EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

EuPRAXIA at LNF

a plasma-based accelerator user facility for the next decade

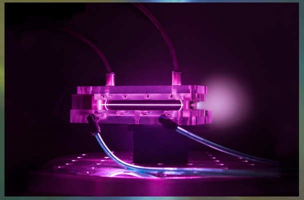
M. Ferrario (INFN-LNF)

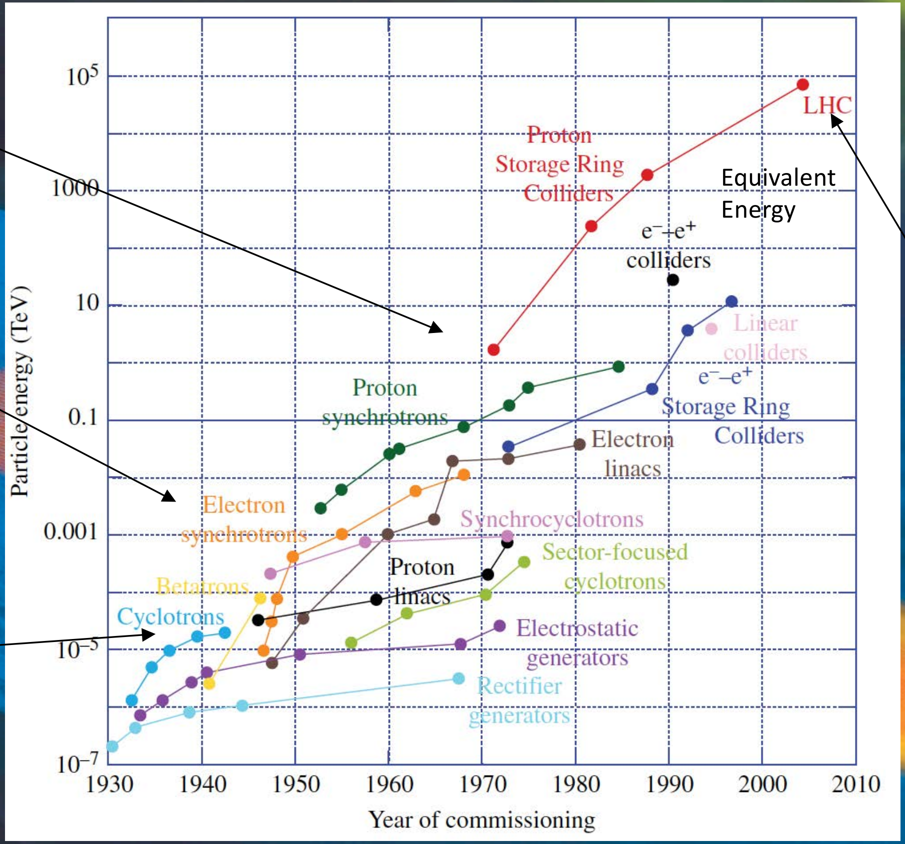
On behalf of the EuPRAXIA Collaboration


XIX Vulcano Workshop
FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS
Ischia, Campania (Italy)
May 26th - June 1st, 2024

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

Livingstone Diagram





Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

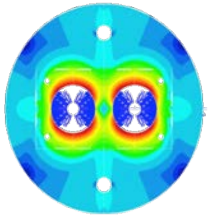
Options towards higher energies

Hadron (p) circular collider

$$p = e \cdot R \cdot B_y$$

Increase bending field
SC bend magnet work (FCC-hh)

Increase radius = size (FCC-hh)



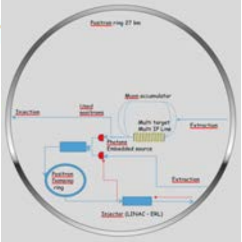
Lepton (e-,e+) circular collider

$$p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0}$$

Increase supplied RF vol
(FCC-ee)

Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee)



Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

Increase length (ILC, CLIC)

Compact and Cost Effective….

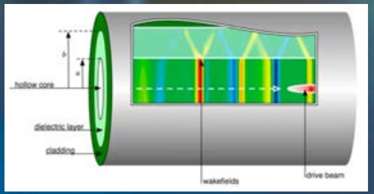
High Gradient Options

Metallic accelerating structures =>

100 MV/m < E_{acc}< 1 GV/m

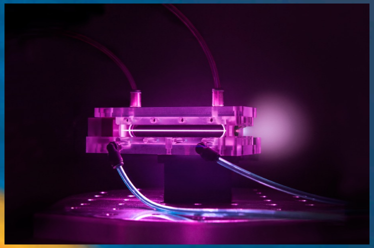
Dielectrict structures, laser or particle driven =>

E_{acc} < 10 GV/m



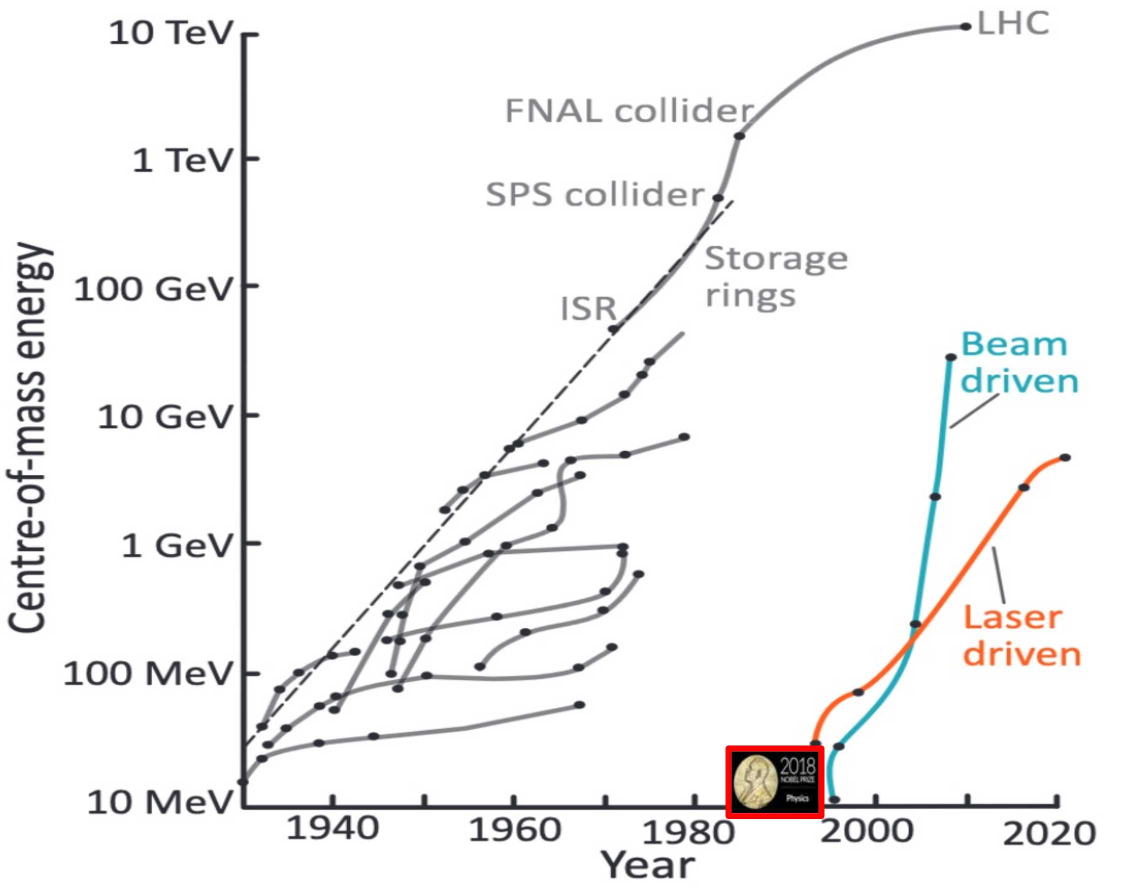
Plasma accelerator, laser or particle driven =>

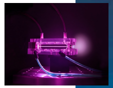
E_{acc} < 100 GV/m



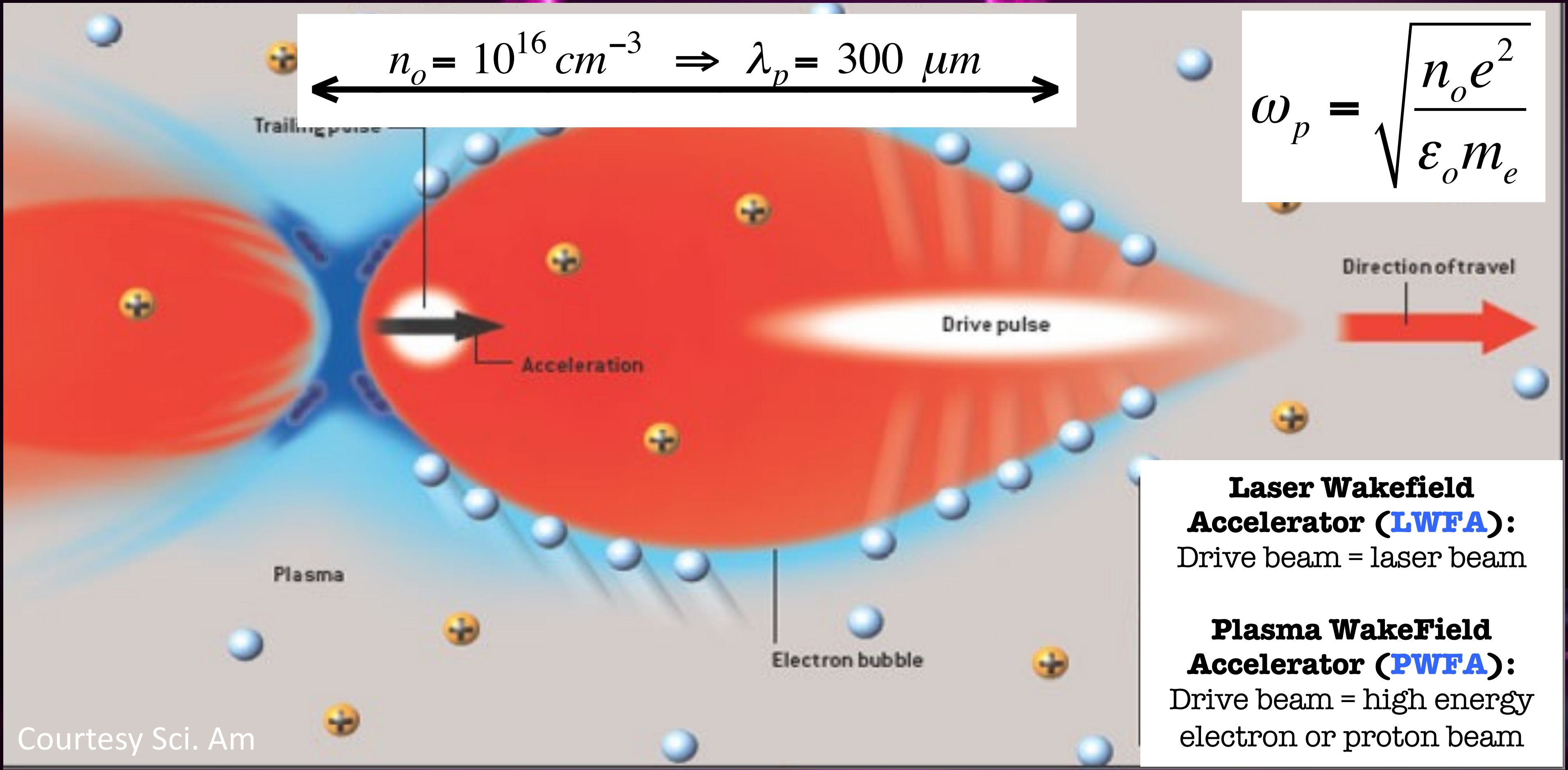
Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (μm) spot to match high gradients

