1st workshop on Fundamental research and applications with the EuPRAXIA facility at LNF

TEX Facility

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on behalf of the TEX Technical team

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INFN-LNF, Frascati, Italy
04-06/12/2024

Outline

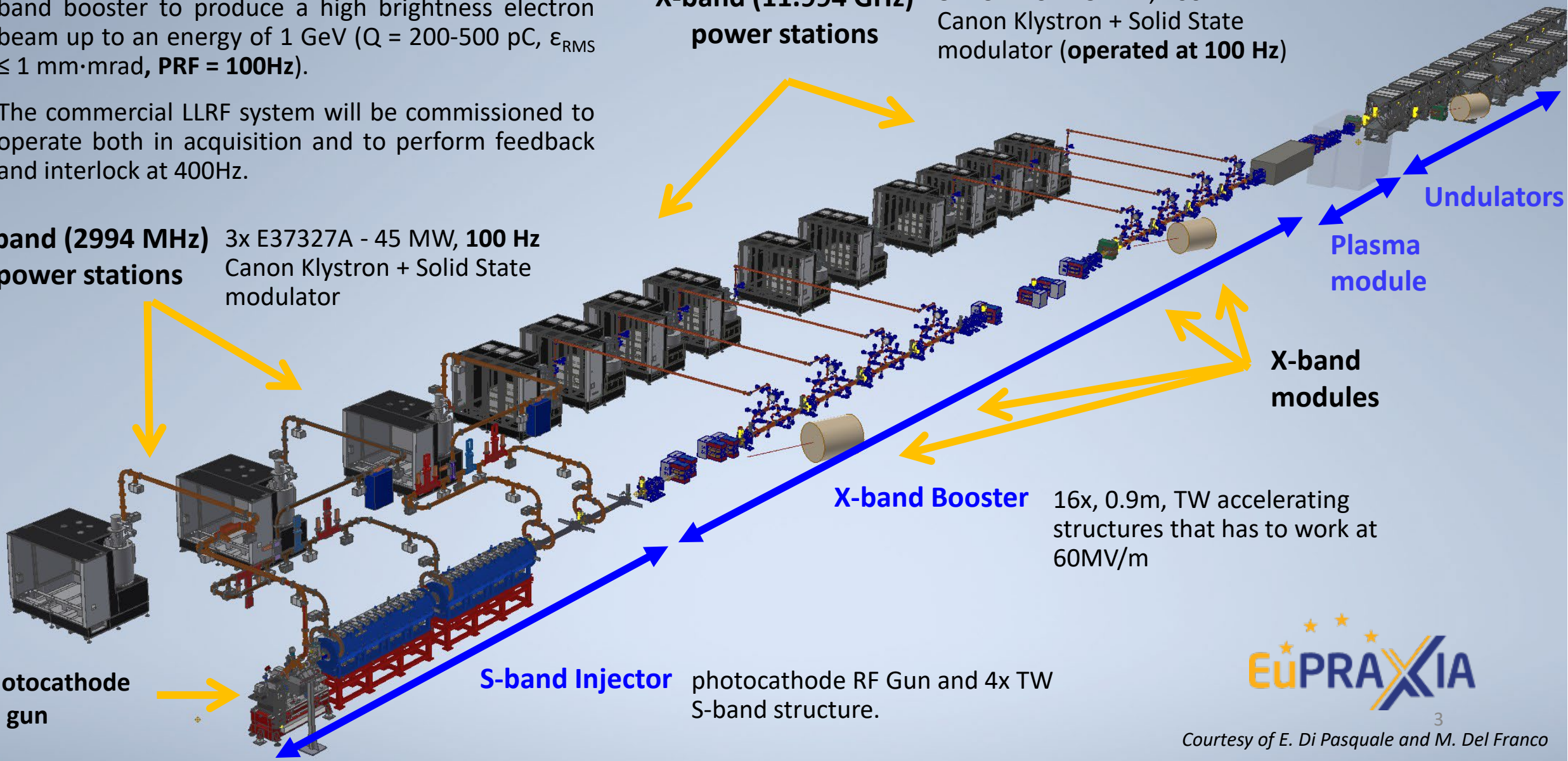
1. Status of EuPRAXIA@SPARC_LAB RF Linac
2. X-band module layout
3. TEX Facility
    - Components tested
    - X-band structure design and first test
4. TEX Upgrade
5. C-band photoinjector: FRINGE
    - High gradient C-band Gun design and test
6. Highlights and future activities

Status of the EuPRAXIA RF 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 commercial LLRF system will be commissioned to operate both in acquisition and to perform feedback and interlock at 400Hz.

X-band (11.994 GHz) power stations 8x E37119 - 25 MW, **400 Hz** Canon Klystron + Solid State modulator (**operated at 100 Hz**)

S-band (2994 MHz) power stations 3x E37327A - 45 MW, **100 Hz** Canon Klystron + Solid State modulator



Undulators

Plasma module

X-band modules

X-band Booster 16x, 0.9m, TW accelerating structures that has to work at 60MV/m

Photocathode RF gun

S-band Injector photocathode RF Gun and 4x TW S-band structure.

Courtesy of E. Di Pasquale and M. Del Franco

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**

Power Source: Solid State Pulsed Modulator + 25 MW Klystron

25 MW
1.5 us
100 Hz

6 m

Transport line: Low loss Circular waveguide

140-70 MW
130 ns
100 Hz

70-35 MW
130 ns
100 Hz

Accelerating module

2.3 m

Mode converter
(INFN/SLAC design)

BOC pulse compressor
(PSI design or INFN brazing free)

Spiral RF LOADS
(CERN Design)

circular waveguide Pumping units

Hybrid
(CERN design)

