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PIANO NAZIONALE DI RIPRESA E RESILIENZA
EuPRAXIA Advanced Photon Sources

Betatron radiation from laser wakefield acceleration: ongoing experiments at SPARC_LAB

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On behalf of SPARC_LAB & EuAPS collaborations

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Contents

✓ Laser WakeField Acceleration: bubble regime

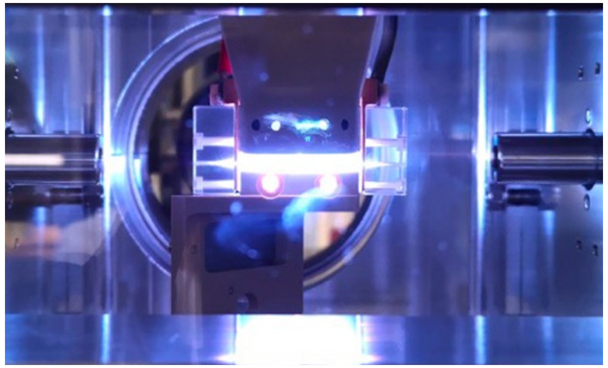
➢ Betatron radiation from LWFA

➢ The FLAME Laser @SPARC_LAB

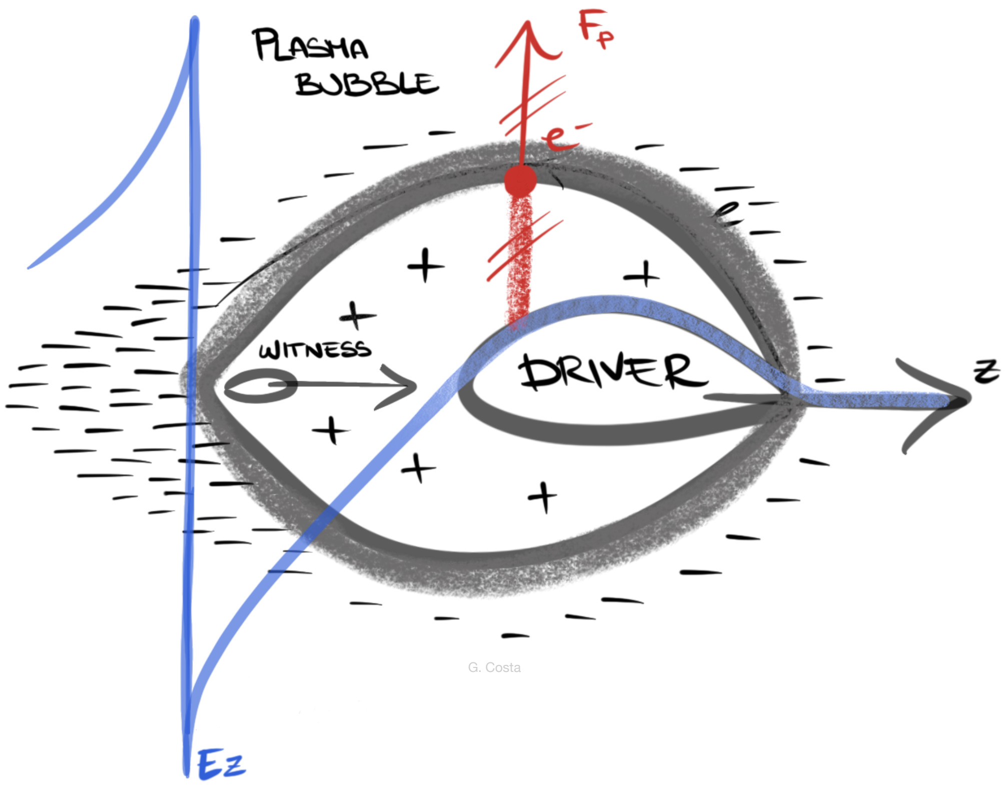
➢ The EuAPS project @SPARC_LAB and Experimental setup

Conventional RF structures:
(20 – 40) MV/m
range *m - km*

Plasma module:
$E\ [GV/m] \approx 96\ (n_e\ [cm^{-3}])^{1/2}$
$n_e = 10^{18}\ cm^{-3}$ => 100 GV/m
range *mm - cm*



LWFA



Laser pulse
$I = 10^{18}\ W/cm^2$ and $c\tau < \lambda_p/2$

Plasma frequency
$\omega_p = (n_e\ e^2/\varepsilon_0\ m_e)^{1/2}$

$a_0 >> 1$
non-linear regime
Self-injection

Tajima and Dawson (1979)

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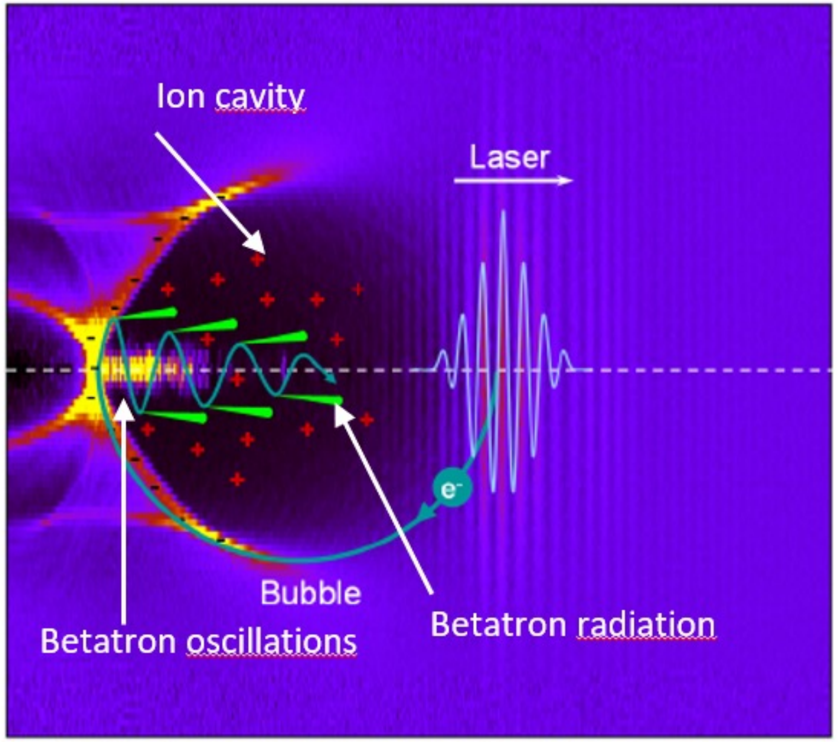
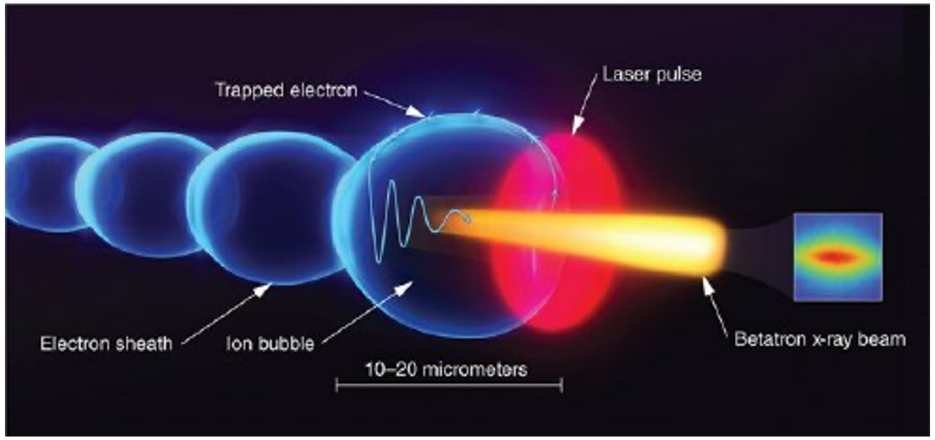
Betatron radiation emission



