Radiation Sources

from relativistic electron beams:
Compton back scattering, Free Electron Lasers, THz radiators

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Contributions from INFN- MI team, S. Lupi (La Sapienza), Sparc and EupraXia team

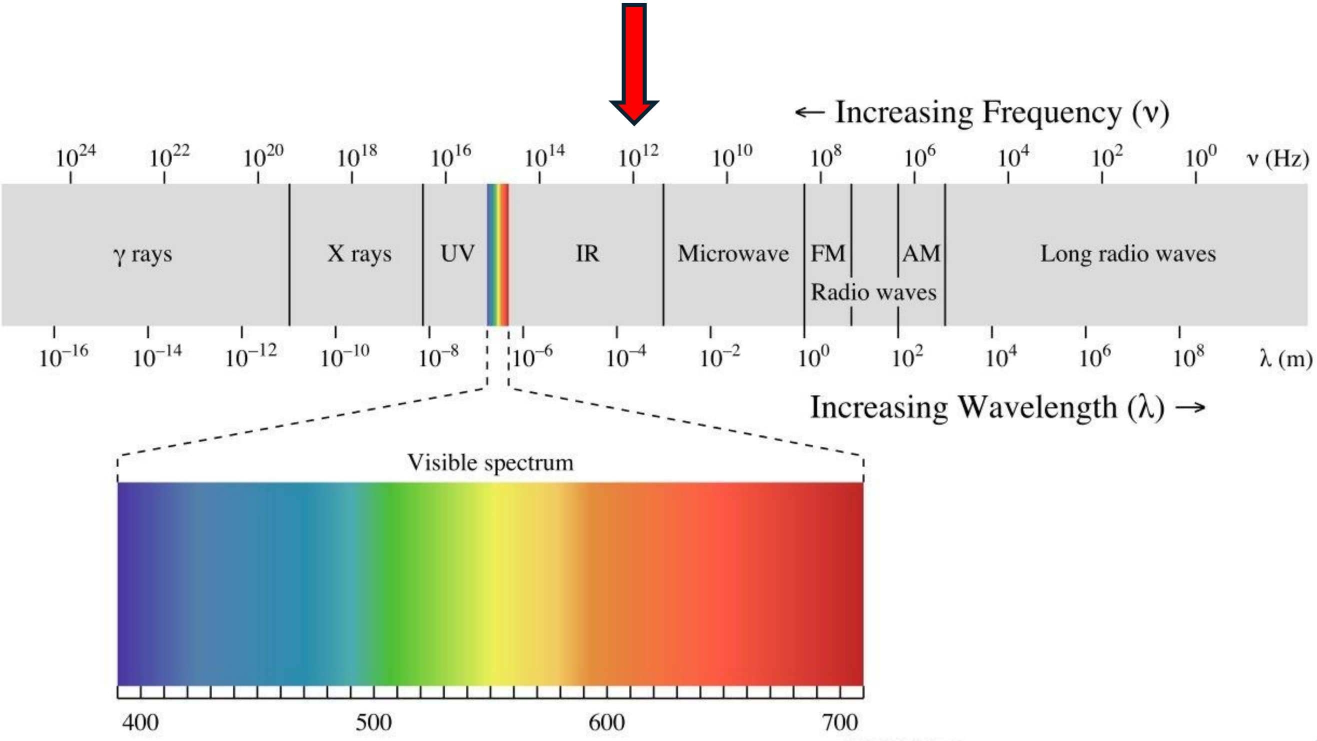
25/11/2024

Accelerator Physics and Technology PhD: meeting first year students

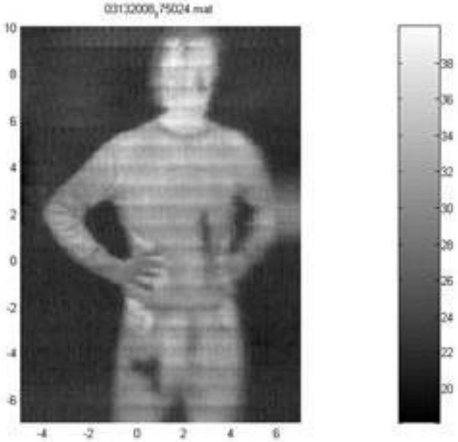
Outlook

- INFN Research activities on radiation sources at LNF (SPARC-Lab, EupraXia, Sabina), Roma1 (Sissi), Milan-LASA (Star, BriXinO), Ferrara (THECNO-CLS)
- Emphasis on radiation sources generated by Electron Beams of High Phase Space Density (i.e. peak and/or average brightness, such as Free-Electron laser, Compton Sources and Synchrotrons)
- We will see the radiation sources in ascending order of frequency

Terahertz Radiation



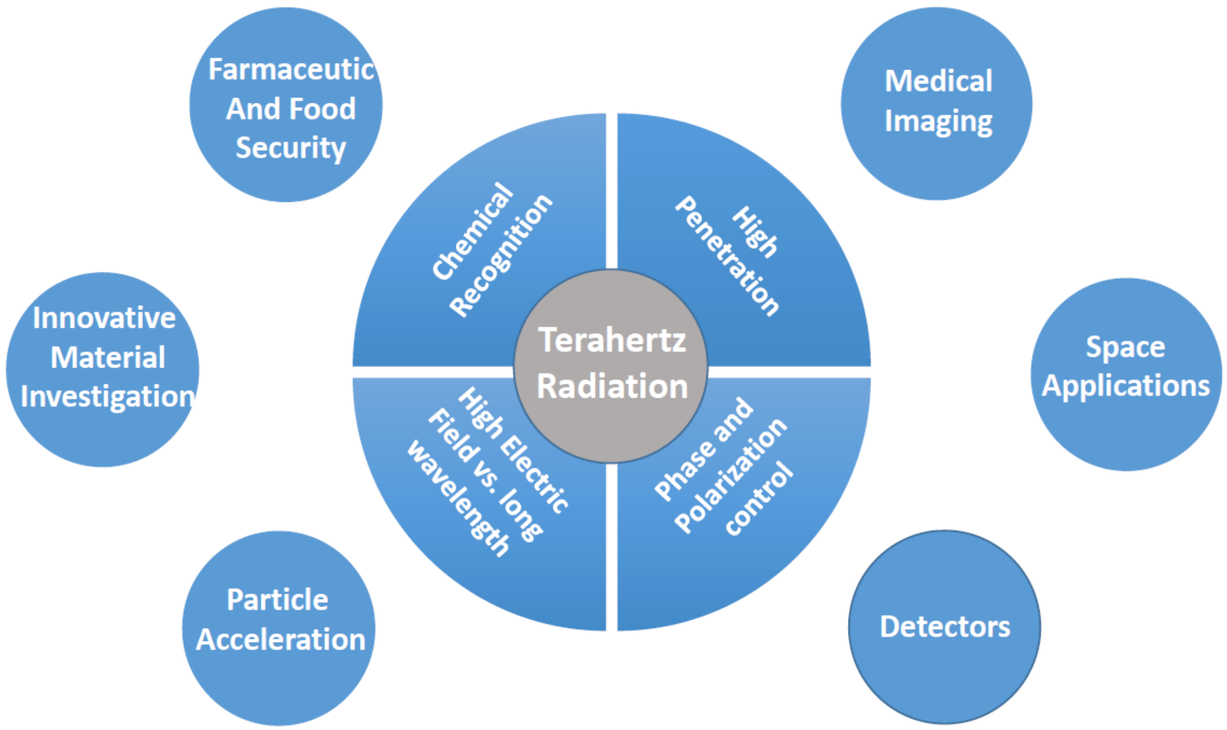
Frequency: 0.1 – 10 THz
Wavelength: 3 mm – 30 μm
Energy: 0.4 – 40 meV



THz light sources:

- Solid state oscillators
- Free electron-based sources
- Laser based THz sources

THz Multidisciplinarity



Terahertz Radiation

Chemical Recognition

High Penetration

High Electric Field vs. long wavelength

Phase and Polarization control

Farmaceutic And Food Security

Medical Imaging

Innovative Material Investigation

Space Applications

Particle Acceleration

Detectors

SABINA (SOURCE OF ADVANCED BEAM IMAGING FOR NOVEL APPLICATIONS) : FEL in the terahertz range in commissioning @LNF

Project leader: Lucia.Sabbatini@lnf.infn.it

Other informations on possible experimental thesis:

Alberto.Petralia@enea.it

- **GOAL:** Enhancment of the SPARC_LAB research facility at LNF INFN (Frascati, Italy) → increase of the uptime and improvement of the accelerator performances:
  I. Technological plant renewal
  II. Substitution of the ancillary systems and upgrade of the facility in terms of technology
  III. Creation of two user facilities:

    FLAME: High power laser for solid target experiments

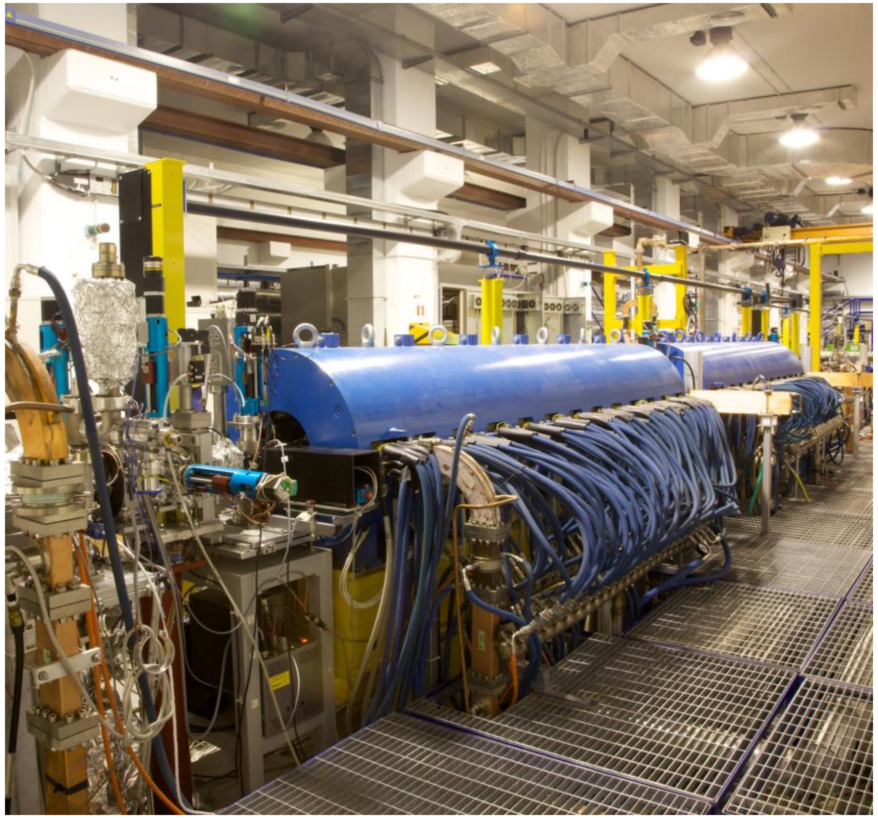
    THz/IR FEL: radiation source for optical spectroscopy (pump probe), also at cryogenic T

Monochromatic Light with ps/sub-ps time duration

Tunable Frequency between 3 – 30 THz

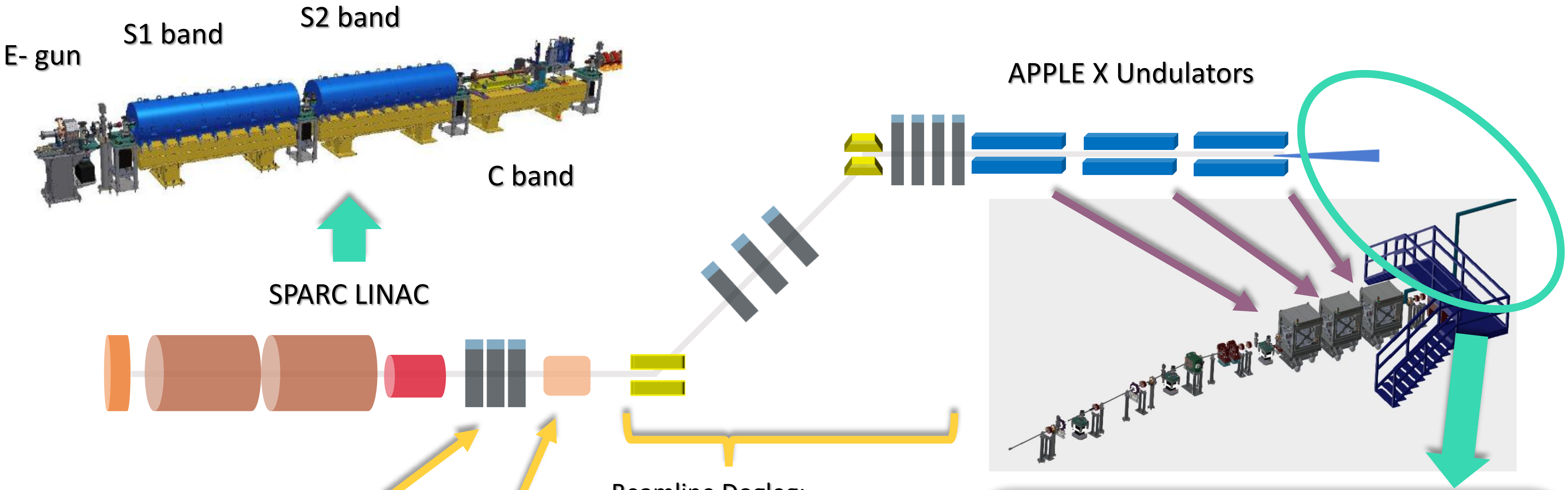
Tunable Polarization Linear, Circular and Elliptical

- **FUNDS:** *Project co-founded by Regione Lazio within POR-FESR 2014-2020 funds and INFN*



FEL Beamline Layout

Information: stefano.lupi@roma1.infn.it
Experimental and simulative PhD thesis



Quadrupole triplet
(Focusing)

S-Band RF
deflector

Beamline Dogleg:
- 2 Bending Magnets
- 1 Quadrupole Triplet
- 1 Set of Quadrupole for beam matching

Open Research Activity:
Simulation and propagation of the THz/IR radiation produced by the FEL undulators
Applications:
Realization of a beamline to Transport THz/IR radiation to an external user facility

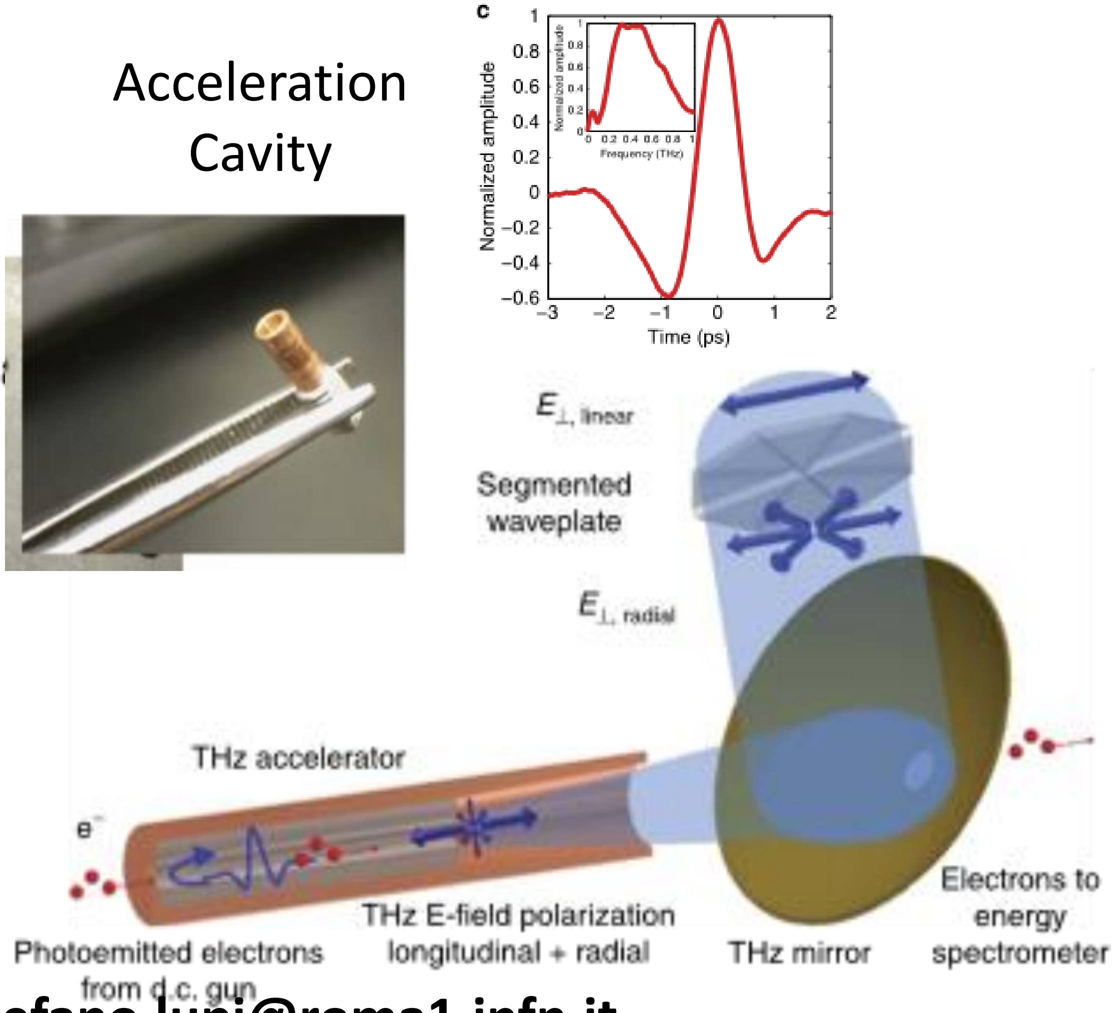
stefano.lupi@roma1.infn.it

Other ways for producing terahertz radiation;:
Terahertz (THz) Radiation Projects

