EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Advanced Photon Source

EuPRAXIA Advanced Photon Sources

M. Ferrario, INFN

INFN Istituto Nazionale di Fisica Nucleare
LNF-LNS-MI
Consiglio Nazionale Ricerche
INO-ISM
Università di Roma Tor Vergata

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

Bando PNRR

Published on December 28th, 2021

Funded by the European Union

Finanziato dall'Unione europea
NextGenerationEU

MUR

REFORMS AND INVESTMENTS UNDER THE RECOVERY AND RESILIENCE PLAN
NextGenerationEU

Call for proposals

Intervention field 6: Investment in digital capacities and deployment of advanced technologies
DESI dimension 4: Integration of digital technologies + ad hoc data collections
055 - Other types of ICT infrastructure (including large-scale computer resources/equipment, data centres, sensors and other wireless equipment)

Mission 4 – "Education and Research"
Component 2: from research to business
Investment 3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures
Action 3.1.1 "Creation of new research infrastructures strengthening of existing ones and their networking for Scientific Excellence under Horizon Europe

- Total available funds 400 M€
- Minimal request 15 M€ of which 40% to the Southern Regions
- Personell funding allowed provided that 40% is reserved to women
- **To be completed no later than December 31rst 2025**

Nome IR	Capofila	Ambito e Tipo	
ACTRIS	CNR	ENV	Distributed
ANAEE	CNR	H&F	Distributed
Auger	INFN	PSE	Single site
BBMRI	CNR	H&F	Distributed
BRIEF	SS S. Anna	DIGIT	Distributed
CERIC-ERIC	Area Sci. Park	PSE	Distributed
CESSDA	CNR	SCI	Distributed
CLARIN-IT	CNR	SCI	Distributed
CTA	INAF	PSE	Distributed
DANUBIUS-RI	CNR	ENV	Distributed
DARIAH ERIC	CNR	SCI	Distributed
DiSSCo	CNR	ENV	e-IR
DTT	ENEA	ENE	Single site
EATRIS	CNR	H&F	Distributed
EBRAINS	CNR	H&F	Distributed
ECCSEL	OGS	ENE	Distributed
ECORD	CNR	ENV	Distributed
ECRIN	CNR	H&F	Distributed
E-ELT	INAF	PSE	Single site
EGO	INFN	PSE	Single site
EIRENE RI	CNR	ENV	Distributed
ELETTRA	Area Sci. Park	PSE	Single site
ELI	CNR	PSE	Distributed
ELIXIR - IT	CNR	H&F	Distributed
eLTER	CNR	ENV	Distributed
EMBRC	SZN	H&F	Distributed
EMSO	INGV	ENV	Distributed
EPOS	INGV	ENV	Distributed
E-RIHS	CNR	SCI	Distributed
ESRF Grenoble	CNR	PSE	Single site
ESS ERIC	INAPP	SCI	Distributed
ESS ERIC (Spallation)	INFN	PSE	Single site
ET	INFN	PSE	Single site
EUFAR	CNR	ENV	Distributed
EuPRAXIA	INFN	PSE	Distributed
Euro-Argo	OGS	ENV	Distributed
EURO-BIOIMAGING	CNR	H&F	Distributed
EUROFEL	Area Sci. Park	PSE	Distributed
EuroNanoLab (ENL)	CNR	PSE	Distributed
EVN - JIVE	INAF	PSE	Distributed
FERMI	Area Sci. Park	PSE	Single site
Fondazione CMCC	INGV	ENV	Distributed
GARR-X	GARR	DIGIT	e-IR
IBISBA-IT	CNR	H&F	Distributed
ICOS	CNR	ENV	Distributed
ILL	CNR	PSE	Single site
INFRAFRONTIER	CNR	H&F	Distributed
INSTRUCT-ERIC	CNR	H&F	Distributed
ISBE	CNR	H&F	Distributed
ISIS	CNR	PSE	Distributed
KM3-NET	INFN	PSE	Distributed
LBT	INAF	PSE	Single site
LENS	CNR	PSE	Single site
LIFEWATCH	CNR	ENV	Distributed
LNF	INFN	PSE	Single site
LNGS	INFN	PSE	Single site
LNL	INFN	PSE	Single site
LNS	INFN	PSE	Single site
LOFAR	INAF	PSE	Distributed
METROFOOD-RI	ENEA	H&F	Distributed
MIRRI	Torino	H&F	Distributed
NFFA	CNR	PSE	Distributed
OPENAIRE	CNR	DIGIT	Distributed
OPERAS	CNR	SCI	Distributed
Phen-Italy - nodo IT di EMPHASIS	CNR	H&F	Distributed
PRACE-Italy	OGS	DIGIT	e-IR
RESILIENCE	CNR	SCI	Distributed
RFX	CNR	ENE	Single site
SESAME	INFN	PSE	Single site
SHARE-ERIC	CNR	SCI	Distributed
SIOS	CNR	ENV	Distributed
SKA	INAF	PSE	Distributed
SoBigData	CNR	DIGIT	Distributed
TNG	INAF	PSE	Single site

Tabella 10: IR ad alta priorità

From the EuPRAXIA CDR

Funded by the European Union

The EuAPS proposal benefits from the preparatory work done in the conceptual design phase of EuPRAXIA, both for the scientific case and the technology. It focuses on an ambitious but technically achievable goal and builds on the pre-existing investments at the SPARC_LAB facilities. As stated in the EuPRAXIA CDR the following EuPRAXIA Flagship Goals will be addressed by the EuAPS Project:

Flagship Innovation Goal 2: EuPRAXIA will develop together with laser industry a **new generation of high peak power lasers,** advancing the presently leading technology into the regime of 20 - 100 Hz repetition rate […].

Flagship Science Goal 2*:* EuPRAXIA will deliver **betatron X rays with up to 10^{10} photons per pulse,** up to 100 Hz repetition rate and an energy of 5-18 keV to users from the medical area. […].

Flagship Science Goal 7*:* EuPRAXIA will provide access to cutting edge laser technology with **short pulse length in combination with high energy photon pulses** […].

We expect that the focus on a mature part of the EuPRAXIA project strongly supports project completion on the timescales that are required by PNRR.

Betatron Radiation Source

EuPRAXIA Advanced Photon Source

Funded by the European Union

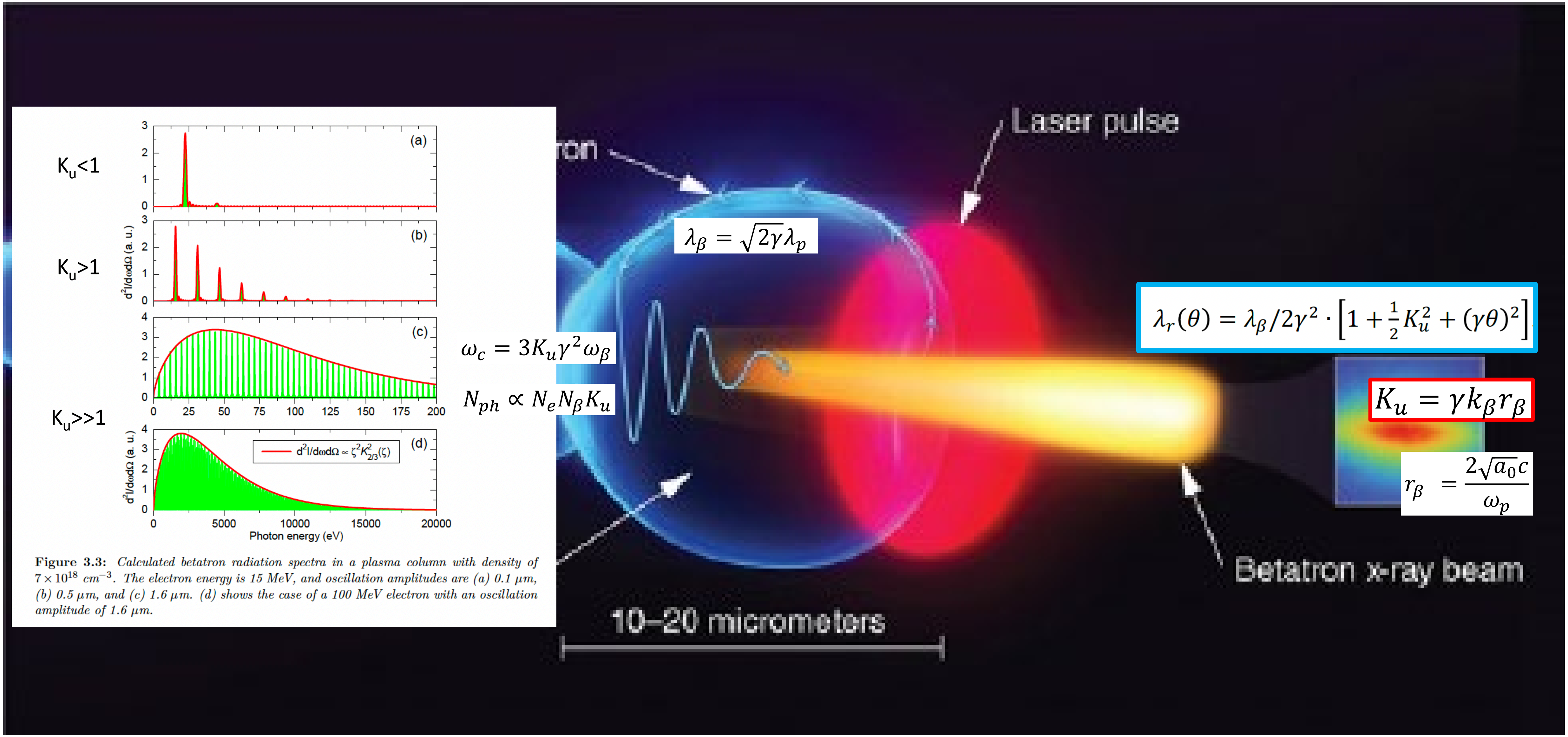


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 μm, (b) 0.5 μm, and (c) 1.6 μm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 μm.*

