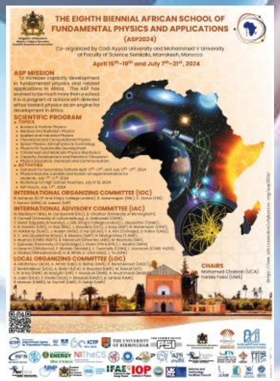
EUROPEAN
PLASMA RESEARCH
ACCELERATOR
WITH
EXCELLENCE IN
APPLICATIONS

The EuPRAXIA Project

a plasma-based accelerator user facility for the next decade

Massimo Ferrario (INFN-LNF)

On behalf of the EuPRAXIA Collaboration



THE EIGHTH BIENNIAL AFRICAN SCHOOL OF FUNDAMENTAL PHYSICS AND APPLICATIONS
(ASP2024)
Co-organized by Cadi Ayyad University and Mohammed V University at Faculty of Science Semlalia, Marrakesh, Morocco
April 15th–19th and July 7th–21st, 2024

ASP MISSION

To increase capacity development in fundamental physics and related applications in Africa. The ASP has evolved to be much more than a school. It is a program of actions with directed ethos toward physics as an engine for development in Africa.

SCIENTIFIC PROGRAM

INTERNATIONAL ORGANIZING COMMITTEE (IOC)

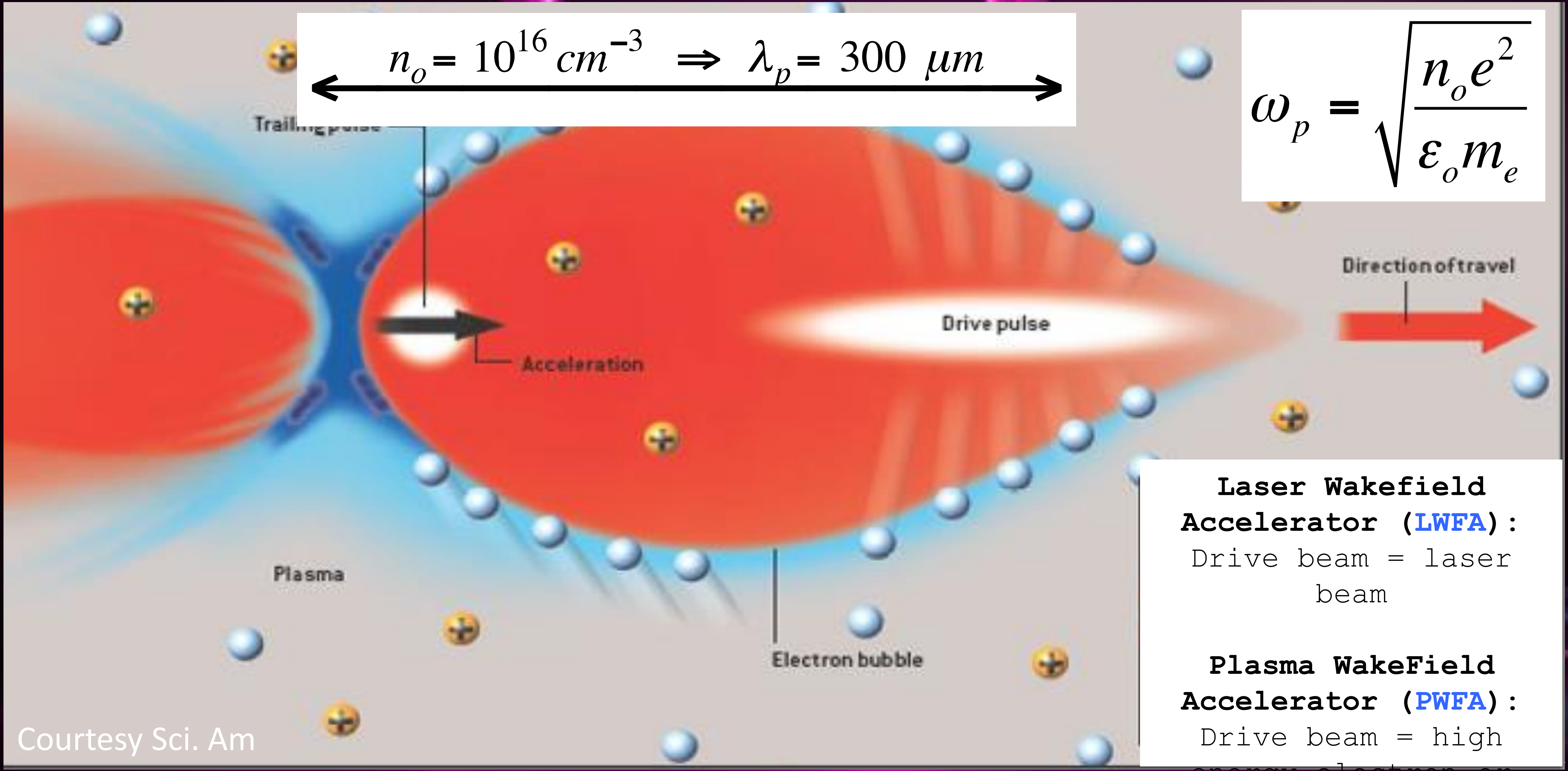
INTERNATIONAL ADVISORY COMMITTEE (IAC)

LOCAL ORGANIZING COMMITTEE (LOC)

CHAIRS
Mohamed Chabab (UCA)
Farida Fassi (UM5)

African School of Physics
Marrakech– 17 July 2024

Principle of plasma acceleration



$$n_o = 10^{16}\,cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

Courtesy Sci. Am

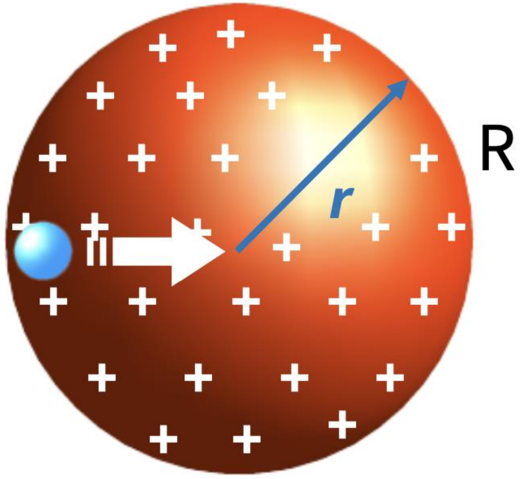
Laser WakeField Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

Principle of plasma acceleration

From Maxwell's equations, the electric field in a (positively) charged sphere with uniform density ***n_i*** at location **r** is

$$\vec{E}(r) = \frac{q_i n_i}{3\epsilon_0} r$$



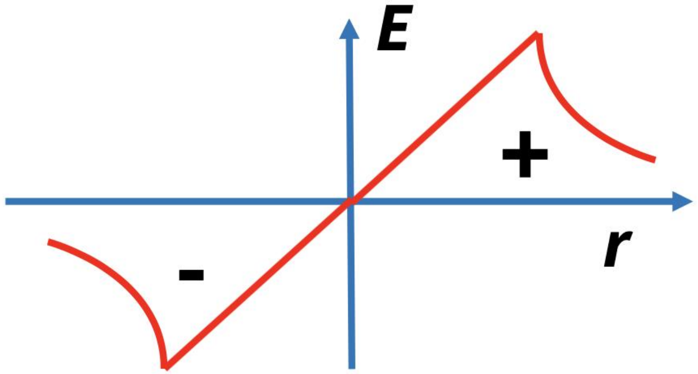
The field is **increasing** inside the sphere

Let's put some numbers

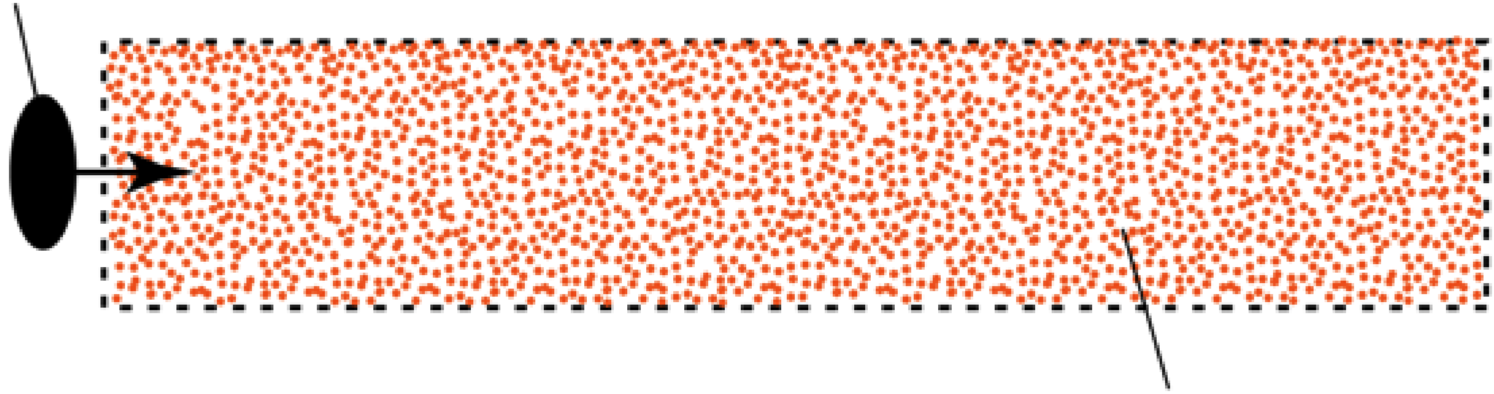
$n_i = 10^{16}$ cm^{-3}

R=0.5

$$E \approx 10 \frac{GV}{m}$$



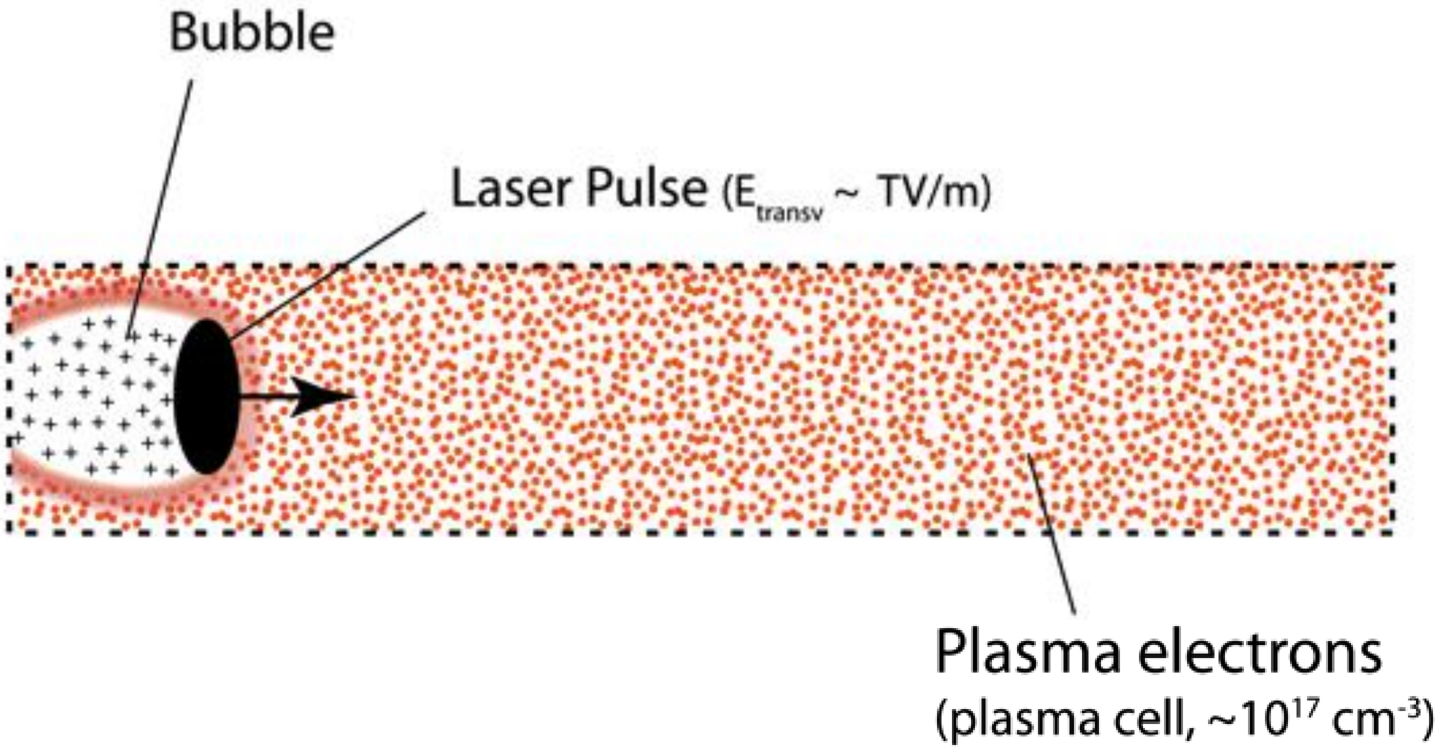
Plasma Wake-Acceleration



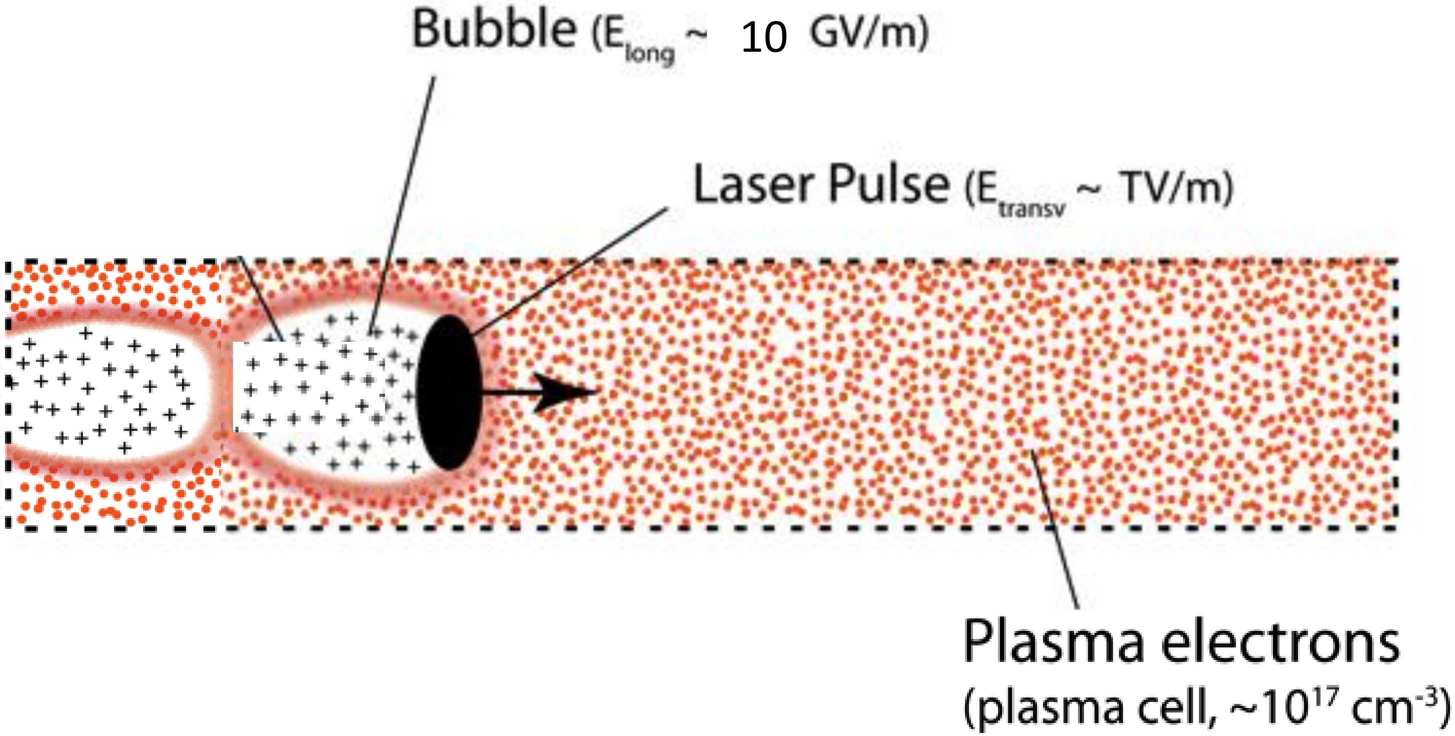
Laser Pulse (200 TW, ~30 fs, E_{transv} ~ TV/m)

Plasma electrons
(plasma cell, ~10^{17} cm^{-3})

