Istituto Nazionale di Fisica Nucleare

X-band linac and TEX facility

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(INFN-LNF)

SUMMARY

1. *TDR X BAND LINAC: STATUS*
2. *TEX FACILITY UPDATE*
3. *NEXT STEPS*

7th EuPRAXIA@SPARC_LAB TDR Review Committee, 26–28 June 2024

TDR X BAND LINAC: STATUS

1.2 X band RF module

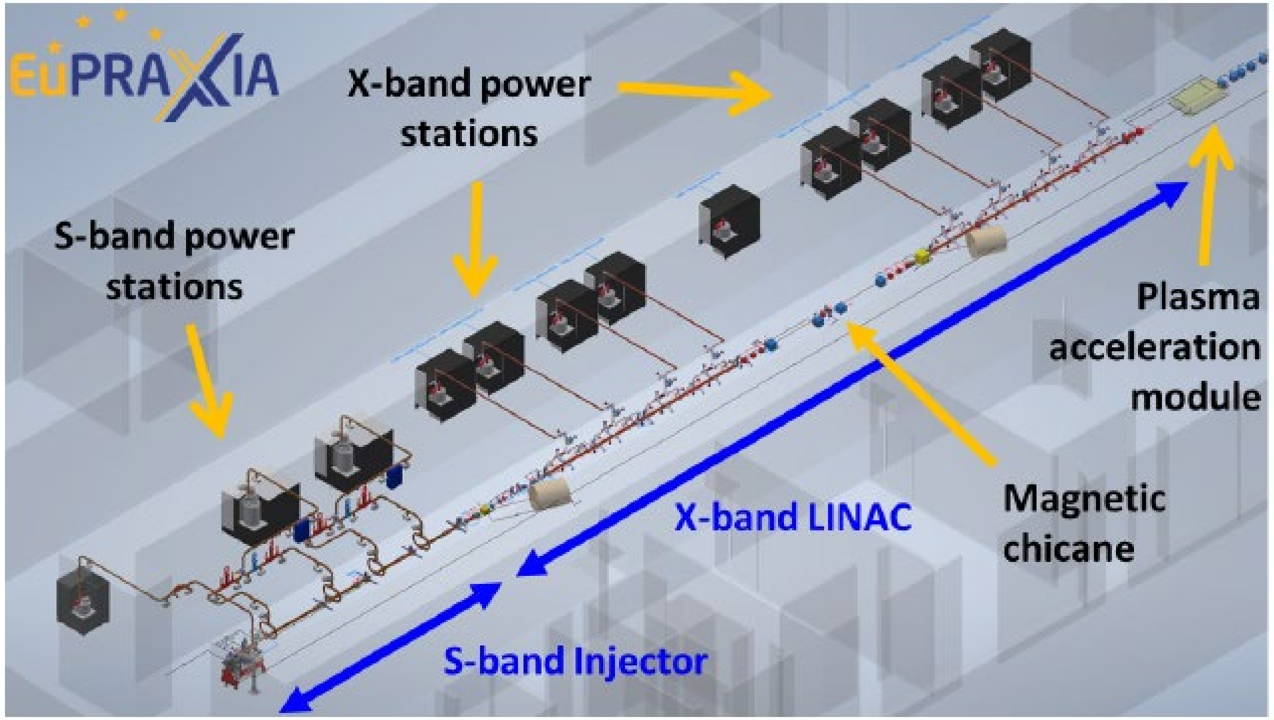

Figure 1.1: X band linac layout.