Stefano Lupi and Massimo Petrarca, INFN and Sapienza University

1) TERA (THz-ERA): THz Technology for Particle Acceleration

Acceleration Cavity



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Why Terahertz

- λ_{THz}=100 microns>>$L_{e\text{-beam}}$

à Relaxed conditions with respect to NIR/VIS Laser

- Same laser for e-beam and THz production:

à Low jitter and good synchronization

- Surface Resistence increases with $\omega^{1/2}$

à Breakdown effects at higher electric field

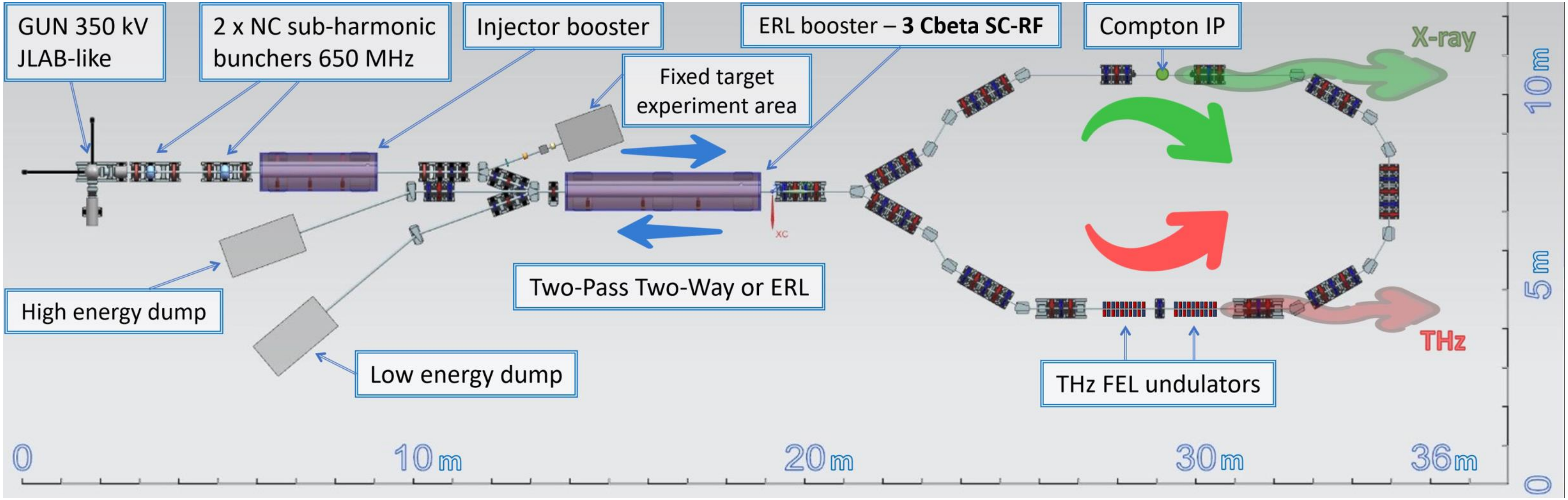
- Multiple THz production mechanisms

PhD Proposal (experimental and theoretical):
Development of THz Technology for THz Acceleration
From Acceleration Cavities to Detectors
massimo.petrarca@uniroma1.it

BriXSinO

Brilliant source of X-rays based on Sustainable and innOvative accelerators

INFN
LASA
Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

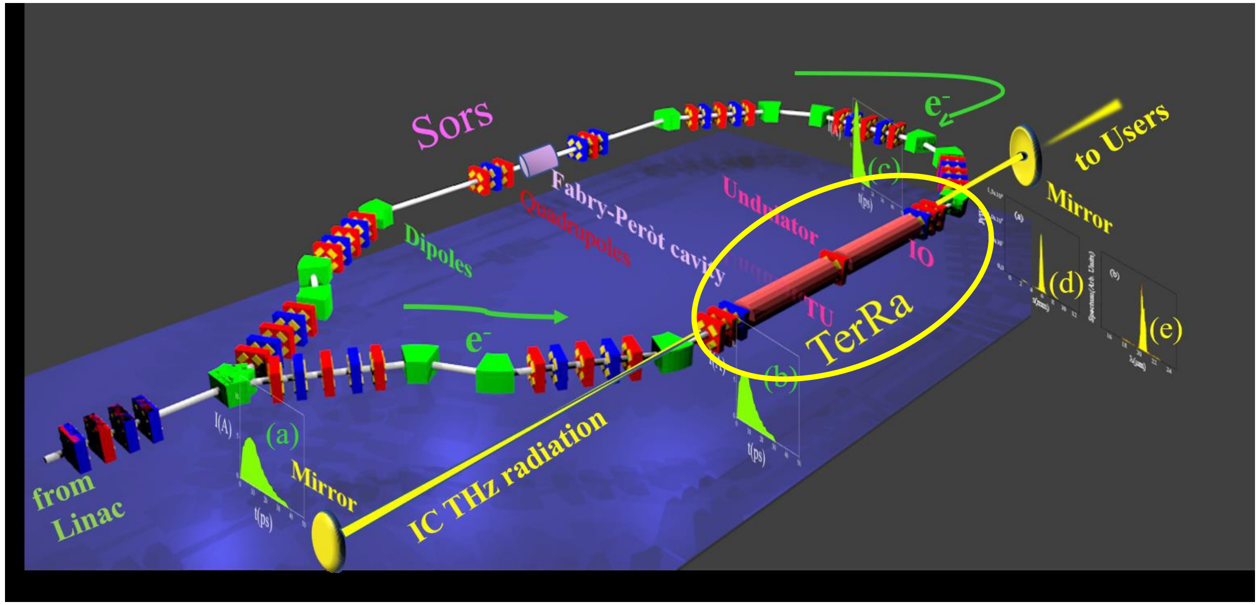


BRIXSINO HIGH-FLUX DUAL X-RAY AND THZ RADIATION SOURCE BASED ON ENERGY RECOVERY LINACS

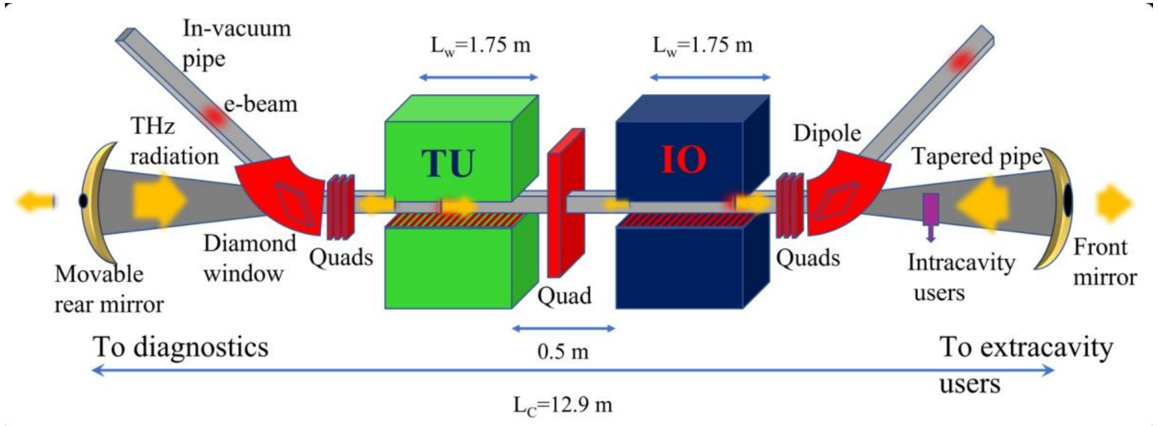
Two main working mode:
- As ERL for light source at electrons energy ~45 MeV
- And double acceleration up to 80 MeV

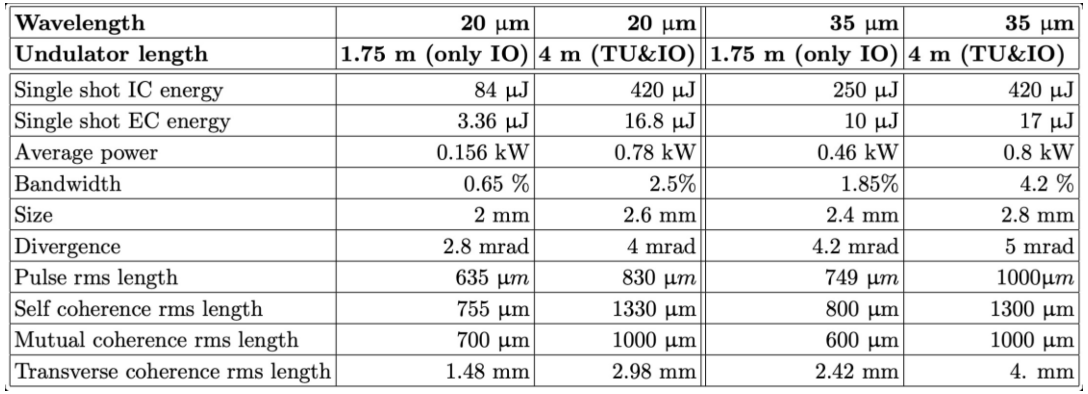
Light sources installed in the arc :
- X-rays based on Compton Scattering
- A FEL Oscillator for THz radiation

BriXSinO TheraHertz oscillator



PhD thesis (theoretical and simulative)
petrillo@mi.infn.it



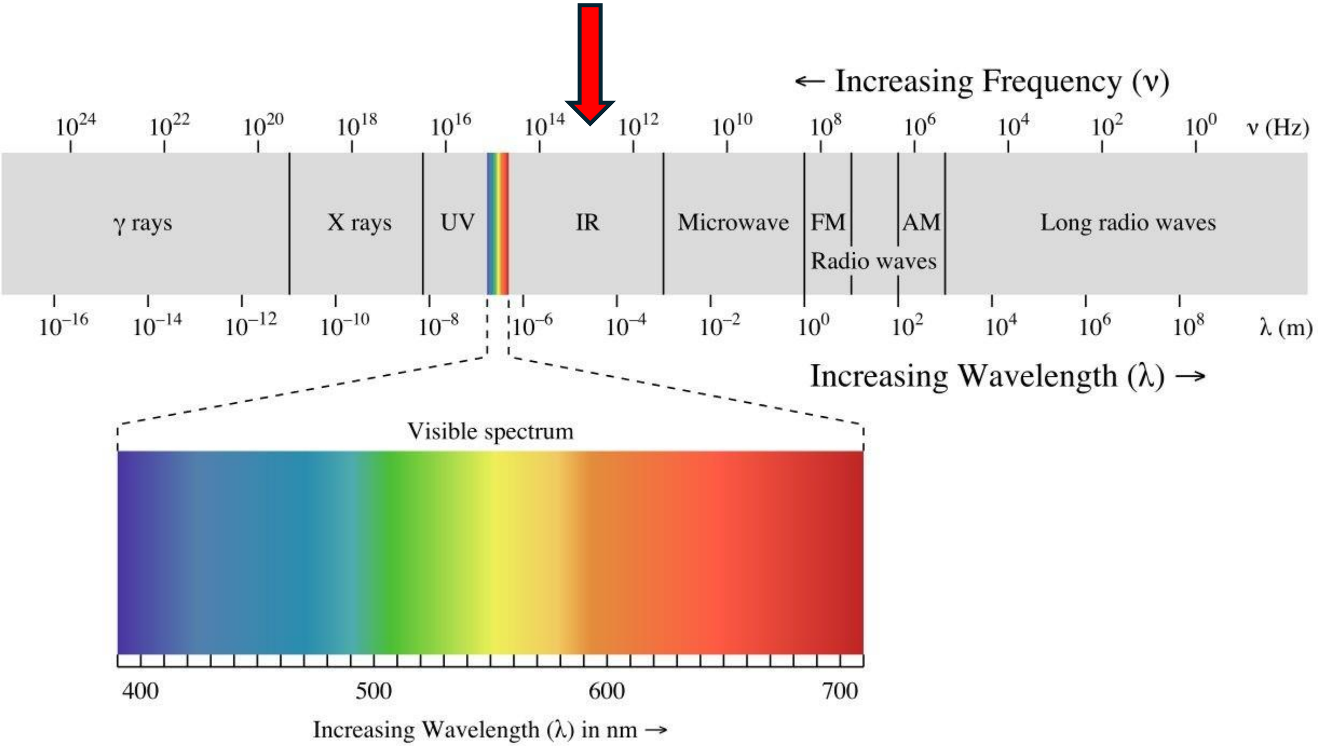


Wavelength	**20 μm**	**20 μm**	**35 μm**	**35 μm**
Undulator length	**1.75 m (only IO)**	**4 m (TU&IO)**	**1.75 m (only IO)**	**4 m (TU&IO)**
Single shot IC energy	84 μJ	420 μJ	250 μJ	420 μJ
Single shot EC energy	3.36 μJ	16.8 μJ	10 μJ	17 μJ
Average power	0.156 kW	0.78 kW	0.46 kW	0.8 kW
Bandwidth	0.65 %	2.5%	1.85%	4.2 %
Size	2 mm	2.6 mm	2.4 mm	2.8 mm
Divergence	2.8 mrad	4 mrad	4.2 mrad	5 mrad
Pulse rms length	635 μ*m*	830 μ*m*	749 μ*m*	1000μ*m*
Self coherence rms length	755 μm	1330 μm	800 μm	1300 μm
Mutual coherence rms length	700 μm	1000 μm	600 μm	1000 μm
Transverse coherence rms length	1.48 mm	2.98 mm	2.42 mm	4. mm

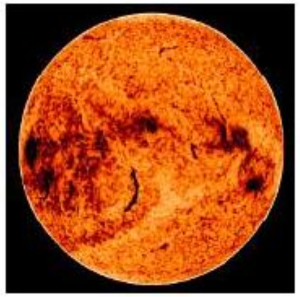
Characteristics of the radiation at λ = 20 μm and λ = 35 μm. IC: intra-cavity, EC: extra-cavity.
Round trip losses=7%, extraction efficiency 4%.
Repetition rate= 46.4 MHz

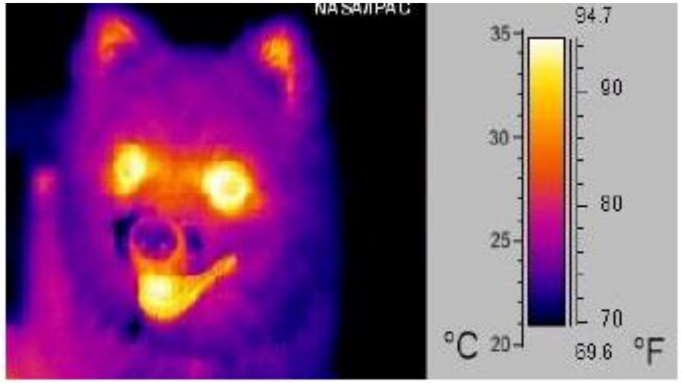
V. Petrillo et al, NIMA 1040, 2022, 167289, 10.1016/j.nima.2022.167289

