EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

The EuPRAXIA@SPARC_LAB RF system

Luca Piersanti, Fabio Cardelli INFN-LNF

Funded by the European Union

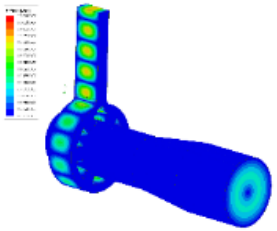
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

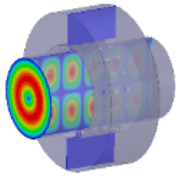
X-band module

Funded by the European Union

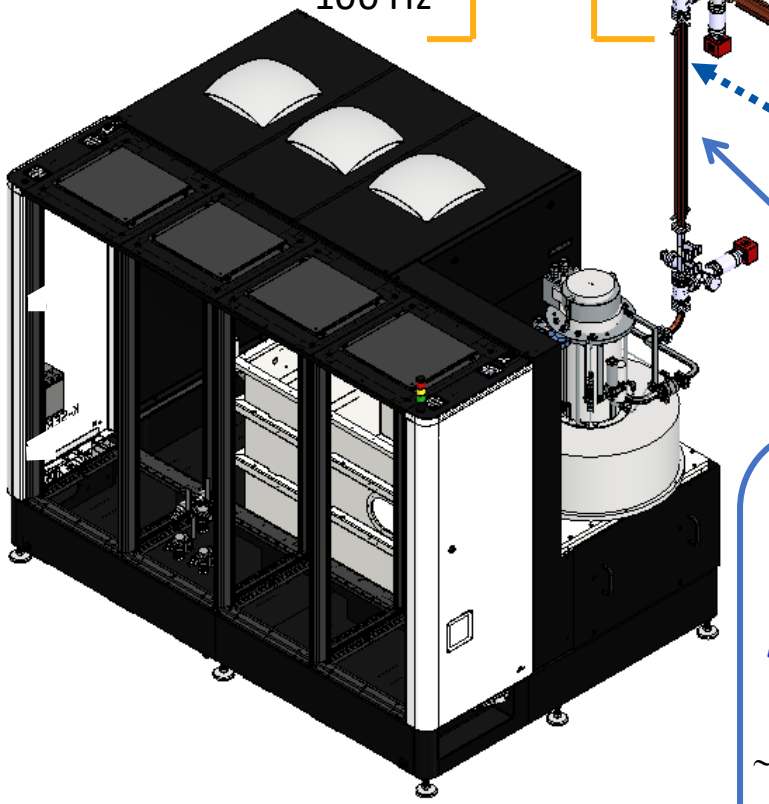
25 MW
1.5 us
100 Hz

Mode converter





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**
Klystron RF pulse length [µs]	**1.5**
Repetition Rate [Hz]	**100**



Power Source:
Solid State Modulator +
25 MW Canon E37119 Klystron

6 m

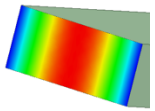
Transport line:
Low-loss Circular waveguide

140-70 MW
130 ns
100 Hz

Pulse Compressor

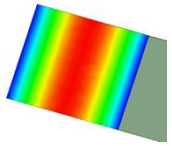
SURFACE FIELDS

WR90



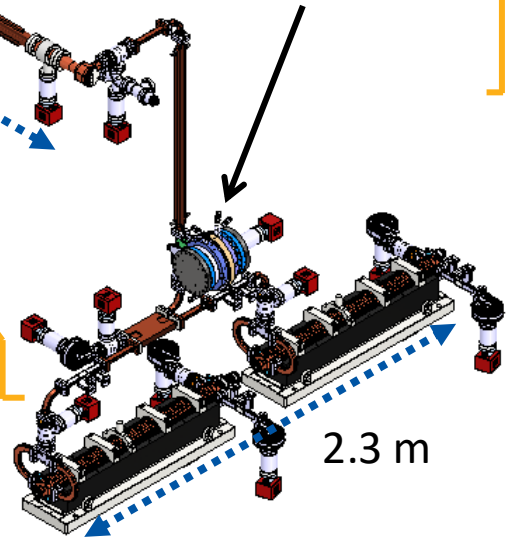
~33 MV/m

DHWR90



~23 MV/m
(equivalent to C band
@ 300 MW)

70-35 MW
130 ns
100 Hz



2.3 m

Accelerating module

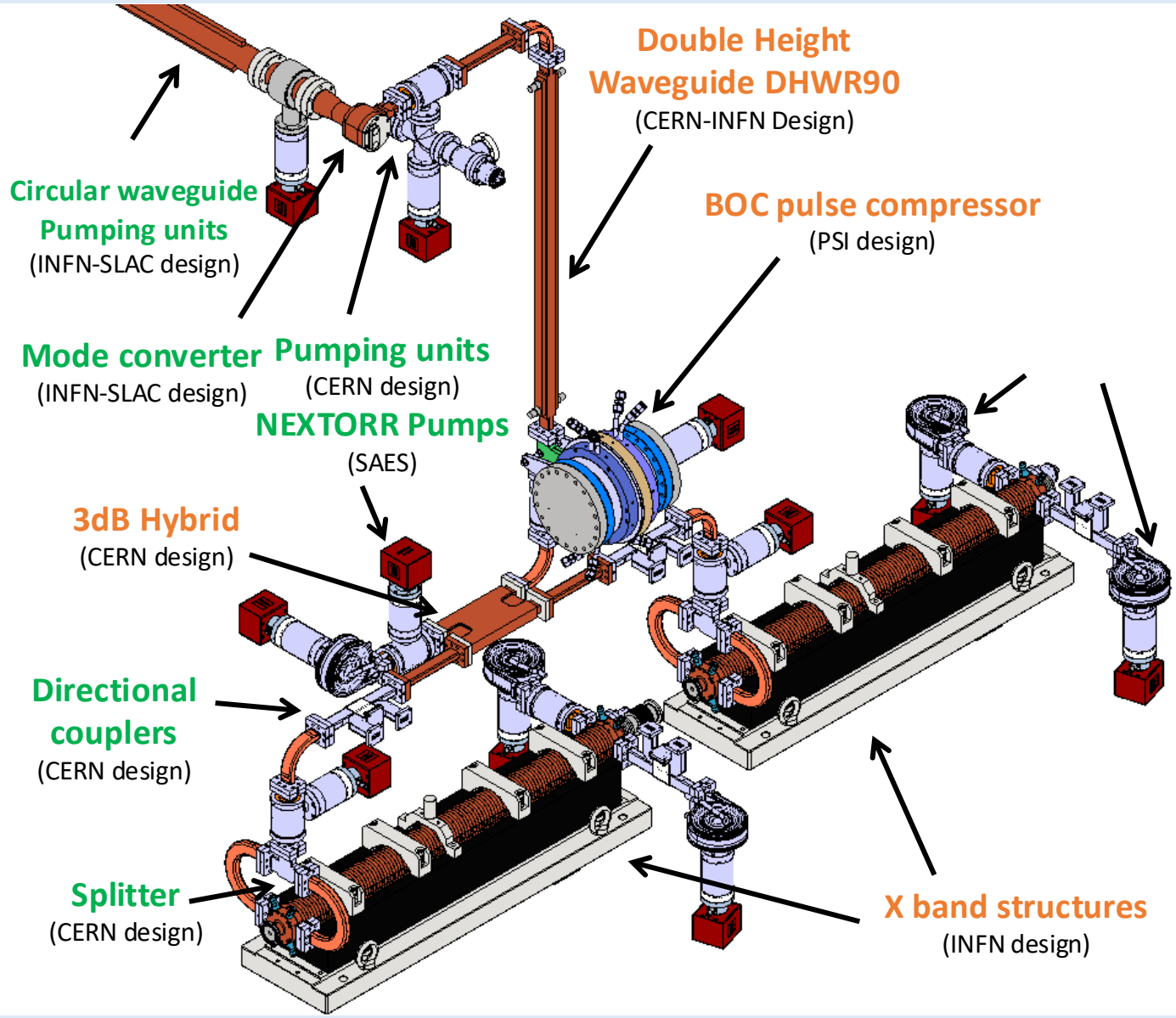
R&D of X-band components

Funded by the European Union

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. WG)	CERN	Fabricated and installed @ TEX facility	45 MW, 1 μs, 50 Hz
Directional coupler	CERN	Fabricated and installed @ TEX facility	45 MW, 1 μs, 50 Hz
Splitter	CERN	Fabricated and installed @ TEX facility	35 MW, 0.6 μs, 50 Hz
RF load	CERN	Fabricated and installed @ TEX facility	17 MW, 0.6 μs, 50 Hz, P_{avg} = 0.5 kW
Mode converter circular/rectangular	INFN/ SLAC	Fabricated and installed @ TEX facility	21 MW, 1 μs, 50 Hz
Pump unit (circ. WG)	INFN/ SLAC	Fabricated and installed @ TEX facility	21 MW, 1 μs, 50 Hz
3dB hybrid	CERN	Delivered	To be tested
BOC pulse compressor	PSI	Delivered and installed @ TEX facility	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 realization

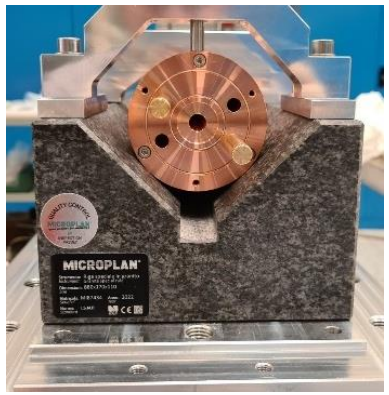
Funded by
the European Union

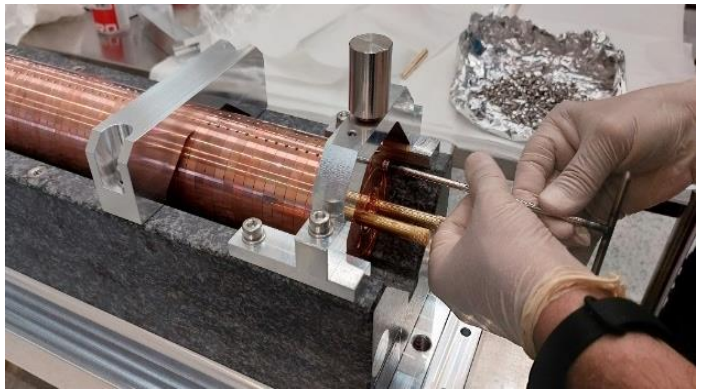
2x Mechanical prototypes for brazing optimization and realization technique test