Longitudinal electric field → acceleration along the laser propagation axis

Radial electric field → oscillations around the reference trajectory

Emission of synchrotron-like radiation = **Betatron radiation**

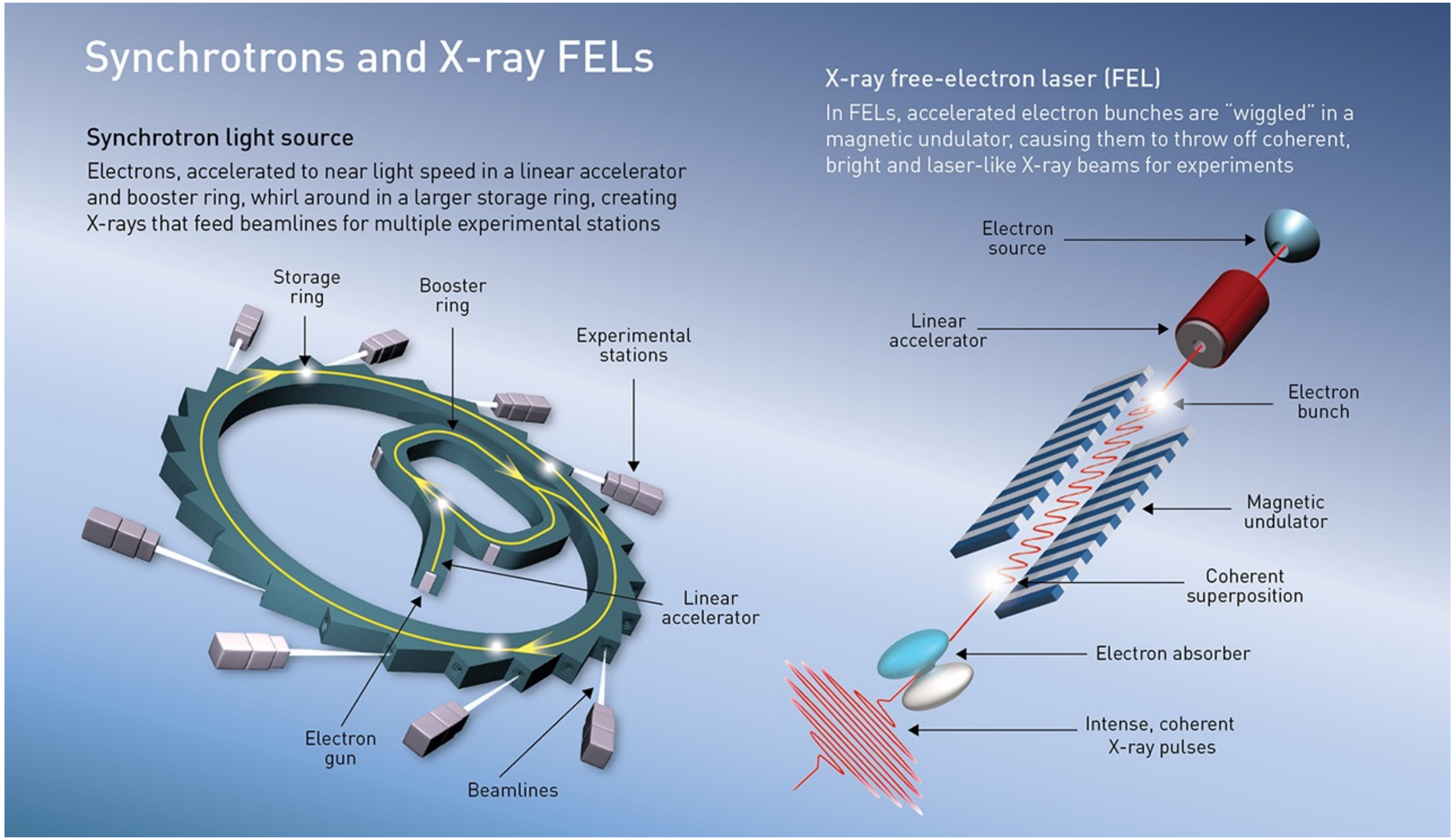


- Energy from soft to hard X-rays
- High peak brilliance

$$B \approx 10^{20} \frac{Photons}{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%\ BW}$$

- Spatially coherent
- Temporally incoherent
- Pulse ~ few fs

Synchrotrons vs FELs



- Large bandwidth like a Synchrotrons
- Short pulse duration like a FEL

$$B = \frac{d^4 N}{dt\, d\Omega\, dS\, d\lambda / \lambda}$$

Ph/ (s mm^2 mrad^2 0.1% of bandwidth)

Patricia Daukantas Synchrotron Light Sources for the 21st Century Optics & Photonics News Settembre 2021

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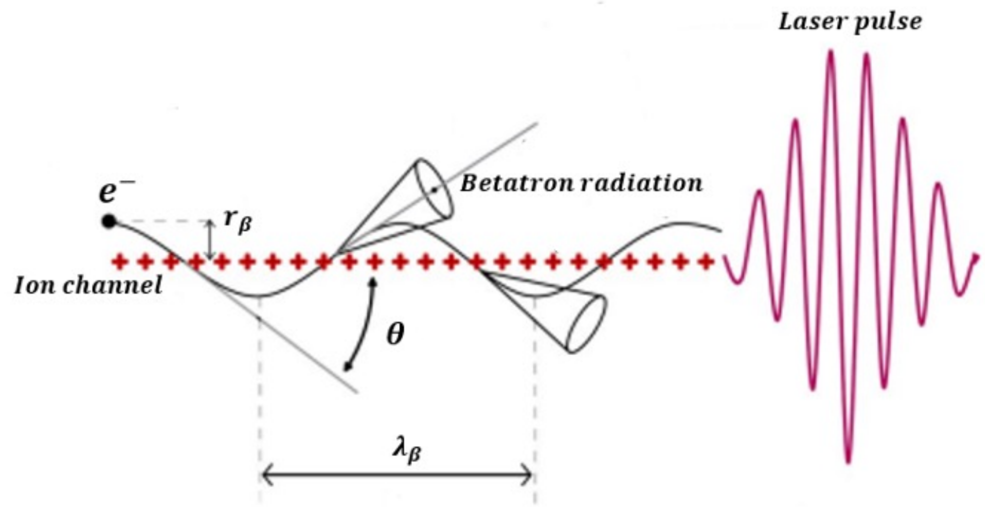
Wiggler or undulator?

