

PWFA Research at SPARC_LAB for EuPRAXIA

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(on behalf of EuPRAXIA Collaboration)

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EuPRAXIA@SPARC_LAB

A New European Plasma-Based User Facility

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

Main arguments:

- **FEL is the most challenging application besides colliders**
- **There is a general need for ultrashort X-ray sources**
- **Test-bed for PWFA and for X-band technology**
- **Pan-European endeavor**

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



CERN Courier, May 2023



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



Several National Nodes. Roles
to be fully defined

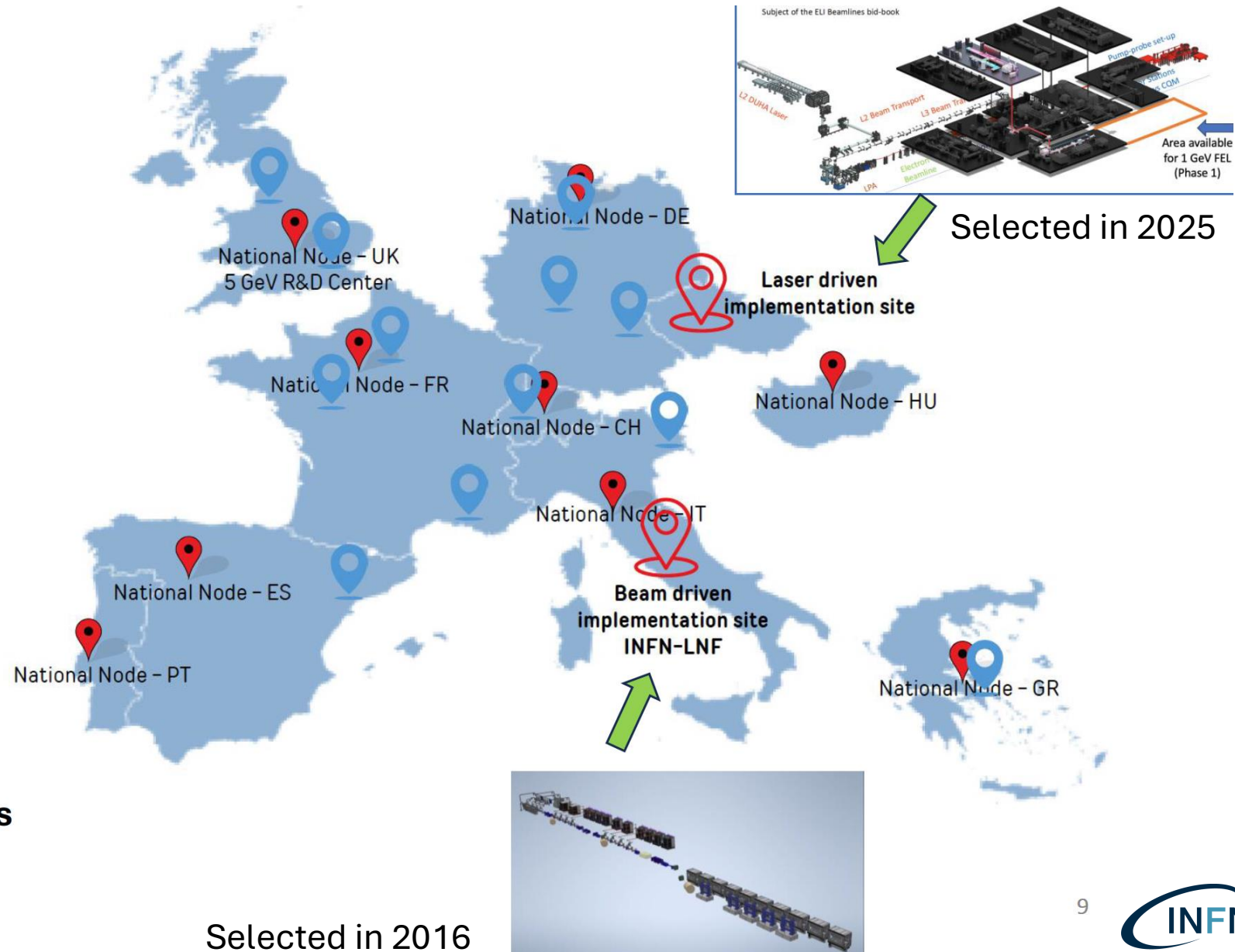


Project Clusters

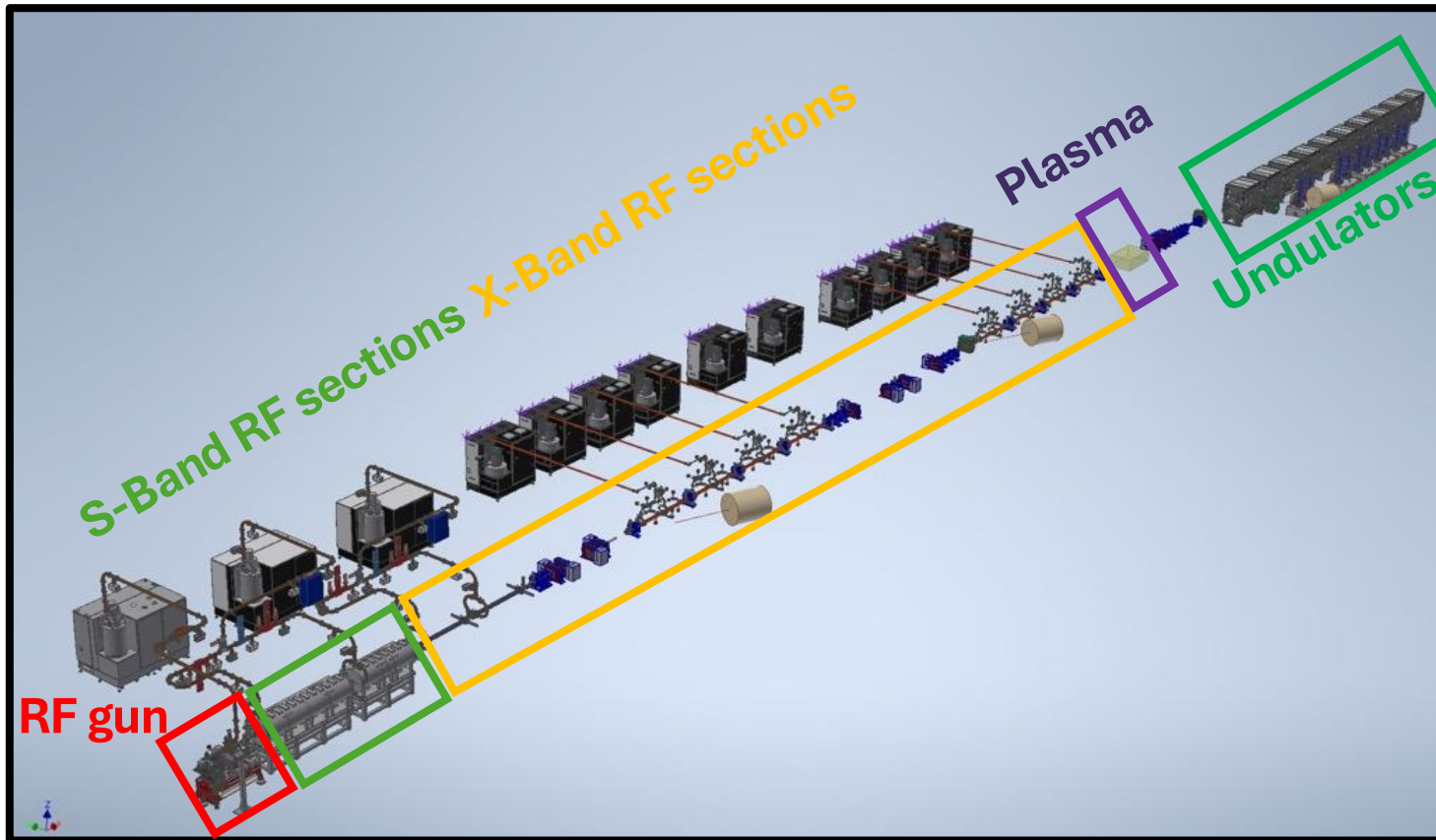
A large collection of European
know-hows in accelerators, lasers and
plasma technologies

Network organization

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



- Soft X-ray ($\sim 4\text{nm}$) 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 $\sim$ end of 2026
 - Installation starting $\sim$ 2029
 - Commissioning starting $\sim$ 2030



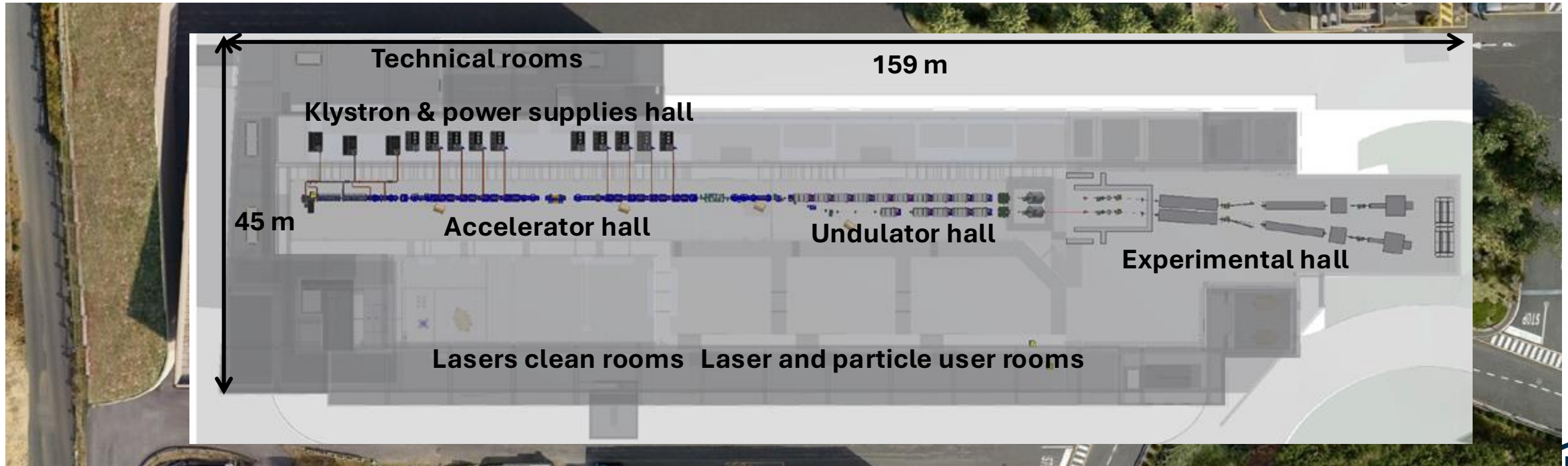
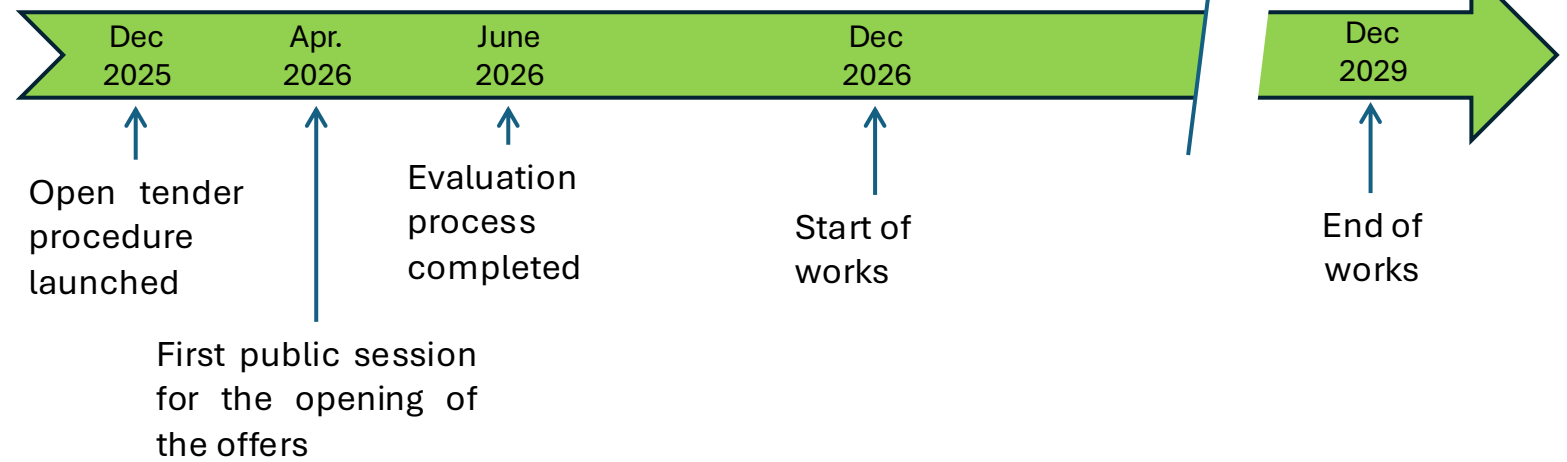
User-oriented plasma-based FEL



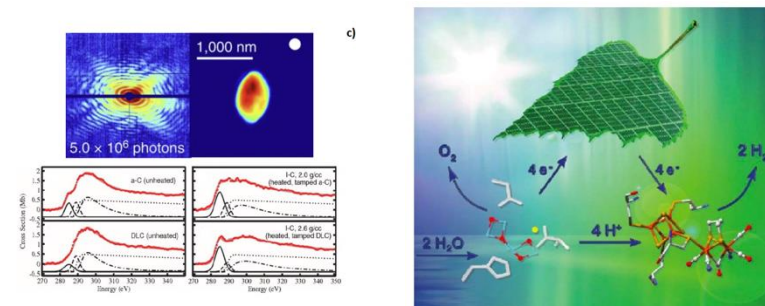
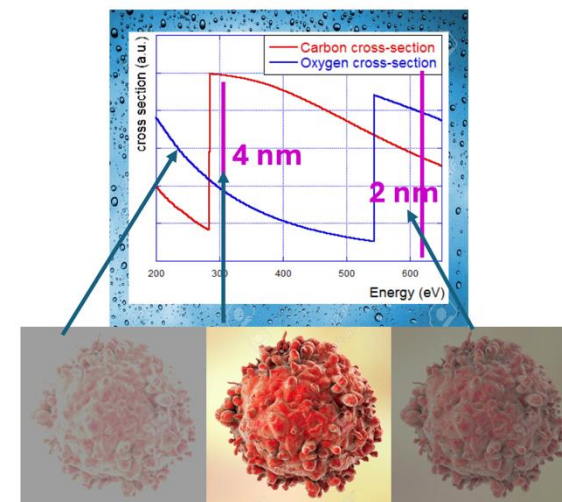
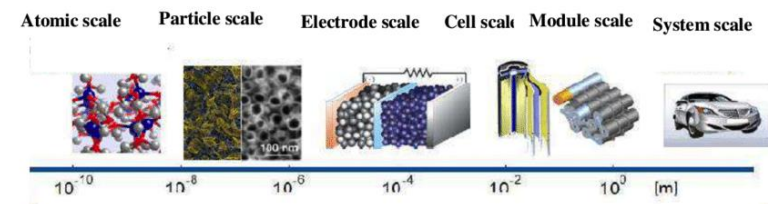
**Transition from experiment to “real”
accelerator
Building up from results and expertise from
SPARC**

