Study and characterization of betatron radiation source from Laser Wakefield Accelerator

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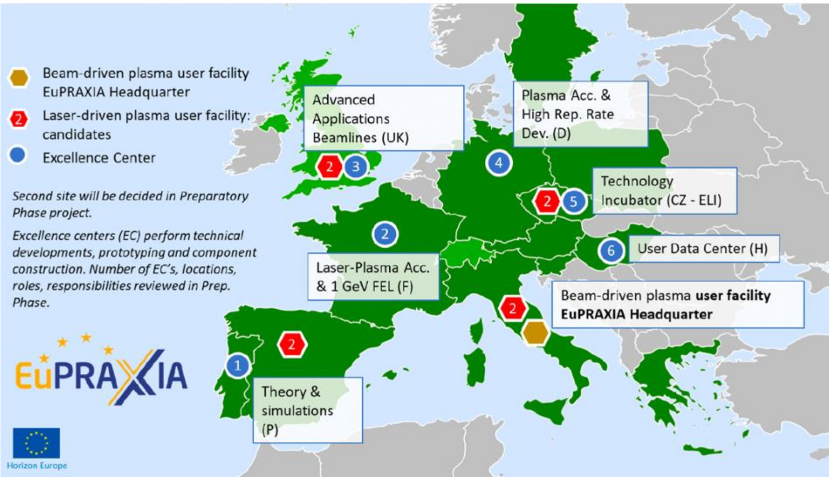
Outline

- Introduction
  - Eupraxia/Eupas
- Theory
  - Plasma acceleration
  - Betatron radiation
  - Equation of motion
  - Calculated radiated spectrum
- Simulation
  - PIC simulations
- Experiment
  - Centro de Laseres Pulsados Ultracortos CLPU
  - Experimental setup
  - Measumentts
  - Phase Contrast Imaging

Introduction



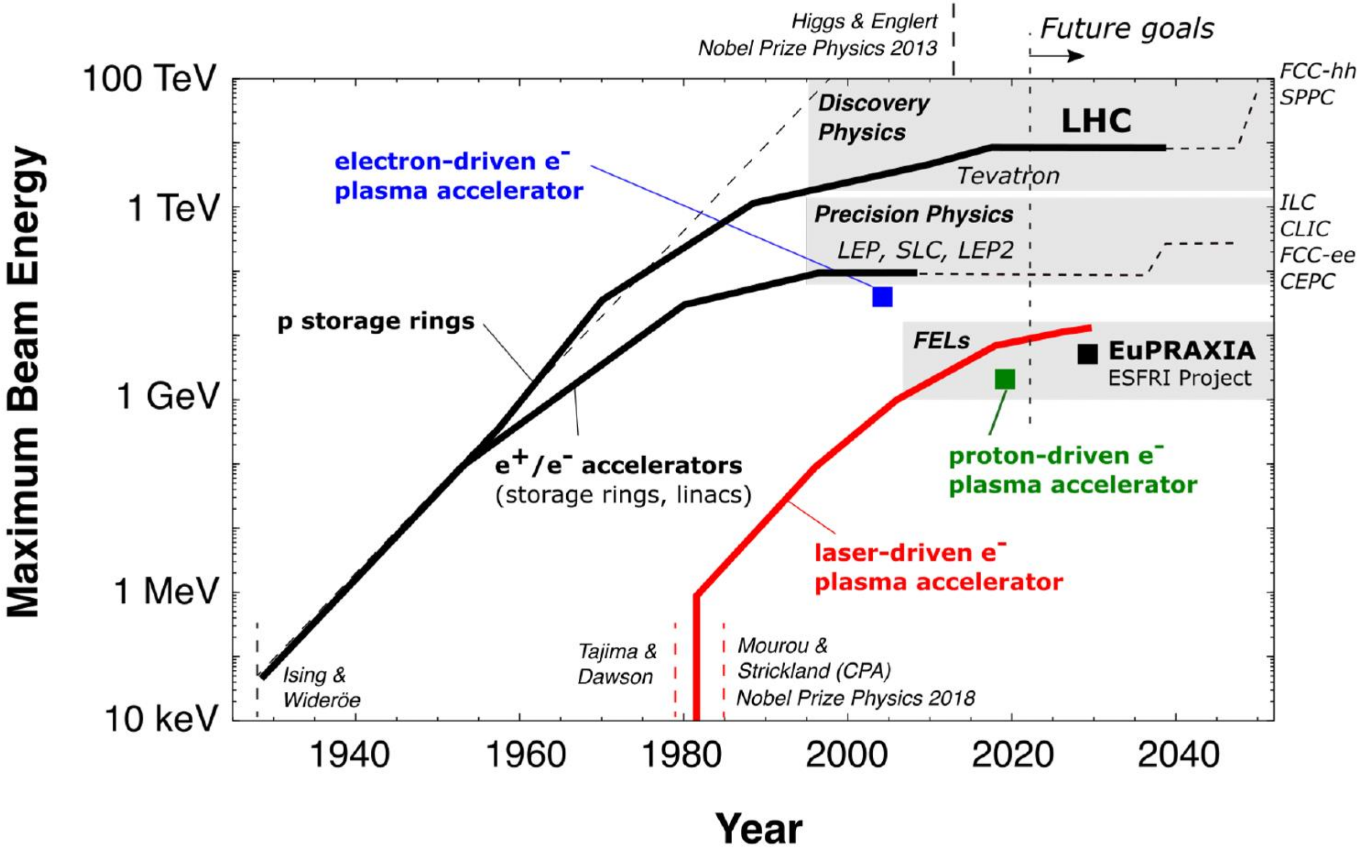
Eupraxia

- *First plasma accelerator based user facility*

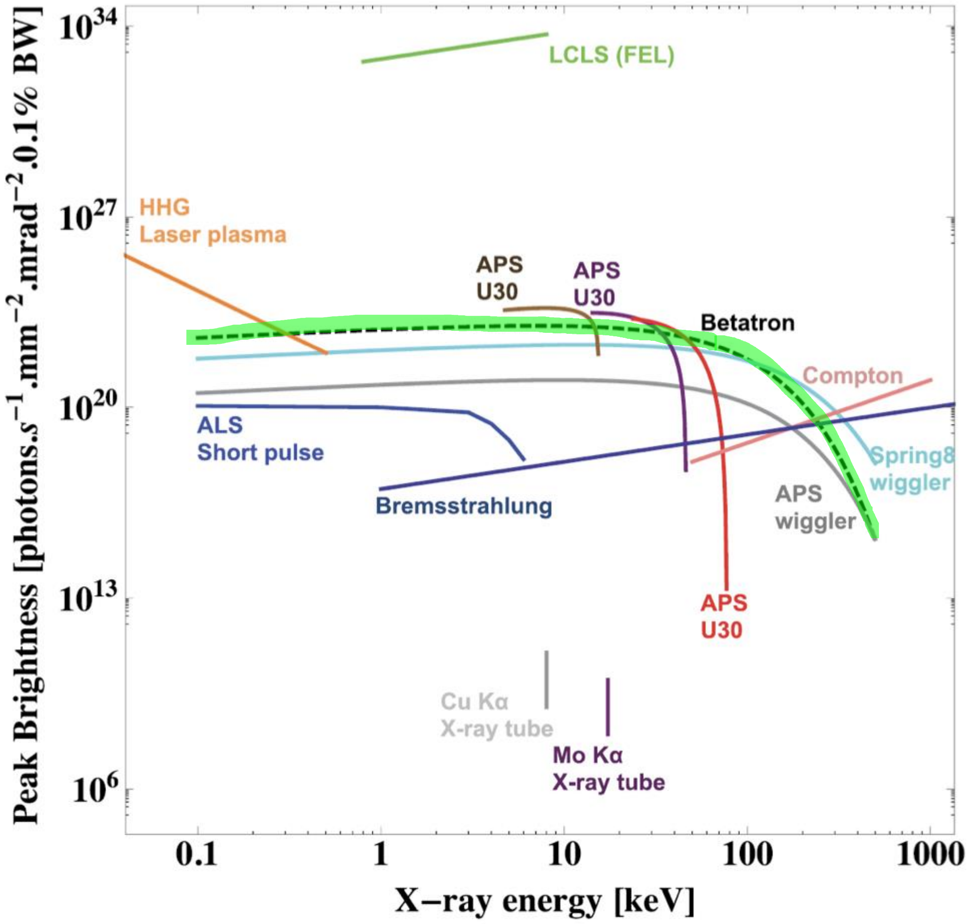
EuAPS

- *EuPRAXIA Advanced Photon Sources project*
- *Collaboration*
    - INFN
    - CNR
    - University of Tor Vergata
- *Objective: development a compact photon sources to drive plasma accelerators and the setup of ultra-compact, high performing X ray and particle sources for users*

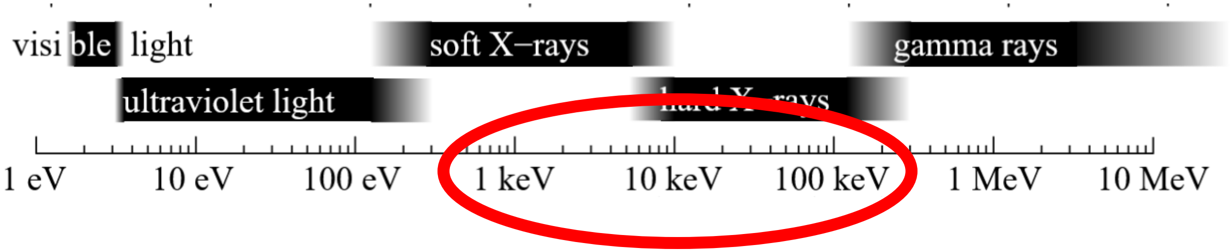
Betatron Radiation



Why Betatron Radiation?



Albert F and Thomas A G R 2016 Plasma Phys. Control. Fusion



Applications

Imaging

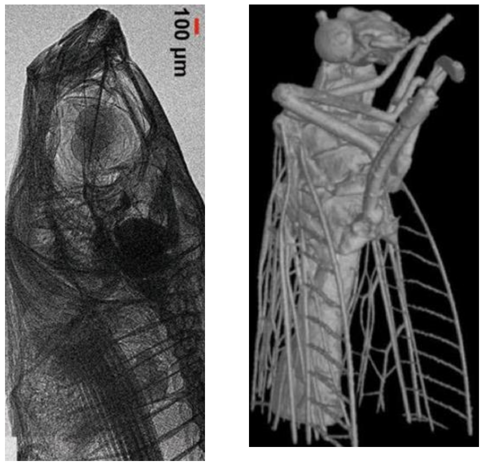
- Phase contrast imaging PCI
- PCI edge illumination (PCI-EI)
- PCI Beam tracking (PCI-BT)

Spectroscopy

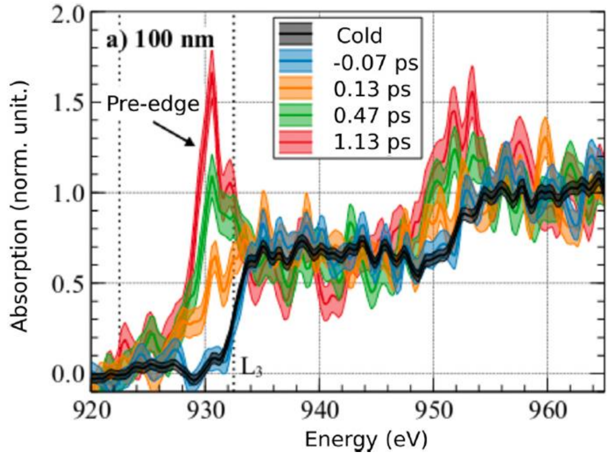
- Xray absorption XAS
- XANES
- EXASF

Ultrafast Studies

- Pump-probe experiment

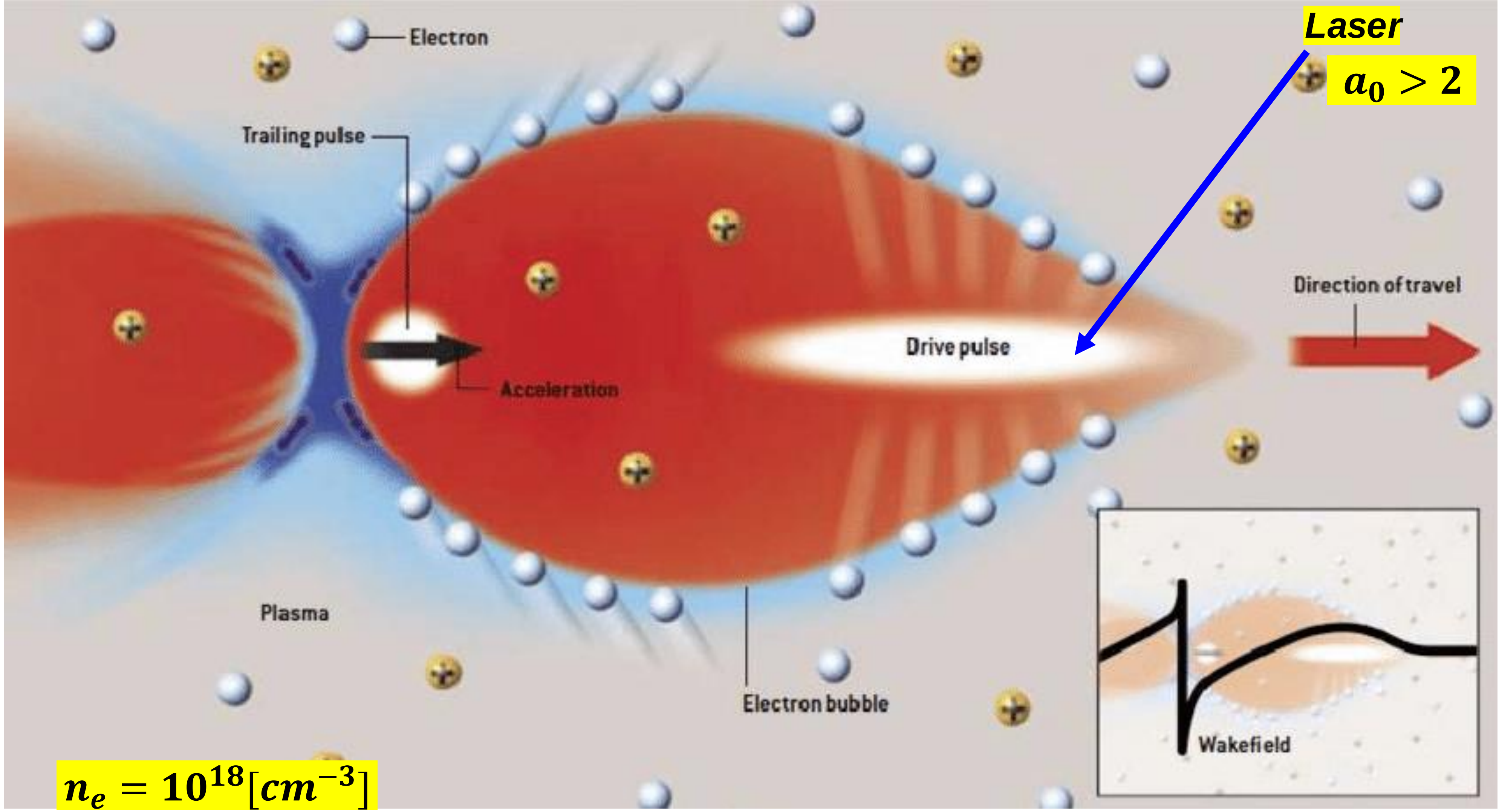


Wenz *et al.* Nature communications 2015
Bo Guo *et al.* Scientific reports 2019



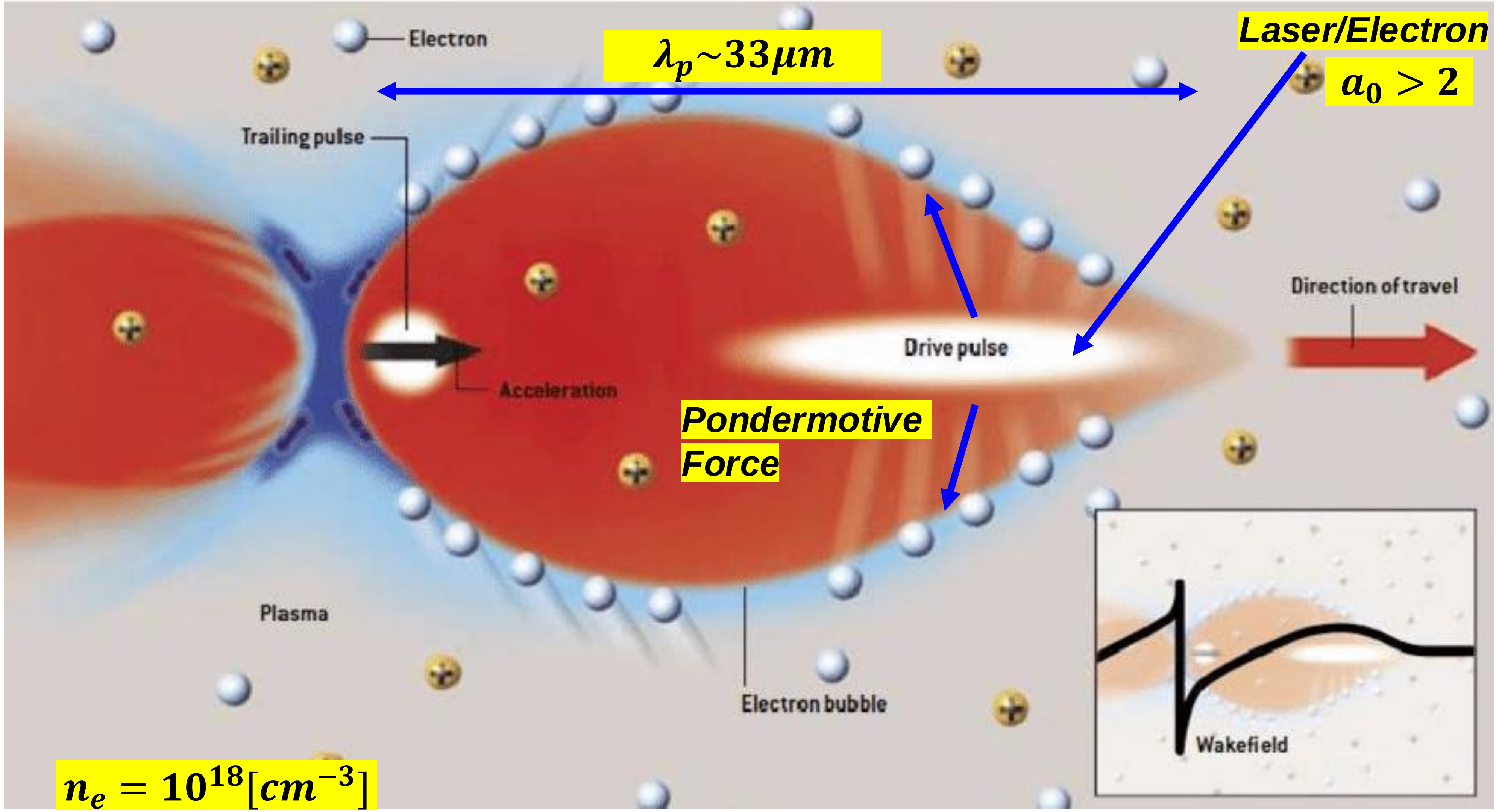
F. Dorchies et al. Structural dynamics 2023

