The EuPRAXIA project: a plasma-based accelerator user facility for the next decade

Livio Verra
(on behalf of EuPRAXIA Collaboration)

29.07.2026

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Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

EuPRAXIA@SPARC_LAB

A New European Plasma-Based User Facility

EuPRAXIA@SPARC_LAB

EuPRAXIA:
European Plasma Research Accelerator with eXcellence In Applications

1) Technology case:
Building facilities powered by very-high-field plasma accelerators
1 – 100 GV/m accelerating field
Shrink down the facility size and improve Sustainability

2) Science case:
Producing particles and photons to support urgent and timely research
Drive Advanced Acceleration Sources
Pave the way for future linea colliders

From the Greek
$\varepsilon\upsilon$ - good
$\pi\rho\alpha\xi\iota\sigma$ – action
Literally: good action, acting correctly
More generally: effective, appropriate, and goal-directed behavior

ESFRI has included EuPRAXIA in the 2021 Roadmap of EU Research Infrastructures: 10-year time to implement the facility (ready by 2032)

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 *DESY and INFN*, **Massimo Ferrario** *INFN*, **Carsten Welsch** *University of Liverpool/INFN.*

CERN Courier, May 2023

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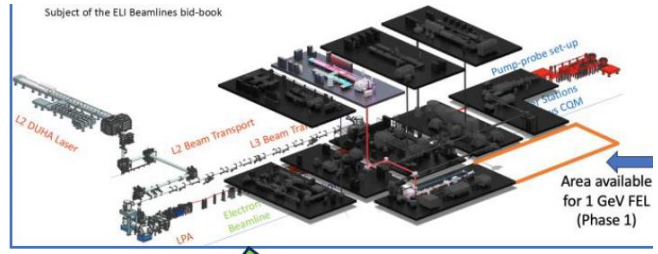
EuPRAXIA Consortium

EuPRAXIA@SPARC_LAB

2 Implementation Pillars
@ INFN – LNF & @ ELI-ERIC

Several National Nodes. Roles to be fully defined

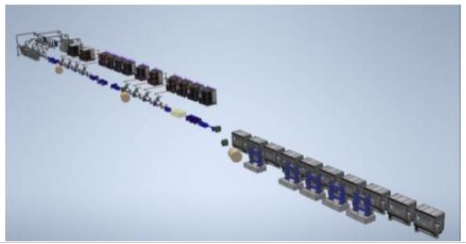
Project Clusters



Selected in 2025

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

Network organization
- **Sites (PWFA/LWFA): new users facilities**
- **National nodes**
- **Technology clusters**



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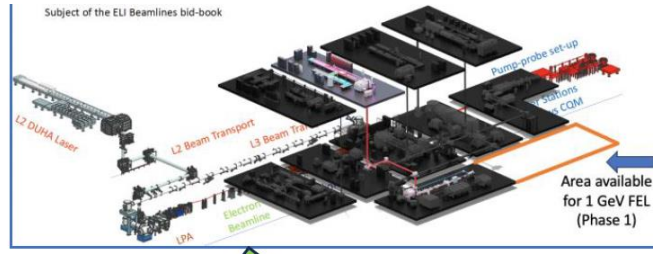

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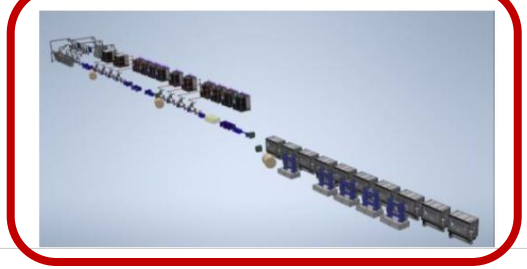

Selected in 2016

Istituto Nazionale di Fisica Nucleare
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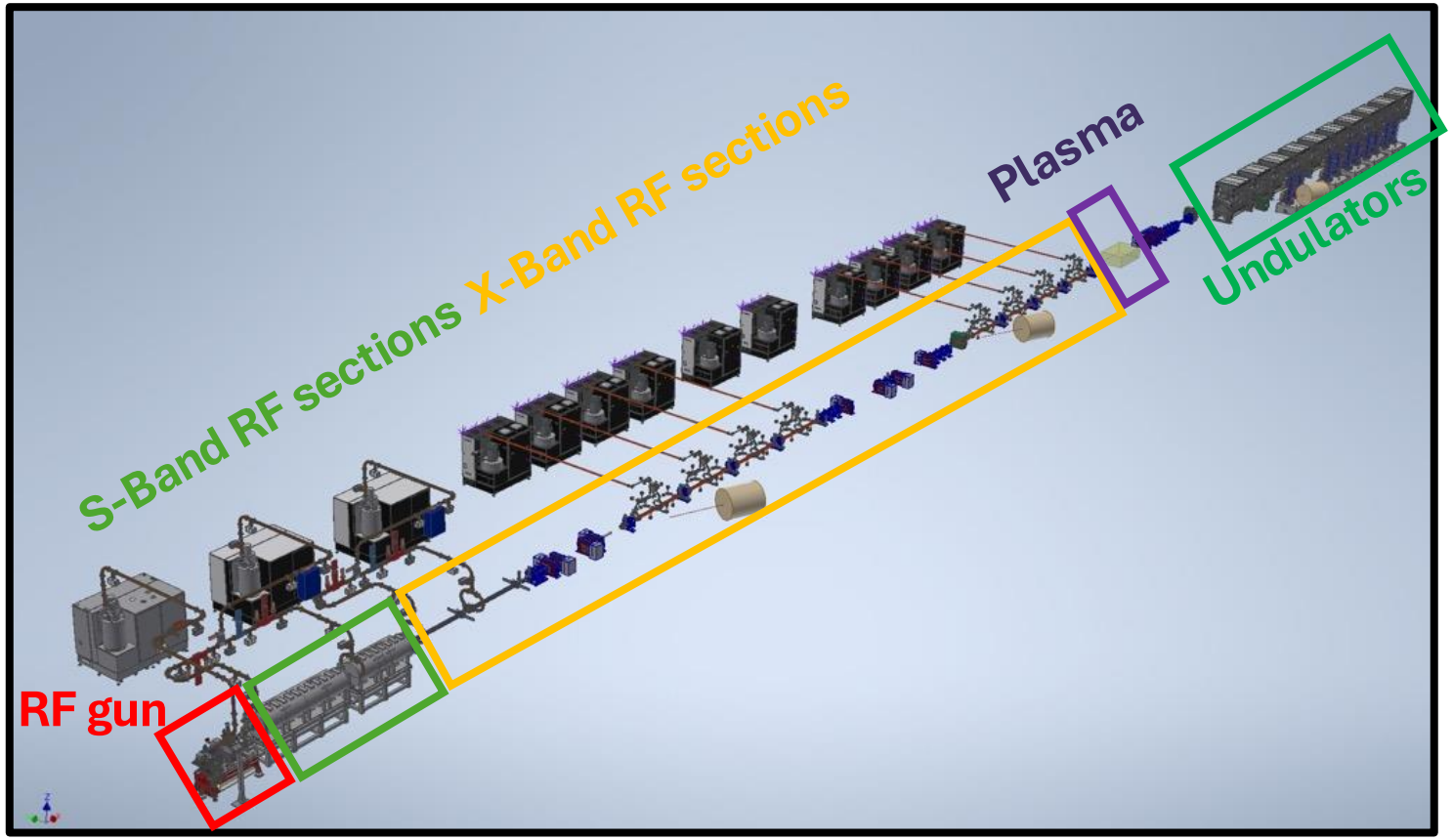
EuPRAXIA@SPARC_LAB

- Soft X-ray (~4nm) FEL based on Beam-Driven PWFA at INFN/Frascati
- 500 MeV 30 pC witness bunch boosted to 1 GeV in 60-cm-long discharge-plasma capillary



- Construction starting ~ end of 2026
- Installation starting ~ 2029
- Commissioning starting ~ 2030

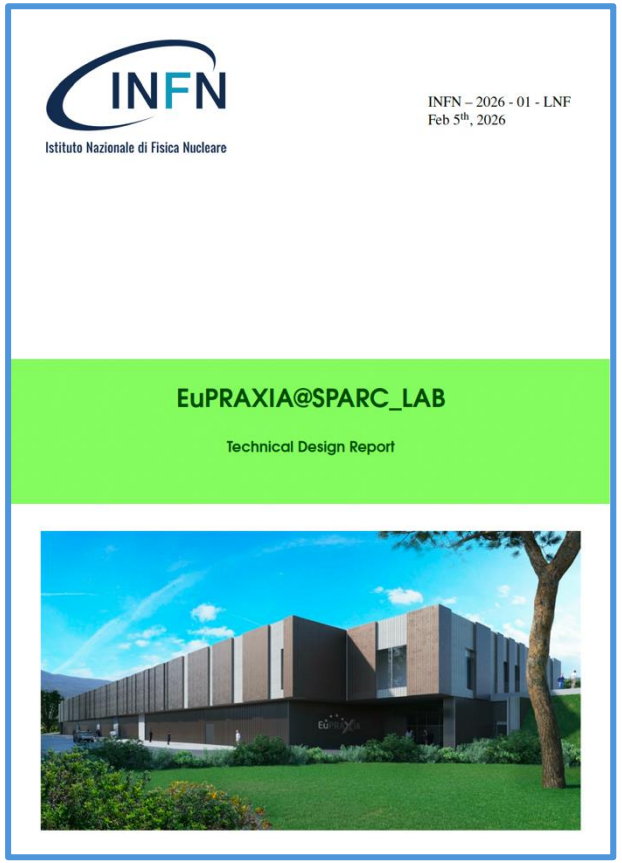
User-oriented plasma-based FEL

Transition from experiment to "real" accelerator
Building up from results and expertise from SPARC

Working on some of the main issues for a future linear collider (e.g. matching-extraction, driver-witness separation, etc..)

EuPRAXIA@SPARC_LAB: **TDR**

Technical Design Report:
→ Summarizing the technical details of the entire machine
→ Realized by LNF
→ Reviewed and Advised by External Review Committee
→ Published on Feb 5th 2026 (https://doi.org/10.15161/oar.it/k57qz-5qk09)
→ Supported by intense R&D activity!



Real Implementation that bring LNF into a **new era**

Final TDR Review Report

EuPRAXIA@SPARC_LAB Project Review Committee

Committee Members:
Deepa Angal-Kalinin (UKRI STFC, UK)
Martin Beye (Stockholm University, Sweden)
Patric Muggli (MPP, Germany, chair)
Marco Pedrozzi (PSI, Switzerland)
Luigi Scibile (CERN, Switzerland)

February 5, 2026

The general conclusion of the Review Committee is that, while acknowledging the well identified challenges inherent to this innovative and ambitious project [....]

⇒ the objectives of the project are **realistic**, and **no critical showstopper** has been identified.
⇒ All critical issues of the project have been properly addressed.
⇒ The Review Committee **strongly supports the project**.

EuPRAXIA@SPARC_LAB: **Injector**

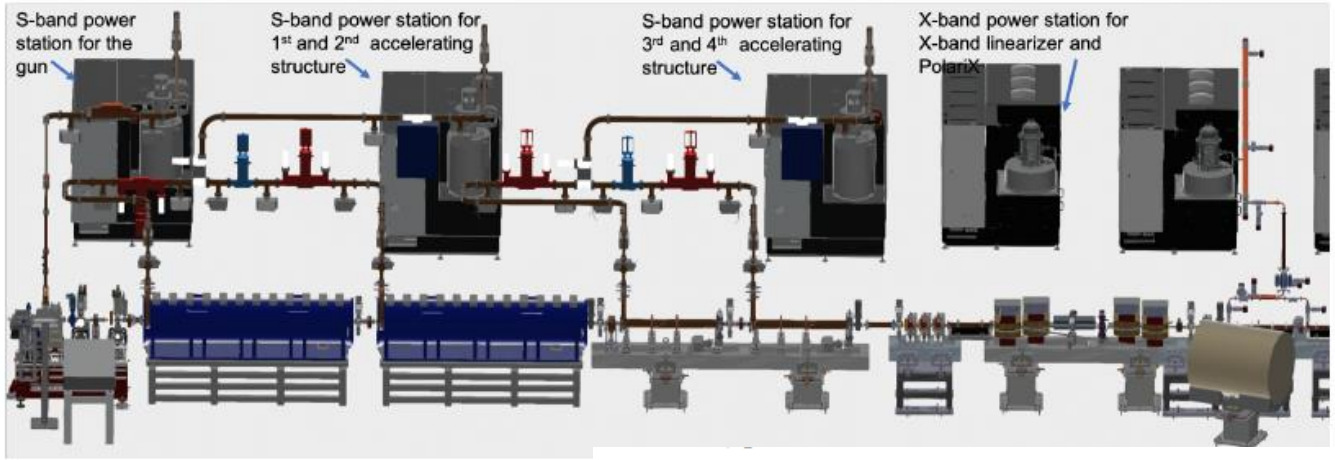
⇒ **SPARC_LAB type** RF-photo injector operating at the S-band frequency (**2.998 GHz**) and **100 Hz**

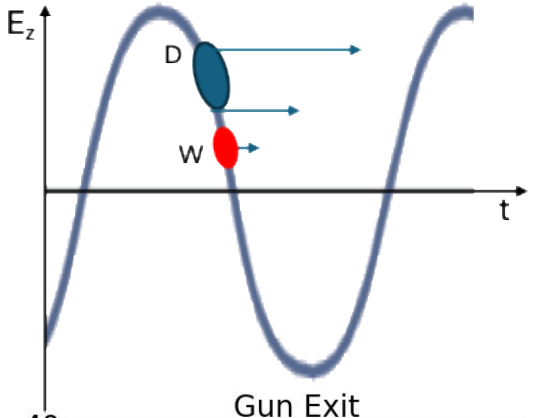
⇒ **Three 3-m-long TW** structures and two solenoids

⇒ **Three Canon E37327A** klystron+ Scandinova K400 Modulators (45 MW, 4.5 us, 100 Hz)

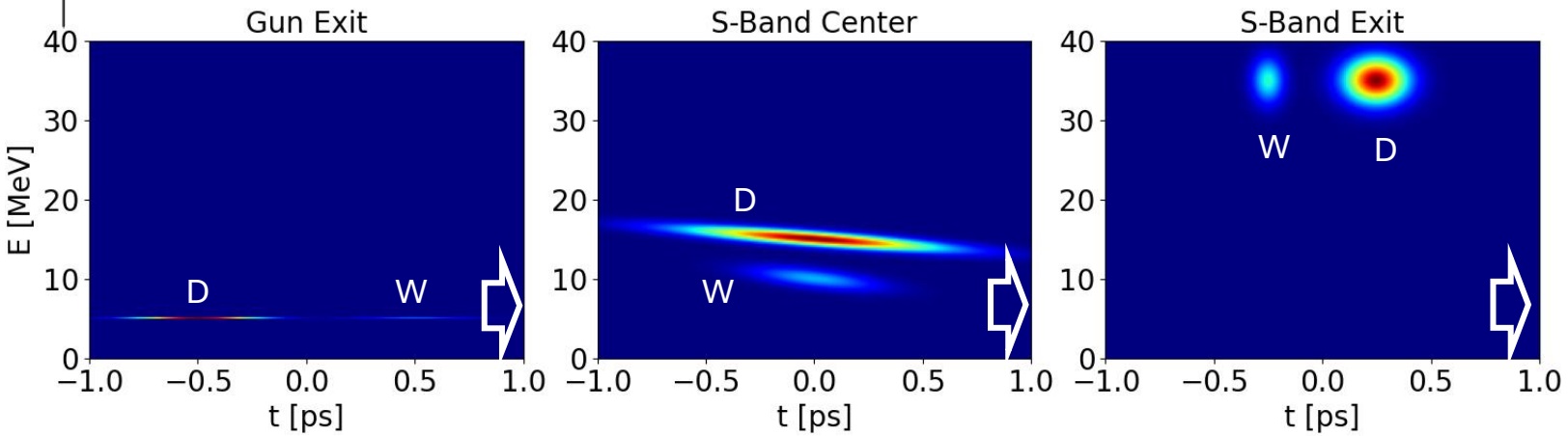
⇒ **2-Bunch Configuration and compression with Velocity Bunching** (multiple driver configuration available)

L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87 (2001)
M. Ferrario et al., Phys. Rev. Lett. 104, 054801 (2010)





Spatial crossing of the bunches



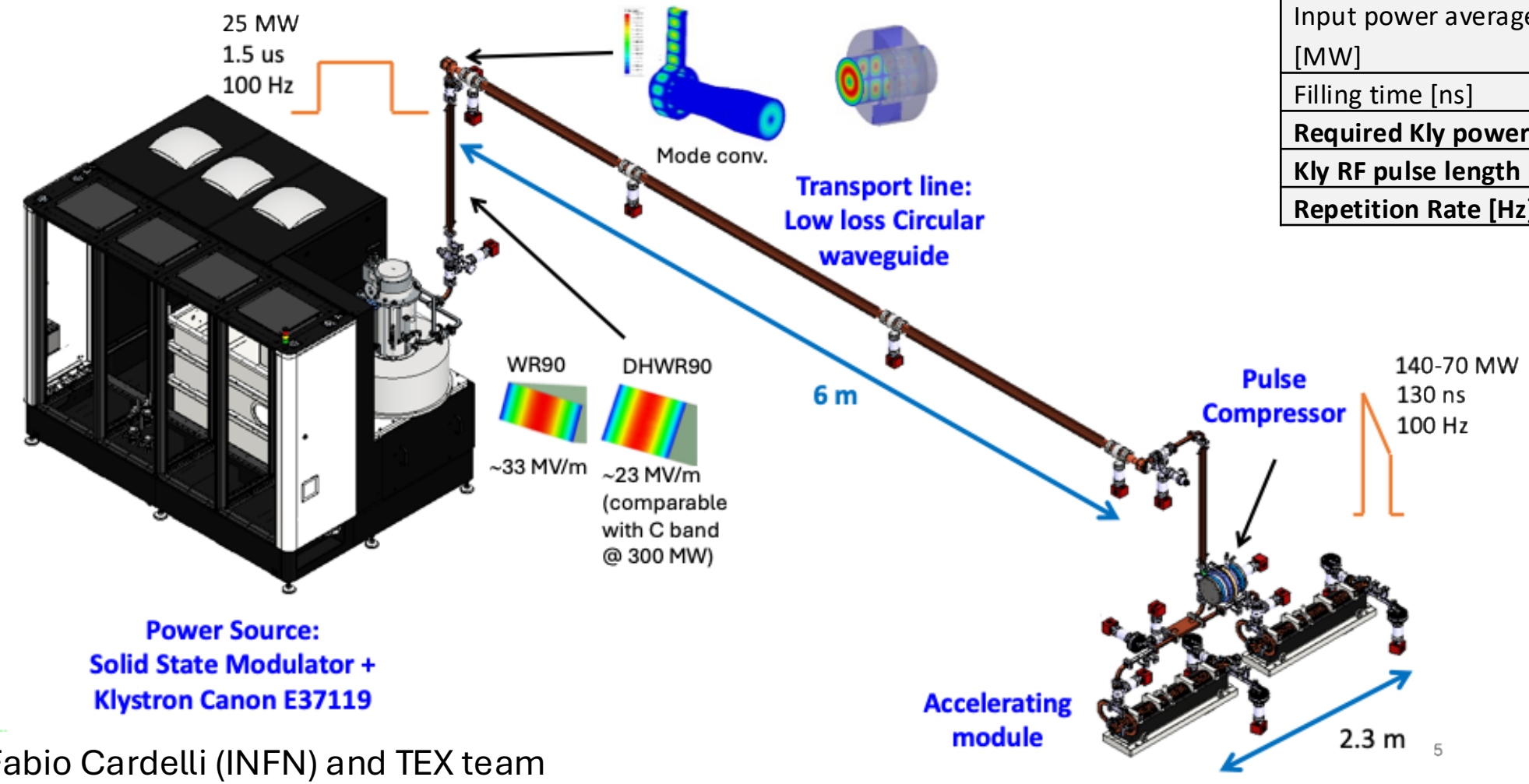
Parameter	Symbol	Unit	Value
# of bunches			2
Driver Charge	Q_D	pC	200
Witness Charge	Q_W	pC	30
Beam energy	$E_{D/W}$	MeV	119/118
Driver normalized emittance	ε_{nD}	mm mrad	1.5
Witness normalized emittance	ε_{nW}	mm mrad	0.7
Driver energy spread	σ_{ED}	%	0.7
Witness energy spread	σ_{EW}	%	0.1
Driver bunch duration	σ_{tD}	fs	193
Witness bunch duration	σ_{tW}	fs	17

E. Chiadroni (Roma-Sapienza Univ.), A. Giribono (INFN) and team

EuPRAXIA@SPARC_LAB: **X-Band Linac**

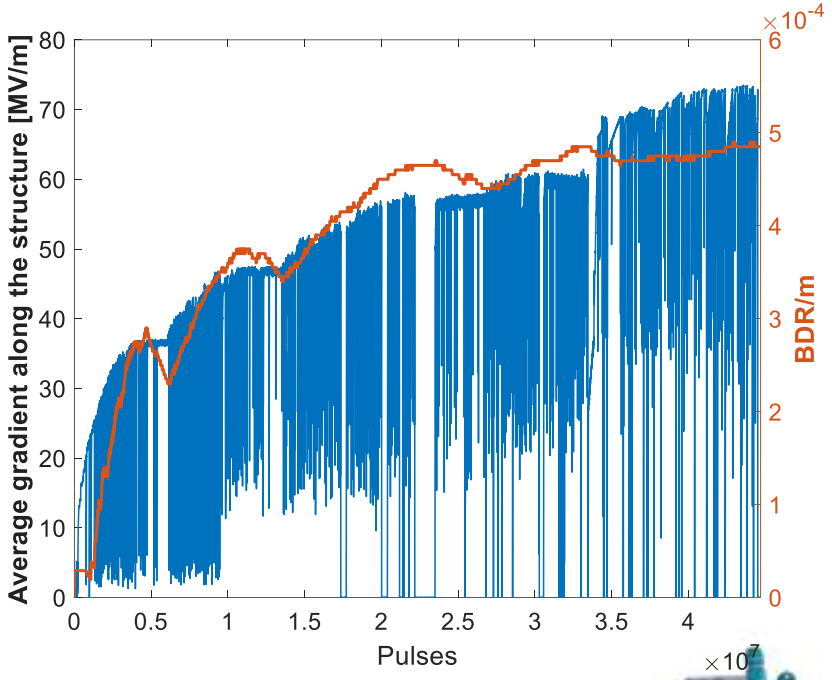
⇒ **16 1-m-long TW** structures
⇒ (**11.994 GHz**) and **100 Hz**
⇒ **Eight Canon E37327A** klystron+
Scandinova K400 Modulators (45 MW, 4.5 us, 100 Hz)

PARAMETER	Value
Frequency [GHz]	11.9942
Average acc. gradient [MV/m]	**60**
Structures per module	2
Peak input power per structure [MW]	70
Input power averaged over the pulse [MW]	51
Filling time [ns]	130
Required Kly power per module [MW]	**22.5**
Kly RF pulse length [μs]	**1.5**
Repetition Rate [Hz]	**100**

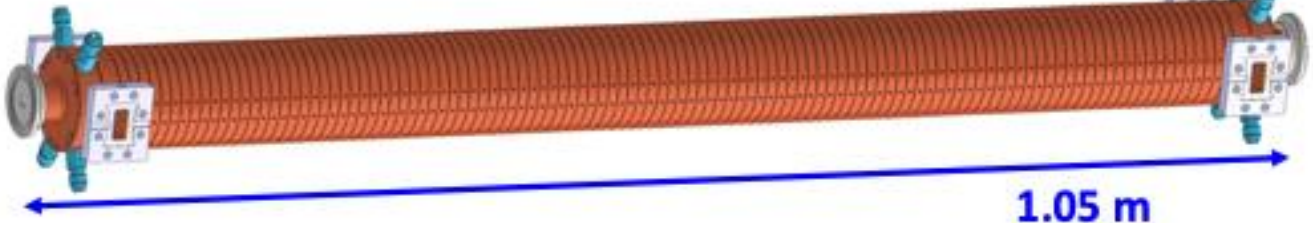


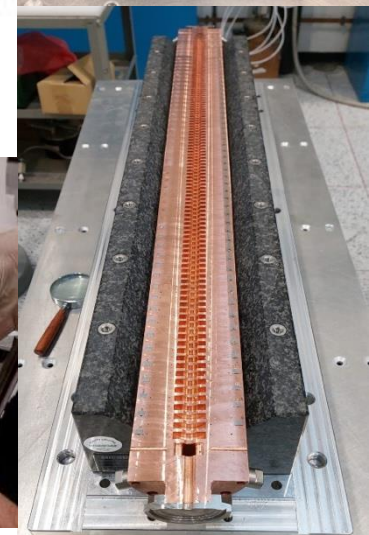
EuPRAXIA@SPARC_LAB: **X-Band Linac**

- ⇒ **Prototype brazed and vacuum tested**
- ⇒ **Straightness <±15 μm** obtained after brazing on both the prototypes (±30 μm required by BD)
- ⇒ 21 cells, **constant impedance**, RF prototype (the real structure will be 1 m long).
- ⇒ Reached input pulse of **35 MW, 100 ns length at 50 Hz repetition rate**, corresponding to an **average gradient ~ 74 MV/m**
- ⇒ **Further testing with BOC pulse compressor (PSI)** installed on the line.



