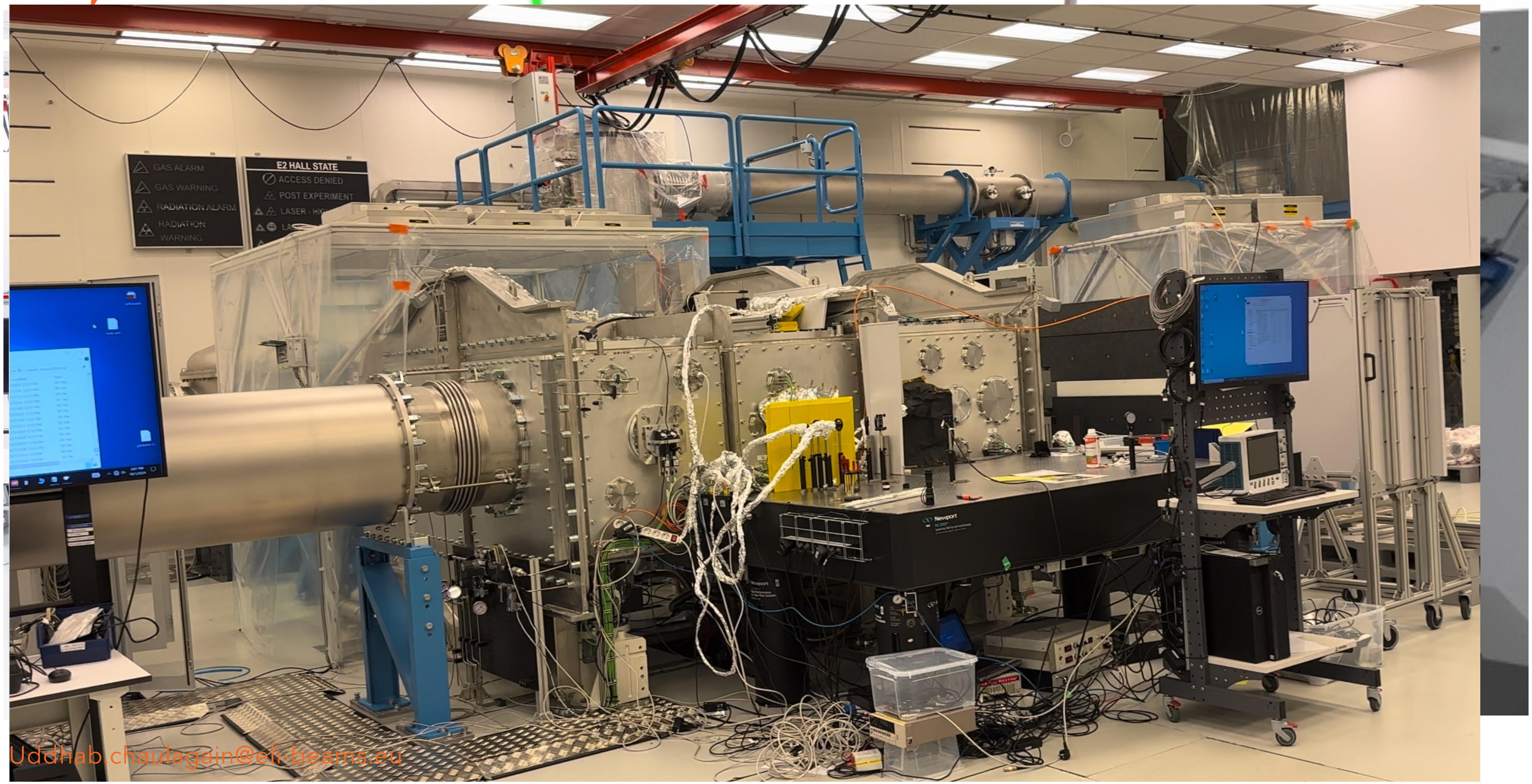
ELI Gammatron Beamline



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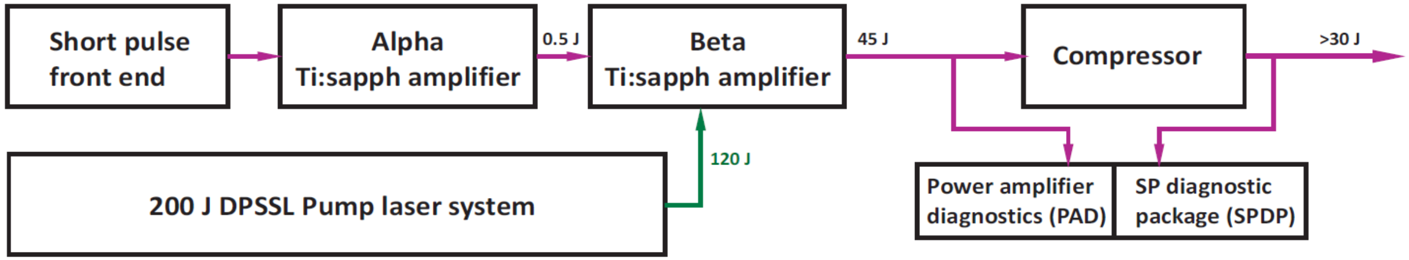
Laser drivers: L3 HAPLS

HAPLS: High repetition rate Advanced Petawatt Laser System



L3-HAPLS with compressor at ELI-Beamlines

Parameter	Design	Current
Peak power	1 PW	**500 TW**
Repetition rate	10 Hz	**3.3 Hz**
Pulse energy	30 J	**15 J**
Pulse duration	30 fs	**30 fs**
Central wavelength	820 nm	

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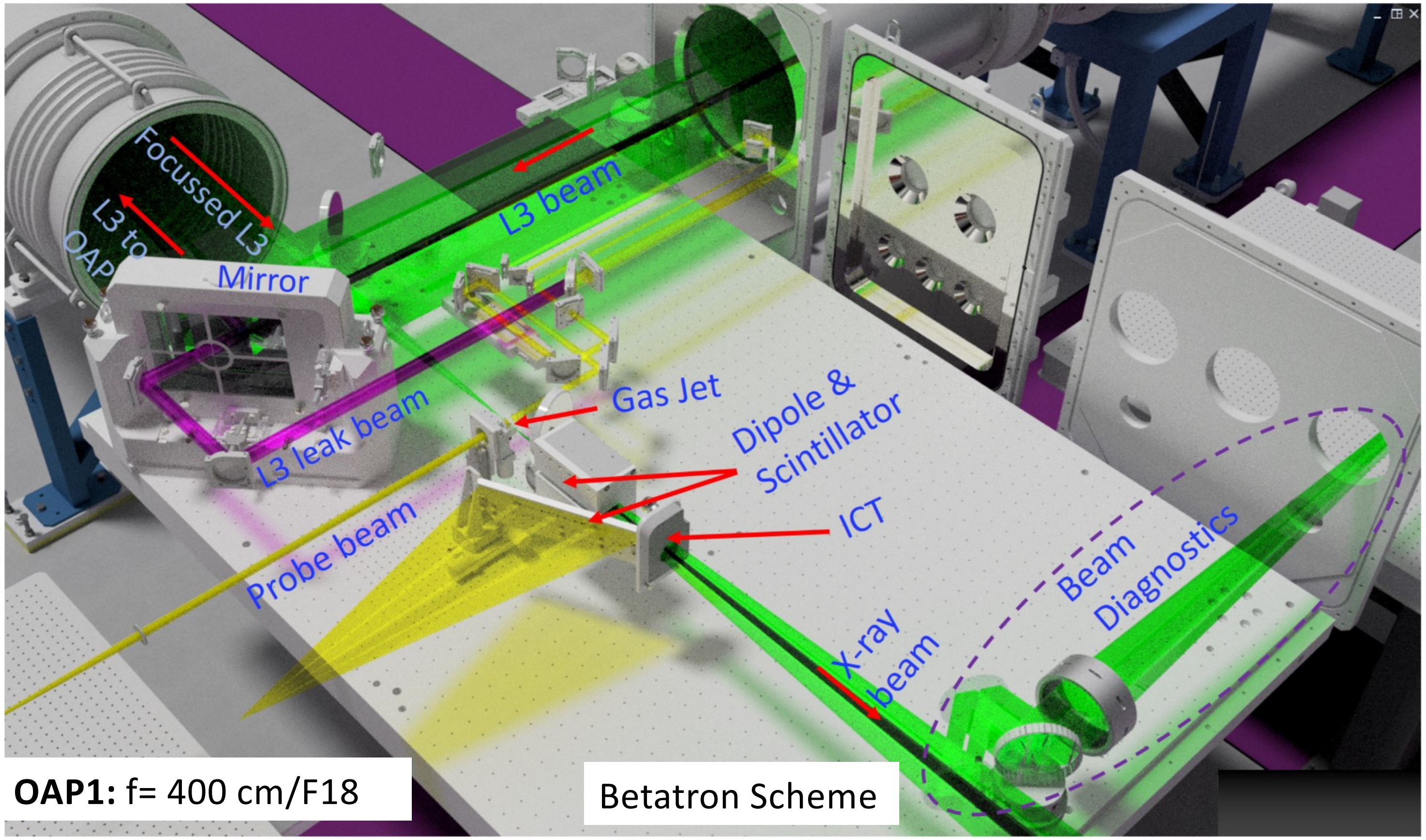
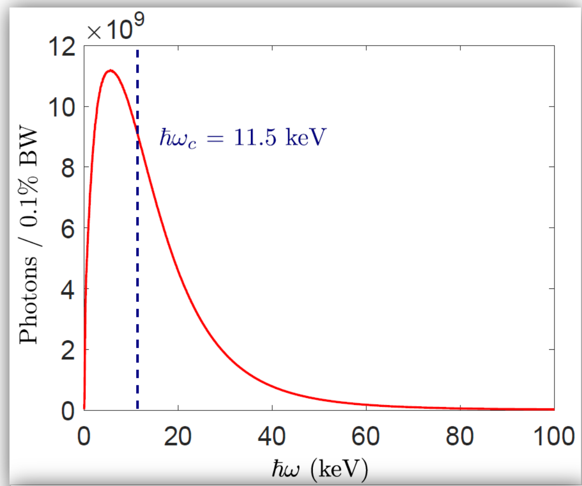
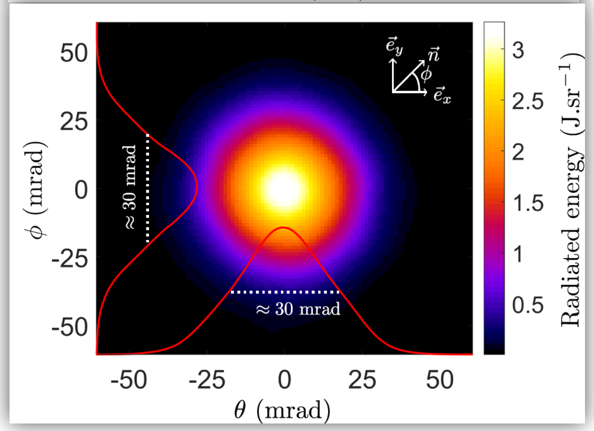
ELI Gammatron Beamline