Plasma acceleration



Credits: C. Joshi, UCLA

Plasma acceleration



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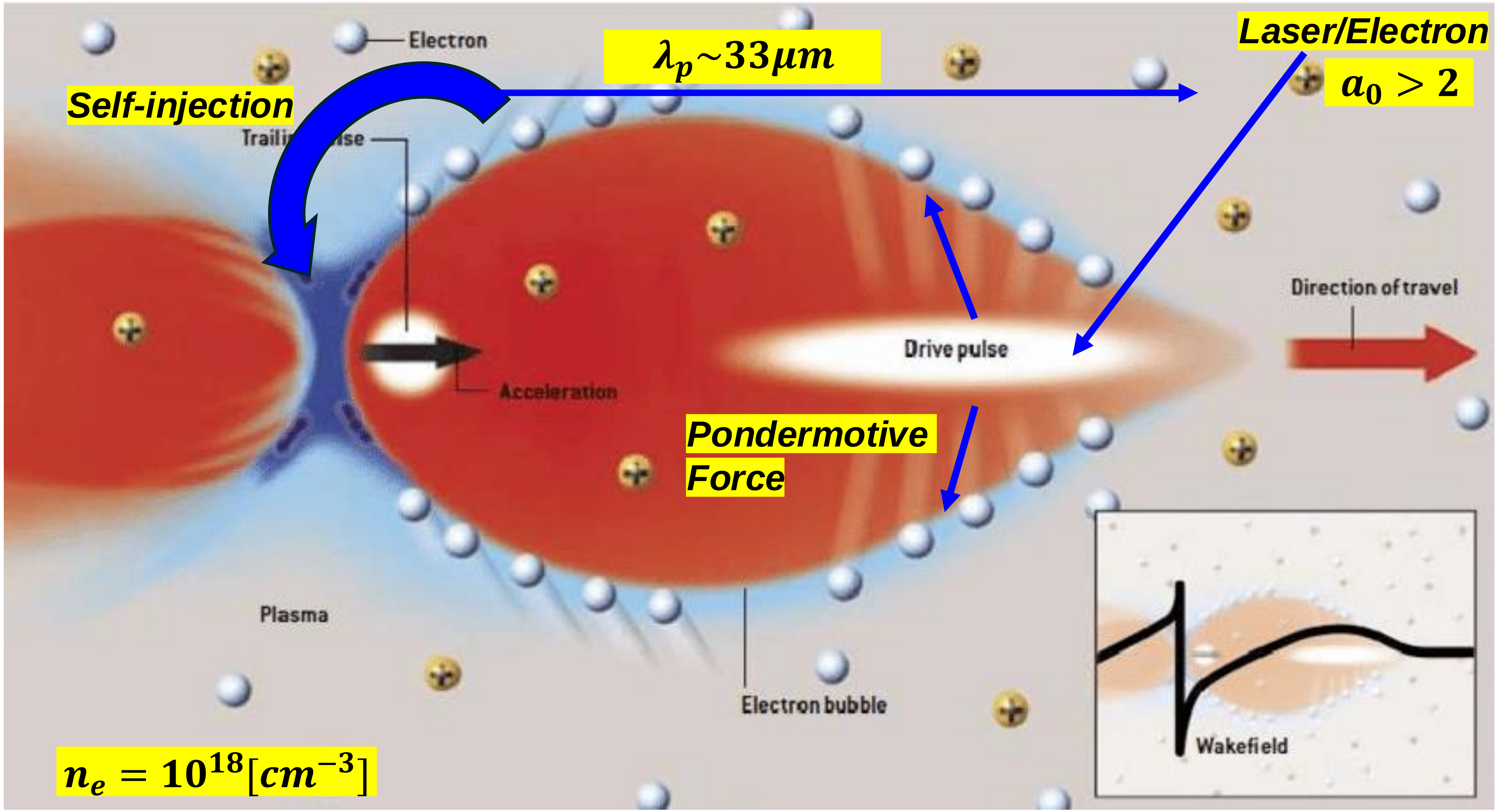
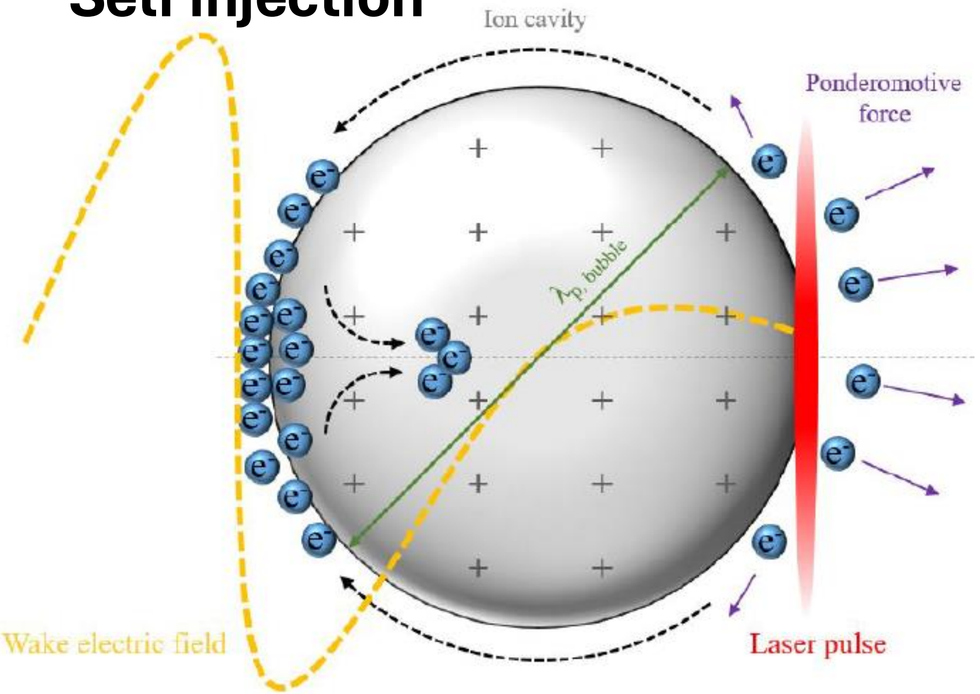
Plasma acceleration



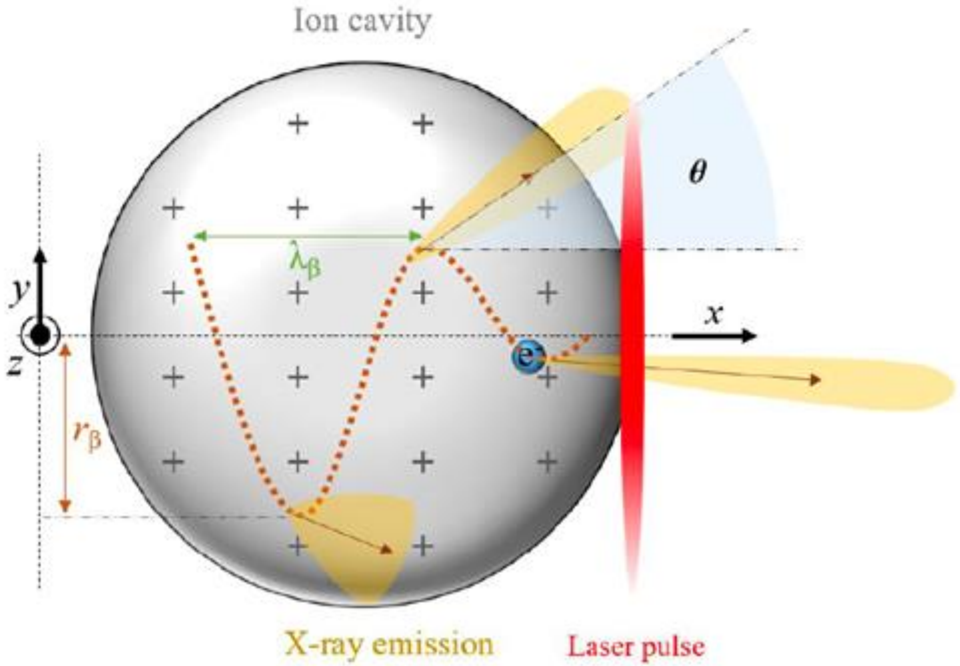
Credits: C. Joshi, UCLA

Strong longitudinal and transverse force

Self injection



Electron Oscillation in plasma bubble



Strong longitudinal and transverse force

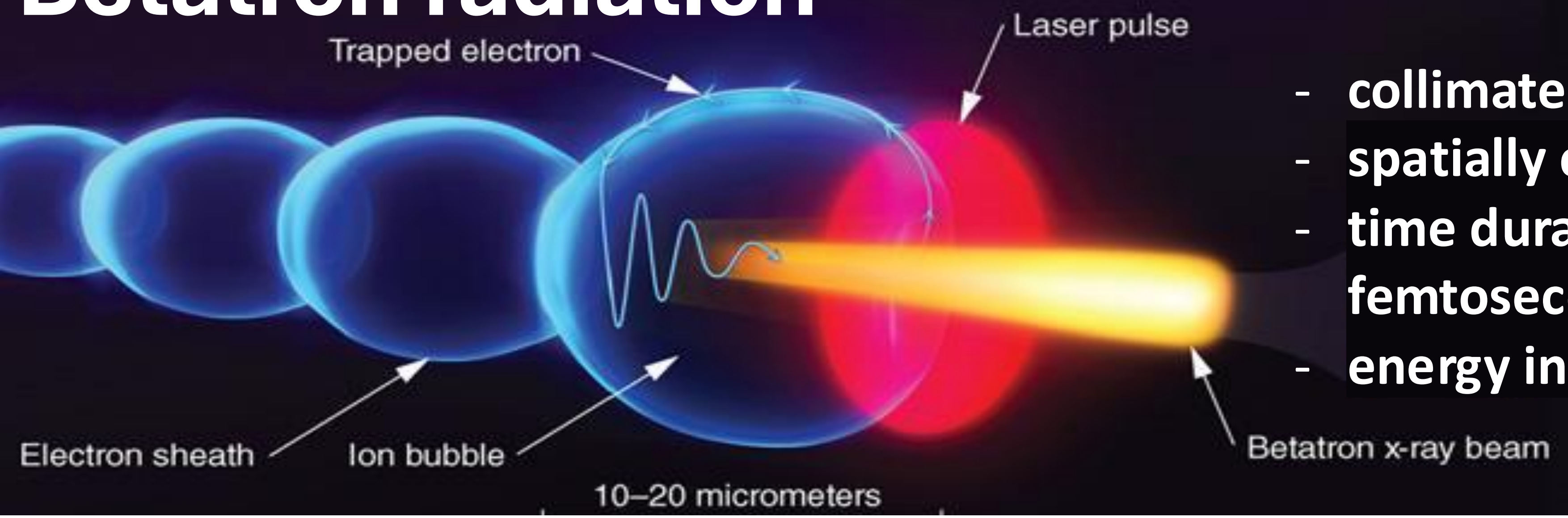
$$E_z[V/m] = \frac{m_e c \omega_p \sqrt{a_0}}{e}$$

$$E_r[V/m] = \frac{m_e \omega_p^2 r}{2e}$$

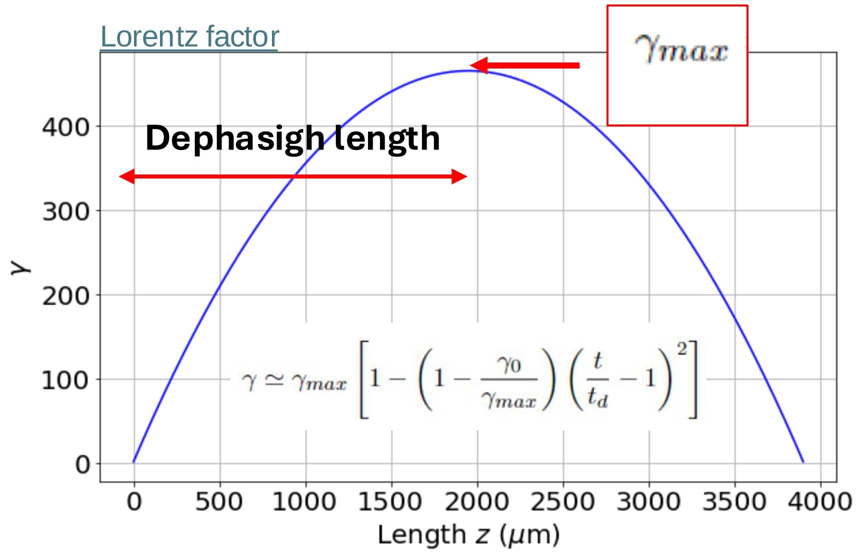
$\approx GV/m$

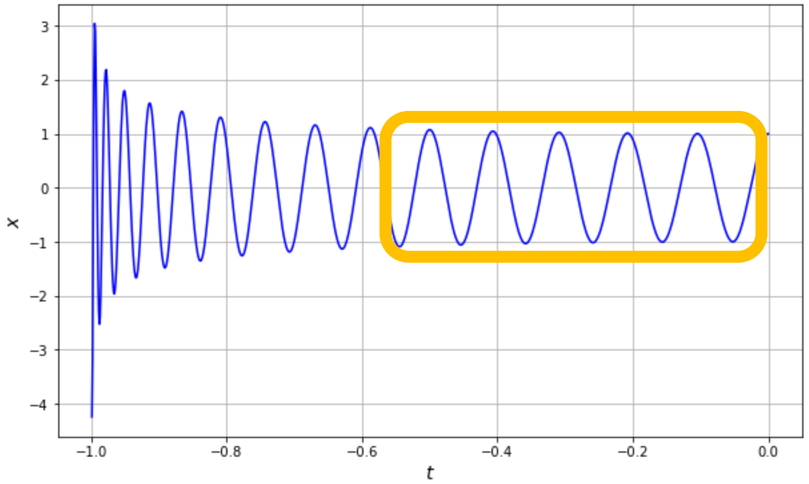
Betatron radiation

F.Albert et al. “Laser wakefield accelerator based light sources: Potential applications and Requirements “, Plasma Phys. Control. Fusion



- collimated beam of X-ray
- spatially coherent
- time duration in the femtosecond range
- energy in the keV range





The period and amplitude of betatron oscillations stabilize near the maximum energy gain

Betatron frequency $\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$

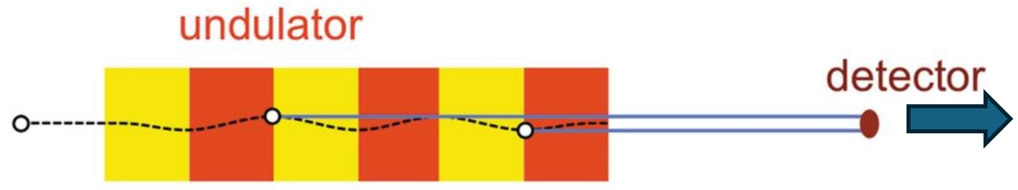
Trajectories $x(t) \simeq x_0 \cos\left(\omega_\beta t + \phi_x\right)$