Livingstone Diagram with PWFA





Principle of plasma acceleration



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

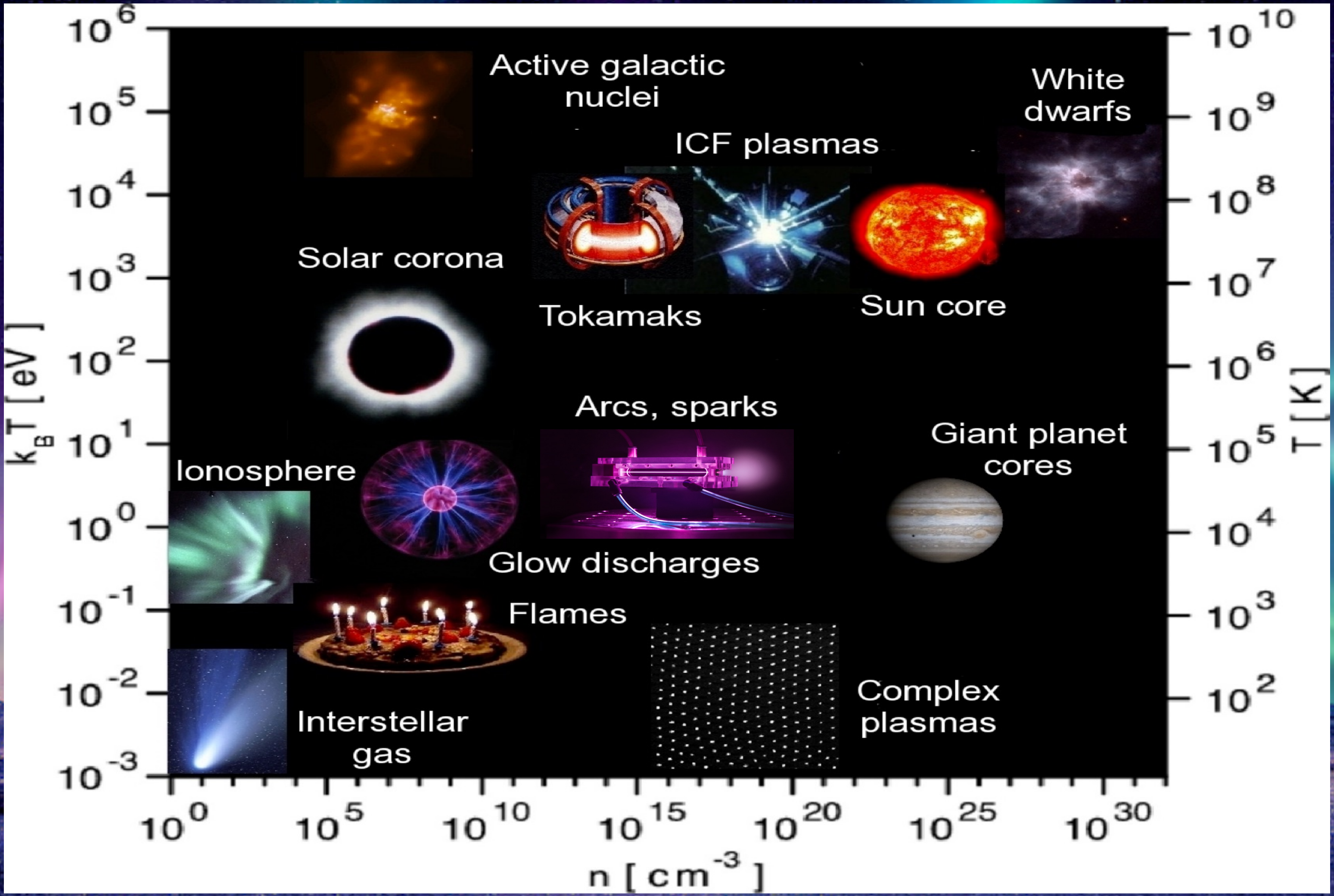
$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

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

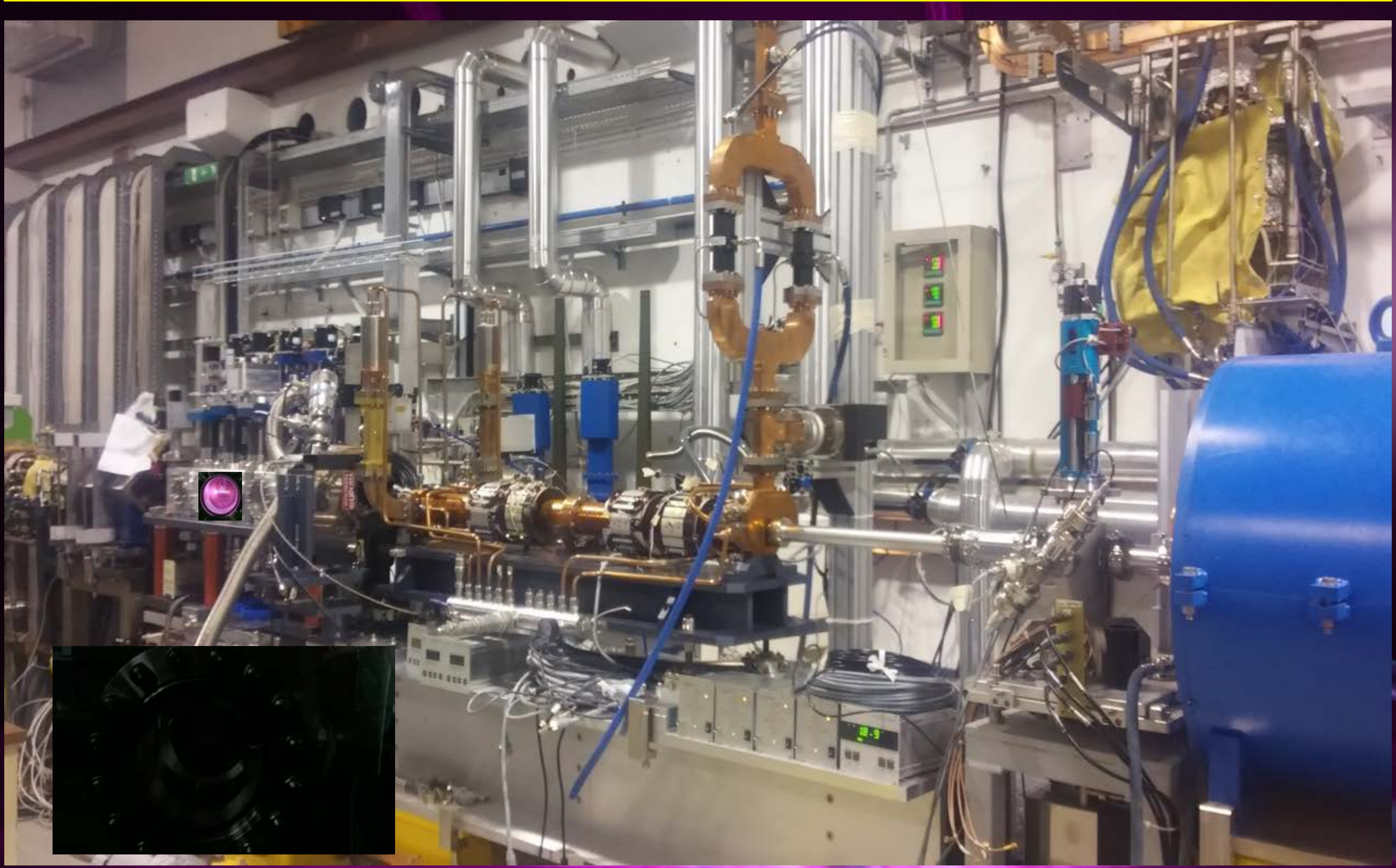
Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