Betatron strength parameter for a single electron

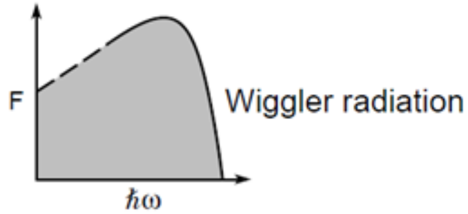
$$K = \frac{eB_0}{m_e c k_u} = \frac{eB_0 \lambda_u}{2\pi m_e c} = 0.934 \cdot B_0[T] \cdot \lambda_u[cm]$$

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

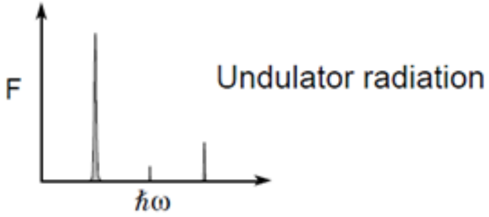
- θ radiation cone opening angle
- k_β amplitude of the oscillation
- $k_\beta = \omega_\beta / c$ betatron wavenumber



K >> 1 wiggler regime

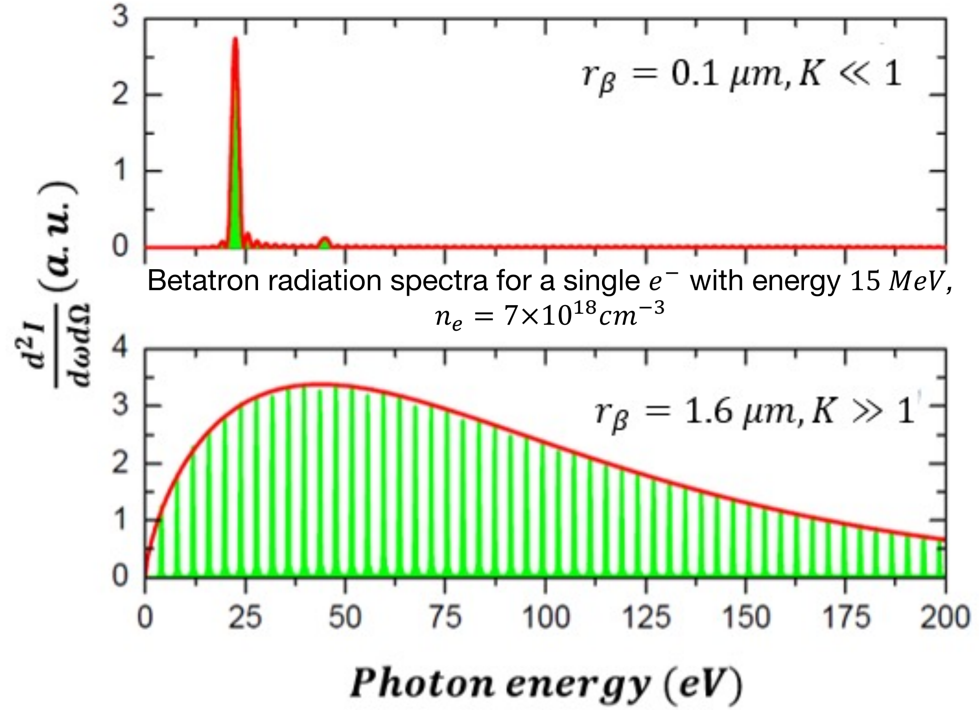


K ≤ 1 undulator regime



Spectral flux and critical energy

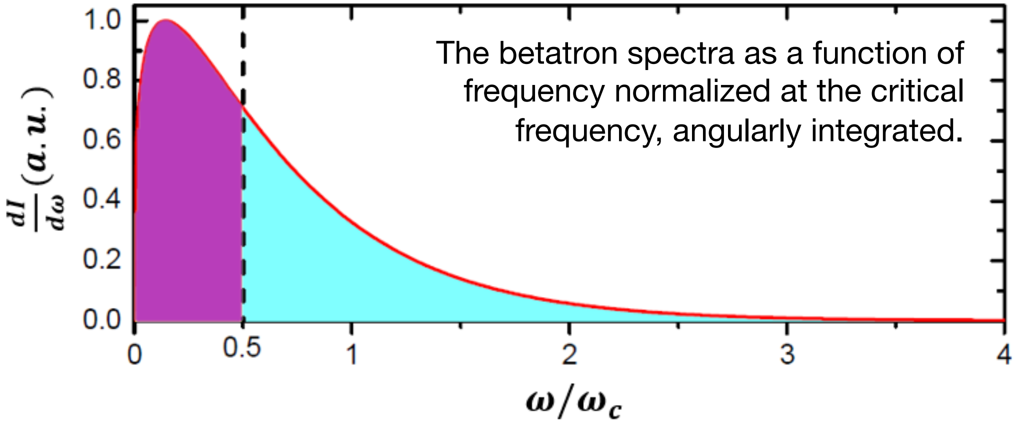
$$\frac{d^2 I}{d\omega d\Omega} \approx \frac{3e^2}{2\pi^3 \epsilon_0 c} N_\beta \gamma^2 K_{2/3}^2(\zeta)\zeta^2$$



Betatron radiation spectra for a single e^- with energy 15 MeV, $n_e = 7\times10^{18} cm^{-3}$

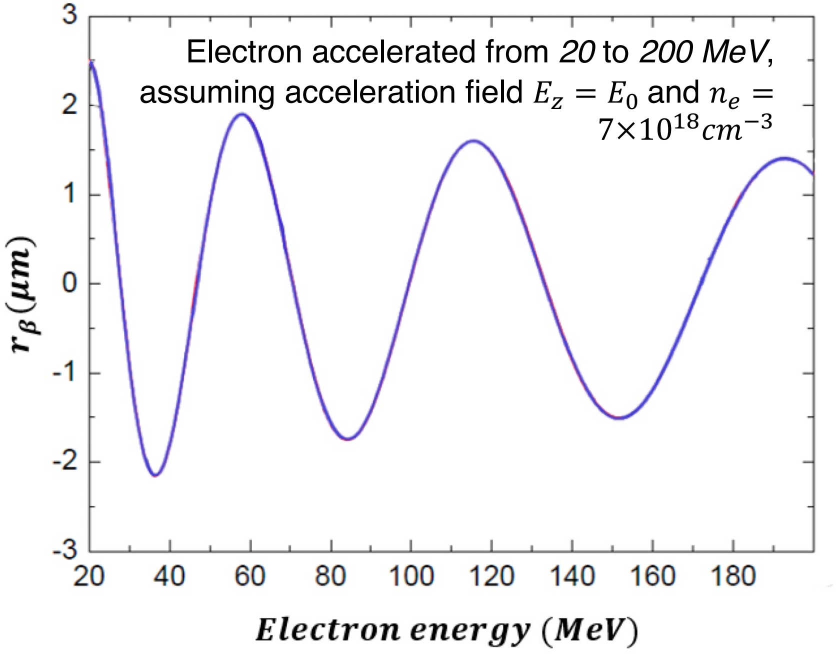
- critical frequency $\omega_c = 3\gamma^2 K_\beta \omega_\beta$
- critical energy $\boldsymbol{E_c \propto \gamma^2 K \omega_\beta}$