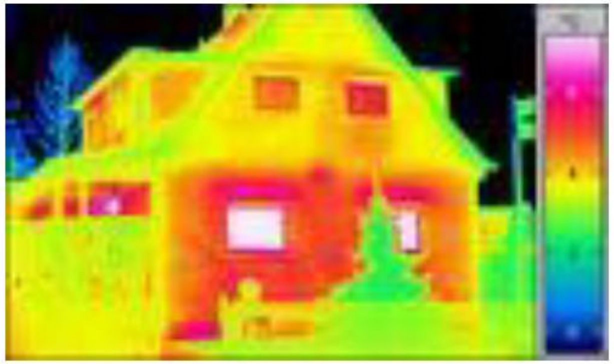
IR Radiation



Frequency: 10 – 400 THz
Wavelength: 30 μm – 800 nm
Energy: 0.04 – 1.5 eV







Introduction to ELETTRA 2.0

- **Elettra** is a third generation synchrotron light source, located at Trieste,Italy, with:
  - a storage ring of $259.2\ m$
  - operation energy of 2 and $2.4\ GeV$
  - 28 beamlines available for external users

A **major upgrade** towards what is called the 'ultimate' light source is currently underway for this facility

The upgrade allows for a great reduction of transverse **emittance**

- Higher brilliance:

$$\mathcal{B} = \frac{\dot{N}_\gamma}{4\pi^2\sigma_x\sigma_y\sigma_{x'}\sigma_{y'}(0.1\%\mathrm{BW})}$$

- Increased coherence

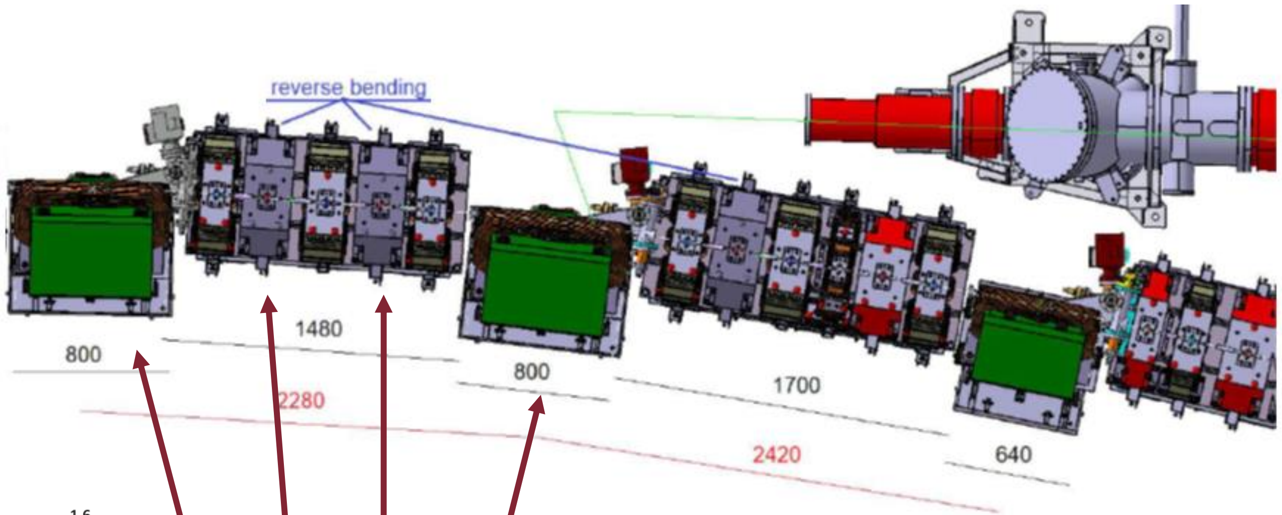
$$C = [hc/(2hv)]^2[1/(\sigma_\mathrm{x}\sigma_\mathrm{y}\theta_\mathrm{x}\theta_\mathrm{y})],$$

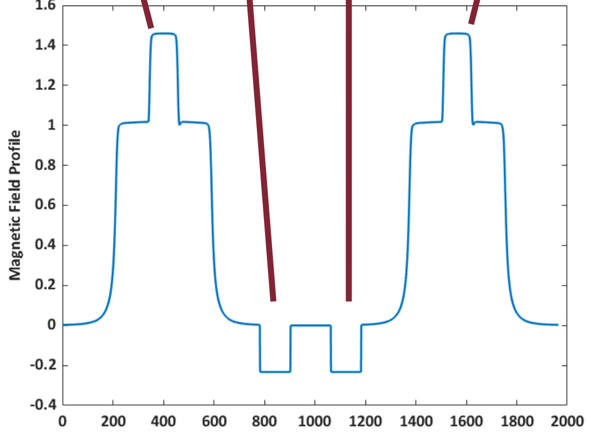
Replacement of **magnetic optics**:
new modified multi bend achromats dipoles with reverse bending

- **SISSI** (Synchrotron Infrared Source for Spectroscopy and Imaging): Beamline involved in the upgrade and one of the first to be funded

SISSI 2.0; project leader: **stefano.lupi@roma1.infn.it**

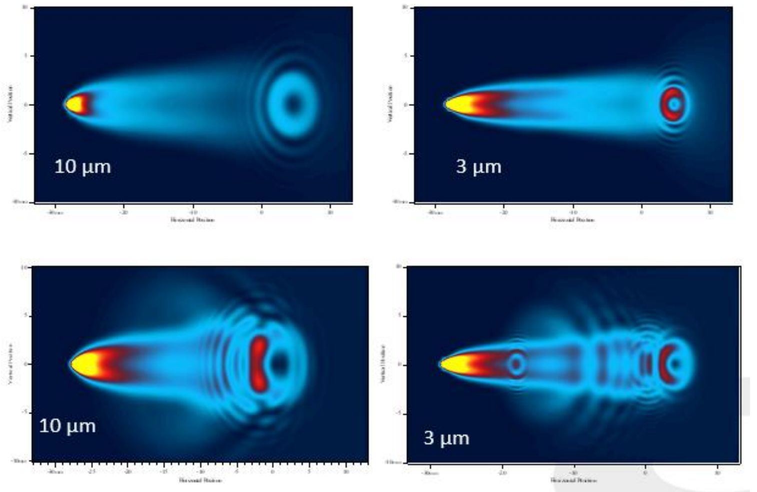
- The SISSI infrared beamline at Elettra extracts the IR and visible components of synchrotron radiation generated by bending magnets to perform spectroscopy, microspectroscopy and imaging. PhD experimental thesis at ELETTRA





- The new magnetic layout introduces several steep variations in the magnetic field

Complicated interference effects between conventional synchrotron radiation and Edge radiation appear



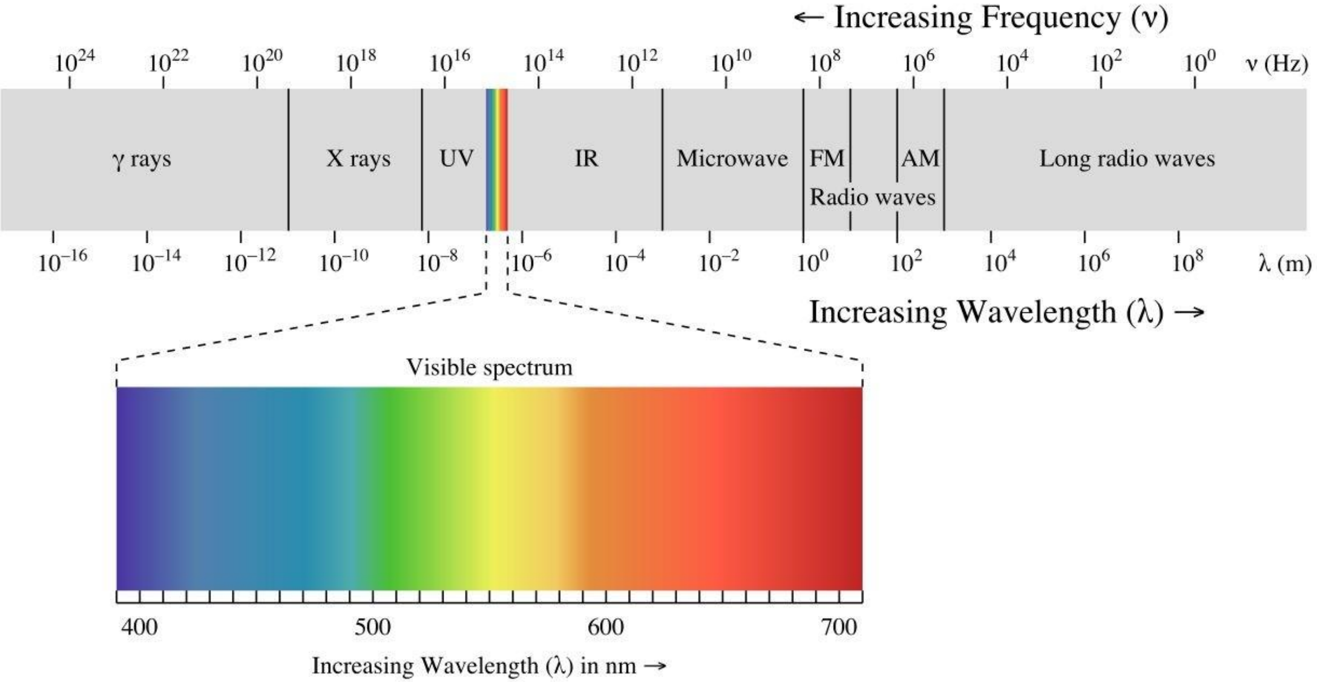
Open Research Activity:

Analysis of the Interference effects by means of numerical simulations

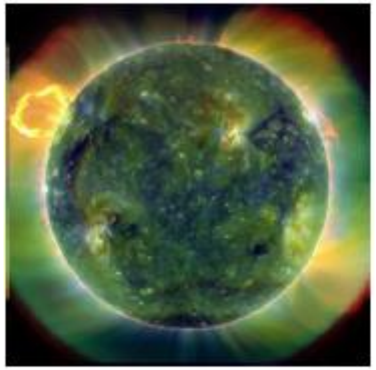
Applications:

Radiation characterisation and optical beamline extraction design

Visible and near UV Radiation



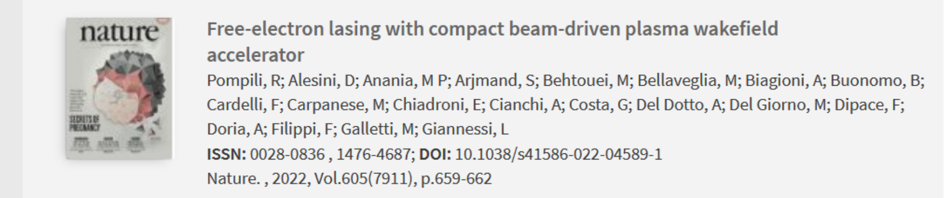
Frequency: $10^{14} – 10^{17}$ THz
Wavelength: 800 – 10 nm
Energy: 1.5 – 124 eV



Wood's lamp

SPARC_Lab

First demonstration of FEL light from plasma beam driven accelerator

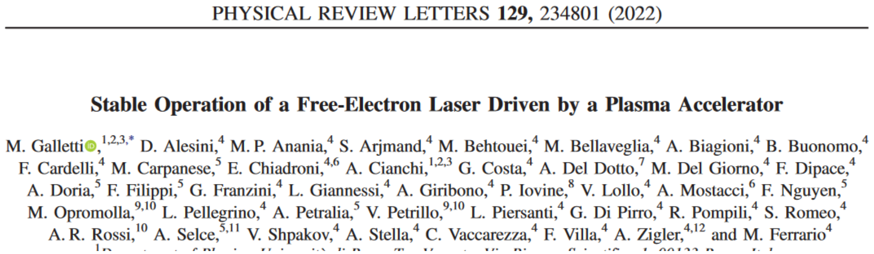


Free-electron lasing with compact beam-driven plasma wakefield accelerator

Pompili, R; Alesini, D; Anania, M P; Arjmand, S; Behtouei, M; Bellaveglia, M; Biagioni, A; Buonomo, B; Cardelli, F; Carpanese, M; Chiadroni, E; Cianchi, A; Costa, G; Del Dotto, A; Del Giorno, M; Dipace, F; Doria, A; Filippi, F; Galletti, M; Giannessi, L

ISSN: 0028-0836 , 1476-4687; **DOI:** 10.1038/s41586-022-04589-1

Nature. , 2022, Vol.605(7911), p.659-662



PHYSICAL REVIEW LETTERS **129,** 234801 (2022)

Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti,[1,2,3,*] D. Alesini,[4] M. P. Anania,[4] S. Arjmand,[4] M. Behtouei,[4] M. Bellaveglia,[4] A. Biagioni,[4] B. Buonomo,[4] F. Cardelli,[4] M. Carpanese,[5] E. Chiadroni,[4,6] A. Cianchi,[1,2,3] G. Costa,[4] A. Del Dotto,[7] M. Del Giorno,[4] F. Dipace,[4] A. Doria,[5] F. Filippi,[5] G. Franzini,[4] L. Giannessi,[4] A. Giribono,[4] P. Iovine,[8] V. Lollo,[4] A. Mostacci,[6] F. Nguyen,[5] M. Opromolla,[9,10] L. Pellegrino,[4] A. Petralia,[5] V. Petrillo,[9,10] L. Piersanti,[4] G. Di Pirro,[4] R. Pompili,[4] S. Romeo,[4] A. R. Rossi,[10] A. Selce,[5,11] V. Shpakov,[4] A. Stella,[4] C. Vaccarezza,[4] F. Villa,[4] A. Zigler,[4,12] and M. Ferrario[4]

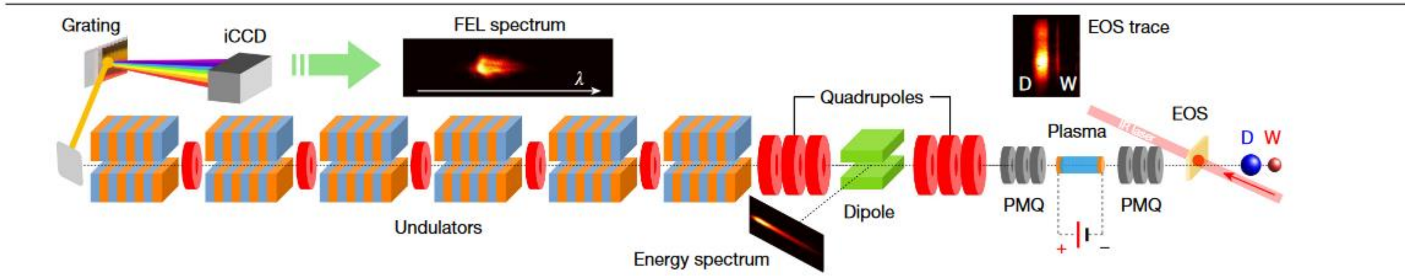
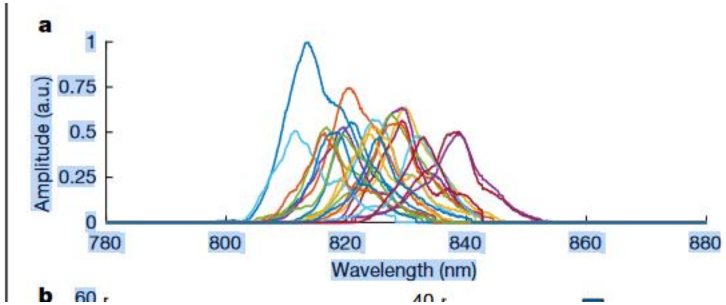
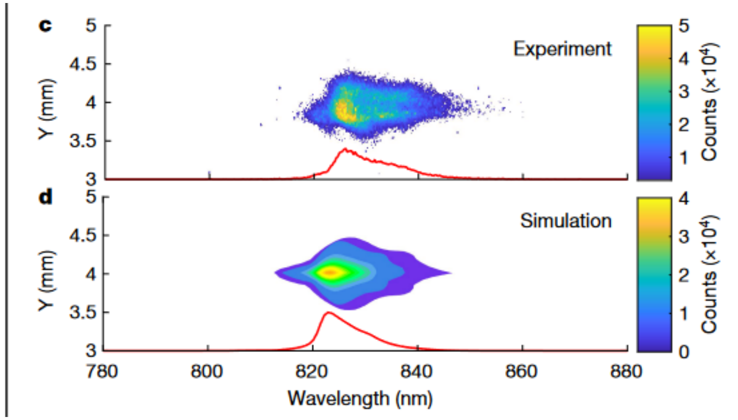


Fig. 1 | Experimental setup. The driver (D) and witness (W) electron bunches are produced by the photo-injector and their temporal separation is continuously monitored with a non-intercepting EOS diagnostics. The bunches are focused by a triplet of PMQs in a 3-cm-long capillary containing the plasma produced by ionizing hydrogen gas with a high-voltage discharge. The accelerated witness is extracted by a second triplet of PMQs and transported using six electromagnetic quadrupoles. A dipole spectrometer is used to measure its energy with a scintillator screen installed on a 14° beamline. The FEL beamline consists of six planar undulators with tunable gaps and five quadrupoles in between to transport the beam. The emitted FEL radiation is collected by an in-vacuum metallic mirror and measured with an imaging spectrometer equipped with a diffraction grating and a cooled intensified camera (iCCD).





