X-band activities for the EuPRAXIA@SPARC_LAB Linac

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on behalf of the TeX technical team and the EuPRAXIA@SPARC_LAB team

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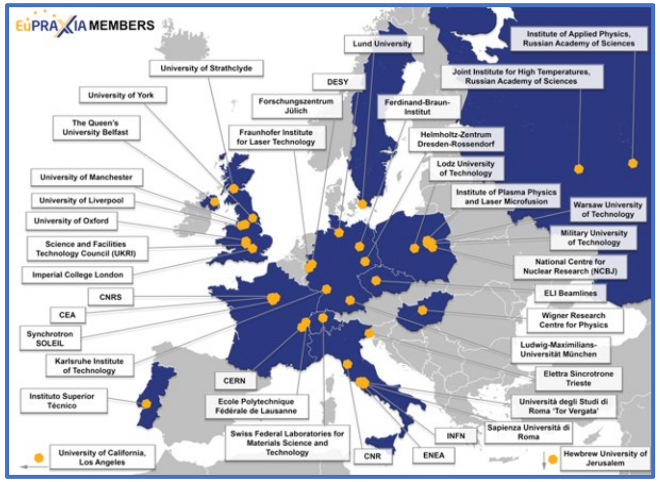
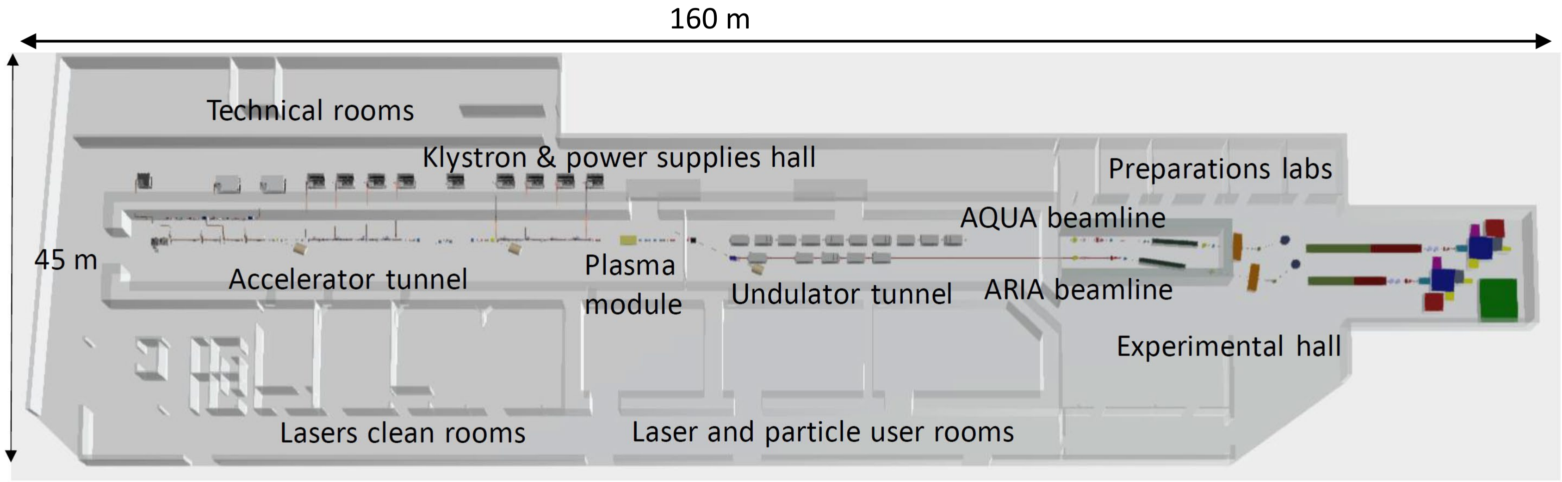
INFN LNF Istituto Nazionale di Fisica Nucleare

EuPRAXIA

EuPRAXIA@SPARC_LAB Project

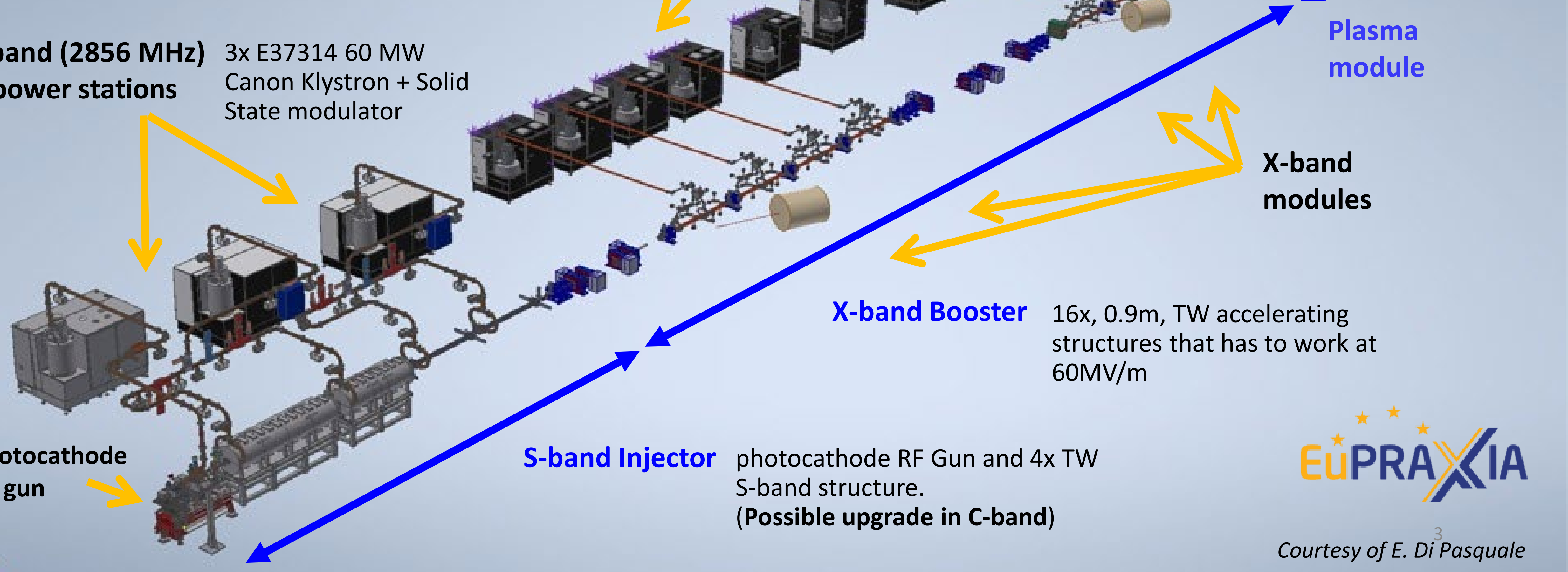
- The project is one of the pillars of the **European Project EUPRAXIA** (http://www.eupraxia-project.eu/) – European Plasma Research Accelerator with excellence in Applications
- EuPRAXIA has **been included in the ESFRI 2021 Roadmap**
- The project EuPRAXIA@SPARC_LAB is the pillar of the EuPRAXIA project based on beam driven plasma wakefield acceleration (PWFA). It aims at constructing a FEL radiation source (two FEL lines λ_{FEL}=4 nm and 50-180nm) combining:
  - **1GeV RF X-band Linac with an high brightness injector**
  - **Plasma module for PWFA**.
- The project is currently in the preparatory phase of the Technical Design Report (end 2025).
- A **new building**, now under executive design phase, will host the new Facility at LNF, the construction should start in September 2026.





