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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

EuPRAXIA
Advanced Photon Sources

EuAPS
EuPRAXIA
Advanced Photon Source – WP2

Alessandro Cianchi

University of Rome Tor Vergata & INFN

On behalf of SPARC_LAB & Eupraxia collaborations

South East Rome, within 10km, several research institutions

Slightly less than 30,000 students

Faculty of Economics.
Faculty of Law.
College of Engineering.
Faculty of Literature and Philosophy.
Faculty of Medicine and Surgery.
Faculty of Mathematical, Physical and Natural Sciences.

EuPRAXIA Galaxy @ TOR VERGATA

- Alessandro Cianchi – PNRR and EuPRAXIA beam instrumentation
- Francesco Stellato – PNRR and EuPRAXIA user experiments
- Mario Galletti –PNRR and laser
- Federico Galdenzi – PNRR users experiments
- Federica Stocchi – PNRR
- Mauro Sbragaglia – EuPRAXIA Simulations
- Daniele Simeoni - EuPRAXIA Simulations
- Fabio Guglietta - EuPRAXIA Simulations
- Gianmarco Parise –EuPRAXIA Simulations

Outline

- What we are going to do?
  - Betatron source
- Where?
  - In the SPARC tunnel @ LNF
- Who?
  - INFN-LNF, INFN-Mi, CNR-Montelibretti, CNR-Potenza, Tor Vergata
- To do what?
  - Applications

Principal Investigator
M. Ferrario (INFN-LNF)
22.350.588,00

High repetition lasers
L. Labate (CNR)

4.863.150,00

Betatron X rays source
A. Cianchi (Tor Vergata)

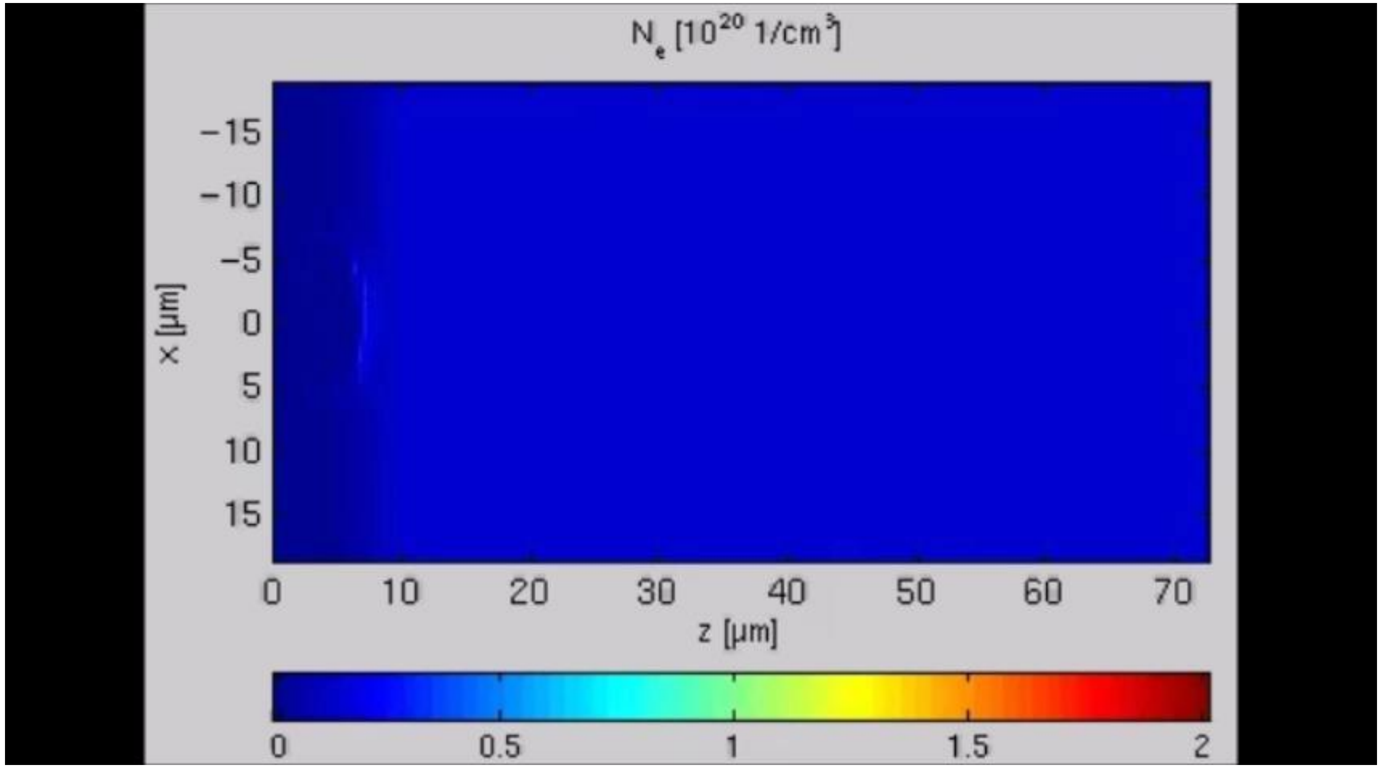
9.457.088,00

High power lasers
P. Cirrone (INFN)

7.864.500,00

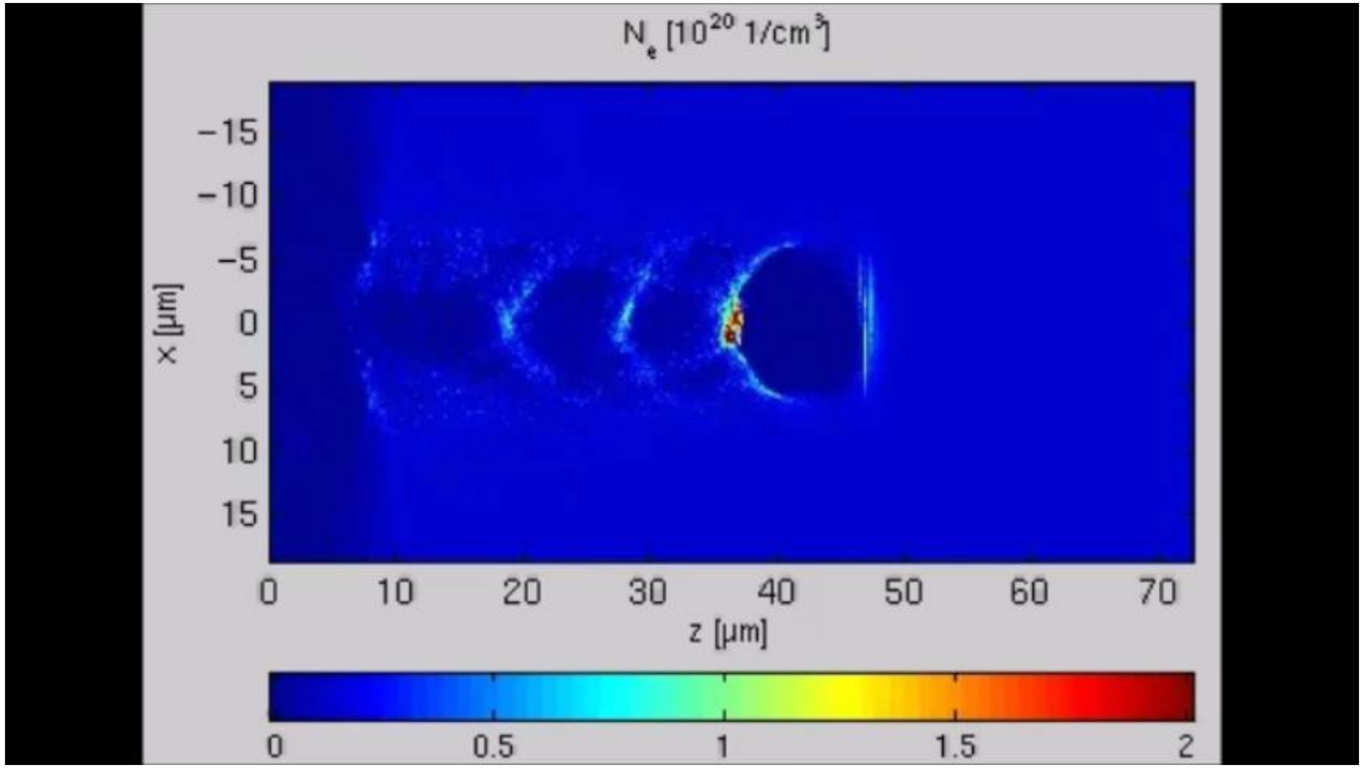
Management & Financial office
A. Falone (INFN)

Plasma acceleration in a nutshell



- High power laser ionize the gas and create a plasma bubble
- Electron are self injected in the back of the bubble
- These charges are accelerated by intense electric field (>GV/m)
- The uncontrolled injection produces betatron oscillation