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

EuPRAXIA@SPARC_LAB: High-level Schedule



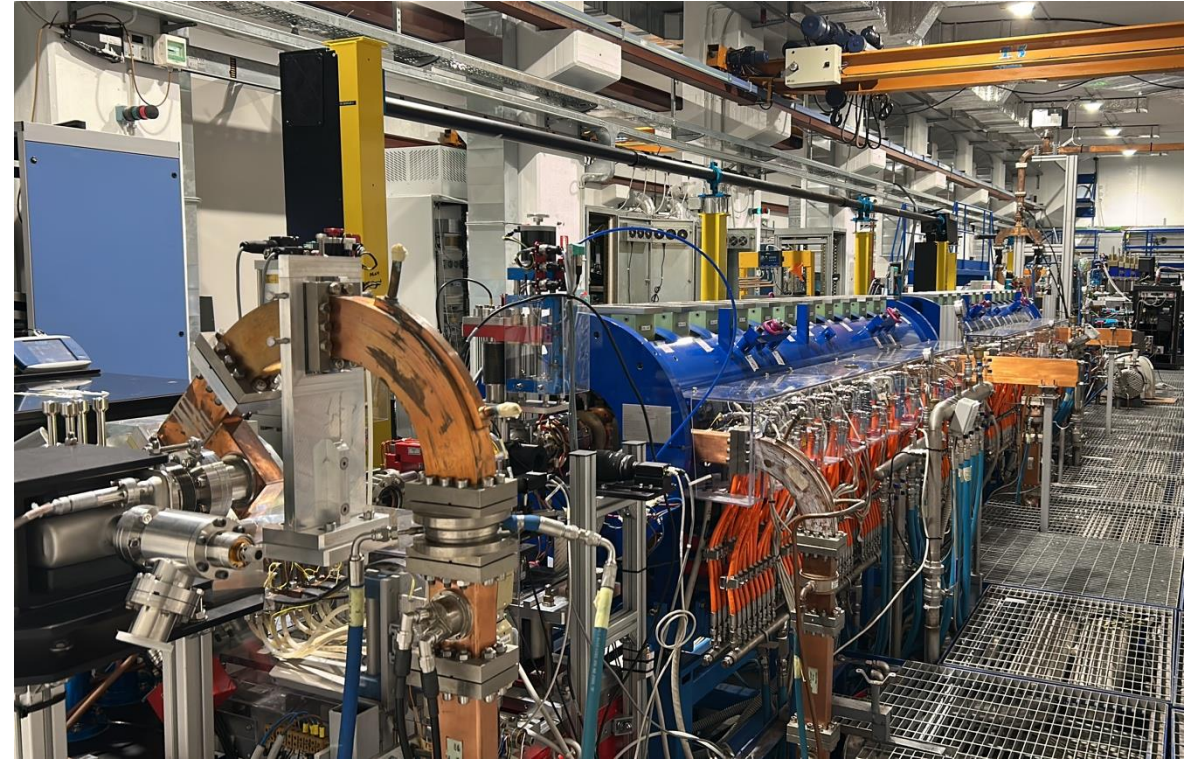
Application Area	Scientific Focus	Techniques	Key Impact
Renewable Energy	- Charge transport in solar cells & catalysts - Photocatalytic H₂ production - PFAS/PCIAS analysis	XAS, XES, PI-MS	- Efficient solar materials - Clean hydrogen production - Environmental remediation
Warm Dense Matter (WDM)	- Extreme 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/NO_x oxidation - Aerosol dynamics	PI-MS, ion spectroscopy	- Pollution models - Climate studies
Astrochemistry	- Radiation chemistry in space - Organic molecule formation	XAS, photochemistry	Space molecular evolution



New facility within SPARC_LAB at LNF:

- 1) SPARC: 100 MeV, 100's fs electron bunches with mm-mrad emittance (single or multi-bunch)
 - 2) FLAME: 5 J high-power laser for LWFA and betatron radiation source
- Proof-of-principle demonstration of:
 - Bunch compression via velocity bunching [1,2]
 - Tapered FEL [3], high-harmonic seeded [4], Superradiance [5], time-domain modulation [6] Two-color generation [7] etc..
 - PWFA with energy spread preservation [8]
 - Lasing of PWFA beam [9,10]
 - Resonant, high-transformer ratio acceleration [11]
 - And many other..

➔ Right expertise and environment to realize a PWFA-FEL user facility



- [1] M. Ferrario et al., Phys. Rev. Lett. 104, 054801 (2010)
- [2] D. Filippetto et al., Phys. Rev. ST Accel. Beams 14, 092804 (2011)
- [3] L. Giannessi et al., Phys. Rev. Lett. 106, 144801 (2011)
- [4] M. Labat et al., Phys. Rev. Lett. 107, 224801 (2011)
- [5] L. Giannessi et al., Phys. Rev. Lett. 110, 044801 (2013)
- [6] V. Petrillo et al., Phys. Rev. Lett. 111, 114802 (2013)
- [7] A. Petralia et al., Phys. Rev. Lett. 115, 014801 (2015)
- [8] R. Pompili et al., Nature Physics 17, 499 (2021)
- [9] R. Pompili et al., Nature (London) 605, 659 (2022)
- [10] M. Galletti et al., Phys. Rev. Lett. 129, 234801 (2022)
- [11] L. Verra et al., Phys. Rev. E 112, 045205 (2025)

Key R&D elements:

- High gradient and high energy gain (energy doubling) with quality preservation
→ Jitters and tolerances investigation
- Long discharge plasma source at 100 Hz
- X-band linac operating at 10- Hz
- Driver safe dumping and witness bunch transport + lasing
- Advanced compact diagnostics

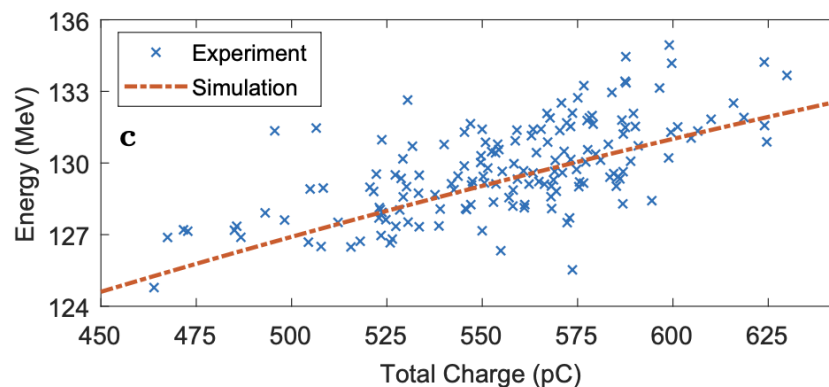
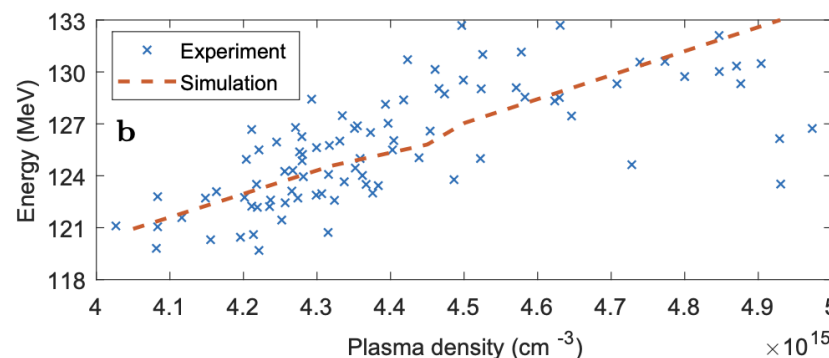
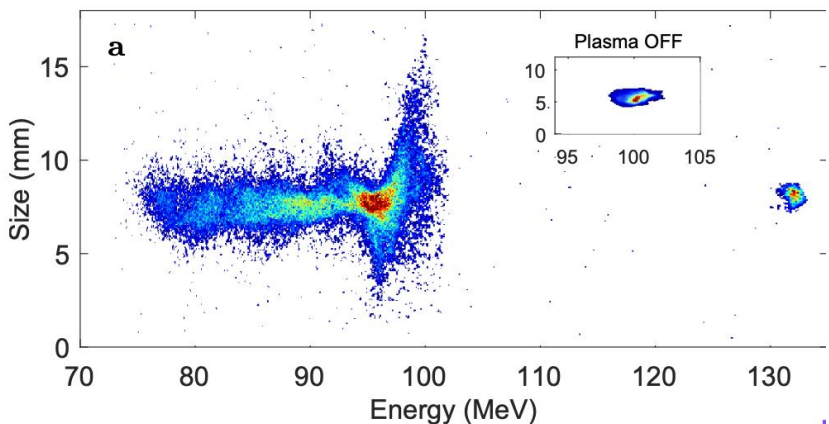
Lasing electron bunch parameters (after PWFA):

- 1 GeV
- 30 pC – **15fs** (linac challenge)
- **<1 mm-mrad, <0.1% energy spread** (PWFA challenge)

Driver bunch parameters:

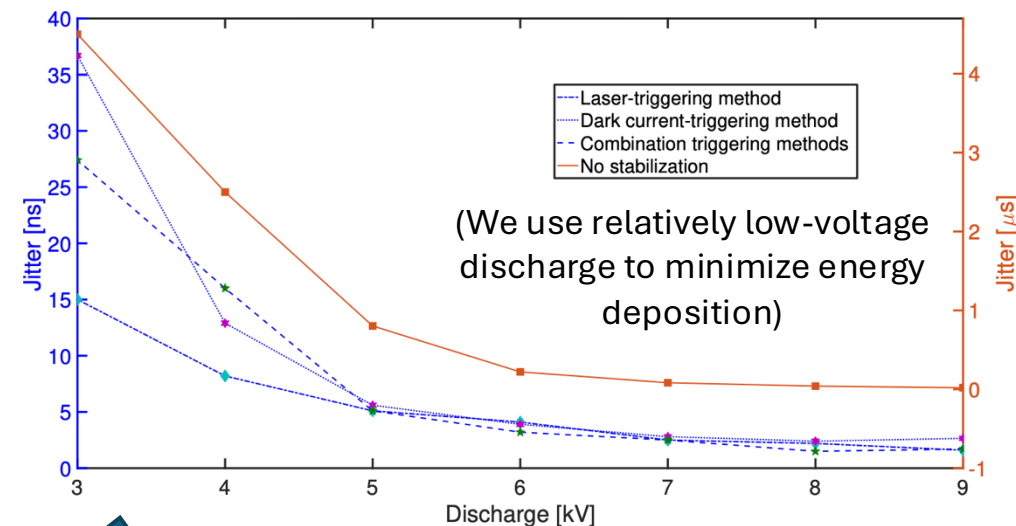
- 500 MeV
- 200 pC – 350 fs





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

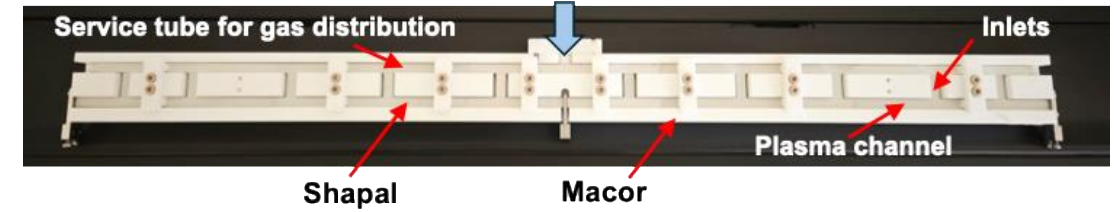
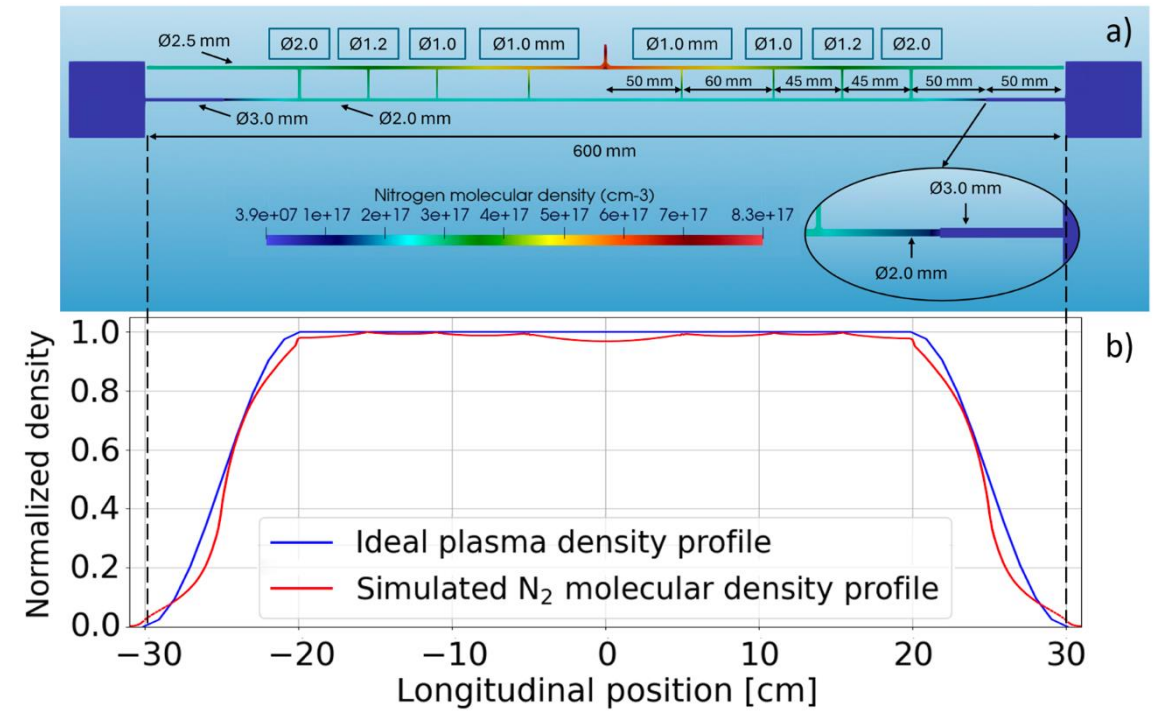
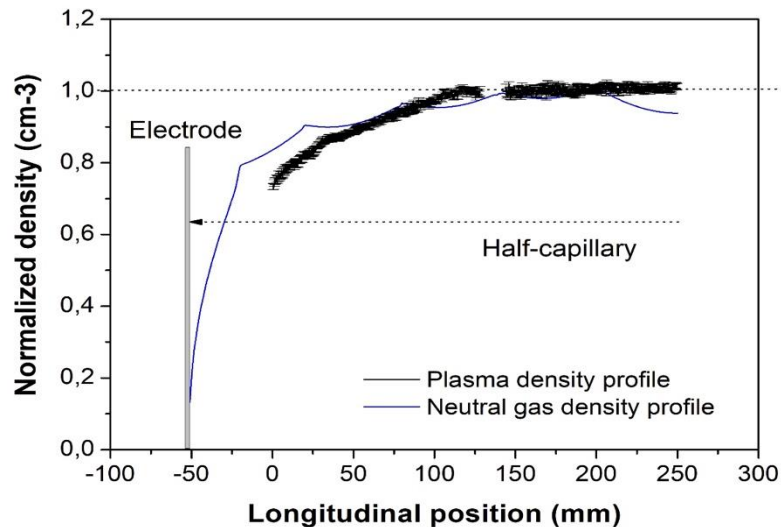
- **Plasma Density jitter dominates when discharge is not stabilized**



