7th European Advanced Accelerator Conference
EAAC2025

High gradient X-band linac as a driver for PWFA user facility

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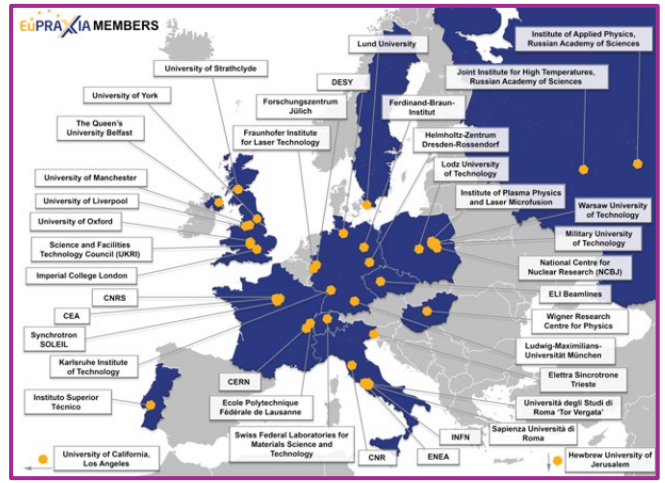
La Biodola Bay, Isola d'Elba, Italy
Sept 21 – 27, 2025

Outline

1. Context and Motivations
2. RF Linac for the EuPRAXIA@SPARC_LAB Project
3. X-band module layout and RF components
4. TEX Facility and Upgrade
5. X-band structure realization and testing activities results
6. ASTERIX project and future perspective

Motivation and context

- **Compact plasma-based FEL user facility**
  - The project EuPRAXIA@SPARC_LAB aims at constructing a FEL radiation source (λ_{FEL}=4 nm) combining **Normal Conducting RF X-band Linac** with **Plasma Acceleration Stage (PWFA)**.
  - Presently in the final phase of submission of the Technical Design Report.
  - A **new building**, now under executive design phase, will host the new Facility at LNF, the construction will start in September 2026.

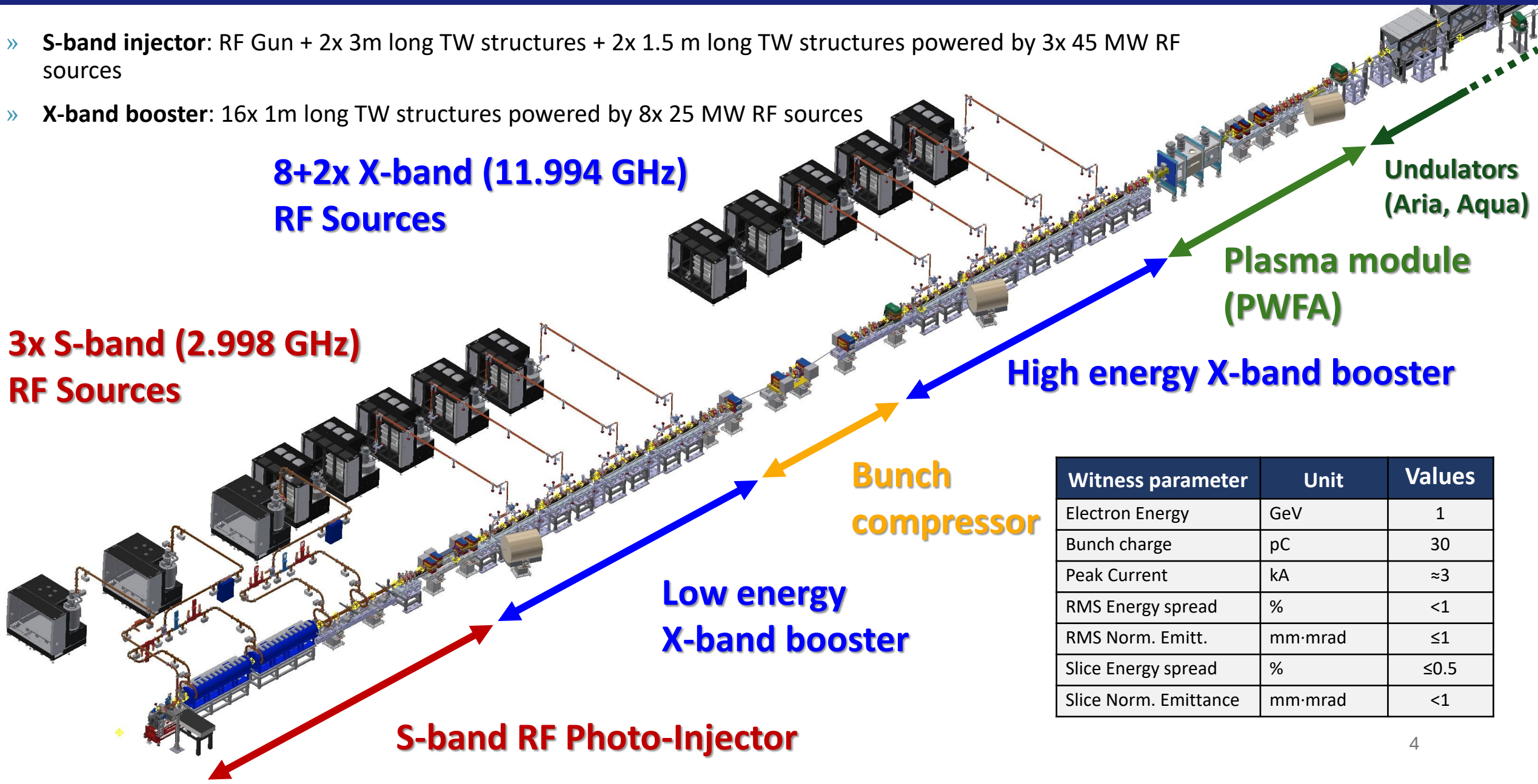


- **Beam requirements at plasma entrance:**
  - Energy: ≥ 500 MeV (driver bunch)
  - Normalized emittance: < 1 mm·mrad
  - Bunch length: < 100 fs

- **Reduced linac length → high gradient X-band (11.994 GHz) technology**
  - **≥ 60 MV/m** to reach GeV-class beam energies in compact footprint
  - Aligned with others international projects

Layout of the EuPRAXIA RF Linac

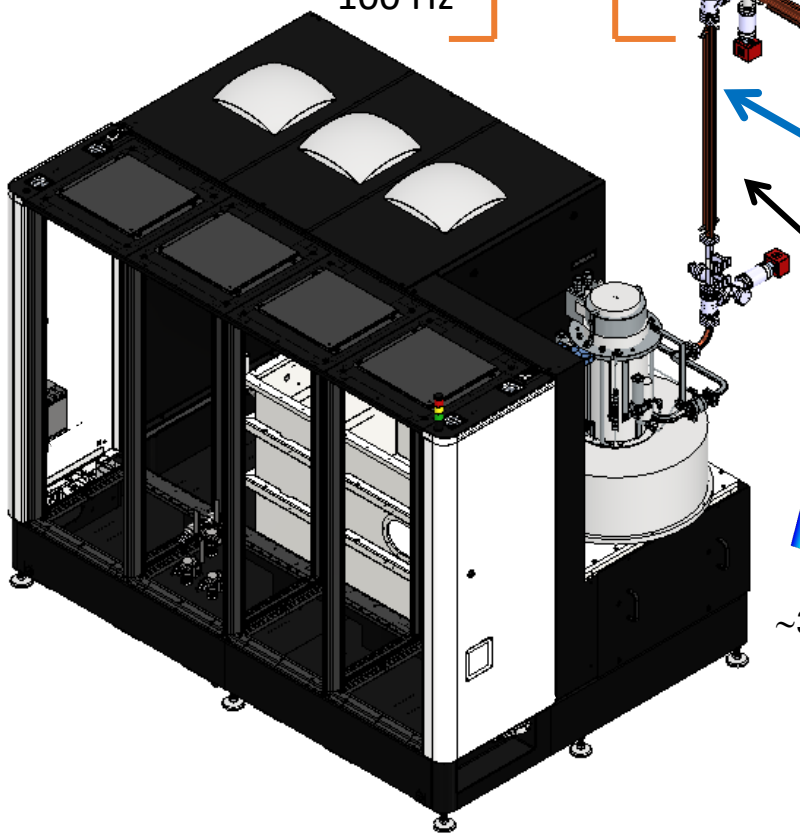
- **S-band injector**: RF Gun + 2x 3m long TW structures + 2x 1.5 m long TW structures powered by 3x 45 MW RF sources
- **X-band booster**: 16x 1m long TW structures powered by 8x 25 MW RF sources



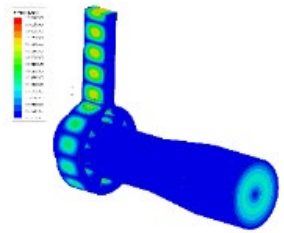
Witness parameter	Unit	Values
Electron Energy	GeV	1
Bunch charge	pC	30
Peak Current	kA	≈3
RMS Energy spread	%	<1
RMS Norm. Emitt.	mm·mrad	≤1
Slice Energy spread	%	≤0.5
Slice Norm. Emittance	mm·mrad	<1

X-band module layout

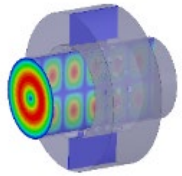
25 MW
1.5 us
100 Hz



Power Source:
Solid State Modulator +
Klystron Canon E37119



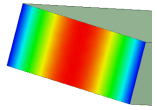
Mode conv.



Transport line:
Low loss Circular waveguide

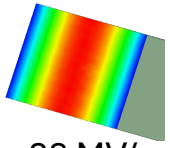
6 m

WR90



~33 MV/m

DHWR90



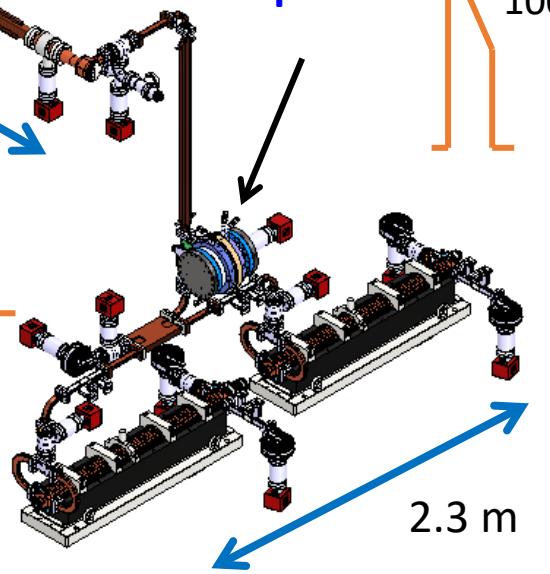
~23 MV/m
(comparable with C band @ 300 MW)