Contact people:

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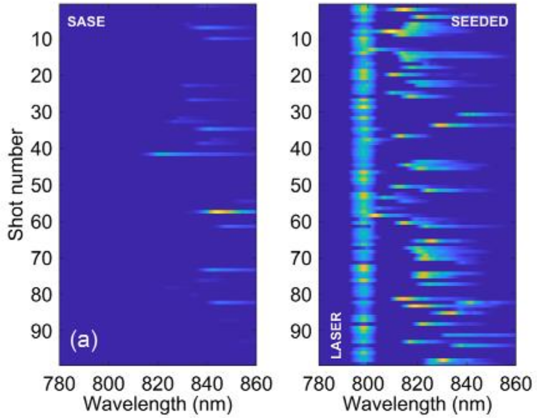
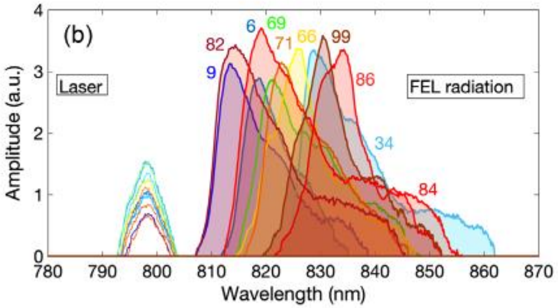
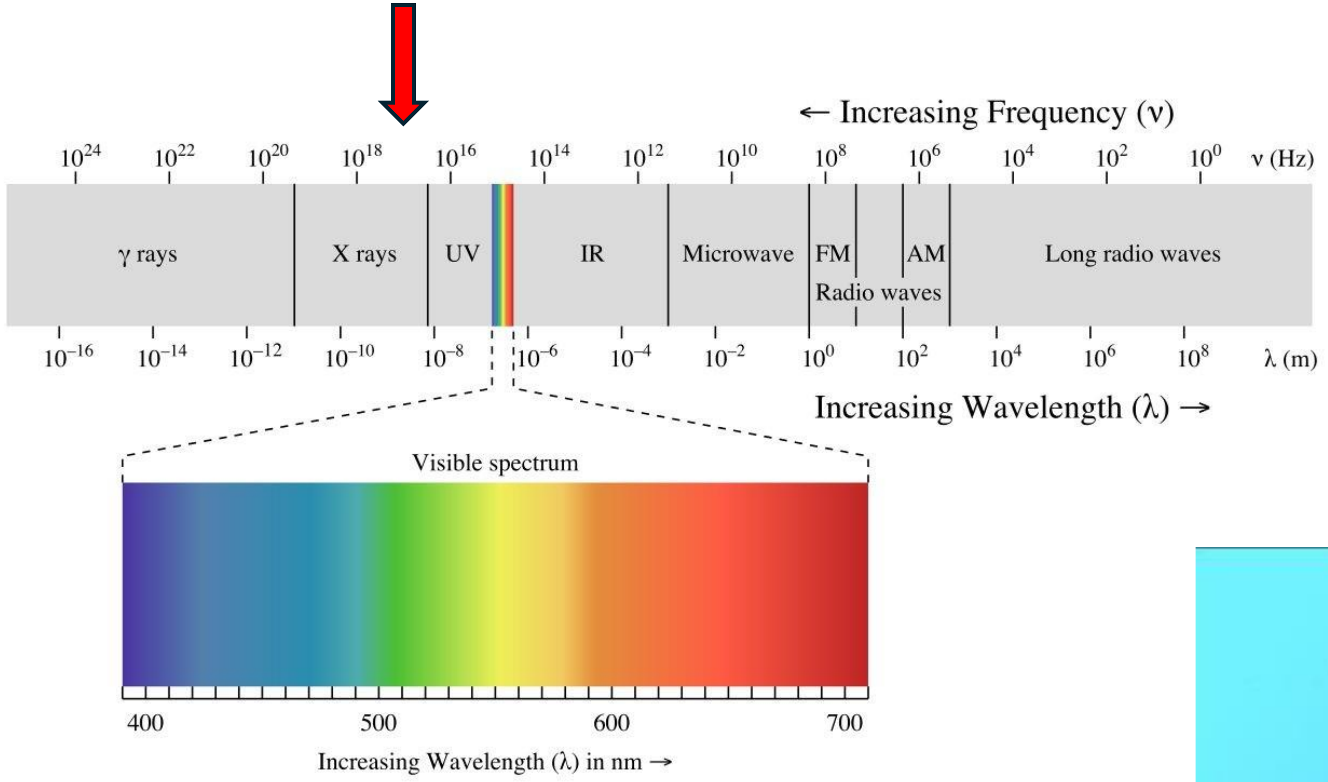
Mario.Galletti@lnf.infn.it

Alberto.Petralia@enea.it



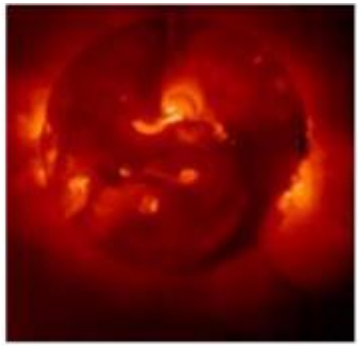


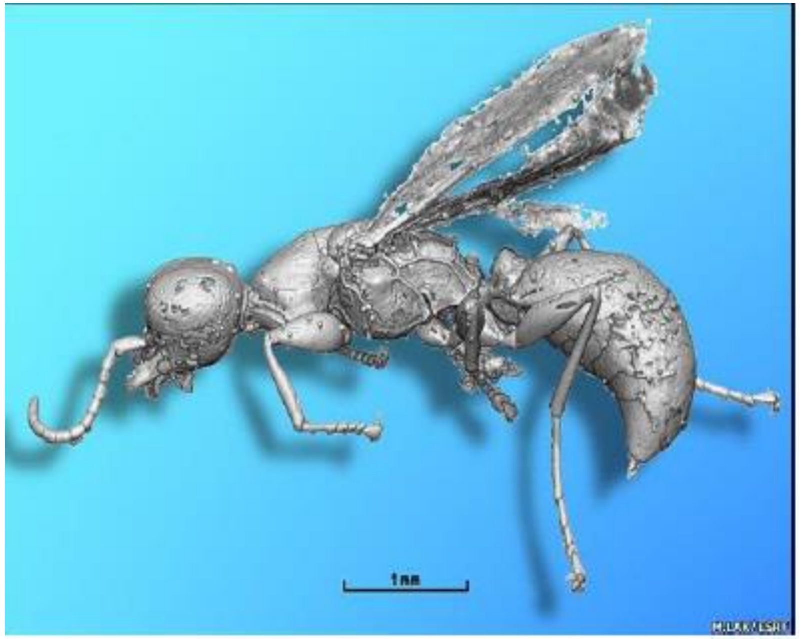
Far UV and X Radiation



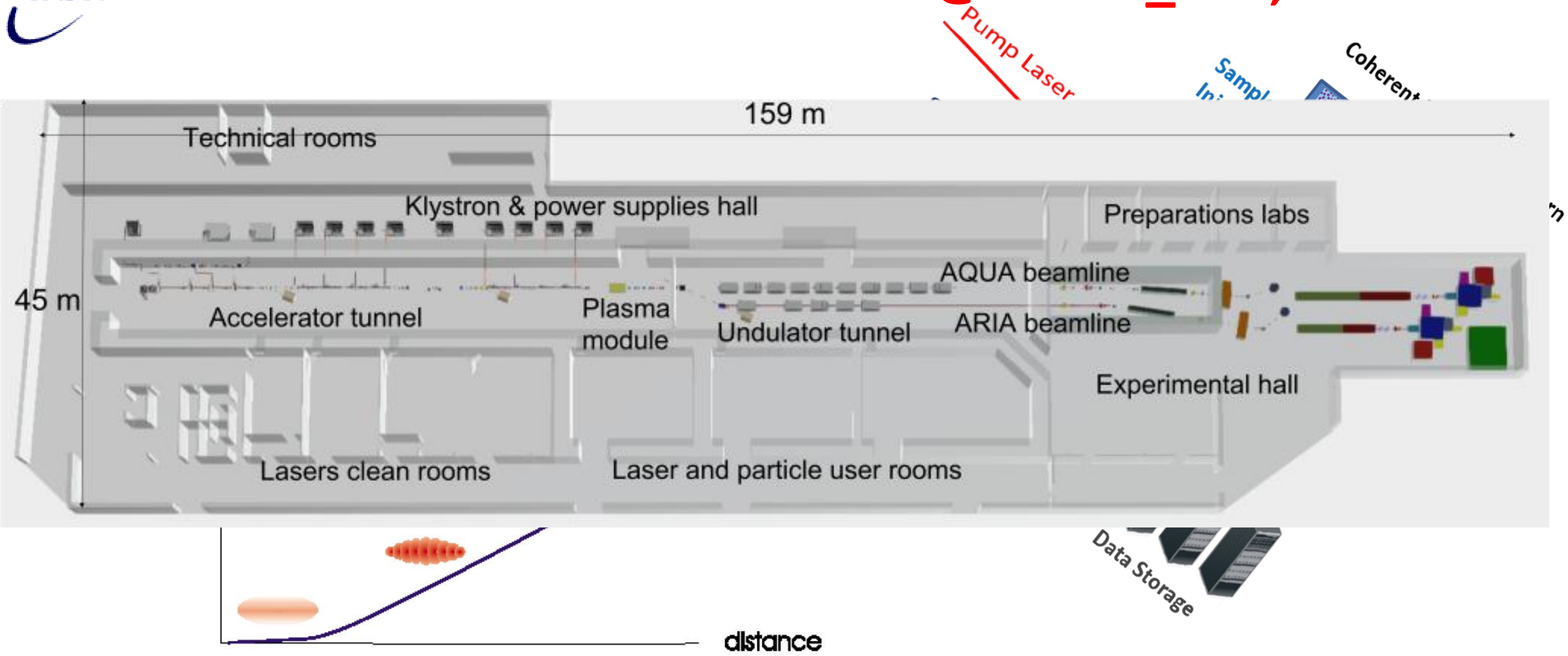
Frequency: $10^{17} – 10^{20}$ THz
Wavelength: 10 – 0.01 nm
Energy: 124 eV – 124 keV

X-ray Sources:
- **X-ray tube**
- **Betatron**
- **Synchrotron**
- **FEL**
- **ICS sources**





Free Electron laser at EuPRAXIA@SPARC_LAB, LNF



PhD Thesis Projects on FELs at EuPRAXIA@SPARC_LAB, LNF
Project leader: Massimo.Ferrario@lnf.infn.it

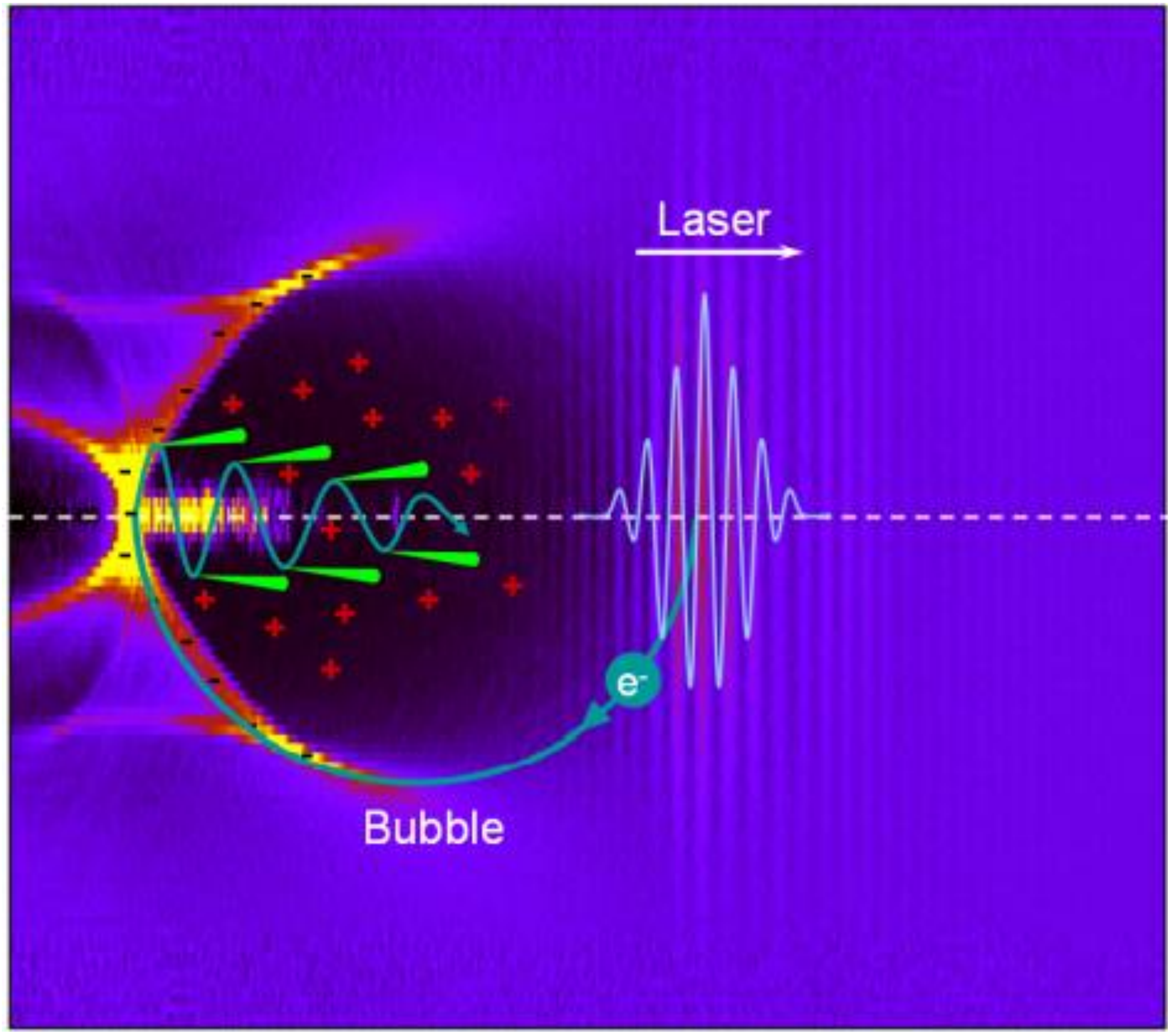
Massimo.Ferrario@lnf.infn.it Luca.Giannessi@lnf.infn.it
Petrillo@mi.infn.it
Alberto.Petralia@enea.it
Federico.nguyen@enea.it

1) Seeded free-electron laser for the generation of UV ultrashort coherent pulses from a plasma-wake accelerator (ARIA)
2) Design of a narrow bandwidth, seeded free-electron laser for the generation of VUV light (ARIA)
3) Undulator design
4) Wakefield effect on radiation