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

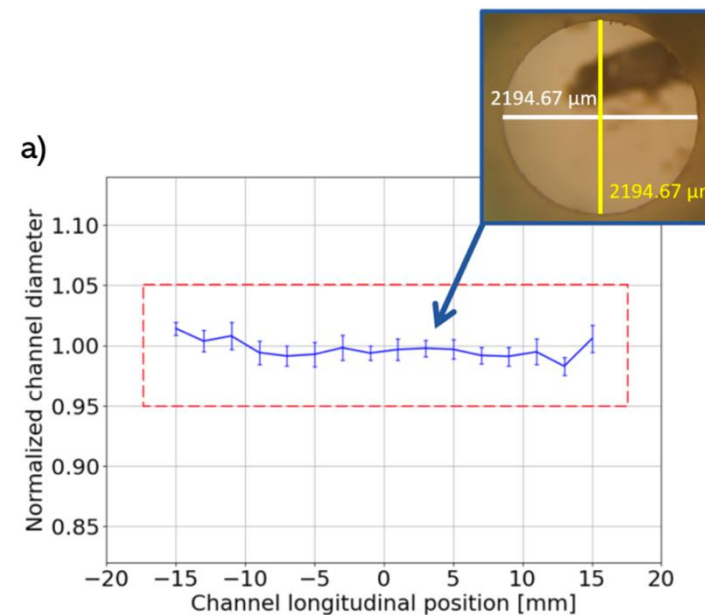
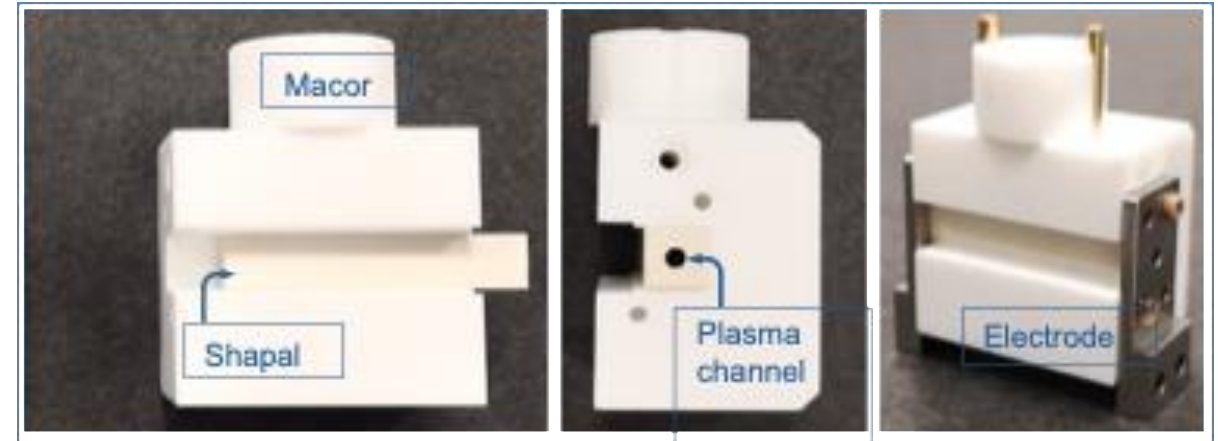
- **Charge jitter dominates otherwise
→ further improvements on photocathode laser and RF system**

- 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

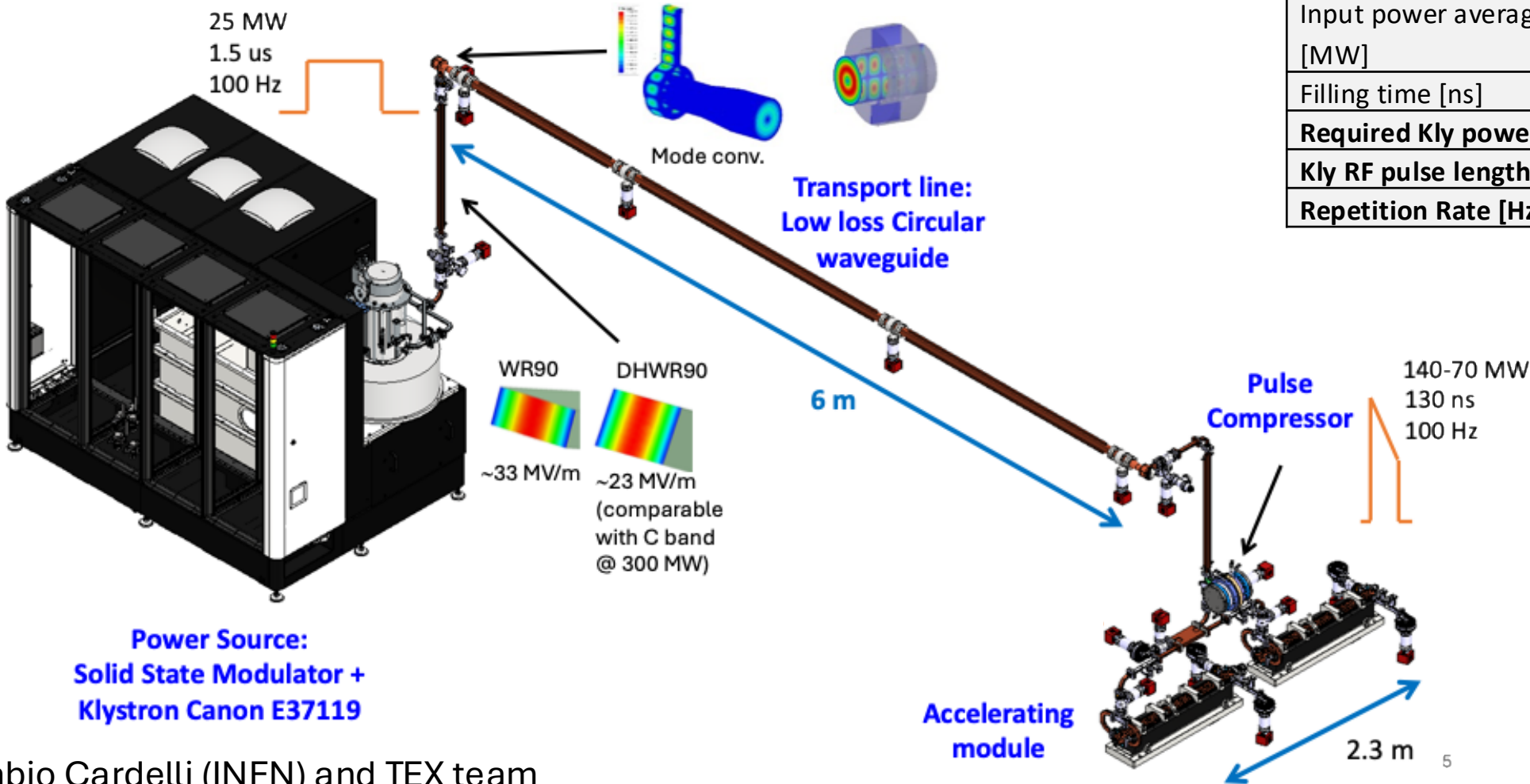


Angelo Biagioni (INFN) and Plasma_Lab team

- 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
- 3-cm-long capillary tested over 20×10^6 shots at 100Hz
 - No damage observed
 - Reproducible density profile
- Additional diagnostics to measure density with despite opaque capillary



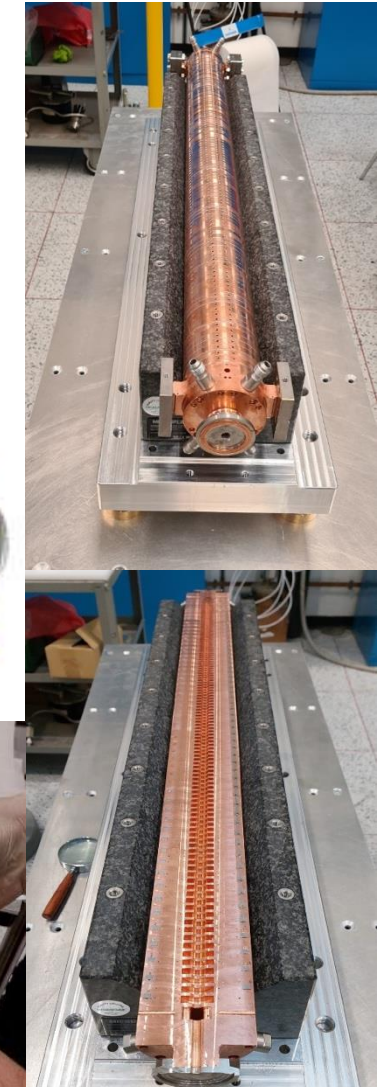
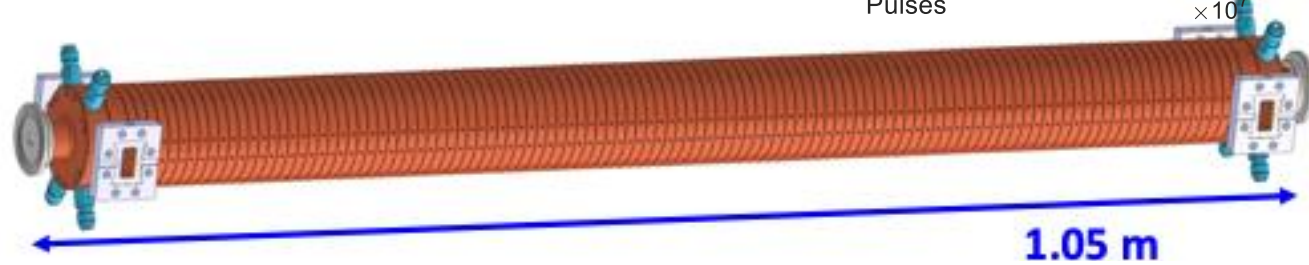
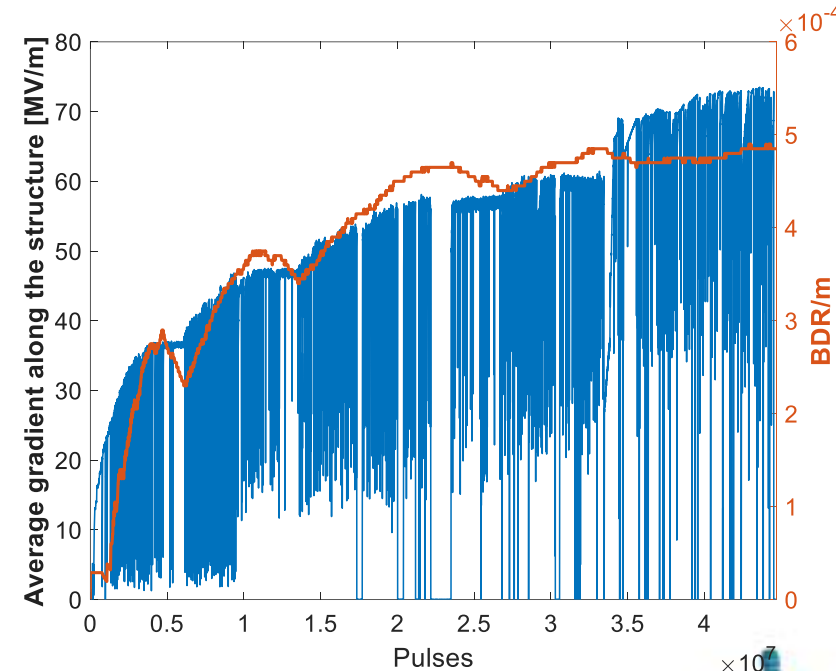
- ⇒ 16 1-m-long TW structures
- ⇒ (11.994 GHz) and 100 Hz
- ⇒ Eight Canon E37327A klystron+
Scandinova K400 Modulators (45 MW, 4.5 us, 100 Hz)