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

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

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

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

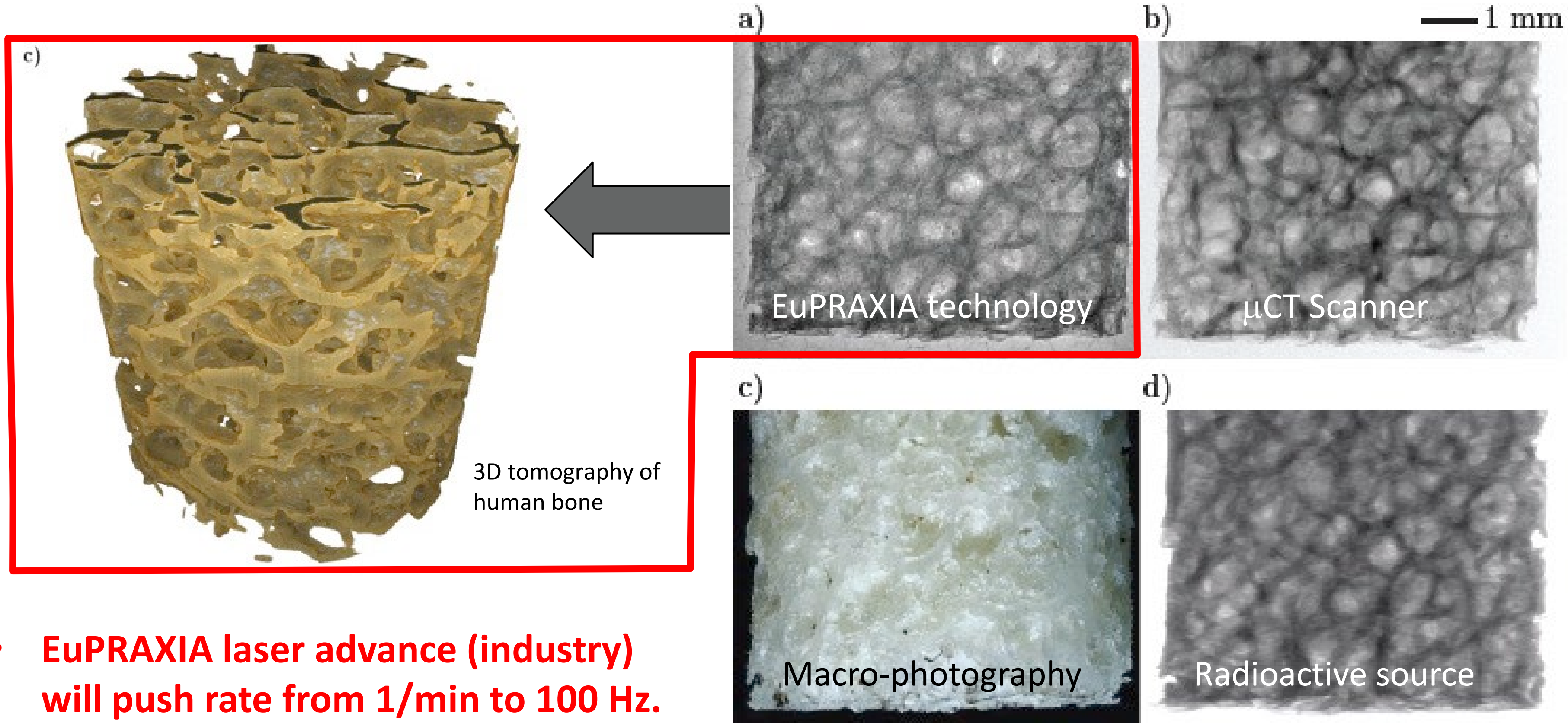
$$K_u = \gamma k_\beta r_\beta$$

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

Betatron X Rays: Compact Medical Imaging

Funded by the European Union

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)

EuPRAXIA Advanced Photon Sources Proposal

Started on February 13th, 2022 - Submitted on February 28th, 2022

Funded by the European Union

EuAPS Scientific Coordinator:
M. Ferrario (INFN-LNF)
EuPRAXIA/EuAPS Integration:
R. Assmann (DESY & INFN)

Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale Ricerche

Università di Roma Tor Vergata

WP1
MANAGEMENT & DISSEMINATION
A. Falone (LNF)

WP3
HIGH POWER LASER BEAM LINE
P. Cirrone (LNS)

WP2
BETATRON RADIATION SOURCE
A. Cianchi (Uni-ToV)

WP4
HIGH REPETITION RATE LASER BEAM LINE
L. Labate (CNR-INO)

Scientific Advisory Committee

Operating Units Board

Scientific and Technical Board

Graduatoria Definitiva

Published on June 20th, 2022

Finanziato dall'Unione europea
NextGenerationEU

I 3.1, Fund for the creation of an integrated system of research and innovation infrastructures Action 3.1.1 " Creation of new IR or strengthening of existing IR involved in the Horizon Europe Scientific Excellence objectives and the establishment of networks "					
Graduatoria definitiva ESFRI area: PSE - Physical Sciences and Engineering					
Position	**Proposal code**	**Applicant**	**Eligible costs**	**Total Score**	**Reduction %**
1	EuAPS	INFN	22.350.588,00 €	191	-17.6
2	I-PHOQS	Consiglio Nazionale Ricerche	50.000.000,00 €	188	-16.7
3	LNGS	INFN	20.058.826,53 €	185	-19.0
4	K3NET	INFN	67.186.973,06 €	183	-13.0
5	IR0000027	Consiglio Nazionale Ricerche	75.165.077,53 €	182	-21.1
6	IR0000037	ISPRA	16.671.850,52 €	181	-12.5
7	IR0000012	INAF	71.477.540,83 €	181	-19.9
8	IRIS	INFN	59.996.968,15 €	180	-20.0

Qualità scientifica: 50/50;
Impatto: 47/50;
Implementazione: 94/100

EuPRAXIA Advanced Photon Source

Budget Distribution among WPs

Funded by the European Union

Università di Roma Tor Vergata

INFN Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale Ricerche

INFN Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale Ricerche

COSTS (€) WORK PACKAGE [WP.2 - Betatron Radiation Source]

	Costs included in the request for funding		
	To be located within the eight southern Regions	To be located outside the eight southern Regions	**Total requested grant**
a. Fixed term personnel specifically hired for the project	120.000,00	878.000,00	998.000,00
b. Scientific instrumentation and technological equipment, software licenses and patent	1.000.000,00	6.840.400,00	7.840.400,00
c. Open Access, Trans National Access, FAI principal implementation	0,00	0,00	0,00
d. Civil infrastructures and related systems	0,00	0,00	0,00
e. Indirect costs, including running costs	78.400,00	540.288,00	618.688,00
f. Training activities	0,00	0,00	0,00
Total	1.198.400,00	8.258.688,00	9.457.088,00

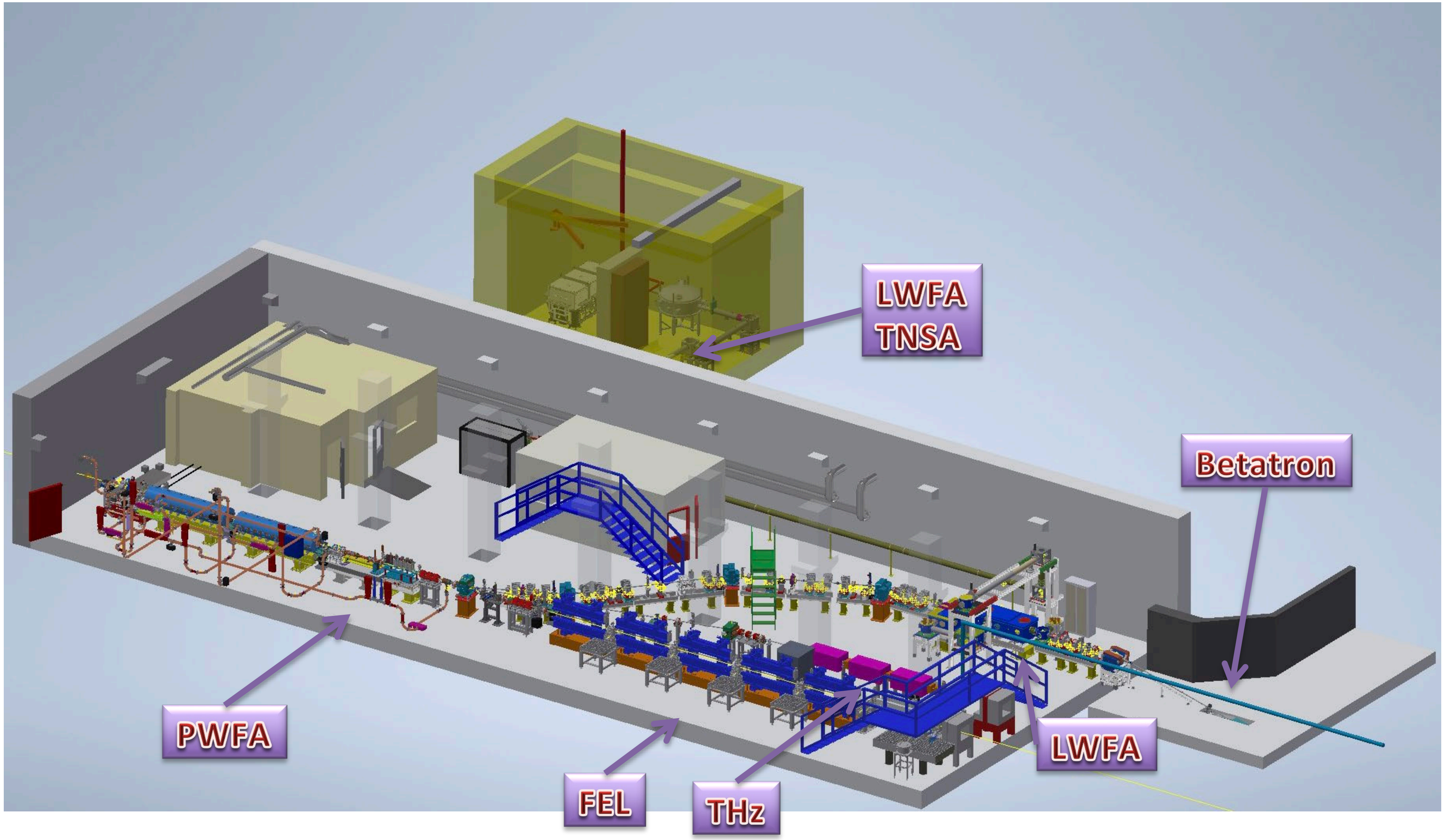
COSTS (€) WORK PACKAGE [WP.3 - High Power Laser Beam Line]