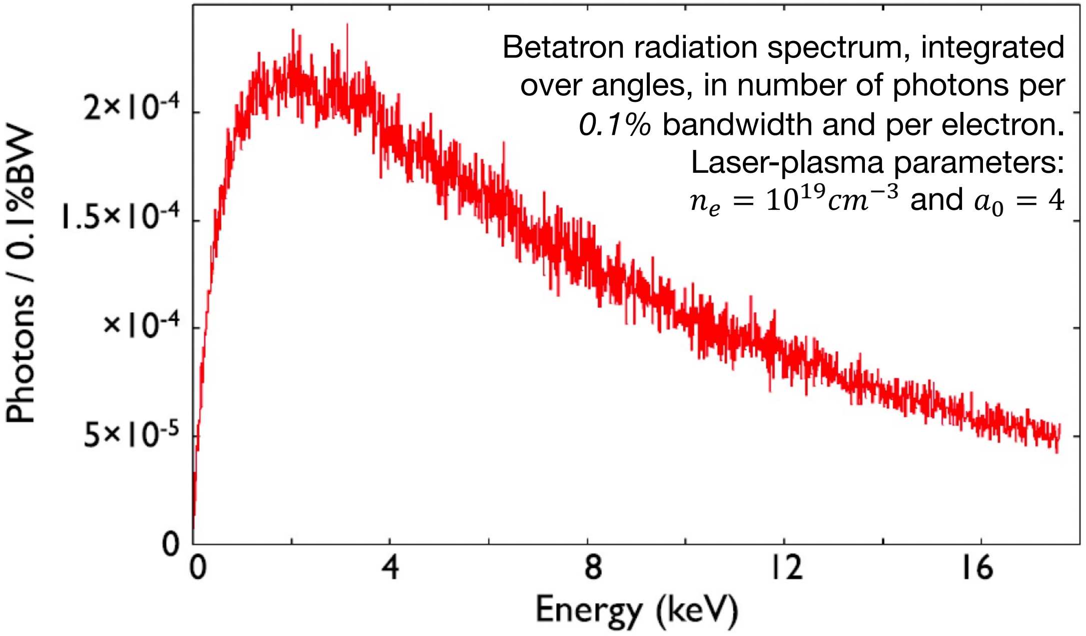
which divides the spectrum in two region each carrying the same amount of energy



$$\frac{dN}{d\omega} = N_e \frac{\sqrt{3}}{2\pi} \frac{e^2\gamma}{\epsilon_0 c \omega_c} \int_{2\omega/\omega_c}^{\infty} K_{5/3}(x)dx$$

Acceleration lead to damped oscillations and inhomogenous brodening





$$\left.\frac{d^2 I_{acc}}{d\omega d\Omega}\right|_{\theta=0} = \frac{3e^2}{2\pi^3 \epsilon_0 c} \int_{\varepsilon_i}^{\varepsilon_f} d\gamma^2 \zeta^2 K_{2/3}^2(\zeta)$$

Electron's strength parameter in a plasma focusing channel depends on the **oscillation amplitude**, leading to inhomogeneous broadening of the radiation spectrum and suppression of the spectral-angular correlations.

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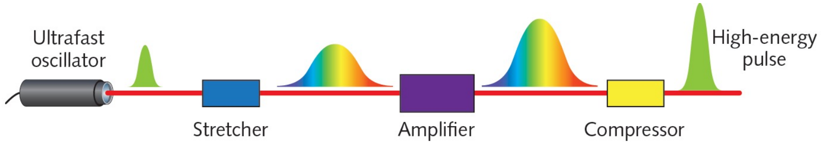
FLAME LASER

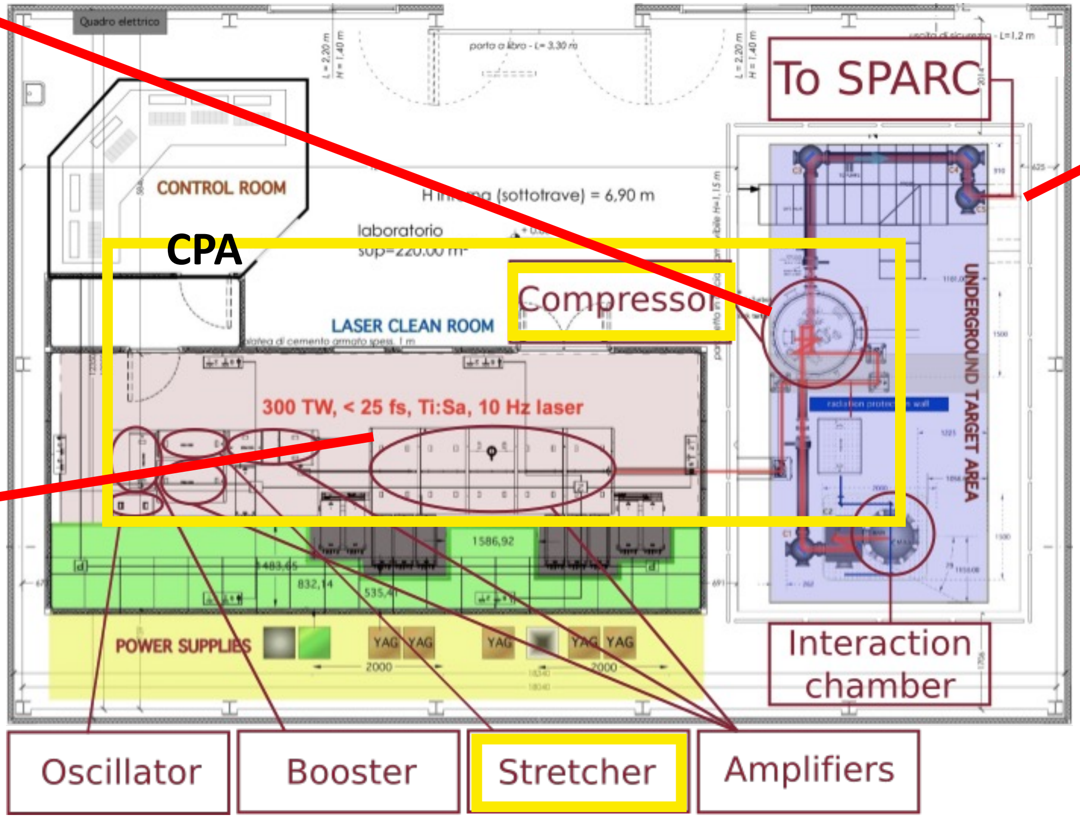
MAIN PULSE	
Peak power	250 TW
Energy on target	7 J
Rep. rate	10 Hz
Temporal length	25 fs
FW $1/e^2$ @ focus	20 μm
Intensity	10^{19} W/cm^2
Contrast-ratio	10^{10}

PROBE PULSE	
Energy on target	10 mJ
Temporal length	50 fs
FW $1/e^2$ @ focus	120 μm
Intensity	10^{16} W/cm^2

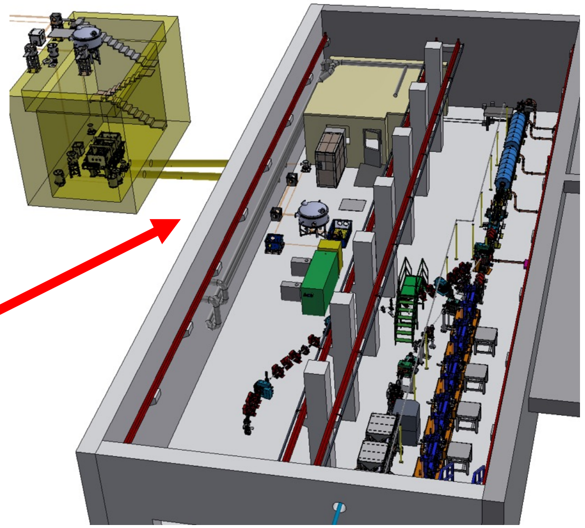
High-power Ti:Sa based laser, ultra-short CPA based pulse