Overview of the LINAC

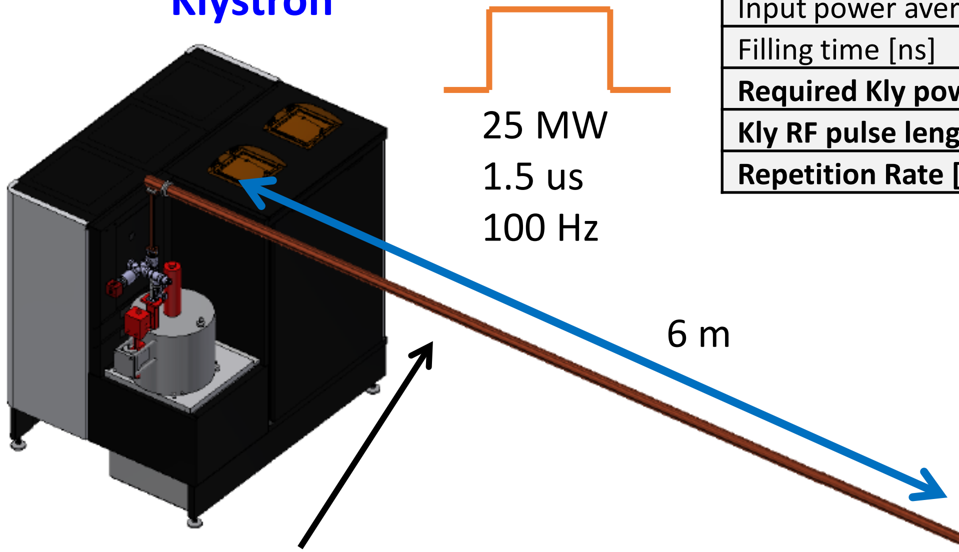
- The Linac uses an S-band injector followed by an X-band booster to produce a high brightness electron beam up to an **energy of 1 GeV** (**Q = 200-500 pC, ε_{RMS} ≤ 1 mm·mrad, PRF = 100Hz**).
- The beam can be either injected directly in the FEL **undulators** or used to drive the **plasma module for PWFA** to further increase the energy.