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**

Pulse Compressor

140-70 MW
130 ns
100 Hz

70-35 MW
130 ns
100 Hz



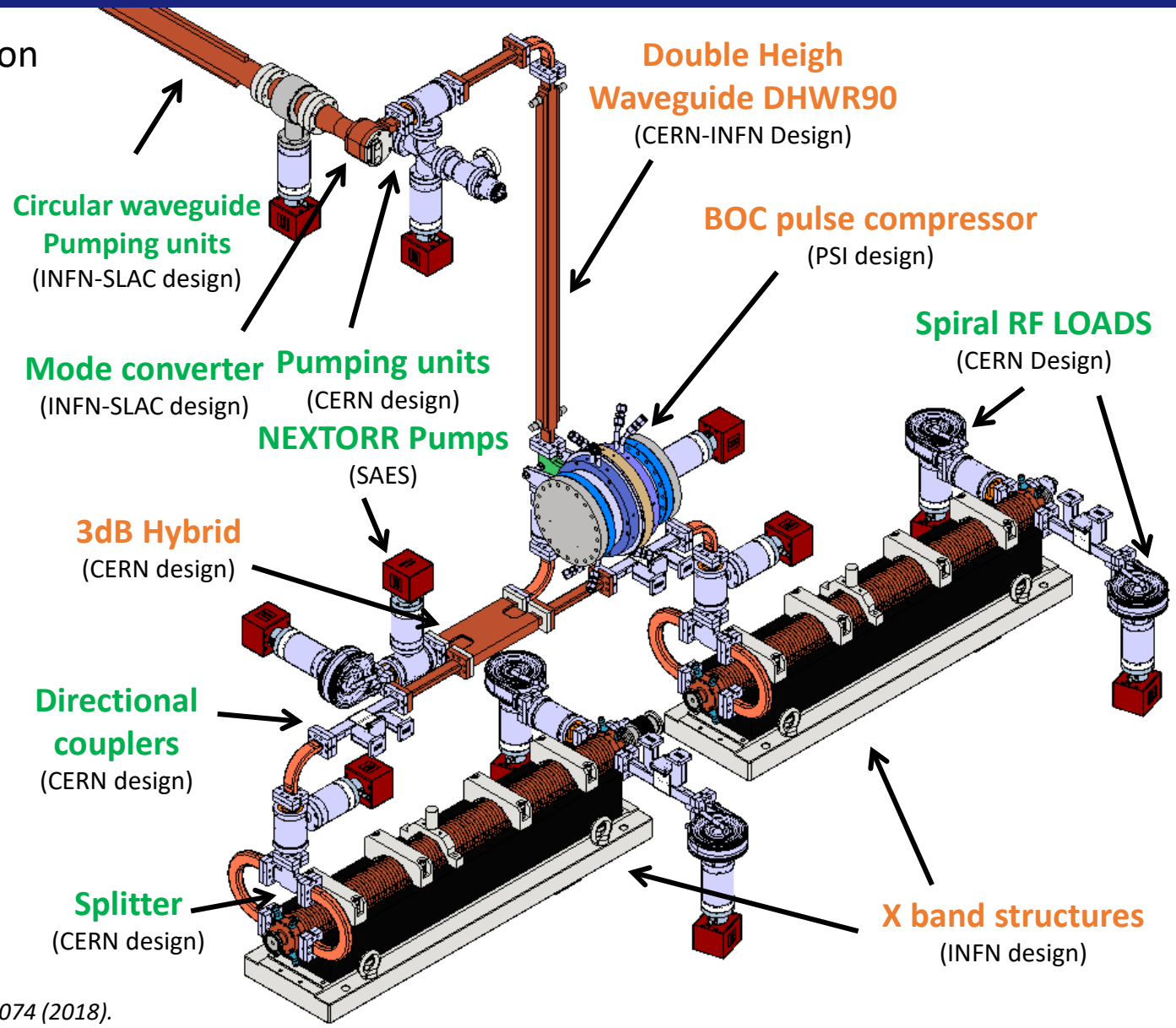
Accelerating module

2.3 m

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

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3dB hybrid	CERN	Delivered	To be tested
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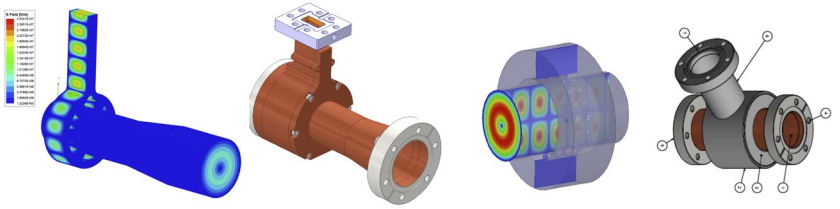
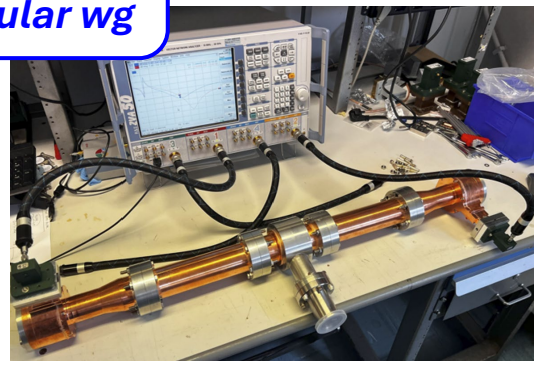
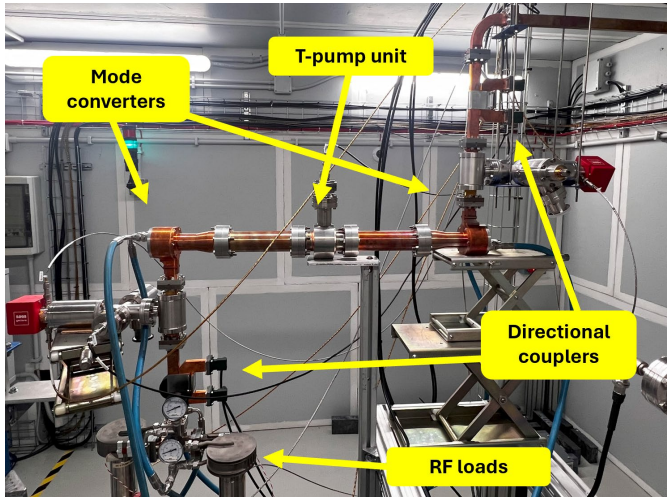
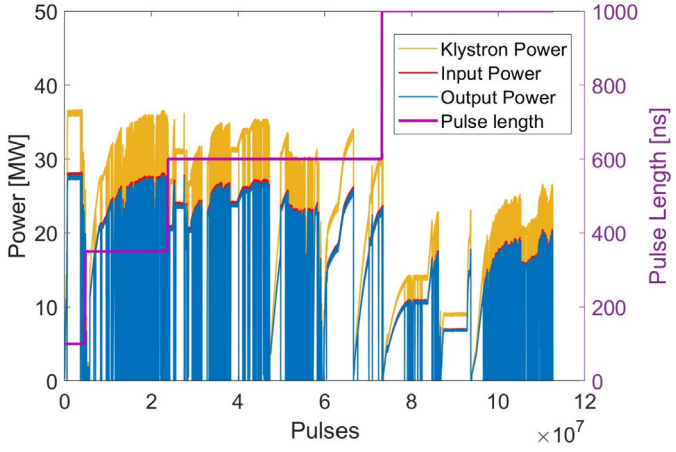
Double height waveguide	INFN/ CERN	Under realization	To be tested

Mode converter and T-pump for circular wg

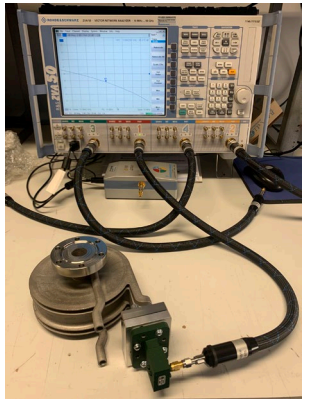








3D printed spiral load



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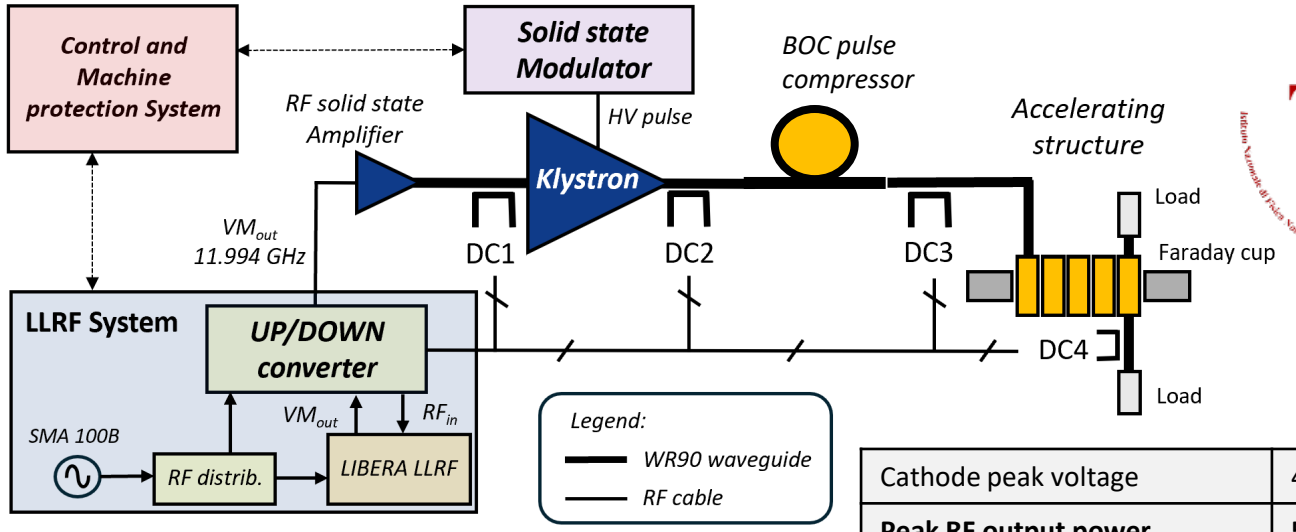
TEX Facility

- The **TEst-stand for X-band (TEX)** is conceived for **R&D and test on high gradient X-band accelerating structures, RF components, LLRF systems, Vacuum system and Control System.**
- It has been co-funded by Lazio region in the framework of the **LATINO project** (Laboratory in Advanced Technologies for INnOvation). The setup has been done in **collaboration with CERN** and it will be also used to test CLIC structures.
- The installation and commissioning of the whole system have been completed by the end of 2022.
- Then started the **testing activity:**



Cathode peak voltage	427 kV
Peak RF output power	**50 MW**
Pulse length	100 ns - 1.5 us
Repetition Rate	**50 Hz**
RF output amplitude stability	< 0.09 %
RF output phase stability	20.9 fs

Period	Device tested at high power
Jan. - Feb. 2023	3D printed Spiral RF loads and wg system
May - Oct. 2023	X-band **T24 CLIC structure**
Nov. - Dec. 2023	X-band Mode converter and circular wg
Jan. - Feb. 2024	X-band RF waterload **design at PSI**
March 2024	21 cells **first EuPRAXIA RF prototype**
Apr. 2024 – May 2025	Upgrade of the facility

50 MW RF Source

VKX8311A Klystron

F. Cardelli et al., 13th Int. Particle Accelerator Conf. IPAC22, Bangkok, Thailand, Jun. 2022, paper TUPOPT061
L. Piersanti et al. "RF power station stabilization techniques and measurements at LNF" In Proc. IPAC24 - TUPR01.
L. Piersanti et al. "Design and test of a klystron intra-pulse phase feedback system for electron linear accelerators" Photonics 2024, 11(5), 413.
F. Cardelli et al., in Proc. IPAC'24, Nashville, TN (2024) paper TUPR02

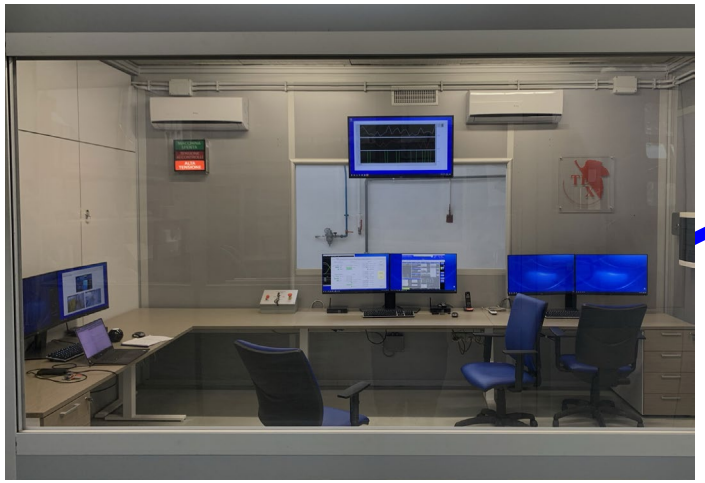
TEX Facility

TEX is located at the building 7 of INFN-LNF that has been completely refurbished to host this facility.

