Betatron radiation from a LWFA

EuPRAXIA@SPARC_LAB

User Workshop 2021

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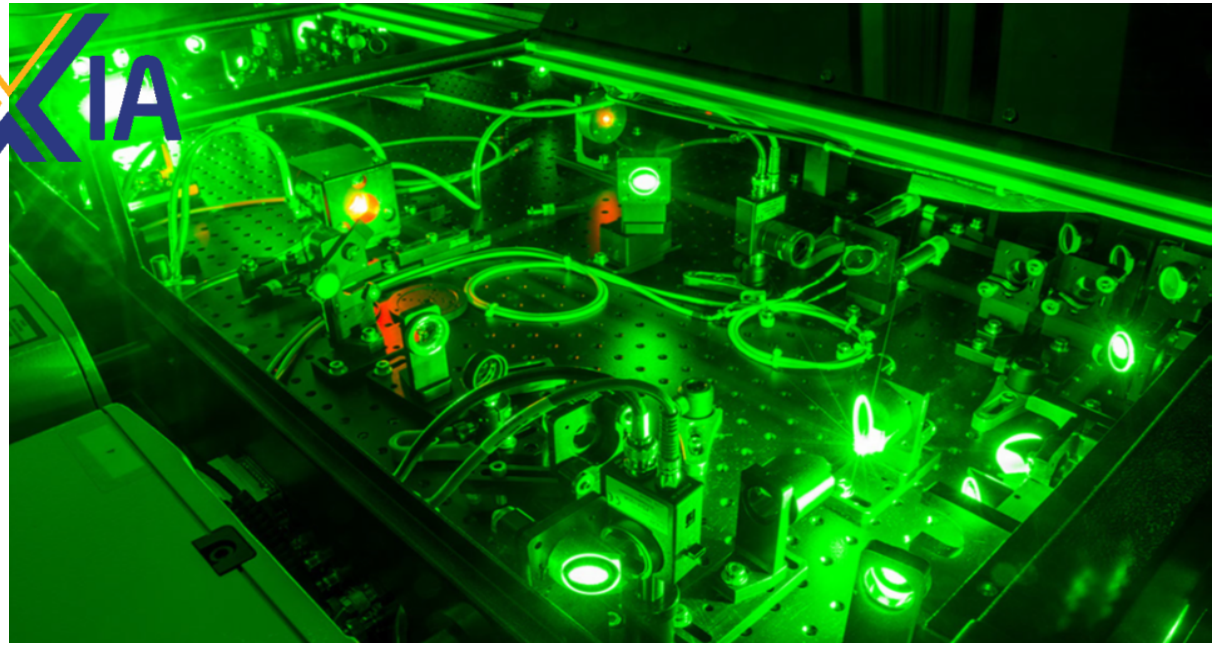
EuPRAXIA framework

In the EuPRAXIA framework, the high-power laser FLAME will be adopted to develop auxiliary **charged particles** and **X-ray** sources available for the users.

Intensive R&D programs are ongoing to fulfil the EuPRAXIA requirements.



Outline

FLAME laser system

FLAME experimental activity

Outlook

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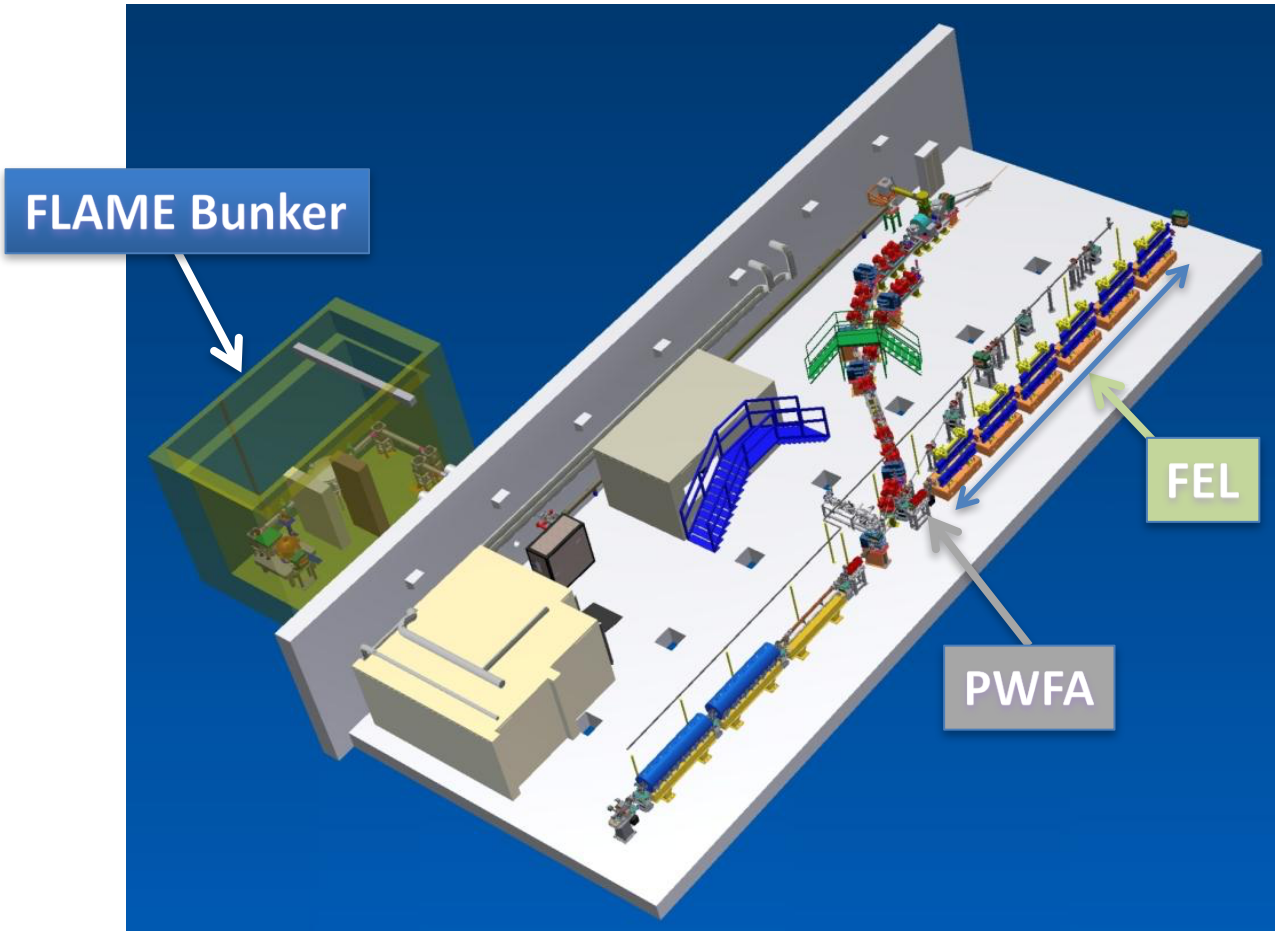
SPARC_LAB Facility

