EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

SPARC_LAB activity

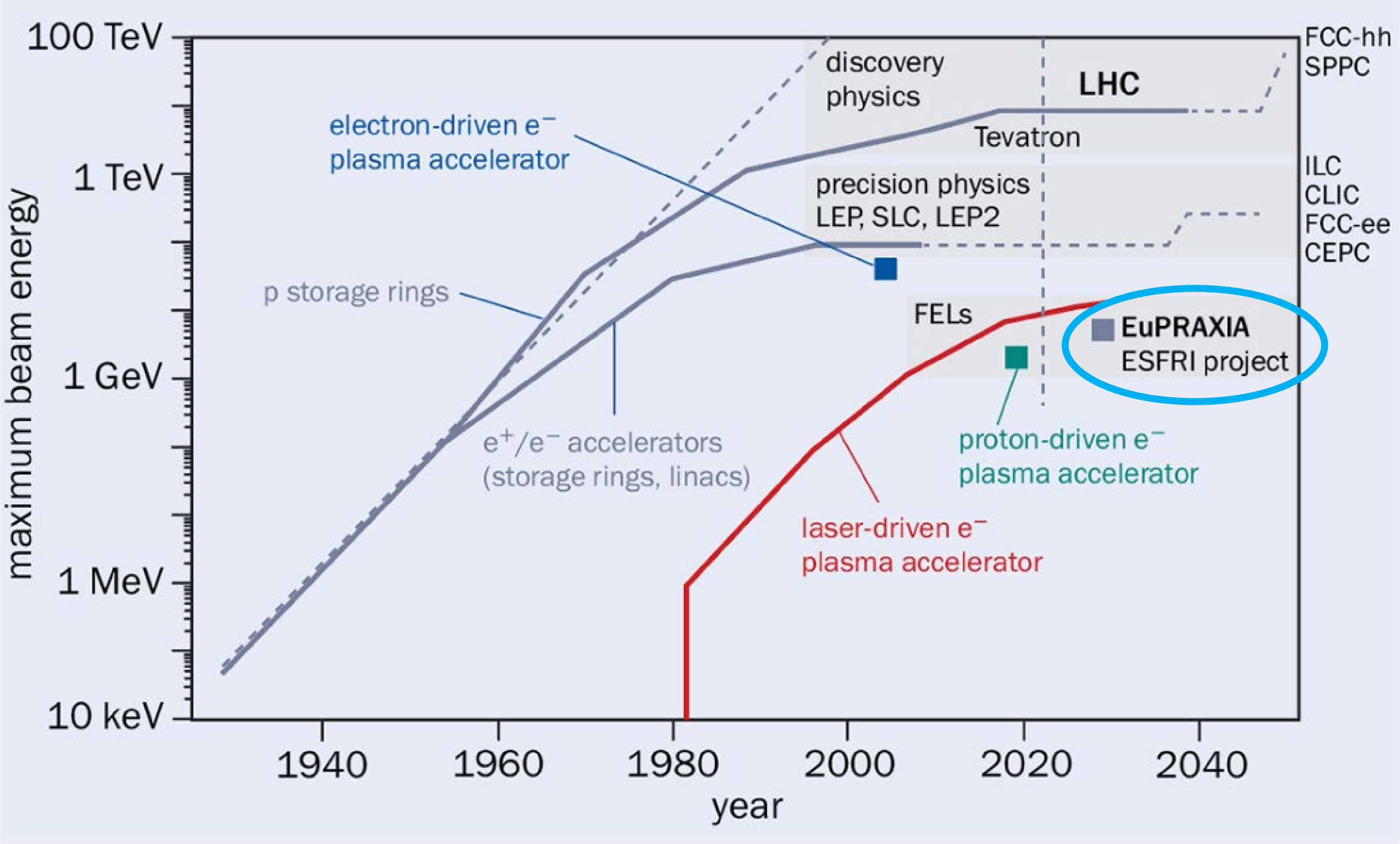
Meeting with PhD students

Angelo Biagioni, INFN-LNF
on behalf of the SPARC_LAB collaboration

20 November 2023

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement
No. 101079773

The Livingston Diagram



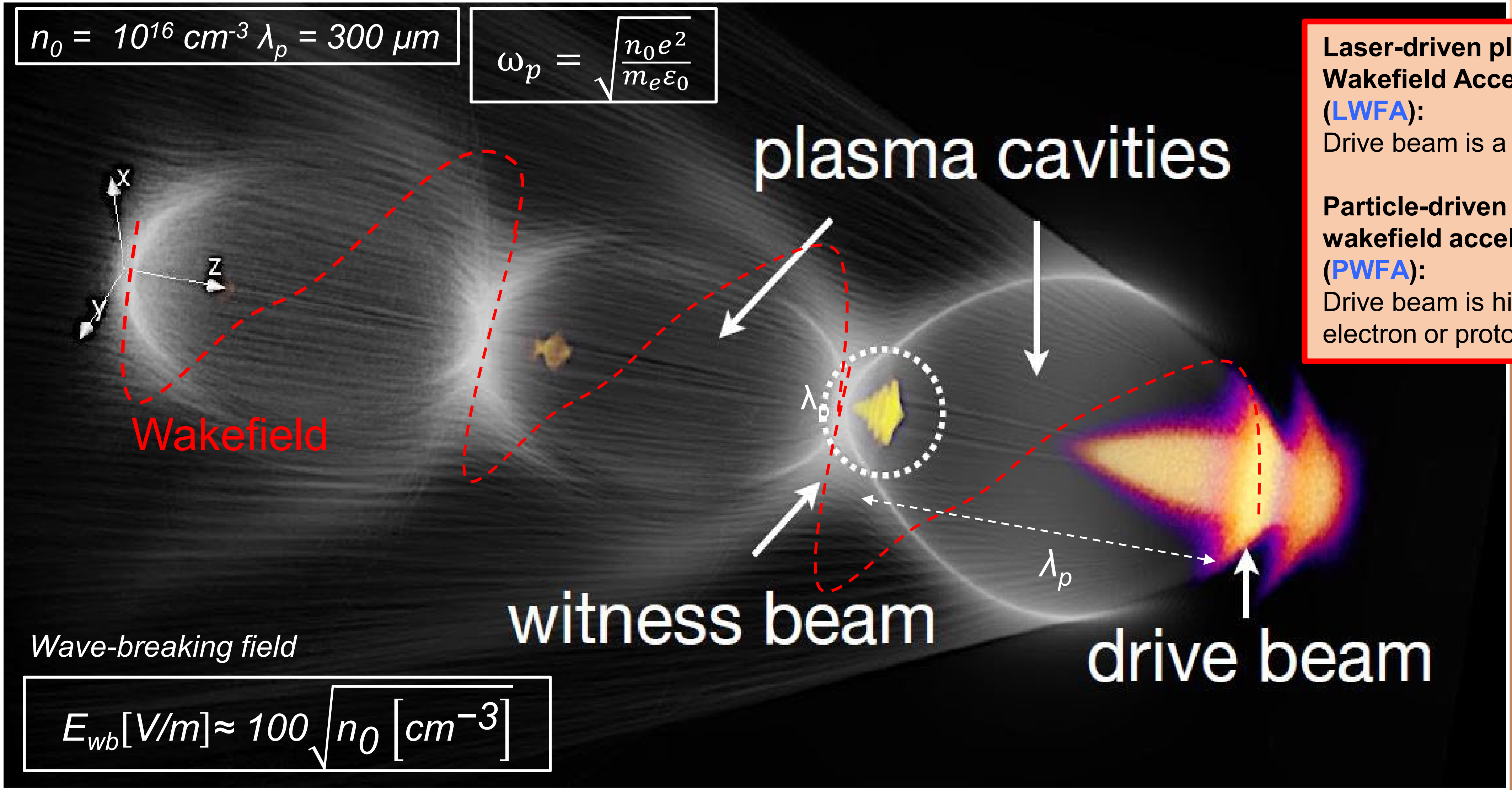
Updated Livingston plot for accelerators, showing the maximum reach in beam energy versus time. Grey bands visualize accelerator applications. A new fork of laser-driven plasma accelerators has emerged in 1980, reaching multi-GeV energies by now.