Plasma acceleration in a nutshell



- High power laser ionize the gas and create a plasma bubble
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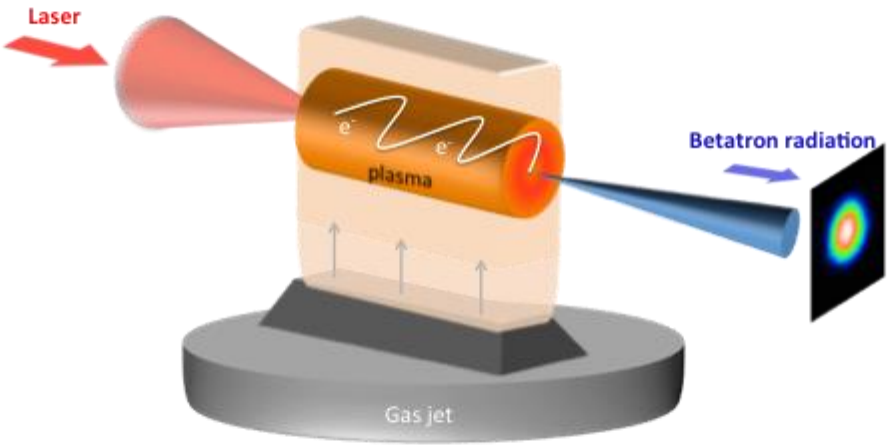
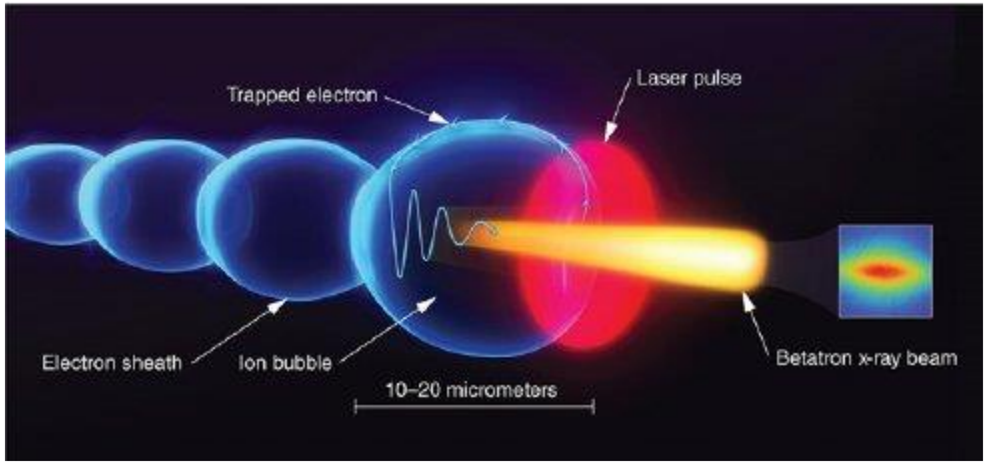
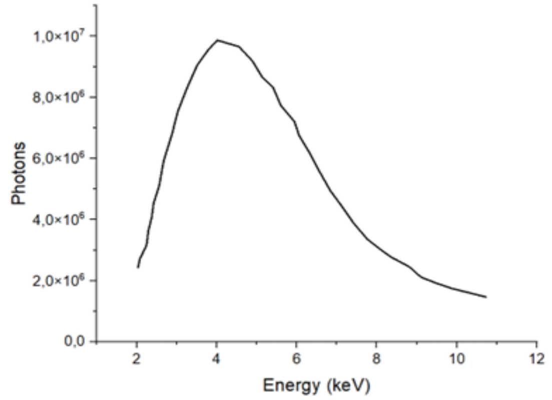
Betatron radiation emission





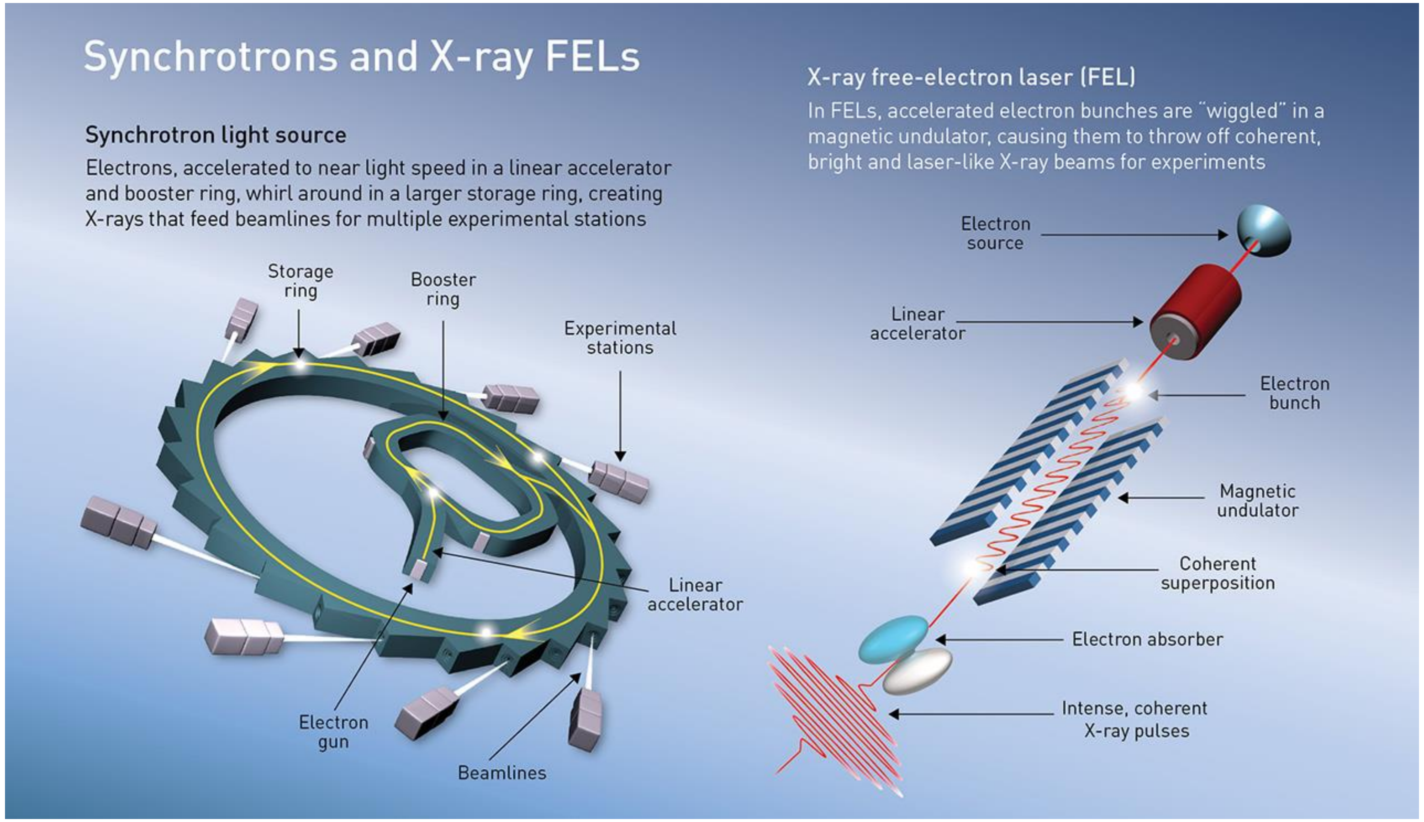
First measurements of betatron radiation at FLAME laser facility

A. Curcio[a,b,*], M. Anania[a], F. Bisesto[a,b], E. Chiadroni[a], A. Cianchi[a], M. Ferrario[a], F. Filippi[a,b], D. Giulietti[c], A. Marocchino[a], F. Mira[b], M. Petrarca[d], V. Shpakov[a], A. Zigler[a,e]



- The radiation has its characteristics of both FELs and synchrotrons
  - Large bandwidth similar to Synchrotrons
  - Short pulse duration like a FEL

Synchrotrons vs FELs



Synchrotrons and X-ray FELs

Synchrotron light source

Electrons, accelerated to near light speed in a linear accelerator and booster ring, whirl around in a larger storage ring, creating X-rays that feed beamlines for multiple experimental stations

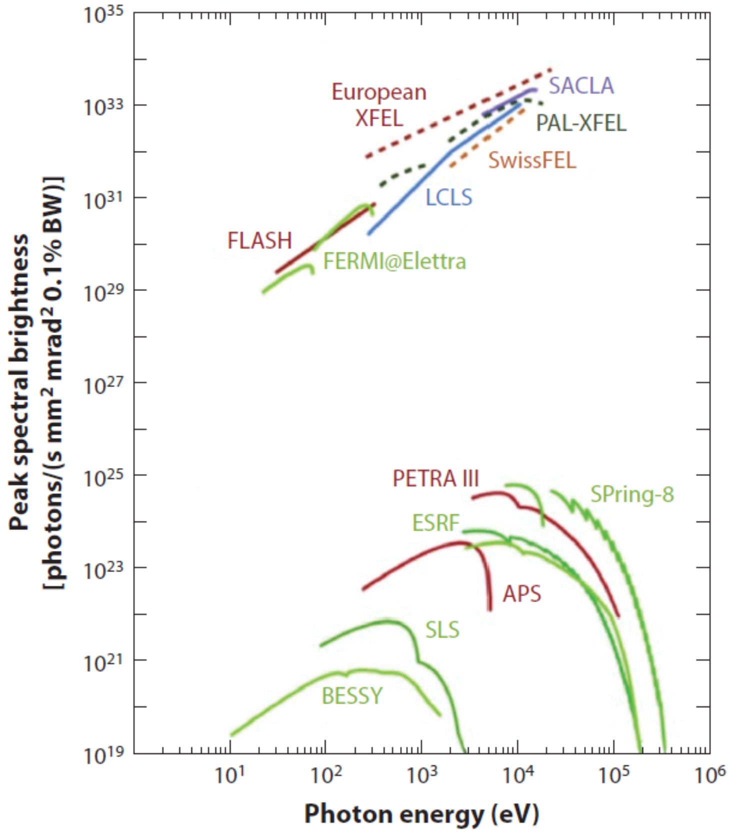
X-ray free-electron laser (FEL)