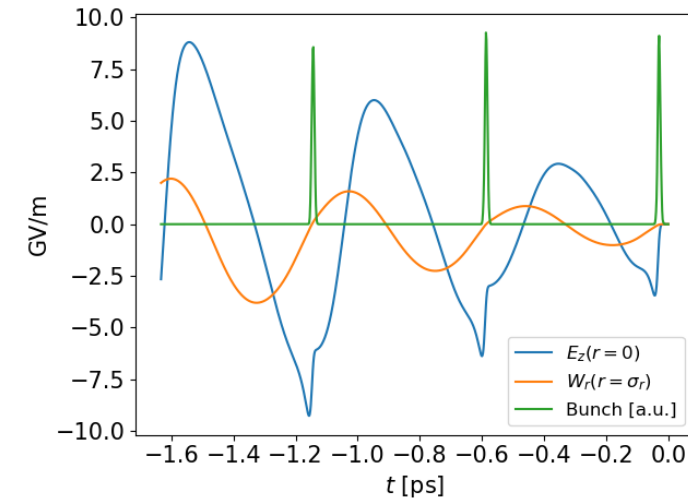
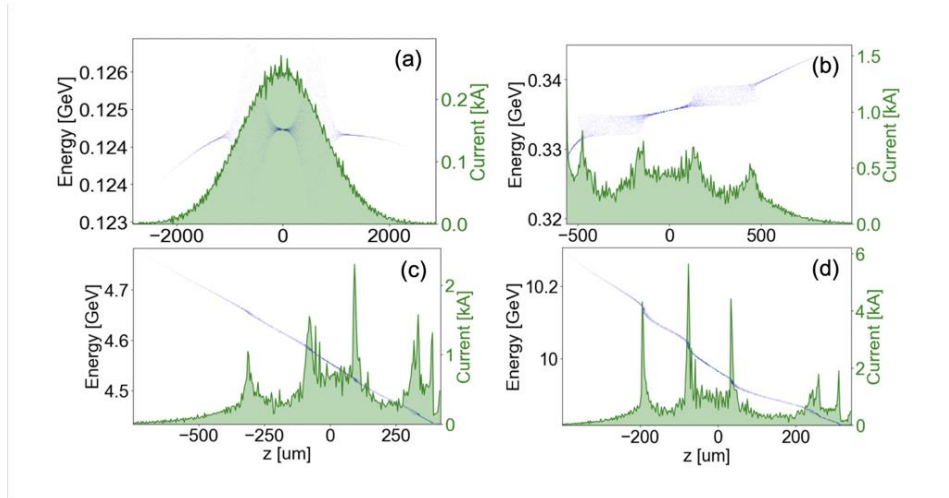
PARAMETER	Value
Frequency [GHz]	11.9942
Average acc. gradient [MV/m]	60
Structures per module	2
Peak input power per structure [MW]	70
Input power averaged over the pulse [MW]	51
Filling time [ns]	130
Required Kly power per module [MW]	22.5
Kly RF pulse length [μs]	1.5
Repetition Rate [Hz]	100

- ⇒ **Prototype brazed and vacuum tested**
- ⇒ **Straightness** $< \pm 15 \mu\text{m}$ obtained after brazing on both the prototypes ($\pm 30 \mu\text{m}$ 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** $\sim 74 \text{ MV/m}$
- ⇒ **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 [M Ω /m]	100
Effective shunt Imp. $R_{sh \text{ eff}}$ [M Ω /m]	347
Filling time [ns]	30
Repetition Rate [Hz]	100



- Opportunities on all aspects that we cannot test until we have the operating machine:
 - Resonant, high-transformer ratio scheme with multi-GeV beams (**BeamNetUS experiment in October at FACET-II**)
C. Emma et al., Phys. Rev. Lett. **134**, 085001 (2025)

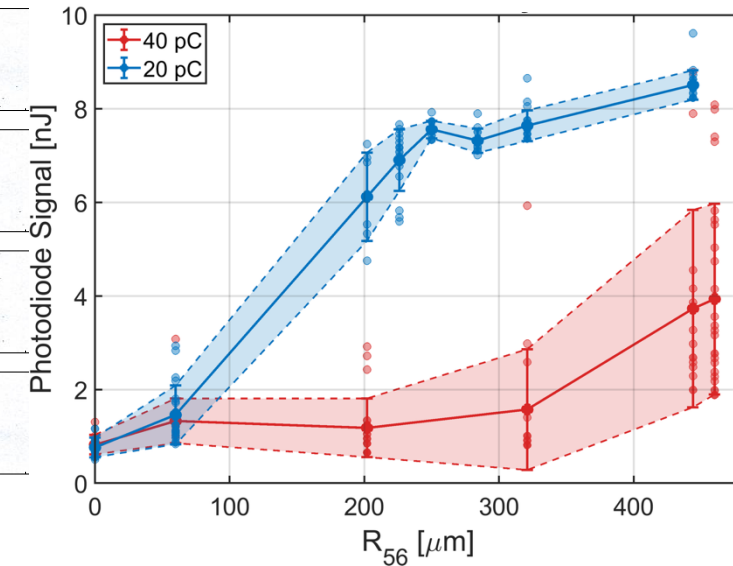
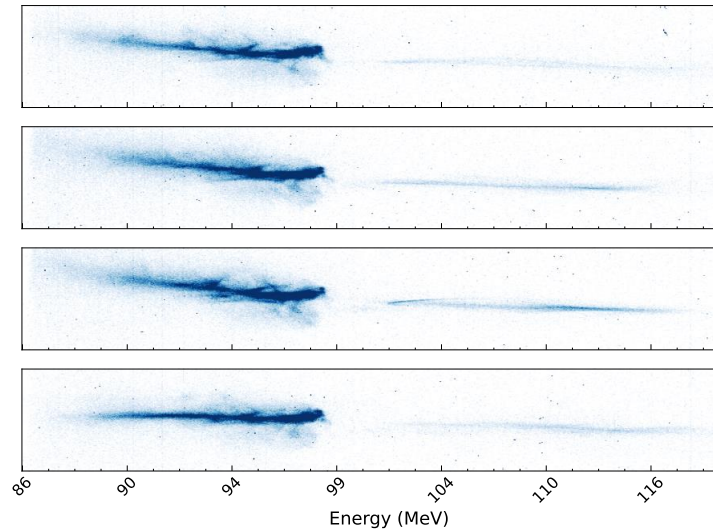
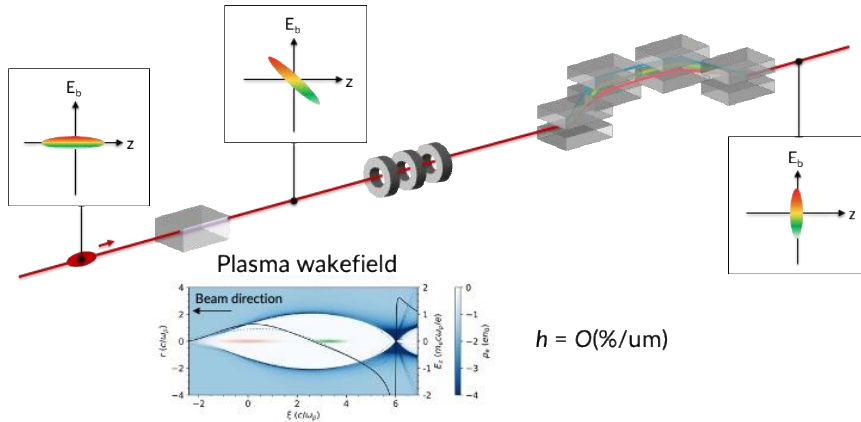


- Discharge plasma source with multi-GeV beams (**BeamNetUS proposal submitted by A. Biagioni to test at FACET-II**)
- Test of diagnostics with multi-GeV beams and very high peak currents (e.g. wire scanner, diffraction radiation monitors..)
- Similarly, we mutually benefit from low-energy tests of future ideas for FACET (e.g. PAX experiment at SPARC)

Plasma-based compression of electron beams

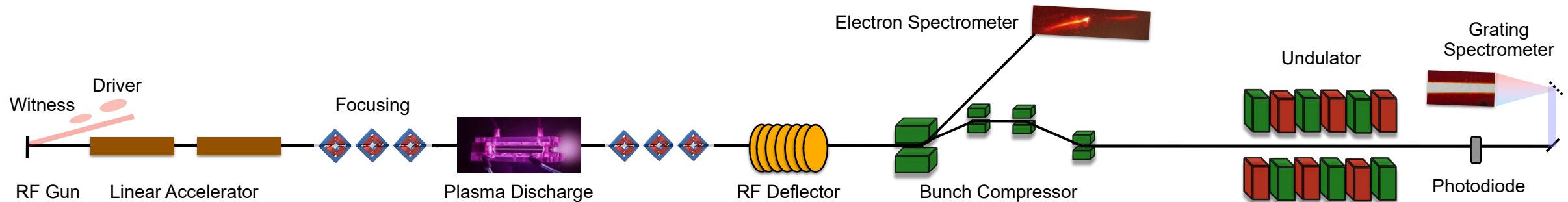
- Experimental Results obtained at SPARC with SLAC collaboration

The longitudinal electric field in a plasma wakefield accelerator can impart chirps orders of magnitude larger than RF cavities

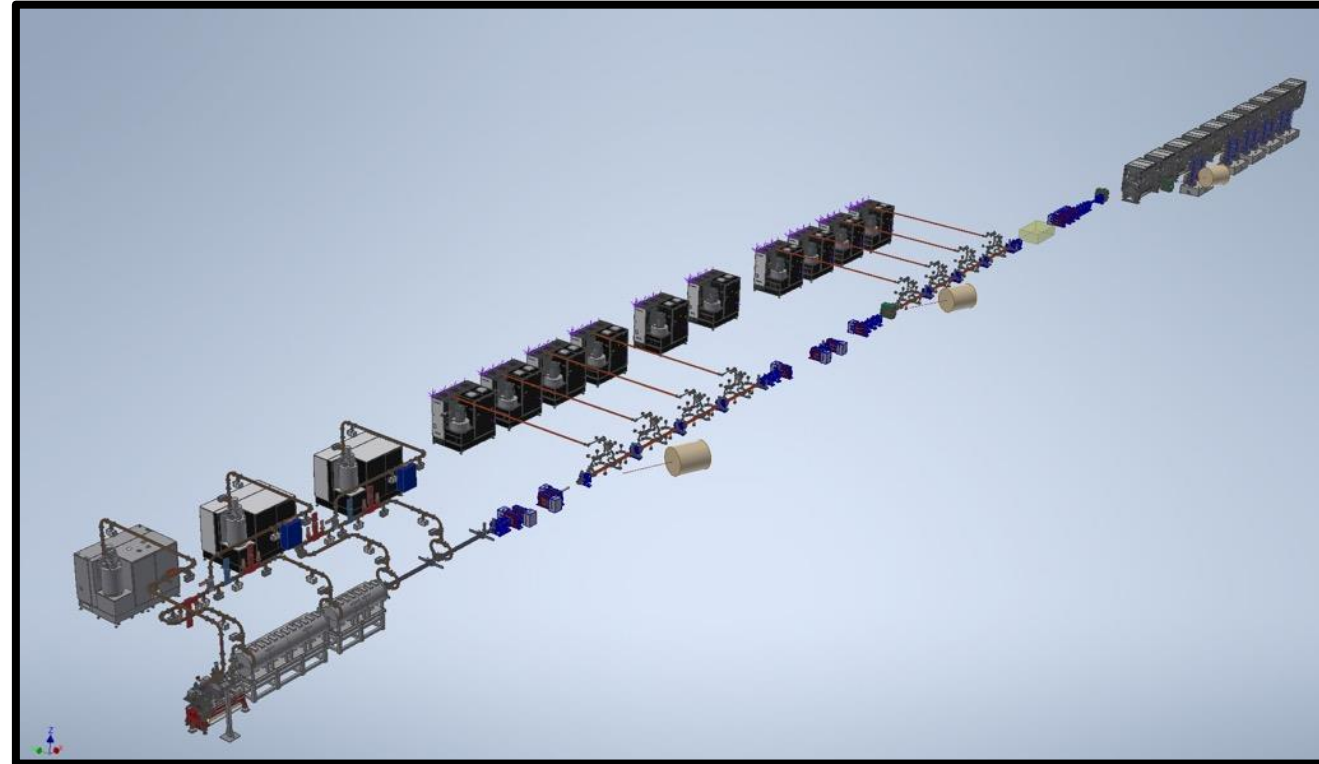


Chirps x1000 larger possible in a plasma wakefield (%/um) compared with RF cavity (%/mm)

11



- EuPRAXIA is a distributed infrastructure with the goal of realizing plasma-based light sources
 - Clear user case
- In-house effort to build the first user-oriented FEL powered by PWFA
 - Opportunity to do experiments and “get ready” using SPARC
- 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
- **Many areas of potential collaboration**



Thank You For Listening!

Backup

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!