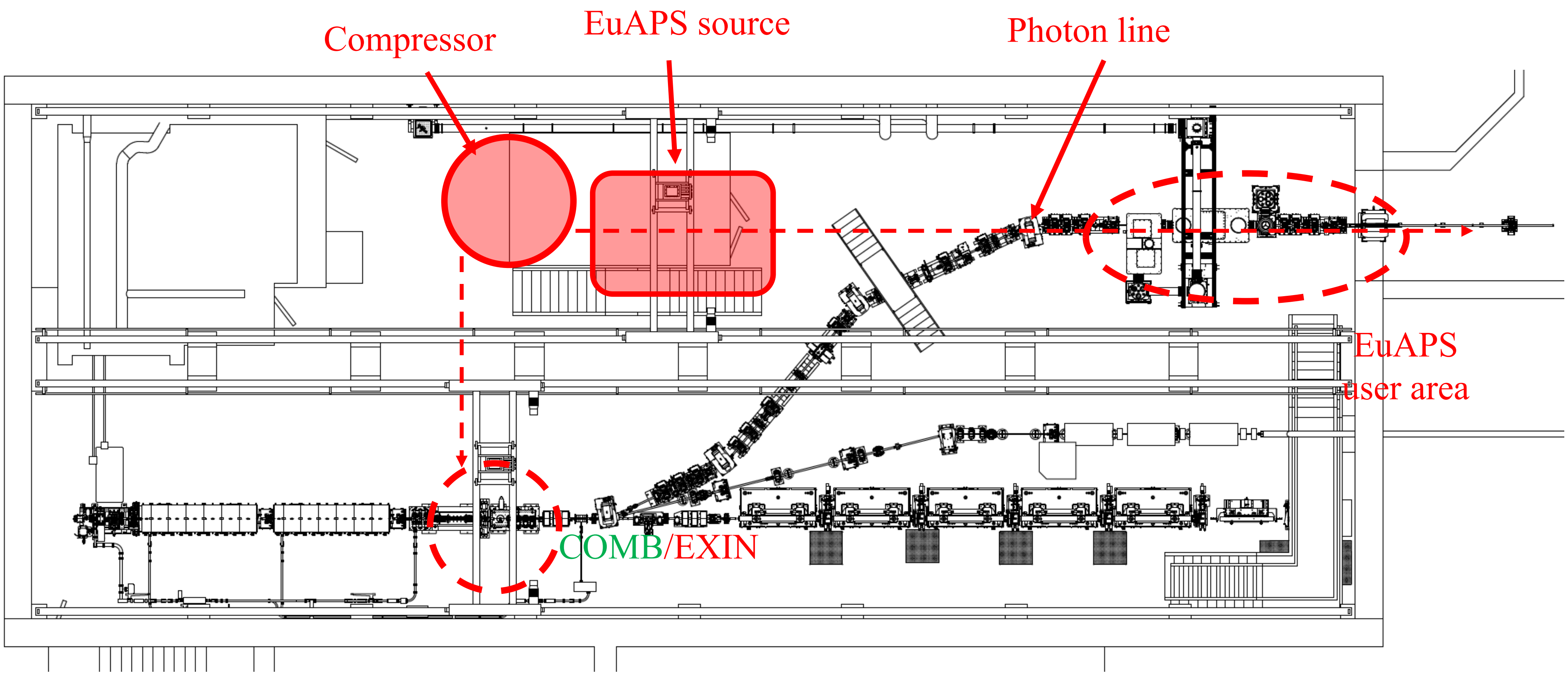
	Costs included in the request for funding		
	To be located within the eight southern Regions	To be located outside the eight southern Regions	**Total requested grant**
a. Fixed term personnel specifically hired for the project	150.000,00	0,00	150.000,00
b. Scientific instrumentation and technological equipment, software licenses and patent	5.917.812,47	0,00	5.917.812,47
c. Open Access, Trans National Access, FAI principal implementation	0,00	0,00	0,00
d. Civil infrastructures and related systems	1.300.006,38	0,00	1.300.006,38
e. Indirect costs, including running costs	496.681,15	0,00	496.681,15
f. Training activities	0,00	0,00	0,00
Total	7.864.500,00	0,00	7.864.500,00

COSTS (€) WORK PACKAGE [WP.4 - High Repetition Rate Laser Beam Line]

	Costs included in the request for funding		
	To be located within the eight southern Regions	To be located outside the eight southern Regions	**Total requested grant**
a. Fixed term personnel specifically hired for the project	0,00	240.000,00	240.000,00
b. Scientific instrumentation and technological equipment, software licenses and patent	0,00	4.024.986,00	4.024.986,00
c. Open Access, Trans National Access, FAI principal implementation	0,00	0,00	0,00
d. Civil infrastructures and related systems	0,00	280.000,00	280.000,00
e. Indirect costs, including running costs	0,00	318.164,00	318.164,00
f. Training activities	0,00	0,00	0,00
Total	0,00	4.863.150,00	4.863.150,00

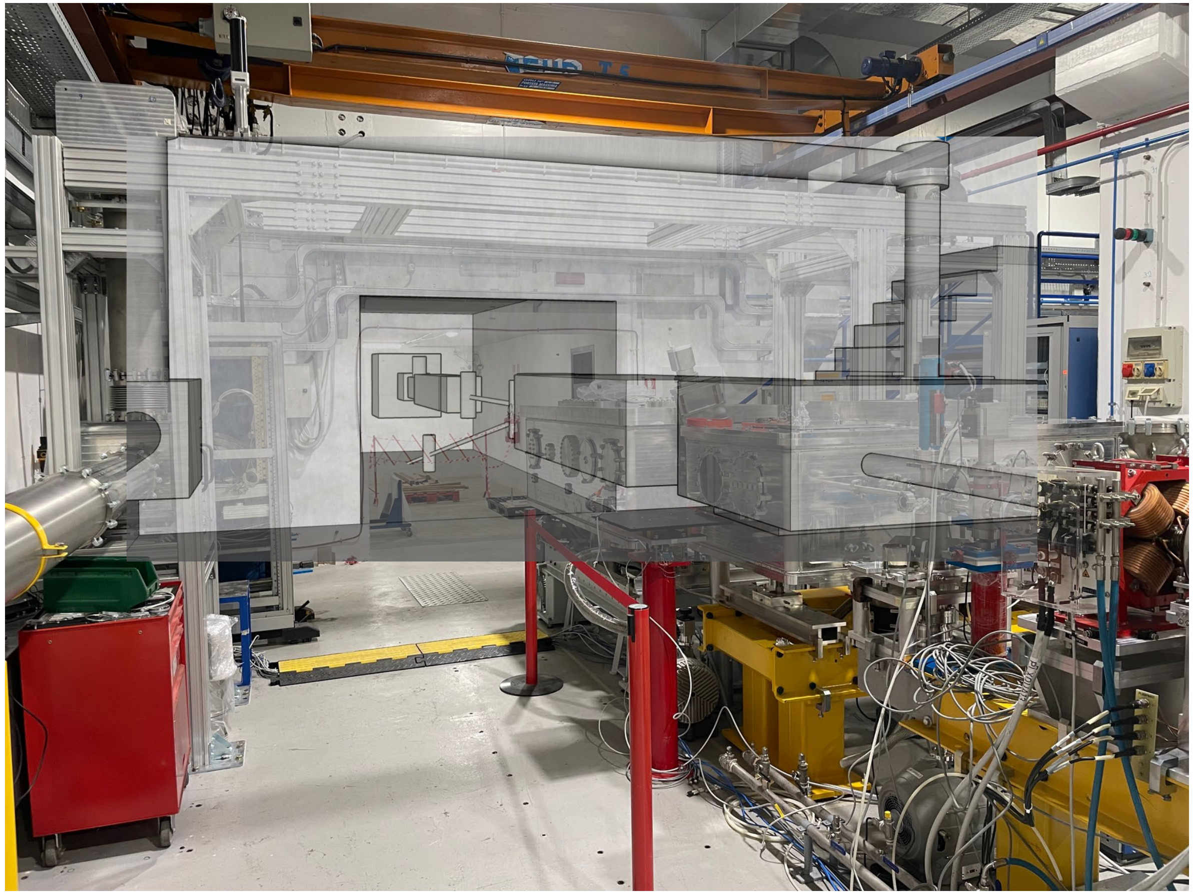
WP2 - Betaron Radiation Source at SPARC_LAB




Compressor
EuAPS source
Photon line
EuAPS user area
COMB/EXIN

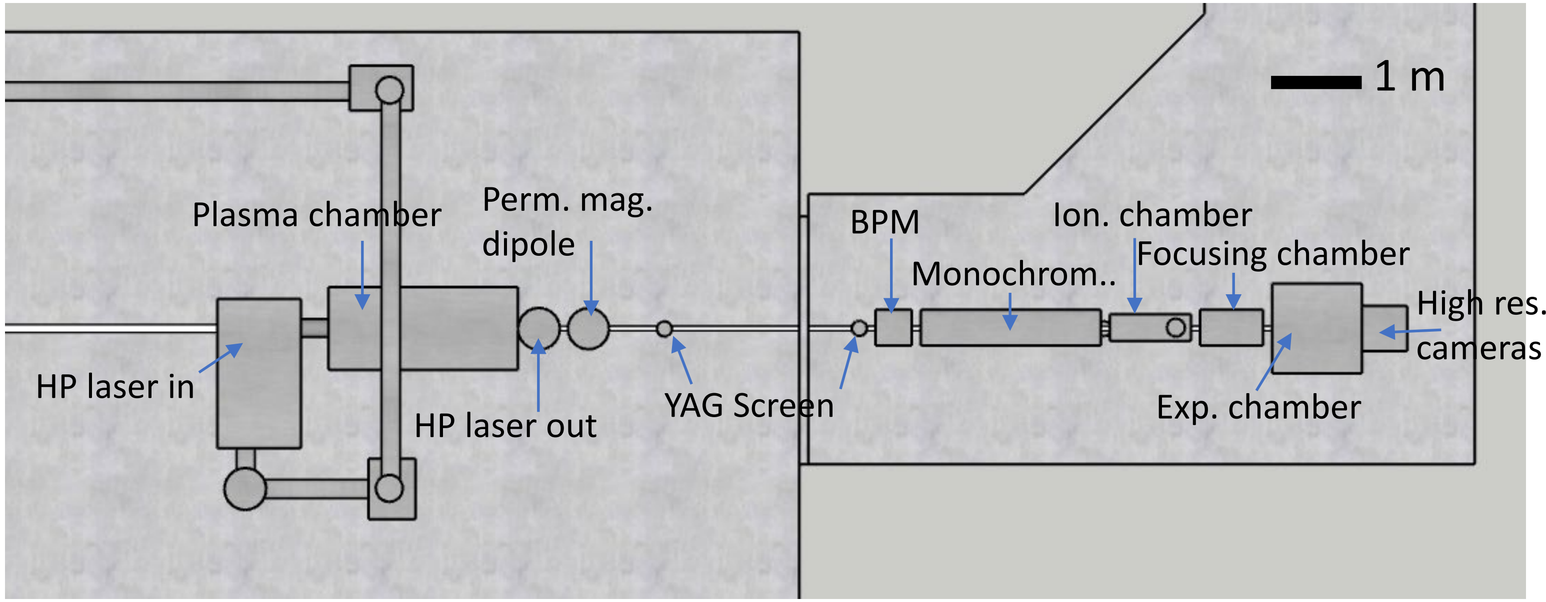
WP2 - Betaron Radiation Source at SPARC_LAB

- Laser/Plasma interaction chamber at SPARC_LAB just intalled and possible betatron radition user's beam line



WP2 - Betaron Radiation Source at SPARC_LAB

Electron beam Energy [MeV]	100-500
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^{6} – 10^{8}



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]

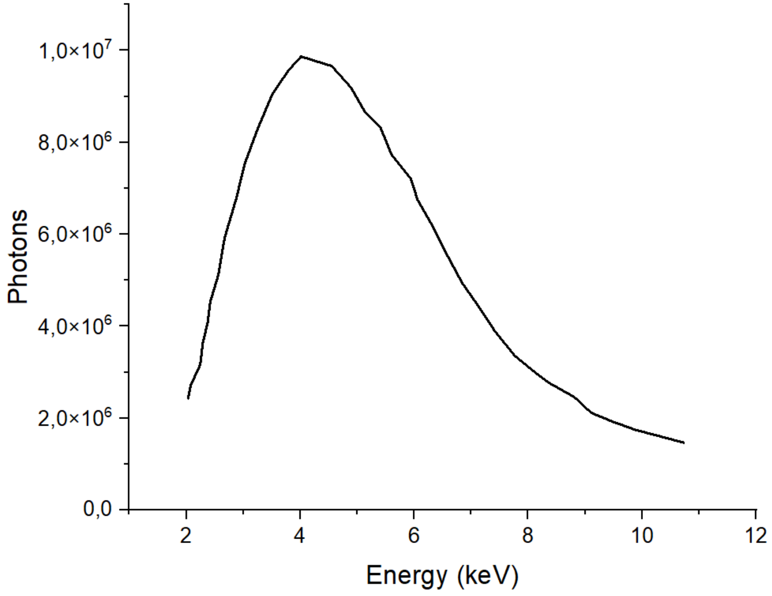


Fig. 6. Betatron radiation spectrum detected by the *CdTe* spectrometer. Laser, plasma and electron parameters: energy per pulse $E_L = 1.5$ J, pulse duration $\tau = 35$ fs, focus rms radius $\sigma_r \sim 5$ µm. Electron plasma density $n_e \sim 6 \pm 1 \times 10^{18}$ cm^{-3}, electron mean energy 200 MeV, energy spread 30%, electron beam divergence 12 mrad, bunch charge 20 pC. The acceleration length was 1 mm.