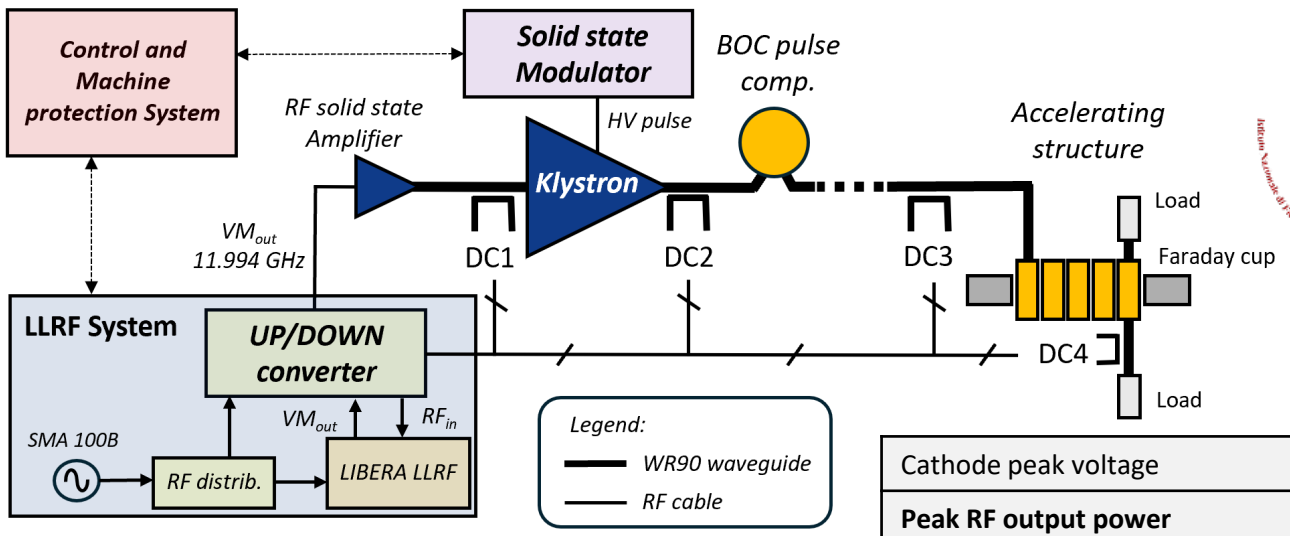
X band structures
(INFN design)

Pumping units
(CERN design)
NEXTORR Pumps
(SAES)

DC
(CERN design)

TEX Facility

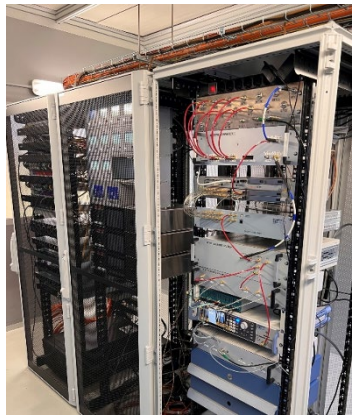
- The **TEst-stand for X-band (TEX)** is conceived for **R&D and test on high gradient X-band accelerating structures, RF components, LLRF systems, Vacuum system and Control System**
- It has been co-funded by Lazio region in the framework of the **LATINO project** (Laboratory in Advanced Technologies 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 (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 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 **from PSI**
March 2024	20 cells **first EuPRAXIA RF prototype**
April 2024 - Now	**Upgrade of the facility**

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

LLRF system



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

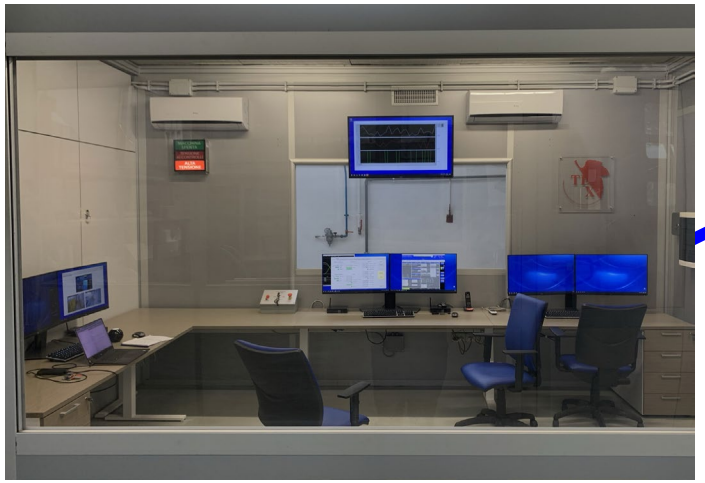
TEX facility (2)

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

Rack Room

Bunker

Experimental hall



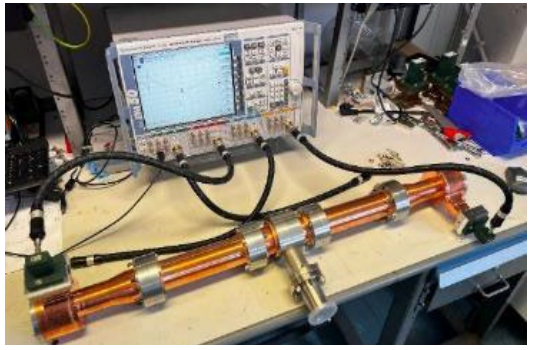
Control Room

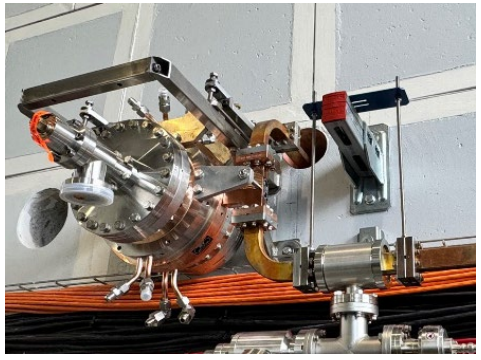
X-band RF components tested at TEX

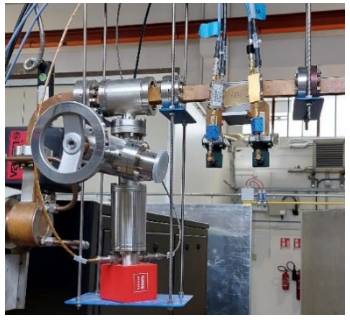
- Many of the X-band components needed for the EuPRAXIA module are based on CERN design (i.e. **directional couplers, pumping units, splitter, 3dB hybrid, RF loads**). Other has been designed at INFN and manufactured by Italian companies (i.e. **rectangular to circular mode converters, T-pumping unit for circular waveguide**). All of them have been manufactured and purchased.
- The X-band BOC pulse compressor has been purchased from PSI and integrated in the test facility in June 24.