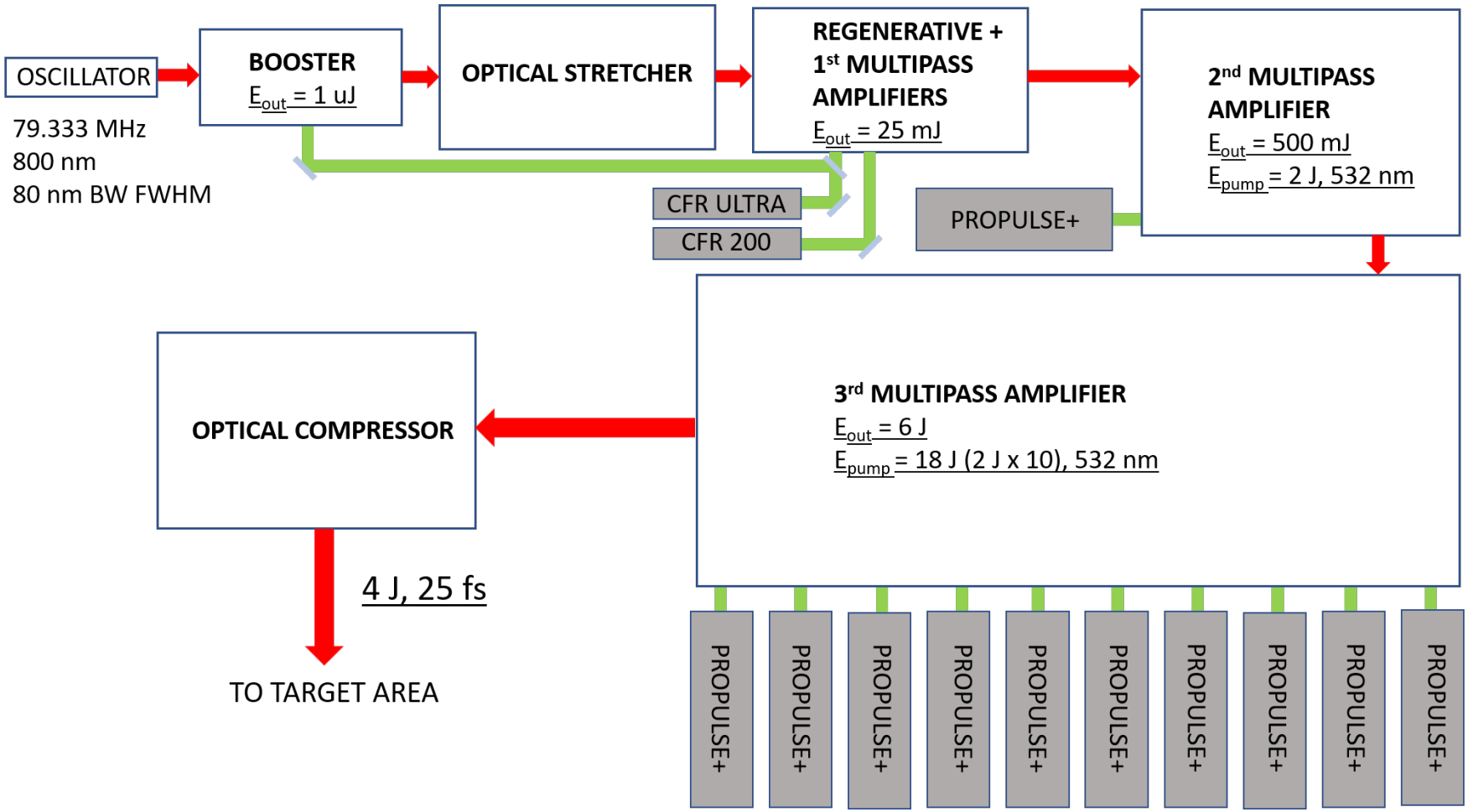


Sources for **P**lasma **A**ccelerators and **R**adiation **C**ompton with **L**asers and **B**eams

SPARC_LAB is a multi-disciplinary TEST Facility composed by a high brightness LINAC and the high-power laser FLAME.

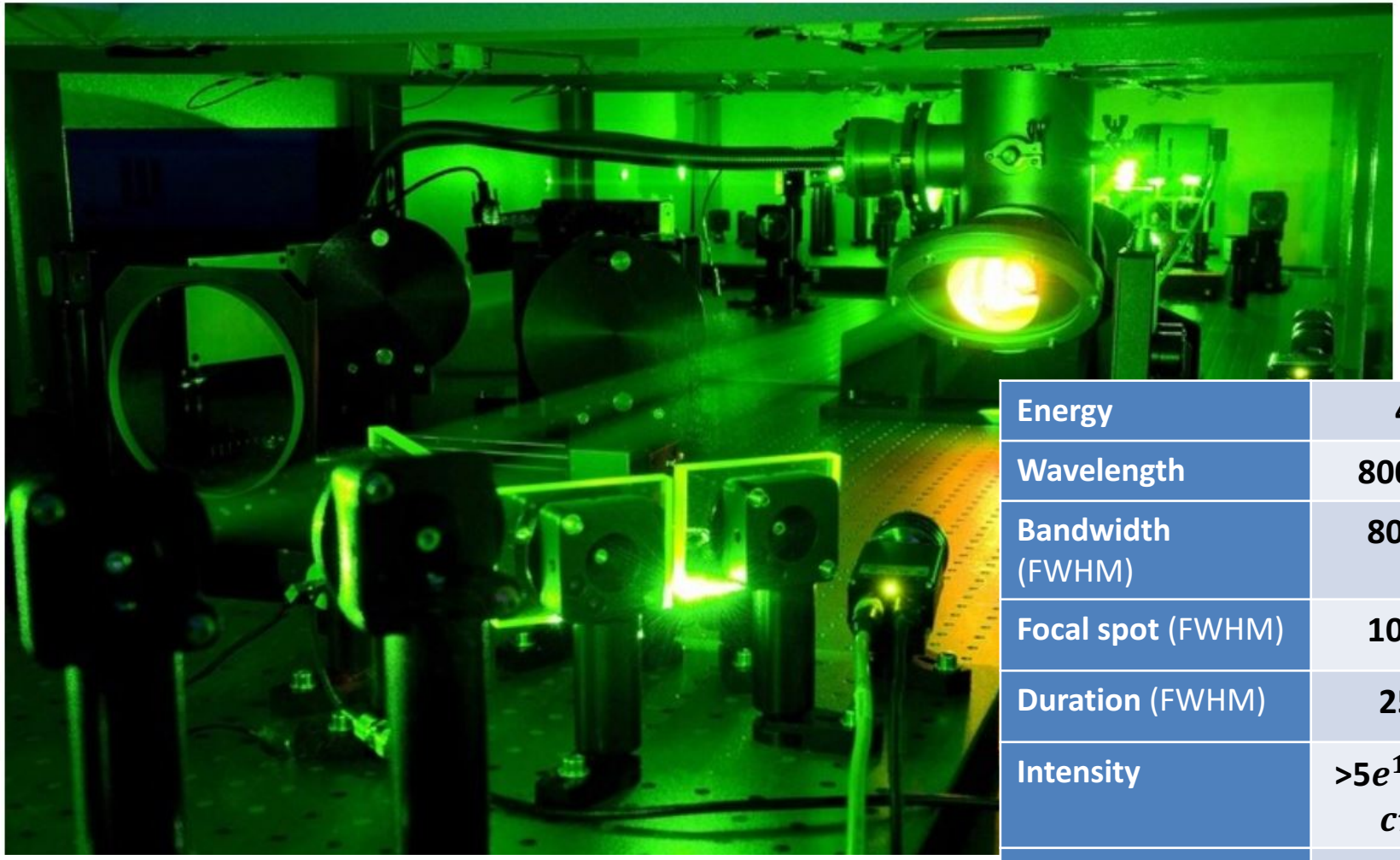
M. Ferrario, et al. NIM B 309 (2013): 183-188