Plasma Accelerator Achievements

- Gradients up to **100 GV/m**
- Beam energy > 10 **GeV** of electron beams
- Basic beam **quality for FEL** demonstrated

The most demanding in terms of beam brightness, stability and control

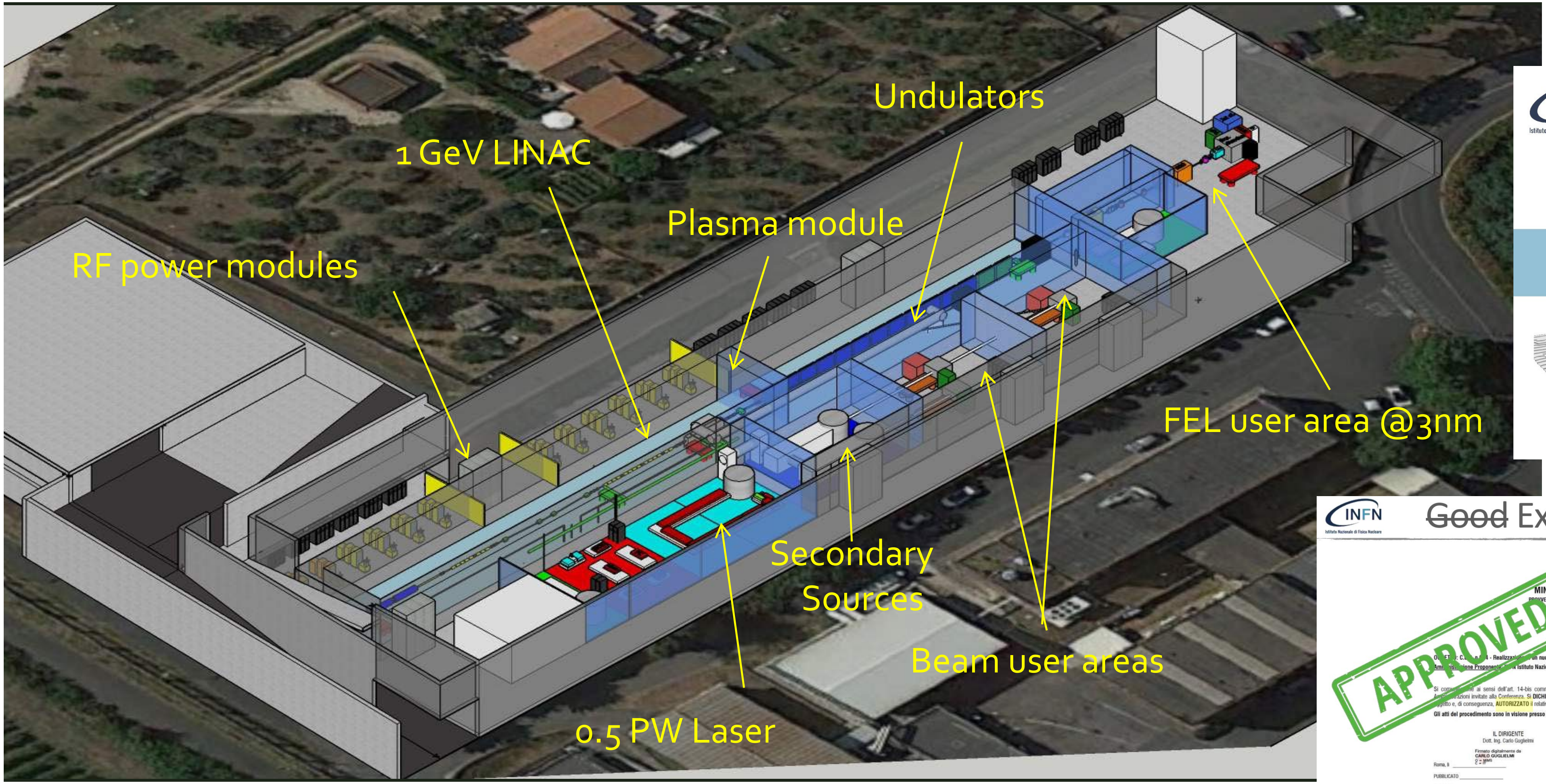
Principle of plasma acceleration

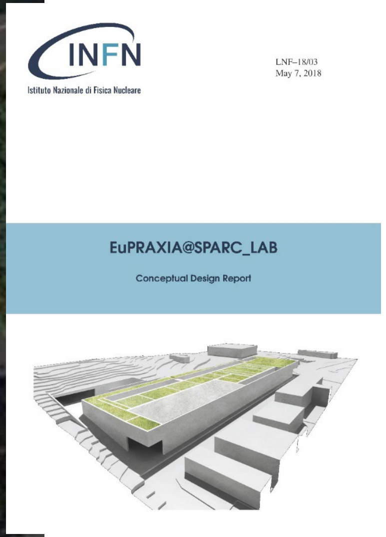


Laser-driven plasma Wakefield Accelerator (LWFA):
Drive beam is a laser pulse

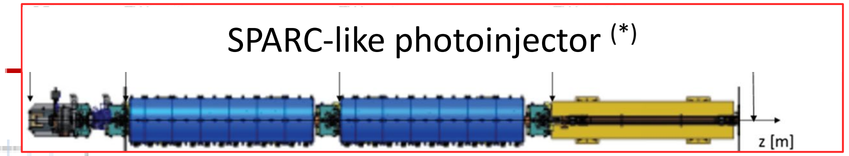
Particle-driven plasma wakefield accelerator (PWFA):
Drive beam is high energy electron or proton beam

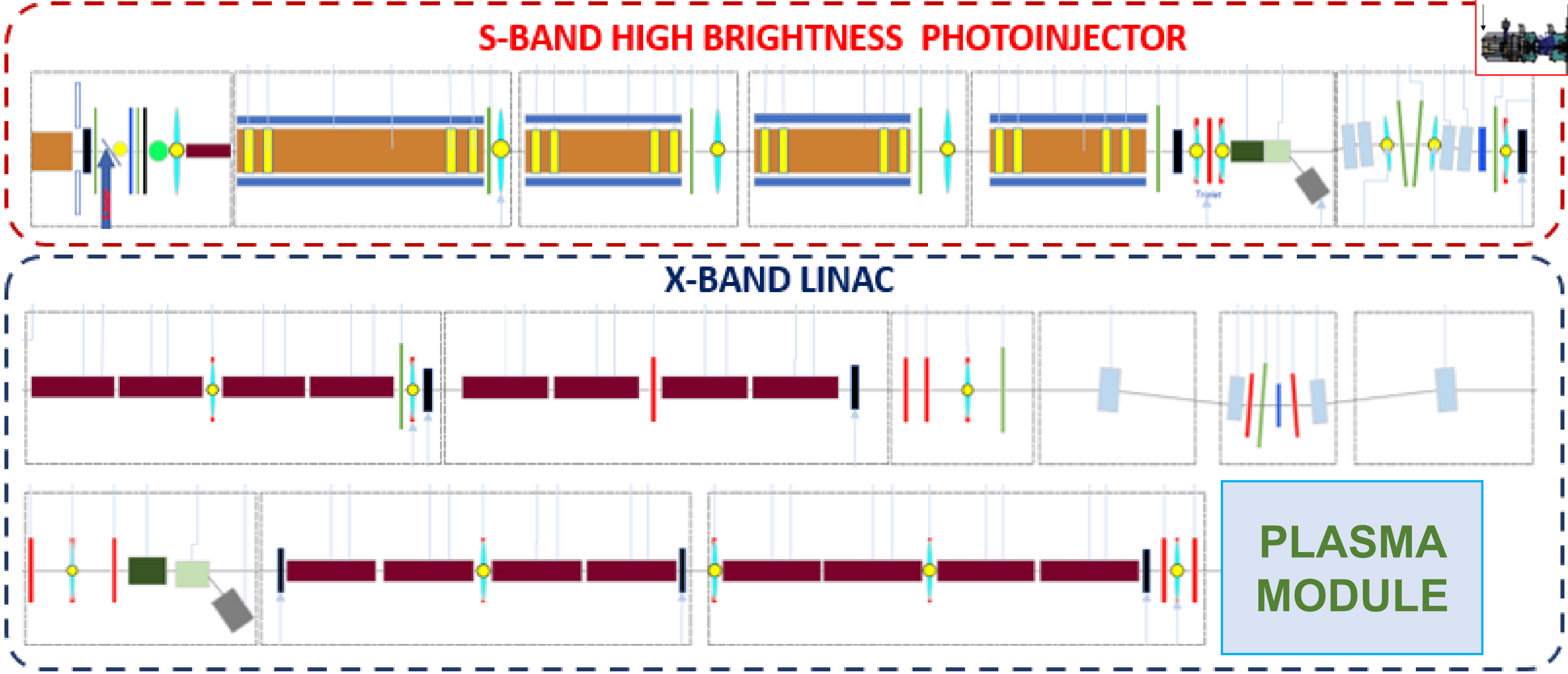
EuPRAXIA@SPARC_LAB





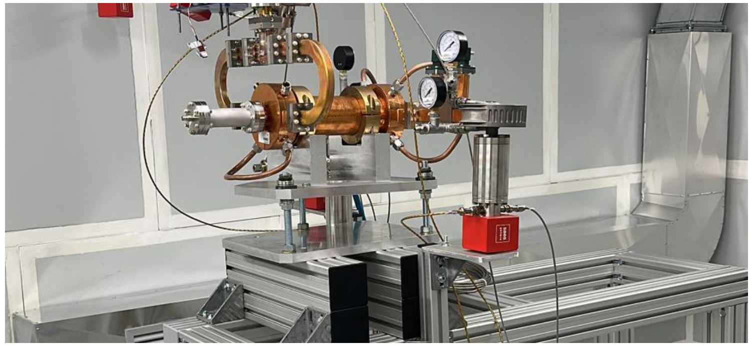
EuPRAXIA@SPARC_LAB: a high brightness PWFA