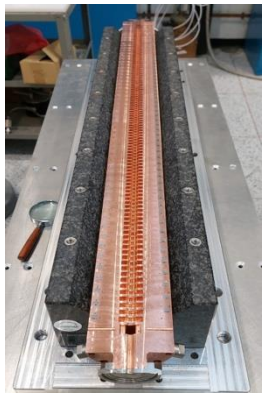
To preserve alignment and cell-to-cell straightness during and after the brazing process, a **dedicated assembly technique** was developed at LNF

Each cell is constrained to the adjacent one using screws and mounted on a high-precision granite support

This approach also **facilitates cell assembly** and enables **RF testing of the structure prior to brazing**







Results:

Successful vacuum test after brazing
Straightness within ± 15 μm for both prototypes (± 30 μm required)

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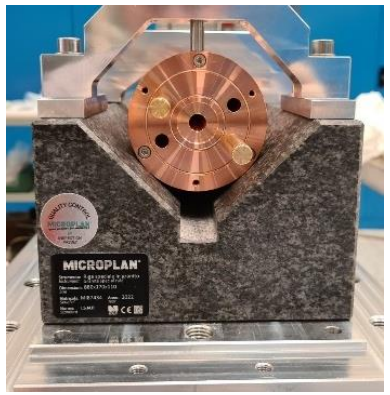
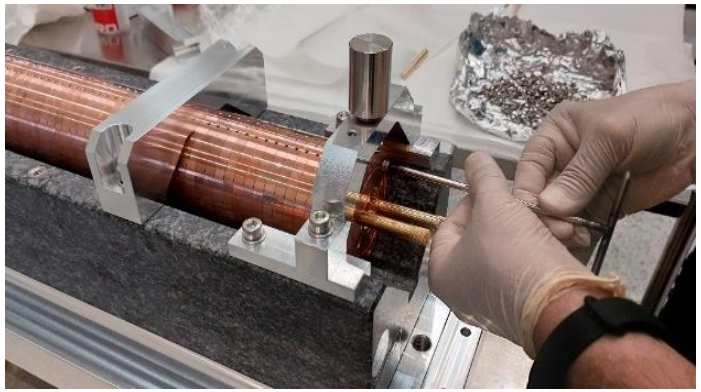
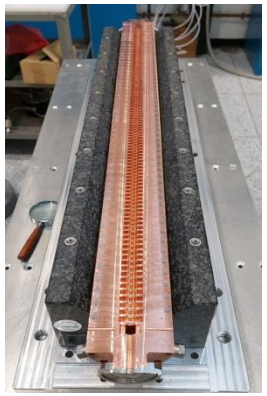




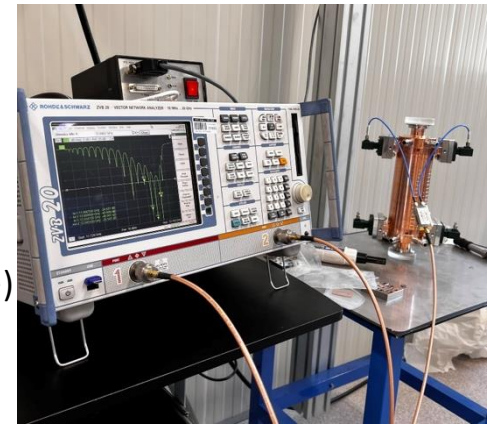


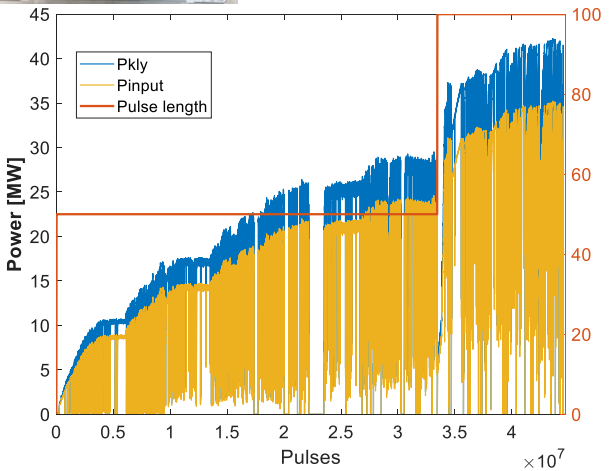
"Short" (21 cells - CI) RF prototype

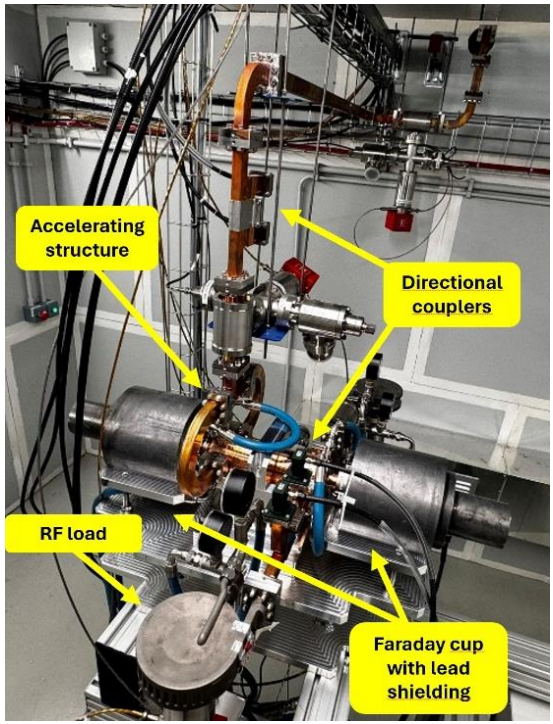
NO tuners on the cells, only 2 on the in/out couplers

Low power measurements performed:

- before and after brazing (custom assembly technique)
- after the tuning of the couplers







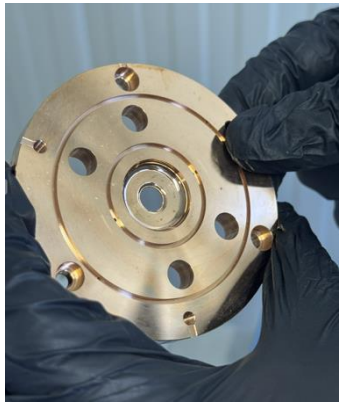
high power measurements performed (< 2 weeks):

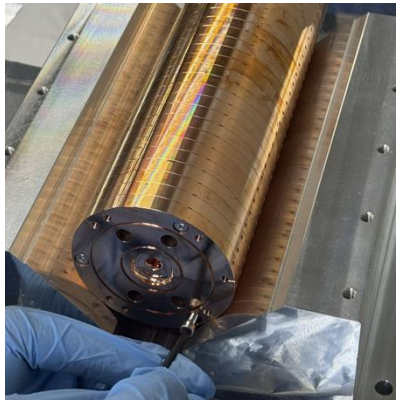
- Peak power of **35 MW, 100 ns pulse length at 50 Hz repetition rate** → **average gradient** of **74 MV/m (peak** of **80 MV/m)** with a BDR/m ≈ 5e-4
- **The test of this prototype is currently ongoing**, with the **BOC pulse compressor (PSI)** installed on the line.

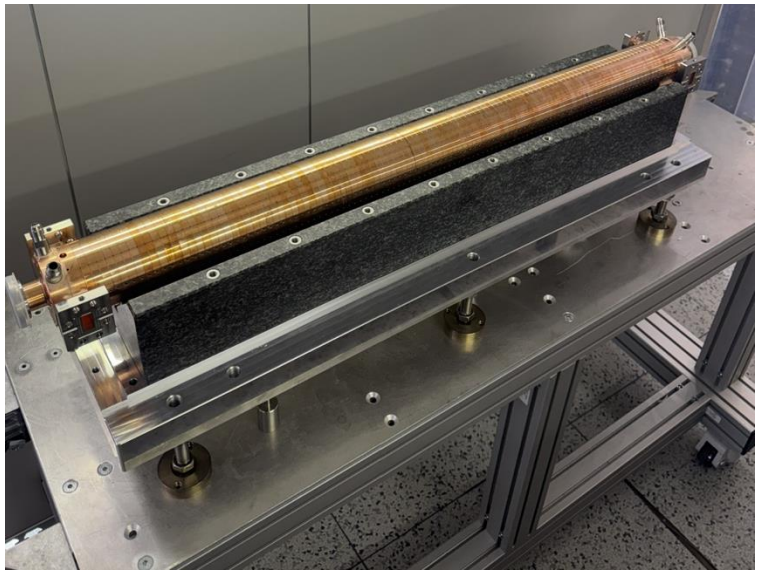
First EuPRAXIA@SPARC_LAB X-band structure

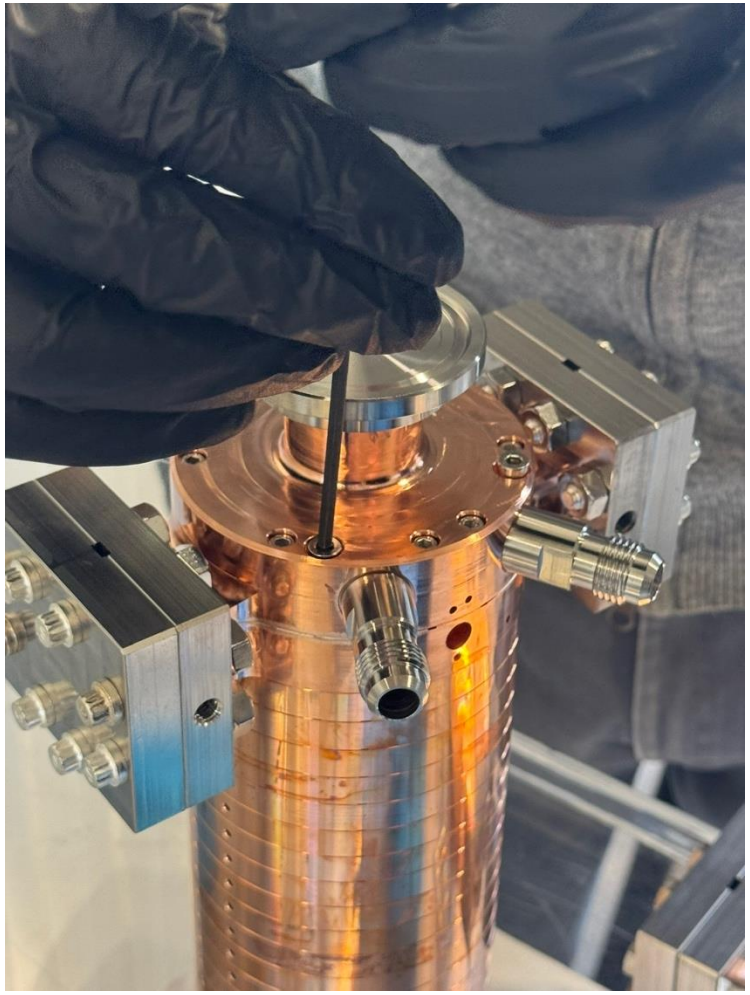
Funded by the European Union

At the end of 2024 started the realization of the **first full-scale X-band accelerating structure.**
Cell-machining realized by Comeb, **final assembly and brazing performed at INFN-LNF**
Structure manufactured without frequency tuners, by machining the accelerating cells and the couplers with micrometer precision
After brazing, the **vacuum test was successful**