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



INFN – 2026 - 01 - LNF
Feb 5th, 2026

EuPRAXIA@SPARC_LAB

Technical Design Report

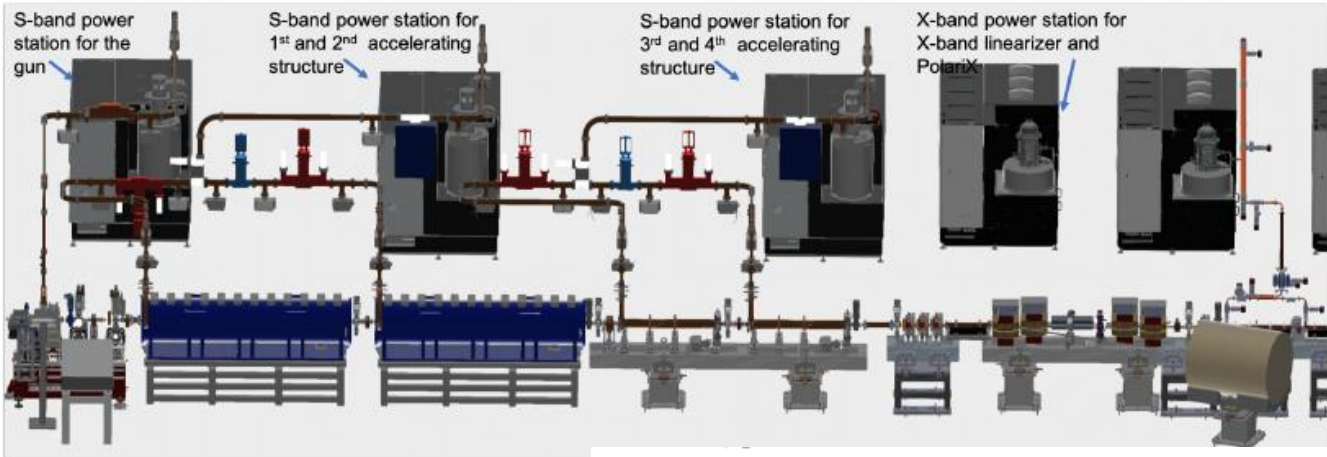
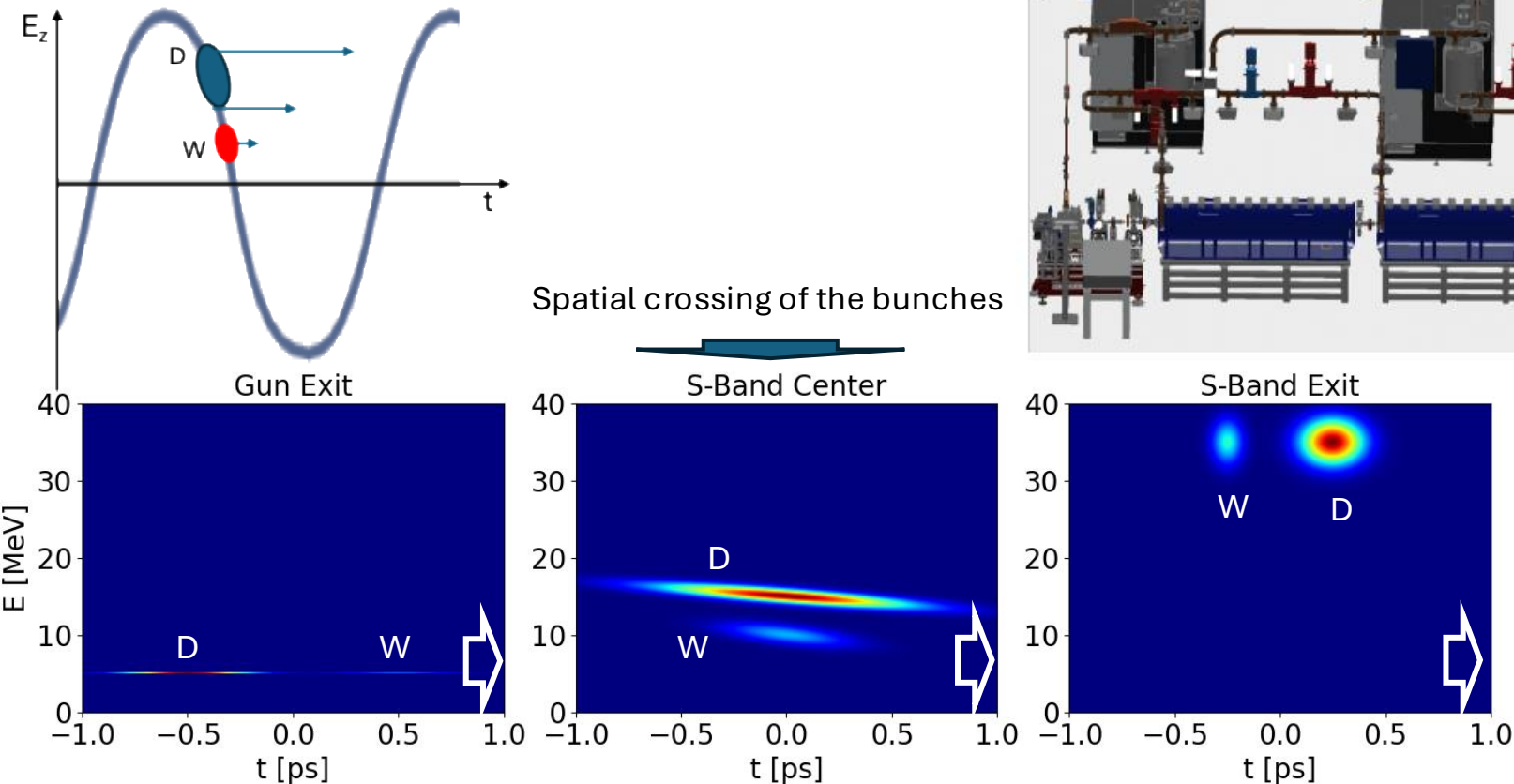


**Real Implementation
that bring LNF into a
new era**

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

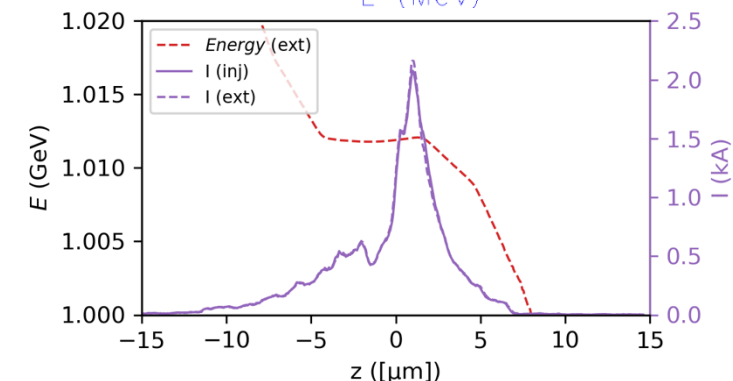
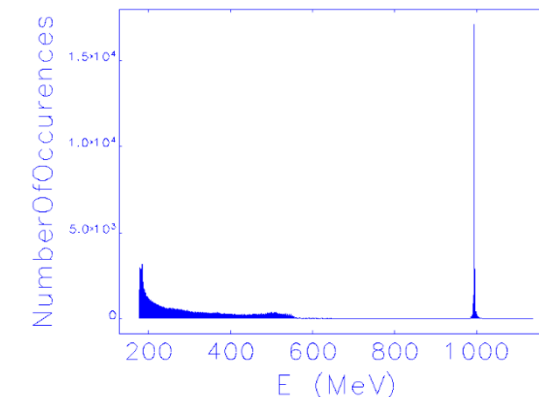
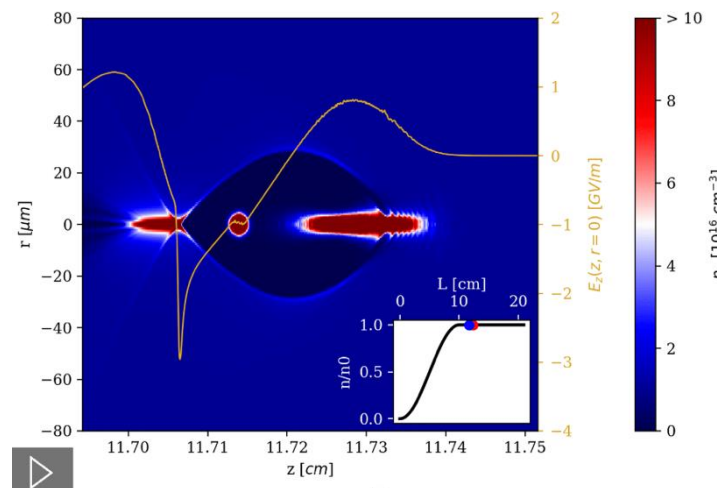
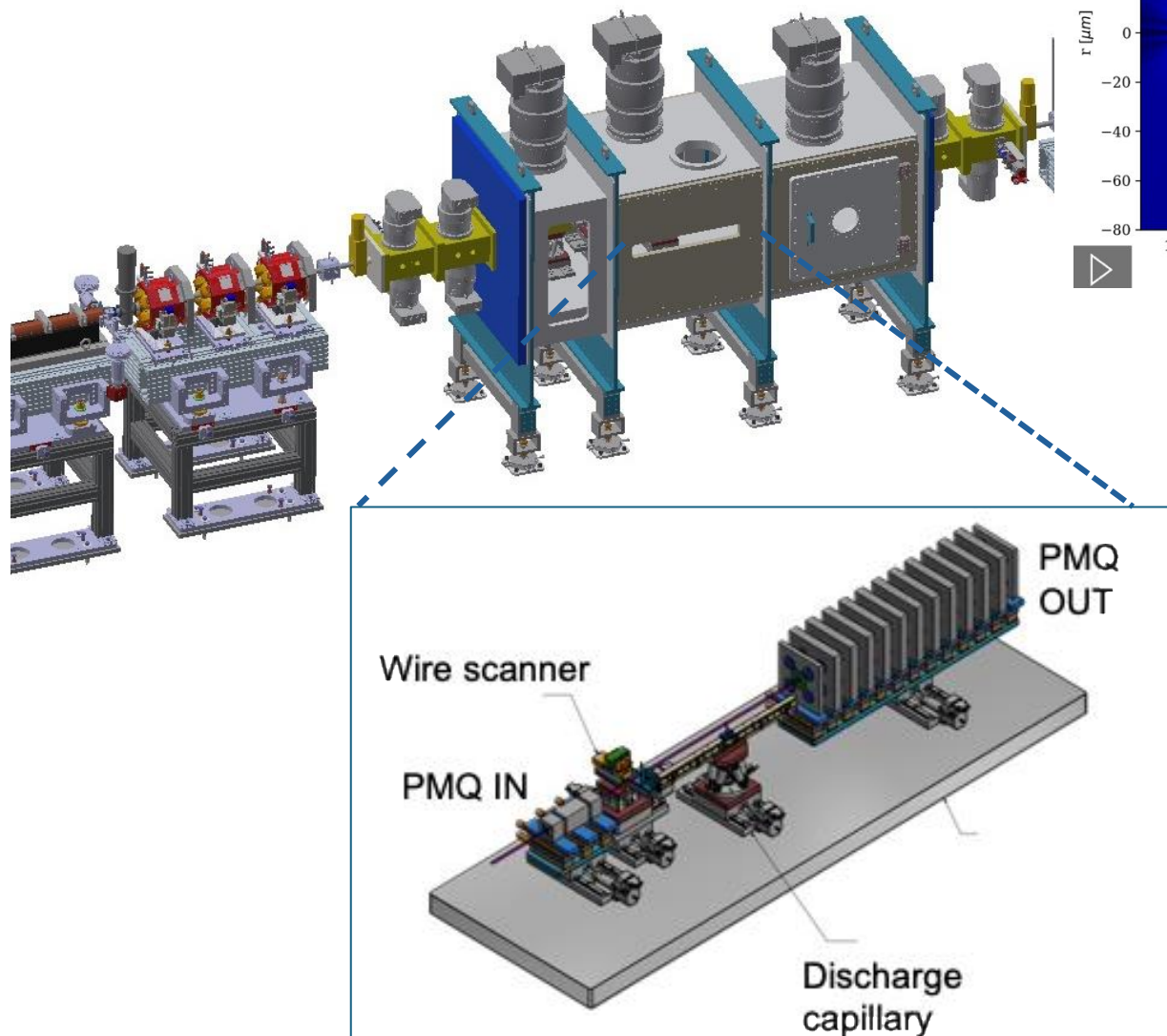
- ⇒ the objectives of the project are **realistic**, and **no critical showstopper** has been identified.
- ⇒ All critical issues of the project have been properly addressed.
- ⇒ The Review Committee **strongly supports the project.**

- ⇒ **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)

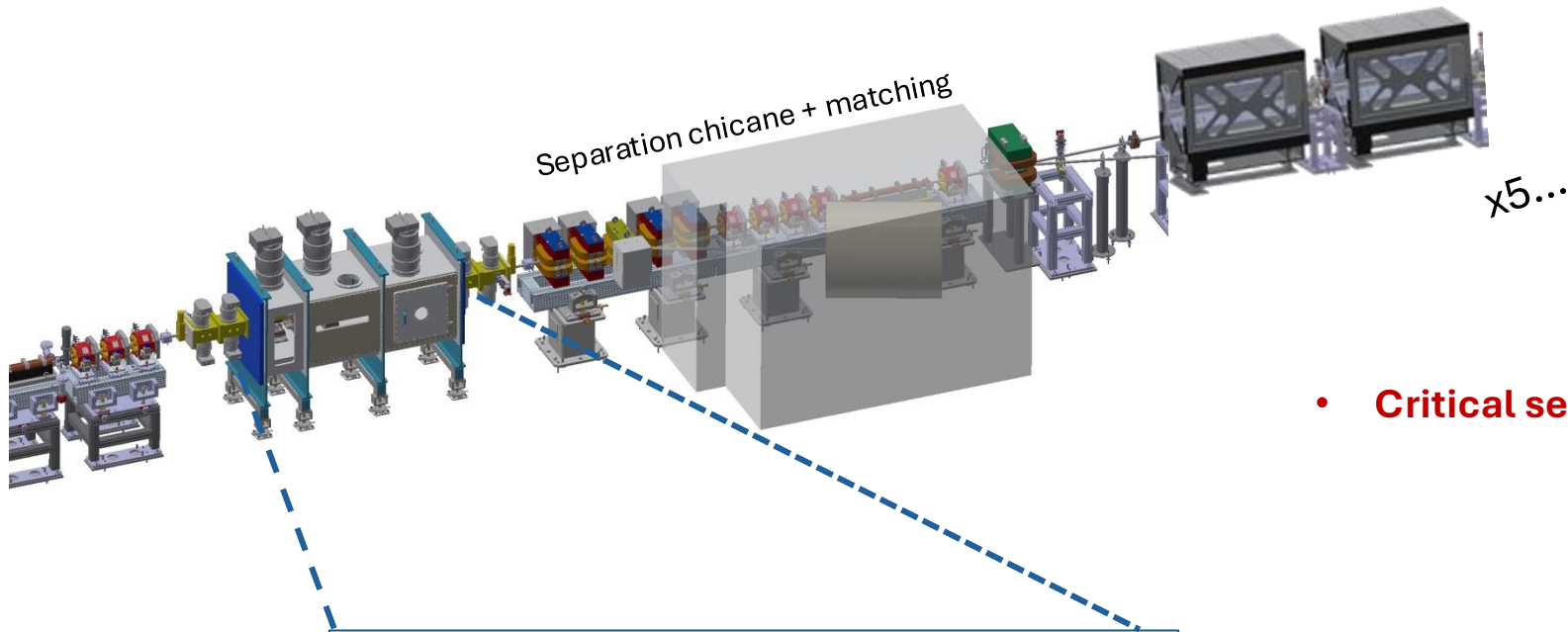


Parameter	Symbol	Unit	Value
# of bunches			2
Driver Charge	Q_D	pC	200
Witness Charge	Q_W	pC	30
Beam energy	$E_{D/W}$	MeV	119/118
Driver normalized emittance	ϵ_{nD}	mm mrad	1.5
Witness normalized emittance	ϵ_{nW}	mm mrad	0.7
Driver energy spread	σ_{E_D}	%	0.7
Witness energy spread	σ_{E_W}	%	0.1
Driver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

