

EUROPEAN  
PLASMA RESEARCH  
ACCELERATOR  
WITH  
EXCELLENCE IN  
APPLICATIONS



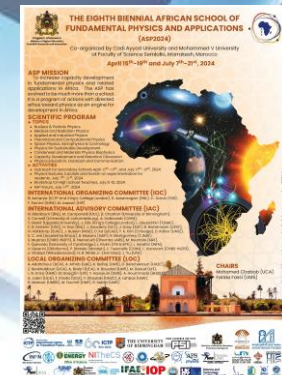
## The EuPRAXIA Project

a plasma-based accelerator user facility for the next decade

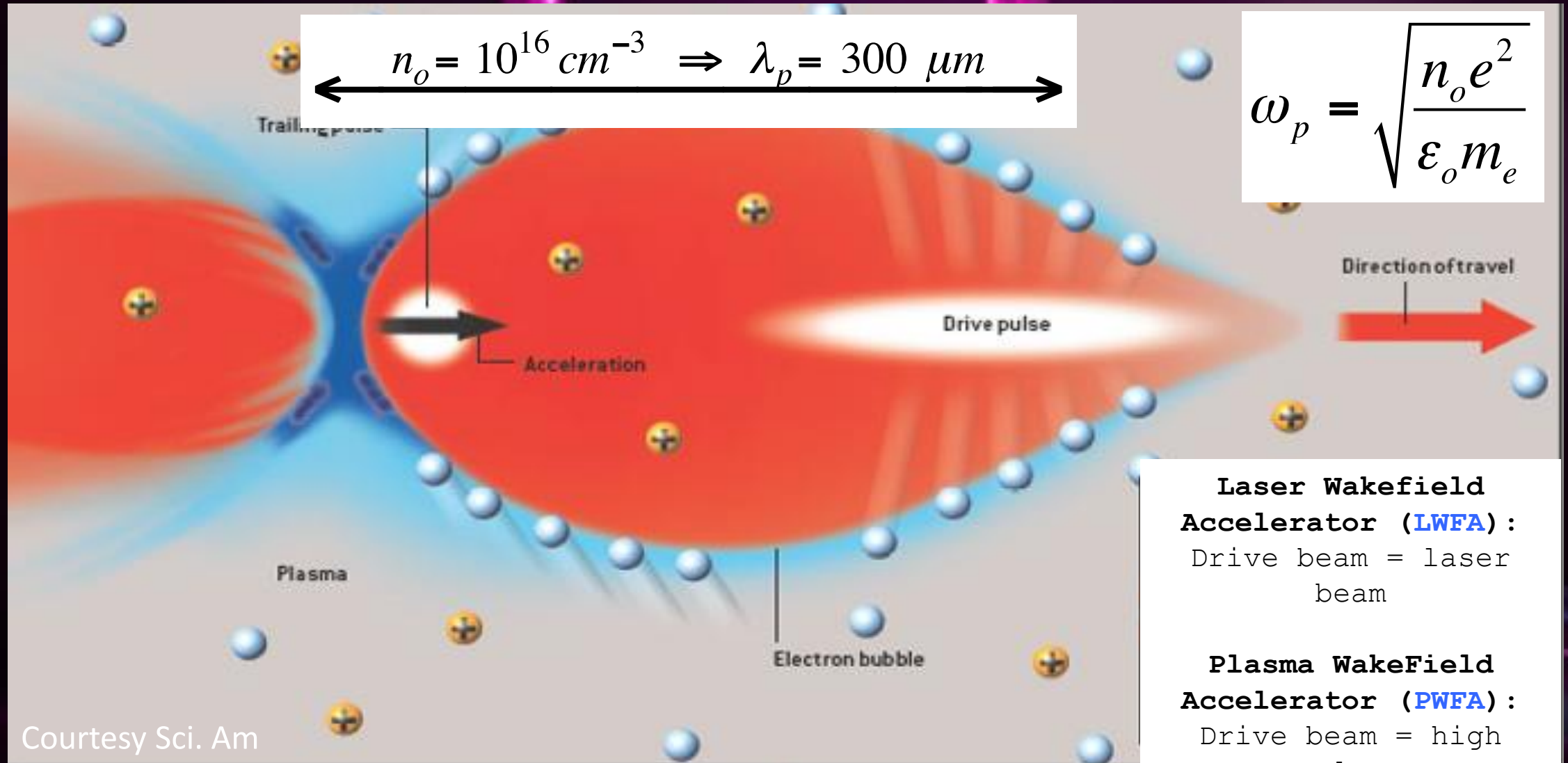
Massimo Ferrario (INFN-LNF)

On behalf of the EuPRAXIA Collaboration

African School of Physics  
Marrakech– 17 July 2024



# Principle of plasma acceleration



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

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

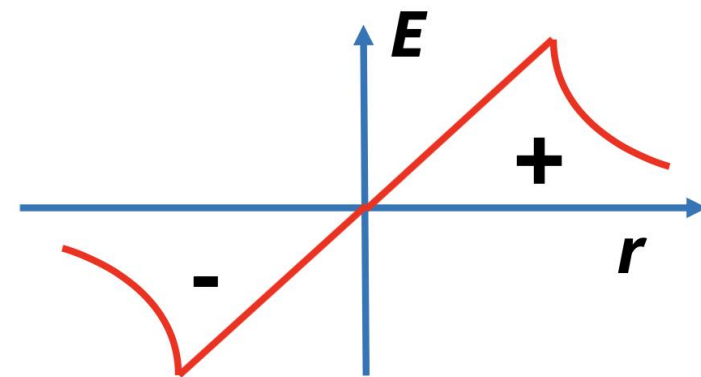
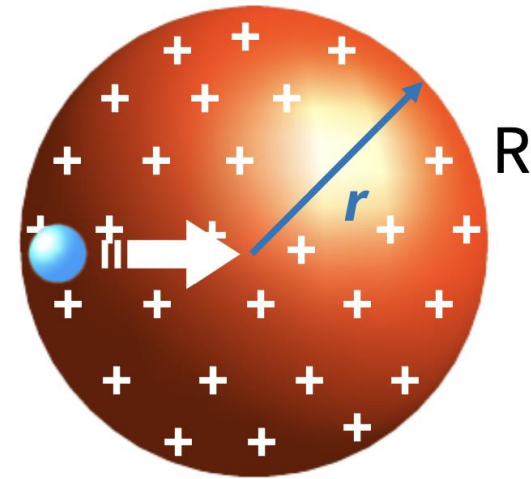
The field is **increasing** inside the sphere

Let's put some numbers

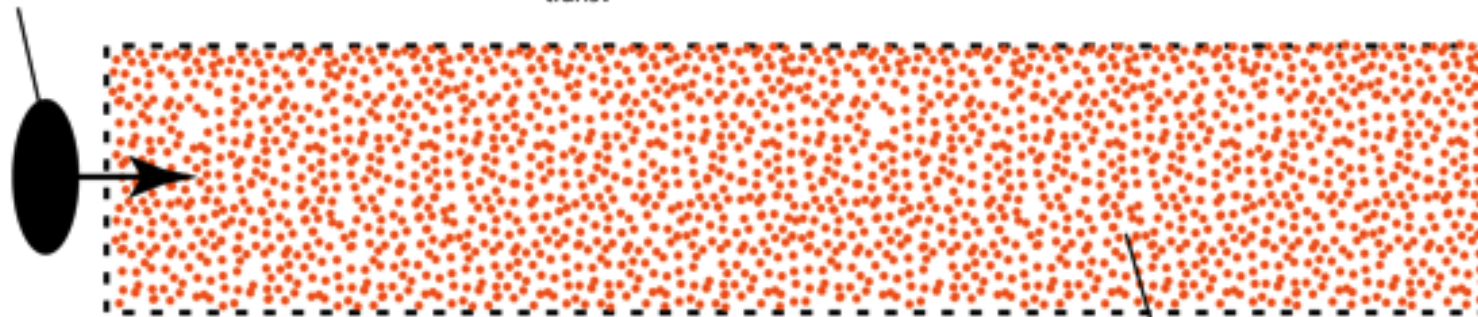
$$n_i = 10^{16} \text{ cm}^{-3}$$

$$R = 0.5$$


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

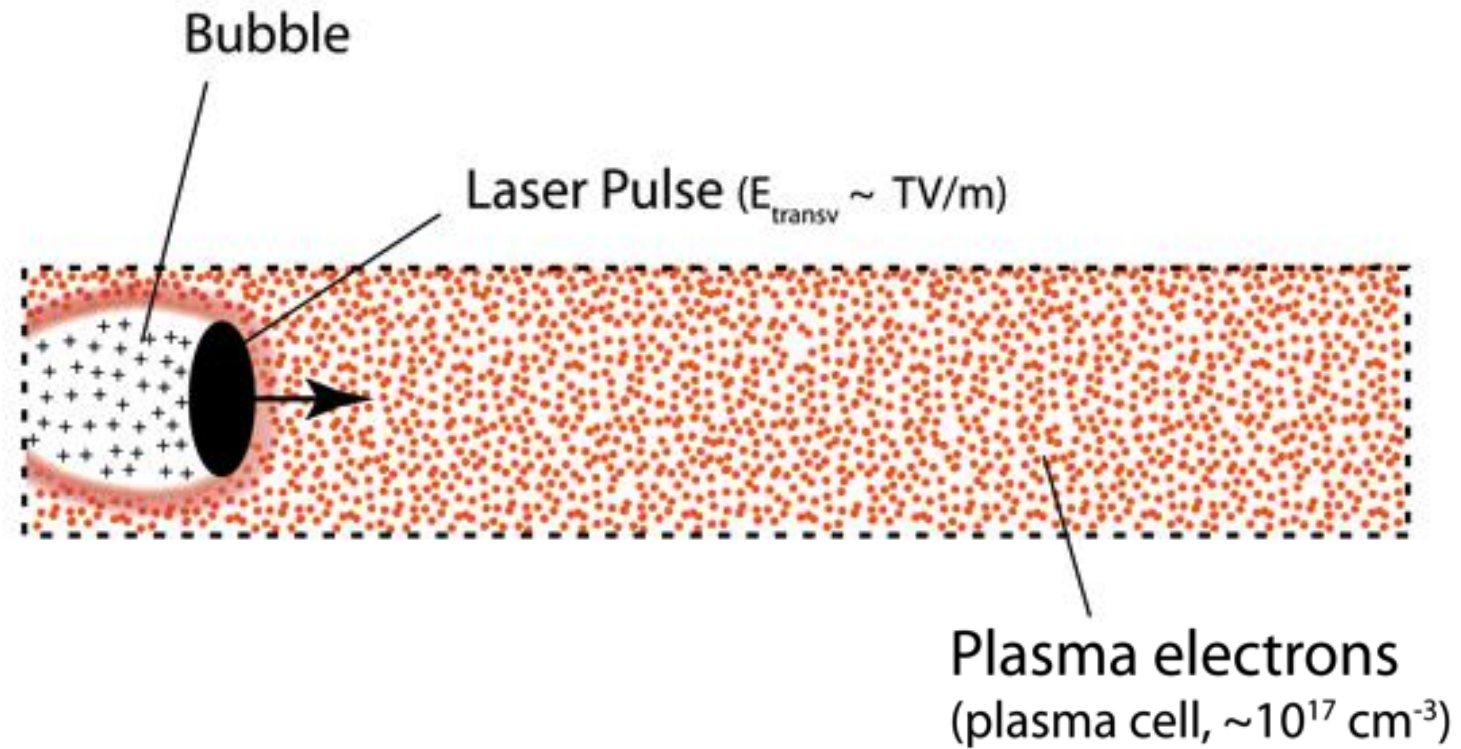


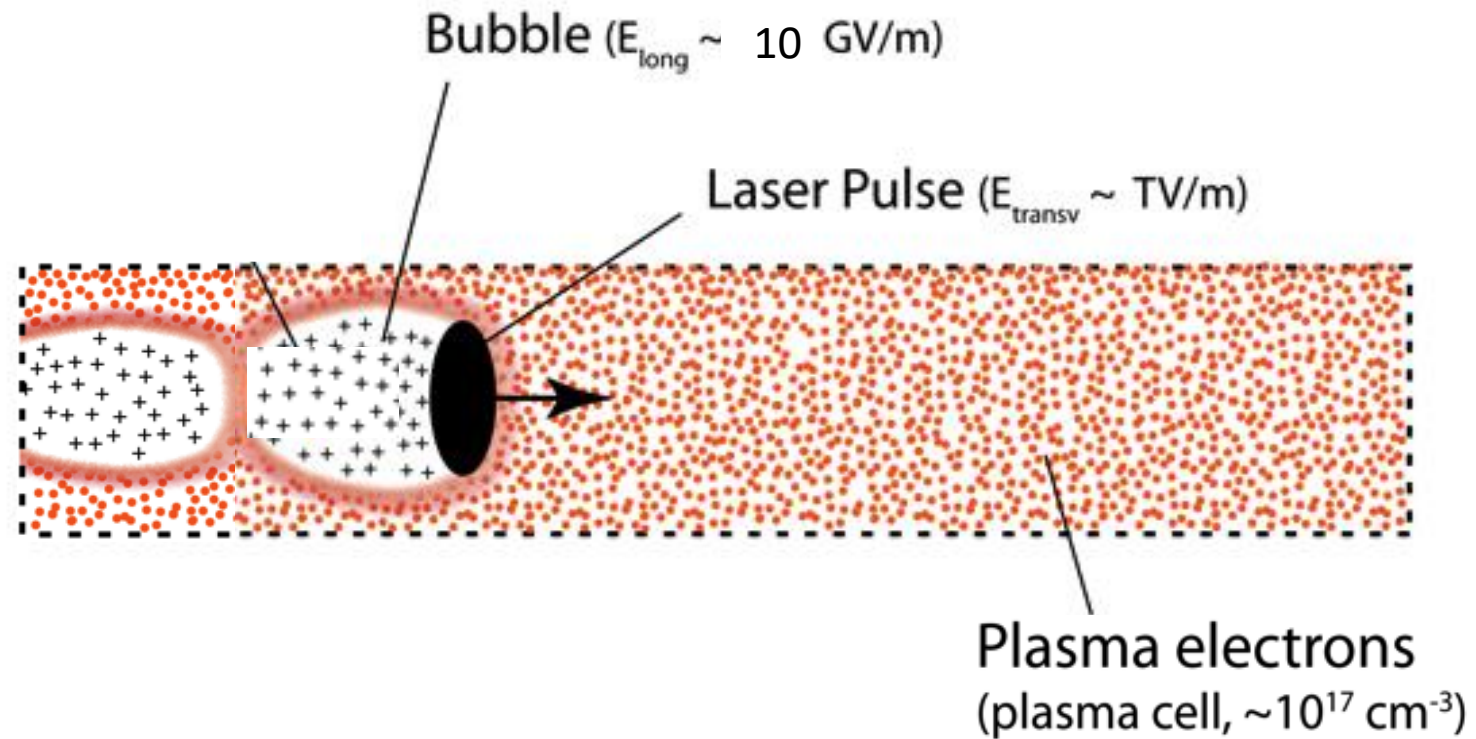
Laser Pulse (200 TW, ~30 fs,  $E_{\text{transv}} \sim \text{TV/m}$ )

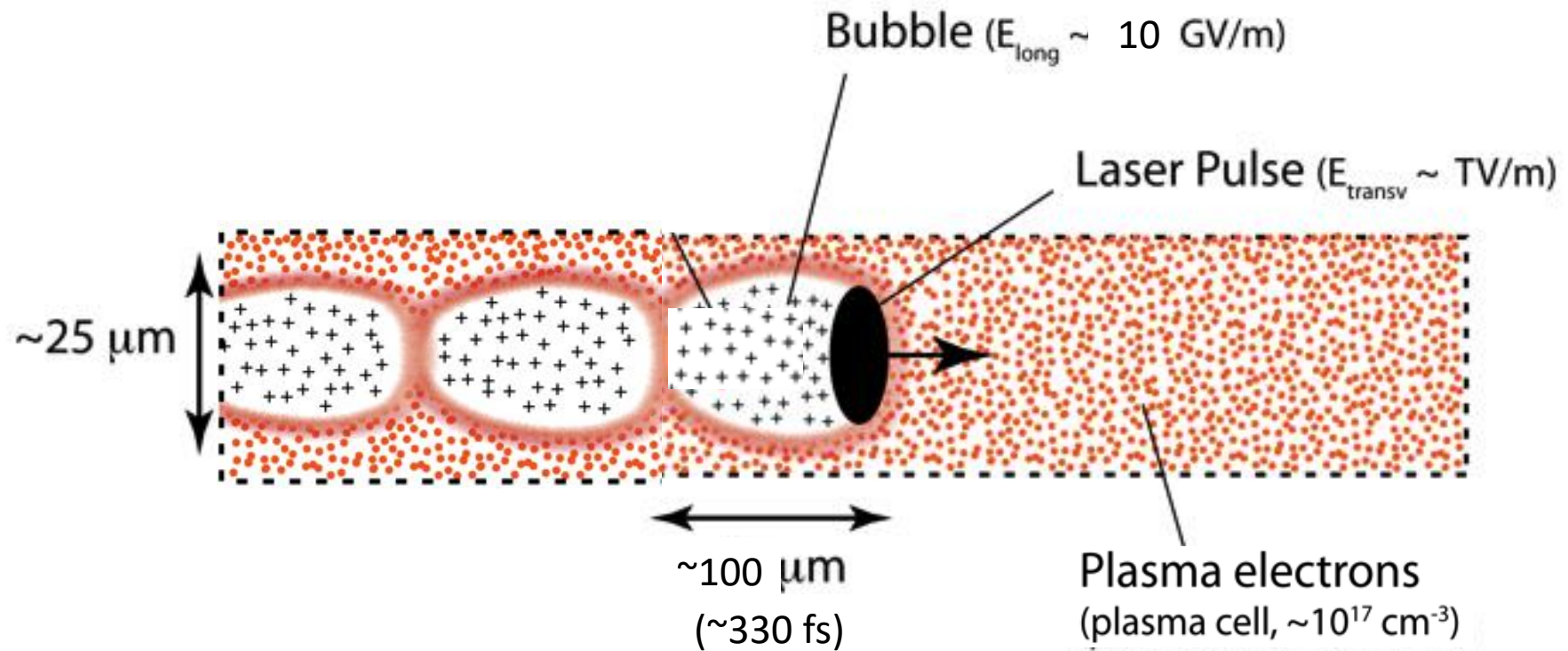


Plasma electrons  
(plasma cell,  $\sim 10^{17} \text{ cm}^{-3}$ )



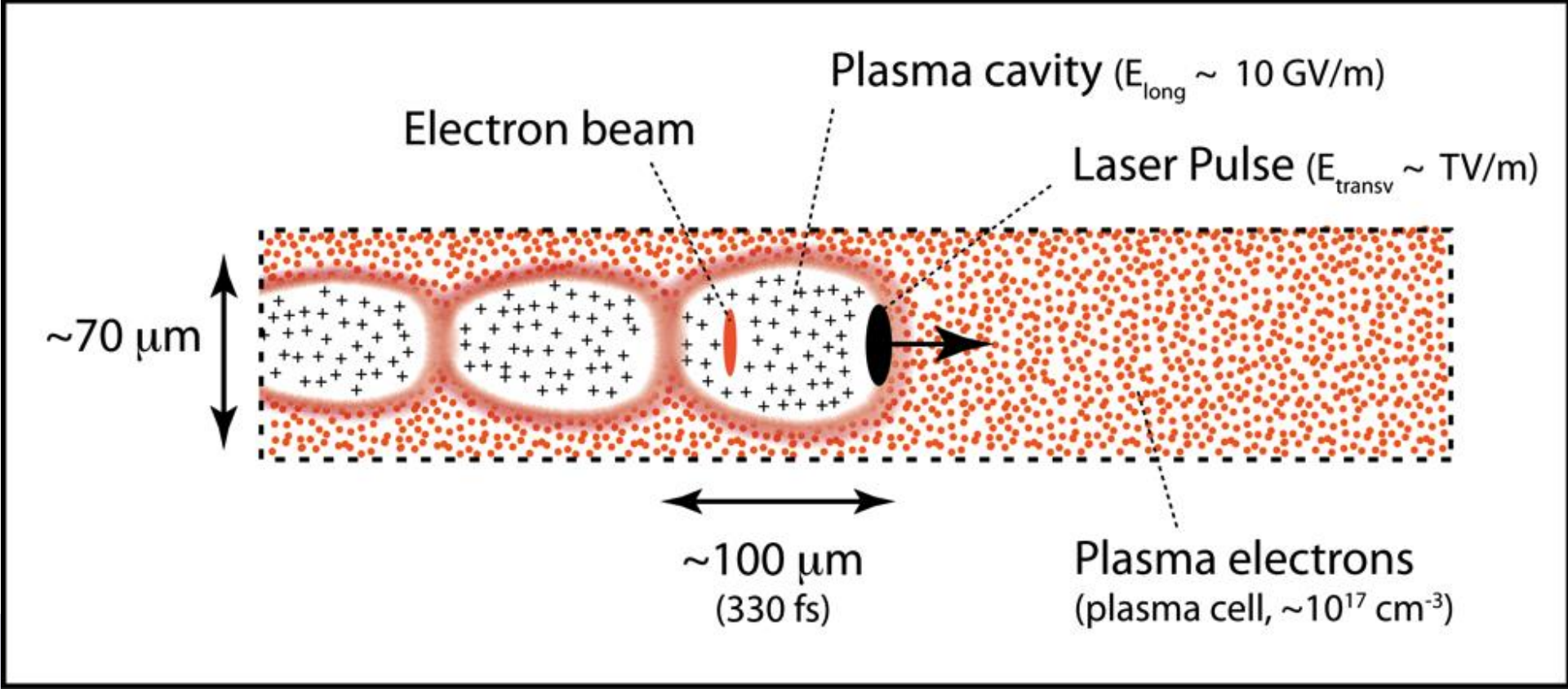
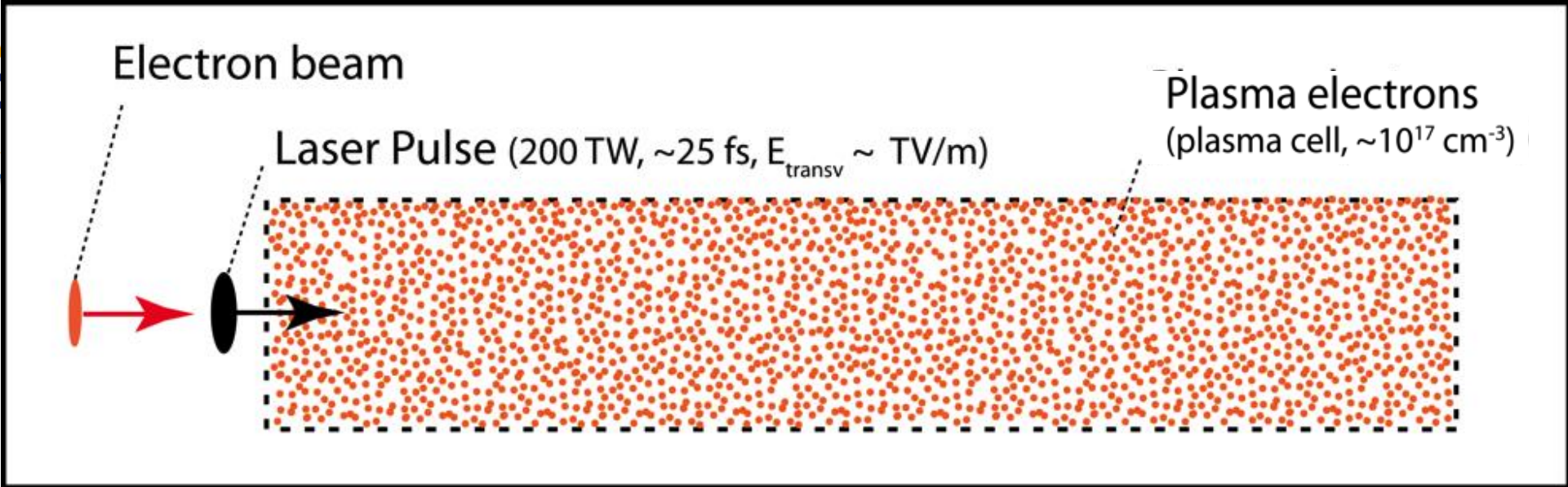