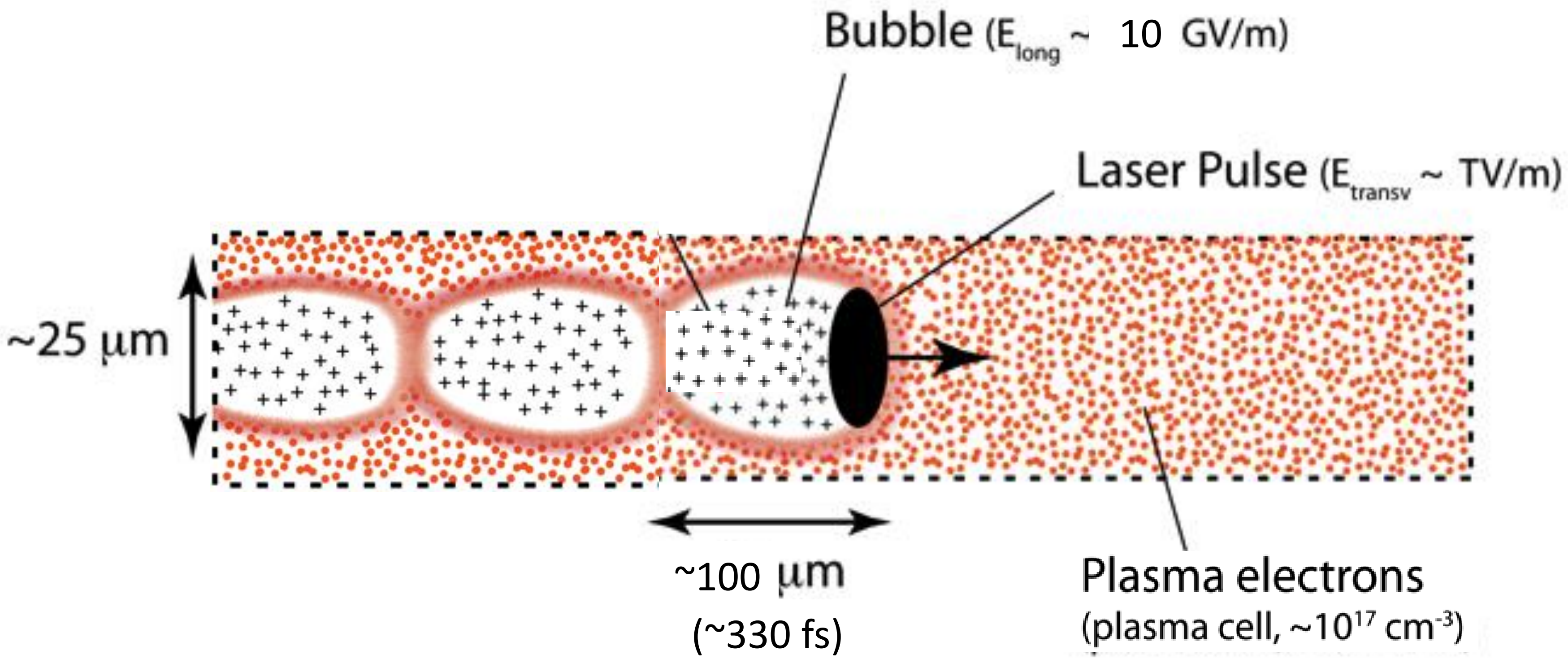
Plasma Wake-Acceleration



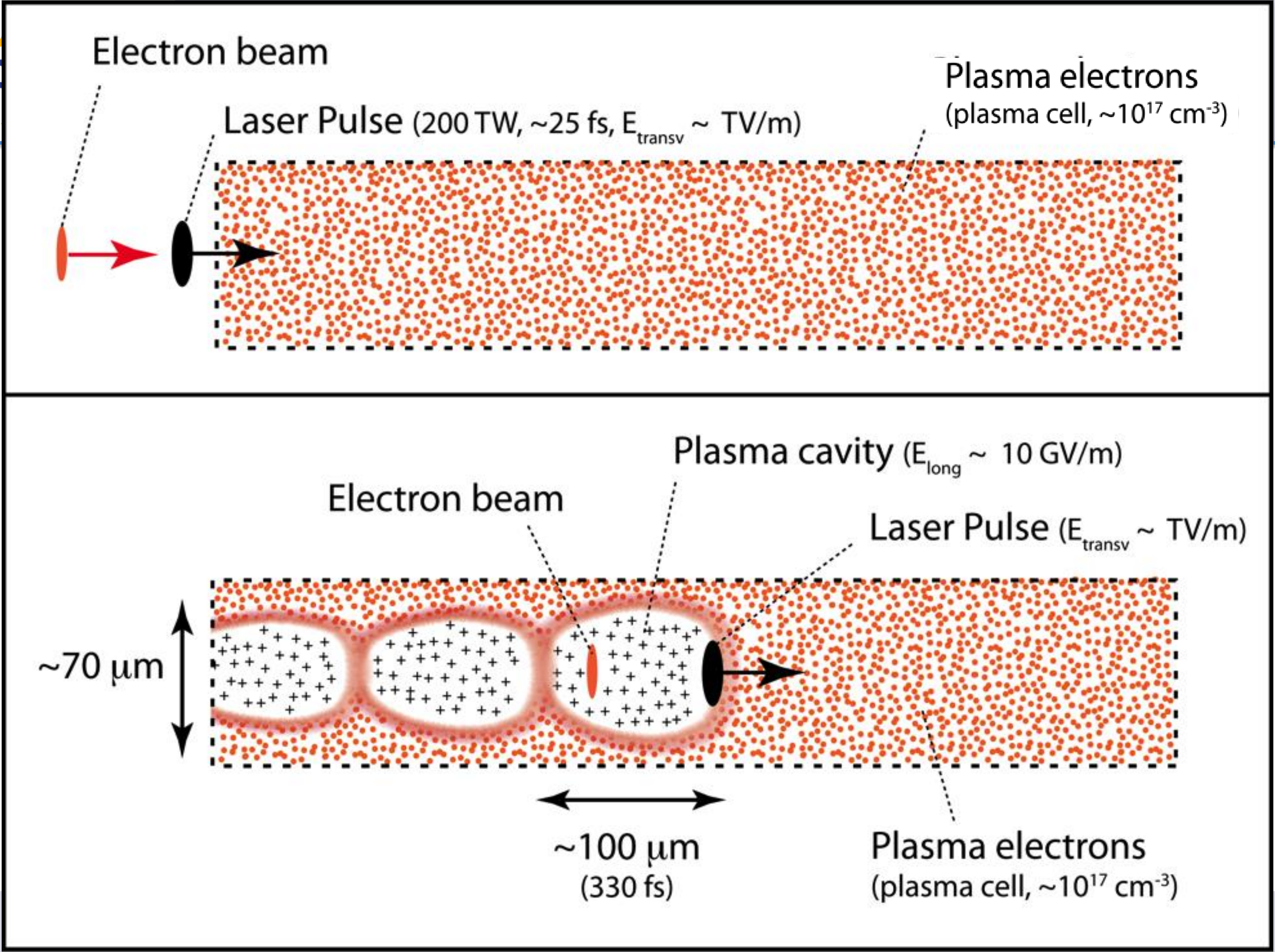
Plasma Wake-Acceleration



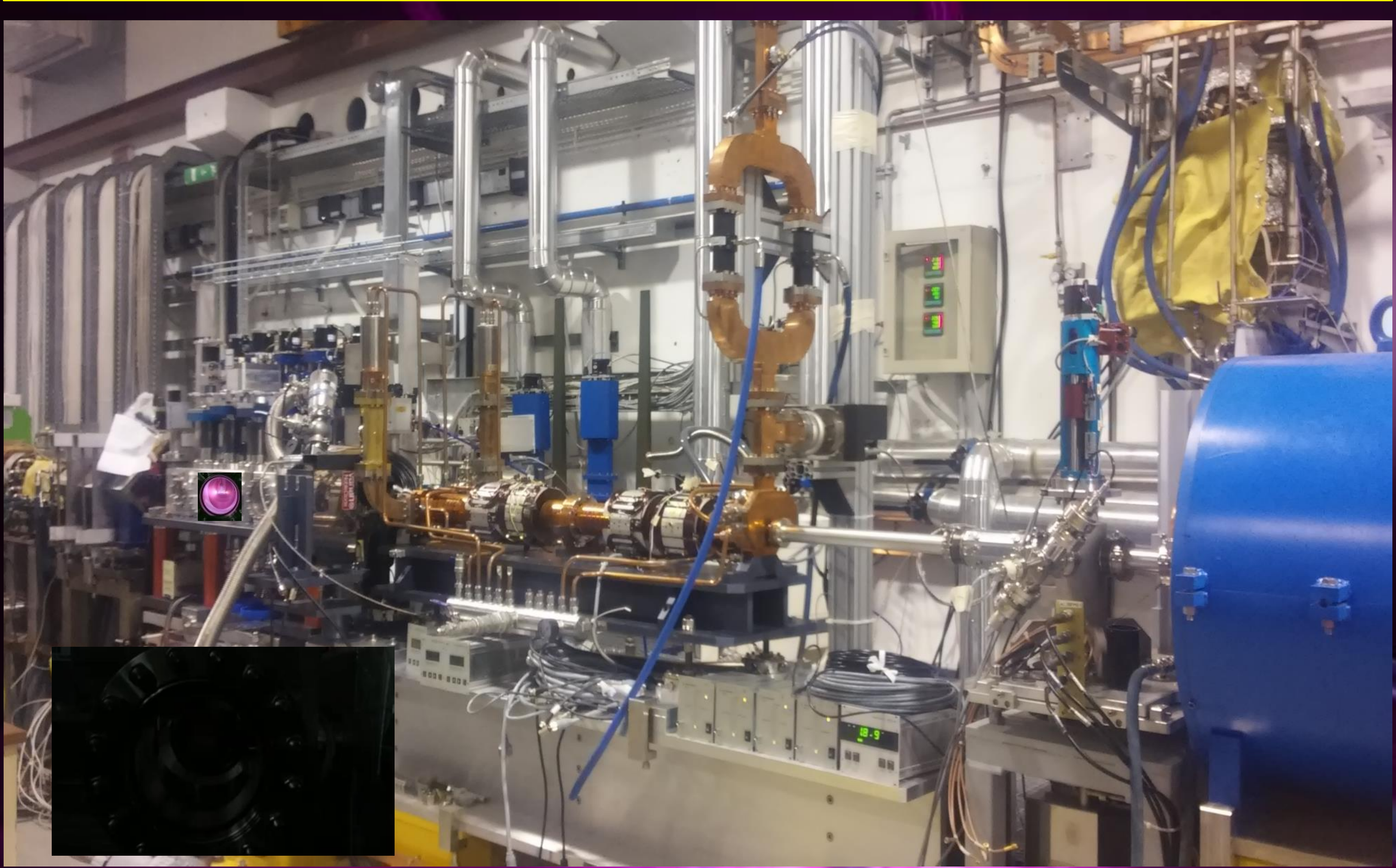
Plasma Wake-Acceleration

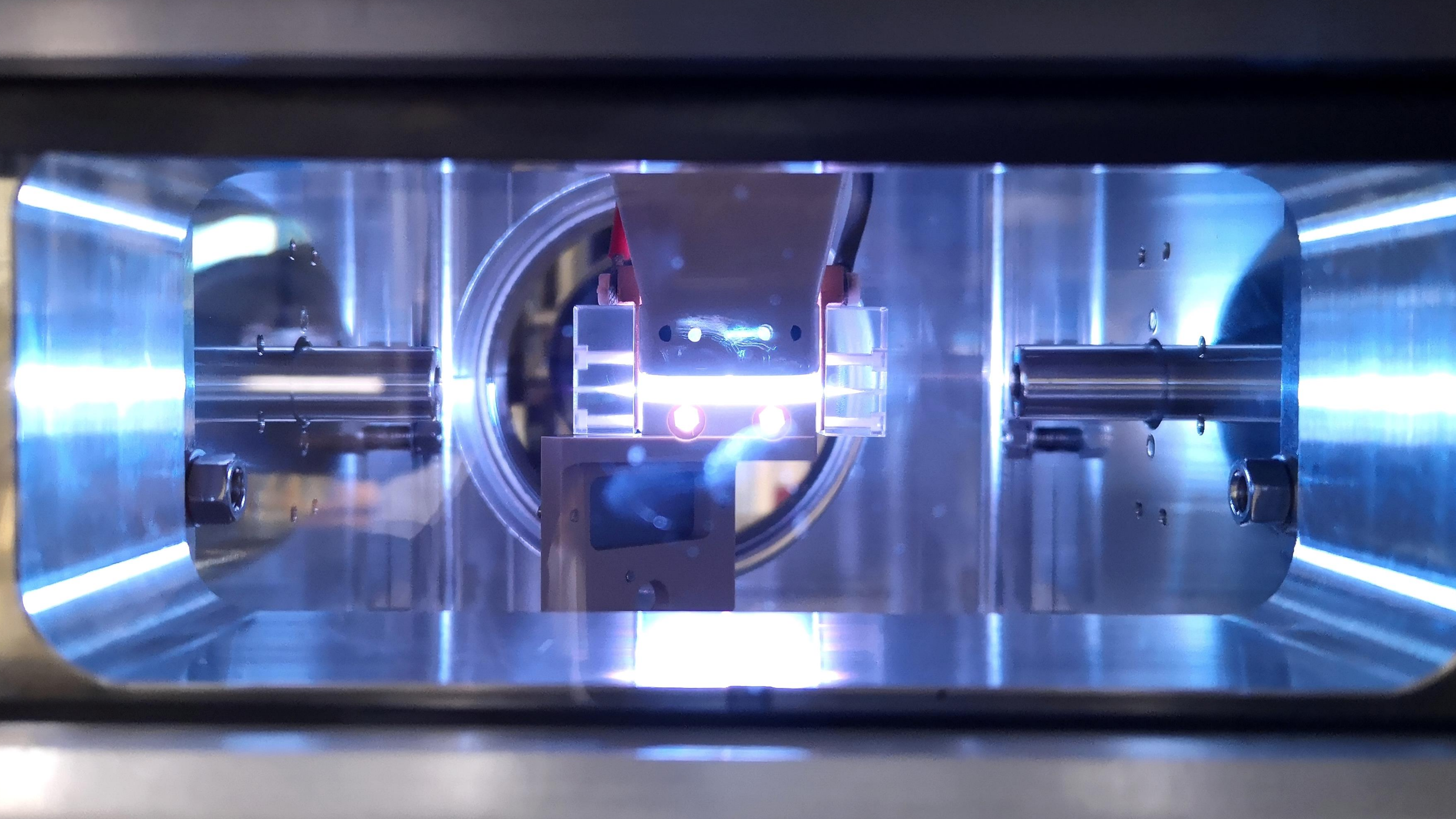


This accelerator fits into a human hair!


Electron beam
Laser Pulse (200 TW, ~25 fs, E_{transv} ~ TV/m)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})
Plasma cavity (E_{long} ~ 10 GV/m)
Electron beam
Laser Pulse (E_{transv} ~ TV/m)
~70 μm
~100 μm
(330 fs)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})

PWFA beam line at SPARC_LAB





A New European High-Tech User Facility

Funded by the European Union

1

Building a facility with very high field plasma accelerators, driven by lasers or beams
1 – 100 GV/m accelerating field

Shrink down the facility size
Improve Sustainability

2

Producing particles and photons to support several urgent and timely science cases

Drive short wavelength FEL
Pave the way for future Linear Colliders

FEATURE EuPRAXIA

A Martinez de la Ossa/DESY

Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini "beta squeeze" in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

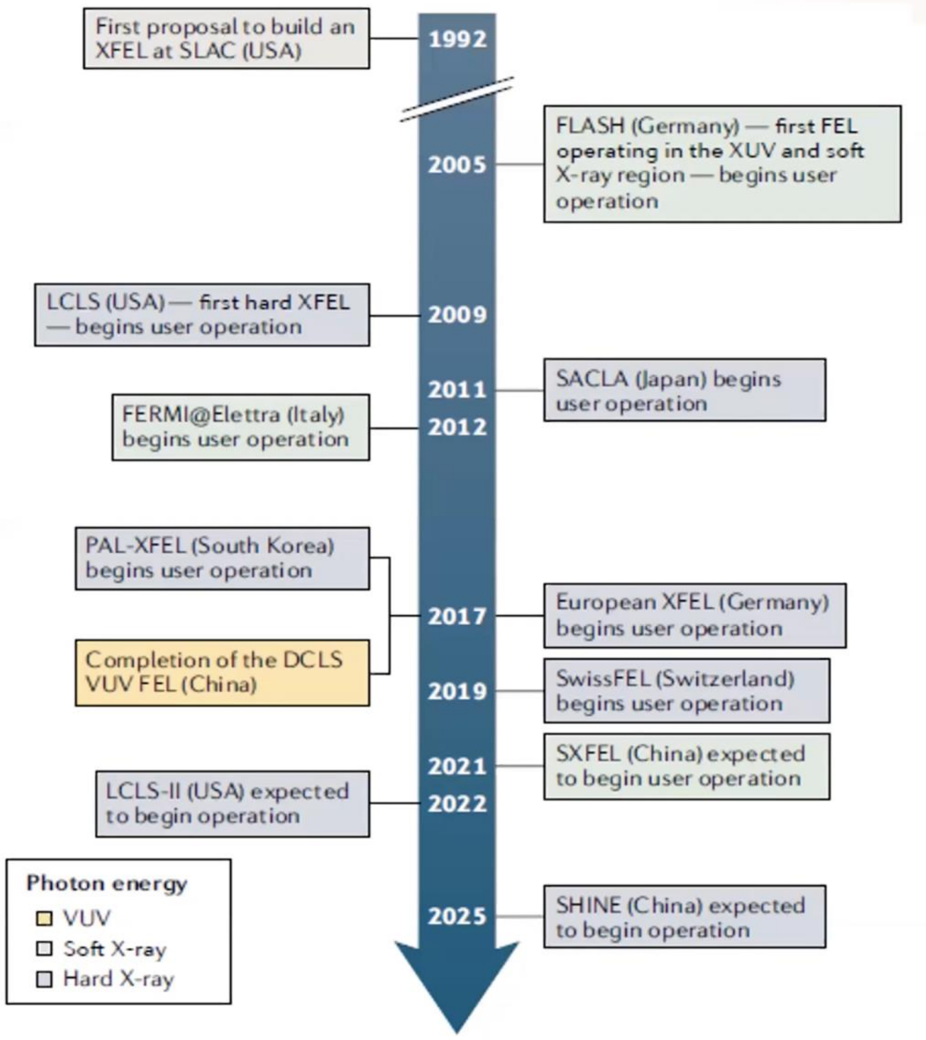
THE AUTHORS
Ralph Assmann *DESY and INFN,* **Massimo Ferrario** *INFN,* **Carsten Welsch** *University of Liverpool/INFN.*

https://www.eupraxia-facility.org/

FEL is a well established technology

(But a widespread use of FEL is partially limited by its size and costs)

Funded by the European Union

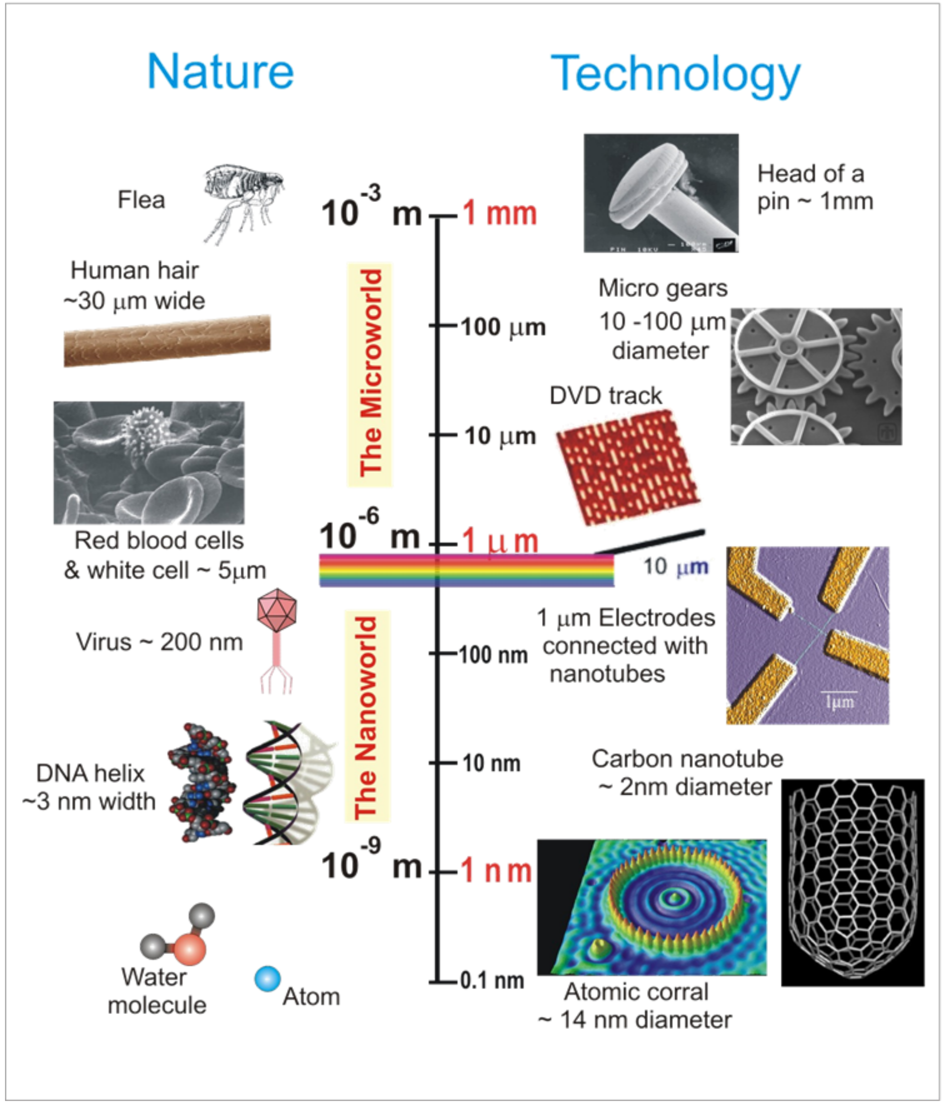


New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

Iulia Georgescu

X-Rays have opened the Ultra-Small World
X-FELs open the Ultra-Small and Ultra-Fast Worlds

Ultra-Small



Nature

Technology

Flea

10^{-3} m — 1 mm

Head of a pin ~ 1mm

Human hair ~30 μm wide

The Microworld

100 μm

Micro gears 10 -100 μm diameter

10 μm

DVD track

Red blood cells & white cell ~ 5μm

10^{-6} m — 1 μm

10 μm

1 μm Electrodes connected with nanotubes

Virus ~ 200 nm

100 nm

The Nanoworld

DNA helix ~3 nm width

10 nm

Carbon nanotube ~ 2nm diameter

10^{-9} m — 1 nm

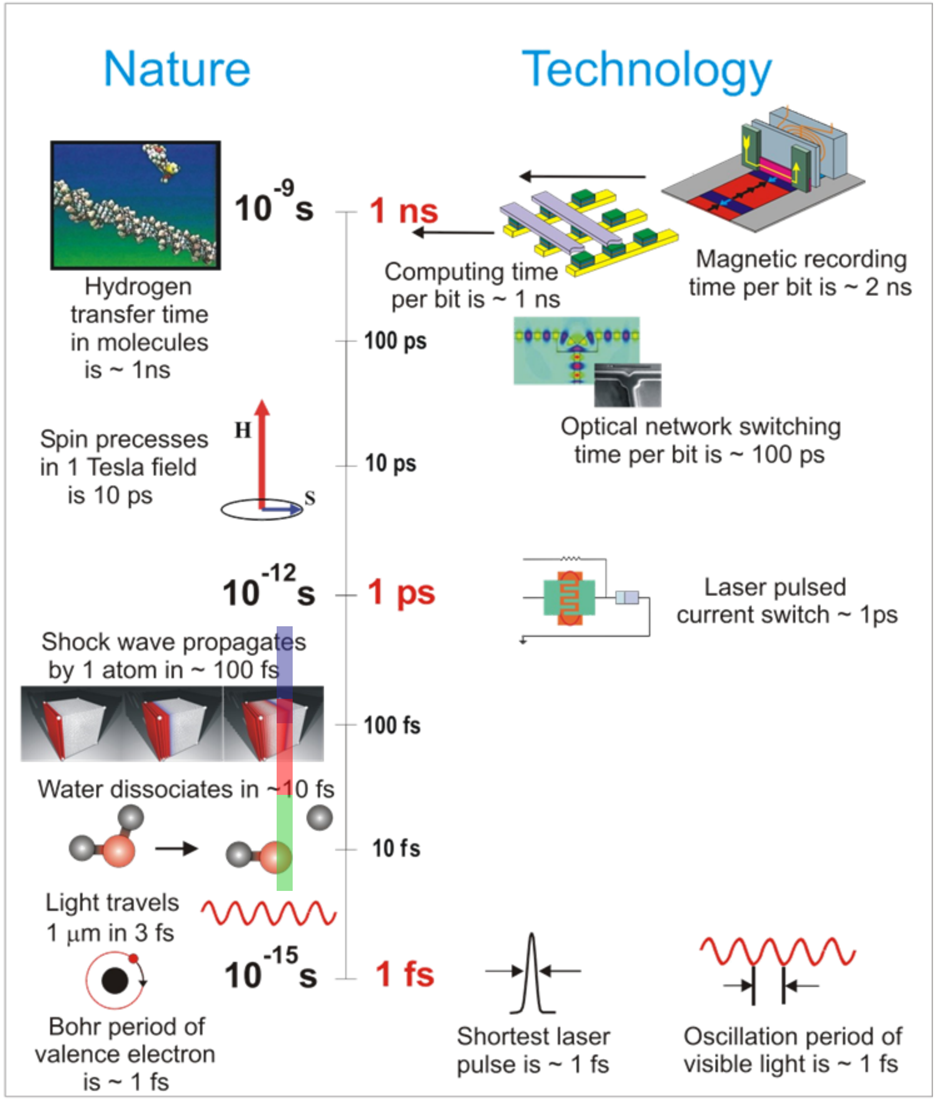
Atomic corral ~ 14 nm diameter

0.1 nm

Water molecule

Atom

Ultra-Fast



Nature

Technology

Hydrogen transfer time in molecules is ~ 1ns

10^{-9} s — 1 ns

Computing time per bit is ~ 1 ns

Magnetic recording time per bit is ~ 2 ns

100 ps

Optical network switching time per bit is ~ 100 ps

Spin precesses in 1 Tesla field is 10 ps

10 ps

10^{-12} s — 1 ps

Laser pulsed current switch ~ 1ps

Shock wave propagates by 1 atom in ~ 100 fs

100 fs

Water dissociates in ~10 fs

10 fs

Light travels 1 μm in 3 fs

10^{-15} s — 1 fs

Bohr period of valence electron is ~ 1 fs

Shortest laser pulse is ~ 1 fs

Oscillation period of visible light is ~ 1 fs

Animation: DNA replication

The dynamics and molecular shapes were based on X-ray crystallographic models and other published scientific data sets.

Helicases are enzymes that bind and may even remodel nucleic acid or nucleic acid protein complexes.

There are DNA and RNA helicases. DNA helicases are essential during DNA replication because they separate double-stranded DNA into single strands allowing each strand to be copied.

During DNA replication, DNA helicases unwind DNA at positions called origins where synthesis will be initiated. DNA helicase continues to unwind the DNA forming a structure called the replication fork, which is named for the forked appearance of the two strands of DNA as they are unzipped apart.

The process of breaking the hydrogen bonds between the nucleotide base pairs in double-stranded DNA requires energy. To break the bonds, helicases use the energy stored in a molecule called ATP, which serves as the energy currency of cells.

DNA helicases also function in other cellular processes where double-stranded DNA must be separated, including DNA repair and transcription. RNA helicases are involved in shaping the form of RNA molecules, during all processes involving RNA, such as transcription, splicing, and translation.

To study single protein structures we need Light

We wish a Static Picture of the
acro-molecules involved

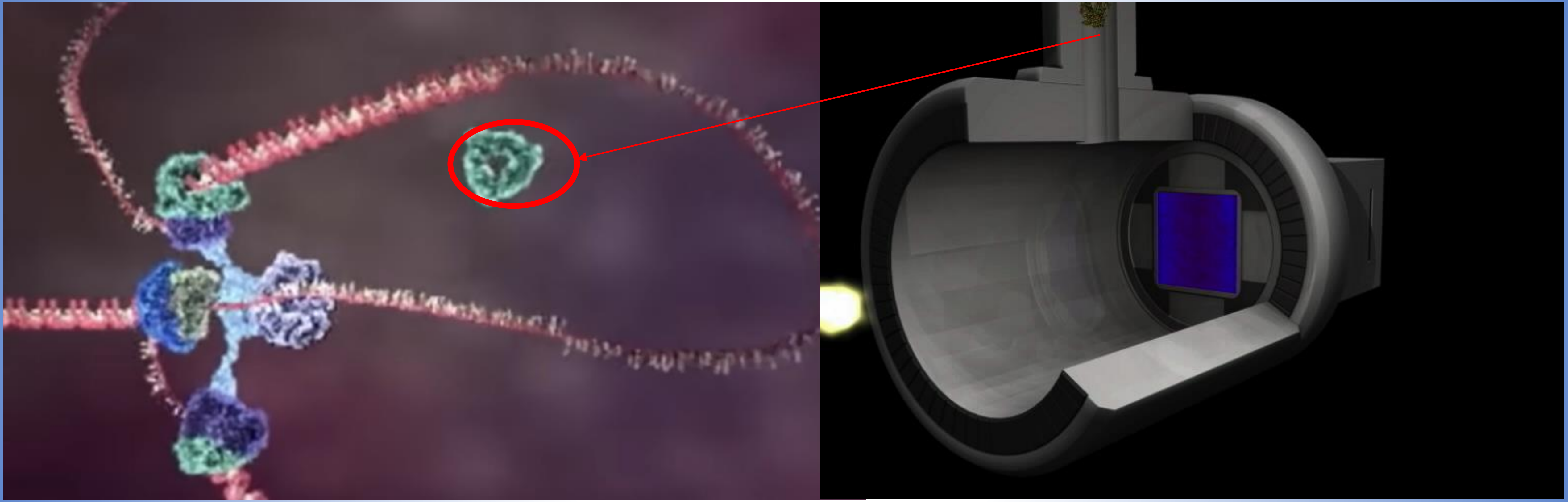
Light Required properties

- Short wavelength (X-ray)
- High energy per pulse
- Ultra-short pulse (few femtoseconds)
- Coherence

Funded by the
European Union

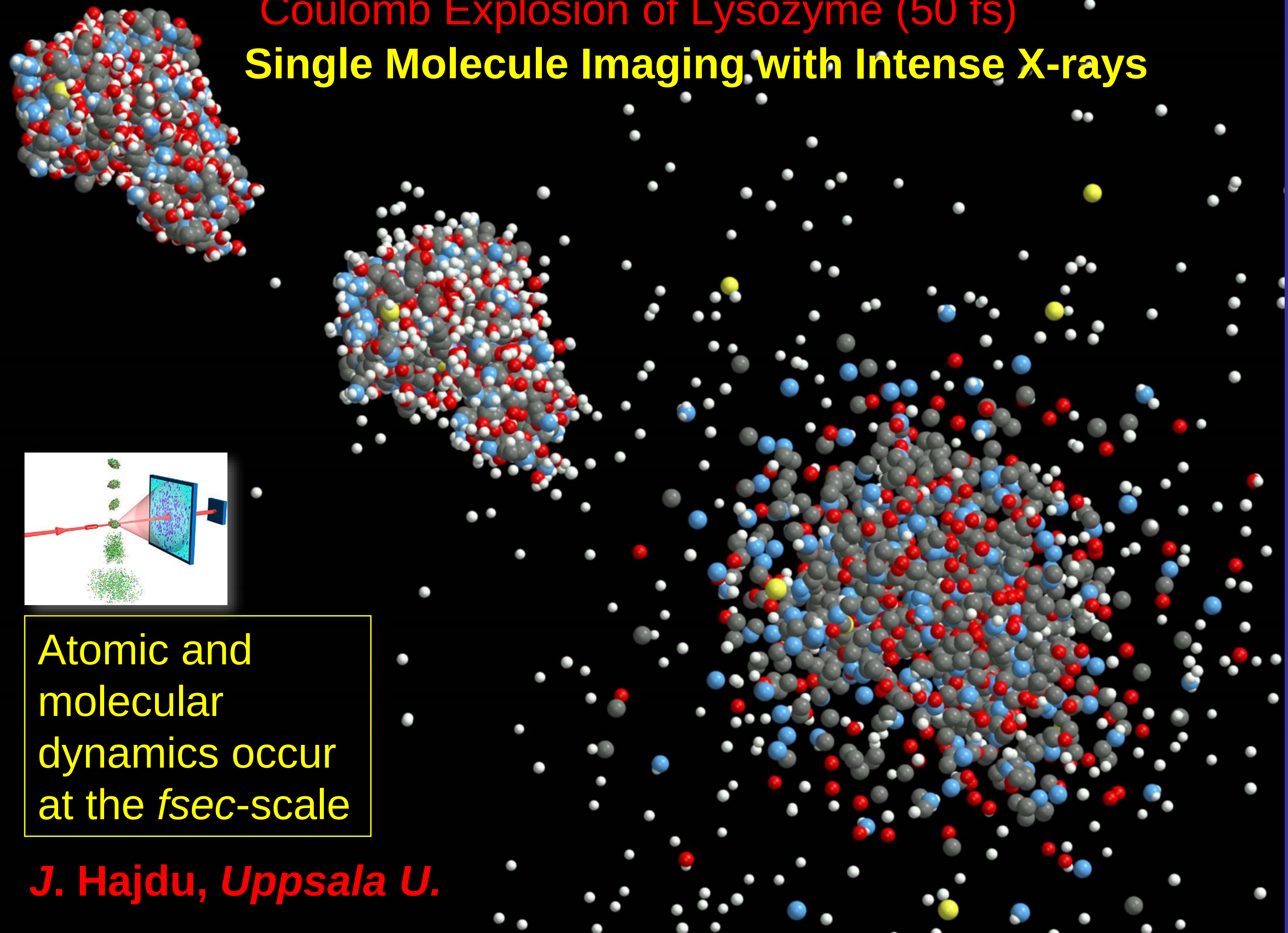
Single Molecule Imaging with Intense ultra-short X-rays pulses

Funded by the European Union



Coulomb Explosion of Lysozyme (50 fs)

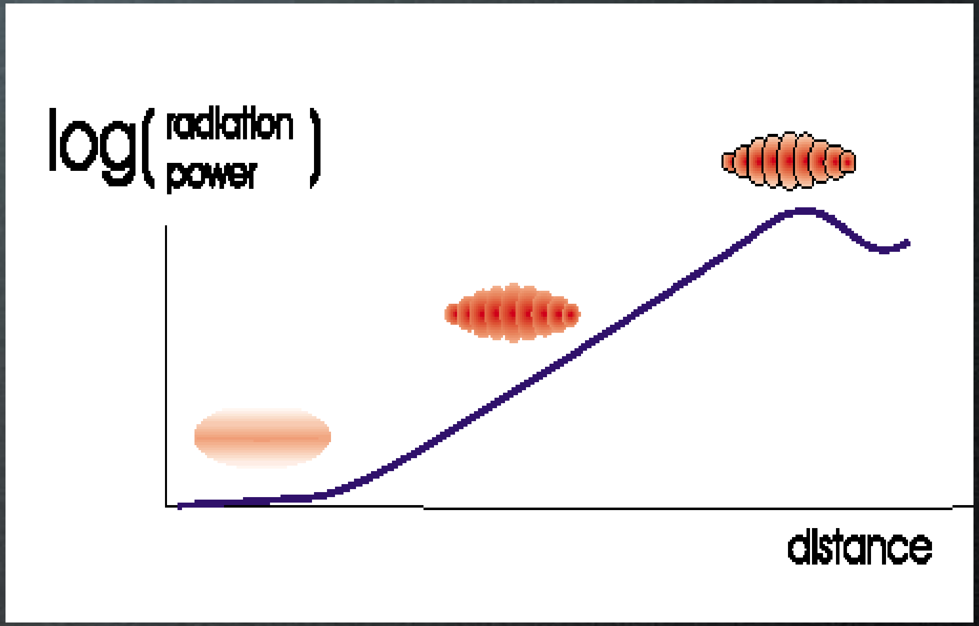
Single Molecule Imaging with Intense X-rays