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

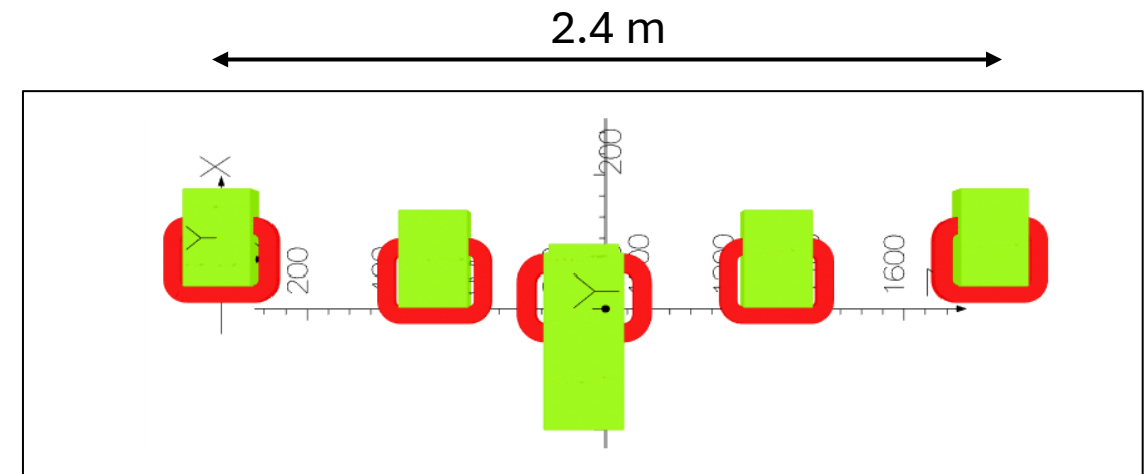
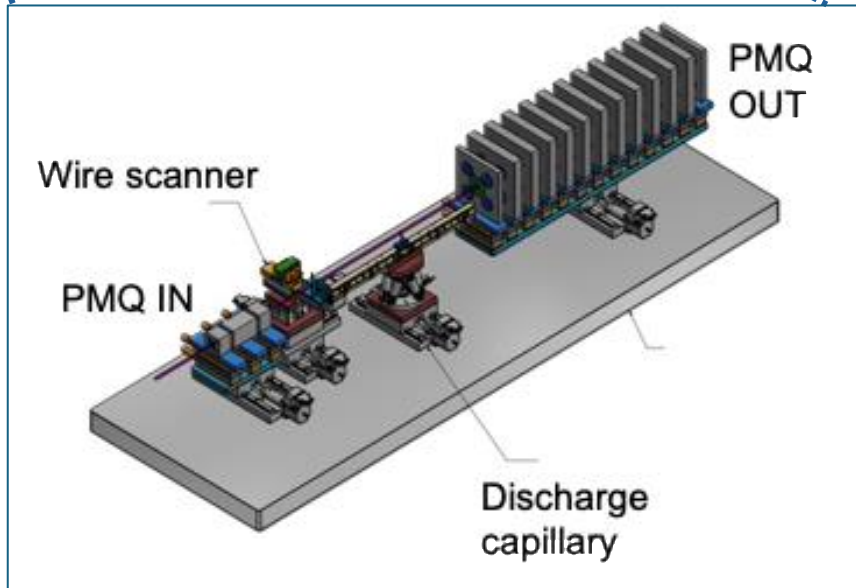


- Three differential pumping stations:
vacuum levels $<10^{-9}$ mbar in the adjacent sections
- Main chamber:
 - 60-cm-long capillary
 - Sets of PMQs
 - Wire scanner
- Side chambers:
Screens, EOS, etc..

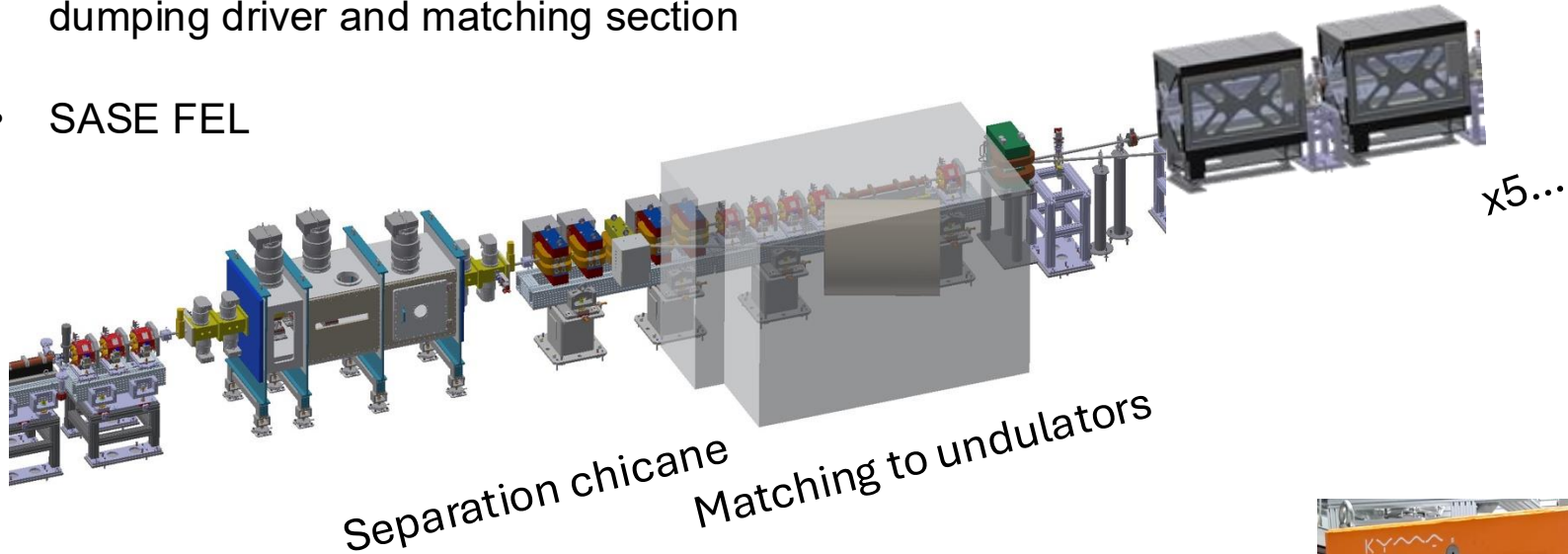


- Long PMQ section to transport both witness and depleted driver
- Magnetic chicane with septum to dump the driver
- Final FODO to match the witness beam to the undulators

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

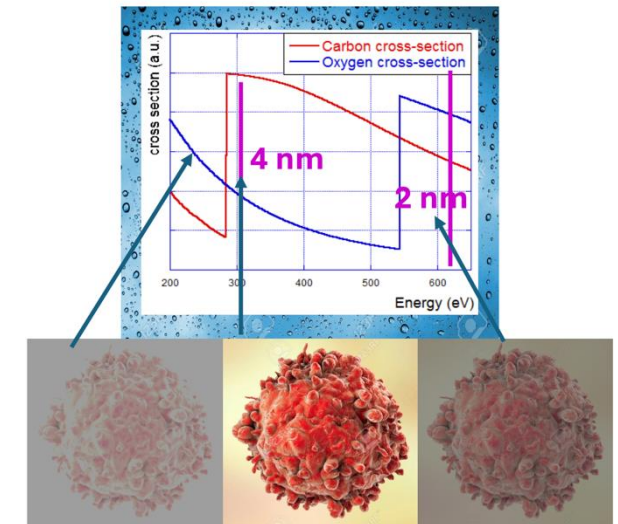


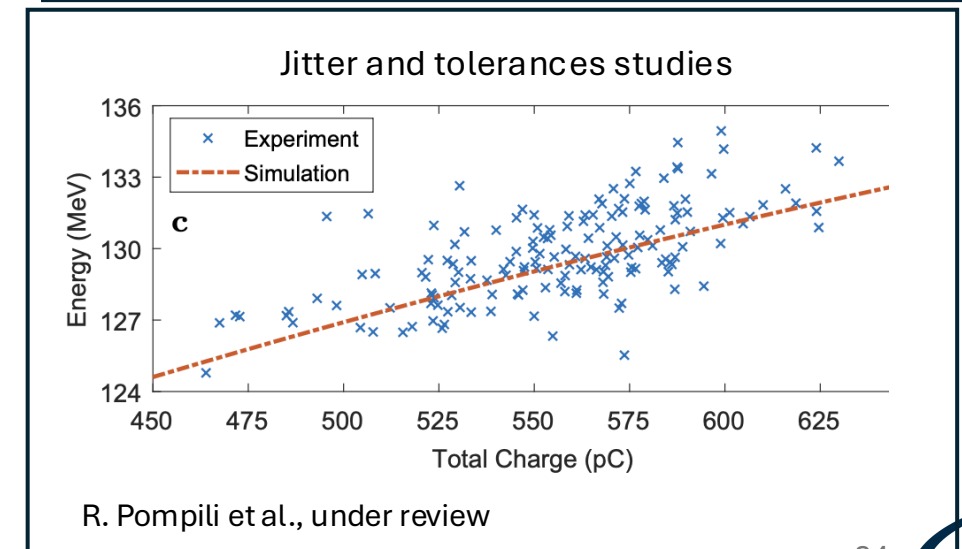
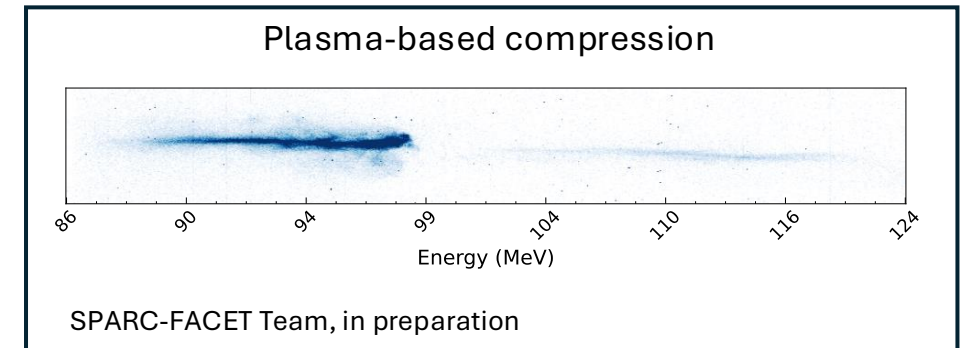
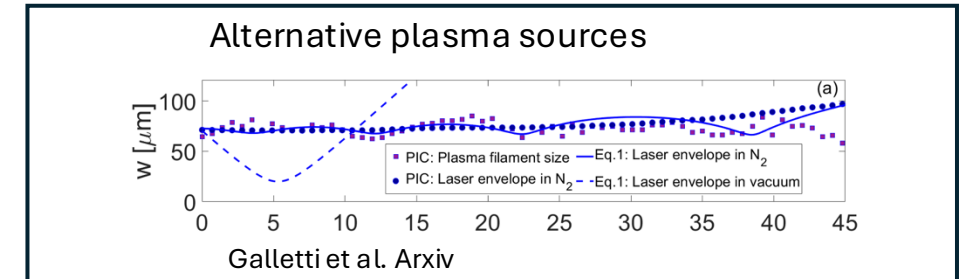
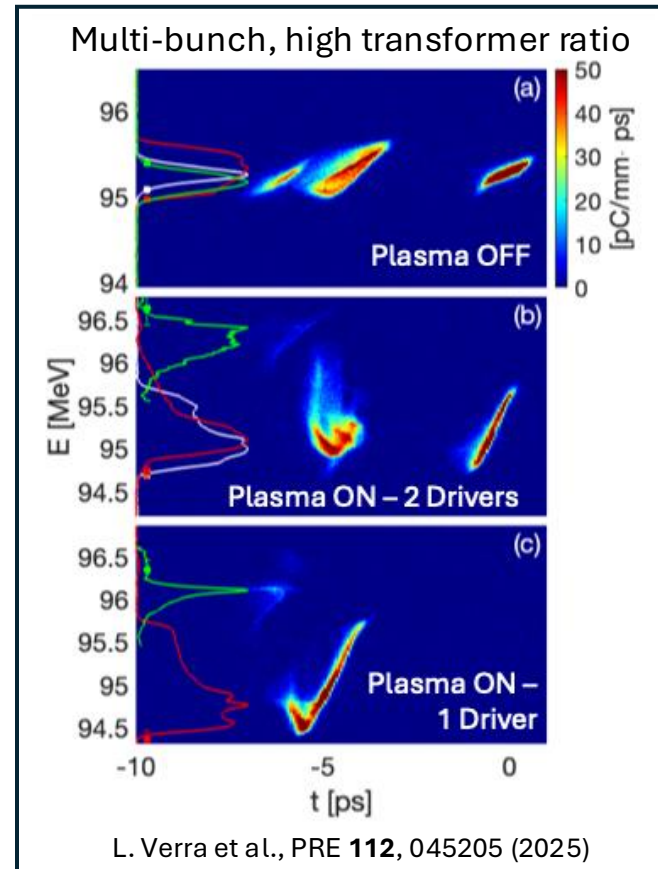
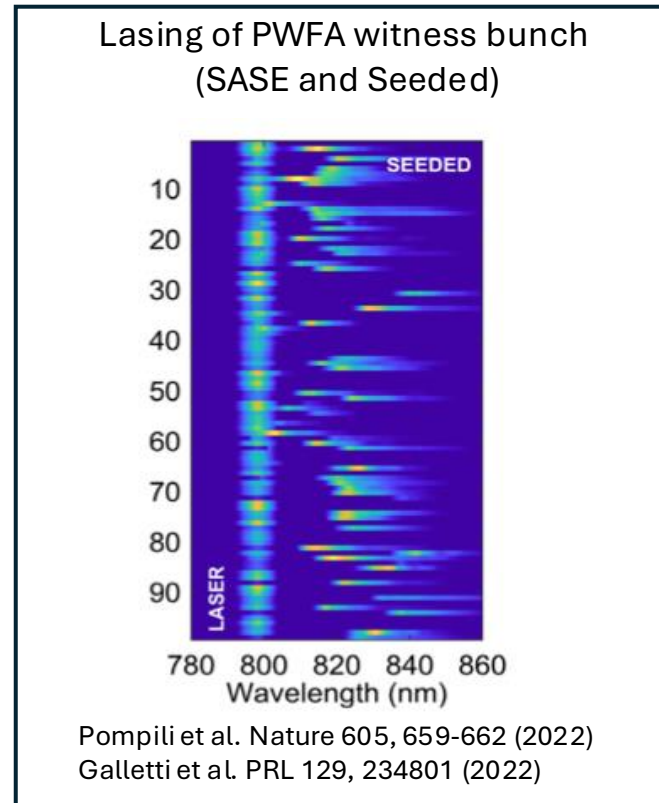
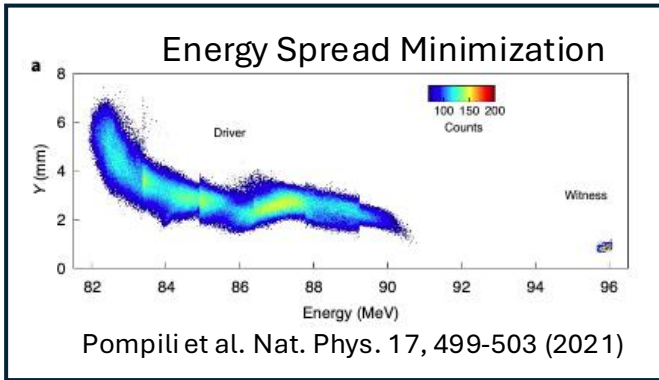
- Witness bunch delivered to undulators after dumping driver and matching section
- SASE FEL