Courtesy Sci. Am

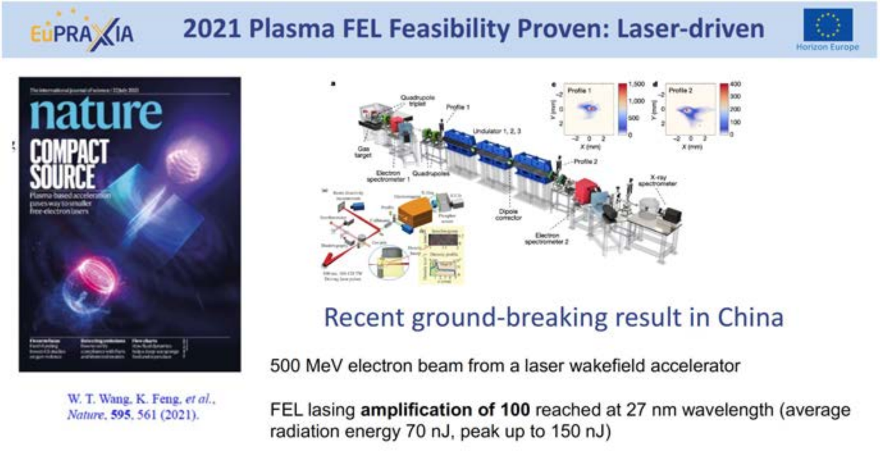
plasma temperature and density



PWFA beam line at SPARC_LAB



Basic beam quality achieved in pilot FEL experiments



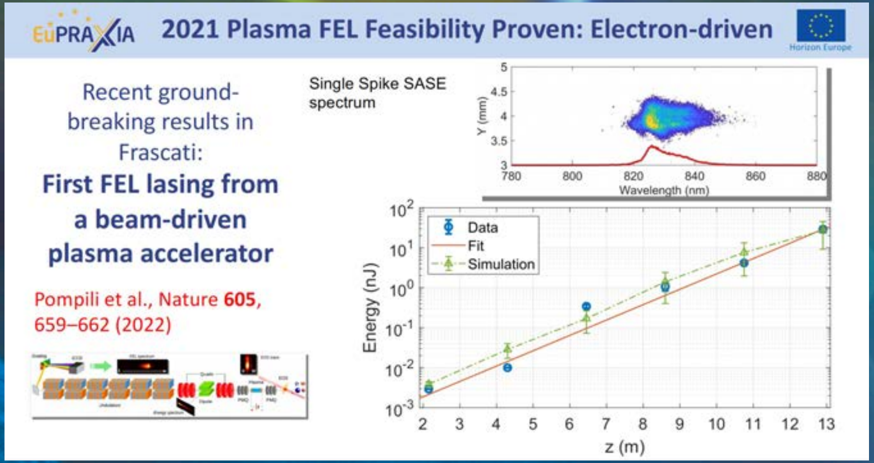
2021 Plasma FEL Feasibility Proven: Laser-driven

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)



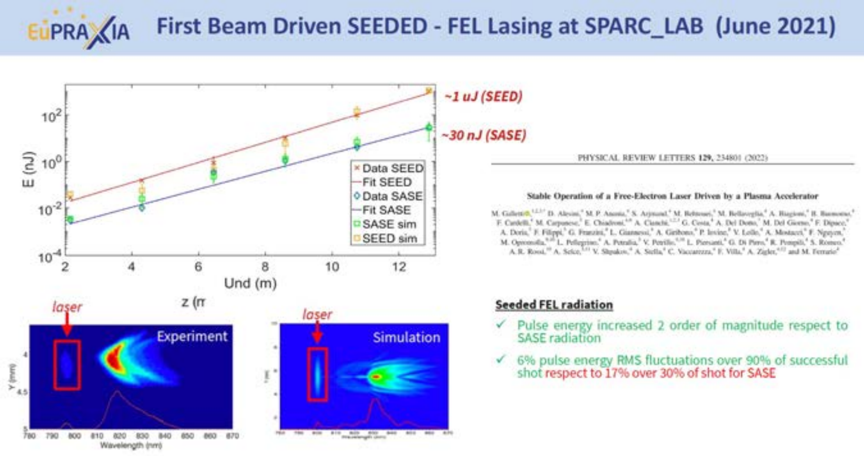
2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

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

Single Spike SASE spectrum



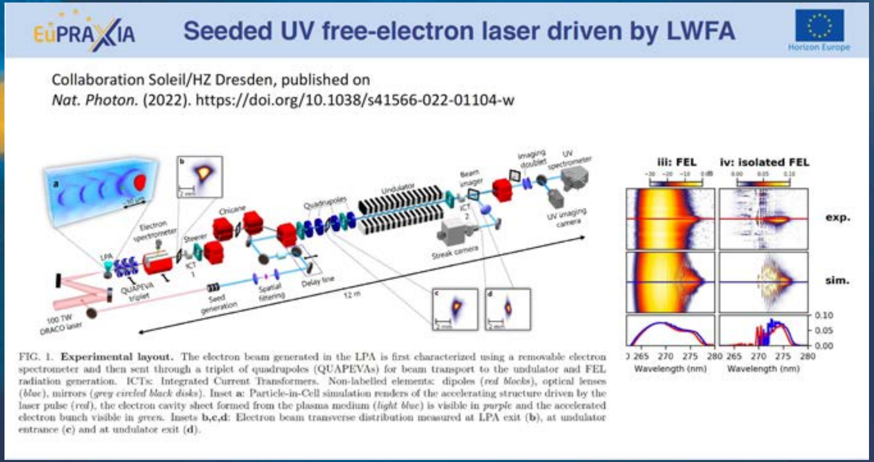
First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

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

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

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**).

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

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

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.

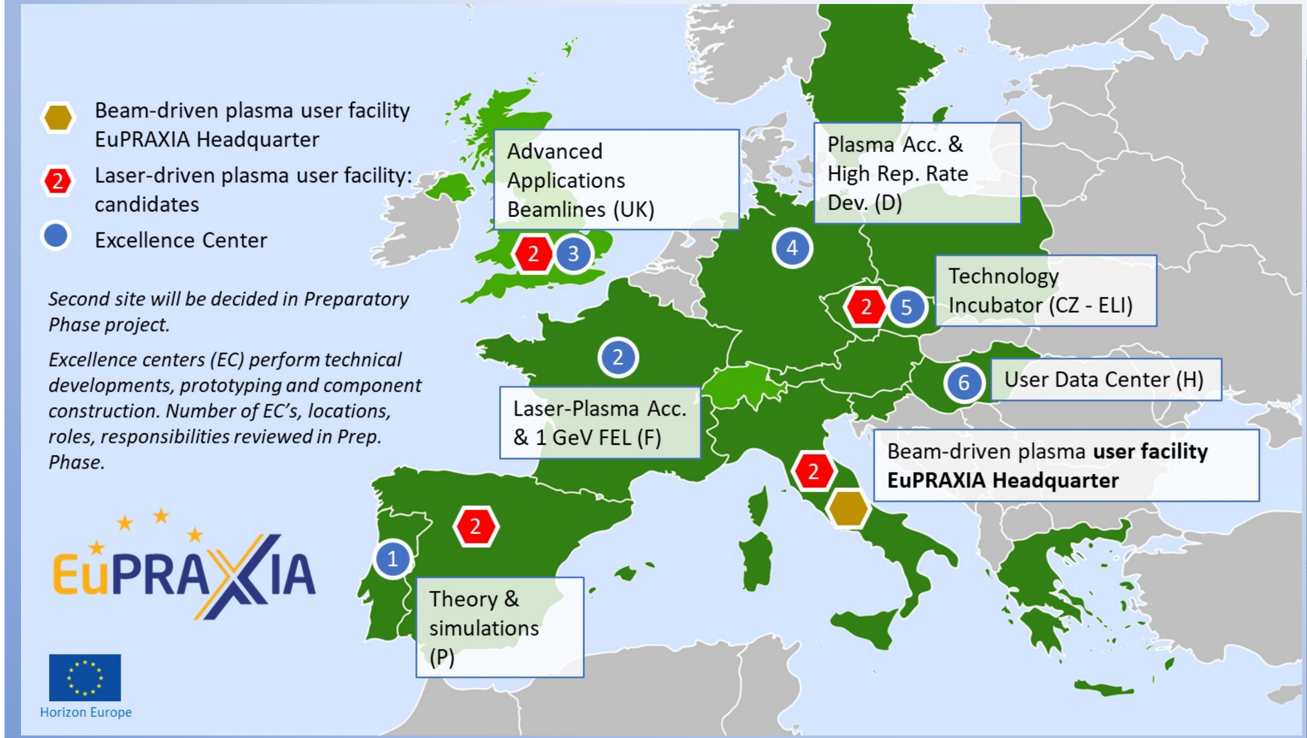
This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the 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.*

Funded by the European Union

Distributed Research Infrastructure and Phased Implementation



⬢ Beam-driven plasma user facility EuPRAXIA Headquarter

⬢ Laser-driven plasma user facility: candidates

● Excellence Center

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.

Phased Implementation

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

FEL is a well established technology

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

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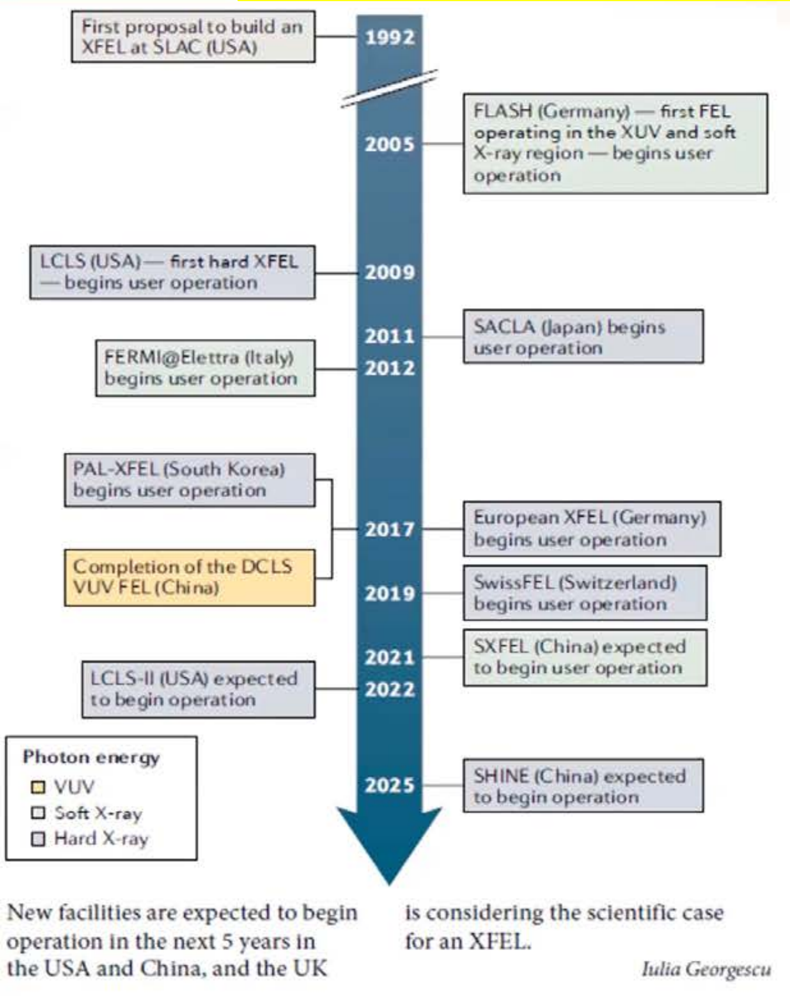