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

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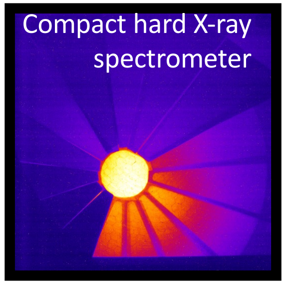
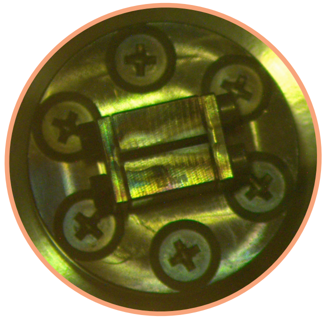
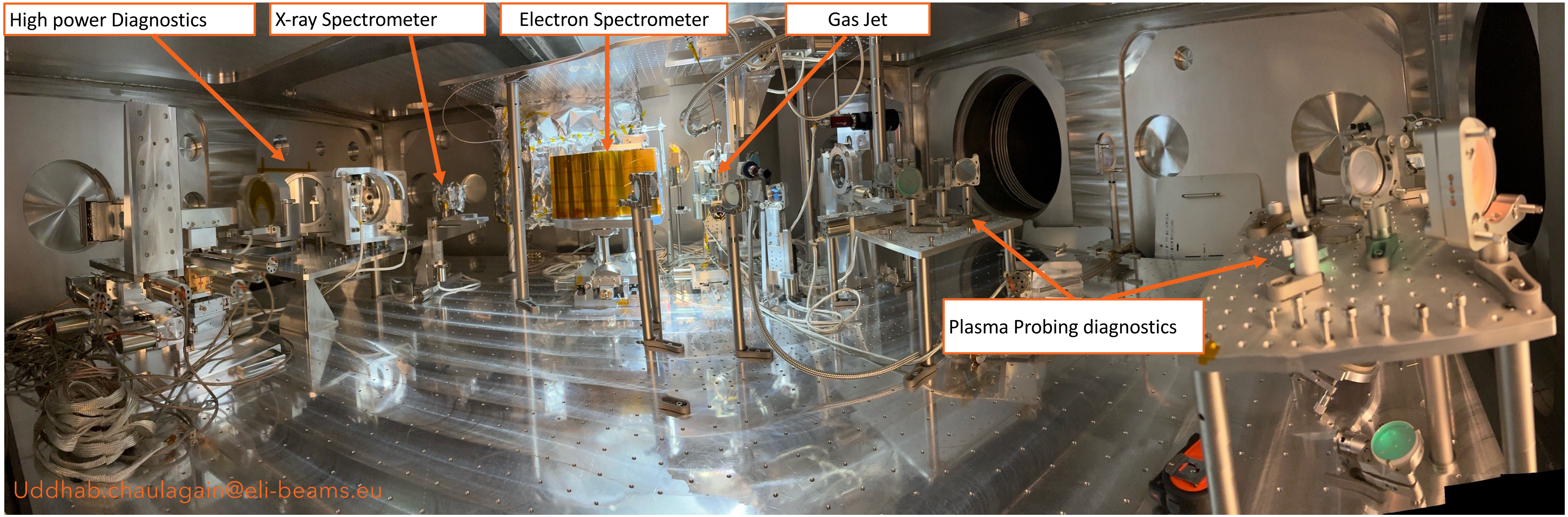




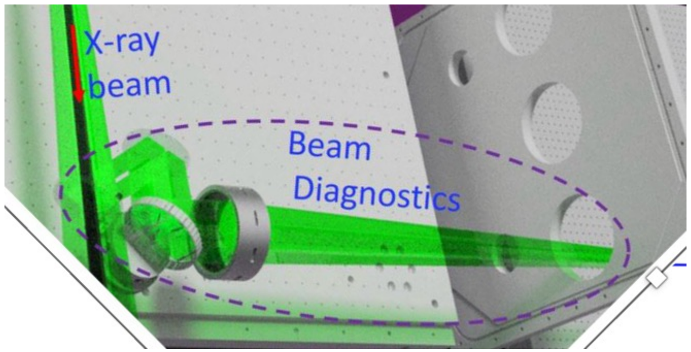


ELI Gammatron Beamline: commissioning results

Laser Parameters

Energy: up to 10 J
Pulse duration: 30-32 fs
Rep rate: Single shot or 0.5 Hz

Focusing Optics,
Off axis Parabolic Mirror
Focal length: 4000 mm
F# = 18



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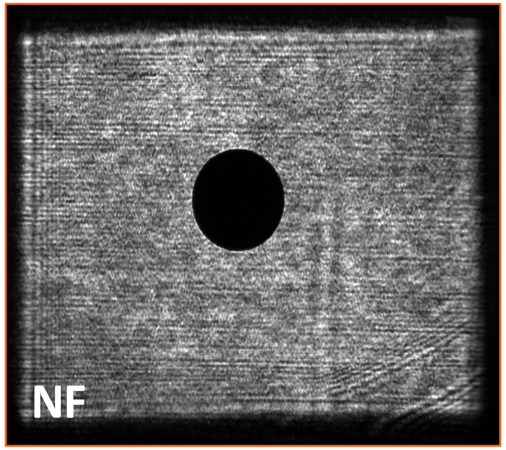
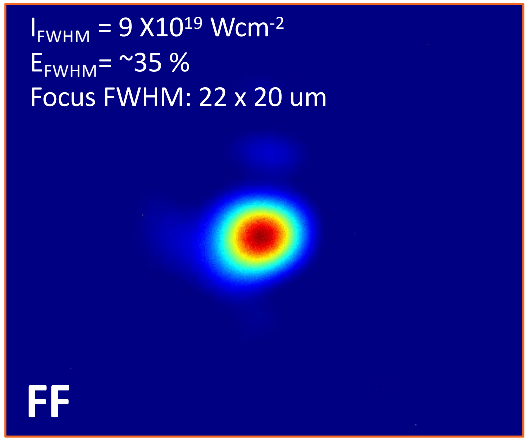
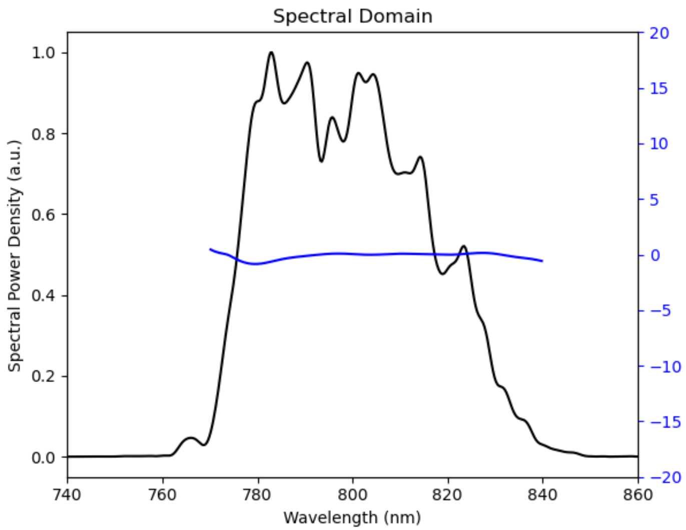
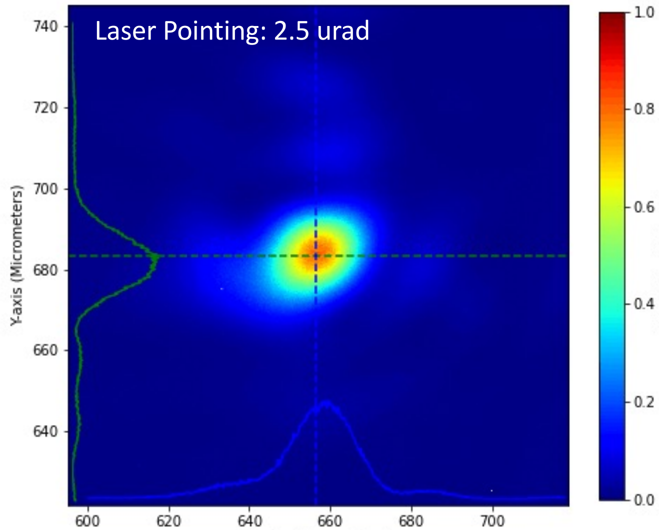
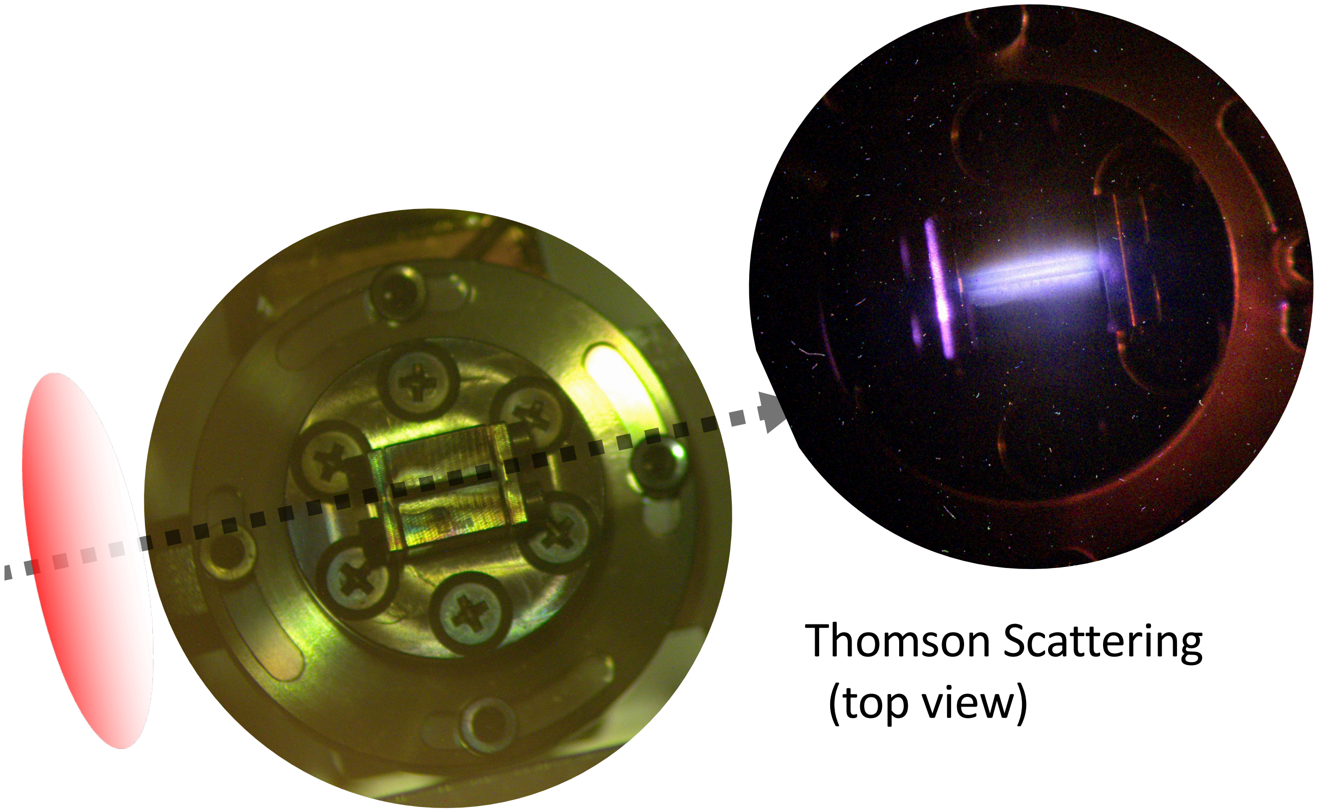