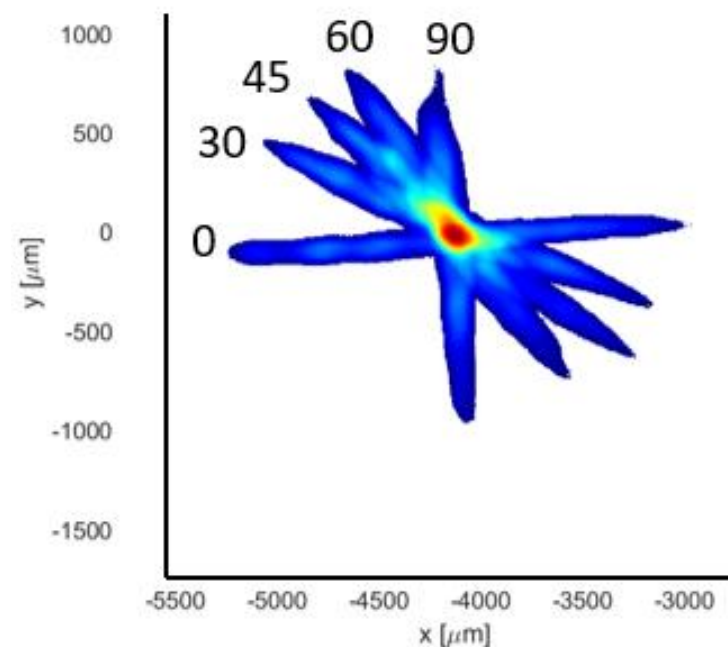
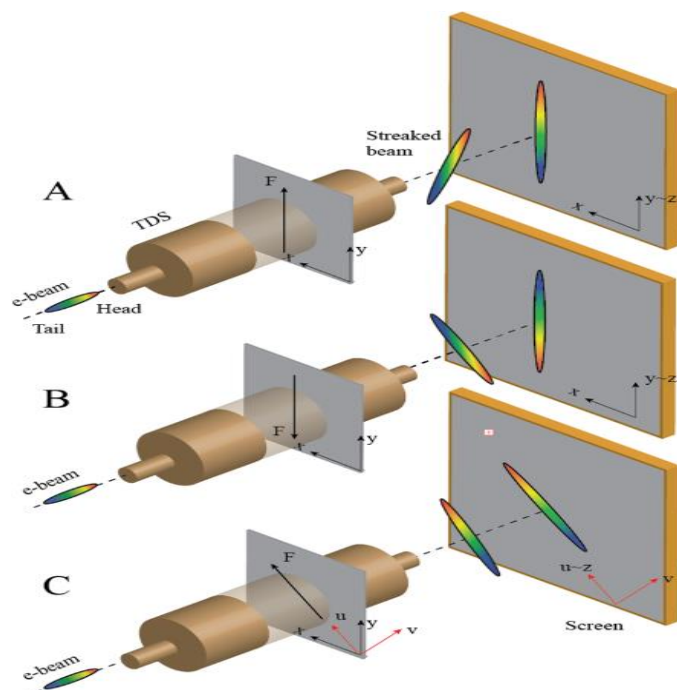
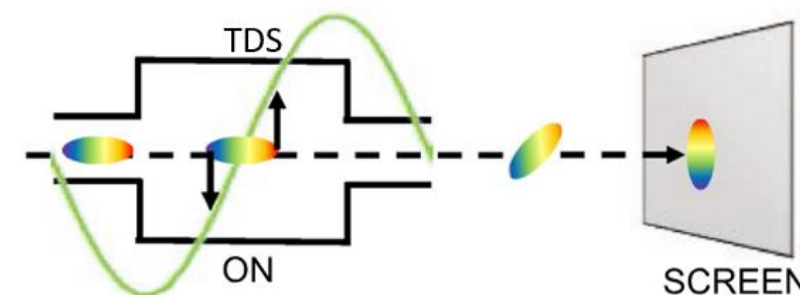
	Units	Value
ρ (3D)	$\times 10^{-3}$	0.77
Saturation length	m	20.5
Radiation wavelength	nm	4.0
Photon Pulse Energy	μJ	16
Photon per pulse	$\times 10^{11}$	3.2
Photon Bandwidth	%	0.4

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





- 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

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

Low-energy beamline:

$E \sim 118 \text{ MeV}$ (witness)

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

Short PolariX TDS $\sim 50 \text{ cells} / 60 \text{ cm}$

Temporal Resolution $\sim 1 \text{ fs}$

High-energy beamline:

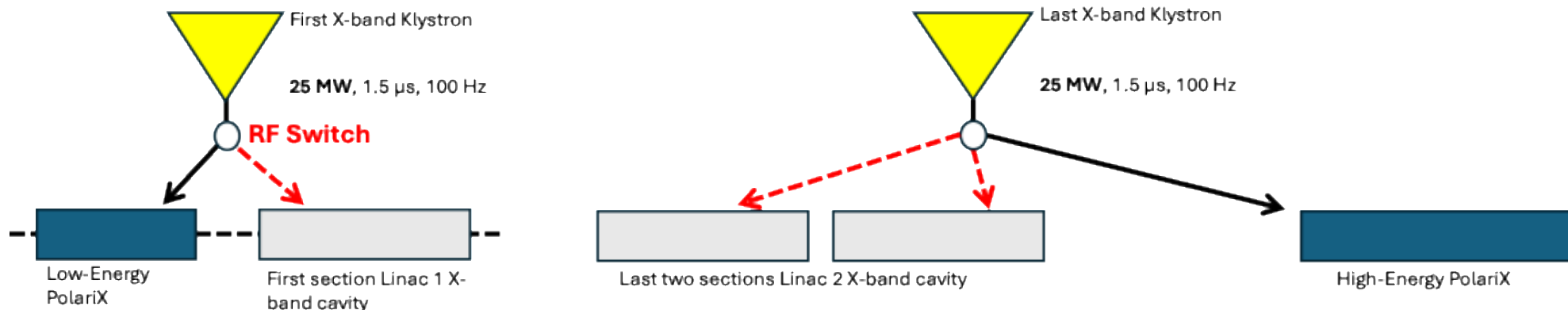
$E \sim 1 \text{ GeV}$ (witness)

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

Long PolariX TDS $\sim 96 \text{ cells} / 96 \text{ cm}$

Temporal Resolution $\sim 1 - 2 \text{ fs}$

- 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



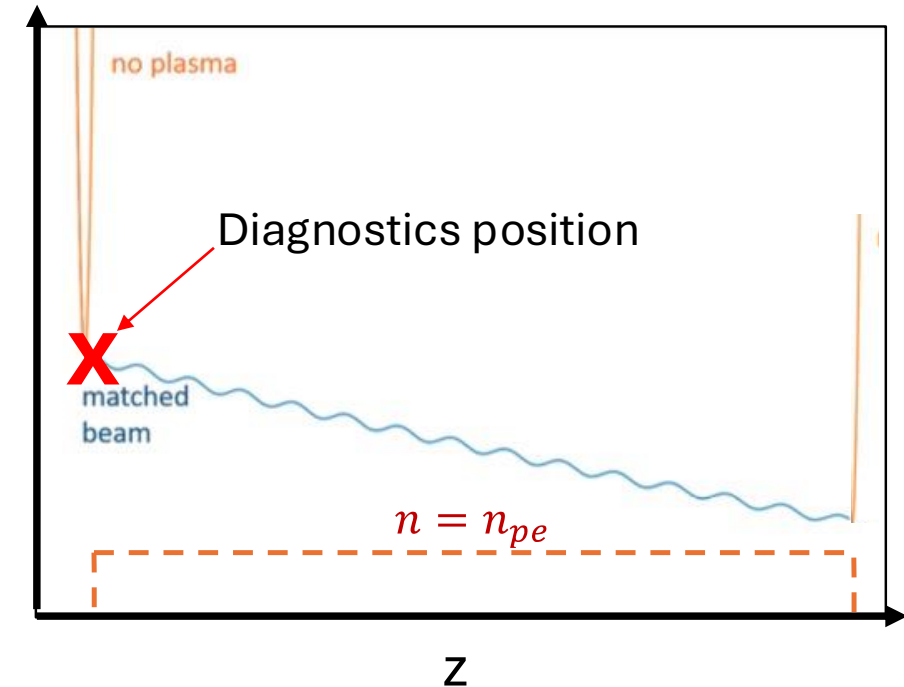
- The witness bunch in non-linear PWFA must be delivered at the plasma entrance with Twiss parameters:

$$\alpha_m = 0 \text{ (injected at waist)}$$

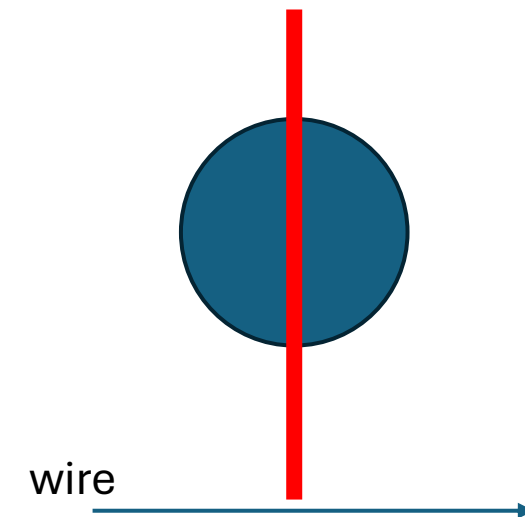
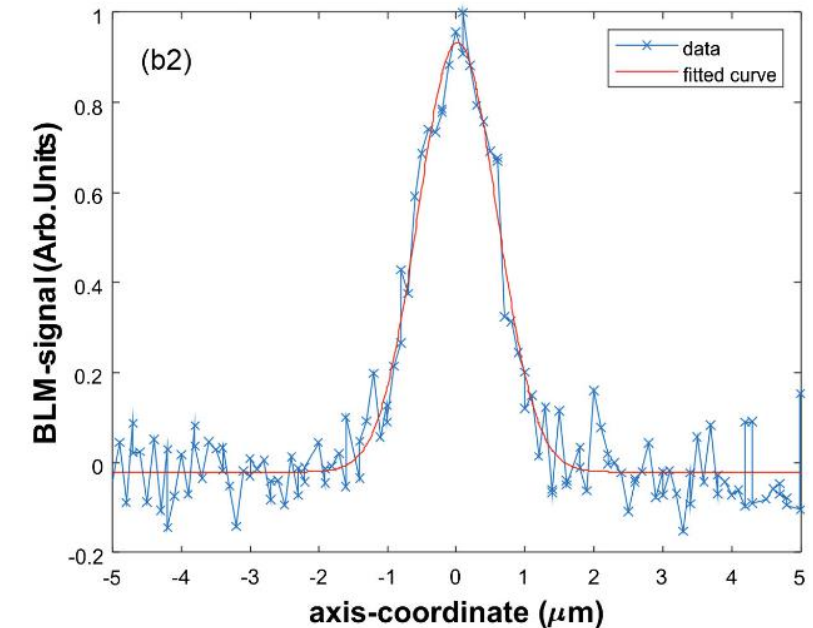
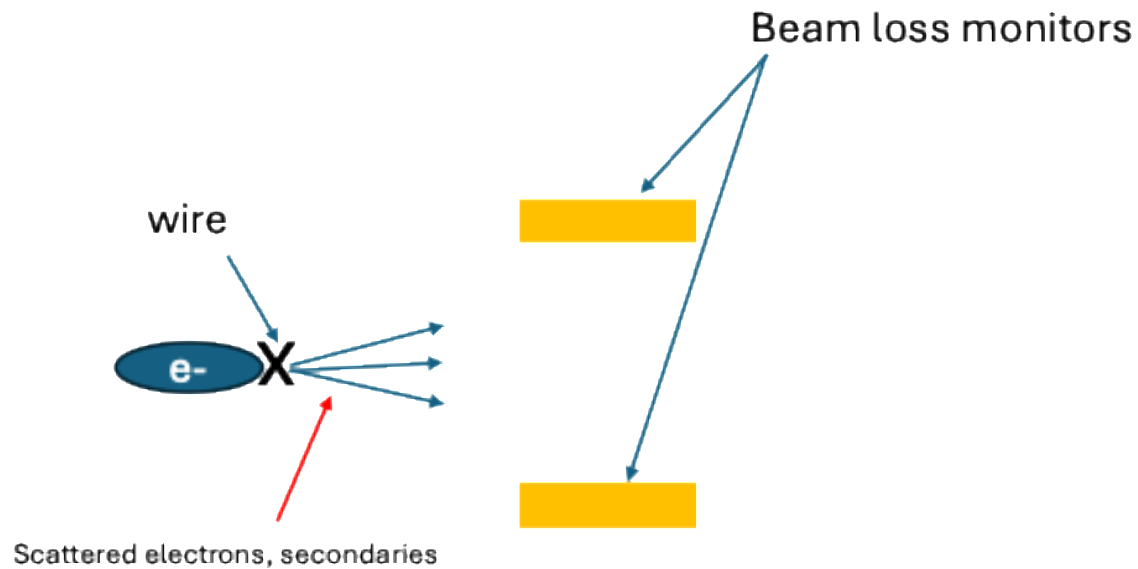
$$\beta_m = \sqrt{\frac{2m_e c^2 \varepsilon_0}{n_{pe} q^2}} \gamma \text{ (matched to the ion column focusing force)}$$

- For EuPRAXIA:
 - $\beta = 7.4 \text{ mm}$
 $\rightarrow \sigma = 3.8 \text{ }\mu\text{m}$