1992 — First proposal to build an XFEL at SLAC (USA)

2005 — FLASH (Germany) — first FEL operating in the XUV and soft X-ray region — begins user operation

2009 — LCLS (USA) — first hard XFEL — begins user operation

2011 — SACLA (Japan) begins user operation

2012 — FERMI@Elettra (Italy) begins user operation

2017 — PAL-XFEL (South Korea) begins user operation

2017 — Completion of the DCLS VUV FEL (China)

2017 — European XFEL (Germany) begins user operation

2019 — SwissFEL (Switzerland) begins user operation

2021 — SXFEL (China) expected to begin user operation

2022 — LCLS-II (USA) expected to begin operation

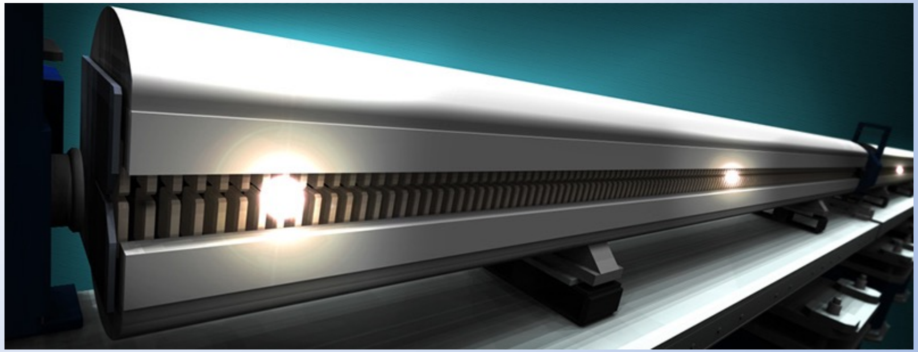
2025 — SHINE (China) expected to begin operation

Photon energy

- ☐ VUV
- ☐ Soft X-ray
- ☐ Hard X-ray

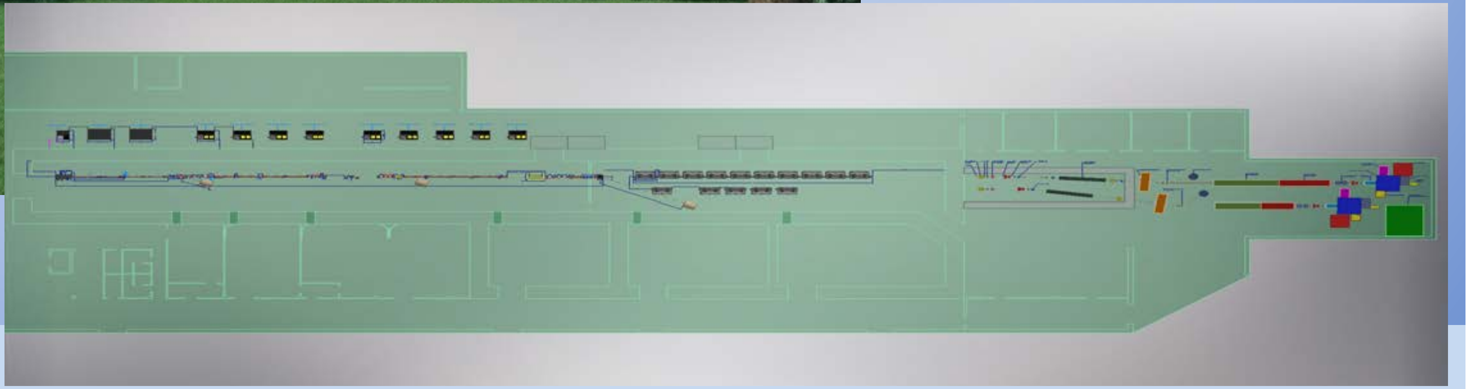
New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