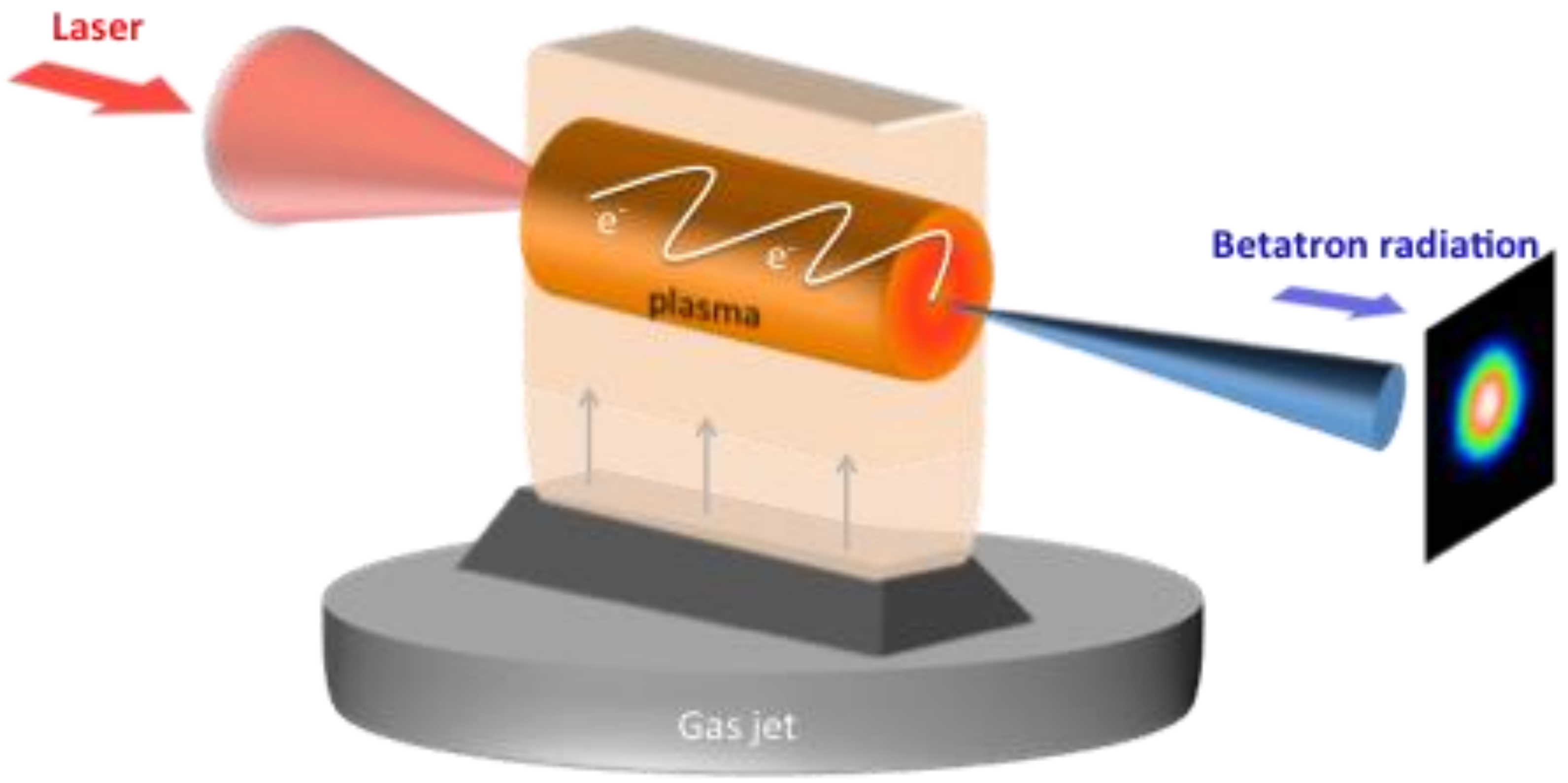
A. Ghigo, A. Curcio
5) Possibility of using the betatron radiation to seed an X-ray FEL (AQUA)

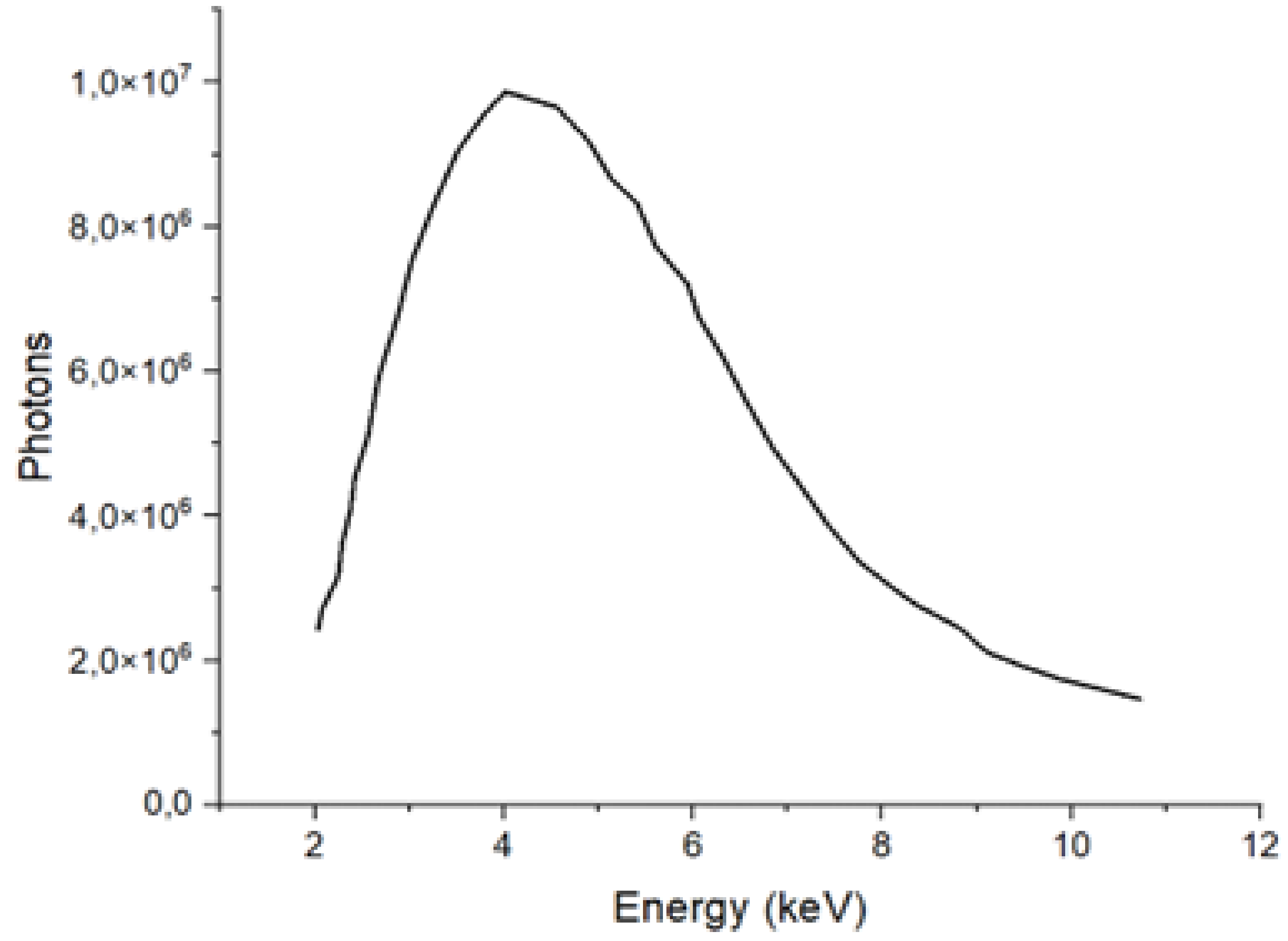
Betatron radiation @ EuAPS

- Betatron radiation is emitted by electrons accelerated in a plasma bubble due to their wiggling motion
- Plasma is a natural continuous focusing channel
- There are betatron oscillations in any accelerator, but their contribution is usually negligible
- In a plasma stage, there are about tens of oscillations in a typical accelerating length
- The spectrum extends from visible to X-rays



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

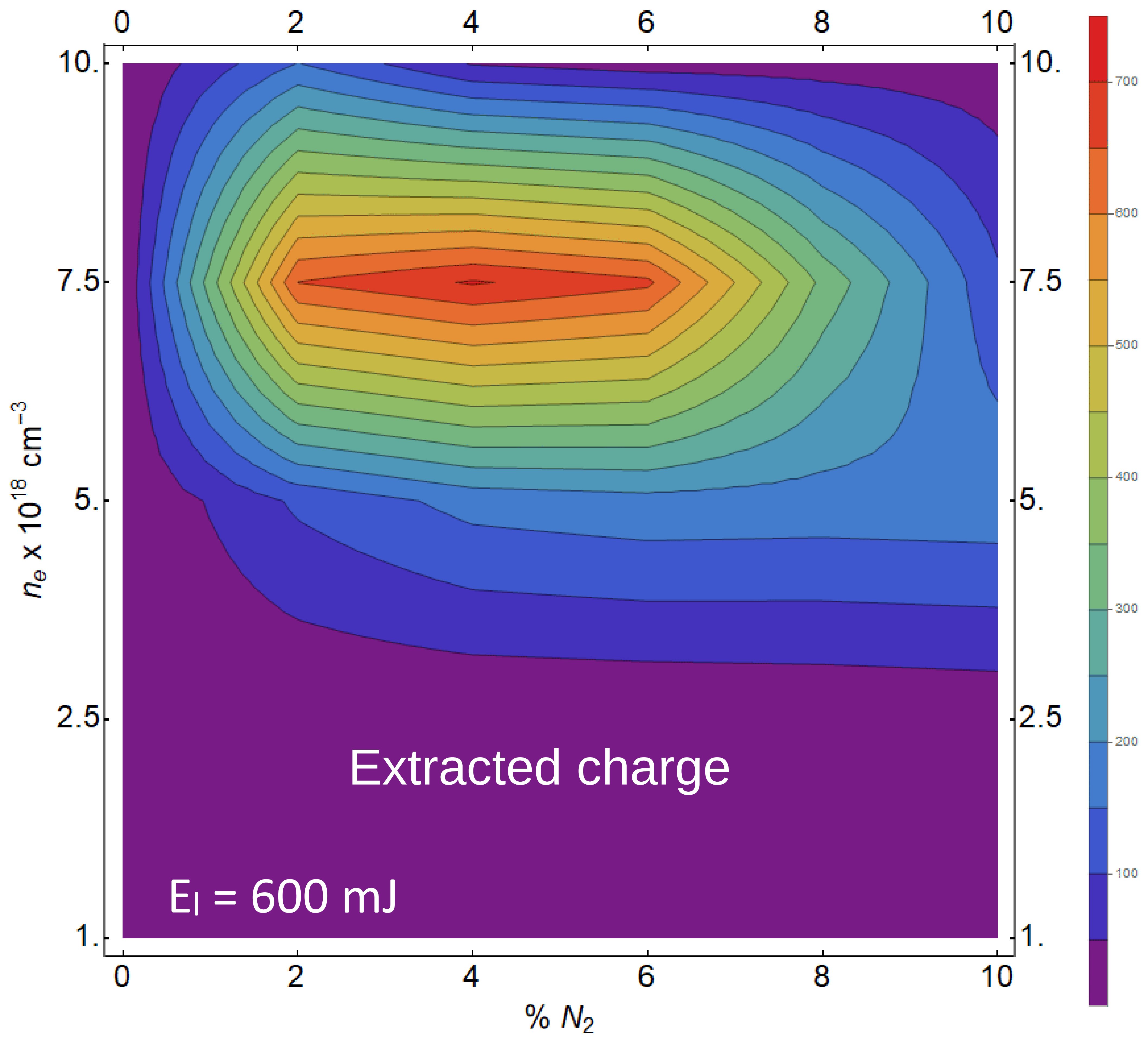




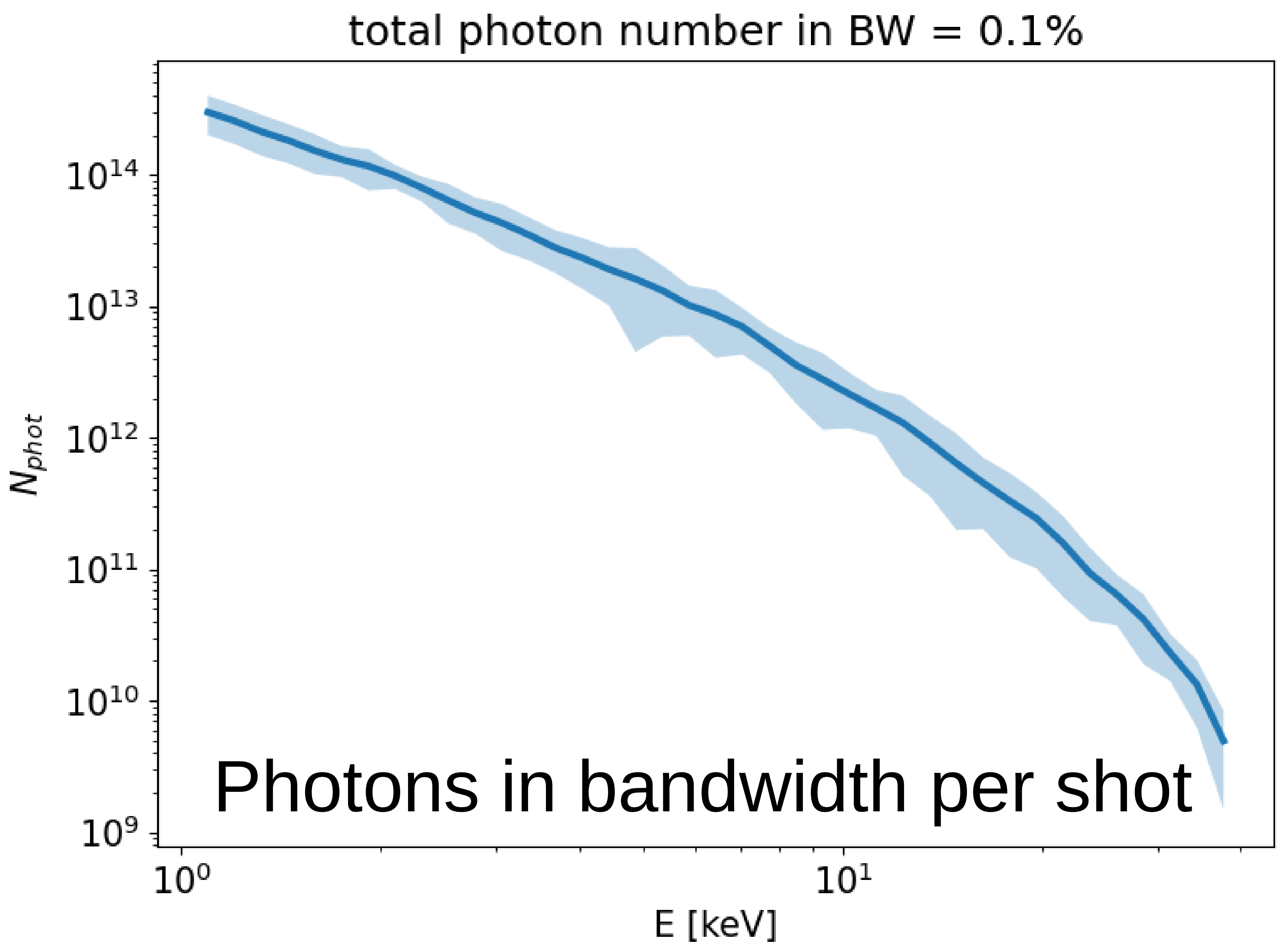
Contact: Andrea R. Rossi - andrea.rossi@mi.infn.it