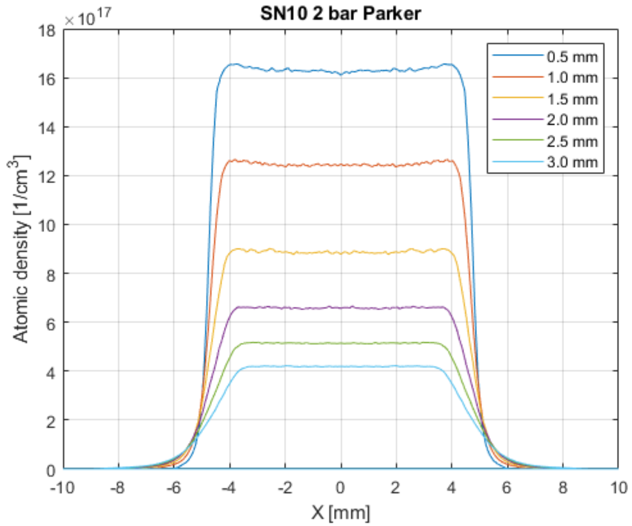




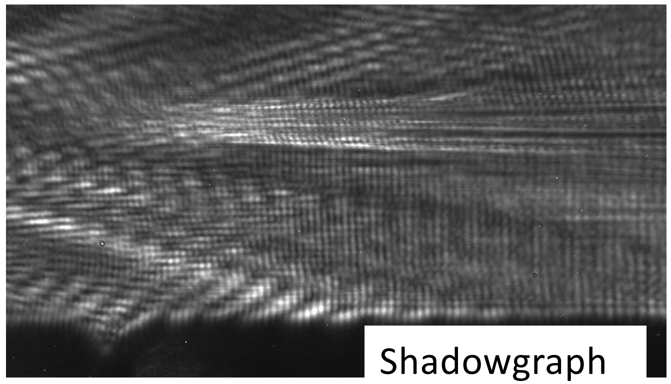
ELI Gammatron Beamline: commissioning results



Thomson Scattering (top view)



Visit Poster: Development of gas targets for laser-plasma accelerators (S. Lorenz)



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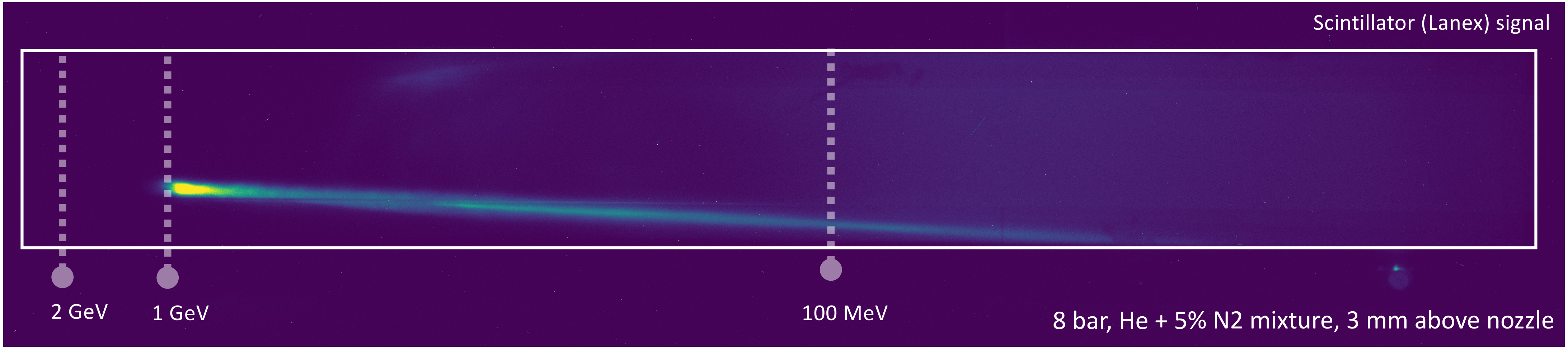
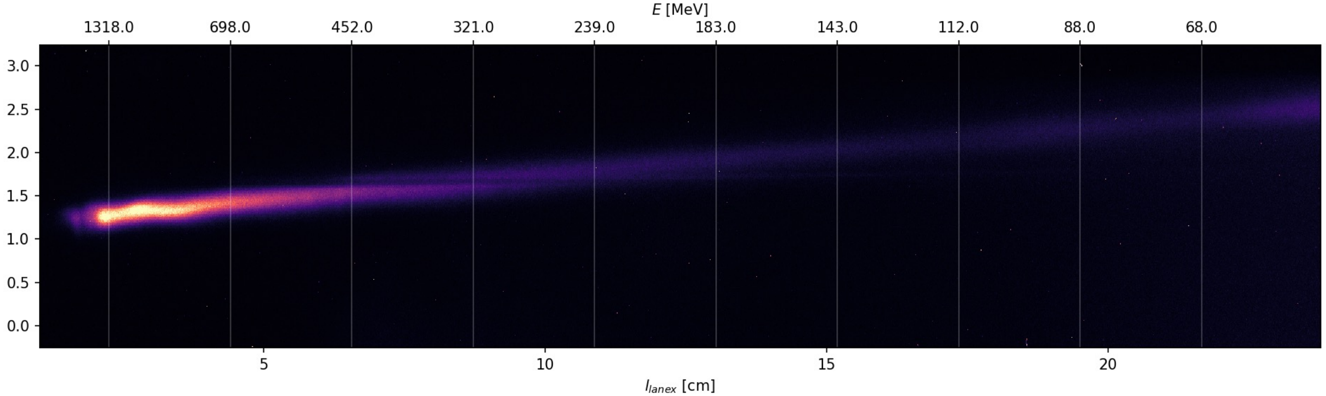
ELI Gammatron Beamline: commissioning results





- Stable GeV electron beam
- Very weak Betatron X-ray beam

=> Increase plasma density to increase K

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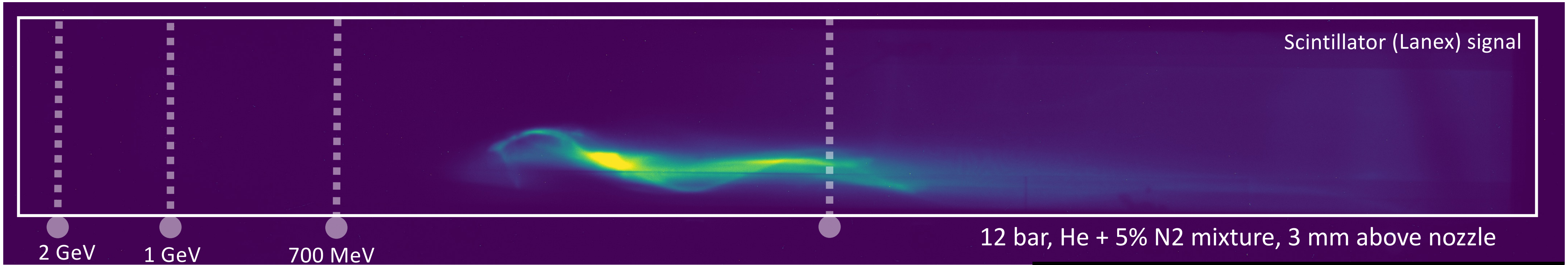
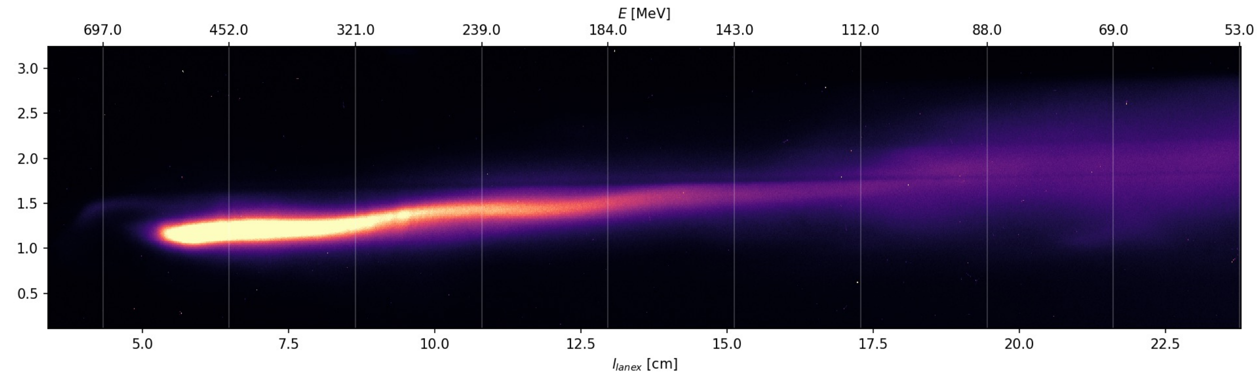
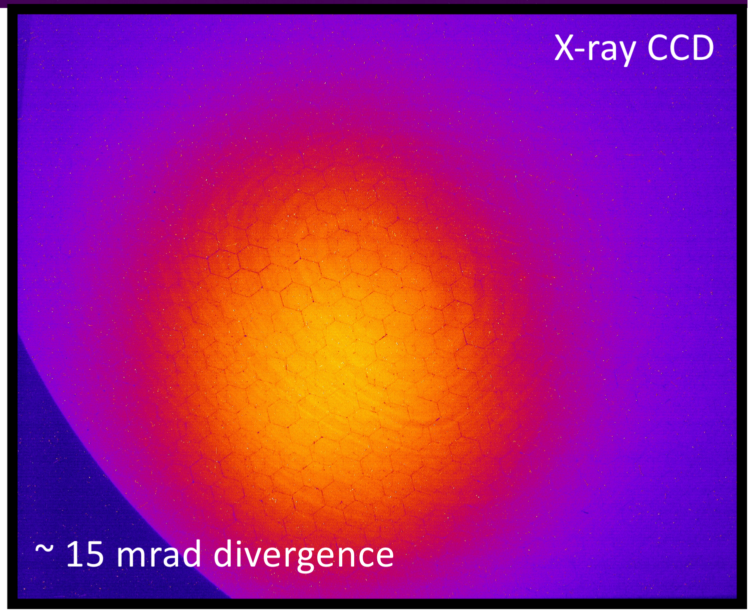
ELI Gammatron Beamline: commissioning results