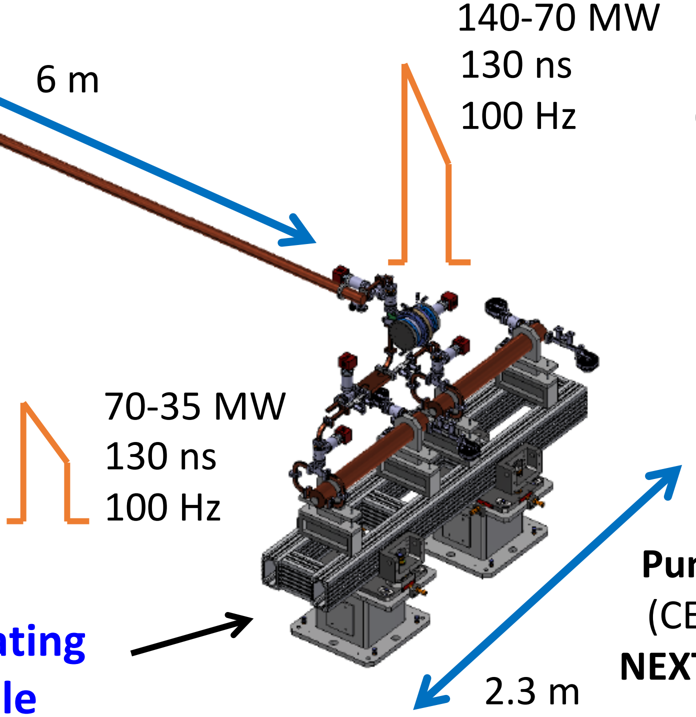


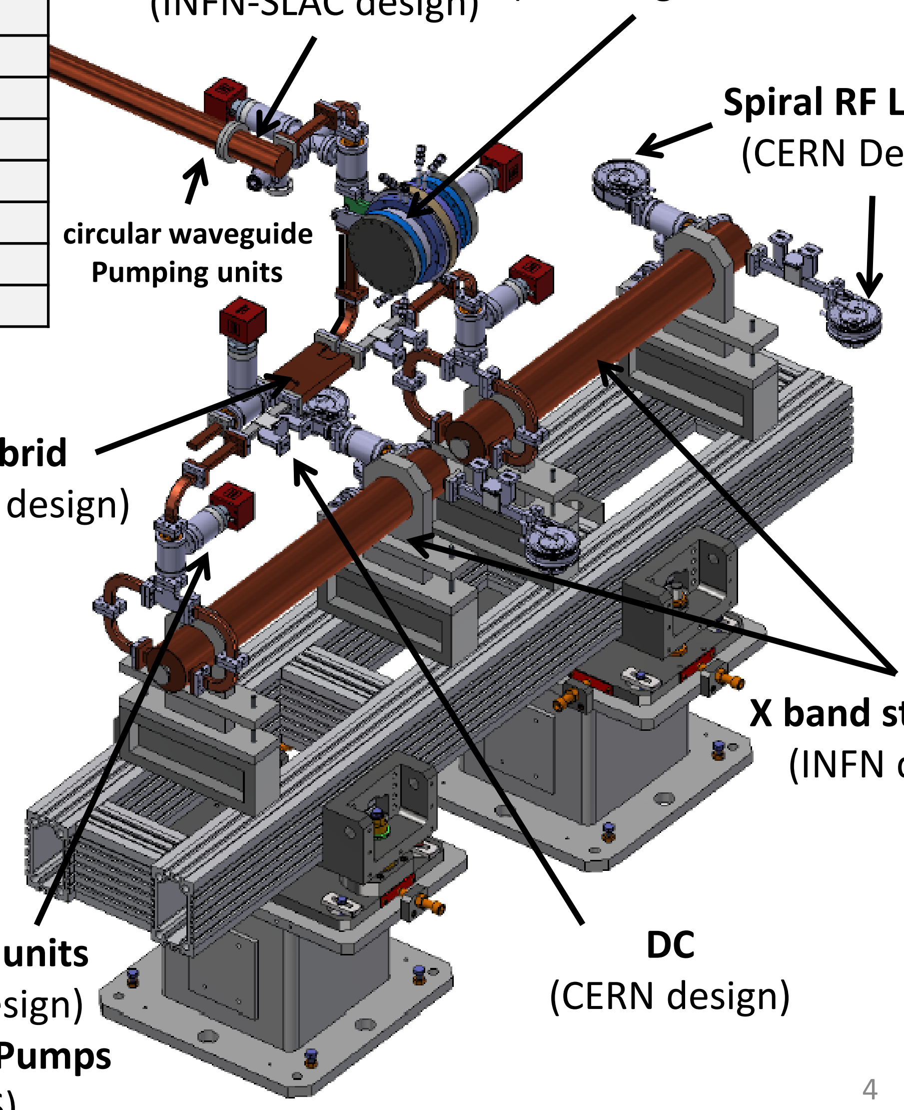
Courtesy of E. Di Pasquale

X-band RF Module Layout

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**







X-band RF Power Sources

Currently, the test stand is based on **CPI VKX8311A** Klystron on loan from CERN already **commissioned** and **in operation**

Two other X-band klystrons will be tested at TEX:

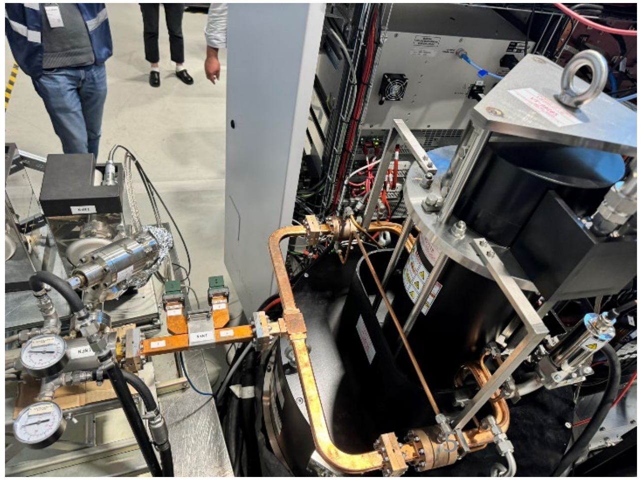
1. **CANON E37119**
   - » Low modulator peak power requirement but very high average power to work at 400Hz
   - » Very high repetition rate (Interesting for a future upgrade of the machine)
   - » 8x power sources for the linac booster

   Status:
   - *FAT of the klystron done @CANON on a PFN modulator 11/2023, 25 MW, 10 Hz, t=1.5us*
   - *FAT of the RF source @Scandinova 05/2024, full power in diode mode*
   - *Modulator and klystron positioned at TEX*
2. **CPI High efficiency VKX8311HE**
   - » collaboration CERN/INFN/CPI
   - » High efficiency

   Status:
   - Tender has been done, realization phase (expected delivery from CPI May 2025)

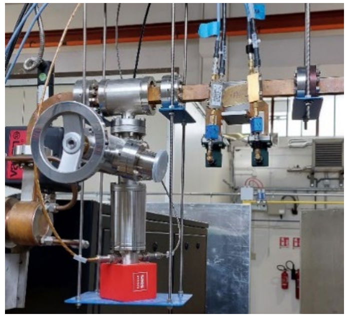
Parameter	Unit	Canon E37119	CPI VKX8311HE	CPI VKX8311
Frequency	MHz	11994		
Vk beam voltage	kV	312	415	420
Ik cathode current	A	199	201	320
Peak RF output Power	MW	25	50	50
Average RF output power	kW	15	7,5	7,5
Modulator Average power	kW	80	25	48
RF pulse length	µs	1,5		
Repetition Rate	Hz	400	100	100
Gain	dB	47	50	47
Efficiency	%	40	55	38
Perveance	µp	1.16	0.75	1.15