In FELs, accelerated electron bunches are "wiggled" in a magnetic undulator, causing them to throw off coherent, bright and laser-like X-ray beams for experiments

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

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

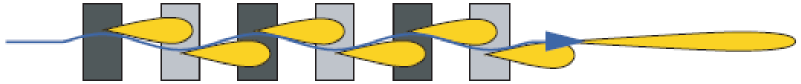
Ph/ (s mm^2 mrad^2 0.1% of bandwidth)



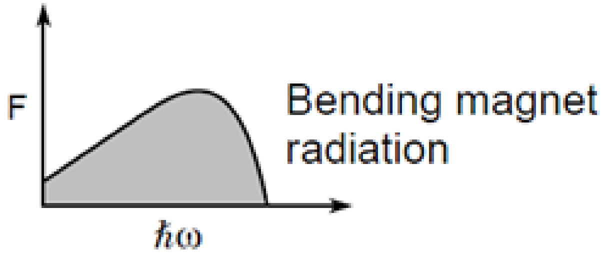
Wiggler or undulator?

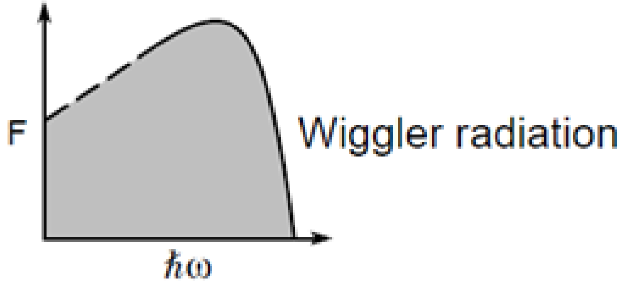
$$K = \frac{eB_0}{m_e c k_u} = \frac{eB_0 \lambda_u}{2\pi m_e c} = 0.934 \cdot B_0\,[\mathrm{T}] \cdot \lambda_u\,[\mathrm{cm}]$$

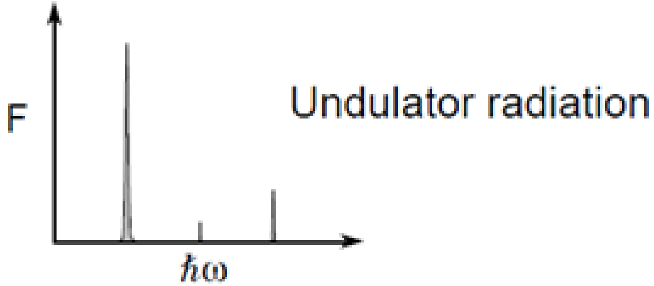
K>>1



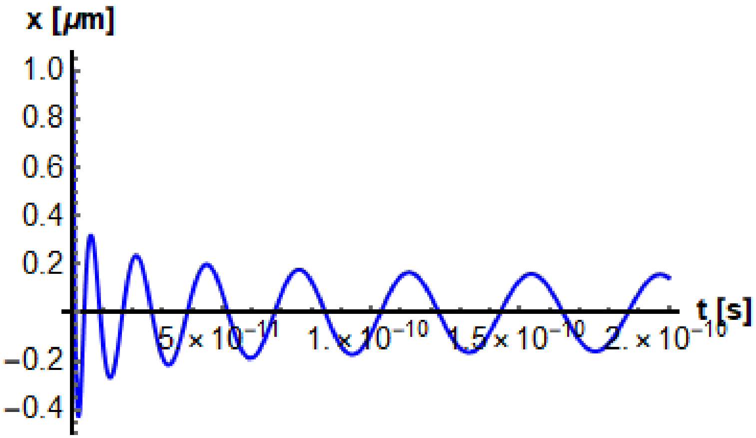
K≤1







Damped oscillations and acceleration lead to inhomogenous brodening

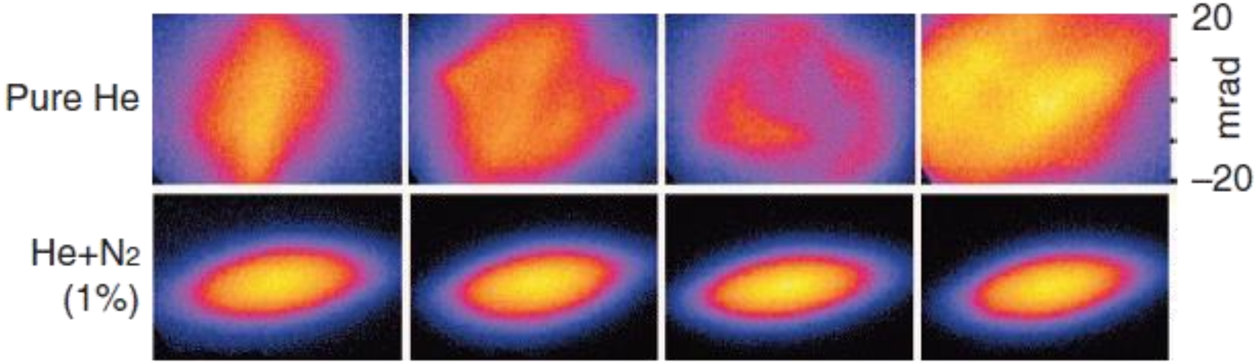


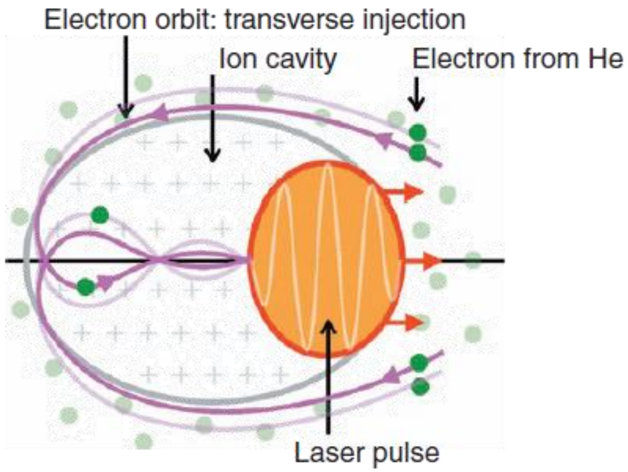
- Differently from a wiggler, the oscillation amplitude and frequency depend upon time.
- Furthermore, each electron corresponds to a different initial amplitude (position of injection) : this will bring to an **inhomogeneous broadening** of the radiation spectrum.
- In a magnetic undulator, the strength parameter is approximately **the same** for all electrons and depends only on physical constants and the magnetic field.
- Each electron's strength parameter in a plasma focusing channel differs. It depends on the **oscillation amplitude**, leading to inhomogeneous broadening of the radiation spectrum and suppression of the spectral-angular correlations.
- Another cause for inhomogeneous broadening is undoubtedly the energy spread, common to both a magnetic undulator and a plasma-focusing cannel.

Betatron Radiation		***Synchrotron Radiation***
$\omega_x(t) = \frac{3\gamma^2 K_\beta^4 \omega_\beta}{2K_x^3}\left(1+\frac{K_y^2}{2K_x^2}\right)^{-3/2} \propto \gamma^{7/4}(t)$ $\omega_y(t) = \frac{3\gamma^2 K_\beta^4 \omega_\beta}{2K_y^3}\left(1+\frac{K_x^2}{2K_y^2}\right)^{-3/2} \propto \gamma^{7/4}(t)$	Critical frequency On-axis	$\omega_c \propto \gamma^3$
$P(t) \propto \gamma^{3/2}(t)$ Peak	Power	$P \propto \gamma^4$ Mean
Cumbersome expression, where Bessel K functions are integrated upon time. No appearance of Bessel $K_{5/3}$. This enhances low-frequency photons compared to the Synchrotron Radiation spectrum (effect of the acceleration).	Spectral Density	$S = \frac{9\sqrt{3}\omega}{8\pi\omega_c}\int_{\omega/\omega_c}^{\infty} K_{5/3}(x)\,dx$