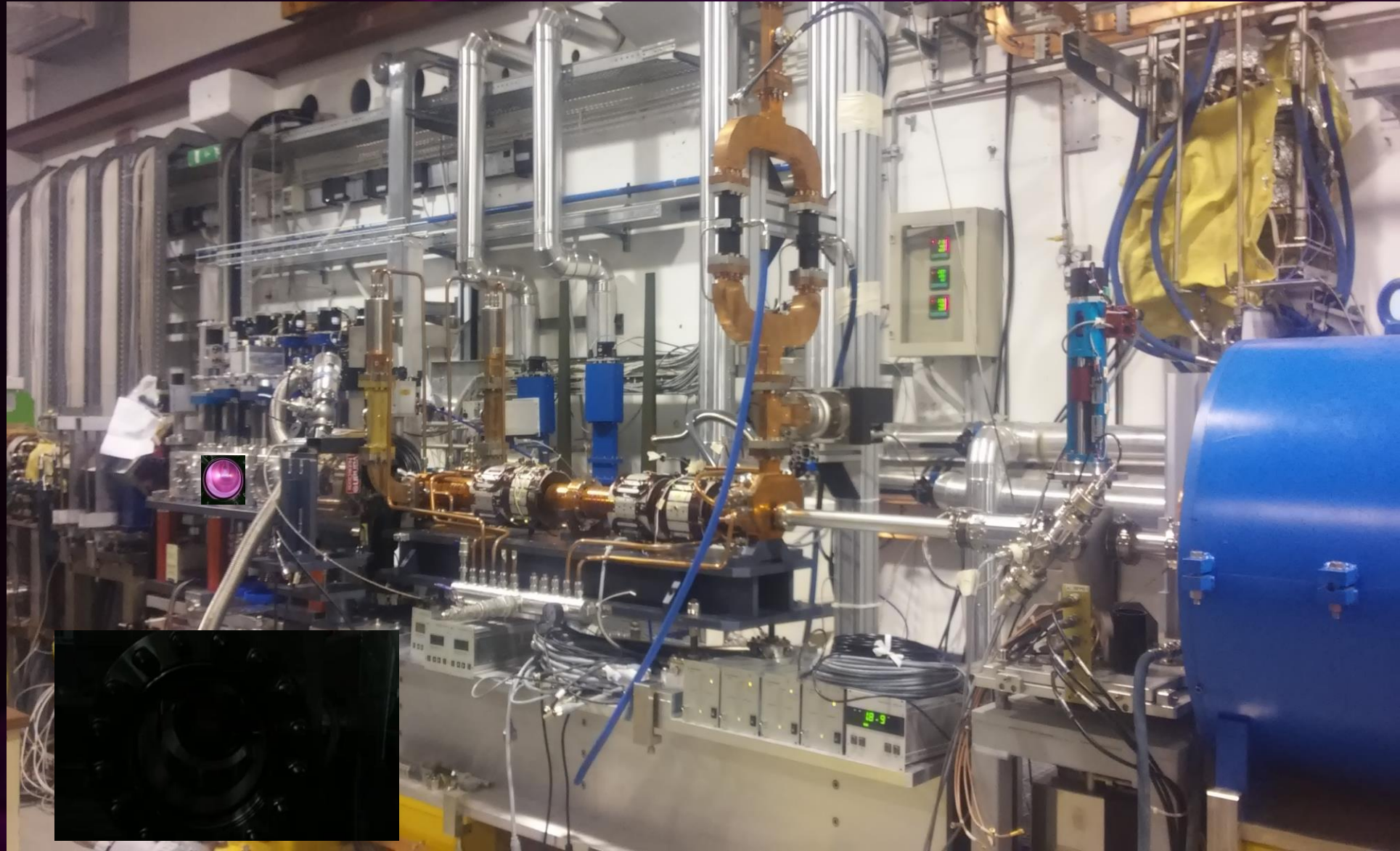
**This accelerator fits into a human hair!**



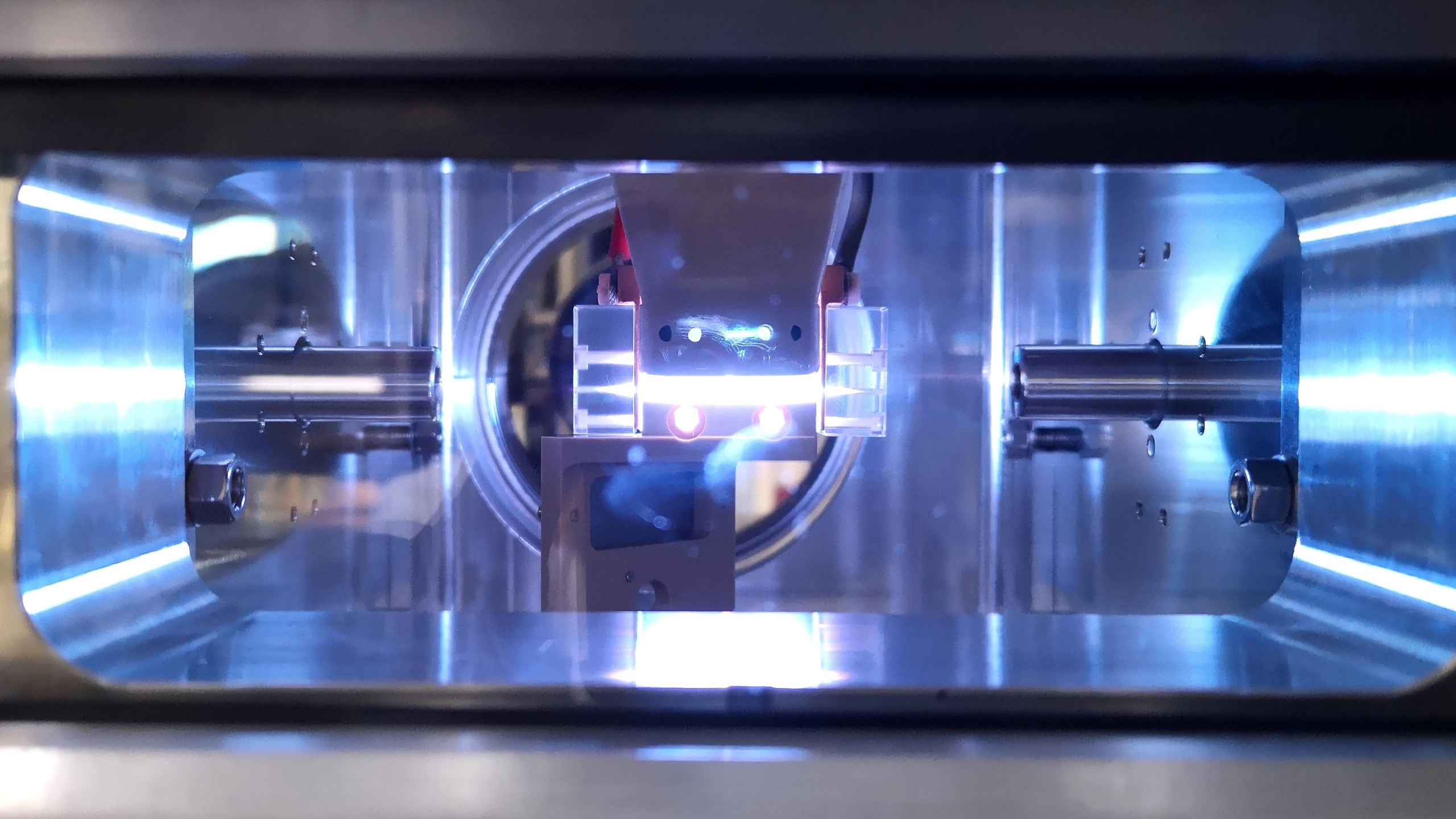




# PWFA beam line at SPARC\_LAB









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**

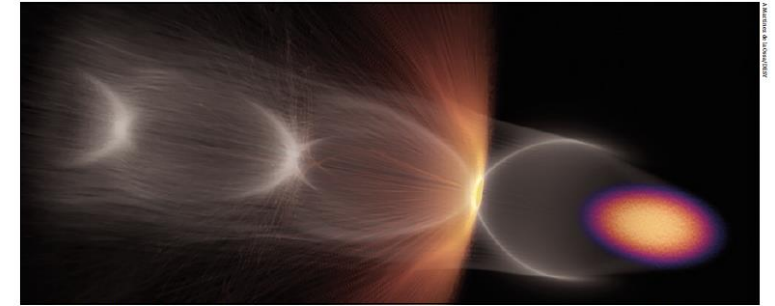
2

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

**Drive short wavelength FEL**  
**Pave the way for future Linear Colliders**

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

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.

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.

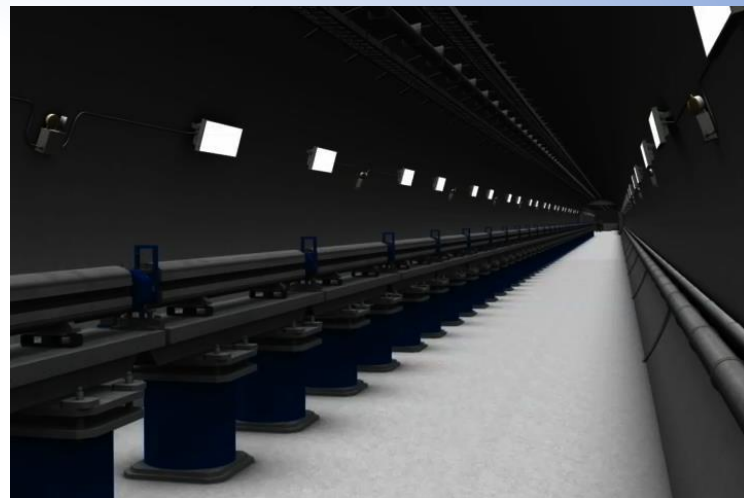
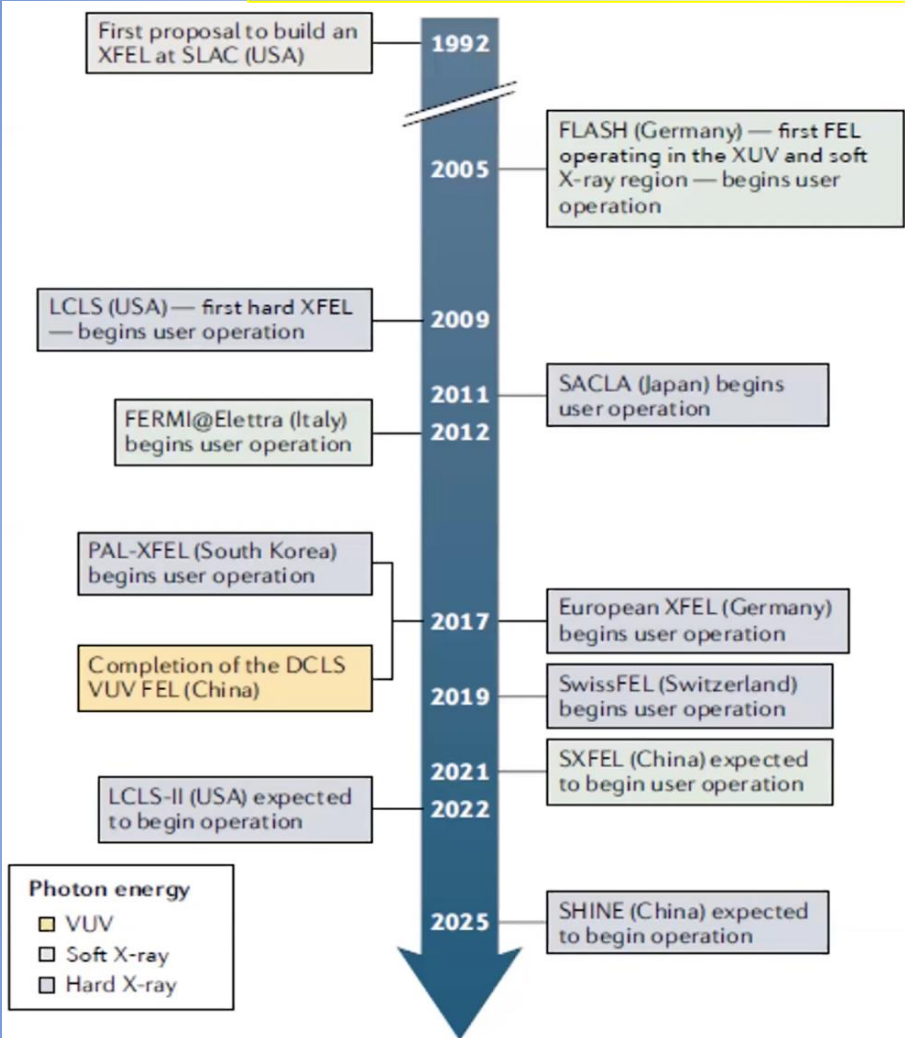
However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

**THE AUTHORS**

Ralph Assmann  
DES and INFN,  
Massimo Ferrario  
INFN, Carsten  
Welsch University  
of Liverpool/INFN.

# FEL is a well established technology

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



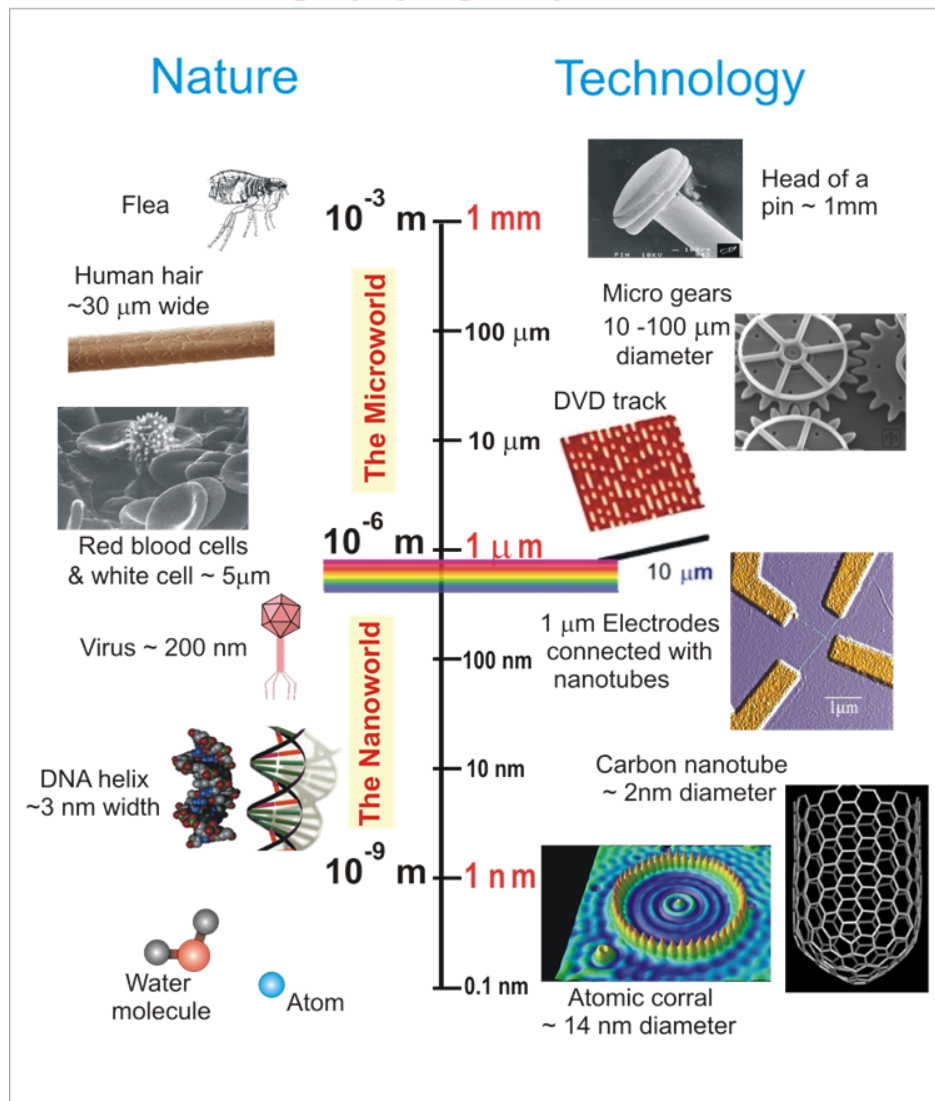
New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

*Iulia Georgescu*

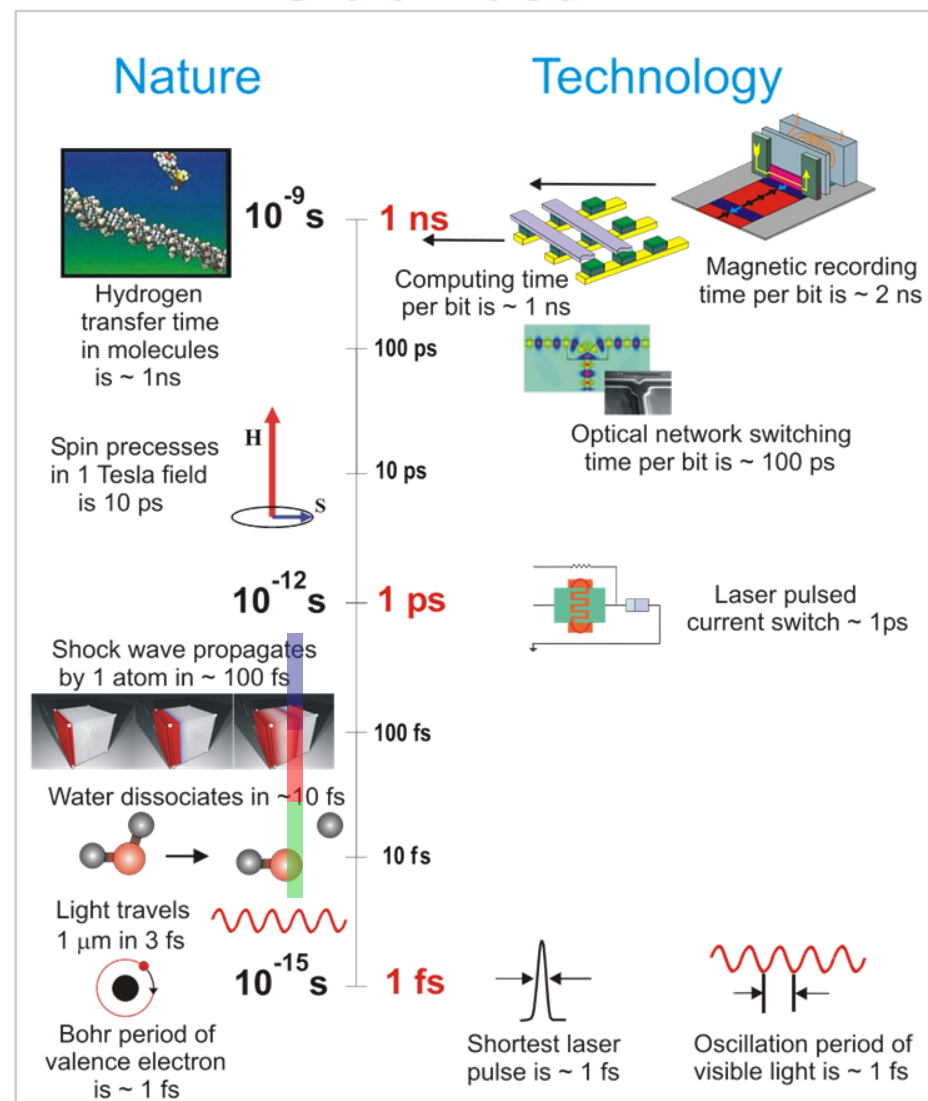


# X-Rays have opened the Ultra-Small World X-FELs open the Ultra-Small and Ultra-Fast Worlds

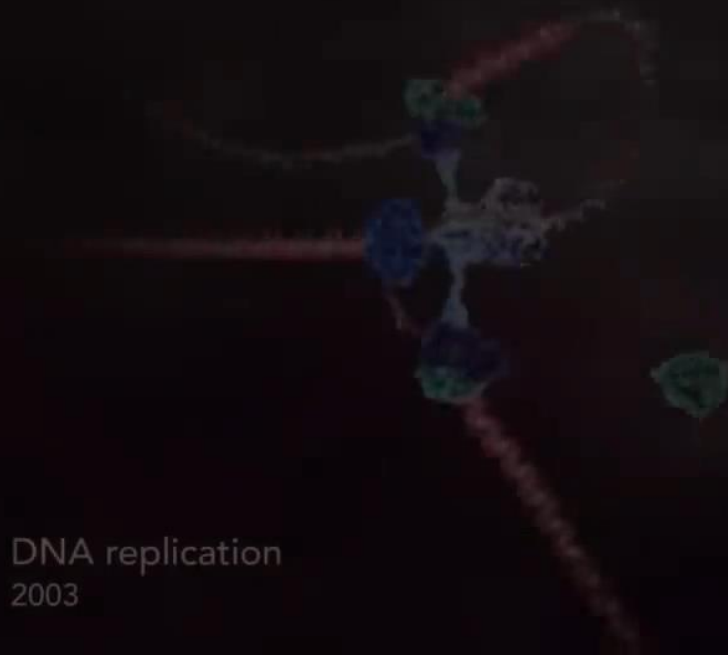
## Ultra-Small



## Ultra-Fast



wehi.tv  
DrewBerry



DNA replication  
2003

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.