12 bar, He + 5% N2 mixture, 3 mm above nozzle





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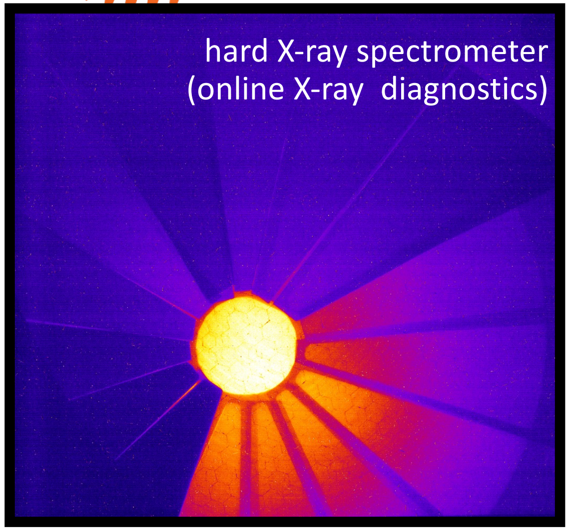
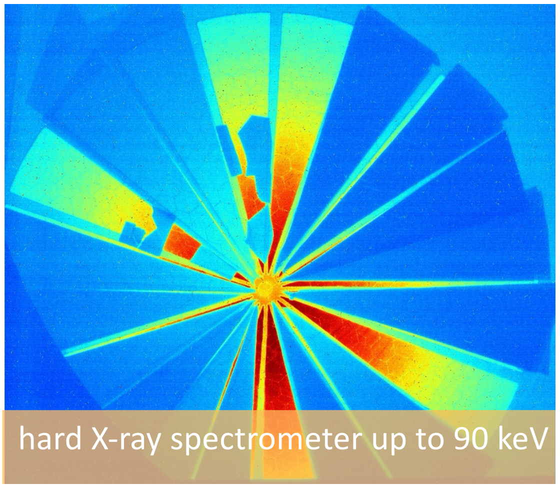
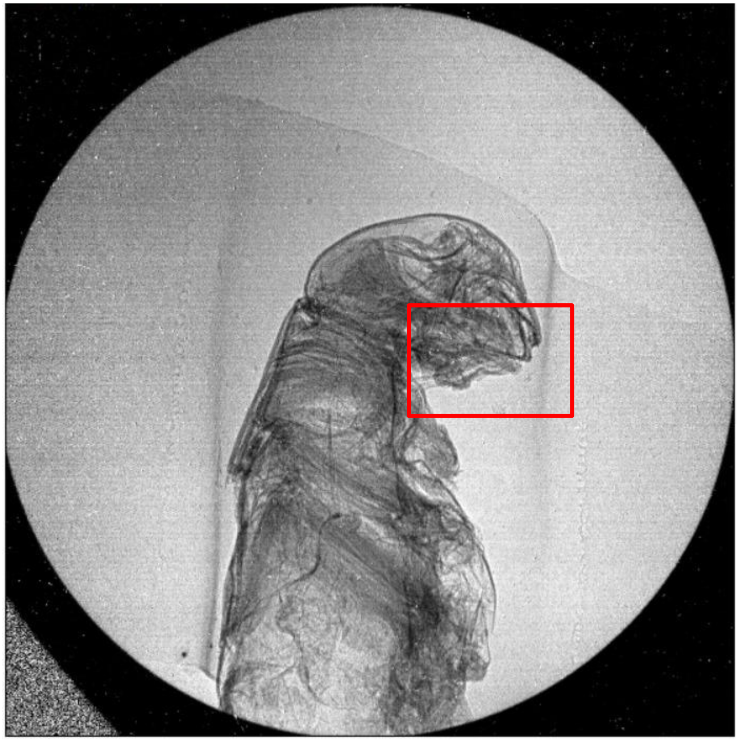
ELI Gammatron Beamline: commissioning results

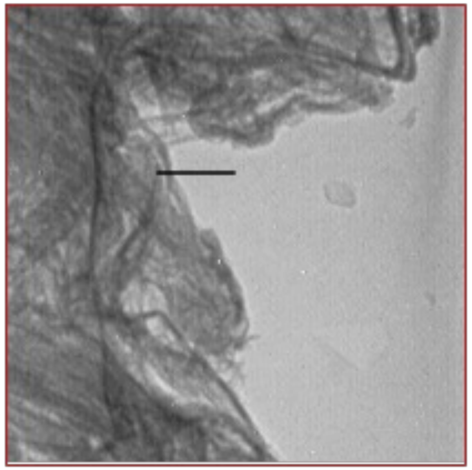


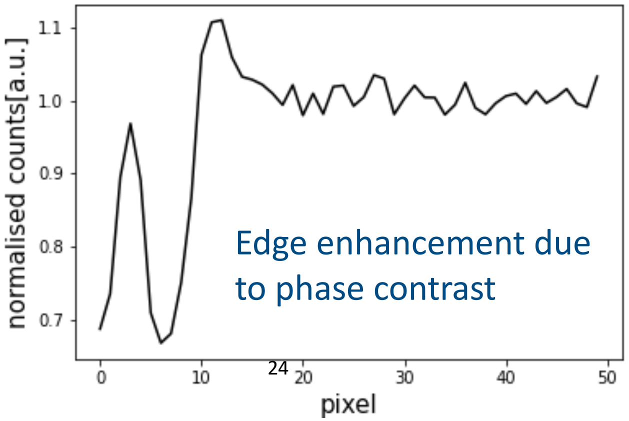


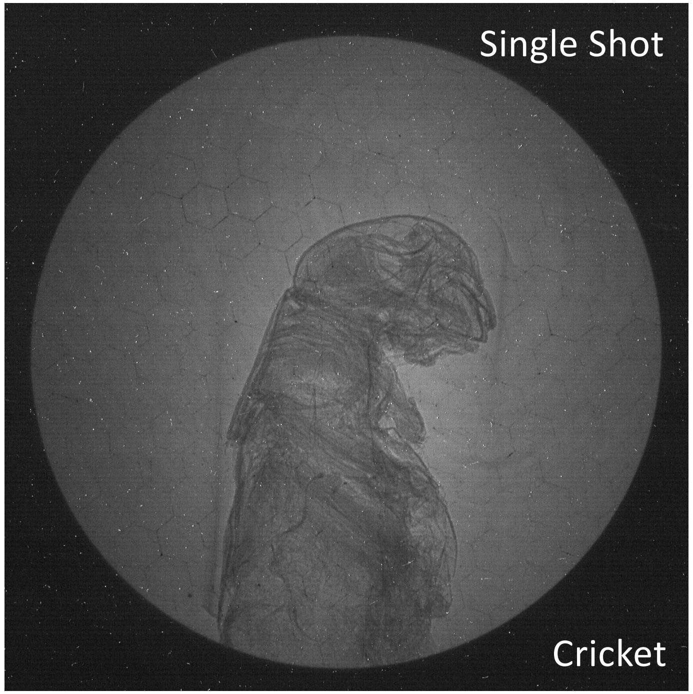
- Stable X-ray Source with a critical Energy over 20 keV
- Small source size (<2 um), small divergence (~15 mrad)
- Total number of Photon ~ 5 x 10^{10} /shot (Direct detection CCD)

ELI Gammatron Beamline: Recent results









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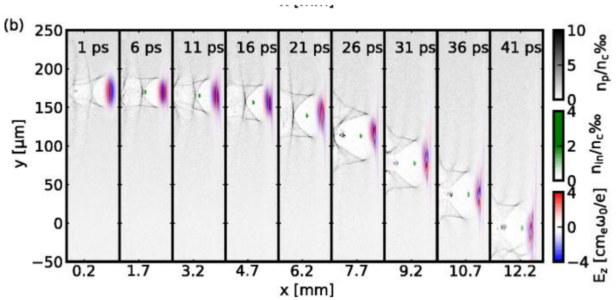
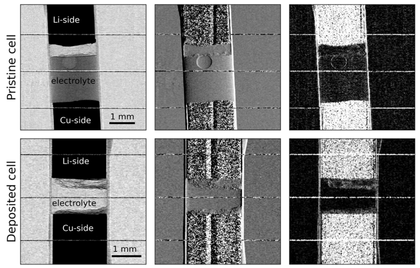
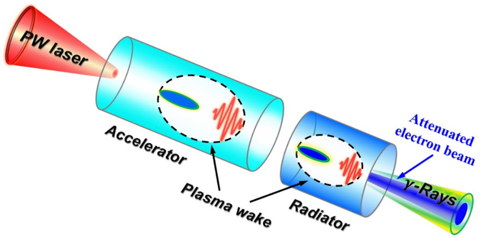
Highlights from users experiments



Ma et al., PRL , 132.22 (2024):225001.