DESIGN PARAMETER	Value
Frequency [GHz]	11.9942
Average acc. gradient [MV/m]	**60**
Structures per module	2
Iris radius a [mm]	**3.5**
Struct. length L_s act. Length [m]	**0.2**
No. of cells	20
Shunt impedance R [MΩ/m]	100
Effective shunt Imp. $R_{sh\ eff}$ [MΩ/m]	347
Filling time [ns]	30
Repetition Rate [Hz]	**100**

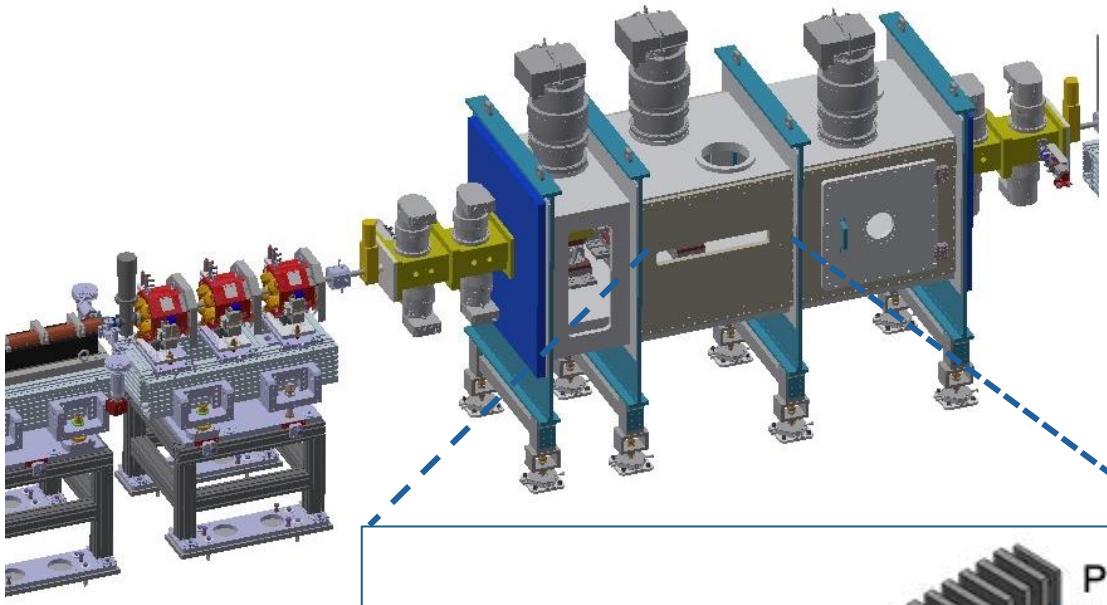


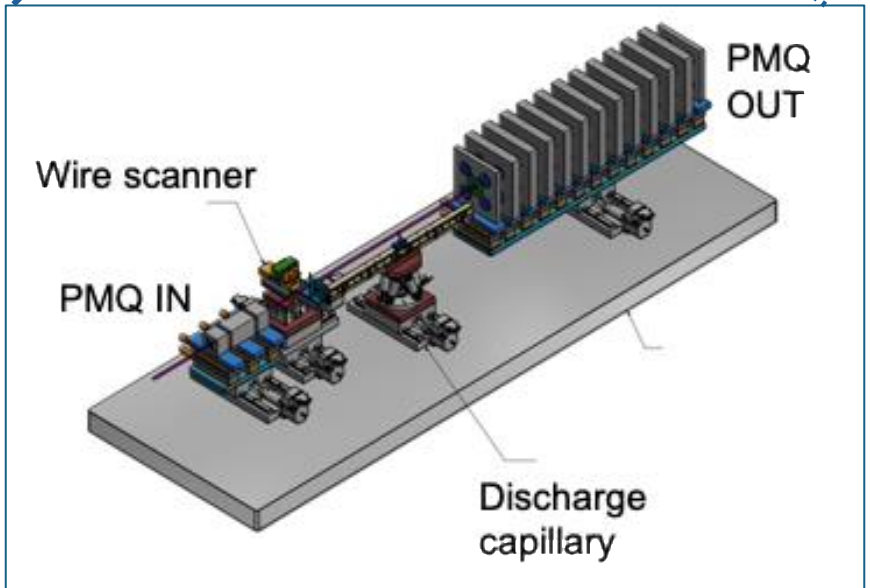


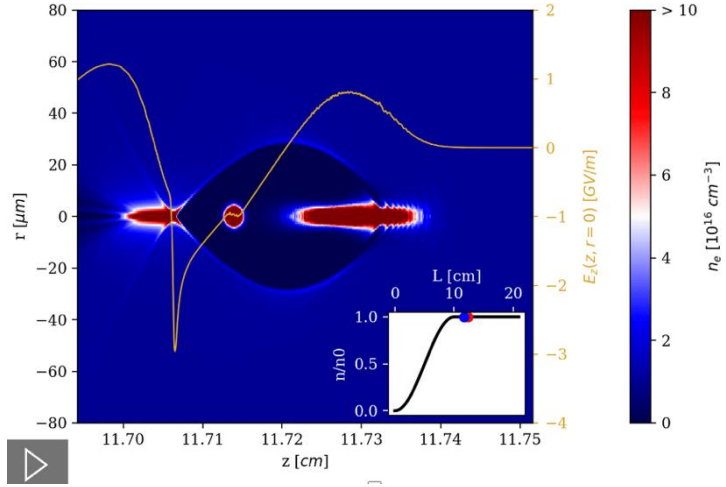
Fabio Cardelli (INFN) and TEX team

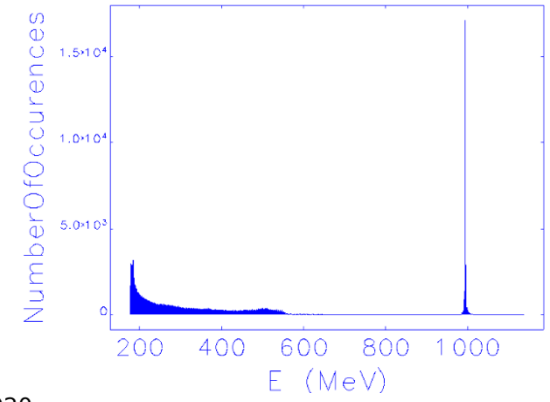
EuPRAXIA@SPARC_LAB: **Plasma**

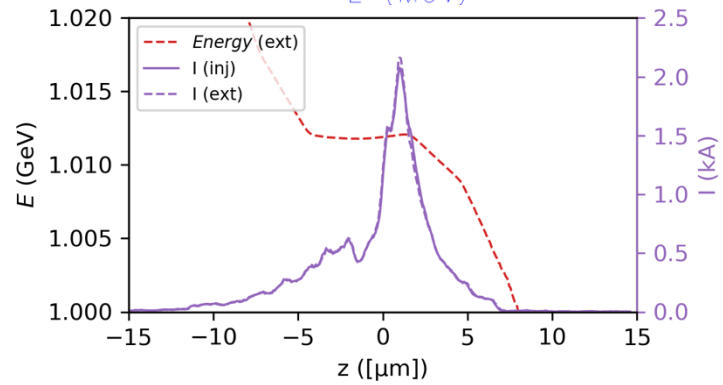
- 60-cm long discharge capillary
- GV/m high-quality acceleration
  ➔ Witness energy doubling











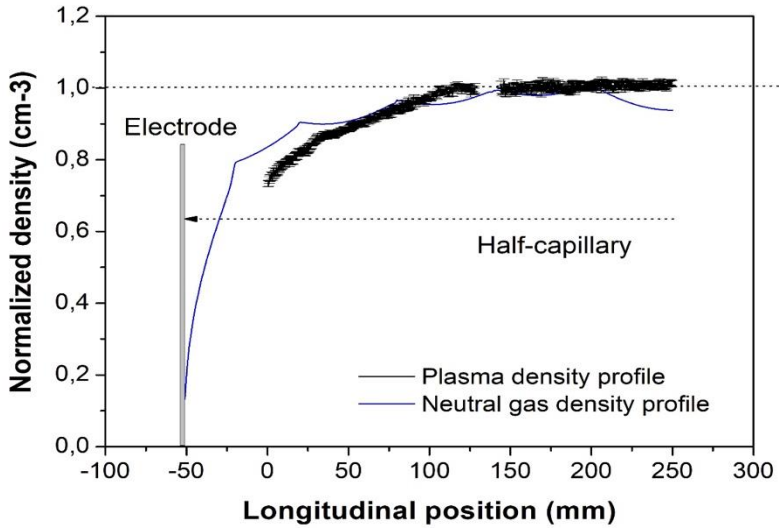
- Three differential pumping stations: vacuum levels <10^{-9}mbar in the adjacent sections

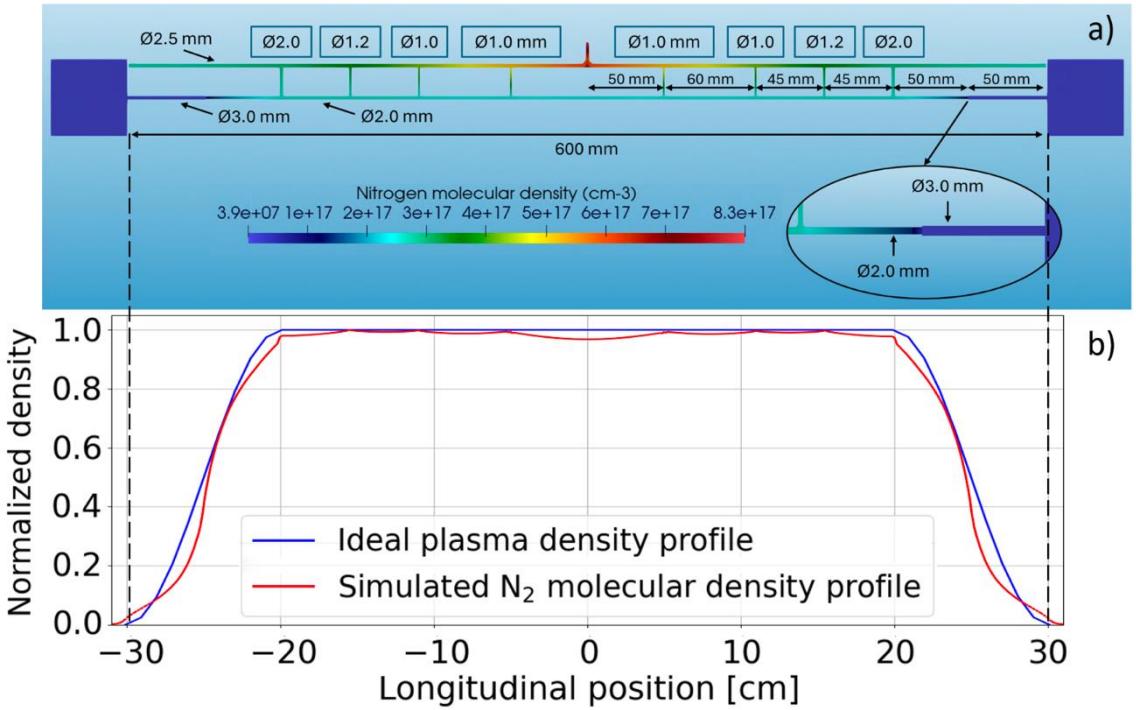
- Main chamber:
  - 60-cm-long capillary
  - Sets of PMQs
  - Wire scanner

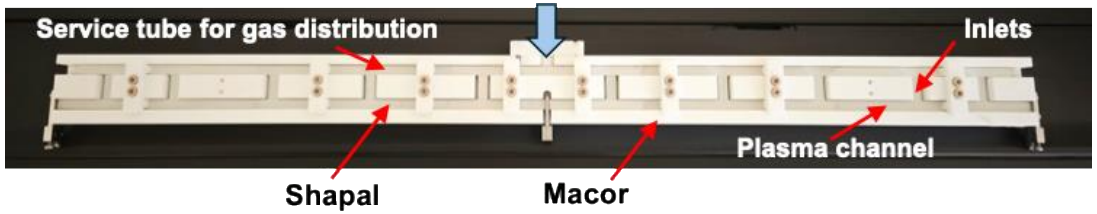
- Side chambers: Screens, EOS, etc..

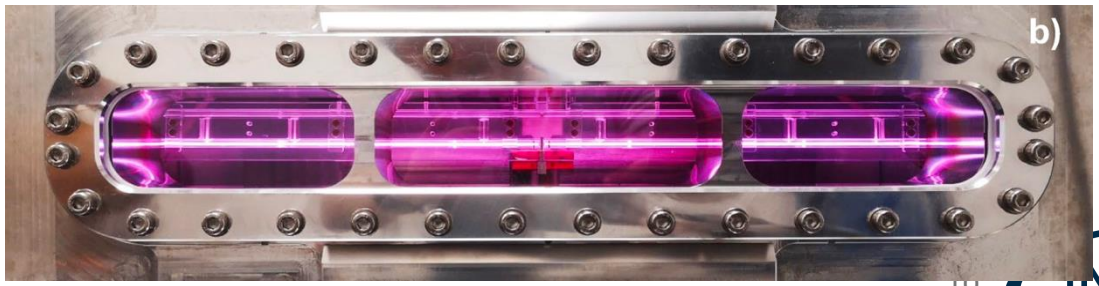
EuPRAXIA@SPARC_LAB: **Plasma**

- Support structure for gas injection and electrode mounting, integrating the gas injectors and the plasma channel.
- Plasma density measured by Stark broadening
- Solid-state high repetition-rate discharge system
- Density range 10^{15} -10^{17} cm^{-3} 12 kV - 500 A, 100 Hz rep rate
- 1% shot-to-shot stability
- High temperature-resistant materials capable of withstanding the plasma thermal load
- Fabrication by machining with 10 increasing diameter inlets









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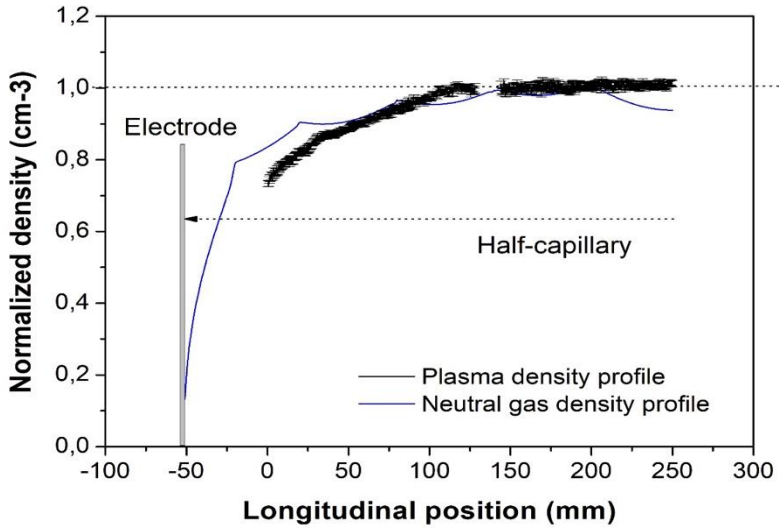