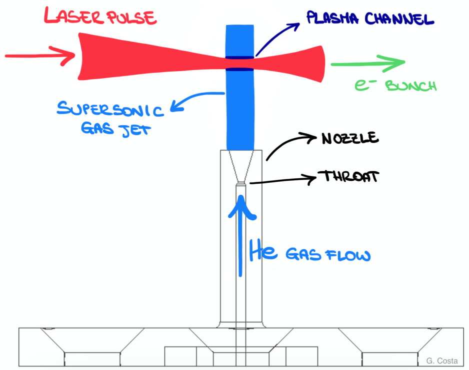
Strickland and Mourou 1985
Nobel Prize in Physics 2018

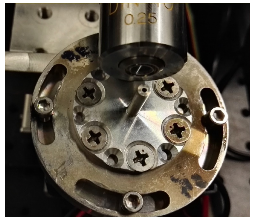


80 MHz, 220 mW

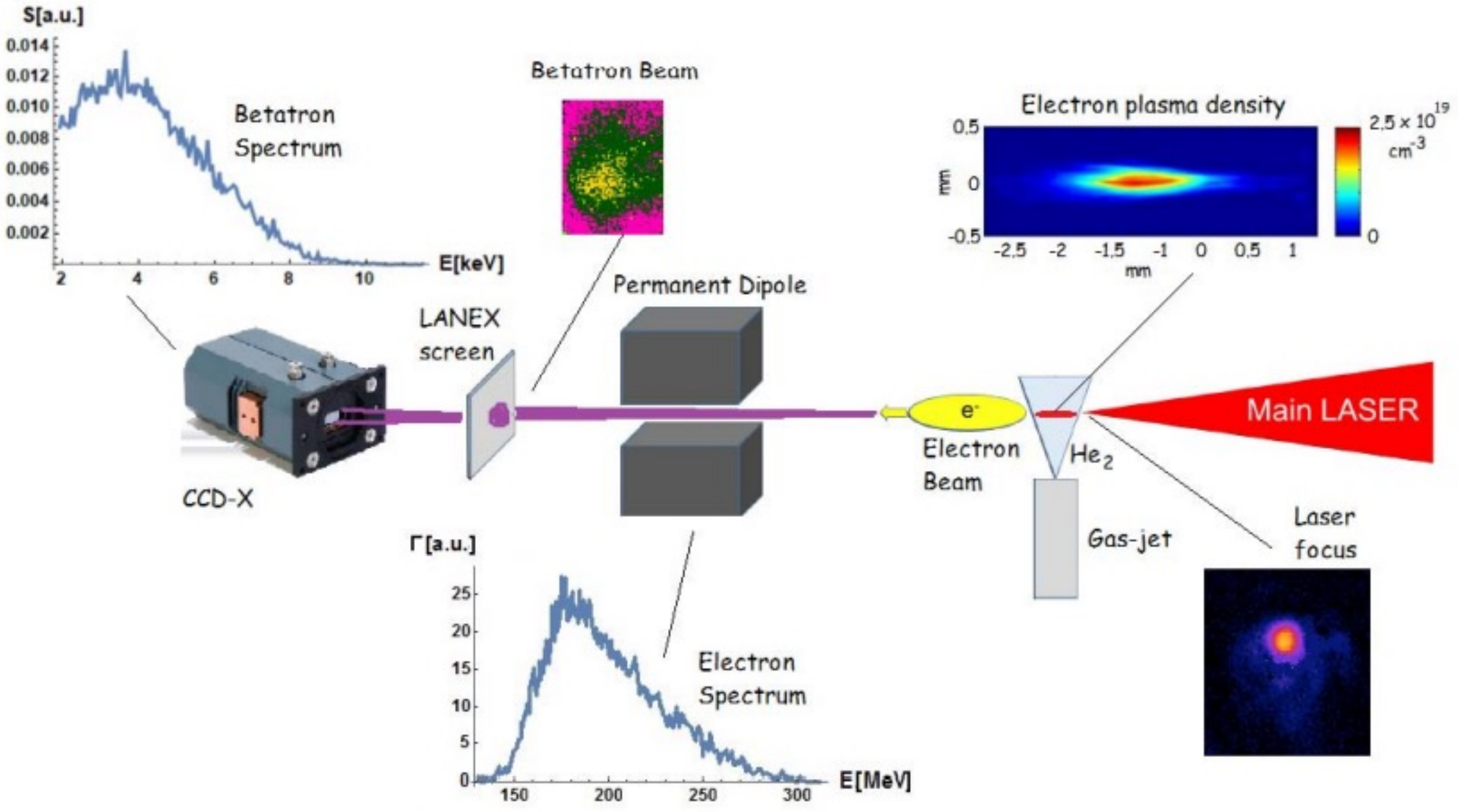


supersonic nozzle for self-injection experiments and X-rays radiation emission

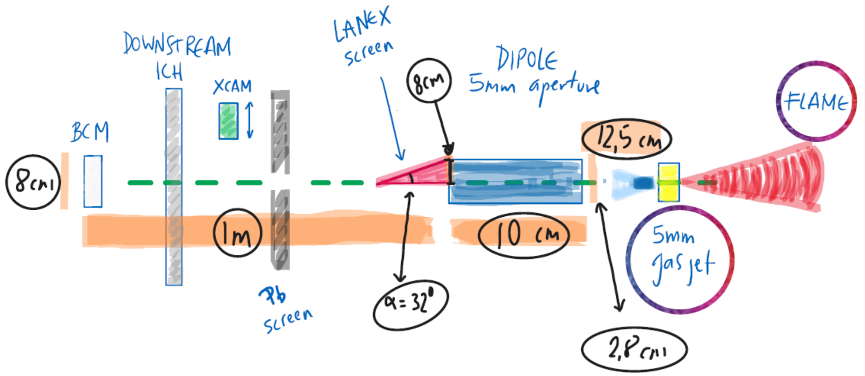




FLAME experimental setup for betatron radiation source



- Laser energy *6 J*
- Laser temporal length *30 fs FWHM*
- Laser focal spot *18-20 μm FWHM*



Courtesy M Galletti

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The PNRR EuAPS Project WP2

EuAPS will be the first brick of EuPRAXIA, a user facility based on the radiation emitted by electrons plasma accelerated

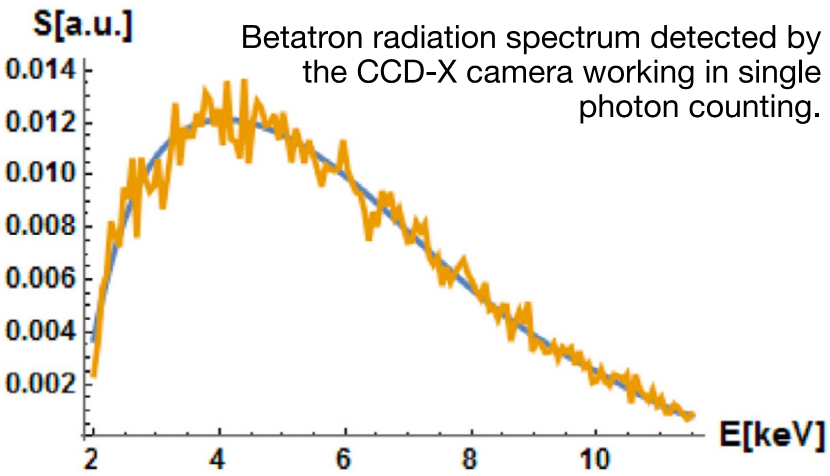
- The source will be hosted at LNF-INFN
- Several parts will be realized at CNR (Photon Diagnostics) and at Tor Vergata (User end Station)
- INFN-Mi will take care of simulation and data analysis
- Trieste University focuses on applications