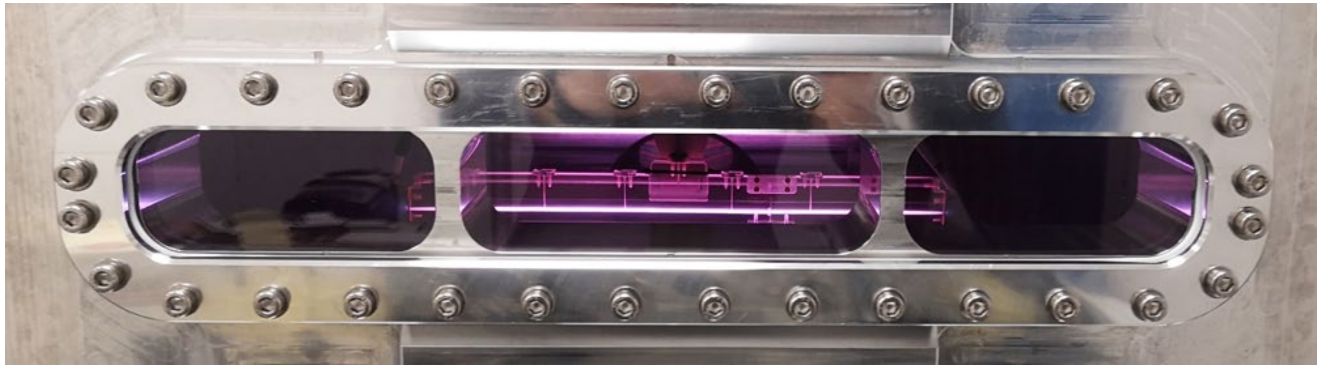
WP1 - Betaron Radiation Source at EuPRAXIA@SPARC_LAB

Funded by the European Union

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]

$$\boxed{\frac{d^2I}{d\omega d\Omega}(\theta=0) \cong \frac{N_\beta 3e^2}{2\,\pi^3\epsilon_0 c}\,\gamma^2\left(\frac{\omega}{\omega_c}\right)^2 K_{\frac{2}{3}}^2\left(\frac{\omega}{\omega_c}\right)}$$



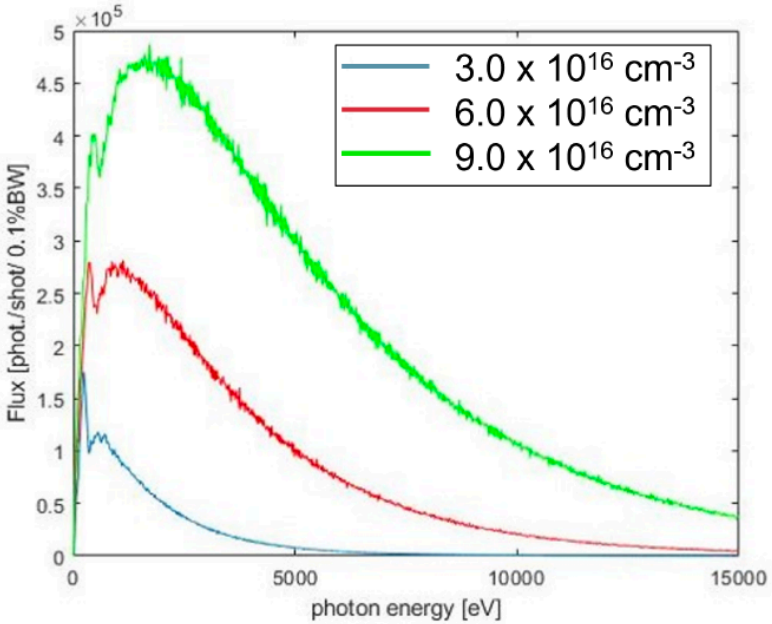


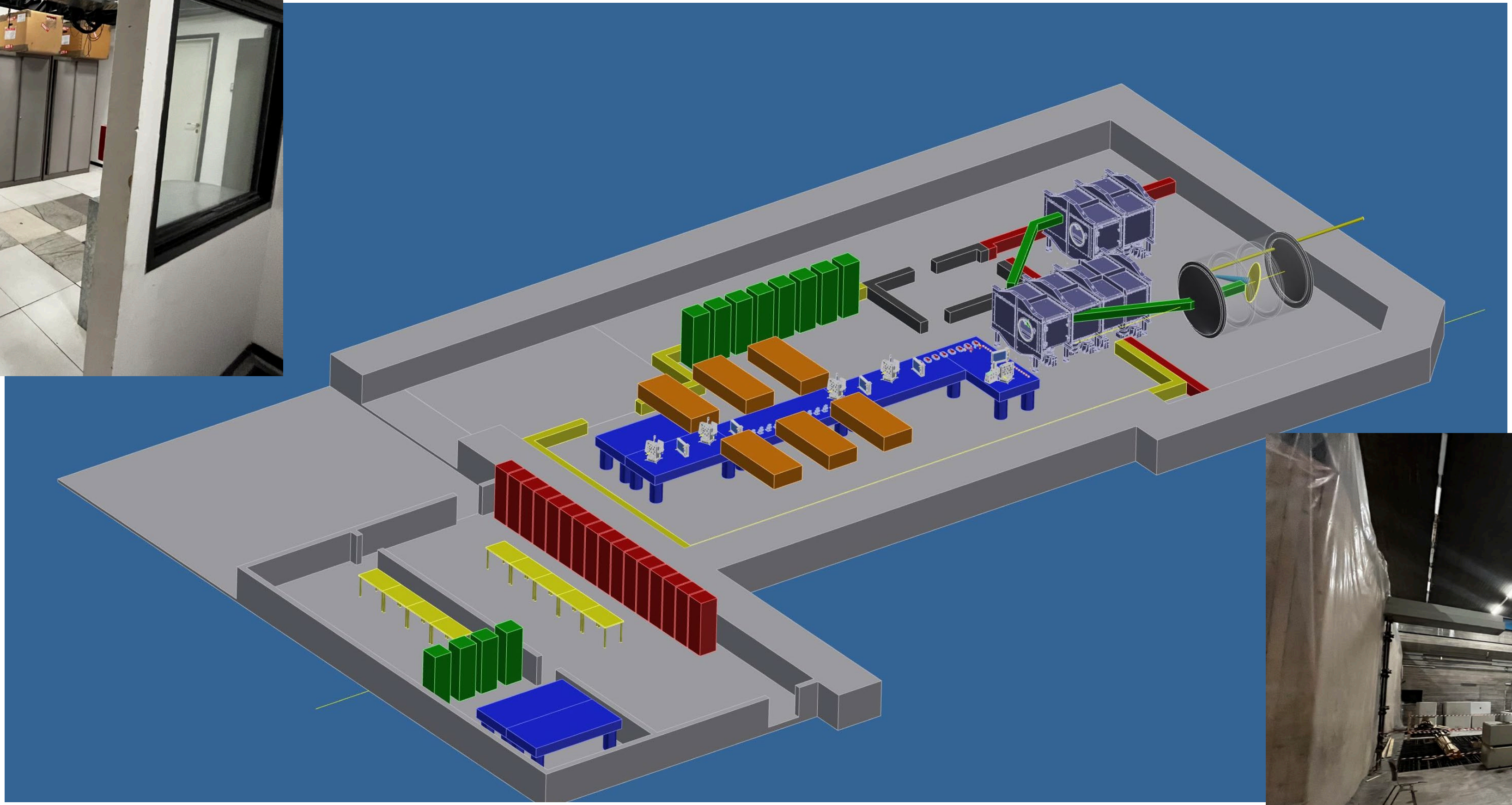
Figure 1. Betatron radiation spectra simulated for a source size of 3 μm and 3 different plasma densities. The total number of photons is 1.7 x ^{9} for the 9.0 x 10^{16} cm^{-3} density, 9.9 x ^{8} for the 6.0 x 10^{16} cm^{-3} density and 4.1 x ^{8} for the 3.0 x 10^{16} cm^{-3} density.

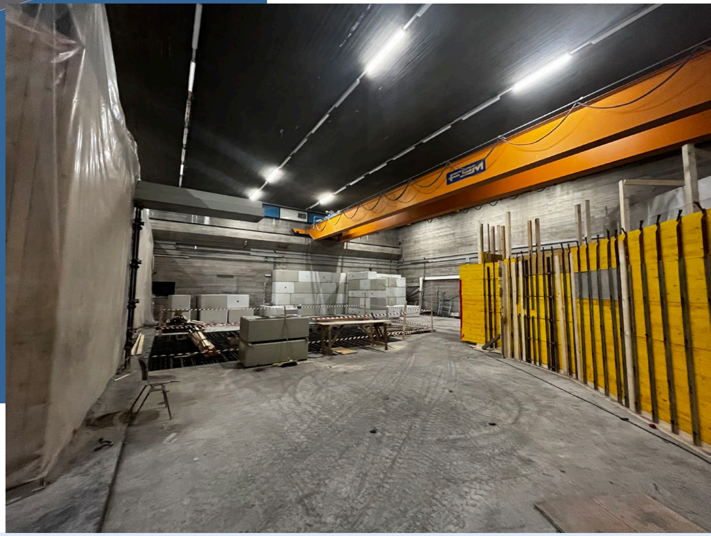
Betatron Imaging (PCI, CT) => sub-μ resolution
Betatron X-ray tme-resoved spectroscopy (XAS)
Beam Diagnostics
FEL Seeding
Betatron coherence

WP3 - I-LUCE INFN-Laser indUced radiation acCEleration

Funded by the European Union

At INFN-LNS-Catania the focus will be placed on high charge secondary particle production with innovative high power lasers.