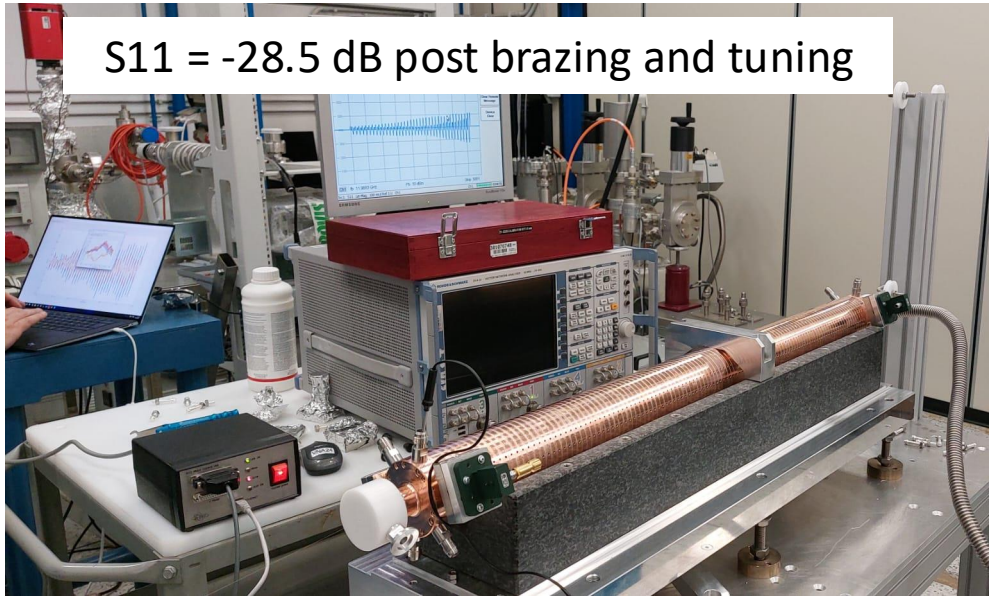




Full-scale structure **RF characterization performed both before and after the brazing process**

After brazing, a **soft tuning** was applied by adjusting the only tuners available on the couplers

The structure has been **installed at the TEX facility**, and it is **ready to be tested** at high RF power



Design of S-band 3m structures

Funded by
the European Union

With the end of the TDR, in Spring 2026 the implementation phase of the project started

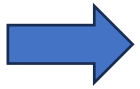
One of the most urgent task is the **design of the S-band accelerating structures**

To maximize the modularity, reducing costs and structure complexity → **3x 3m Constant Impedance** (partially compensates "SLED shaped" pulses)

GOAL: 30 MV/m average gradient → ΔE = 90 MeV per structure

Klystron E37327A maximum ratings:

- $P_k \leq 45$ MW
- $t_k = 4.5$us
- Rep = 100 Hz



Design baseline

- $P_k \leq 40$ MW
- $t_k = 4$us
- Rep = 100 Hz

FERMI spherical pulse compressor used as baseline for effective shunt impedance optimization: $\beta=7.4$ $Q_0=140.000$

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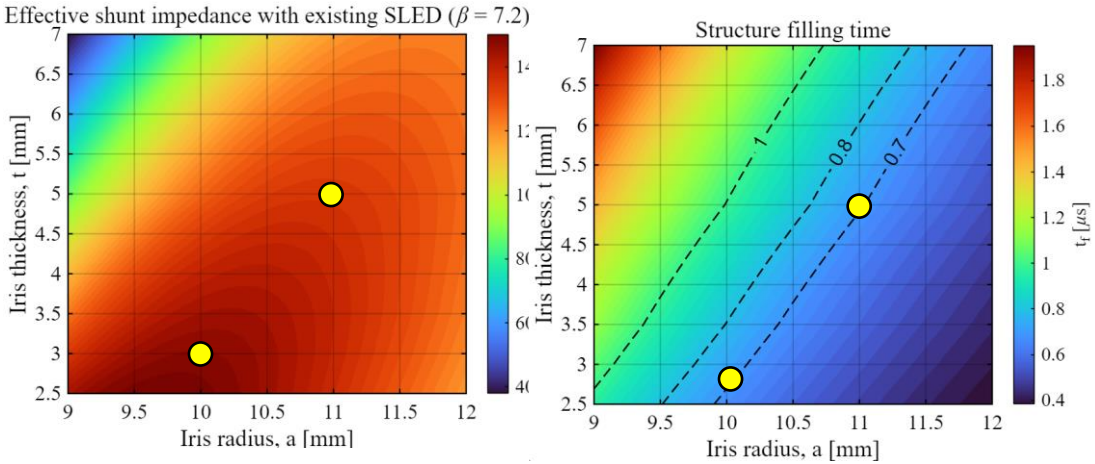

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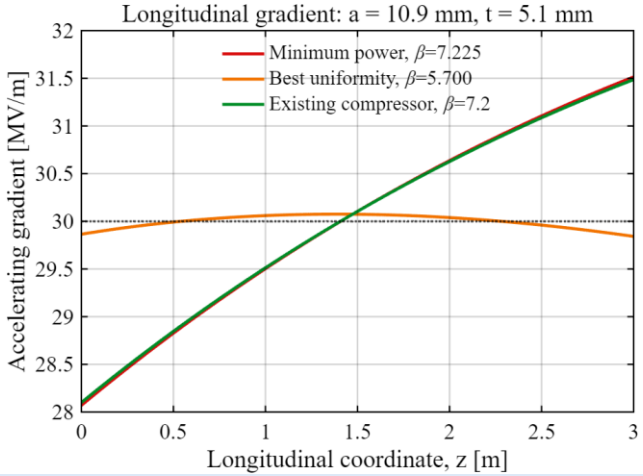

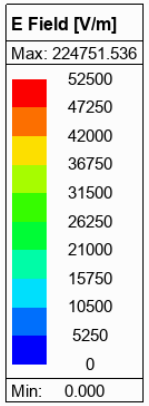

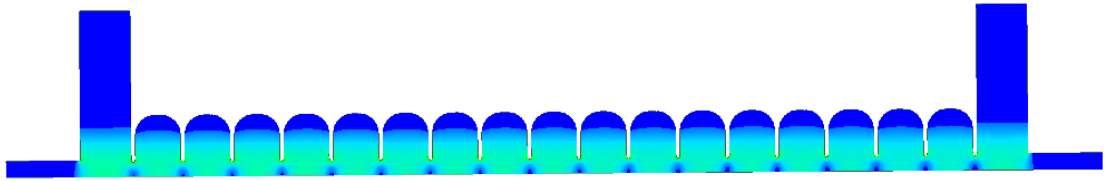

EuPRAXIA@SPARC_LAB synchronization

Funded by the European Union

- Stable and repeatable plasma acceleration requires **beam arrival time jitter** in the plasma chamber **as low as possible**
- In the EuPRAXIA@SPARC_LAB working point the most critical contributions are the **phase jitter of the RF compressor** and **photocathode laser**
- Unfortunately amplitude jitter in the RF gun and phase jitter of X-band cannot be neglected either…

Total jitter budget for RF/laser **sub-systems** (from TDR)

Parameter	Value
RF gun voltage (rms)	0.02 %
RF gun phase (rms)	0.02 deg (≈ 20 fs)
S-band RF phase (rms)	0.02 deg (≈ 20 fs)
X-band RF phase (rms)	0.1 deg (≈ 23 fs)
Photocathode Laser phase (rms)	0.02 deg (≈ 20 fs)

- The **added jitter by the reference distribution** system **is included** in the budget of the BD requirements
- The total jitter of each sub-system is given by the quadratic sum of:
  distribution system ,**client's intrinsic** (out-of-loop) jitter, and **phase-lock** residual jitter

$$\sigma_{Sub-system} = \sqrt[2]{\sigma_{Distr}^2 + \sigma_{Client}^2 + \sigma_{Lock}^2}$$

RF distribution system choice

«State of the art» assumptions	Value
RF plant (LLRF+driver+klystron) phase jitter (rms)	15 fs
RF plant **lock residual jitter** (rms)	0 fs
Laser amplifier phase jitter (rms)	5 fs
Laser **lock residual jitter** (rms)	15 fs

→ RF direct feeding of LLRF/klystrons

$$\sigma_{Sub-system} = \sqrt[2]{\sigma_{Distr}^2 + \sigma_{Client}^2 + \sigma_{Lock}^2}$$

$\sigma_{Distr}^{max} < 13.2\ fs$ RF plants

$\sigma_{Distr}^{max} < 12.3\ fs$ Laser

→ $\sigma_{Distr}^{max} < 10\ fs$

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$\sigma_{Distr}^{max} < 12.3\ fs$ Laser

→ $\sigma_{Distr}^{max} < 10\ fs$

- Depending on the technology, the added jitter can be as low as:
  - **< 8 fs rms** (RF over Fiber transmission)
  - **< 1 fs rms** (Pulsed optical system)

The price to pay is increased complexity, cost and maintenance of the system

ideal for optical clients, RF extraction is much noisier…

- The impact on sub-system jitter is somewhat limited (due to the quadratic sum)