Iulia Georgescu

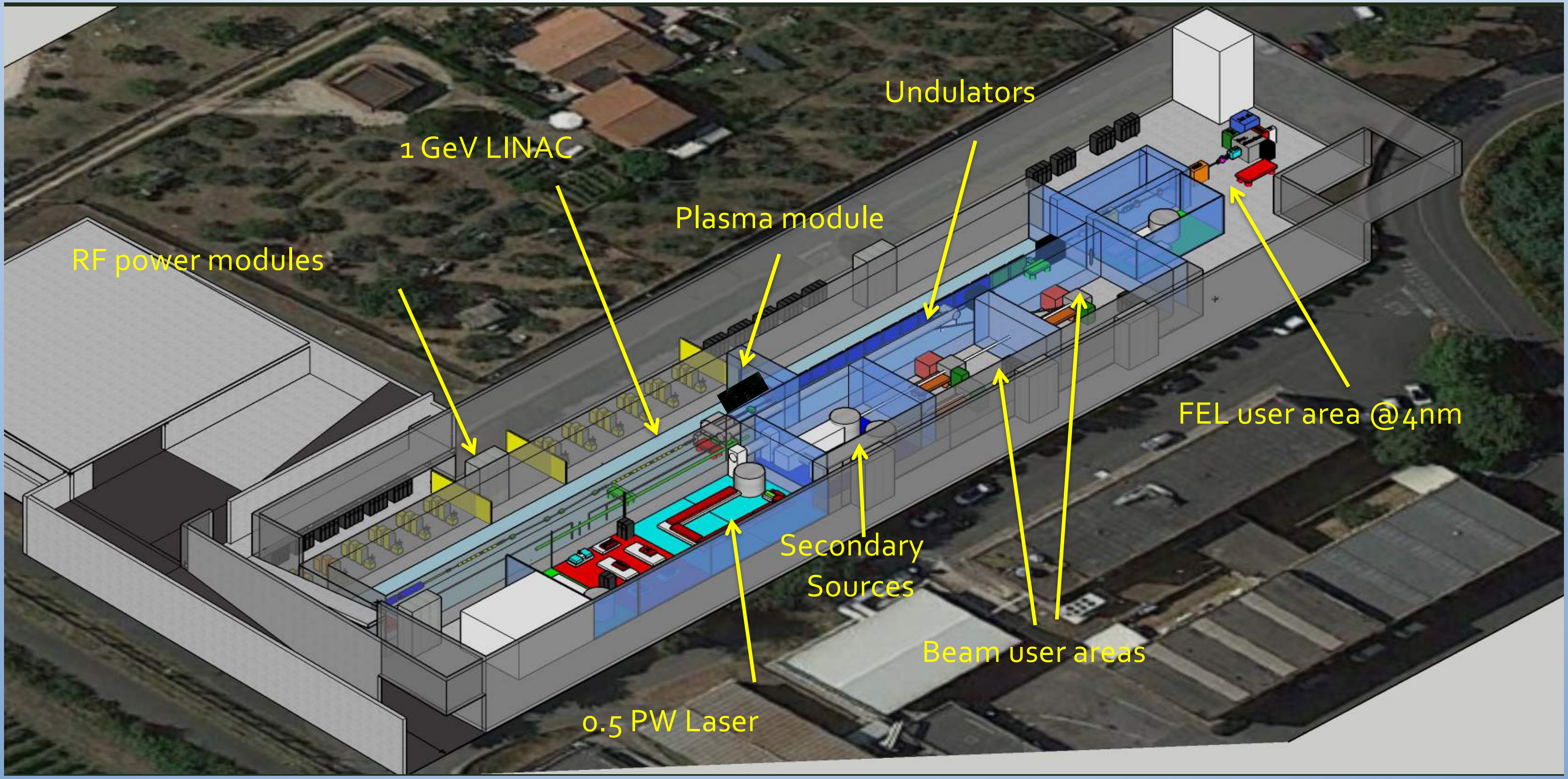


Headquarter and Site 1: EuPRAXIA@SPARC_LAB

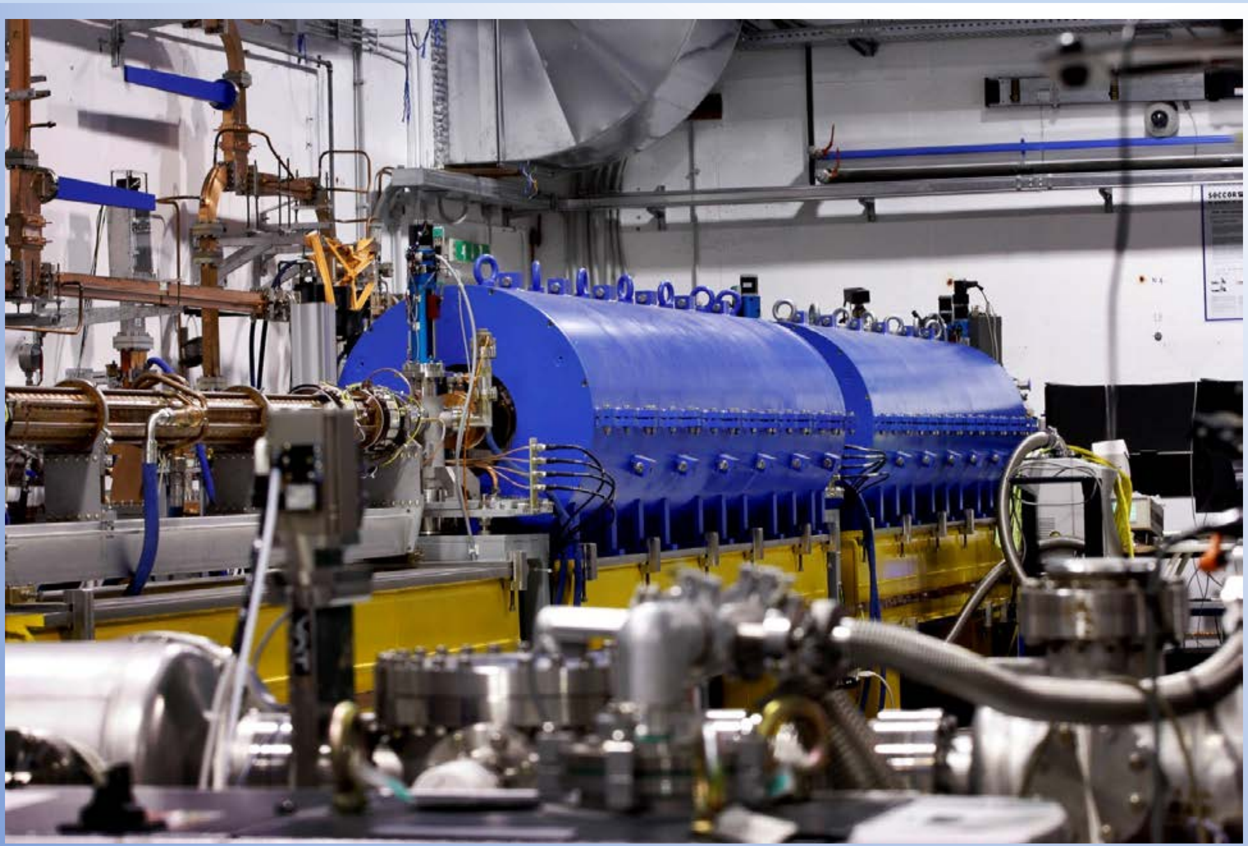
- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

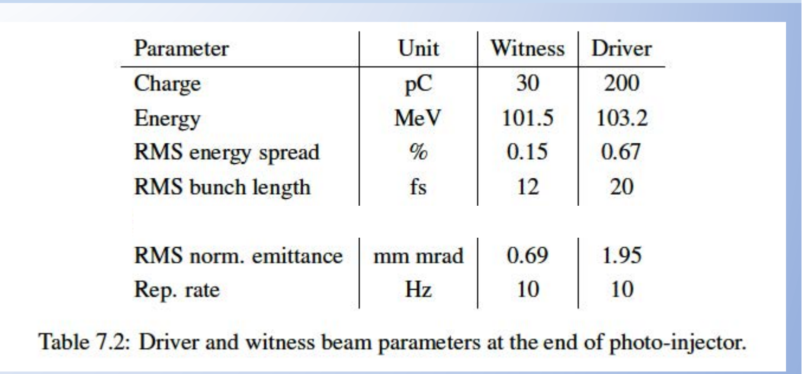


EuPRAXIA@SPARC_LAB



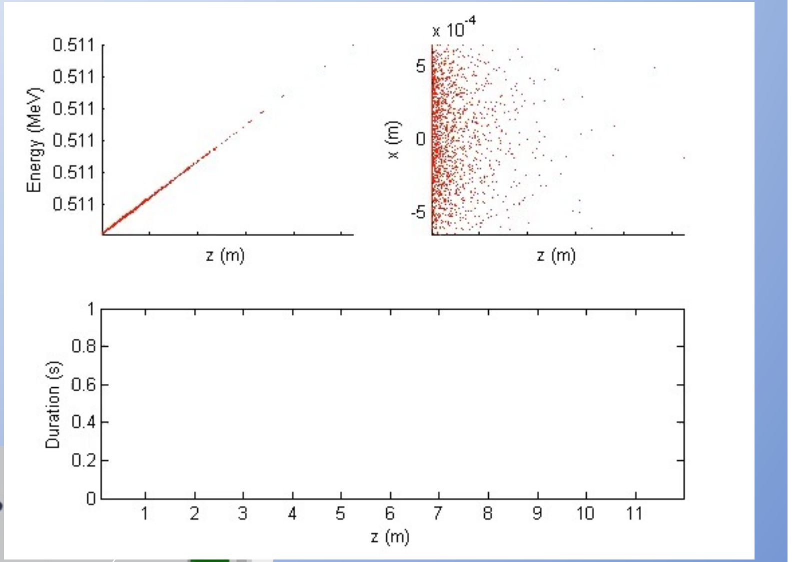
High Quality Electron Beams





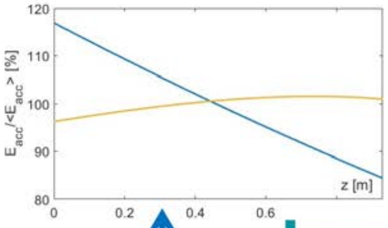
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

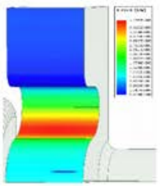
Table 7.2: Driver and witness beam parameters at the end of photo-injector.

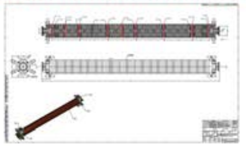


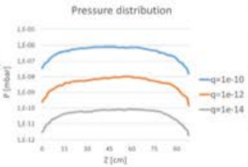
Courtesy E. Chiadroni

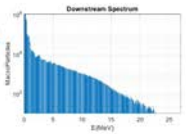
World`s Most Compact RF Linac: X Band





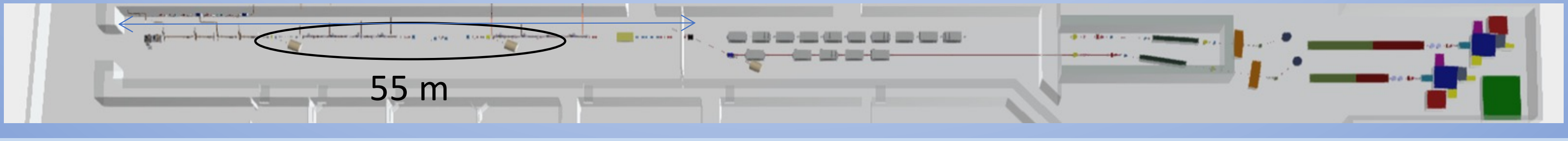






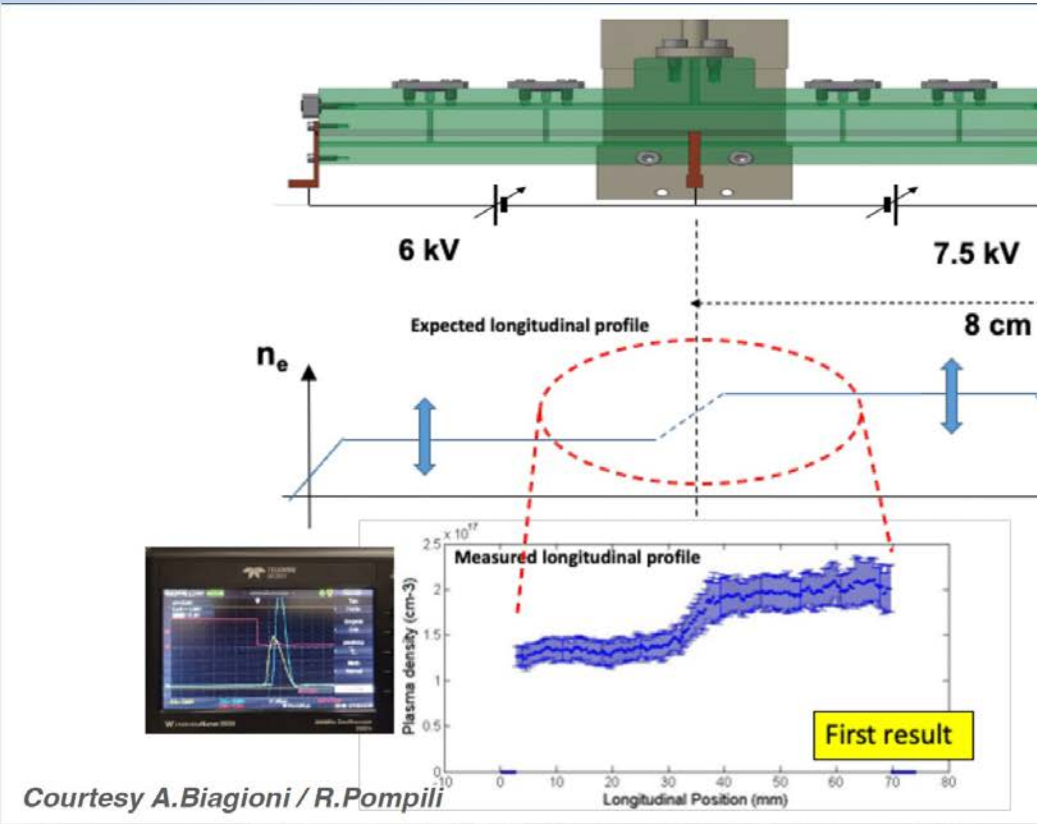
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

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/μm²]	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