Rack Room

Bunker

Experimental hall



Control Room

TEX Upgrade

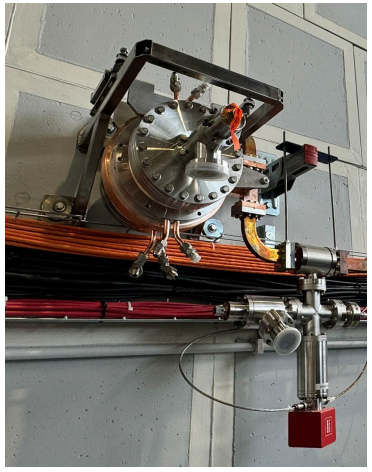
In 2024 thanks to **EuPRAXIA project** and **PNRR Rome Technopole project,** started the **upgrade of the TEX facility.**

1. Upgrade of the first source waveguide system with the installation of a **BOC pulse compressor (PSI)**
2. Procurement of a high efficiency **CPI VKX8311A3 Klystron (CPI-CERN collaboration). FAT and shipment foreseen in March 2026.**
3. Procurement, installation and test of **two new RF sources**, waveguide systems, with a new cooling plant and new LLRF system:
   - **X-band (11994 MHz) 25MW, 1.5us, 400Hz Power Source**
   - **C-band (5712 MHz) 20MW, 2.5us, 400Hz Power Source**

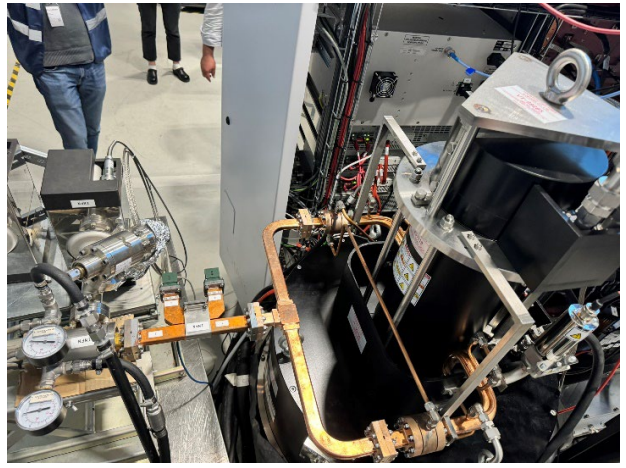
- FAT of the klystron done @CANON on a PFN modulator 11/2023
- FAT of the RF source @Scandinova 05/2024, full power in diode mode
- **Commissioning started in May 2025.**

Parameter	Unit	CPI VKX8311A3	Canon E37119	Canon E37217
Frequency	MHz	11994	11994	5712
Vk beam voltage	kV	415	312	254
Ik cathode current	A	201	199	196
Peak RF output Power	MW	**50**	**25**	**20**
Average RF output power	kW	7.5	15	21
Modulator Average power	kW	25	80	80
RF pulse length	µs	**1.5**	**1.5**	**2.5**
Repetition Rate	Hz	**100**	**400**	**400**
Gain	dB	50	47	50
Efficiency	%	**55**	40	40

BOC pulse compressor



FAT of the two Sources

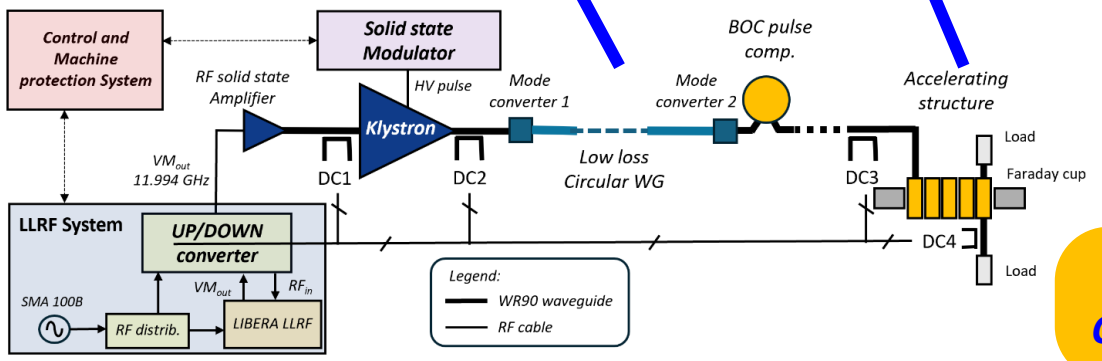


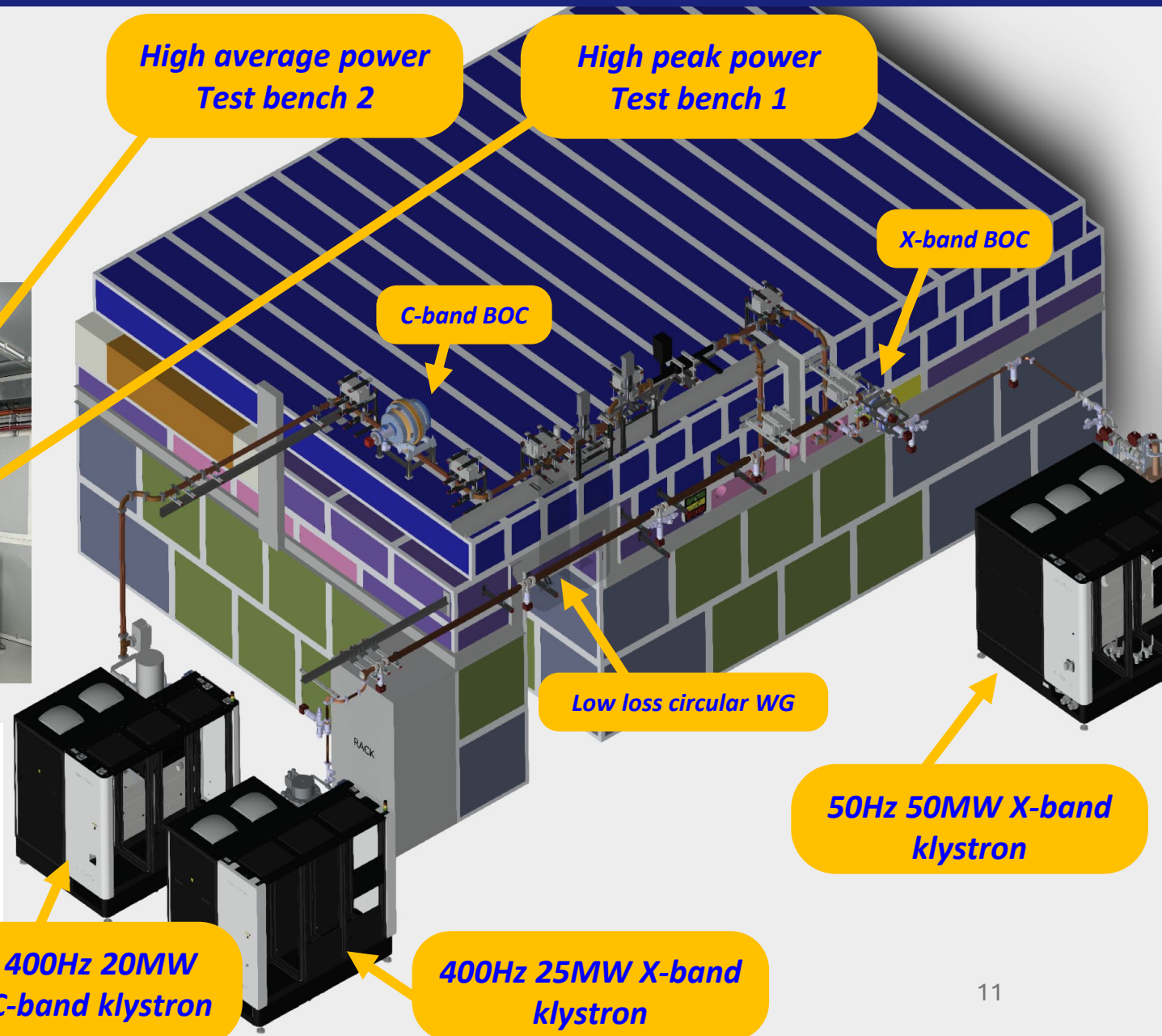
CANON E37119

Installation and test at TEX

TEX Upgrade (II)

- The **second test bench** doubles the TEX X-band testing capabilities and enables high-average-power testing of X-band components.
- The entire waveguide system has been designed, procured, and installed.
- Once the source is connected to the RF system, a 6-m-long X-band circular waveguide line will be conditioned and tested.