$\sigma_{Sub-system}^{RFoF} \approx 17.7\ fs$

$\sigma_{Sub-system}^{pulsed} \approx 15.8\ fs$

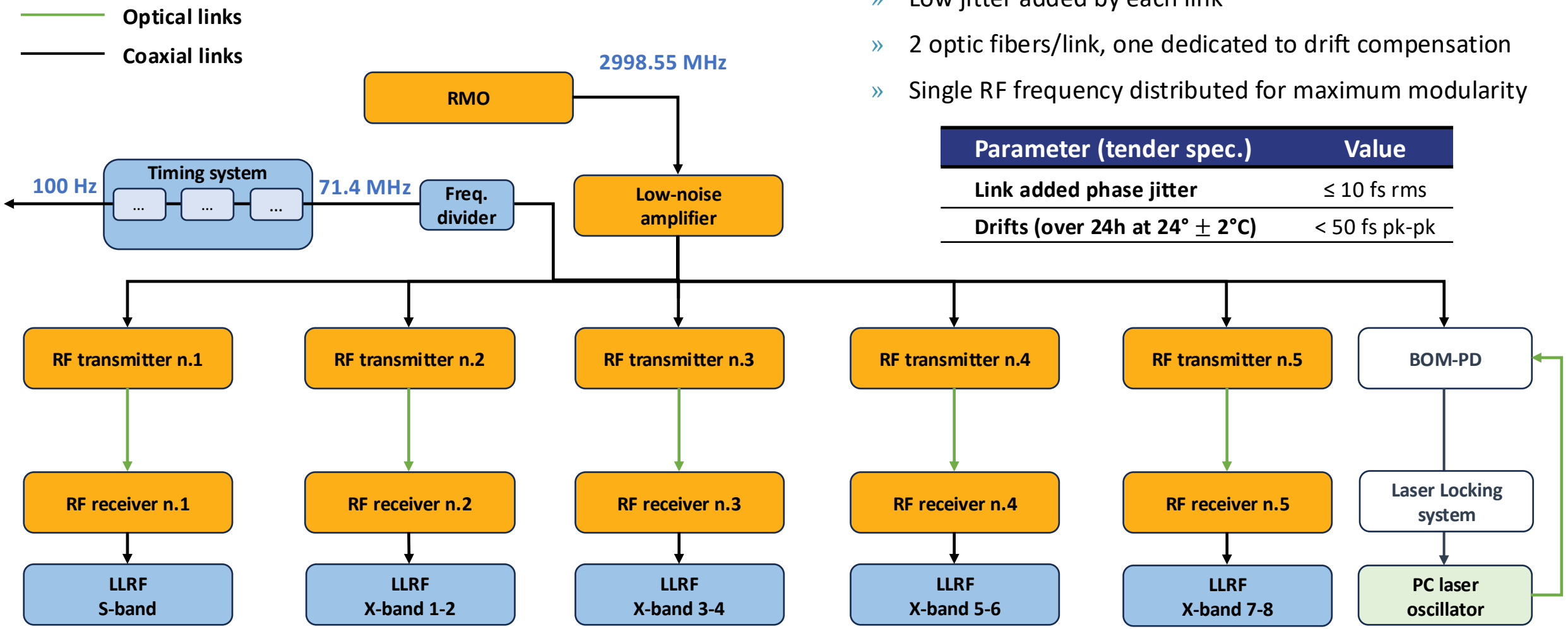
Δ < 2 fs

EuPRAXIA@SPARC_LAB RF reference distribution

Funded by the European Union

- CW laser modulated in amplitude by RF reference
- Low jitter added by each link
- 2 optic fibers/link, one dedicated to drift compensation
- Single RF frequency distributed for maximum modularity

Parameter (tender spec.)	Value
Link added phase jitter	≤ 10 fs rms
Drifts (over 24h at 24° ± 2°C)	< 50 fs pk-pk



EuPRAXIA@SPARC_LAB Low-Level RF system

Funded by the European Union

- Low-Level RF specifications have been finalized for the project TDR
- The tender (**2.3 M€**) is being prepared as we speak, published at the beginning of 2027:
  - **4 S-band systems + 9 X-band systems + RF distibution system**
- Digital platform (FPGA), pulse-to-pulse amplitude and phase feedback, arbitrary pulse shaping, temperature stabilized front-end
- Strong R&D required to meet the EuPRAXIA@SPARC_LAB specifications (especially for X-band systems)

Parameter	S-band	X-band
Amplitude resolution	≤ 0.01% rms	≤ 0.015% rms
Phase resolution	≤ 0.005 deg rms (@ 2.99855 GHz)	≤ 0.015 deg rms (@ 11.9942 GHz)
Added amplitude noise	≤ 0.01% rms	≤ 0.015% rms
Added phase noise	≤ 0.005 deg rms (@ 2.99855 GHz)	≤ 0.015 deg rms (@ 11.9942 GHz)
Drifts (over 24h at 24° ± 2°C)	< 100 fs rms	< 100 fs rms

EuPRAXIA-PP Consortium

Funded by the European Union

Coordinator

Consiglio Nazionale delle Ricerche

Elettra Sincrotrone Trieste

ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

INFN Istituto Nazionale di Fisica Nucleare

Sapienza Università di Roma

Università di Roma Tor Vergata

Imperial College London

Queen's University Belfast

UK Research and Innovation

University of Liverpool

University of Oxford

University of Strathclyde Glasgow

CERN

DESY.

Leibniz Ferdinand Braun Institut

Fraunhofer ILT

GSI

hhu Heinrich Heine Universität Düsseldorf

Helmholtz Zentrum Dresden Rossendorf

Jülich Forschungszentrum

LMU Ludwig-Maximilians-Universität München

Amplitude

cea

cnrs

Thales

eli

Técnico Lisboa

ALBA

CLPU Centro de Láseres Pulsados

Empa Materials Science and Technology

EPFL

Paul Scherrer Institut PSI

The Hebrew University of Jerusalem

IASA

Pécsi Tudományegyetem University of Pécs

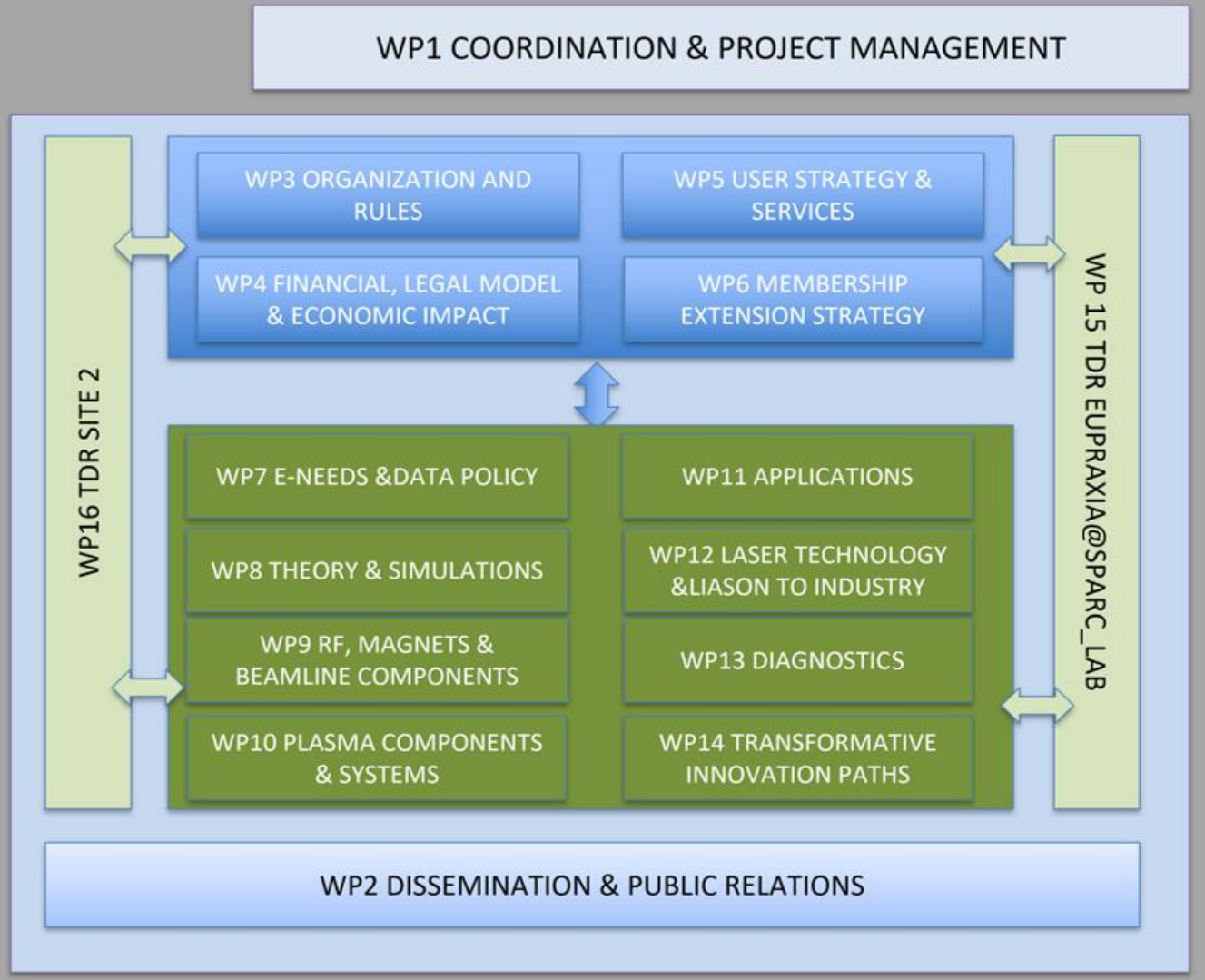
SZTE University of Szeged

Wigner

UCLA

EuPRAXIA-PP Structure

Funded by the European Union



Selected Committees and Boards

GOVERNING BOARD
(decision-making body, 1 representative per institute)

Steering Committee
(coordinator plus WP leaders plus experts)

Scientific/Technical Advisory Board
(external experts in user services, RI implement-tation, ESFRI aspects and technical themes)

Board of Financial Sponsors
(connection to decision makers and funding authorities)

Acknowledgements

EuPRAXIA Preparatory Phase

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EuPRAXIA Doctoral Network

Funded by
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This project has received funding from the European Union´s Horizon Europe research and innovation programme under Grant Agreement No. 101073480 and the UKRI guarantee funds.