Where	Target
INFN-Mi	Simulation & Data Analysis
LNF-INFN	Plasma source
LNF-INFN	Synchronization
CNR-Potenza	Photon Diagnostics
Tor Vergata	End user station
CNR- Montelibretti	Photon time diagnostics

Parameter	Value	unit
Electron beam Energy	*100 - 500*	*MeV*
Plasma Density	10^{18} - 10^{19}	cm^{-3}
Photon Critical Energy	*1 - 10*	*keV*
Number of Photons/pulse	10^{6} - 10^{9}	
Repetition rate	*1 - 5*	*Hz*
Beam divergence	*3 - 20*	*mrad*

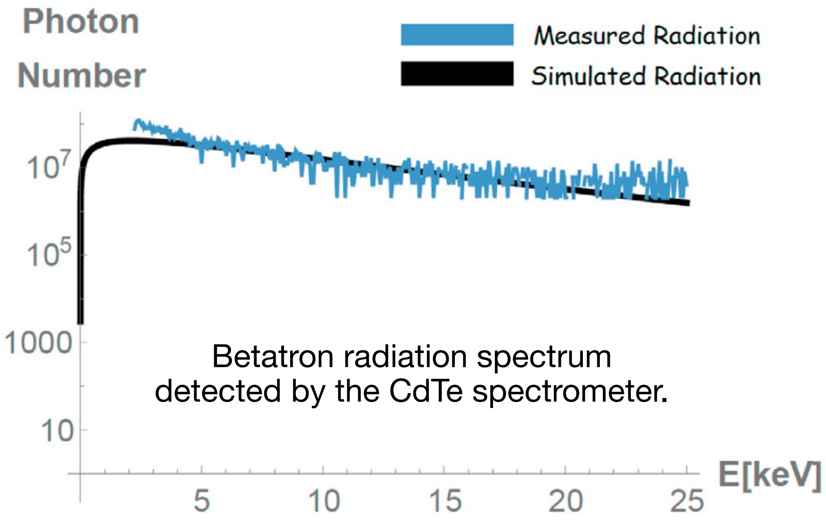
Courtesy A Cianchi

First Betatron test @FLAME 2016



Betatron radiation spectrum detected by the CCD-X camera working in single photon counting.

- Laser energy *1 J* - temporal length *30 fs* - focal spot rms *5* μm
- Plasma density 10^{19} cm^{-3} - acceleration length *1.1 mm*
- e^- energy *300 MeV* - energy spread *20%* - bunch charge *5 pC*



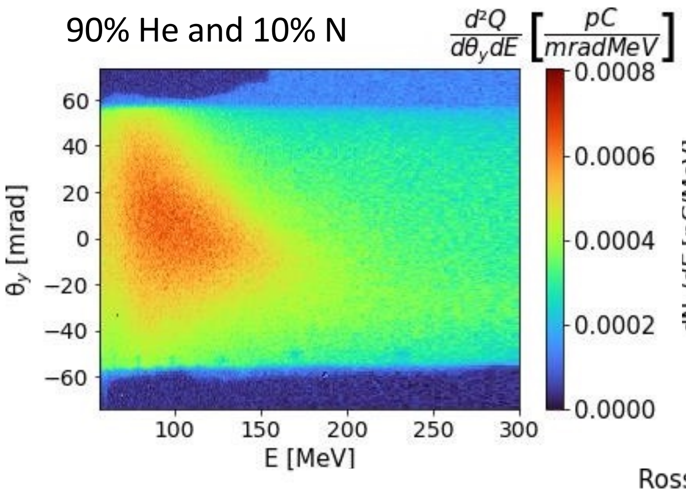
Betatron radiation spectrum detected by the CdTe spectrometer.

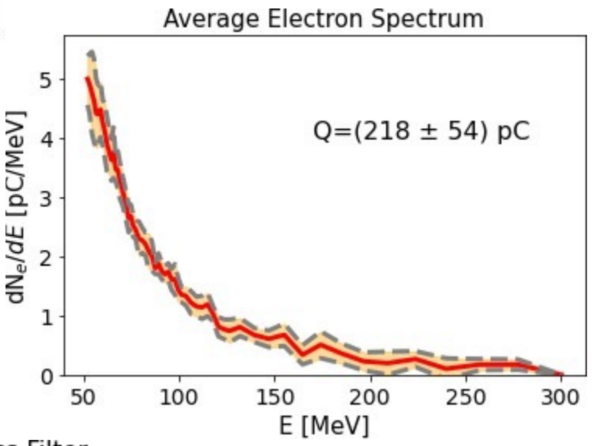
- Laser energy *1.5 J* - temporal length *35 fs* - focal spot rms *5* μm
- Plasma density *6 x* 10^{18} cm^{-3} - acceleration length *1 mm*
- e^- energy *200 MeV* - energy spread *30%* - bunch charge *5 pC*

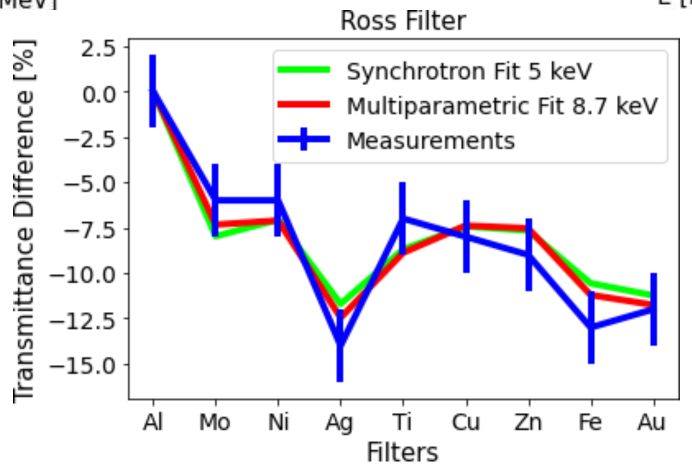
A. Curcio et al., First measurements of betatron radiation at FLAME laser facility, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.03.106