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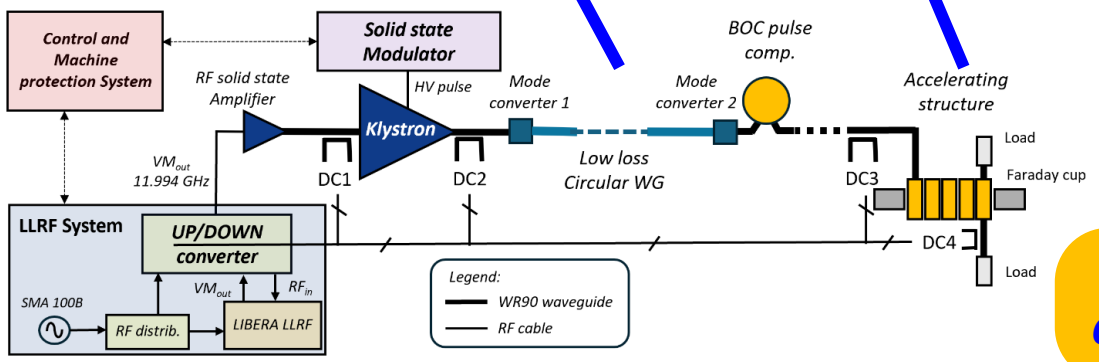
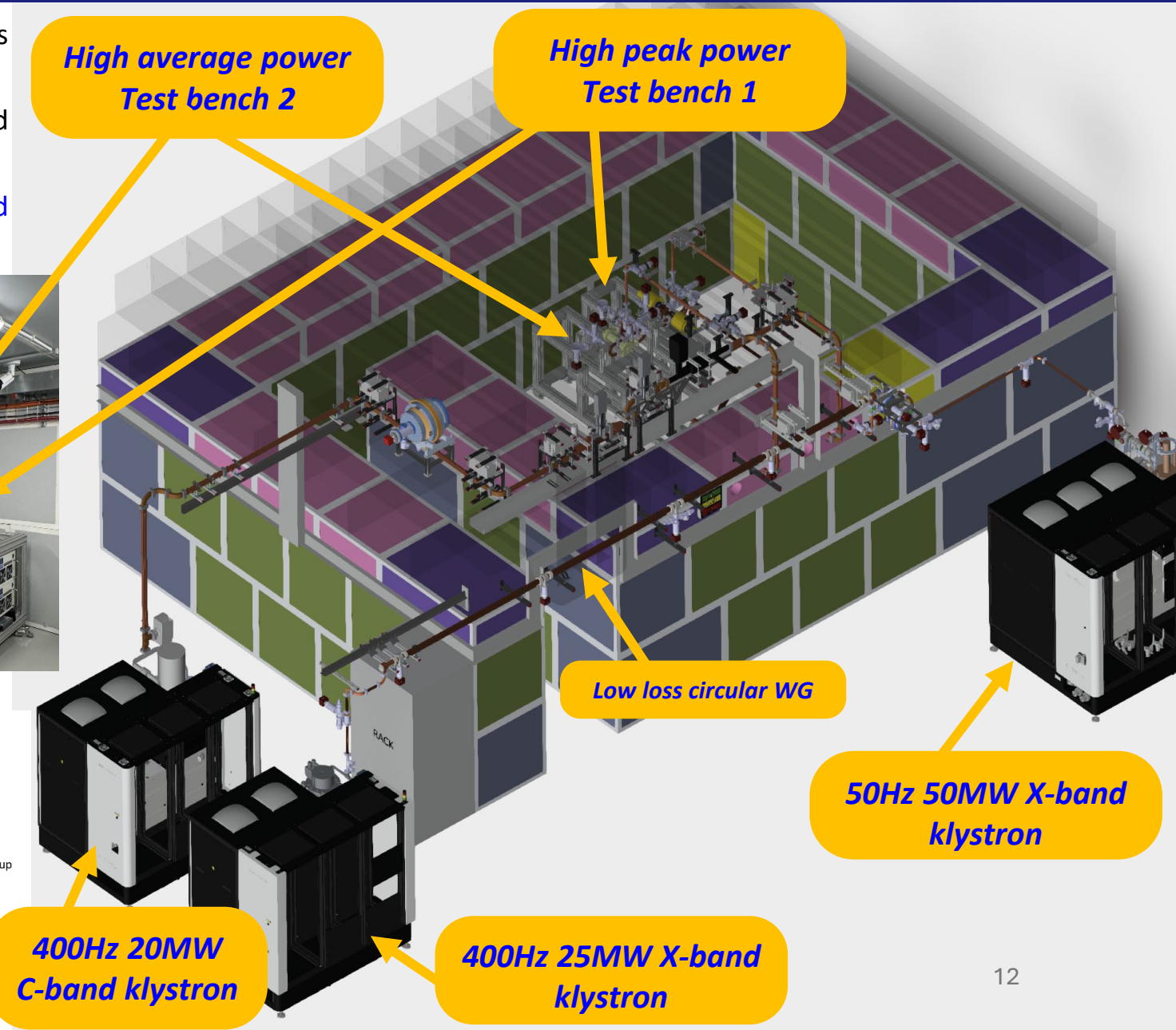
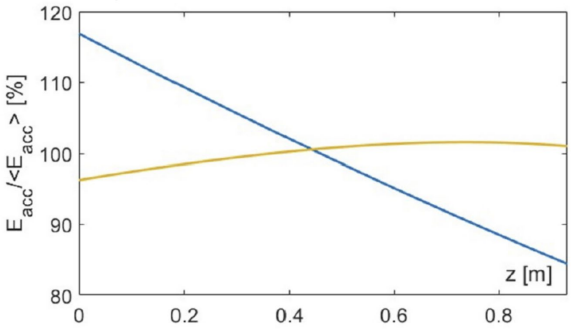
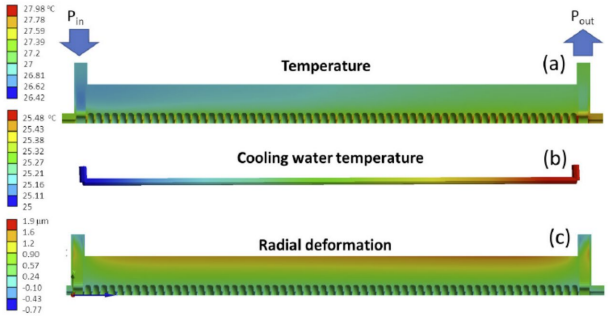


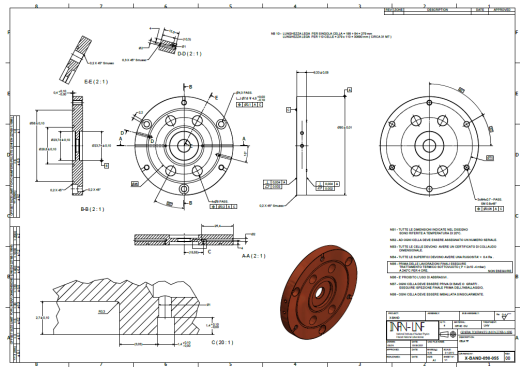


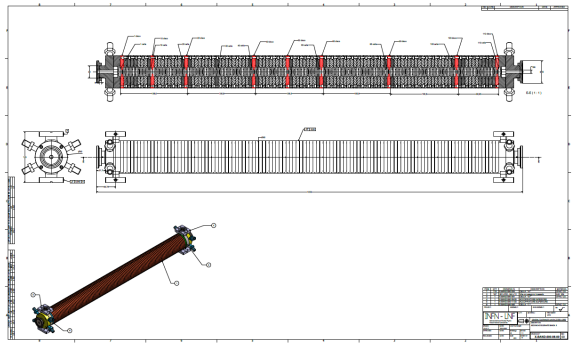
X-band Structure

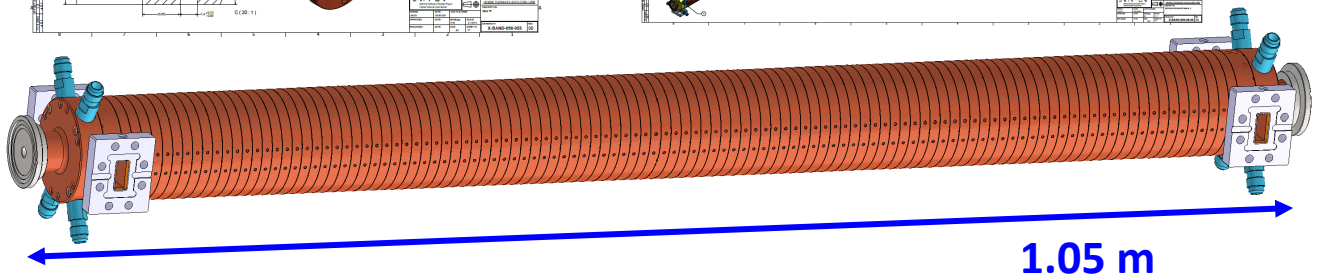
- The **EM design of the structure is completed**: **≈1m long** structures with **3.5 mm average iris radius** design to work with an average acceleration gradient of **60 MV/m.**
- **Thermo-mechanical simulations** to demonstrate the correct sizing of the cooling system (at 100 Hz and 400 Hz)
- Final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











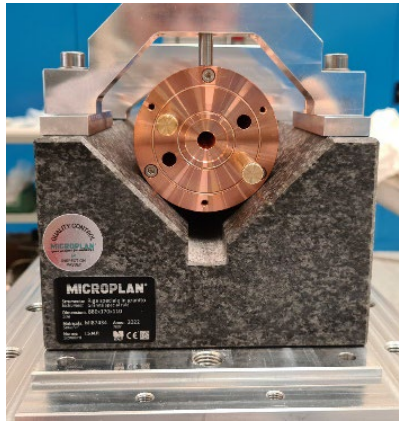
PARAMETER	Value	
	Quasi-Constant Gradient	Constant Impedance
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85 - 3.15**	**3.5**
Tapering angle [deg]	0.04	0
Structure active Length [m]	**0.94**	
No. of cells	113	
Shunt impedance R [MΩ/m]	93-107	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

X-band Structure Realization

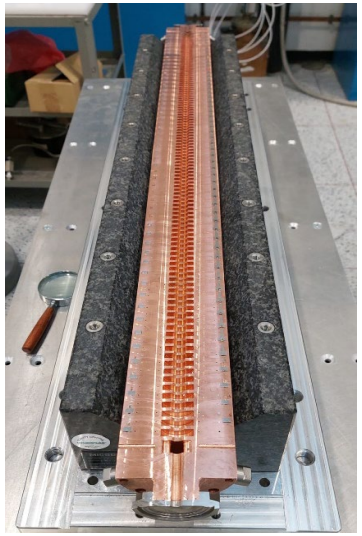
2x Mechanical prototype for brazing optimization and test of the realization technique

To preserve alignment and cell-to-cell straightness during and after the brazing process, a **dedicated assembly technique** was developed at LNF. In this method, each cell is fixed to the next 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

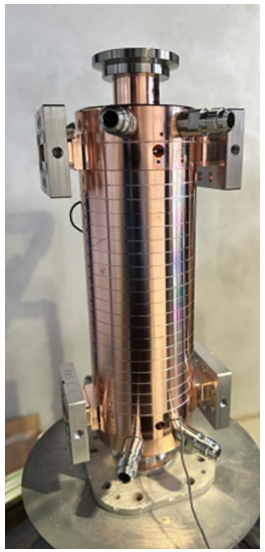
- After brazing the two structure have been succesfully **Vacuum tested.**
- **Straightness <±15 μm** obtained after brazing on both the prototypes (±30 μm required by BD)

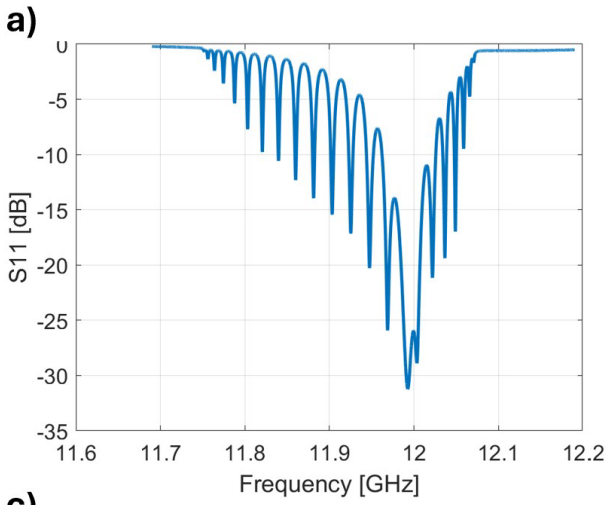


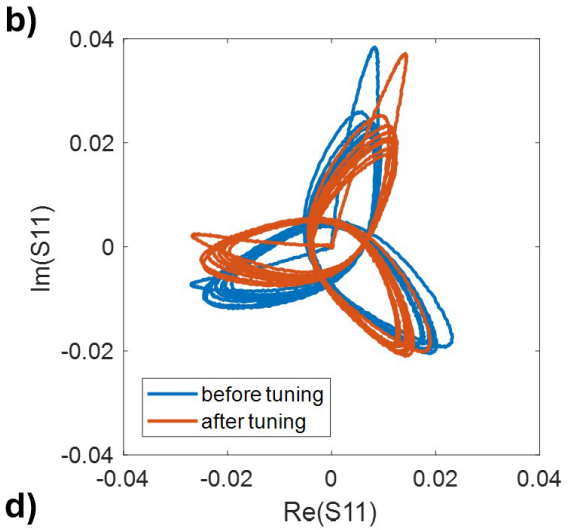
21 cells RF prototype measurements

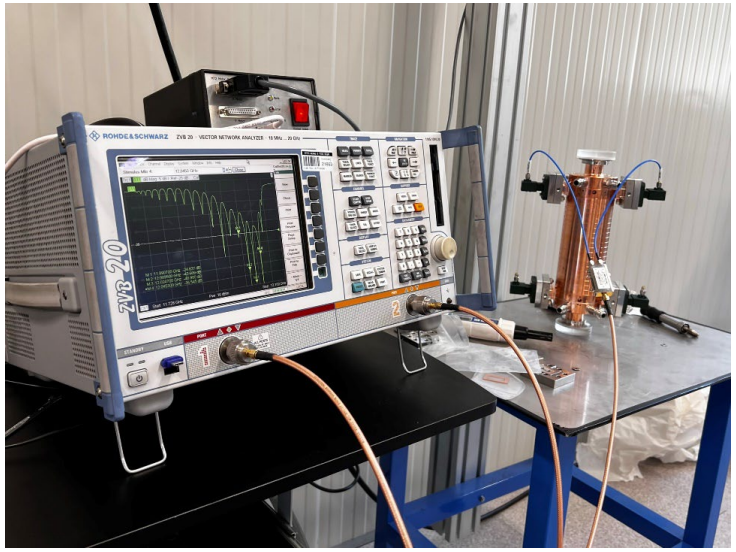
X-band, 21 cells, CI, TW structure prototype