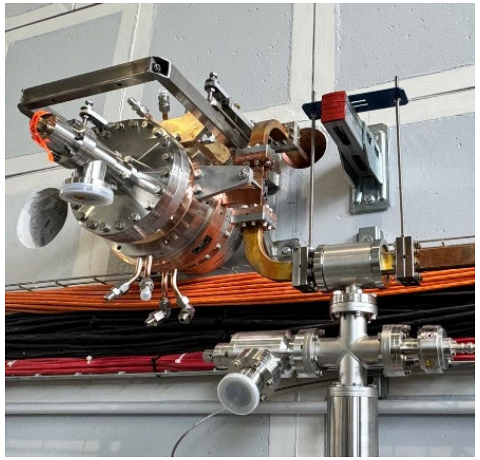
CANON E37119

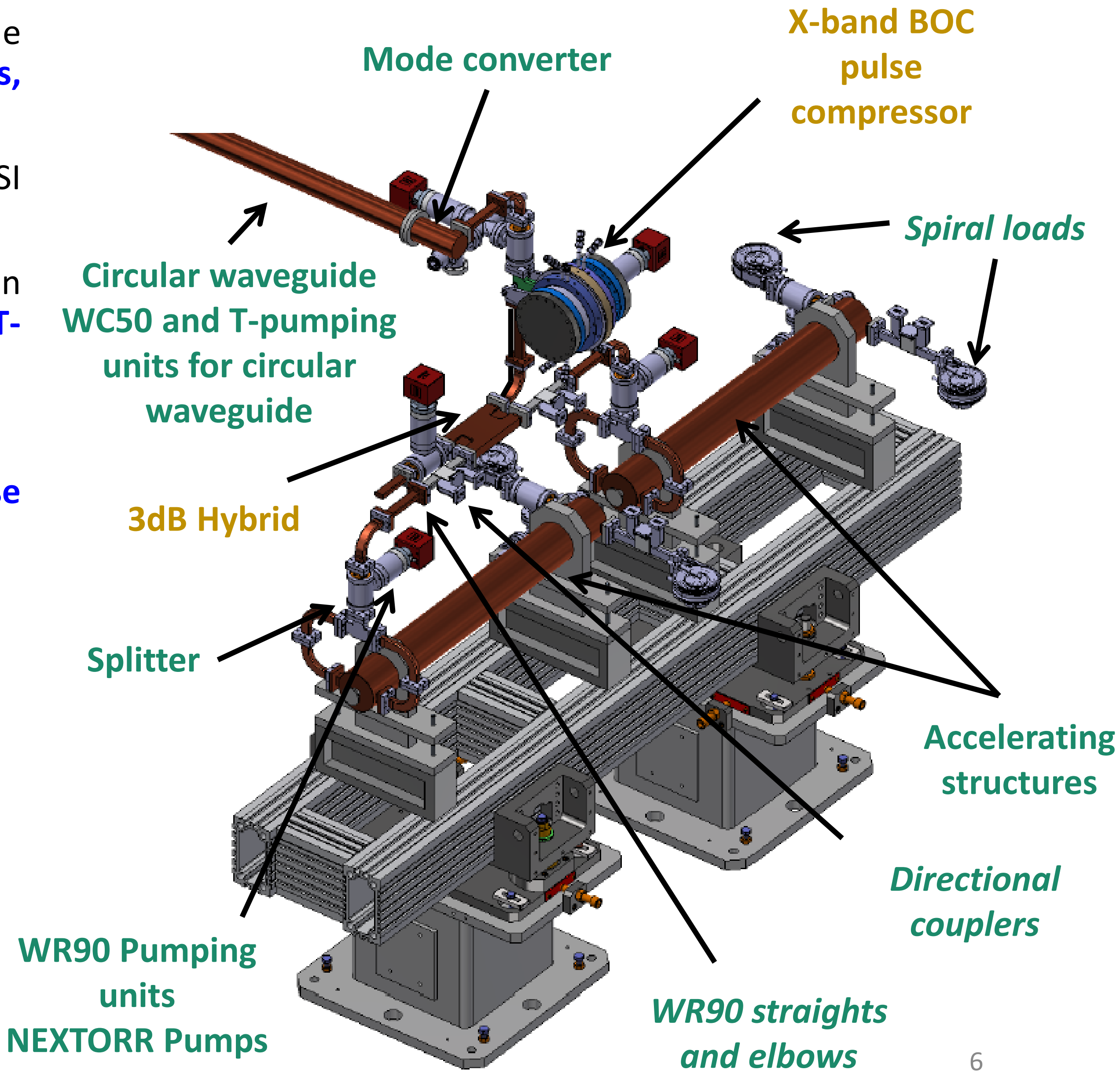


X-band RF components

- Many of the X-band components needed for the EuPRAXIA module are based on CERN design (i.e. **directional couplers, pumping units, splitter, 3dB hybrid, RF loads** [1])
- The X-band BOC pulse compressor has been purchased from PSI and integrated in the test facility in June 24
- Other has been designed at INFN and manufactured by Italian companies (i.e. **rectangular to circular mode converters, T-pumping unit for circular waveguide**)
- All of them have been manufactured and/or purchased
- We are working on an alternative design of the **BOC pulse compressor** to realize without brazing (PACRI project)







[1] *N. Catalan-Lasheras, et al., 9th Int. Particle Accelerator Conf. (IPAC18), Vancouver, BC, Canada, May 2018, paper WEPMF074.*

X-band RF components

COMPONENT	DESIGN BY	STATUS	HIGH POWER TEST
Pump unit (rect. wav.)	CERN	Fabricated and installed @ TEX	45 MW, 1 μs, 50 Hz, P_{avg} = 2.25 kW
Directional coupler	CERN	Fabricated and installed @ TEX	45 MW, 1 μs, 50 Hz, P_{avg} = 2.25 kW
Splitter	CERN	Fabricated and installed @ TEX	35 MW, 0.6 μs, 50 Hz, P_{avg} = 1 kW
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	35 MW, 1 μs, 50 Hz, P_{avg} = 1.75 kW
Pump unit (circ. waveg.)	INFN/SLAC	Fabricated and Installed @ TEX	35 MW, 1 μs, 50 Hz, P_{avg} = 1.75 kW
3dB hybrid	CERN	Delivered	To be tested
BOC pulse compressor	PSI	Delivered and installed @ TEX	To be tested

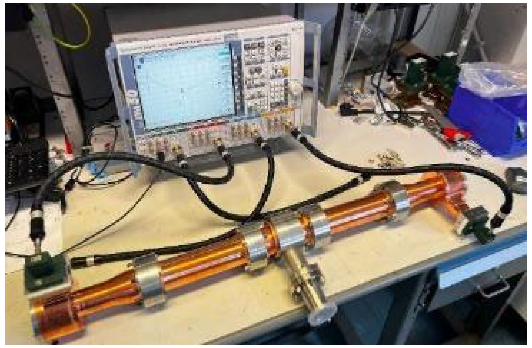
3D printed Ti spiral load

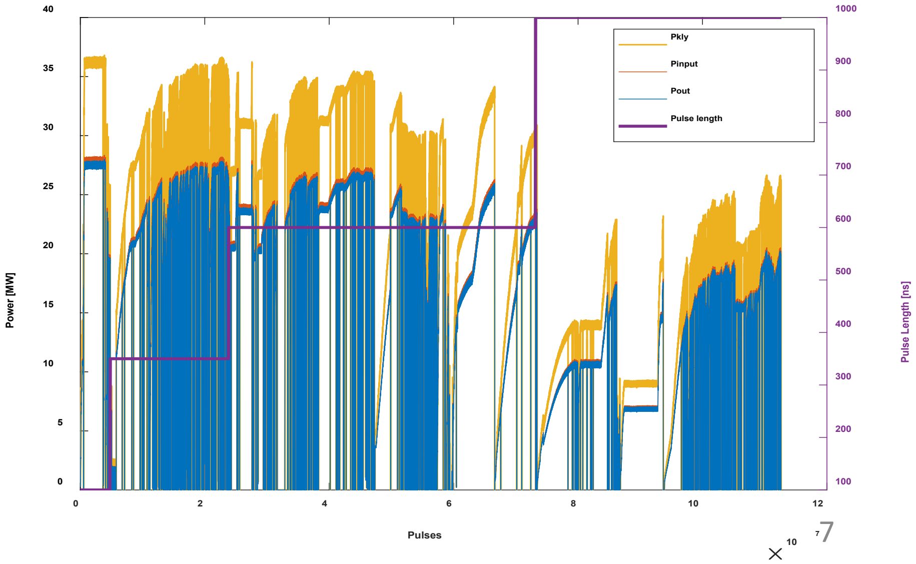
We procured 6 spiral loads realized with additive manufacturing. Based on CERN design [6].