Atomic and molecular dynamics occur at the *fsec*-scale

J. Hajdu, *Uppsala U.*

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



$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

(Tunability - Harmonics)

Plasma accelerated beam driven FEL

It's a CHALLENGE: **the FEL is extremely sensitive to the beam quality.**

Low (geometric) emittances: $\epsilon_{x,y} < \frac{\lambda_0}{4\pi}$

Low relative energy spread σ_γ: $\sigma_\gamma < \frac{1}{2}\rho_{fel}$

Low emittances
Low energy spread
High current

where $$\rho_{fel} = \frac{1}{4\pi}\left[\frac{2\pi^2}{\gamma^3}\left(\lambda_u K\left[JJ\right]\right)^2 \frac{I_{peak}}{\Sigma_e I_A}\right]^{1/3}$$

Exponential growth

$$P(z) = \frac{1}{9}P_0 e^{z/L_g}$$

gain length

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{fel}}$$

saturation

$$P_F \sim 1.6\,\rho_{fel} P_{beam}$$

=> A poor beam quality causes an increase of L_g and a reduction of P_F

Required Bunch Energy Stability

$$E_z(\zeta) = A n_p \sqrt{I_d}\,\zeta$$

$$\frac{\Delta\lambda}{\lambda} \propto \frac{\Delta E}{E} \propto \rho \approx 10^{-3}$$

FEL requirement

$$\left.\frac{\Delta E}{E}\right|_p = \frac{\Delta n_p}{n_p}$$

Plasma density

$$\left.\frac{\Delta E}{E}\right|_Q = \frac{\Delta I_d}{2(I_d)} + \frac{\Delta I_w}{2(I_w)}$$

Bunch charge/length

$$\left.\frac{\Delta E}{E}\right|_{DW} = \frac{a\omega_p}{2\pi}\Delta t_{DW}$$

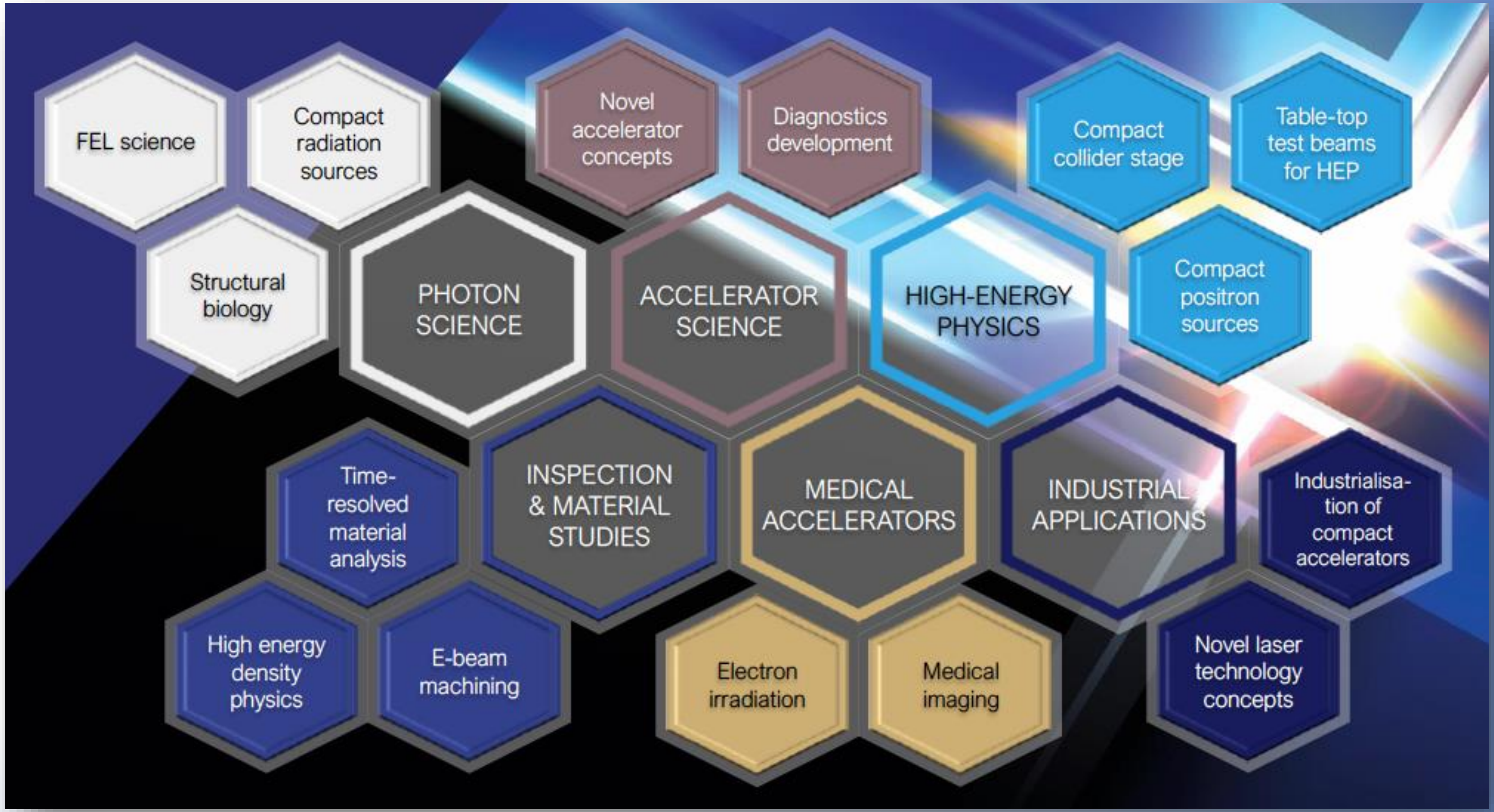
$$2 \le a \le 4$$

Driver/Witness separation

Intense R&D Program on critical components

Funded by the European Union

- **Electrons**
  (0.1-5 GeV, 30 pC)
- **Positrons**
  (0.5-10 MeV, 10^6)
- **Positrons** (GeV source)
- **Lasers**
  (100 J, 50 fs, 10-100 Hz)
- **X-band RF Linac**
  (60 MV/m , up to 400 Hz)
- **Plasma Targets**
- **Betatron X rays**
  (1-10 keV, 10^{10})
- **FEL light**
  (0.2-36 nm, 10^9-10^{13})



FEL science

Compact radiation sources

Novel accelerator concepts

Diagnostics development

Compact collider stage

Table-top test beams for HEP

Structural biology

PHOTON SCIENCE

ACCELERATOR SCIENCE

HIGH-ENERGY PHYSICS

Compact positron sources

Time-resolved material analysis

INSPECTION & MATERIAL STUDIES

MEDICAL ACCELERATORS

INDUSTRIAL APPLICATIONS

Industrialisation of compact accelerators

High energy density physics

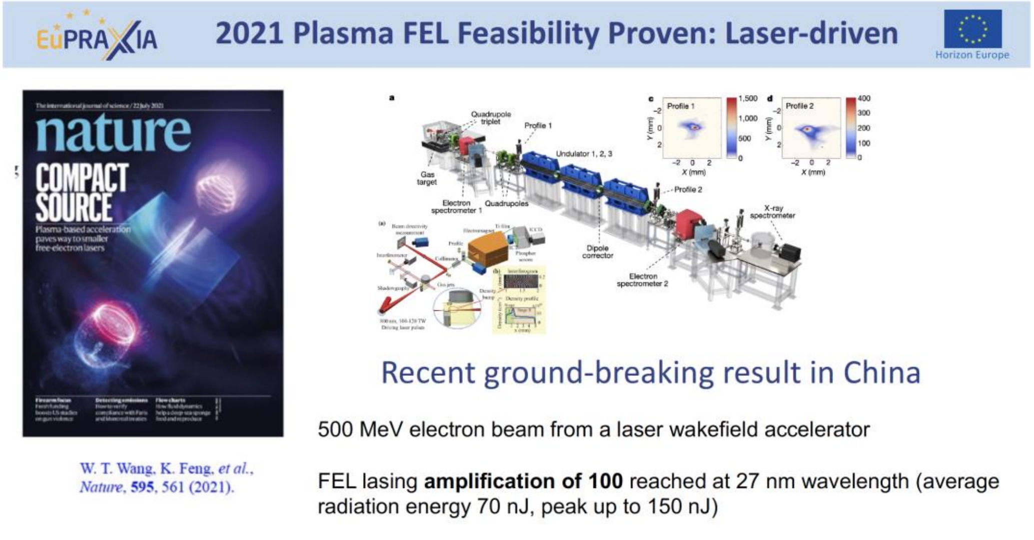
E-beam machining

Electron irradiation

Medical imaging

Novel laser technology concepts

Basic beam quality achieved in pilot FEL experiments



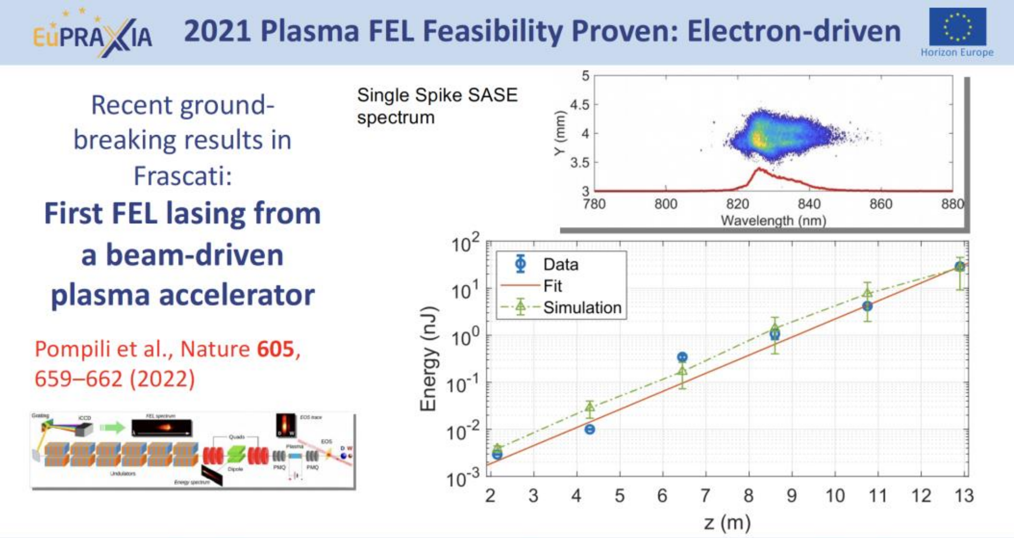
2021 Plasma FEL Feasibility Proven: Laser-driven

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).

Recent ground-breaking result in China

500 MeV electron beam from a laser wakefield accelerator

FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

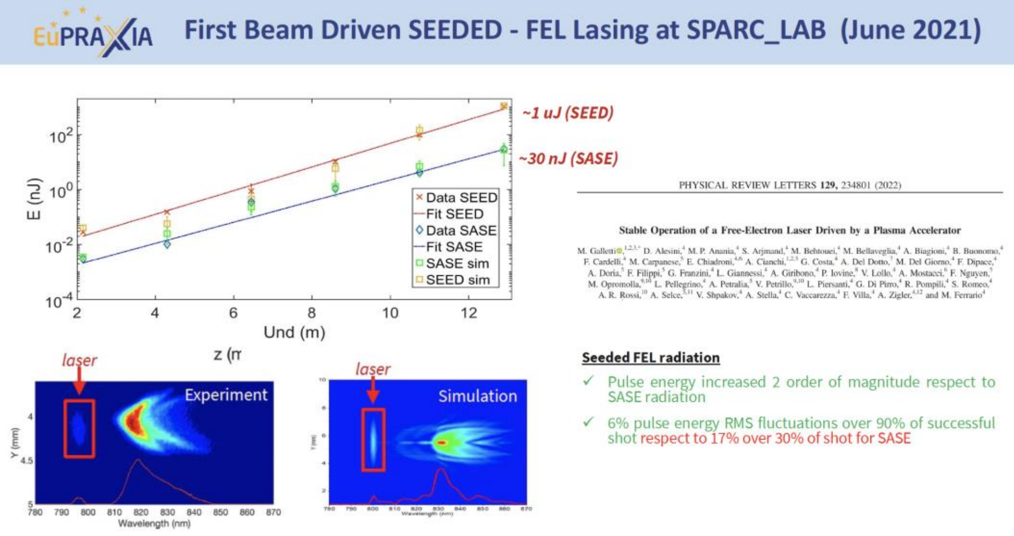


2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

Pompili et al., Nature **605**, 659–662 (2022)



First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

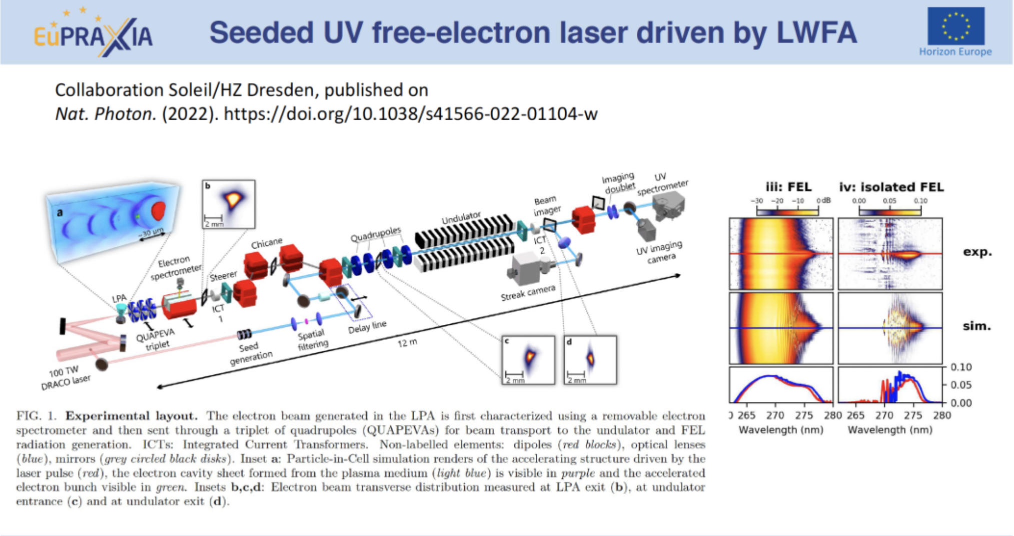
PHYSICAL REVIEW LETTERS **129**, 234801 (2022)

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]

Seeded FEL radiation

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE



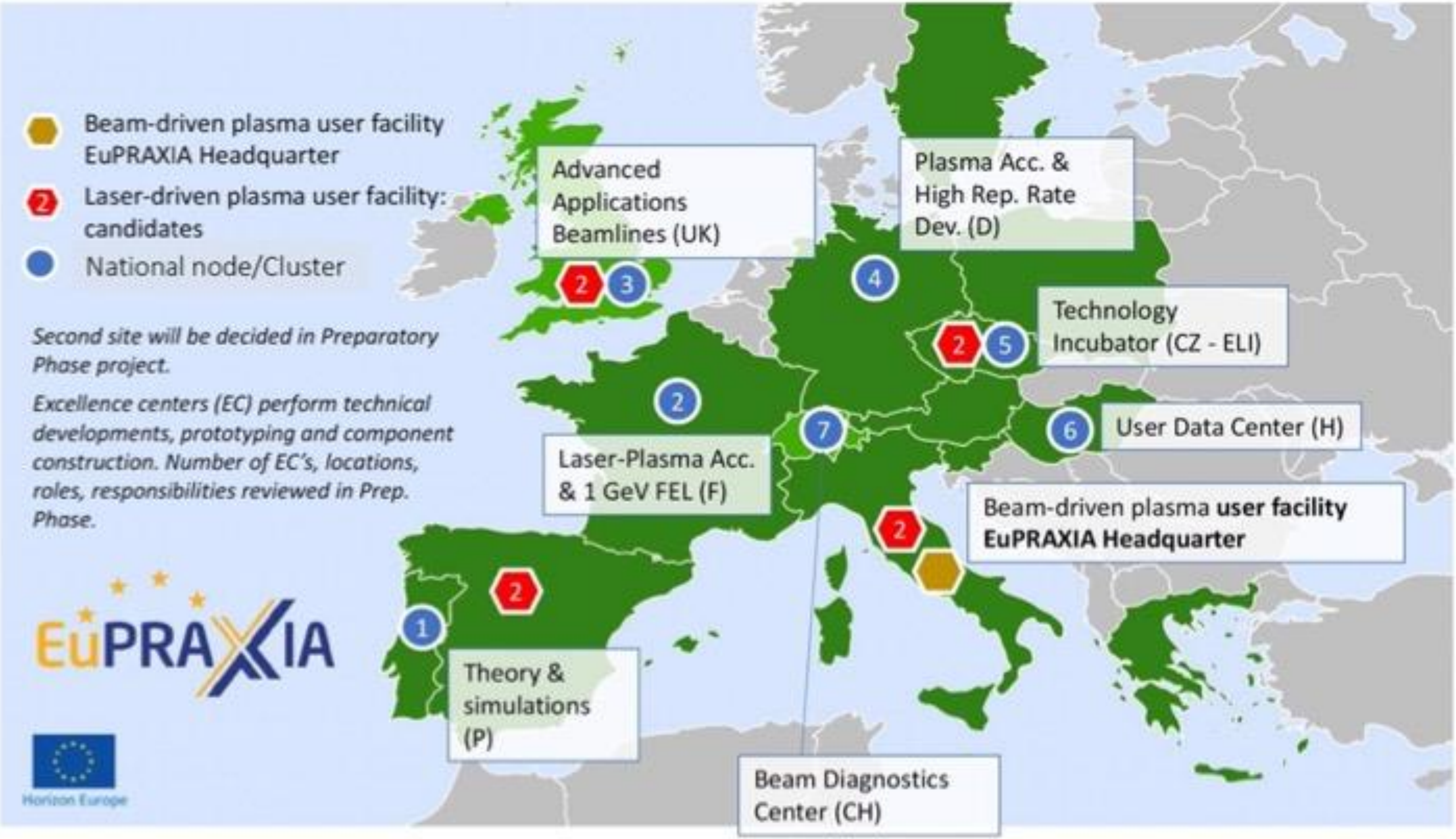
Seeded UV free-electron laser driven by LWFA

Collaboration Soleil/HZ Dresden, published on
Nat. Photon. (2022). https://doi.org/10.1038/s41566-022-01104-w

FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled elements: dipoles (*red blocks*), optical lenses (*blue*), mirrors (*grey circled black disks*). Inset **a**: Particle-in-Cell simulation renders of the accelerating structure driven by the laser pulse (*red*), the electron cavity sheet formed from the plasma medium (*light blue*) is visible in *purple* and the accelerated electron bunch visible in *green*. Insets **b,c,d**: Electron beam transverse distribution measured at LPA exit (**b**), at undulator entrance (**c**) and at undulator exit (**d**).

Distributed Research Infrastructure

Funded by the European Union



Second site will be decided in Preparatory Phase project.

Excellence centers (EC) perform technical developments, prototyping and component construction. Number of EC's, locations, roles, responsibilities reviewed in Prep. Phase.

A large collection of the best European know-hows in accelerators, lasers and plasma technologies

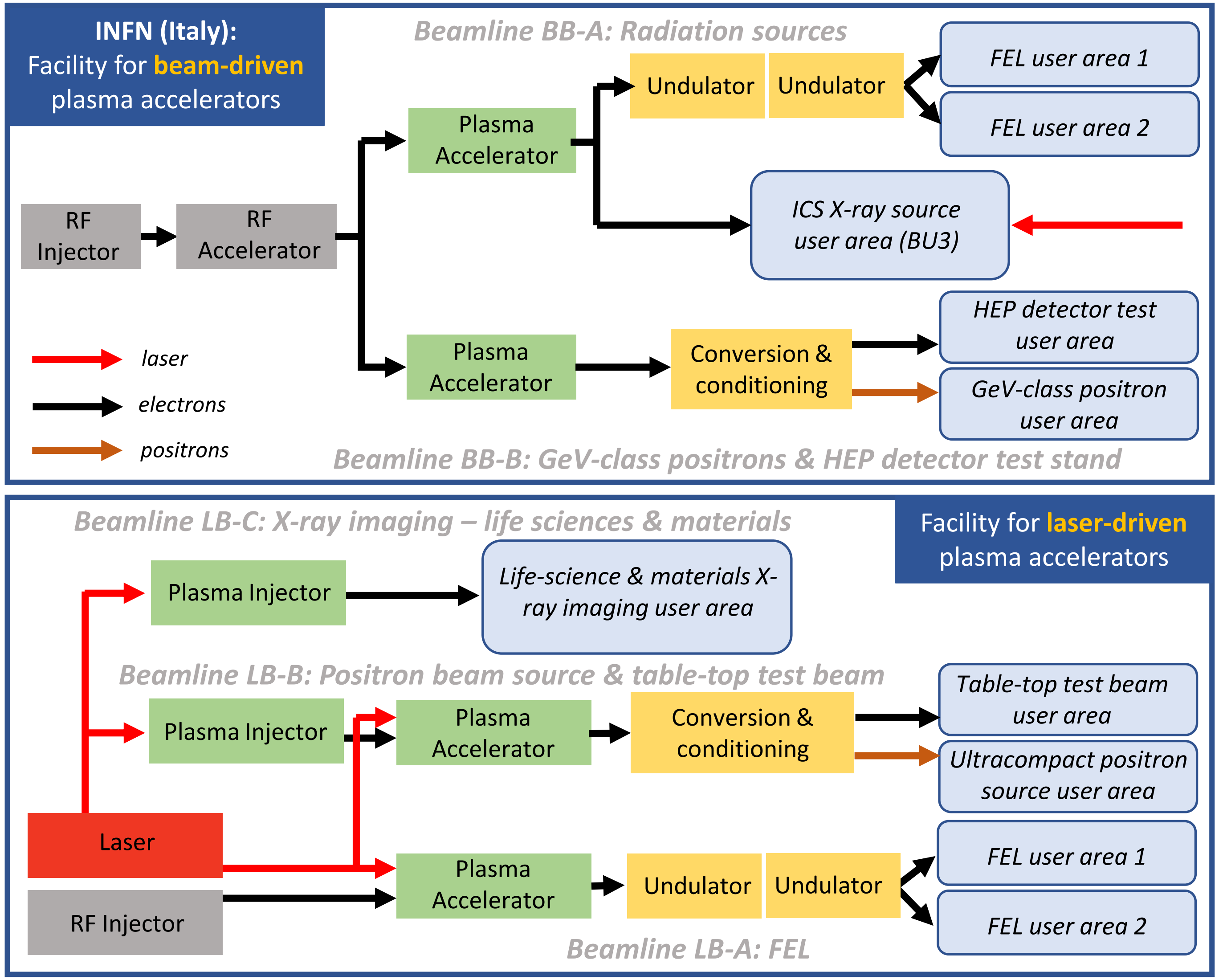
Network organization
- Sites (PWFA/LWFA)
- National nodes
- Technology clusters

4 candidates for LWFA
- CLPU, Salamanca
- CNR-INO, Pisa
- ELI ERIC, Prague
- EPAC-RAL, UK

Phased Implementation of Construction Sites

Funded by the European Union

	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 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area ✓ 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

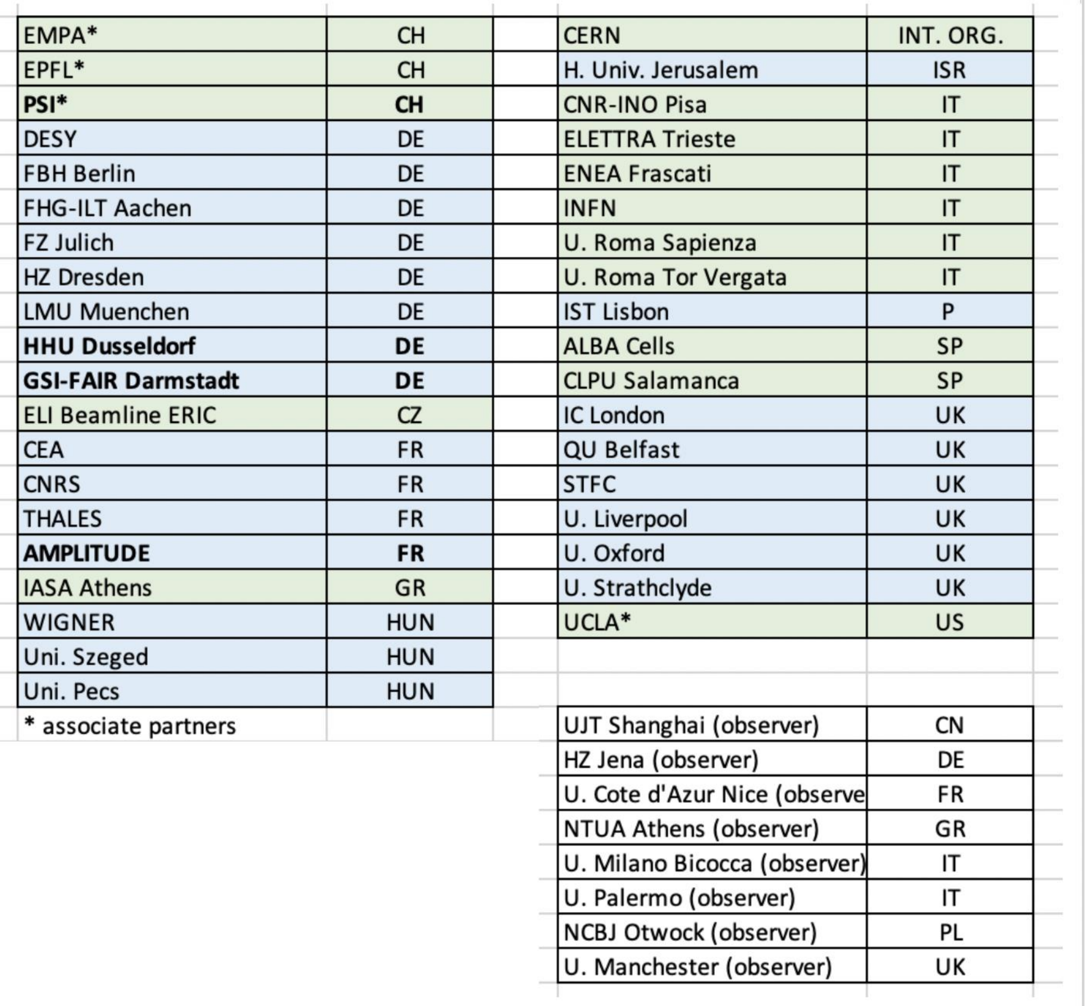


Wide International Collaboration

Funded by the European Union

- **The EuPRAXIA Consortium today: 54 institutes** from **18 countries** plus CERN
- Included in the **ESFRI** Road Map
- **Efficient fund raising:**
  - **Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - **Doctoral Network**