EuAPS

Co-funded by
the European Union

This publication has been made with the co-funding of European Union Next Generation EU.

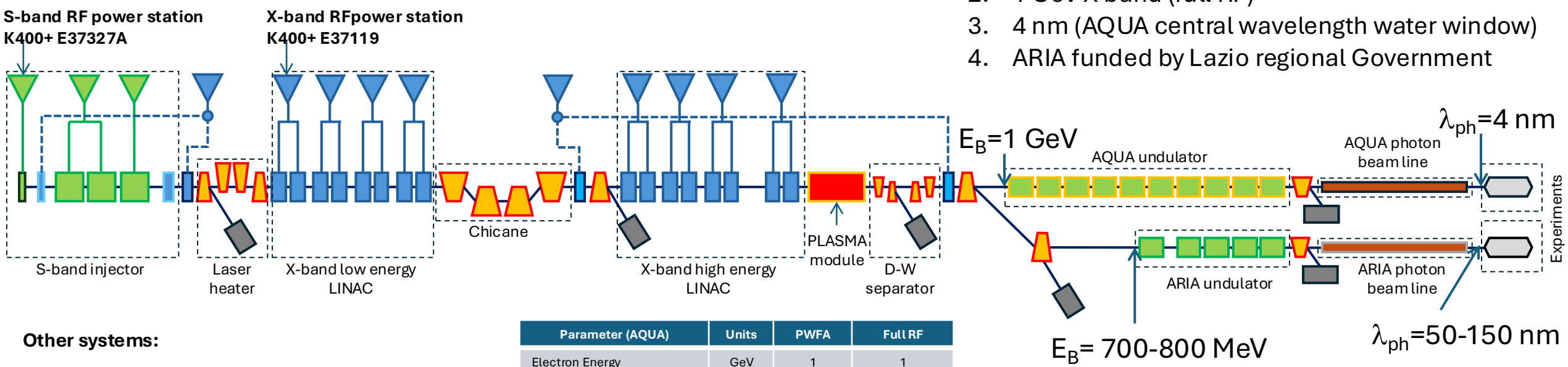
Backup

Funded by
the European Union

Layout of the EuPRAXIA@SPARC_LAB RF linac

Funded by the European Union

1. 1 GeV (500 MeV X band+500 MeV Plasma)
2. 1 GeV X band (full RF)
3. 4 nm (AQUA central wavelength water window)
4. ARIA funded by Lazio regional Government



Other systems:

-LLRF and synchr.

-Power supplies

-Magnets

-Vacuum

-Photocathode Laser

-ARIA Laser

-Diagnostics

-Cooling system

-Control system

S-band gun

S-band structure

X-band structure

X-band linearizers

PolarX

Dump

Parameter (AQUA)	Units	PWFA	Full RF
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
Radiation wavelength	nm	4.06	4.06
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

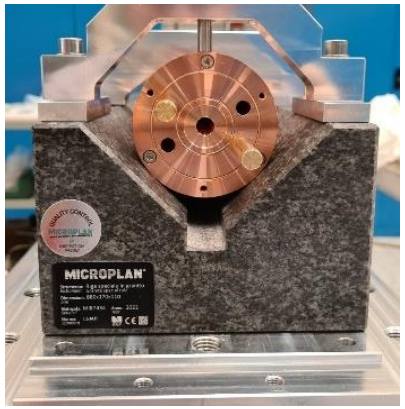
Courtesy of D. Alesini

X-band structure realization

Funded by
the European Union

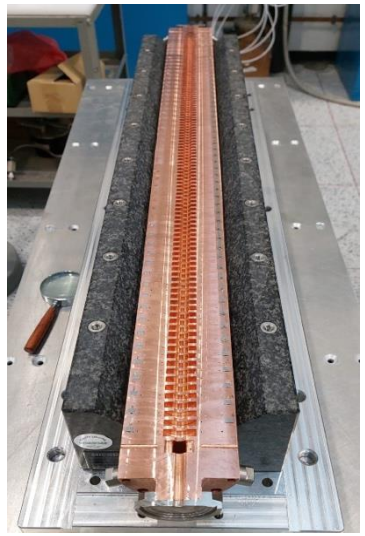
2x Mechanical prototypes for brazing optimization and realization technique test

To preserve alignment and cell-to-cell straightness during and after the brazing process, a **dedicated assembly technique** was developed at LNF.
Each cell is constrained to the adjacent one using screws and mounted on a high-precision granite support.
This approach also facilitates cell assembly and enables RF testing of the structure prior to brazing.



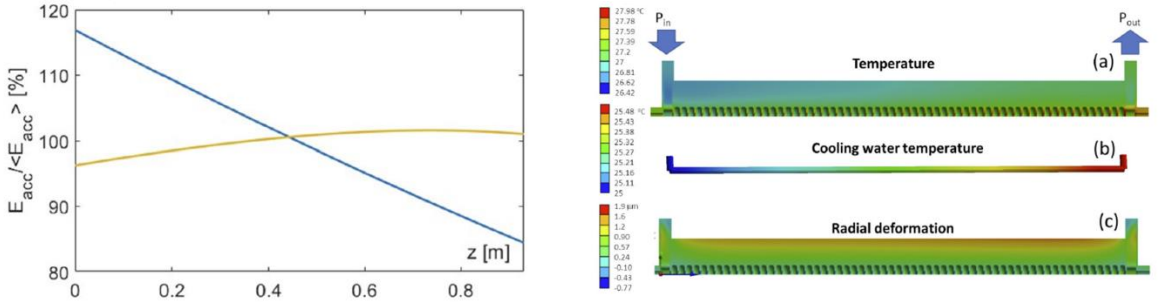
Results on the brazed prototypes

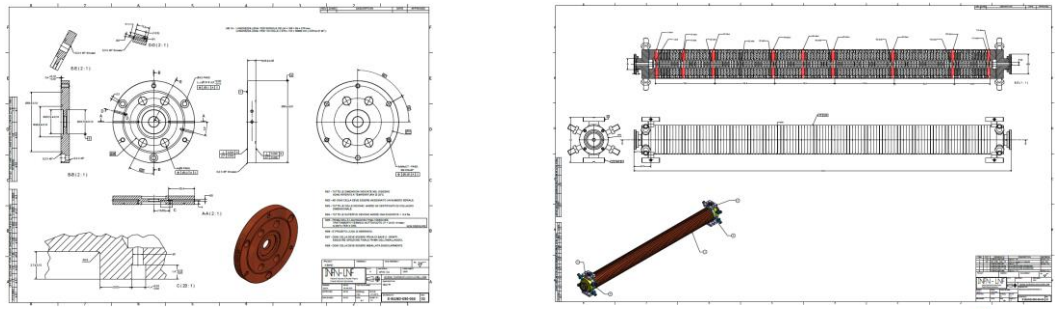
- After brazing the two structures have been **successfully vacuum tested.**
- **Straightness within ± 15 μm** obtained after brazing on both prototypes (± 30 μm required by BD)

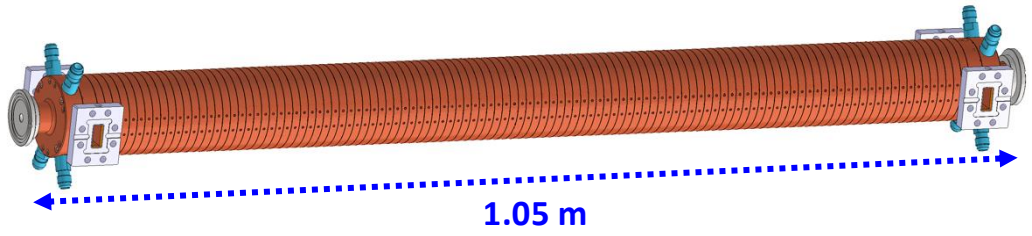


X-band structure

- **EM design of the structure completed:** ≈ 1 m long, **3.5 mm average iris radius** designed to work with an average accelerating gradient of **60 MV/m**
- **Thermo-mechanical simulations completed:** to demonstrate the correct sizing of the cooling system (both at 100 Hz and 400 Hz)
- Final **mechanical design** and **prototyping activity completed:** 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/μm²]	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**	

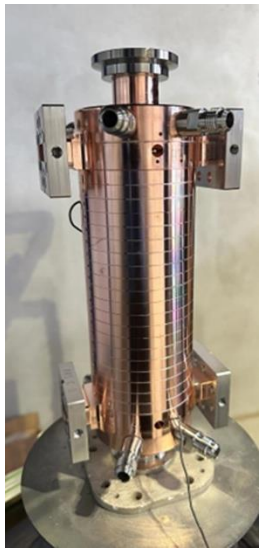
M. Diomede et al. NIM A 909 (2018) 243–246

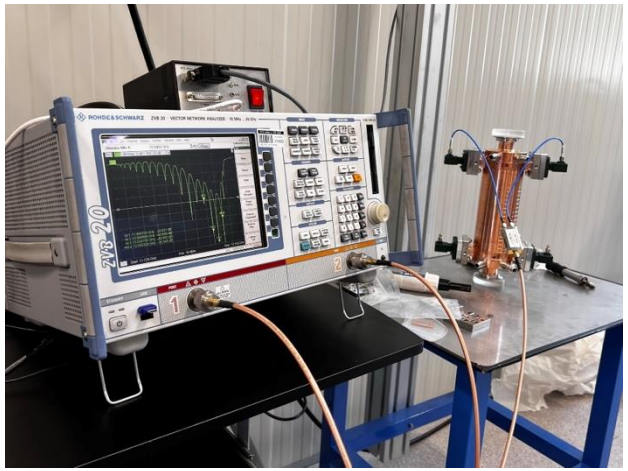
21-cells RF prototype

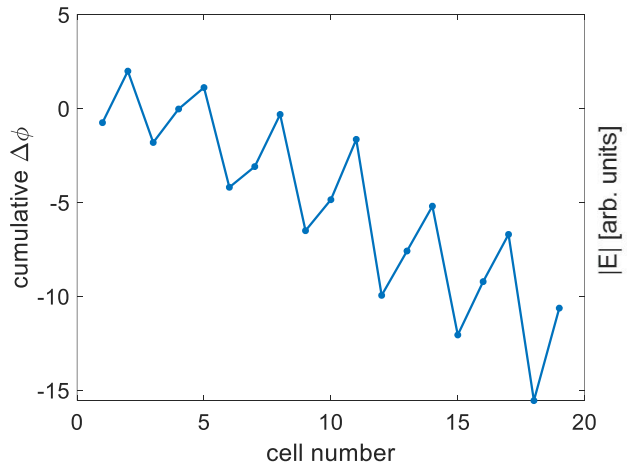
Funded by the European Union

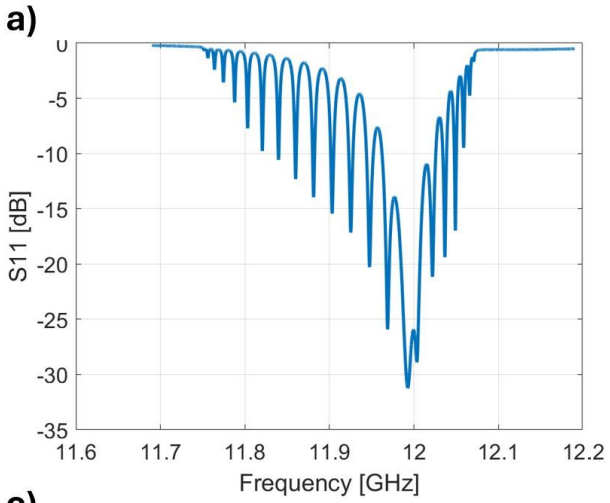
X-band, 21 cells, CI, TW structure prototype