#	Company	S11@f0 [dB]
001	3t am	-31
002	3t am	-30
003	ISC	-37,7
004	ISC	-36,4
005	ISC	-42
006	ISC	-43,9

Mode converter and T-pump for circular wg

- Modified version of the "wrap around" mode converter from $TE_{10}^{\square}$ to TE_{01}° developed at SLAC [2] and pumping port for circular waveguide.
- Machined by a private company and brazed at INFN-LNF
- Low Power RF test and High Power test on spiral Loads



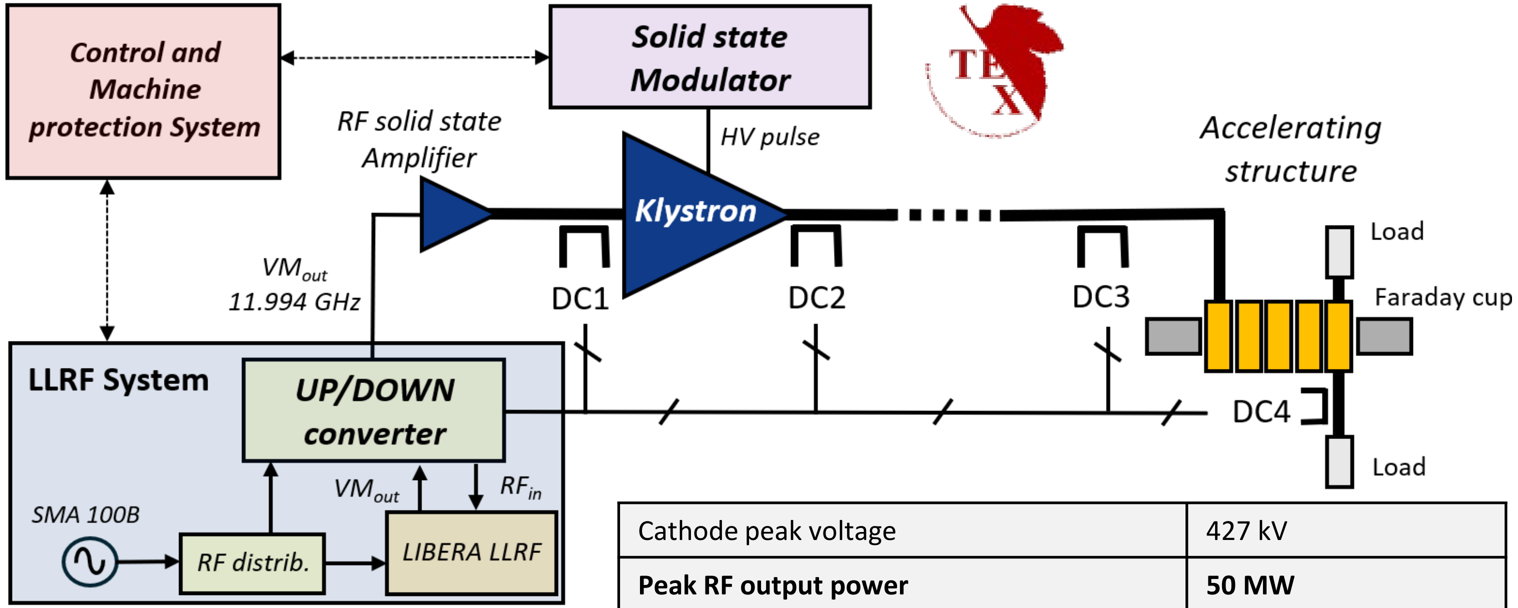


[2] S. Tantawi, et all. (2000). Reviews of Modern Physics – doi: 10.1103/PhysRevSTAB.3.082001

TEX (Test stand for X-band) 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, Beam Diagnostics, 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 (Source and RF network, LLRF, vacuum and EPICS control system) have been completed by the end of 2022 [3,4,5].
- Then started the testing activity:

Period	Device tested at high power
Jan. - Feb. 2023	3D printed Spiral RF loads and wg
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 from PSI
March 2024	20 cells first EuPRAXIA RF prototype



Cathode peak voltage	427 kV
Peak RF output power	**50 MW**
Pulse length	250 ns (1.5 us)
Repetition Rate	**50 Hz**
RF output amplitude stability	< 0.09 %
RF output phase stability	20.9 fs

LLRF system

50 MW RF Source

VKX8311A Klystron

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

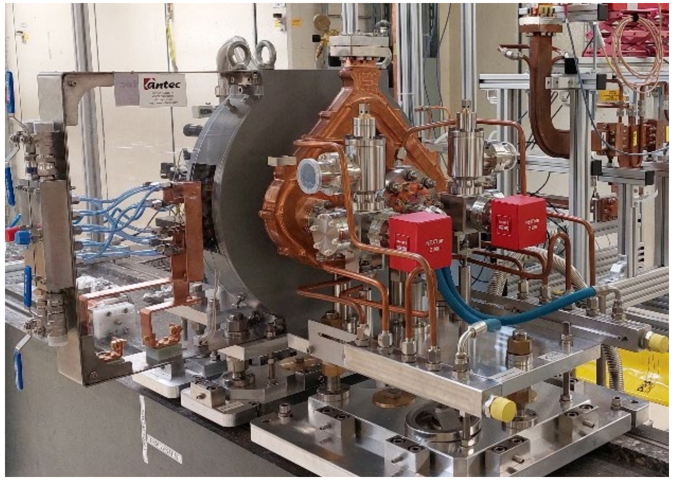
TEX Upgrade and C-band photoinjector

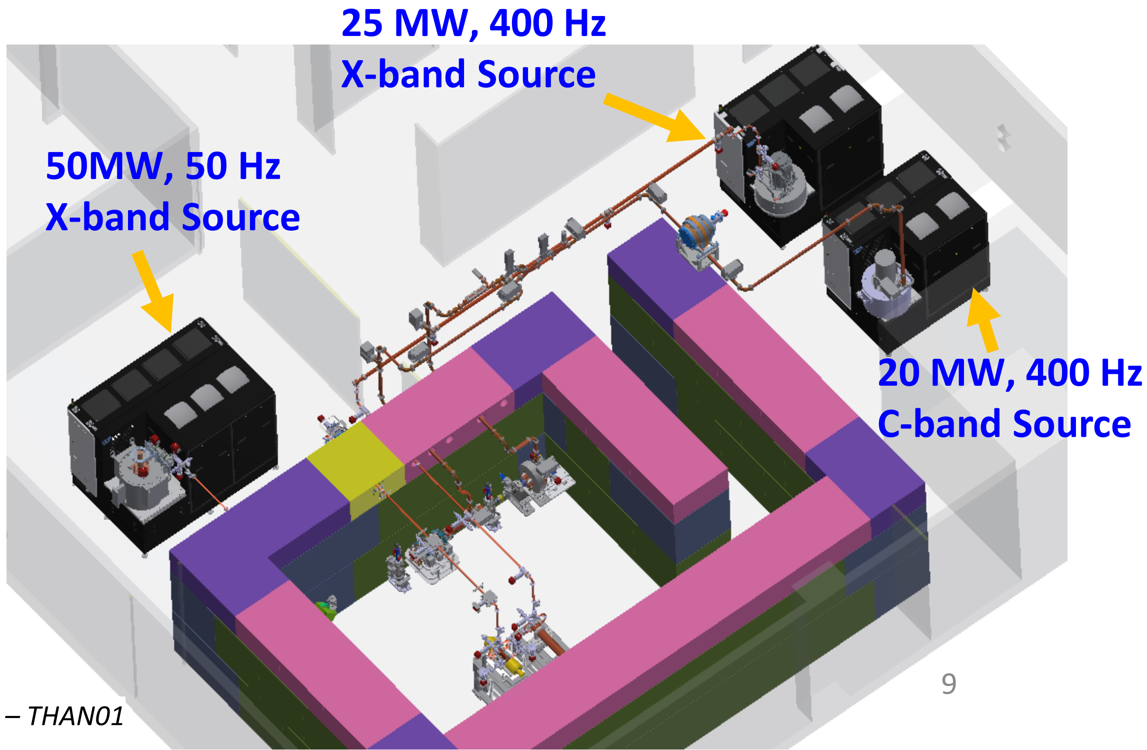
- The TEX facility is currently undergoing an **upgrade** with the installation of two new high repetition rate RF sources.
- Two new sources (modulator + klystron) have been tested in factory at end of May 2024 (at Scandinova) in diode mode at full power. They has been shipped at the beginning of June, positioned, and the klystrons installed. The entire waveguide system is also currently being delivered.
- The commissioning of these sources and the waveguide networks is scheduled for January 2025, after the installation of the cooling and power systems that will serve these sources.