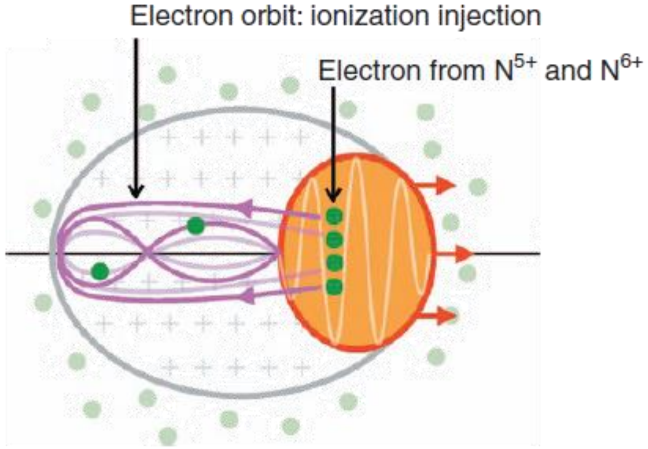
Courtesy A. Curcio

Ionization injection





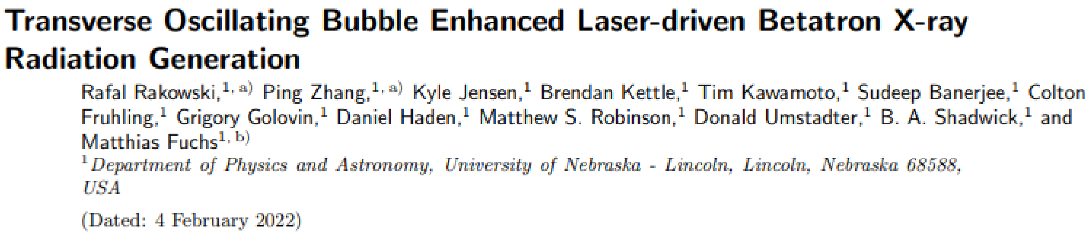
- Electrons that get accelerated have to travel along the cavity sheath and enter the cavity at the back.
- It is found that these electrons originate from a ring-shaped region around the laser axis
- In contrast, in the case of ionization-induced injection electrons are ionized inside the cavity, close to the maximum intensity of the laser. Injection can, therefore, occur longitudinally, and the initial position of trapped electrons is very different
- It results in a better controlled injection and more beam stability



Döpp, Andreas, et al. "Stable femtosecond X-rays with tunable polarization from a laser-driven accelerator." *Light: Science & Applications* 6.11 (2017): e17086-e17086.

Off Axis injection

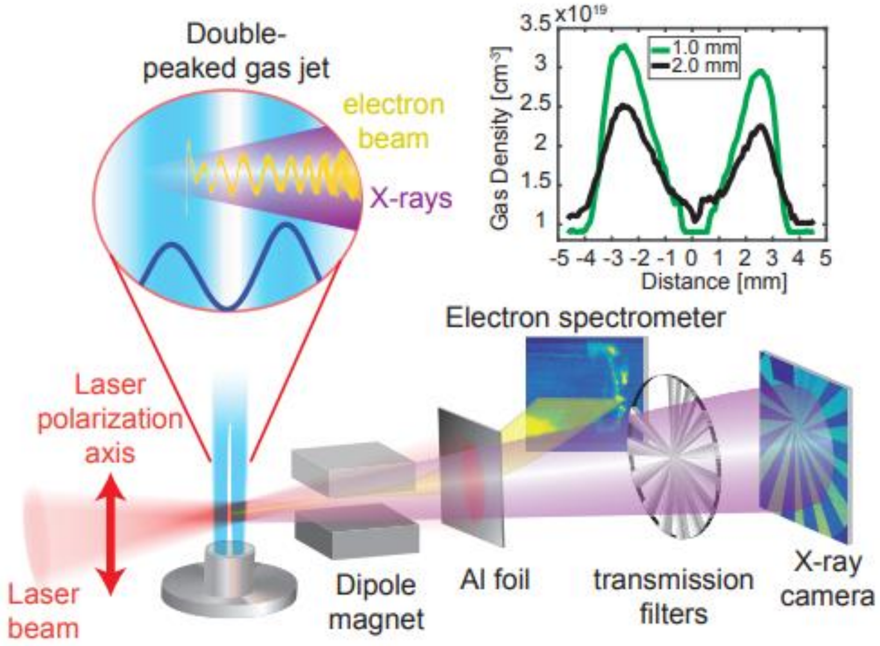
- A high-power laser (red) is focused into a double-peaked "M" shaped gas jet (blue).
- The laser evolution during the first density peak leads to off-axis electron injection during the following density downramp.
- Subsequent large-amplitude betatron oscillations (yellow) cause intense emission of X-ray radiation (purple).



Transverse Oscillating Bubble Enhanced Laser-driven Betatron X-ray Radiation Generation

Rafal Rakowski,[1, a)] Ping Zhang,[1, a)] Kyle Jensen,[1] Brendan Kettle,[1] Tim Kawamoto,[1] Sudeep Banerjee,[1] Colton Fruhling,[1] Grigory Golovin,[1] Daniel Haden,[1] Matthew S. Robinson,[1] Donald Umstadter,[1] B. A. Shadwick,[1] and Matthias Fuchs[1, b)]
[1] *Department of Physics and Astronomy, University of Nebraska - Lincoln, Lincoln, Nebraska 68588, USA*

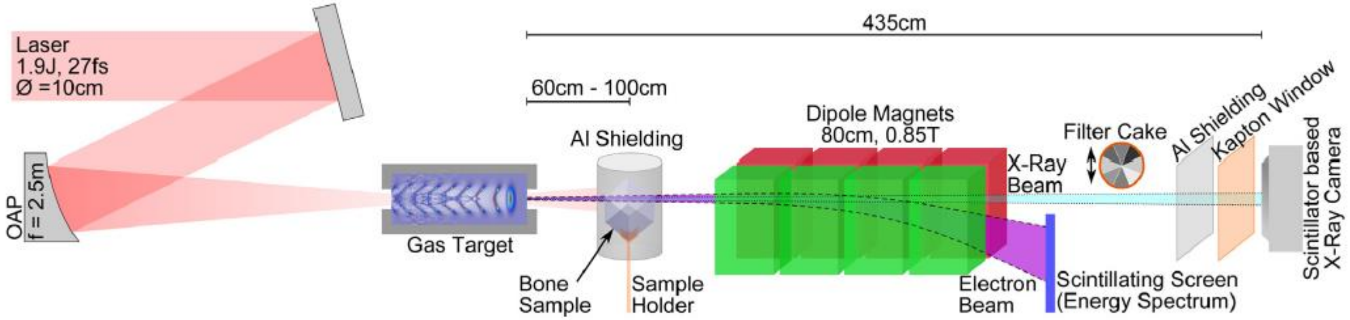
(Dated: 4 February 2022)



Expected Parameters

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

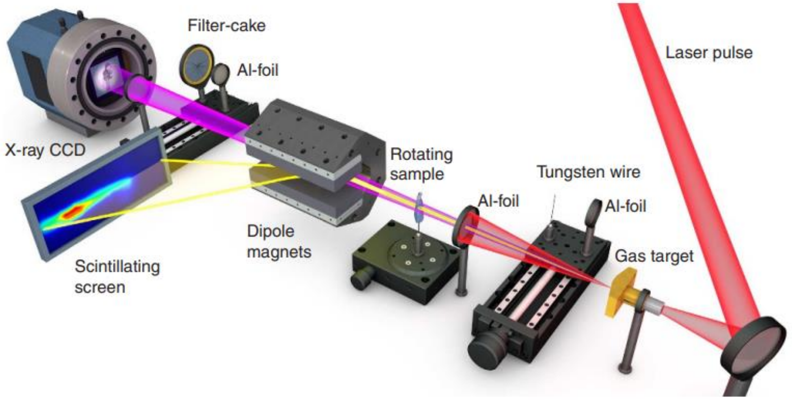
Example of gas cell



- Laser 800 nm, 27 fs, 1.9 ± 0.1 J in a spot size of 30 μm (FWHM intensity), which
- corresponds to a peak intensity of 5.5×10^{18} W⁄cm^2 and a peak power of 70 TW resulting in $a_0 \approx 1.6$.
- Plasma density of 5×10^{18} cm^{-3}
- length 11 mm
- Critical energy at 13.5 keV
- About 700 pC, pure H_2
- $(1.6 \pm 0.35) \times 10^9$ photons/msr/s
- Divergence of 12×6 mrad^2 (s.d.)

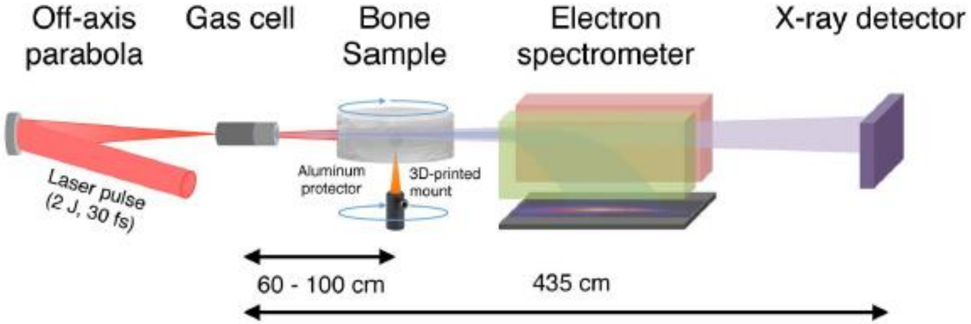
- Götzfried, J., et al. "Research towards high-repetition rate laser-driven X-ray sources for imaging applications." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 909 (2018): 286-289.