FLAME laser system setup



F. Bisesto, et al. NIM A 909 (2018): 452-455.

FLAME laser system interaction parameters



FLAME high-power amplifier

Energy	**4 J**
Wavelength	**800 nm**
Bandwidth (FWHM)	**80 nm**
Focal spot (FWHM)	**10 um**
Duration (FWHM)	**25 fs**
Intensity	**>5e^{19} W/cm^2**
Contrast (@100 ps)	**1e^{10}**

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SPARC_LAB Facility e il laser FLAME

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Experimental activity @ FLAME

Interaction of high-power lasers with matter

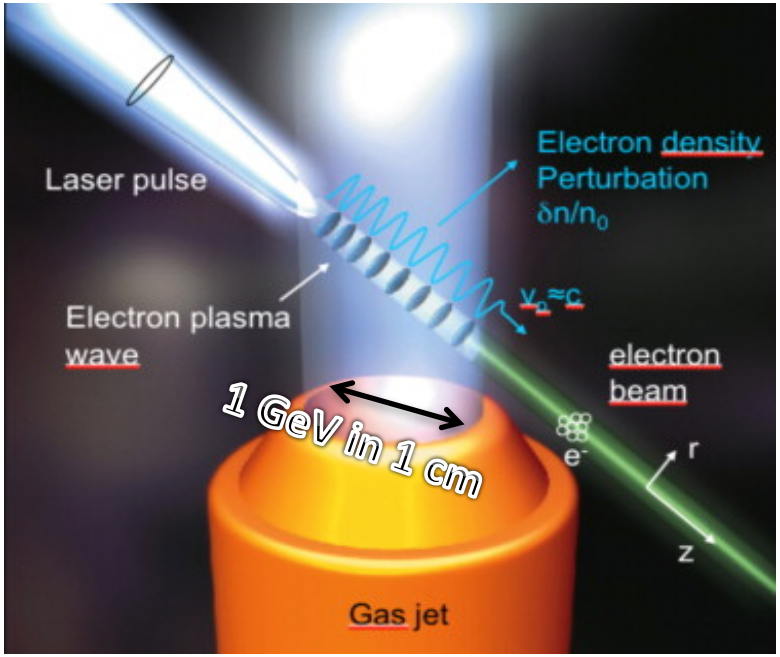
Gas-like target

- Electron acceleration via LWFA in the self-injection scheme.
- Study and implementation of single-shot diagnostic techniques.
- Study of secondary radiation produced by acceleration such as betatron radiation.

Solid state-like target

- Diagnostics based on Electro-Optic Sampling to characterize electrons and the evolution of their electric field.
- Simultaneous characterization of protons and electrons in TNSA experiments.

Accelerators based on LWFA



Laser wakefield-based accelerators (LWFA) are a new type of accelerator capable of producing accelerating fields up to several hundred GV/m.