Parameter	Unit	Canon E37217	Canon E37119
Frequency	MHz	**5712**	**11994**
Peak RF output Power	MW	**20**	**25**
Average RF output power	kW	21	15
Modulator Average power	kW	80	80
RF pulse length	us	**2.5**	**1.5**
Repetition Rate	Hz	**400**	**400**
Gain	dB	50	47
Efficiency	%	40	40

High gradient C-band Gun

(IFAST project, now under test @PSI [6])





[6] D. Alesini et al. "Design, realization and high power test of the new brazed free C-band Photo-Gun" In Proc. IPAC24 – THAN01

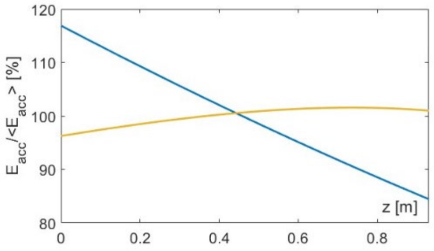
X-band Accelerating structures design

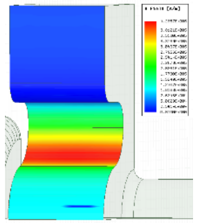
» The **EM design of the structure is completed**: **0.9 m long** structures with **3.5 mm average iris radius** design to work with an average acceleration gradient of **60 MV/m.** The single cell and RF structure optimization has been completed developing a semi-analytical code to consider also the power gain from the BOC pulse compressor [10]: ***done***

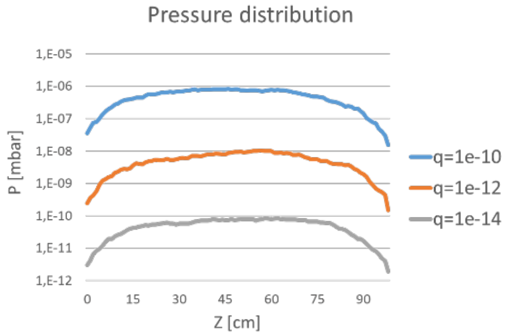
» **Thermo-mechanical simulations** to demonstrate the correct sizing of the cooling system (at 100 Hz and 400 Hz): ***done***

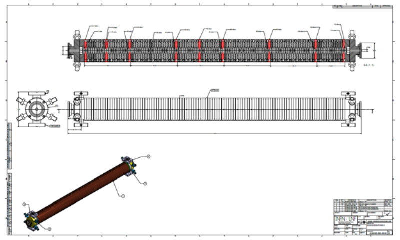
» **Dark current simulations** (CST Particle in cell) have been performed to evaluate the background radiation together with **vacuum calculation** to verify the pression distribution along the structure: ***done***

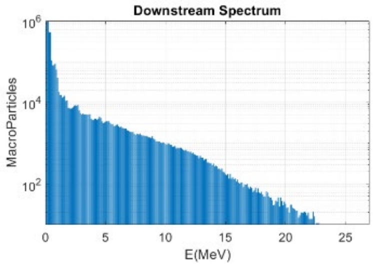
» The final **mechanical design** of the final X-band structure has been under constant review, related to the result of the **pre-prototyping activity**: brazing test, cell to cell alignment, etc: ***done***











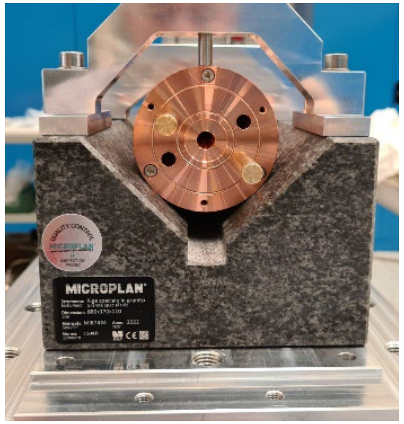
PARAMETER	Value	
	Quasi-Constant Gradient	Constant Impedance
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85 - 3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length [m]	**0.94**	
No. of cells	112	
Shunt impedance R [MΩ/m]	93-107	100
Effective shunt Imp. R_{sh_eff} [MΩ/m]	350	347
Peak input power per structure [MW]	70	
Input power averaged over the pulse [MW]	51	
Average dissipated power [kW]	1	
P_{out}/P_{in} [%]	25	
Filling time [ns]	130	
Peak Modified Poynting Vector [W/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 (400)**	

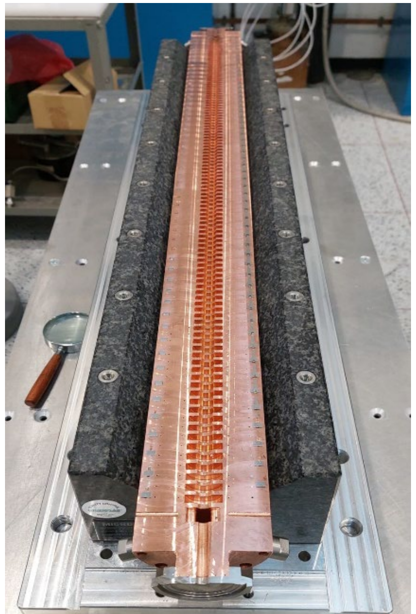
[10] M. Diomede et al. NIM A 909 (2018) 243–246

Full-Scale Mechanical Prototype Brazing

2x Full scale mechanical prototype for brazing optimization and test

To maintain the alignment and cell to cell straightness during and after the brazing process, **each cell is fixed to the next one by means of screws** and mounted on a very precise **granite support**. This ease also the cells assembly