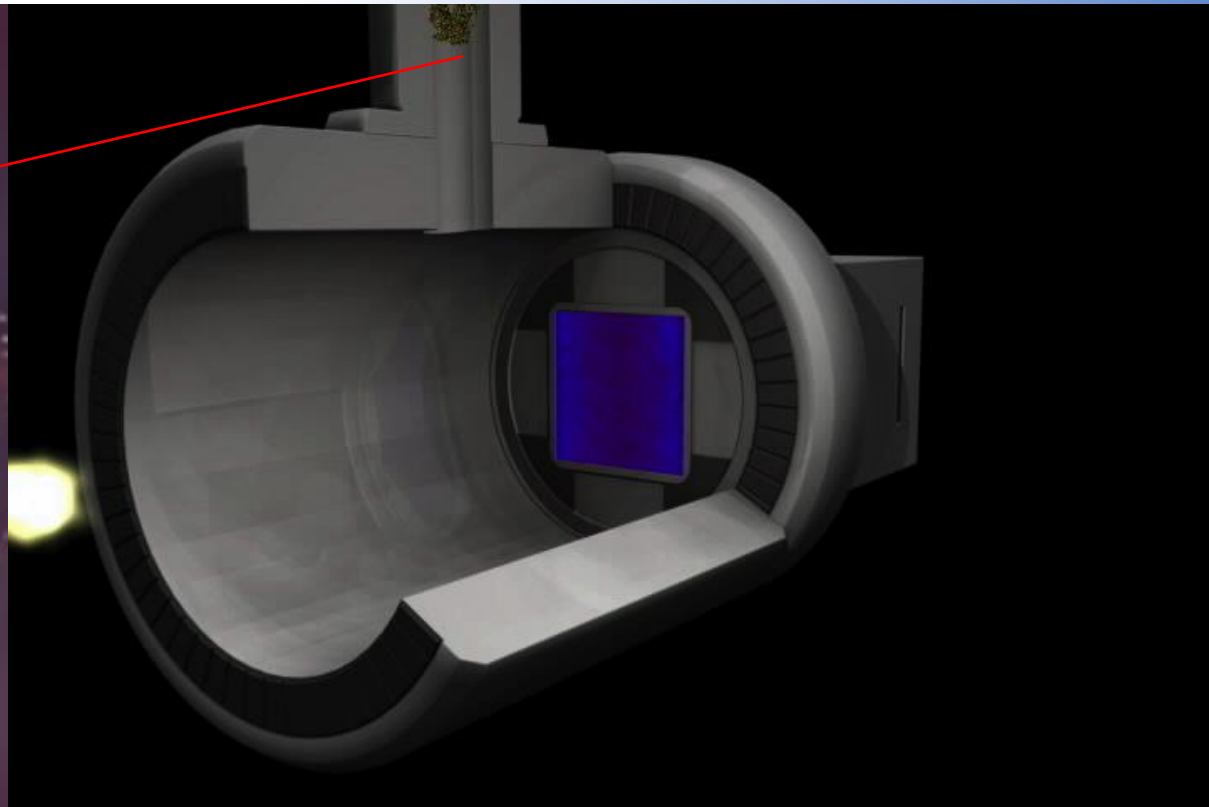
DNA helicases also function in other cellular processes where double-stranded DNA must be separated, including DNA repair and transcription. RNA helicases are involved in shaping the form of RNA molecules, during all processes involving RNA, such as transcription, splicing, and translation.



We wish a Static Picture of the acro-molecules involved

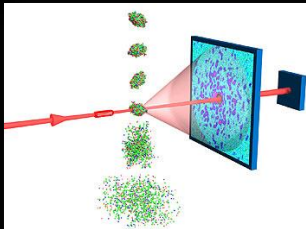
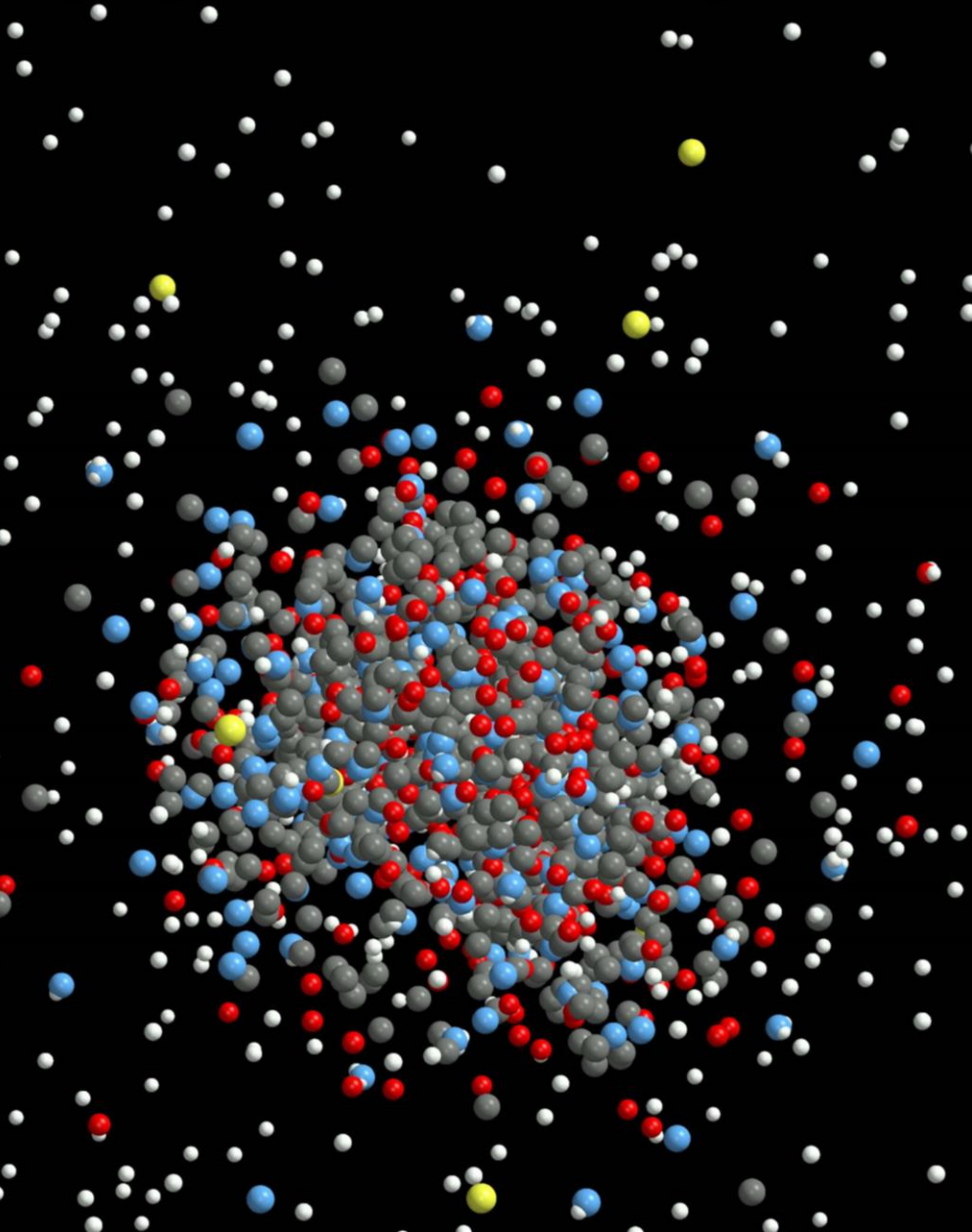
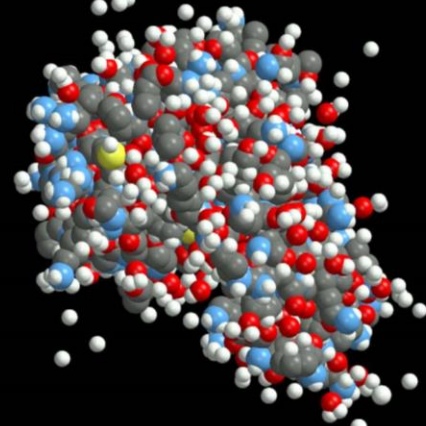
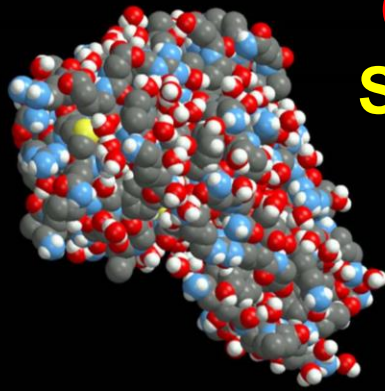
## Light Required properties

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





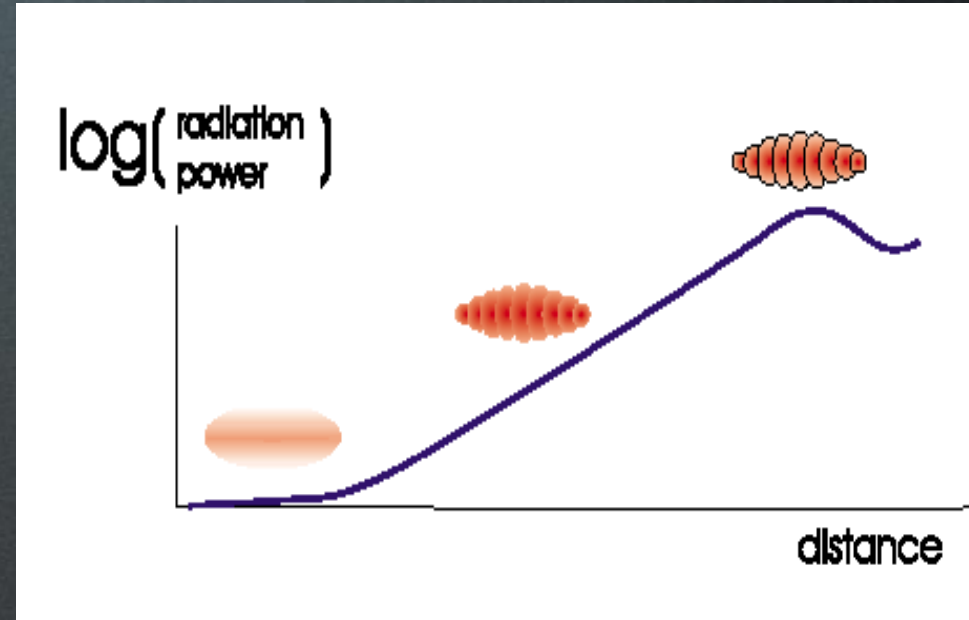
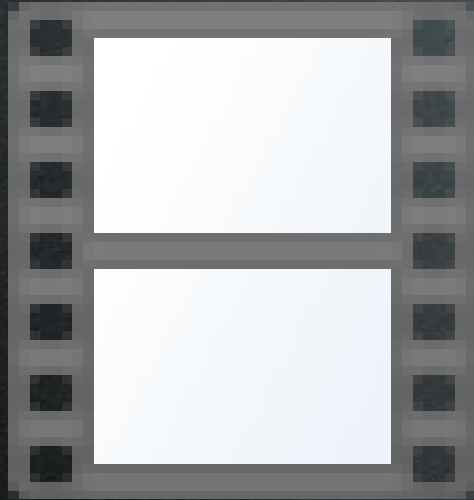
# Coulomb Explosion of Lysozyme (50 fs) Single Molecule Imaging with Intense X-rays



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)**

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  $\sigma_\gamma$ :  $\sigma_\gamma < \frac{1}{2}\rho_{fel}$

where

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

Low emittances  
Low energy spread  
High current

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  $P_F$**

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

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

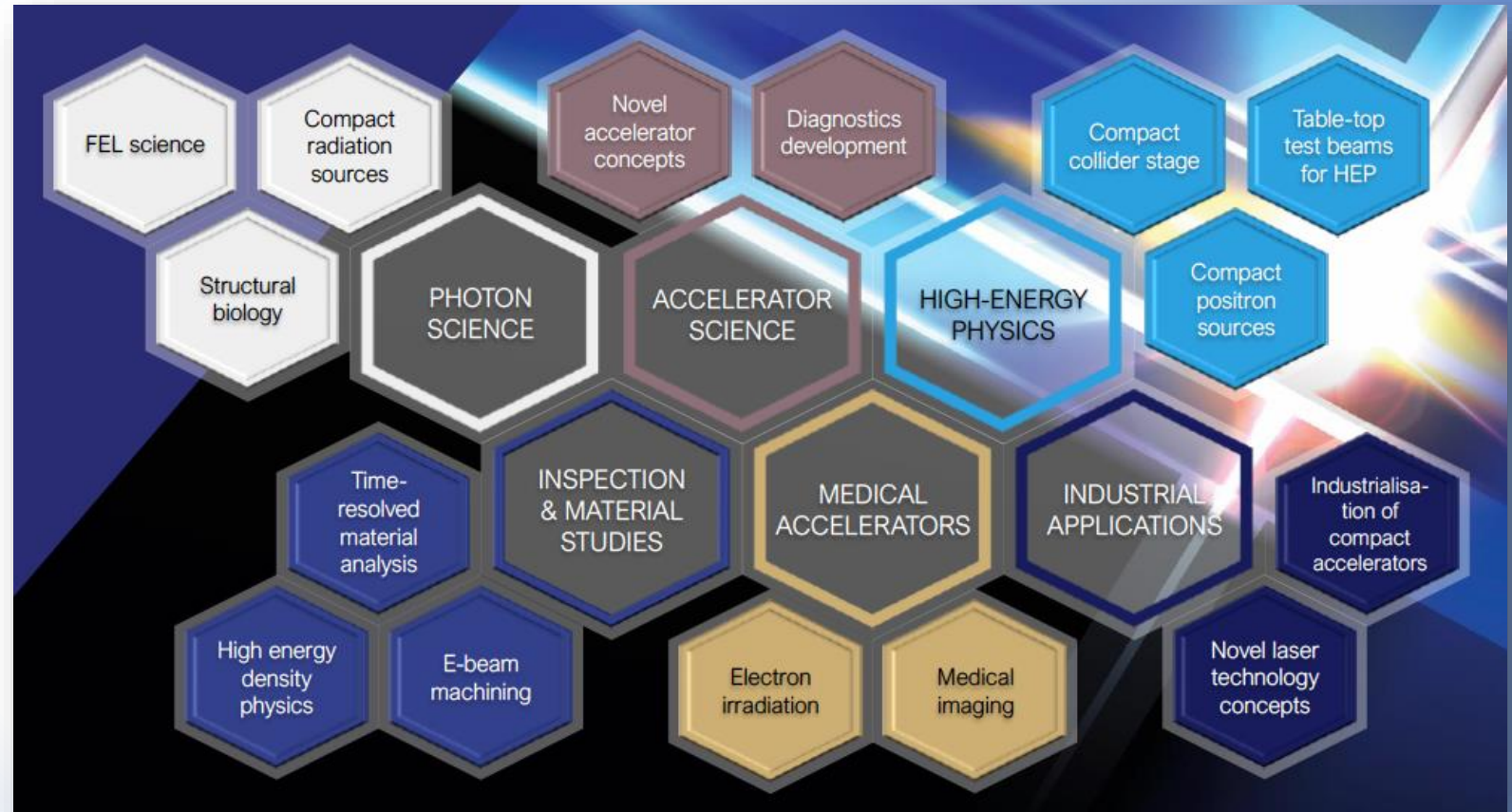
$$\left. \frac{\Delta E}{E} \right|_{DW} = \frac{a\omega_p}{2\pi} \Delta t_{DW}$$

$$2 \leq a \leq 4$$

Driver/Witness separation



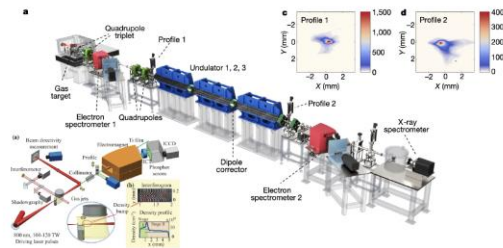
- **Electrons**  
(0.1-5 GeV, 30 pC)
- **Positrons**  
(0.5-10 MeV,  $10^6$ )
- **Positrons (GeV source)**
- **Lasers**  
(100 J, 50 fs, 10-100 Hz)
- **X-band RF Linac**  
(60 MV/m , up to 400 Hz)
- **Plasma Targets**
- **Betatron X rays**  
(1-10 keV,  $10^{10}$ )
- **FEL light**  
(0.2-36 nm,  $10^9$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



# Basic beam quality achieved in pilot FEL experiments



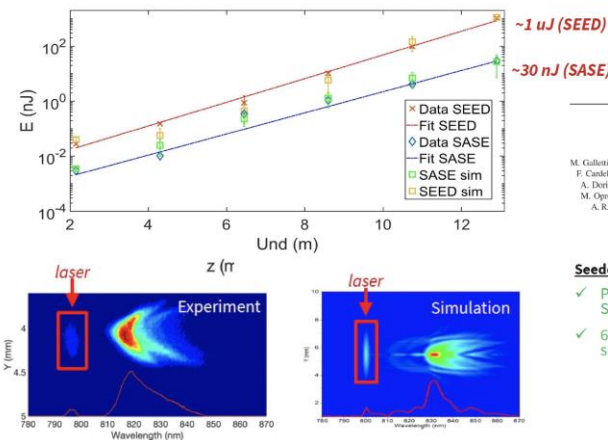
W. T. Wang, K. Feng, et al., Nature, 595, 561 (2021).



## 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)



PHYSICAL REVIEW LETTERS 129, 234801 (2022)

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

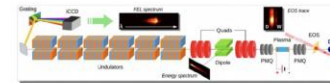
M. Gallorini,<sup>1,2,3</sup> D. Akhmanov,<sup>4</sup> M. P. Anania,<sup>5</sup> S. Arjmand,<sup>6</sup> M. Bellariva,<sup>7</sup> A. Bugnon,<sup>8</sup> B. Bonomo,<sup>9</sup> F. Caselli,<sup>10</sup> M. Carpanese,<sup>11</sup> E. Chiriac,<sup>12</sup> A. Cianchi,<sup>13</sup> G. Cozzani,<sup>14</sup> M. Del Duca,<sup>15</sup> M. Del Guercio,<sup>16</sup> F. Di Pasquale,<sup>17</sup> A. Doria,<sup>18</sup> F. Filippini,<sup>19</sup> G. Franzini,<sup>20</sup> L. Giannessi,<sup>21</sup> A. Gibboni,<sup>22</sup> P. Iovine,<sup>23</sup> V. Lollo,<sup>24</sup> A. Mostacci,<sup>25</sup> F. Nguyen,<sup>26</sup> M. Opromolla,<sup>27</sup> L. Pellegrino,<sup>28</sup> A. Petralia,<sup>29</sup> V. Petralia,<sup>30</sup> L. Piaranti,<sup>31</sup> G. Di Piro,<sup>32</sup> R. Pompili,<sup>33</sup> S. Romeo,<sup>34</sup> A. R. Rossi,<sup>35</sup> A. Sele,<sup>36</sup> V. Shpakov,<sup>37</sup> A. Stella,<sup>38</sup> C. Vaccarezza,<sup>39</sup> F. Villa,<sup>40</sup> A. Ziegler,<sup>41,42</sup> and M. Ferrario<sup>43</sup>

**Seeded FEL radiation**

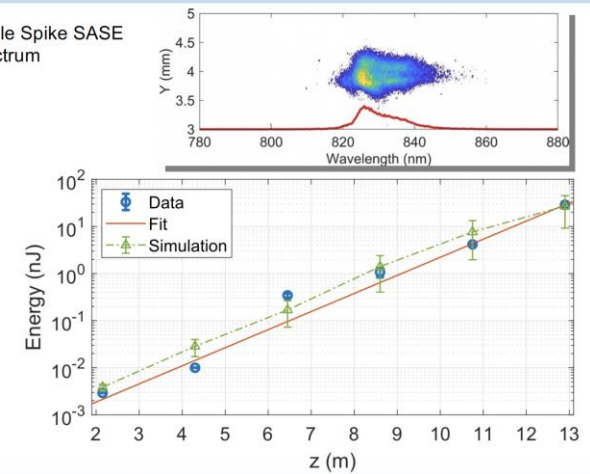
- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