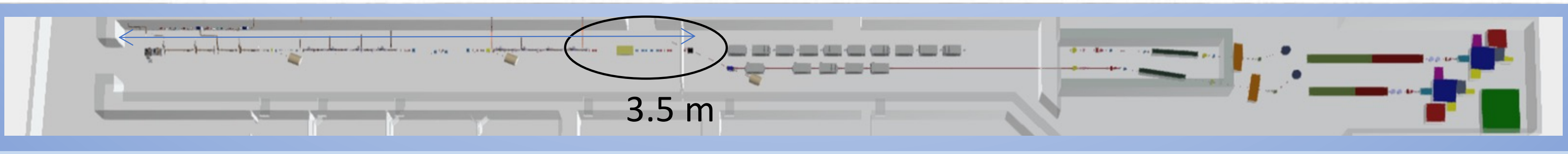
Plasma Module



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

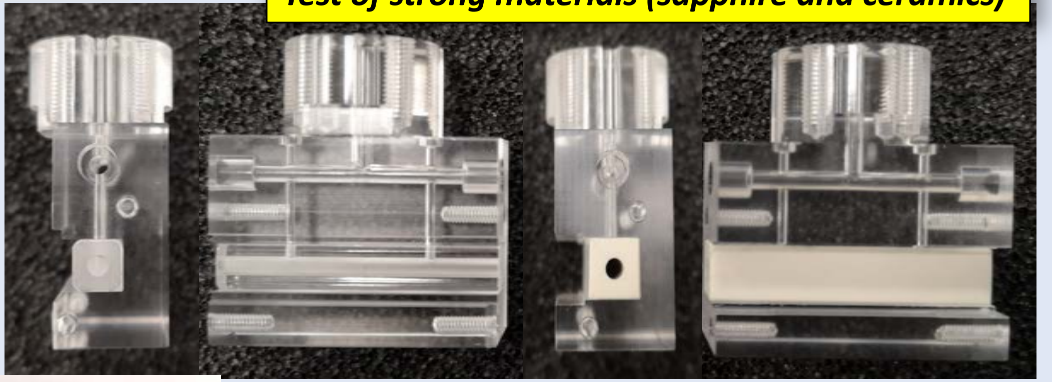
High repetition Rate capillary for EuPRAXIA

To operate at high repetition rate the key point is the thermal dissipation

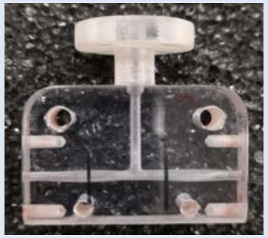
1. Solid-state high repetition-rate discharge system
2. Strong materials capable of dissipating thermal energy
3. Vacuum systems suitable for continuous flow gas injection (turbo and primary pumps cooling system)

50 Hz repetition rate discharges

Test of strong materials (sapphire and ceramics)

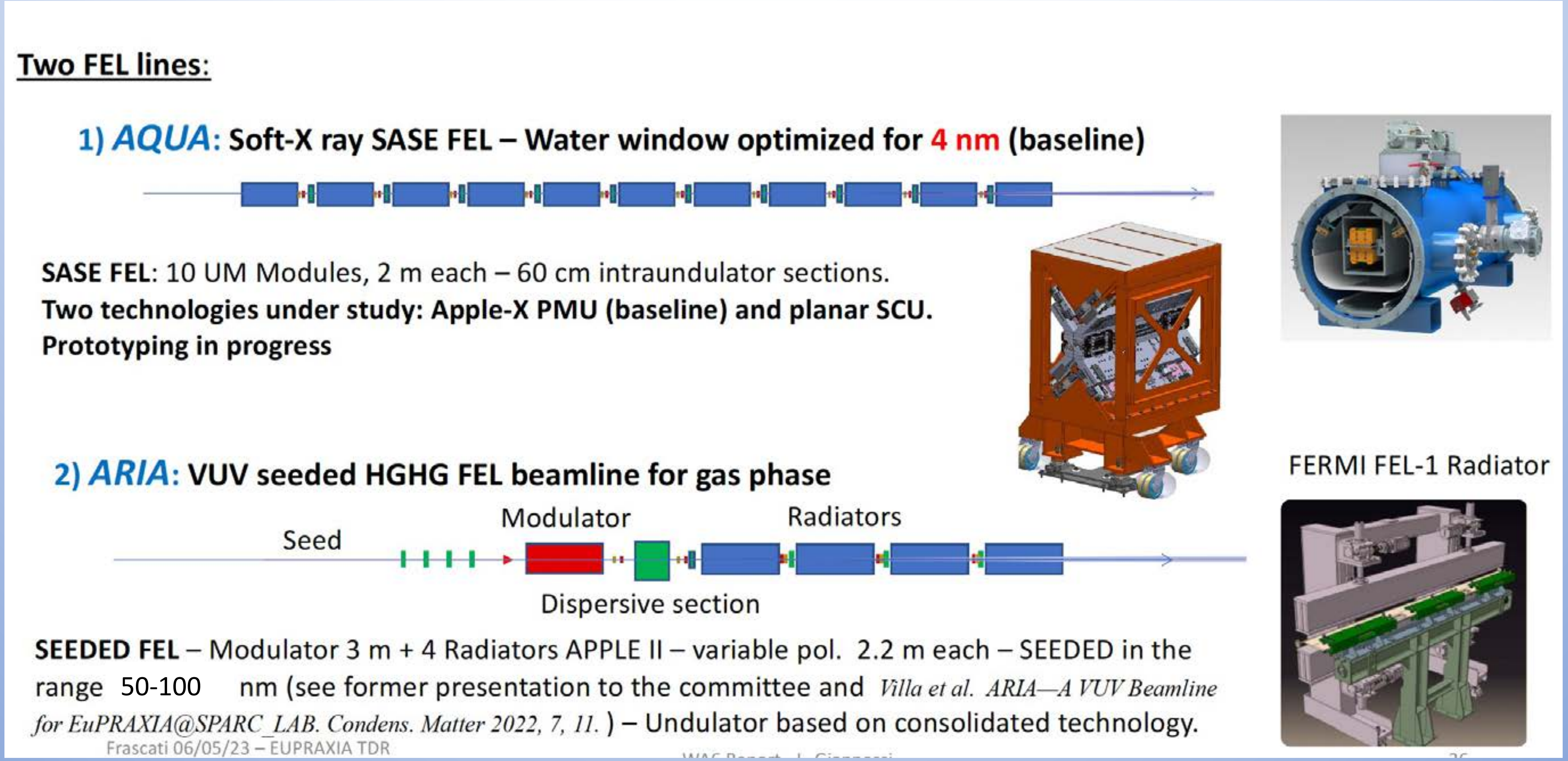


High repRATE can cause a rapid degradation of unsuitable soft materials



Courtesy A. Biagioni, L. Crincoli

Radiation Generation: FEL



Two FEL lines:

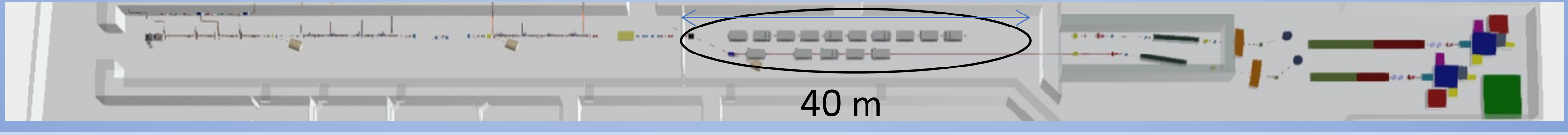
1) ***AQUA*: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)**

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

FERMI FEL-1 Radiator

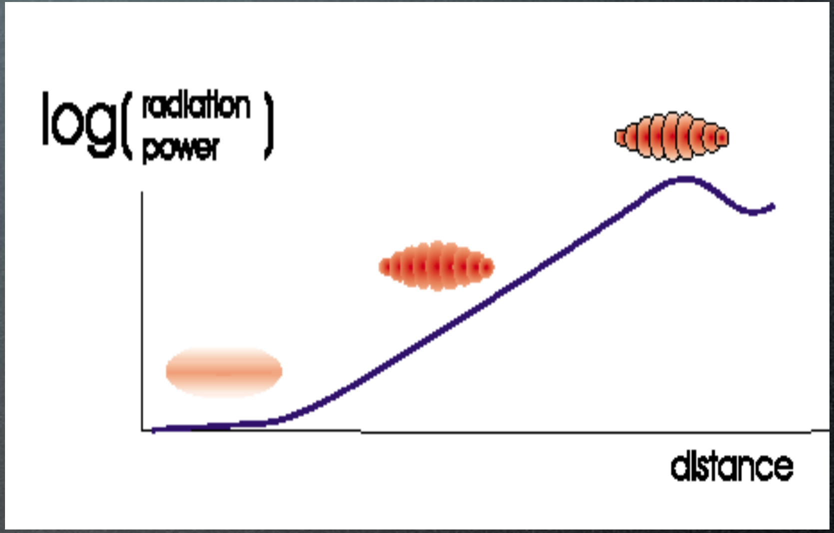
2) ***ARIA*: VUV seeded HGHG FEL beamline for gas phase**

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.



Courtesy L. Giannessi

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



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

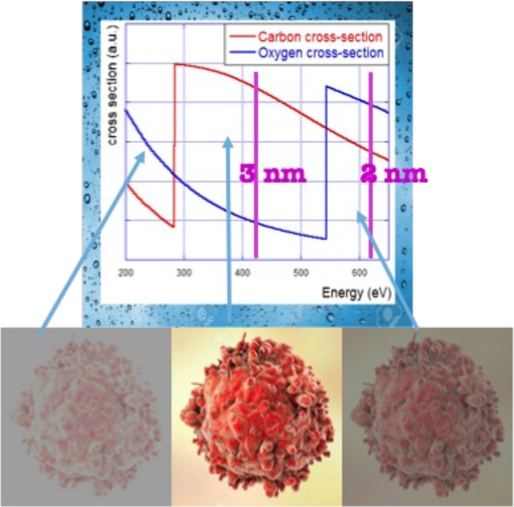
(Tunability - Harmonics)

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	$s\, mm^2 mrad^2$ $bw(0.1\%)$	$\mathbf{1-2\times 10^{28}}$	1×10^{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