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

Mode converter and T-pump for circular wg

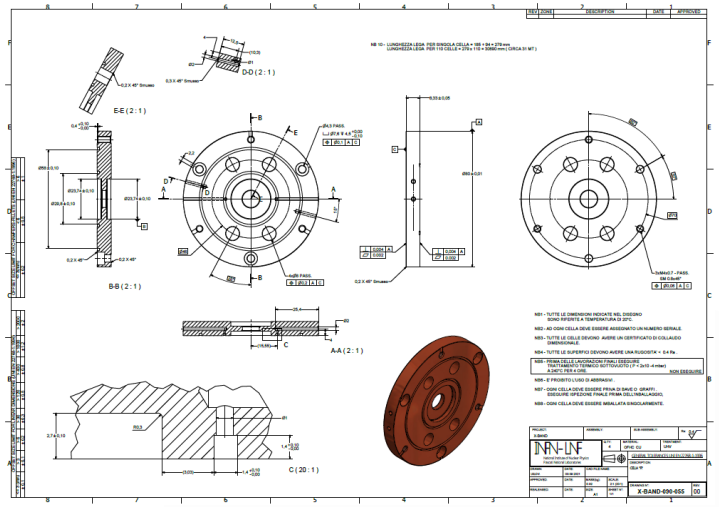


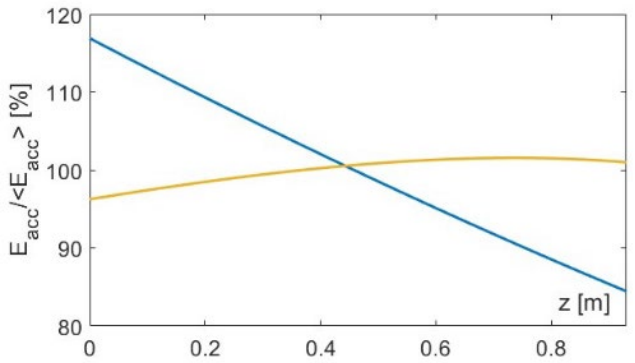


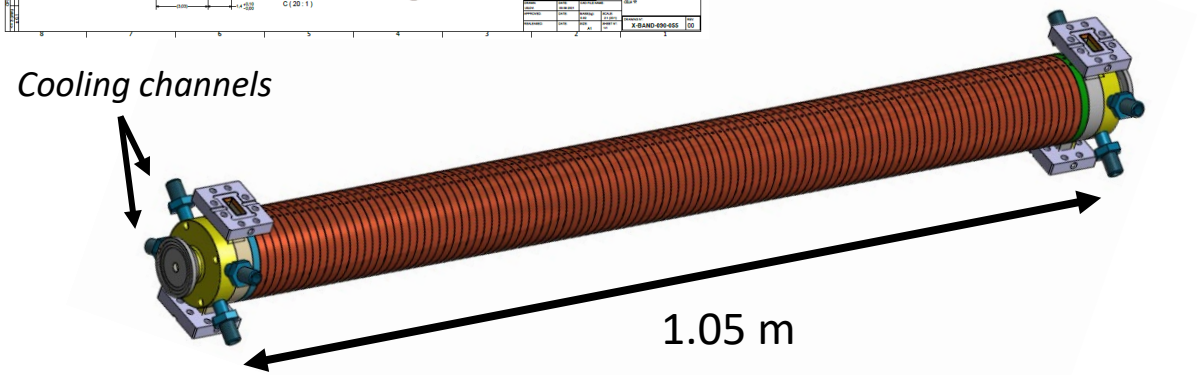


X-band Accelerating structures design

- The **EM design of the structure is completed**: **1.05 m long** structures with **3.5 mm average iris radius** design to work with an average acceleration gradient of **60 MV/m.**
- Integrated cooling system consists of 4 cooling channels with 4 mm radius
- Working temperature = 25 °C







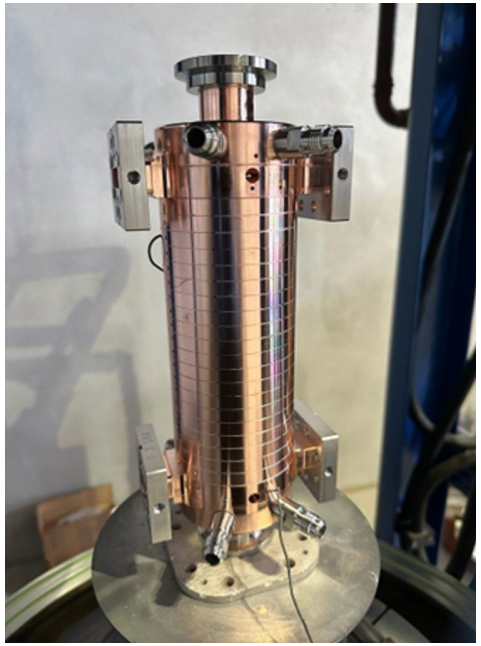
PARAMETER	Value	
	Quasi-Constant Gradient	Constant Impedance
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85 - 3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length [m]	**1.05**	
No. of cells	112	
Shunt impedance R [MΩ/m]	93-107	100
Effective shunt Imp. R_{sh_eff} [MΩ/m]	350	347
Peak input power per structure [MW]	70	
Input power 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 (400)**	

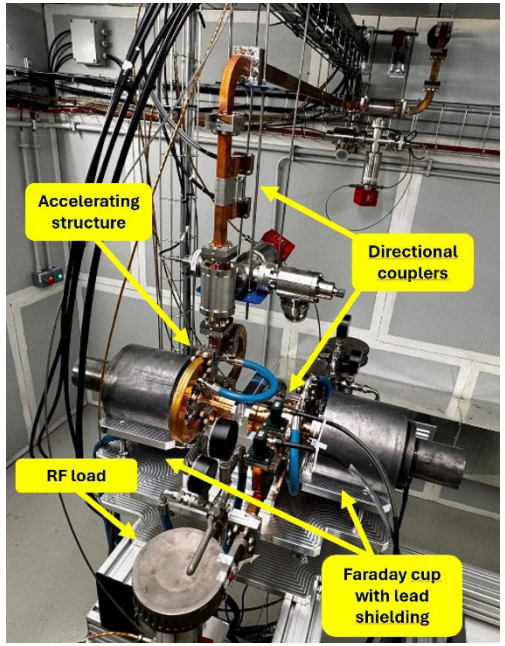
M. Diomede et al. NIM A 909 (2018) 243–246