    (funding EU, UK, in-kind)
  - **EuPRAXIA@SPARC_LAB** (Italy, in-kind)
  - **EuAPS Project** (Next Generation EU)
  - **PACRI just approved 10 MEuro** (funding EU, Switzerland)

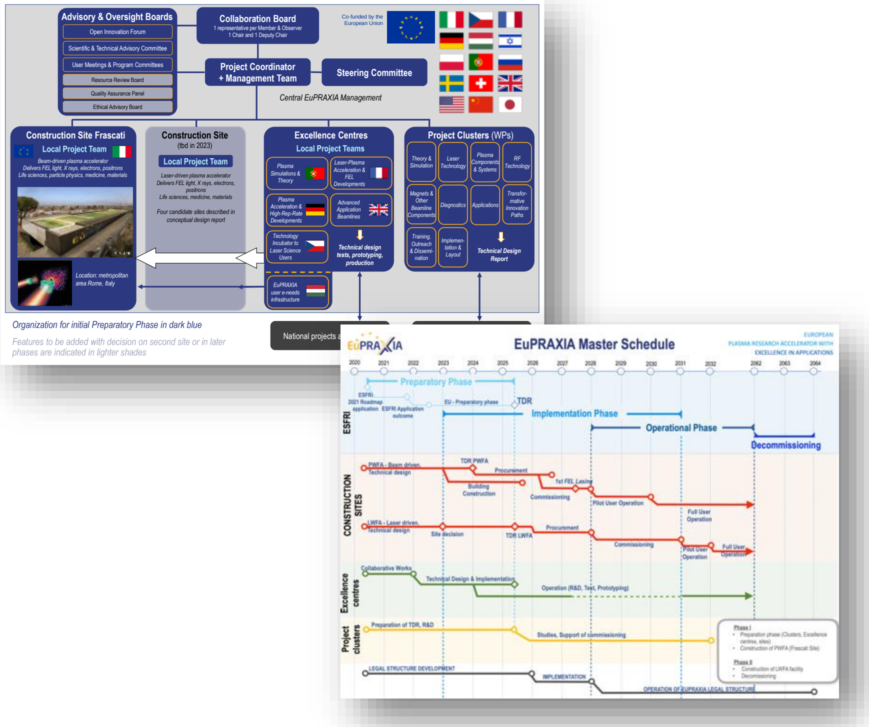


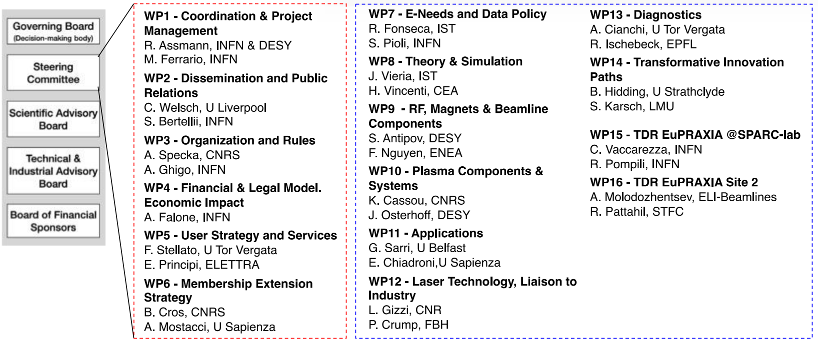
EMPA*	CH	CERN	INT. ORG.
EPFL*	CH	H. Univ. Jerusalem	ISR
PSI*	**CH**	CNR-INO Pisa	IT
DESY	DE	ELETTRA Trieste	IT
FBH Berlin	DE	ENEA Frascati	IT
FHG-ILT Aachen	DE	INFN	IT
FZ Julich	DE	U. Roma Sapienza	IT
HZ Dresden	DE	U. Roma Tor Vergata	IT
LMU Muenchen	DE	IST Lisbon	P
HHU Dusseldorf	**DE**	ALBA Cells	SP
GSI-FAIR Darmstadt	**DE**	CLPU Salamanca	SP
ELI Beamline ERIC	CZ	IC London	UK
CEA	FR	QU Belfast	UK
CNRS	FR	STFC	UK
THALES	FR	U. Liverpool	UK
AMPLITUDE	**FR**	U. Oxford	UK
IASA Athens	GR	U. Strathclyde	UK
WIGNER	HUN	UCLA*	US
Uni. Szeged	HUN		
Uni. Pecs	HUN		
* associate partners		UJT Shanghai (observer)	CN
		HZ Jena (observer)	DE
		U. Cote d'Azur Nice (observe	FR
		NTUA Athens (observer)	GR
		U. Milano Bicocca (observer)	IT
		U. Palermo (observer)	IT
		NCBJ Otwock (observer)	PL
		U. Manchester (observer)	UK

Preparatory Phase Main Goals

Funded by the European Union

- Managerial WP`s
  - **Outreach** to public, users, EU decision makers and industry
  - **Define** legal model (how is EuPRAXIA governed?), financial model, rules, user services and membership extension for full implementation
  - Works with **project bodies and funding agencies** → Board of Financial Sponsors
- Technical WP‘s (correspond to Project Clusters):
  - **Update of CDR** concepts and parameters, towards technical design (full technical design requires more funding)
  - Specify in detail **Excellence Centers and their required funding**: TDR related R&D, prototyping, contributions to construction
  - Help in defining funding applications for various agencies
- Output defined in **milestones & deliverables** with dates





Governing Board (Decision-making body)

Steering Committee

Scientific Advisory Board

Technical & Industrial Advisory Board

Board of Financial Sponsors

WP1 - Coordination & Project Management
R. Assmann, INFN & DESY
M. Ferrario, INFN

WP2 - Dissemination and Public Relations
C. Welsch, U Liverpool
S. Bertellii, INFN

WP3 - Organization and Rules
A. Specka, CNRS
A. Ghigo, INFN

WP4 - Financial & Legal Model. Economic Impact
A. Falone, INFN

WP5 - User Strategy and Services
F. Stellato, U Tor Vergata
E. Principi, ELETTRA

WP6 - Membership Extension Strategy
B. Cros, CNRS
A. Mostacci, U Sapienza

WP7 - E-Needs and Data Policy
R. Fonseca, IST
S. Pioli, INFN

WP8 - Theory & Simulation
J. Vieria, IST
H. Vincenti, CEA

WP9 - RF, Magnets & Beamline Components
S. Antipov, DESY
F. Nguyen, ENEA

WP10 - Plasma Components & Systems
K. Cassou, CNRS
J. Osterhoff, DESY

WP11 - Applications
G. Sarri, U Belfast
E. Chiadroni,U Sapienza

WP12 - Laser Technology, Liaison to Industry
L. Gizzi, CNR
P. Crump, FBH

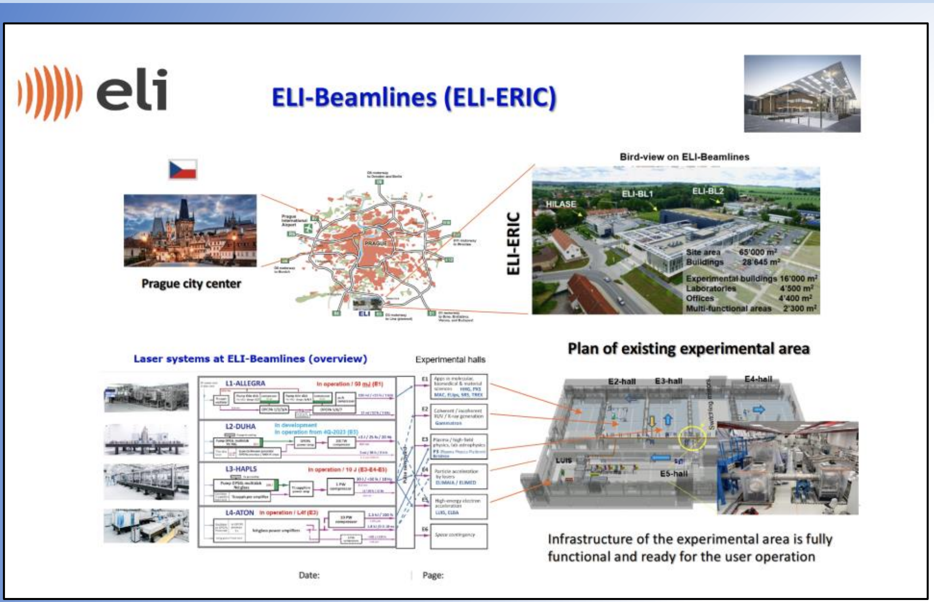
WP13 - Diagnostics
A. Cianchi, U Tor Vergata
R. Ischebeck, EPFL

WP14 - Transformative Innovation Paths
B. Hidding, U Strathclyde
S. Karsch, LMU

WP15 - TDR EuPRAXIA @SPARC-lab
C. Vaccarezza, INFN
R. Pompili, INFN

WP16 - TDR EuPRAXIA Site 2
A. Molodozhentsev, ELI-Beamlines
R. Pattahil, STFC

Current Candidates for EuPRAXIA Laser Site



ELI-Beamlines (ELI-ERIC)

Prague city center

ELI-ERIC

Bird-view on ELI-Beamlines

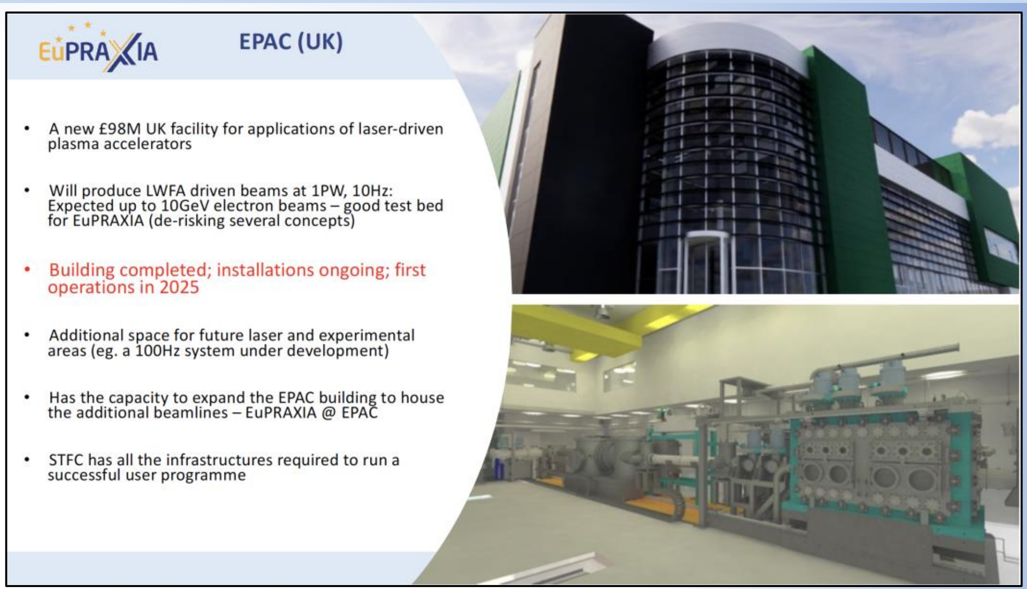
Site area	65'000 m²
Buildings	28'645 m²
Experimental buildings	16'000 m²
Laboratories	4'500 m²
Offices	4'400 m²
Multi-functional areas	2'300 m²

Laser systems at ELI-Beamlines (overview)

Plan of existing experimental area

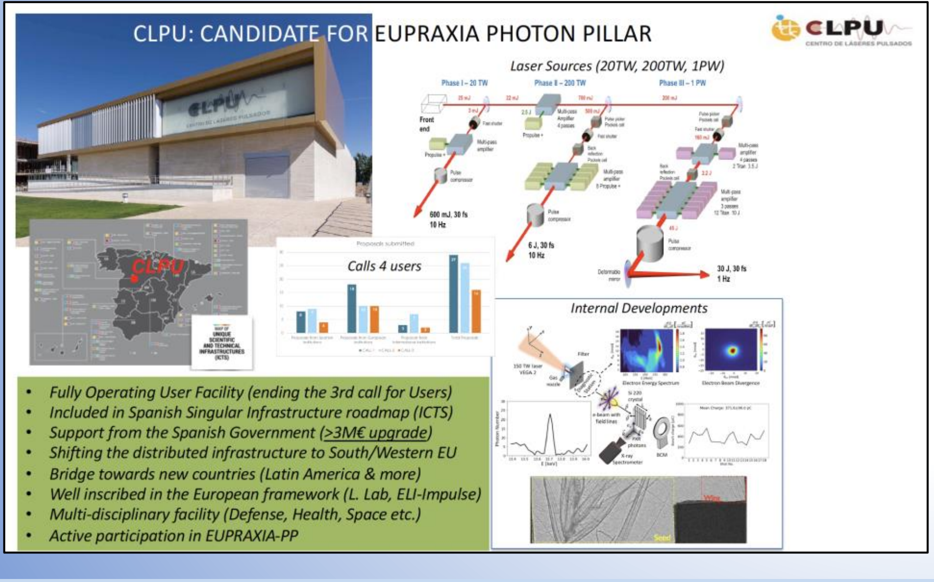
Infrastructure of the experimental area is fully functional and ready for the user operation

Date: | Page:



EPAC (UK)

- A new £98M UK facility for applications of laser-driven plasma accelerators
- Will produce LWFA driven beams at 1PW, 10Hz: Expected up to 10GeV electron beams – good test bed for EuPRAXIA (de-risking several concepts)
- Building completed; installations ongoing; first operations in 2025
- Additional space for future laser and experimental areas (eg. a 100Hz system under development)
- Has the capacity to expand the EPAC building to house the additional beamlines – EuPRAXIA @ EPAC
- STFC has all the infrastructures required to run a successful user programme

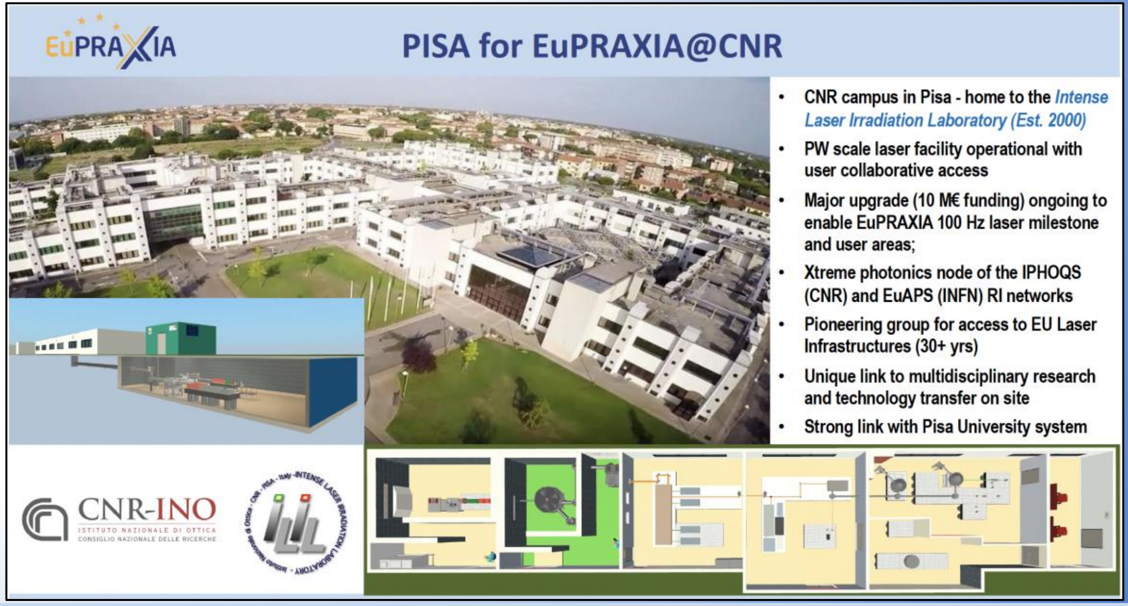


CLPU: CANDIDATE FOR EUPRAXIA PHOTON PILLAR

CLPU CENTRO DE LÁSERES PULSADOS

Laser Sources (20TW, 200TW, 1PW)

- *Fully Operating User Facility (ending the 3rd call for Users)*
- *Included in Spanish Singular Infrastructure roadmap (ICTS)*
- *Support from the Spanish Government (>3M€ upgrade)*
- *Shifting the distributed infrastructure to South/Western EU*
- *Bridge towards new countries (Latin America & more)*
- *Well inscribed in the European framework (L. Lab, ELI-Impulse)*
- *Multi-disciplinary facility (Defense, Health, Space etc.)*
- *Active participation in EUPRAXIA-PP*

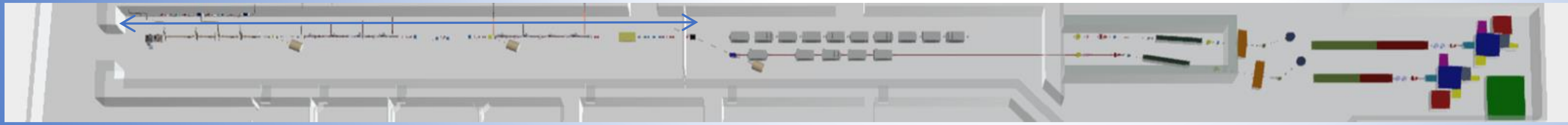


PISA for EuPRAXIA@CNR

- CNR campus in Pisa - home to the *Intense Laser Irradiation Laboratory (Est. 2000)*
- PW scale laser facility operational with user collaborative access
- Major upgrade (10 M€ funding) ongoing to enable EuPRAXIA 100 Hz laser milestone and user areas;
- Xtreme photonics node of the IPHOQS (CNR) and EuAPS (INFN) RI networks
- Pioneering group for access to EU Laser Infrastructures (30+ yrs)
- Unique link to multidisciplinary research and technology transfer on site
- Strong link with Pisa University system

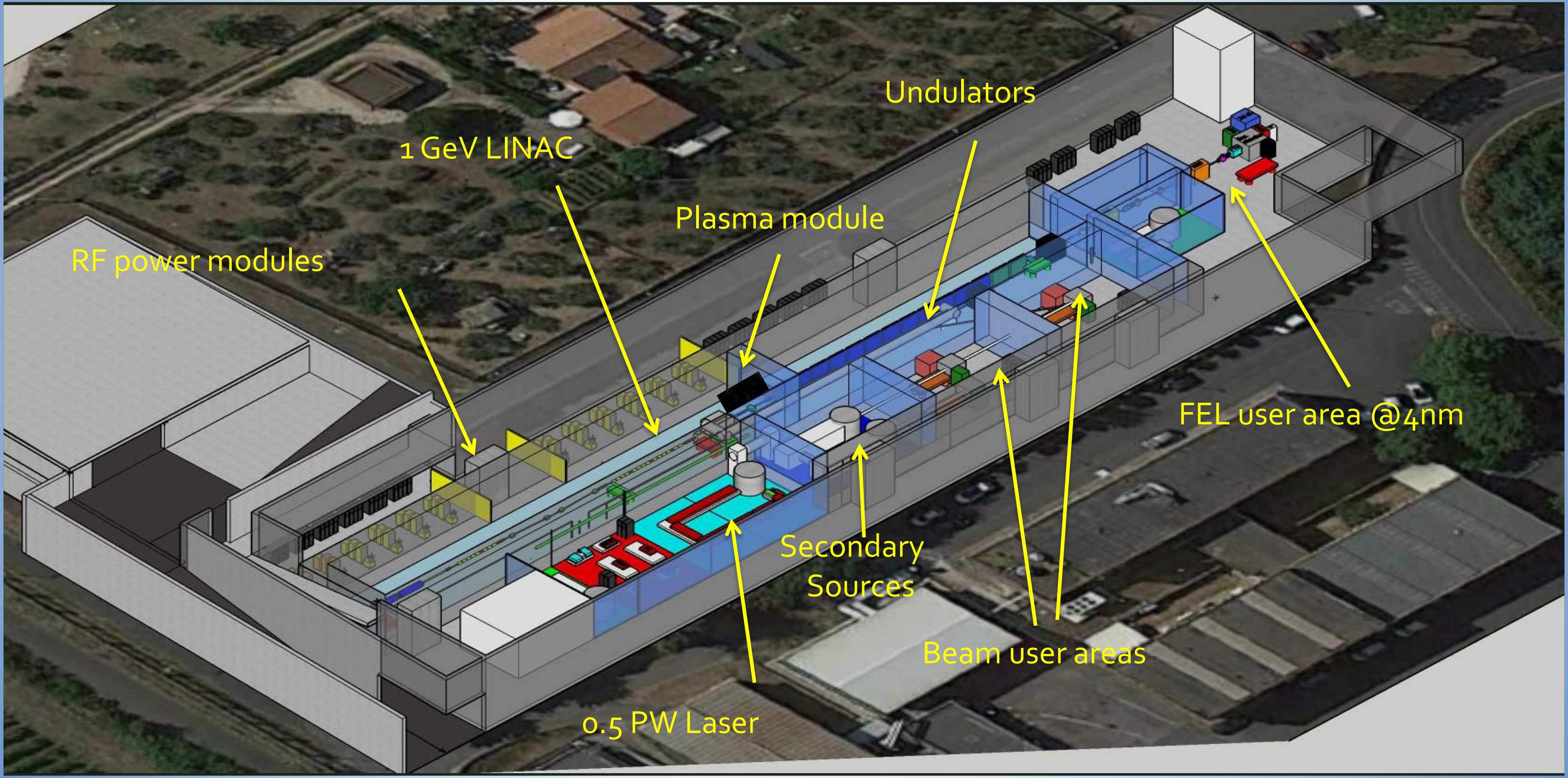
CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

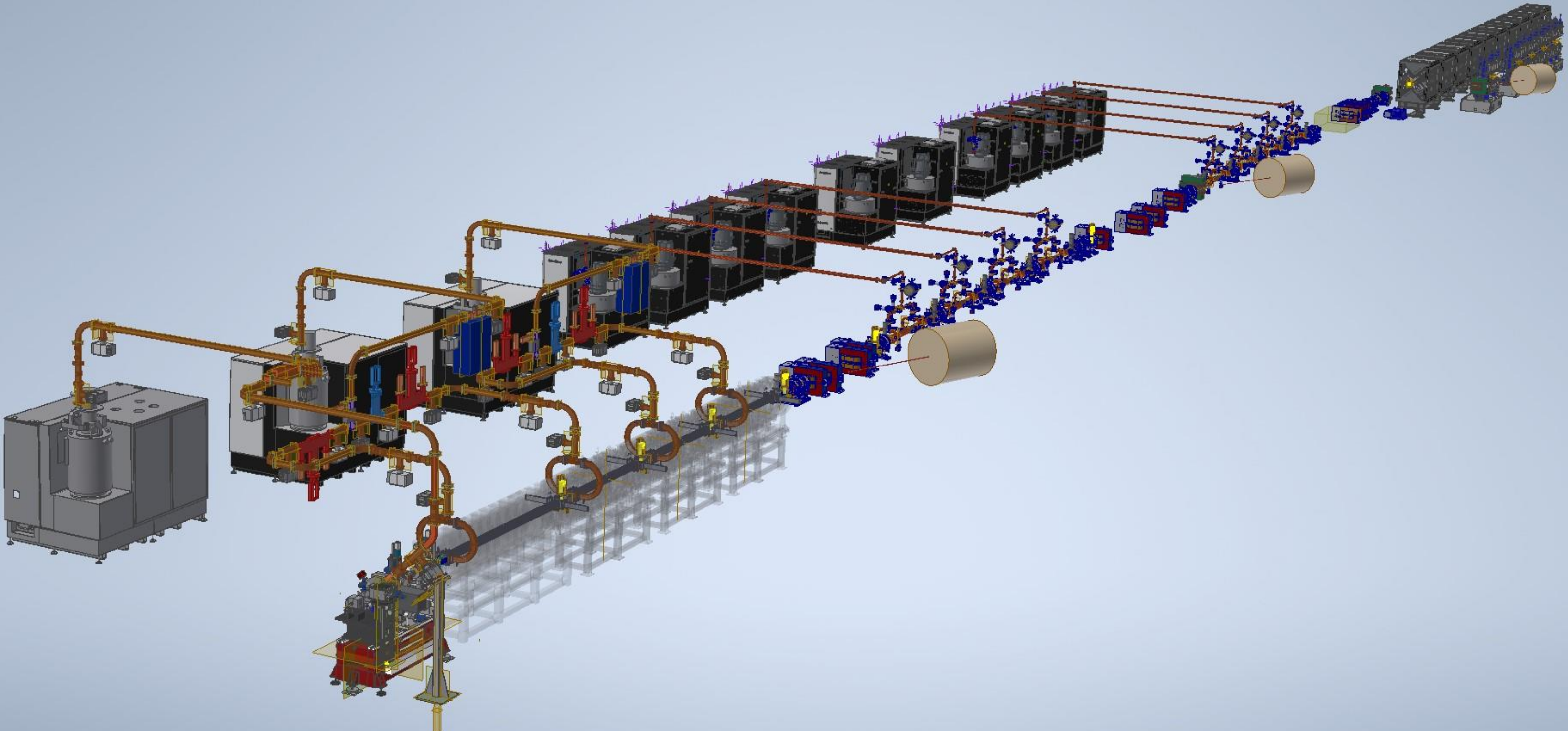
Headquarter and Site 1: EuPRAXIA@SPARC_LAB