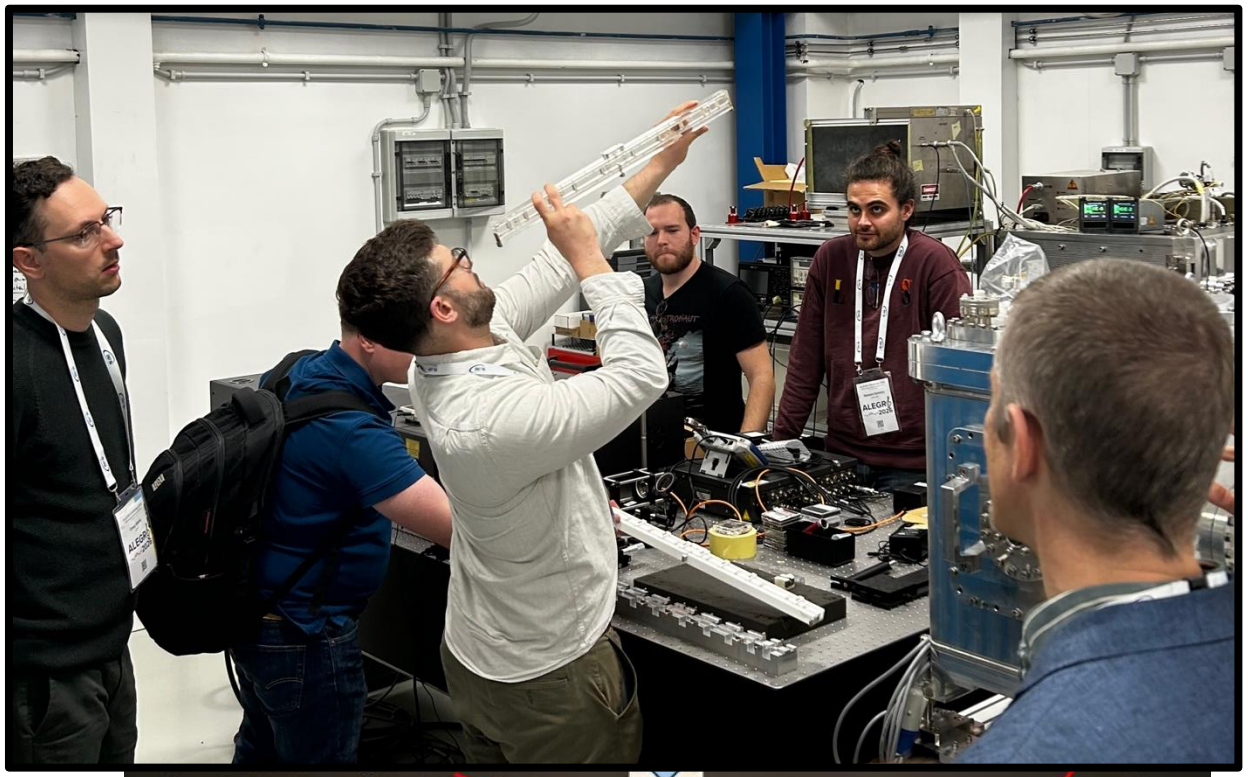

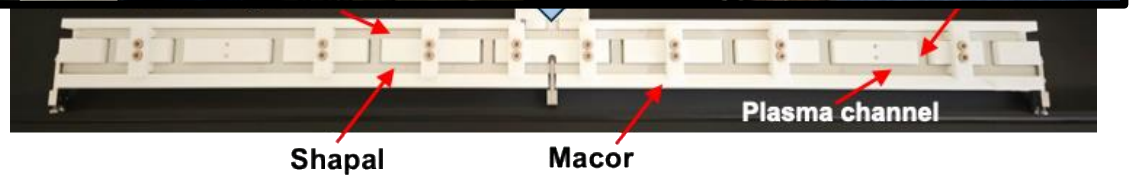

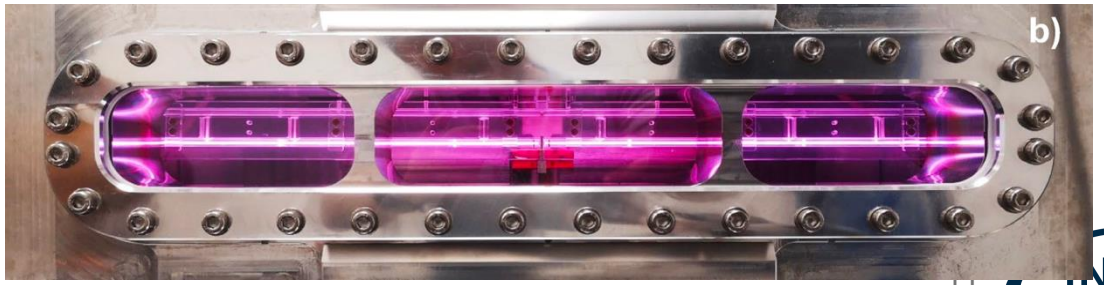

Angelo Biagioni (INFN) and Plasma_Lab team

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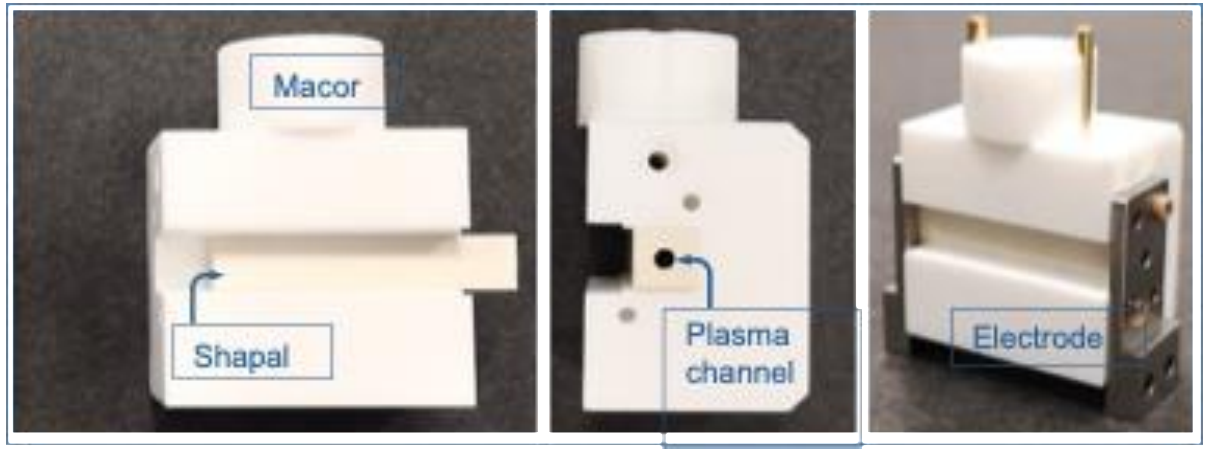
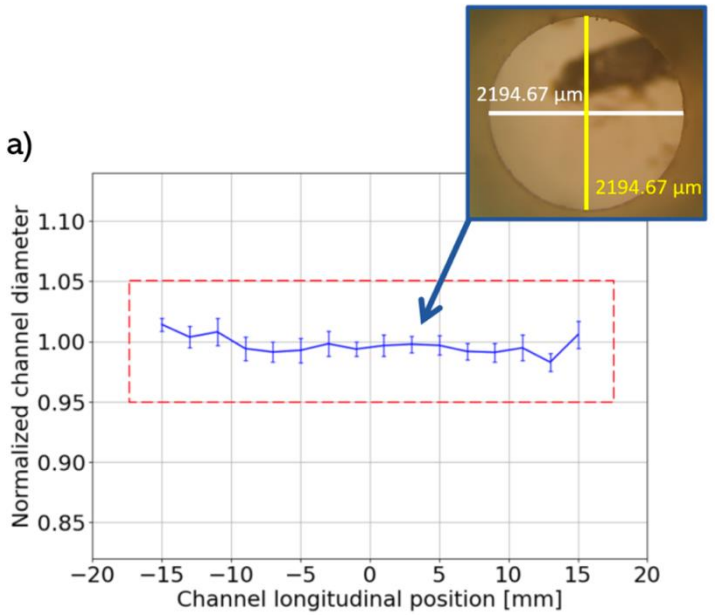
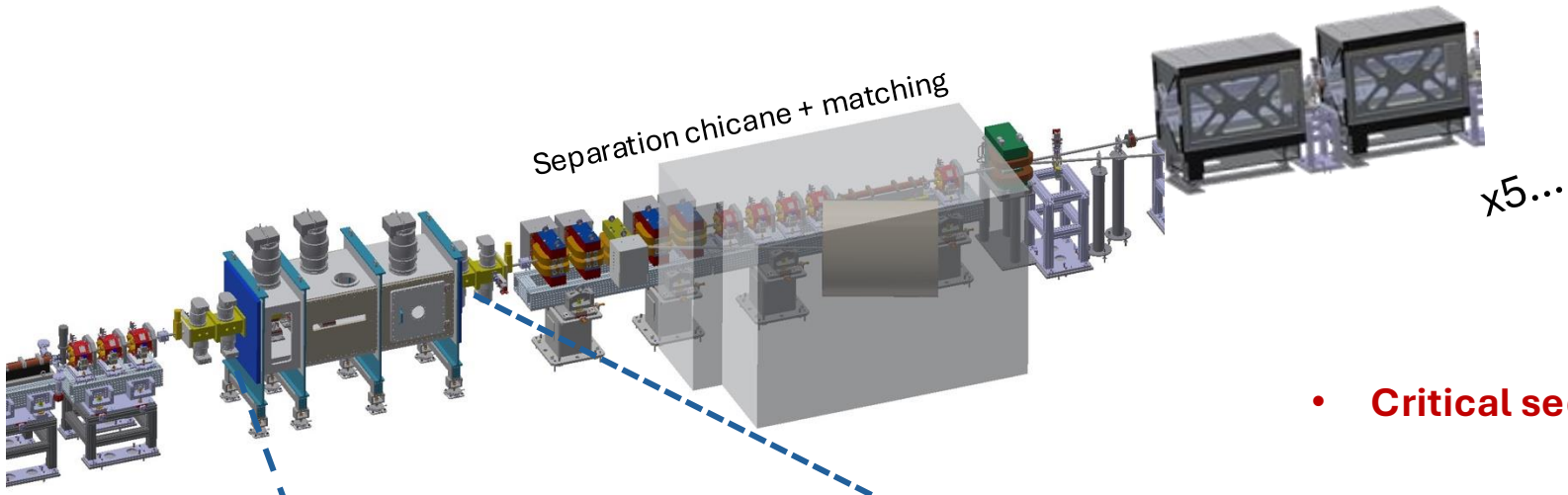
- 1% shot-to-shot stability
- High temperature-resistant materials capable of withstanding the plasma thermal load
- Fabrication by machining with 10 increasing diameter inlets
- 3-cm-long capillary tested over 20 x 10^6 shots at 100Hz
  - → No damage observed
  - → Reproducible density profile
- Additional diagnostics to measure density with despite opaque capillary



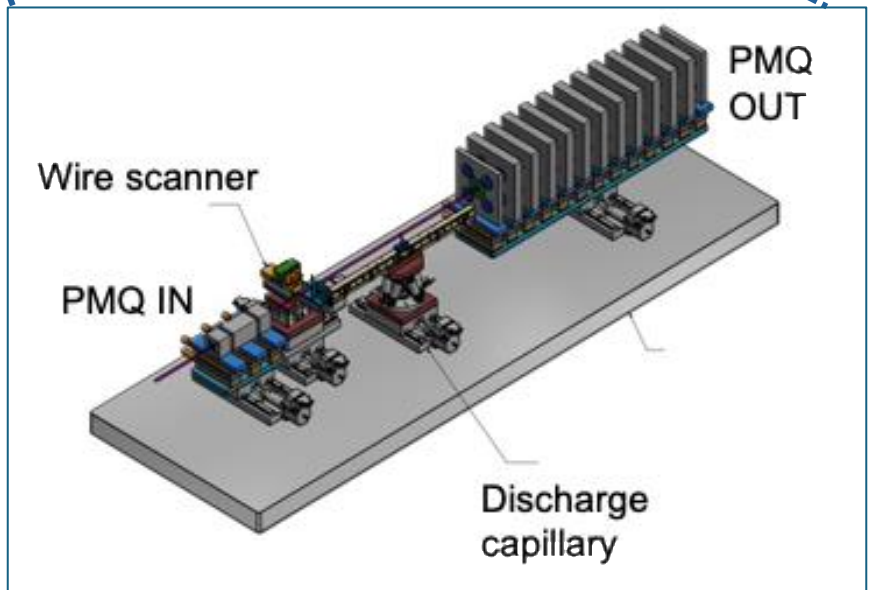


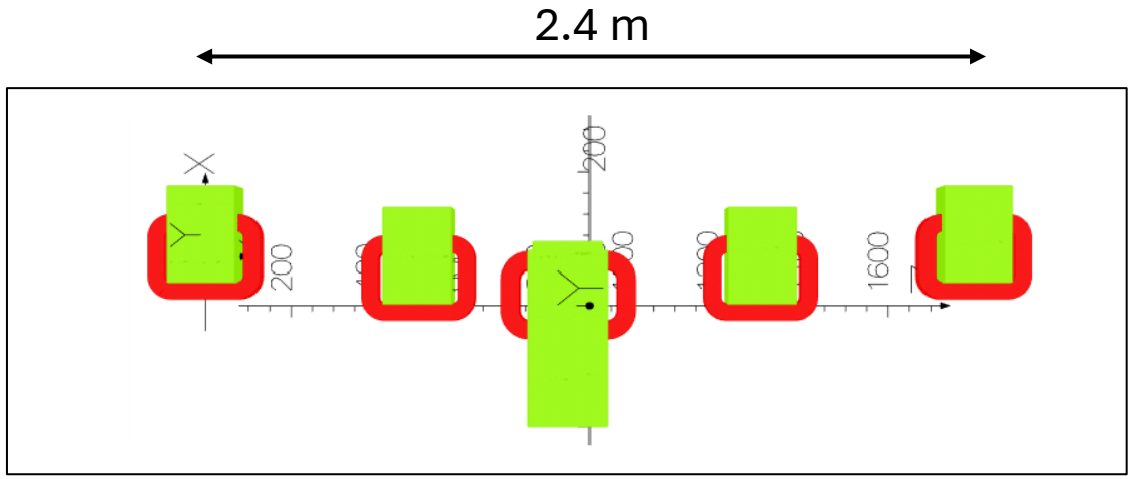
EuPRAXIA@SPARC_LAB: **Separation Section**



- Long PMQ section to transport both witness and depleted driver
- Magnetic chicane with septum to dump the driver
- Final FODO to match the witness beam to the undulators

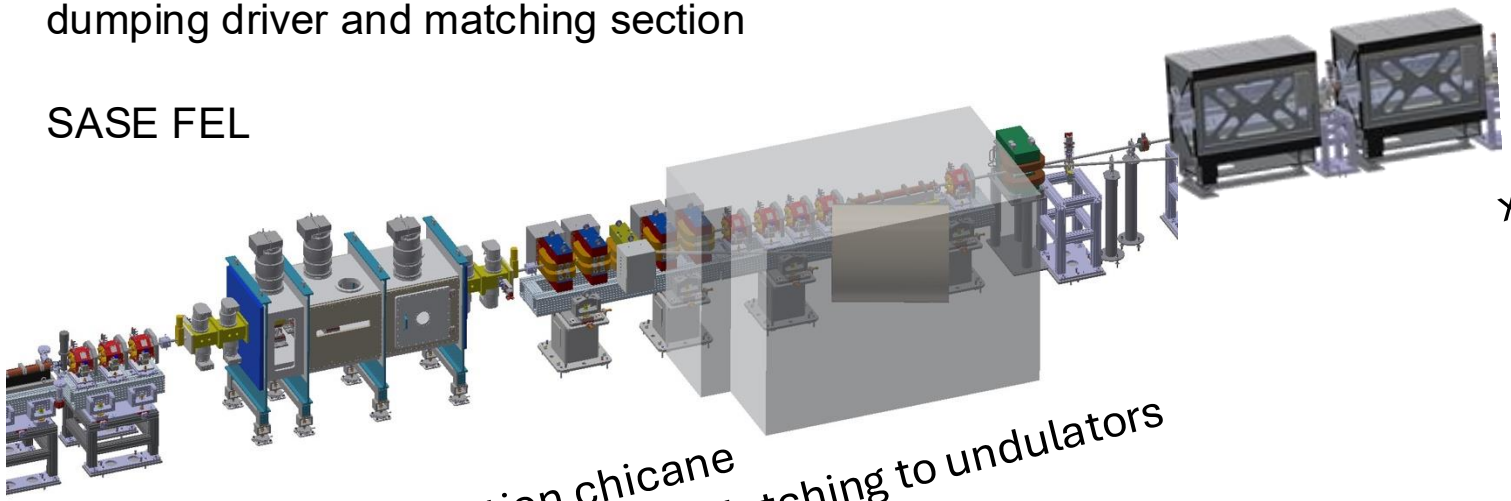
- **Critical section for radiation and machine protection**





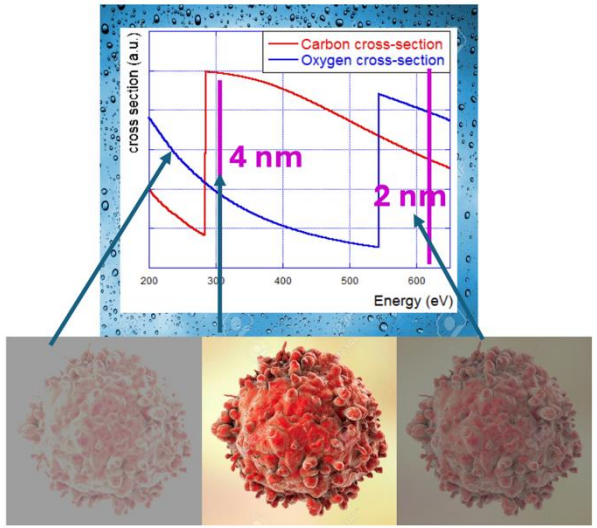
EuPRAXIA@SPARC_LAB: **FEL**

- Witness bunch delivered to undulators after dumping driver and matching section
- SASE FEL



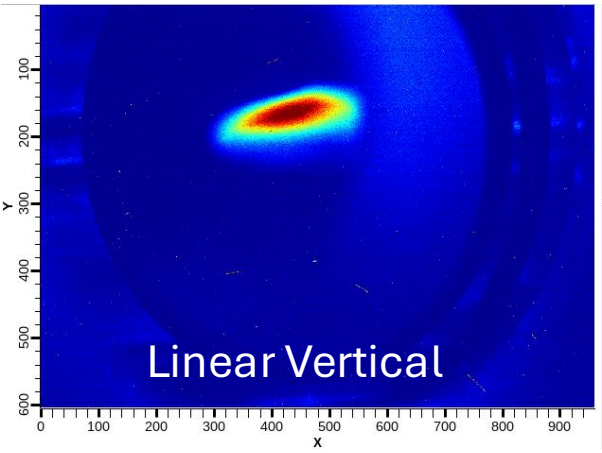
	Units	Value
ρ (3D)	$\times 10^{-3}$	0.77
Saturation length	m	20.5
Radiation wavelength	nm	4.0
Photon Pulse Energy	μJ	**16**
Photon per pulse	$\times 10^{11}$	3.2
Photon Bandwidth	%	0.4

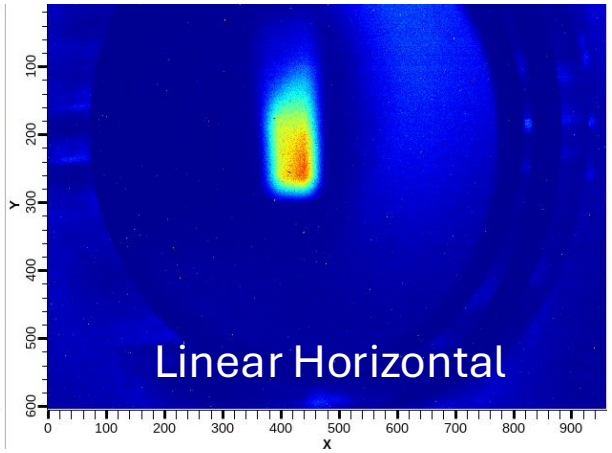
- Undulators with adjustable polarization
  → Similar design under commissioning right now at SPARC

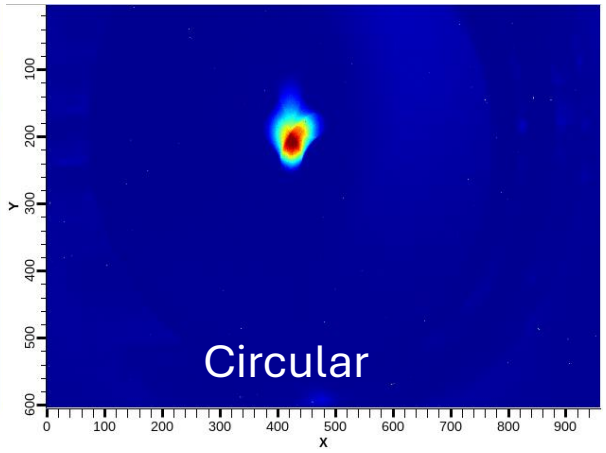


EuPRAXIA@SPARC_LAB: **FEL**

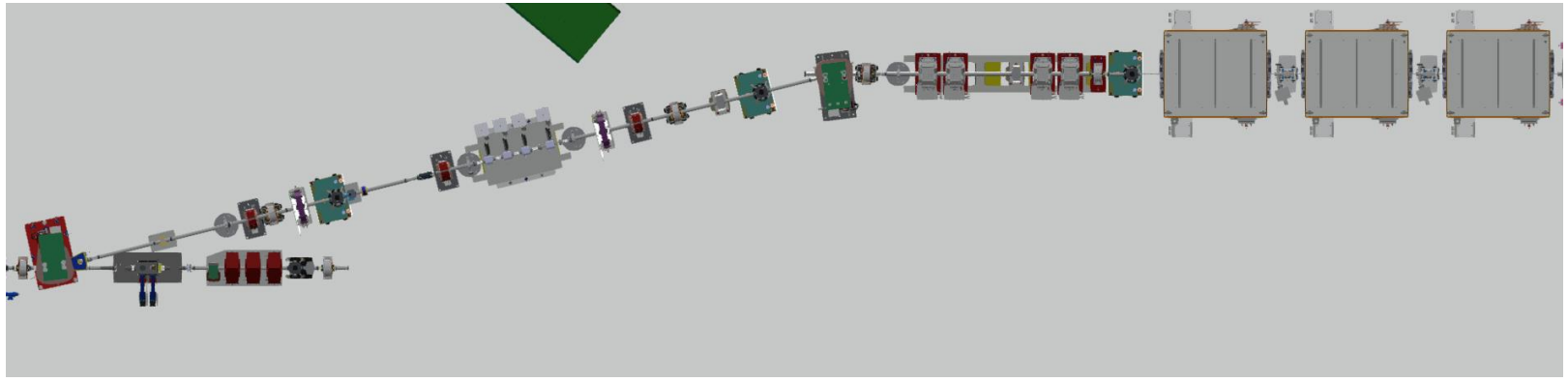
- THz FEL “SABINA” Beamline under commissioning at SPARC
- Undulators with same design as APPLE-X
- 4 rails of permanent magnets
- Adjustable gap and polarization







SPARC



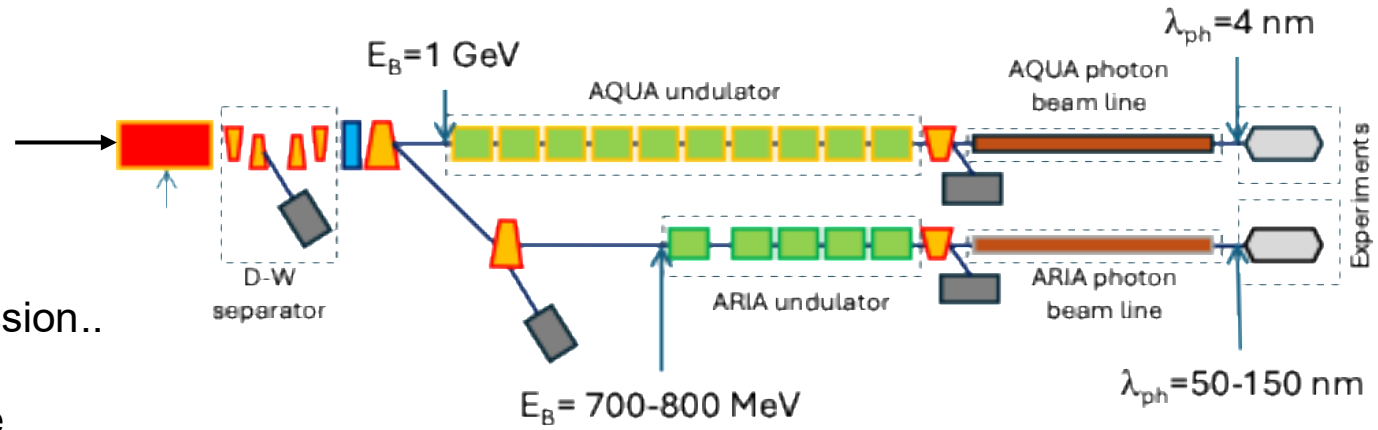
EuPRAXIA@SPARC_LAB: **ARIA**

- Second Beamline funded by Lazio regional government

- **VUV seeded HGHG FEL beamline**
- **Emision in range** 50-150 nm with variable polarization

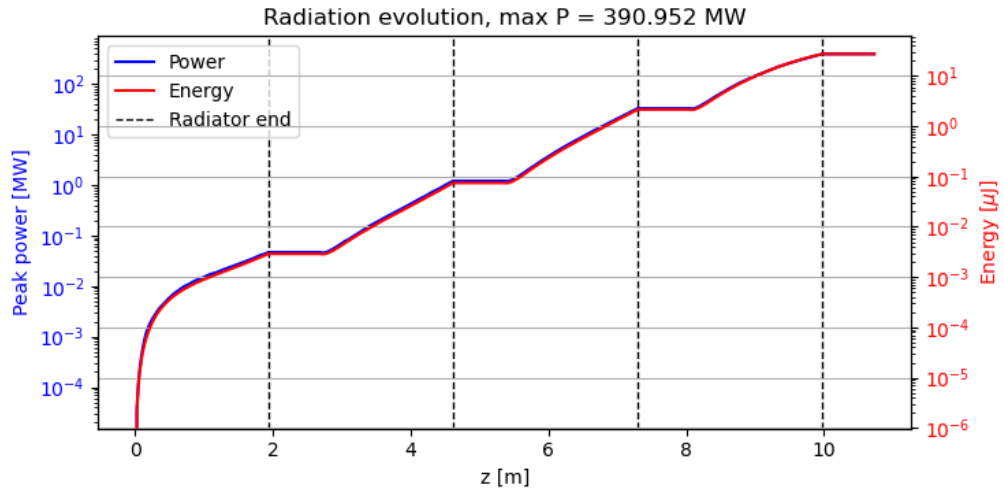
- Only RF beamline, but easier to implement and commission..