## Recent ground-breaking results in Frascati: First FEL lasing from a beam-driven plasma accelerator

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



### Single Spike SASE spectrum



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

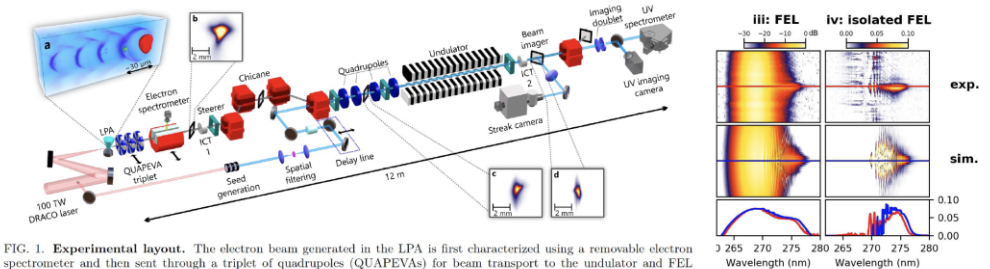
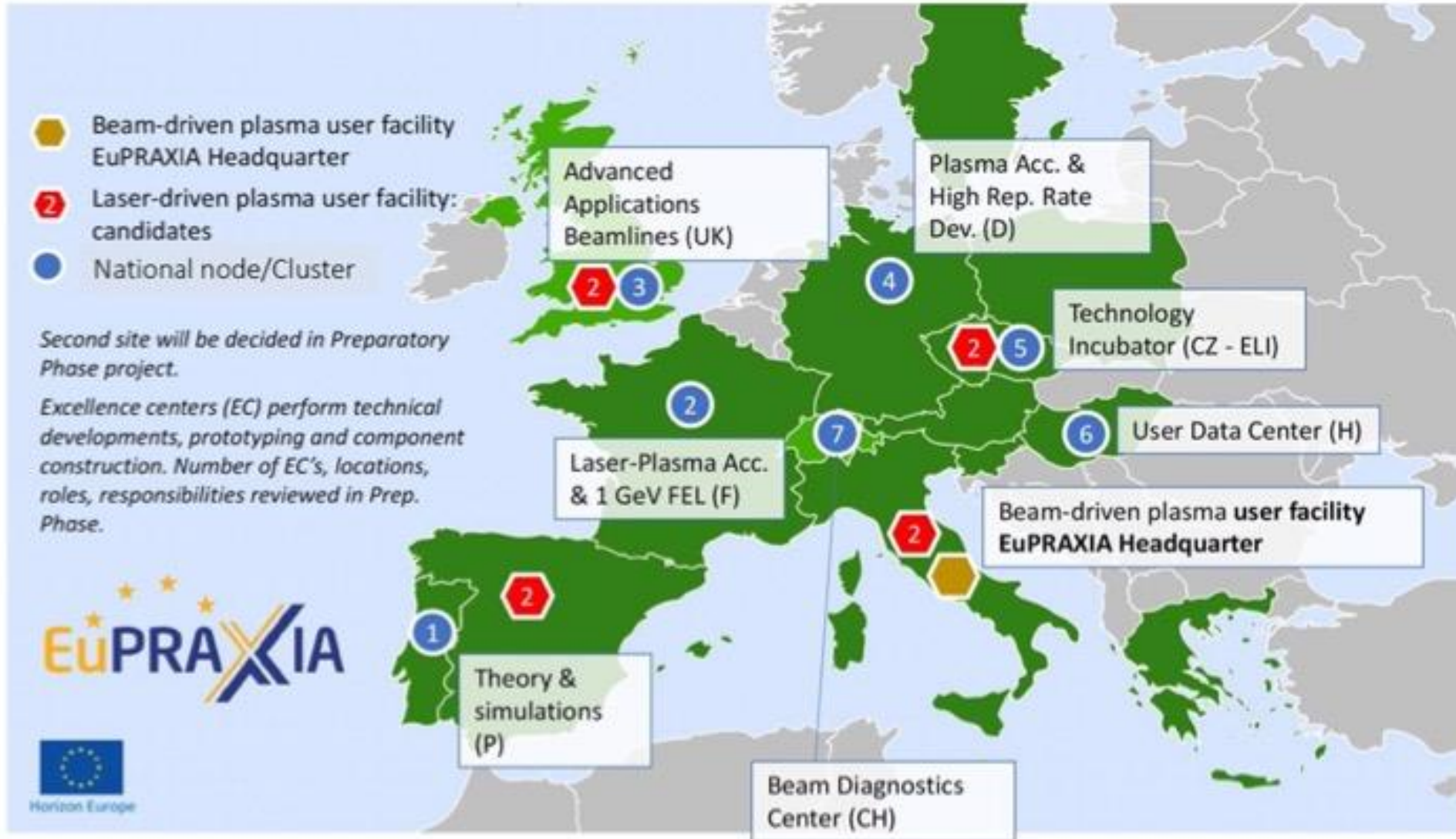


FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAS) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled 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).





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

Network organization

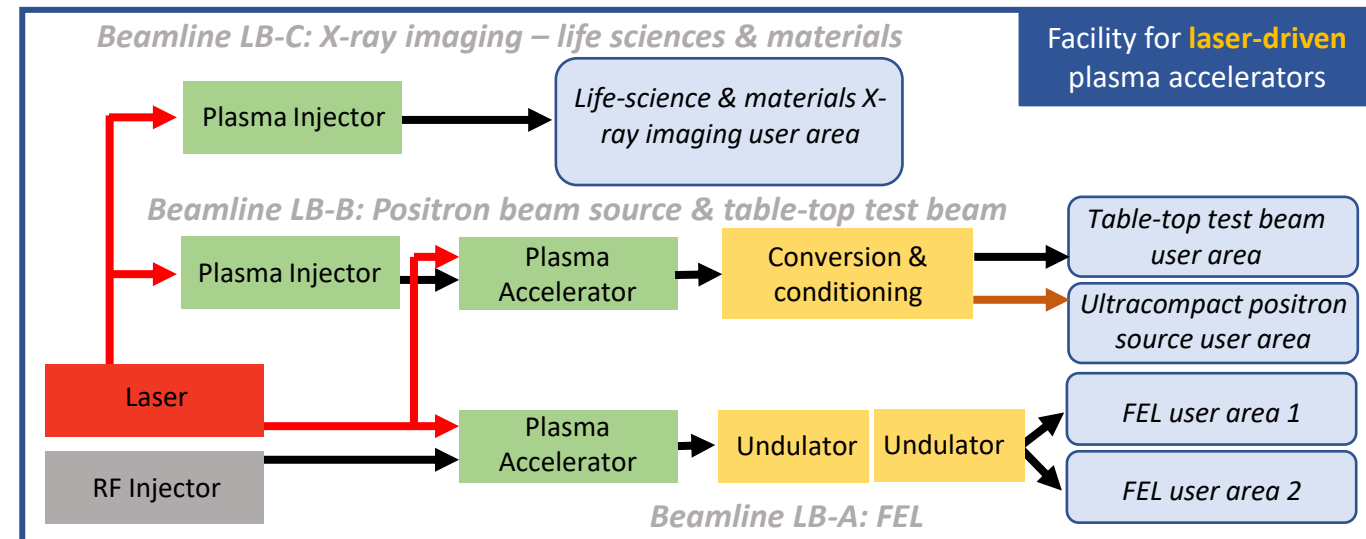
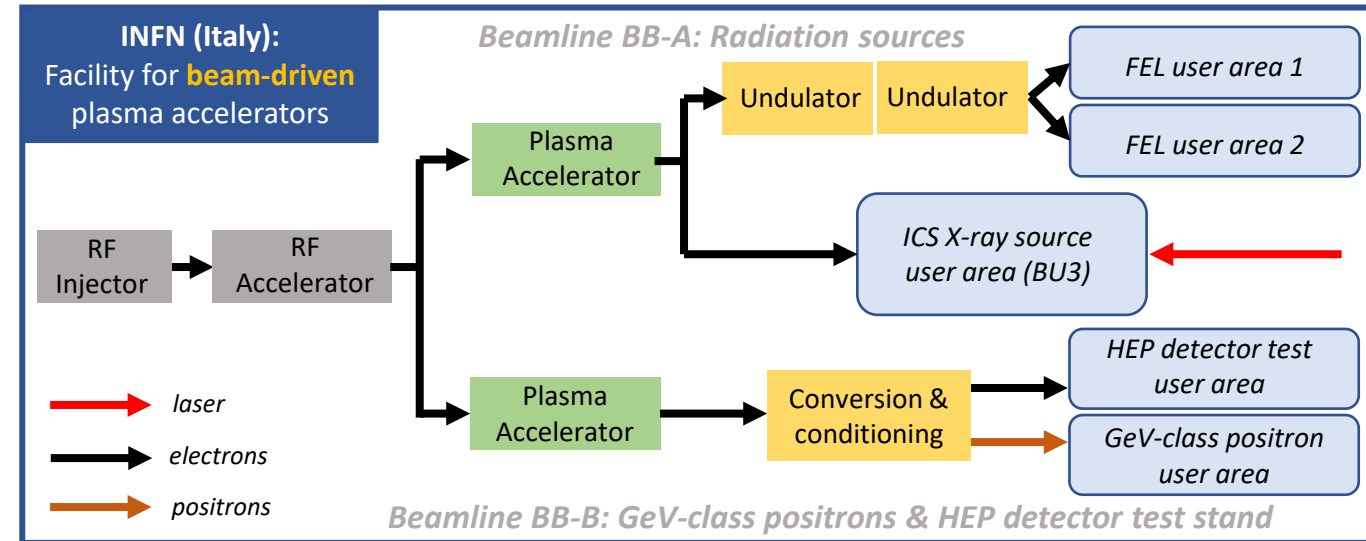
- Sites (PWFA/LWFA)
- National nodes
- Technology clusters

4 candidates for LWFA

- CLPU, Salamanca
- CNR-INO, Pisa
- ELI ERIC, Prague
- EPAC-RAL, UK



	Laser-driven	Beam-driven
<b>Phase 1</b>	<ul style="list-style-type: none"> <li>✓ FEL beamline to 1 GeV + user area 1</li> <li>✓ Ultracompact positron source beamline + positron user area</li> </ul>	<ul style="list-style-type: none"> <li>✓ FEL beamline to 1 GeV + user area 1</li> <li>✓ GeV-class positrons beamline + positron user area</li> </ul>
<b>Phase 2</b>	<ul style="list-style-type: none"> <li>✓ X-ray imaging beamline + user area</li> <li>✓ Table-top test beams user area</li> <li>✓ FEL user area 2</li> <li>✓ FEL to 5 GeV</li> </ul>	<ul style="list-style-type: none"> <li>✓ ICS source beamline + user area</li> <li>✓ HEP detector tests user area</li> <li>✓ FEL user area 2</li> <li>✓ FEL to 5 GeV</li> </ul>
<b>Phase 3</b>	<ul style="list-style-type: none"> <li>✓ High-field physics beamline / user area</li> <li>✓ Other future developments</li> </ul>	<ul style="list-style-type: none"> <li>✓ Medical imaging beamline / user area</li> <li>✓ Other future developments</li> </ul>



- 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 (observer)	FR
		NTUA Athens (observer)	GR
		U. Milano Bicocca (observer)	IT
		U. Palermo (observer)	IT
		NCBJ Otwock (observer)	PL
		U. Manchester (observer)	UK

- 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



<b>Governing Board</b> (Decision-making body) <b>Steering Committee</b> <b>Scientific Advisory Board</b> <b>Technical &amp; Industrial Advisory Board</b> <b>Board of Financial Sponsors</b>	<b>WP1 - Coordination &amp; Project Management</b> R. Assmann, INFN & DESY M. Ferrario, INFN <b>WP2 - Dissemination and Public Relations</b> C. Welsch, U Liverpool S. Bertelli, INFN <b>WP3 - Organization and Rules</b> A. Specka, CNRS A. Ghigo, INFN <b>WP4 - Financial &amp; Legal Model, Economic Impact</b> A. Falone, INFN <b>WP5 - User Strategy and Services</b> F. Stellato, U Tor Vergata E. Principi, ELETTRA <b>WP6 - Membership Extension Strategy</b> B. Cros, CNRS A. Mostacci, U Sapienza	<b>WP7 - E-Needs and Data Policy</b> R. Fonseca, IST S. Pilo, INFN <b>WP8 - Theory &amp; Simulation</b> J. Viera, IST H. Vincenti, CEA <b>WP9 - RF, Magnets &amp; Beamline Components</b> S. Antipov, DESY F. Nguyen, ENEA <b>WP10 - Plasma Components &amp; Systems</b> K. Cassou, CNRS J. Osterhoff, DESY <b>WP11 - Applications</b> G. Sarri, U Belfast E. Chiadroni, U Sapienza <b>WP12 - Laser Technology, Liaison to Industry</b> L. Glizzi, CNR P. Crump, FBH	<b>WP13 - Diagnostics</b> A. Cianchi, U Tor Vergata R. Ischebeck, EPFL <b>WP14 - Transformative Innovation Paths</b> B. Hidding, U Strathclyde S. Karsch, LMU <b>WP15 - TDR EuPRAXIA @SPARC-lab</b> C. Vaccarezza, INFN R. Pompili, INFN <b>WP16 - TDR EuPRAXIA Site 2</b> A. Molodtshentsev, ELI-Beamlines R. Pattahit, STFC
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## ELI-Beamlines (ELI-ERIC)

**Bird-view on ELI-Beamlines**

Prague city center

ELI-ERIC

Size area: 49 000 m<sup>2</sup>  
Buildings: 28 645 m<sup>2</sup>  
Experimental buildings: 16 000 m<sup>2</sup>  
Laboratories: 4 500 m<sup>2</sup>  
Offices: 4 400 m<sup>2</sup>  
Multi-functional areas: 2 300 m<sup>2</sup>

**Plan of existing experimental area**

Experimental halls: E2-hall, E3-hall, E4-hall, E5-hall

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

**Laser systems at ELI-Beamlines (overview)**

System	Operational Status
L1-ALLEGRA	In operation (100 Hz) (E1)
L2-DUNA	In operation (100 Hz) (E2)
L3-MAPLS	In operation (10 Hz) (E3-E4-E5)
L4-ARCON	In operation (10 Hz) (E1)

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

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

Phase I - 20 TW, Phase II - 200 TW, Phase III - 1 PW

**Internal Developments**

300 fW laser, 100 fs, 10 Hz

6.4, 30 fs, 10 Hz

30 J, 30 fs, 1 Hz

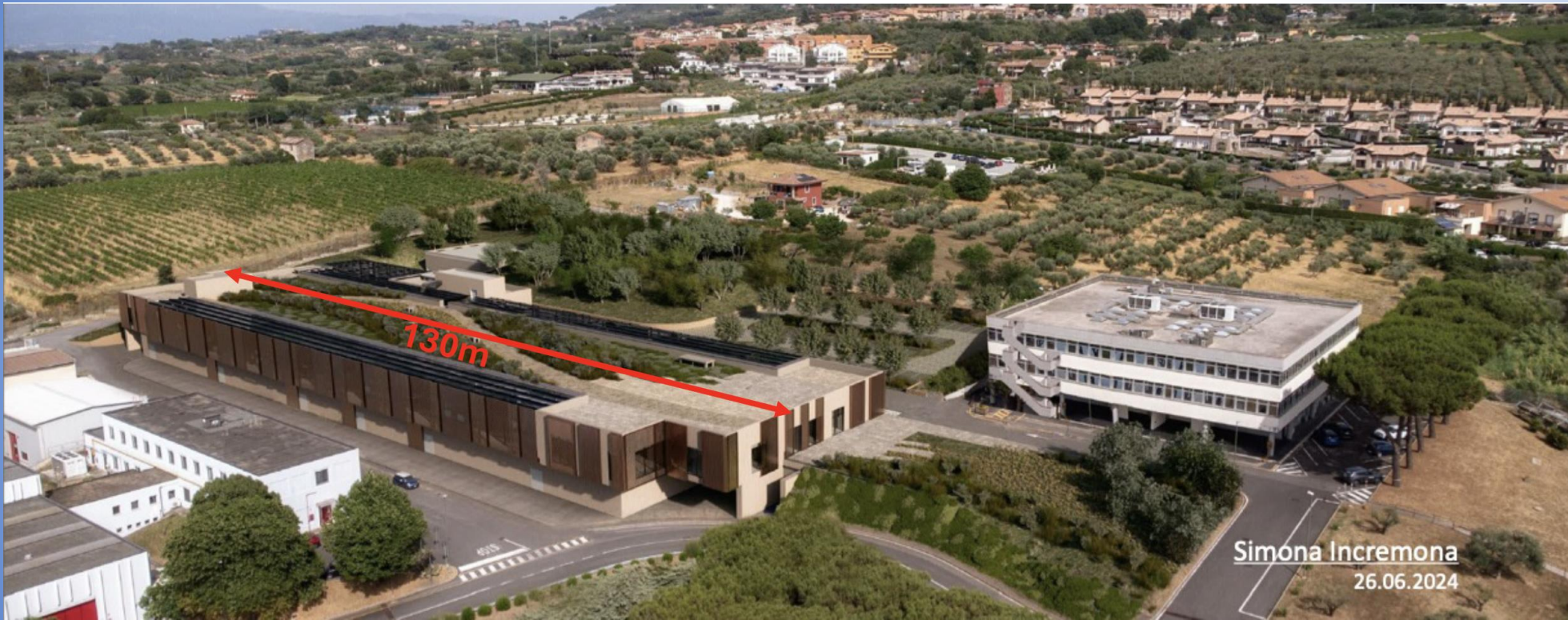
Calls 4 users

- Fully Operating User Facility (ending the 3rd call for Users)
- Included in Spanish Singular Infrastructure roadmap (ICTS)
- Support from the Spanish Government (>3ME 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