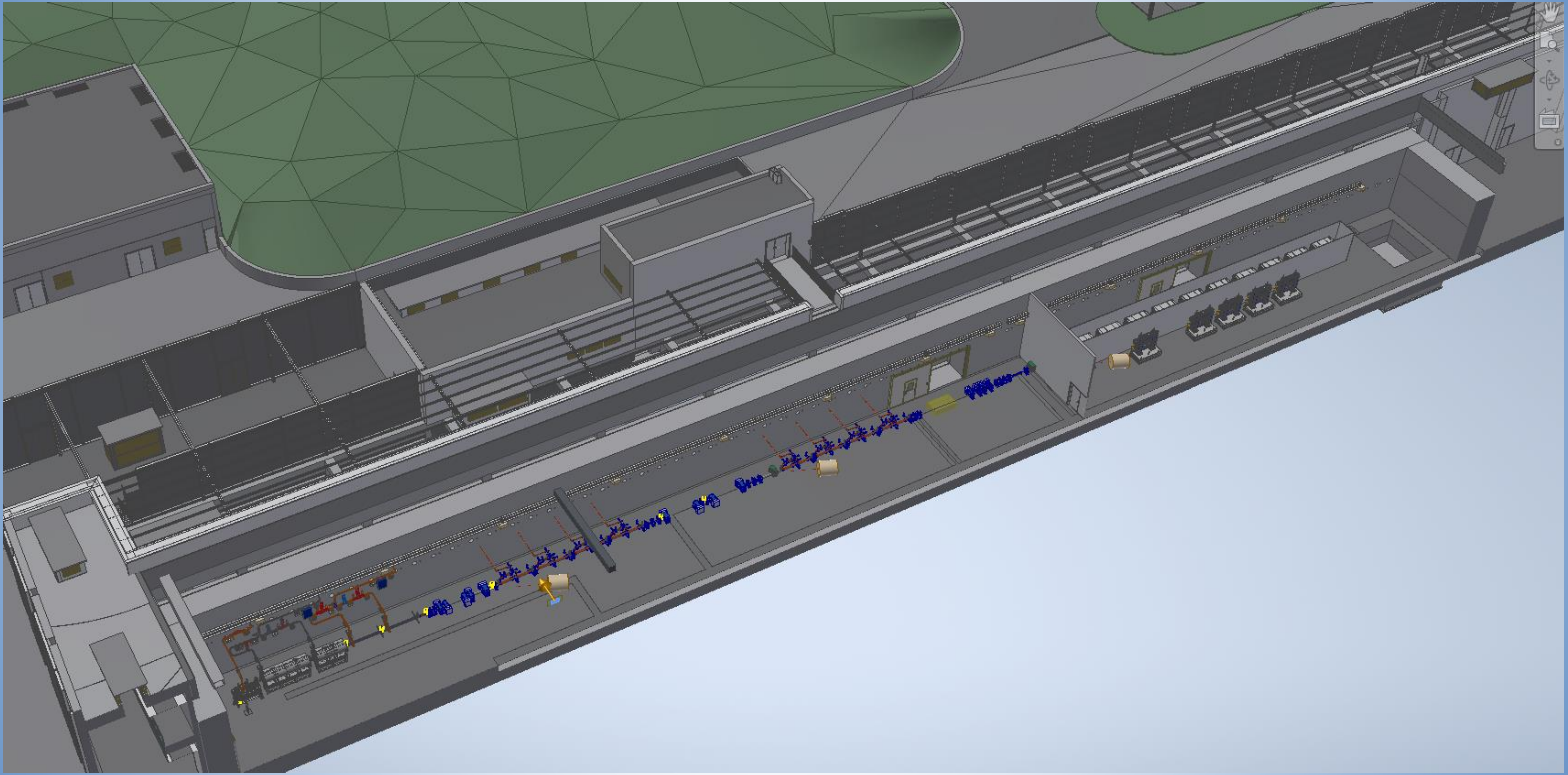


- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

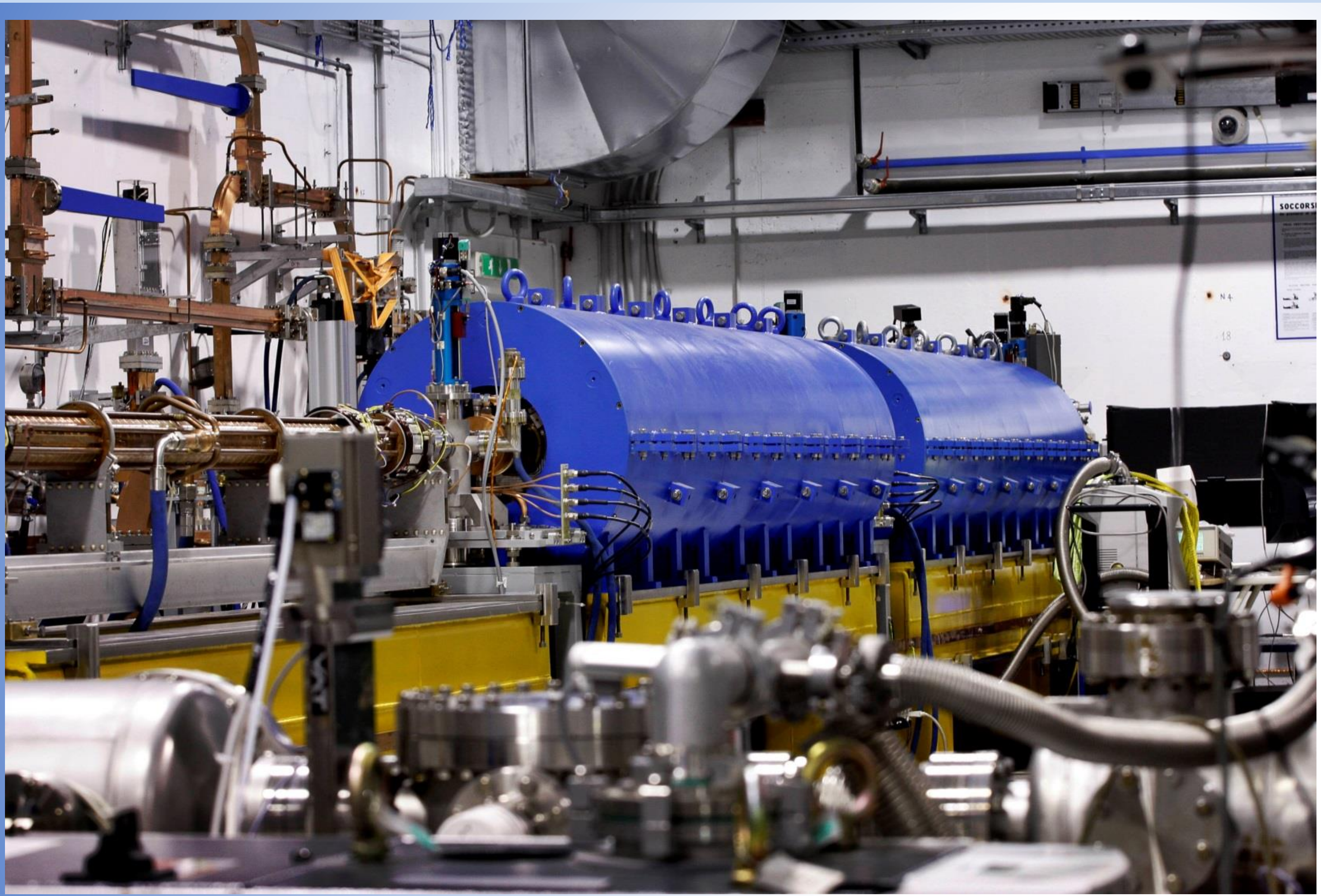
EuPRAXIA@SPARC_LAB

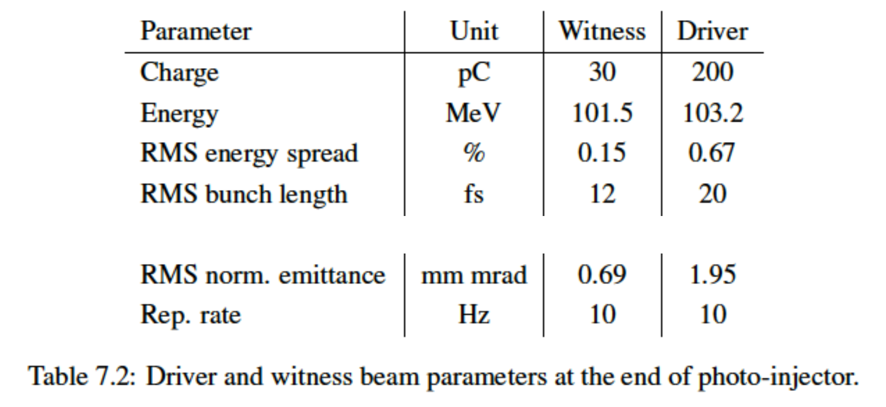






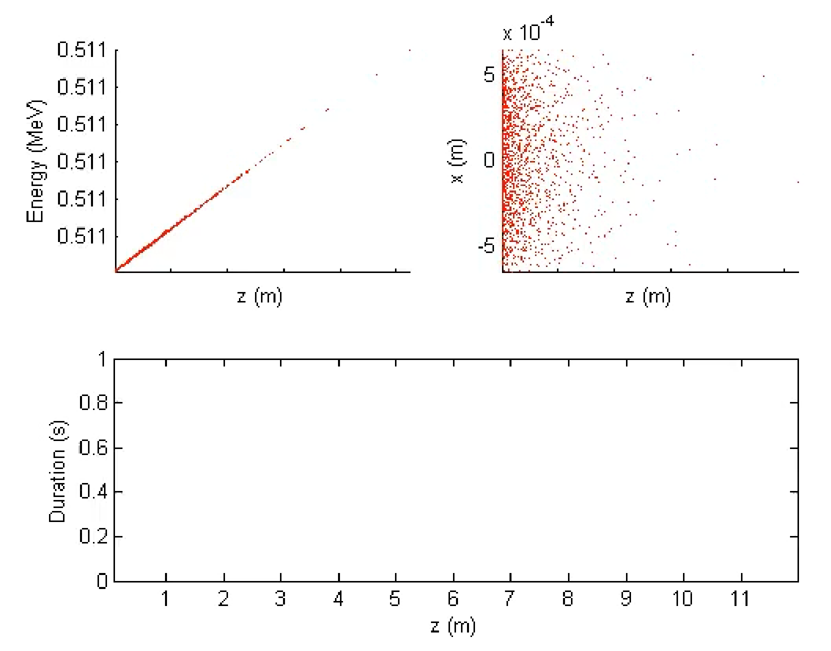
High Quality Electron Beams





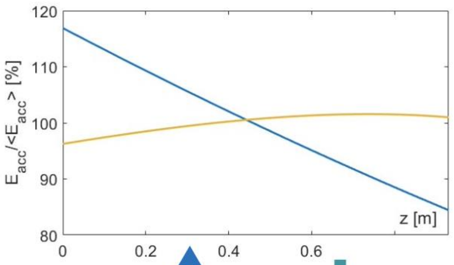
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

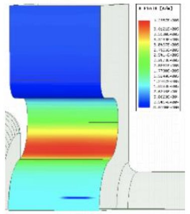
Table 7.2: Driver and witness beam parameters at the end of photo-injector.

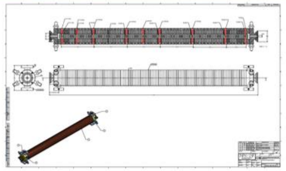


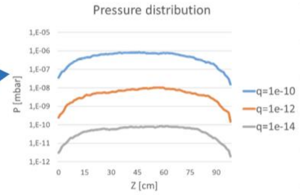
Courtesy E. Chiadroni

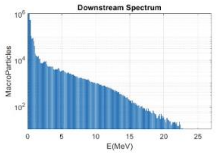
World`s Most Compact RF Linac: X Band





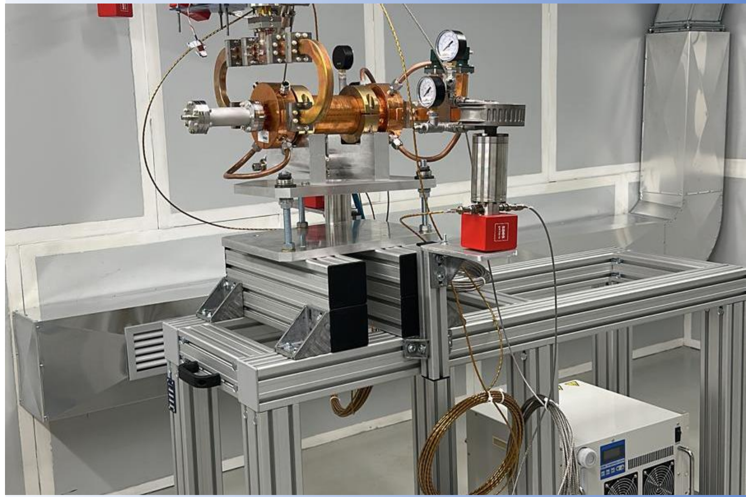


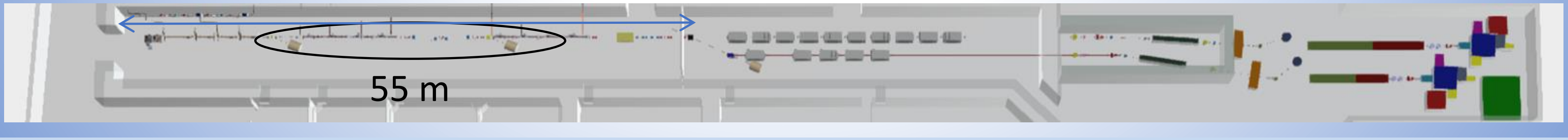




1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

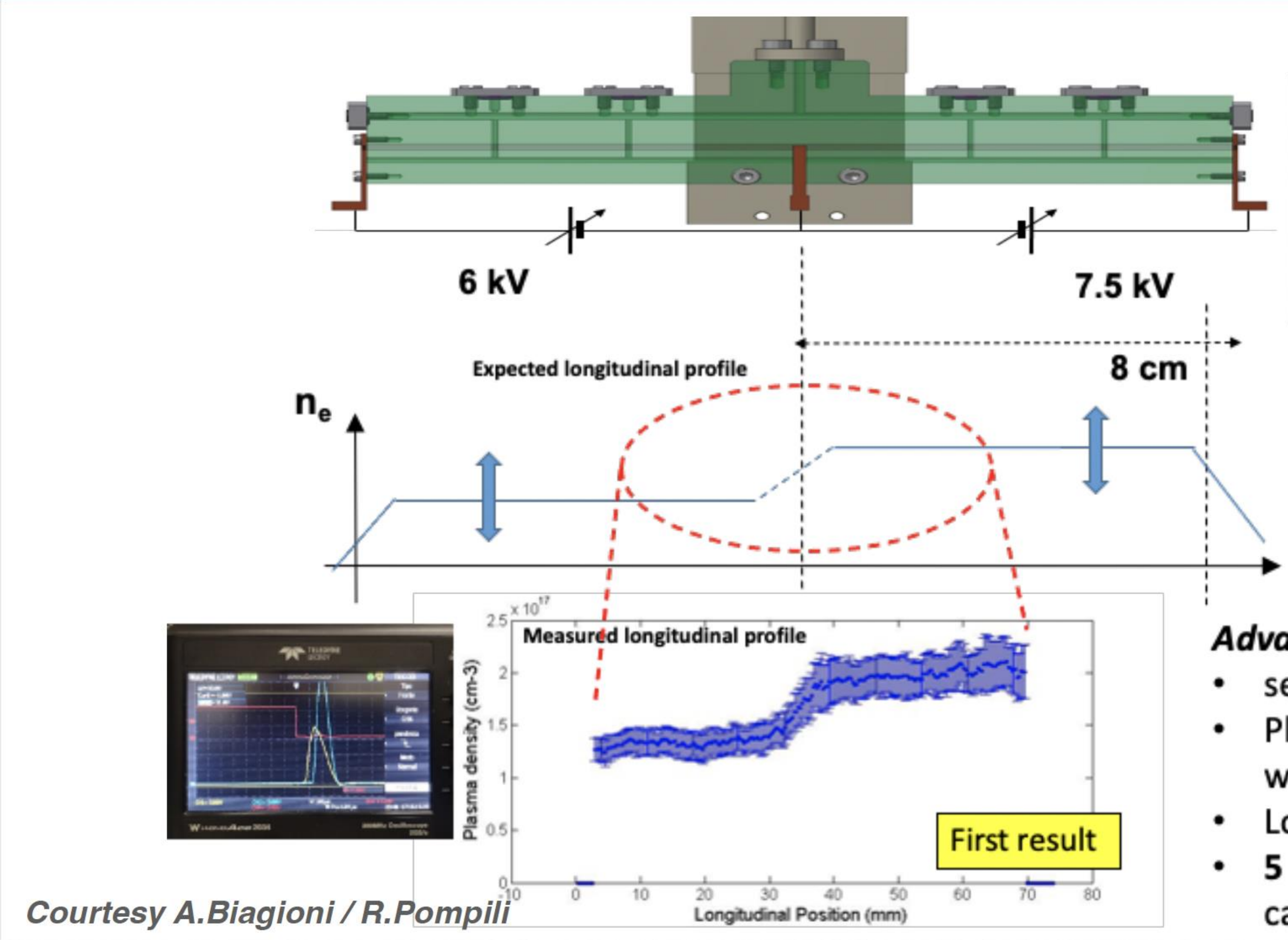
PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt impedance R [MΩ/m]	93-107	100
Effective shunt Imp. $R_{sh\ eff}$ [MΩ/m]	350	347
Peak input power per structure [MW]	70	
Input power averaged over the pulse [MW]	51	
Average dissipated power [kW]	1	
P_{out}/P_{in} [%]	25	
Filling time [ns]	130	
Peak Modified Poynting Vector [W/μm^2]	3.6	4.3
Peak surface electric field [MV/m]	160	190
Unloaded SLED/BOC Q-factor Q_0	150000	
External SLED/BOC Q-factor Q_E	21300	20700
Required Kly power per module [MW]	**20**	
RF pulse [μs]	**1.5**	
Rep. Rate [Hz]	**100**	



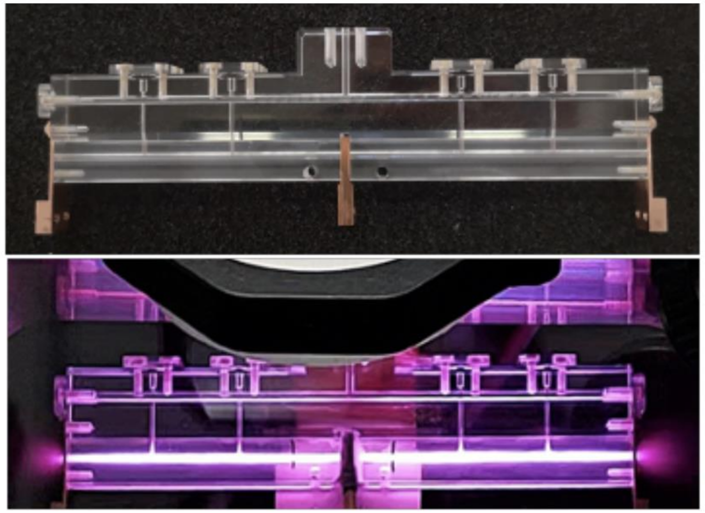


Courtesy D. Alesini

Plasma Module

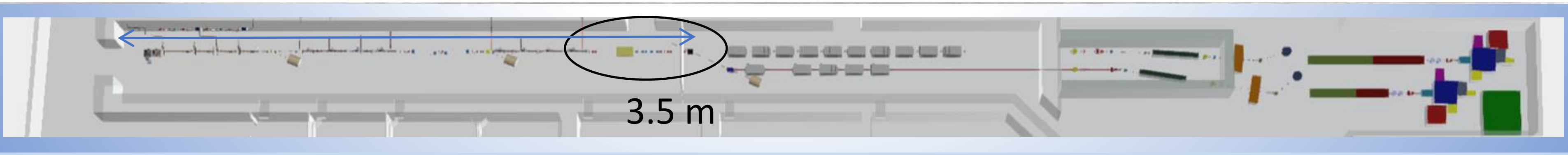


Courtesy A.Biagioni / R.Pompili



Advantages:

- several independently controllable sections
- Plasma sources larger than 40 cm (m-scale) with HV pulses less than 10 kV
- Longitudinal density modulation
- **5 GeV** case for EuPRAXIA (1.5 GV/m m-scale capillary - density 10^{16} cm-3)

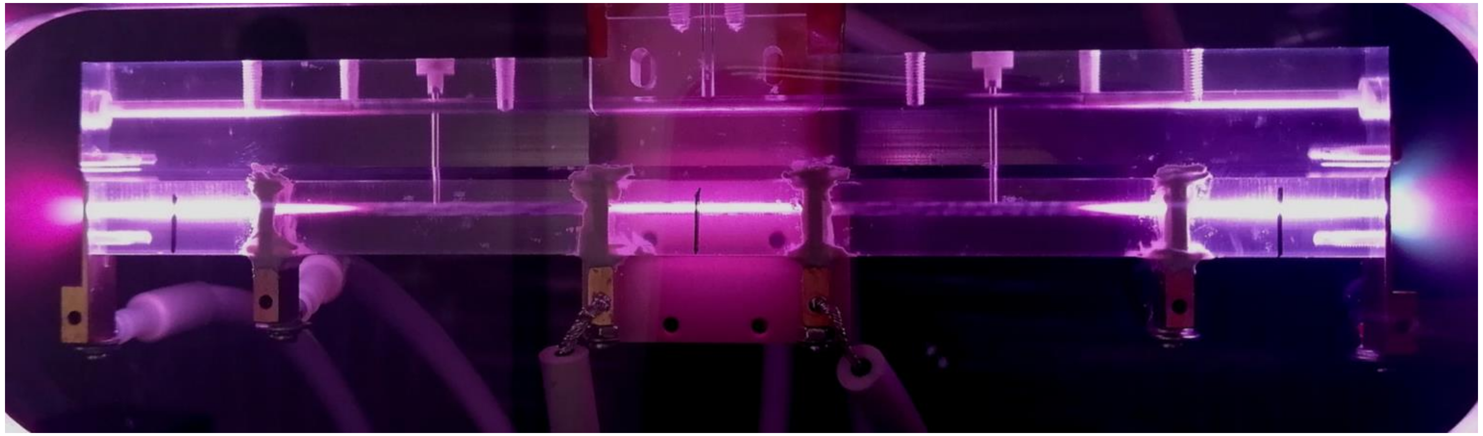


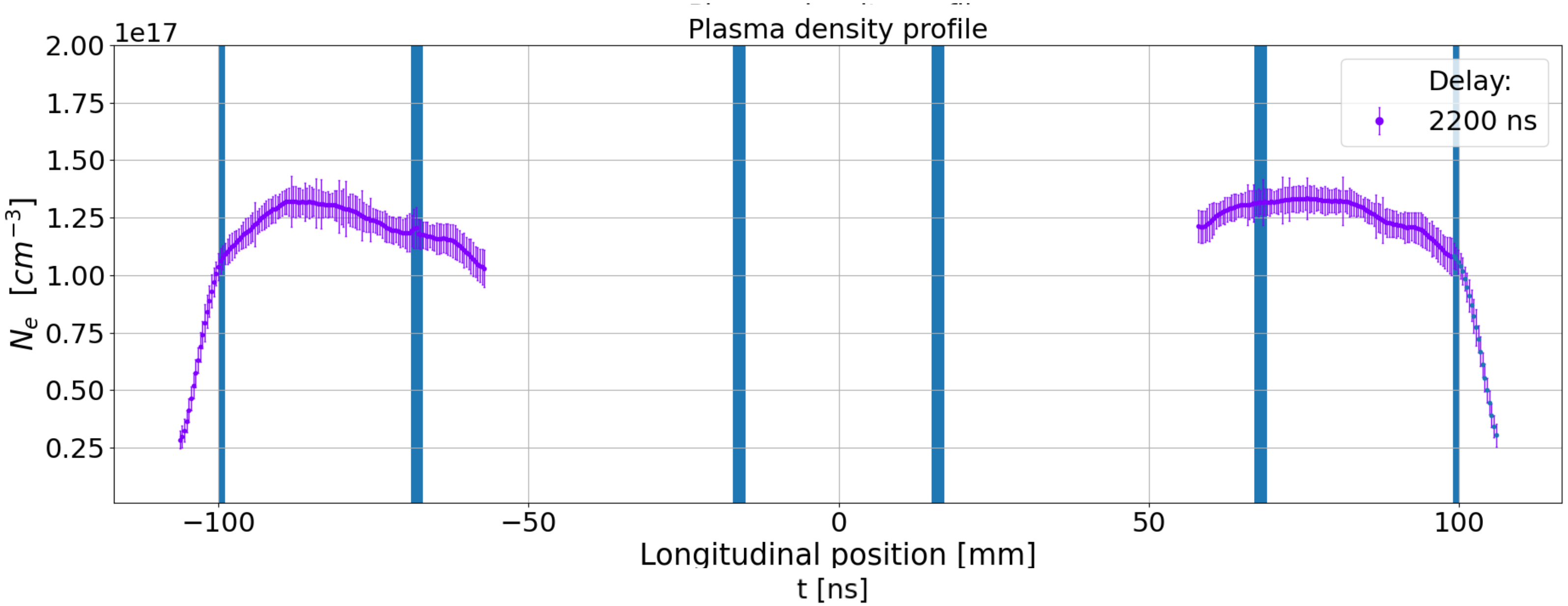
Courtesy A. Biagioni, R. Pompili

Novel schemes for long sources and staged acceleration

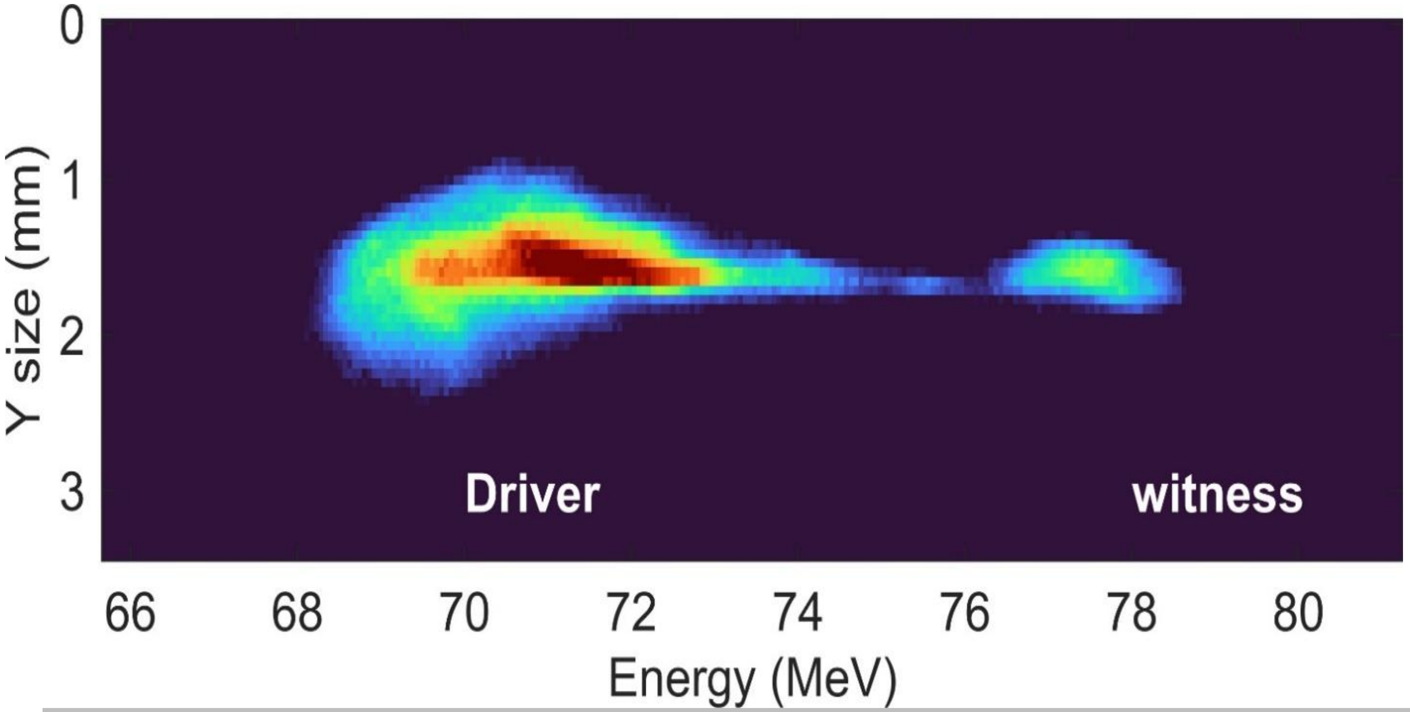
Operating properties

- Discharges synchronization
  - Lenses synchronized with the beam entrance
  - Central discharge applied 3 μs before for plasma acceleration
- 10 kV voltage resulting in:
  - 500 A on the lenses
  - 250 A in the accelerator