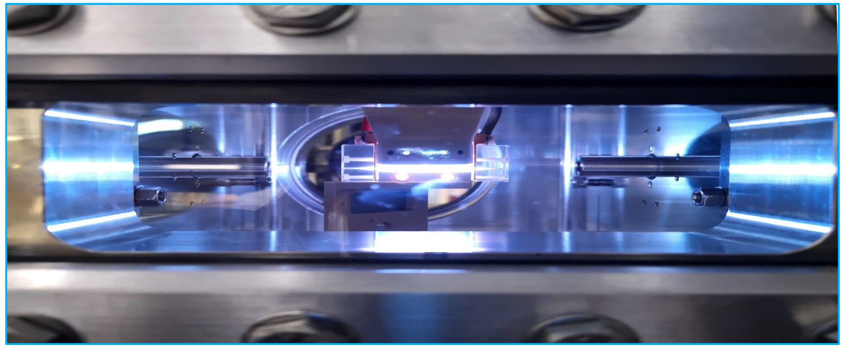




A combination of
cutting edge technology:

- *high brightness RF injector*
- *X-band linac*
- *Plasma module for PWFA*
- *FEL user area @3nm*

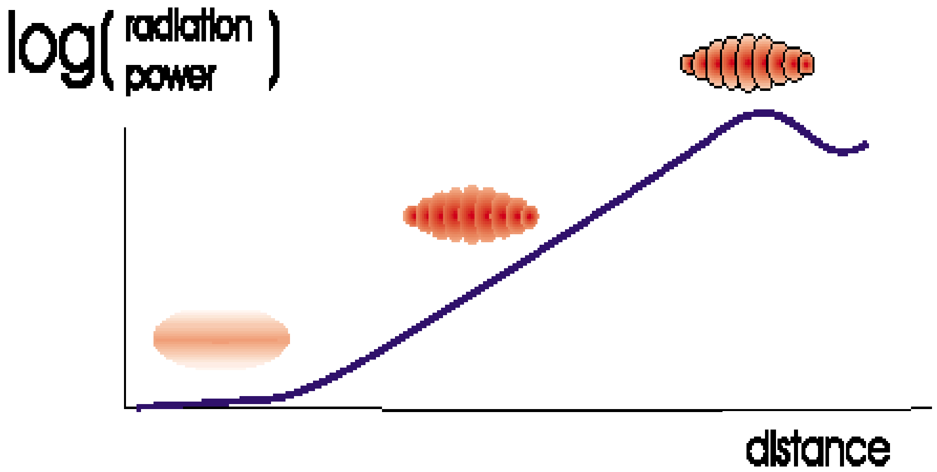


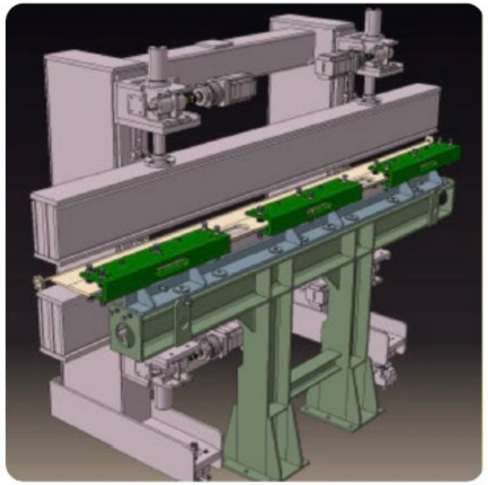


Intense R&D Program on critical components

Radiation generation: FEL

A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator

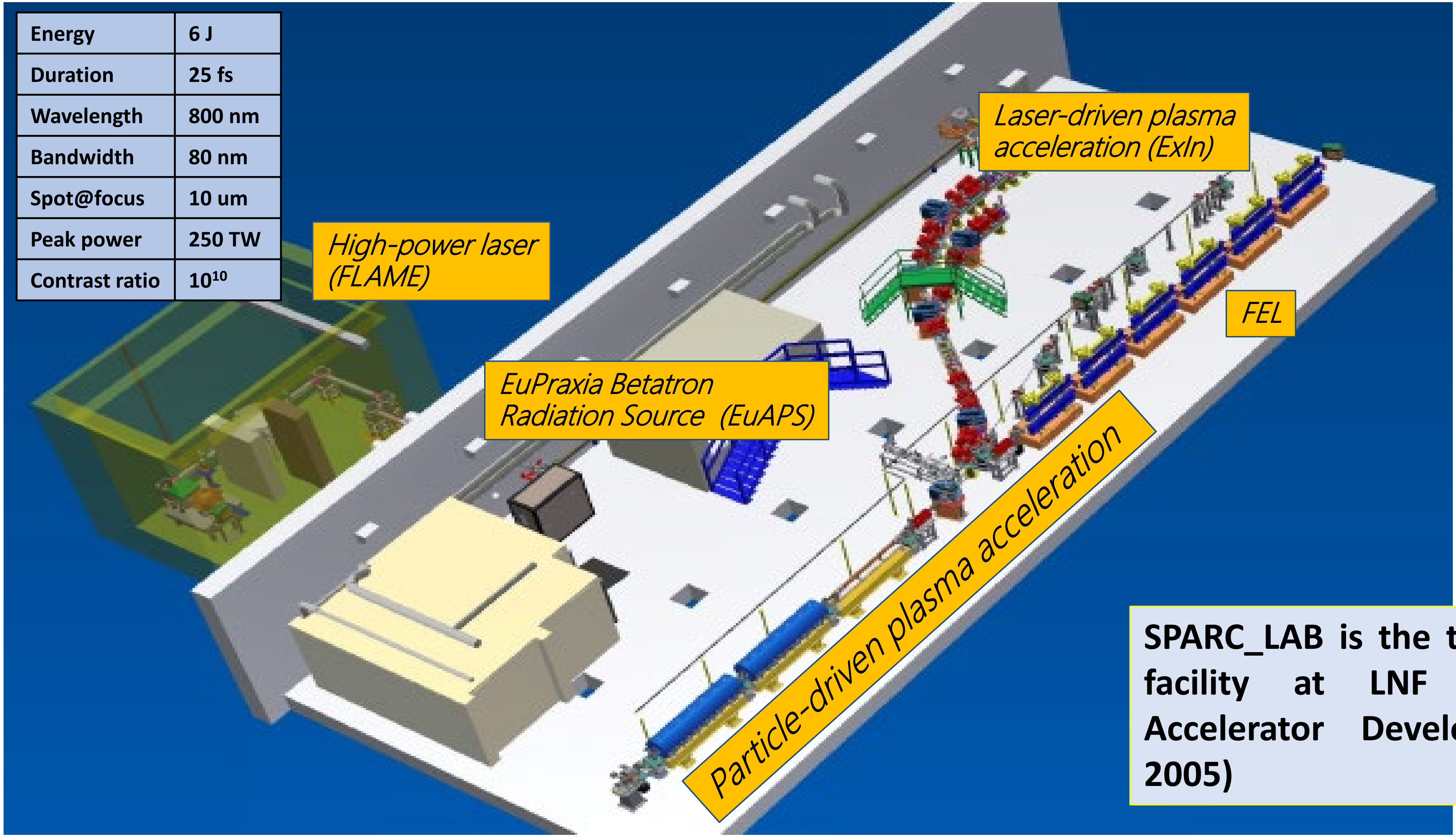




$$\lambda_r = \lambda_u(1 + K^2)/(2\gamma^2) \qquad K = eB_u\lambda_u/(2\pi mc^2)$$