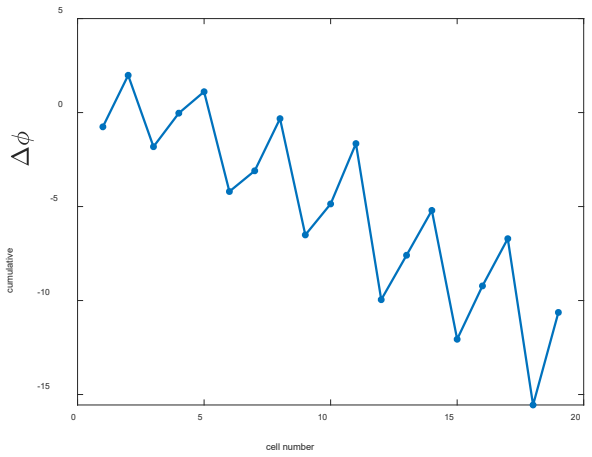
- It has been realized **without tuners** on the cells, we just have a couple of tuners on the two couplers
- We perform **low power measurements before cells brazing** (thank to the screws), **after the brazing** and then aftert the tuning of the couplers.
- During the measurements and the tuning procedures the structure has been continuosly fluxed with nitrogen.
- All the cells seems to be smaller to obtain the best response from the cells we have to increase the working temperature → $\mathbf{T_{cav} = 35\ °C}$

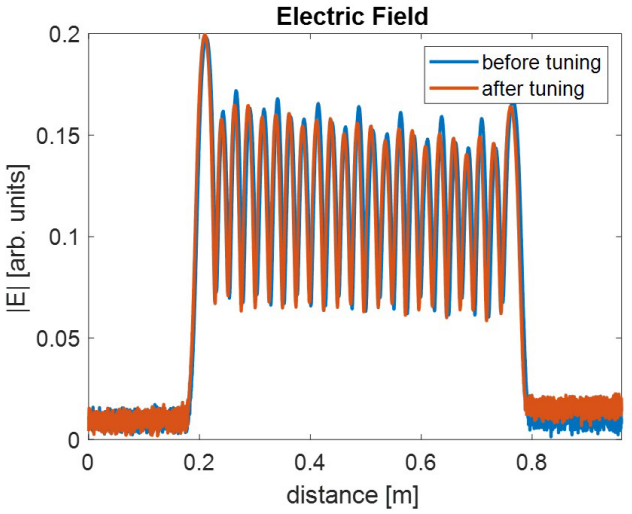


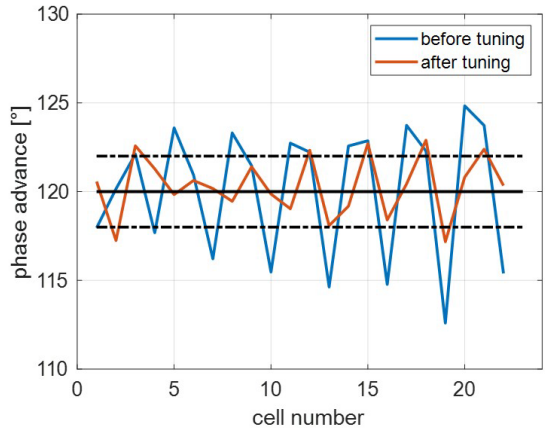








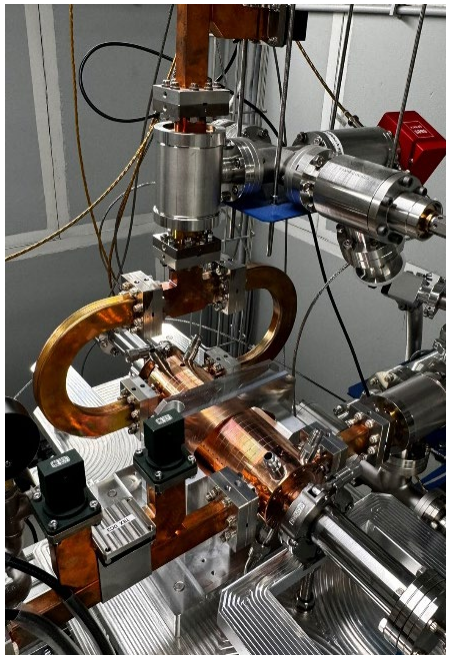


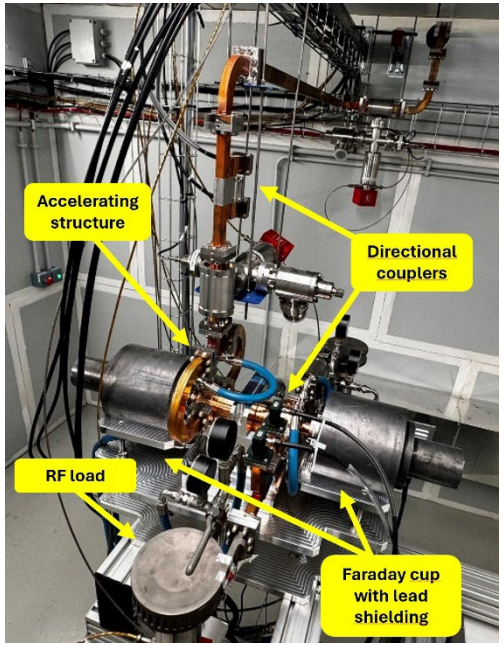


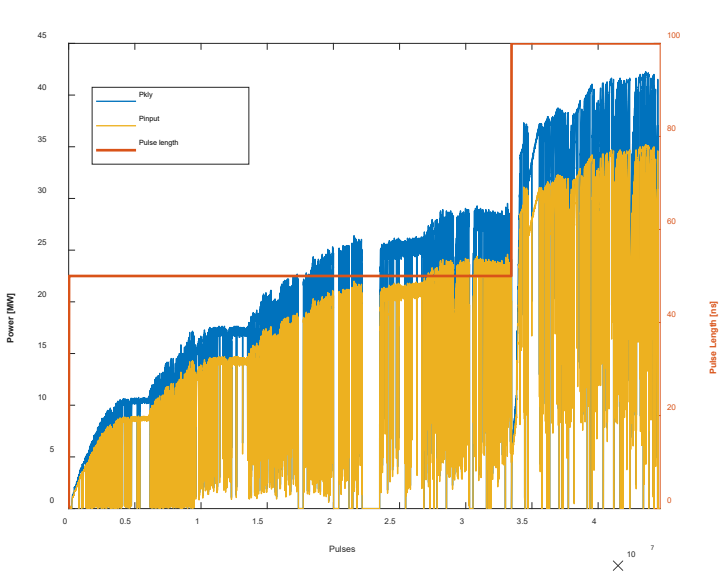
21 cells RF prototype preliminar high power test

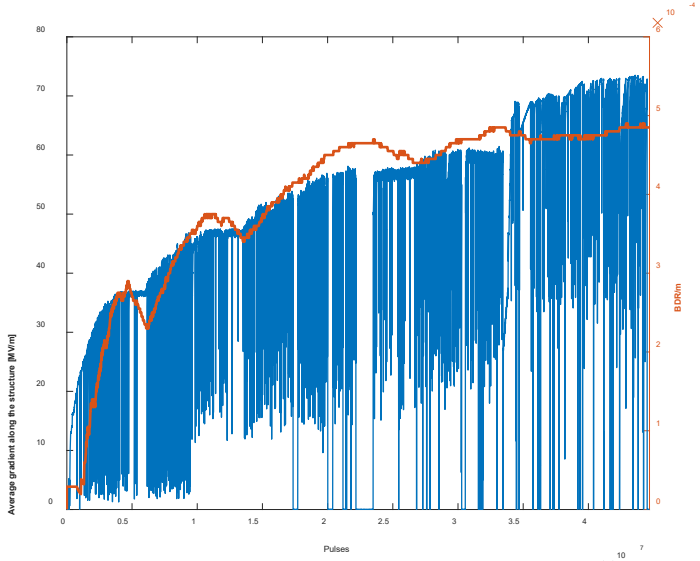
- In spring 2024 we started the **high-power test of the first EuPRAXIA@SPARC_LAB X-band structure prototype**.
- 21 cells, **constant impedance**, RF prototype (the real structure will be 1 m long).
- In nearly 12 days we reach an input pulse of **35 MW, 100 ns length at 50 Hz repetition rate**, that correspond to an **average gradient** along the structure equal to **74 MV/m** and a peak gradient at the structure input of 80 MV/m with a BDR/m nearly 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**