Betatron radiation

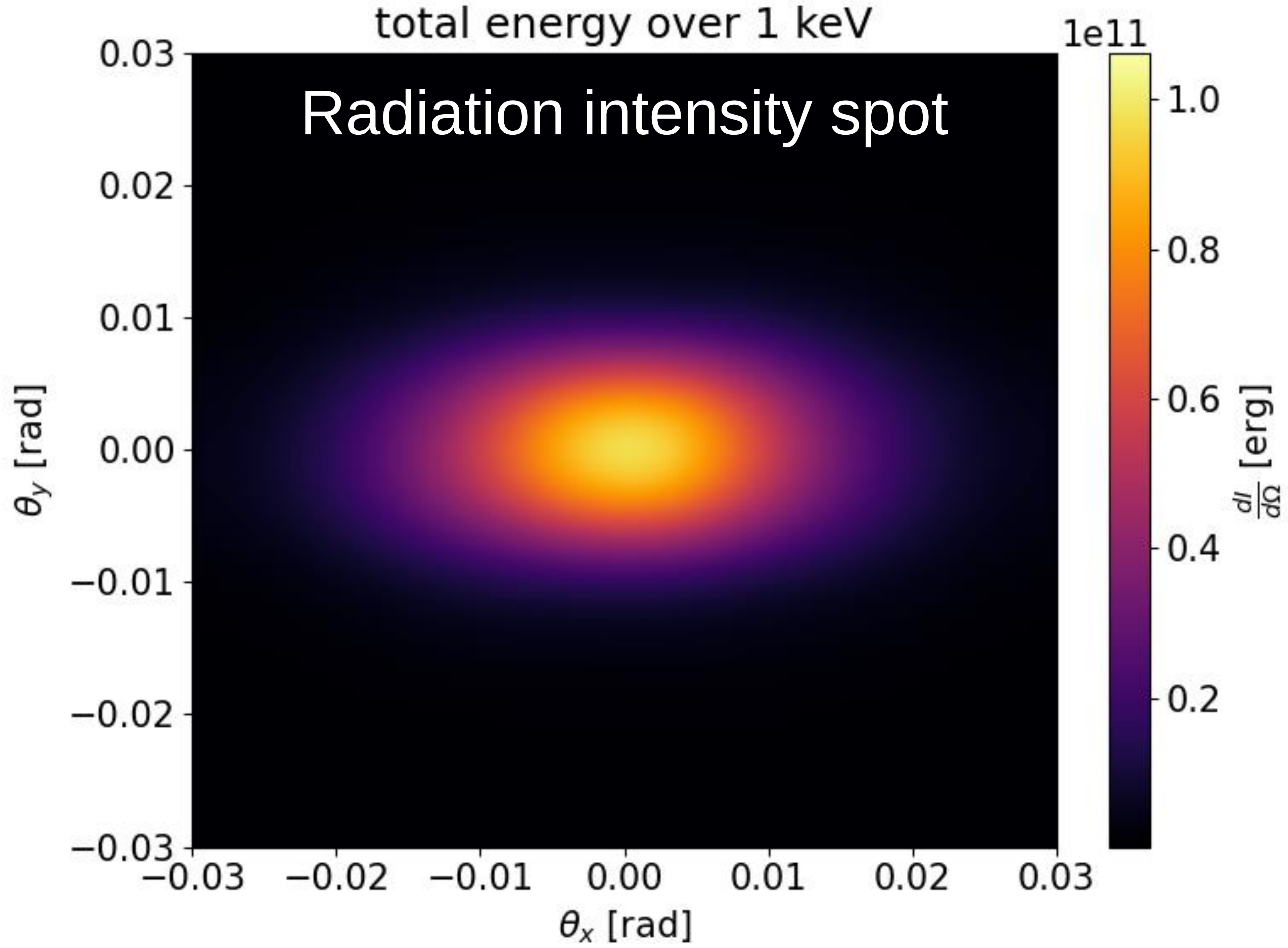
Thesis proposal: numerical optimization of the betatron radiation source by scan of the input parameter space (laser energy, plasma density, dopant concentration) and engineering of the plasma target


Extracted charge

E_l = 600 mJ


total photon number in BW = 0.1%

Photons in bandwidth per shot


total energy over 1 keV

Radiation intensity spot

Contact: Andrea R. Rossi - andrea.rossi@mi.infn.it

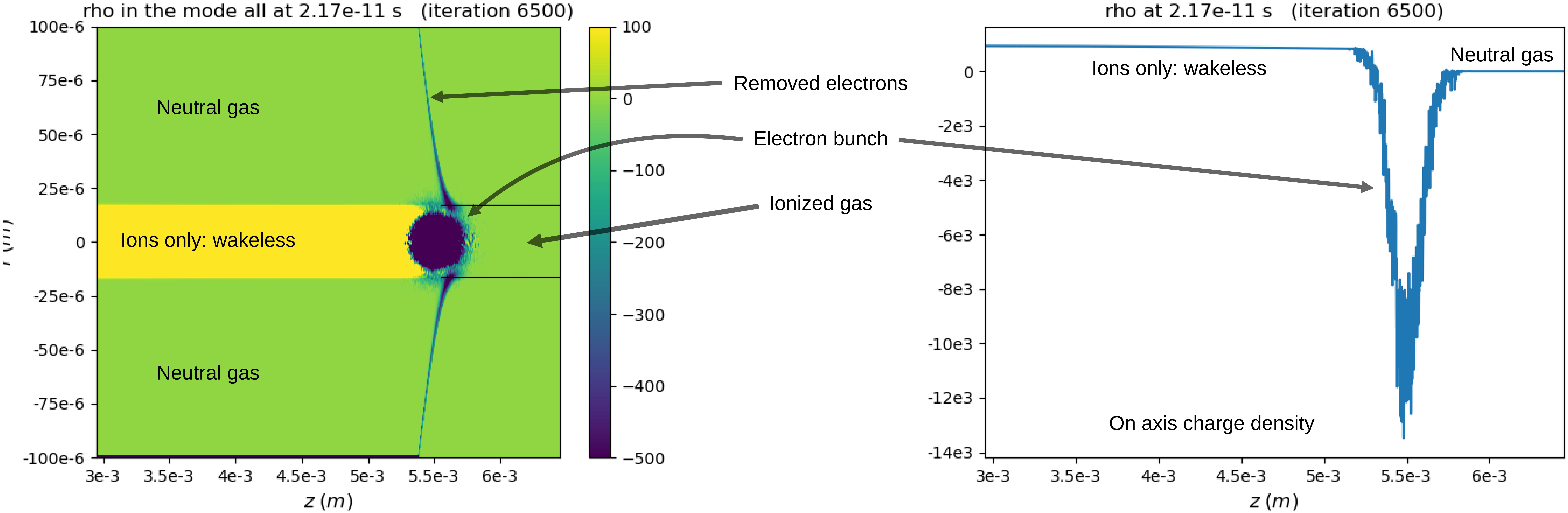
Ion Channel Laser (ICL)

An ICL is formed by ionizing a small cylinder in a neutral gas. If free electrons are removed from the cylinder (ICL formation) the result is a **wakeless** plasma:

- only transverse (focusing) electric field
- no accelerating component.
- betatron radiation should have a **smaller bandwidth** and may lead to betatron FEL

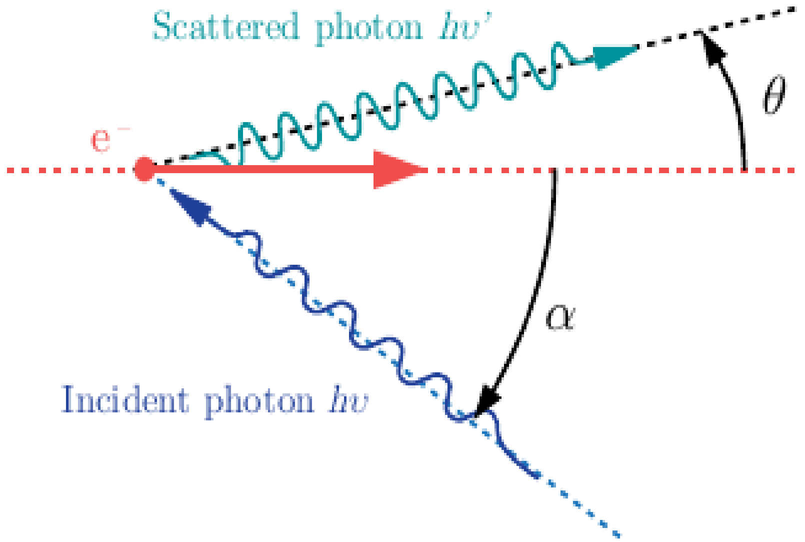
Possible thesis opportunities:

- Study of ICL formation conditions
- Optimization of radiation emission
- Investigation of radiation coherence properties

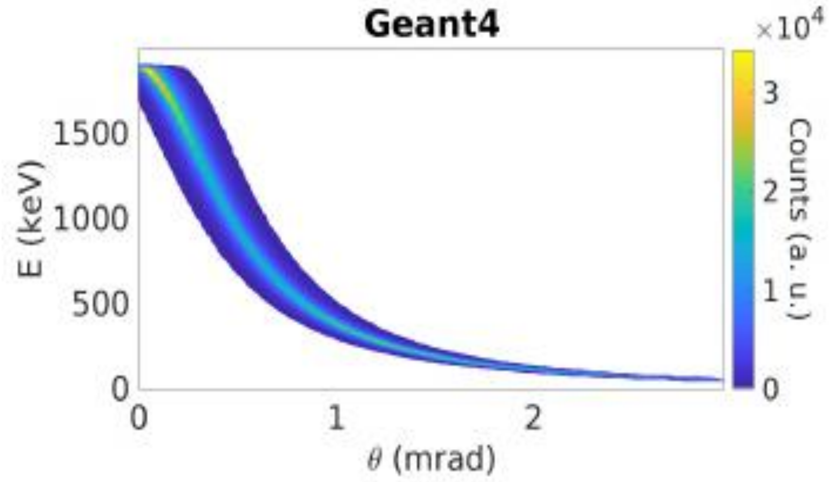


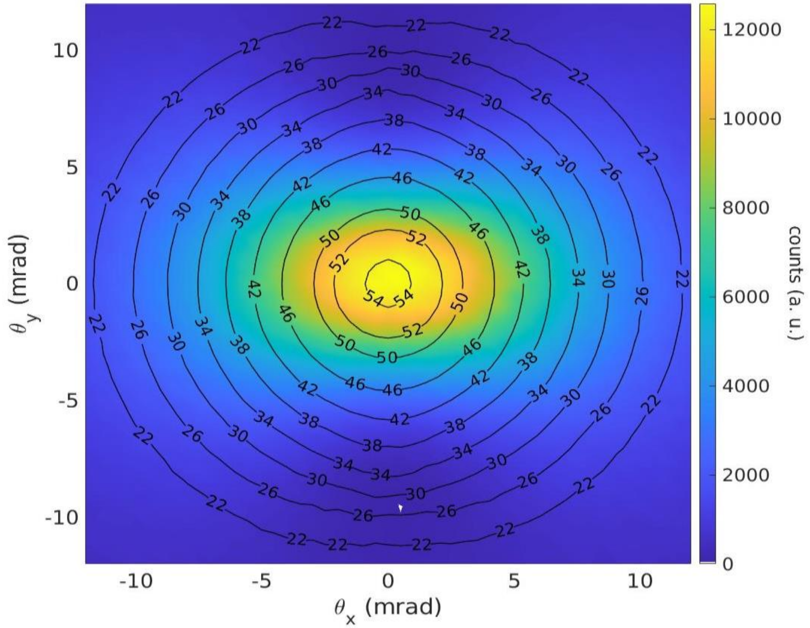
Contact: Andrea R. Rossi - andrea.rossi@mi.infn.it

Inverse Compton Scattering



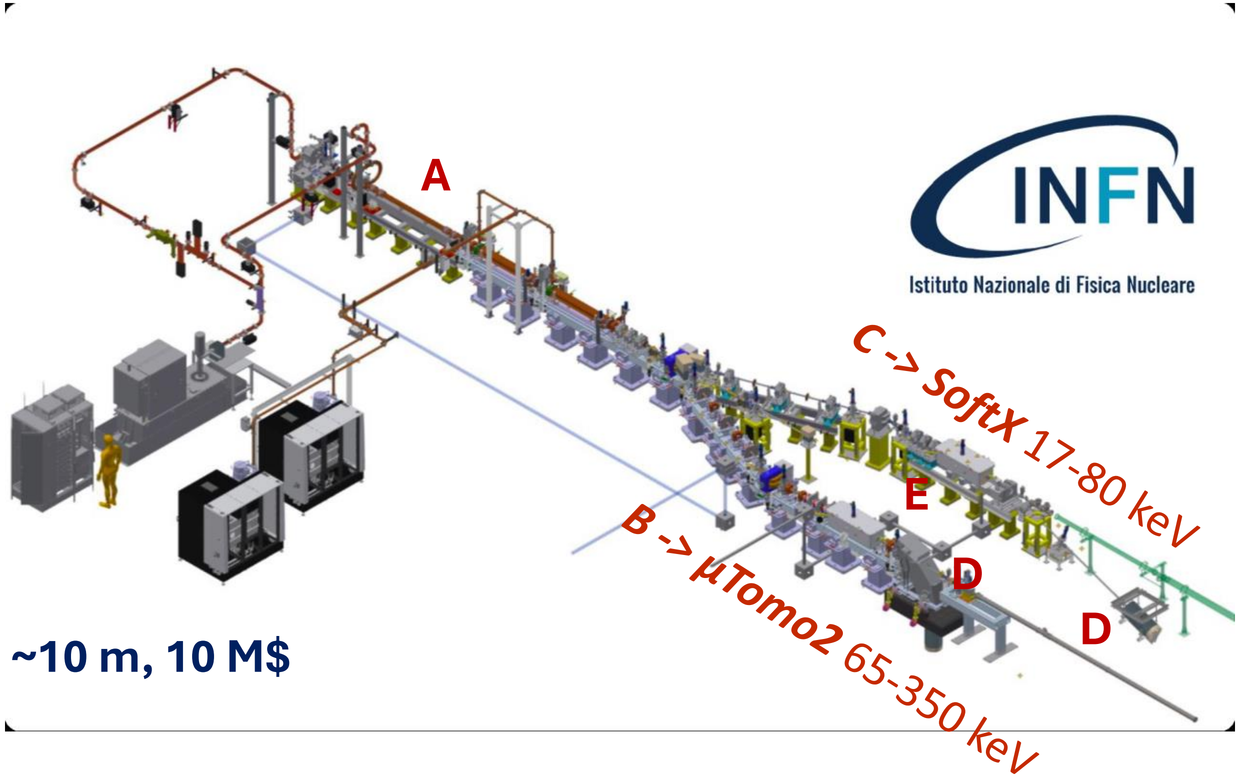
$$E_\gamma \approx \frac{2\gamma^2(1+\cos\alpha)}{1+(\gamma\theta)^2+\frac{4\gamma E_L}{m_e c^2}} E_L$$





STAR

Southern Europe Thomson backscatteing source for Applied Research



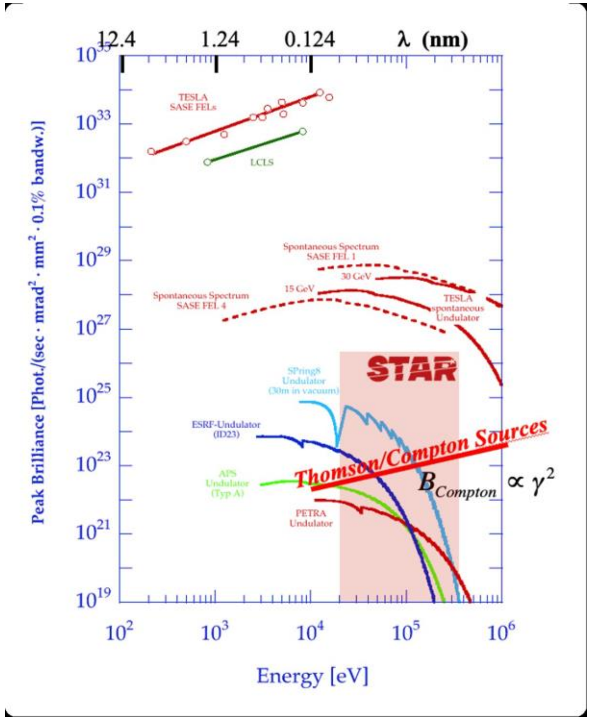


Table 1: STAR-HEL Electron Beam Quality Parameters at the Interaction Point (IP).