Other gas cell examples

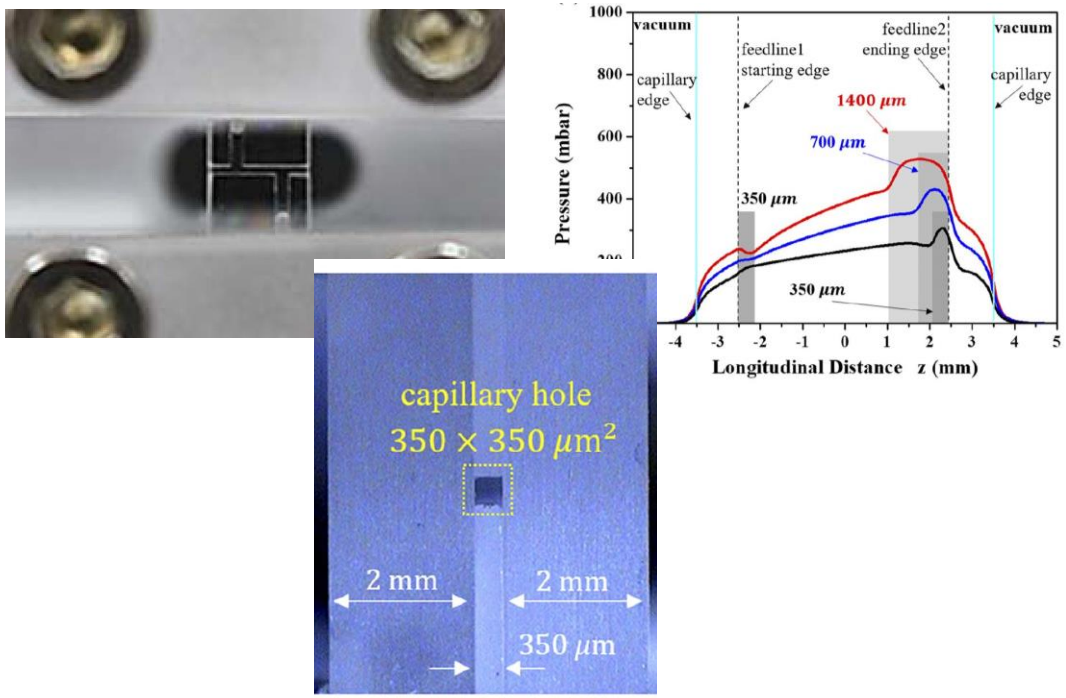


- Wenz, Johannes, et al. "Quantitative X-ray phase-contrast microtomography from a compact laser-driven betatron source." *Nature communications* 6.1 (2015): 1-6.

Döpp, A., et al. "Quick x-ray microtomography using a laser-driven betatron source." *Optica* 5.2 (2018): 199-203.



Gas cell (Pallas Collaboration)



J. Kim et Al., RSI 25, 92, 023511 (2021)

- The high brightness beam target developed by PALLAS project in collaboration with LNF could be an interesting *opportunity*.

- No strong modifications to the Interaction chamber
- Vacuum pumping system
- Rep Rate (10 Hz)
- Neutral gas pressure(1 bar)

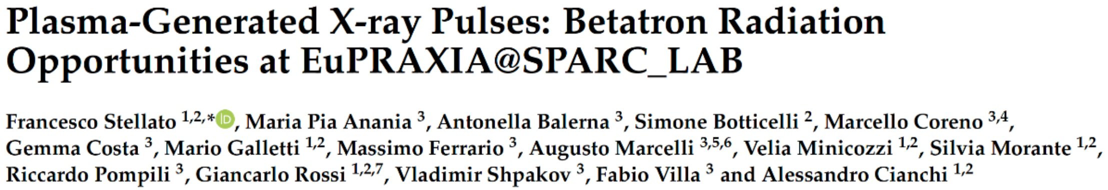
- Laser ablation/sapphire materials
- Complicate machining

Courtesy A. Biagioni

Betatron sources have already allowed performing X-ray measurements

EuAPS is not aiming at reinventing the wheel, but we can build up and improve moving from the wheels that have already been invented.

Photon Science @ EuAPS



Plasma-Generated X-ray Pulses: Betatron Radiation Opportunities at EuPRAXIA@SPARC_LAB

Francesco Stellato [1,2,*], Maria Pia Anania [3], Antonella Balerna [3], Simone Botticelli [2], Marcello Coreno [3,4], Gemma Costa [3], Mario Galletti [1,2], Massimo Ferrario [3], Augusto Marcelli [3,5,6], Velia Minicozzi [1,2], Silvia Morante [1,2], Riccardo Pompili [3], Giancarlo Rossi [1,2,7], Vladimir Shpakov [3], Fabio Villa [3] and Alessandro Cianchi [1,2]

Condensed Matter 7.1 (2022): 23.

- 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
  - Relatively easy, but does not exploit the radiation time structure
- Ultra-fast X-ray spectroscopies exploiting ultra-short betatron pulses
  - More complicated, requires timing between pump and probe pulses, but fully exploits the fs pulse duration
- Time-resolved imaging (ultrafast dynamics)
- Wide angle scattering, diffraction
  - Depending on the samples, requires monochromatic beams with high flux

Courtesy F. Stellato

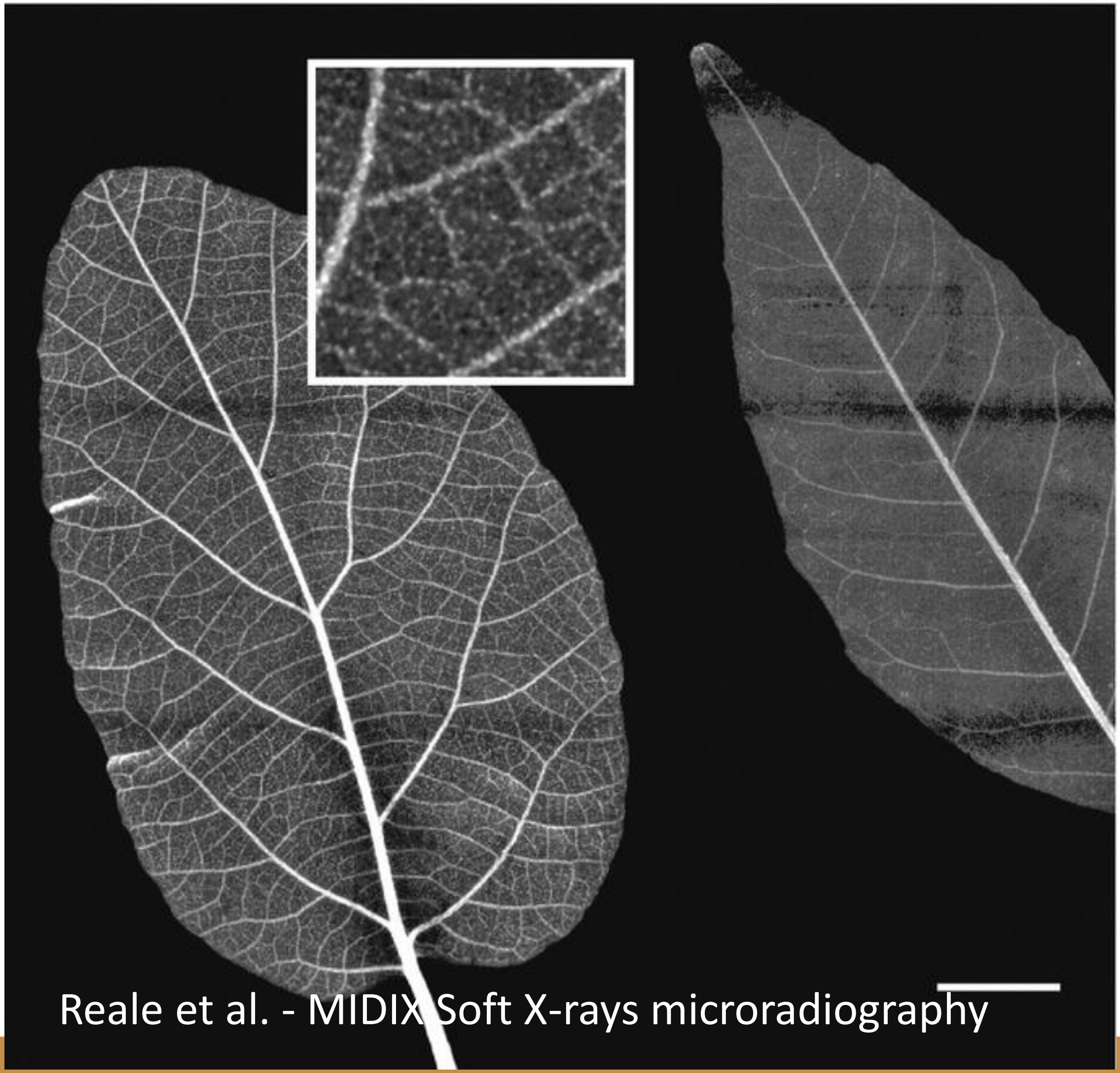
Imaging – The pilot experiment

Green science

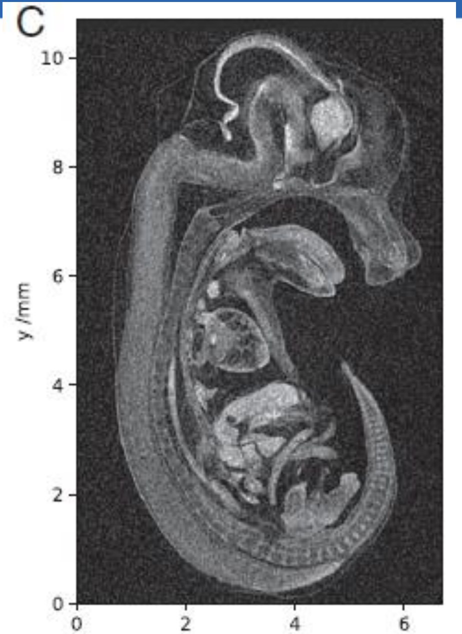
X-ray imaging of leaves (and wood)