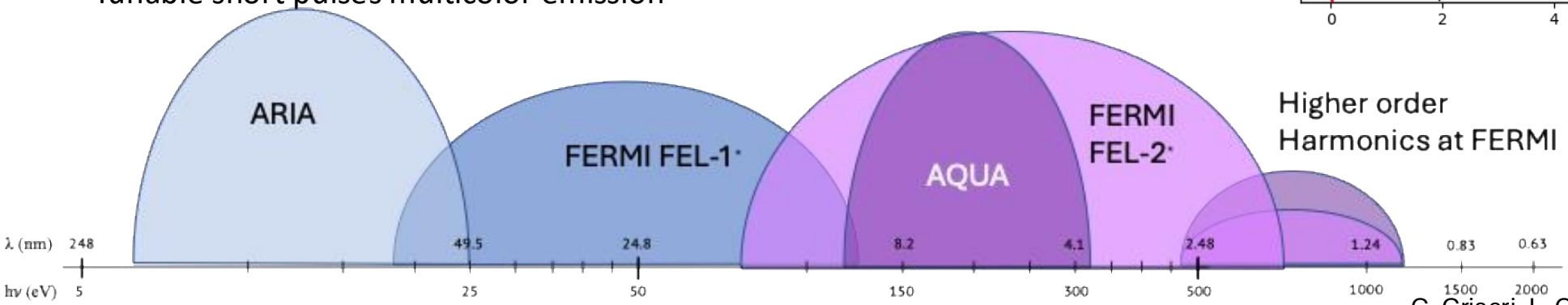
- Laser system for seed may serve as front-end for future high-power laser



VUV seeded HGHG FEL beamline for gas phase

- Modulator: 1.98 m, 9.0 cm period
- 4 Radiators APPLE X: 1.93 m each, variable pol., 4.6 cm period
- Seeding in the range $\boldsymbol{\lambda = [350, 600] nm}$
- Emission in the range $\boldsymbol{\lambda = [50, 150] nm}$, complementary with FERMI
- Tunable short pulses multicolor emission





G. Griseri, L. Giannessi (INFN) and team

EuPRAXIA@**ELI**

EuPRAXIA@SPARC_LAB

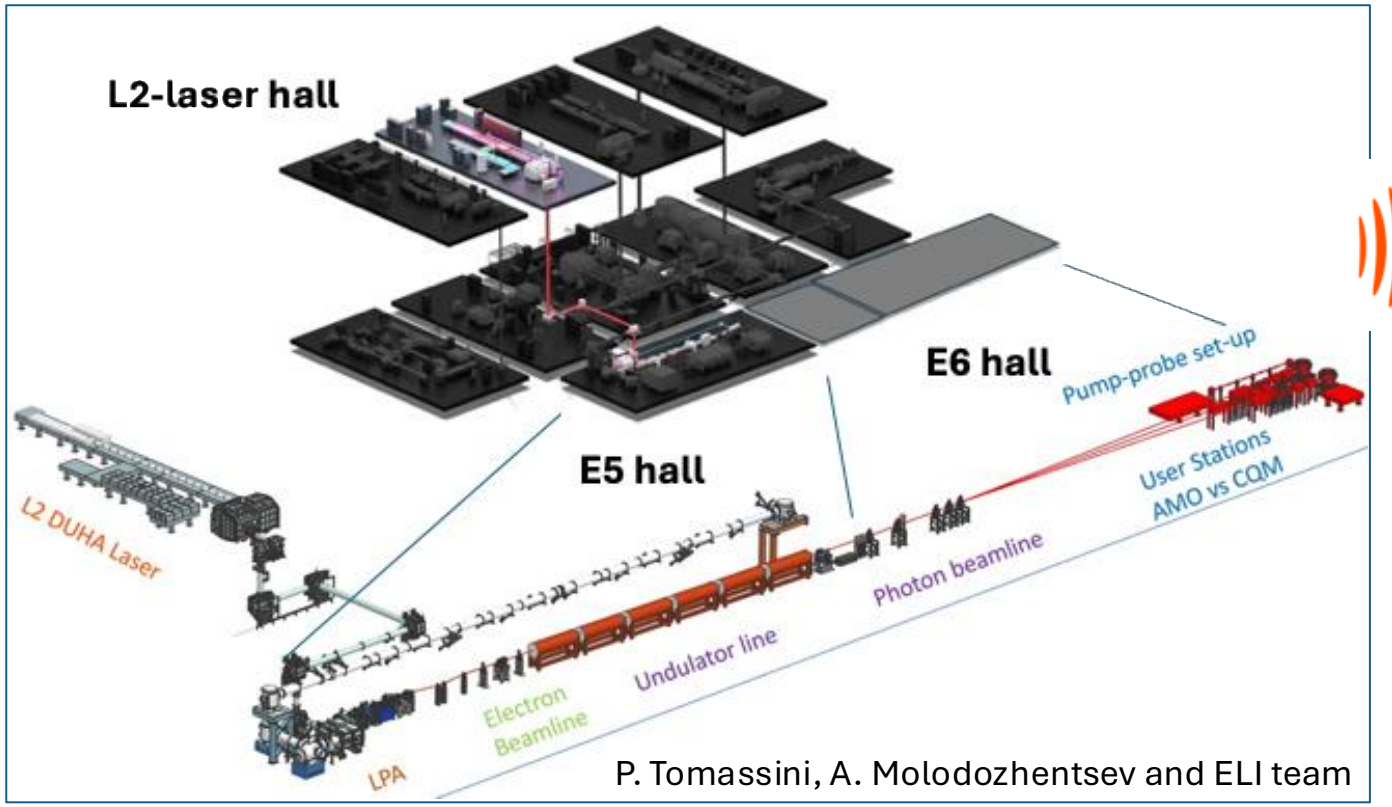
- LWFA Pillar of EuPRAXIA
- Main Objectives:
  - High-quality **1 GeV** electron beam
  - High repetition rate **50-100 Hz**
  - Soft X-ray **"water-window" SASE FEL**

+ **Betatron source (L3 LPA-based)**
+ **Positron source (L1 LPA-based)**

KYE PARAMETERS	COMMISSIONING 2026 - 2028	GOAL 2029-2030
LASER	DPSSL-pumped OPCPA	
Energy per pulse [J]	**3**	**5**
Repetition rate [Hz]	**20 (50)**	**50(100)**
Pulse duration [fsec]	25	25
Laser power [TW]	**100**	**200**
Laser beam quality		
Contrast ratio [-]	10^{-11}	TBD
Pointing stability [μrad]	2	1
Beam profile	Round (D=120mm)	
Energy stability [%]	1	
Temporal characteristics	TBD	TBD
Laser synchronization capabilities		AUX beam fully synchron.

		EUV FEL HPMU (U19)	Soft X-ray FEL HMPU (U15)
ELECTRON BEAM			
Electron beam energy	MeV	**350**	**1000**
Bunch charge (I_p)	pC (kA)	30 (2.5)	30 (2.5)
RMS energy spread (slice)	%	0.22	0.15
RMS normalized emittance (slice)	π.mm.mrad	0.3	0.3
Repetition rate	Hz	20	50 (100)

		EUV FEL HPMU (U19)	Soft X-ray FEL HMPU (U15)
PHOTON BEAM (h=1)			
Wavelength / Energy	nm / eV	**43 / 29**	**3.4 / 368**
Bandwidth	%	1.5	0.4
Photons per pulse	× 10^{12}	12	0.2
Brilliance ph/pulse/mm²/mrad²/0.1%bw	× 10^{30}	0.13	1.4
Photon beam peak power	GW	4.5	1.8
Saturation length	m	**4**	**16**



P. Tomassini, A. Molodozhentsev and ELI team

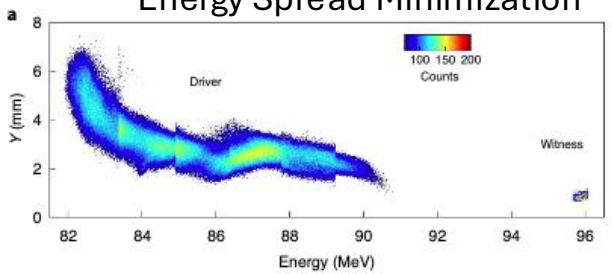
eli

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

Preliminary Studies at SPARC

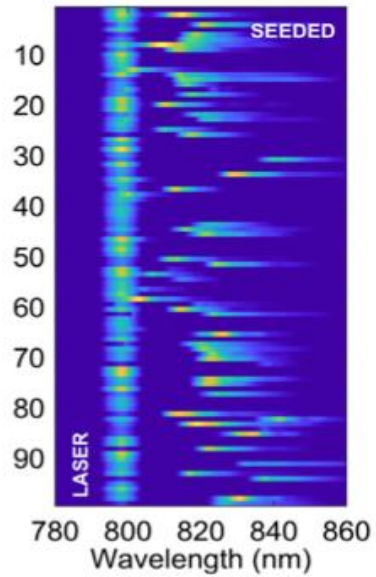
EuPRAXIA@SPARC_LAB

Energy Spread Minimization



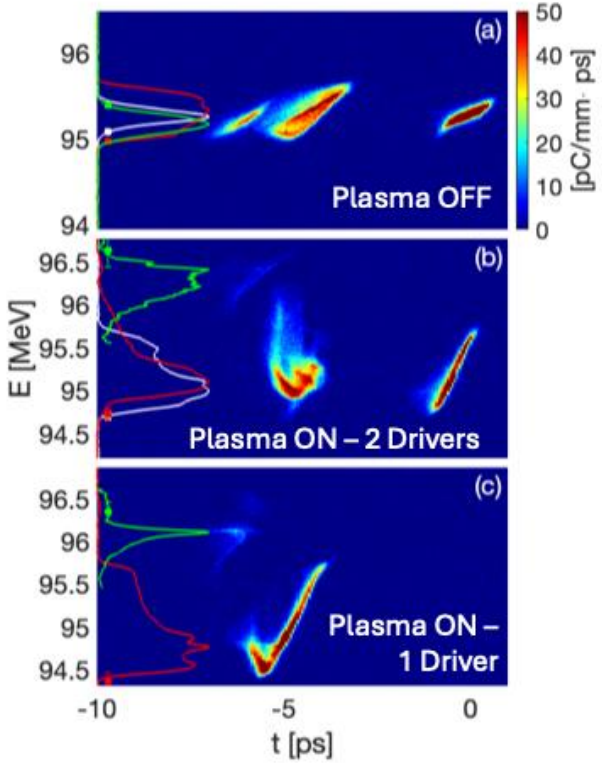
Pompili et al. Nat. Phys. 17, 499-503 (2021)

Lasing of PWFA witness bunch (SASE and Seeded)



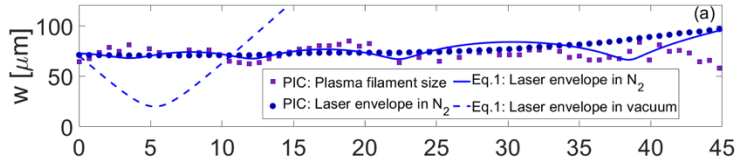
Pompili et al. Nature 605, 659-662 (2022)
Galletti et al. PRL 129, 234801 (2022)

Multi-bunch, high transformer ratio



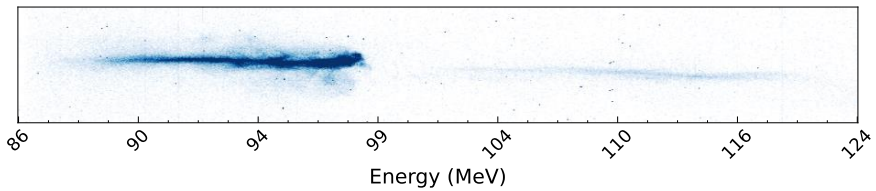
L. Verra et al., PRE **112**, 045205 (2025)

Alternative plasma sources



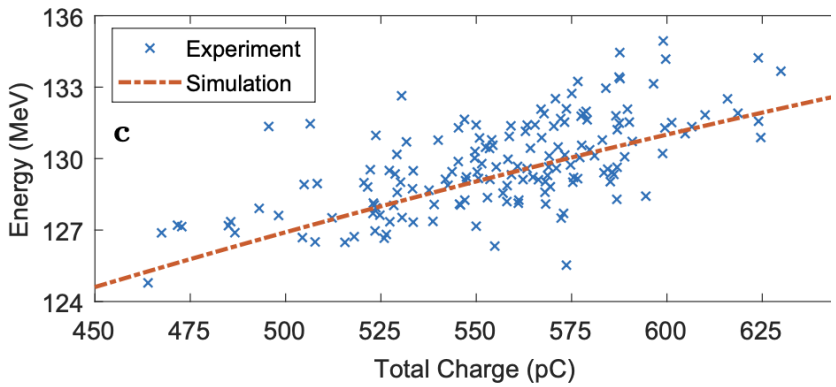
Galletti et al. Arxiv

Plasma-based compression



SPARC-FACET Team, in preparation

Jitter and tolerances studies

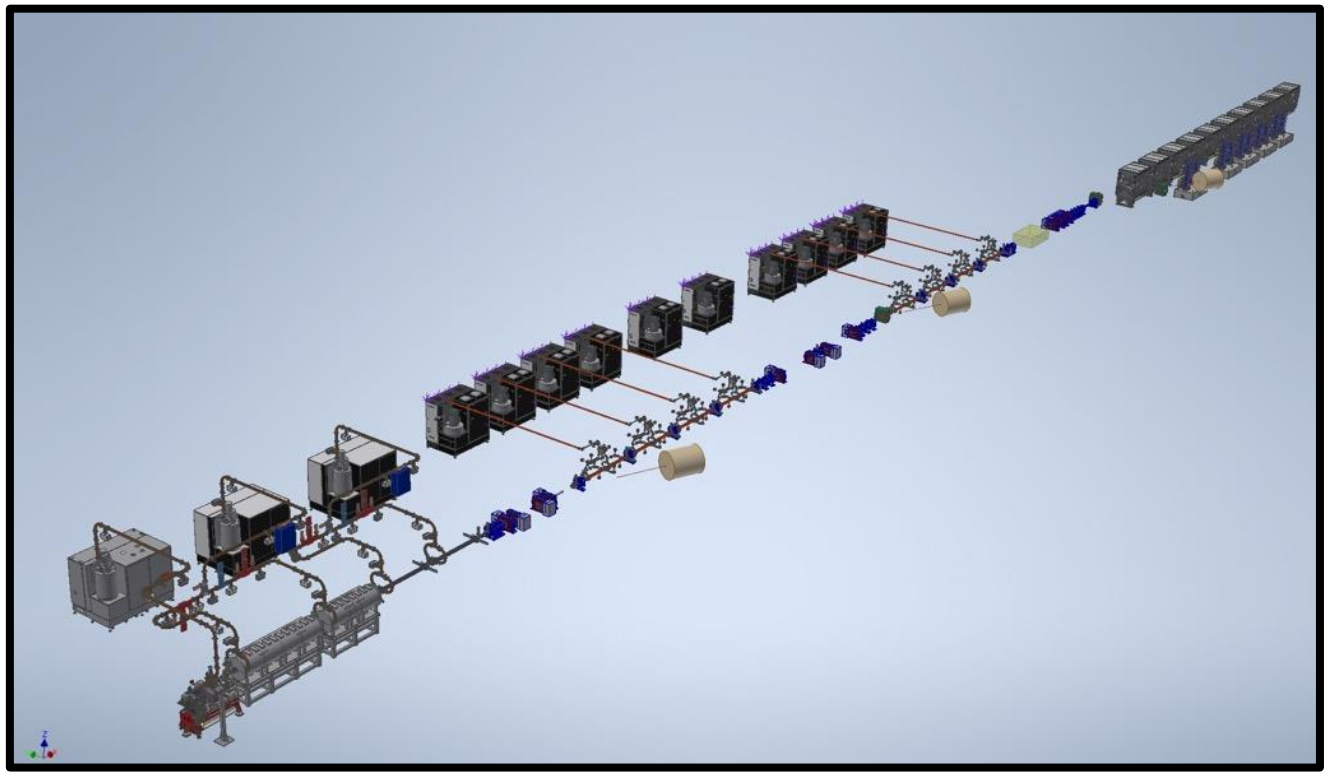


R. Pompili et al., under review

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Conclusions

- EuPRAXIA is a distributed infrastructure with the goal of realizing plasma-based light sources
- In-house effort to build the first user-oriented FEL powered by PWFA
- EuPRAXIA will provide a platform for future R&D dedicated to HEP
- SPARC facility serves as testbed for schemes and technologies that could be used in EuPRAXIA

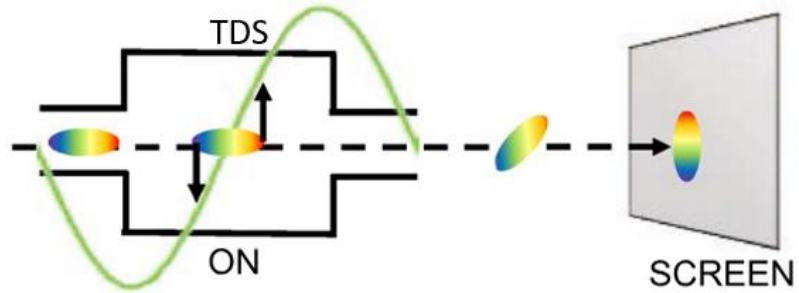


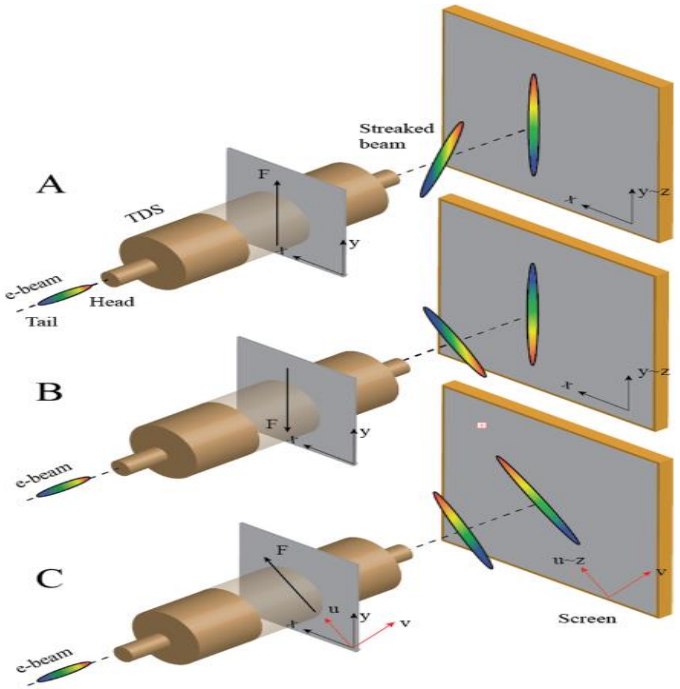
Thank You For Listening!

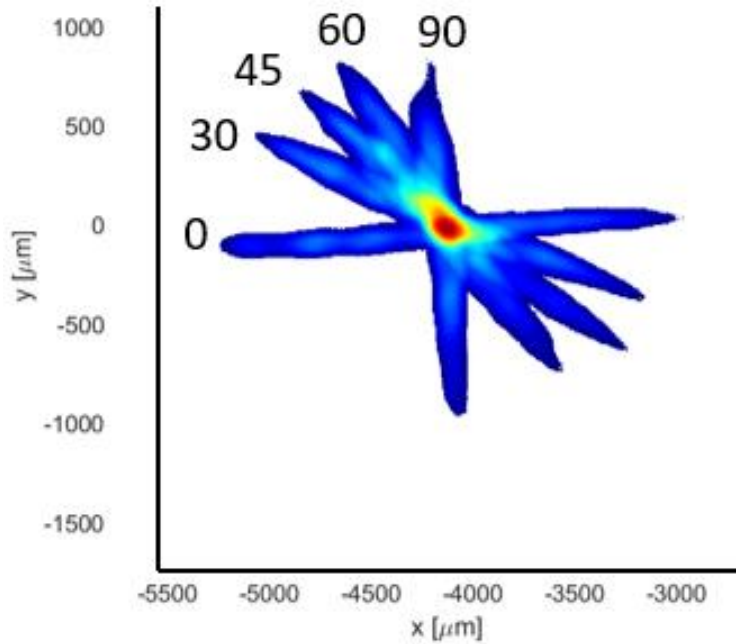
Backup

EuPRAXIA@SPARC_LAB: **Longitudinal Diagnostics**

- We will employ the state-of-the art transverse deflecting structure: PolariX
  → Adjustable streaking direction for full characterization
- Developed within a DESY–PSI–CERN collaboration and already installed and used in several facilities.







Streaked images at different polarization angles provide the projections required for 3D/5D tomographic reconstruction.

Allows streaking in both x and y plane with the same structure for slice emittance measurements

EuPRAXIA@SPARC_LAB: **Longitudinal Diagnostics**

- We will employ the state-of-the art transverse deflecting structure: PolariX

  → Adjustable streaking direction for full characterization
- Developed within a DESY–PSI–CERN collaboration and already installed and used in several facilities.

Low-energy beamline:

$E \sim 118$ MeV *(witness)*

$\sigma_{t_{rms}} \sim 17\ fs$ *(witness)*

Short PolariX TDS ~ 50 *cells* /60 *cm*

Temporal Resolution ~ $1\ fs$

High-energy beamline:

E ~ 1 GeV (witness)

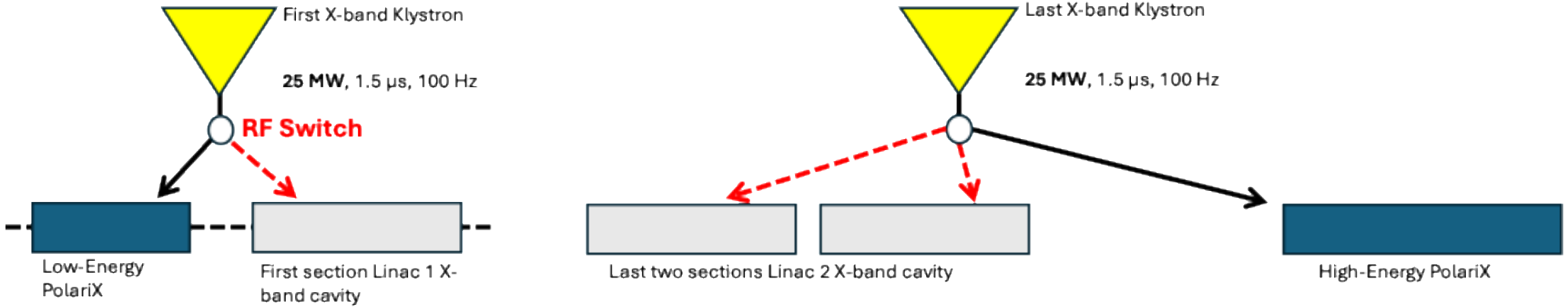
$\sigma_{t_{rms}} \sim 15\ fs$ (witness)

Long PolariX TDS ~ 96 *cells* /96 *cm*

Temporal Resolution ~ $1 - 2\ fs$

- Klystron/modulator system feeds both X-band linac and PolariX
  → Need to develop dedicated RF switch for X-band

- Bunch length and longitudinal profile
- Longitudinal phase space with dipole
- Slice emittance in both planes using variable polarization
- Advanced diagnostics: 3D/5D tomography and ML-based reconstruction

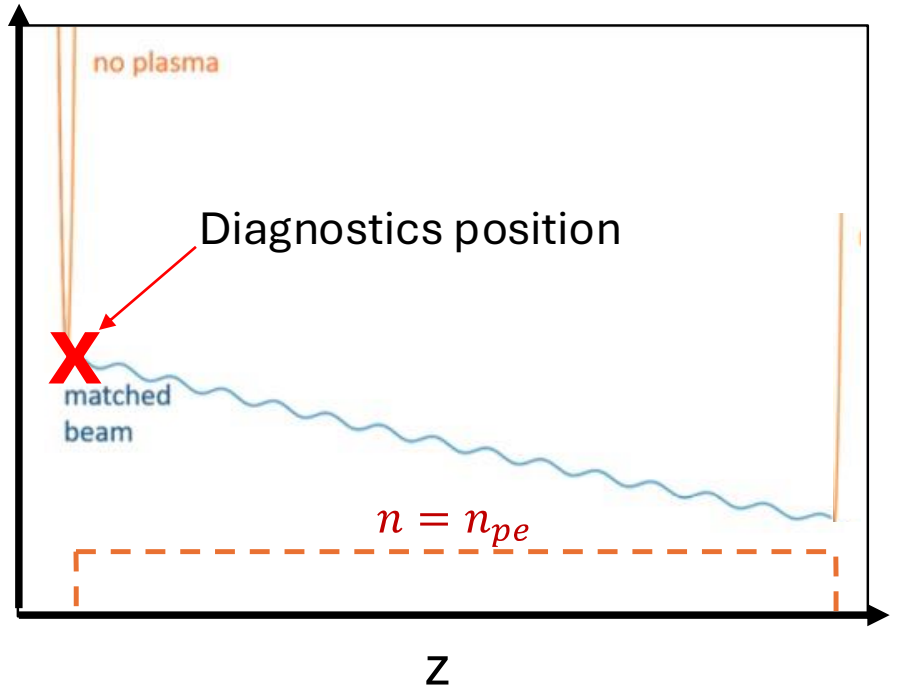


EuPRAXIA@SPARC_LAB: **Plasma Entrance Diagnostics**

- The witness bunch in non-linear PWFA must be delivered at the plasma entrance with Twiss parameters:

$\alpha_m = 0$ (injected at waist)