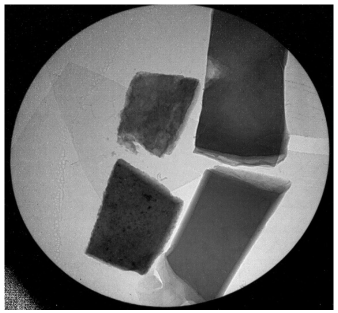


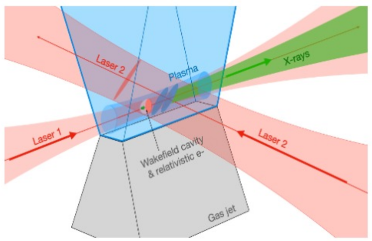
Doherty et al.,Comm. Physics, 2023



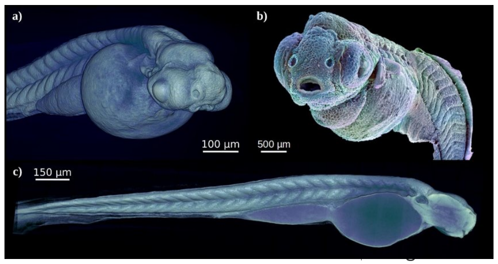
Ferri et al. PRL, 120.25 (2018): 254802

Zhu, et al. Sci. adv. 6.22 (2020): eaaz7240..

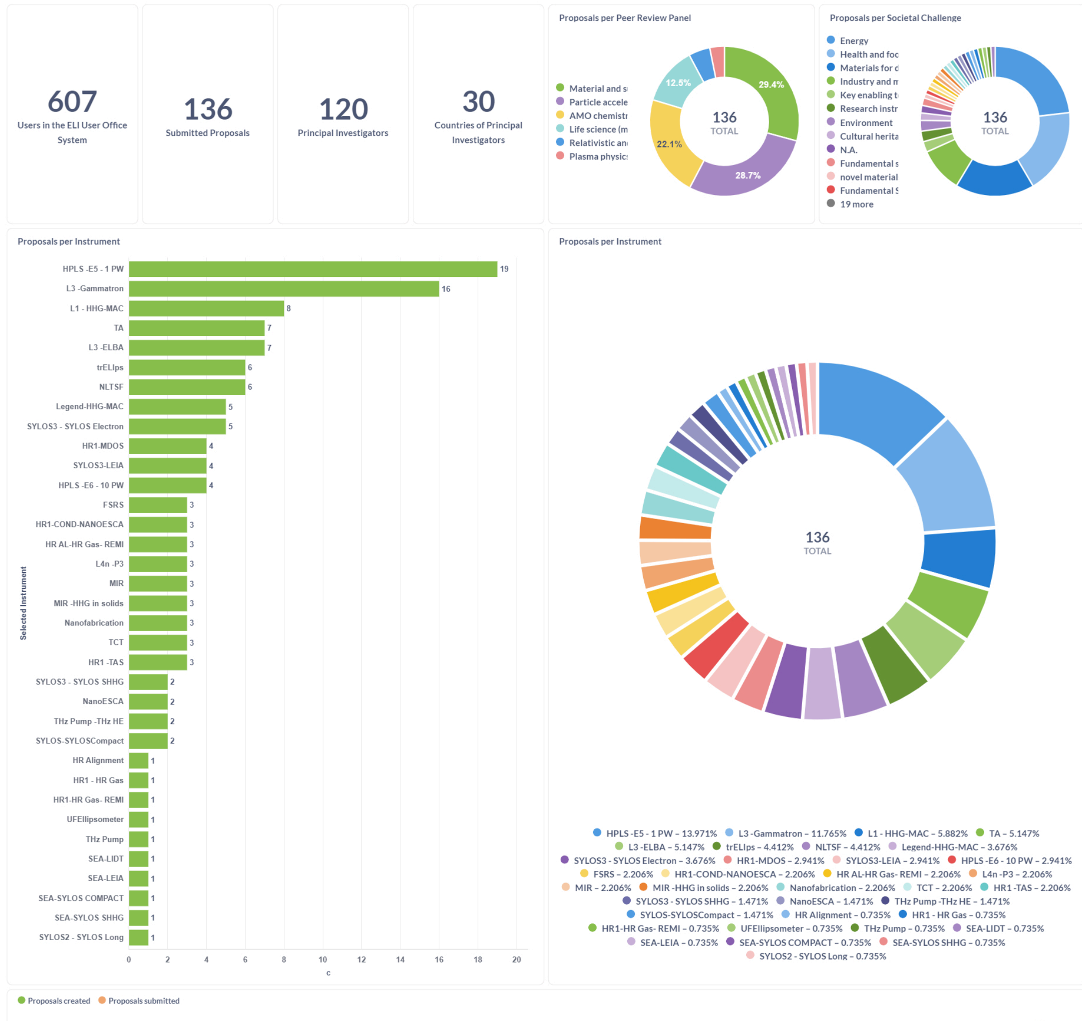




Super betatron Schemes



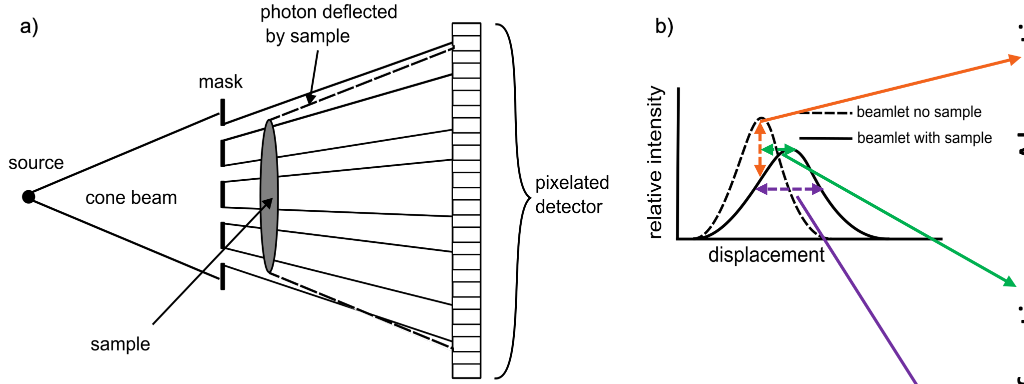
Ferstl et al. *Microsc. Microanal* 24.S2 (2018): 184-185.

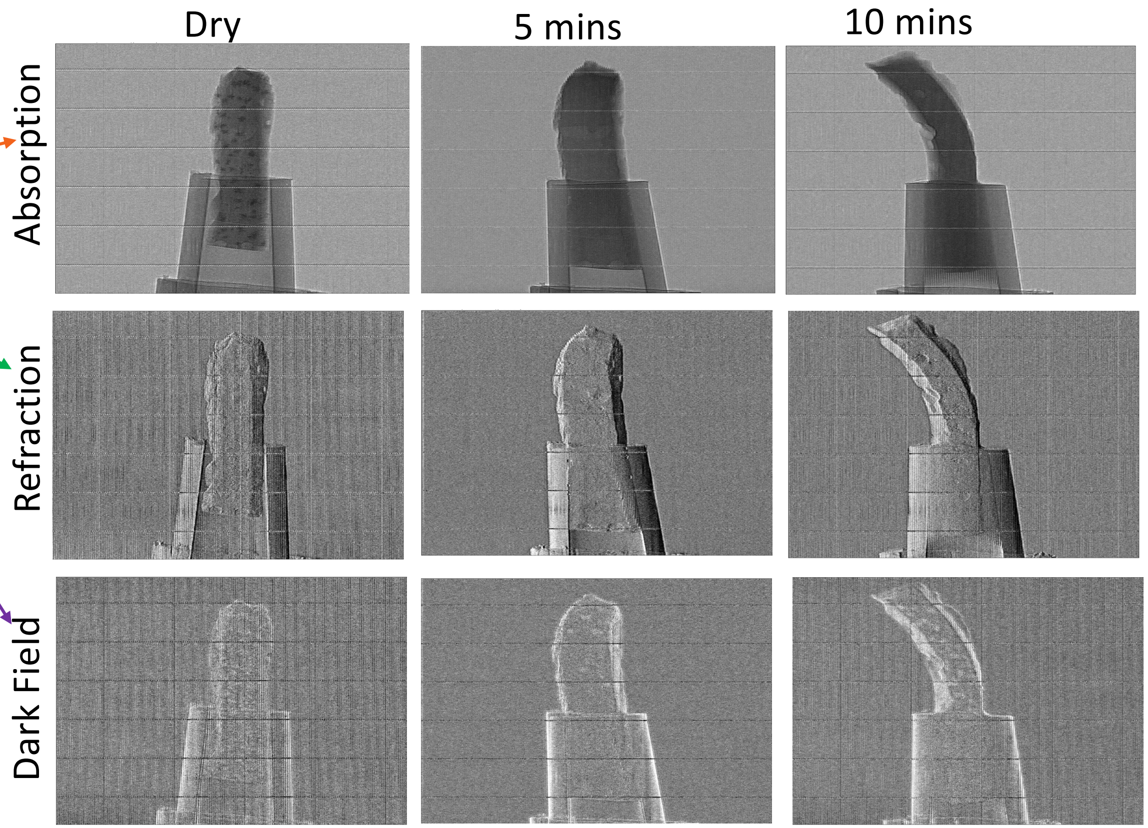


Highlights from users experiments

Investigation of the structural properties of polymer materials for Tissue Engineering

(PI: R. Oliveira Silva, HZB, Germany)





An absorbing mask splits the X-ray beam into beamlets which are imaged with a pixelated detector. **b** the presence of the sample between the mask and the detector changes the beamlets

Sample: Pure Siloxane@PLA-PEO Hybrid material (50-50H)
Method: beam tracking phase contrast with betatron source
4 dithering steps and Pixelated detector (13.6 um)