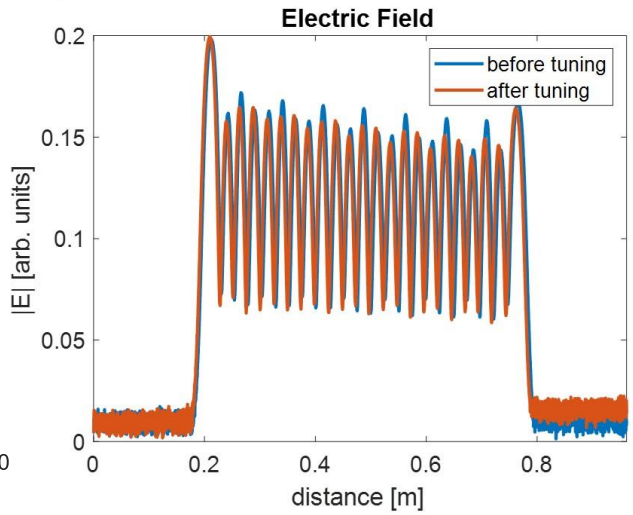
- Realized **without tuners** on the cells, only 2 tuners on the two couplers
- **Low power measurements performed:**
  - **before cells brazing** (thanks to the custom assembly technique)
  - **after the brazing**
  - after the tuning of the couplers
- During the measurements and the tuning procedures the structure has been continuosly fluxed with nitrogen
- All the cells seem to be slightly smaller than design. To maximize the acceleration efficiency the working temperature needs to be increased → T_{cav} = 35 °C

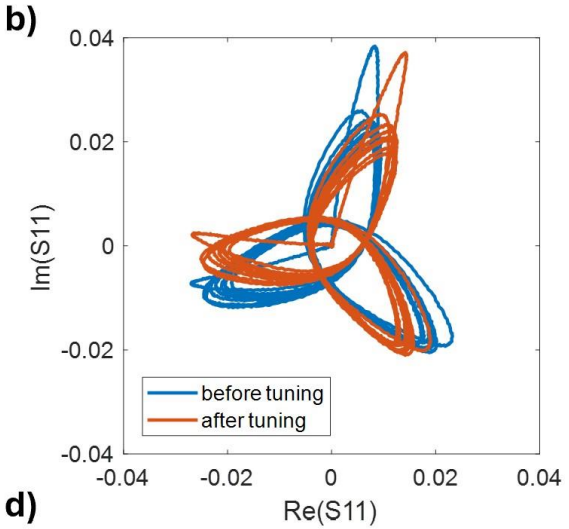


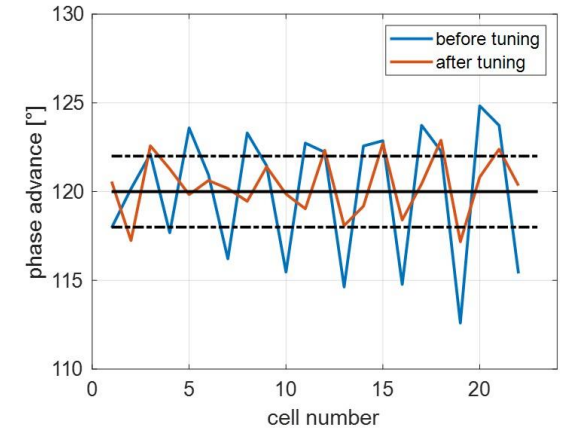










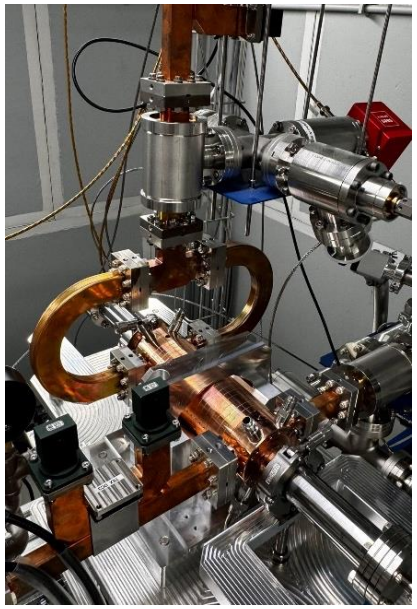


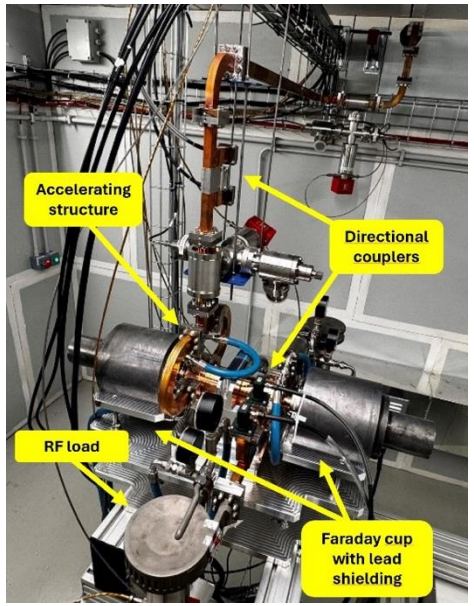
21-cells RF prototype high power tests

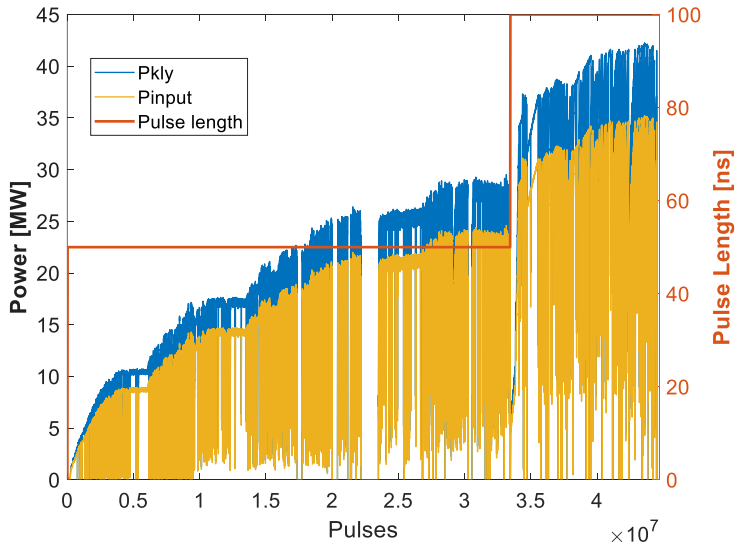
Funded by the European Union

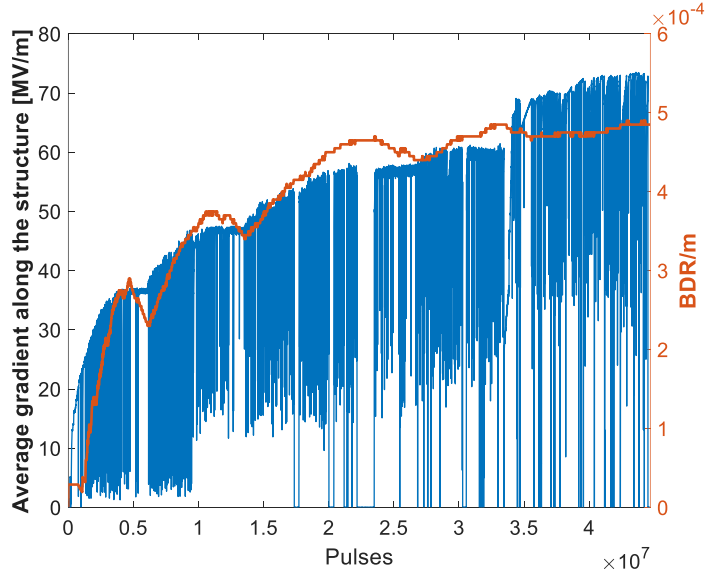
- In spring 2024 started the **high-power test of the first EuPRAXIA@SPARC_LAB X-band structure prototype**
- 21 cells, **constant impedance**, RF prototype (the real structure will be 1 m long).
- In nearly 12 days we reached a peak power of **35 MW, 100 ns pulse length at 50 Hz repetition rate** → **average gradient** of **74 MV/m**
  peak gradient at the structure input of **80 MV/m** with a BDR/m ≈ 5e-4
- **The test of this prototype is currently ongoing**, with the **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**