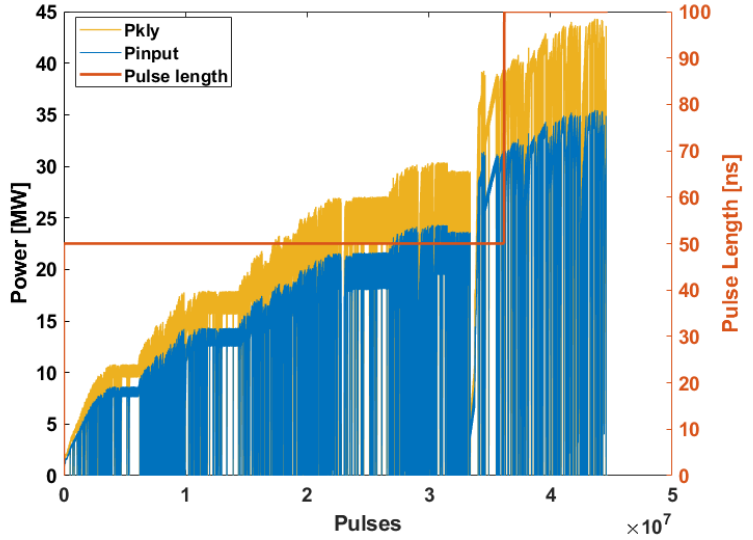
First EuPRAXIA structure high power test

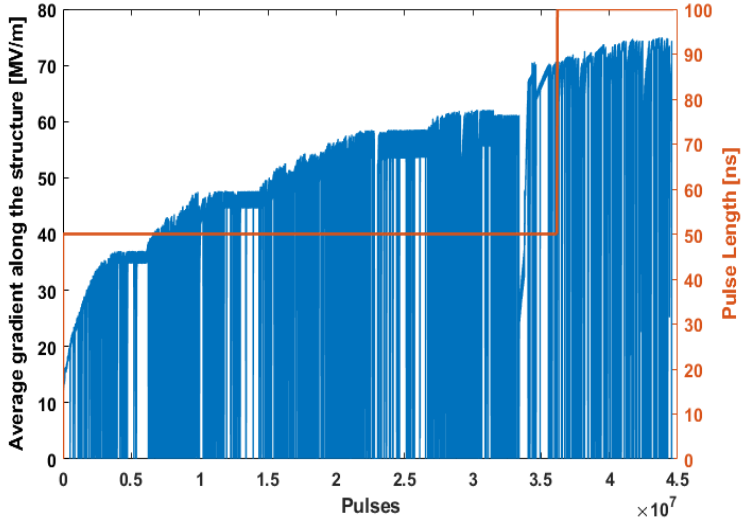
- In March 2024 we perform the **high-power test of the first EuPRAXIA@SPARC_LAB X-band structure prototype**.
- 20 cells, constant impedance, RF prototype (the real structure will be 1 m long).
- In 10 days we reach an input pulse of **35 MW, 100 ns length at 50 Hz repetition rate**, that correspond 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 the TEX upgrade**, with the BOC pulse compressor installed on the line.
- **The realization of a full-scale RF prototype is ongoing**.

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**









TEX Upgrade

» Thanks to **PNRR Rome Technopole project**, €3M have been allocated for the **upgrade of the TEX facility and Latino project.**

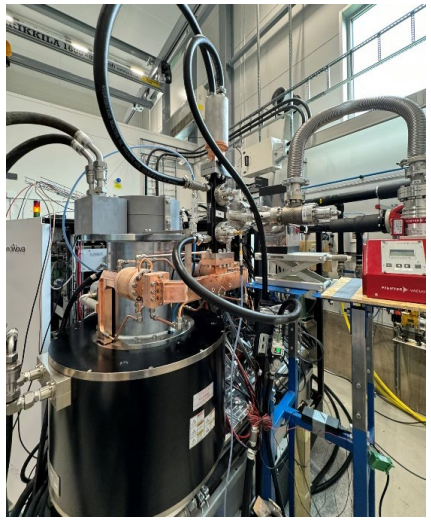
» Procurement, installation and test of **two new RF sources** and waveguide system:

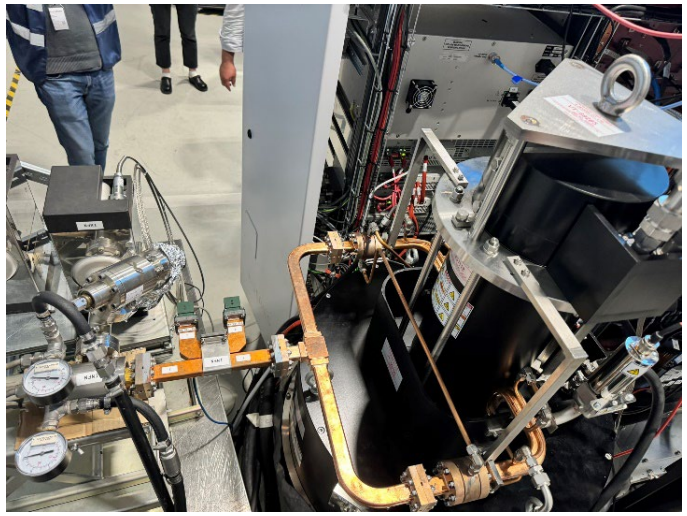
1. **X-band (11994 MHz) 25MW, 400Hz Power Source**
2. **C-band (5712 MHz) 20MW, 400Hz Power Source**
   - FAT of the klystron done @CANON on a PFN modulator 11/2023
   - FAT of the RF source @Scandinova 05/2024, full power in diode mode
   - Modulator and klystron positioned at TEX
   - SAT with Scandinova and Canon is **scheduled at the beginning of 2025** depending on the dry cooler commissioning