Strength parameter K

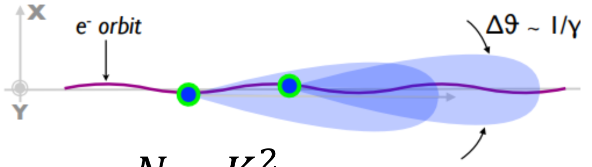
Plasma frequency
Oscillation amplitude
Lorentz factor

Strength parameter $K = \frac{eB\lambda_u}{2\pi mc}$

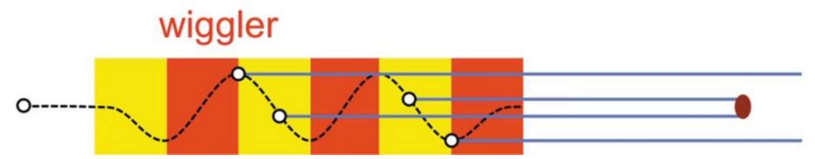
Betatron Strength parameter $K_\beta = \gamma r \omega_\beta / c$



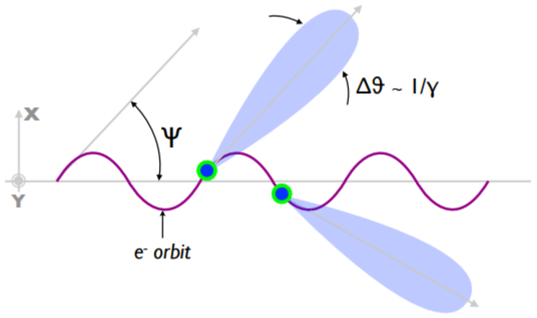
$K < 1$



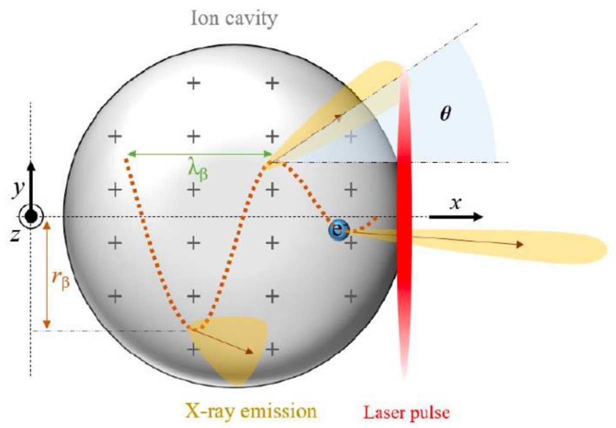
$N_\gamma \sim K^2$



$K \gg 1$



$N_\gamma \sim K$



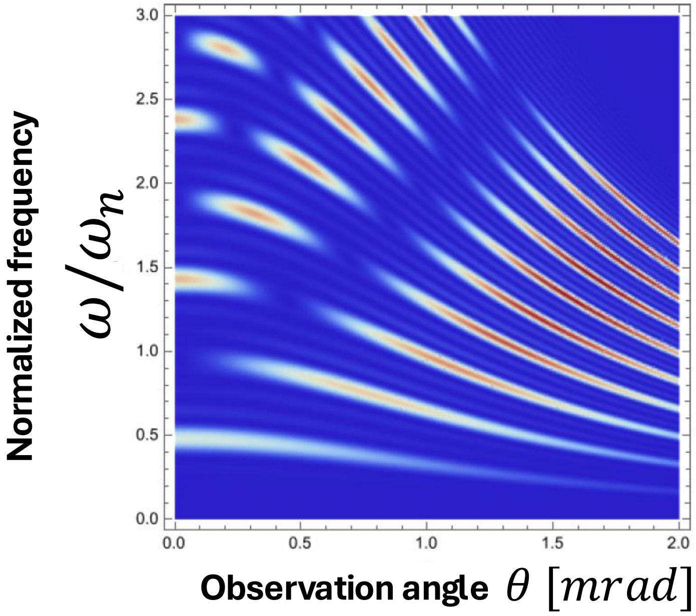
Wiggler + Undulator

Corde, Sébastien, et al. "Femtosecond x rays from laser-plasma accelerators." *Reviews of Modern Physics* 85.1 (2013): 1.

Irradiated spectrum

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{16\pi^3 \varepsilon_0 c} \left| \int_{-\infty}^{\infty} \frac{\mathbf{n} \times [(\mathbf{n} - \boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}}]}{(1 - \mathbf{n} \cdot \boldsymbol{\beta})^2} e^{i\omega(t - \mathbf{n}\cdot\mathbf{r}/c)} \, dt \right|^2$$

Spectral lines vs angle



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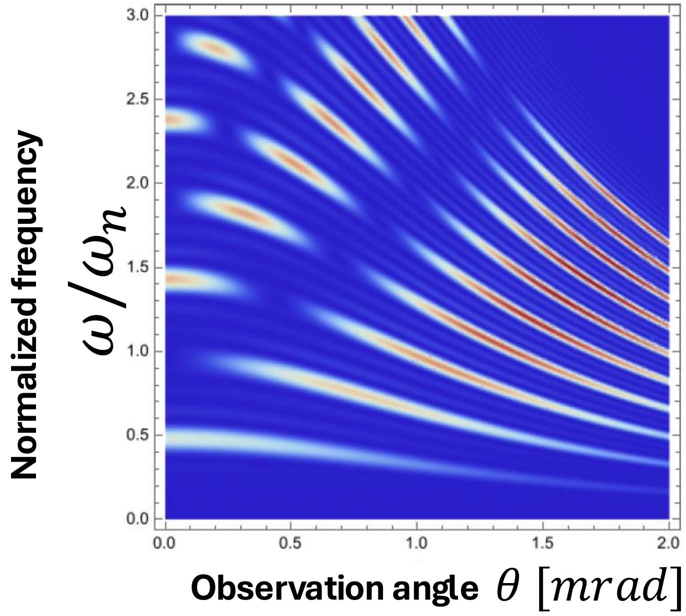
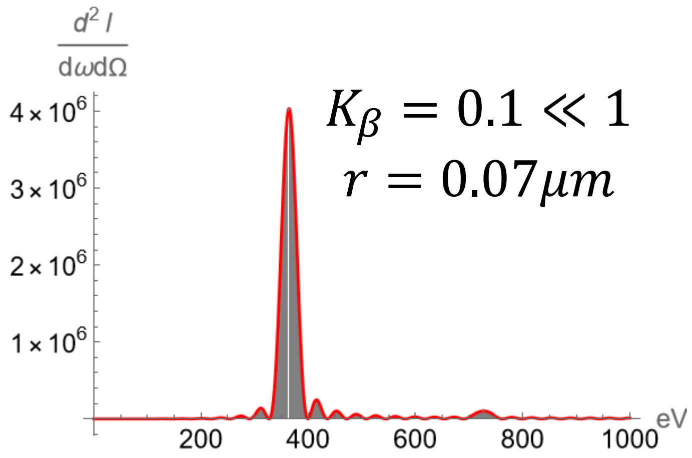
From Liénard–Wiechert potential

Spectral lines vs angle

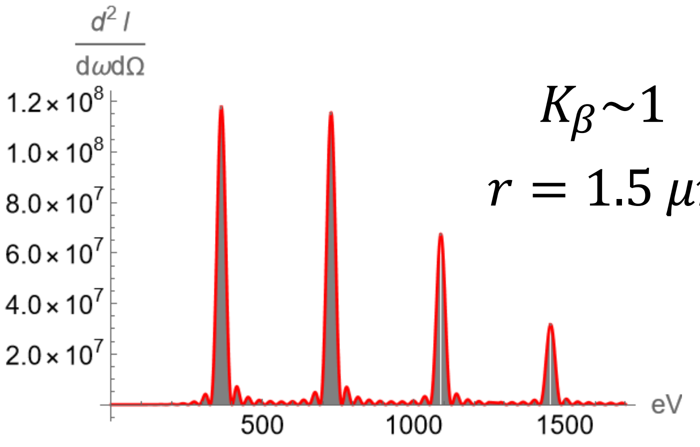


Spectral lines on axis

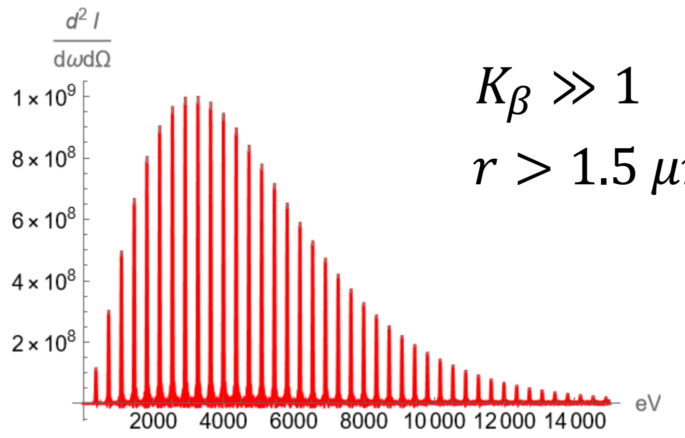
$\theta = 0$



$K_\beta = 0.1 \ll 1$
$r = 0.07\mu m$



$K_\beta \sim 1$
$r = 1.5\ \mu m$



$K_\beta \gg 1$
$r > 1.5\ \mu m$

Undulator-like

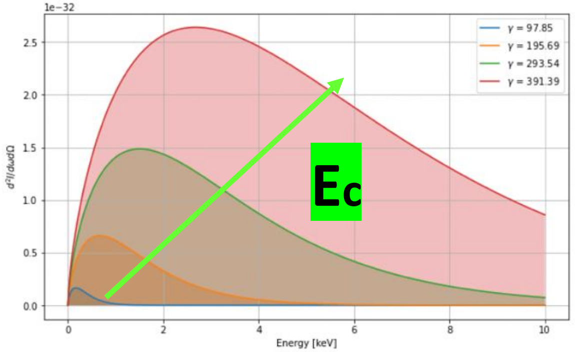
Wiggler like

Asymptotic limit spectrum

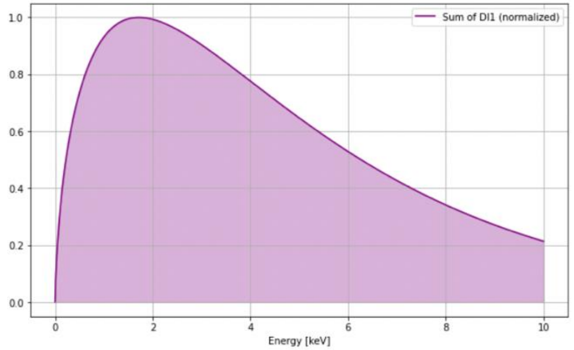
$$\left.\frac{d^2I}{d\omega d\Omega}\right|_{\theta=0} \simeq N_\beta \frac{3e^2}{2\pi^3\epsilon_0 c}\gamma^2\zeta^2\mathcal{K}_{2/3}^2(\zeta)$$

How does the spectrum change for:

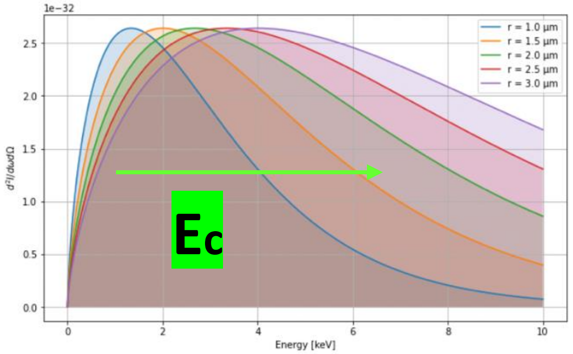
Different energies



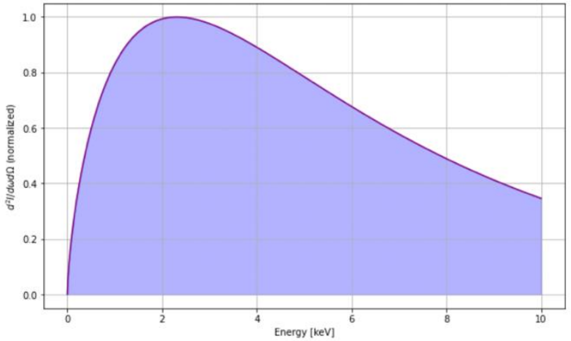
Sum of contribution



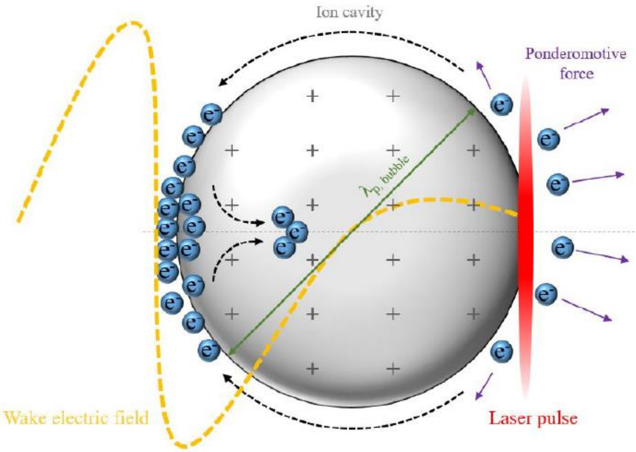
Different radius



Sum of contribution



Ec = critical energy



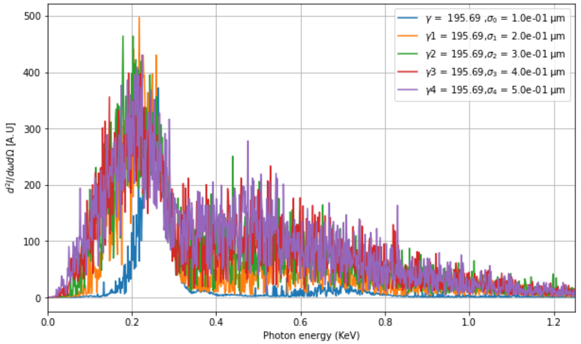
The radiation at the detector is the sum of different contribution:

- Radiation of Electron with different energies
- Radiation of electron with different amplitude of oscillation

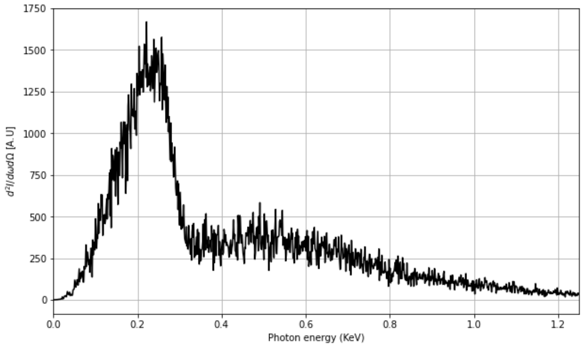
Study of the spectra (no asymptotic limit)

$$\frac{d^2I}{d\omega d\Omega}(\theta=0)=\sum_{n=1}^{\infty}\frac{e^2}{\pi\epsilon_0 c}\frac{\omega}{\omega_n}\frac{\gamma^2N_\beta^2F_nR_n}{1+K_\beta^2/2},$$

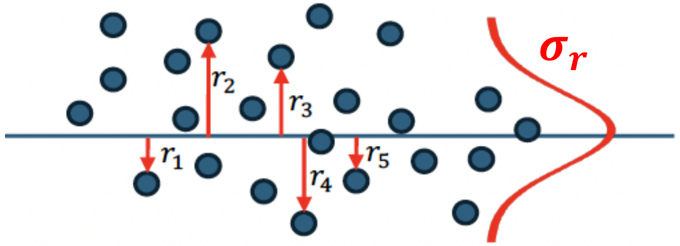
Different radius



Sum of contribution

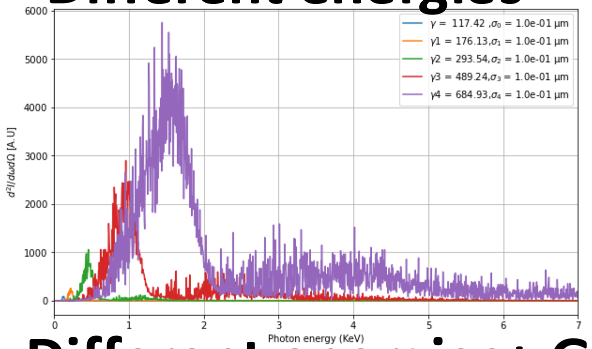


Considering a Gaussian bunch around the axis

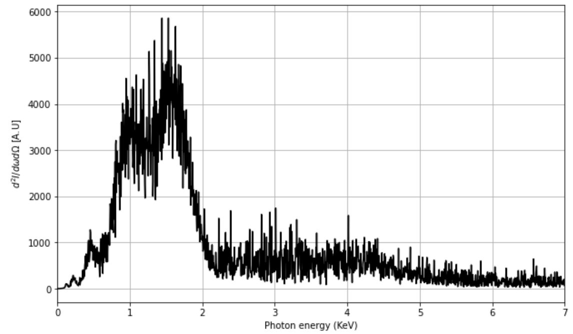


$$\left.\frac{d^2I}{d\omega d\Omega}\right|_{\theta=0}=\sum_{r=1}^{\infty}f(r)\sum_{n=1}^{\infty}\frac{e^2\omega}{\pi\epsilon_0 c\omega_n(r)}\frac{\gamma^2N_\beta^2F_n(r)R_n(r)}{1+K_\beta(r)^2/2}$$