$\beta_m = \sqrt{\frac{2m_e c^2 \varepsilon_0}{n_{pe} q^2}}\gamma$ (matched to the ion column focusing force)



- For EuPRAXIA:
  - β = 7.4 mm
    → σ = 3.8 μm

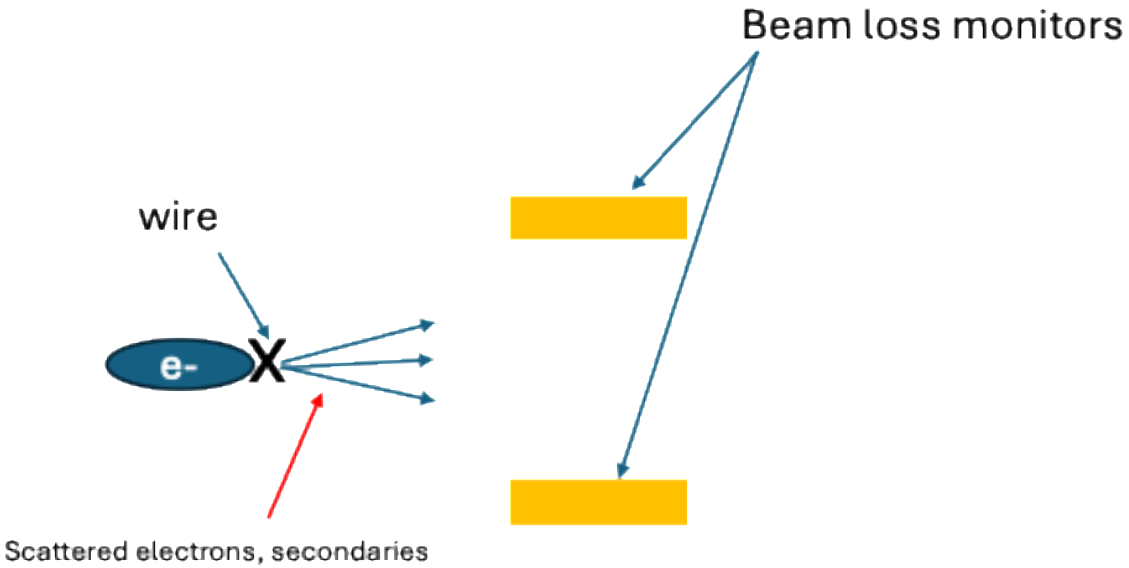
➔ Need a diagnostics to measure the transverse beam size at the plasma entrance location with μm-resolution

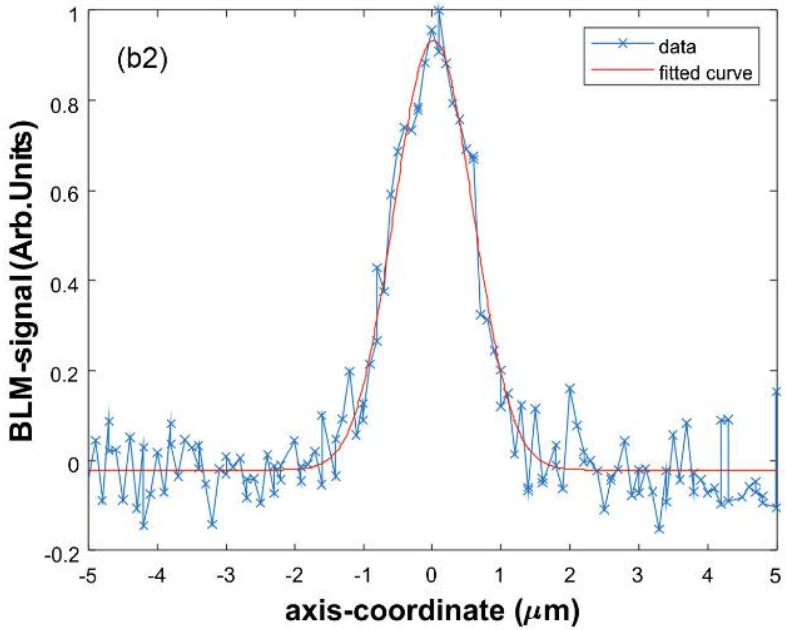
EuPRAXIA@SPARC_LAB: **Plasma Entrance Diagnostics**

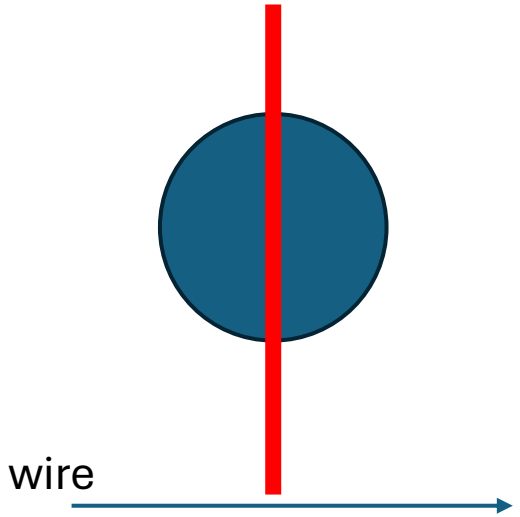
- Wire intercepting electron bunch
  → scattered electrons and generation of secondaries

- Detection of signal with beam loss monitors

- Signal proportional to the portion of bunch intercepted by the wire
  ➔ correlation with wire position
  ➔ transverse distribution in the scanned direction
  ➔ assuming no jitter on beam position







EuPRAXIA@SPARC_LAB: **Plasma Entrance Diagnostics**

- Wire intercepting electron bunch
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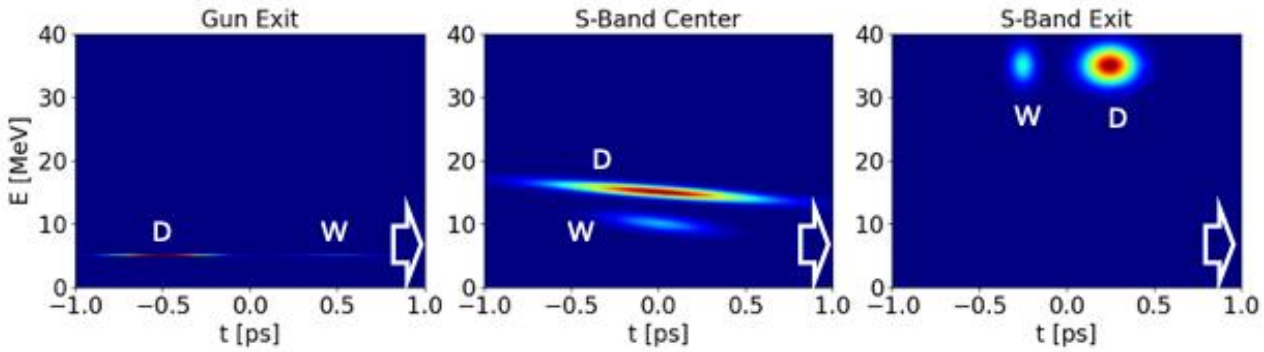
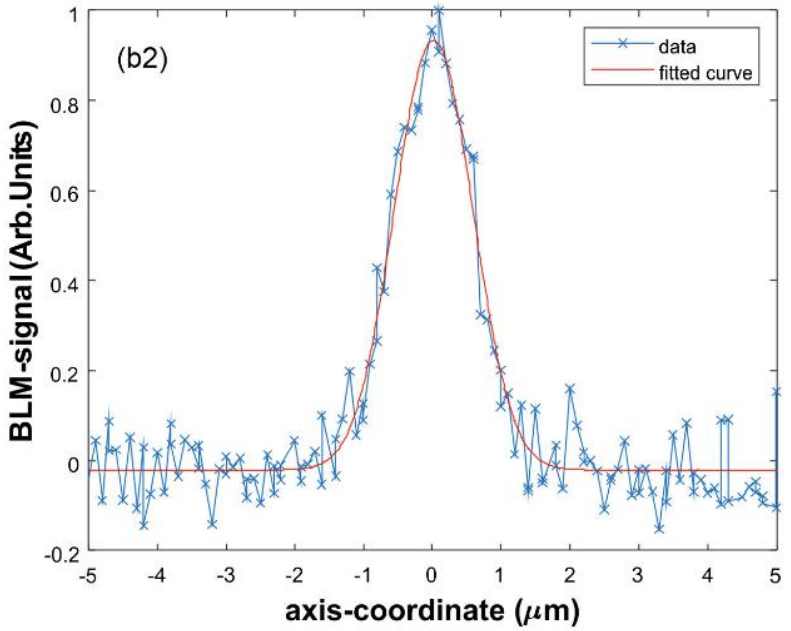
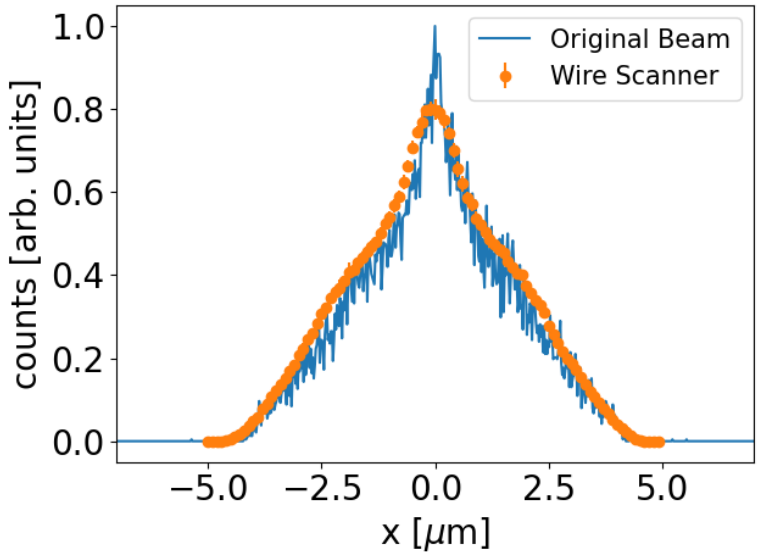
- Detection of signal with beam loss monitors

- Signal proportional to the portion of bunch intercepted by the wire
  ➔ correlation with wire position
  ➔ transverse distribution in the scanned direction
  ➔ assuming no jitter on beam position

- Main difficulty: can we retrieve the witness beam distribution over the driver beam distribution?
  → Cannot turn off driver due to velocity bunching effect!



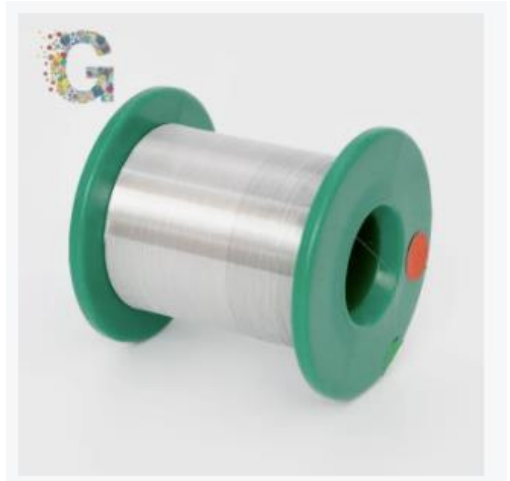




EuPRAXIA@SPARC_LAB: **Plasma Entrance Diagnostics**

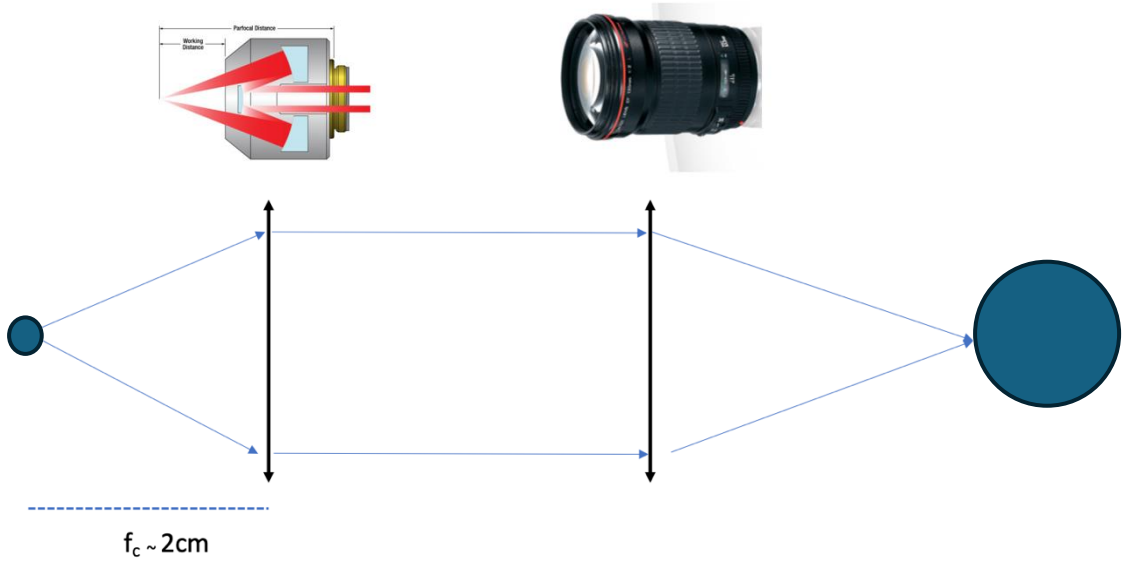
- Resolution for squared wire ~ $\frac{w_0}{\sqrt{12}}$

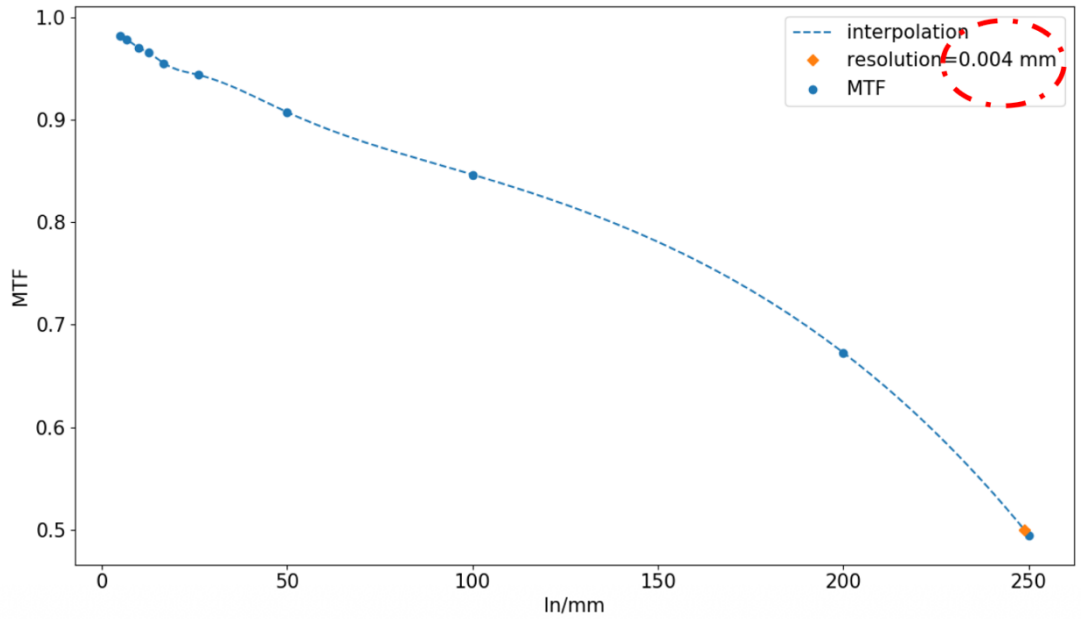
  ➔ ~1.1 μm for $w_0 = 4$ μm (off-the-shelf Tungsten reel)



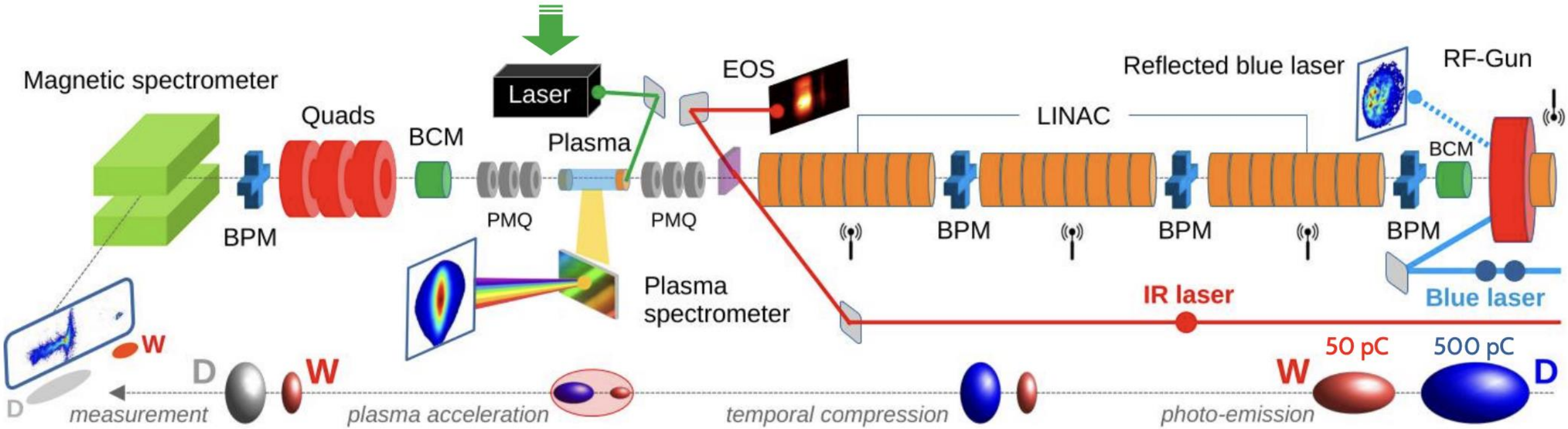
- Nanofabricated gold wires exist, but difficult to machine and very fragile
  - Achieved sub- μm resolution with <pC charge

- Alternative option: high-resolution optical system imaging OTR light
  - Screen damage remain an issue





Preliminary Studies at SPARC

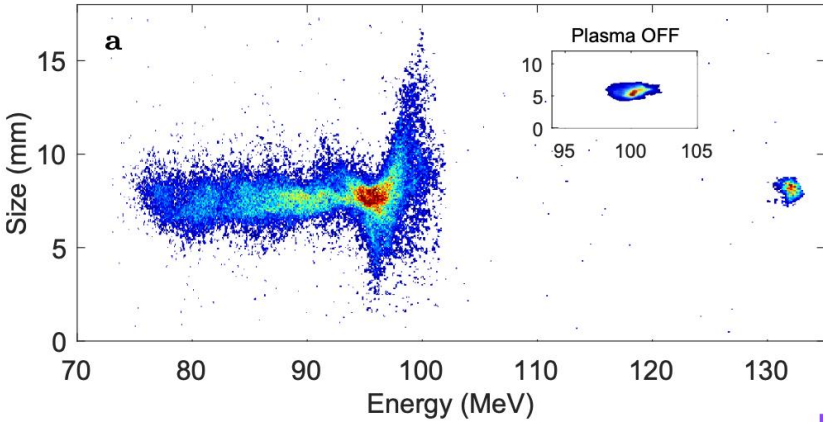


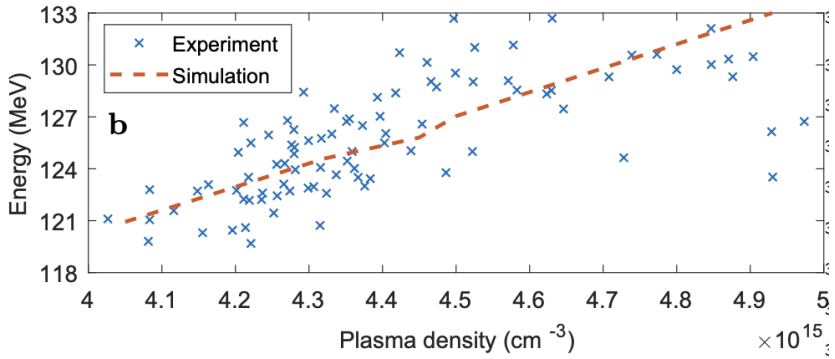
Goals of the experiment: cross-correlate all the jitter sources affecting the plasma acceleration process. Fundamental in view of EuPRAXIA, where high shot-to-shot repeatability is required.

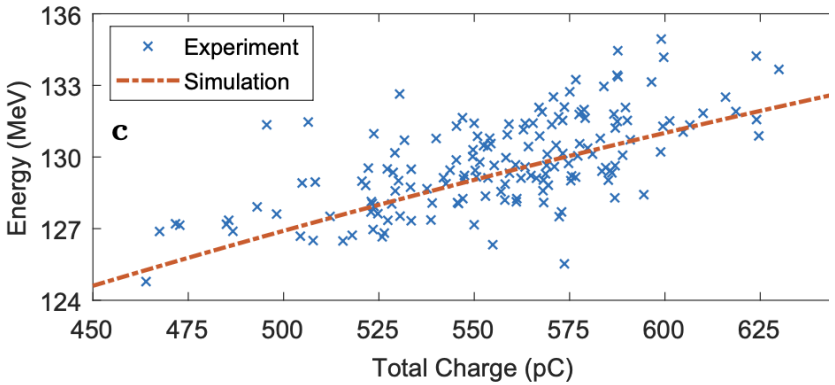
Demonstration of plasma density jitter reduction using an external laser

All the observables are simultaneously probed using single-shot non-destructive diagnostics.