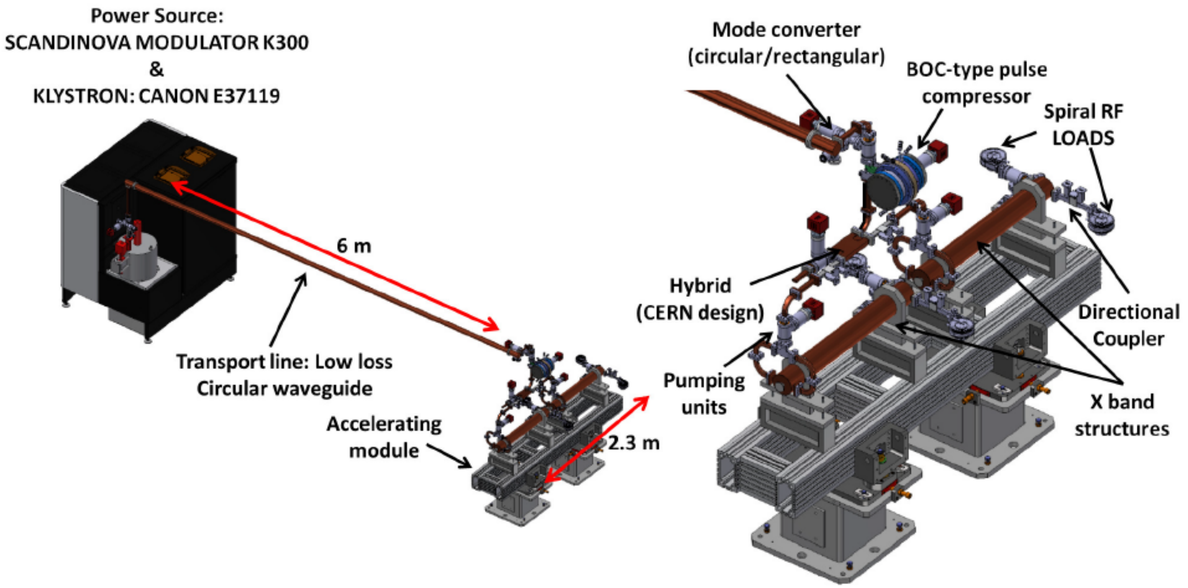

Figure 1.2: X band RF module mechanical layout.

The mechanical layout of the RF module is reported in Fig.1.2 while its schematic layout is given in Fig. 1.3. It includes a 25 MW RF power source (implemented by a Scandinova modulator K300 combined with a Canon klystron E37119, as described in par.1.6), that is connected to a RF pulse compressor of the BOC type through a low loss ≈ 6 meters long circular waveguide.

The module integrates several waveguide components such as pumping units, directional couplers to meaure the forward and refected powers, splitters for a symmetric feeding of the structures, spiral RF loads at the end of the structures to dissipate the residual power out from the TW sections. The