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

ROME TECHNOPOLE INNOVATION ECOSYSTEM

FAT of the two Sources



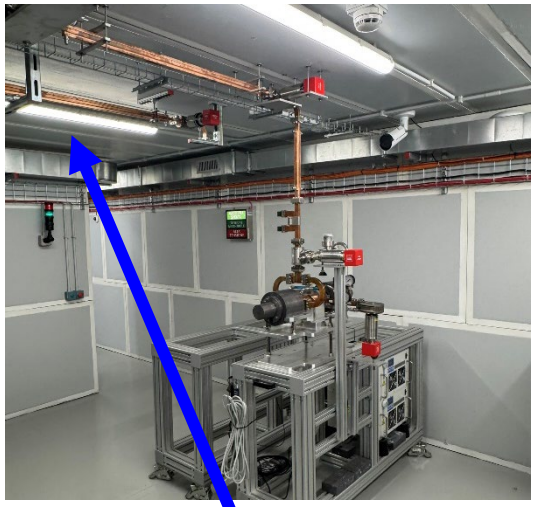


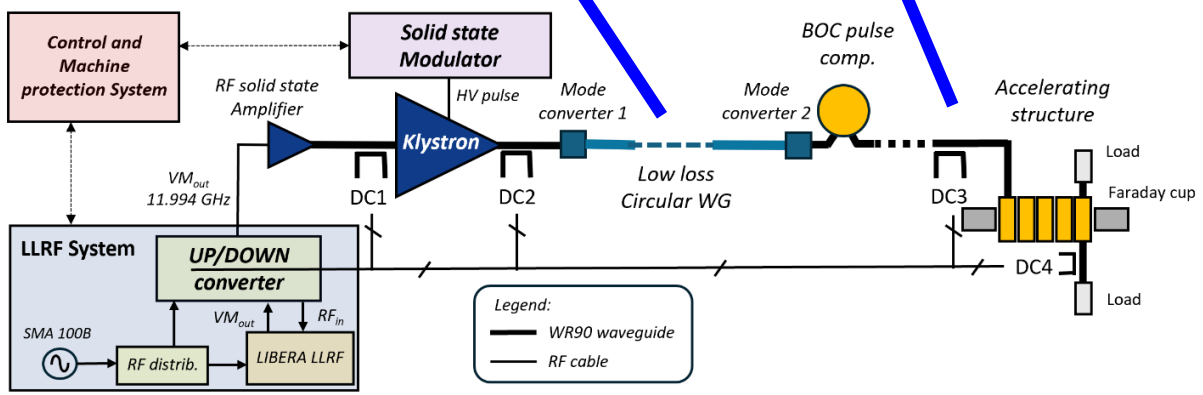
CANON E37119

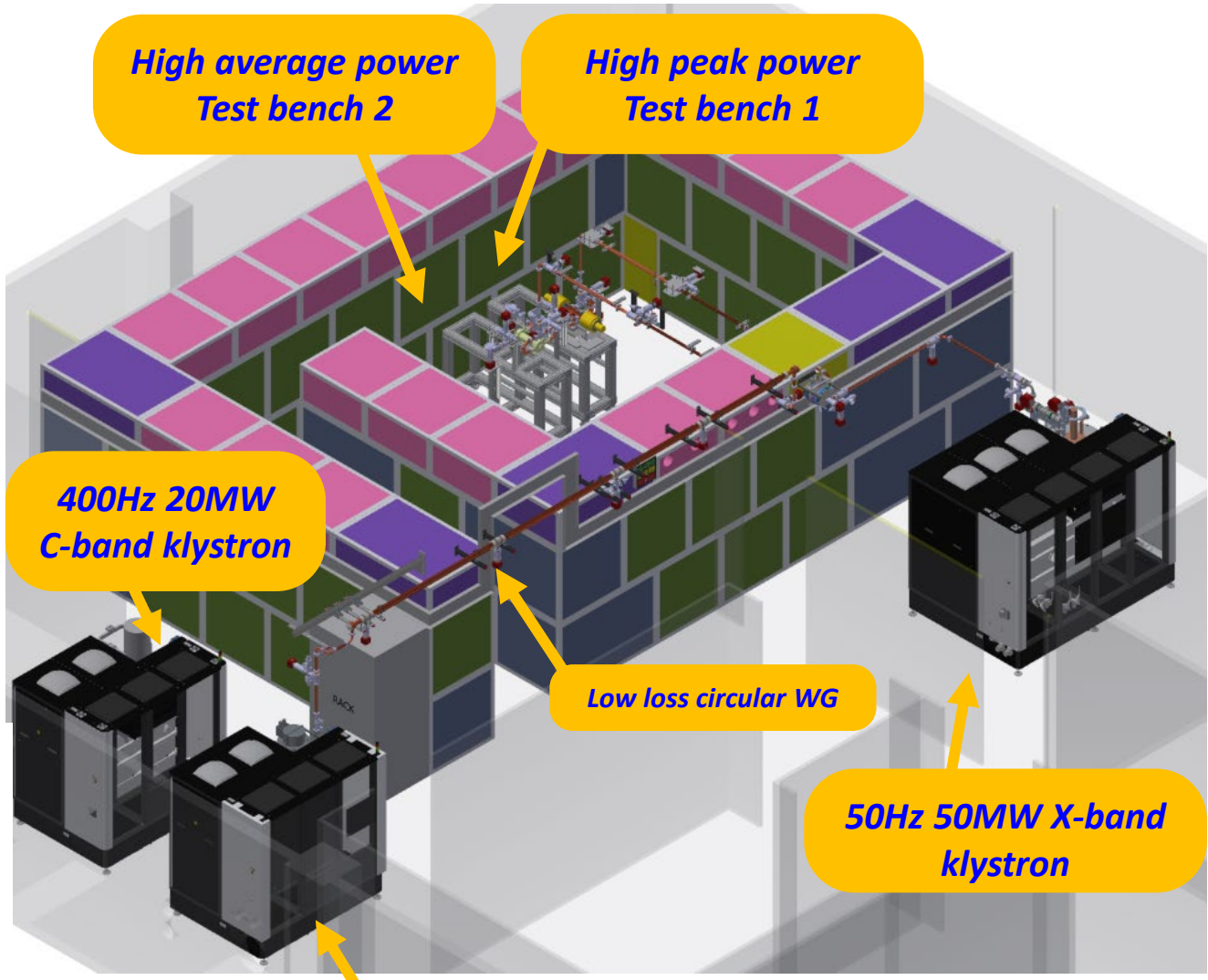
Installation at TEX

TEX Upgrade (2)

- The 2nd **test bench will double the TEX X-band testing capabilities** and will allow for high average power test of X-band components.
- The 1st test bench has been moved and the waveguide network modified.
- **All the waveguide system has been already designed and procured and his installation is ongoing**:



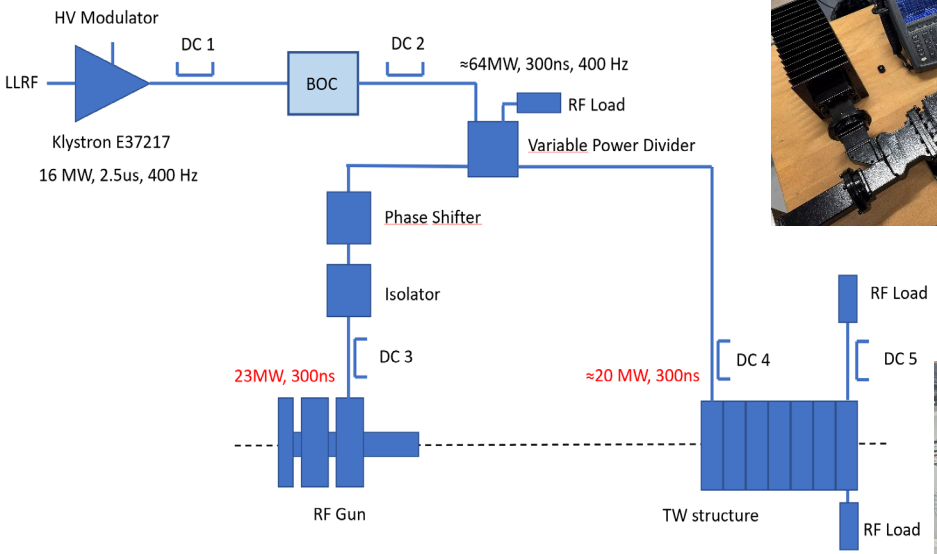


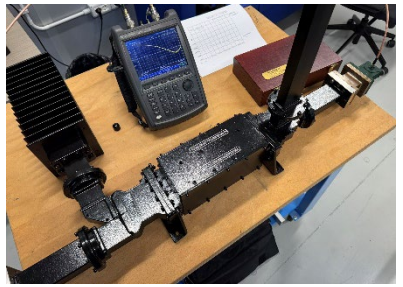


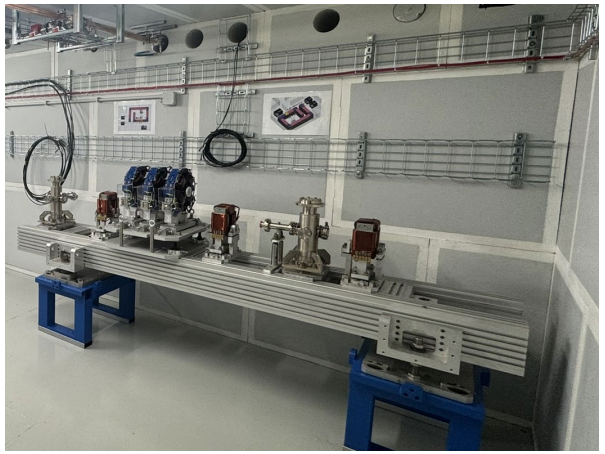
C-band Gun and FRINGE photoinjector

- The **C-band source** will be used to **power and test at high repetition rate a C-band RF photogun** realized in the framework of the IFAST project.
- In a second phase it will be integrated with a traveling wave (TW) structure to form a **compact photoinjector** and will be used for the generation of **high brightness beam and experimental studies**.
- This will be a **first test facility for a full C-band injector** operating at 400Hz for the EuPRAXIA@SPARC_LAB project.

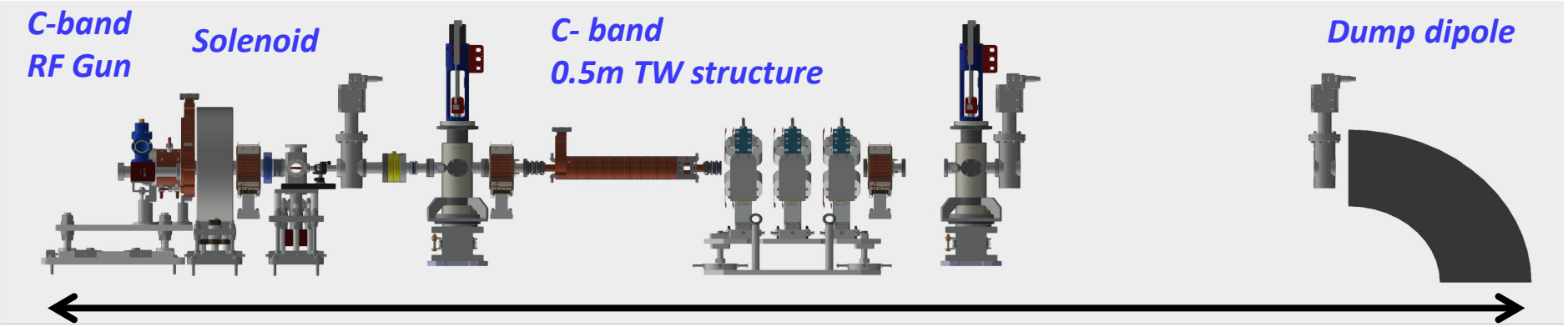
RF wg layout







Photoinjector Preliminary Layout



Preliminary working ponts:

- Laser pulse length 100 fs
- Bunch charge 750/250/50 pC
- Bunch length 300 um rms
- Emittance 3.5/0.5/0.3 mm-mrad

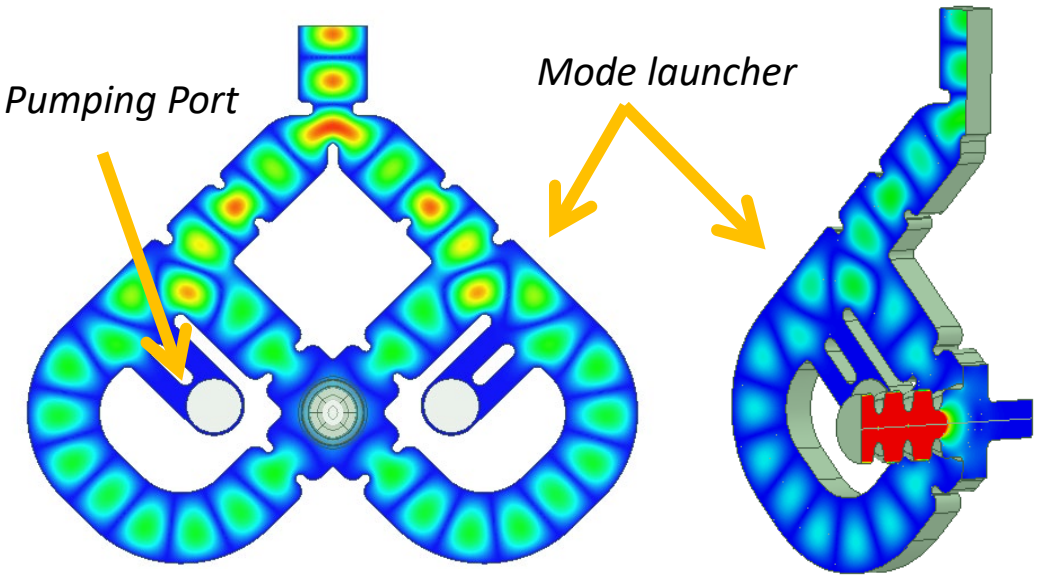
Courtesy of E. Di Pasquale, L. Faillace, S. Pioli, A. Giribono, G. Costa and L. Spallino.