SPARC_LAB test facility

Energy	6 J
Duration	25 fs
Wavelength	800 nm
Bandwidth	80 nm
Spot@focus	10 um
Peak power	250 TW
Contrast ratio	10^{10}

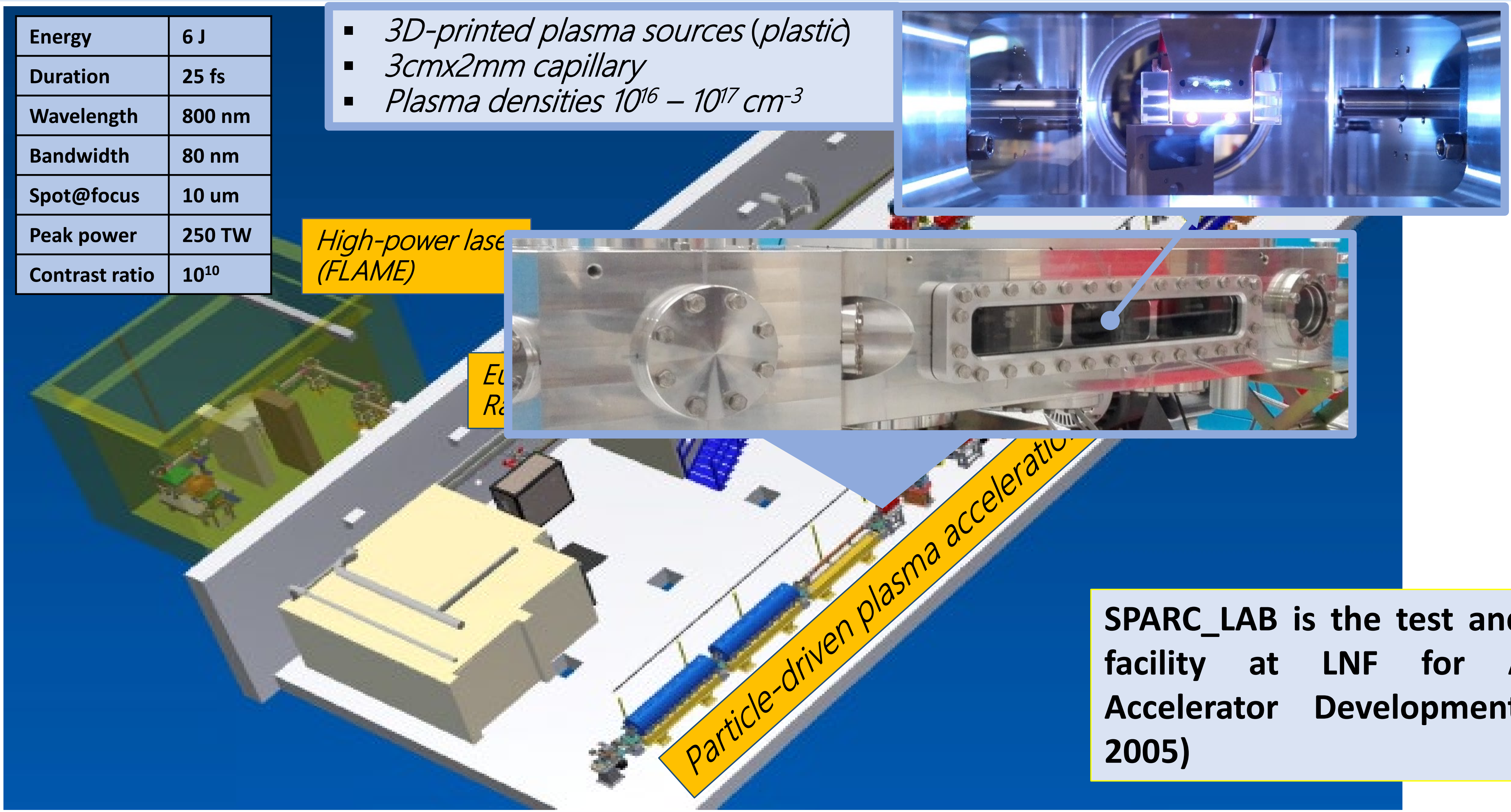


SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

SPARC_LAB test facility

Energy	**6 J**
Duration	**25 fs**
Wavelength	**800 nm**
Bandwidth	**80 nm**
Spot@focus	**10 um**
Peak power	**250 TW**
Contrast ratio	**10^{10}**

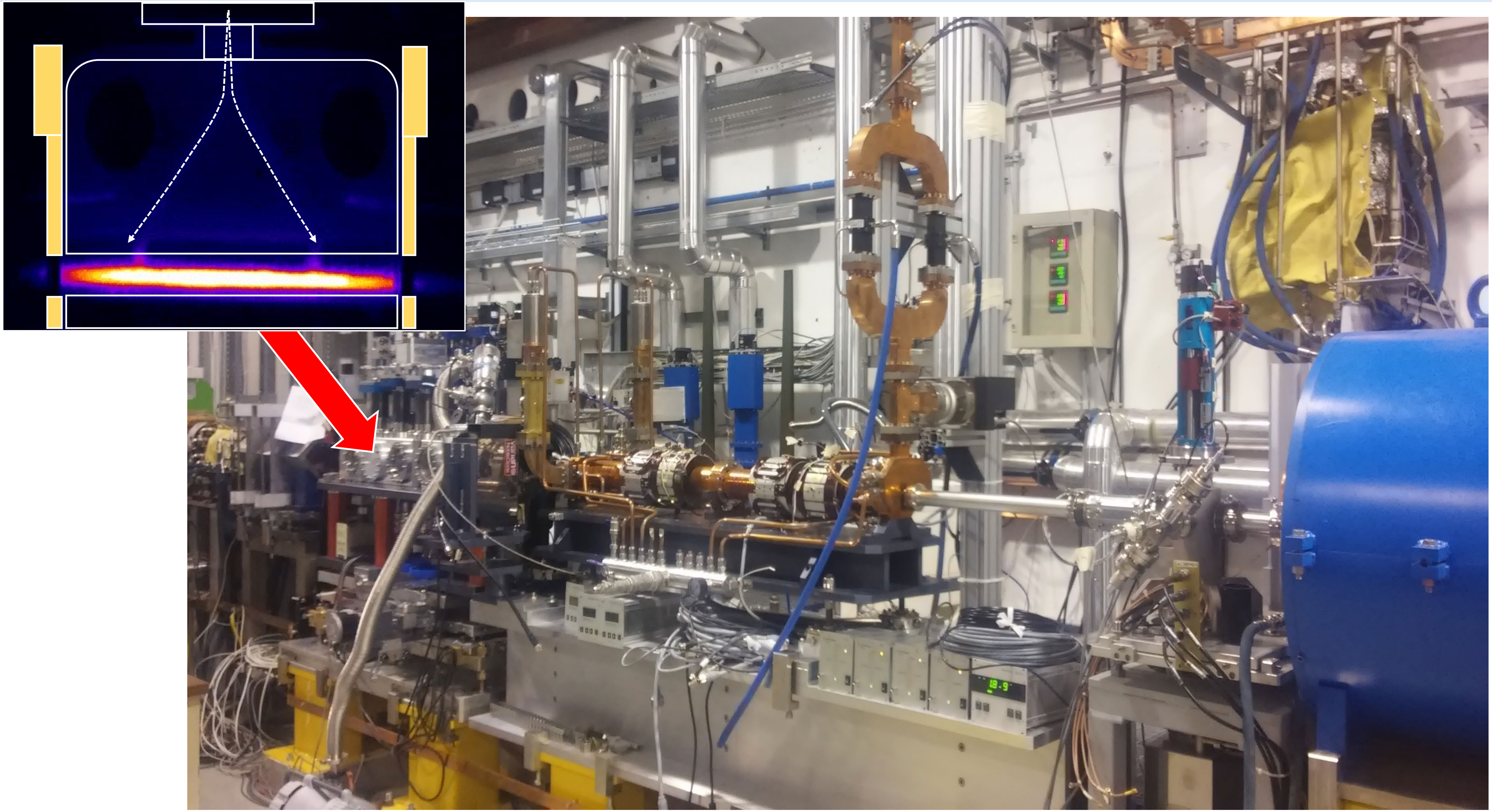
- *3D-printed plasma sources (plastic)*
- *3cmx2mm capillary*
- *Plasma densities $10^{16} – 10^{17}$ cm^{-3}*



SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

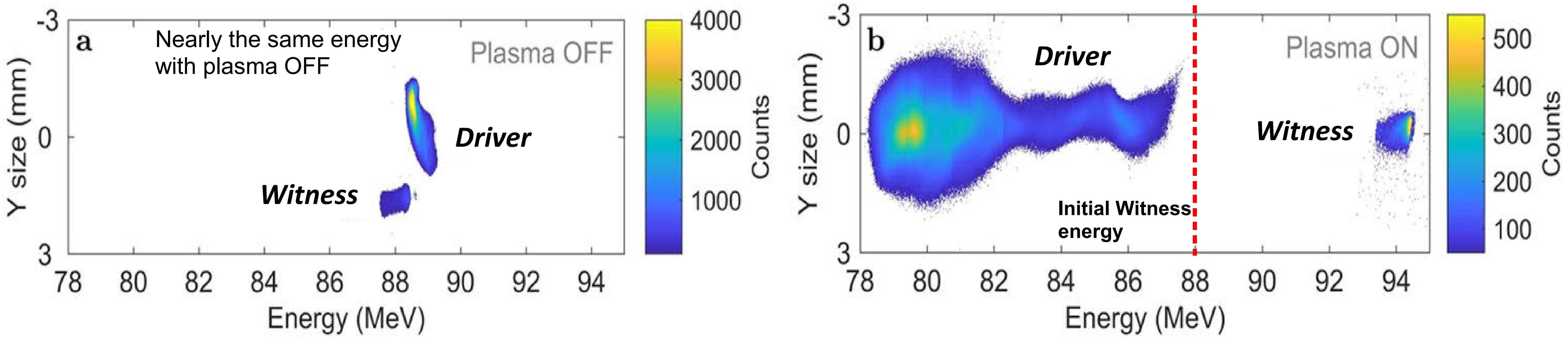
Angelo.Biagioni@lnf.infn.it

SPARC_LAB test facility



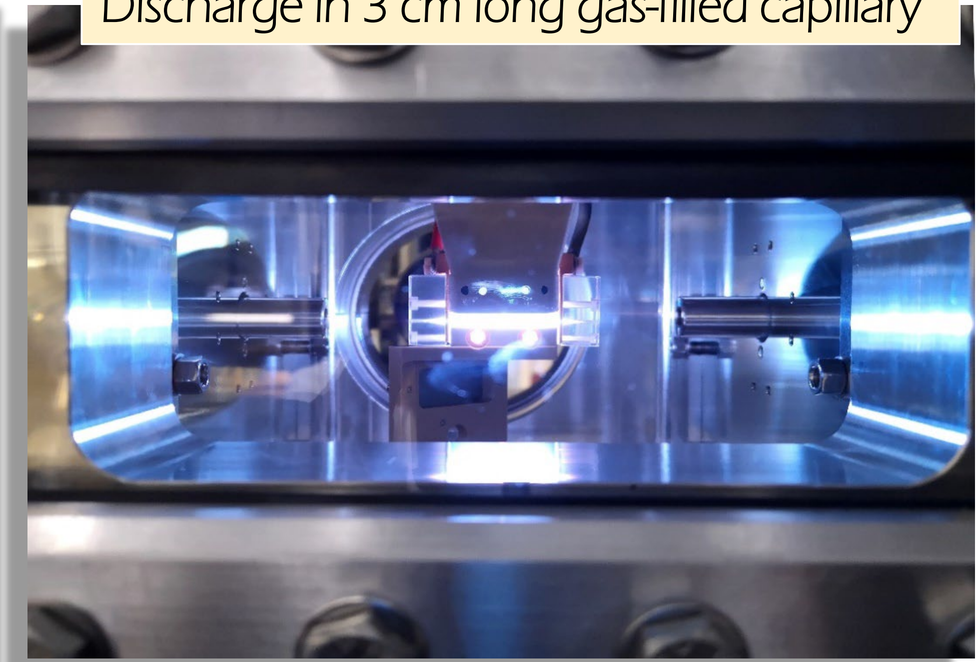
Angelo.Biagioni@lnf.infn.it

SPARC_LAB: Plasma acceleration

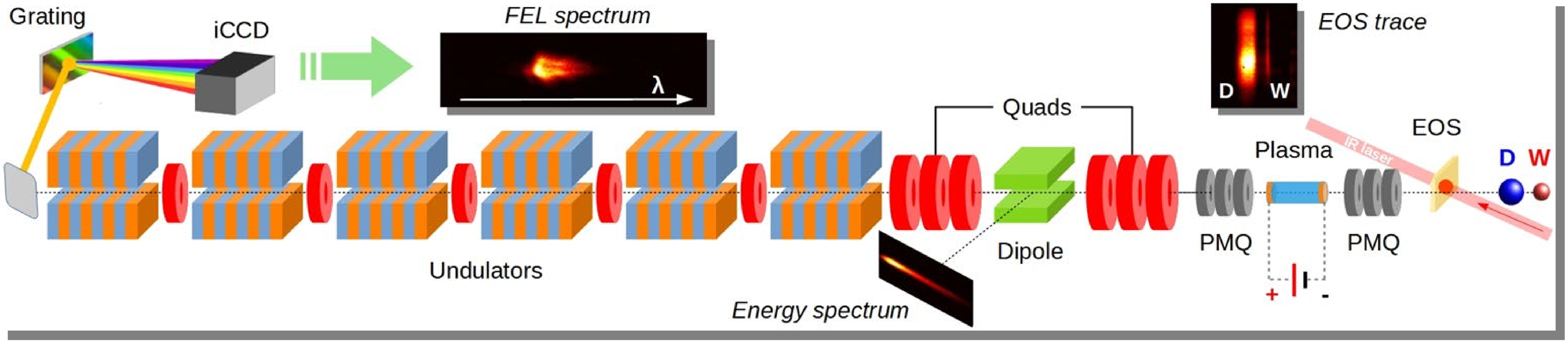


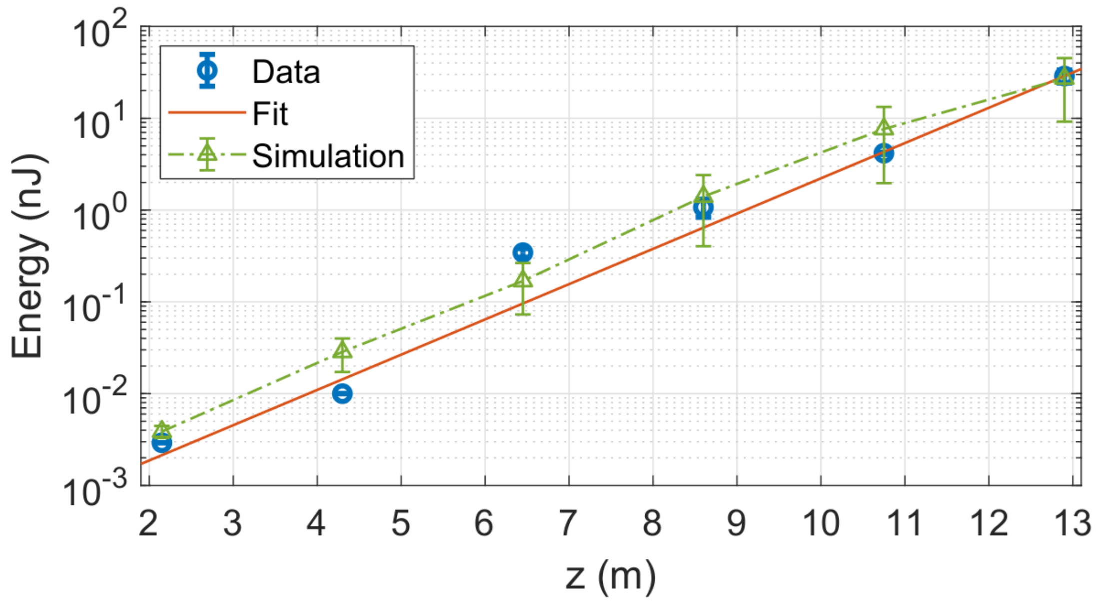
- ***6 MeV acceleration in 3 cm long plasma capillary with 200 pC driver/20 pC witness***
  - Plasma density set to 2×10^{15} cm^{-3}
  - ~200 MV/m accelerating gradient (RF structures in the range 20-60 MV/m)
  - Driver decelerated by almost 10 MeV
  - During last experiments, accelerating gradient close to ***1 GV/m*** has been reached
- ***Demonstration of energy spread compensation***
  - *Total projected spread from 0.2 MeV to 0.12 MeV*