Preliminary Studies at SPARC



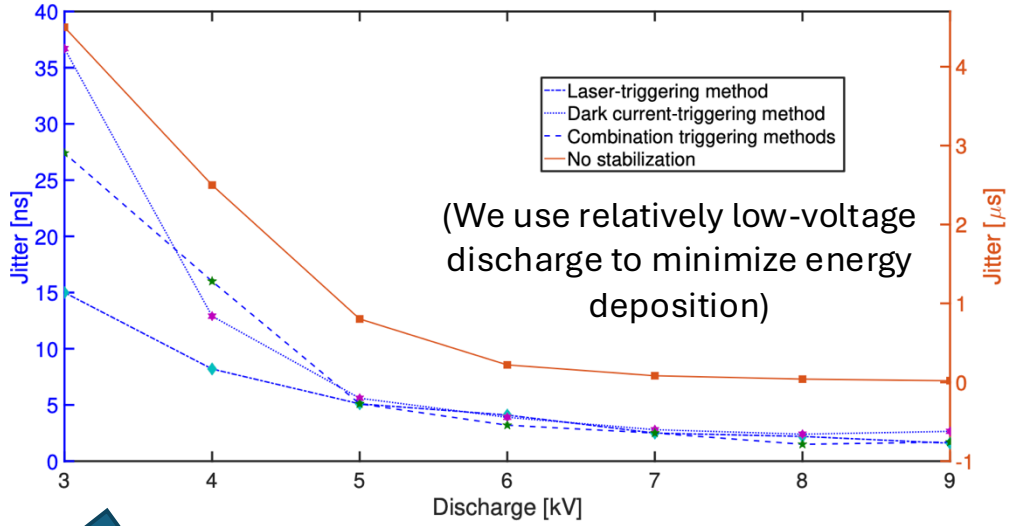




R. Pompili et al., under review

- **>1 GV/m reproducible acceleration**

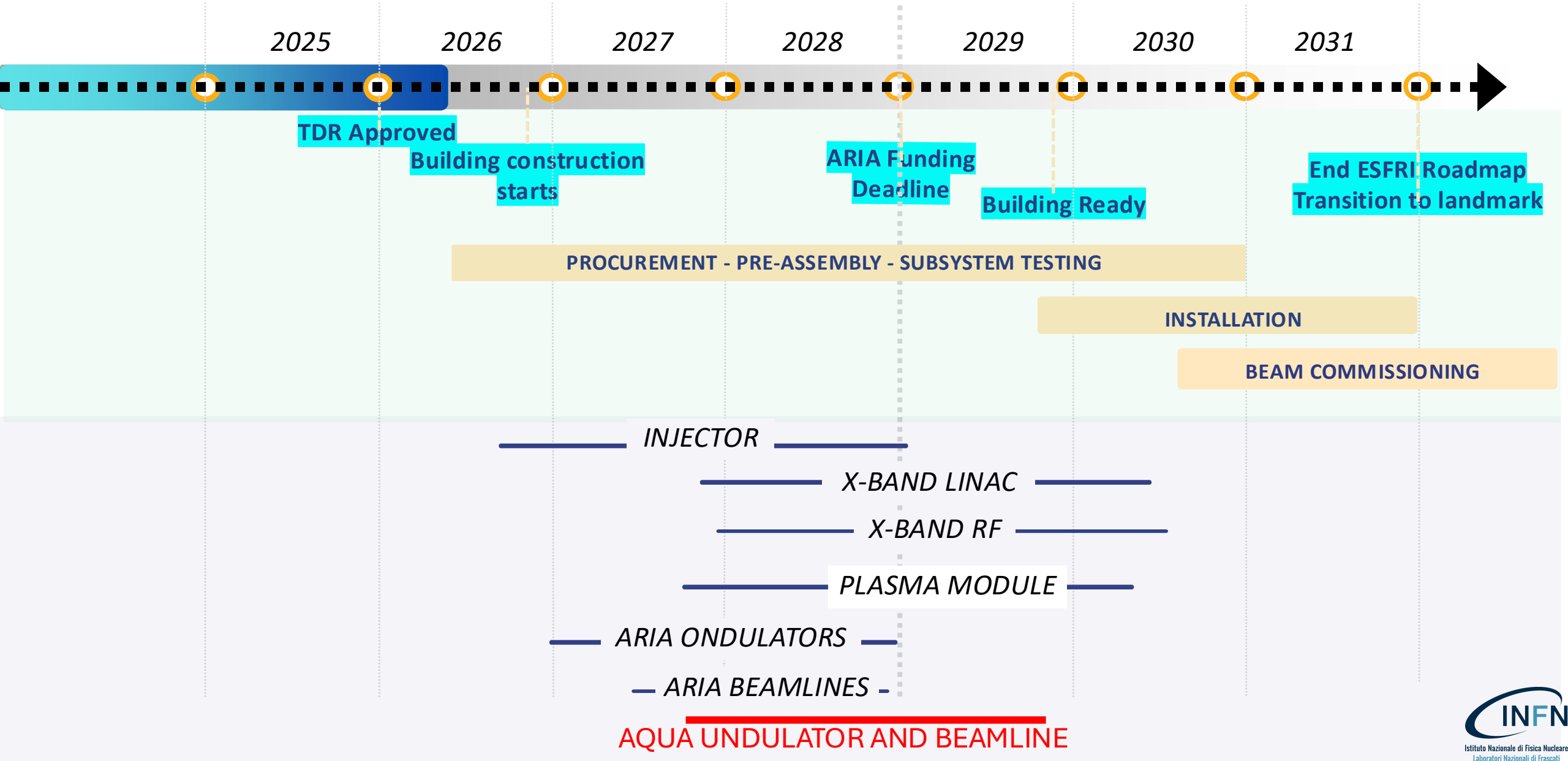
- **Plasma Density jitter dominates when discharge is not stabilized**



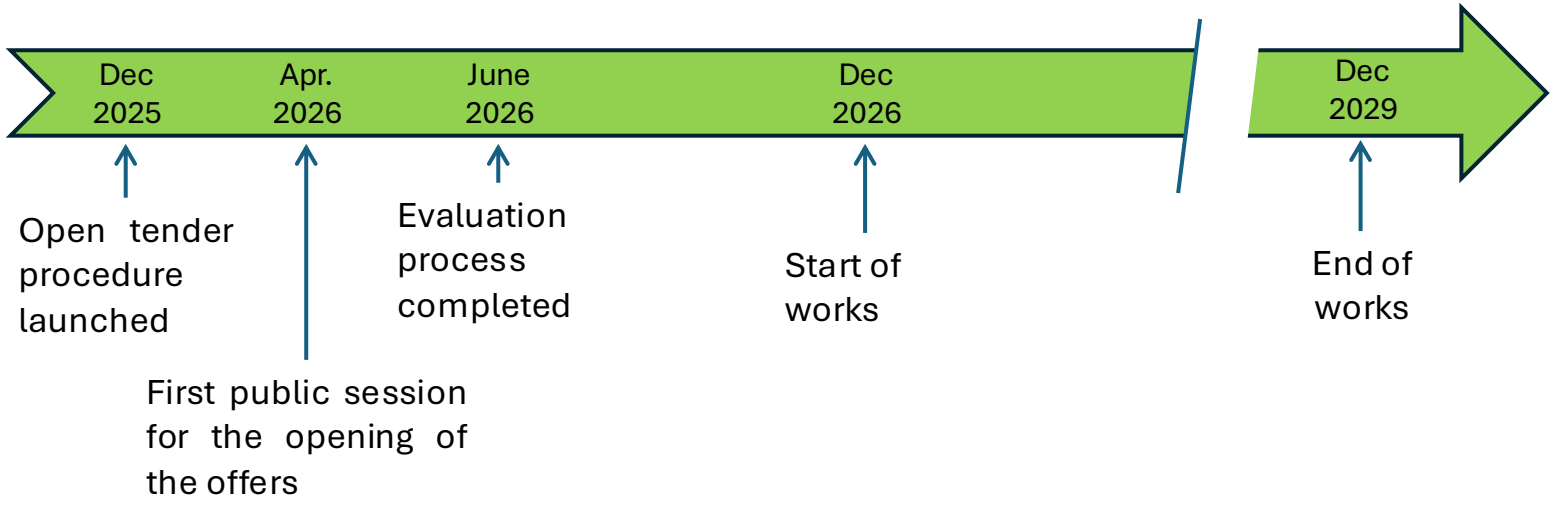
M. Galletti et al., *Symmetry* **2022**, *14*(3), 450

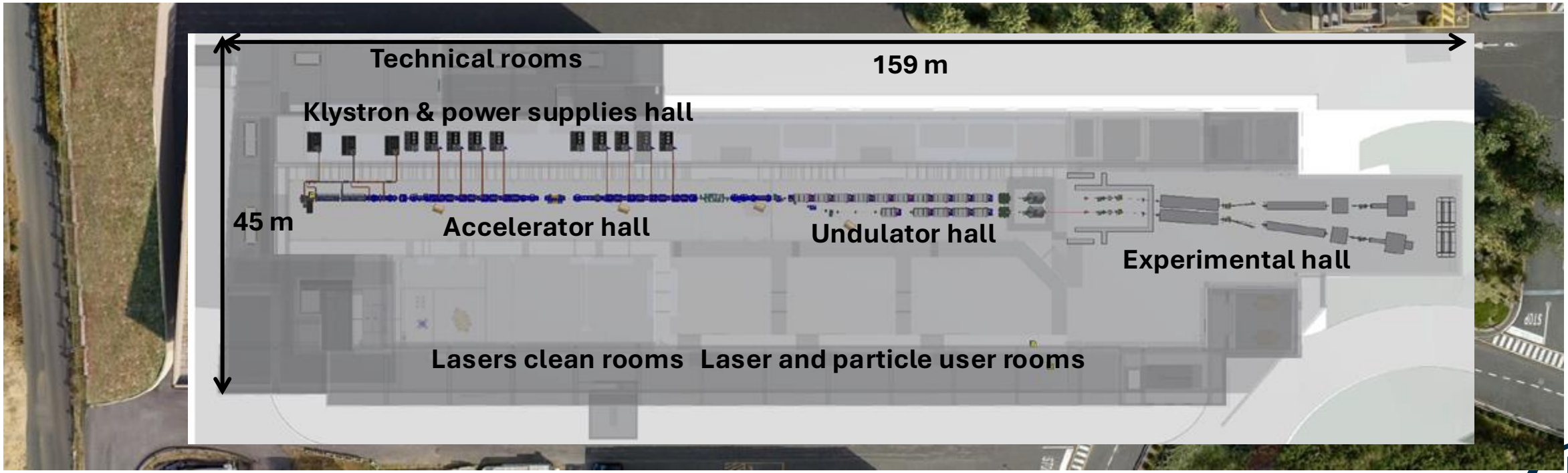
- **Charge jitter dominates otherwise → further improvements on photocathode laser and RF system**

EuPRAXIA@SPARC_LAB: **High-level Schedule**



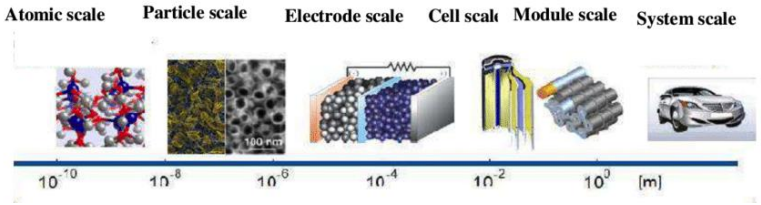
EuPRAXIA@SPARC_LAB: **High-level Schedule**

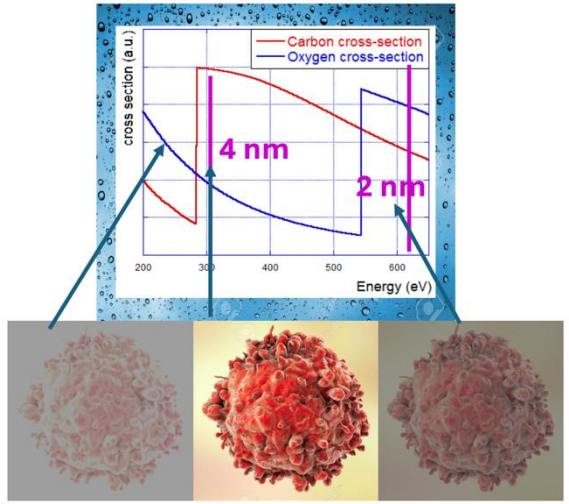


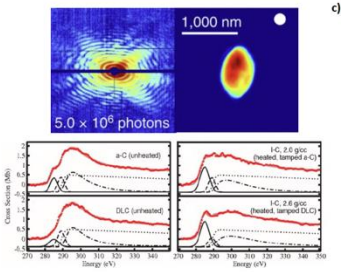


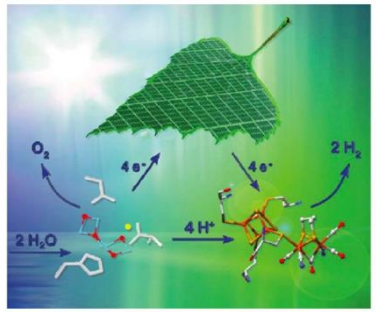
EuPRAXIA@SPARC_LAB: **User Experiments**

Application Area	Scientific Focus	Techniques	Key Impact
Renewable Energy	• Charge transport in solar cells & catalysts • Photocatalytic H_2 production • PFAS/PClAS analysis	XAS, XES, PI-MS	• Efficient solar materials • Clean hydrogen production • Environmental remediation
Warm Dense Matter (WDM)	• Extreme temperature/density • Astrophysics & fusion	Time-resolved XAS, TR-XES	• Stellar/planetary modeling • Fusion research support
Battery Technology	• Ion migration & interfaces • Solid-state battery study	XAS, non-linear X-ray spectroscopy	• Safer, longer-life batteries • High energy density
Structural Biology	• Live-cell imaging • Cellular processes (stress, DNA damage)	CDI, XAS, CEI	• Real-time biomolecular studies • Disease mechanism insight
Health & Radiobiology	• DNA damage by radiation	X-ray pump–probe, photo-fragmentation	• Radioprotection • Cancer treatment improvement
Atmospheric Chemistry	• VOC/NOx oxidation • Aerosol dynamics	PI-MS, ion spectroscopy	• Pollution models • Climate studies
Astrochemistry	• Radiation chemistry in space • Organic molecule formation	XAS, photochemistry	• Space molecular evolution









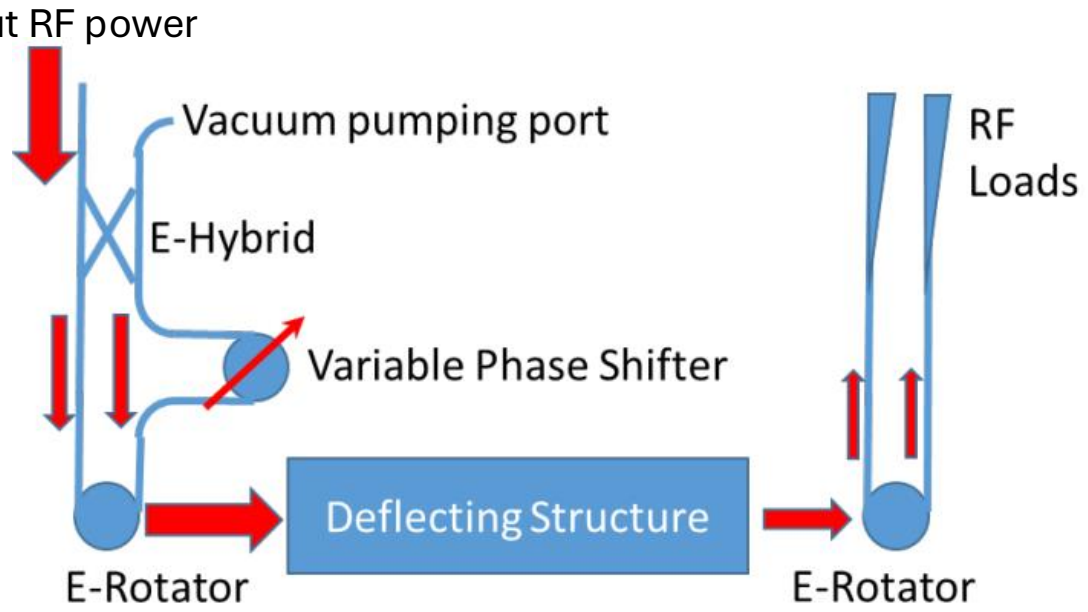
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

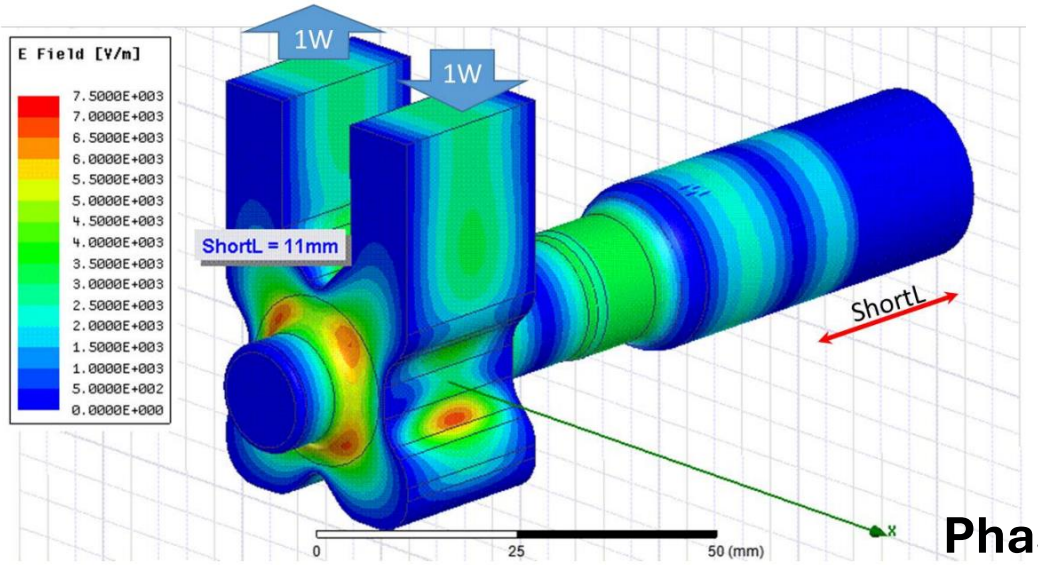
EuPRAXIA@SPARC_LAB: **Longitudinal Diagnostics**

- We will employ the state-of-the art transverse deflecting structure: PolariX

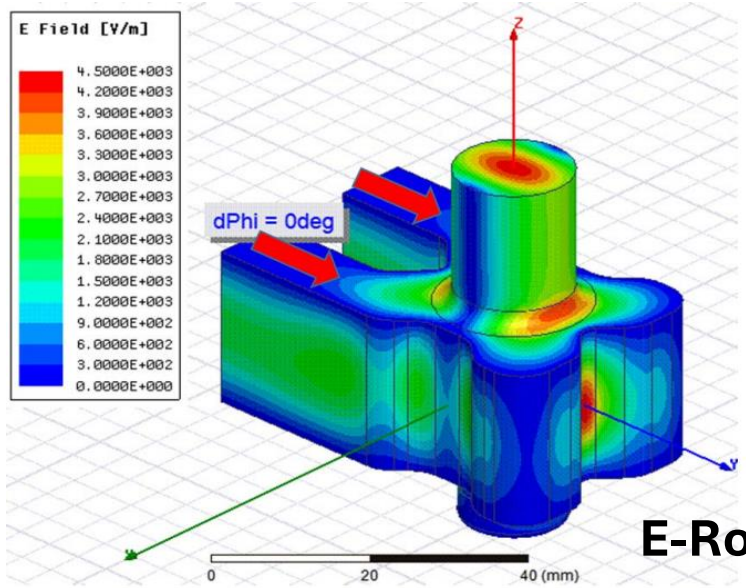
  → Adjustable streaking direction for full characterization
- Developed within a DESY–PSI–CERN collaboration and already installed and used in several facilities.

- The input RF power is split into two branches
- A variable phase shifter controls the phase difference between branches
- E-rotator recombines the waves, defining the RF input polarization





Phase Shifter



E-Rotator

F. Demurtas (Univ. Tor Vergata)

EuPRAXIA@SPARC_LAB: **Plasma Entrance Diagnostics**

- Tungsten wires are routinely used in FEL facilities for commissioning and MD
  - Measurement performed while lasing
  - Much wider beam size

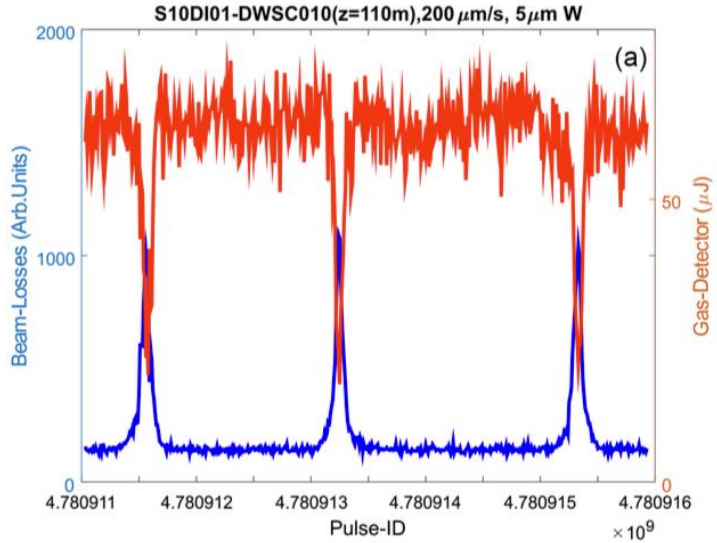
- Damage on wire due to beam energy deposition
  - Energy deposition is almost entirely due to collisional losses (no radiative losses because thickness<< X_0)
  - Each electron loses about $\Delta E_e \sim 14$ keV in 5um wire
  - $E = N\Delta E_e$

  - For $Q = 100$ pC, N $= 6.2 \times 10^8$, $E = N\Delta E_e = 1.4 \times 10^{-6}$J
  - Since there is no time for heat diffusion, the volume within which energy is deposited is ~πr^3 (round beam)
  - For Tungsten: $\rho = 19300$ kg/m3, $c = 130$ J/(kg K)

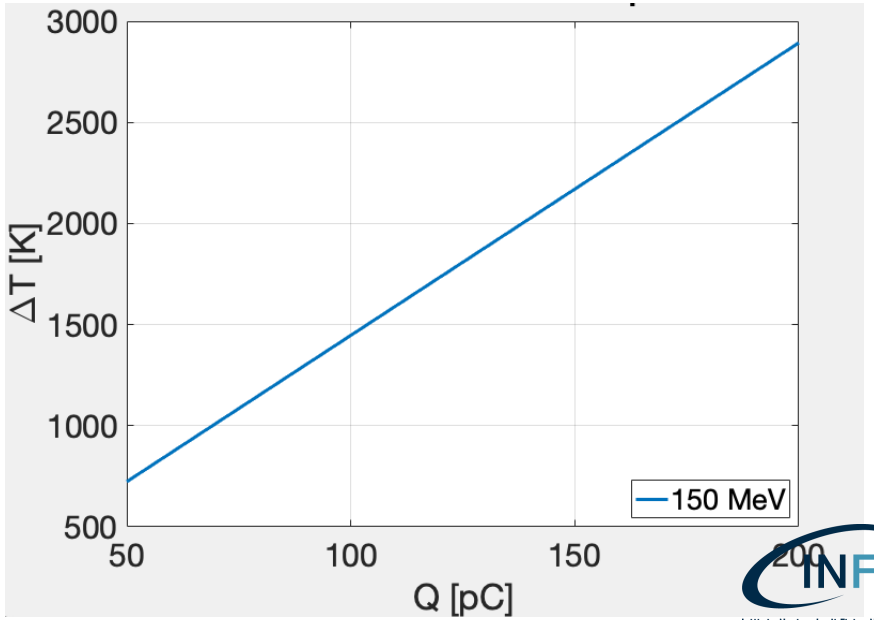
➔ $\Delta T = 1.4 \times 10^3 K$
(Melting point: 3695K)

BUT: The wire covers at most only $\pm 0.5\sigma$ ➔ only 38% of the particles interact with the wire

➔ $\Delta T \sim 532\ K$
➔ Still quite high.. And we need to include build up of temperature at 100 Hz



Orlandi et al., PRAB 23, 042802 (2020)



ESFRI: why being in the ESFRI Roadmap is important

⇒ **ESFRI** (European Strategy Forum on Research Infrastructures) **supports** the development of **EU strategic Research Infrastructures** :

- identifying priorities
- promoting the integration of national efforts
- fostering coordination and long-term sustainability

⇒ Being in ESFRI means:

- **Status** of infrastructure of **European relevance**
- **Dedicated calls:** around **30 M€** approximately dedicated to ESFRI projects and/or landmarks
- **Funding attractiveness** (e.g. PNRR – Next Gen-EU)
- Framework to **foster for international collaboration**
- Specific life-cycle to follow

⇒ The inclusion in **ESFRI roadmap lasts 10 years**, in which it is supposed to **implement the infrastructure**.