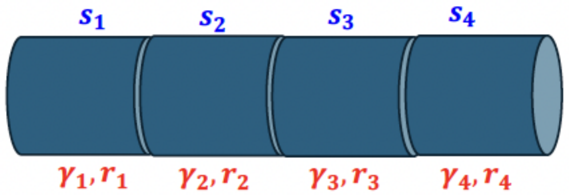
Different energies



Sum of contribution

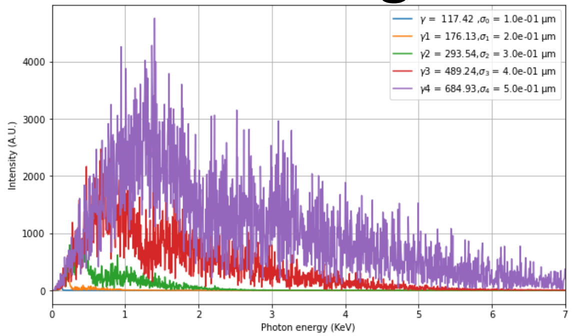


Considering a different values of energies

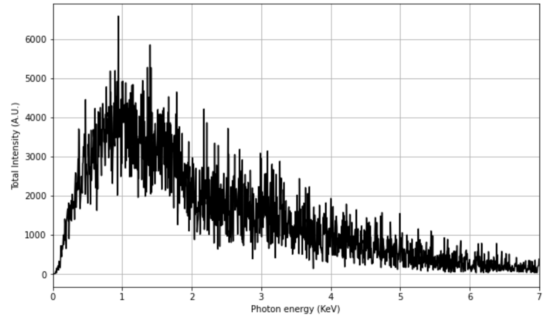


$$\left.\frac{d^2I}{d\omega d\Omega}\right|_{\theta=0}=\sum_{s=1}^{N}\sum_{r=1}^{\infty}f(r)\sum_{n=1}^{\infty}\frac{e^2\omega}{\pi\epsilon_0 c\omega_n(r)}\frac{\gamma^2N_\beta^2F_n(r)R_n(r)}{1+K_\beta(r)^2/2}$$

Different energies+ Gaussian bunch



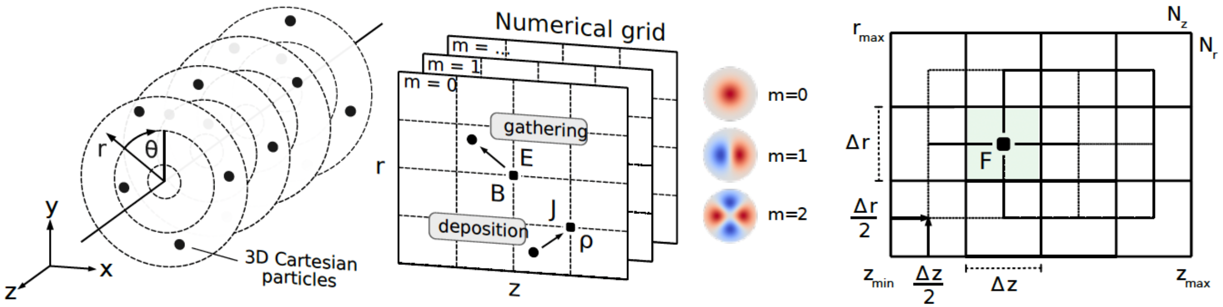
Sum of contribution



Particle in cell simulations

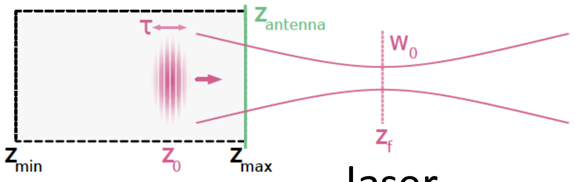
Simulations model the interaction between charged particles and electromagnetic fields, commonly used in plasma physics and accelerator studies

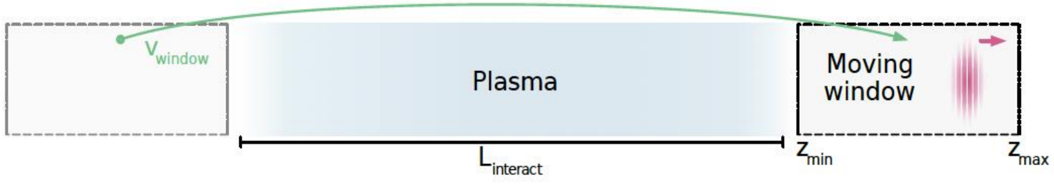
FBPIC → Trajectory → Synchrad → Radiation



Azimuthal mode decomposition

Initialization of laser parameters
Initialization of simulation box parameters
Initialization of initial particle parameters



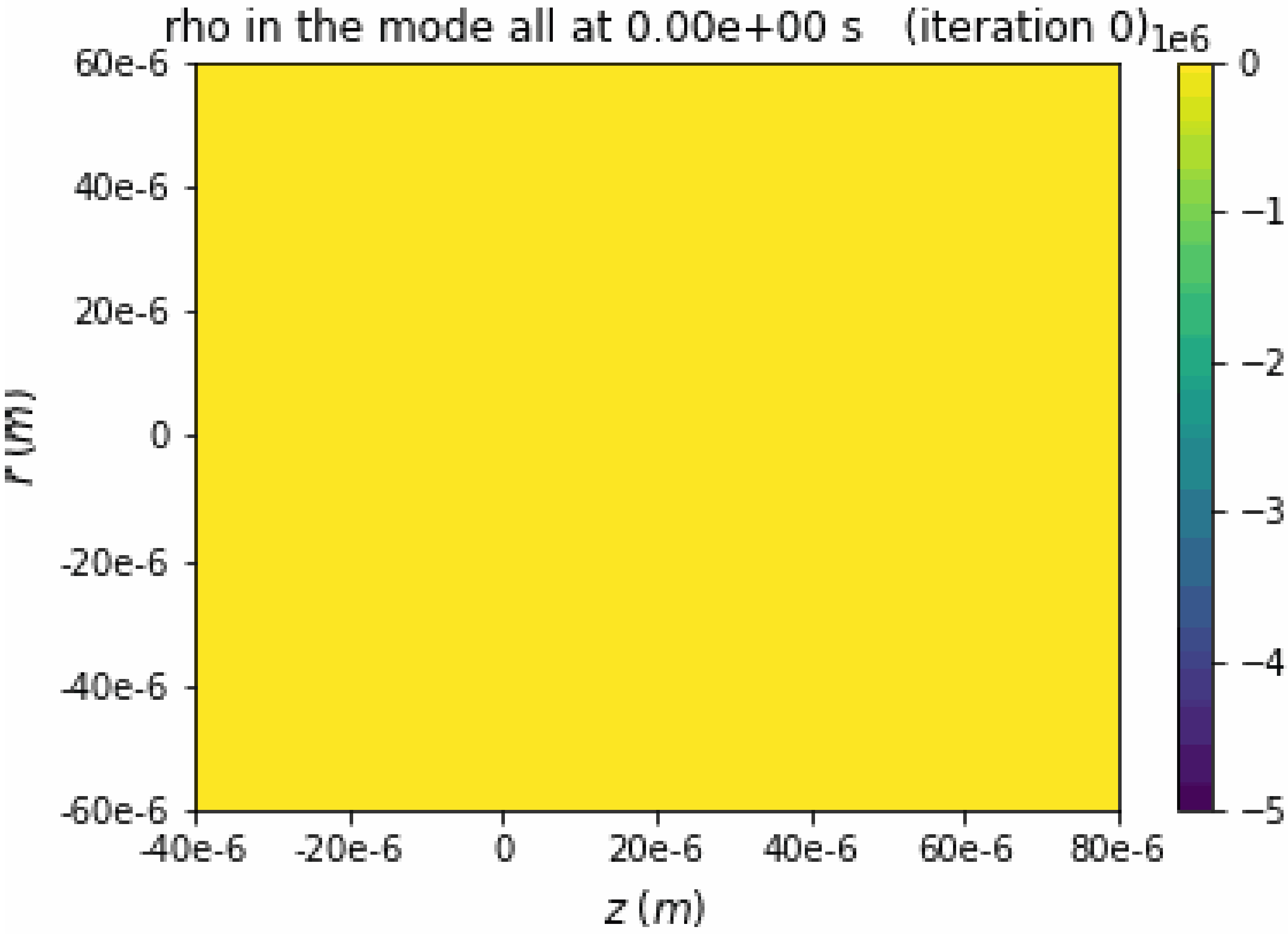


Parameter	Value
a_0	1.6
w_0	24.2 μm
τ	26 fs
z_0	15 μm

Parameter	Value
Nz	1024
zmax	80 μm
zmin	-40 μm
Nr	256
rmax	60 μm
Nm	2
dt	$(zmax - zmin)/Nz/c$

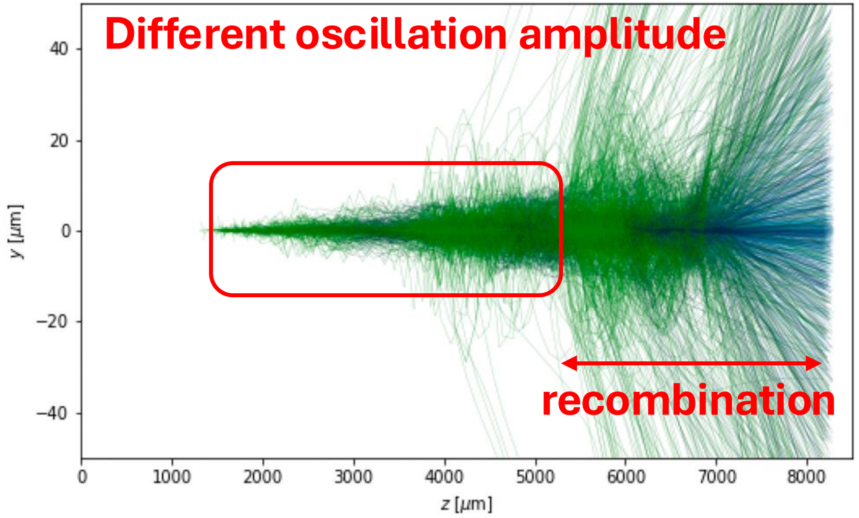
FBPIC-simulation

Electron density evolution: **Bubble formation** – **Self-injection** – **electron oscillation - recombination**