1.2 X band RF module

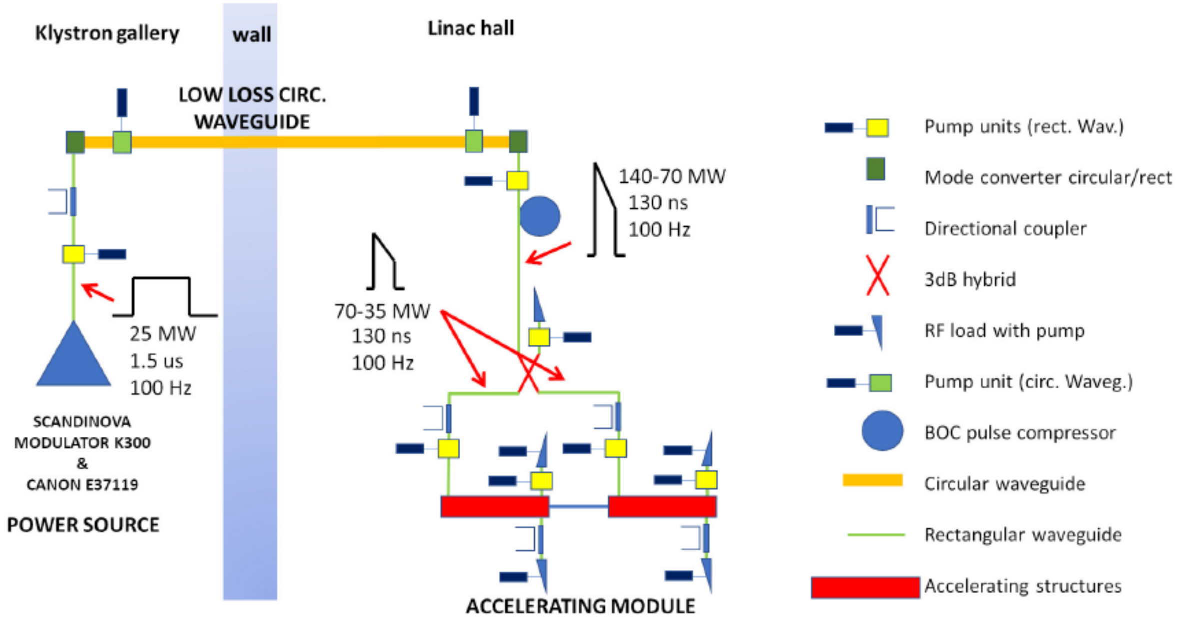

Figure 1.3: X band RF module schematic layout.

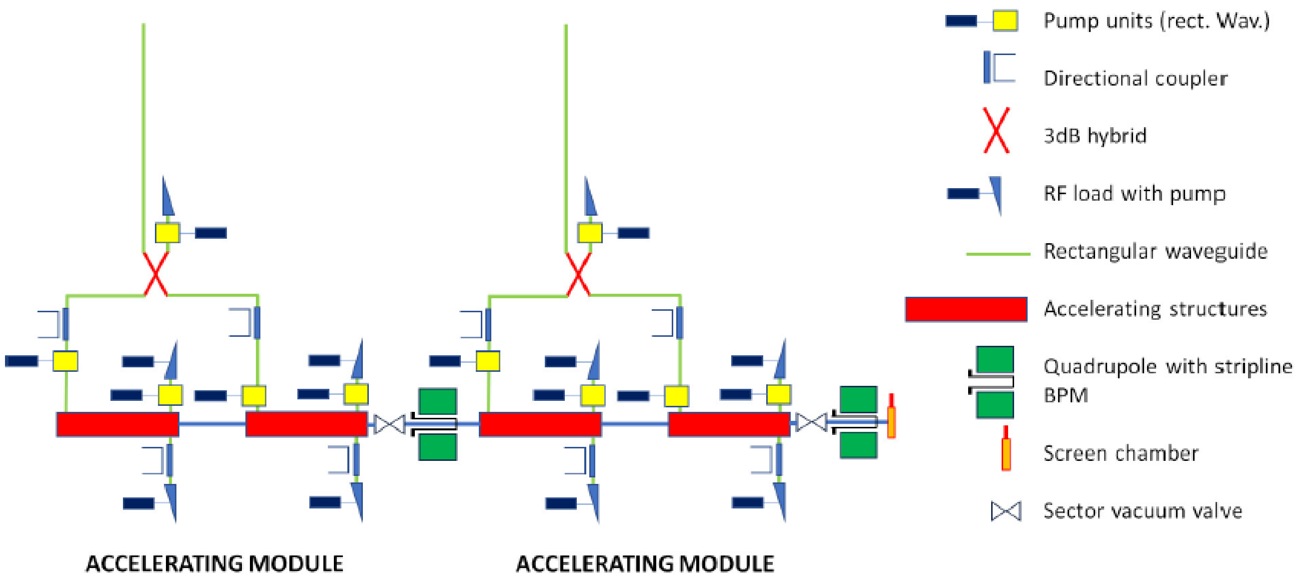

Figure 1.4: Schematic layout of two consecutive modules.

RF loads at the end of the structures to dissipate the residual power out from the TW sections. The schematic layout of two consecutive modules is reported in Fig. 1.4. Between the modules we have a quadrupole with an embedded stripline as described in par. [magnet paragraph and diagnostic paragraph] and every two modules we have a screen chamber as described in par. [diagnostic paragraph]