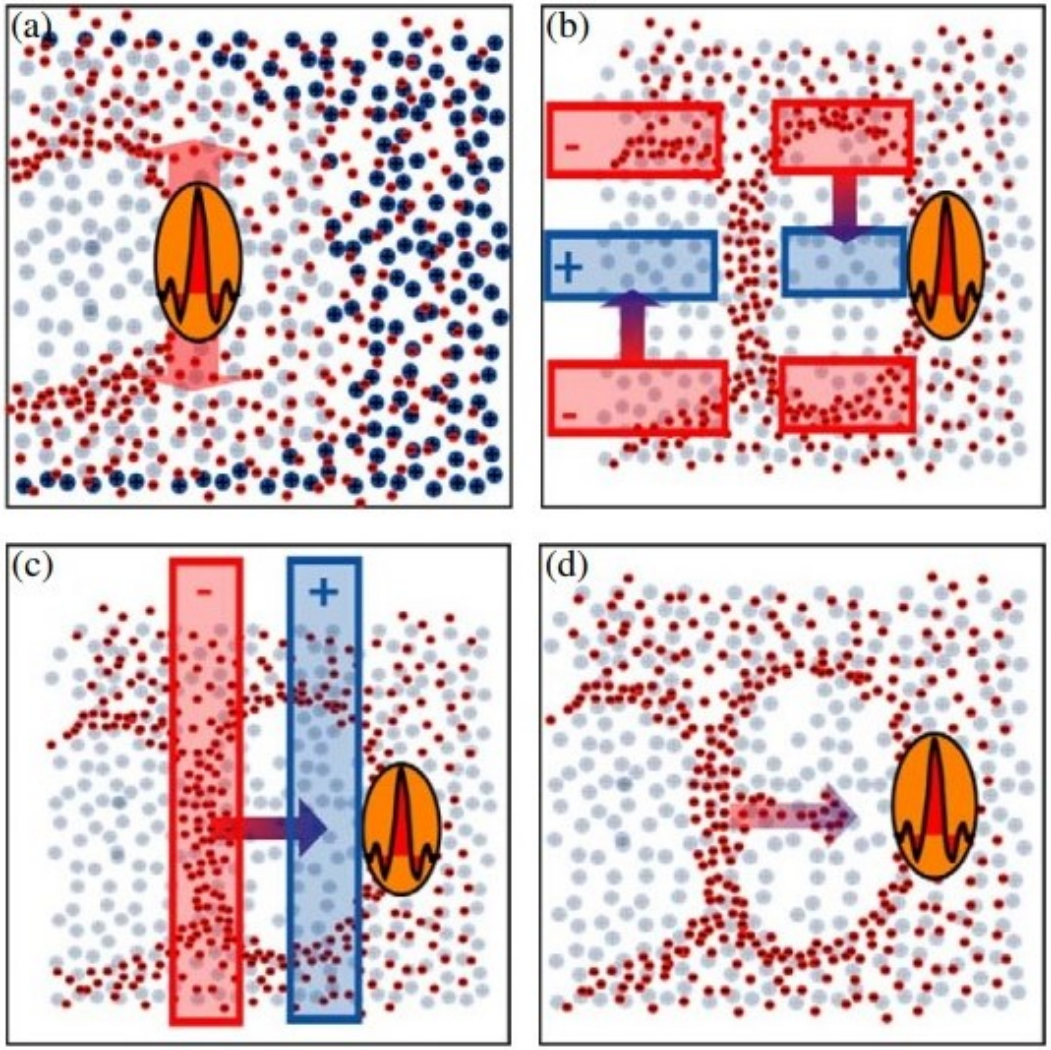
Advantages

- Cost of facilities
- Compactness: TABLE TOP systems
  - Accelerating gradient 100 GV/m so the accelerator size: mm - cm

Disadvantages

- Instability of accelerated beams
- Quality of accelerated beams

Laser wakefield acceleration



a) High intensity laser in a gas immediately produces a plasma. **The ponderomotive force** pulls outward the electrons in all directions, leaving behind the ions.

b) The electrons produce a **bubble-like structure**.

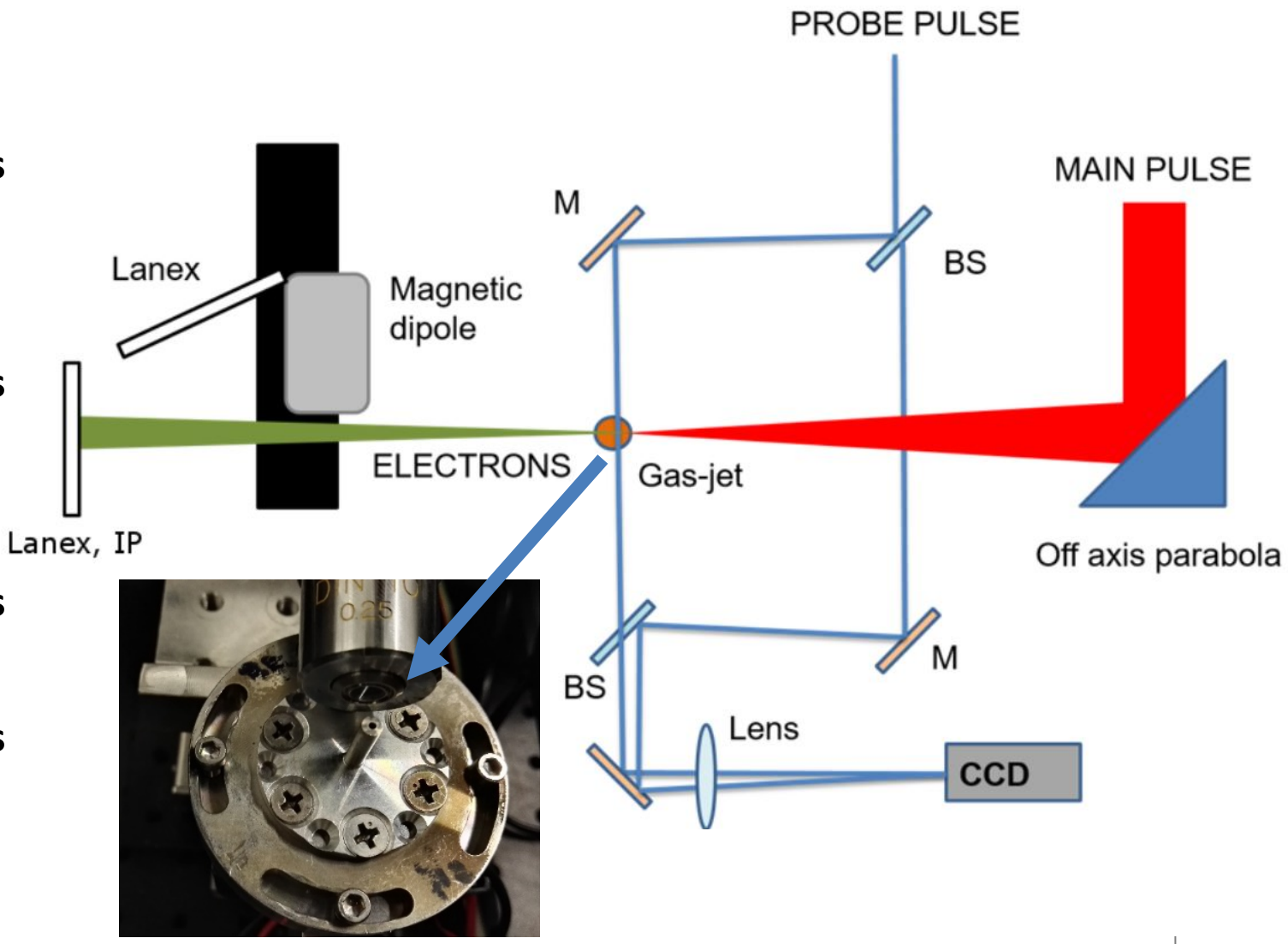
c) Inside the bubble, there are only **ions** and a huge electric field is established.

d) The **electrons are injected** in the trailing area of the bubble and experience an acceleration.