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**



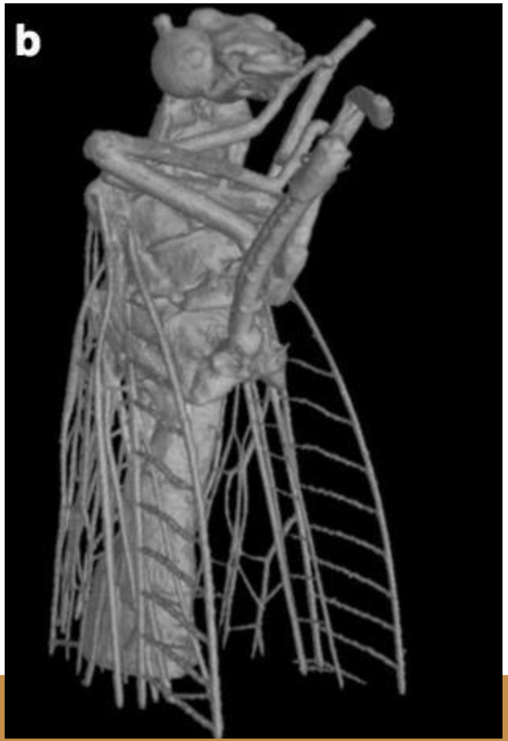
Reale et al. - MIDIX Soft X-rays microradiography



Imaging – CT and Phase Contrast

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

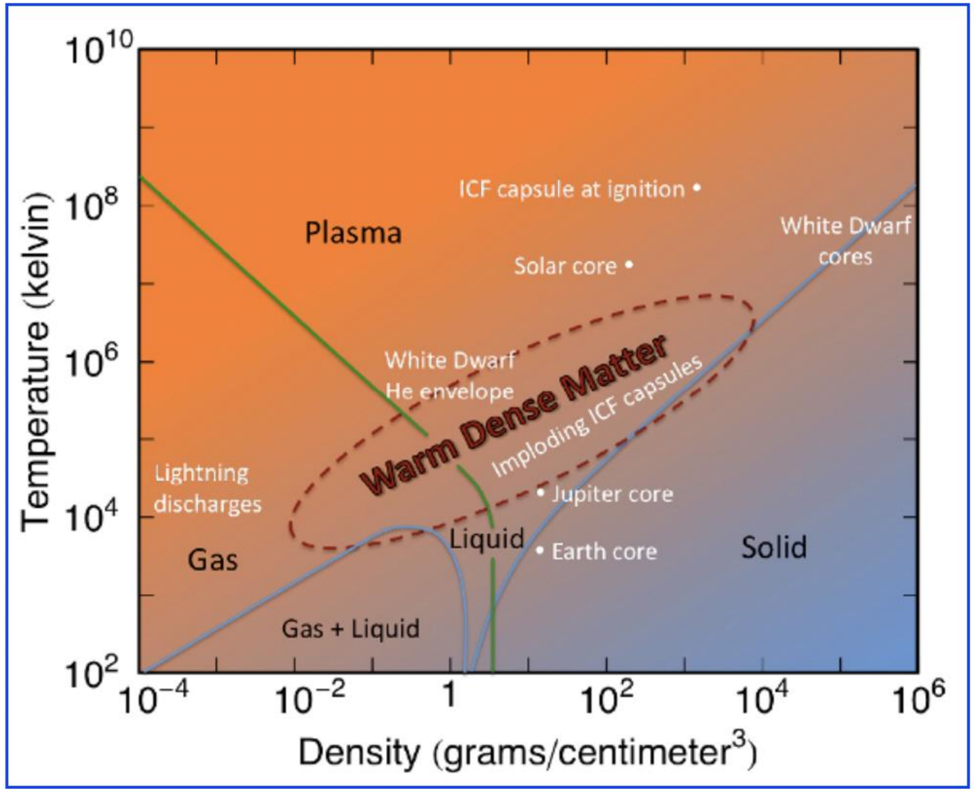
Guo *et al.* Scientific Reports 2019
Cole *et al.* PNAS 2018



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

PCI provides better **contrast** than radiography, especially when dealing with biological samples. Wenz *et al.* Nature communications 2015

Material Science Applications: Warm Dense Matter (WDM)



Mahieu, B., et al. "Probing warm dense matter using femtosecond X-ray absorption spectroscopy with a laser-produced betatron source." *Nature Communications* 9.1 (2018): 3276.

WDM occurs in:

- **Cores of large planets;**
- **Systems that start solid and end as a plasma;**
- **X-ray driven inertial fusion implosion (aspects of indirect-drive inertial fusion).**

The **investigation of such warm dense matter (WDM) is one of the great challenges of contemporary physics**.

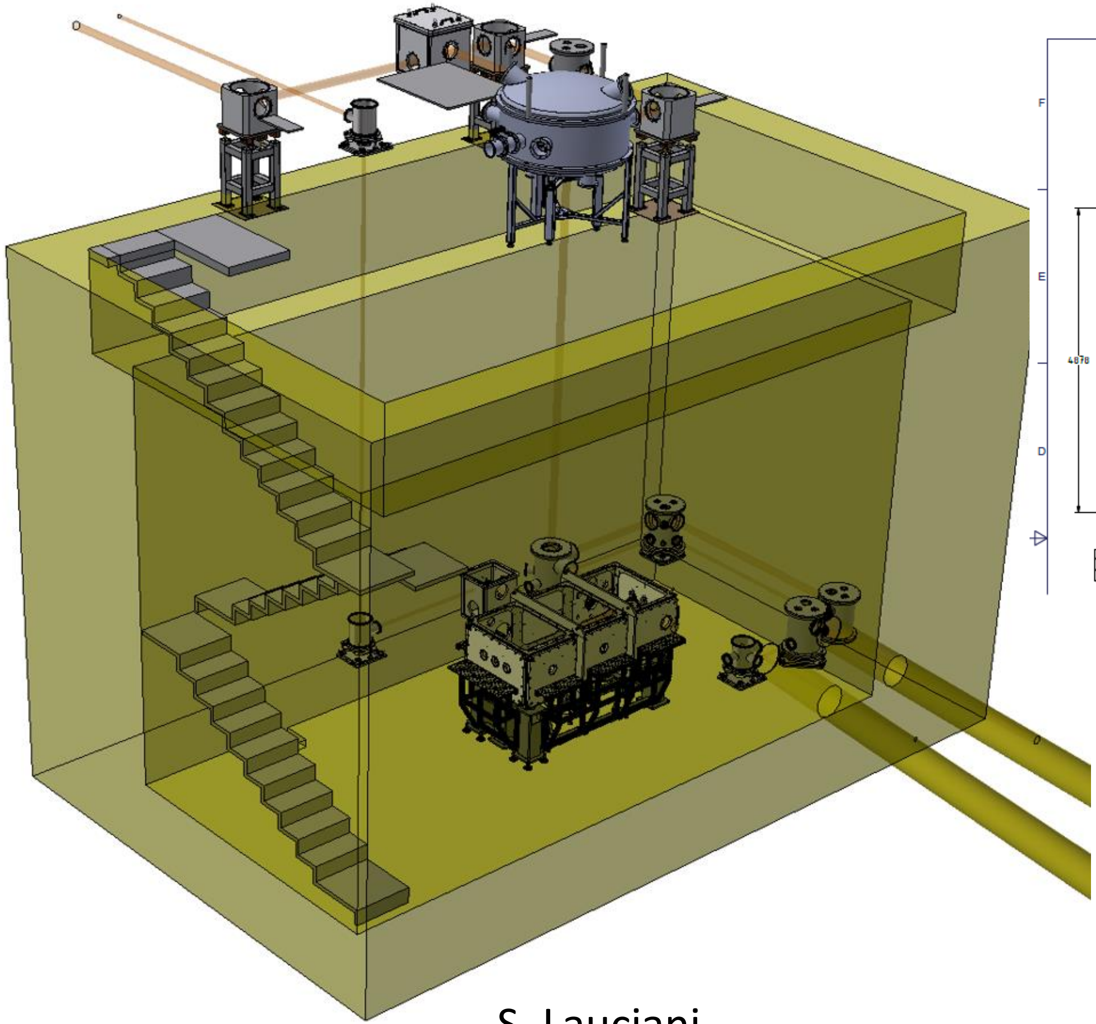
Femtosecond lasers can rapidly heat matter, leading to ultrafast solid-liquid-WDM transitions, followed by a more complex **multiphase expansion at a picosecond time scale**. Highly nonequilibrium states of matter are expected, due to the finite rate of energy transfer from the excited electrons to the lattice.

As the atomic structure modification is supposed to be driven by the photoexcited electrons, it is of primary importance to determine the respective time scales of the evolution of both electron and atomic structures.