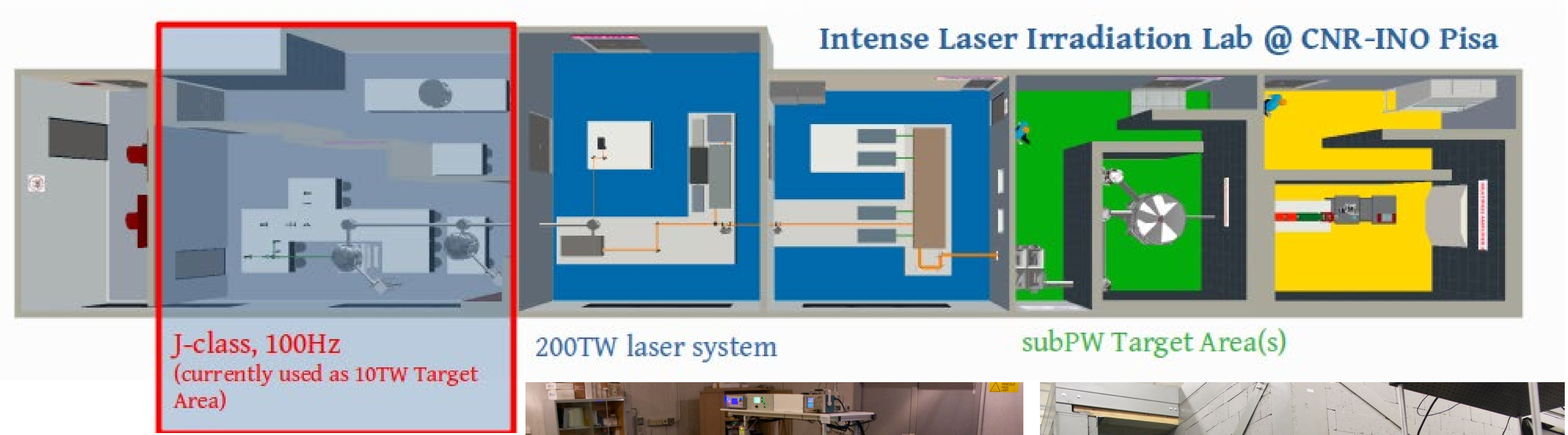


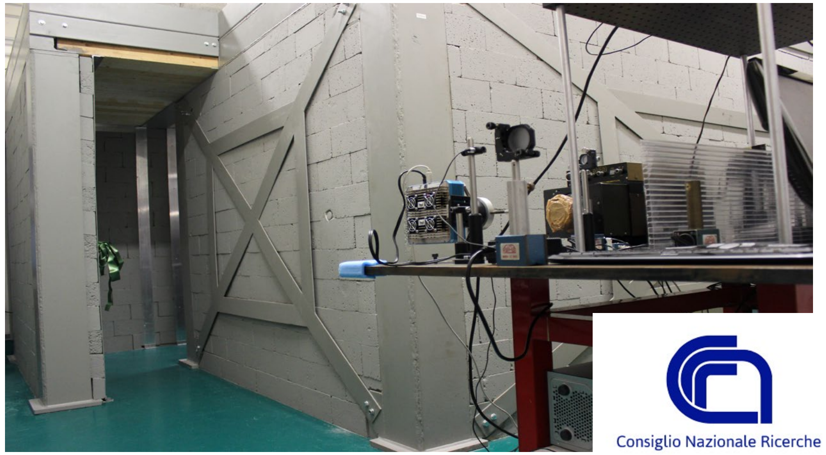
INFN
Istituto Nazionale di Fisica Nucleare
LNS

WP4 - J-class, 100Hz laser infrastructure @CNR-INO Pisa

Funded by the European Union

At CNR-Pisa the consortium will establish user access to the next generation of kW scale high repetition rate laser.





The new ultrashort, J-class, high rep rate laser facility is expected to be hosted in the 10TW Target Area (~100m2 excluding room for ancillaries) currently available.

Consiglio Nazionale Ricerche

Conclusions

- One of the ambitions of EuAPS is to be the first operating brick of the EuPRAXIA project well in advance compared to the EuPRAXIA time scale.

- Thus bringing together laser, plasma and advanced accelerator scientists with radiation user's experts to promote the blooming of a new scientific community well prepared to efficiently exploit the scientific opportunities of EuPRAXIA.

- Significant advancement in Laser Technology for EuPRAXIA

- X-ray users beam line scientific case in preparation, medical applications

- A lot of new interesting beam physics still possible (various plasma configurations, plasma undulator and FEL, beam diagnostics, limitation for LC)

Thanks for your attention

SPARC_LAB Tour at 14:30

Funded by the European Union

Towards EuPRAXIA 2nd Site

Eupraxia laser development is aimed at delivering more efficient, kW class PW laser driver for plasma acceleration at >100 Hz rate

- **EuPRAXIA**
- PW class,
- 100 Hz repetition rate,
- multi kW average power,
- diode pumped
- Full thermal load transport

Advanced Photon Sources

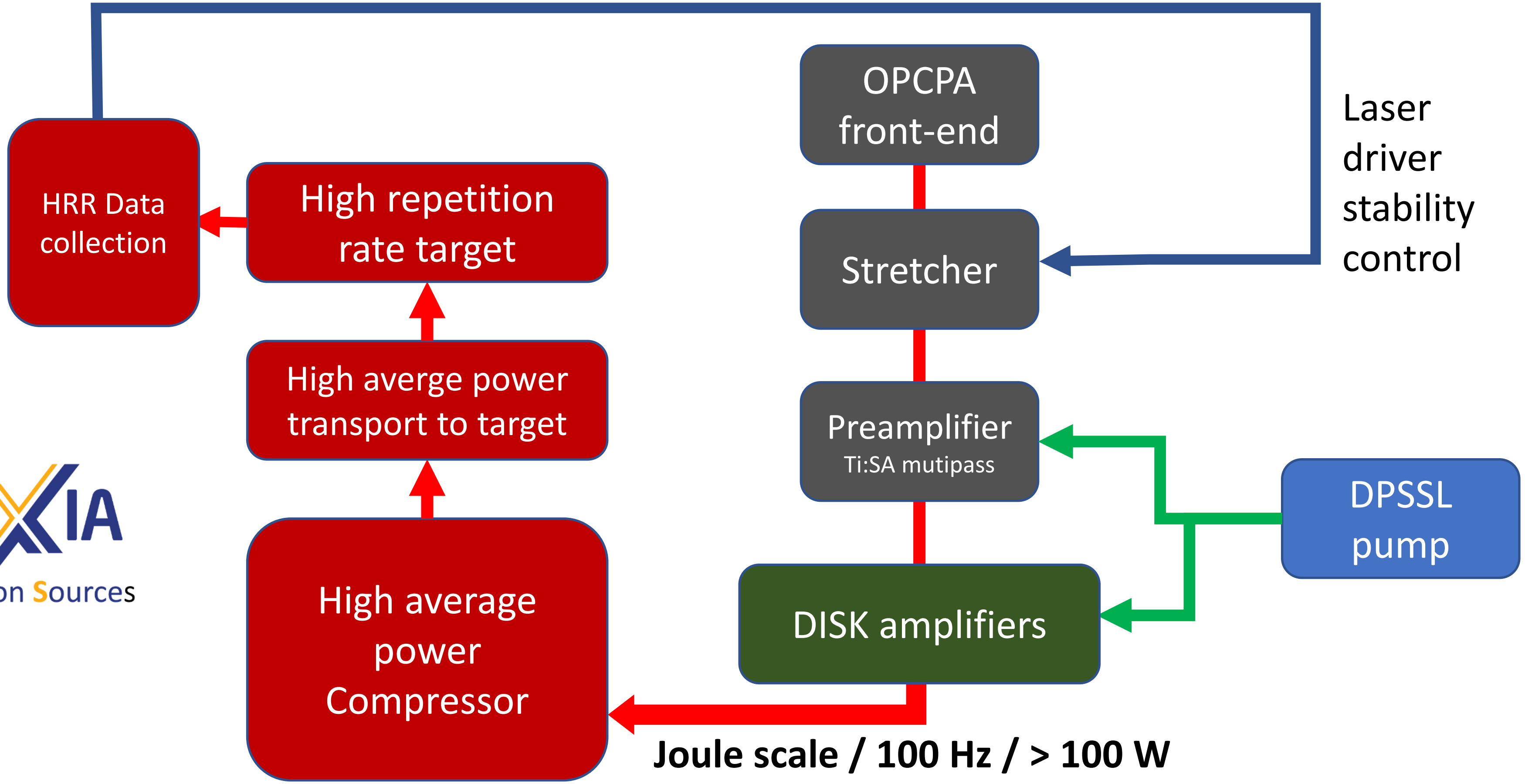
- **EuAPS**
- 50 TW peak power
- 100 Hz repetition rate
- 100 W average power
- Diode pumped
- Thermal load effects

- **CURRENT**
- **PW class,**
- **Hz repetition rate,**
- **≈10 W average power**
- **flashlamp pumped**
- **No thermal load transport**

EuPRAXIA Front-end development ongoing

Funded by the European Union

100 Hz operation at Joule level pulse energy is outstanding and a unique opportunity to address HAP issues



EuPRAXIA Advanced Photon Sources

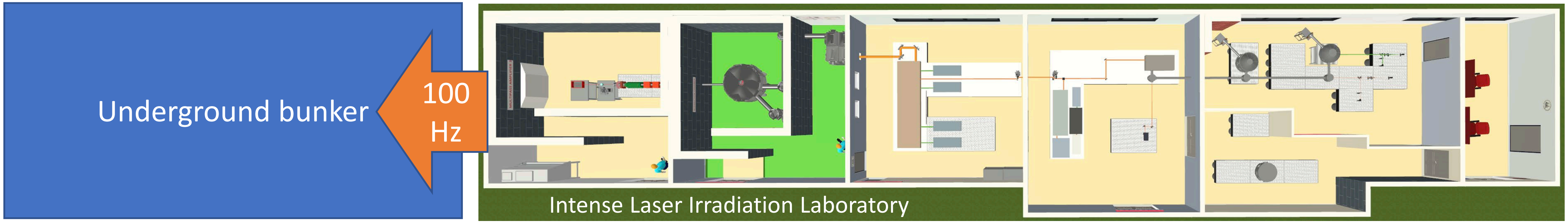
Part of the EUAPS (Eupraxia Advanced Photon Sources, 4.8 M€ dedicated funding @ CNR-Pisa)