T. Tajima & J. Dawson. Phys. Rev. Lett. 43, 267–270 (1979)

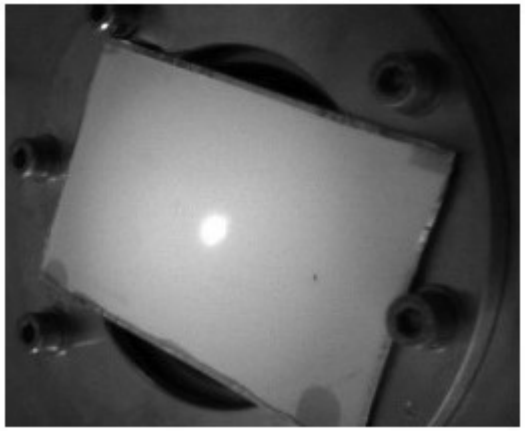
Acceleration setup via LWFA @ FLAME

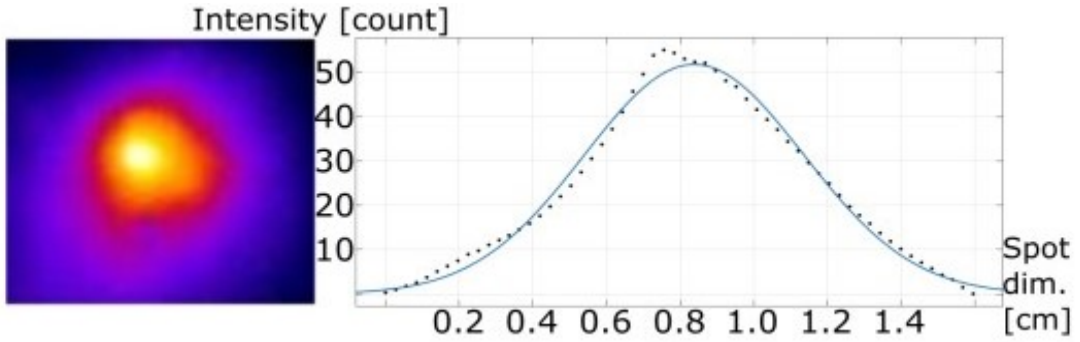
- He gas jet
- **Energy measurements** via 1T magnetic spectrometer
- **Density measurements** via Mach-Zehnder Interferometer
- **Spatial measurements** via LANEX
- **Charge measurements** via a Fuji BAS Imaging Plates

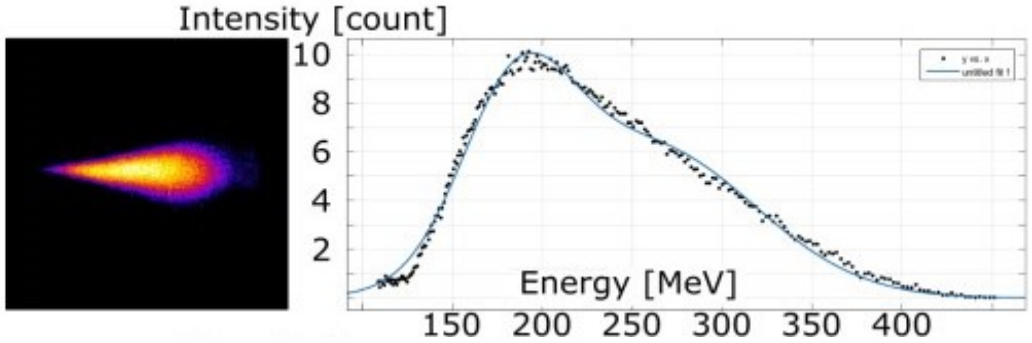


Characterization of electron beams

Parameters	
Dimensions	5-15 mm
Divergence	5-15 mrad
Max/Peak energy	400/200 MeV
Spread	30 %
Accelerating field	200 GV/m
Charge	200 pC

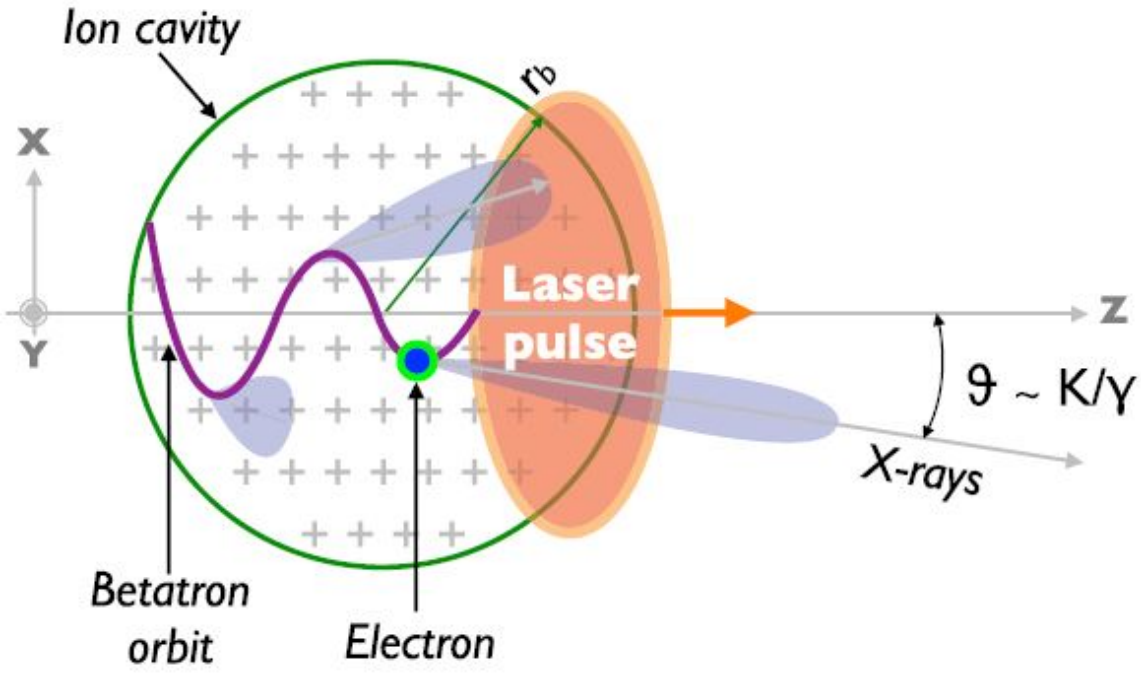






Betatron radiation from LWFA

The electrons, trapped and accelerated, also begin to oscillate transversely.



A collimated beam of X-ray called **betatron radiation** is emitted. It has the following characteristics:

- time duration in the **femtosecond range** and
- energy in the **KeV range**.