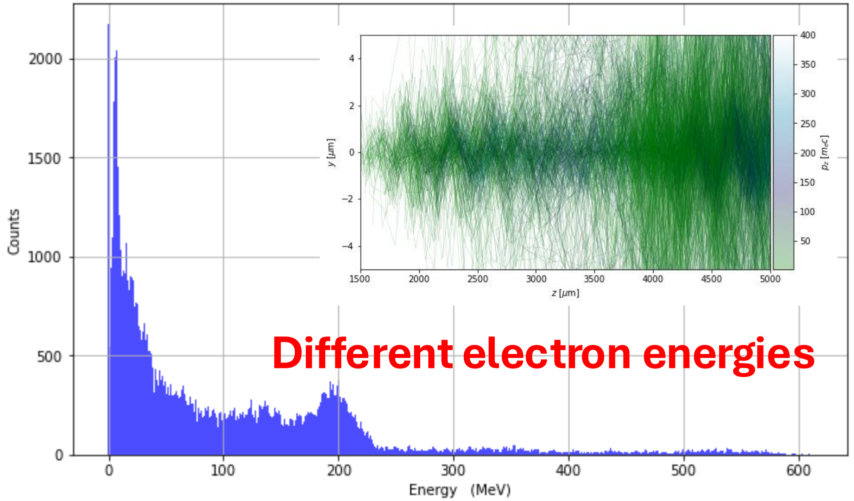


Result of simulations

Trajectories on PIC simulation

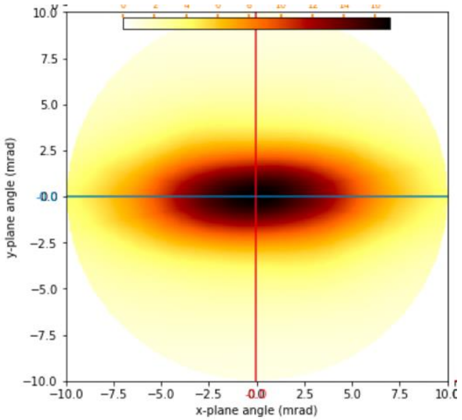


Energy distribution PIC

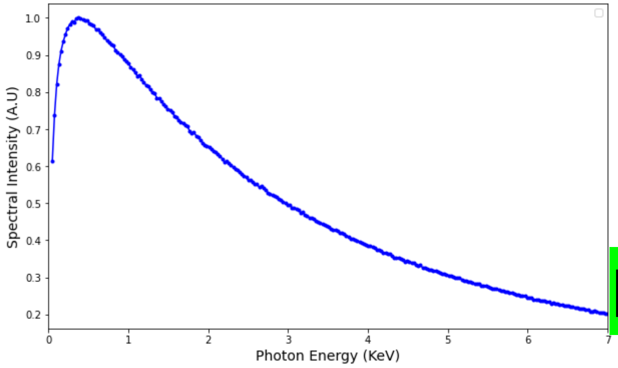


Synchrad

Photon spot

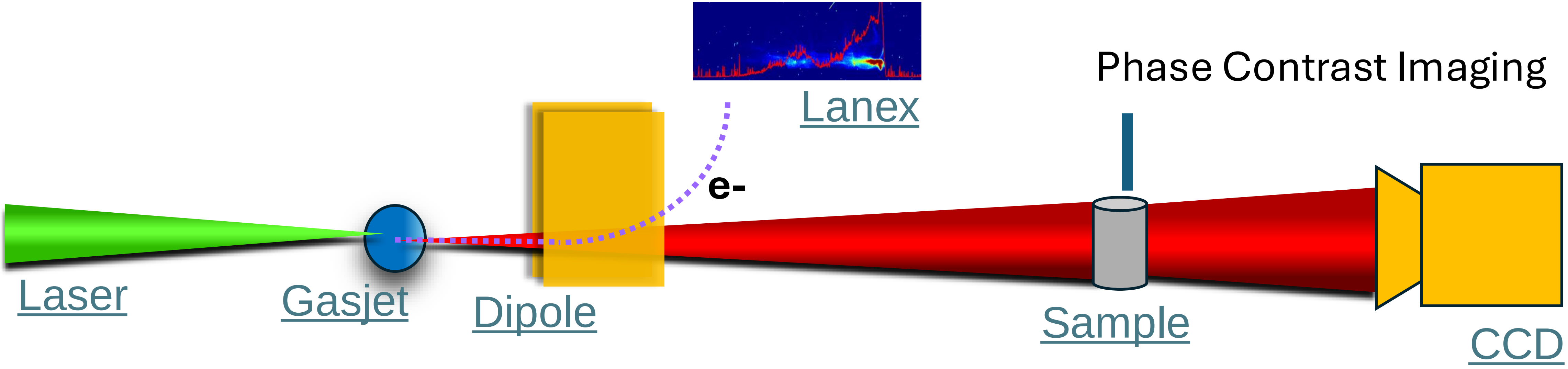


Photon Spectrum



Ec=2.1keV

Experimental campain:
LWFA experiment and characterization of betatron radiation



Density
characterization

Electon
characterizations

Dipole-lanex
calibration

Radiation
characterization

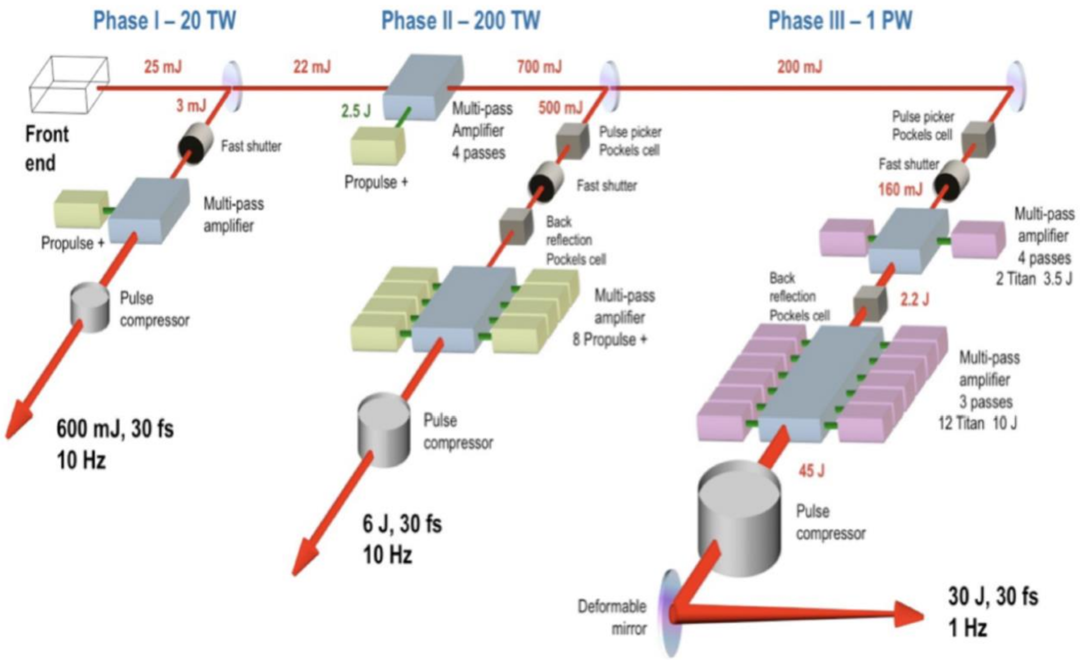
EUV range
Monochormator

X-ray range
Single photon counitng

Experimental campaign

CENTRO DE LÁSERES PULSADOS

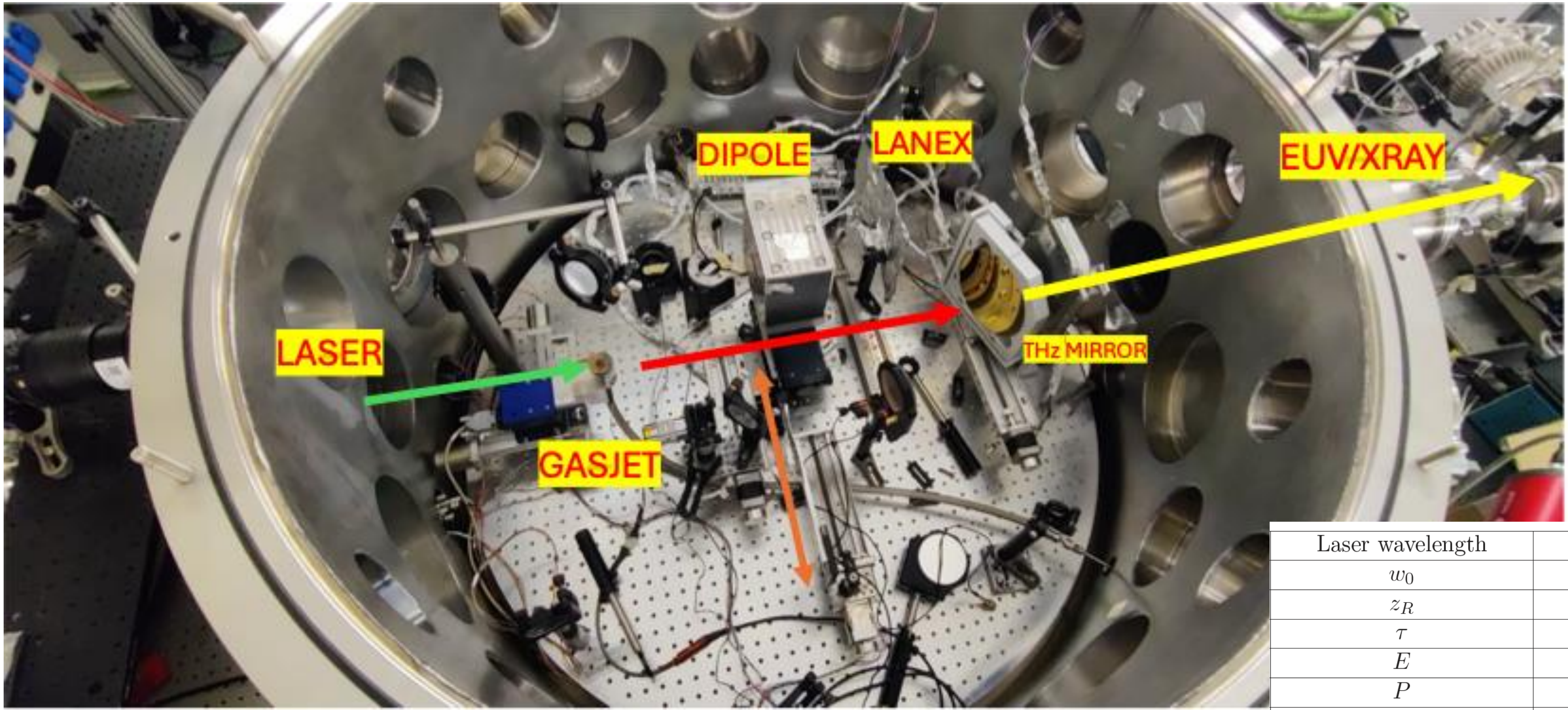
Laser system



Laser Vega II parameter used

	Peak Power	Energy/shot	pulse	Rep.Rate	Central @
VEGA II	~200 TW	~4 J	~30 fs	10 Hz	800 nm

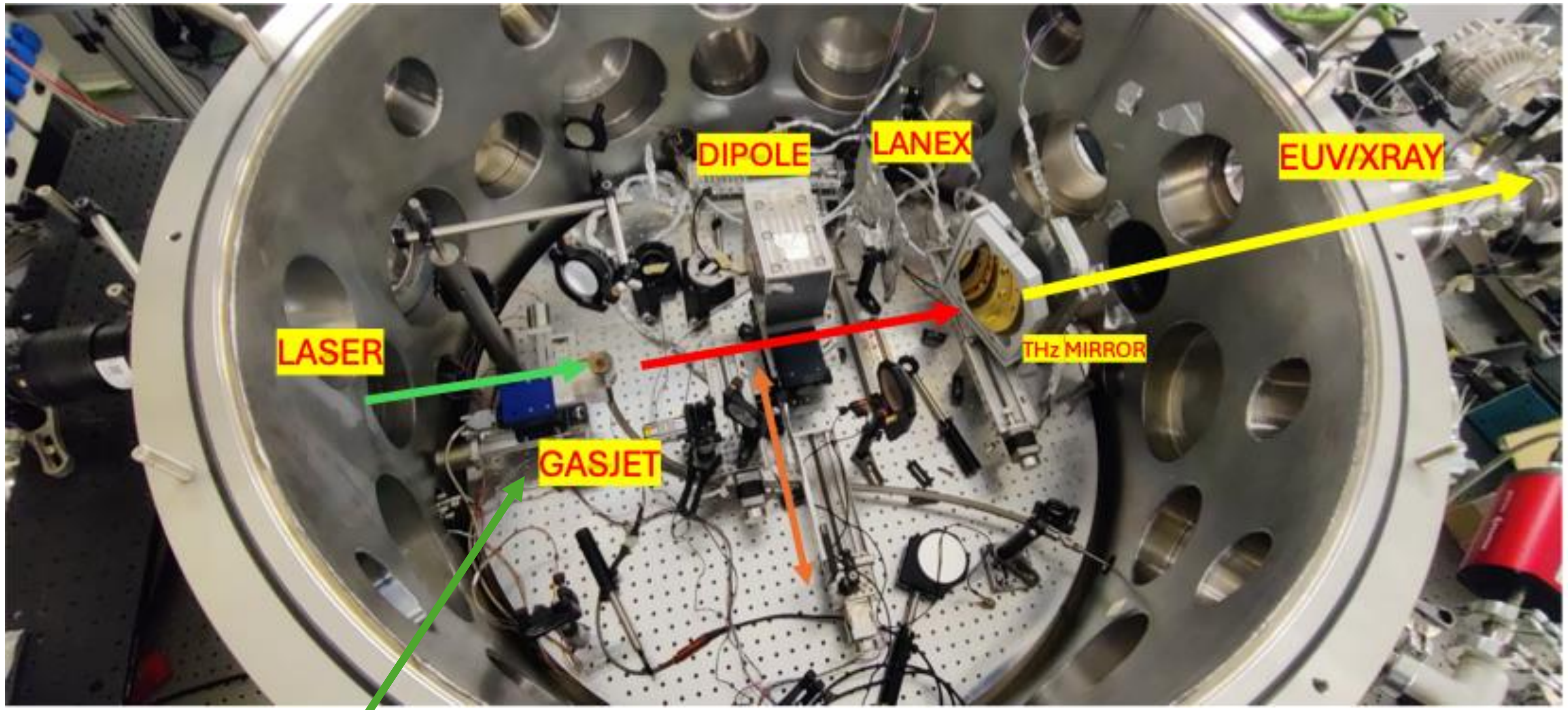
Vacuum chamber of the experiment



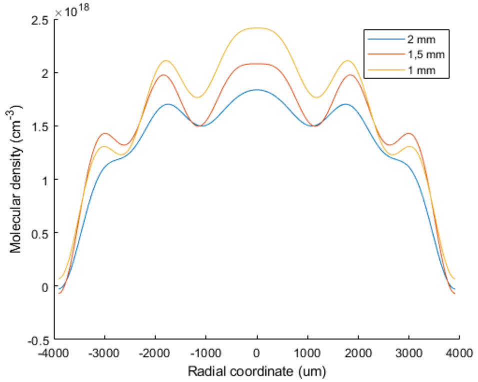
Laser wavelength	800 nm
w_0	$21.3 \pm 0.3\,\mu m$
z_R	$1.8 \pm 0.1\,mm$
τ	$27 \pm 1\,fs$
E	$4.0 \pm 0.5\,J$
P	$139 \pm 21\,TW$
I_0	$(1.9 \pm 0.4) \times 10^{19}\,W/cm^2$
a_0	3.0 ± 0.3
Plasma electron density	3-4 (10^{18} cm^{-3})
gas pressure	30 bar

Parameter of the experiment

Vacuum chamber of the experiment



Gas density measurment



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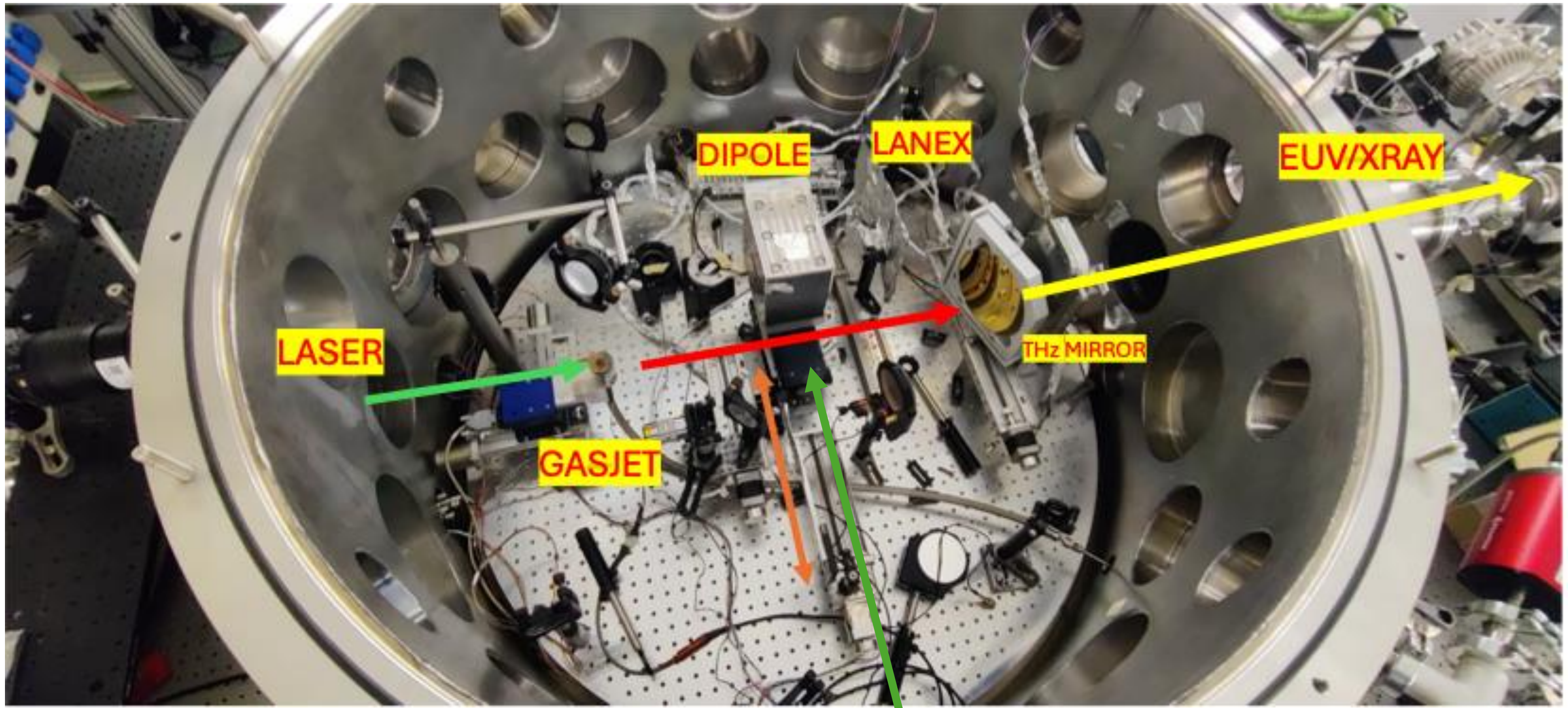

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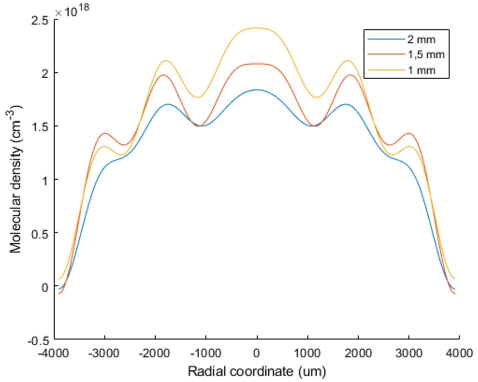
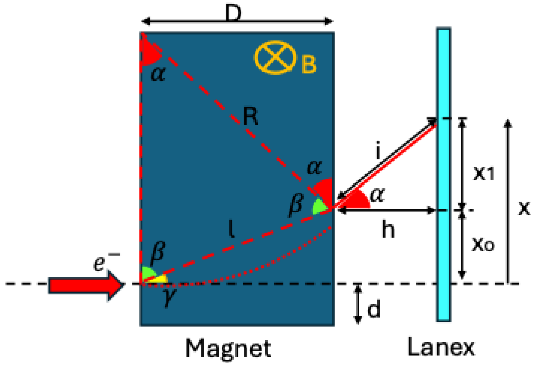


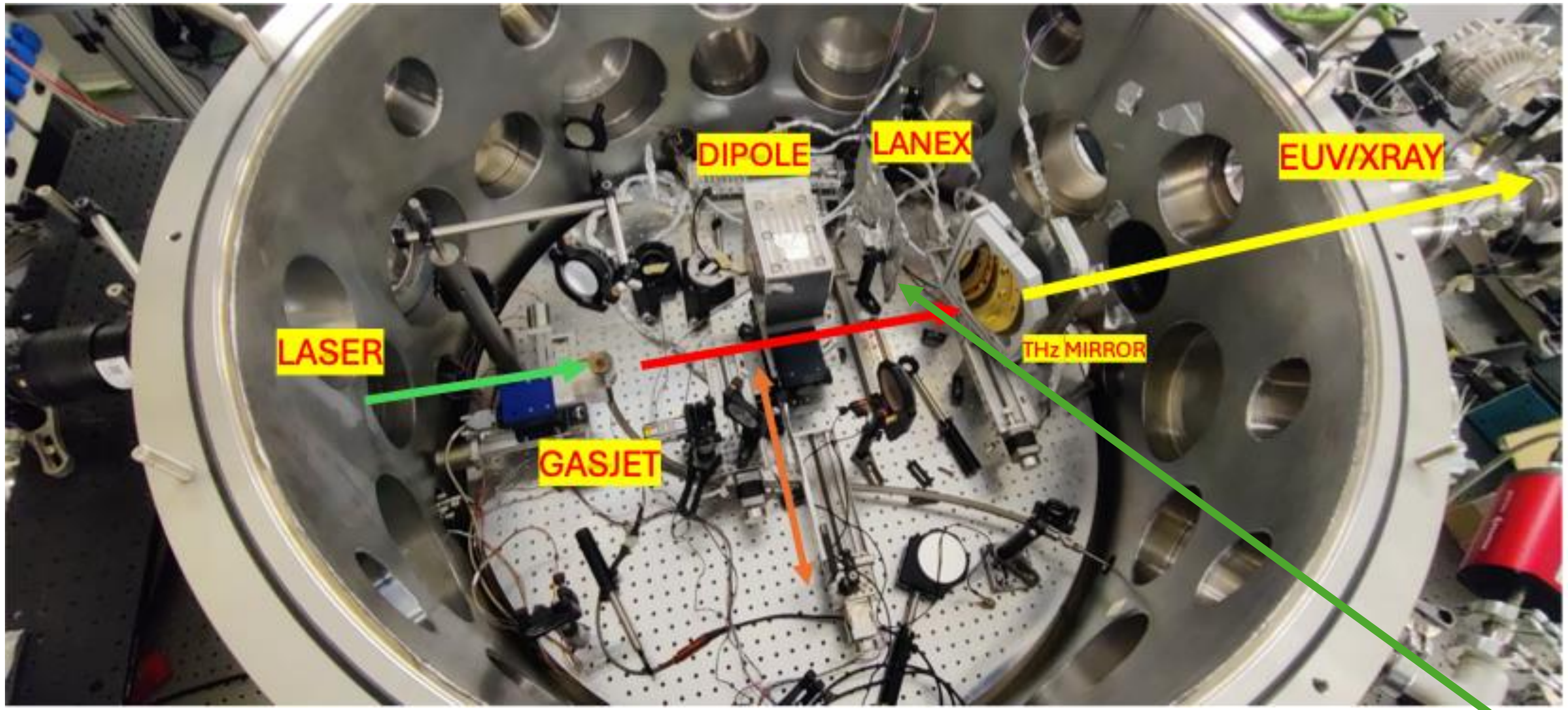
Dipole calibration for energy measurements