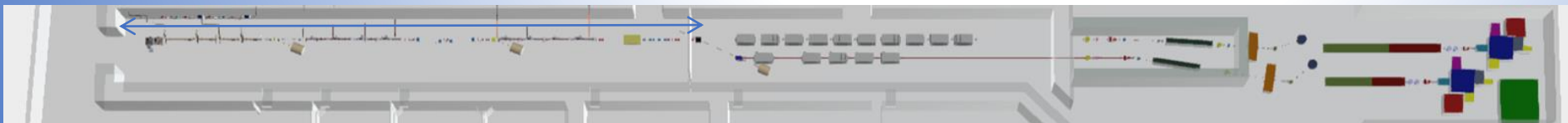
## PISA for EuPRAXIA@CNR

- 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



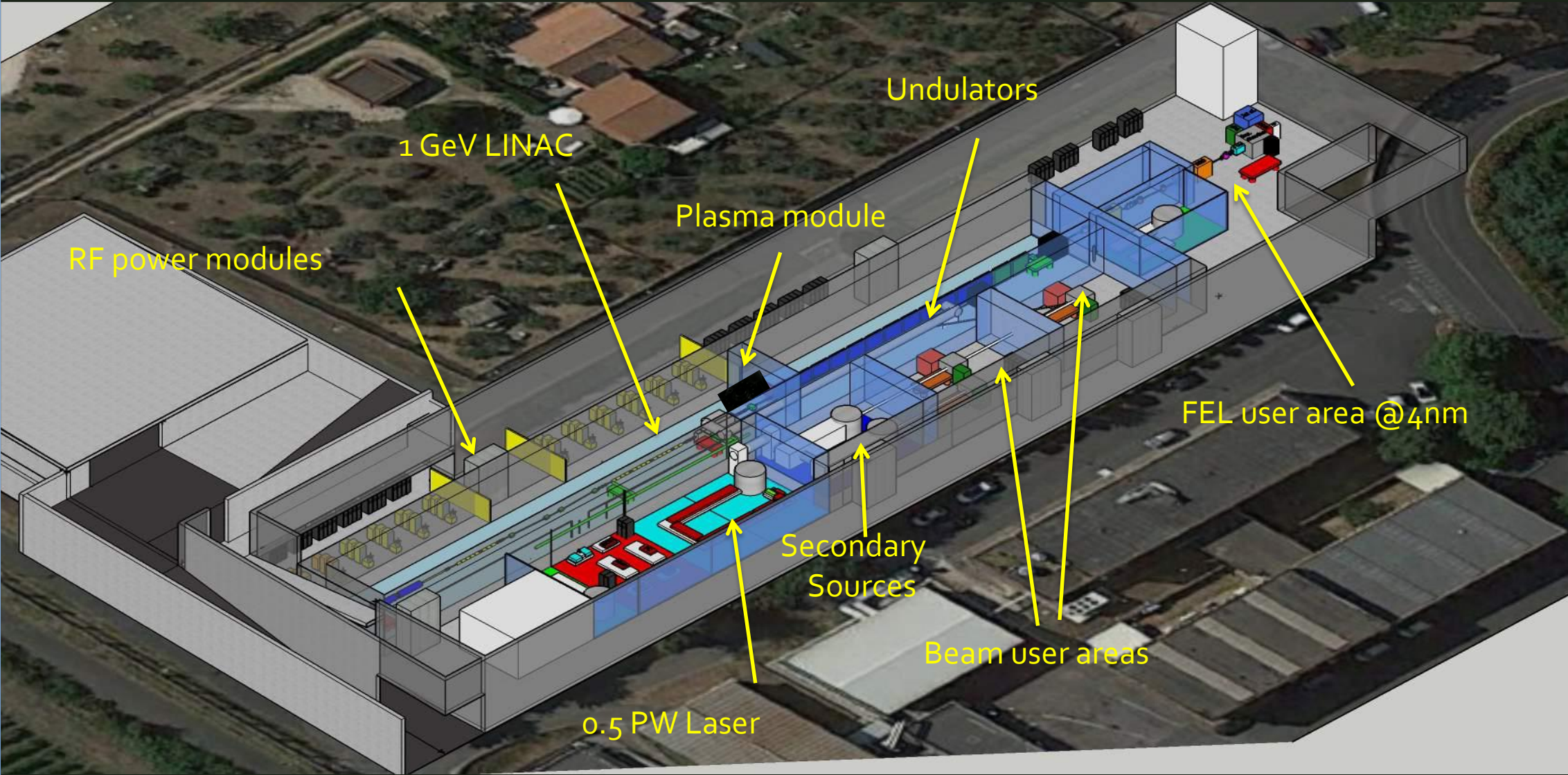


- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

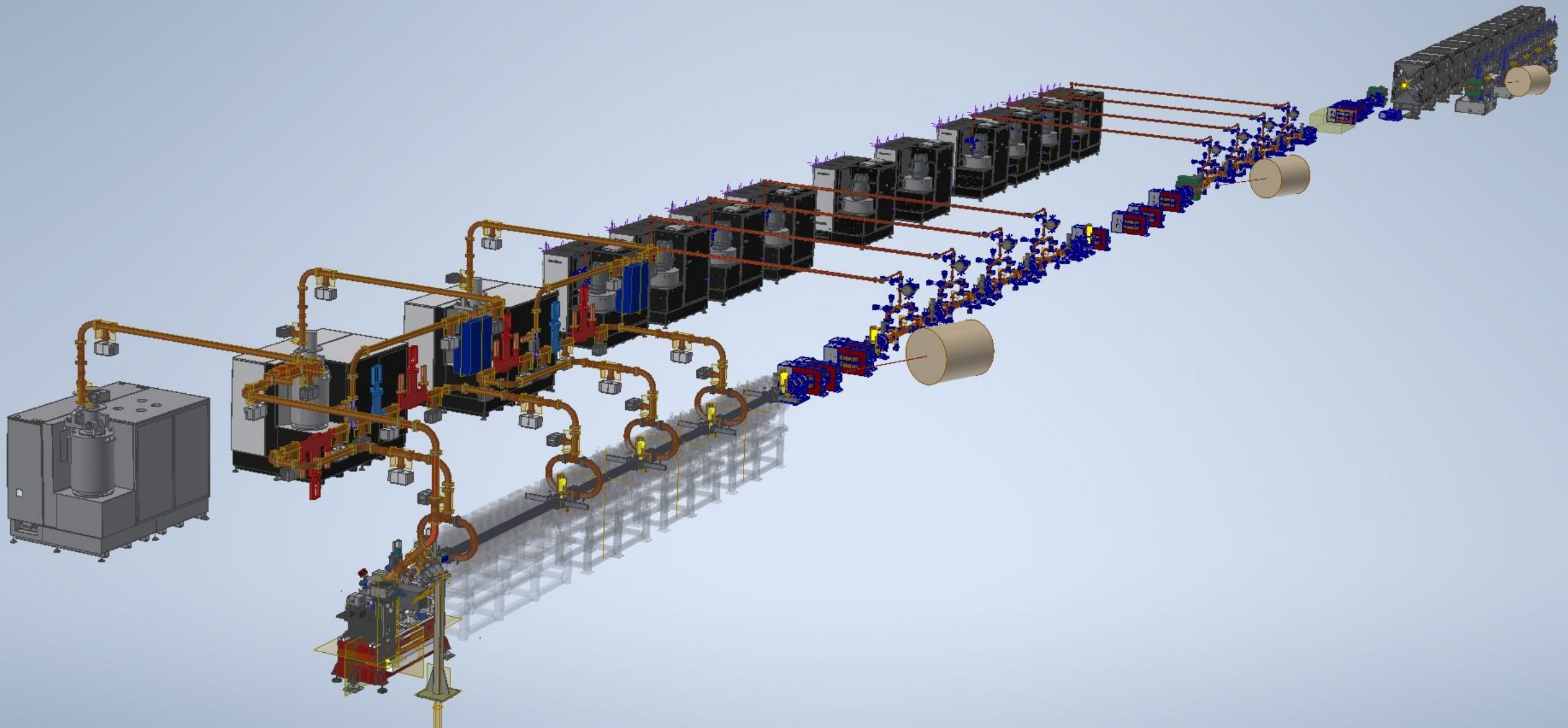


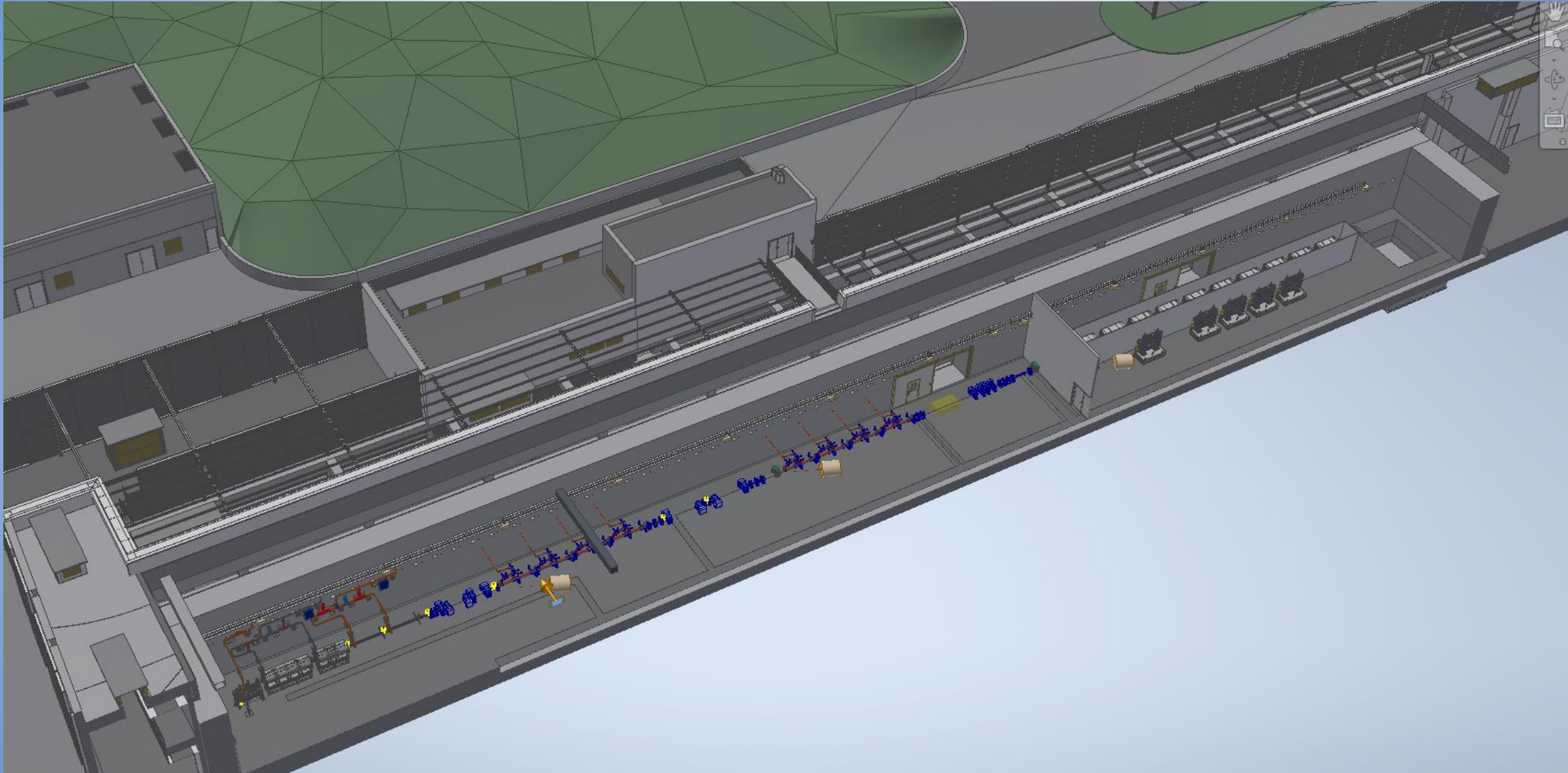


# EuPRAXIA@SPARC\_LAB

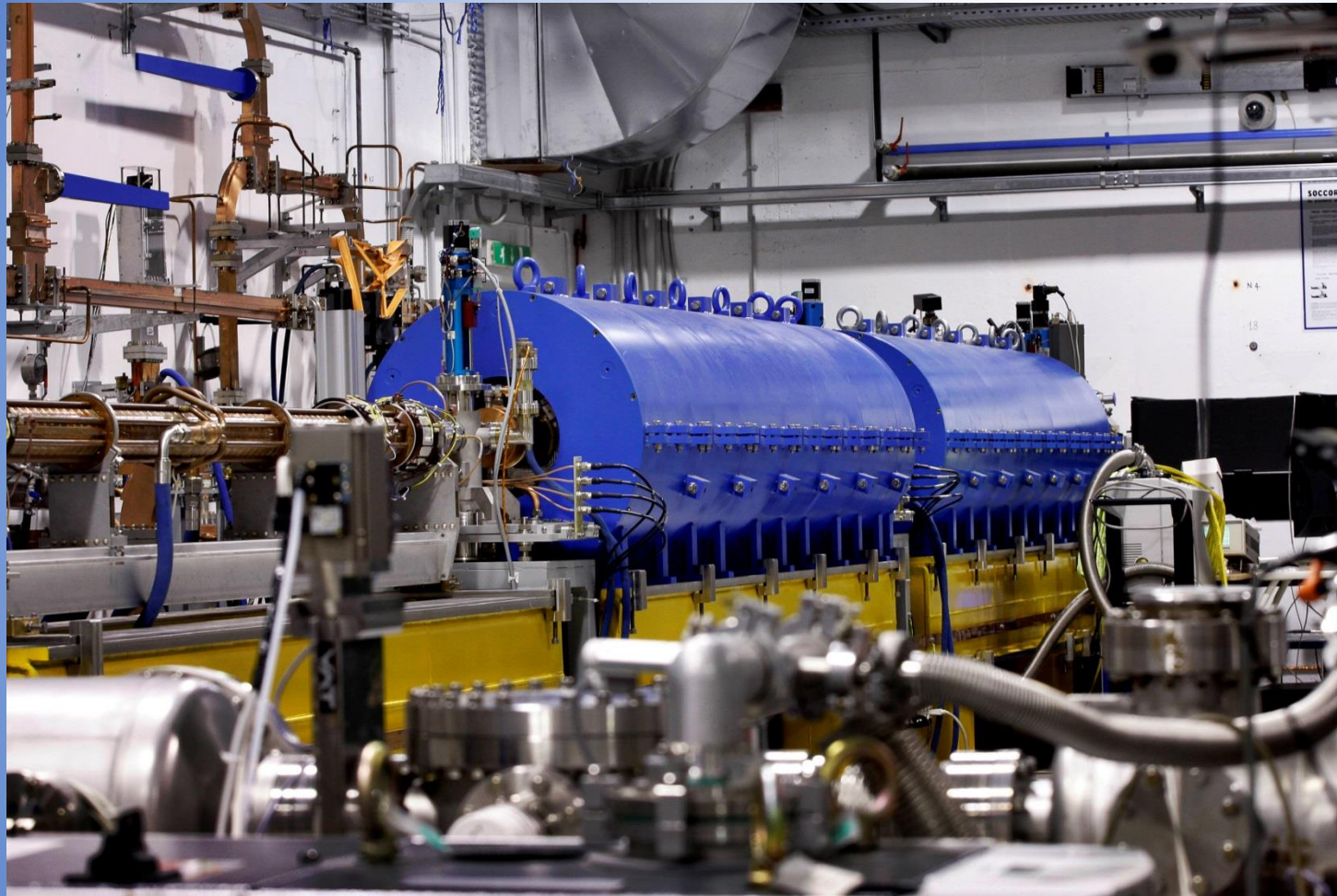






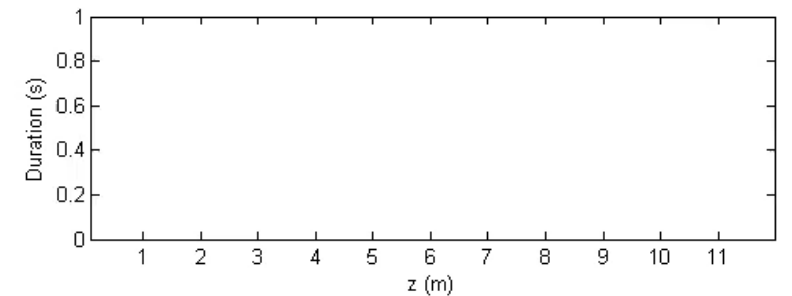
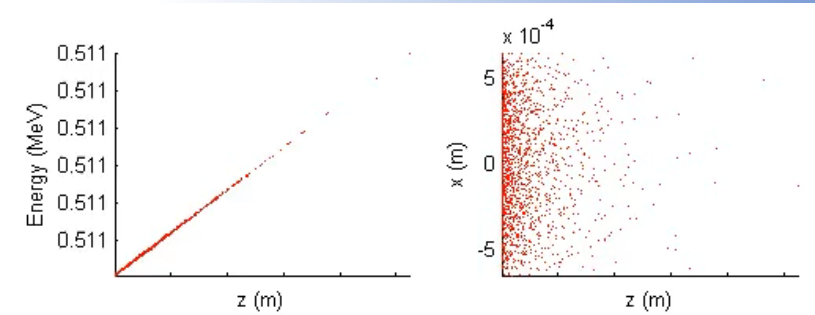




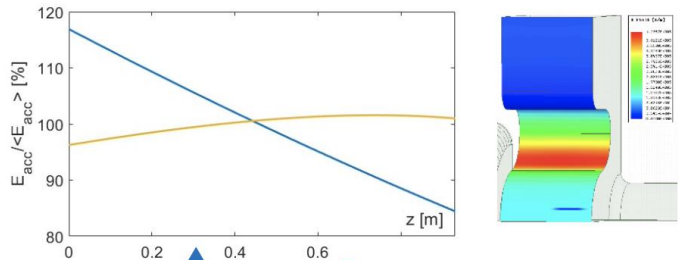


Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

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







1. E.m. design: *done*

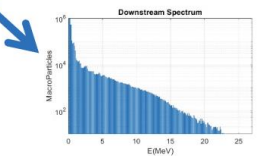
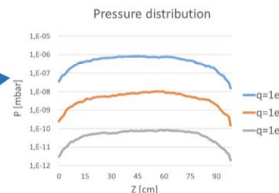
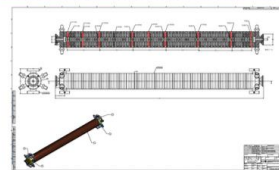
2. Thermo-mechanical analysis: *done*

3. Mechanical design: *done*

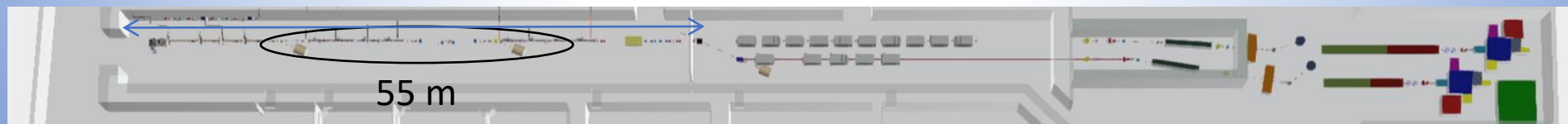
4. Vacuum calculations: *done*

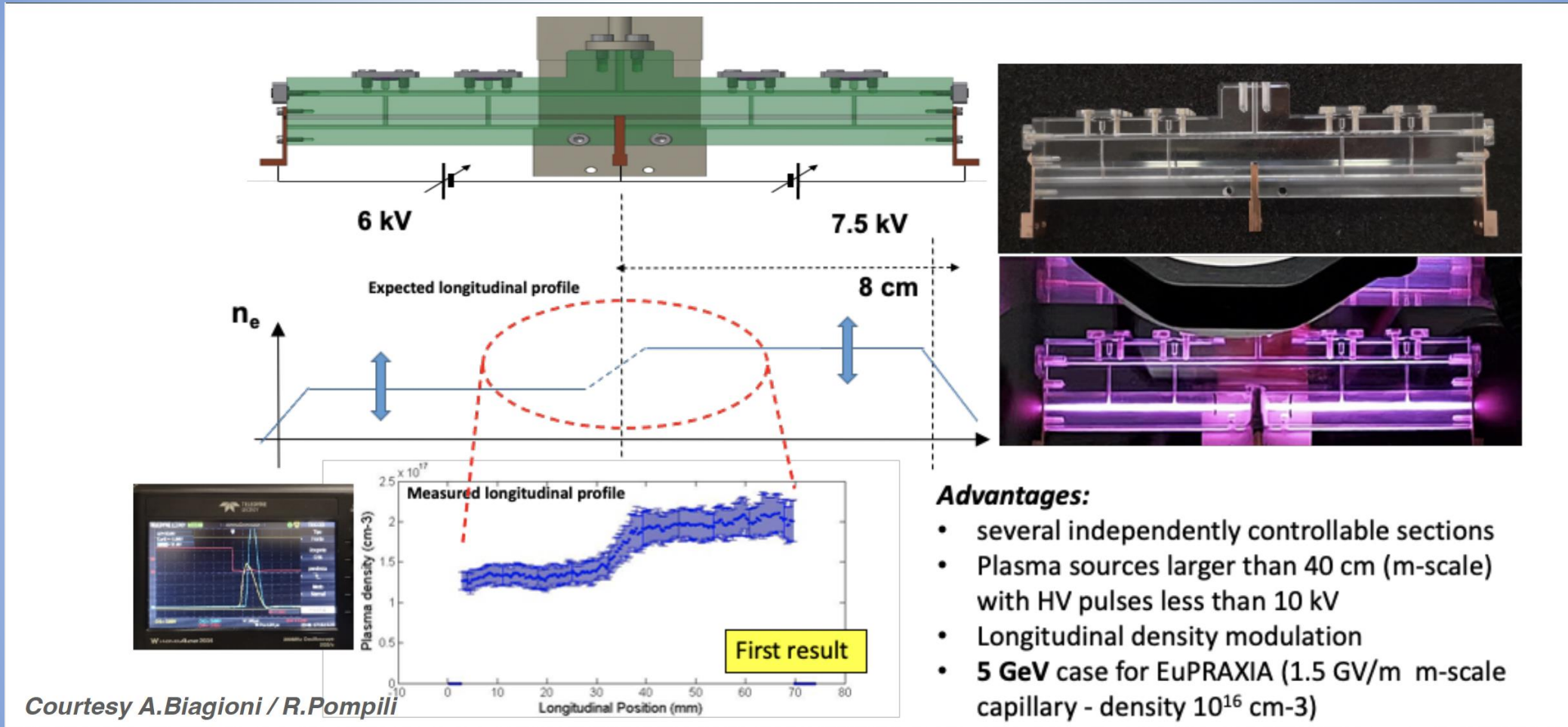
5. Dark current simulations: *done*

6. Waveguide distribution simulation with attenuation calculations: *done*

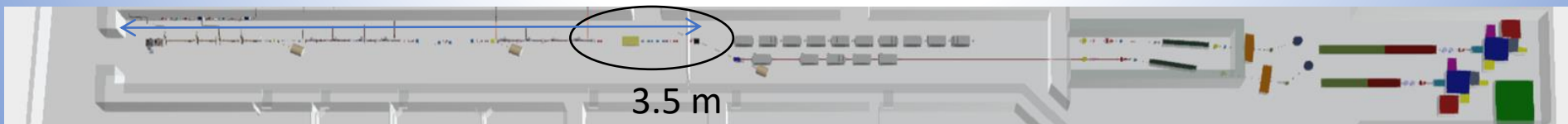


PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	60	
Structures per module	2	
Iris radius a [mm]	3.85-3.15	3.5
Tapering angle [deg]	0.04	0
Struct. length $L_s$ act. Length (flange-to-flange) [m]	0.94 (1.05)	
No. of cells	112	
Shunt impedance R [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 <sup>2</sup> ]	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	





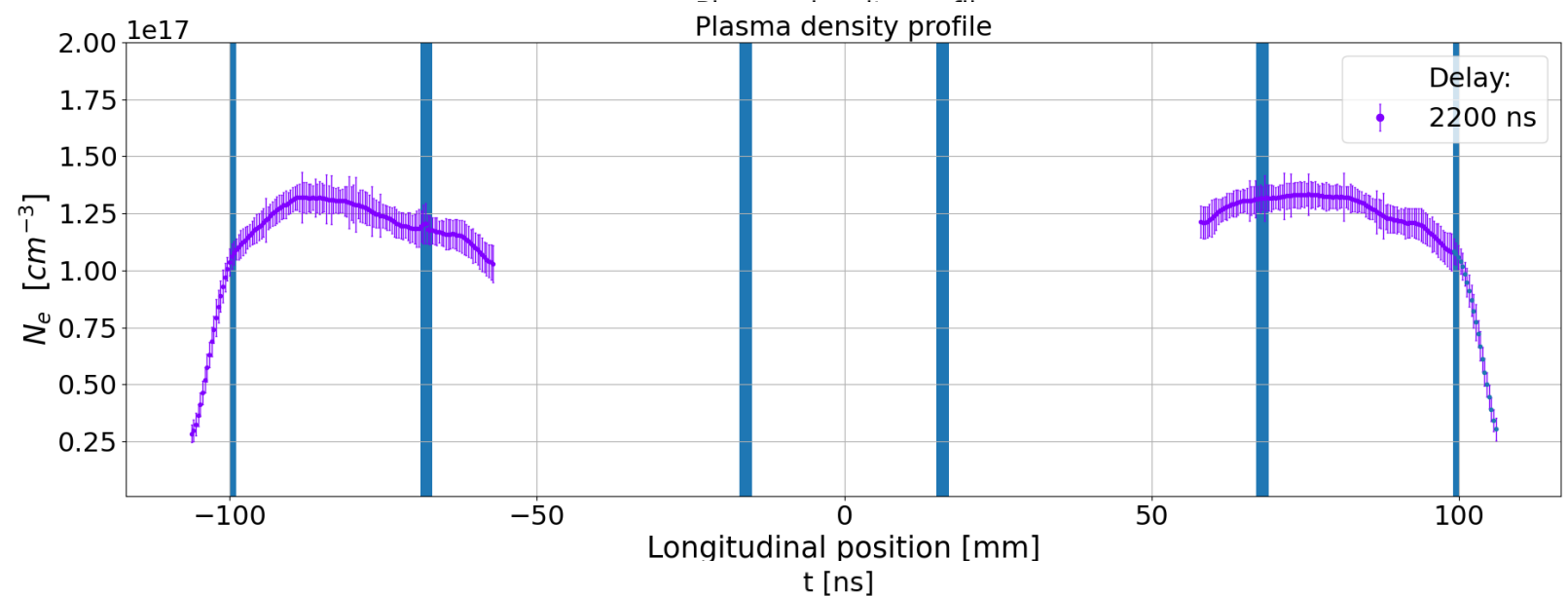
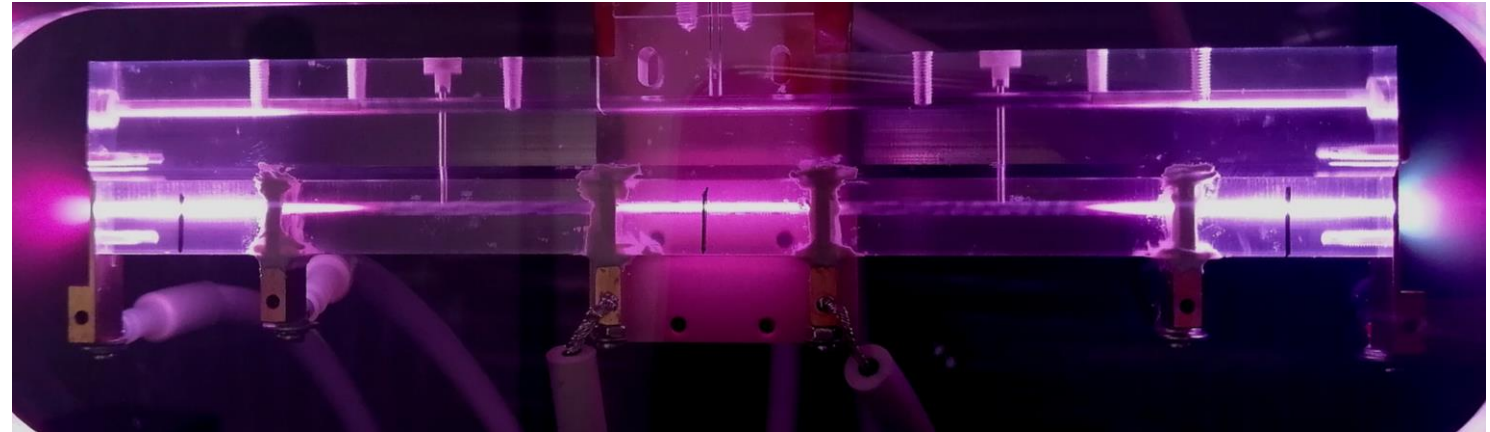
Courtesy A. Biagioni / R. Pompili