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

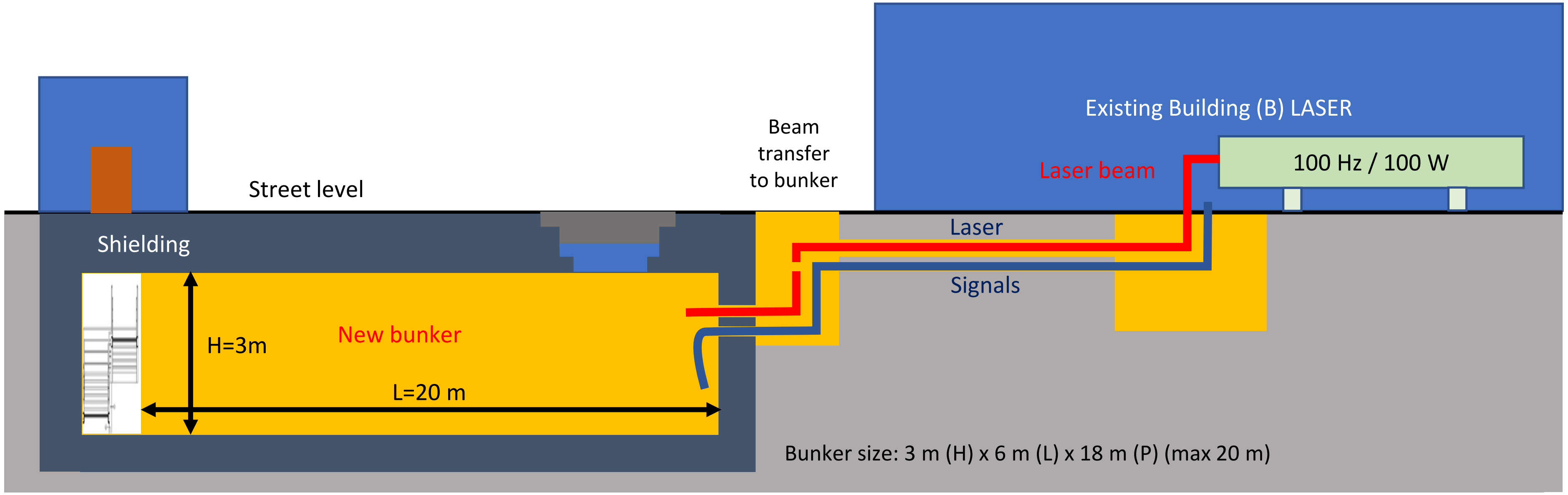
User Facility Upgrade at CNR-Pisa (EULAb-Med)

Funded by the European Union

Full 100 Hz system at Joule level will allow to tackle operational issues and mechanical stability

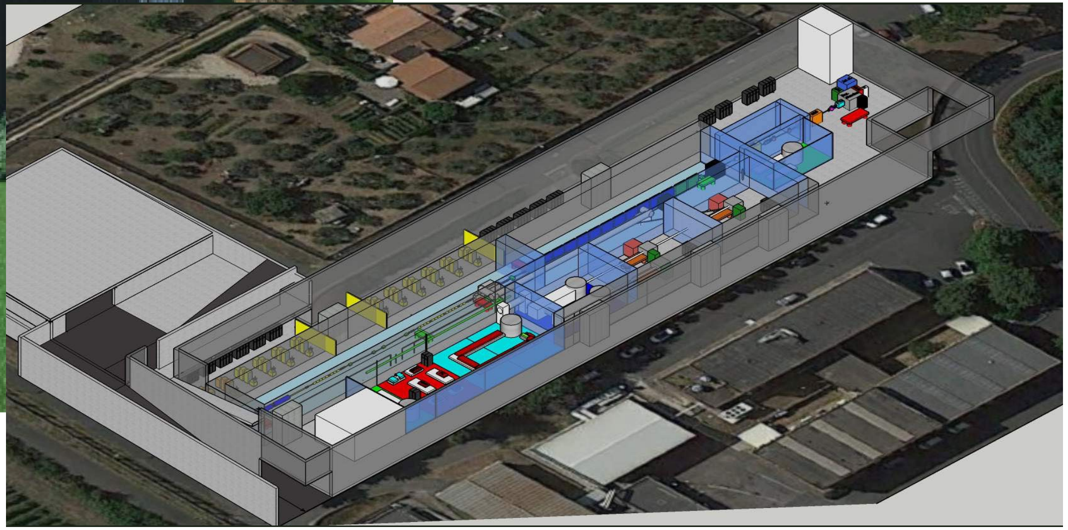


New bunker
Designed for high dose irradiation (100 Hz)



Part of the IPHOQS (ELI/LENS/CUSBO Photonics Infrastructure), and Tuscan Health Ecosystem 4.5 M€ dedicated funding @ CNR-Pisa)

Headquarter and Site 1: EuPRAXIA@SPARC_LAB



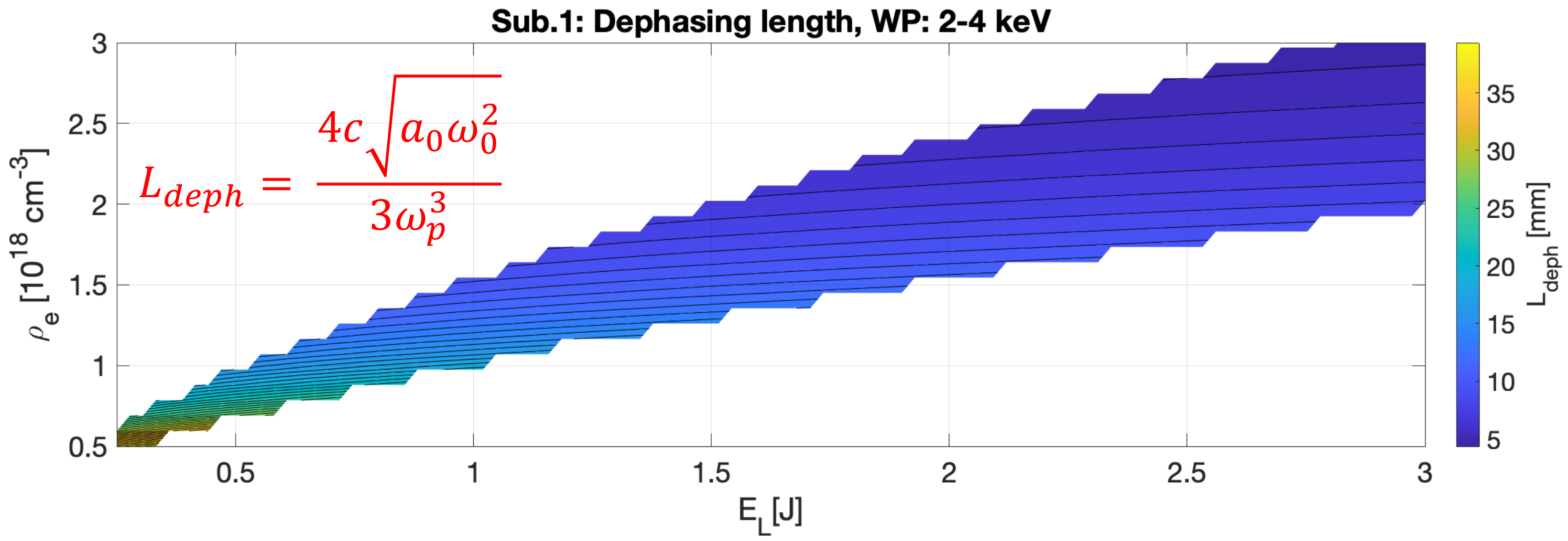
Laser-plasma parameters

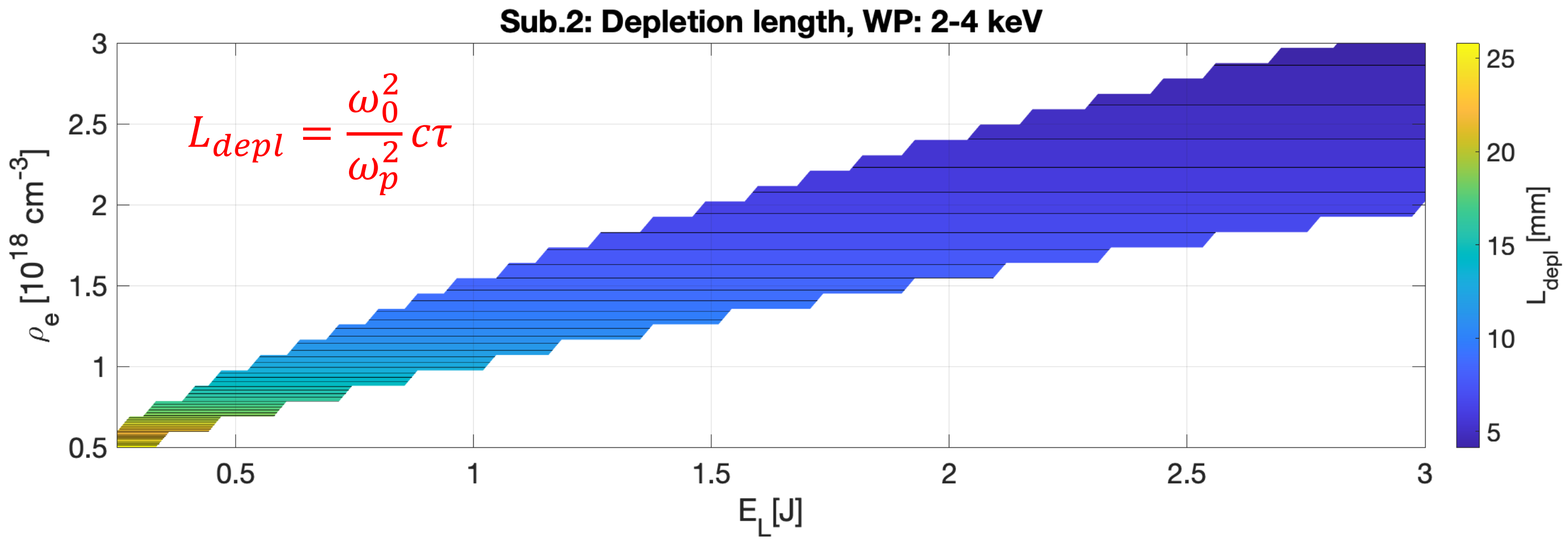
SCAN:

Minimun Energy	*0.25 J*
Maximum Energy	*3 J*
Temporal length	*25 fs*
Wave length	*800 nm*
Beam Waist ✻	*15 µm*
Min Plasma Density	*10^{17} cm^{-3}*
Max Plasma Density	*10^{19} cm^{-3}*