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1.3 X band TW structures

1.3.1 Electromagnetic design

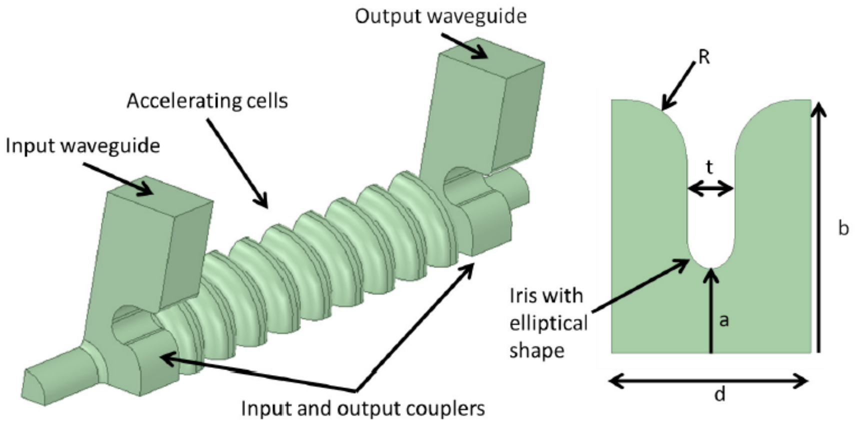


Figure 1.5: HFSS model of the X band accelerating structure (reduced number of cells)

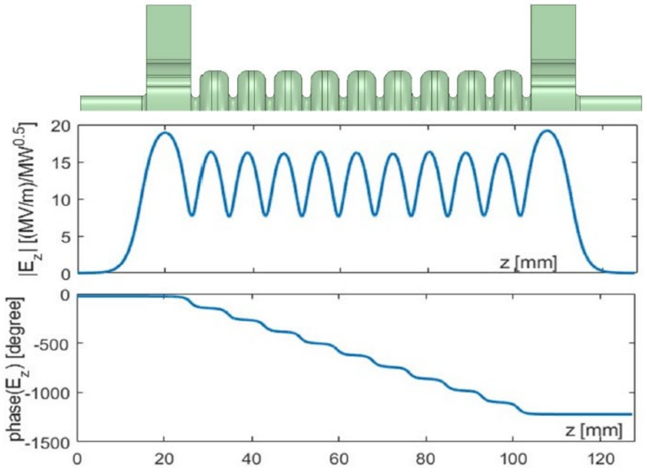


Figure 1.6: Amplitude and phase of the accelerating field along the structure (ANSYS-HFSS simulation result with a reduced number of cells)

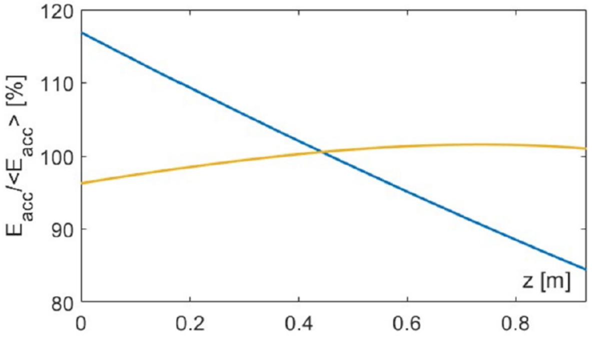


Figure 1.7: Accelerating field sampled by the bunch in case of constant impedance (blue curve) and tapered irises (green curve) structures

Accelerating structures parameter	Symbol	Unit	Value
Frequency	f_{RF}	GHz	11.9942
Average accelerating field	E_{acc}	MV/m	60
Iris radius (linear tapered)	a	mm	3.85-3.15 (3.5)
Structure active length	L_s	m	0.94
Number of cells	N_{cell}		112
Shunt impedance per unit length	R	$M\Omega/m$	93-107 (100)
Effective shunt impedance per unit length	R_s	$M\Omega/m$	350 (347)
Peak input power per structure	P_{peak}	MW	70
Input power per structure averaged over the pulse	P_{in}	MW	51
P_{out}/P_{in}		%	25
Filling time	τ_F	ns	130
Peak mod. Poynting Vector	S_c	$W/\mu m^2$	3.6 (4.3)
Peak Surf. E field	E_P	MV/m	160 (190)
Quality factor	Q		6400
Phase advance per cell	ϕ		$2\pi/3$
Repetition rate	f_{rep}	Hz	100

Table 1.1: parameters of the EuPRAXIA@SPARC_LAB accelerating structures (in parenthesis the value in the case of a constant impedance structure).