$$R = \frac{\gamma m_e \beta c}{eB}$$

$$p[cm] = 2Rsin^2(\frac{\alpha}{2}) + dtg(\alpha)$$

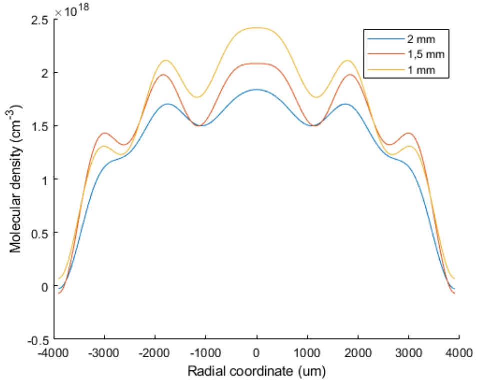
Vacuum chamber of the experiment



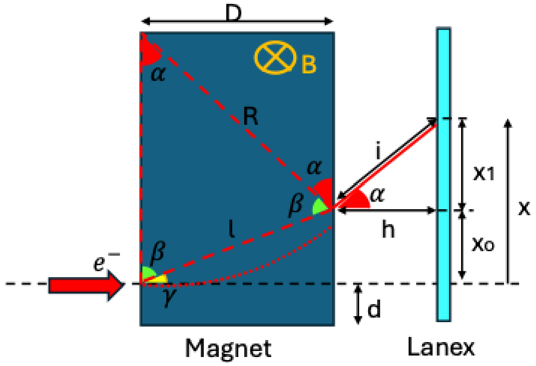
Parameter of the experiment

Laser wavelength	800 nm
w_0	$21.3 \pm 0.3\,\mu$m
z_R	1.8 ± 0.1 mm
τ	27 ± 1 fs
E	4.0 ± 0.5 J
P	139 ± 21 TW
I_0	$(1.9 \pm 0.4) \times 10^{19}$ W/cm^2
a_0	3.0 ± 0.3
Plasma electron density	3-4 (10^{18} cm^{-3})
gas pressure	30 bar

Gas density measurment



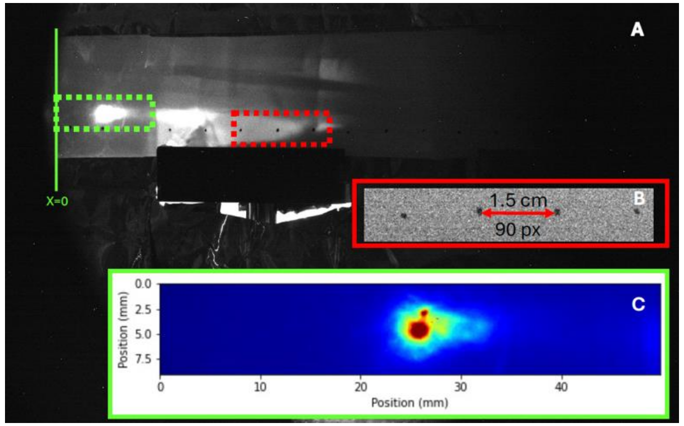
Dipole calibration for energy measurements



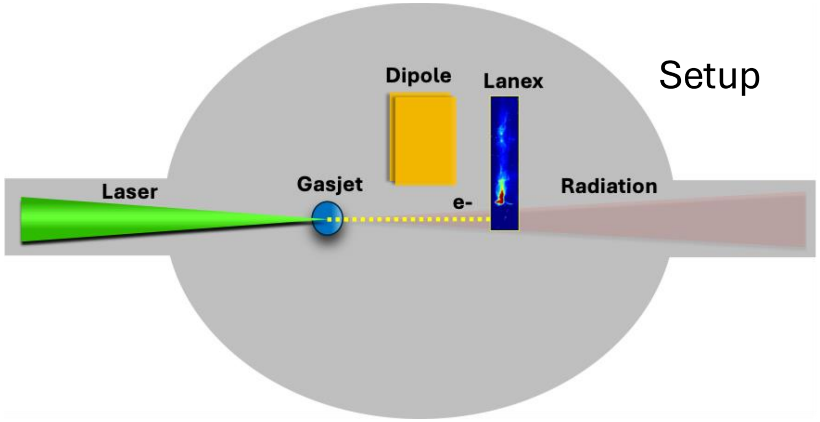
$$R = \frac{\gamma m_e \beta c}{eB}$$

$$p[cm] = 2Rsin^2(\frac{\alpha}{2}) + dtg(\alpha)$$

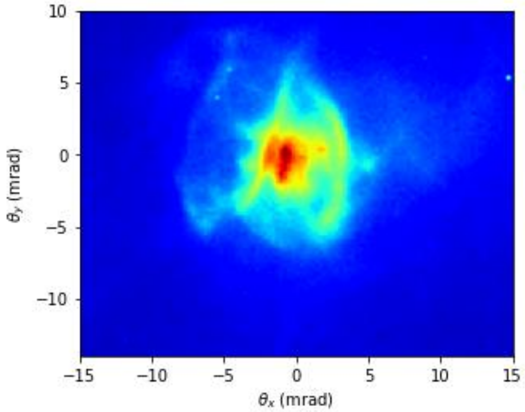
Lanex calibration and post-processing of images



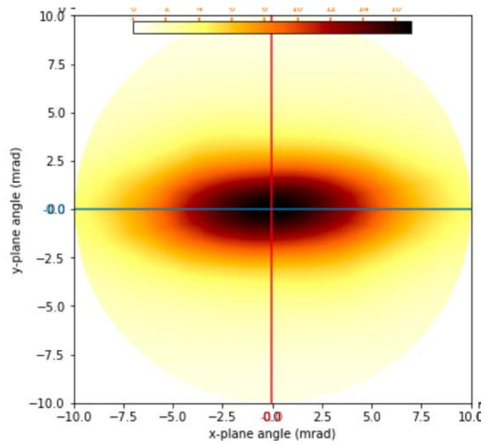
Electron spotsize measurements



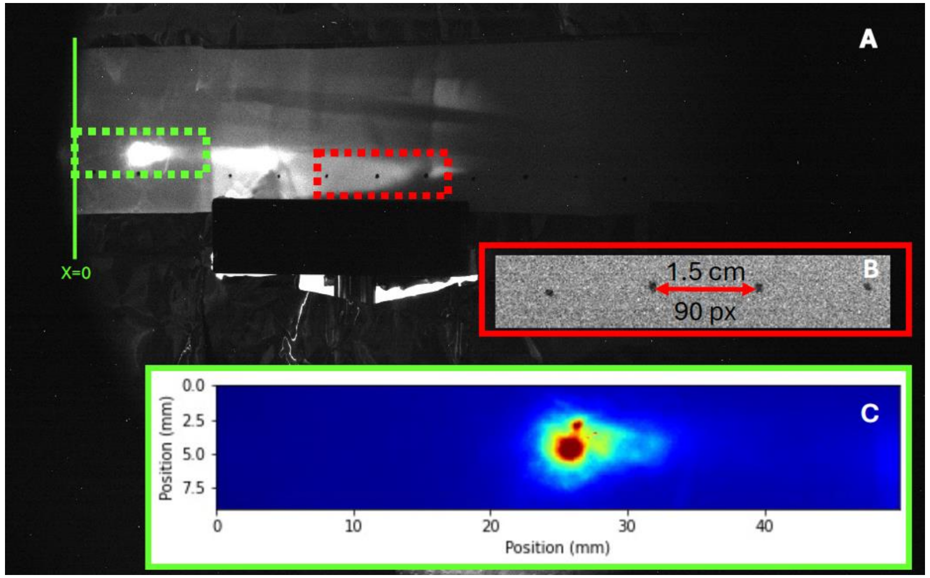
Measurements



Simulation



Lanex screen



Data

Shot n.	θ_x mrad	θ_y mrad	σ_x mrad	σ_y mrad
Shot 1	14.000	7.200	7.000	3.600
Shot 2	10.360	9.400	5.180	4.700
Shot 3	12.180	7.400	6.090	3.700
Shot 4	10.660	6.200	5.330	3.100
Shot 5	8.344	8.386	4.172	4.193
Shot 6	7.720	9.260	3.860	4.630
Shot 7	10.036	8.614	5.018	4.307
Shot 8	7.862	7.800	3.931	3.900
Shot 9	7.862	8.608	3.931	4.304
Shot 10	7.440	8.054	3.720	4.027
Mean	**9.6464**	**8.0922**	**4.8232**	**4.0461**

Divergence

$$\theta = \sqrt{\theta_x^2 + \theta_y^2} = \sqrt{9.64^2 + 8^2} = 12.52\text{mrad}$$

$$K = r_\beta \gamma k_\beta$$

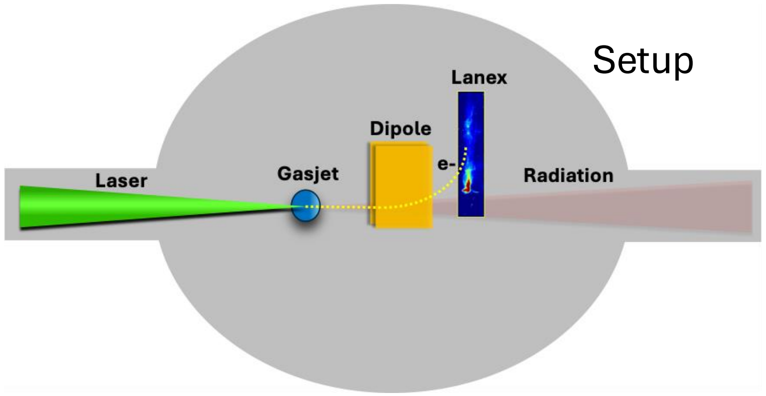
$$\theta = K/\gamma$$

We need the energy to calculate the amplitude of oscillation

$$r_\beta = \frac{\theta}{K}$$

Amplitude of oscillation

Electron energy measurements

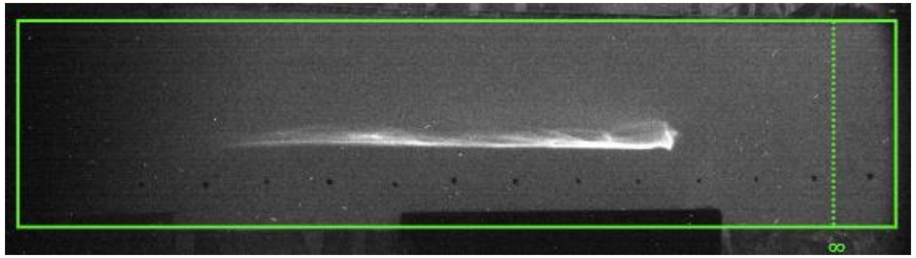


Setup

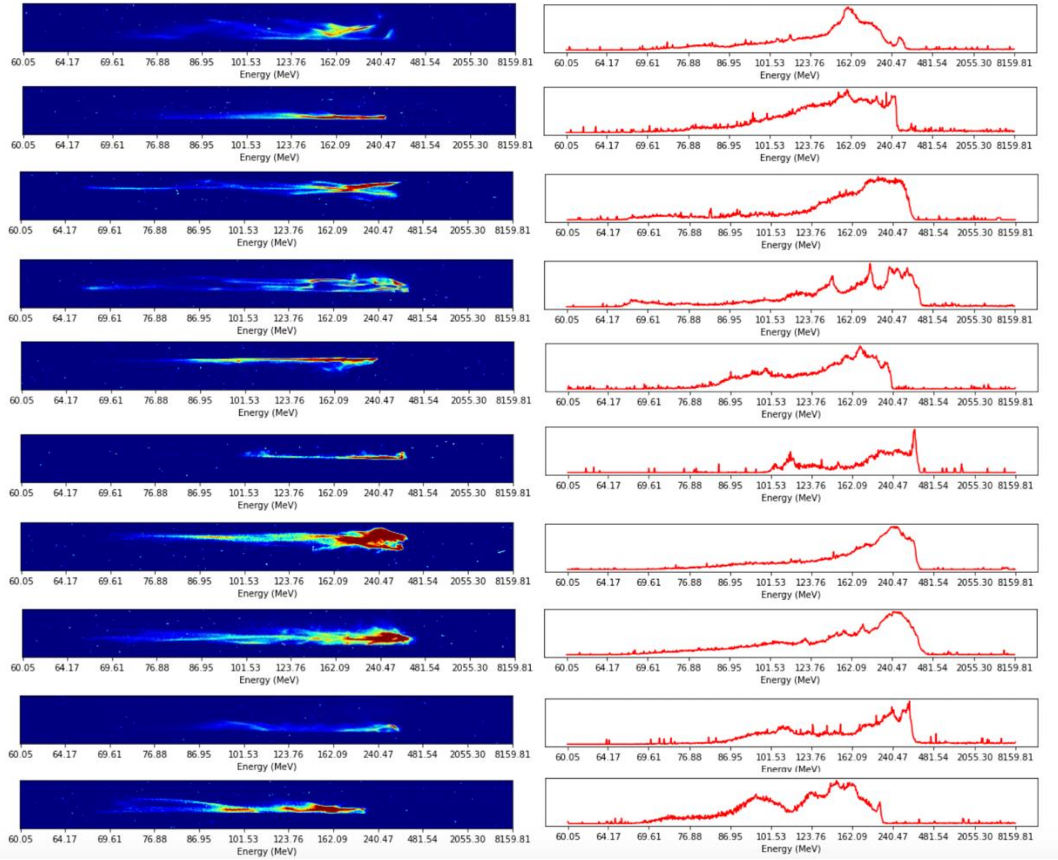
Shot n.	$\langle E \rangle$ (MeV)	σ_E (MeV)
Shot 1	160.47	59.58
Shot 2	229.88	78.49
Shot 3	184.2	56.32
Shot 4	194.73	77.17
Shot 5	144.29	42.37
Shot 6	215.23	120.18
Shot 7	197.82	68.48
Shot 8	189.16	74.42
Shot 9	193.17	109.68
Shot 10	157.83	308.23
Average	186.59	99.08

$$\langle \gamma \rangle = \frac{\langle E \rangle}{E_0} = 364.19 \quad \Rightarrow \quad r_\beta = 0.88\,\mu\text{m}$$

Energy spectrum (RAW data)

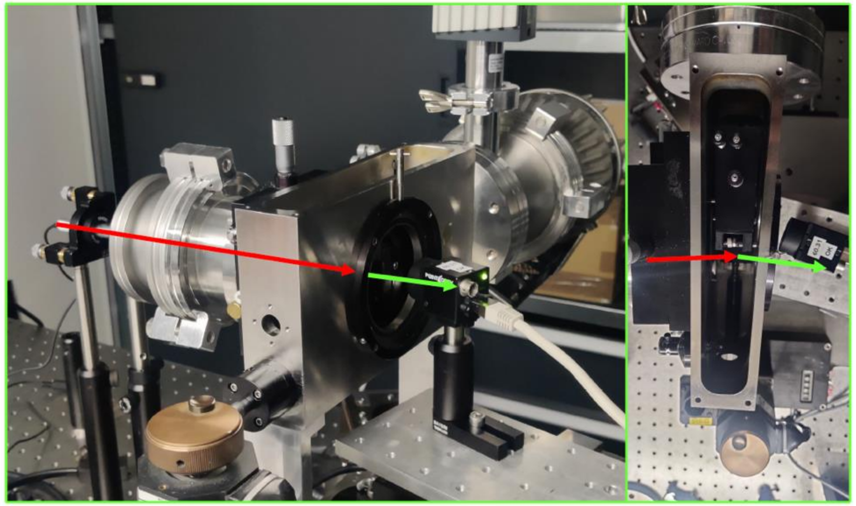


Energy spectrum (post processed data)