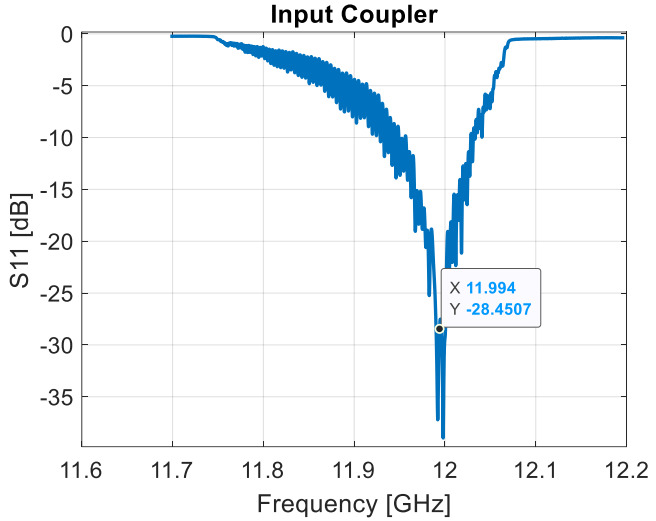


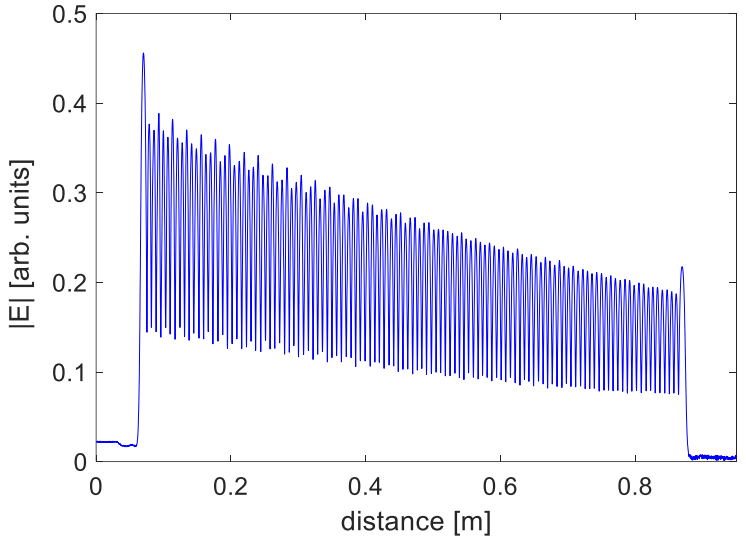


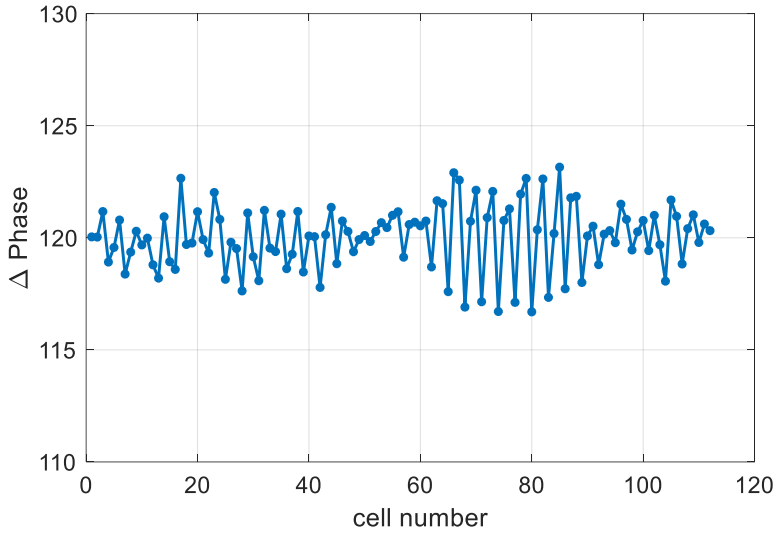
First EuPRAXIA@SPARC_LAB X-band structure

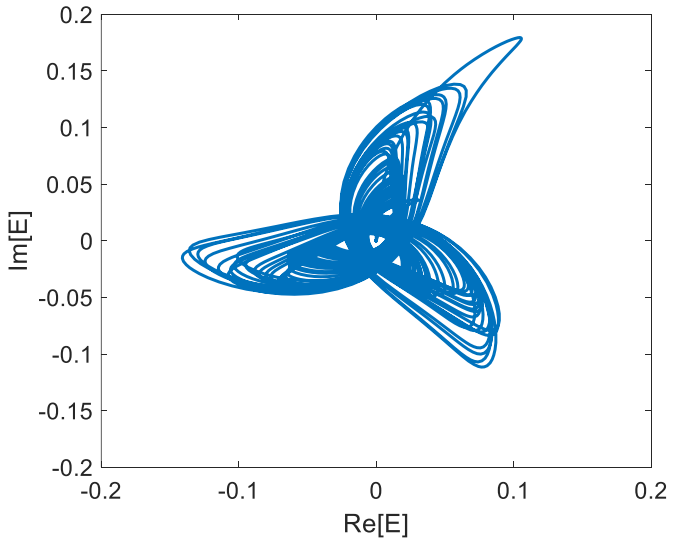
Funded by the European Union

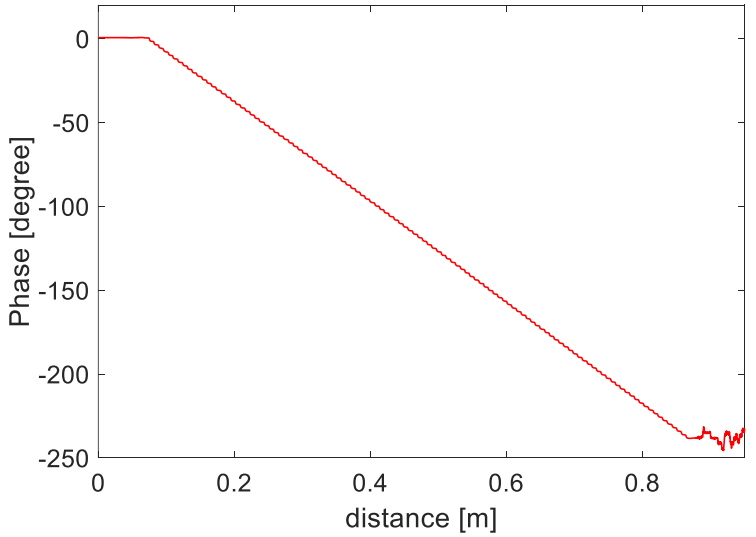
The structure has been installed for high power tests at TEX facility that should start in the next months

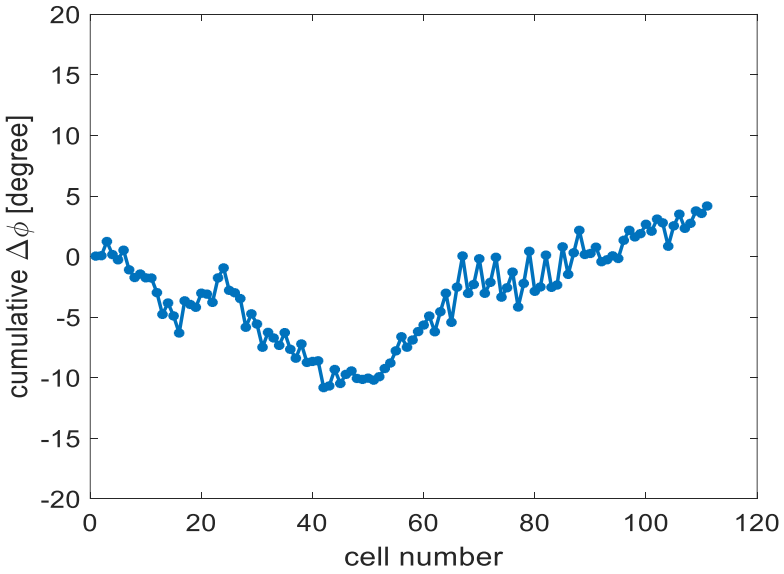












First EuPRAXIA@SPARC_LAB X-band structure

Funded by the European Union

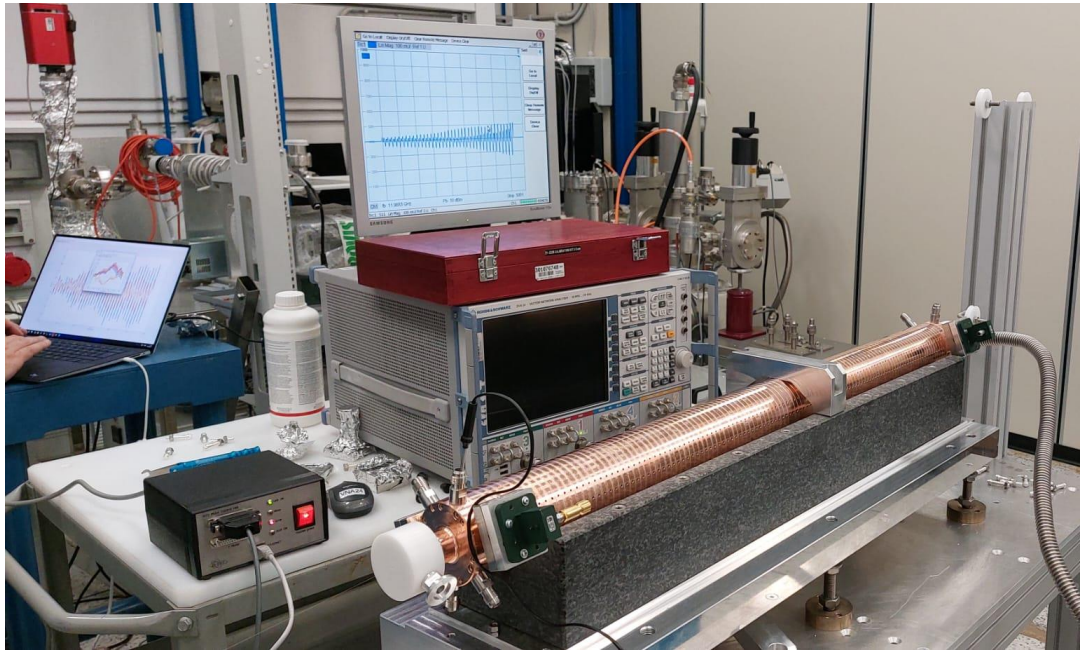
Following the machining of the cells and couplers by Comeb, preliminary RF measurements using **bead-pull technique** were carried out on selected groups of cells to verify fabrication accuracy and perform **quality check control**