Discharge in 3 cm long gas-filled capillary



SPARC_LAB: FEL Radiation generation

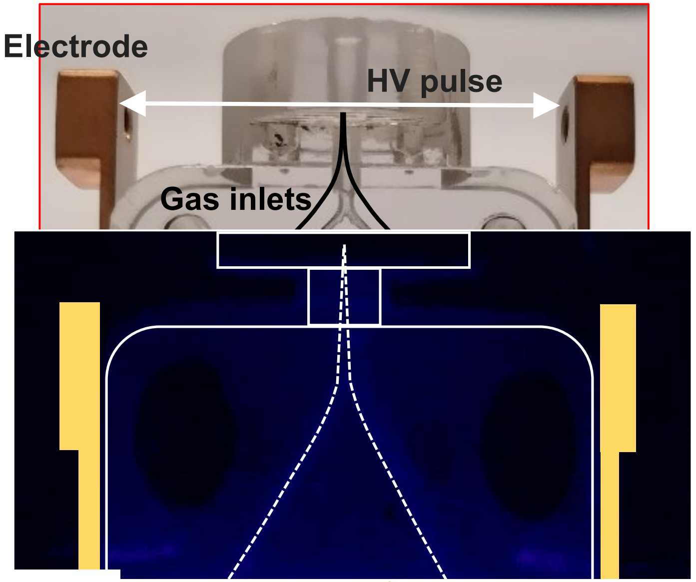




FEL single-shot spectrum

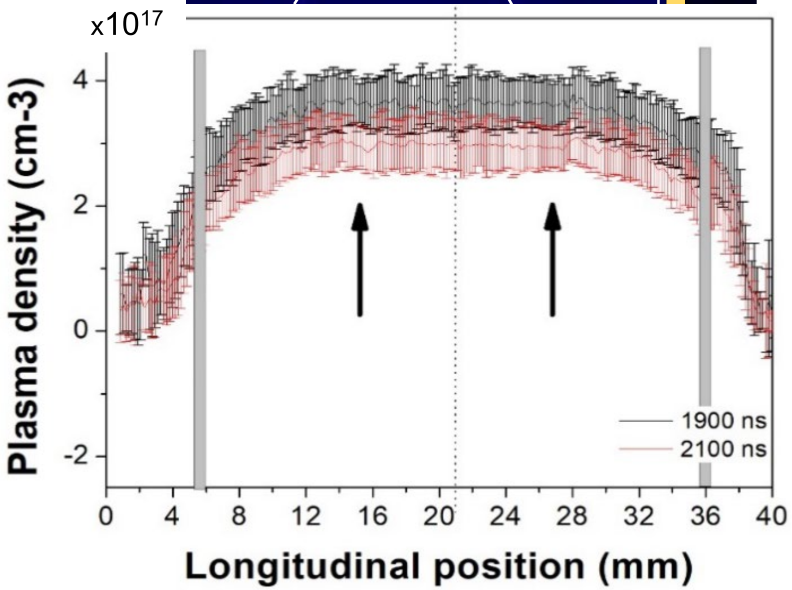
- 30% shot-to-shot reproducibility
- Centered @827 nm with 5 nm BW
- Pulse energy up to 30 nJ

SPARC_LAB: Plasma sources



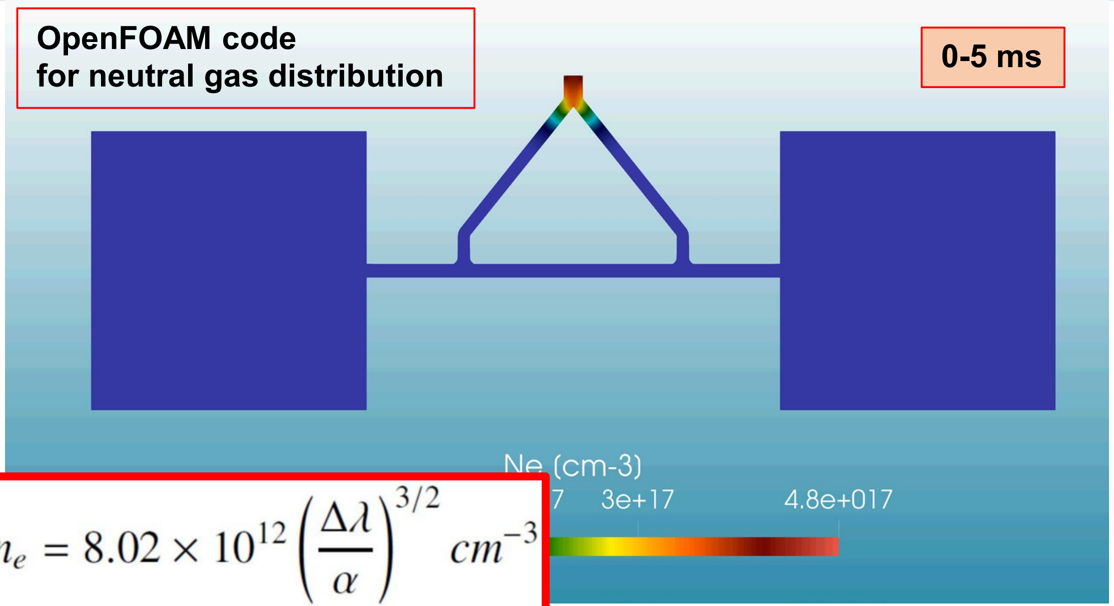
thin capillaries are used to confine a neutral gas (H, Ar, N…), which is injected through several inlets into the plasma channel

the plasma formation process is triggered by a high voltage pulse at the ends of the capillary

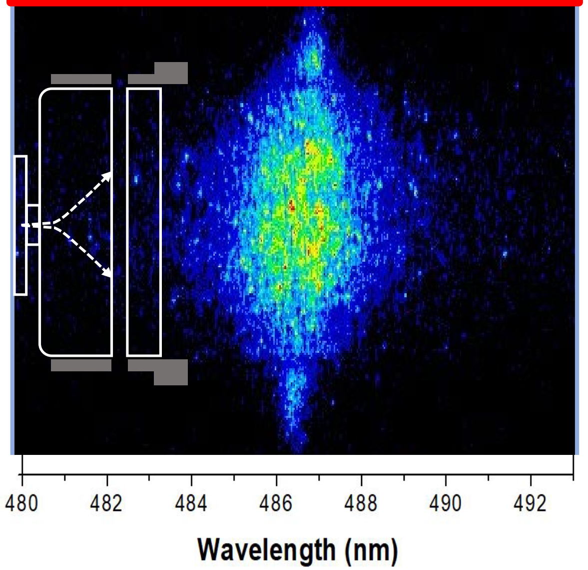


The plasma characterization is based on spectroscopic techniques (Stark broadening effect)

$$n_e = 8.02 \times 10^{12} \left(\frac{\Delta\lambda}{\alpha}\right)^{3/2} cm^{-3}$$

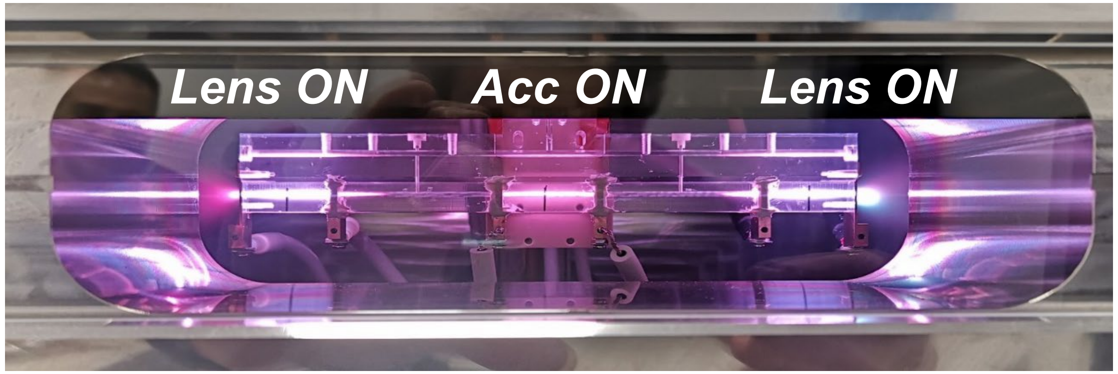


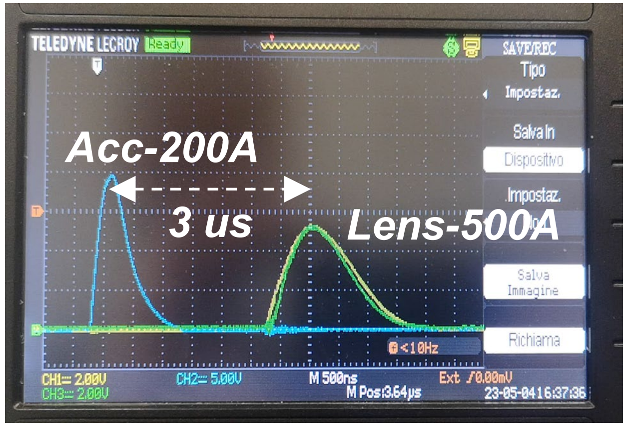
$$n_e = 8.02 \times 10^{12} \left(\frac{\Delta\lambda}{\alpha}\right)^{3/2} cm^{-3}$$