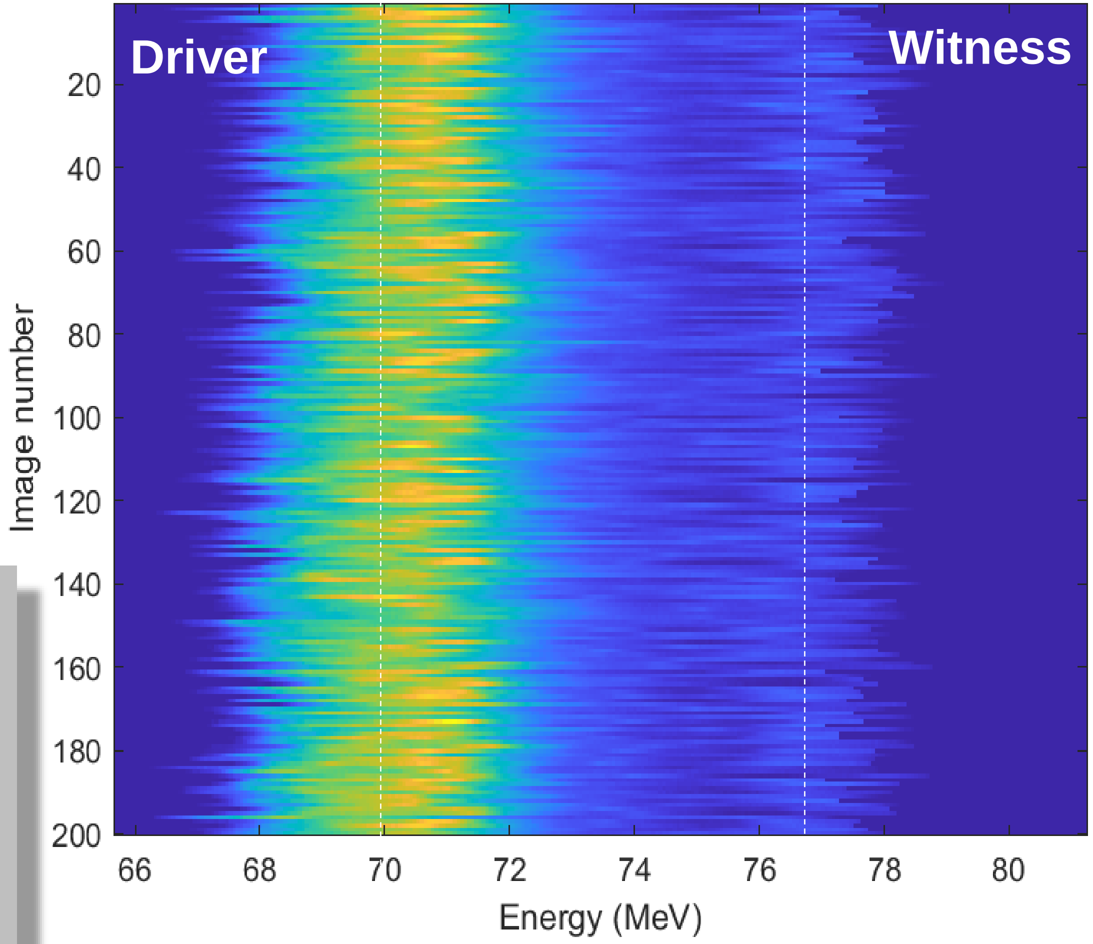




Beam acceleration in the integrated plasma module

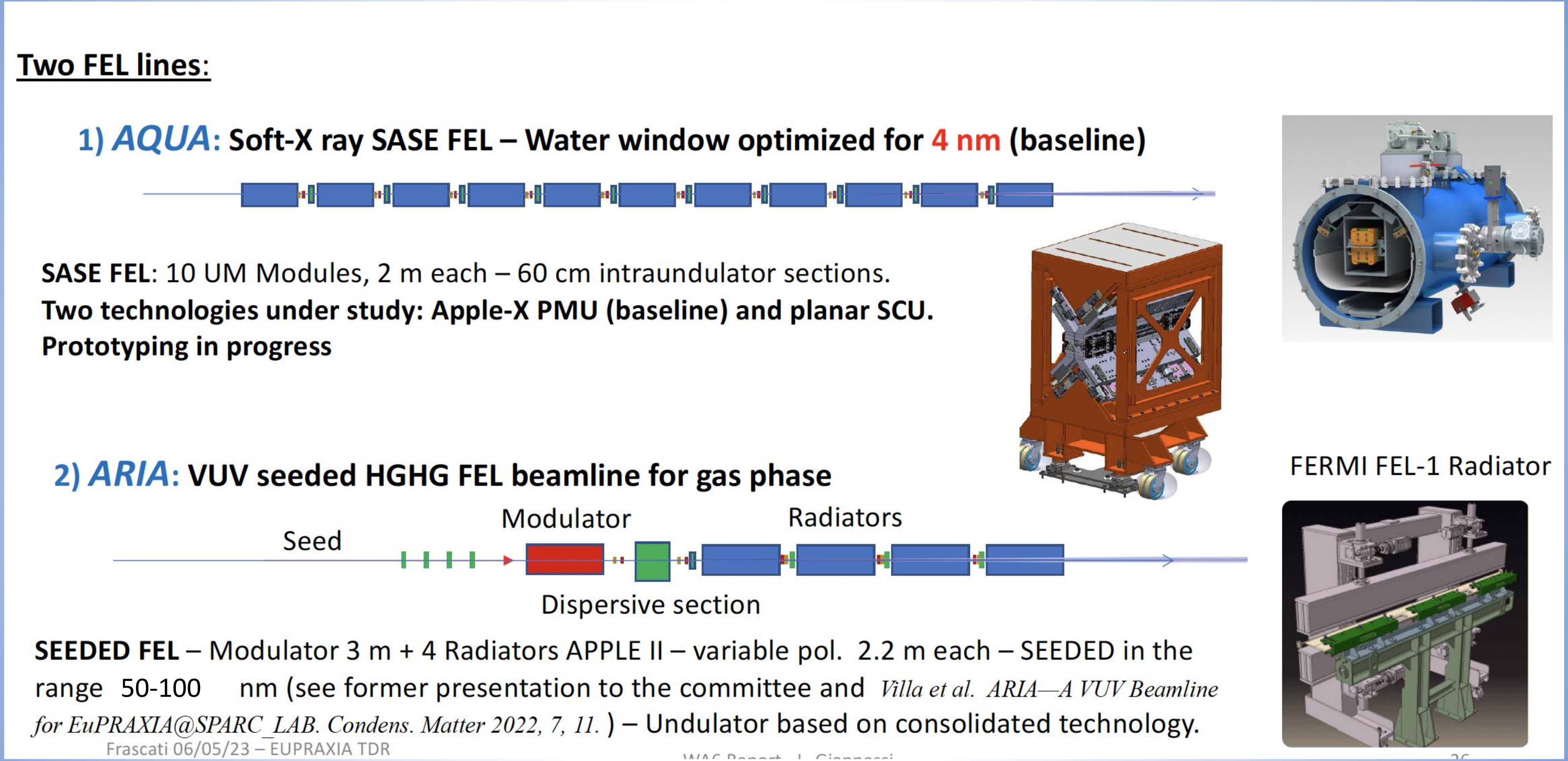


200 consecutive shots taken with accelerated beam



- ***5 MeV/3cm acceleration in 19 cm long integrated plasma module with 200 pC driver/50 pC witness***
    - 3 cm long accelerator with 200 A ionization current
    - 3 cm long plasma lenses with 500 A ionization current
    - Plasma density inside the accelerator set to 2x10^{15} cm^{-3}
    - ~150 MV/m accelerating gradient
    - Stability of the accelerated beam

Radiation Generation: FEL



Two FEL lines:

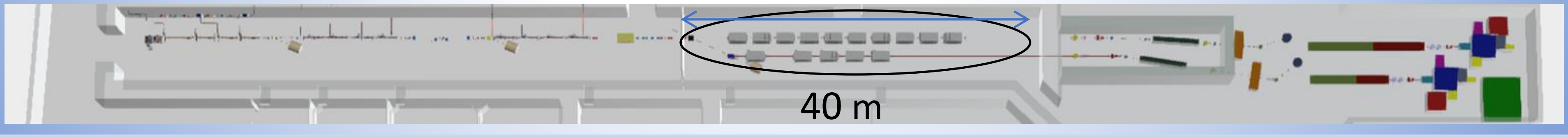
1) ***AQUA*: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)**

SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress

2) ***ARIA*: VUV seeded HGHG FEL beamline for gas phase**

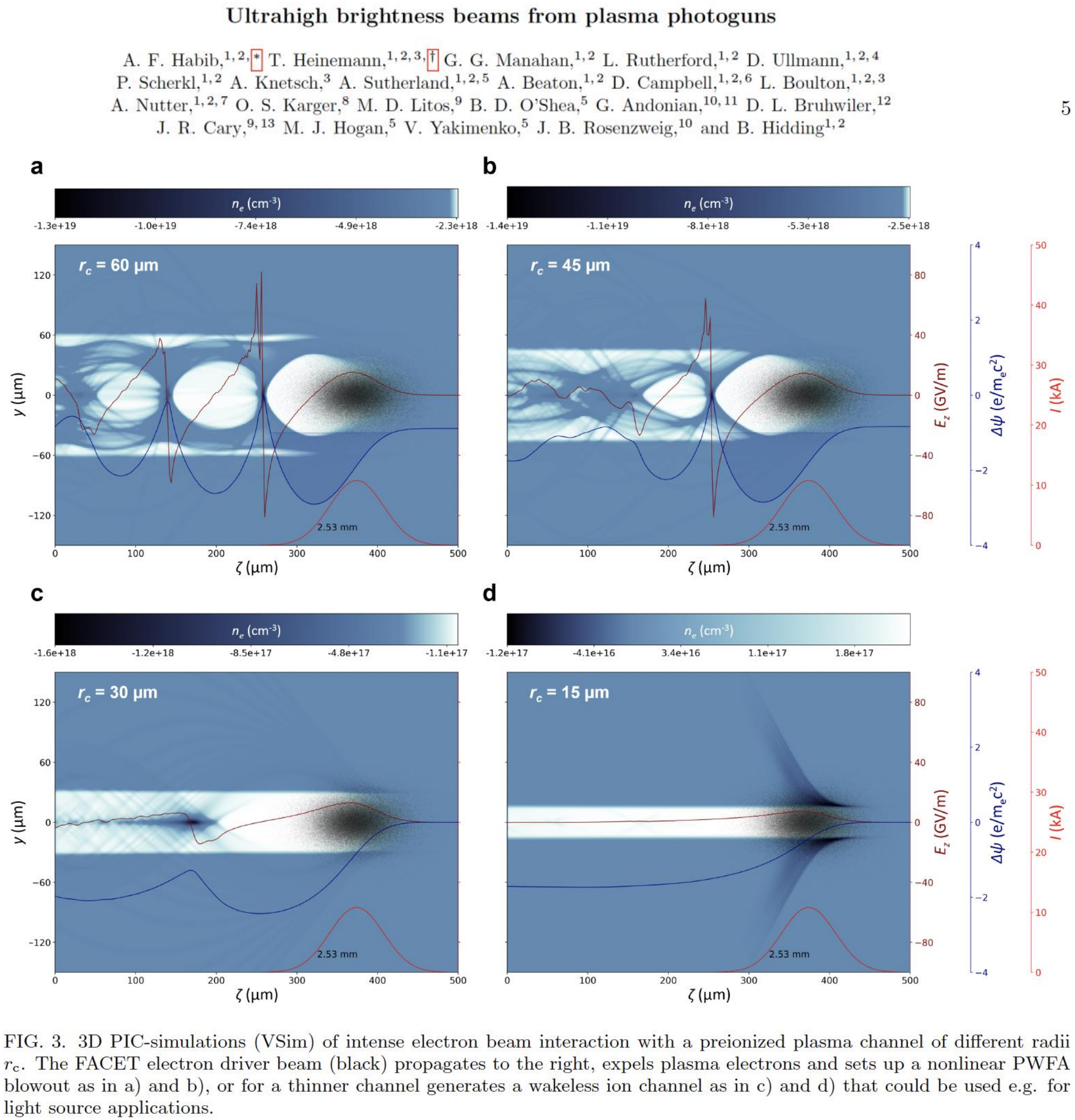
FERMI FEL-1 Radiator

SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 50-100 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.



Courtesy L. Giannessi

Towards a Plasma Undulator for FEL



Ultrahigh brightness beams from plasma photoguns

A. F. Habib,[1,2,*] T. Heinemann,[1,2,3,†] G. G. Manahan,[1,2] L. Rutherford,[1,2] D. Ullmann,[1,2,4]
P. Scherkl,[1,2] A. Knetsch,[3] A. Sutherland,[1,2,5] A. Beaton,[1,2] D. Campbell,[1,2,6] L. Boulton,[1,2,3]
A. Nutter,[1,2,7] O. S. Karger,[8] M. D. Litos,[9] B. D. O'Shea,[5] G. Andonian,[10,11] D. L. Bruhwiler,[12]
J. R. Cary,[9,13] M. J. Hogan,[5] V. Yakimenko,[5] J. B. Rosenzweig,[10] and B. Hidding[1,2]

5

FIG. 3. 3D PIC-simulations (VSim) of intense electron beam interaction with a preionized plasma channel of different radii r_c. The FACET electron driver beam (black) propagates to the right, expels plasma electrons and sets up a nonlinear PWFA blowout as in a) and b), or for a thinner channel generates a wakeless ion channel as in c) and d) that could be used e.g. for light source applications.

➔ Neutral plasma creation through ionization laser

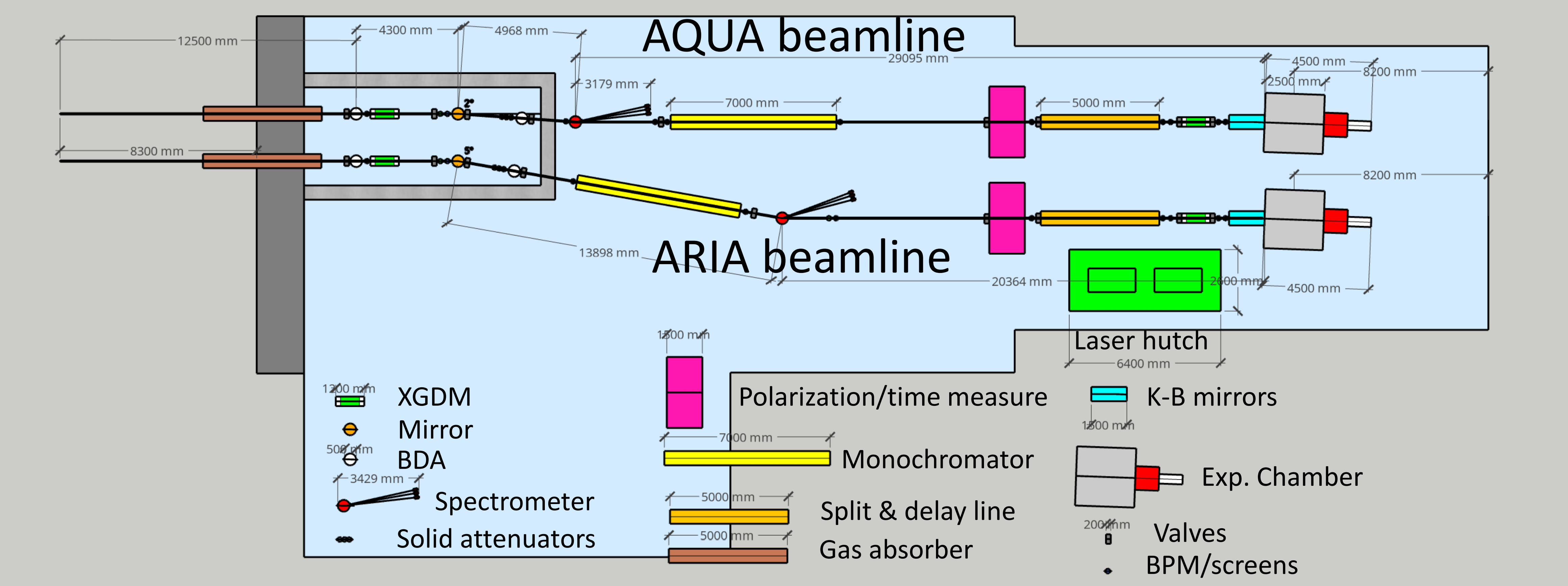
➔ Blowout of the plasma electrons through the driver beam

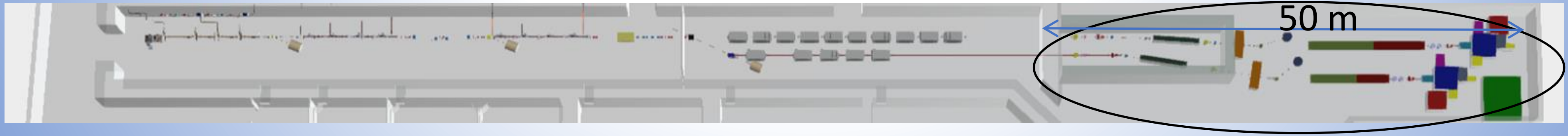
◆**plasma electrons are expelled from the plasma region toward the neutral gas region**

- **negligible restoring force** outside column
- **negligible accelerating force** inside column
- **linear restoring force** inside column

E. Chiadroni et al., INFN-CSN5 project "Beta-test" at SPARC_LAB

FEL Beamlines



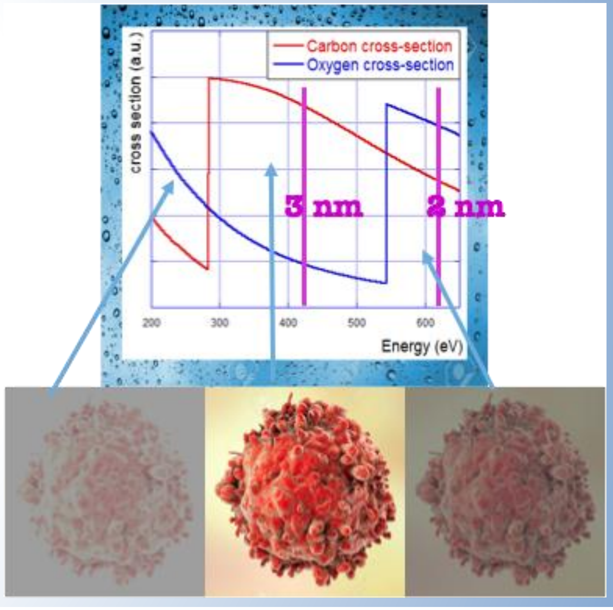


Expected SASE FEL performances

Parameter	**Unit**	PWFA	Full X-band
Electron Energy	GeV	**1**-*1.2*	1
Bunch Charge	pC	**30**-***50***	**200**-***500***
Peak Current	kA	1-2	1-2
RMS Energy Spread	%	**0.1**	0.1
RMS Bunch Length	μm	6-3	24-20
RMS norm. Emittance	μm	1	1
Slice Energy Spread	%	≤0.05	≤0.05
Slice norm Emittance	mm-mrad	0.5	0.5

Parameter	**Unit**	PWFA	Full X-band
Radiation Wavelength	nm	**3-4**	**4**
Photons per Pulse	$\times 10^{12}$	**0.1- 0.25**	1
Photon Bandwith	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$s\,mm^2 mrad^2$ $bw(0.1\%)$	$\mathbf{1-2\ \times 10^{28}}$	$1\ \times 10^{27}$

In the Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10 ^{11} photons/pulse needed

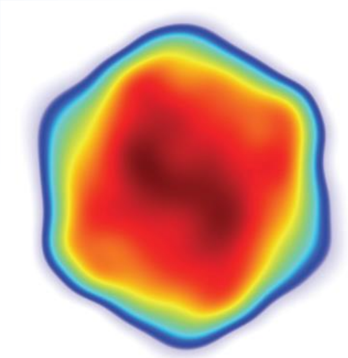
Courtesy F. Stellato, UniToV

Courtesy C. Vaccarezza/L. Giannessi

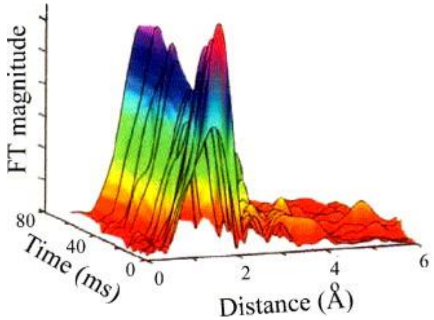
AQUA beamline scientific case

Experimental techniques and typology of samples

Coherent imaging



X-ray spectroscopy



Raman spectroscopy

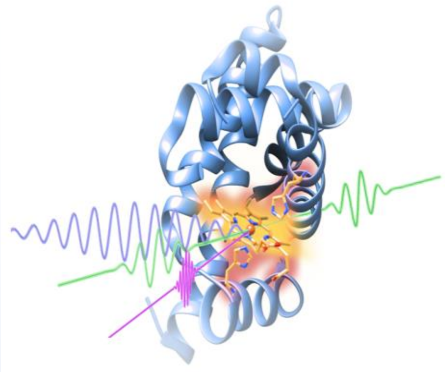
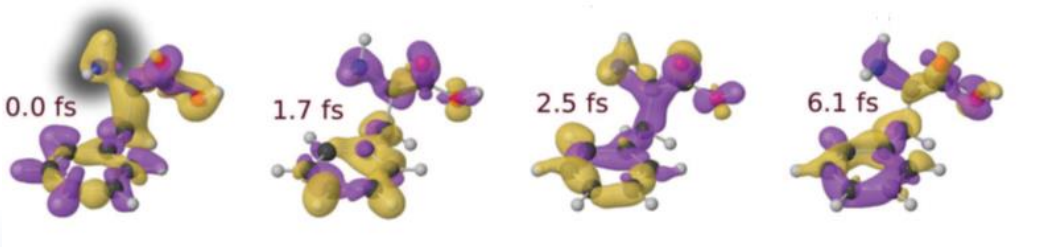


Photo-fragmentation of molecules



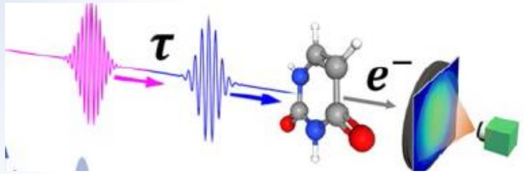
(Large) Viruses
Organelles
Bacteria/Cells
Metals
Semiconductors
Superconductors
Magnetic materials
Organic molecules

Courtesy F. Stellato

ARIA beamline scientific case

Defining experimental **techniques** and typology of samples (and applications)