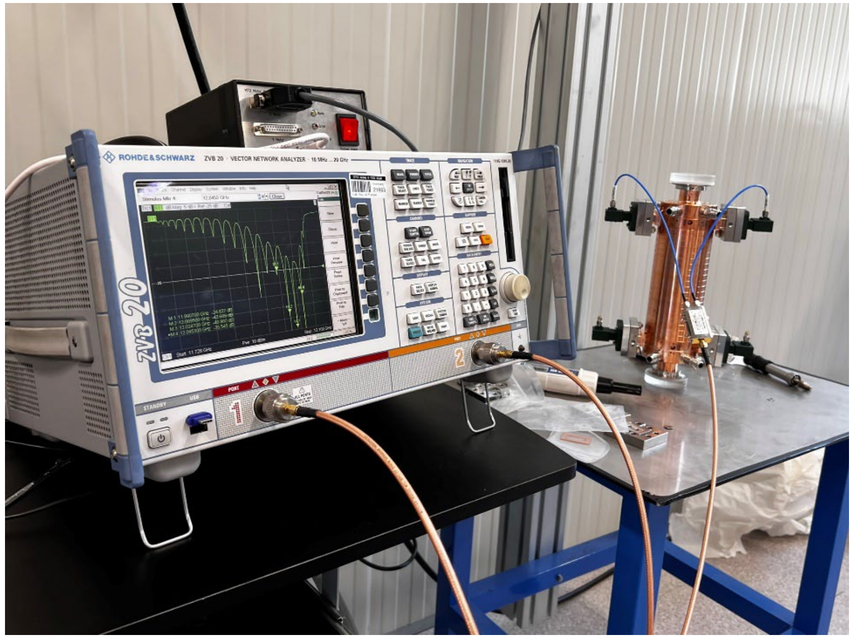
Results on the brazed structure

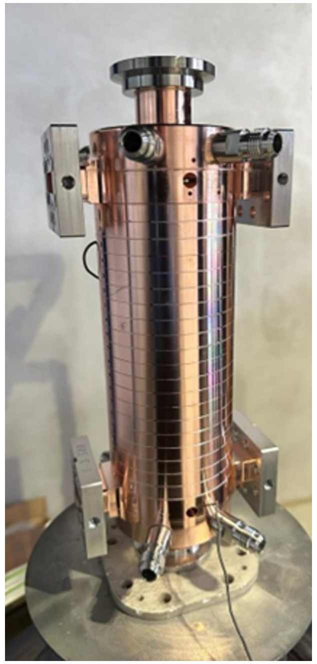
- **Vacuum test OK** (except one coupler for a miss-positioning of the brazing alloy)
- **Straightness <±15 μm** obtained after brazing on both the prototypes (±30 μm required by BD)

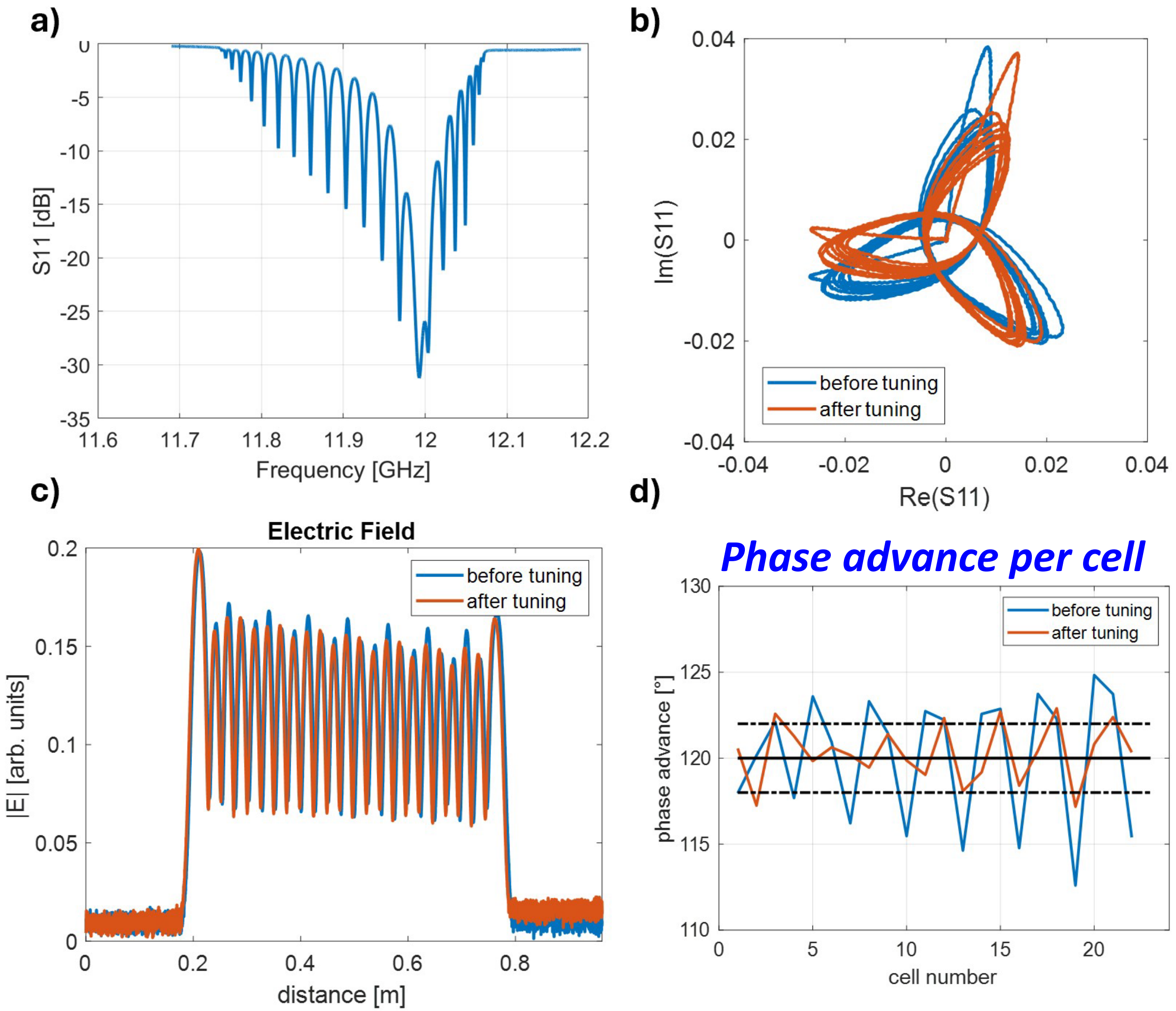
X-band structure RF prototype

X-band, 20 (+2) cells, CI, travelling wave 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 (2-3 um on the diameter) to obtain the best response from the cells we will increase the working temperature → **T_{cav} = 30 – 35 °C**