Ongoing experiments @FLAME

90% He and 10% N



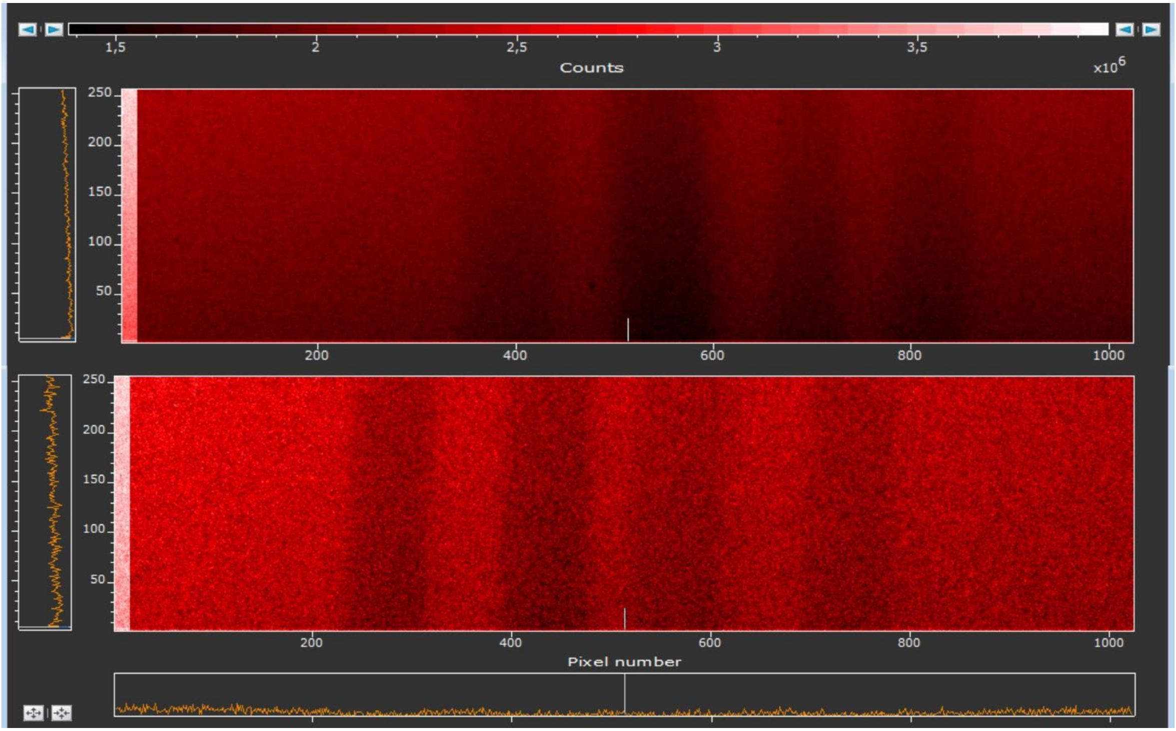




Ross-filter:

Ti 15 μm – Ag 33 μm – Ni 7 μm – Mo 4 μm

Au 6 μm – Fe 25 μm – Zn 10 μm – Cu 8 μm



G Costa, A Curcio, M Del Giorno, V Dompè, M Galletti, F Stocchi

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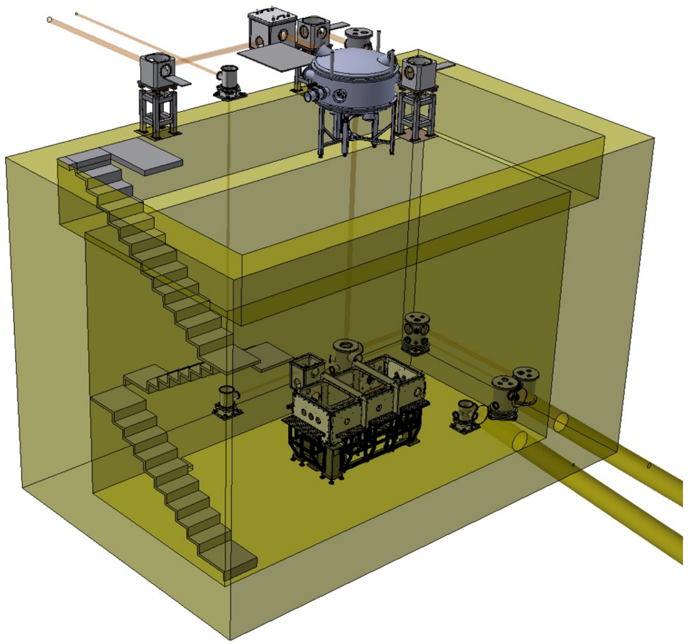
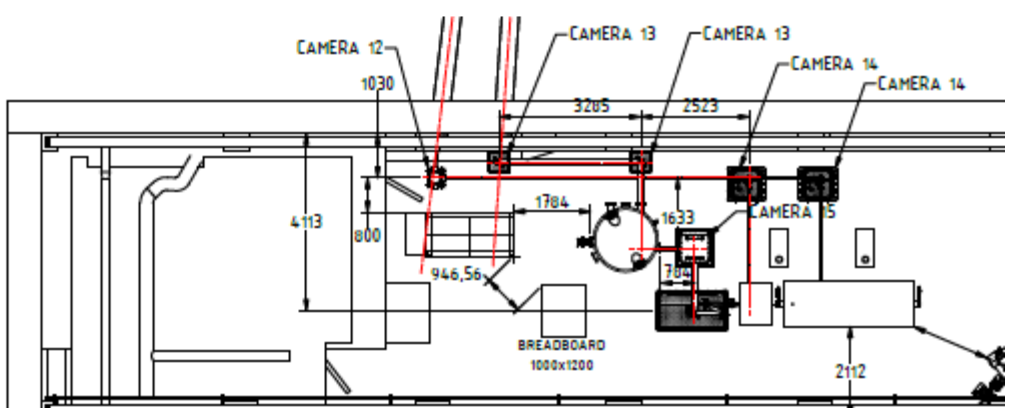
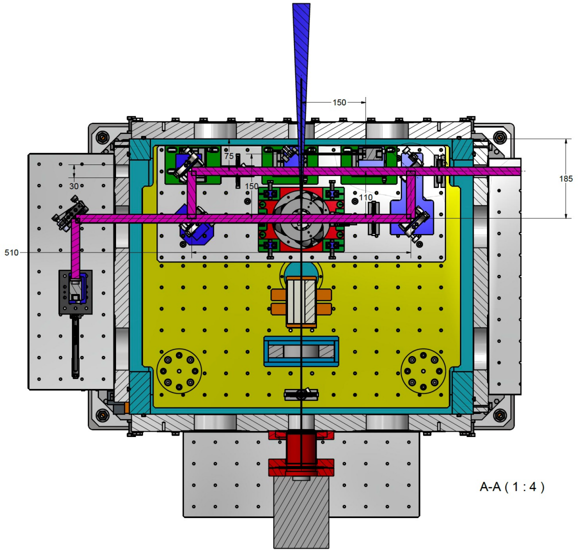
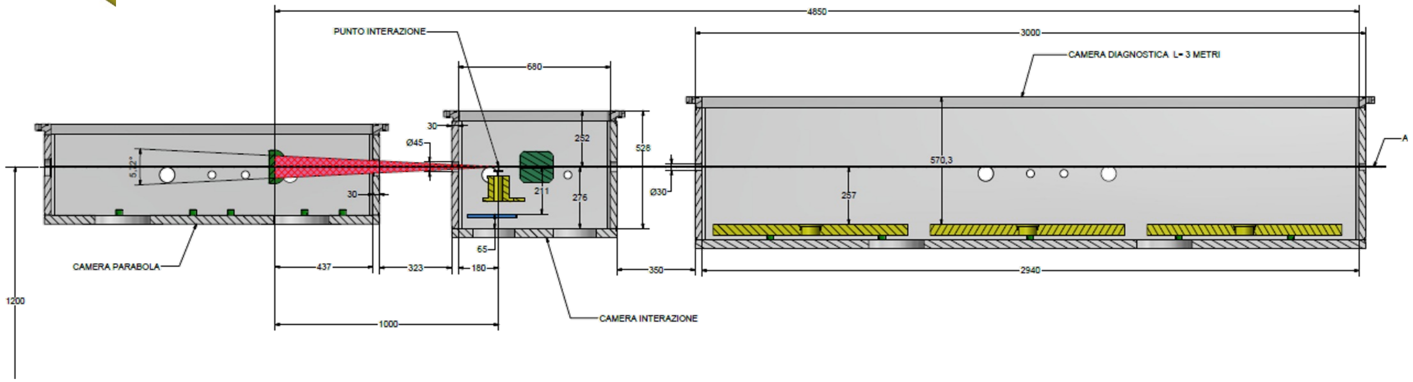
The EuAPS Layout: FLAME and SPARC bunker