The electromagnetic (e.m.) design of the cells and couplers has been performed using the 3D e.m. code ANSYS Electronics Desktop [5] and the final simulated model is given in Fig. 1.5. An elliptical shape of the irises has been considered in the single cell profile to minimize the modified Poynting vector and surface peak electric. The average radius of the cells has been fixed, according to beam dynamics simulations and beam break-up limits, to a value of 3.5 mm, while the overhall iris radii have a linear tapering along the structure that has been optimized to maximize the effective shunt impedance [2]. The input and output couplers have a symmetric dual feeding and a racetrack

1.3 X band TW structures

1.3.2 Thermo-mechanical design

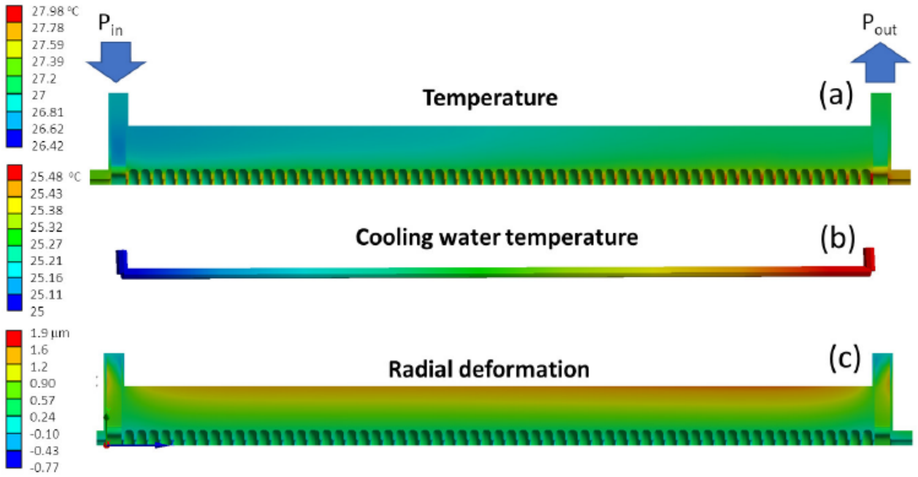


Figure 1.9: Results of the thermo-mechanical analysis performed by ANSYS (model with a reduced number of cells)

mechanical analysis in ANSYS workbench [5]. Each structure requires a total flow rate of 16 liter/minute while the working temperature of each structure has been fixed to 25 C. The calculated equilibrium temperature at full power is reported in Fig. 1.9. In the same figure we have also reported the mechanical radial deformations. The increase in temperature under powering detunes the structure and we have calculated that, to compensate this temperature increase the input water temperature has to be reduced by 2 C. The temperature stability required for the water is ±0.05C.

1.3.4 Prototyping activity

Several prototypes of the X band accelerating structure have been fabricated. The performed activities are illustrated in [8] and have been oriented to demonstrate the feasibility of the proposed scheme.