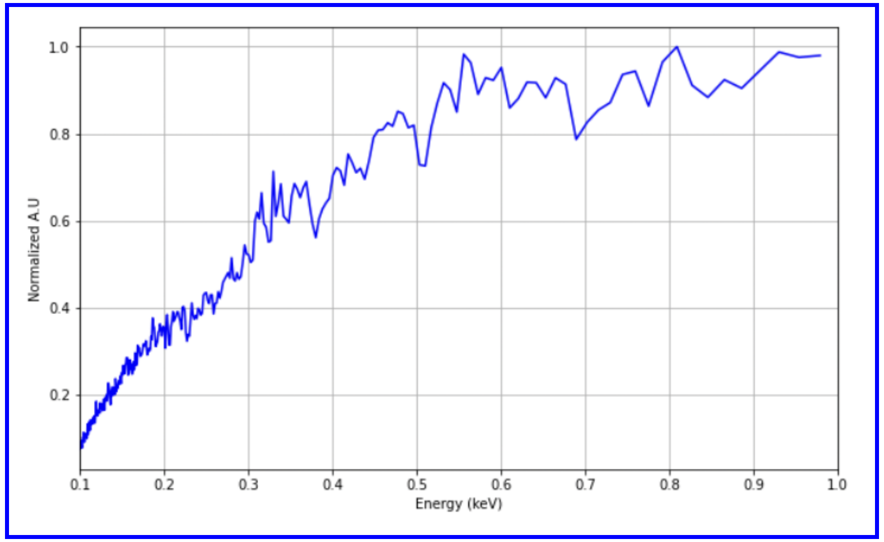


Spectra reconstruction

Using: Grazing Incidence Monochromator

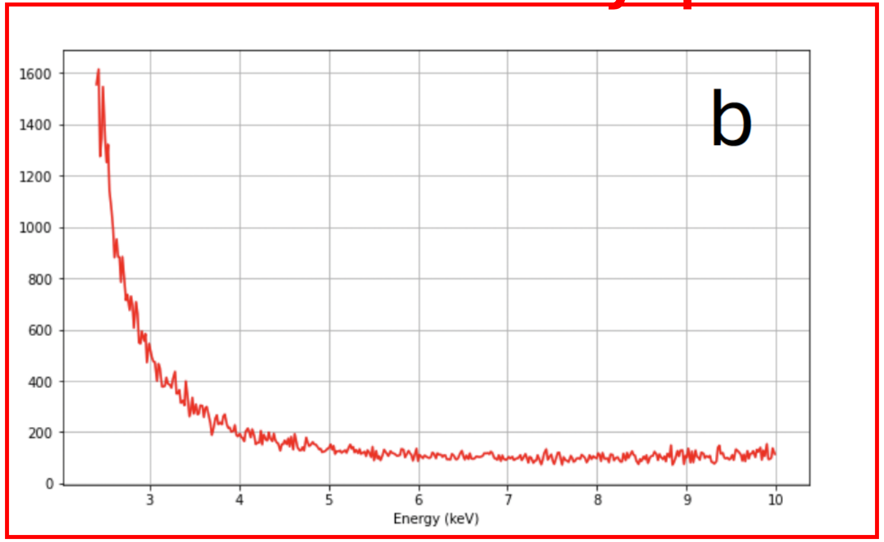


Measurements of EUV spectrum

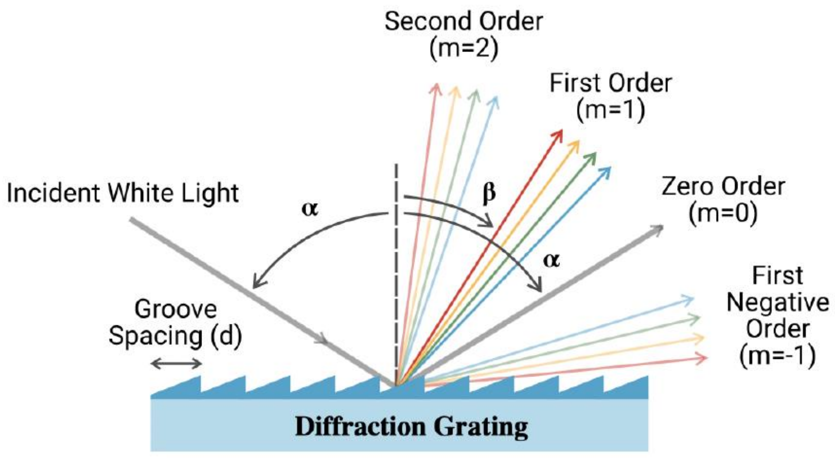


Using: Single photon counting

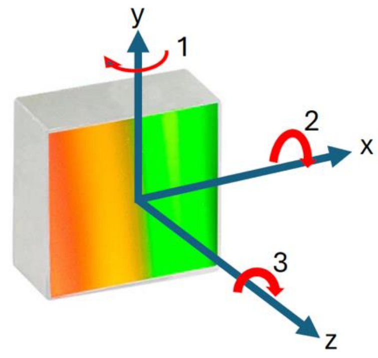
Measurements of X ray spectrum



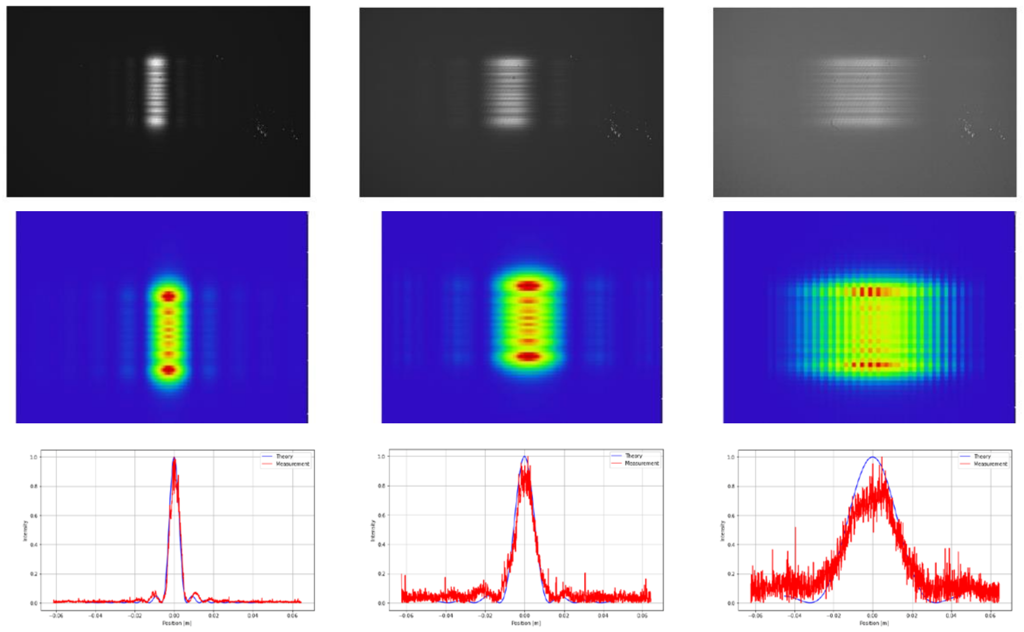
Grazing Incidence Monochromator



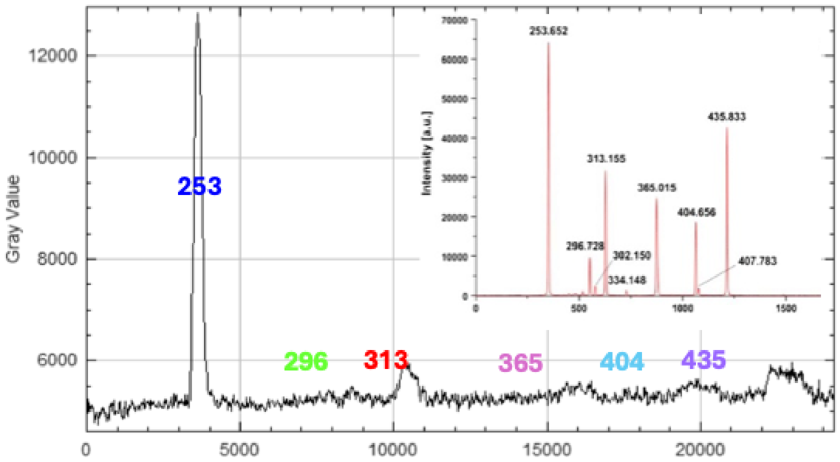
1) Alignment



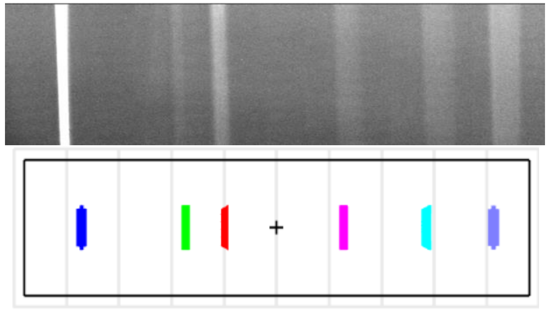
2) Slit measurement



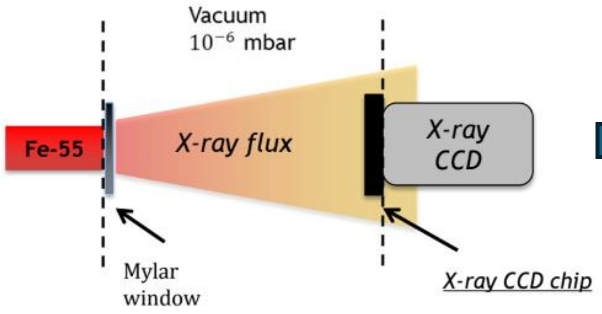
3) Calibration for EUV with mercury lamp and Zemax



Mercury line

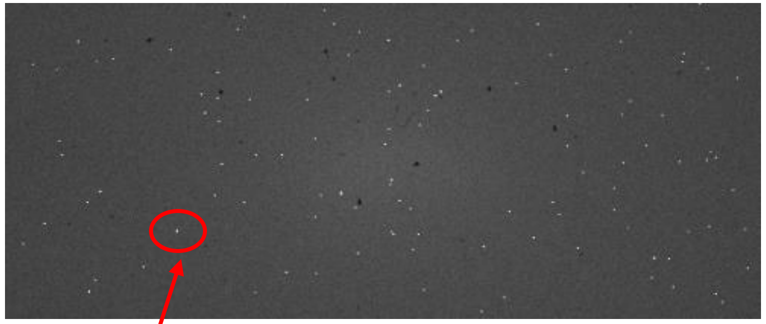


Single photon counting



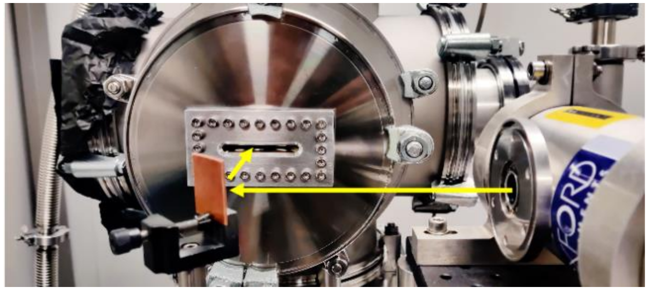
Photons directly hit the CCD camera.

The number of photons must be very low, and the pixels that will be hit will have a very low density

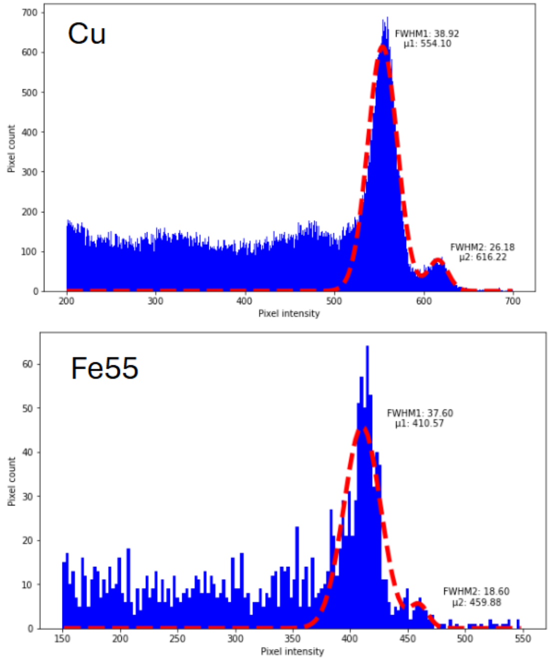


Single pixel illuminated

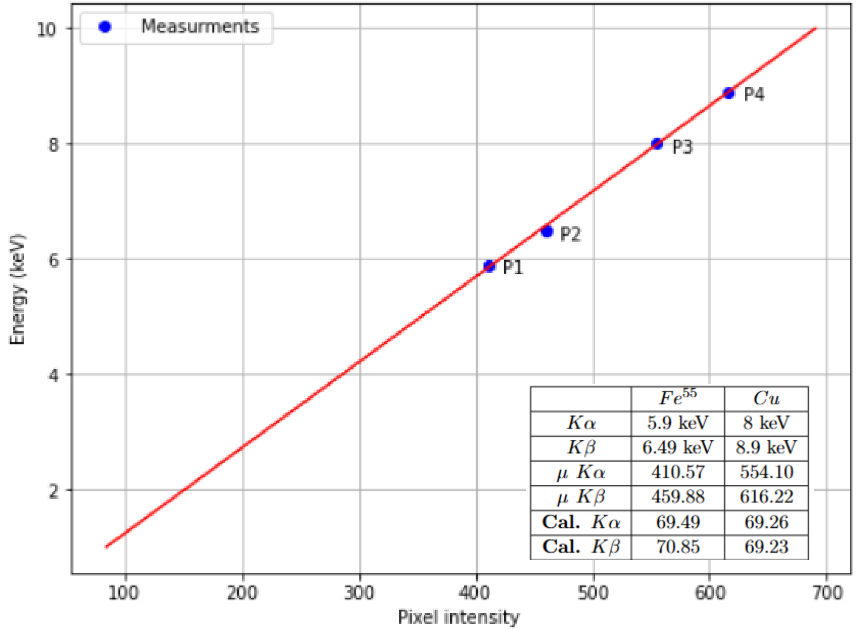
Calibration



Two sources were used:
Fe55 and Cu



The intensity histogram is compared with the typical emission line

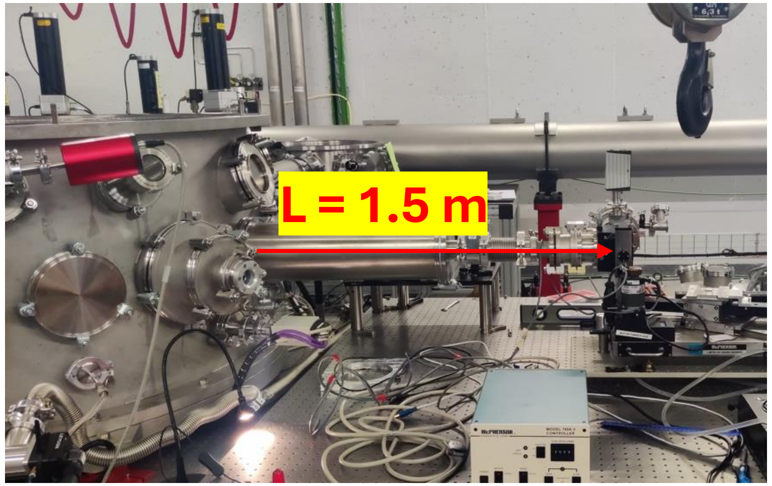


	Fe^{55}	Cu
$K\alpha$	5.9 keV	8 keV
$K\beta$	6.49 keV	8.9 keV
$\mu\ K\alpha$	410.57	554.10
$\mu\ K\beta$	459.88	616.22
Cal. $K\alpha$	69.49	69.26
Cal. $K\beta$	70.85	69.23