Betatron radiation from LWFA

The spectrum of betatron radiation can derived by the following formula:

$$\frac{d^2E}{d\omega d\Omega} \approx \frac{N_\beta eQ}{L_{acc}} \frac{\mu_0 \omega^2 \sigma_0^2}{3\pi^3 c} \int_0^{L_{acc}} dz \left(1 + \frac{\gamma^2(z)\theta^2}{\gamma^2(z)}\right)\left(K_{\frac{2}{3}}^2(\xi(z)) + \frac{\gamma^2(z)\theta^2}{1+\gamma^2(z)\theta^2} K_{\frac{1}{3}}^2(\xi(z))\right)$$

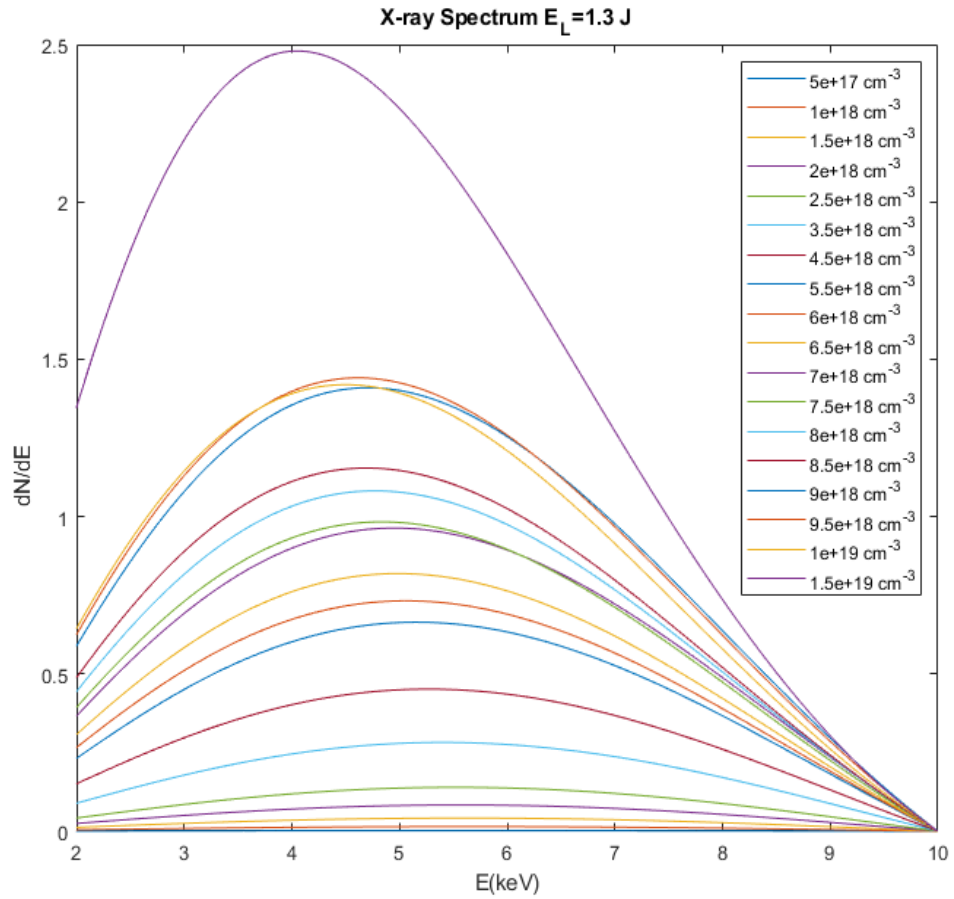
$$\xi(z) = \left(\frac{\omega}{3\gamma^3(z)\sigma_0 k_\beta^2(z) c}\right)(1+\gamma^2(z)\theta^2)^{\frac{3}{2}}$$

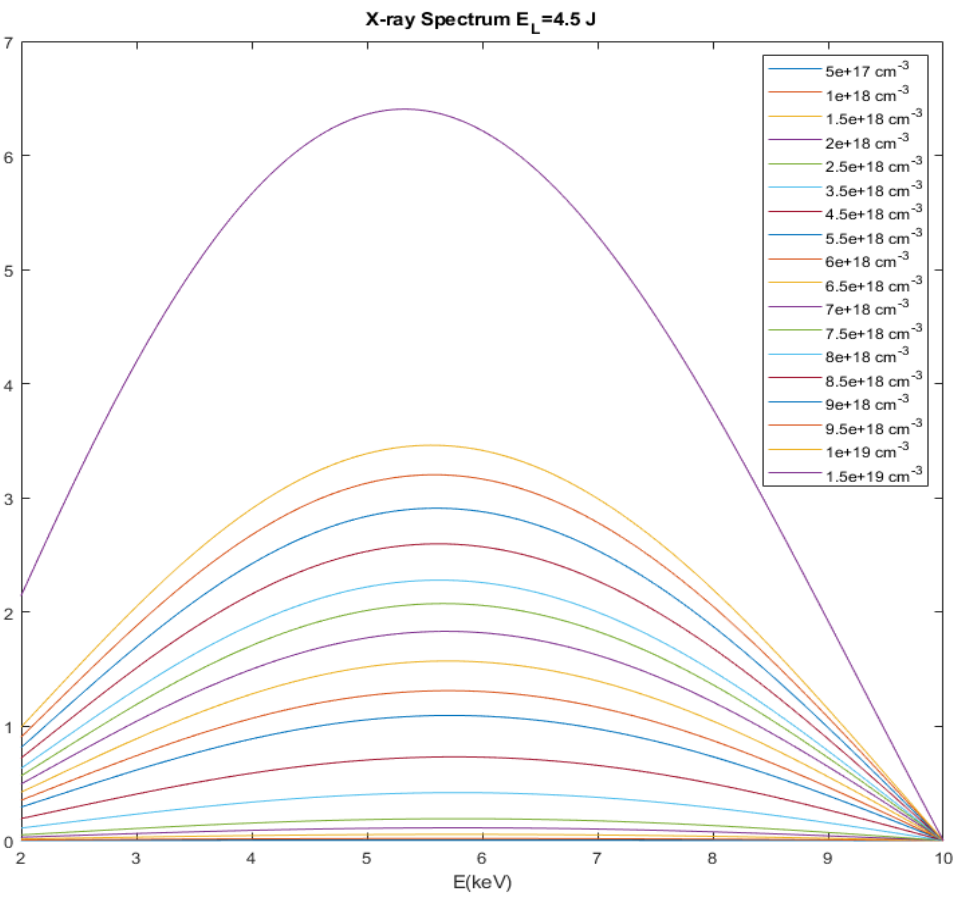
Number of oscillations and wave vector

$$N_\beta \sim \frac{k_p L_{deph}(\gamma_{max})}{(3\gamma_{max})^{\frac{1}{2}}} \text{ e } k_\beta(z) = \frac{k_p}{(3\gamma(z))^{\frac{1}{2}}}$$

Q and $\boldsymbol{\sigma_0}$ are the charge and size of the electron beam in the bubble, respectively. Through the developed code it is possible to replicate the measured spectrum and derive the characteristics of the electron beam in the bubble.