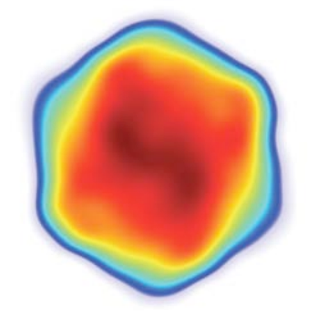
Courtesy F. Stellato, UniToV

Courtesy C. Vaccarezza/L. Giannessi

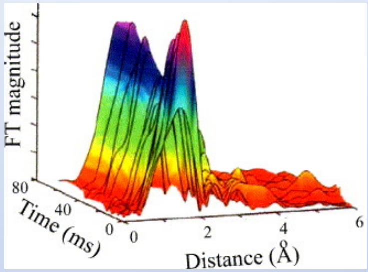
AQUA beamline scientific case

Experimental techniques and typology of samples

Coherent imaging



X-ray spectroscopy



Raman spectroscopy

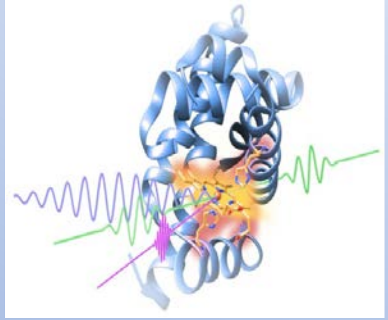
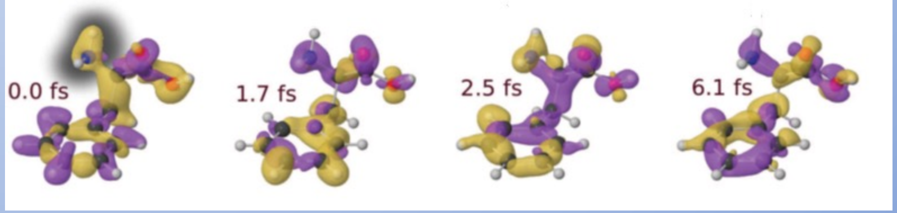


Photo-fragmentation of molecules



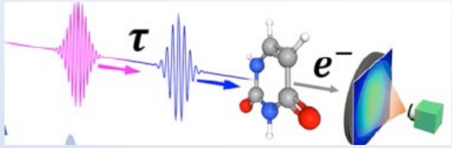
(Large) Viruses
Organelles
Bacteria/Cells
Metals
Semiconductors
Superconductors
Magnetic materials
Organic molecules

Courtesy F. Stellato

ARIA beamline scientific case

Defining experimental techniques and typology of samples (and applications)

Photoemission
Spectroscopy



Photoelectron Circular
Dichroism

Raman spectroscopy

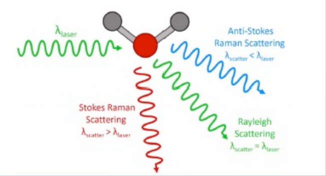
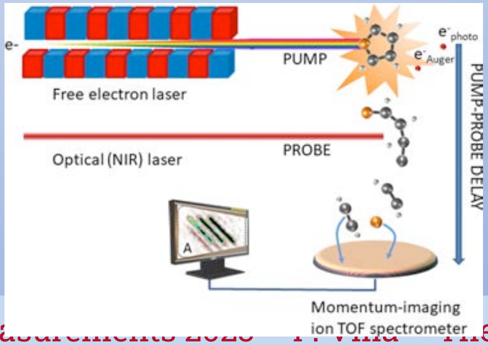


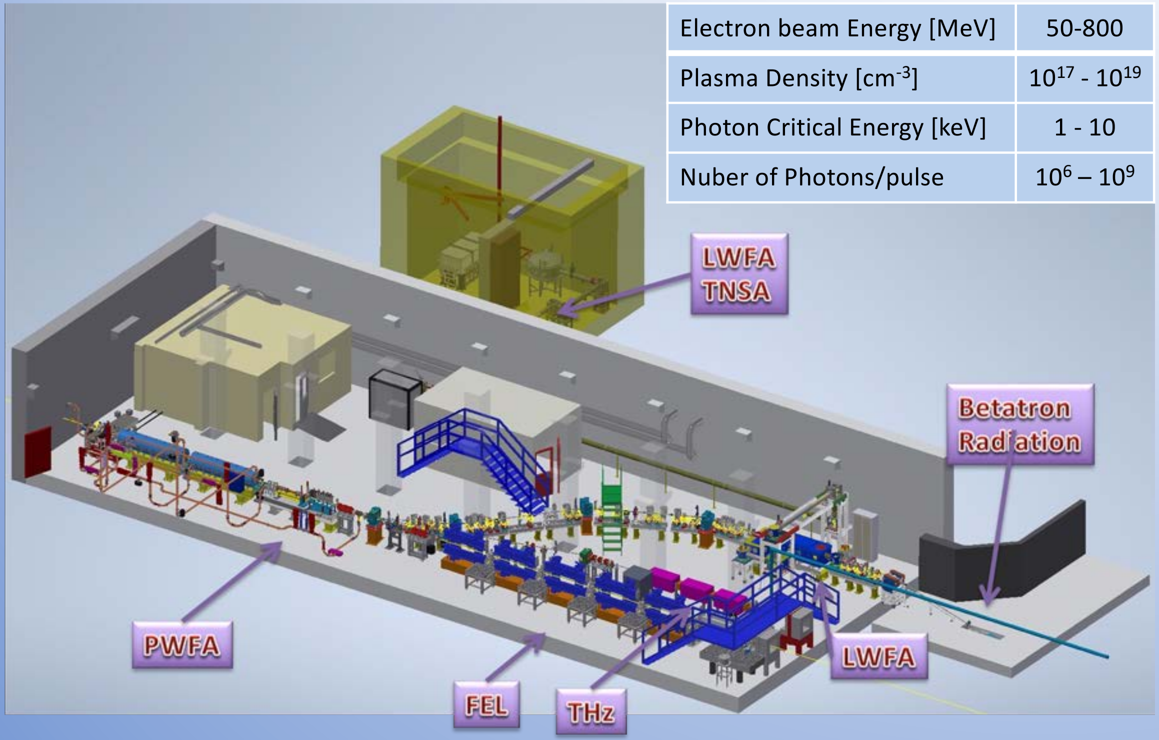
Photo-fragmentation of molecules
Time of Flight Spectroscopy



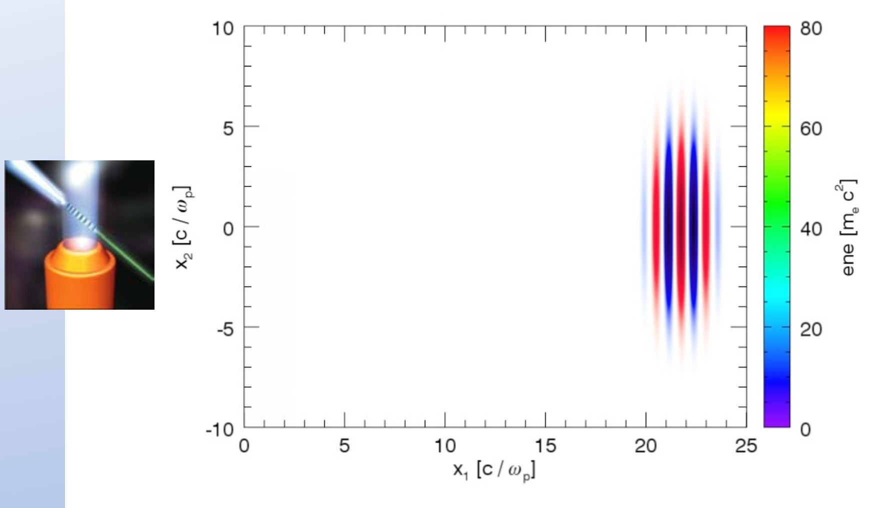
Gas phase & Atmosphere
(Earth & Planets)
Aerosols
(Pollution, nanoparticles)
Molecules & gases
(spectroscopies, time-of-flight)
Proteins
(spectroscopies)
Surfaces
(ablation & deposition)