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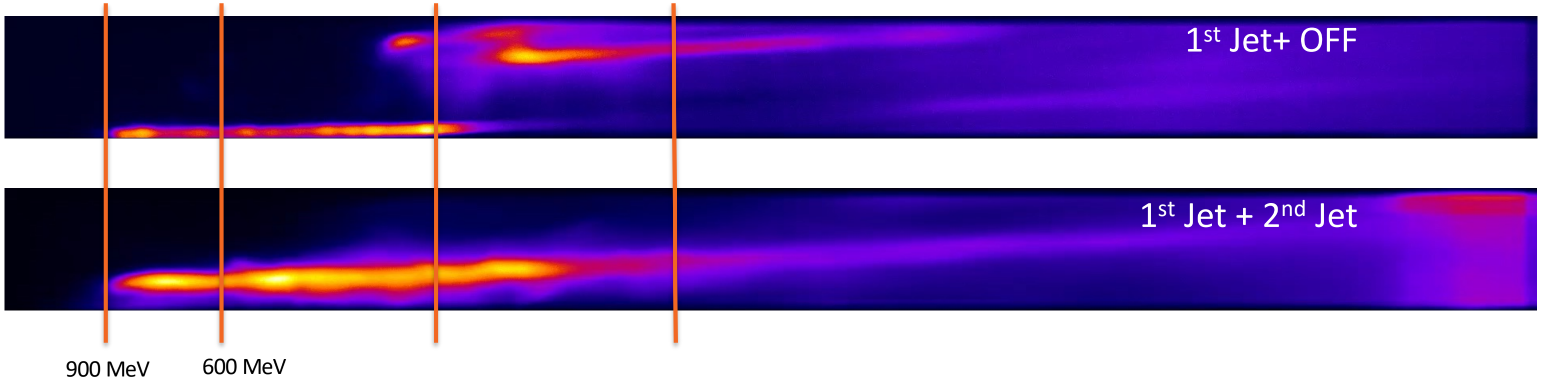
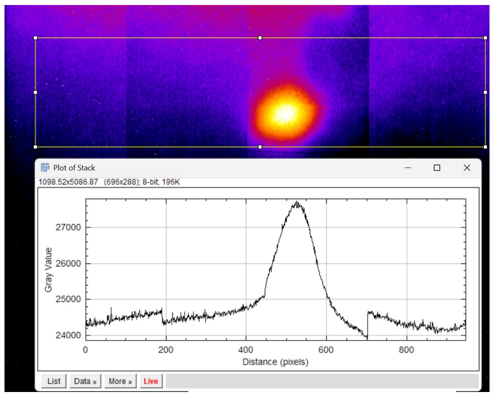
Highlights from users experiments

Dual slit nozzle LWFA betatron radiation enhancement (PI: G. Manahan), Uni. Strathclyde

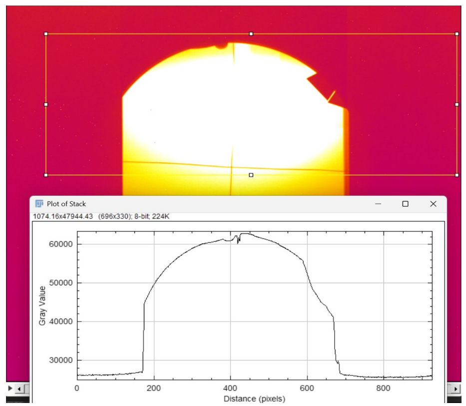
Conditions: 14 bar (~$6.5\times10^{18}/cm^3$) + 10 bar (~ $5\times10^{18}/cm^3$) of He+5%N_2, -2mm, 10J, 28 fs



Beam profile in Flat panel detector (<40 keV)



Single Jet



Double Jet

Date:

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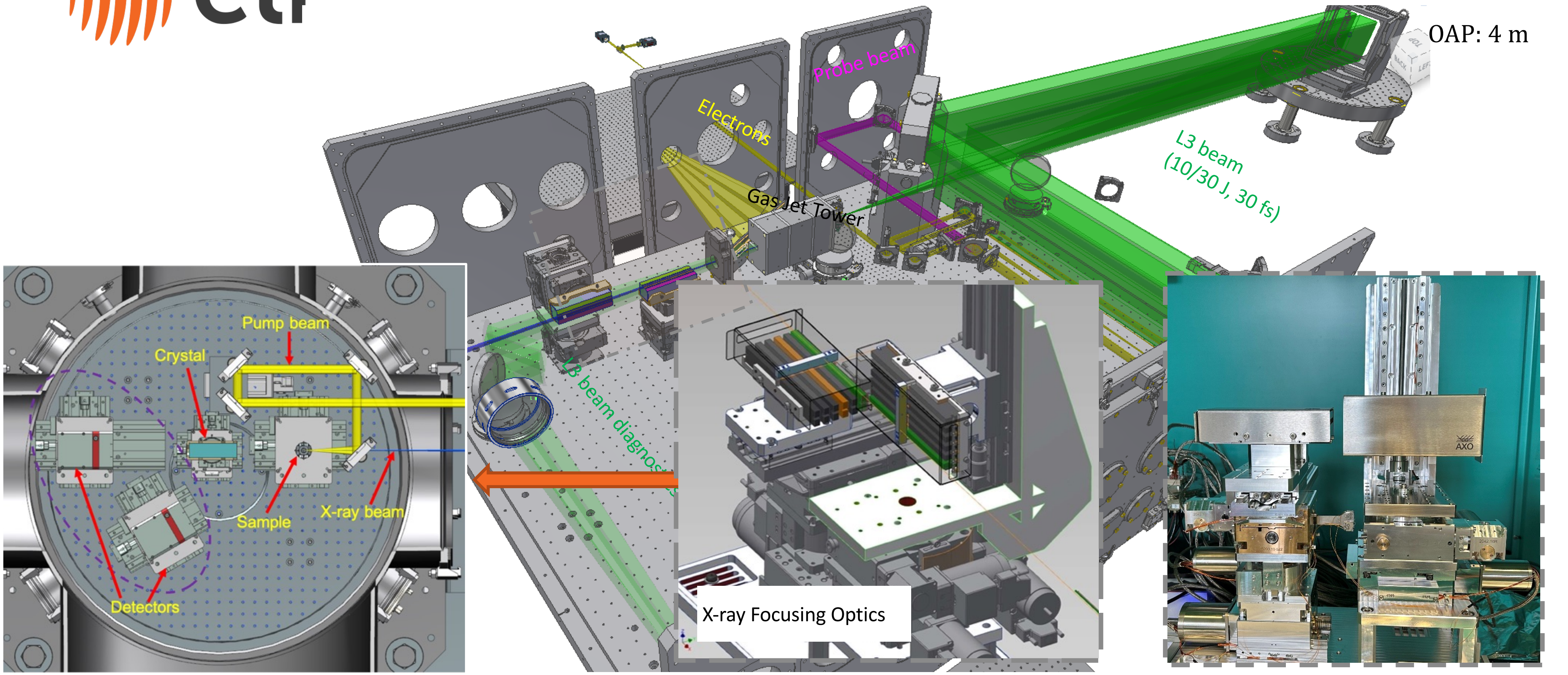
Dual slit nozzle LWFA betatron radiation enhancement (PI: G. Manahan), Uni. Strathclyde

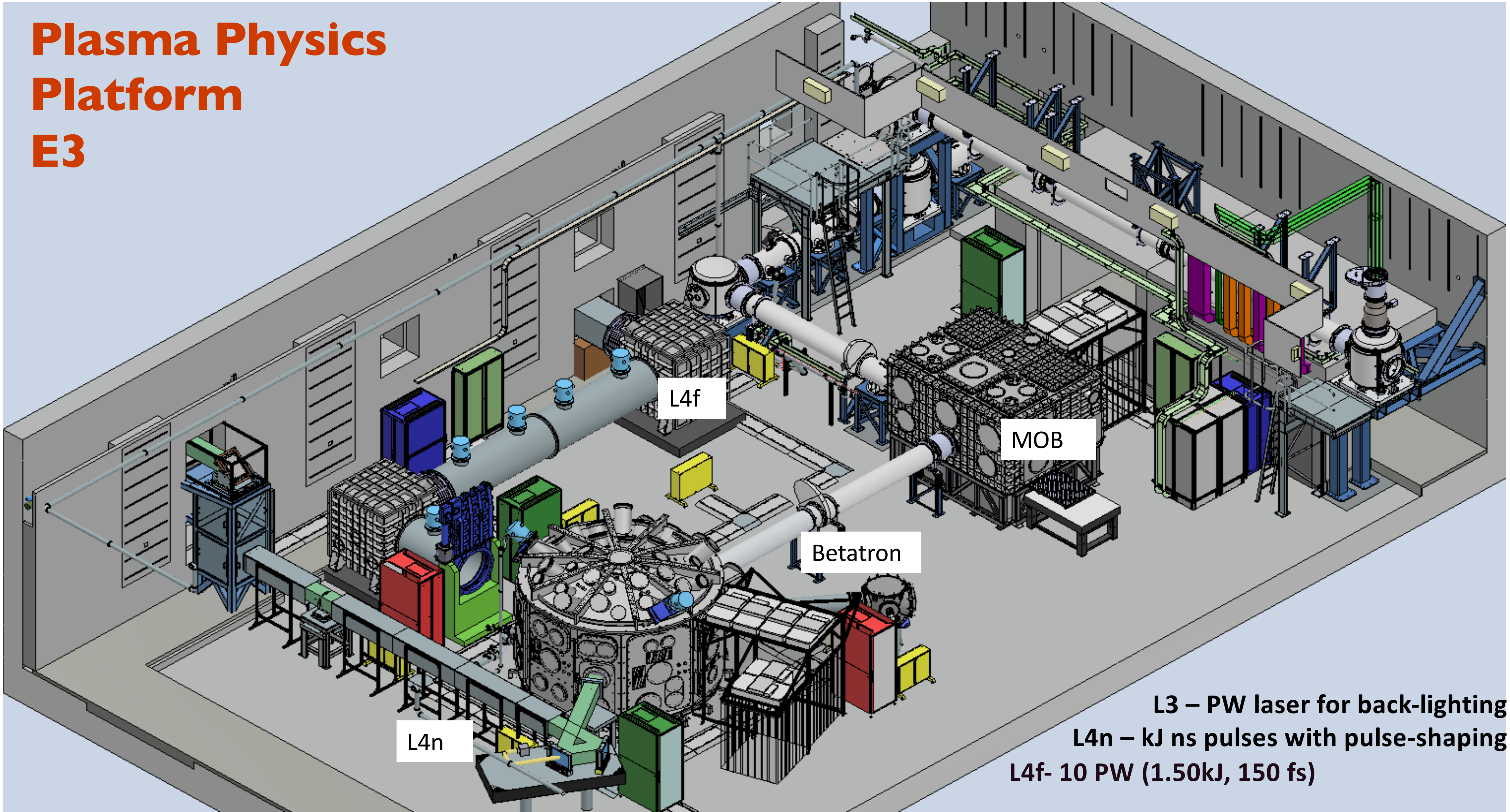
Conditions: 14 bar (~$6.5x10^{18}/cm^3$) + 10 bar (~ $5x10^{18}/cm^3$) of He+5%N_2, -2mm, 10J, 28 fs