✻ FWHM Intensity

NB: $z_R = \dfrac{\pi\omega_0^2}{\lambda} = 0.9\ mm$



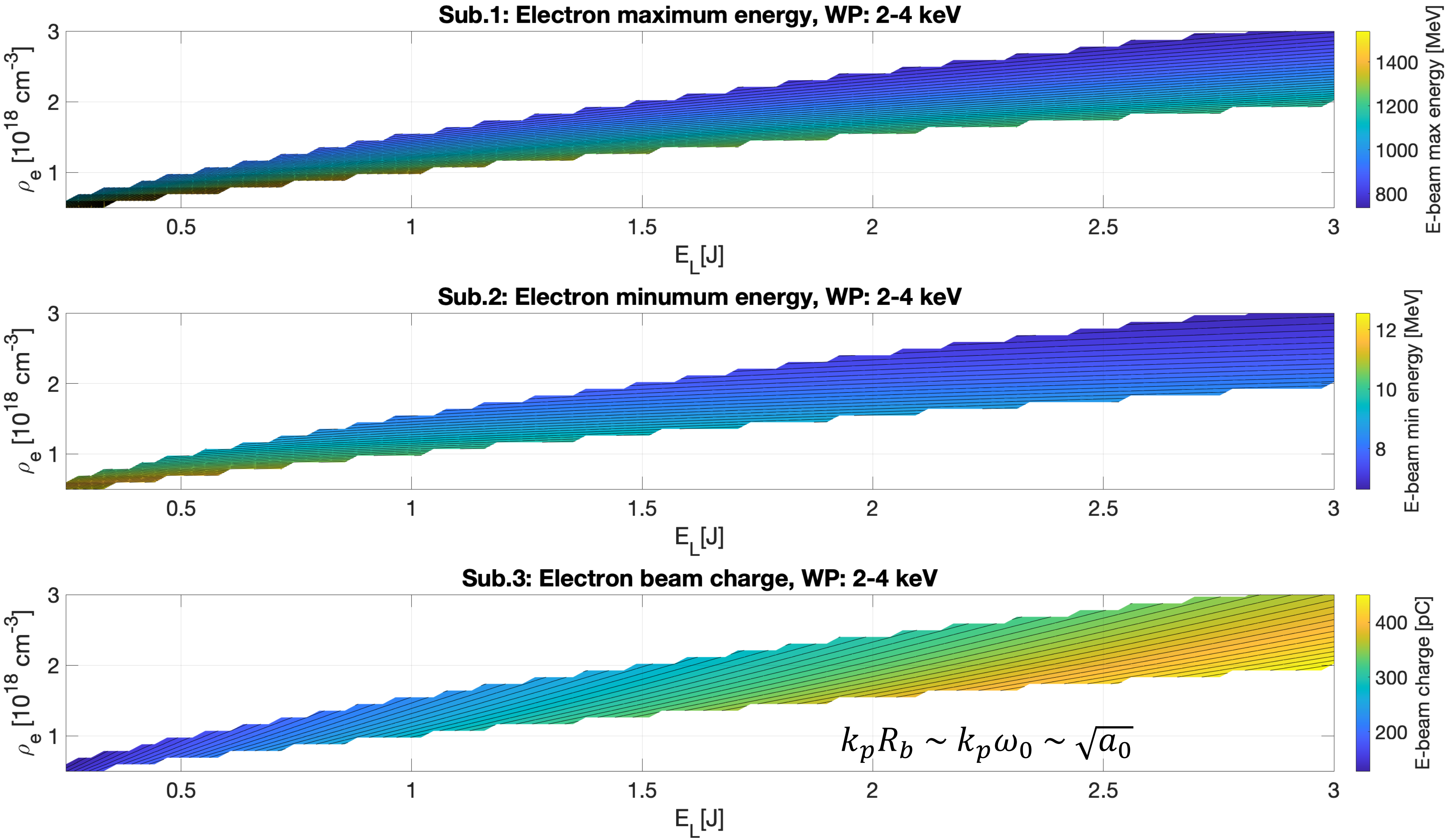


Electron beams

$$E_{max} = \frac{2}{3} a_0 \frac{\omega_0^2}{\omega_p^2} mc^2$$

$$E_{min} \sim \sqrt{\frac{a_0^{1/2} L_{acc}}{\pi \omega_0} mc^2}$$

$$Q = \frac{(2\sqrt{a_0})^3 q}{30\, k_p r_e}$$

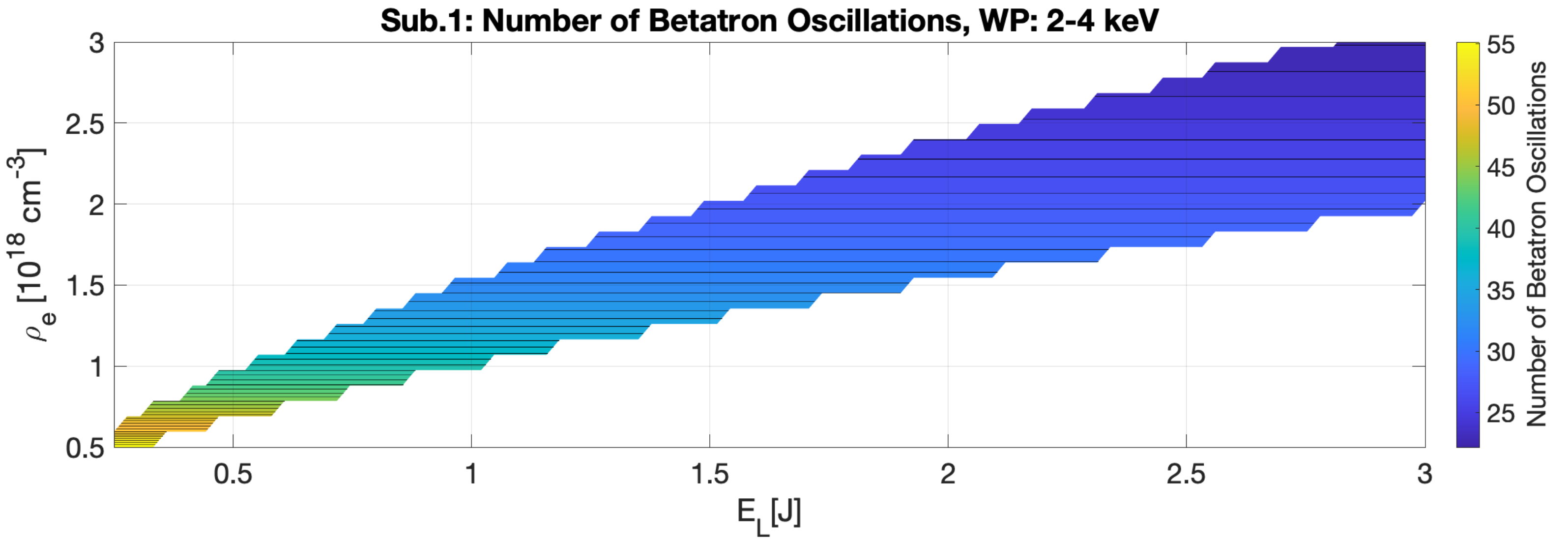


Betatron Radiation

Number of Betatron Oscillations:

$$N_b \sim \frac{k_p \;\; L_{deph}(E_{max})}{\sqrt{3\, E_{max}}}$$

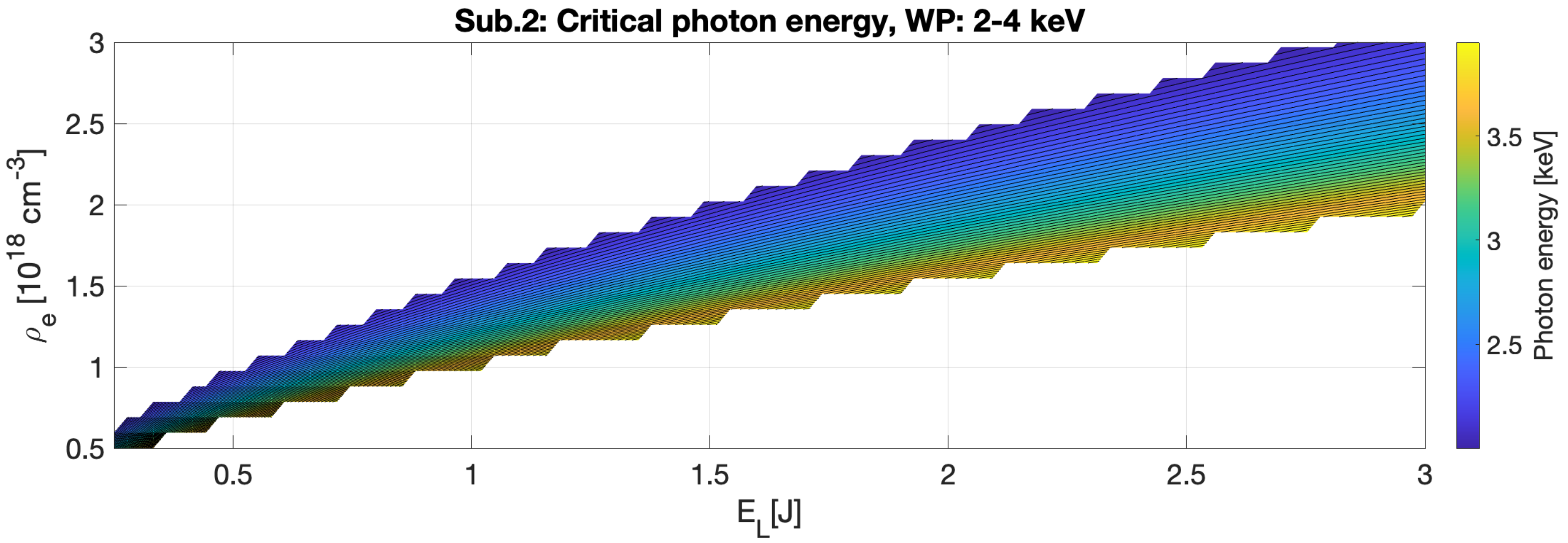
maximum electron energy E_{max}



Critical photon energy:

$$E_c \sim 1.5\, \hbar\, E_{max}^3 \sigma\, k_\beta^2(E_{max}) c$$

where $k_\beta(z) = \, k_p/\sqrt{3\gamma(z)}$



Betatron Radiation Energy $E_c = 2 - 4\ keV$

$1.9\ keV < E_c < 2.1\ keV$

$E_L\ (J)$	$\rho\ (10^{18}\ cm^{-3})$	$L_{deph}\ (mm)$	$L_{depl}\ (mm)$	$E_{max}\ e^-\ (MeV)$	$E_{min}\ e^-\ (MeV)$	$Q\ e^-\ (pC)$	N_b
1.5	2	7	6	800	8	260	28
2	2.5	6	5	800	8	300	25
2.5	2.8	5	4.5	740	7	330	23

$2.9\ keV < E_c < 3.1\ keV$

$E_L\ (J)$	$\rho\ (10^{18}\ cm^{-3})$	$L_{deph}\ (mm)$	$L_{depl}\ (mm)$	$E_{max}\ e^-\ (GeV)$	$E_{min}\ e^-\ (MeV)$	$Q\ e^-\ (pC)$	N_b
2.6	2.1	7.5	6.1	0.98	8	390	27
2.8	2.2	7	5.7	1	8	400	26
3	2.3	6.7	5.6	1	8	410	25

$3.9\ keV < E_c < 4.2\ keV$

$E_L\ (J)$	$\rho\ (10^{18}\ cm^{-3})$	$L_{deph}\ (mm)$	$L_{depl}\ (mm)$	$E_{max}\ e^-\ (GeV)$	$E_{min}\ e^-\ (MeV)$	$Q\ e^-\ (pC)$	N_b
2.9	1.9	9	7	1.2	9	450	29