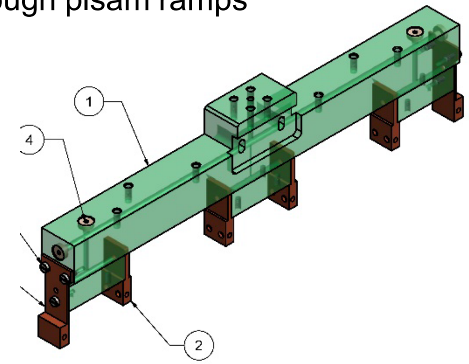
SPARC_LAB: Plasma sources

1. Integrated capillary

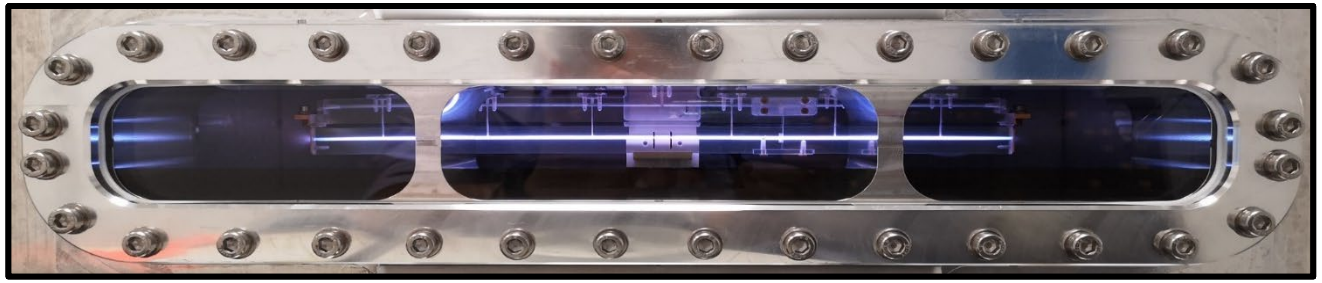




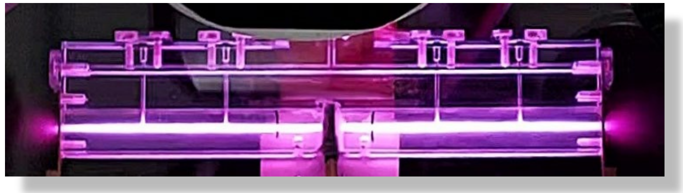
Studies on cross-talk effects:
Design of electrodes and HV-circuits to reduce the interaction among discharges through plsam ramps



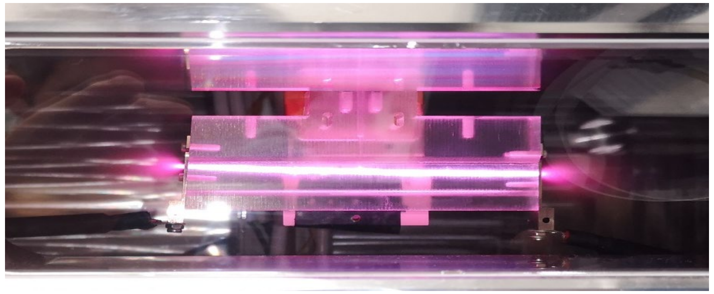
2. Very long capillary



Design of m-scale capillaries for EuPRAXIA project by using segmented capillaries: design of HV-voltage circuits and discharge synchronization



3. Curved capillary for APD



Design of new geometries for curved channels:
HV-circuits to allow high current pulses

SPARC_LAB: Betatron source (EuAPS Project)

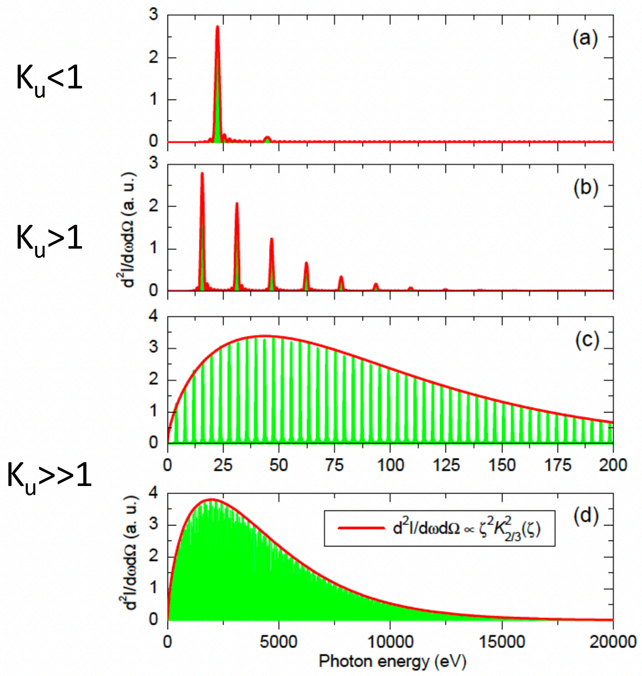
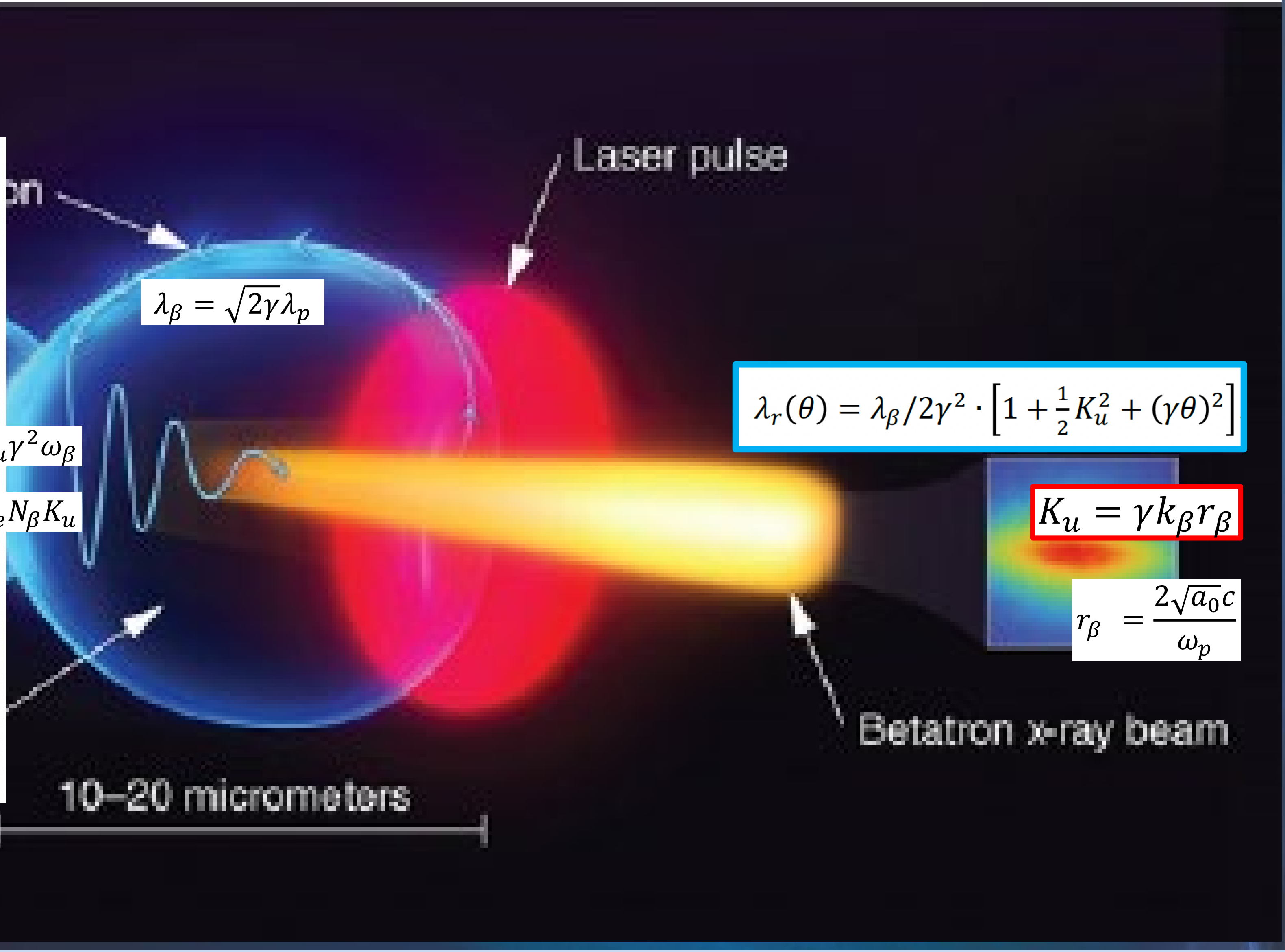