Perspectives



Unique platform for time-resolved X-ray studies at fs scale

Plasma Physics Platform E3



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

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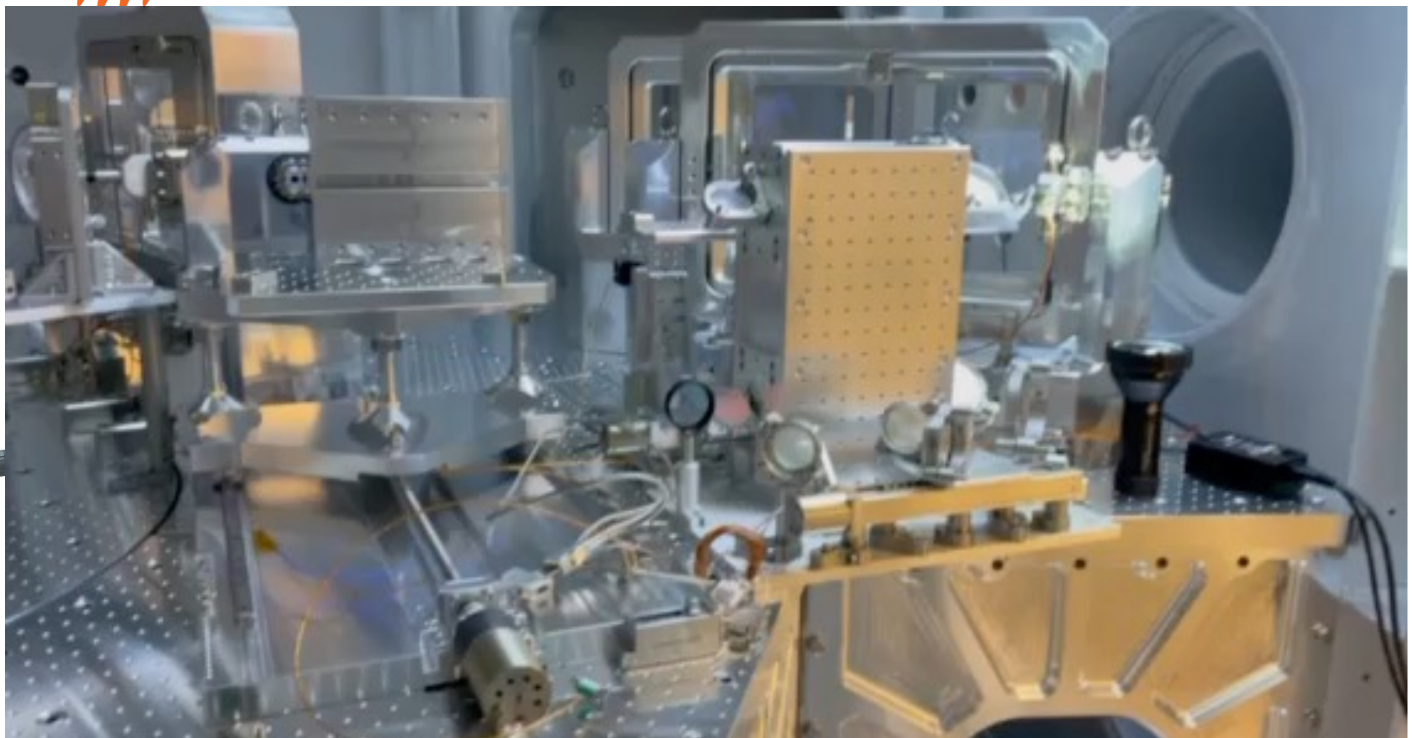
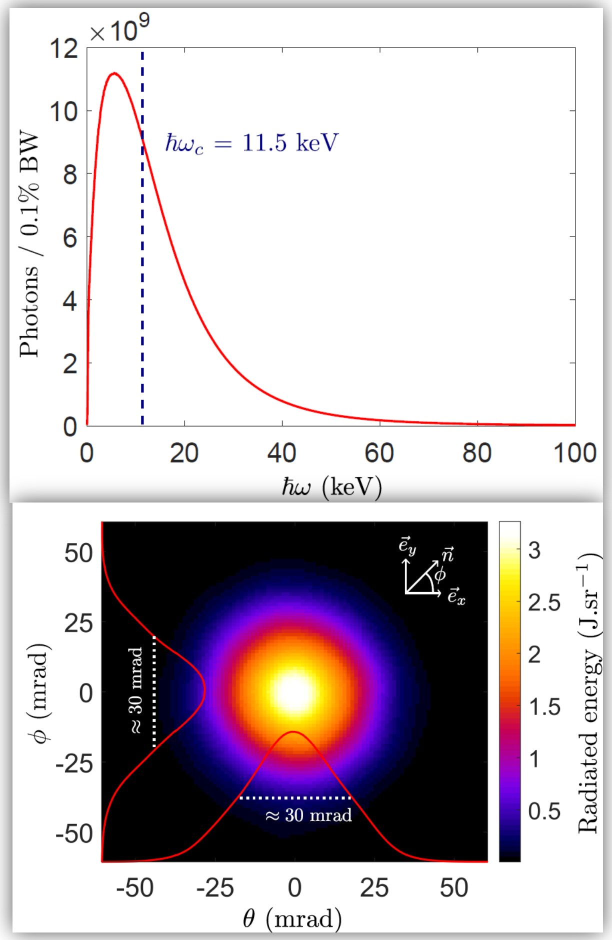
S. Weber, et. al, MRE 2, no. 4 (2017)., N. Jourdain, U. Chaulagain et. al, MRE,6, no. 1 (2021).

Betatron Source at Plasma Physics Platform



Long focal length (Betatron) setup and it's diagnostics inside P3



First Light (Q4 2024)

Source commissioning (Q4 2025)

User call (Q1 2026)

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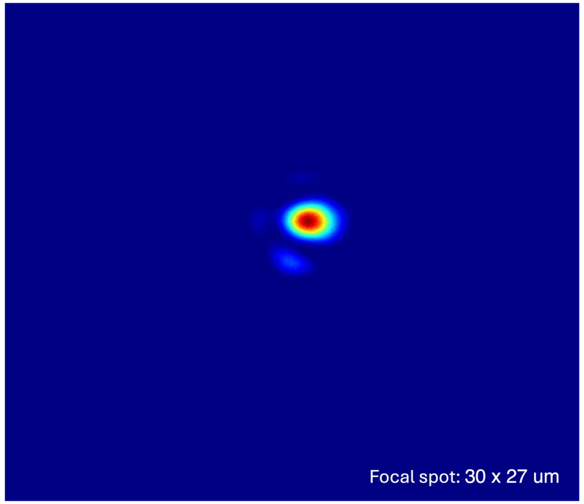
N. Jourdain, U. Chaulagain et al., MRE 6.1 (2021): 015401, U. Chaulagain et al., SPIE (2020)

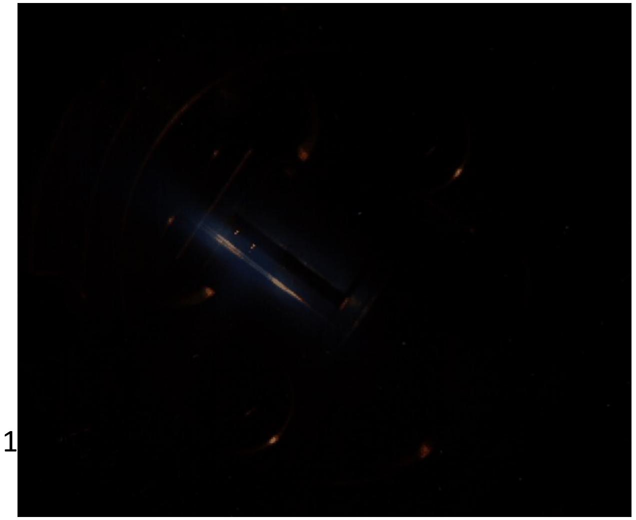
Betatron Source at Plasma Physics Platform

First light results

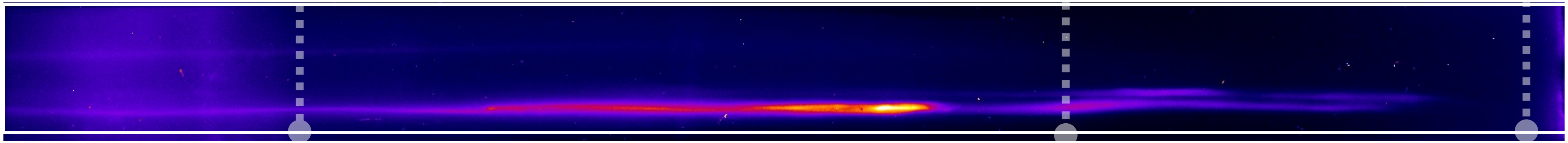


Far field

1



Thomson Spectra



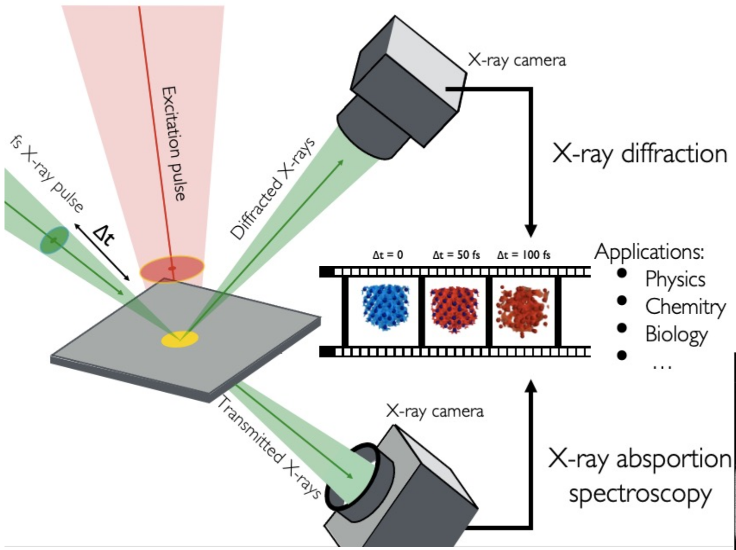
100 MeV Electron Spectra (raw) 500 MeV 1 GeV