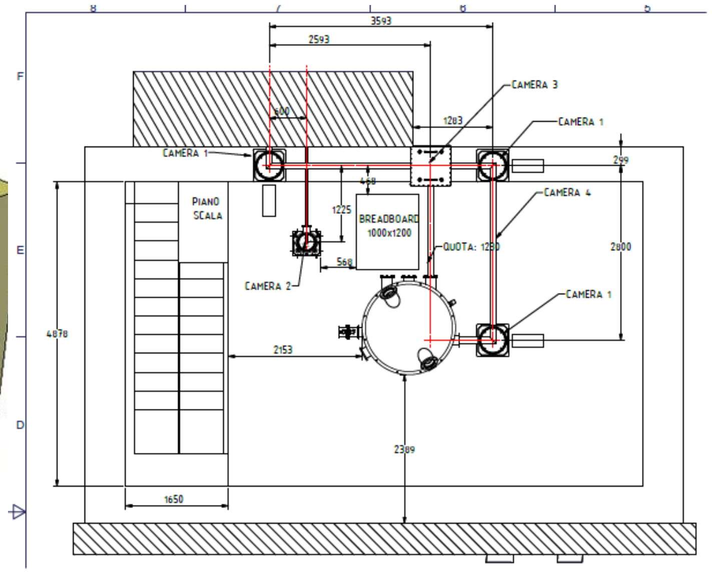
Where?

- 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
- There is now a contribution from Trieste university that focuses on applications

Activity	Where	Target
2.1	INFN-Mi	Simulation & Data Analysis
2.2	LNF-INFN	Plasma source
2.3	LNF-INFN	Synchronization
2.4	CNR-Potenza	Photon Diagnostics
2.5	Tor Vergata	End user station
2.6	CNR- Montelibretti	Photon time diagnostics