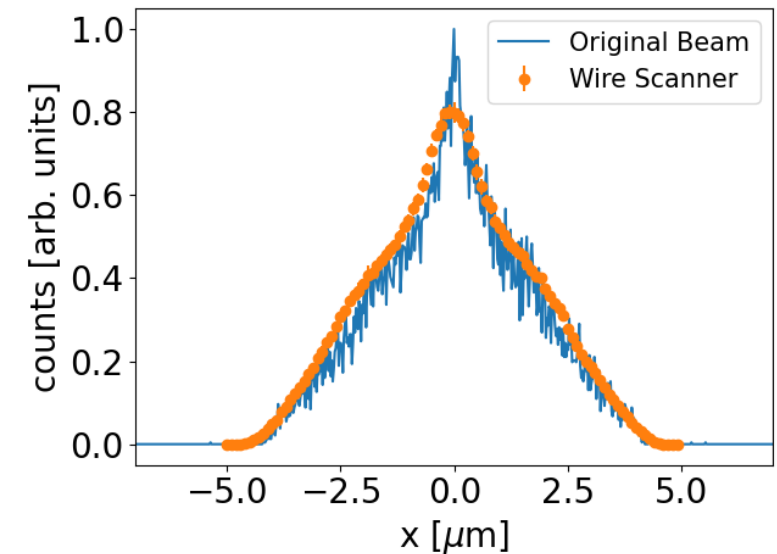
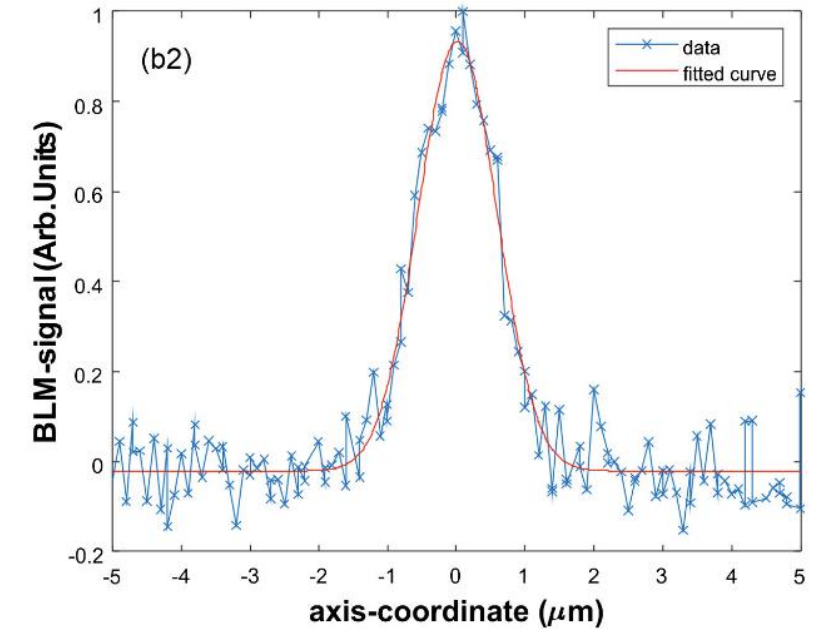
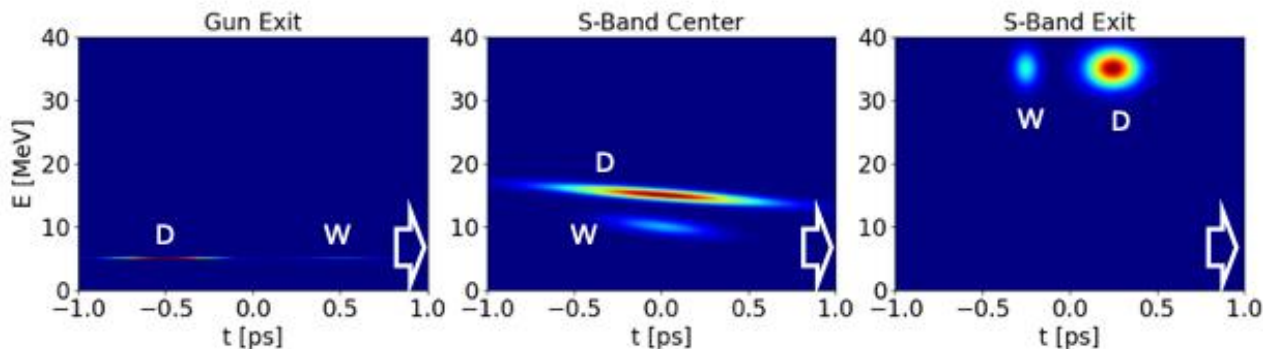
➔ Need a diagnostics to measure the transverse beam size at the plasma entrance location with μm -resolution



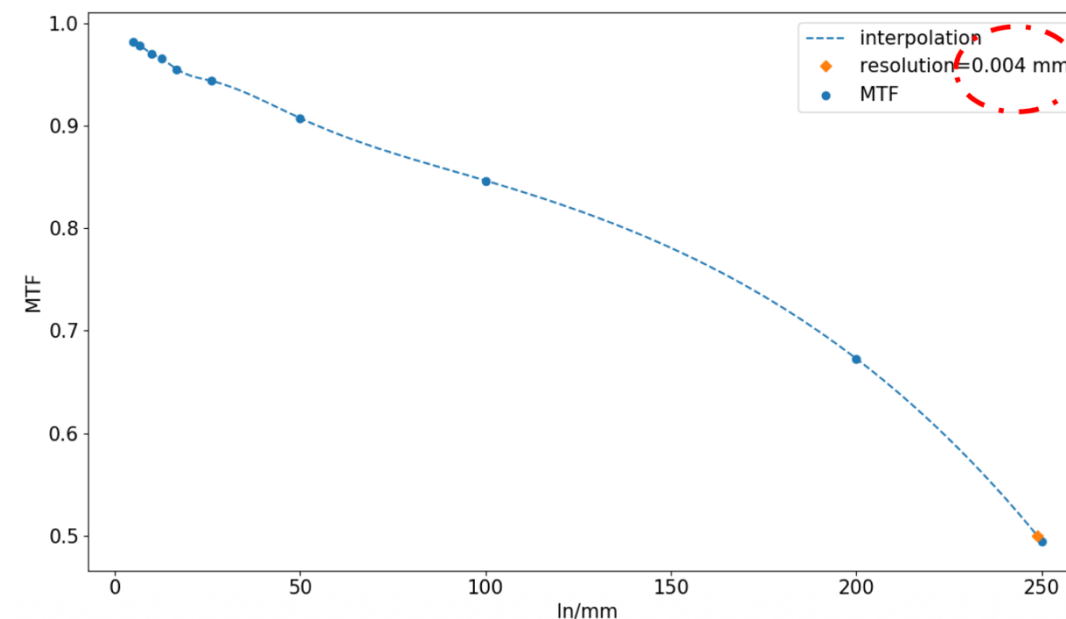
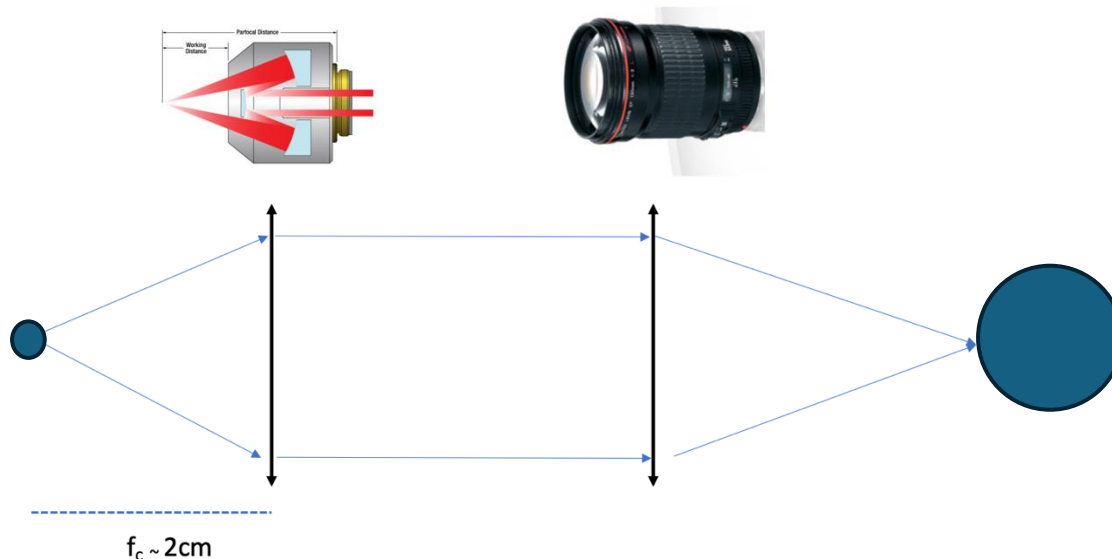
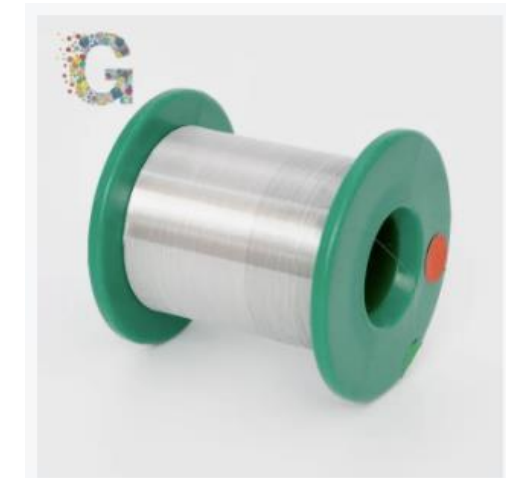
- Wire intercepting electron bunch
→ scattered electrons and generation of secondaries
- Detection of signal with beam loss monitors
- Signal proportional to the portion of bunch intercepted by the wire
 - correlation with wire position
 - transverse distribution in the scanned direction
 - assuming no jitter on beam position



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



- Resolution for squared wire $\sim \frac{w_0}{\sqrt{12}}$
→ $\sim 1.1 \mu\text{m}$ for $w_0 = 4 \mu\text{m}$ (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



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

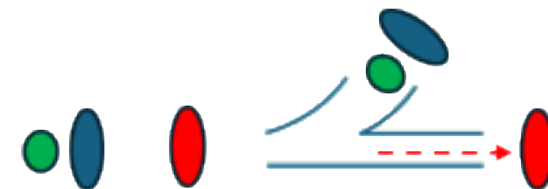
⇒ The inclusion in **ESFRI roadmap lasts 10 years**, in which it is supposed to **implement the infrastructure**.

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

⇒ Being a ESFRI Landmark implies several advantages:

- Institutionalized framework for **maintaining 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).

- 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 $\ll$ ns

Option 2: Curved Discharge Plasma Capillary

- 3) Staging experiment(s)



S-band Injector

X-band Linac

Undulators

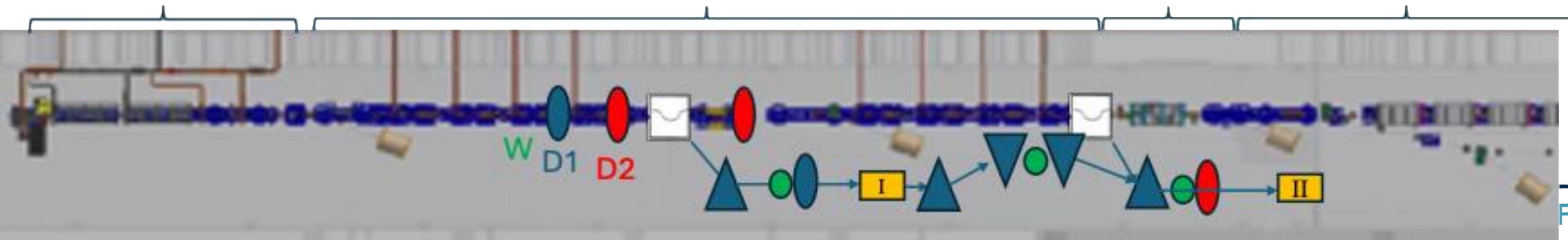


Table 1.1: Major Short-Wavelength FEL User Facilities

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, Switzerland	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	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	Full RF
		Velocity bunching	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

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

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	-

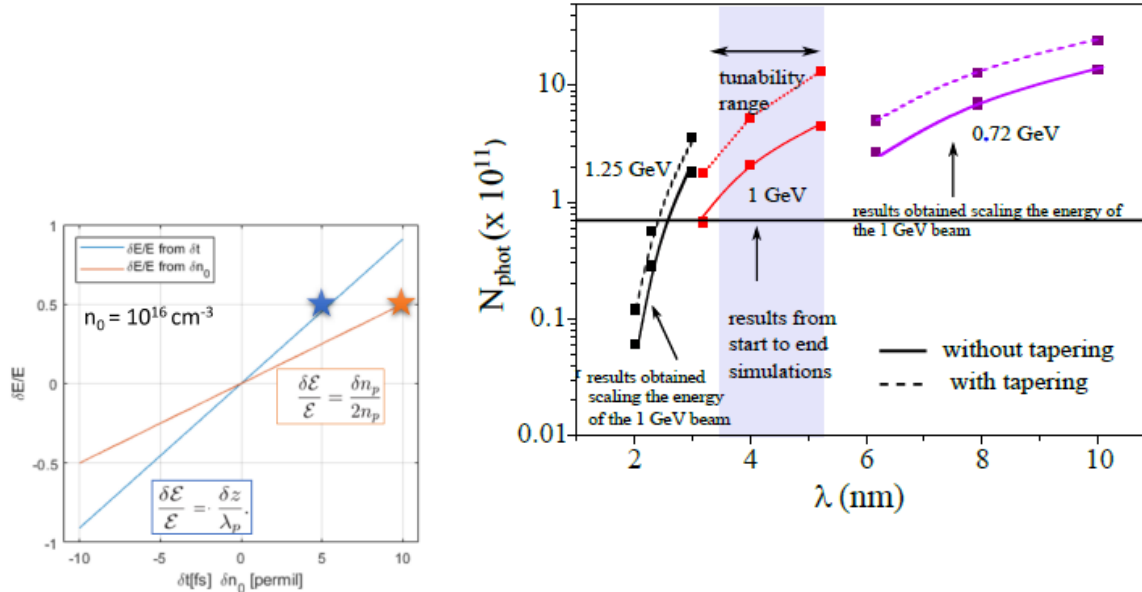


Figure 3.15: Analytical evaluation of the plasma vs the linac contribution to energy gain jitter at the plasma exit [7]. The stars represent the contribution to the energy spread due to the 5 fs jitter of the witness and driver temporal separation (blue) and the contribution due to the 1% plasma density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

Table 3.10: 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

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

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 3.13: 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

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