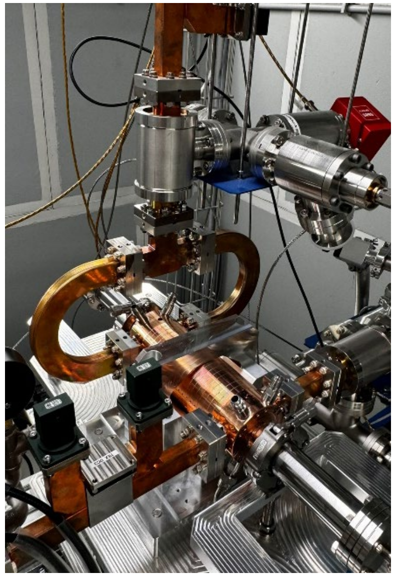


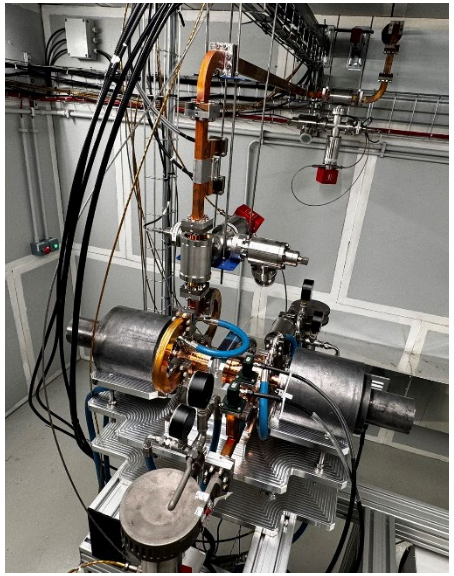


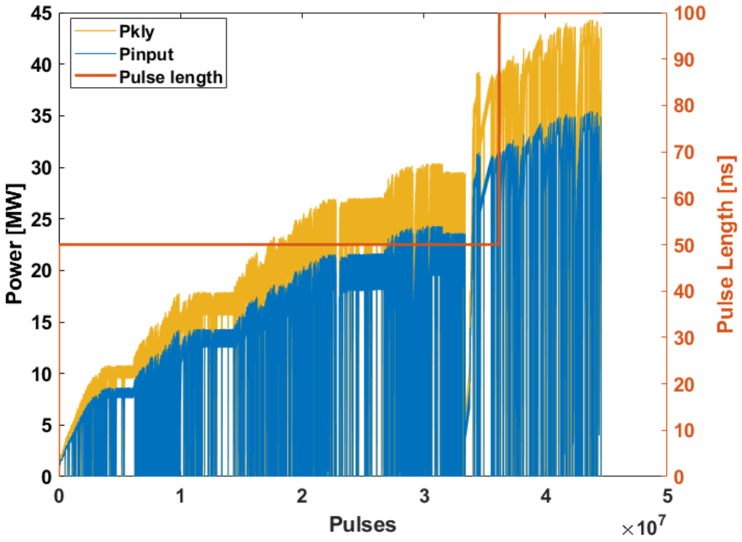
20 cells EuPRAXIA X-band structure high power test

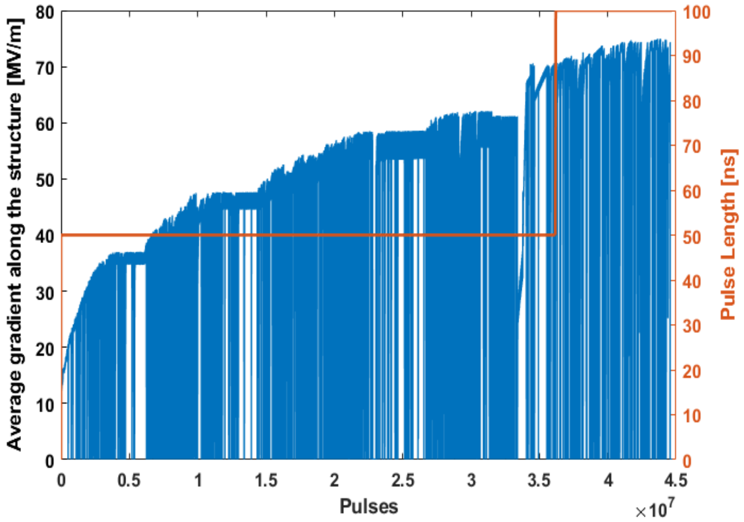
- From the 6th to the 17th of March we perform the high power test of the first EuPRAXIA@SPARC_LAB X-band structure prototype
- It is a 20 cells, constant impedance, RF prototype (the real structure will be 1 m long)
- In 10 days we reach an input pulse of 35 MW, 100 ns length at 50 Hz repetition rate, 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 nearly 1e-5.
- The test will continue, after an initial phase of installations for the TEX upgrade, with the BOC pulse compressor also 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**









Highlights and future activities

- **EuPRAXIA@SPARC_LAB** is the next INFN-LNF facility. It is the beam driven pillar of the EuPRAXIA project, included in the ESFRI 2021 Roadmap. The TDR of the machine will be completed by the end of 2025.
- **TEX (Frascati Test stand for X-band)**: has been completely commissioned and used to test several components
  - A new X-band RF source based on the **E37119 klystron** (25 MW, 400Hz) has been tested and will be commissioned at TEX in the next months, together with a C-band source for C-band photoinjector testing.
  - A **high efficiency klystron 50 MW VKX8311HE** developed by CPI/CERN should be commissioned in 2025.
- Many **X-band RF components** of the EuPRAXIA RF module have been purchased and tested at nominal power other will be tested soon:
  - The X-band BOC from PSI has been installed at TEX and will allow to reach very high peak power for RF testing.
  - **A brazing free BOC pulse compressor is in design phase**
- **X-band structures**: An intensive prototyping activity is ongoing exploiting the new vacuum furnace at LNF.
  1. Two **full-scale mechanical prototypes** has been realized and tested**:** brazing test gives optimum results in term of straightness and vacuum tightness
  2. The **20 cells CI RF prototype** has been realized
     - Low power RF measurements showed the cells are all the same but smaller by approx ±2 µm
     - A preliminar high power test show promising results
  3. A **full-scale 0.9m RF prototype** for high power test is in production**.**

Aknowledgements:

INFN-LNF: *D. Alesini, S. Bini, B. Buonomo, S. Cantarella, G. Catuscelli, R. Clementi, L. Faillace, M. Ferrario, A. Gallo, C. Di Giulio, E. Di Pasquale, G. Di Raddo, G. Latini, A. Liedl, V. Lollo, L. Piersanti, S. Pioli, B. Serenellini, L. Spallino on behalf of the, INFN-LNF Accelerator Division and Technical Division*

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