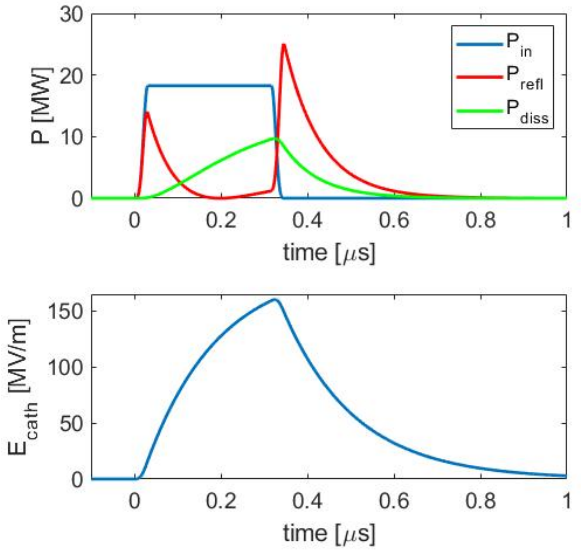
IFAST high gradient C-band Gun

C-band (6 GHz) RF Gun enables **higher achievable cathode peak fields** (>120MV/m) and due to its **increased efficiency**, is also suitable for high repetition rates operation (1 KHz). This should lead to **better quality of the generated beam**.

C-Band RF gun design and realization has been funded by the **European I.FAST project and INFN Commission V**

- The **electromagnetic design** has been guided to minimize surface peak fields, Modified Poynting vector and Pulsed heating
- **Mechanical realization** with Hard copper and clamping technology: Reduced costs and risks of failure, Low BDR, Low conditioning time





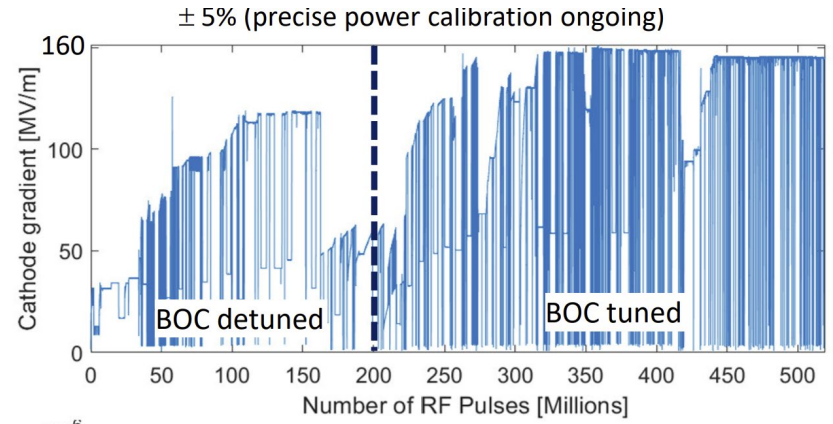
Parameter	Unit	Value
Frequency	MHz	5712
Peak input power	MW	23 (19)
Cathode peak field	MV/m	180 (160)
Rep. Rate	Hz	100 (400)
Quality factor		11900
Filling time	ns	166
Coupling coefficient		3
Rf pulse length	ns	300
E_{surf}/E_{cath}		0,96
Mod. Poy. vector	W/um^2	3.2 (2.5)
Pulsed heating	°C	20 (16)
Average diss. Power	W	320 (1000)

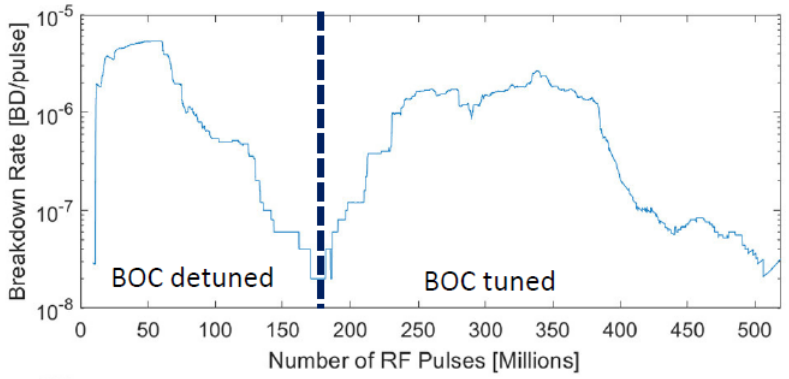
D. Alesini et al., MOPOMS021, IPAC2022, Bangkok, Thailand, p. 679, 2022
D. Alesini et al., TUPA009, IPAC2023, Venezia, Italy, p. 1356, 2023
A. Giribono et al., PRAB 26, 083402, 2023
F. Cardelli, Nuovo Cimento issue 5 (2024)