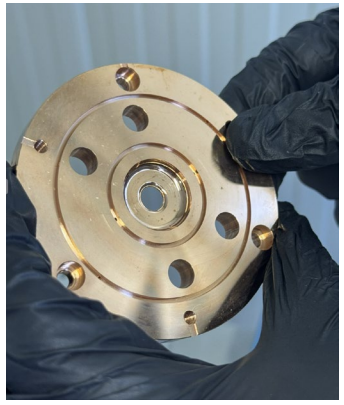
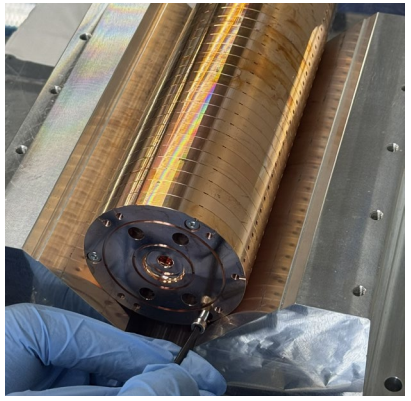
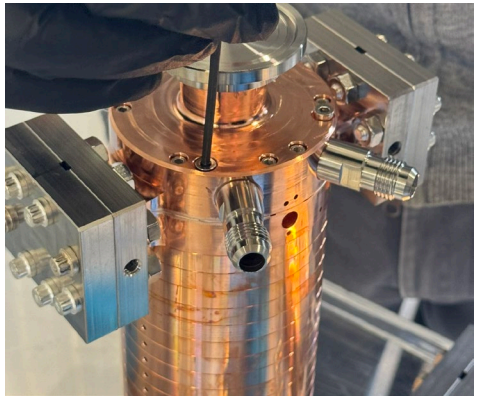
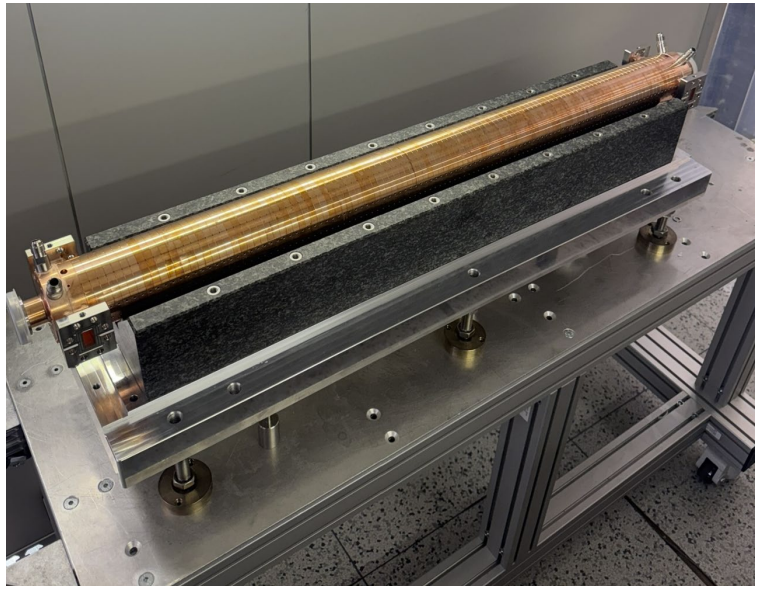
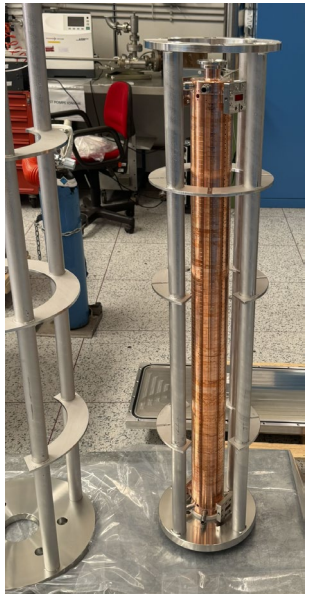
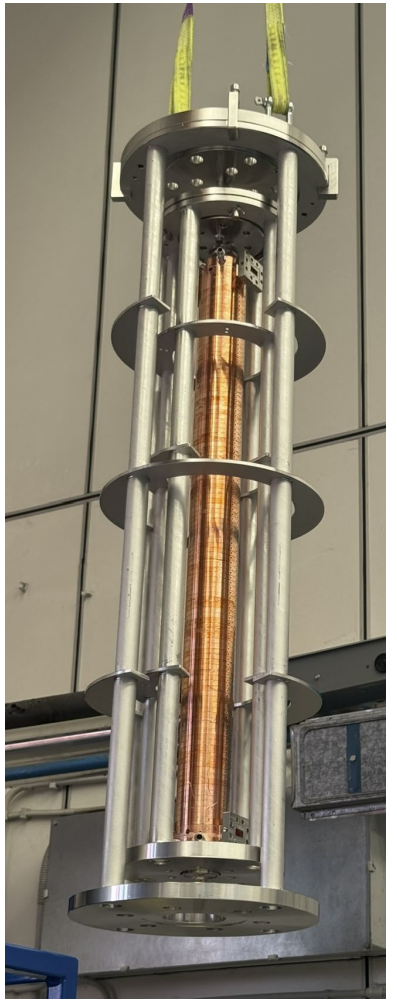
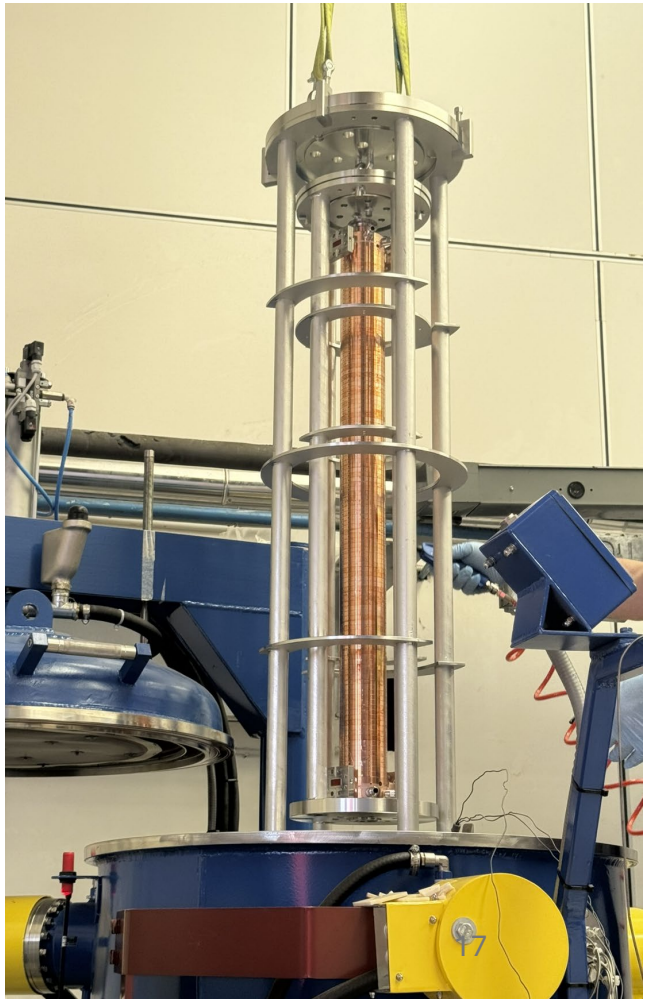






First EUPRAXIA@SPARC_LAB X-band accelerating structure

By th end of 2024 started the realization of the **first full-scale X-band accelerating structure** of the EuPRAXIA@SPARC_LAB project. The cells machining has been realized by an italian private company, then the final assembly and brazing have been performed at INFN-LNF. The structure was manufactured without post-machining tuning, by machining the accelerating cells and the two couplers with micrometer precision. After brazing, the **vacuum test was successfully passed**.

First EUPRAXIA@SPARC_LAB X-band accelerating structure

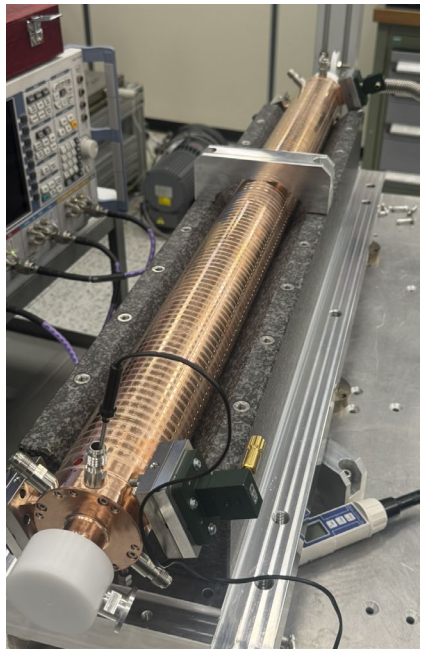
Following the machining of the cells and couplers by the company, preliminary RF measurements using **bead-pull technique** were carried out on selected groups of cells to verify fabrication accuracy and perform **quality check control**.

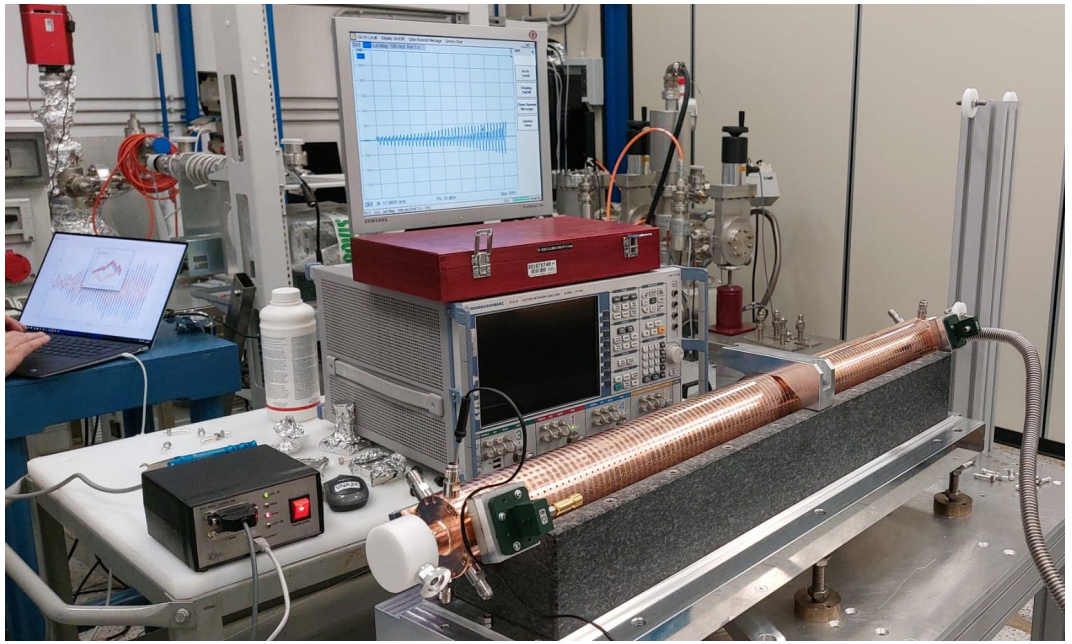
The full-scale structure was then assembled, and **RF characterization was performed both before and after the brazing process**.

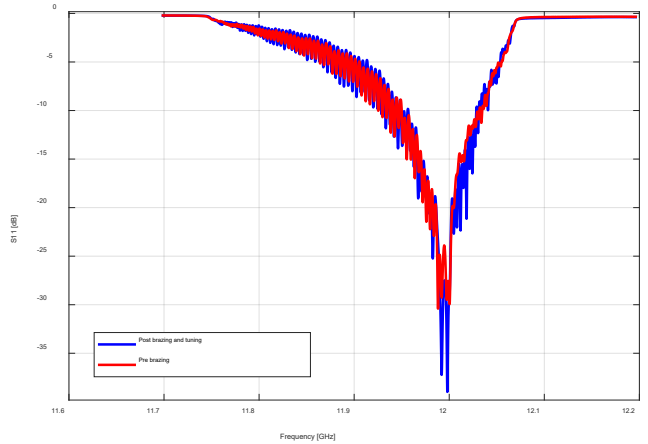
After brazing, a **soft tuning** was applied by adjusting the only tuners available on the couplers.