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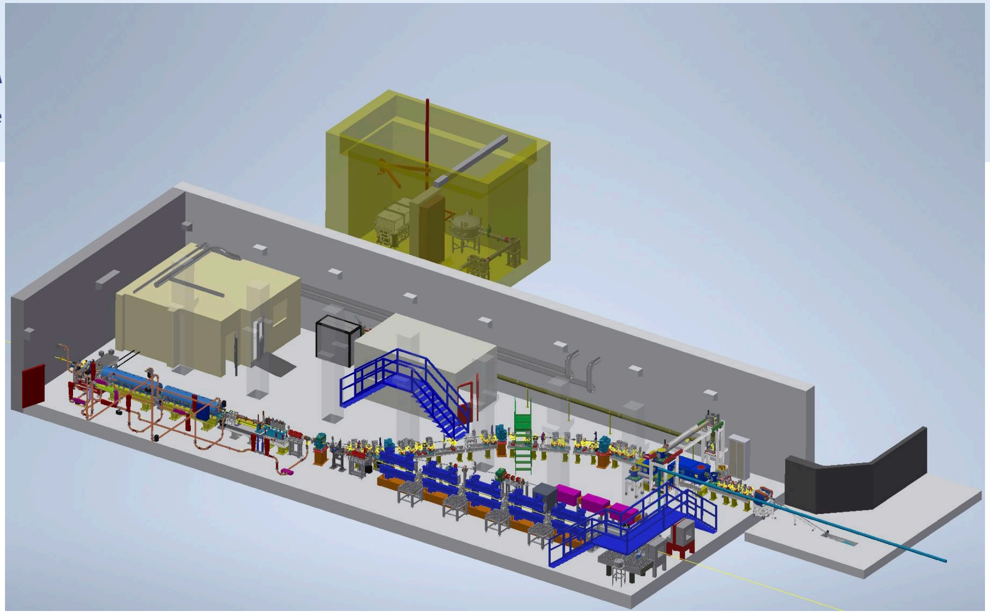

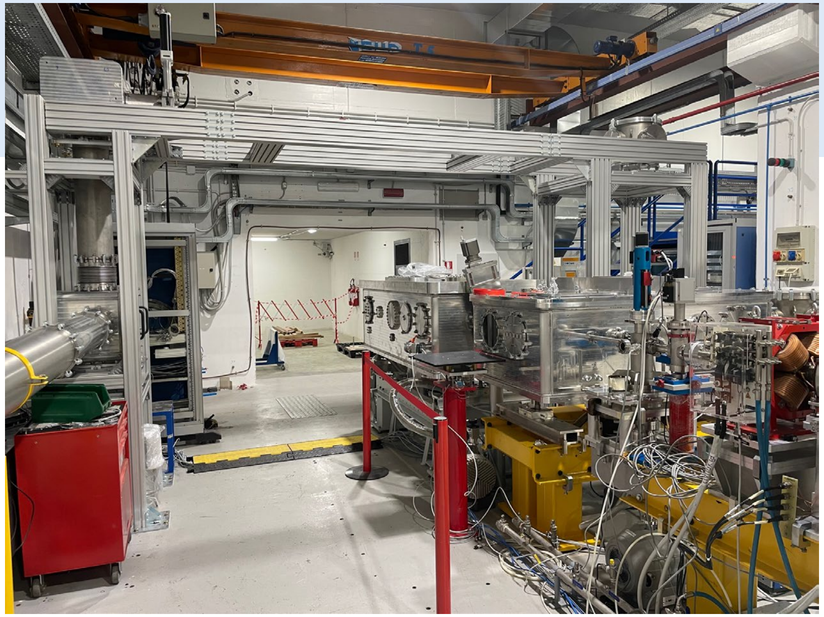

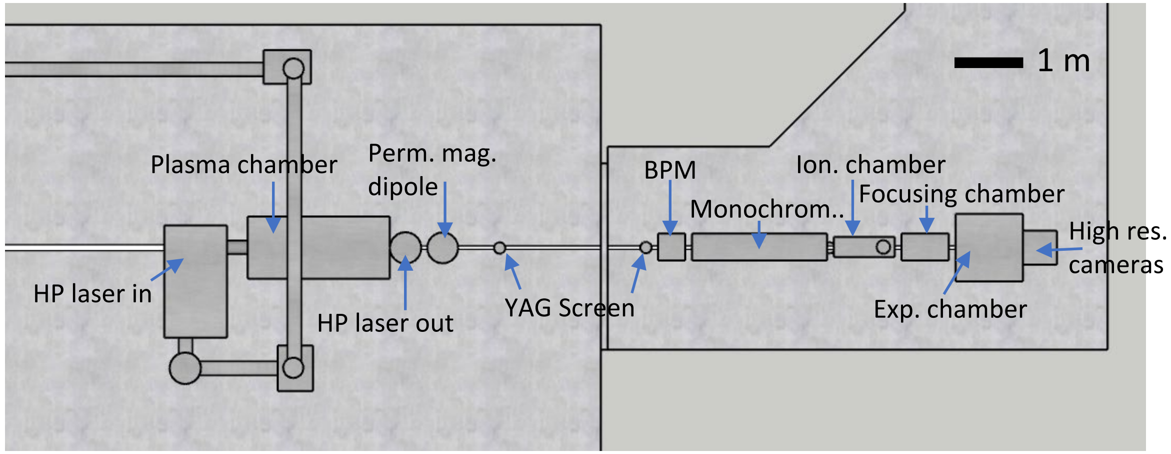

Electron beam Energy [MeV]	100-500
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^{6} – 10^{8}

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]

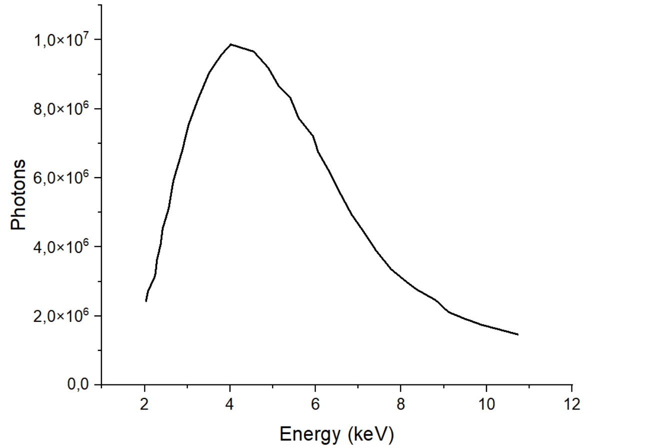

Fig. 6. Betatron radiation spectrum detected by the *CdTe* spectrometer. Laser, plasma and electron parameters: energy per pulse $E_L = 1.5$ J, pulse duration $\tau = 35$ fs, focus rms radius $\sigma_r \sim 5$ µm. Electron plasma density $n_e \sim 6 \pm 1 \times 10^{18}$ cm^{-3}, electron mean energy 200 MeV, energy spread 30%, electron beam divergence 12 mrad, bunch charge 20 pC. The acceleration length was 1 mm.

Phased Implementation of Construction Sites

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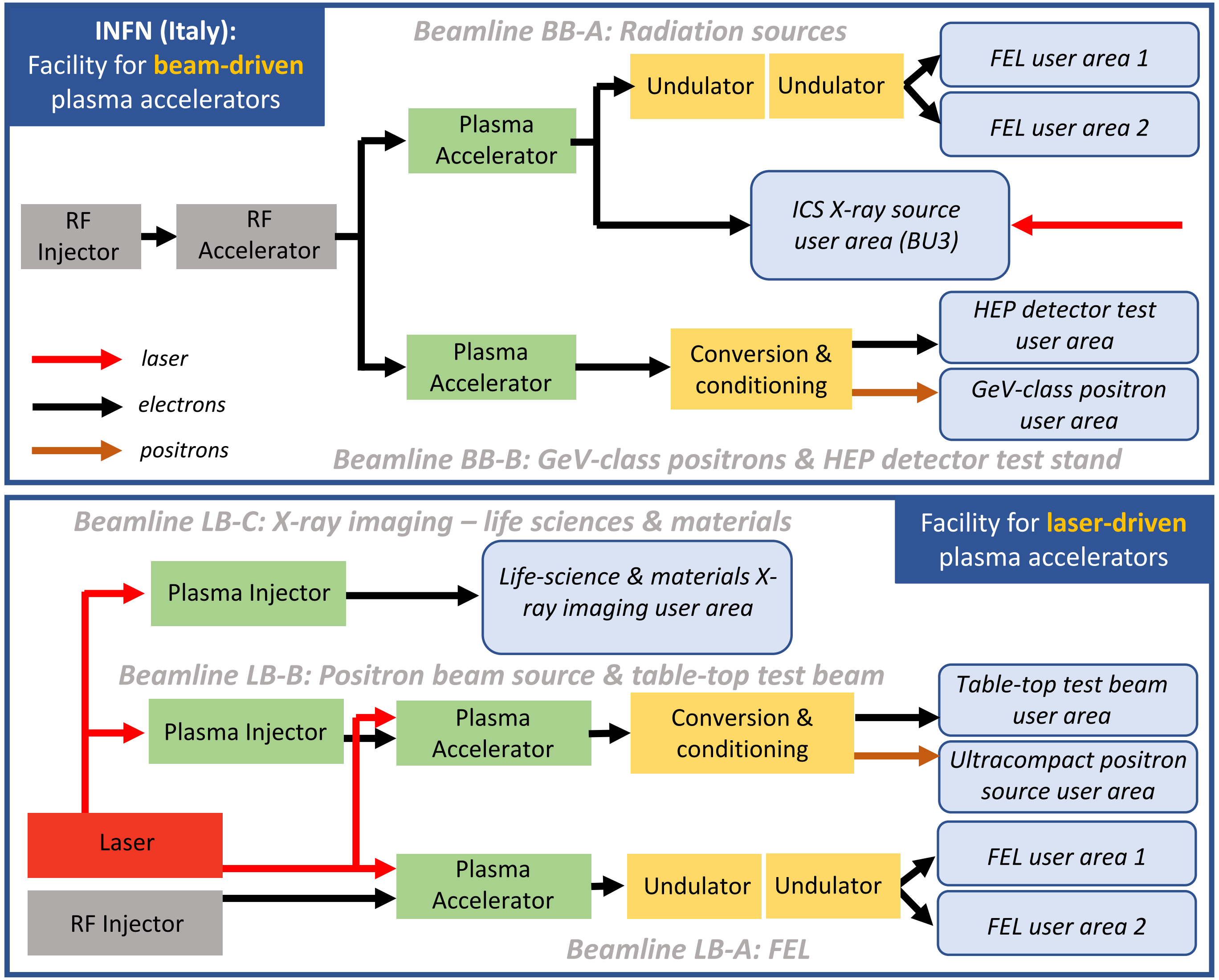
	Laser-driven	Beam-driven
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ Ultracompact positron source beamline + positron user area	✓ FEL beamline to 1 GeV + user area 1 **1** ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area **2** ✓ Table-top test beams user area ✓ FEL user area 2 ✓ FEL to 5 GeV	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ High-field physics beamline / user area ✓ Other future developments	✓ Medical imaging beamline / user area ✓ Other future developments

1: INFN-LNF construction funding 108 M€

2: INFN/CNR/TorVer demo facility 22 M€ (PNRR)



Courtesy R. Assmann