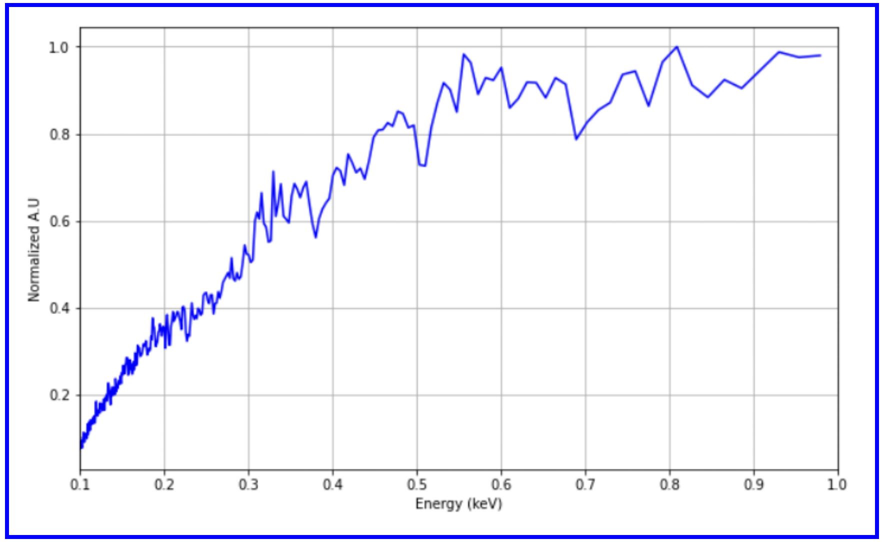
Calibration curve for the CCD camera

Spectra reconstruction

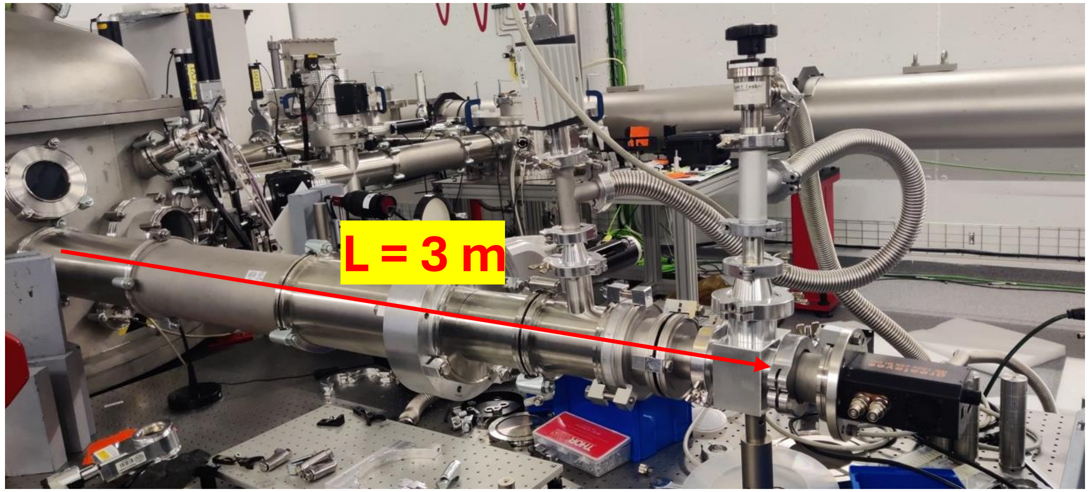
Plasma → Grating → Al filter → CCD



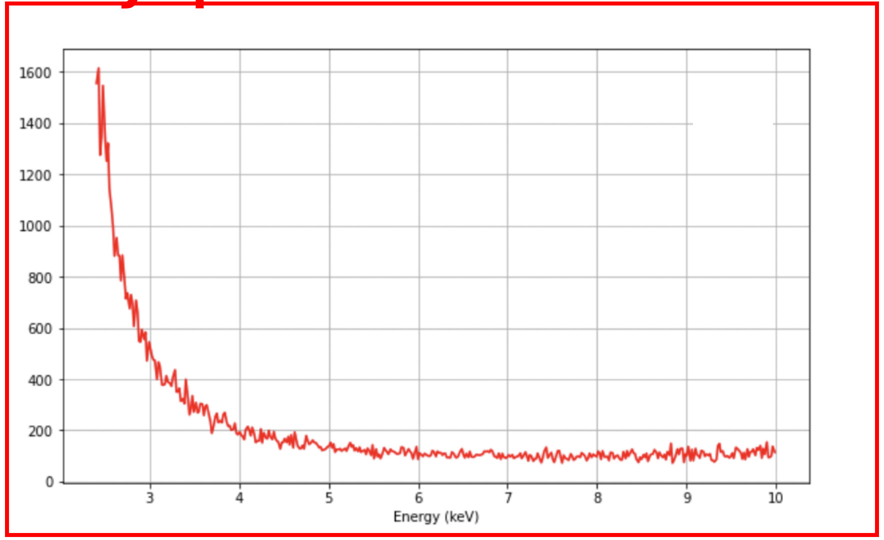
EUV spectrum



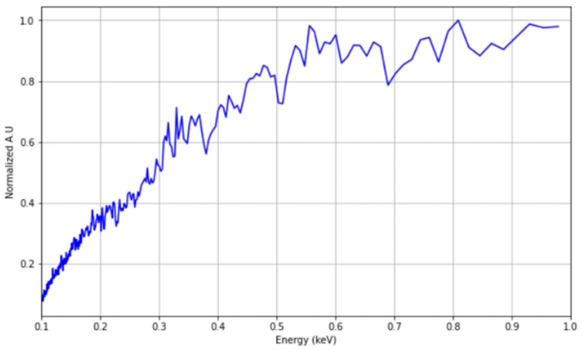
Plasma → Al filter → CCD

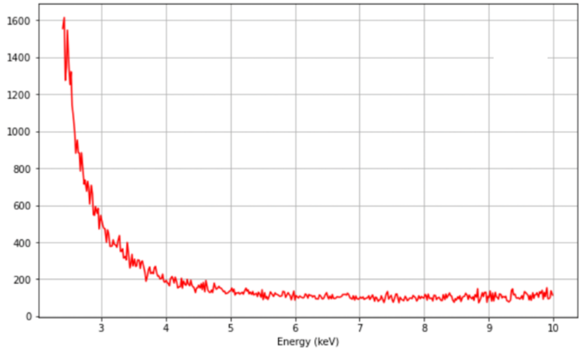


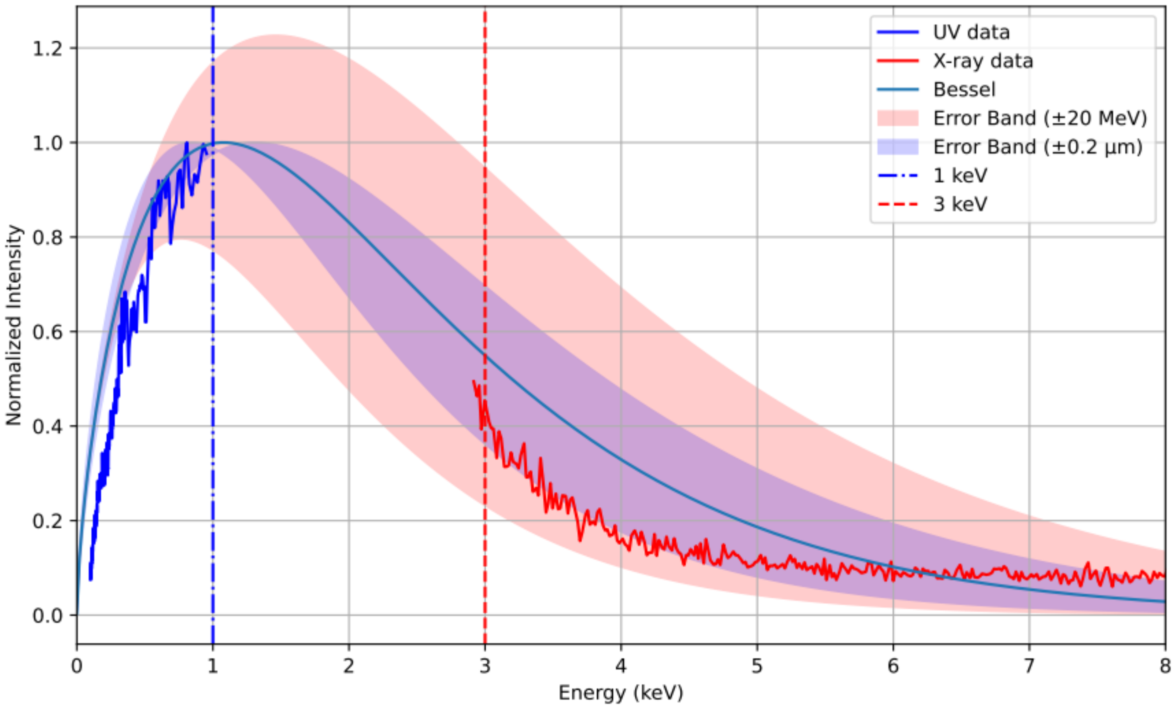
X ray spectrum



Spectra reconstruction EUV + X







Merging of the two part of the spectra using the asymptotic equation

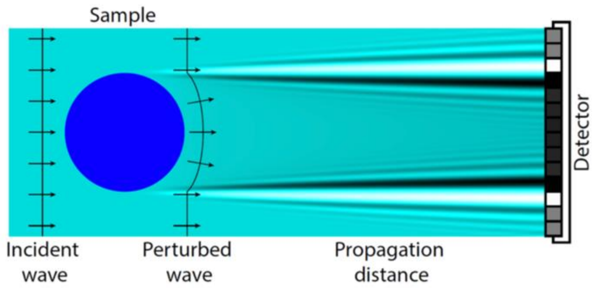
$$\left.\frac{d^2 I}{d\omega d\Omega}\right|_{\theta=0} \simeq N_\beta \frac{3e^2}{2\pi^3 \varepsilon_0 c} \gamma^2 \zeta^2 \mathcal{K}^2_{2/3}(\zeta)$$

Possible errors in the evaluation of the energy, the amplitude of oscillation or in the deconvolution

Parameter	value
n_e	$4 \times 10^{18}\,\mathrm{cm}^{-3}$
γ	364.19
θ	12.52 mrad
r_β	0.88 μm
E	186.59 ± 20 MeV
σ_E	$99.08 \pm$ MeV
E_c	2.3 keV

X-Ray phase contrast imaging (XPCI)

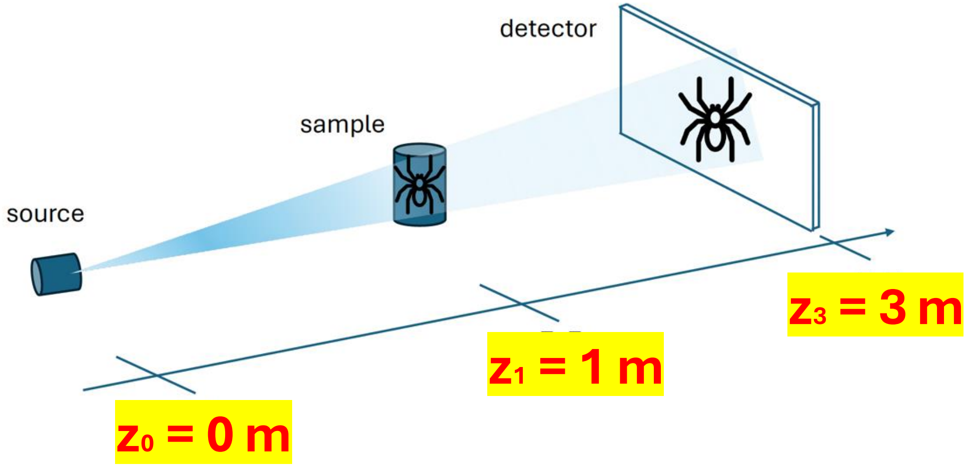
Propagation-Based

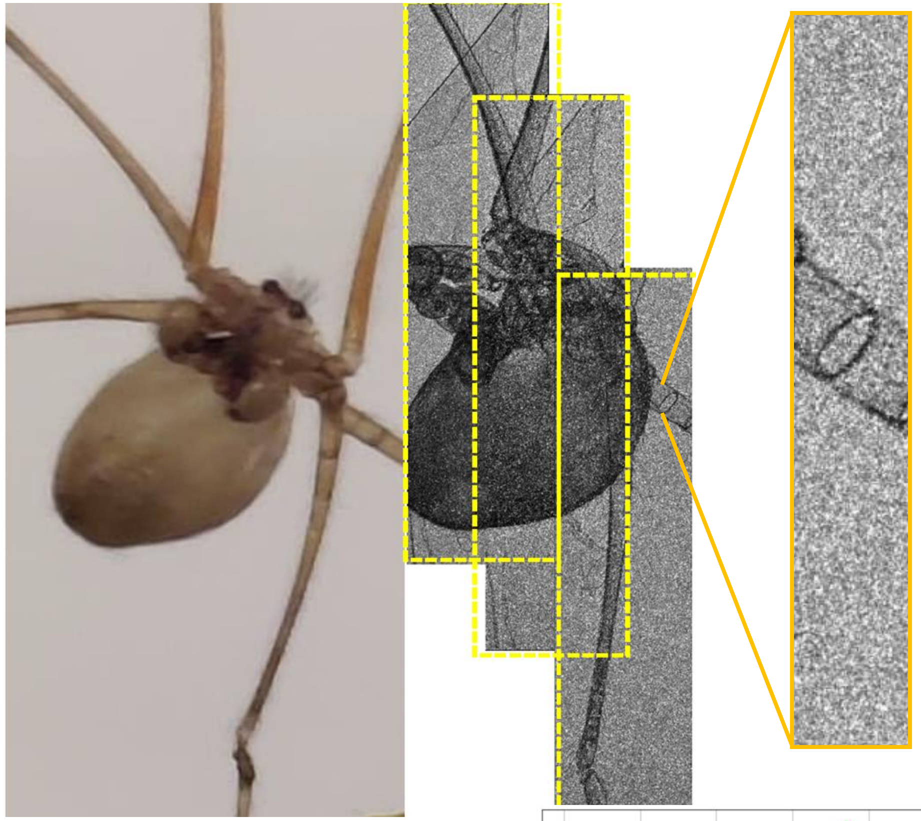


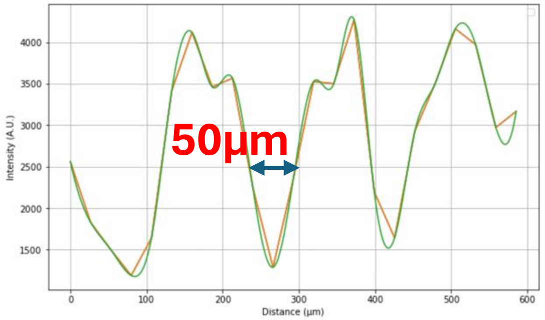
$$\eta = 1 - \delta + i\beta$$

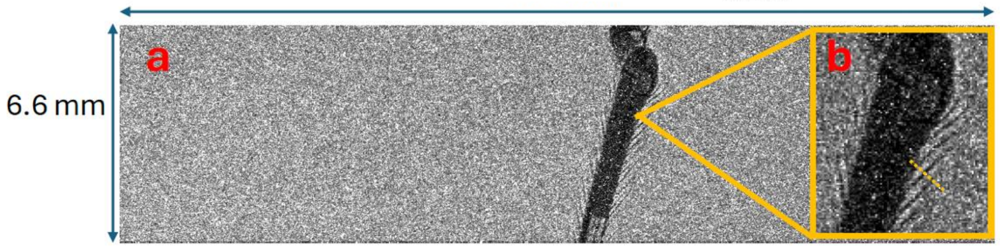
XPCI $\delta >> \beta$

at high x-ray energies







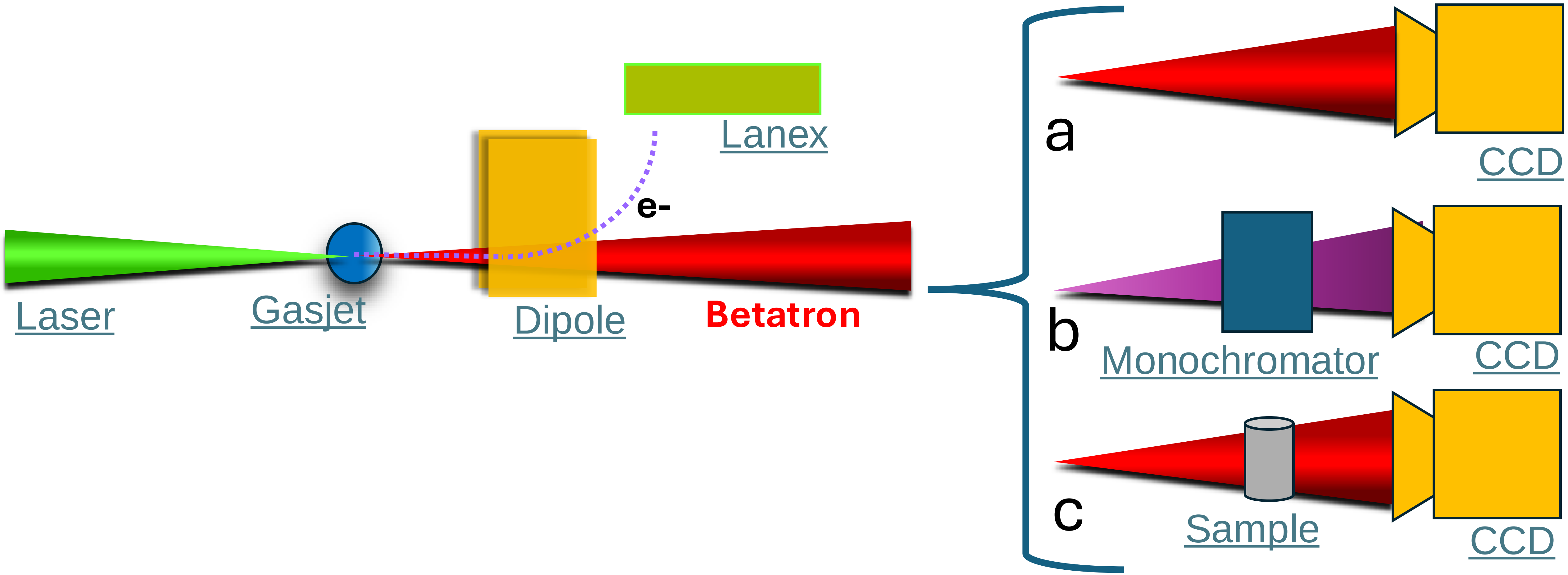


Magnification

$$M = \frac{Z_3}{Z_1} = 3$$

Conclusion

- Introduced the EuAPS project, outlining its objectives and significance.
- Provided an overview of the Laser Wakefield Acceleration (LWFA) theory.
- Explored the theory of betatron radiation, emphasizing key parameters such as electron density, electron energy, and oscillation radius, which define the betatron strength parameter.
- Analyzed how variations in electron energy and oscillation amplitude influence the shape of the radiation spectra.
- Presented simulations conducted with FBPIC and Synchrad.
- Described the experimental setup and results from the CLPU facility in Spain.



Lanex
e-
Laser
Gasjet
Dipole
Betatron
a
CCD
b
Monochromator
CCD
c
Sample
CCD