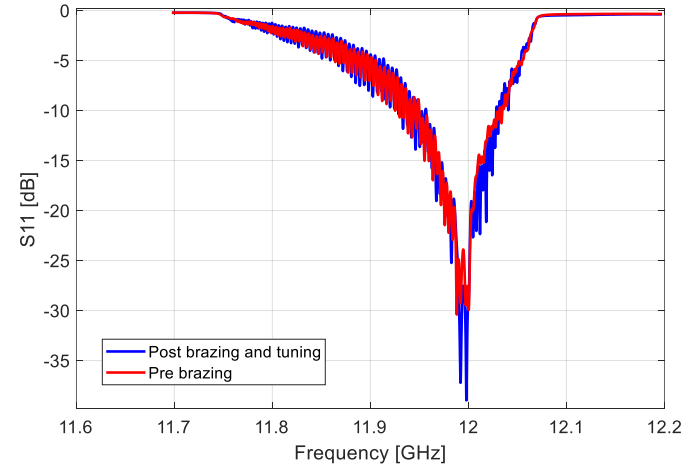
The full-scale structure was then assembled, and **RF characterization was performed both before and after the brazing process**

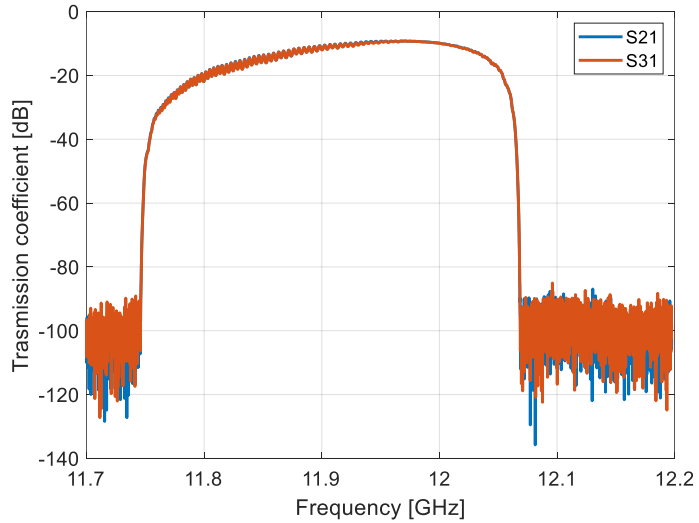
After brazing, a **soft tuning** was applied by adjusting the only tuners available on the couplers

S11@11.994GHz = -24.5 dB pre brazing
S11@11.994GHz = -28.5 dB post brazing and tuning in vacuum @22°C

The structure has been **installed at the TEX facility**, and it is **ready to be tested** at high RF power



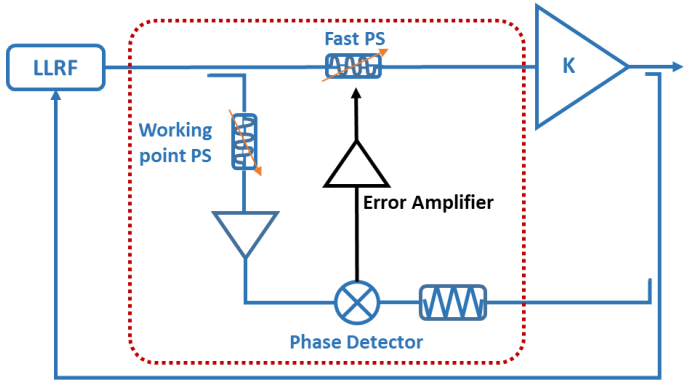


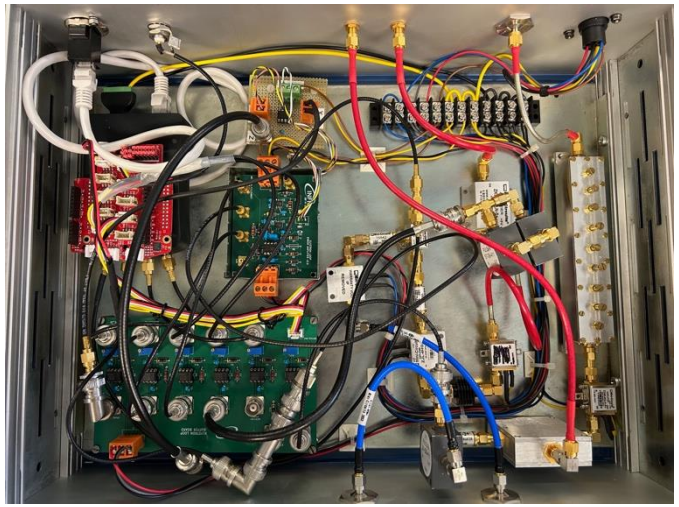


Enhancing RF plant stability – Intra-pulse feedback

Funded by the European Union

- Developed at LNF-INFN in 2008 to meet the stability requirements of the first SPARC_LAB FEL experiments
- **Analog loop electronics** (no latency) + **fast actuator** (phase shifter, > 50 MHz bandwidth)
- Klystron phase compared to LLRF reference, **phase correction applied within the RF pulse** (few hundreds of ns)

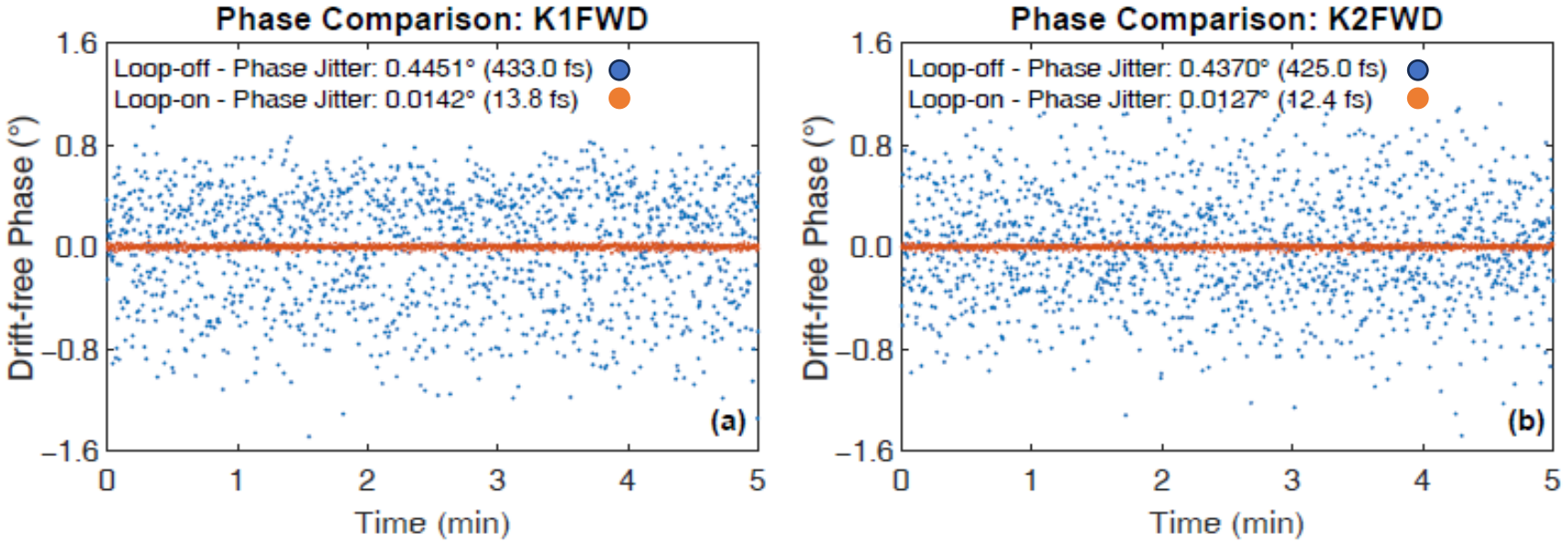
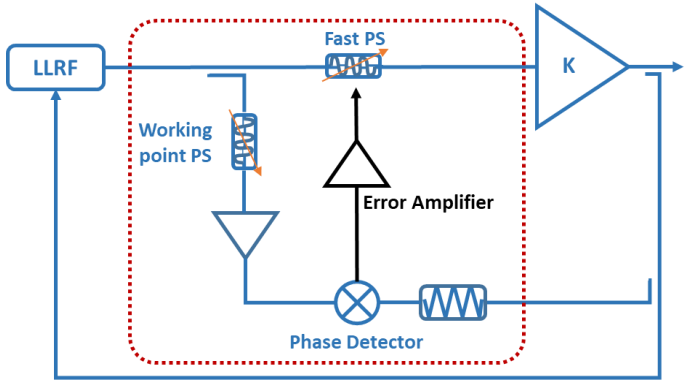
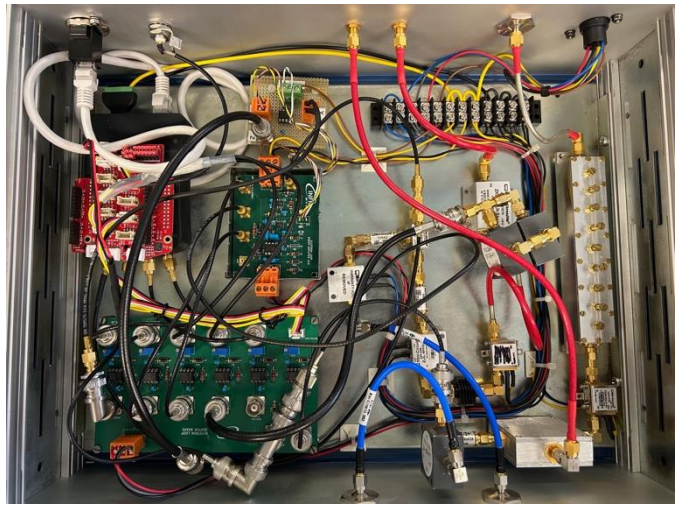




Enhancing RF plant stability – Intra-pulse feedback

Funded by the European Union

- Developed at LNF-INFN in 2008 to meet the stability requirements of the first SPARC_LAB FEL experiments
- **Analog loop electronics** (no latency) + **fast actuator** (phase shifter, > 50 MHz bandwidth)
- Klystron phase compared to LLRF reference, **phase correction applied within the RF pulse** (few hundreds of ns)
- Several upgrades in the last 3 years, remarkable **plant stability of < 15 fs rms** on both S-band klystrons (w. PFN modulators)



X. Fang et al. Appl. Sci. 2026, 16(12), 5733