⇒ Final assessment at the end of the roadmap and **transition to the status of LANDMARK**.

⇒ Being a ESFRI Landmark implies several advantages:

- Instituzionalized framework for **mantaining the international collaboration** for upgrades and R&D
- **Dedicated calls** in the different framework program (FP10 and EIC)
- **Legal entity** able to operate autonomously on several aspects (depending on the legal framework chosen).

Conclusions

⇒ **EuPRAXIA@SPARC_LAB** is the **main project at LNF** and is entering the **implementation phase**.

⇒ It is a ambitious new research infrastructure that **pioneers the use of PWFA for a FEL user facility**.

⇒ It is a facility that also serves as an **R&D platform** for next-generation accelerators, with multiple potential applications.

⇒ The **TDR, published in Feb. 2026**, has been reviewed by the TDR Committee with a positive endorsement.

⇒ A **dedicated team** will carry forward its implementation.

⇒ EuPRAXIA@SPARC_LAB is a **pillar of the EuPRAXIA European** project, and it is essential that it remains within **ESFRI** and gains **access to the Landmark phase after 2031**.

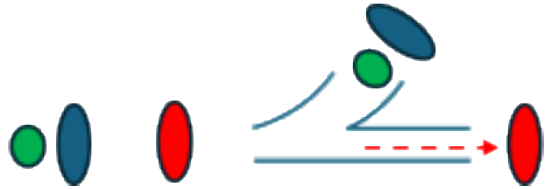
⇒ It is equally crucial to keep the **budget under control** and ensure stable cash flow; this will be possible through close **collaboration with INFN management**.

⇒ It is also important to **guarantee an adequate number of researchers, technologists, and technicians** who will be involved first in the construction phase and later in operation, maintenance, upgrades, also in connection with all other activities in which LNF is involved.

THANK YOU FOR YOUR ATTENTION!

EuPRAXIA@SPARC_LAB: **Synergies with HEP**

1) Preserve witness beam quality after separation from driver in chicane and delivery to application
   → included in Eupraxia's goals (delivery to undulators)

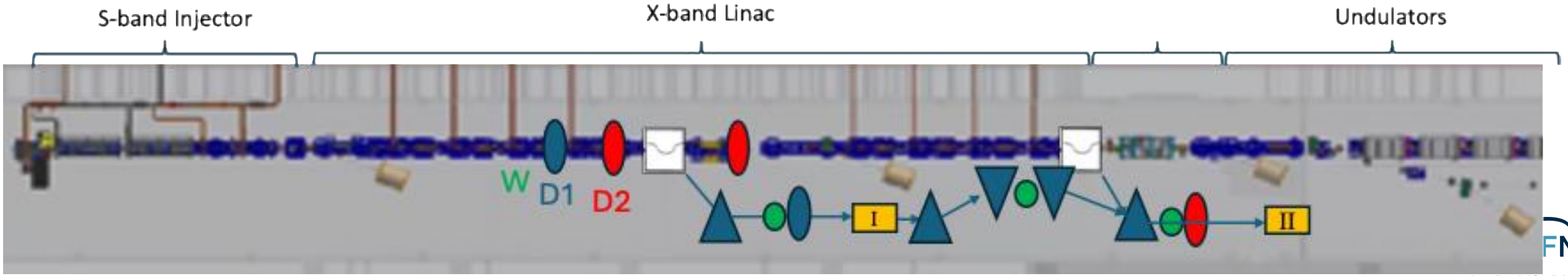


2) Development of VERY FAST deflection system for driver bunch distribution
   → Need to separate by 10's mrad bunches with ~few ps separation

   Option 1: RF kicker (benefit from experience with rings) with ~50 MV deflecting voltage and rise/decay time<<ns

   Option 2: Curved Discharge Plasma Capillary

3) Staging experiment(s)

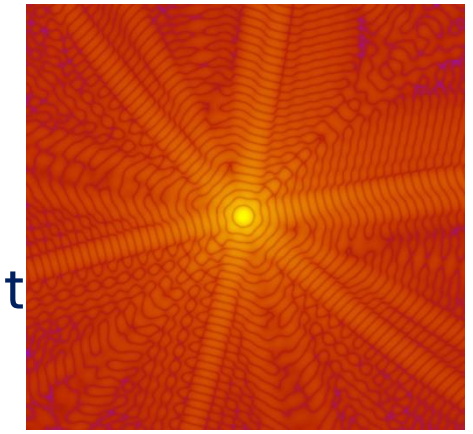


Experimental Techniques

Day-one techniques

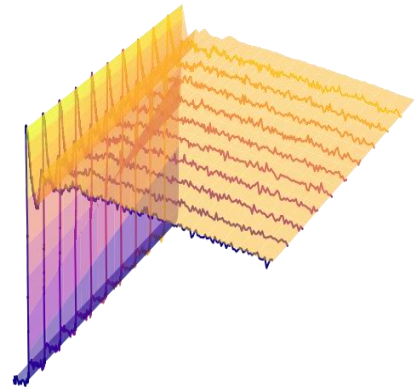
Coherent Diffraction Imaging (CDI):

- Lensless imaging of biological/non-crystalline samples.
- “Diffraction-before-destruction” approach with fs pulses.
- Single-particle imaging, pump–probe dynamics, 2D and 3D reconstruct

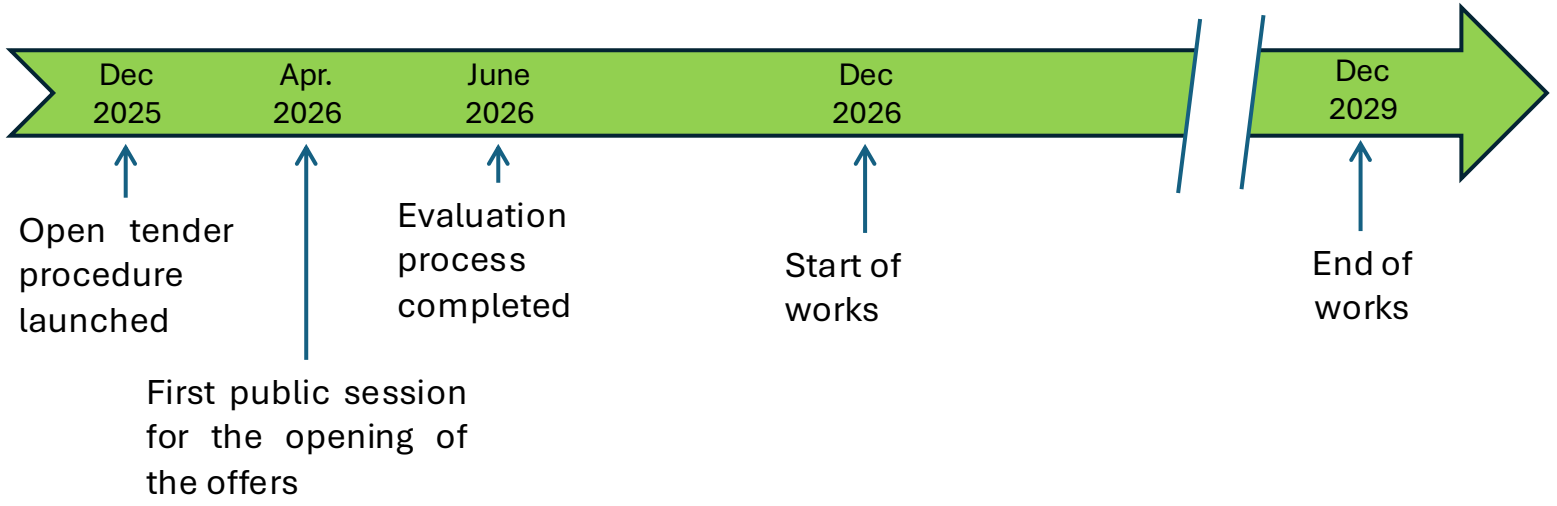


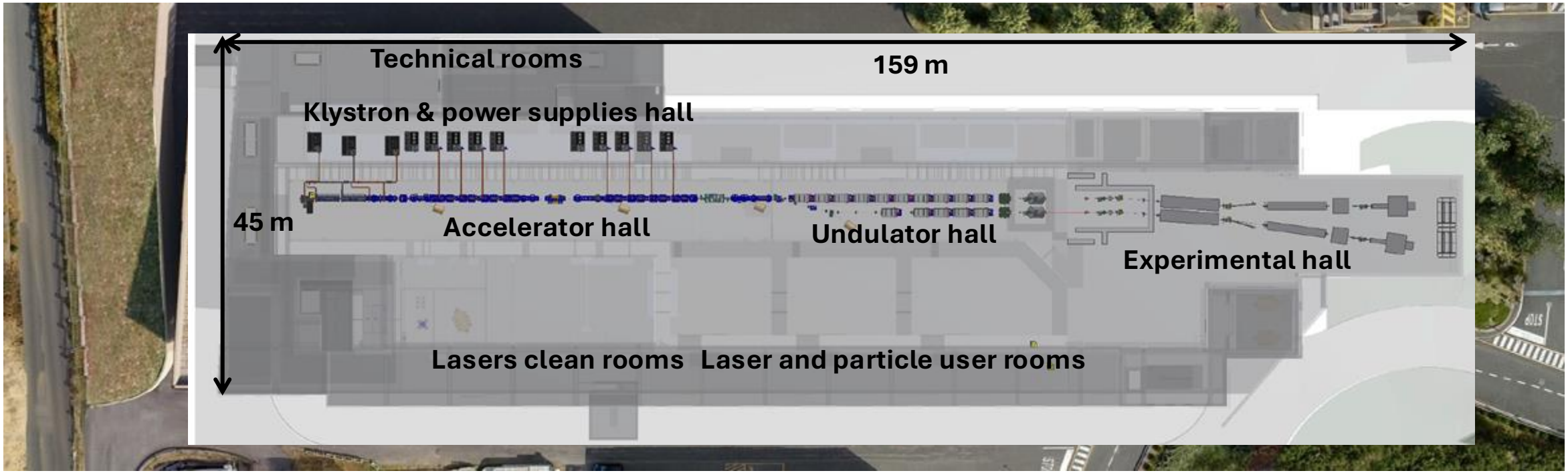
X-ray Absorption Spectroscopy (XAS):

- AQUA accessible energy range spans K, L and M edges, allowing XAS measurements on different elements.
- “Ghost spectroscopy” and correlation-based methods—ideal for SASE
- Time-resolved pump–probe studies of ultrafast processes.



EuPRAXIA@SPARC_LAB: New Building





High Level Schedule

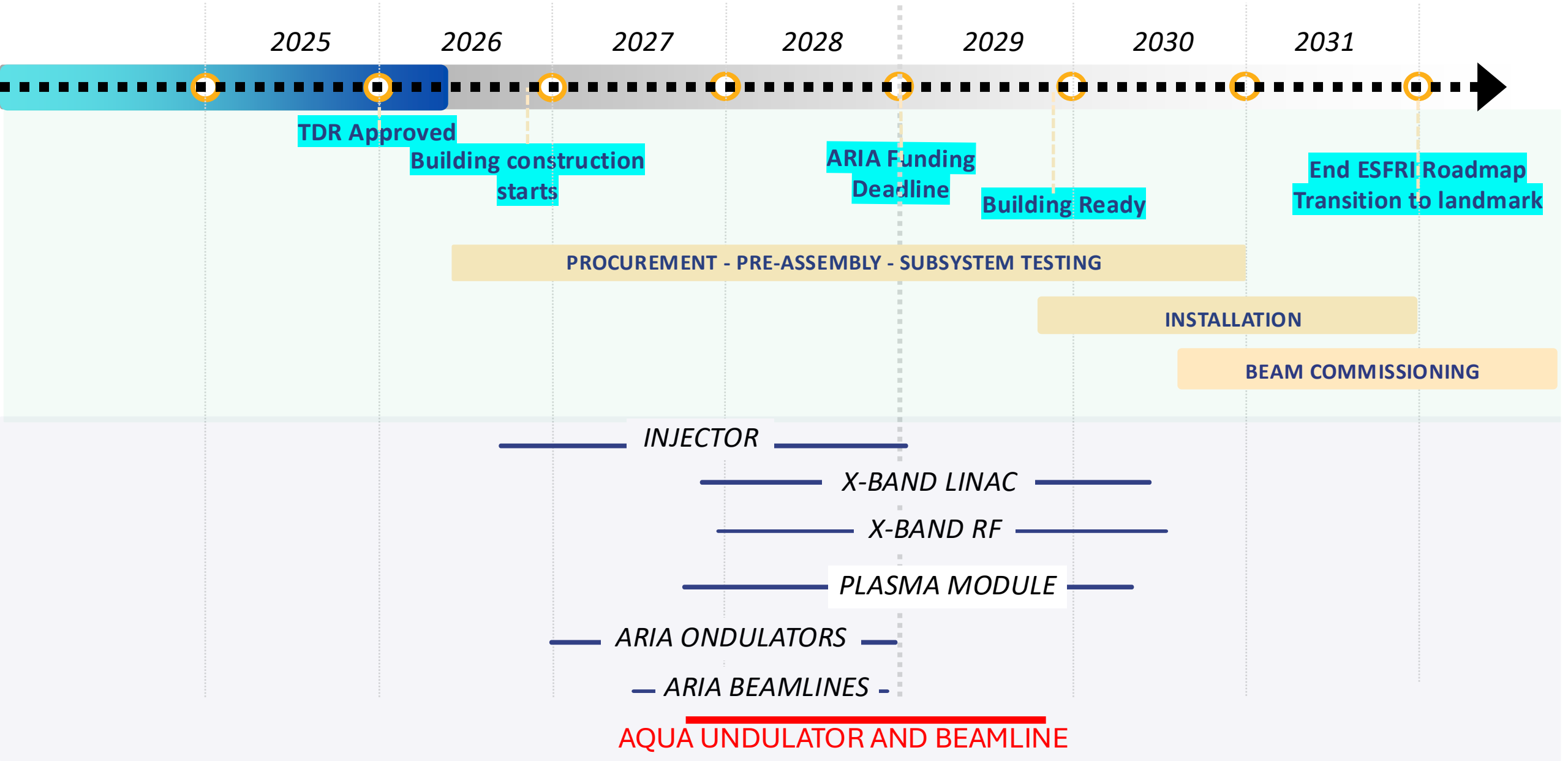


Table 1.1: Major Short-Wavelength FEL User Facilities

Facility	Location	Wavelength [nm]	Linac [km]	Energy [GeV]	RF (MV/m)	Key Features
Soft X-rays radiation						
AQUA	Frascati, Italy	3.2 – 10	<0.05	1.0	X/Plasma (60/1000)	Compact facility; targets the water window.
FLASH [56, 57]	Hamburg, Germany	4.1 – 45	0.2	1.25	L (30)	Pioneering SASE FEL; testbed for SC RF and FEL technologies.
FERMI [58]	Trieste, Italy	10 – 100	0.15	1.67	S (28)	Seeded FEL; very high spectral purity in VUV – soft X-ray region.
SXFEL [59]	Shanghai, China	1.2 – 24	0.3	1.5	S / C (27/38)	First Chinese soft X-ray FEL; seeded + SASE operation.
Hard X-ray radiation						
LCLS 1 [60]	SLAC, United States	0.13 – 6.2	1.0	14	S (25)	First hard X-ray FEL; ultrafast imaging capabilities.
European XFEL [61]	Hamburg, Germany	0.05 – 4.7	2.1	17.5	L (24)	High rep-rate; multi-beamline architecture.
SACLA [62]	Harima, Japan	0.06 – 0.2	0.4	8.5	C (38)	Compact design; hard X-ray operation.
SwissFEL [63]	Villigen, Switzer-land	0.1 – 5.0	0.5	5.8	C (28)	Two beamlines covering soft + hard X-ray.
PAL-XFEL [64]	Pohang, South Korea	0.06 – 4.5	0.78	10	S (27)	Covers both soft and hard X-ray.
SHINE/ HXFEL [65]	Shanghai, China	0.06 – 0.3	1.2 – 1.5	8 – 12	S (27)	High-repetition-rate hard X-ray FEL; multibeamline; under commissioning.

Table 1.2: Main application areas, associated scientific focus, experimental techniques, expected impact, and planned implementation phase.

Application Area	Scientific Focus	Techniques	Phase	Key Impact
Atomic, Molecular, and Optical Physics	Ultrafast electron dynamics, core-level excitation, fragmentation pathways	Time-resolved photoabsorption, photoemission, ion/electron spectroscopy (time-of-flight (TOF), velocity map imaging (VMI)), Coulomb explosion imaging	**P1**	Fundamental insights into charge migration, excited-state dynamics, and molecular structure
Ion & Electron Spectroscopy (Gas Phase)	Ionization and fragmentation of molecules, clusters, aerosols; selected environmental and astrochemical model systems	Photo-ionization mass spectroscopy (PI-MS), TOF detectors, momentum imaging	**P1**	Proof-of-principle user experiments; benchmarking FEL performance and machine stability
Warm Dense Matter	Non-equilibrium states, ultrafast structural transitions, electron–ion equilibration	Time-resolved XAS/XES	**P2**	Advances in planetary science, dense plasmas, and fusion-relevant materials
Biology & Soft-Matter Imaging	CDI of hydrated biological specimens (viruses, macromolecular assemblies)	CDI, and single-pulse "diffraction-before-destruction"	**P2**	High-resolution reconstructions in the water window; foundations for future bio-imaging program

Table 1.3: Electron beam and FEL radiation main parameters at the undulator entrance for the two considered machine configurations: plasma acceleration (PWFA) and conventional (Full RF) one. For both the two configurations we reach saturation inside the undulator length at $\lambda_r = 4$ nm with the expected number of photons per second.

	Units	PWFA Velocity bunching	Full RF Velocity Bunching + Magnetic Compression
Electron Energy	GeV	1	1
Repetition Rate	Hz	100	100
Bunch charge	pC	30	200
Peak current	kA	3.3	3.4
RMS bunch length	μm	1.4	16.9
RMS normalized emittance (x,y)	mm mrad	0.7, 0.7	2.1, 1.0
RMS energy spread	%	0.5	0.2
Slice length	μm	0.5	0.5
Slice normalized emittance (x,y)	mm mrad	0.7, 0.7	0.3, 0.3
Slice energy spread	%	0.04*	0.02
ρ 3D	$\times 10^{-3}$	0.77	1.49
Radiation wavelength	nm	4.06	4.06
Saturation length	m	20.5	20.0
Photon Pulse Energy	μJ	16	150
Photon per pulse	$\times 10^{11}$	3.2	31.3
Photon pulse length (FWHM)	fs	2.33	33.0
Photon bandwidth	%	0.4	0.5
Average photon brilliance	$\#\times 10^{30}$	0.12	2.1

$\#= N_{phot}/s/m^2/rad^2/0.1\%bw$.

Table 3.11: Undulator parameters for $\lambda_r = 4$ nm at 1 GeV

Parameter	Value
λ_w	1.8 cm
K_{rms}	0.84
Electron energy	1 GeV
λ_r	4 nm
Quadrupole gradient	8 T/m
tapering	step-like, see Table 3.8
polarization	circular

Table 3.3: Reference input parameters at the injector for comb beam production.

Parameter	Symbol	Unit	Value
Number of bunches			2
Witness Charge	Q_W	pC	30
Driver Charge	Q_D	pC	200
RMS Laser pulse length (W/D)	σ_t	fs	350/550
RMS Laser pulse spot size (W/D)	σ_r	μm	175/285
Laser pulses separation at the cathode	Δt	ps	4.8
Peak electric field on the cathode	E_{acc}	MV/m	120
Solenoid center longitudinal position (with respect to cathode)		m	0.204
Solenoid peak field	B_{max}	T	0.38
S1-S2 average accelerating field	E_{acc}	MV/m	21
S3-S4 average accelerating field	E_{acc}	MV/m	35

Table 3.7: Main radiation parameters for the reference beam (PWFA case). Case with 200 pC of charge in the driver and 30 pC in the witness. Without tapering (column 3) and with the tapering of Table 3.8 (column 4). In bold, the nominal working point with plasma acceleration.

Parameter	(Unit)	Without tapering	With tapering
Radiation wavelength	nm	4.05	**4.06**
3-D ρ	$\times 10^{-3}$	0.77	**0.77**
3-D gain length	m	1	**1**
3-D cooperation length	μm	0.26	**0.26**
Pulse energy	μJ	6.5	**15.8**
Photon number	$\times 10^{11}$	1.31	**3.22**
Saturation length	m	22	**20.5**
Bandwidth	%	0.48	**0.44**
Transverse size	μm	220	**230**
Divergence	μrad	34	**34**
FWHM length	μm	4.8	**0.7**
FWHM time duration	fs	16	**2.33**
Average brilliance	$\# \times 10^{30}$	0.048	**0.12**
x,y displacements	μm	-12.1, 7	**4.58, 6.7**
x,y angular deviation	μrad	0.93, 1.15	**0.07, 8.6**

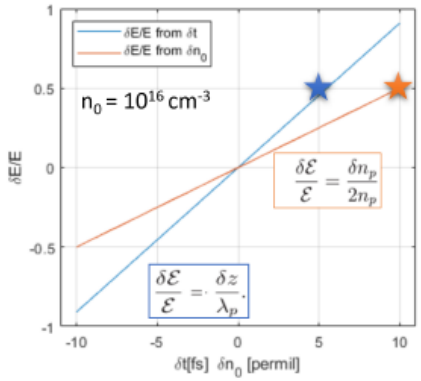
$\#= N_{phot}/s/m^2/rad^2/0.1\%bw$.

Table 3.8: Undulator parameter values of the various sections in the case of step-tapering.

Undulator	1	2	3	4	5	6	7	8	9	10
K_{rms}	0.84	0.84	0.84	0.84	0.8392	0.8384	0.8376	0.8368	0.836	0.8352

Table 3.2: Electron beam parameters at plasma entrance for the reference working point.

Parameter	Symbol	Unit	Witness	Driver
Charge	Q	pC	30	200
Energy at plasma module entrance	E	MeV	562.5	563.8
RMS energy spread	$\Delta\gamma/\gamma$	(%)	0.06	0.13
RMS normalized emittance	ε_n	mm mrad	0.7	1.6
RMS bunch length	σ_z	μm	5.4	46
Slice length	$\sigma_{z-slice}$	μm	0.50	0.50
Slice peak current	$I_{peak-slice}$	kA	2.1	0.5
Witness-Driver separation	Δl	μm	162	-



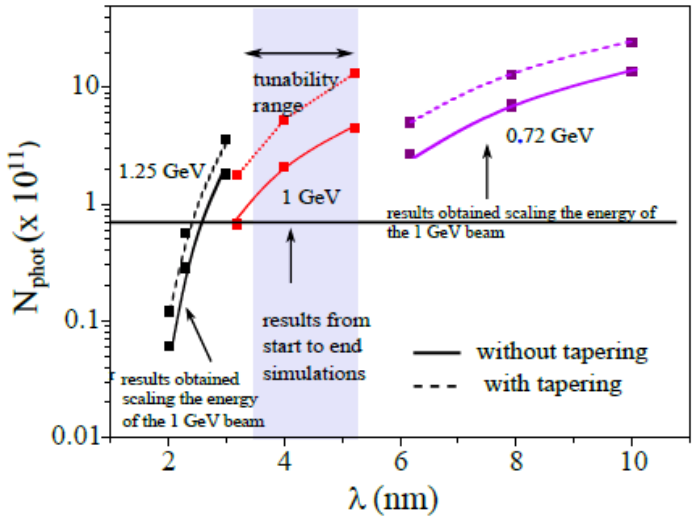


Figure 3.15: Analytical evaluation of the plasma vs the linac contribution to energy gain jitter at the plasma exit [7]. The stars represent the contribution to the energy spread due to the 5 fs jitter of the witness and driver temporal separation (blue) and the contribution due to the 1% plasma density variation (orange)

Table 3.9: Summary of jitter values used in the sensitivity analysis. The quantities are intended as RMS values, except for charge and spot size of the cathode laser system, which are instead drawn from uniform distributions and oscillate within the indicated range.