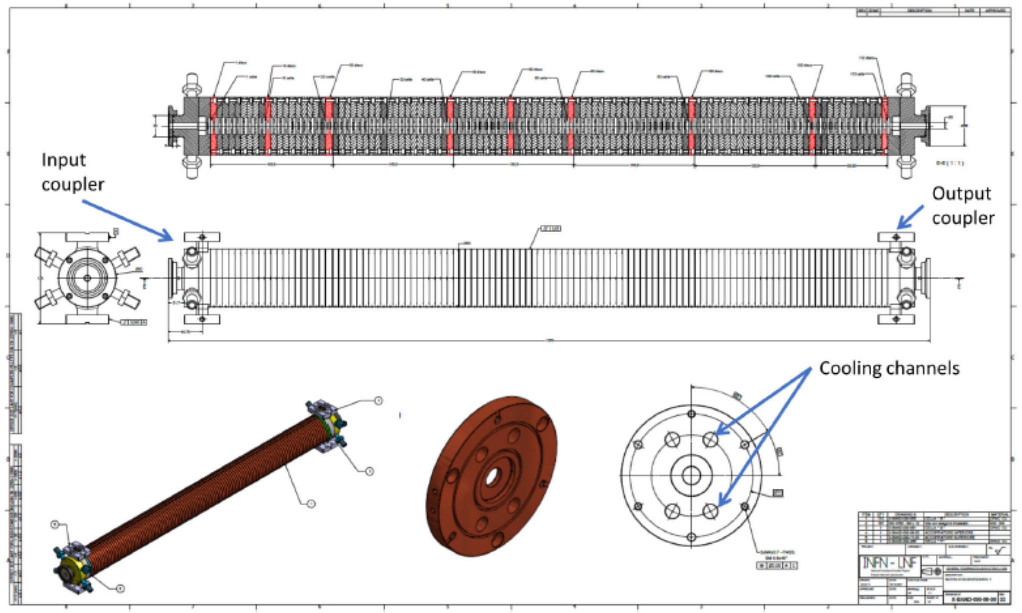
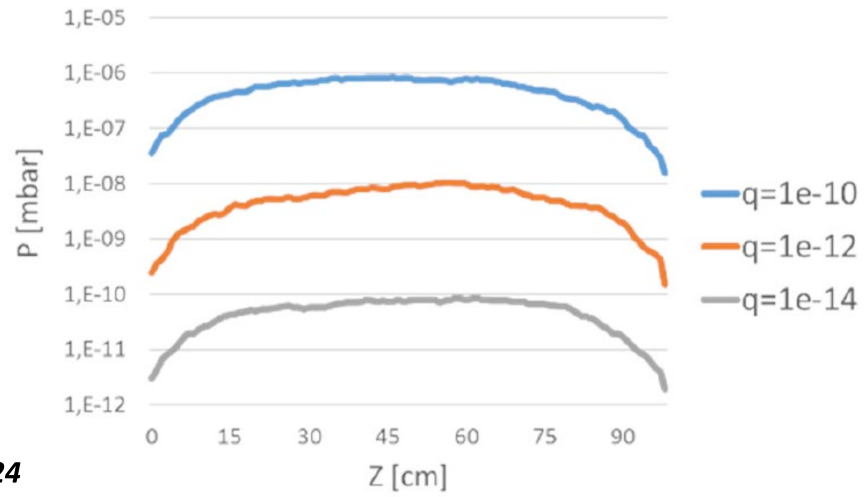


Figure 1.8: Mechanical drawing of the X band structure

1.3.3 Vacuum



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1.4 X band waveguide components

The waveguide standard we adopted is WR284 and the RF module integrate several different waveguide components. Many of them are based on design developped at CERN [9] while, for the others, we have not found an already developed or available commercial solution and they have been designed by INFN. All the waveguide components have been (or will be) tested at their nominal power in the INFN-LNF TEX Facility [10, 11]. Fig.1.11 shows some of them under test. For all the waveguide components we have adopetd the International Vacuum Flange given in Fig. 1.12. Below we report the complete list of these components:

- circular to rectangular waveguide mode converter (INFN design based on [12], shown in Fig. 1.13);
- circular waveguide pumping unit (INFN design, shown in Fig. 1.13);
- 3dB hybrid (CERN design, shown in Fig. 1.14);
- 60 dB directional couplers (CERN design, shown in Fig. 1.14);
- pumping units (CERN design, shown in Fig. 1.14);
- power divider (CERN design, shown in Fig. 1.14);
- spiral loads (CERN design);