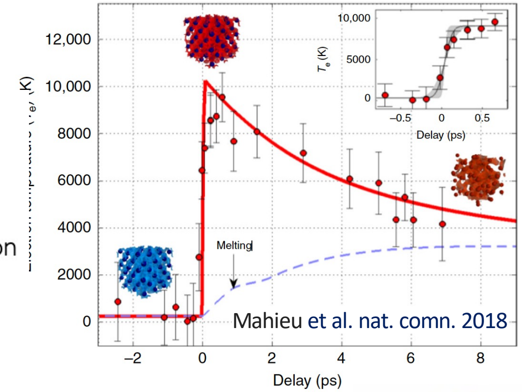
Uddhab.chaulagain@eli-beams.eu

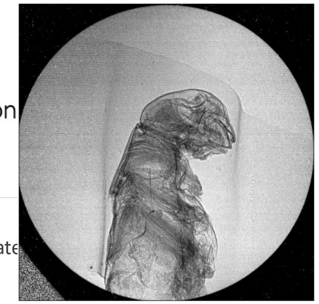
Betatron/Compton Sources in ELI Beamlines

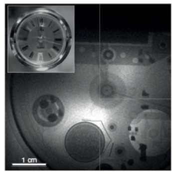
Gammatron Beamline: ultrafast X-ray science

- Time-resolved XAS & XES, radiography, Phase contrast imaging, Diffraction etc.
- User access from Q4 2024 **(part of call 7)**





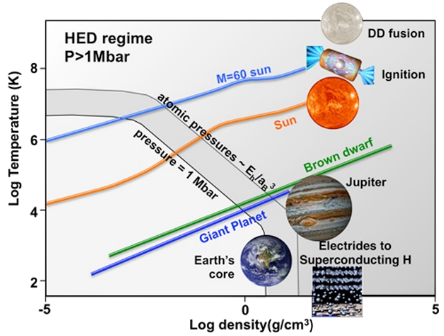


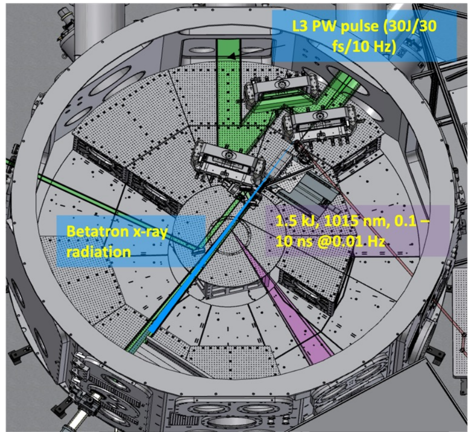


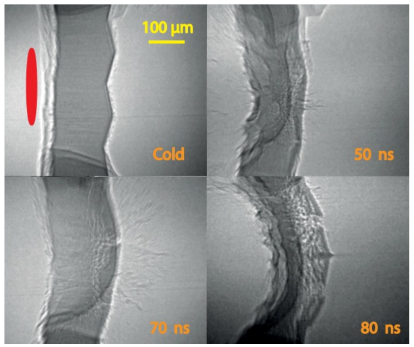
Döpp, et al. PPCF, 58.3 (2016): 034005.

E3: Plasma Physics platform (P3)

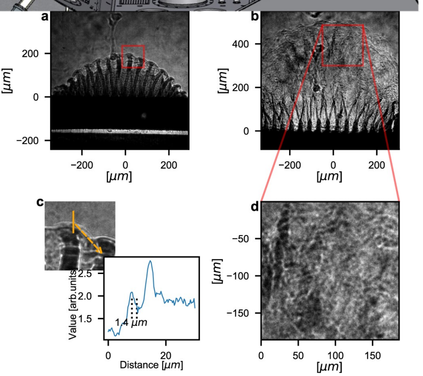
- Betatron source for plasma and WDM/IFE diagnostics
- Operational from Q4 2025







Wood et al., sci. report. 2018

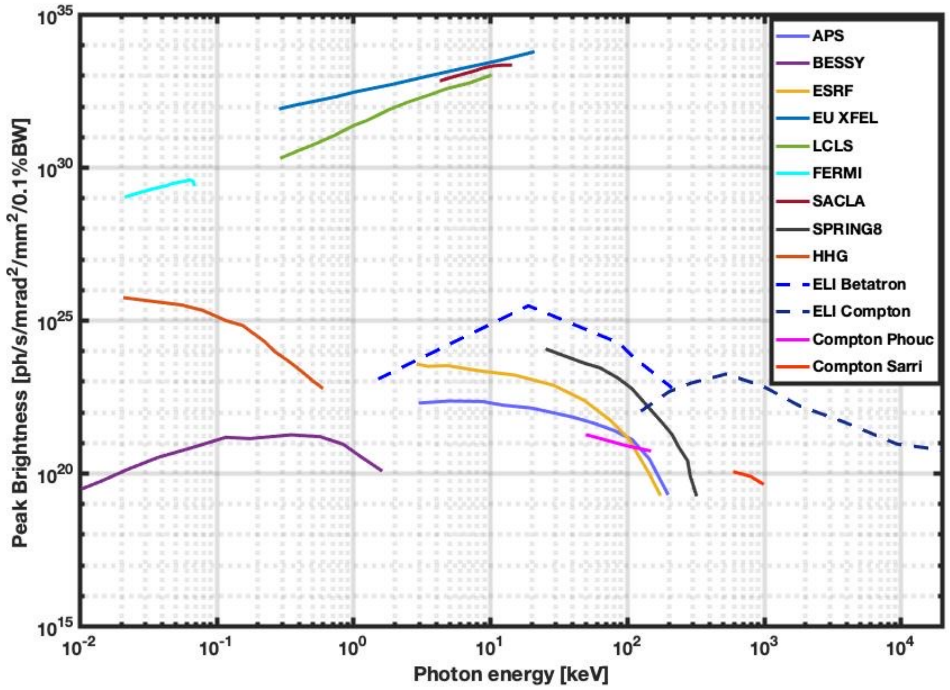


Rigon et al., nat. comn. 2021

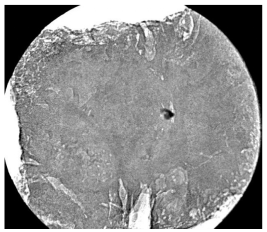
Summary

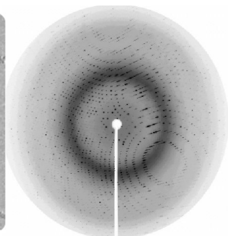
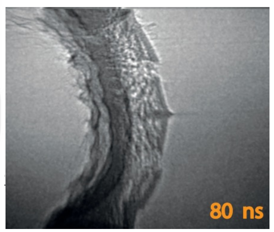
ELI Gammatron beamline

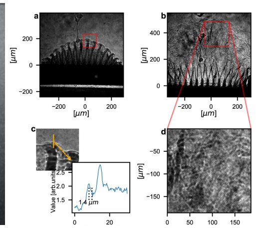
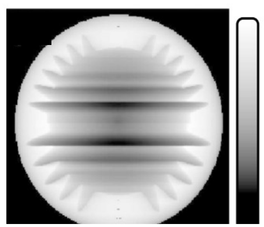
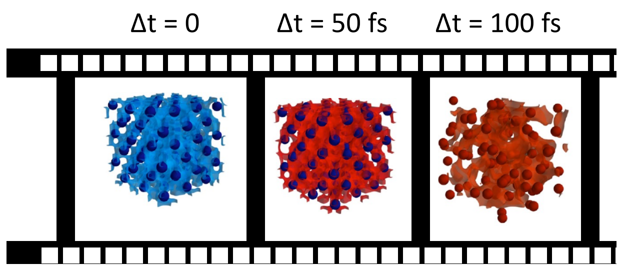
- ✓ Compact synchrotron X-ray source (1-100’s keV)
  - ✓ ~10 fs, micron source size, collimated beam
  - ✓ Expected photon flux over 10^{10} photons/shot
  - ✓ 10% flux variation & 10% energy variation
  - ✓ *Energy tunable*
- ✓ Equipped with most of the electron and X-ray diagnostics (X-ray CCDs, crystals, scintillators etc)
- ✓ Pump beam (800 nm, 400 nm or 266 nm)



Science case details: Chaulagain et al., Photonics 2022, 9(11), 853 (2022)



User Portal

https://up.eli-laser.eu

eli User Portal | User calls | Instruments | User guide | Terms and Conditions | Contact | My proposals

Access ELI's world-class lasers, instruments and facilities

Call for proposals: **Open** deadline 29th **Oct.** 2025

have an idea?

Contact us and apply for beamtime!

Instruments /

Gammatron

Apply for beamtime →

Description

Gammatron Beamline

Contact person	Uddhab Chauglain (uddhab.chaulagain[@]eli-beams.eu)

Acknowledgements

M. Lamač, O. Morvai, D. Čap, V. Janota, S. Lorentz, A. Morabito, P. Odstrčil, F. Vanek, J. Nejdl (ELI Beamlines), K. Ta Phouc, J. Gautier, S. Sebban (LOA/CNRS FR), S. Cipiccia, A. Olivo (UCL, UK), C. Armstrong, R. Pathalil (STFC, UK), G. Manahan, W. Pring (Uni. Strathclyde, UK), R. O. Silva (HZB, DE), B. Hidding et al. (HHU, DE), V. Tomkus (FTMC, LT), S. Fourmaux, J. C. Kieffer (INRS, CA), V. Malka, E. Kroupp (WIS, IL)

Thank you for your attention!

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