	HE-linac	LE-linac
Energy range	40-150 MeV	23-65 MeV
Rep. rate	100 Hz	
Bunch charge range	100 – 500 pC	
Normalized Emittance (x,y)	2.0 µm	
Bunch energy spread	0.5 %	
Bunch length – rms [ps]	≤ 5 ps	
Bunch spot dimensions (x,y) at IP	40 µm	

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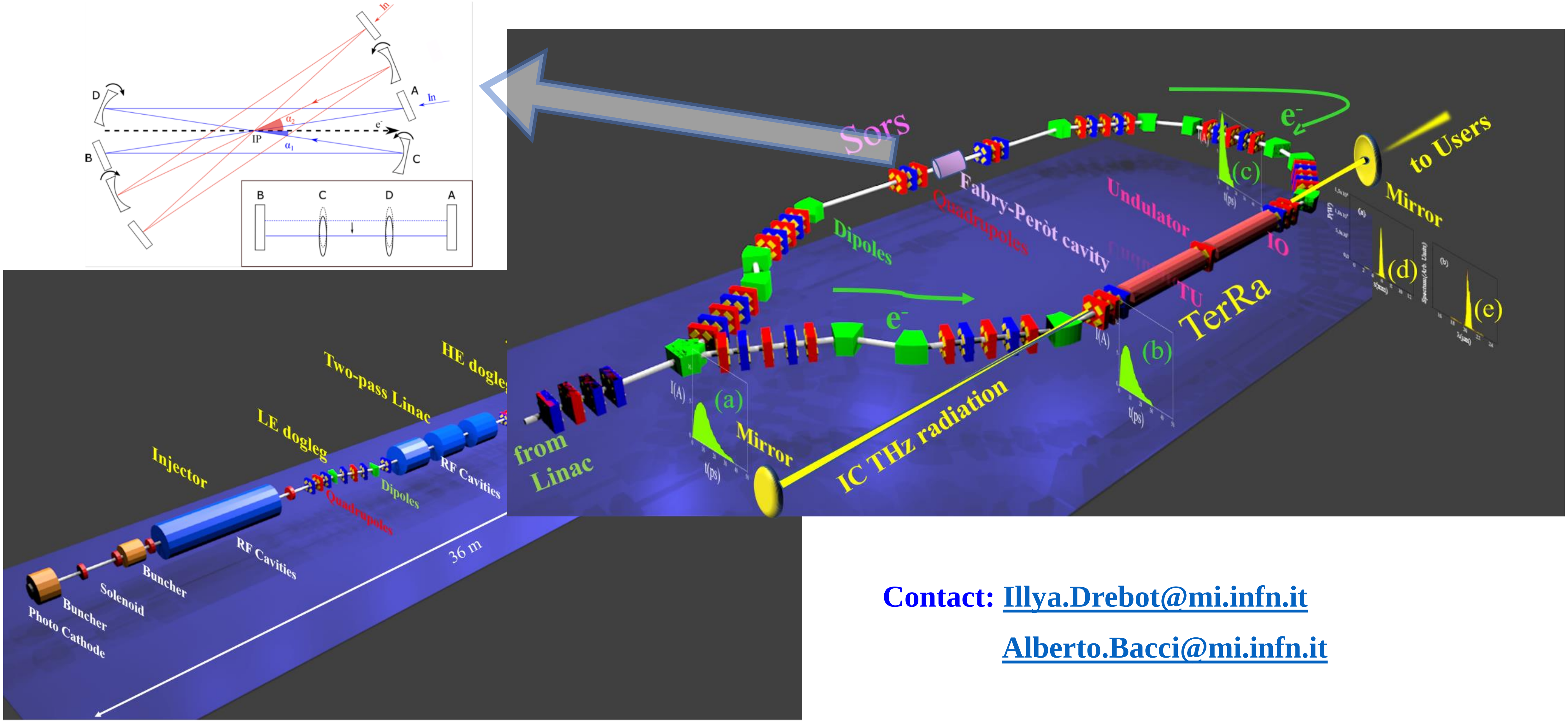
STAR ICS SOURCE

A. Accelerating section (1 S-band and 2 C-band LINACs)
B. High Energy branch «STAR-HE-Linac»
C. Low Energy branch «STAR-LE-Linac»
D. Beam dumps
E. Impact chambers

- *A. Bacci et al., The Star project, Proceedings of IPAC2014, Dresden, Germany*
- *A. Bacci et al., Status of the Star project, Proceedings of IPAC2016, Busan, Korea*
- *A. Bacci et al., Photoinjector Emittance Measurement at STAR", Proceedings of IPAC2017, openhagen, Denmark*
- *A. Bacci et al., STAR HE-Linac Complete Detailed Design Report, arXiv:2109.10351*

BriXSinO ERL Compton Scattering



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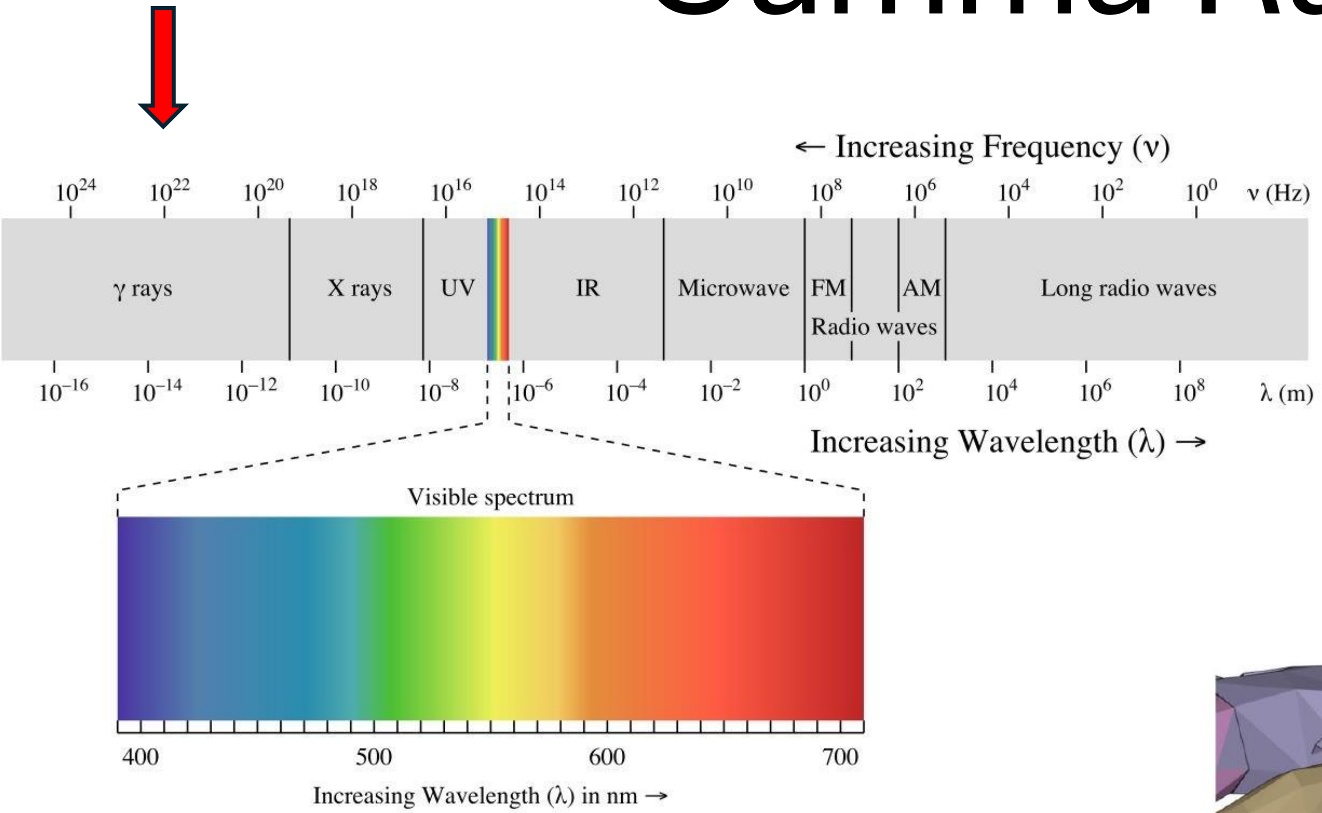
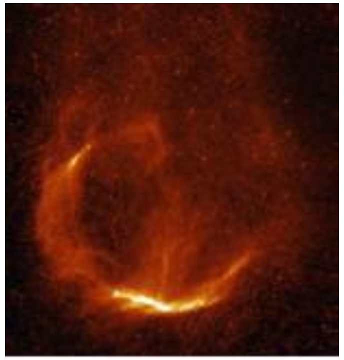
Gamma Radiation

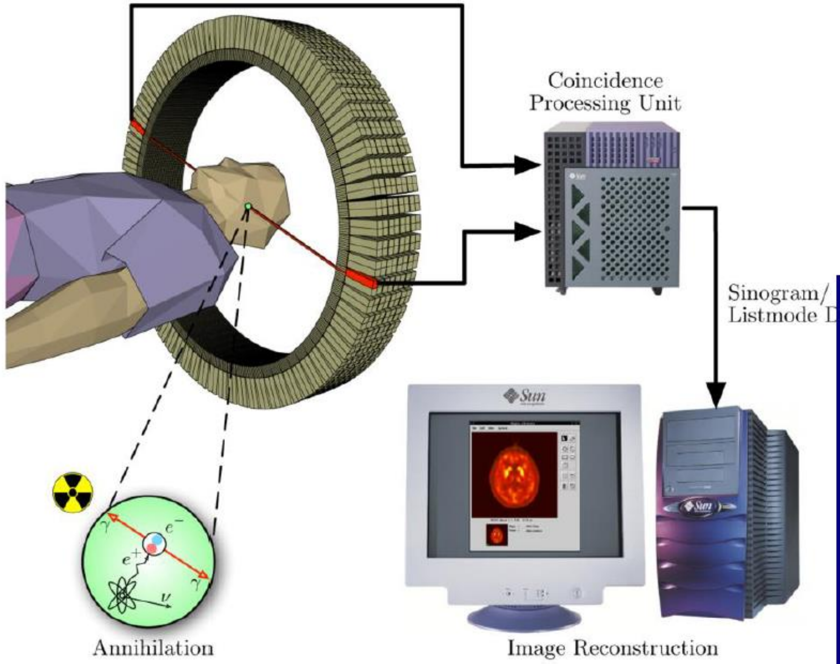


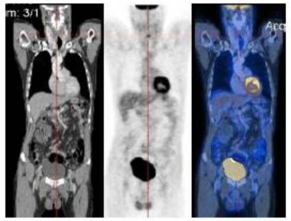
Frequency: > 10^{20} THz
Wavelength: < 0.01 nm
Energy: > 124 keV

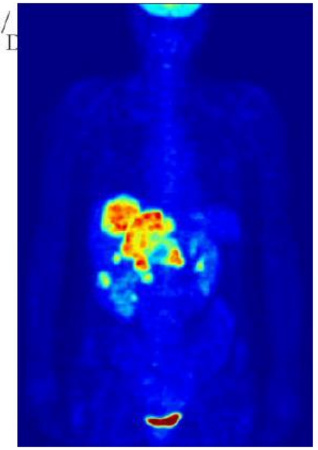
γ-ray Sources:

- **Particle decays**
- **ICS sources**
- **Coherent interactions of charged particles in oriented crystals**







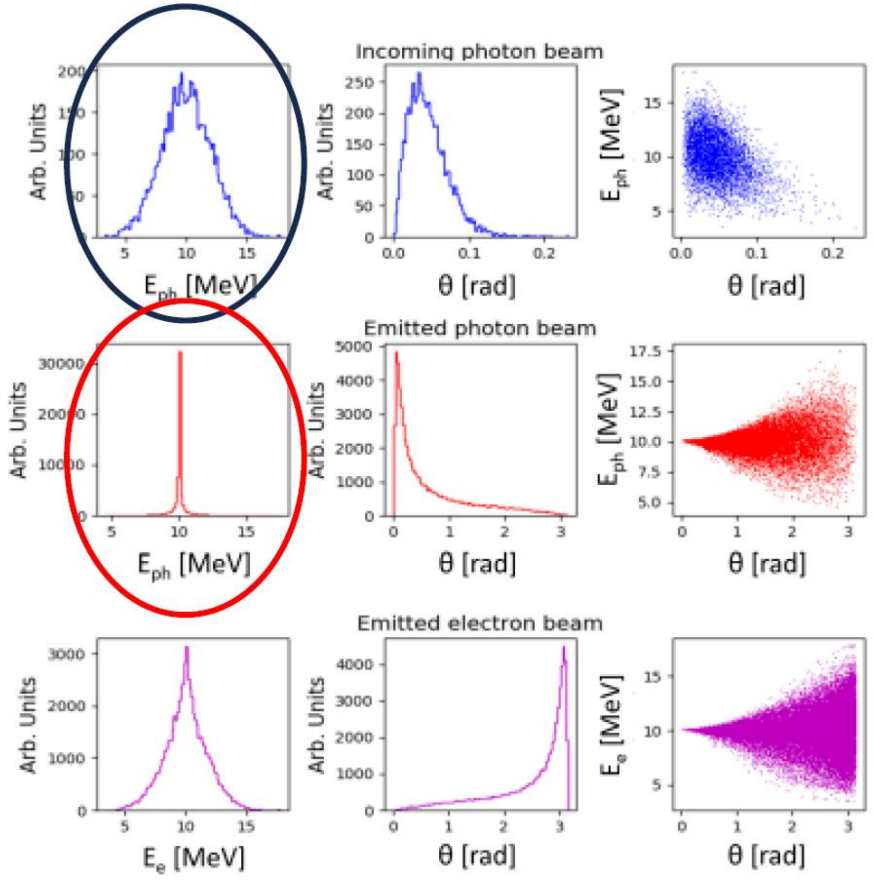


Symmetric Compton Scattering

Full Inverse Compton Scattering

new ideas from **L. Serafini**: Luca.Serafini@mi.infn.it

A particular regime ($k_{ph} = p_e$) in ICS where the spectrum of the X or gamma-rays can be changed from white to extremely monochromatic.


Incoming photon beam

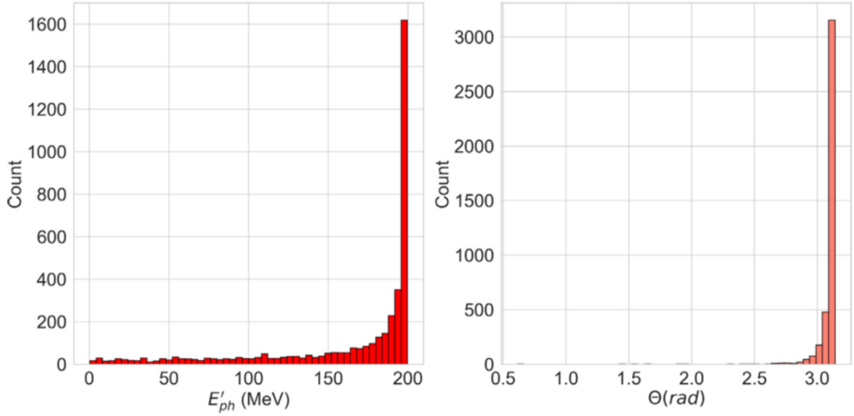
Emitted photon beam

Emitted electron beam

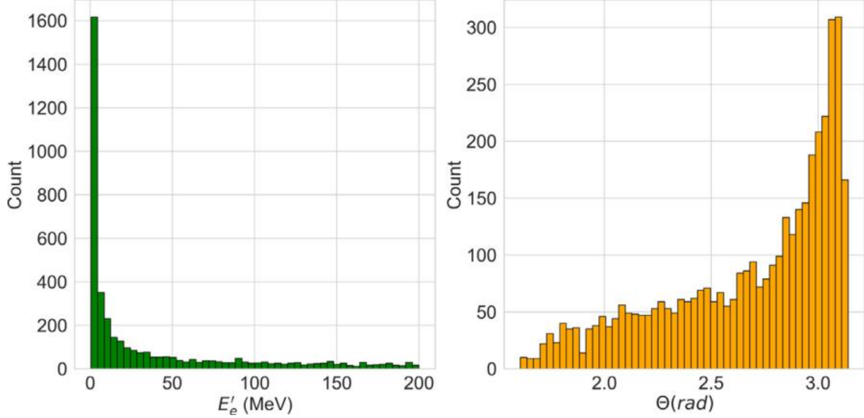
Serafini et al. Fundamental Plasma Physics 7 (2023) 100026

Photons with an energy of 255 keV = $m_ec^2/2$ can stop an electron beam of any energy

Scattered Photons



Scattered electrons (E_{in} = 200 MeV)



Serafini et al. NIM A 1069 (2024) 169964

G.A. 101046458

EIC PATHFINDER OPEN TECHNO-CLS “Crystal-based gamma-ray light sources”

TECHNO-CLS

- The project started on 1 June 2022 and has a duration of 5 years.