Betatron radiation spectrum parameters scan

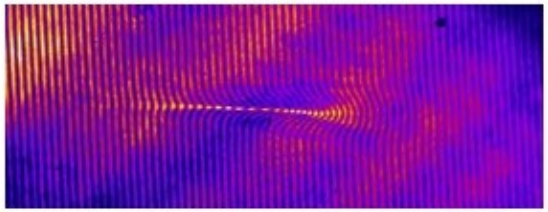


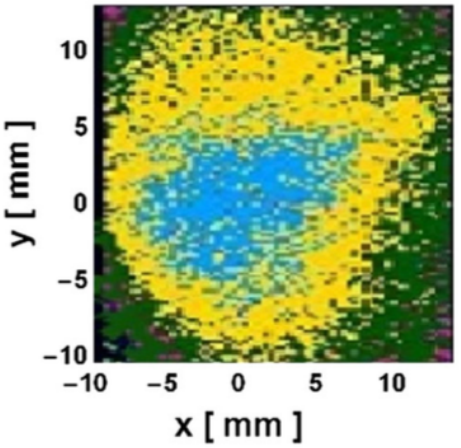


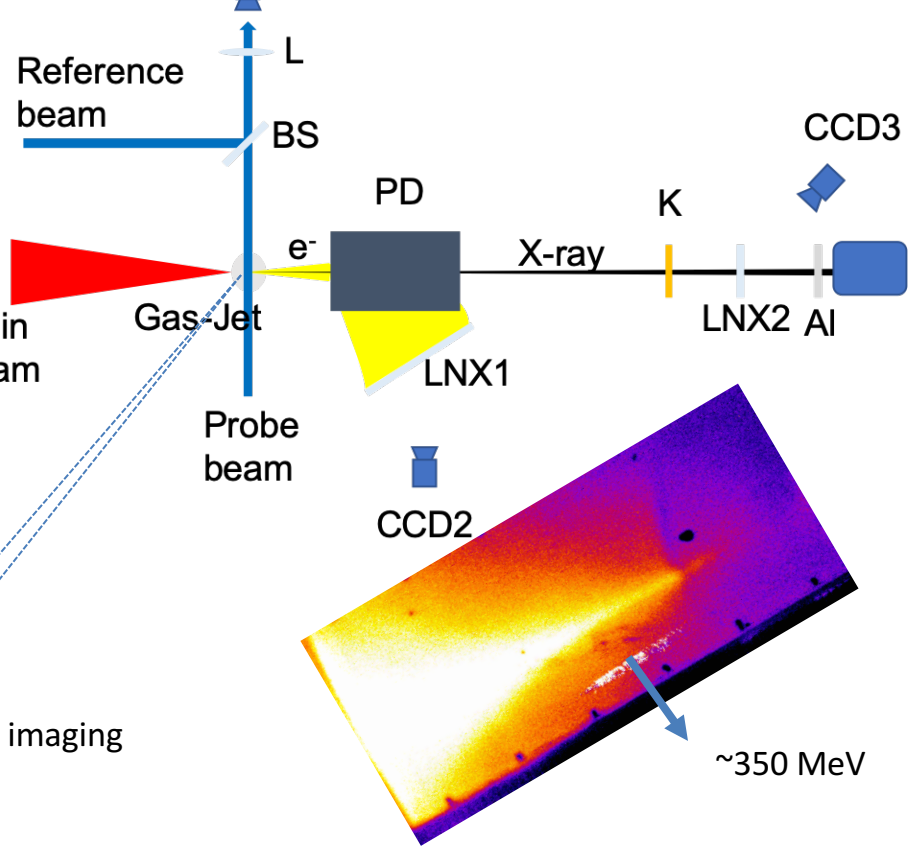
By increasing the laser energy, the peak/total energy of the betatron increases, therefore the spectrum that shifts towards higher energies. While, increasing the density of plasma the spectrum becomes narrower around its maximum.