Subsystem	Parameter	Symbol	Jitter
S-band Gun and Accelerating Sections	RF Voltage	ΔV	0.02 %
	RF Phase	$\Delta\phi$	0.02°
X-band Accelerating Sections	RF Voltage	ΔV	0.02 %
	RF Phase	$\Delta\phi$	0.10°
Plasma Accelerator	Density	n_0	1%
Cathode Laser System	Time of arrival	Δt	20 fs
	Charge	ΔQ	±1 %
	Spot size	$\Delta\sigma$	±1 %

Table 3.10: Statistical values of the whole witness bunch main parameters at the beginning of the undulator. All quantities are averaged over 100 events.

Parameter	Units	Value	Absolute error	Relative % error
Charge	pC	29.51	0.06	0.2
Electron energy	GeV	1.001	0.011	1.1
γ		1959.5	22	1.1
Peak current	kA	3.075	0.6	19
(x,y) proj. norm. emittance	mm mrad	0.68, 0.67	0.023, 0.021	3.4, 3.1
(x,y) slice emittance	mm mrad	0.73, 0.69	0.22, 0.2	30, 29
Proj. energy spread	%	0.44	0.02	4.5
Slice energy spread	%	0.26	0.05	19
x,y rms dimension	µm	43.4, 43.4	10.4, 16.2	24, 37

Table 3.12: 3-D Theoretical radiation parameters (Pierce parameter ρ, gain and cooperation length) as given by the Ming Xie analytical analysis [5]) and averaged radiation simulation results (PWFA case) for $\lambda_r = 4$ nm at 1 GeV.

Parameter	Unit	No tapering	RMS Error	With tapering	RMS Error
3-D ρ	$\times 10^{-3}$	0.66	0.46	0.66	0.46
3-D gain length	m	1.98	1.72	1.98	1.72
3-D cooperation length	µm	0.3	0.06	0.3	0.06
Pulse energy	µJ	10.54	5.2	25.54	11.6
Photon number	$\times 10^{11}$	2.1	1	5.26	2.33
Saturation length	m	20.5	2	20.16	1.3
Peak wavelength	nm	4.003	0.085	4.003	0.085
Bandwidth	%	0.37	0.09	0.27	0.06
Transverse size	µm	150	41	160	43.4
Divergence	µrad	28.5	4.2	30.31	4.3
FWHM length	µm	3.55	2.2	1.7	0.8
FWHM time duration	fs	11.7	7.3	5.6	2.6
Average brilliance	#$\times 10^{30}$	0.77	0.92	1.66	1.39
x,y displacements	µm	-11.1, 2.5	10, 9	-11.9, 6.2	4.2, 6.2
x,y angular deviation	µrad	2.7, 10.6	5, 4.6	6, 8.6	4, 2.9

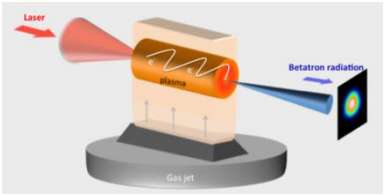
#= N_{phot}/s/m^2/rad^2/0.1%bw.

Table 3.13: 3-D Theoretical radiation parameters (Pierce parameter ρ, gain and cooperation length) as given by the Ming Xie analytical analysis [5]) and statistical values of FEL radiation parameters (PWFA case): average values over the 100 events. Random displacements in x and y (Gaussian distribution with rms width equal to 50 µm) and angular deviations in x and y (Gaussian distribution of θ_x and θ_y with rms width of 25 µrad) have been superimposed to the 100 shots of the electron beam ensemble, leading to an increase in the deviations of the displacement and exit angle of the radiation.

Parameter	Unit	No tapering	RMS Error	With tapering	RMS Error
3-D ρ	$\times 10^{-3}$	0.66	0.46	0.66	0.46
3-D gain length	m	1.98	1.72	1.98	1.72
3-D cooperation length	µm	0.3	0.06	0.3	0.06
Pulse energy	µJ	5.81	3.8	10.2	6.9
Photon number	$\times 10^{11}$	1.16	0.76	2.04	1.37
Saturation length	m	22.9	1.6	23.4	1.2
Bandwidth	%	0.59	0.18	0.48	0.16
Transverse size	µm	175	52.5	178	45
Divergence	µrad	33.5	5.8	36	5.2
FWHM length	µm	2.1	1.5	1.3	0.44
FWHM time duration	fs	7	5	4.2	1.5
Average brilliance	#$\times 10^{30}$	0.22	0.36	0.17	0.2
x,y displacements	µm	0.14, 15.5	127, 66	9, 15	132, 50
x,y angular deviation	µrad	0.7, 1.1	20, 14	3, 2	23, 9.6

#= N_{phot}/s/m^2/rad^2/0.1%bw.

Betatron Radiation Source



SCIENCE CASE

Single-shot **phase-contrast imaging**

Ultrafast **structural dynamics**

Incoherent broadband applications

SOURCE PARAMETERS

Source size	< 2 μm
Divergence	~ 10 mrad half-angle
Pulse duration	~ 10 fs
Critical energy	> 10 keV
Peak brightness	~ 10^{23} ph/s/mm^2/mrad^2/0.1%BW
Repetition rate	3 Hz (L3 Laser)

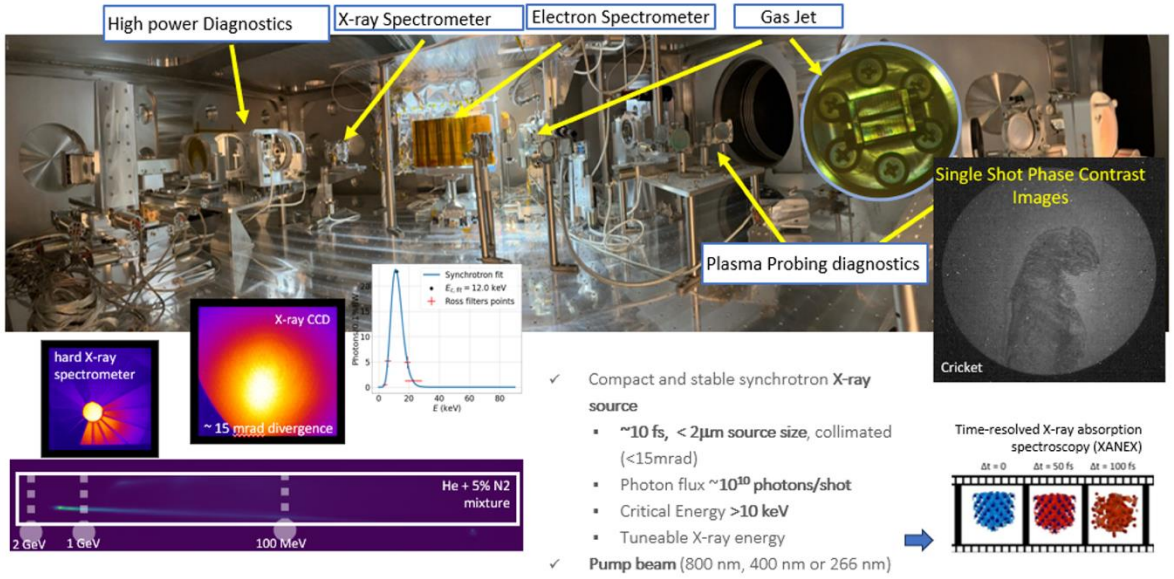
CURRENT STATUS

User-operation ongoing using L3 laser

3 Hz GeV-class electron beam was demonstrated

Proof-of-principle for **ultrafast X-ray imaging**

Technology Readiness at ELI Beamlines



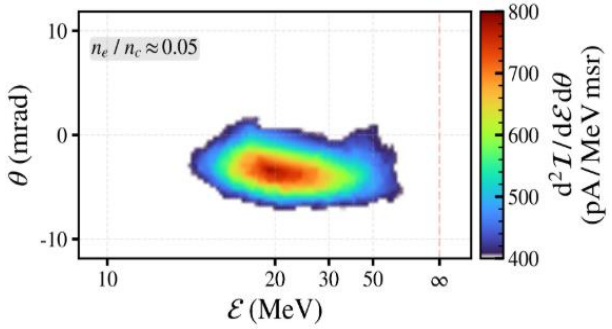
Positron Source:
Ultrafast Science with Antimatter

Unique at ELI ERIC

kHz repetition rate + sub-ps pulses

PALS regime not reachable at conventional sources

L1 laser: 30 mJ / 1kHz



Measured energy spectrum of the electron beam

Applications

Positron Annihilation Lifetime Spectroscopy

Defect characterisation in materials at unprecedented time resolution

Studies of open volumes in polymers, semiconductors, and metals

Key parameters

~ **50 MeV** electron driver energy (kHz LWFA)
Bethe-Heitler pair production in thin converter foil

~ **10^7 e^+/shot** at kHz repetition rate with sub-ps bunch duration

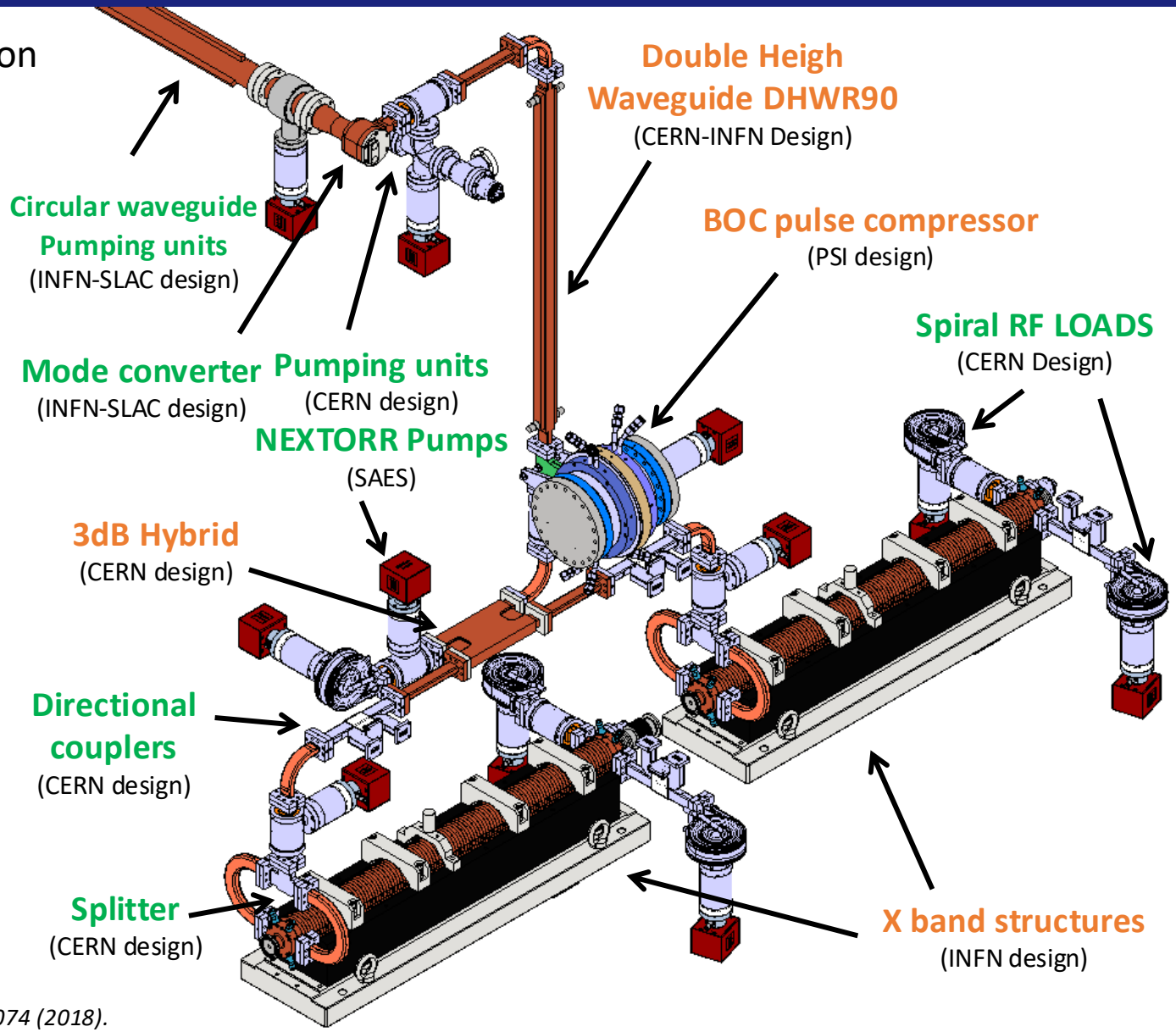
L1-laser + ALFA stations

Conceptual design of the LPA-based positron setup is under preparation.

R&D of X-band Components

The R&D activity has been carried out in close collaboration with international laboratories, including CERN, PSI and SLAC. Summary of the testing activities:

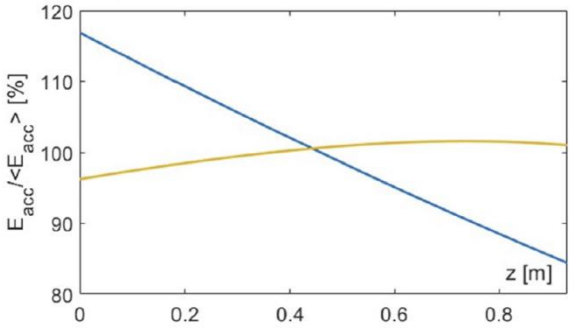
COMPONENT	DESIGN	STATUS	HIGH POWER TEST
Pump unit (rect. wav.)	CERN	Fabricated and installed @ TEX	45 MW, 1 μs, 50 Hz
Directional coupler	CERN	Fabricated and installed @ TEX	45 MW, 1 μs, 50 Hz
Splitter	CERN	Fabricated and installed @ TEX	35 MW, 0.6 μs, 50 Hz
RF load	CERN	Fabricated and installed @ TEX	17 MW, 0.6 μs, 50 Hz, P_{avg} = 0.5 kW
Mode converter circular/rectangular	INFN/ SLAC	Fabricated and Installed @ TEX	21 MW, 1 μs, 50 Hz
Pump unit (circ. waveg.)	INFN/ SLAC	Fabricated and Installed @ TEX	21 MW, 1 μs, 50 Hz
3dB hybrid	CERN	Delivered	To be tested
BOC pulse compressor	PSI	Delivered and installed @ TEX	Test ongoing
Double height waveguide	INFN/ CERN	Under realization	To be tested

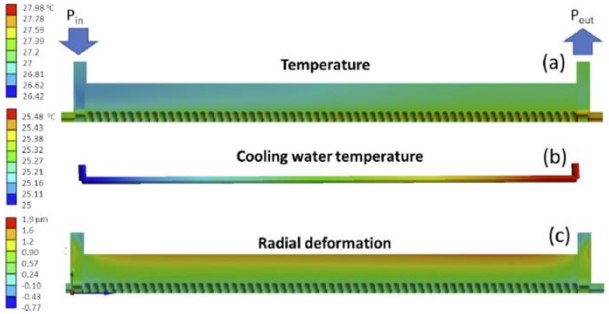


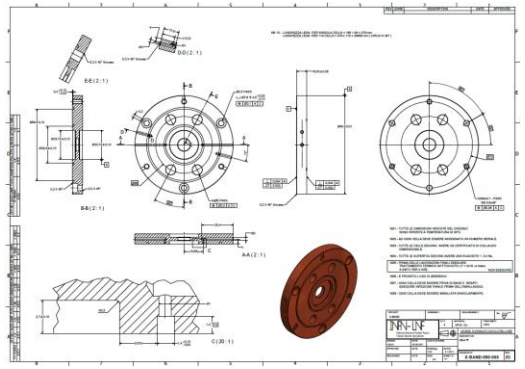
N. Catalan-Lasheras, et al., 9th Int. Particle Accelerator Conf. Vancouver, Canada, paper WEPMF074 (2018).
S. Tantawi, et all. (2000). Reviews of Modern Physics – doi: 10.1103/PhysRevSTAB.3.082001
F. Cardelli et all. The European Physical Journal Special Topics (2025). – doi: 10.1140/epjs/s11734-025-01828-0

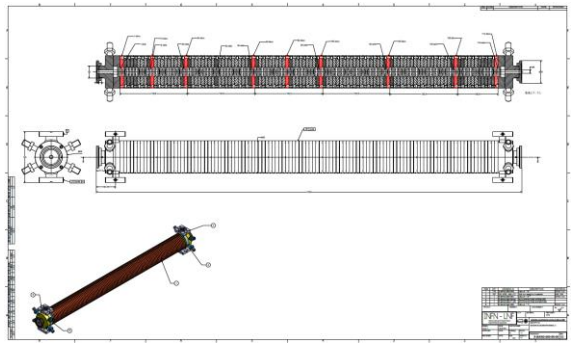
X-band Structure

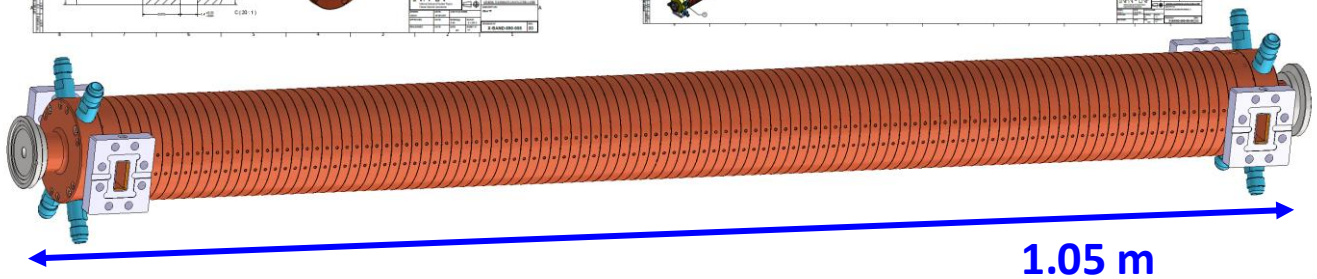
- The **EM design of the structure is completed**: **≈1m long** structures with **3.5 mm average iris radius** design to work with an average acceleration gradient of **60 MV/m.**
- **Thermo-mechanical simulations** to demonstrate the correct sizing of the cooling system (at 100 Hz and 400 Hz)
- Final **mechanical design** and **prototyping activity**: brazing test, cell to cell alignment, etc





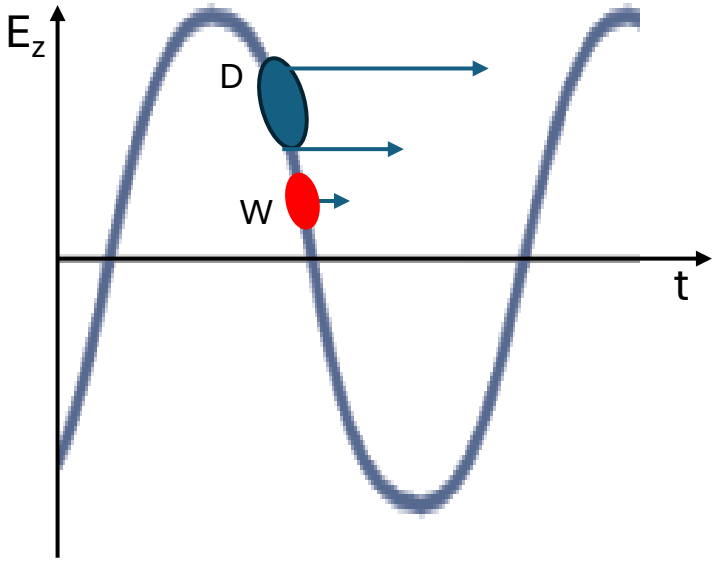






PARAMETER	Value	
	Quasi-Constant Gradient	Constant Impedance
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85 - 3.15**	**3.5**
Tapering angle [deg]	0.04	0
Structure active Length [m]	**0.94**	
No. of cells	113	
Shunt impedance R [MΩ/m]	93-107	100
Effective shunt Imp. R_{sh_eff} [MΩ/m]	350	347
Peak input power per structure [MW]	70	
Input power aver. 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
Required Kly power per module [MW]	**22.5**	
Kly RF pulse length [μs]	**1.5**	
Repetition Rate [Hz]	**100**	

M. Diomede et al. NIM A 909 (2018) 243–246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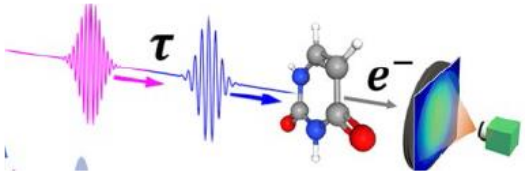
t

ARIA beamline scientific case

Defining experimental techniques and typology of samples (and applications)

Photoemission Spectroscopy



Photoelectron Circular Dichroism

Raman spectroscopy

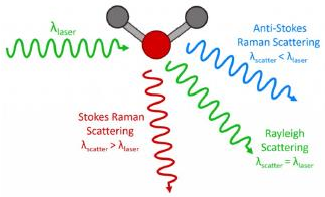
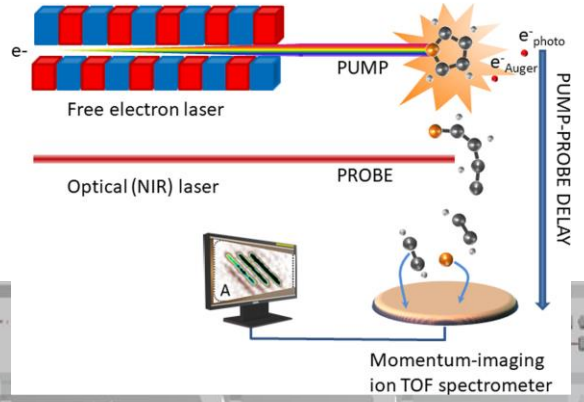
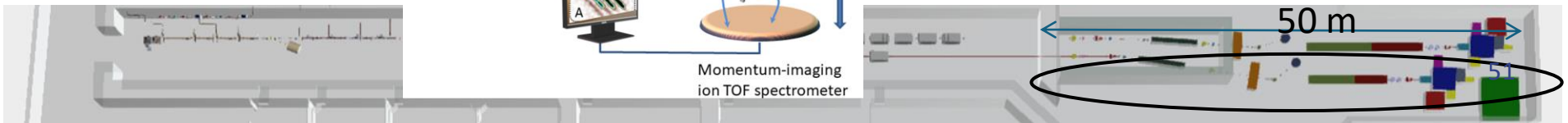


Photo-fragmentation of molecules
Time of Flight Spectroscopy





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