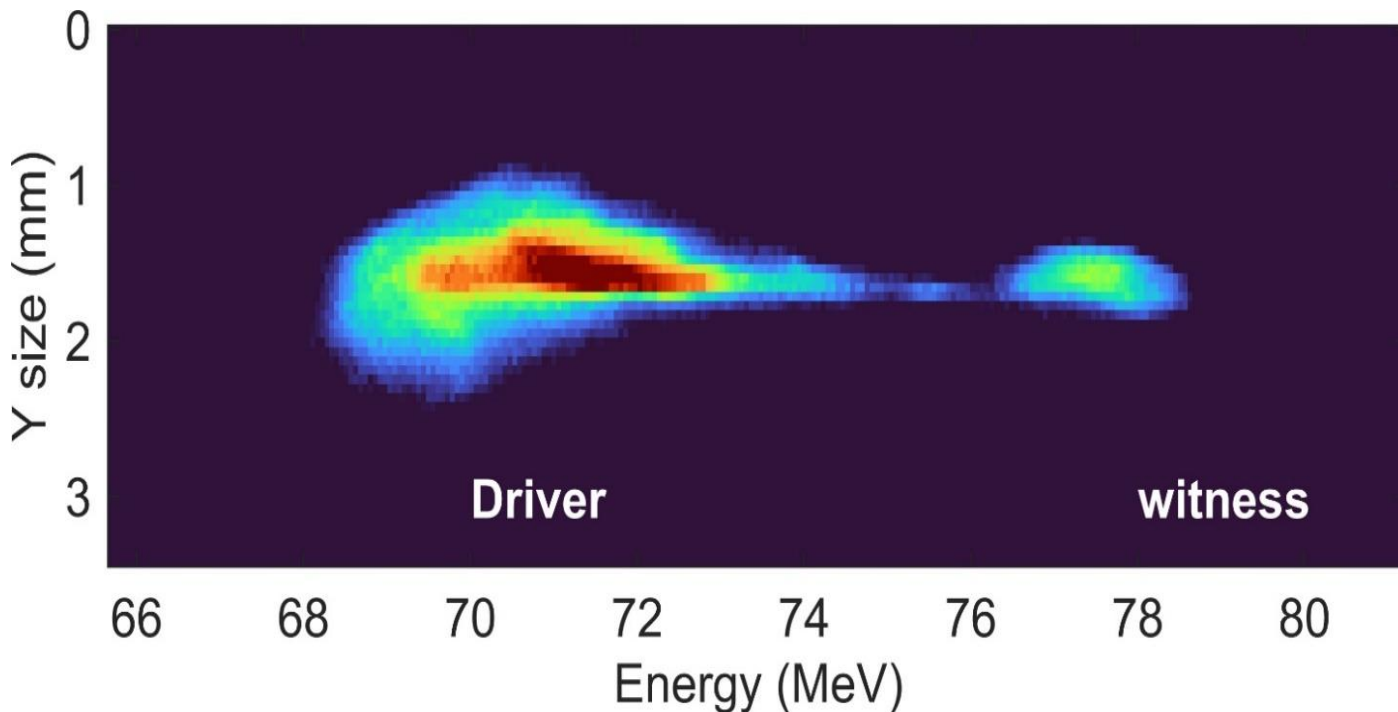




## Operating properties

- Discharges synchronization
  - Lenses synchronized with the beam entrance
  - Central discharge applied **3  $\mu\text{s}$  before** for plasma acceleration
- 10 kV voltage resulting in:
  - 500 A on the lenses
  - 250 A in the accelerator

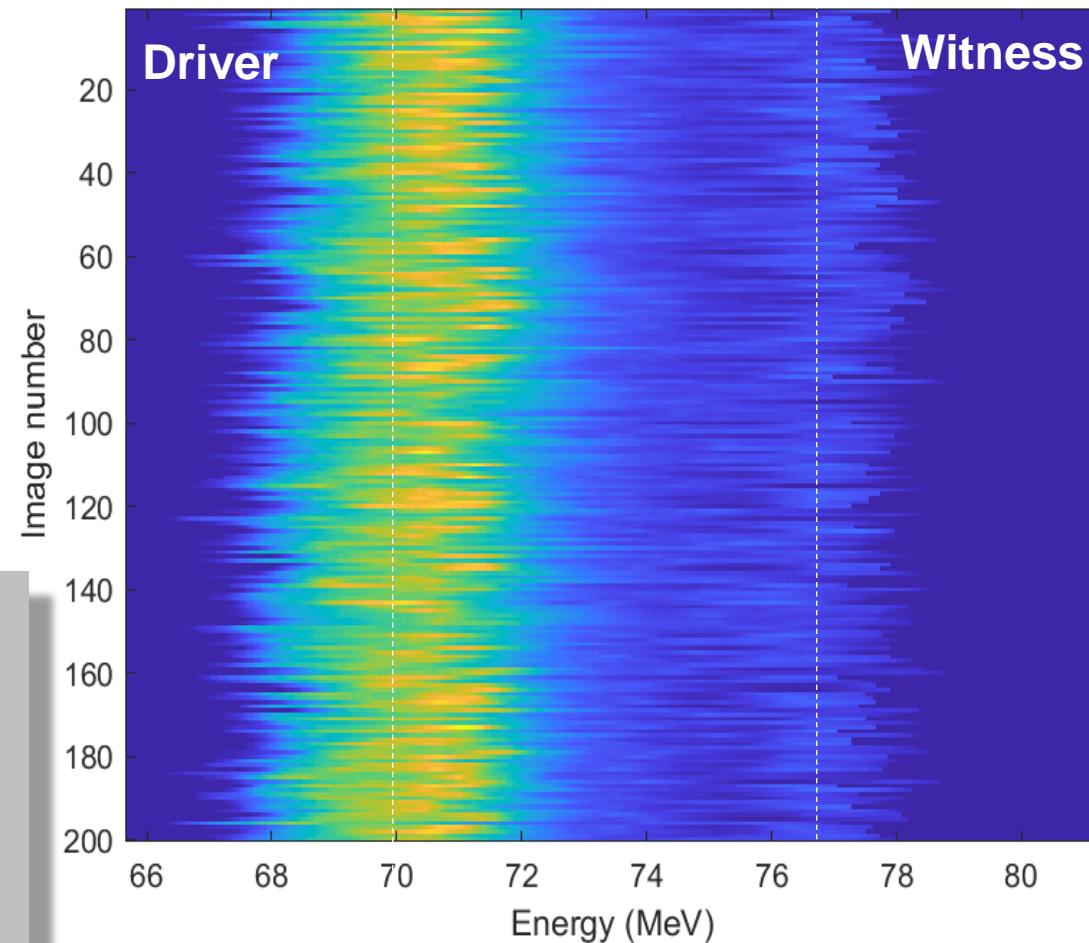




▪ **5 MeV/3cm acceleration in 19 cm long integrated plasma module with 200 pC driver/50 pC witness**

- 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  $2 \times 10^{15} \text{ cm}^{-3}$
- $\sim 150 \text{ MV/m}$  accelerating gradient
- Stability of the accelerated beam

**200 consecutive shots taken with accelerated beam**



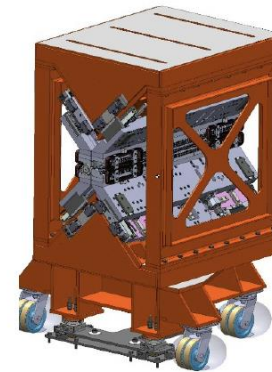


## Two FEL lines:

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

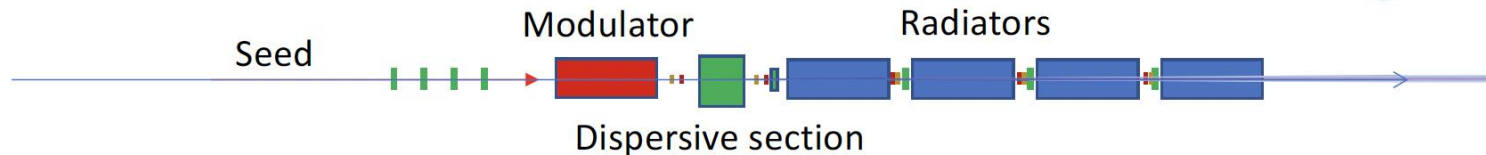


SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.  
 Two technologies under study: Apple-X PMU (baseline) and planar SCU.  
 Prototyping in progress



FERMI FEL-1 Radiator

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

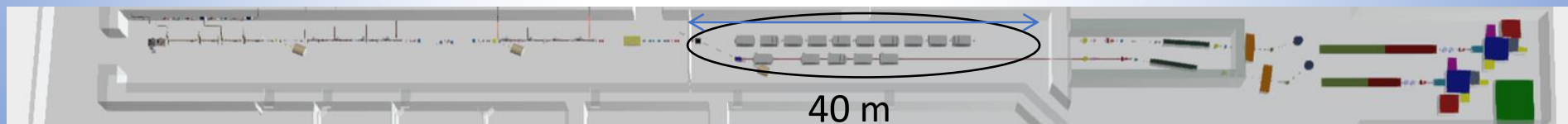


**SEEDED FEL** – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 50-100 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC\_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.

Frascati 06/05/23 – EUPRAXIA TDR

WAC Report L. Giannessi

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## Ultrahigh brightness beams from plasma photoguns

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

5

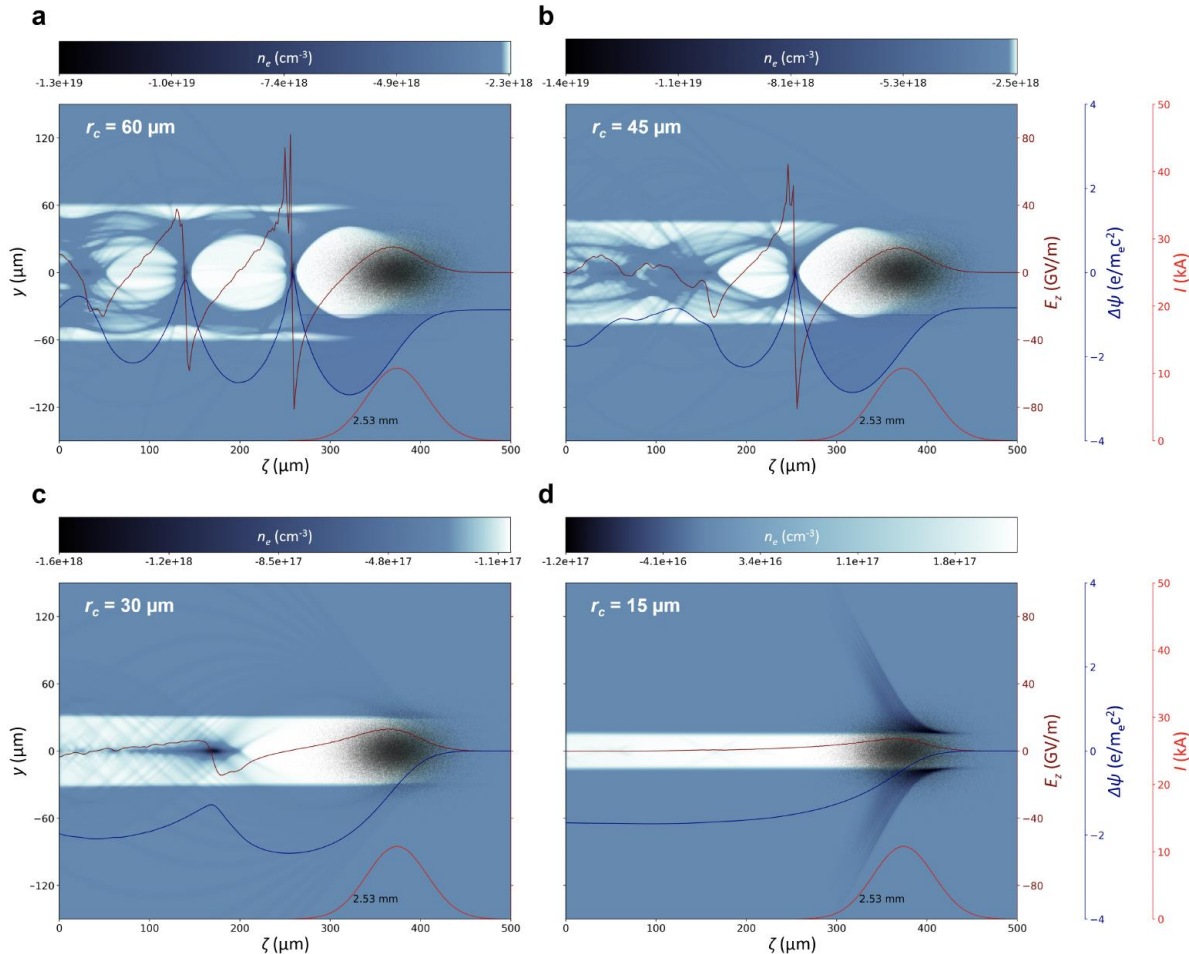


FIG. 3. 3D PIC-simulations (VSim) of intense electron beam interaction with a preionized plasma channel of different radii  $r_c$ . The FACET electron driver beam (black) propagates to the right, expels plasma electrons and sets up a nonlinear PWFA blowout as in a) and b), or for a thinner channel generates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

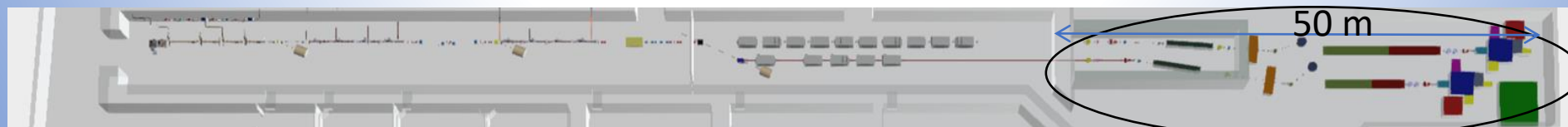
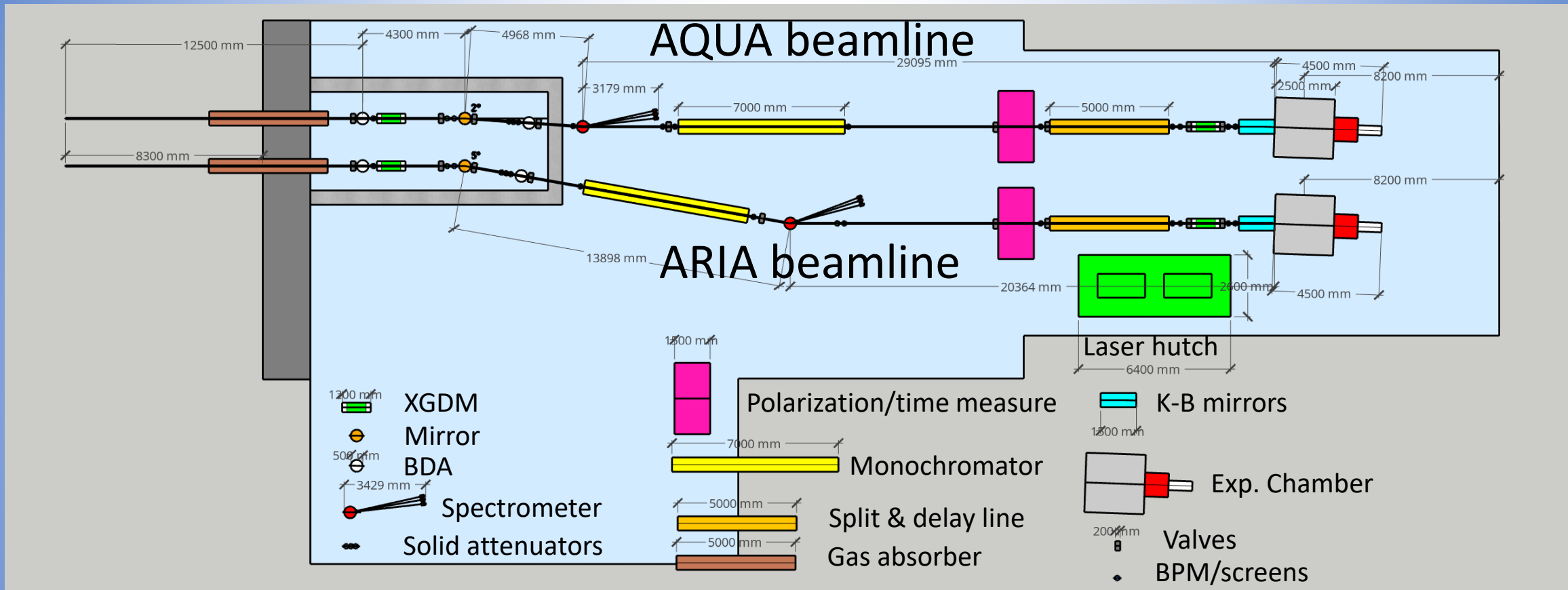
- Neutral plasma creation through ionization laser
- Blowout of the plasma electrons through the driver beam

◆ 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



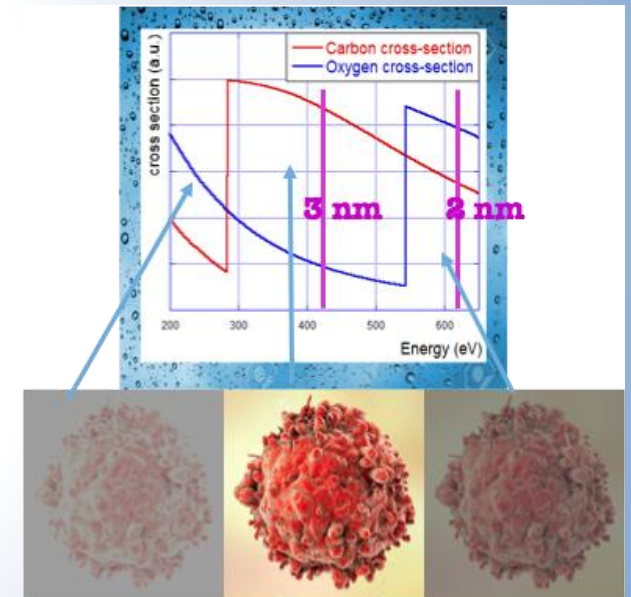


# Expected SASE FEL performances

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	$\mu\text{m}$	6-3	24-20
RMS norm. Emittance	$\mu\text{m}$	1	1
Slice Energy Spread	%	$\leq 0.05$	$\leq 0.05$
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	
$\rho(1D/3D)$	$\times 10^{-3}$	2	2
Photon Brilliance per shot	$s\text{ mm}^2\text{mrad}^2\text{ } bw(0.1\%)$	$1-2 \times 10^{28}$	$1 \times 10^{27}$

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)

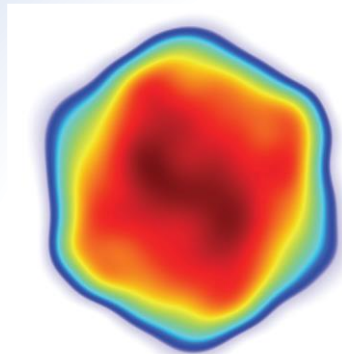


**Coherent Imaging of biological samples**  
 protein clusters, VIRUSES and cells  
 living in their native state  
 Possibility to study dynamics  
 $\sim 10^{11}$  photons/pulse needed

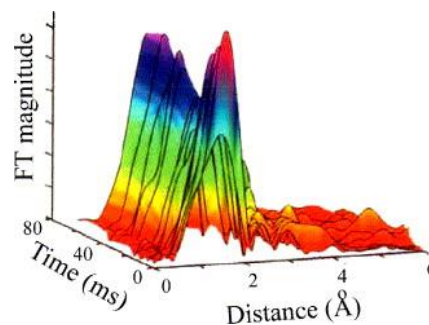


## Experimental techniques and typology of **samples**

Coherent imaging



X-ray spectroscopy



Raman spectroscopy

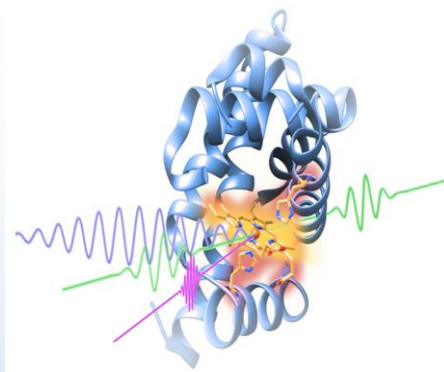
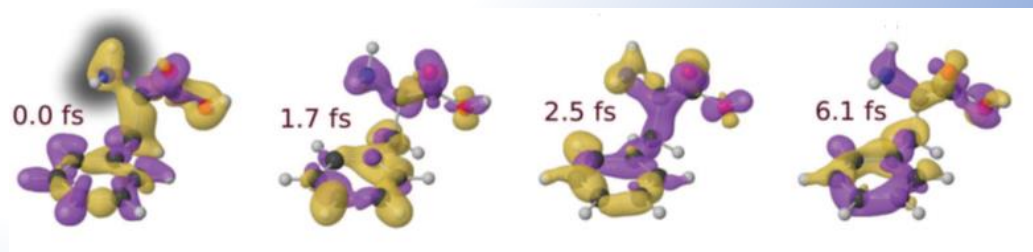