Photoemission Spectroscopy



Photoelectron Circular Dichroism

Raman spectroscopy

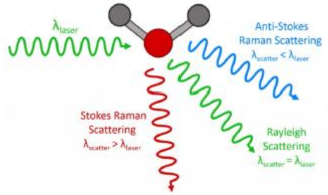
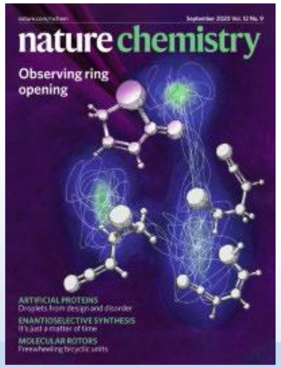
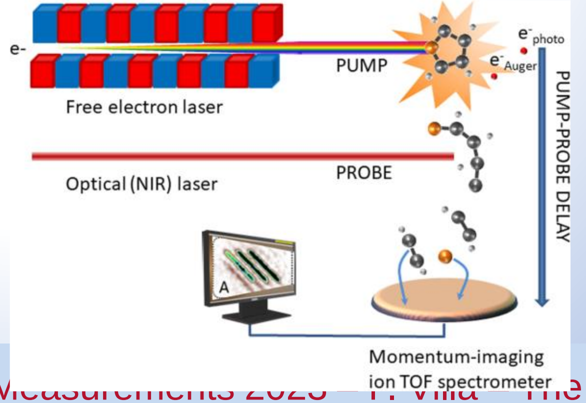


Photo-fragmentation of molecules Time of Flight Spectroscopy

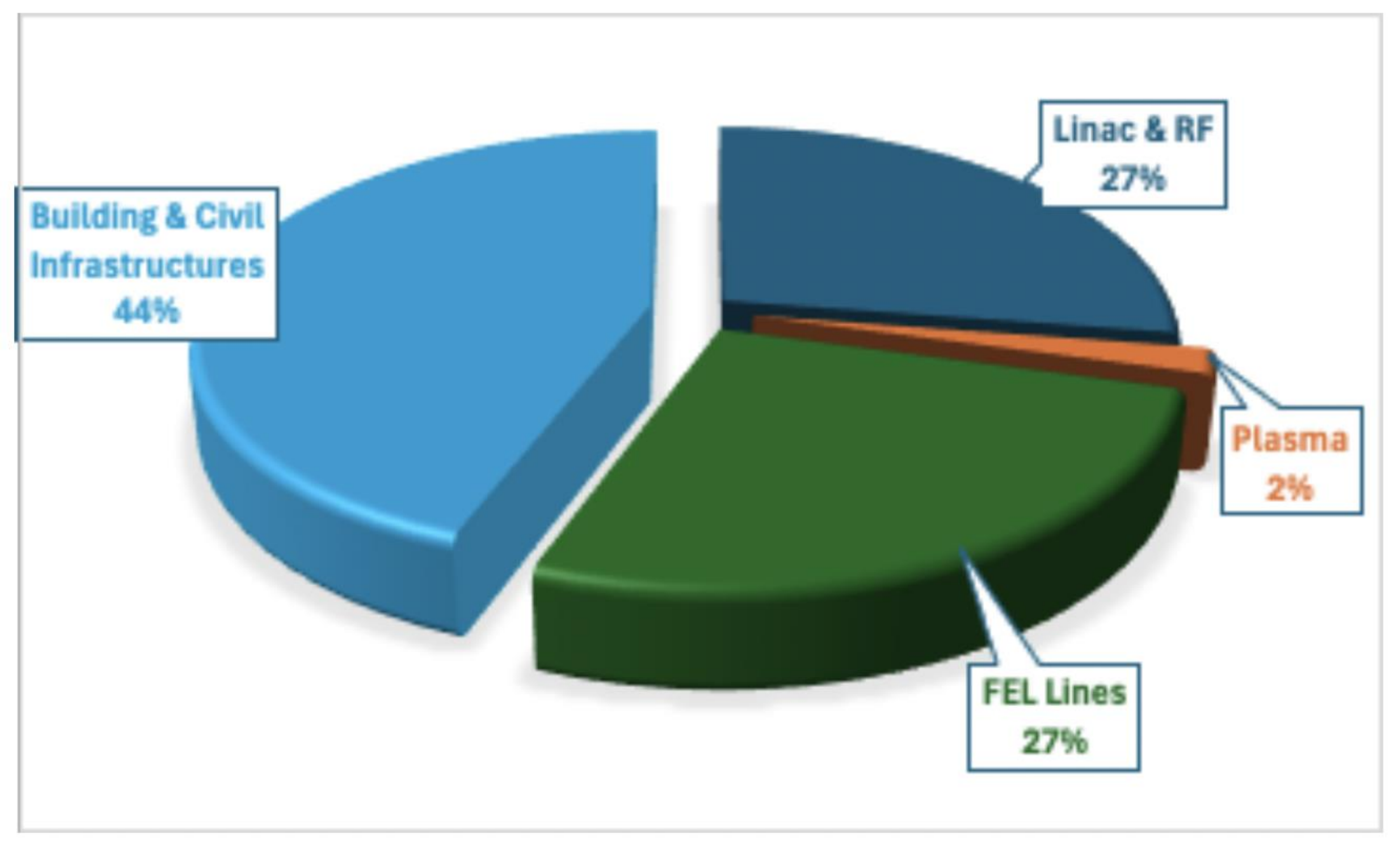




Gas phase & Atmosphere
(Earth & Planets)
Aerosols
(Pollution, nanoparticles)
Molecules & gases
(spectroscopies, time-of-flight)
Proteins
(spectroscopies)
Surfaces
(ablation & deposition)

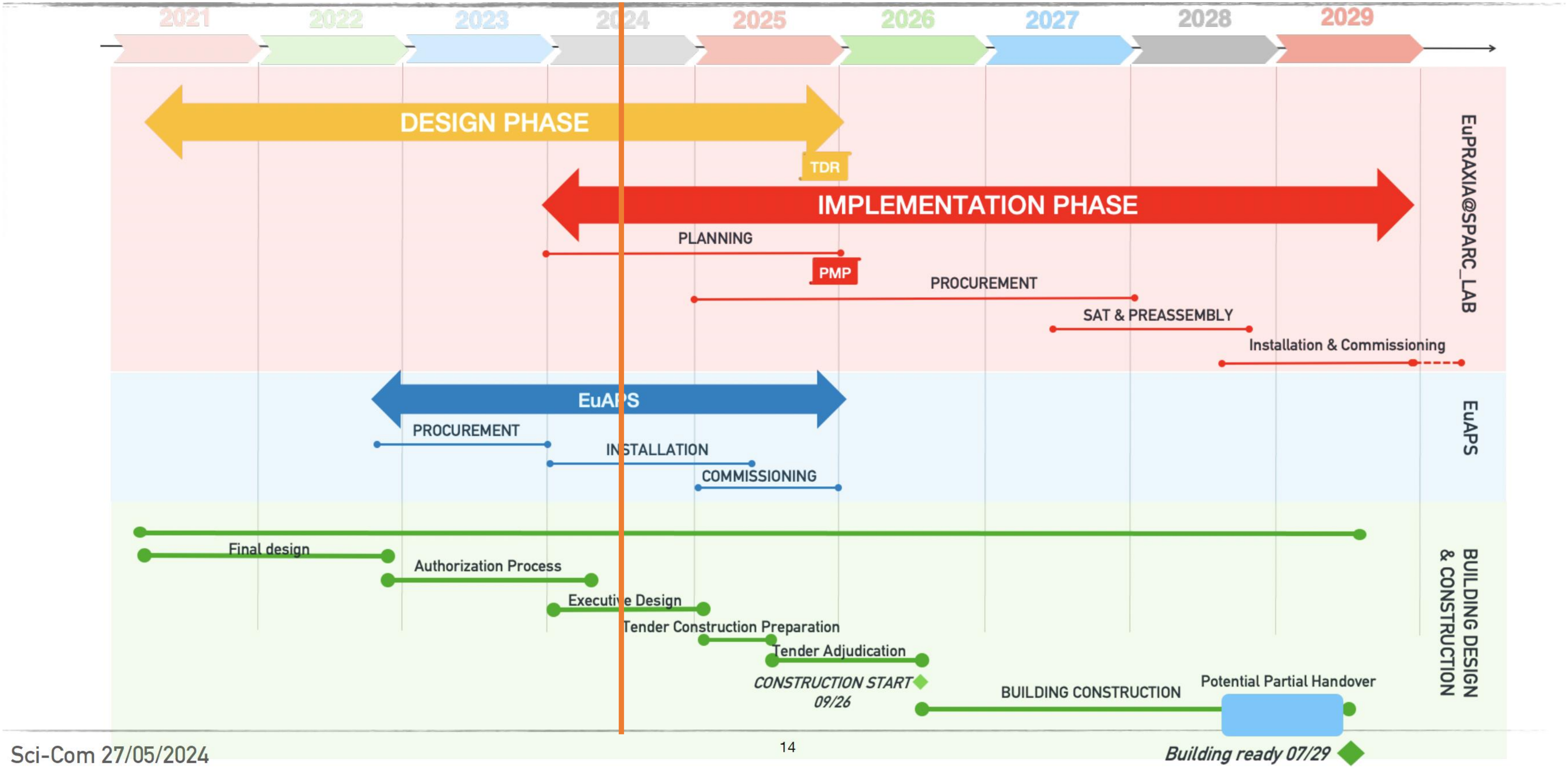
Courtesy F. Stellato

Cost Review



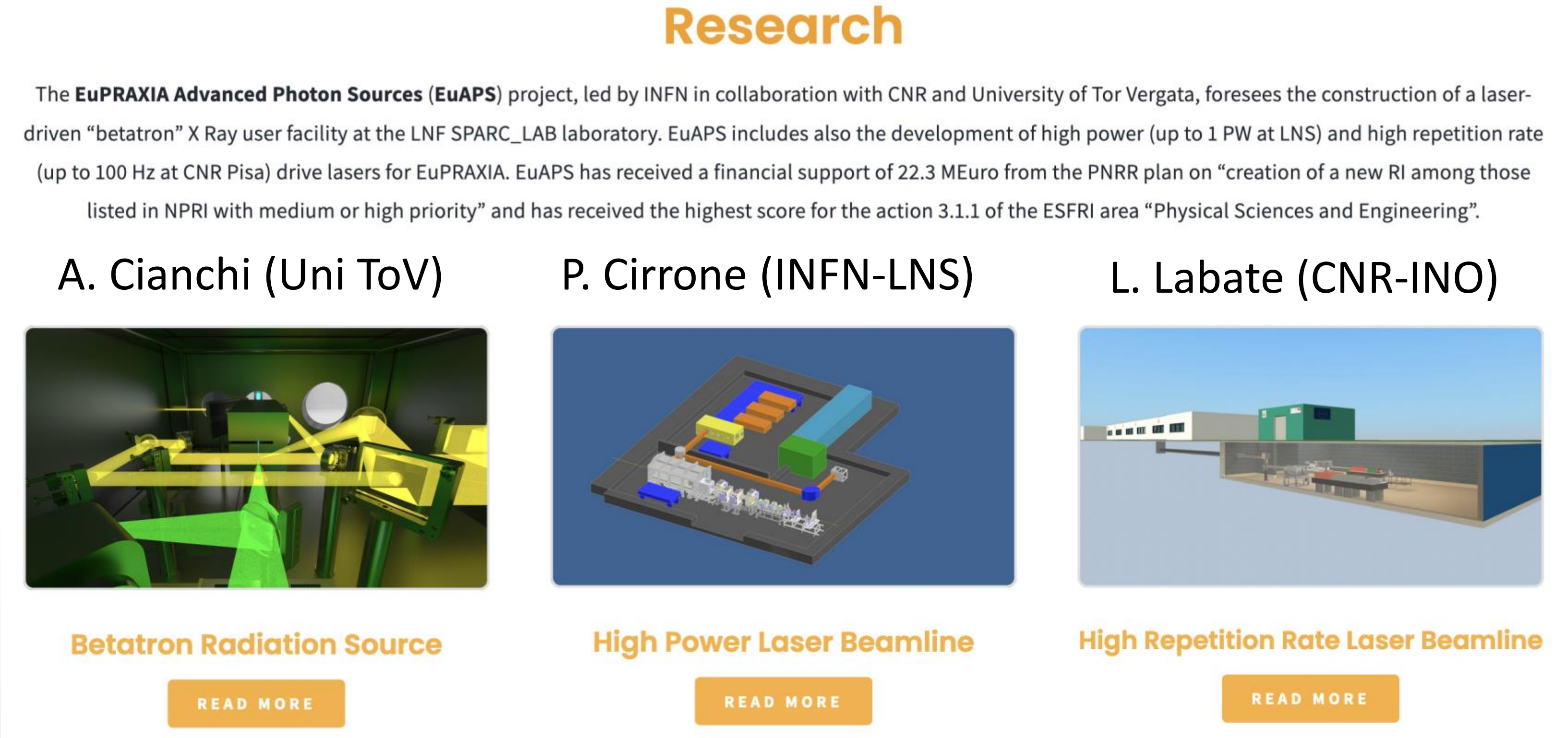
ITEM	Expected Cost
LINAC	17.614.540
Plasma	2.287.000
RF Power	15.760.000
FEL Line Aqua	15.425.000
FEL Line ARIA	4.476.000
Beam Line & User end station AQUA	6.670.000
Beam Line & User end station ARIA	5.590.000
Building & Hi Tech utilities	53.945.500
TOT	121.768.040

EuPRAXIA@SPARC_LAB baseline updating



EuAPS: EuPRAXIA Advance Photon Sources

- Principal Investigator: M. Ferrario,
- Infrastructure Manager: C. Bortolin,
- Management and Dissemination: A. Falone



Research

The **EuPRAXIA Advanced Photon Sources** (**EuAPS**) project, led by INFN in collaboration with CNR and University of Tor Vergata, foresees the construction of a laser-driven "betatron" X Ray user facility at the LNF SPARC_LAB laboratory. EuAPS includes also the development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) drive lasers for EuPRAXIA. EuAPS has received a financial support of 22.3 MEuro from the PNRR plan on "creation of a new RI among those listed in NPRI with medium or high priority" and has received the highest score for the action 3.1.1 of the ESFRI area "Physical Sciences and Engineering".

A. Cianchi (Uni ToV)

Betatron Radiation Source

READ MORE

P. Cirrone (INFN-LNS)

High Power Laser Beamline

READ MORE

L. Labate (CNR-INO)

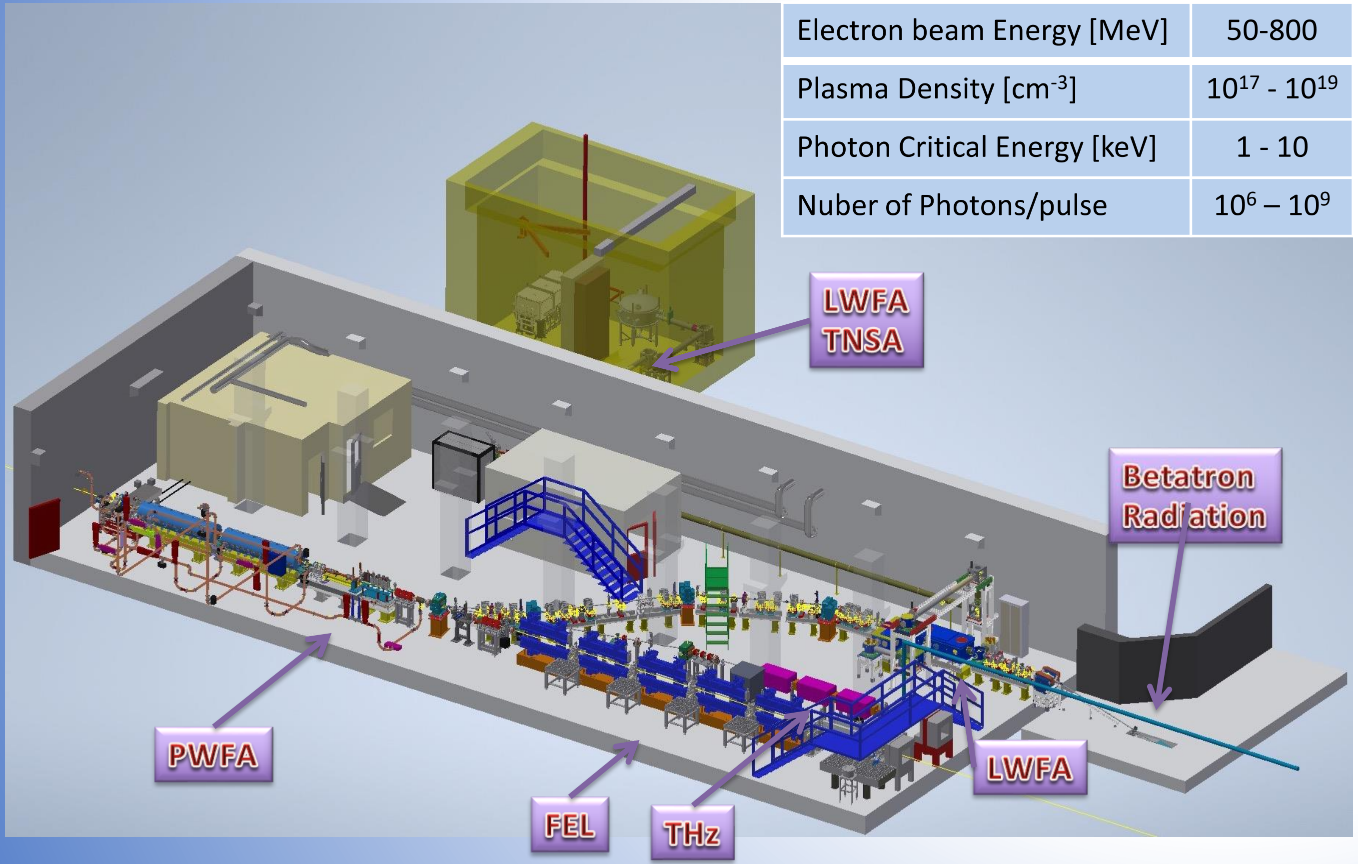
High Repetition Rate Laser Beamline

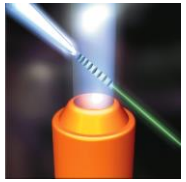
READ MORE

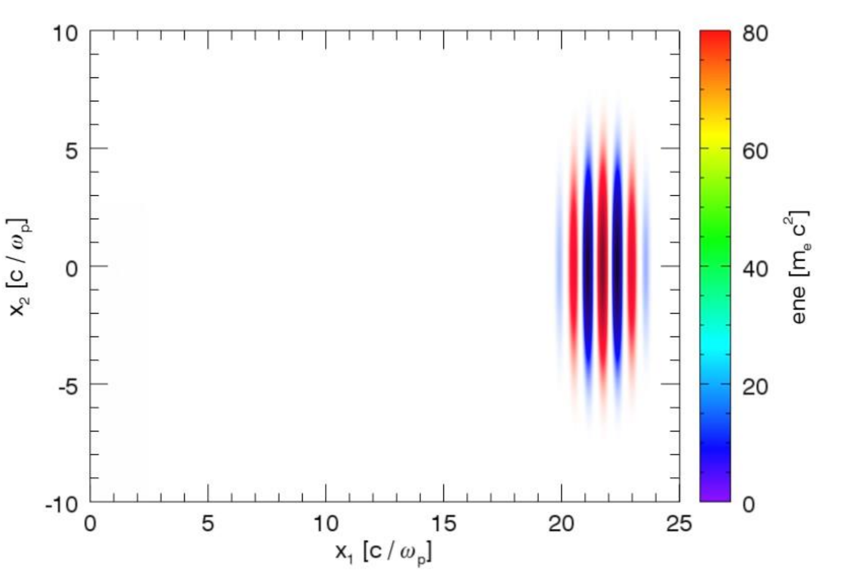
M. Ferrario et al. INFN-23-12-LNF (2023)

Betatron Radiation Source at SPARC_LAB

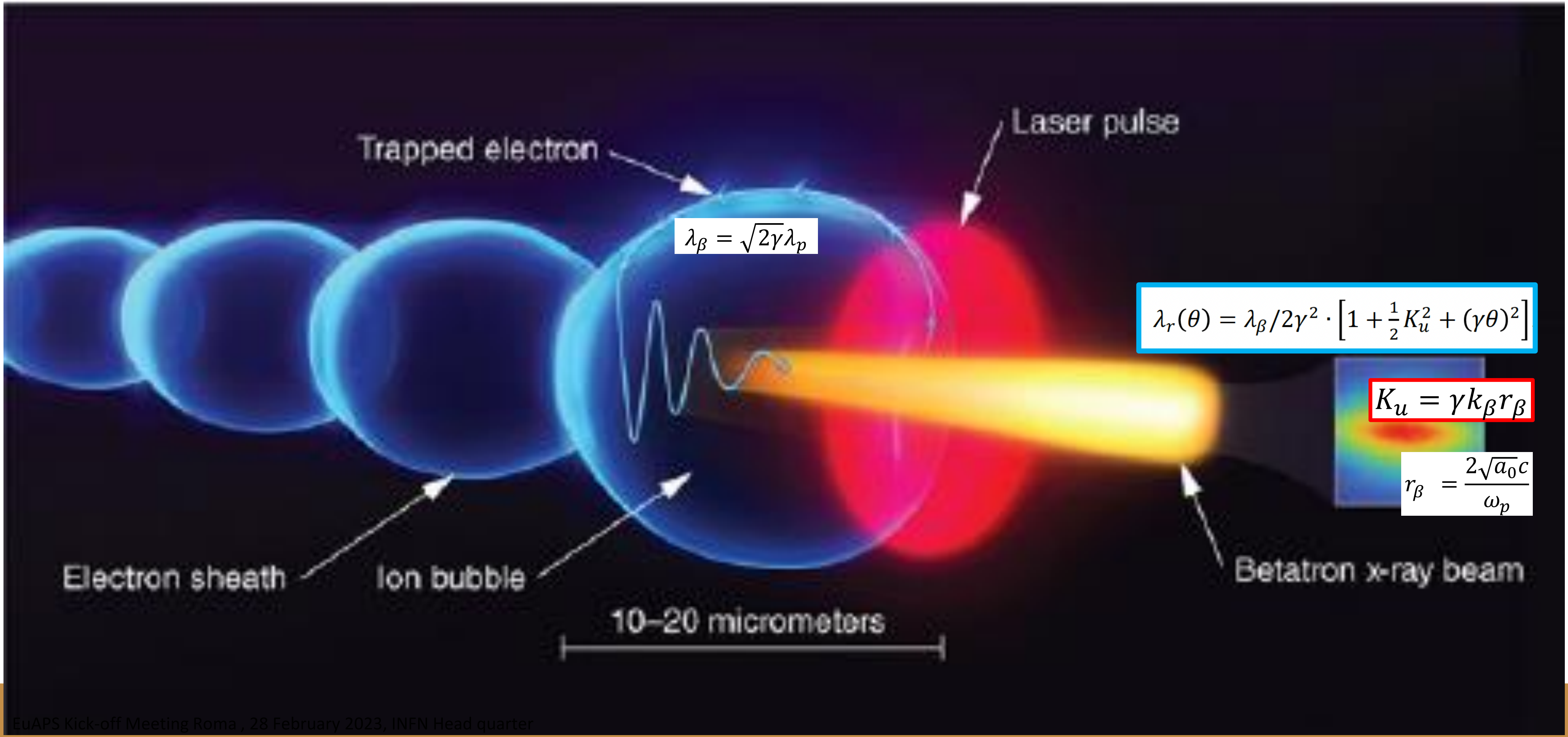
Electron beam Energy [MeV]	50-800
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^{6} – 10^{9}







Courtesy J. Vieira, R. Fonseca/GoLP/IST Lisbon



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

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

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

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

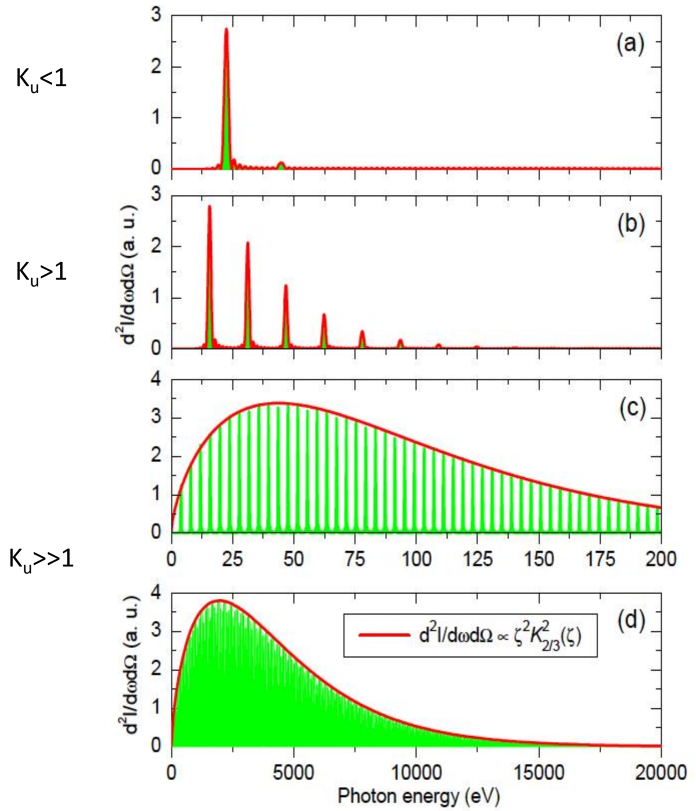


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of* 7×10^{18} cm^{-3}. *The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 µm, (b) 0.5 µm, and (c) 1.6 µm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 µm.*

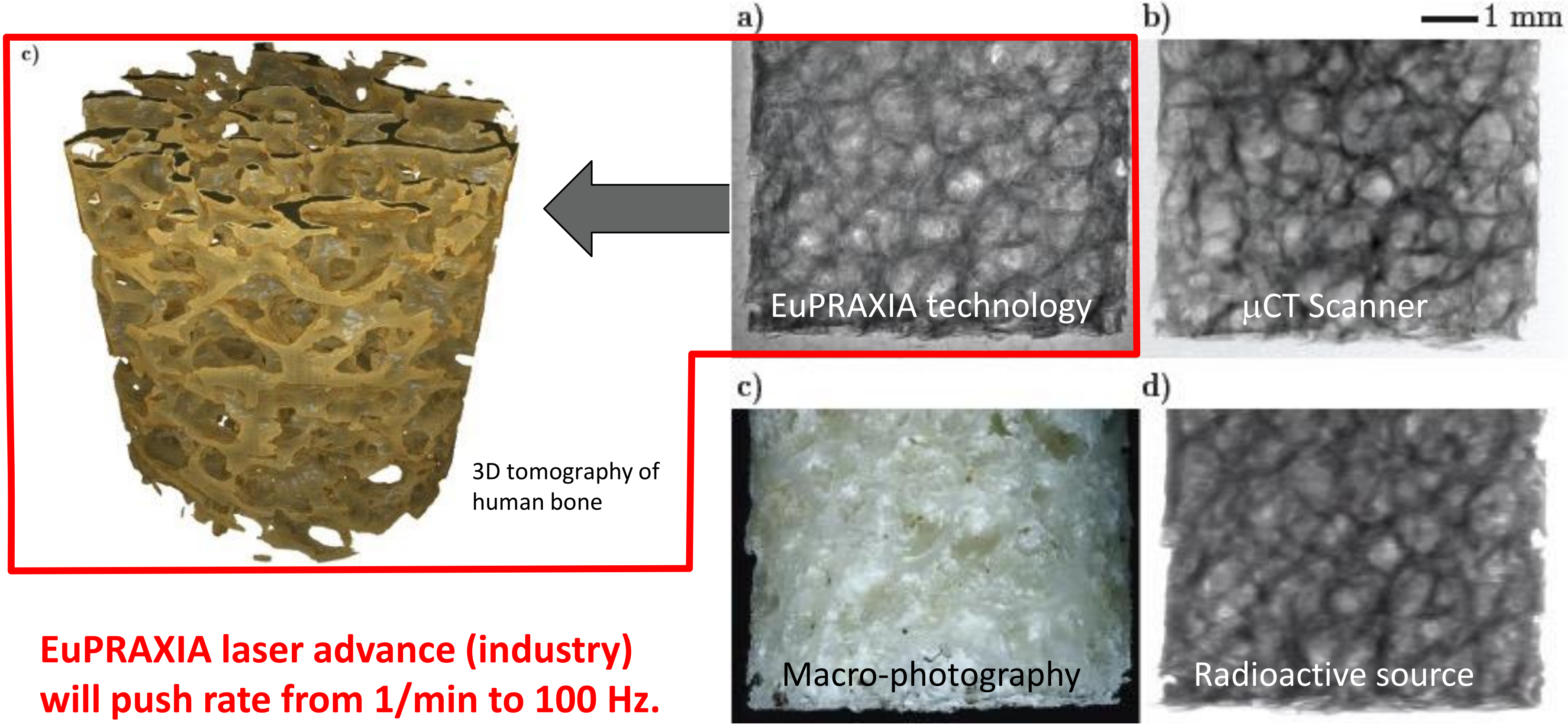
$$\omega_c = 3K_u\gamma^2\omega_\beta$$

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

1) **Ultrafast** - laser pulse duration tens of fs useful for **time resolved experiments** (XFEL tens of fs, synchrotron tens to 100 ps).
2) **Broad energy spectrum -** important for **X-ray spectroscopy**.
3) **High brightness** - small source size and high photon flux for **fast processes**.
4) **Large market** - 50 synchrotron light sources worldwide, 6 hard XFEL's and 3 soft-ray ones (many accelerators operational and some under construction).