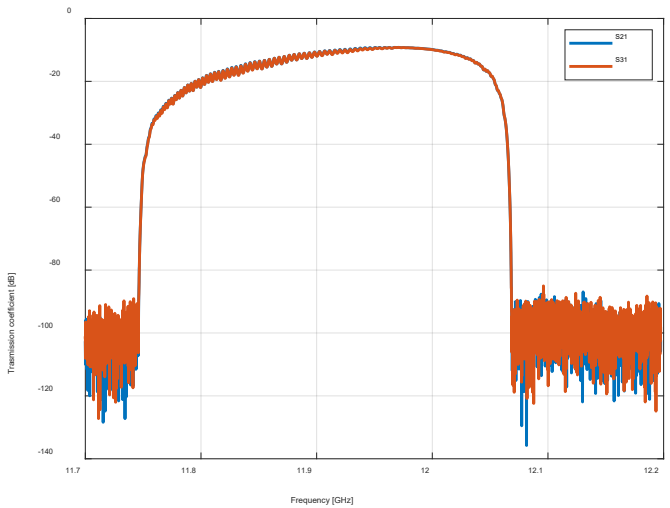
S11@11.994GHz = -24.5 dB pre brazing
S11@11.994GHz = -28.5 dB post brazing and tuning

in vacuum @22°C



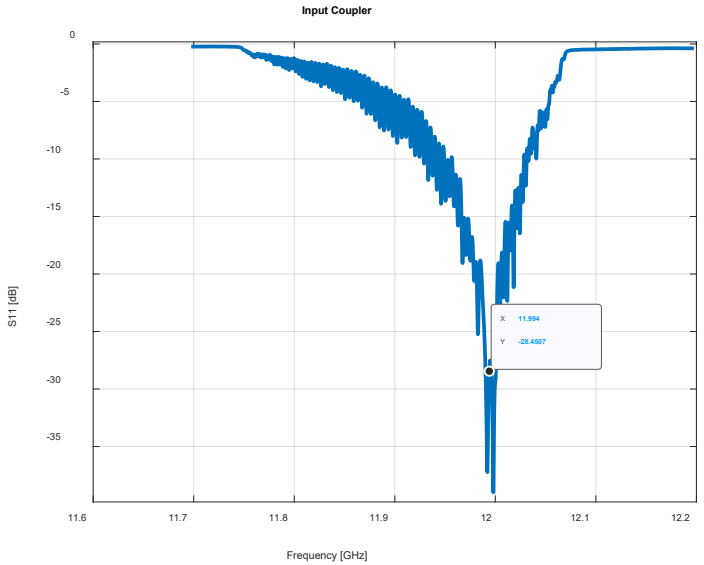


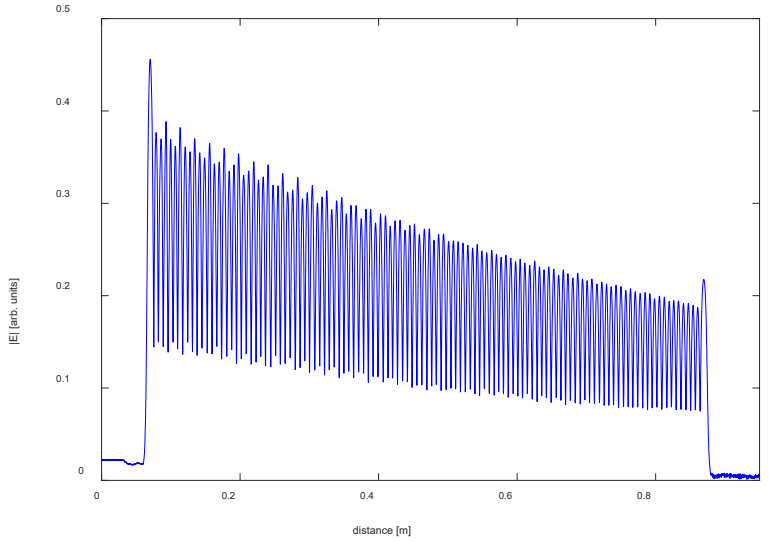


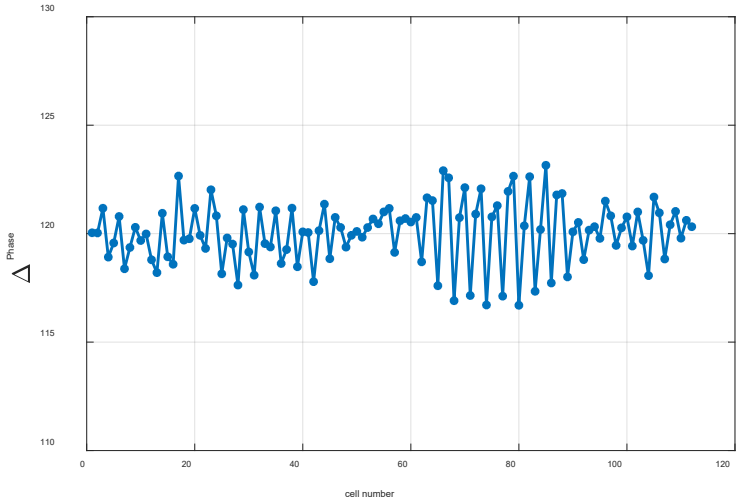


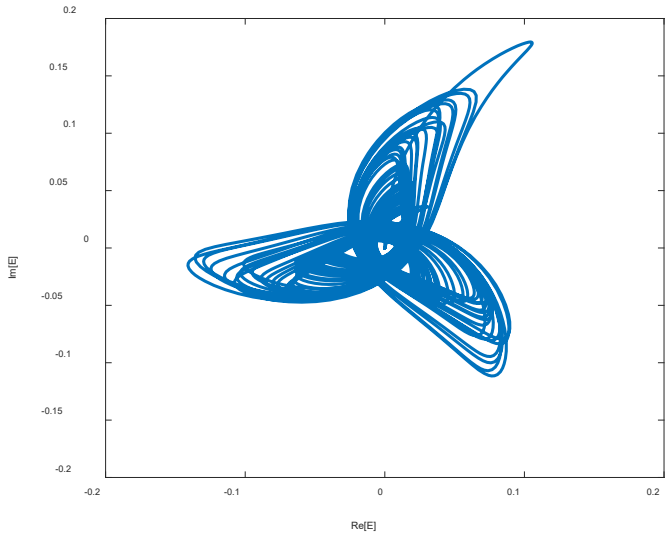
First EUPRAXIA@SPARC_LAB X-band accelerating structure

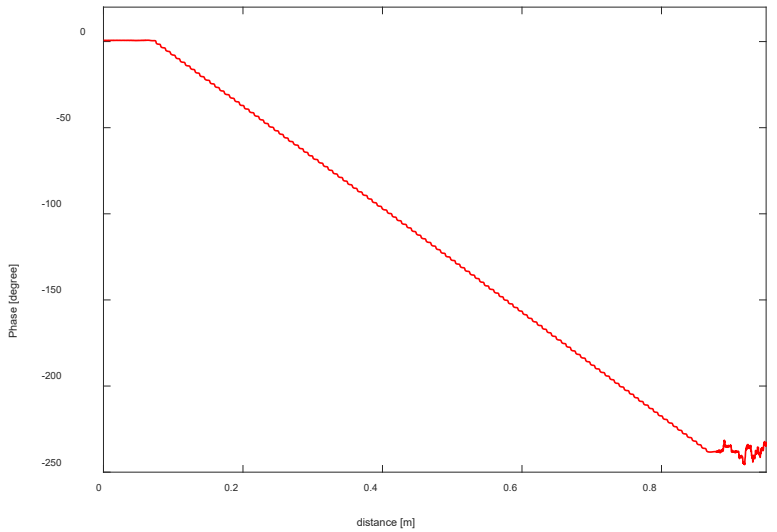
The structure will be installed for high power testing at TEX in the next months.

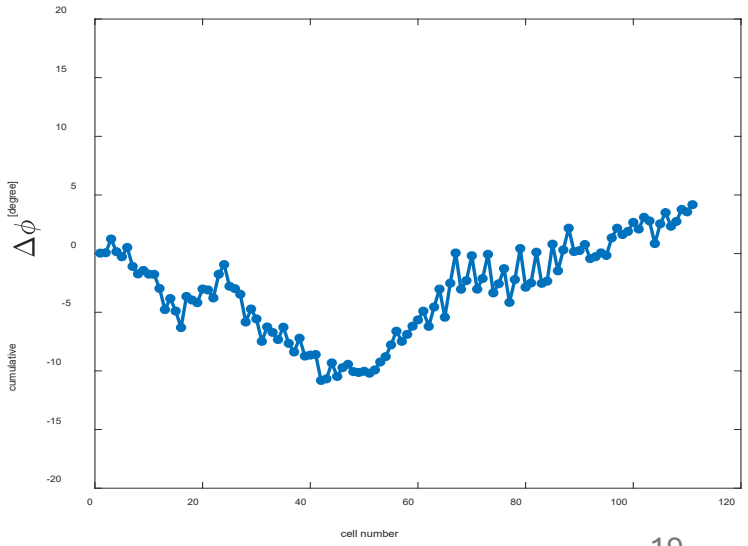












Accelerating Structure made of multiple sectors in X-band

ASTERI*X* (**A**ccelerating **ST**ructures made of multipl**E** secto**R**s **I**n ***X***-Band)

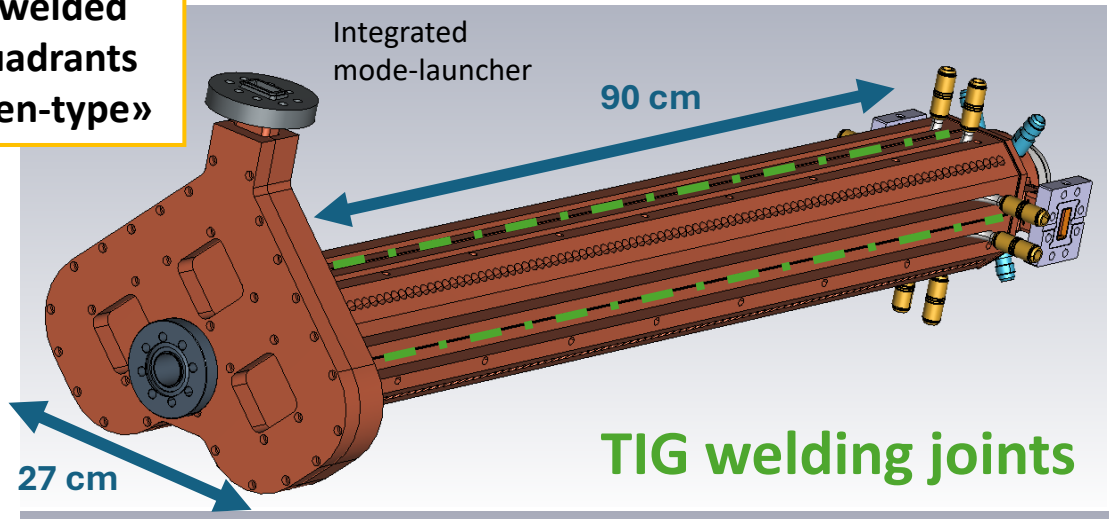
Goal: Demonstration of **practical, meter-long,** X-band RF accelerating structure made by multiple sectors:

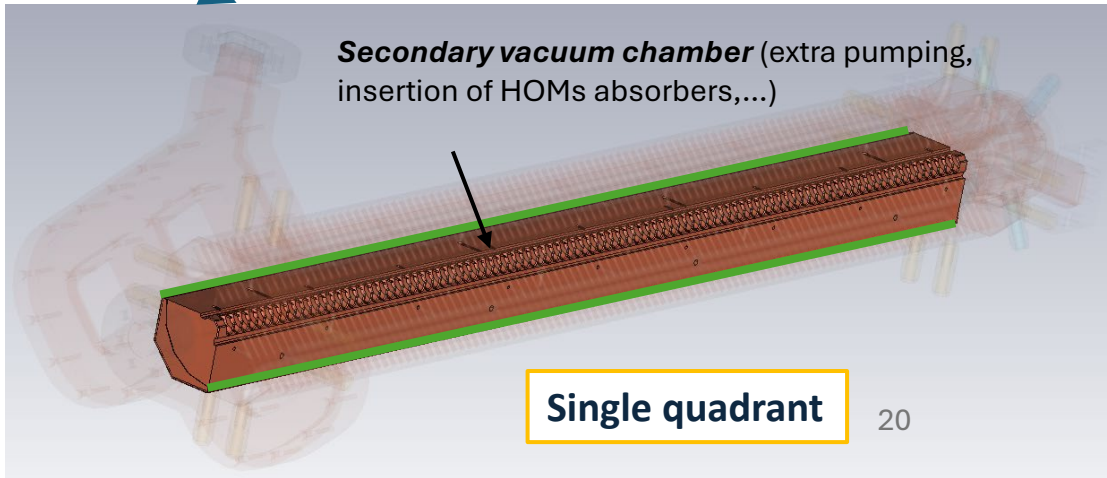
- composed of **four-quadrants** ("open type")
  - cancellation of the dipole and quadrupole EM field components
  - improved pumping speed and easy insertion of HOM
- joined and vacuum sealed by using **TIG welding** ("braze-free" technique).
  - cost-effective and robust manufacturing
- made out **hard copper**
  - Superior high-gradient performance, compared with soft copper
- high **accelerating gradients (>100 MV/m)**

PI: L. Faillace
3 years project (2025-2027)
INFN: LNF, LNS, University Roma1

International external collaboration
SLAC (USA): V. Dolgashev
KEK (Japan): Testuo Abe
USTC (China): Yelong Wei and Zhicheng Huang.