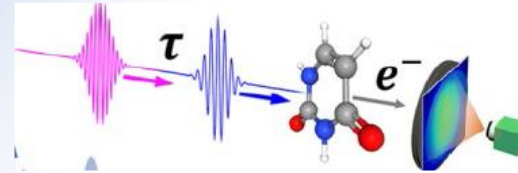
Photo-fragmentation of molecules



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

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

Photoemission Spectroscopy



Photoelectron Circular Dichroism



Raman spectroscopy

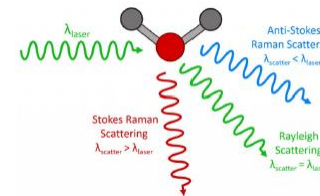
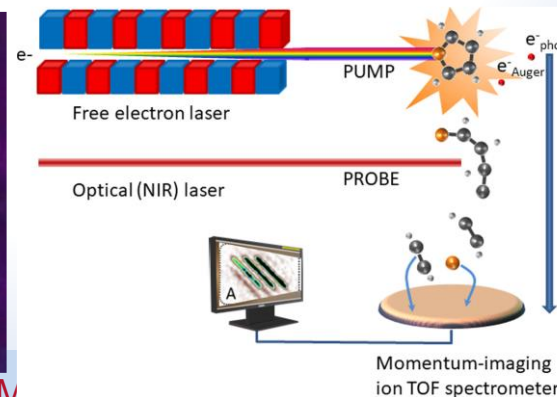
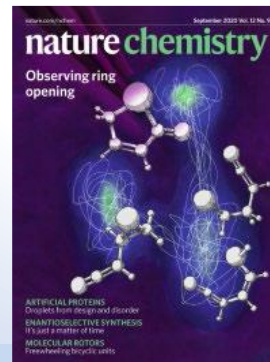
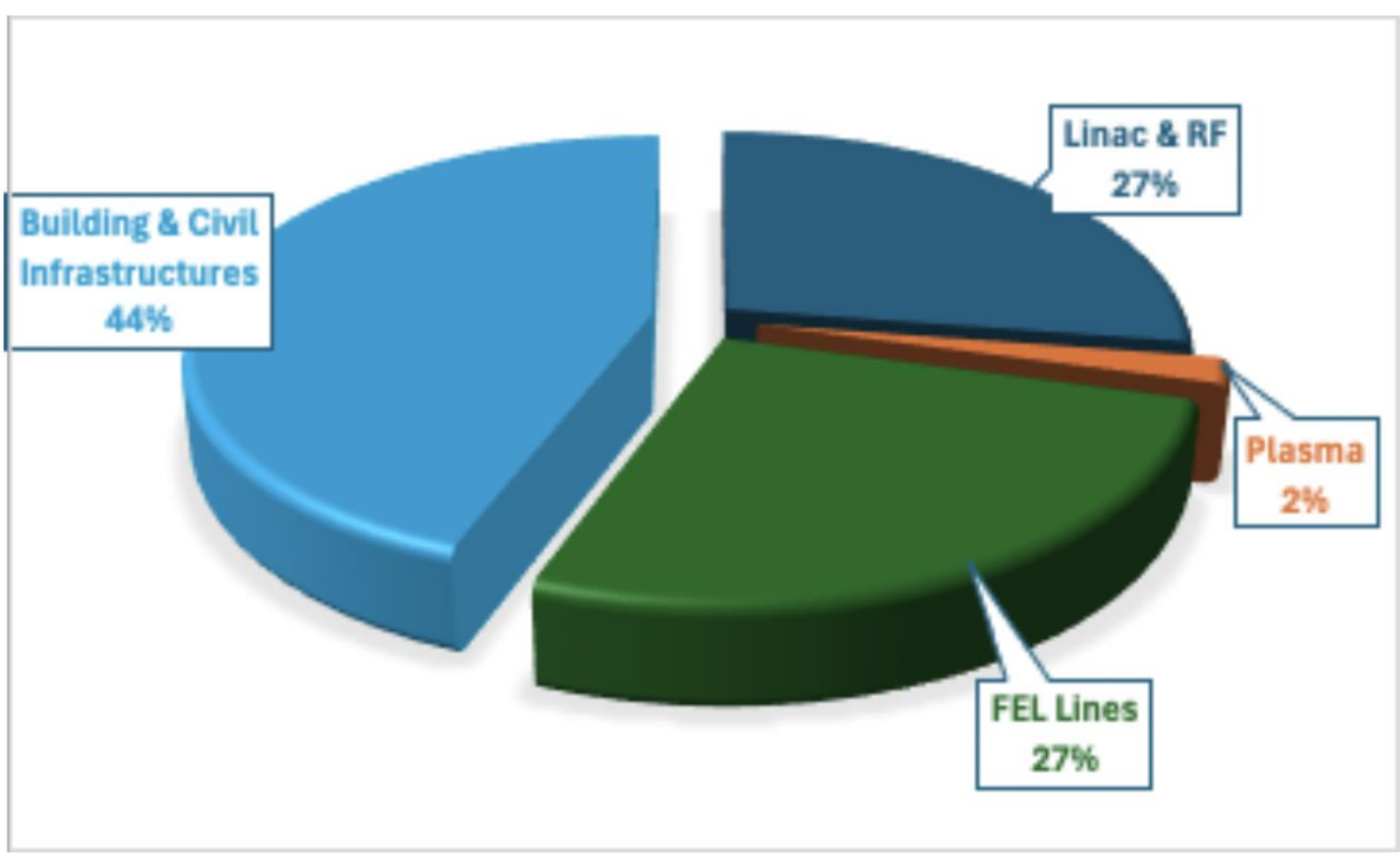


Photo-fragmentation of molecules  
Time of Flight Spectroscopy

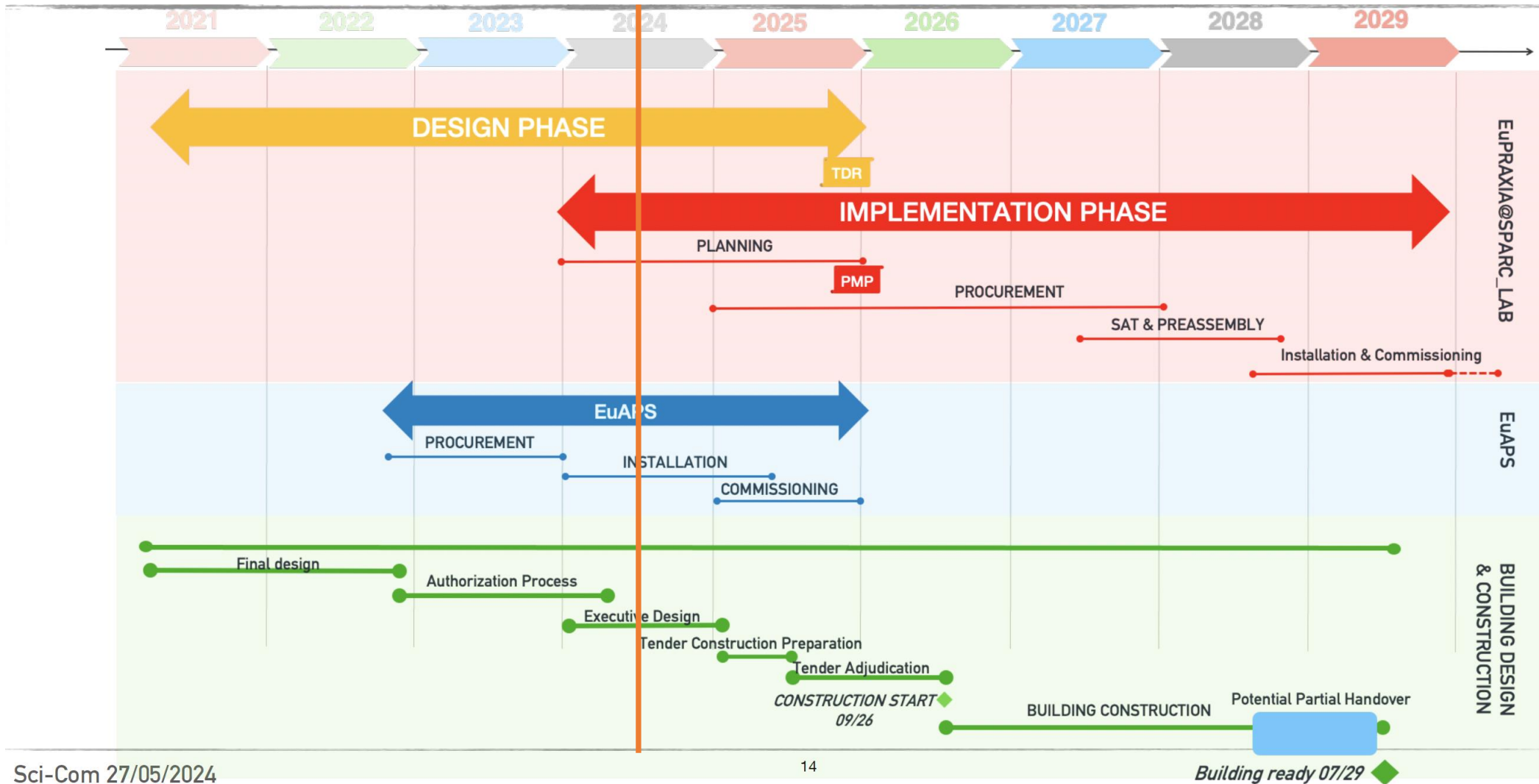


Gas phase & Atmosphere  
*(Earth & Planets)*  
 Aerosols  
*(Pollution, nanoparticles)*  
 Molecules & gases  
*(spectroscopies, time-of-flight)*  
 Proteins  
*(spectroscopies)*  
 Surfaces  
*(ablation & deposition)*





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
<b>TOT</b>	<b>121.768.040</b>





## EuAPS: EuPRAXIA Advance Photon Sources

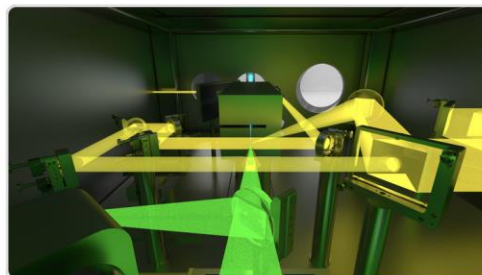
- Principal Investigator: M. Ferrario,
- Infrastructure Manager: C. Bortolin,
- Management and Dissemination: A. Falone



### 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”.

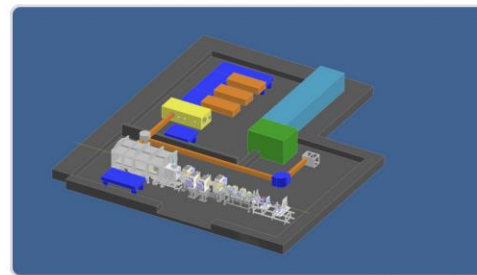
A. Cianchi (Uni ToV)



Betatron Radiation Source

[READ MORE](#)

P. Cirrone (INFN-LNS)



High Power Laser Beamline

[READ MORE](#)

L. Labate (CNR-INO)



High Repetition Rate Laser Beamline

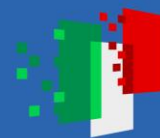
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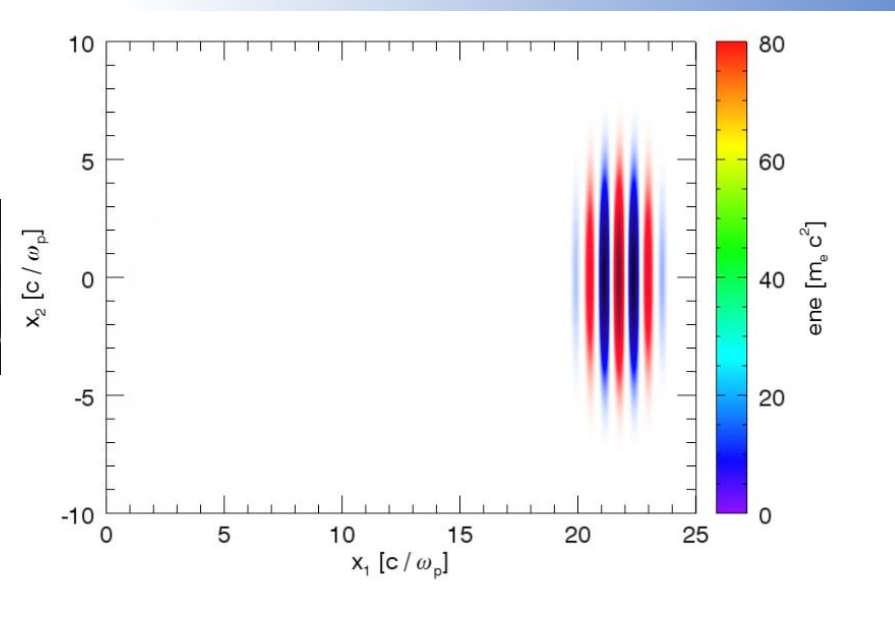
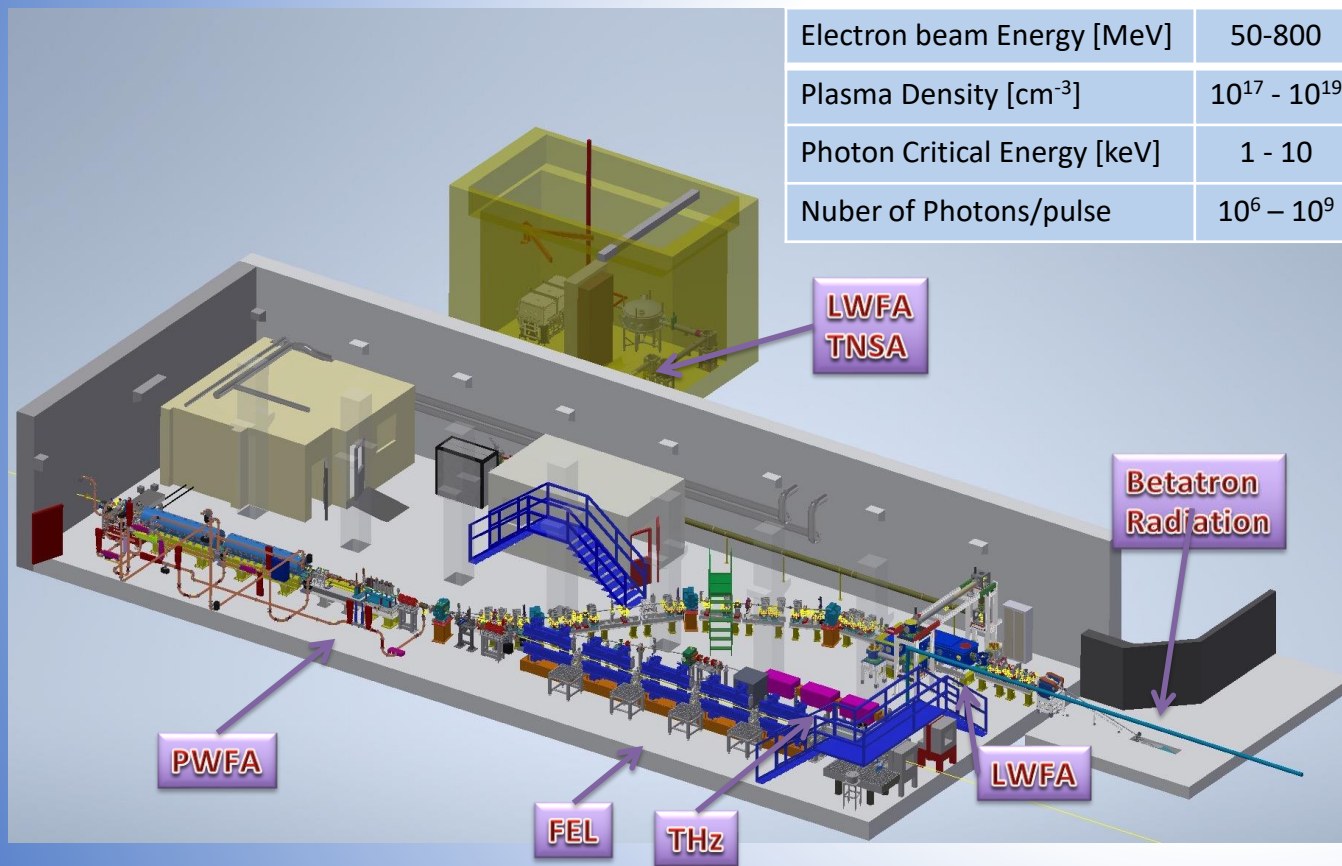
Ministero  
dell'Università  
e della Ricerca



Italiadomani  
PIANO NAZIONALE  
DI RIPRESA E RESILIENZA



## Betatron Radiation Source at SPARC\_LAB



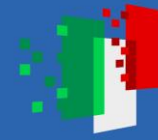
Courtesy J. Vieira, R. Fonseca/GoLP/IST Lisbon



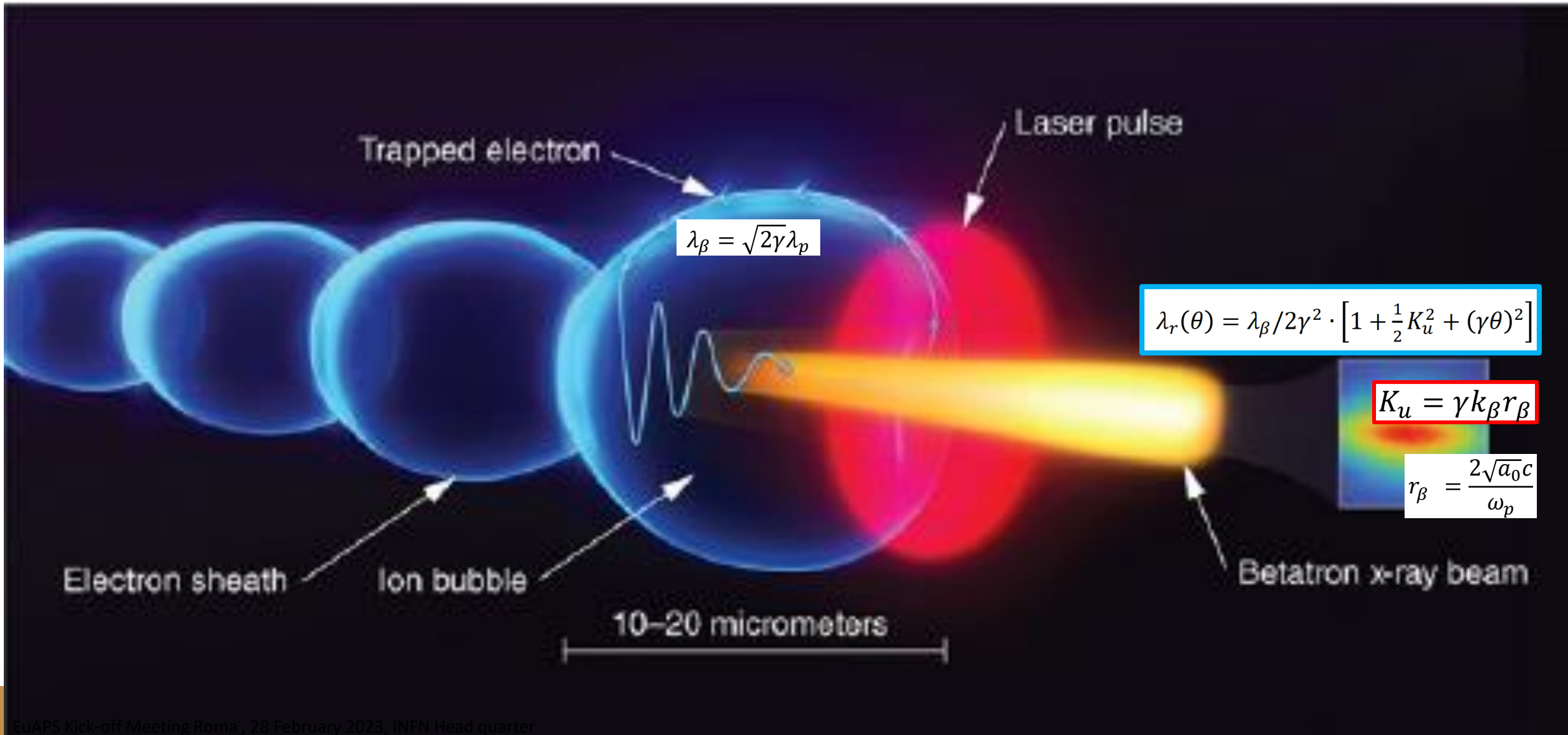
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dall'Unione europea  
NextGenerationEU



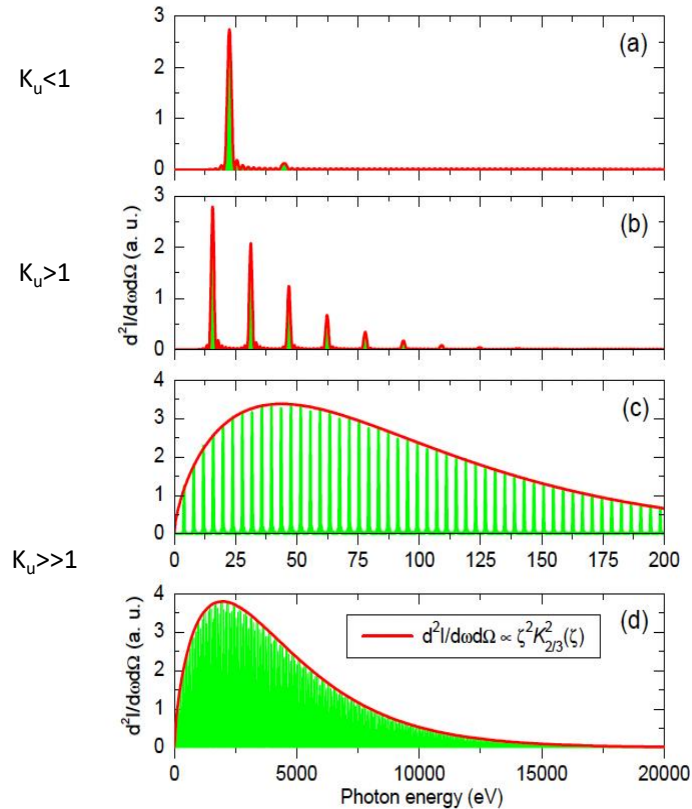
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e della Ricerca