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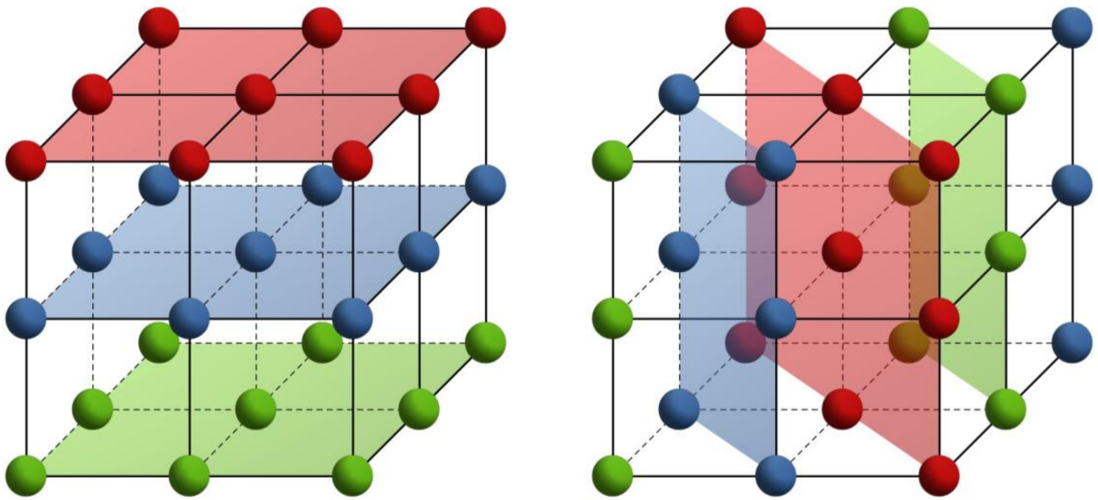
University of Kent

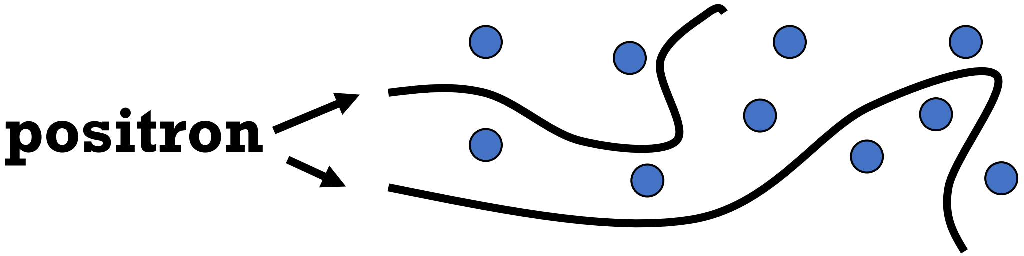
UNIVERSITÀ DEGLI STUDI DI PADOVA

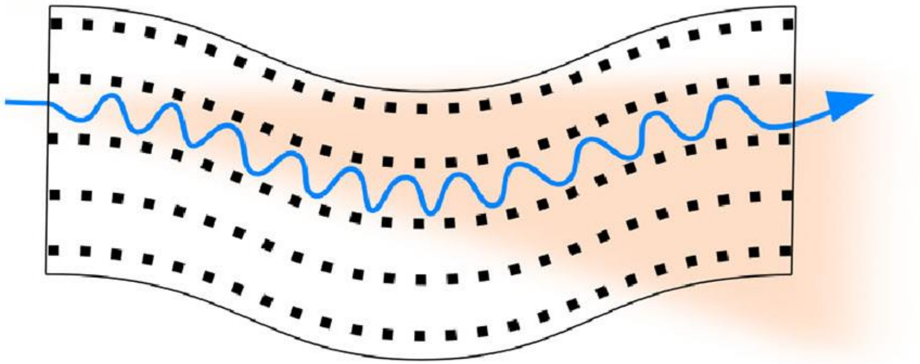
Università degli Studi di Ferrara

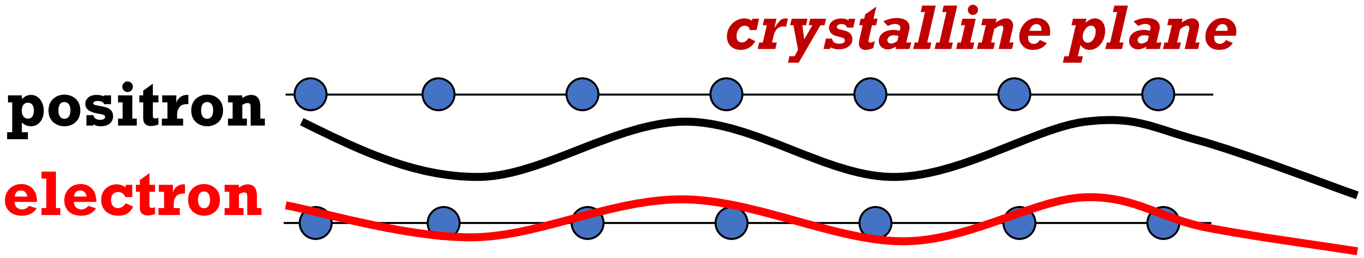
Trapping particles inside crystal channels

If the particle beam is nearly parallel to the crystallographic planes, it can be trapped in the planar potential well





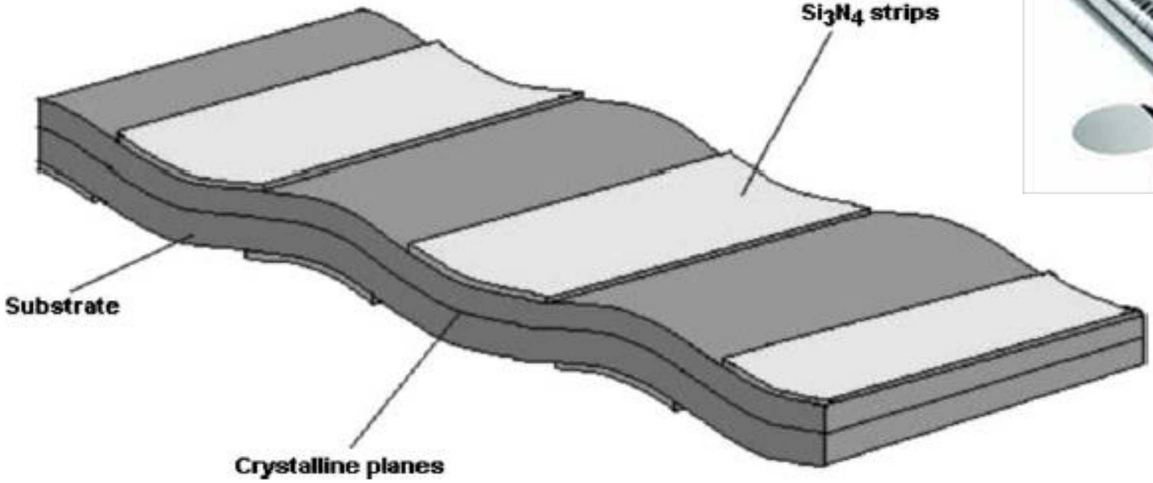




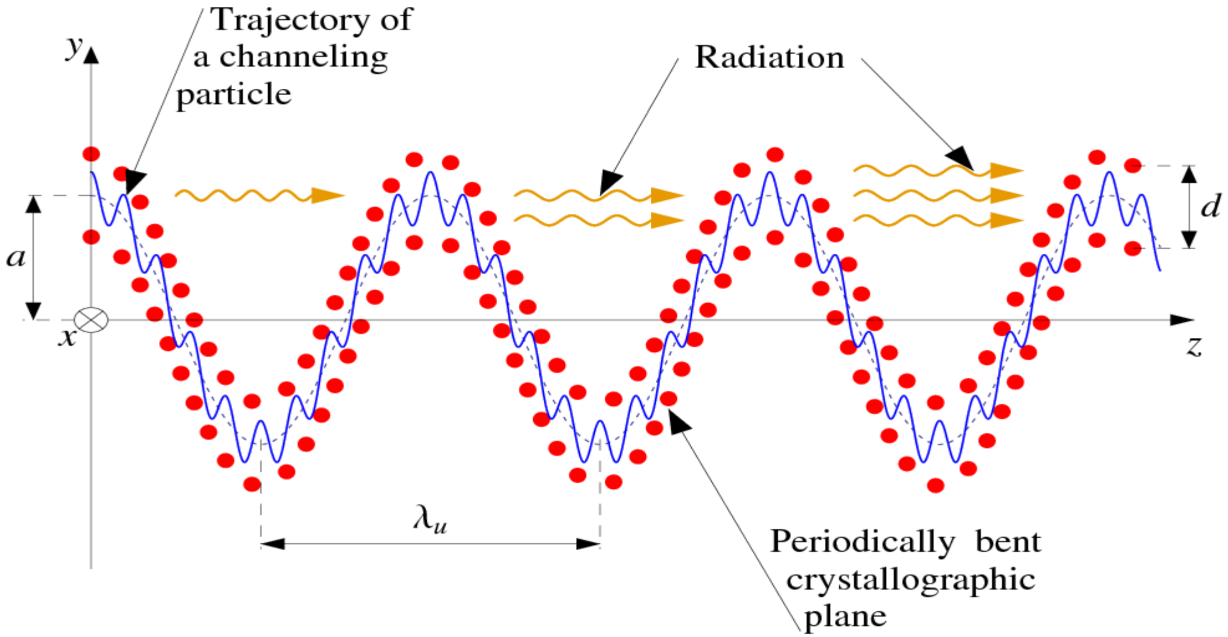
If the crystal is periodically bent, the particle beam follows the bending

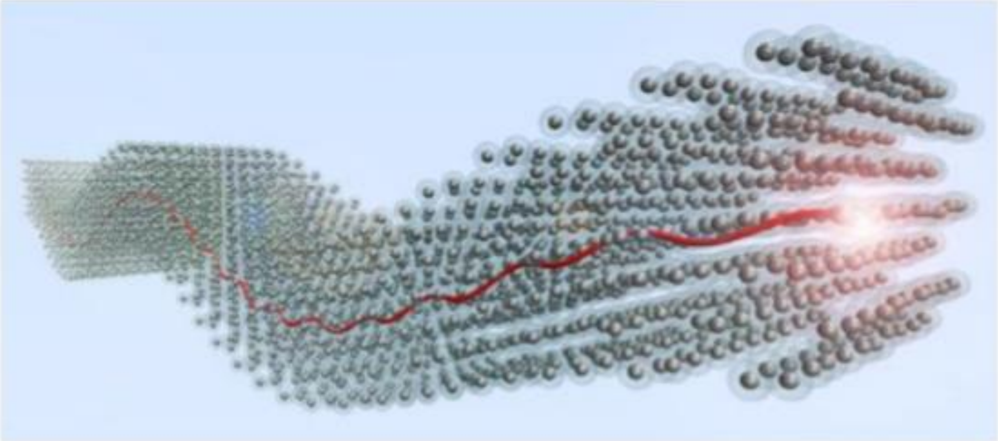
A Crystalline Undulator

A periodically bent crystal can be realized via thin film deposition



Silicon and Germanium





Artistic view of a Crystal-based Light Source (CLS)

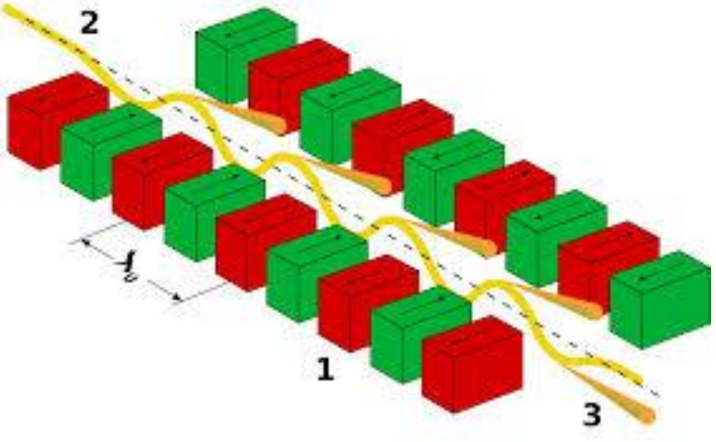
Standard Magnetic Undulator vs Crystal Light Source

TECHNO-CLS

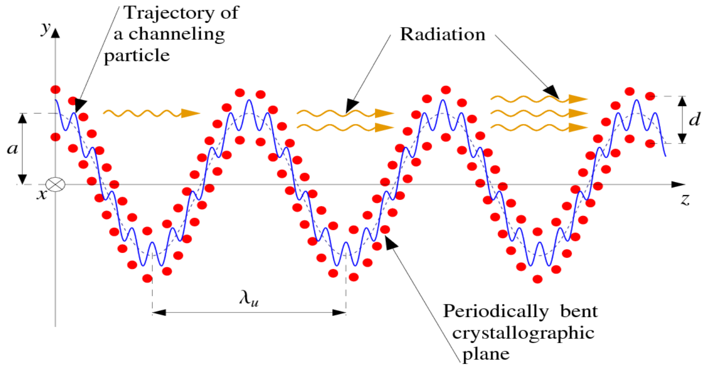
G.A. 101046458

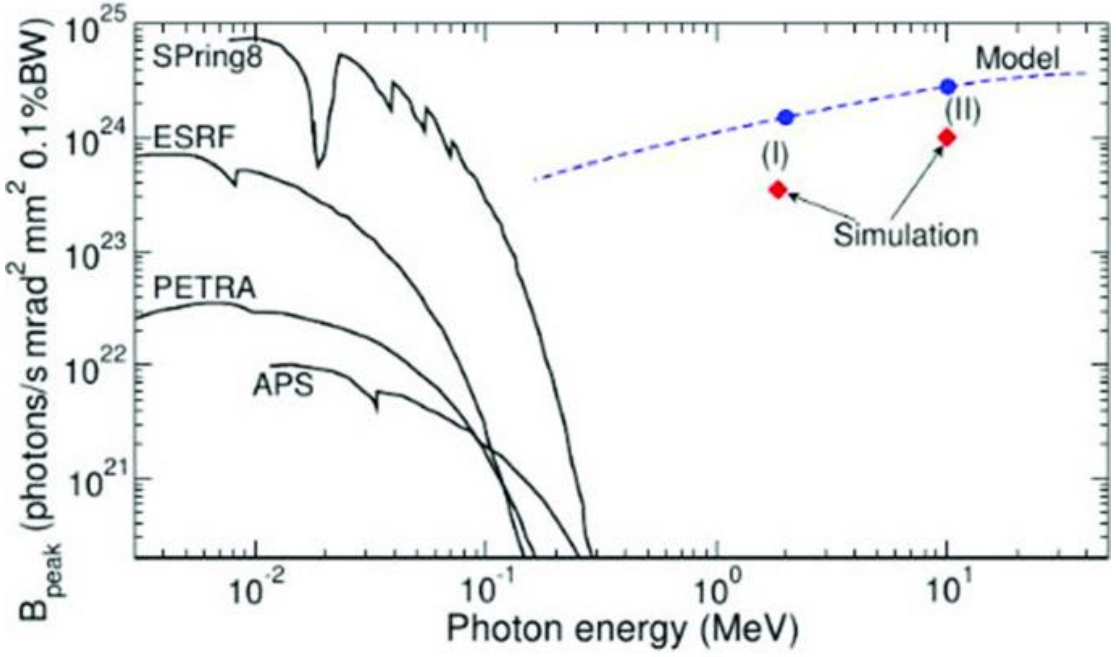
Korol, A.V., Solov'yov, A.V. Eur. Phys. J. D 74, 201 (2020).

Classical scheme: magnetic undulator in a free electron laser
Soft X-rays (10 keV)
$\lambda_u \sim$ cm



Innovative scheme: Crystalline undulator->
Hard X-rays and gamma rays (100 keV - 10 MeV)
$\lambda_u \ll$ mm





A Crystal Undulator is a small, passive and sustainable element that does not require either magnets or power supply

PhD thesis:
- Monte Carlo simulation for CLS optimization; Mechanical design and realization of Periodically Bent Crystals;
- Experimental tests on beam and data analysis.

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