EuAPS beam line in SPARC





Interaction and user chamber

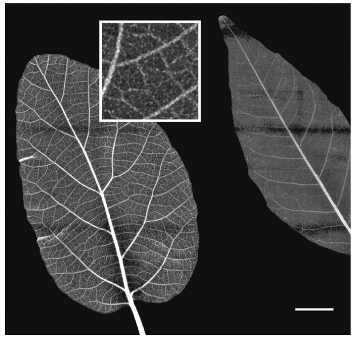
New configuration for EuAPS tests in FLAME

Courtesy S Lauciani

Photon Science @EuAPS

- Imaging of biological and cultural heritage samples:
  Exploits the brilliance and coherence of betatron radiation, requires small divergence and good focusing
- Static X-ray Spectroscopy and Ultra-fast X-ray spectroscopies:
  The second one requires timing between pump and probe pulses, exploits the fs pulse duration
- Wide angle scattering, diffraction:
  Requires monochromatic beams with high flux

Imaging – The pilot experiment

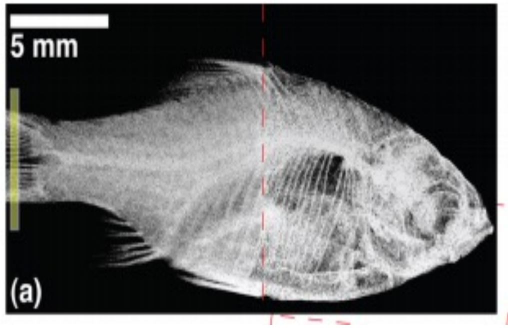


X-ray imaging of leaves (and wood) aiming at the (tens of) microns resolution.

Experiments performed with the broad radiation spectrum filtered by different materials to obtain difference maps emphasizing the presence of heavy metal contaminants → pollution control.

Reale et al. - MIDIX Soft X-rays microradiography

Single shot phase contrast X-ray imaging:



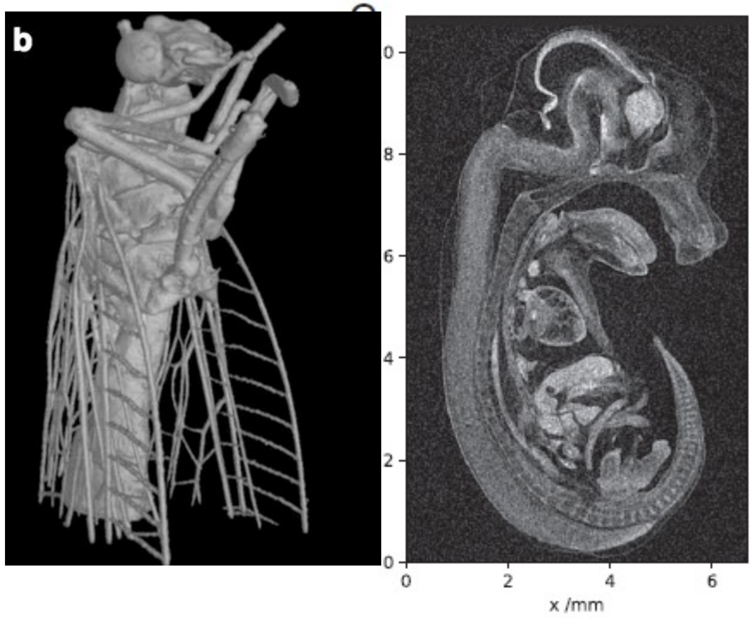
X-ray absorption contrast image of an orange tetra fish. The spectrum is synchrotron like with a critical energy E_c~10 *keV*. The phase contrast images are taken in a single shot *30 fs* exposure.

Ref. Kneip, S., et al. "X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator." **APL** 99.9 (2011): 093701.

Courtesy F Stellato

Imaging, Tomography and Phase Contrast

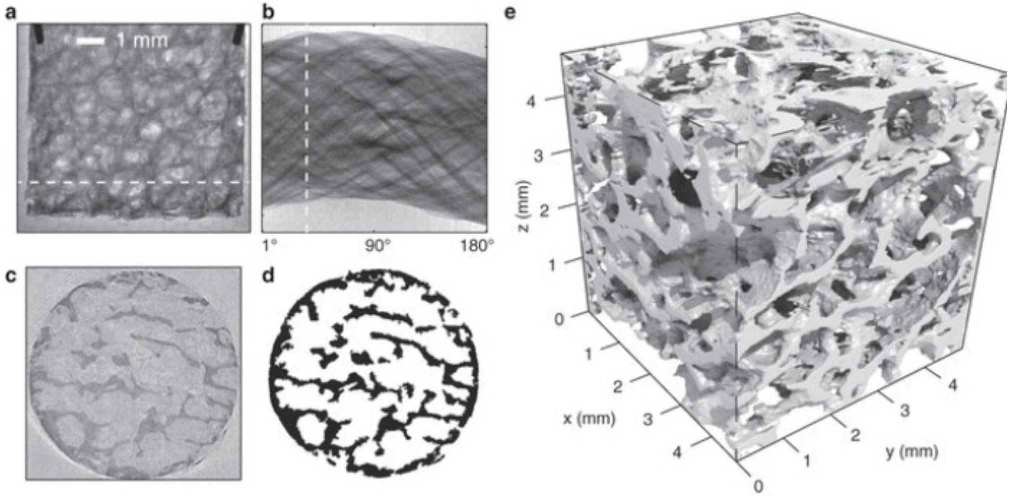
Betatron sources can fill the gap between synchrotrons and X-ray tubes for imaging and **Computer Tomography** (CT)



Guo *et al.* Scientific Reports 2019
Cole *et al.* PNAS 2018
Wenz *et al.* Nature communications 2015

Betatron sources have a spatial coherence that allows performing Phase Contrast Imaging (PCI). In PCI, it is measured the difference in wavefront, while in traditional imaging, it is measured the difference in the X-ray absorption coefficient between different objects.

PCI provides better contrast than radiography, especially when dealing with biological samples.



3D medical imaging: Tomographic reconstruction of bone sample: (a) A raw image of the bone sample recorded on the xray camera. (c) Application of the inverse Radon transform to the sinogram in (b). (d) Pixels are classified as bone (black) or vacuum (white). (e) Stacking together 1300 slices generates a 3 D voxel map of the bone sample. An isosurface marking the detailed structure of the bone surface is constructed, rendered using a ray-tracing method.

Ref. Cole, J. M., et al. "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone." *Scientific reports* 5.1 (2015): 1-7.

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