Characterization of betatron radiation

M. Galletti, et al. Rev. Sc. Instr. 91, 045111.



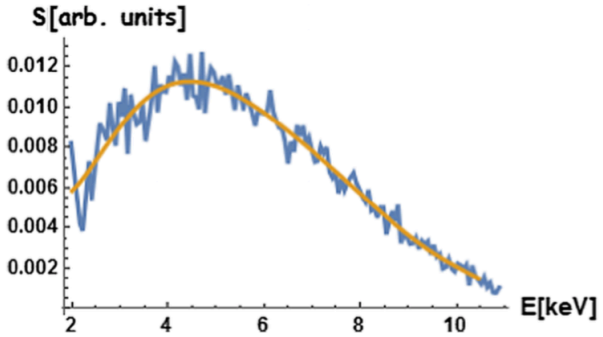




$\theta_\beta \sim 5 - 10\ mrad$

Plasma channel imaging

~350 MeV



$N_{p\beta} \sim 10^8\ per\ bunch$

Spectral code compared with measurements

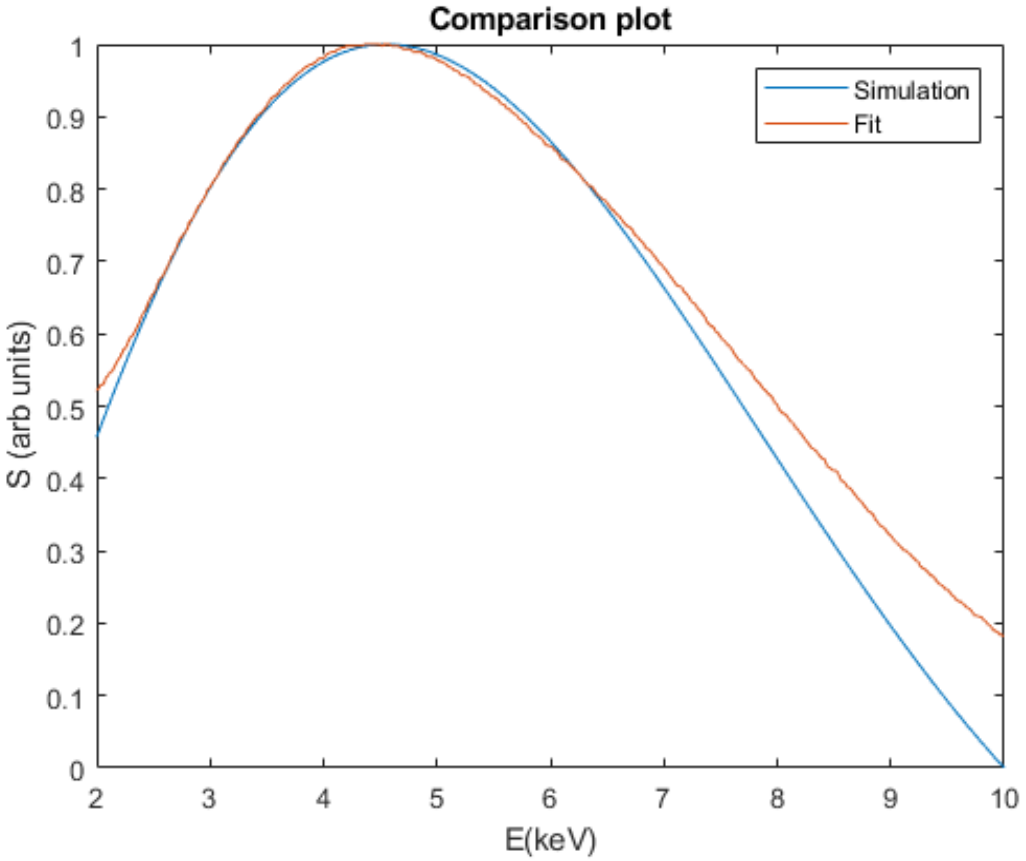
$$E_L = 1.3\ J$$
$$n_e = 8.5 \cdot 10^{18}\ cm^{-3}$$

$$E_{max}^{meas} = 4.4\ keV$$

$$FWHM^{meas} = 6\ keV$$

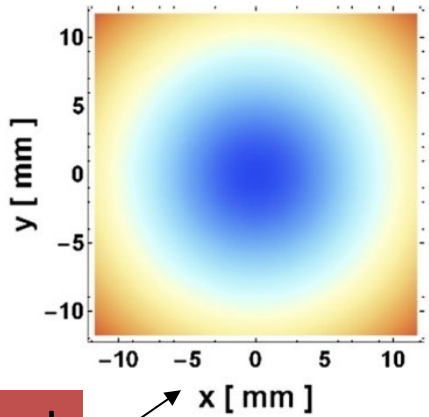
$$E_{max}^{sim} = 4.5\ keV$$

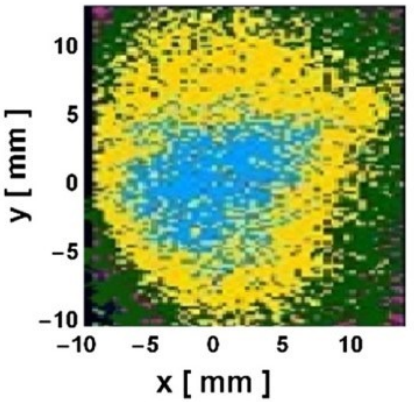
$$FWHM^{sim} = 5.6\ keV$$



Single shot emittance reconstructed from betatron

$$\epsilon_{r_\beta N} = \gamma_0 \sqrt{(\sigma_\gamma/\gamma_0)^2 \sigma_r^2 \sigma_\theta^2 + \epsilon_{r_\beta}^2}$$





Electron spectrum

Betatron spectrum

Algorithm

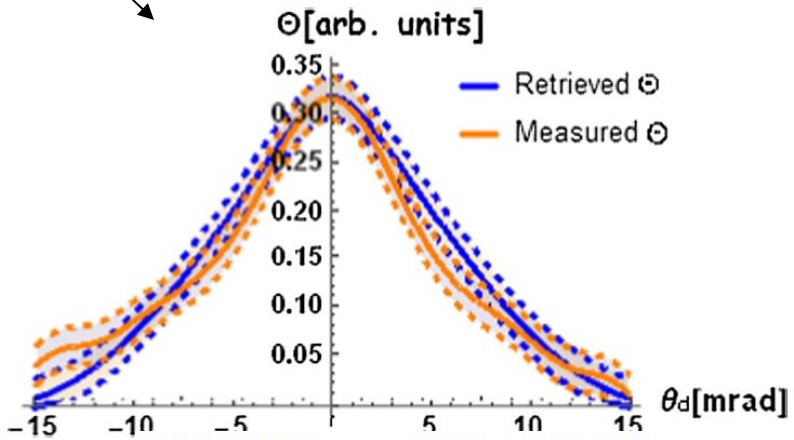
Retrieved Data

$$\theta_\beta \sim \sigma_r k_{\beta 0}$$

$$r^i P^i S_{ij} - \Sigma(E_j) = 0$$

Theoretical spectrum based on plasma density and electron spectrum

Correct betatron spectrum with respect to x-ray absorption during measurement



$$\Theta(\theta_d) \propto P[r(\theta_d)]$$

A. Curcio, et al. PRAB 20.1 (2017): 012801

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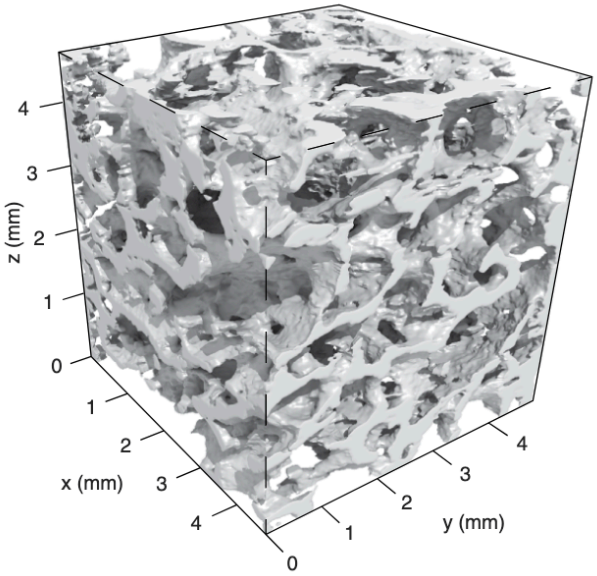
- The FLAME laser system will focus its planning on activities within the EuPRAXIA European project, such as the acceleration of electrons in gaseous targets, and the respective secondary radiation, via LWFA.
- The idea is to obtain a source of e- and X-ray, fully characterized and easily tunable, and to use them for medical / biological / cultural heritage applications.



J. Cole, et al. Sci Rep 5, 13244 (2015)

Thanks for your attention!

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