Courtesy F. Stellato

Betatron Radiation Source at SPARC_LAB

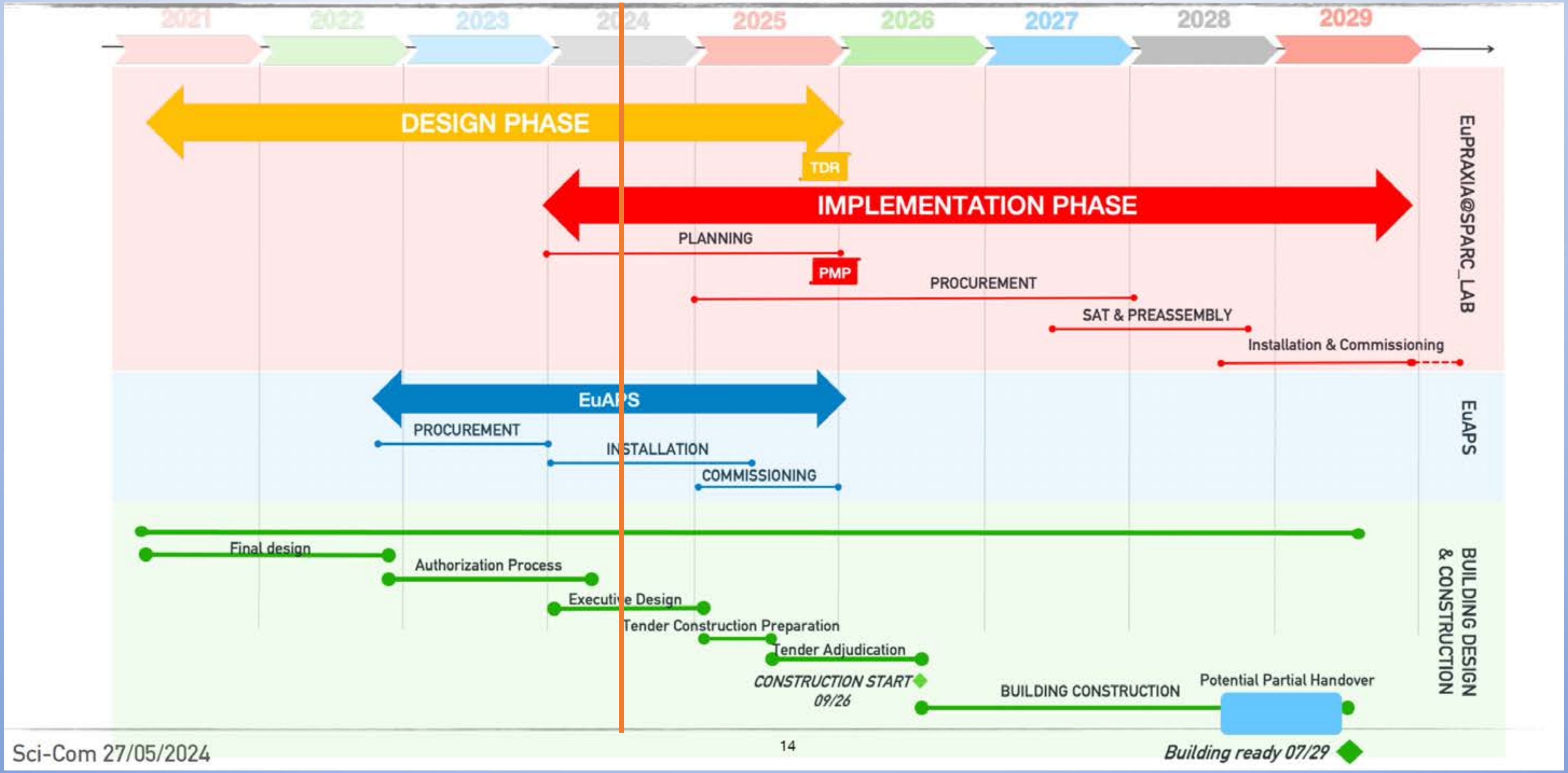


Electron beam Energy [MeV]	50-800
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^{6} – 10^{9}

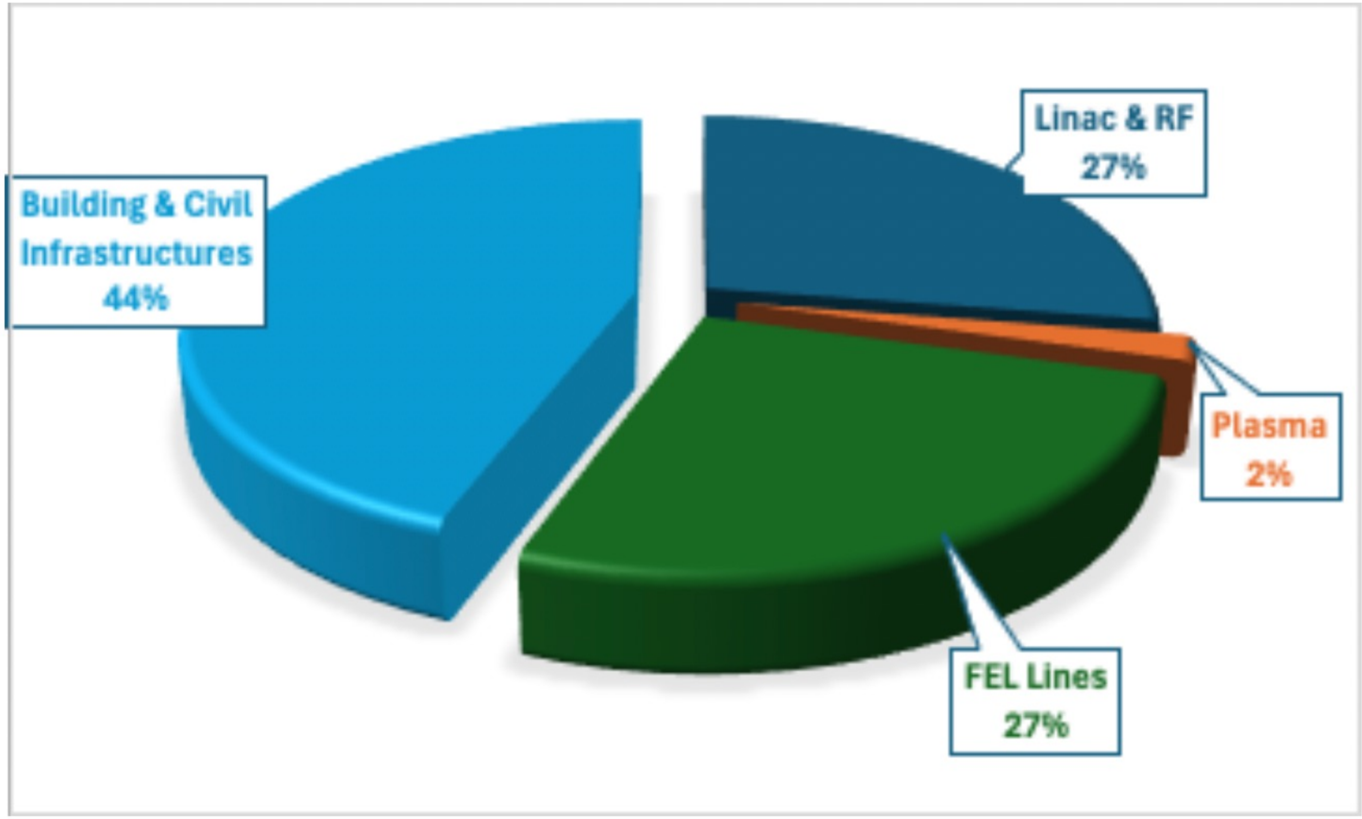


Courtesy J. Vieira, R. Fonseca/GoLP/IST Lisbon

EuPRAXIA@SPARC_LAB baseline updating



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

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]

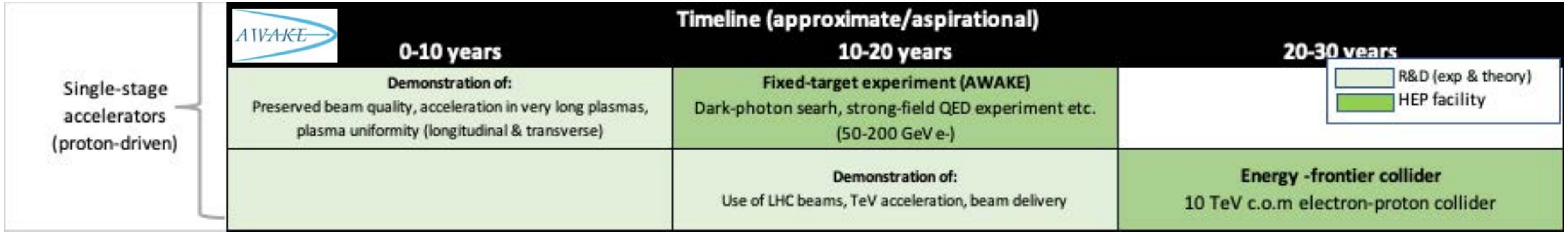
Associated members: C. Geddes[p], M. Hogan[w], W. Lu[v], P. Musumeci[ii]

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

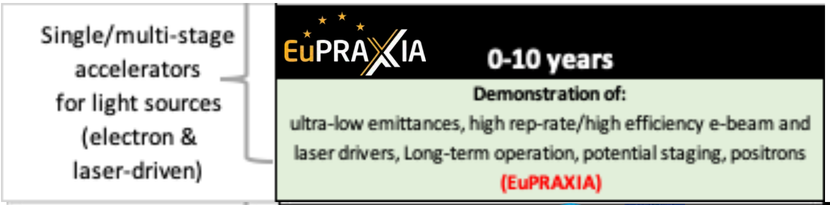
- Development of Plasma Sources for High-Repetition Rate, Multi-GeV Stages
- High Average Power, High Efficiency Laser Drivers and Schemes
- Staging of Electron Plasma Accelerators Including In- and Out-Coupling
- High Transformer Ratio in PWFA for High Efficiency and Low Energy Spread
- Polarised Electrons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

ESPP Roadmap Update – Plasma Accelerators



Single-stage accelerators (proton-driven)	Timeline (approximate/aspirational) 0-10 years	10-20 years	20-30 years
	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

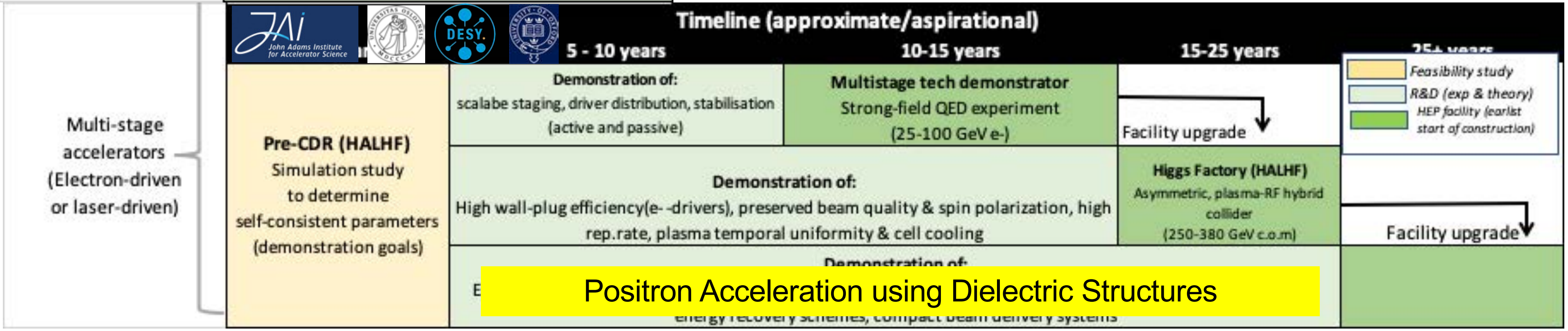
R&D (exp & theory)
🟩 HEP facility



Single/multi-stage accelerators for light sources (electron & laser-driven)	0-10 years
	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



Multi-stage accelerators (Electron-driven or laser-driven)	Timeline (approximate/aspirational)	5 - 10 years	10-15 years	15-25 years	25+ years
	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… energy recovery schemes, compact beam delivery systems			

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

Positron Acceleration using Dielectric Structures

Conclusions

Funded by the European Union

- 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 2029**.
- Second EuPRAXIA FEL site will be selected in next 12 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

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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