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DI RIPRESA E RESILIENZA







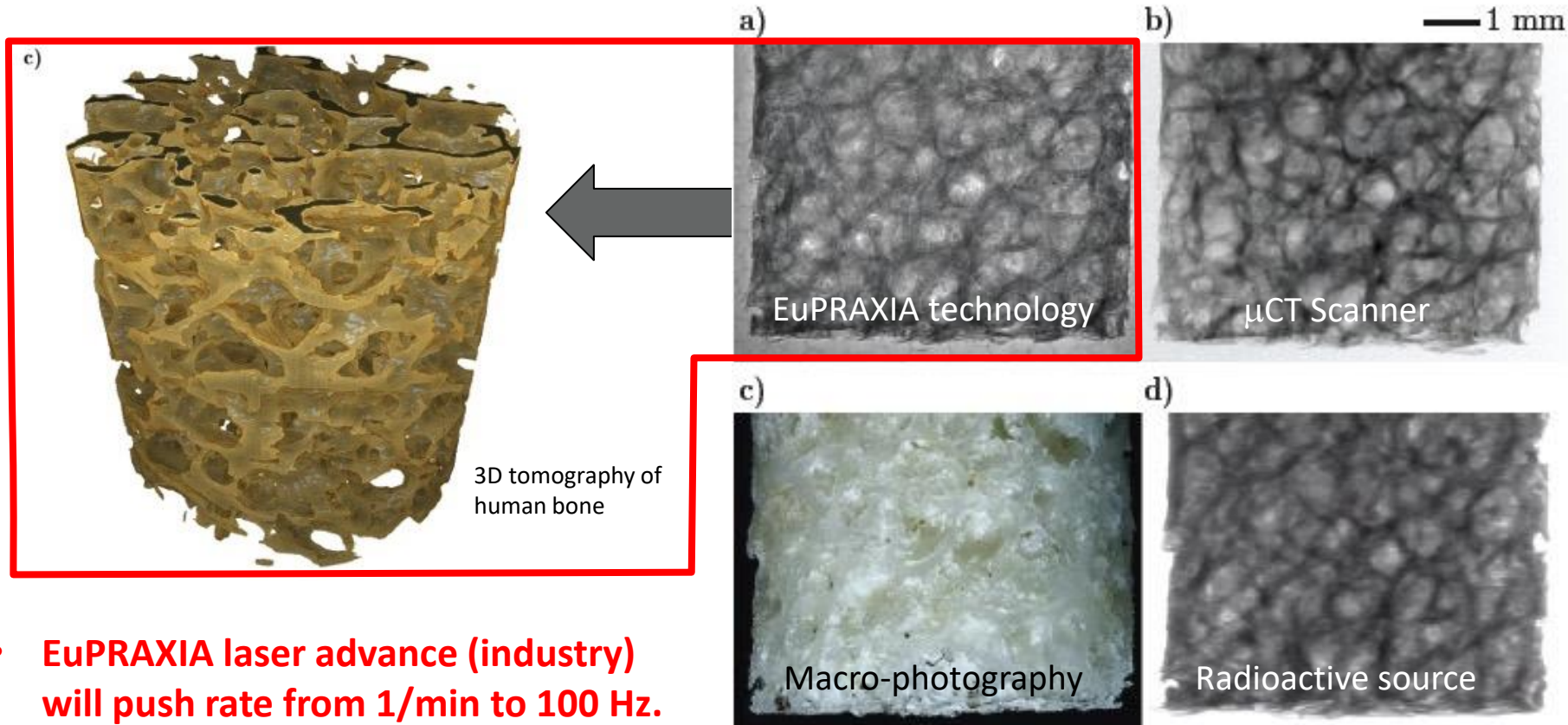
$$\omega_c = 3K_u \gamma^2 \omega_\beta$$

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

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

- 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).

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)



**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 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**

## High-gradient plasma and laser accelerators

*Panel members:* R. Assmann<sup>e,f,\*\*\*</sup> (Chair), E. Gschwendtner<sup>a</sup> (Co-Chair), K. Cassou<sup>c</sup>, S. Corde<sup>z</sup>, L. Corner<sup>r</sup>, B. Cros<sup>aa</sup>, M. Ferrario<sup>f</sup>, S. Hooker<sup>bb</sup>, R. Ischebeck<sup>g</sup>, A. Latina<sup>a</sup>, O. Lundh<sup>cc</sup>, P. Muggli<sup>dd</sup>, P. Nghiem<sup>b</sup>, J. Osterhoff<sup>e</sup>, T. Raubenheimer<sup>uv,ee</sup>, A. Specka<sup>ff</sup>, J. Vieira<sup>gg</sup>, M. Wing<sup>hh</sup>  
*Associated members:* C. Geddes<sup>p</sup>, M. Hogan<sup>w</sup>, W. Lu<sup>v</sup>, P. Musumeci<sup>ii</sup>



EUROPEAN STRATEGY FOR PARTICLE PHYSICS

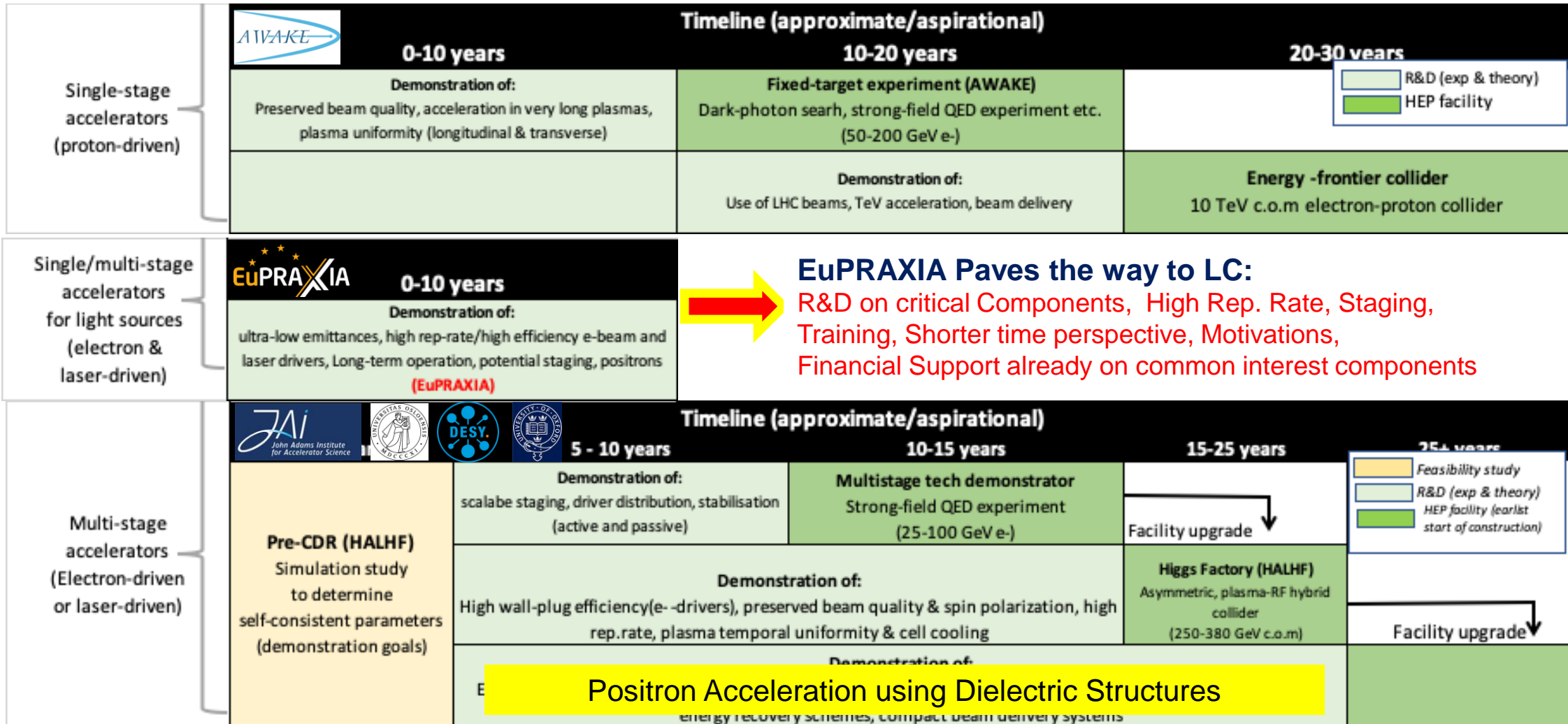
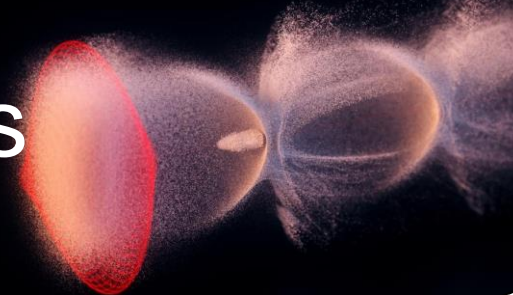
Accelerator R&D Roadmap



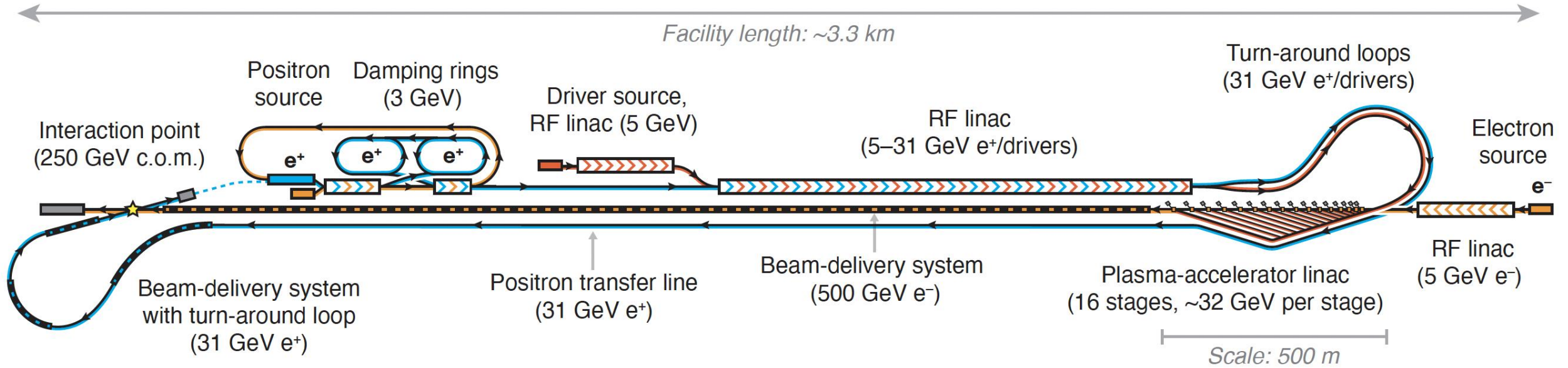
- Development of Plasma Sources for High-Repetition Rate, Multi-GeV Stages
- High Average Power, High Efficiency Laser Drivers and Schemes
- Staging of Electron Plasma Accelerators Including In- and Out-Coupling
- High Transformer Ratio in PWFA for High Efficiency and Low Energy Spread
- Polarised Electrons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



# ESPP Roadmap Update – Plasma Accelerators

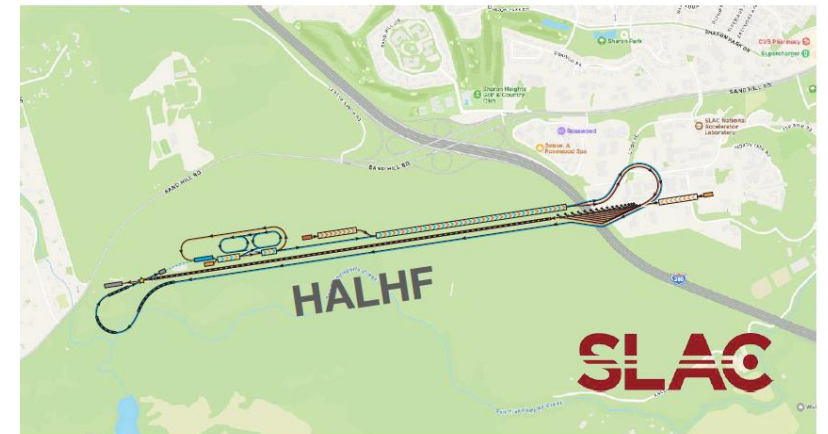


# HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



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

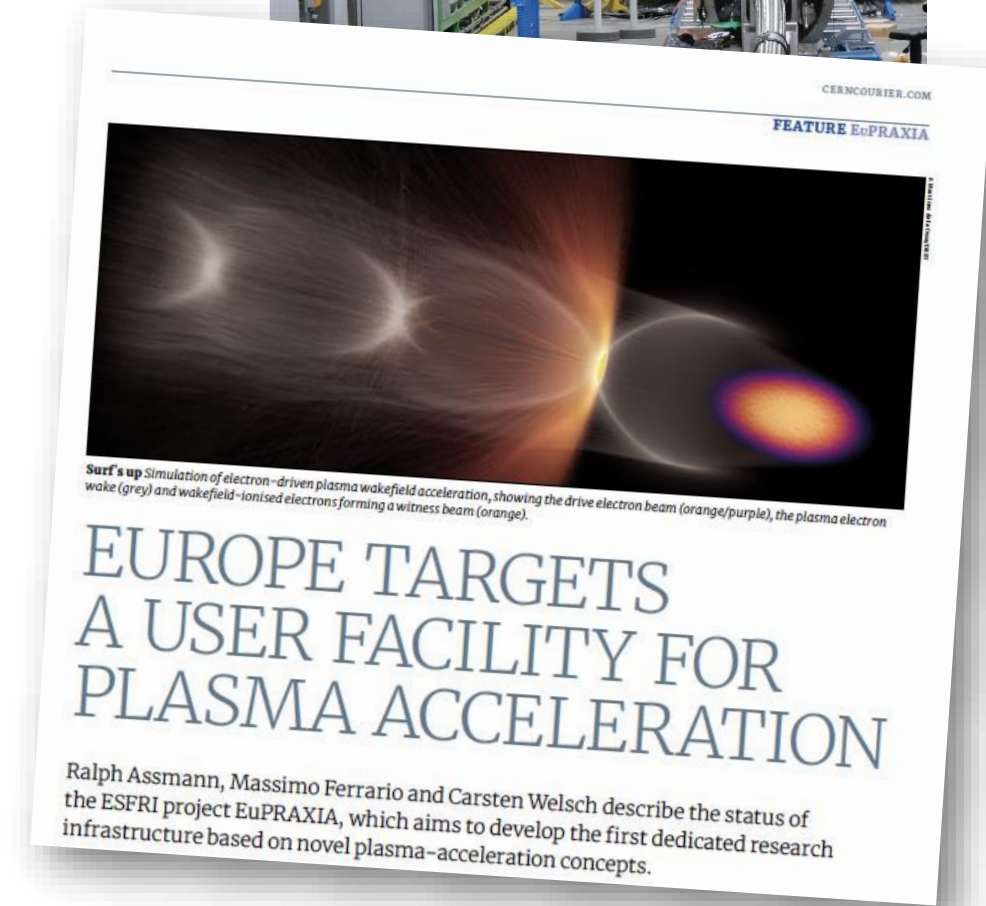
22-27 September 2024

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/>



- 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 continuously going on**

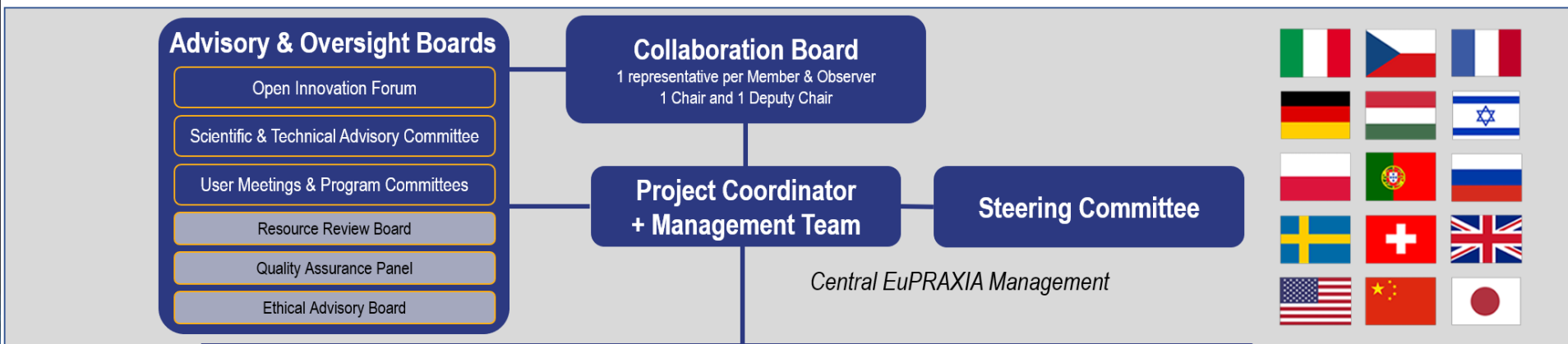






**Thank for your attention**



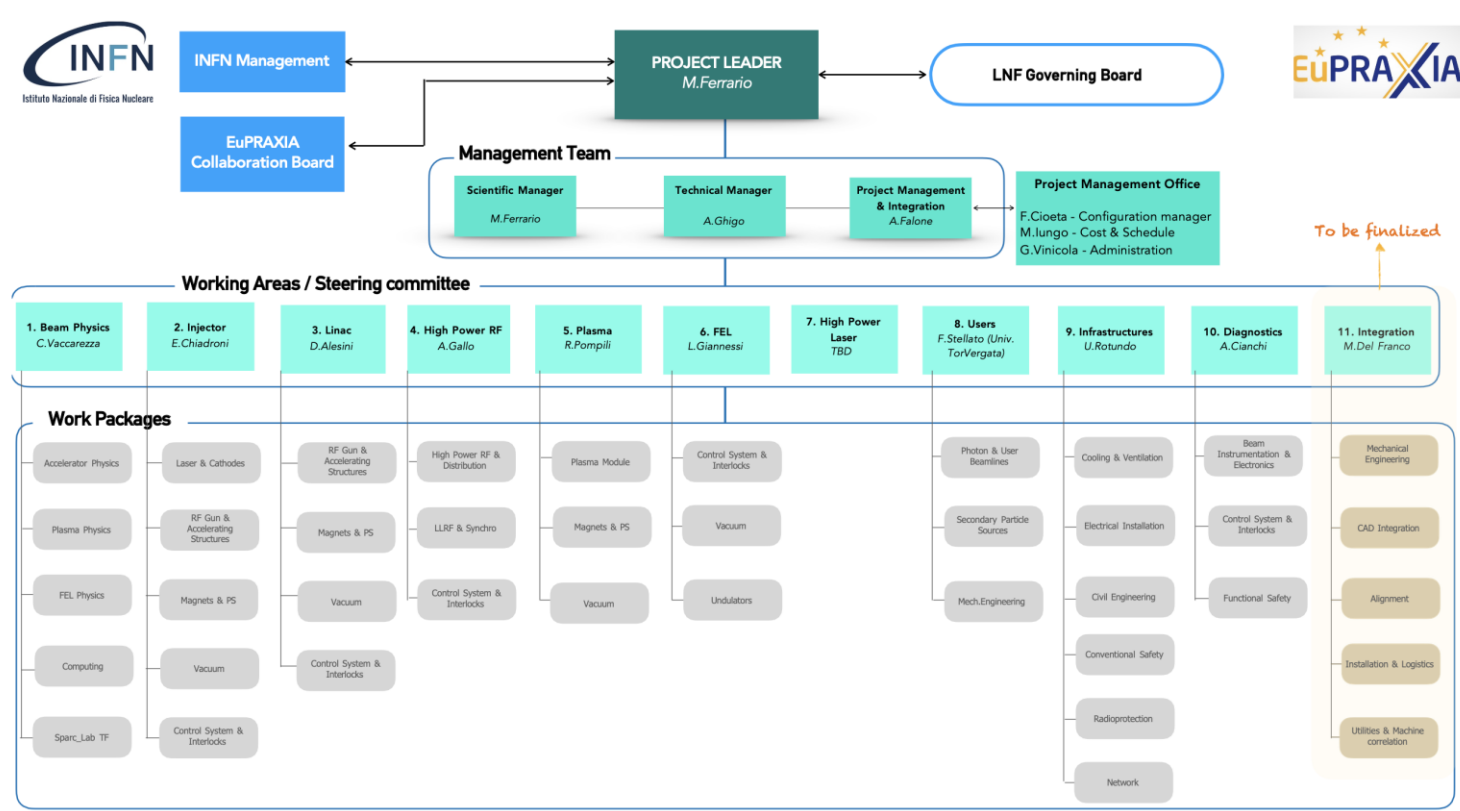


**Construction Site Frascati**

**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*



*Organization for initial Preparatory Ph*  
*Features to be added with decision or phases are indicated in lighter shades*

- 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 SSpA (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	VDLEIG 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 Hochfrequenztechnik	FBH
17	Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento	IST
18	Università degli Studi di Roma La Sapienza	USAP
19	Heinrich-Heine-Universität Duesseldorf	UDUS
20	Deutsches Elektronen-Synchrotron DESY	DESY
21	The Chancellor, Masters and Scholars of the Univ. of Oxford	UOX
22	Ludwig-Maximilians-Universität München	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



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;