Betatron X Rays: 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)

From European Strategy for Particle Physics Accelerator R&D Roadmap (2022)

High-gradient plasma and laser accelerators

Panel members: R. Assmann[e,f,**] (Chair), E. Gschwendtner[a] (Co-Chair), K. Cassou[c], S. Corde[z], L. Corner[i], B. Cros[aa], M. Ferrario[f], S. Hooker[bb], R. Ischebeck[g], A. Latina[a], O. Lundh[cc], P. Muggli[dd], P. Nghiem[b], J. Osterhoff[e], T. Raubenheimer[w,ee], A. Specka[ff], J. Vieira[gg], M. Wing[hh]

Associated members: C. Geddes[p], M. Hogan[w], W. Lu[v], P. Musumeci[ii]

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

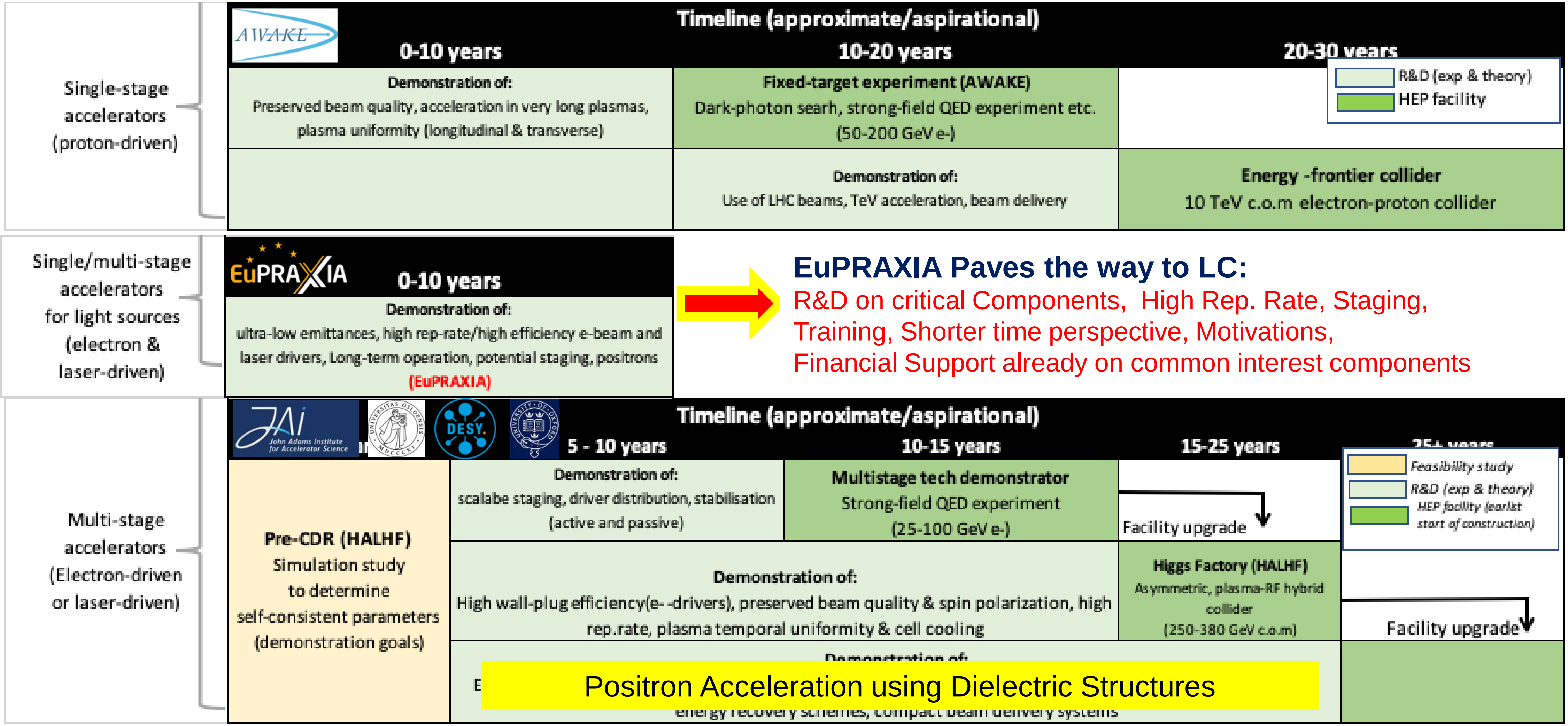
Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group

- Development of Plasma Sources for High-Repetition Rate, Multi-GeV Stages
- High Average Power, High Efficiency Laser Drivers and Schemes
- Staging of Electron Plasma Accelerators Including In- and Out-Coupling
- High Transformer Ratio in PWFA for High Efficiency and Low Energy Spread
- Polarised Electrons
- Positron Bunch Acceleration

ESPP Roadmap Update – Plasma Accelerators



	AWAKE 0-10 years	Timeline (approximate/aspirational) 10-20 years	20-30 years
Single-stage accelerators (proton-driven)	**Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon searh, strong-field QED experiment etc. (50-200 GeV e-)	
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy -frontier collider** 10 TeV c.o.m electron-proton collider

Legend:
- 🟩 R&D (exp & theory)
- 🟩 HEP facility

	EuPRAXIA 0-10 years
Single/multi-stage accelerators for light sources (electron & laser-driven)	**Demonstration of:** ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons (EuPRAXIA)

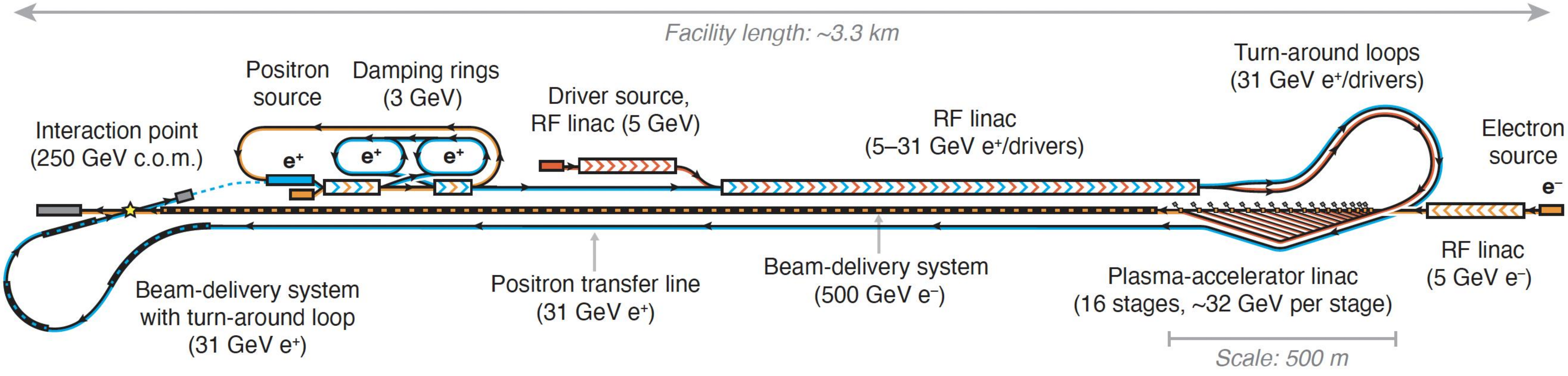
EuPRAXIA Paves the way to LC:

R&D on critical Components, High Rep. Rate, Staging, Training, Shorter time perspective, Motivations, Financial Support already on common interest components

	JAI John Adams Institute for Accelerator Science, DESY.	Timeline (approximate/aspirational) 5 - 10 years	10-15 years	15-25 years	25+ years
Multi-stage accelerators (Electron-driven or laser-driven)	**Pre-CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** scalabe staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25-100 GeV e-)	Facility upgrade	
		Demonstration of: High wall-plug efficiency(e- -drivers), preserved beam quality & spin polarization, high rep.rate, plasma temporal uniformity & cell cooling		**Higgs Factory (HALHF)** Asymmetric, plasma-RF hybrid collider (250-380 GeV c.o.m)	Facility upgrade
		Demonstration of: E Positron Acceleration using Dielectric Structures energy recovery schemes, compact beam delivery systems			

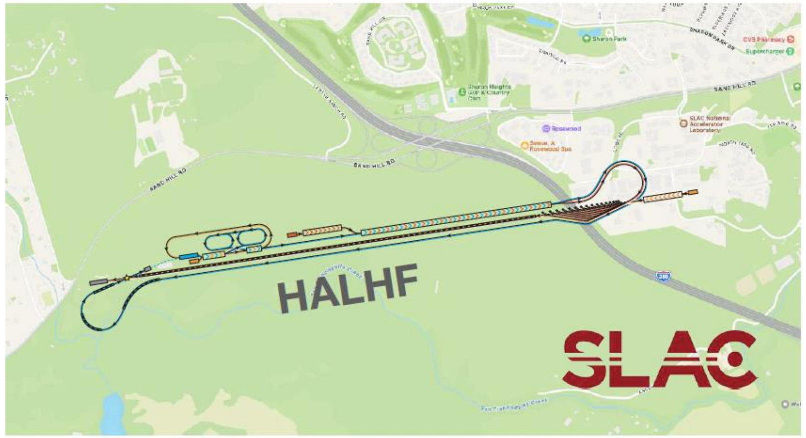
Legend:
- 🟨 *Feasibility study*
- 🟩 *R&D (exp & theory)*
- 🟩 *HEP facility (earlist start of construction)*

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- Beam-driven: Use e^+ RF linac for producing e^- drivers
- Overall footprint: ~3.3 km
  - Length dominated by e^- beam-delivery system
  - Fits in most major particle-physics laboratories



EuPRAXIA Workshop

22-27 September 2024

Elba Island, Tuscany, Italy

- **EuPRAXIA_PP Annual Meeting**
- Workshop on “EuPRAXIA@SPARC_LAB machine upgrade and additional beam lines“
- Outreach Workshop
- https://agenda.infn.it/event/41613/

Conclusions

- Plasma accelerators have advanced considerably in beam quality, **achieving FEL lasing**.
- EuPRAXIA is a design and an ESFRI project for a distributed European Research Infrastructure, **building two plasma-driven FEL´s in Europe**.
- EuPRAXIA FEL site in Frascati LNF-INFN is sufficiently funded for **first FEL user operation in 2028**.
- Second EuPRAXIA FEL site will be selected in next 6 months, among **4 excellent candidate sites**.
- Concept today **works in design and in reality**. Expect (solvable) problems in stability for **24/7 user operation**. Facility needed to demonstrate!
- Paves the way to Linear Collider
- Additional fund raising is continuosly going on

CERNCOURIER

May/June 2023 cerncourier.com

Reporting on international high-energy physics

CERNCOURIER.COM

FEATURE EuPRAXIA

Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

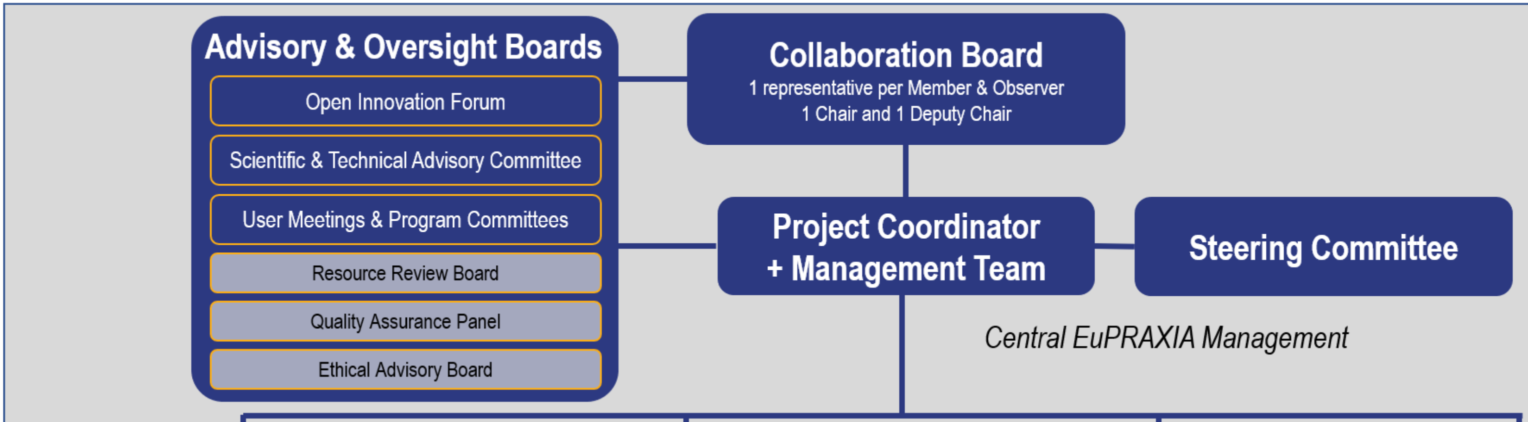
EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Thank for your attention

EuPRAXIA Organisation Chart

EUROPEAN
PLASMA RESEARCH ACCELERATOR WITH
EXCELLENCE IN APPLICATIONS



Advisory & Oversight Boards

- Open Innovation Forum
- Scientific & Technical Advisory Committee
- User Meetings & Program Committees
- Resource Review Board
- Quality Assurance Panel
- Ethical Advisory Board

Collaboration Board

1 representative per Member & Observer
1 Chair and 1 Deputy Chair

Project Coordinator + Management Team

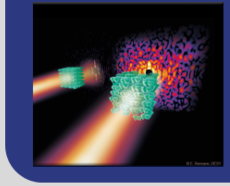
Steering Committee

Central EuPRAXIA Management

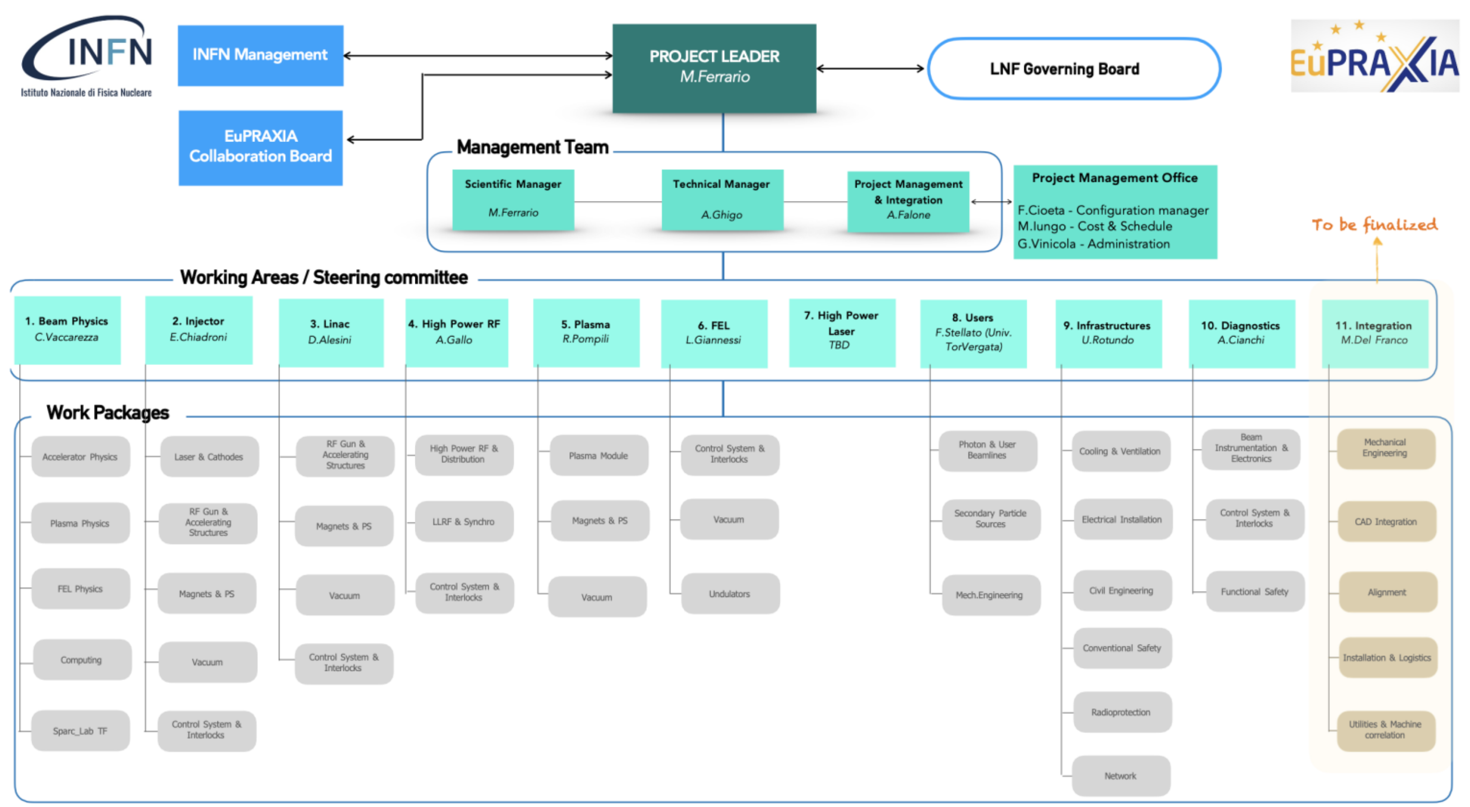
Construction Site Frascati

Local Project Team

Beam-driven plasma accelerator
Delivers FEL light, X rays, electrons, positrons
Life sciences, particle physics, medicine, materials



Location: metropolitan area Rome, Italy



INFN Management

EuPRAXIA Collaboration Board

PROJECT LEADER
M.Ferrario

LNF Governing Board

Management Team

- **Scientific Manager** – *M.Ferrario*
- **Technical Manager** – *A.Ghigo*
- **Project Management & Integration** – *A.Falone*

Project Management Office
F.Cioeta - Configuration manager
M.lungo - Cost & Schedule
G.Vinicola - Administration

To be finalized

Working Areas / Steering committee

- **1. Beam Physics** – *C.Vaccarezza*
- **2. Injector** – *E.Chiadroni*
- **3. Linac** – *D.Alesini*
- **4. High Power RF** – *A.Gallo*
- **5. Plasma** – *R.Pompili*
- **6. FEL** – *L.Giannessi*
- **7. High Power Laser** – *TBD*
- **8. Users** – *F.Stellato (Univ. TorVergata)*
- **9. Infrastructures** – *U.Rotundo*
- **10. Diagnostics** – *A.Cianchi*
- **11. Integration** – *M.Del Franco*

Work Packages

- Accelerator Physics
- Plasma Physics
- FEL Physics
- Computing
- Sparc_Lab TF

- Laser & Cathodes
- RF Gun & Accelerating Structures
- Magnets & PS
- Vacuum
- Control System & Interlocks

- RF Gun & Accelerating Structures
- Magnets & PS
- Vacuum
- Control System & Interlocks

- High Power RF & Distribution
- LLRF & Synchro
- Control System & Interlocks

- Plasma Module
- Magnets & PS
- Vacuum

- Control System & Interlocks
- Vacuum
- Undulators

- Photon & User Beamlines
- Secondary Particle Sources
- Mech.Engineering

- Cooling & Ventilation
- Electrical Installation
- Civil Engineering
- Conventional Safety
- Radioprotection
- Network

- Beam Instrumentation & Electronics
- Control System & Interlocks
- Functional Safety

- Mechanical Engineering
- CAD Integration
- Alignment
- Installation & Logistics
- Utilities & Machine correlation

Organization for initial Preparatory Ph

Features to be added with decision or
phases are indicated in lighter shades

New Proposal Just Accepted (score 14.4/15) : PACRI

Funded by the European Union

- **HORIZON-INFRA-2024-TECH-01-01: R&D for the next generation of scientific instrumentation, tools, methods, solutions for RI upgrade**

Plasma Accelerators for Compact Research Infrastructures

- **Dead line 12 March 2024**
- **Target Budget ~10 MEuro**

25 Members
+
1 Associated partner

19 Universities and Scientific Labs.
+
7 Industries

#	Partner	Acronym
1	Elettra - Sincrotrone Trieste SCpA (Coordinator)	ST
2	European Organization for Nuclear Research	CERN
3	Istituto Nazionale Fisica Nucleare	INFN
4	University of Liverpool	ULIV
5	Thales-MIS	Th-MIS
6	Scandinova Systems AB	SCND
7	VDL ETG Technology & Development BV	VDL
8	COMEB	COMEB
9	United Kingdom Research and Innovation	UKRI
10	Consiglio Nazionale delle Ricerche	CNR
11	Extreme Light Infrastructure ERIC	ELI-ERIC
12	Centre National de la Recherche Scientifique CNRS	CNRS
13	Thales LAS France SAS	Th-LAS
14	Amplitude	Amplitude
15	Centro de LÁSERES Pulsados	CLPU
16	Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Hoechstfrequenztechnik	FBH
17	Associacao do instituto superior Tecnico para a Investigacao e Desenvolvimento	IST
18	Università degli Studi di Roma La Sapienza	USAP
19	Heinrich-Heine-Universitaet Duesseldorf	UDUS
20	Deutsches Elektronen-Synchrotron DESY	DESY
21	The Chancellor, Masters and Scholars of the Univ. of Oxford	UOX
22	Ludwig-Maximilians-Universitaet Muenchen	LMU
23	GSI Helmholtz Centre for Heavy Ion Research	GSI
24	Università degli Studi di Roma Tor Vergata	UTOR
25	SourceLAB	SourceLAB
26	Paul Scherrer Institut **(Associated partner)**	PSI

WP No.	Work Package Title	Lead Partic. Short Name
1	Coordination and project management	**ELETTRA**
2	Scientific and industrial exploitation	**ULIV**
3	Plasma accelerator theory and simulations	**IST**
4	High repetition rate plasma structures	**INFN**
5	Plasma acceleration diagnostics and instrumentation	**CNRS**
6	High efficiency RF generator	**Thales-MIS**
7	High repetition rate modulator	**Scandinova**
8	X-band RF Pulse Compressor (BOC)	**INFN**
9	RF tests and validation	**CERN**
10	High repetition rate high power Ti:Sa amplifier module	**UKRI**
11	Efficient kHz laser driver modules for plasma acceleration	**CNR**
12	High-rep rate pump sources for laser drivers	**ELI-ERIC**
13	Prototype of high average power optical compressor	**Thales-LAS**
14	Laser Driver System Architecture,transport and engineering	**CNRS**

Funded by the
European Union

Plasma Accelerators for Compact Research Infrastructures (PACRI)

The objective of the **PACRI** project is to develop innovative breakthrough technologies, increasing their Technology Readiness Level (TRL) for electron accelerators while taking energy consumption, resource efficiency, costs, and environmental impact into due account. This includes the following draft non-exclusive goals:

- **developing high rep-rate plasma modules,** as required for the EuPRAXIA project, extending its scientific domain from high average brightness radiation sources up to high energy physics;
- **developing key laser components required to upscale high-power high repetition rate Laser technology** as required by the EuPRAXIA and ELI Research Infrastructure.
- **improving the performance of normal conducting technology for X-band linac drivers,** extending them to the kHz regime, with focus on efficiency and energy consumption;
- **supporting development towards compact linear colliders and nuclear physics facilities;**
- **developing compact advanced undulator modules,** in order to reduce the overall size of the future FEL facilities.
- **supporting the availability of compact X-ray facilities (FELs, ICSs, Betatron)** to serve a larger number of users in many scientific fields, industry and society;