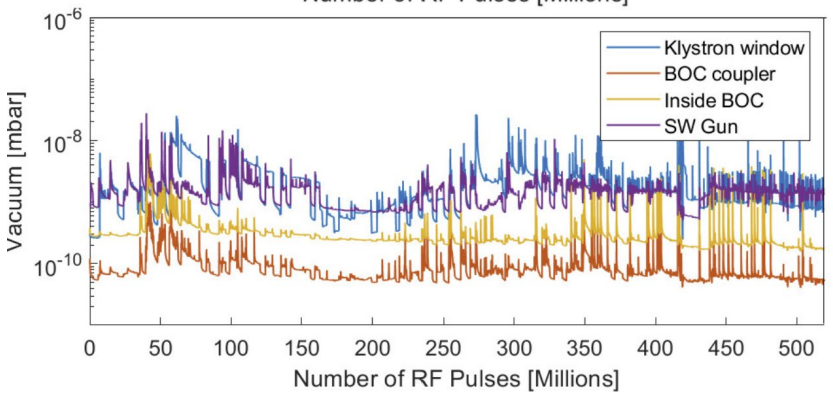
C-band gun high Power test at PSI

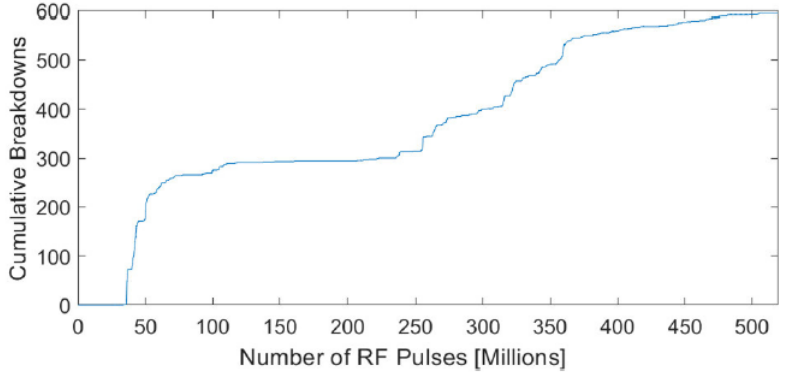
The whole system has then been transported to **PSI and installed in the High Power Test Stand.** RF conditioning began in **February 2024**. The conditioning was done in a semi-automatic way at a repetition rate of **100 Hz.** Conditioning dominated by the vacuum activity in the **waveguide.** Final maximum input power limited by a vacuum **activity in the ceramic of the Klystron.** The cathode peak field reached is about **160 MV/m.**

In **January 2025** the Gun will be shipped back to LNF and installed in the TEX bunker. Once the C-band RF source will be commissioned the conditioning of the Gun will continue increasing the cathode peak field up to 180 MV/m.



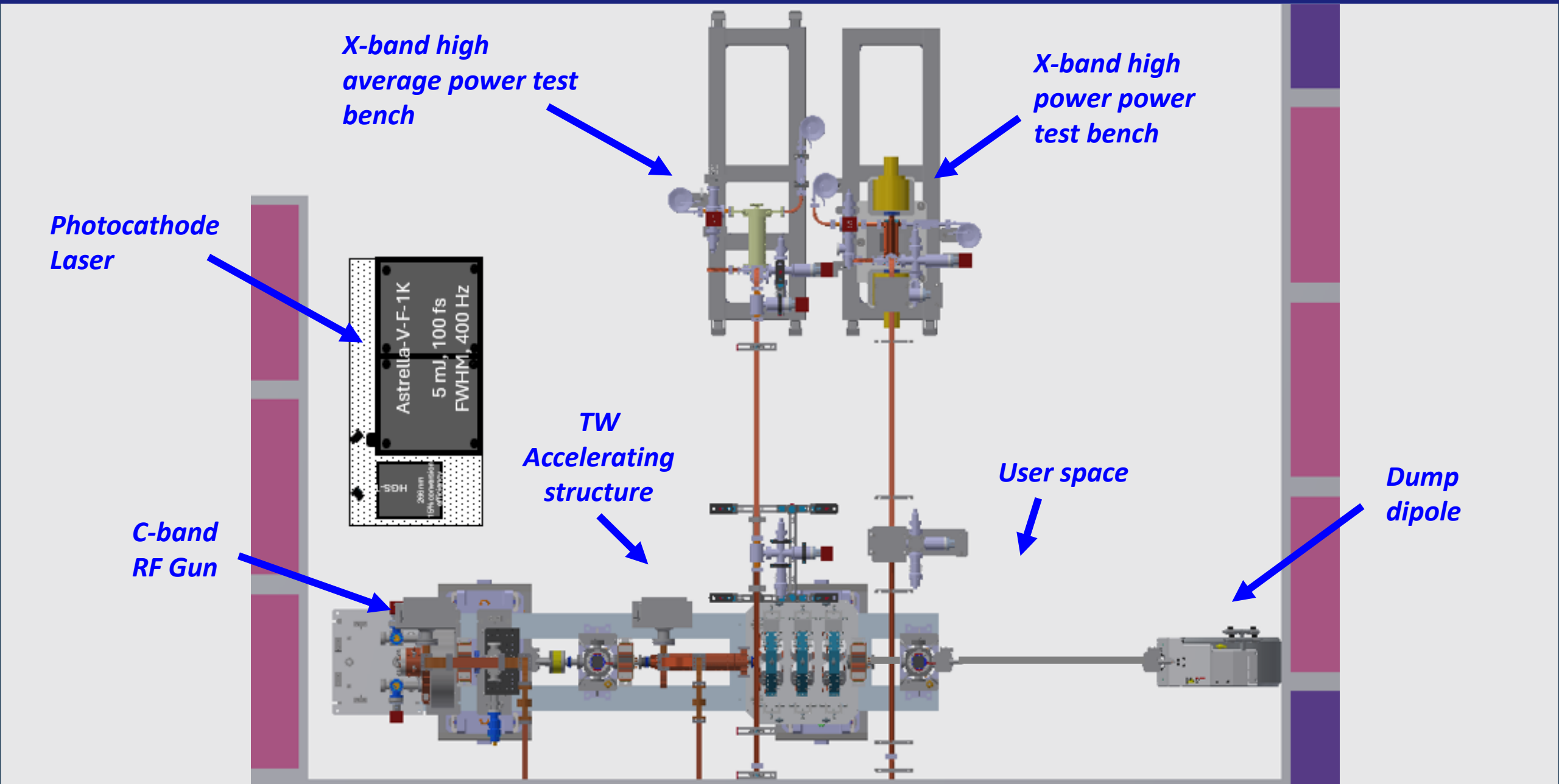






RF Gun Installed @PSI (Switzerland)

TEX final layout



Highlights and future activities

- **TEX (Frascati Test stand for X-band)**: is the test facility for the X-band technology at INFN-LNF.
  - It has been completely commissioned in 2022 and used to test several RF components for the EuPRAXIA@SPARC_LAB project and external users.
- **TEX Upgrade**:
  - Thanks to Rome Technopole project the facility is being **upgraded with the procurement of two new high repetition rate RF s**ources and waveguide system.
  - The new C-band and X-band high repetition rate sources **will be commissioned in February-March 2025**.
  - The installation of the C-band and X-band waveguide network is ongoing.

- **X-band structures and components test** :
  - The test of the first X-band structure prototype will continue at the beginning of 2025.
  - A **full-scale RF prototype of X-band EuPRAXIA@SPARC_LAB structure is under realization**, and it will be tested at TEX.
  - A **high efficiency klystron 50 MW VKX8311HE** developed by CPI/CERN should be tested in October 2025.
- **C-band photogun test and FRINGE Linac:**
  - In January the IFAST **C-band RF gun will return at LNF and will be installed in the TEX bunker**. After the commissioning of the C-band source will start the test of the Gun at high repetition rate.
  - The photocathode laser, dump dipole and other elements procurement has started.

THANK YOU FOR YOUR ATTENTION!

Aknowledgements:
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