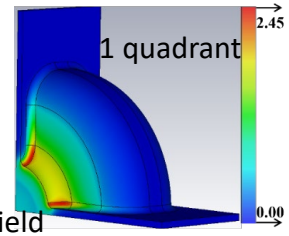
TIG-welded 4-quadrants «open-type»



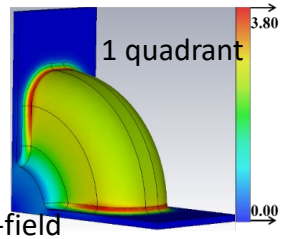


Accelerating Structure made of multiple sectors in X-band

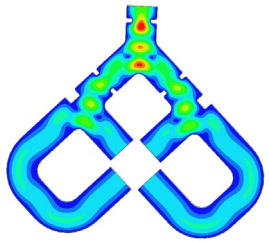
RF design of “single-bunch mode” structure completed
Preliminary Wakefield Analysis shows negligible effects.

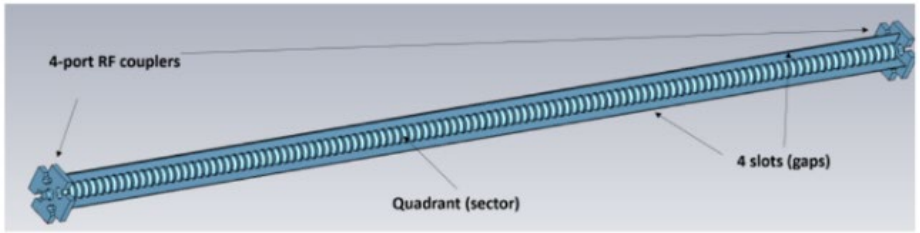


E-field

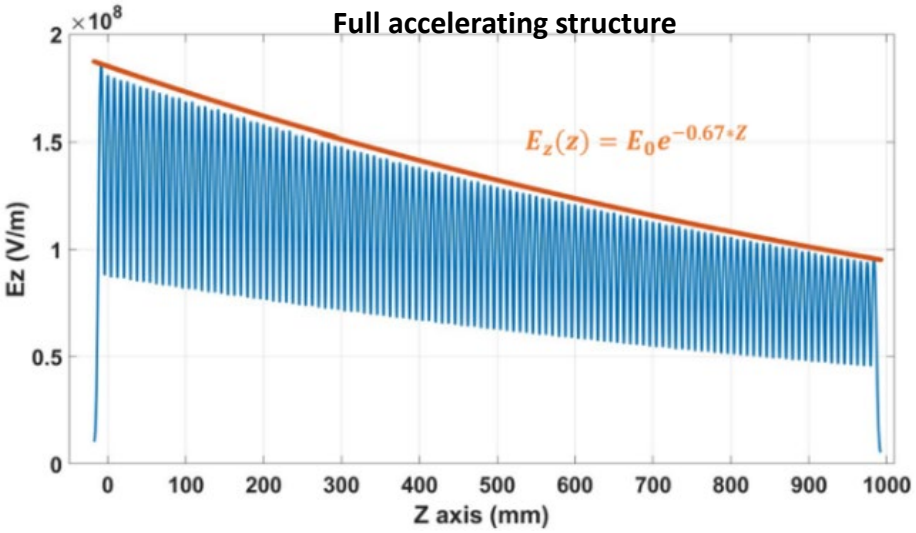


H-field



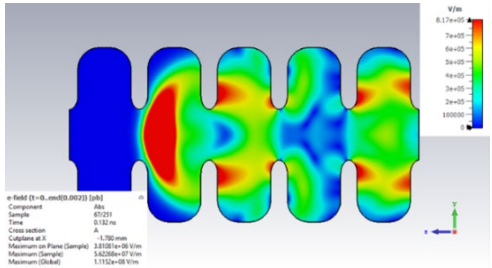


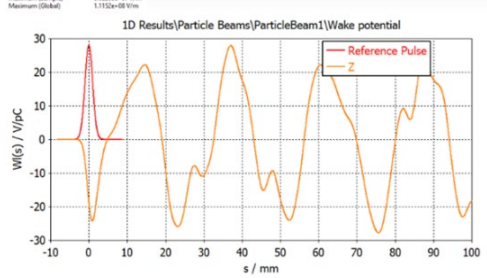
Full accelerating structure



Courtesy of Z. Huang

Parameter	Value
Frequency [GHz]	11.994
Gradient [MV/m]	100
Input power [MW]	77
Operating mode [rad]	$2\pi/3$
Cell length [mm]	8.333
Cell Number	120
Full structure length [m]	1
Disk thickness [mm]	2
Quality factor	6931
Iris radius [mm]	3.5
Shunt impedance [MΩ/m]	97.3
Group velocity [c%]	0.027
Filling time [ns]	123
Attenuation factor	0.6545
Peak S_c [W/μm^2]	8.8
Pulse Heating [K]	24.6
E_p [MV/m]	245



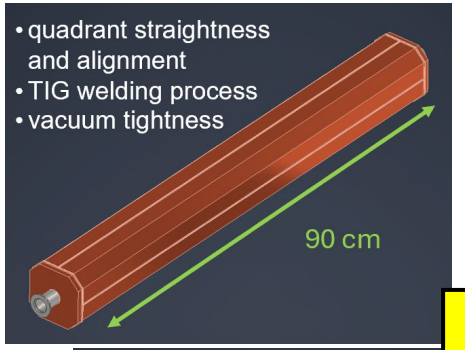


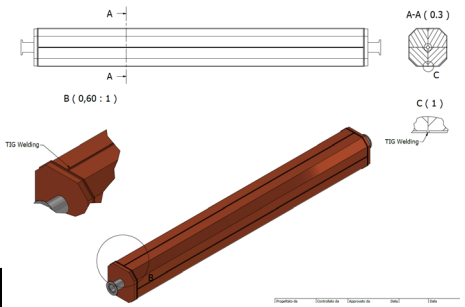
Low-precision Full-scale prototype for fabrication/mechanical characterization

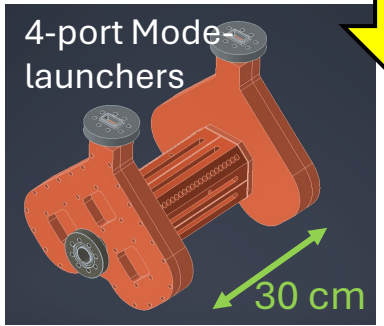
We have performed the Engineering of the low-precision prototype of the single-bunch ASTERIX structure for mechanical/TIG/vacuum testing:

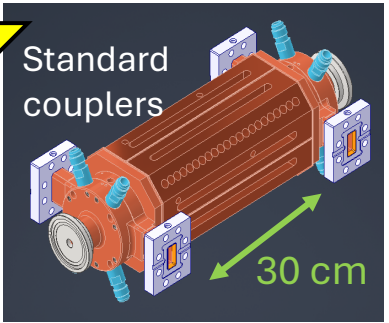
- Quadrant straightness and alignment
- TIG welding process
- Vacuum tightness.

We have started the procurement phase









Conclusions and future work

An extensive prototyping and R&D program on X-band technology is underway at LNF to drive a plasma module for PWFA within the EuPRAXIA@SPARC_LAB project.

» **X-band sources and components R&D**: has been completely commissioned and used to test several components.

- The final stage of the upgrade is nearing completion with the commissioning of the two new sources, X-band E37119 klystron (25 MW, 400Hz) and C-band E37217 klystron (21 MW, 400 Hz).
- A X-band **high efficiency klystron 50 MW VKX8311HE** developed by CPI/CERN should be shipped at LNF in March 2025.

» **EuPRAXIA@SPARC_LAB X-band structure**: An intensive prototyping activity is ongoing exploiting the new vacuum furnace at LNF.

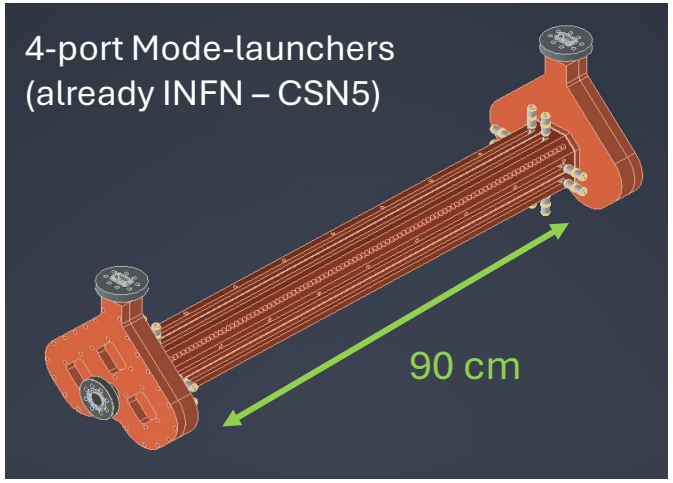
1. The **21 cells CI RF prototype** has been realized
   - Preliminar high power test show promising results and will continue at higher power.
2. The first **full-scale 1m RF prototype** have been realized and pre tested at low power, in the next months we will test it at high power at TEX

» **ASTERIX project**: fabrication and high RF power testing of **four-quadrants ("open-type") X-band RF accelerating structures** made of hard copper

» Single bunch and Multi-bunch type structure RF simulations are ongoing

» Realization of a mechanical prototype in 2025

» Two small scale prototypes with different types of couplers will be realized and high power tested at TEX in 2026 and a **full scale prototype** is foreseen by the end of 2027.



Aknowledgements:
INFN: *D. Alesini, B. Buonomo, S. Cantarella, G. Catuscelli, P. Chimenti, M. Cianfrini, R. Clementi, G. Costa, A. Falone, L. Faillace, A. Gallo, A. Giribono, C. Di Giulio, E. Di Pasquale, G. Di Raddo, G. Latini, A. Liedl, V. Lollo, R. Mascio, L. Piersanti, S. Pioli, L. Sabatini, B. Serenellini, L. Spallino and B. Spataro on behalf of the INFN-LNF Accelerator Division and Technical Division.*
CERN: *N. Catalan Lasheras, A. Grudiev, G. McMonagle, P. M. Sanchez, I. Syratchev.*
PSI: *P. Craievich, T. Lucas, F. Marcellini, R. Zennaro.*
Sapienza University: *L. Giuliano, S. Farina*
SLAC: *V. Dolgashev*
KEK: *Tetsuo Abe*
USTC: *Y. Wei, Z. Huan*