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 µm, (b) 0.5 µm, and (c) 1.6 µm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 µm.*

$$\omega_c = 3K_u\gamma^2\omega_\beta$$

$$N_{ph} \propto N_e N_\beta K_u$$



$$\lambda_\beta = \sqrt{2\gamma}\lambda_p$$

$$\lambda_r(\theta) = \lambda_\beta/2\gamma^2 \cdot \left[1 + \frac{1}{2}K_u^2 + (\gamma\theta)^2\right]$$

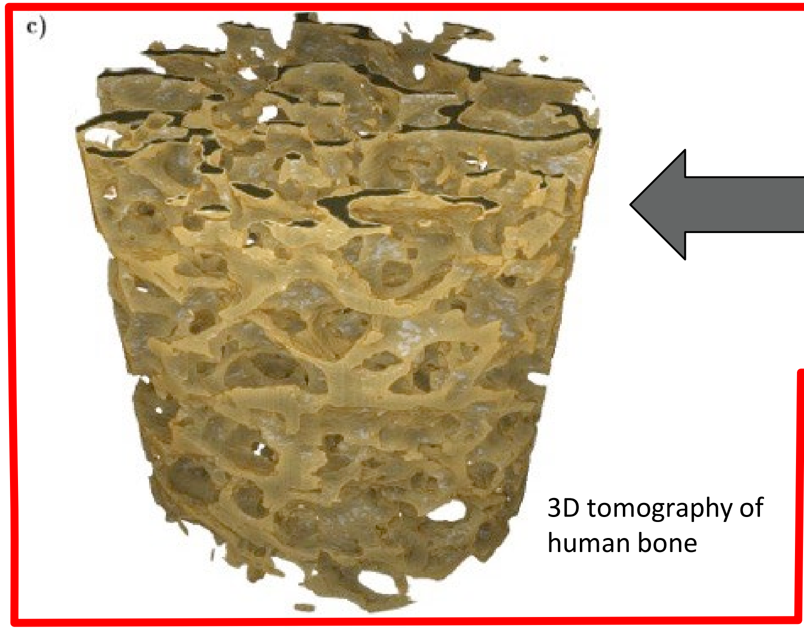
$$K_u = \gamma k_\beta r_\beta$$

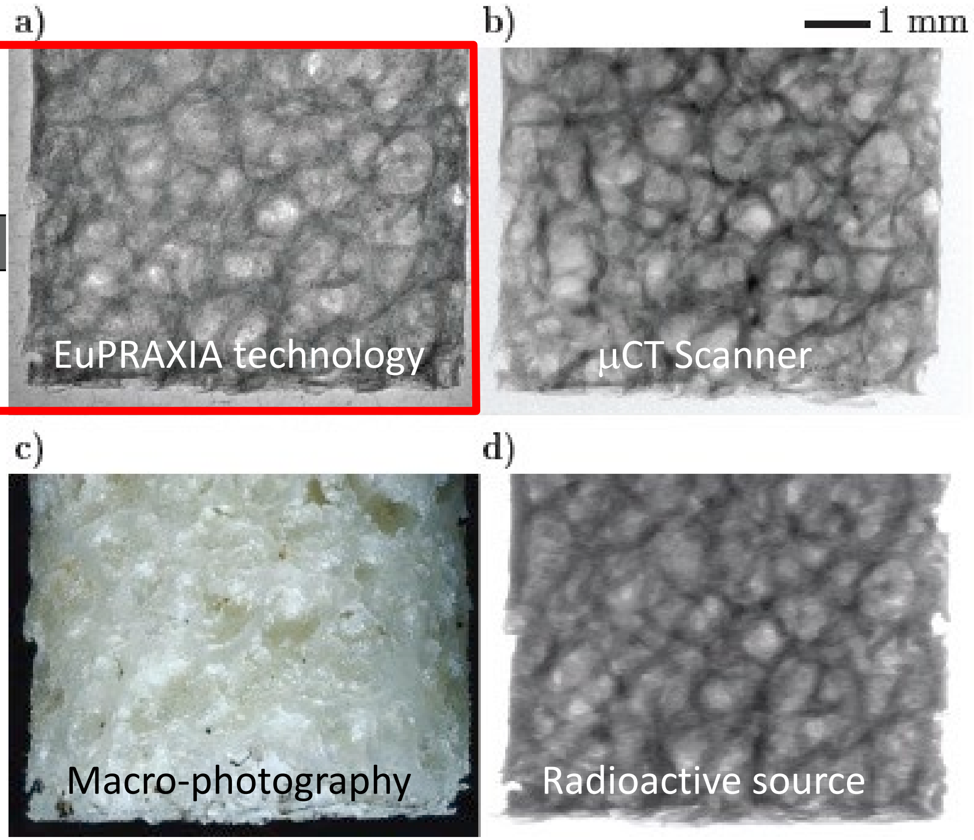
$$r_\beta = \frac{2\sqrt{a_0}c}{\omega_p}$$

Angelo.Biagioni@LNF.INFN.IT

SPARC_LAB: Compact Medical Imaging

J.M. Cole et al, "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone". Nature Scientific Reports 5, 13244 (2015)





- **EuPRAXIA laser advance (industry) will push rate from 1/min to 100 Hz.**
- **Ultra-compact source of hard X rays → exposing from various directions simultaneously is possible in upgrades**

Physics & Technology Background:

- Small EuPRAXIA accelerator → small emission volume for betatron X rays.
- **Quasi-pointlike** emission of X rays.
- **Sharper image from base optical principle.**
- Quality demonstrated and published, but takes a few hours for one image.
- Advancing flux rate with EuPRAXIA laser by factor > 1,000!

Added value

Sharper images with outstanding **contrast**

Identify smaller features (e.g. early detection of cancer at micron-scale – calcification)

Laser advance in EuPRAXIA → **fast imaging** (e.g. following moving organs during surgery)

Angelo.Biagioni@LNF.INFN.IT

Plasma module

- Theoretical studies of plasma discharges in capillary discharge waveguides
- Optimization of active-plasma lens devices for ultra-high focusing gradients
- Deflection of particle beams with active-plasma dipole (curved capillary) lens geometries
- Plasma source study and design for particle acceleration
- Plasma source design for betatron radiation source (interaction between plasma and high power lasers)

Flame Laser

- Femtosecond laser synchronization for external injection of electron bunches in a laser driven plasma wave

- Study of a compact and high efficiency laser removal technique for EUPRAXIA@SPARC_LAB

- Laser plasma acceleration for production of betatron radiation for multi-purpose applications in EuPRAXIA

- Laser plasma acceleration for production of charged and neutral particles for EuPRAXIA. (positrons included)

RF

- Test e commissioning dei sistemi di controllo a radiofrequenza (low level RF) e sincronizzazione opto-elettronica al femto-secondo per il progetto ELI-NP in Romania

FEL

- Studio e caratterizzazione di un canale di trasporto basato su dispositivi a plasma per l'iniezione nel FEL a EuPRAXIA@SPARC_LAB

- Generation of short pulses in Free Electron Laser Amplifiers

- Free electron laser driven by a laser plasma accelerator.

- Design, construction and application of a innovative THz source for applications

- Design and R&D for EUPRAXIA@Sparc-Lab XUV and UV beamlines : Devices for Optics and Vacuum Systems

 Angelo.Biagioni@LNF.INFN.IT


Thank for your attention