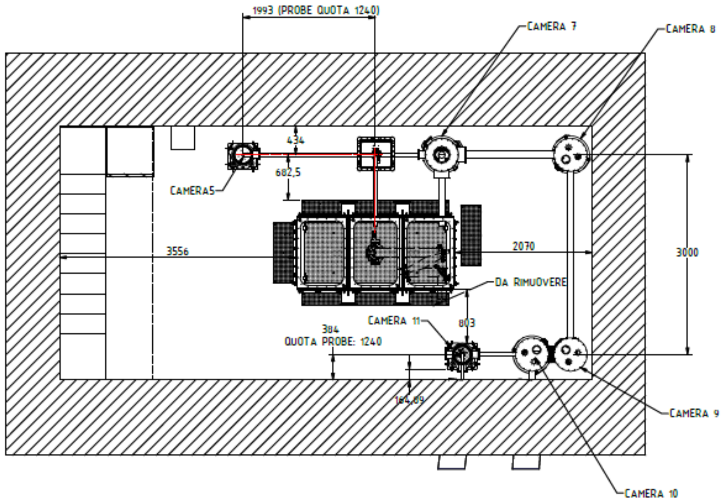


S. Lauciani

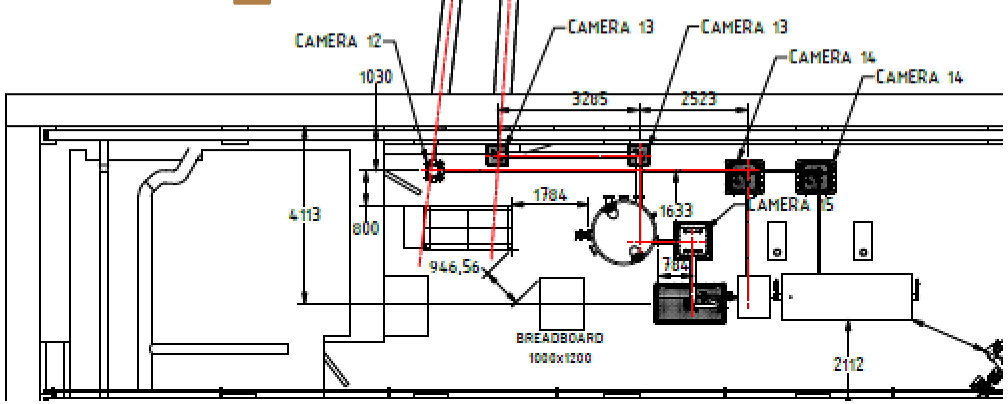


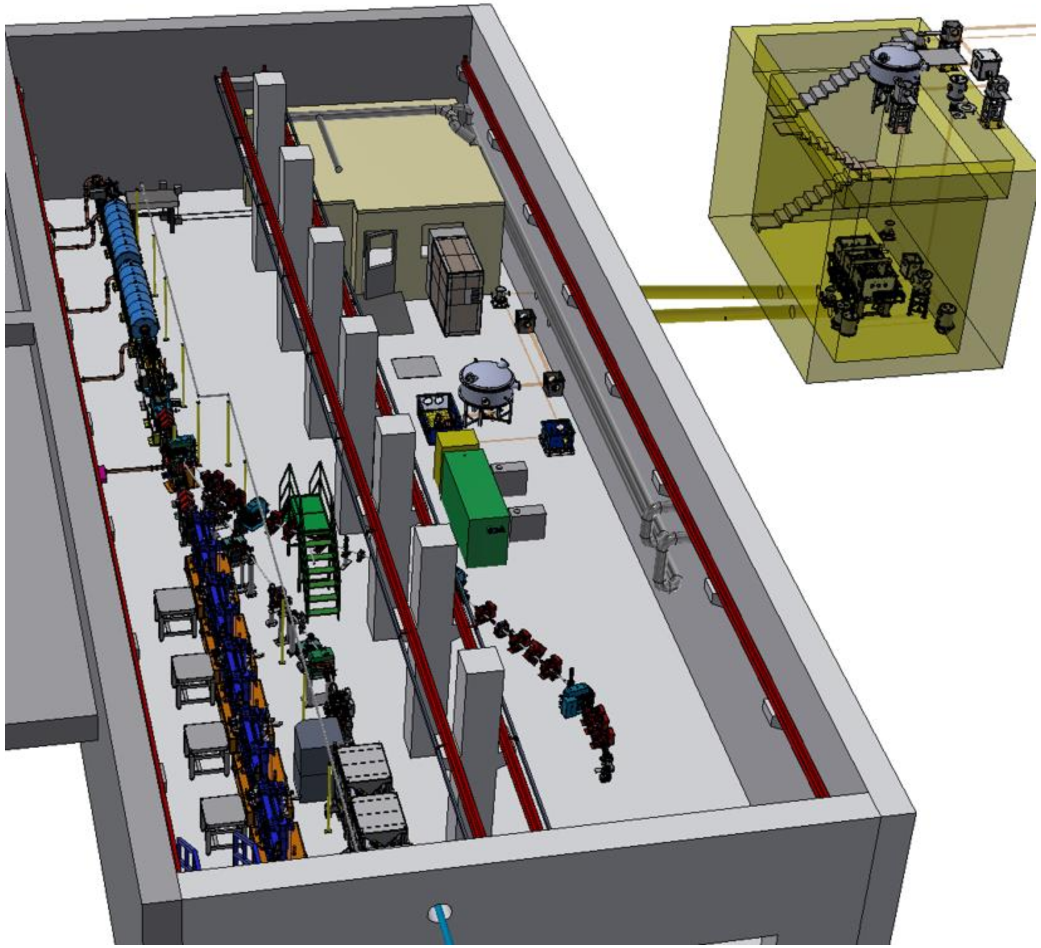
Flame building ground floor

Flame building underground floor



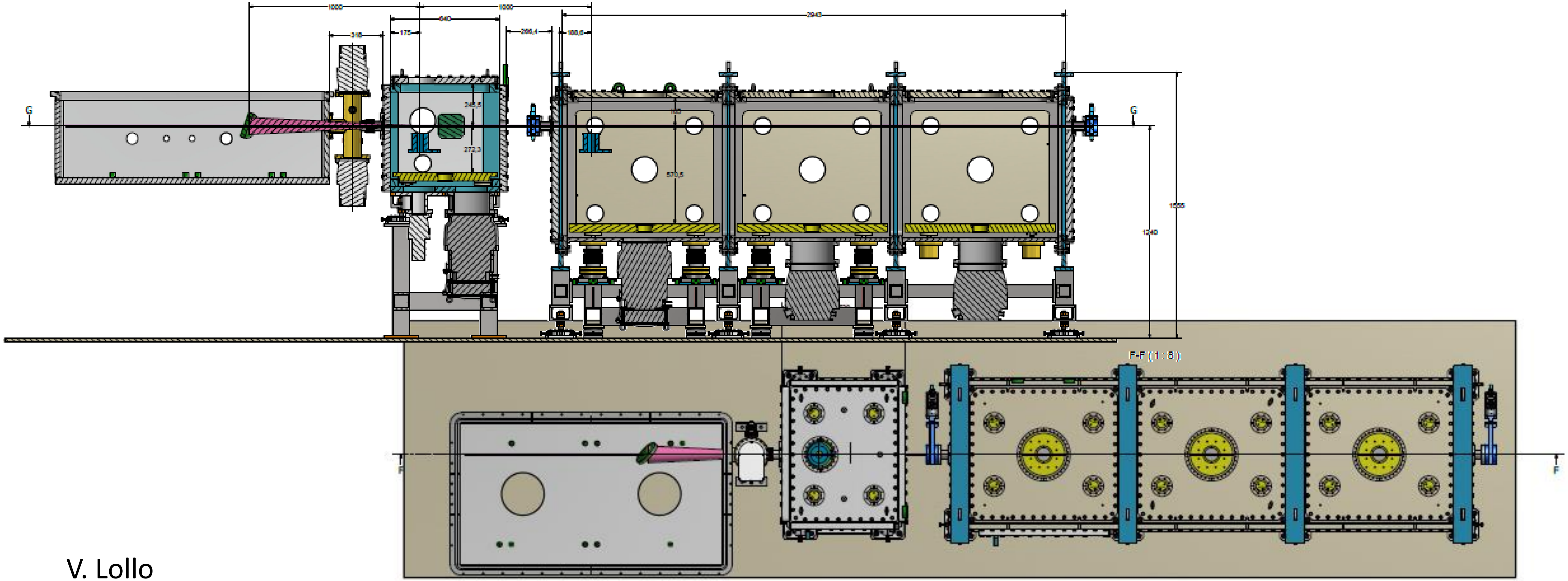
SPARC_LAB bunker





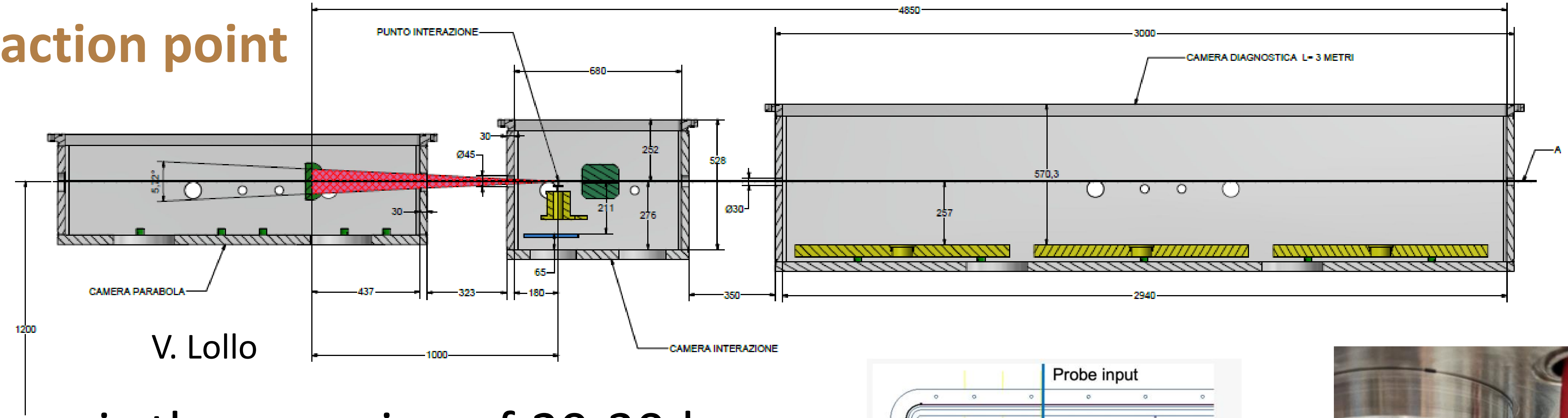
- Layout in the SPARC bunker and connection with FLAME building

Interaction point and experimental chamber



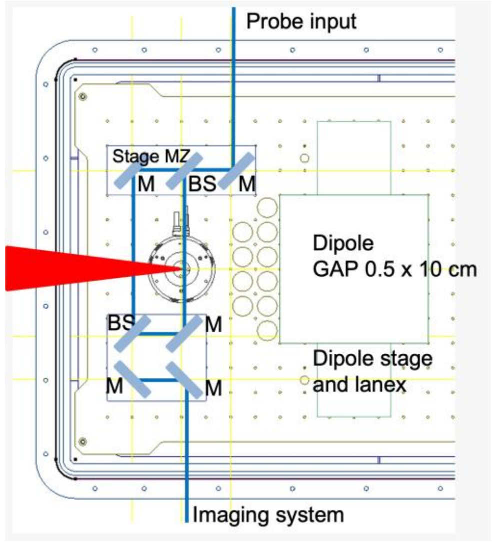
V. Lollo

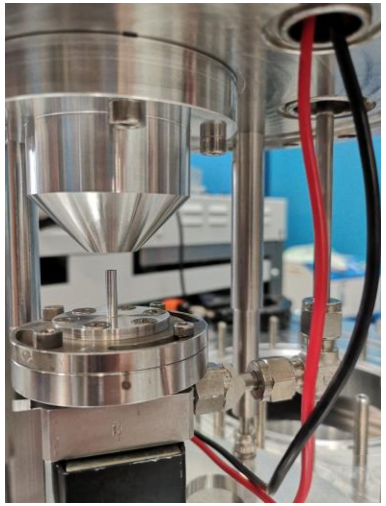
Interaction point



V. Lollo

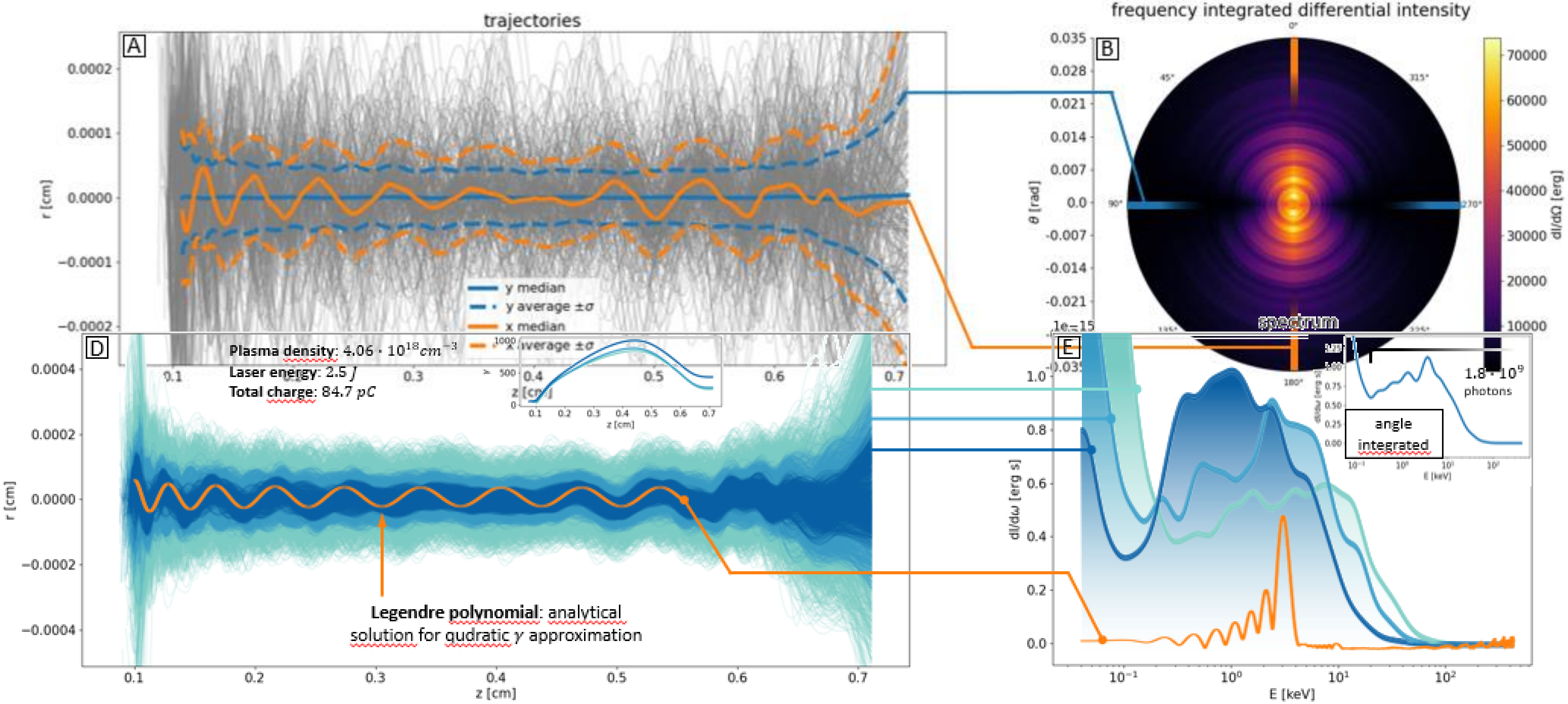
- Main issue is the pumping of 20-30 bar with repetition rate at least 1 Hz
- The focusing parabola has to be at least at 10^{-4} mbar





Ongoing simulations

- Courtesy A.R. Rossi and A. Frazzitta



Two phases

- The betatron X rays source will be developed at FLAME bunker optimizing:
  - Laser parameters
  - Plasma source devices
  - Electron diagnostics
  - X rays spectrum
  - Photon flux

- In the middle of 2024, it will be moved in the SPARC bunker, with the installation of a new compressor and refurbishing the old one.
- The main goal is to make a replica of the source developed at FLAME
- The advanced photon diagnostics and the user end station will be tested and installed during/after the commissioning of the source

Conclusions

- EuAPS will be the first brick of EuPRAXIA, a user facility based on the radiation emitted by electrons plasma accelerated.
- There are several challenges that we have to address to move from a single-shot proof of principle experiment to a user facility
- Users will use an utterly innovative source with properties between Synchrotron radiation and FEL radiation paving the way to imagine and realize completely new experiments

Finally it's over

Thank you for your attention