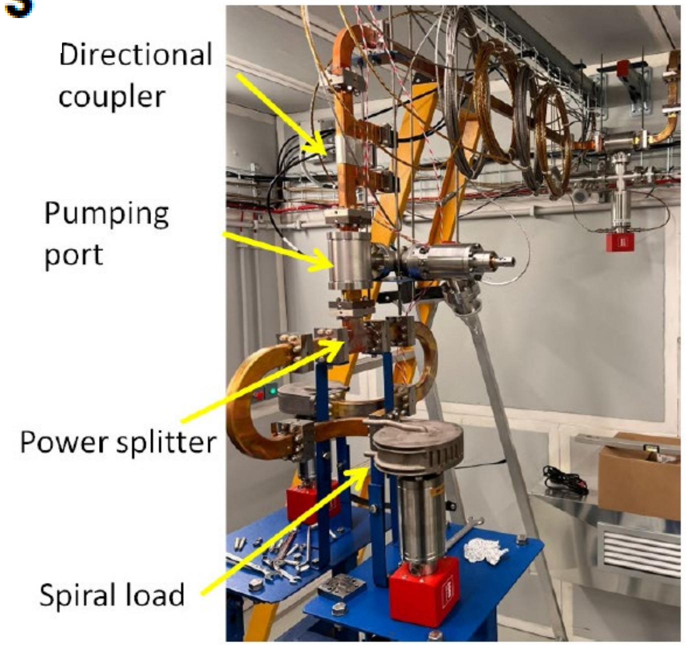

Figure 1.11: X band components under test at the LNF TEX test facility

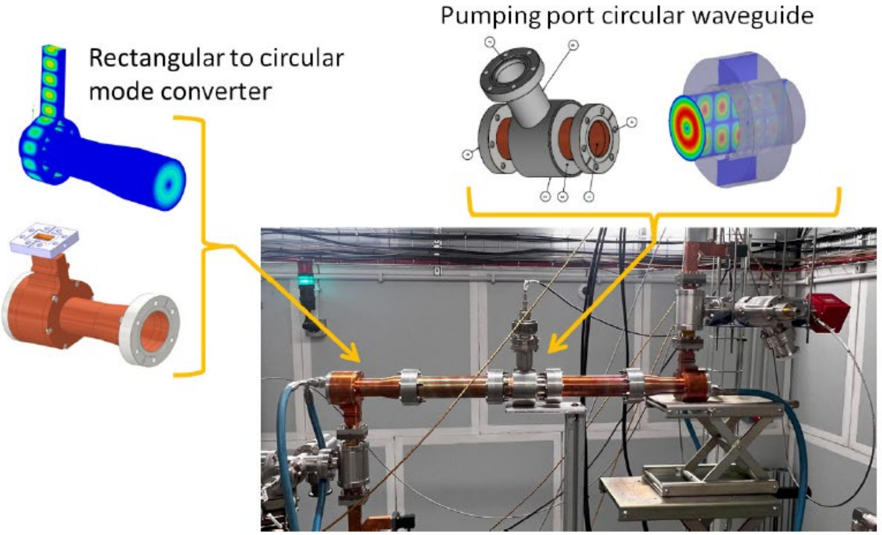

Figure 1.13: Rectangular to circular mode converter, pumping units and circular waveguide installed in the TEX facility

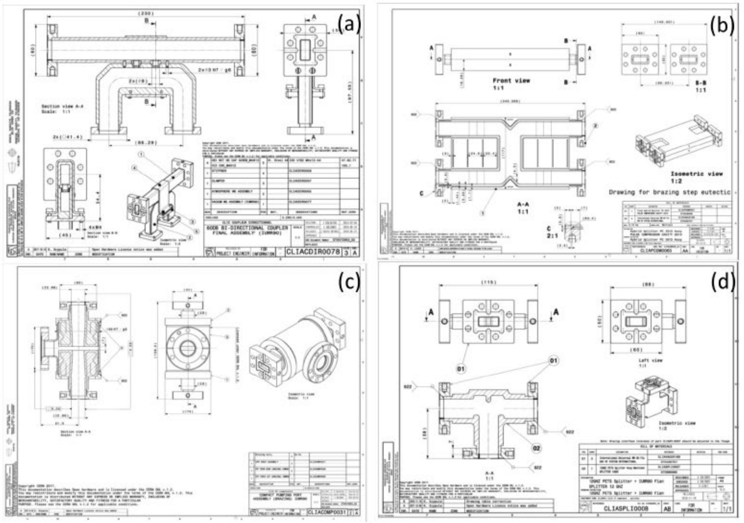

Figure 1.14: Mechanical design of the X band components adopted in the waveguide distribution of the X band linac (CERN design and open source repository)

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1.5 BOC pulse compressor

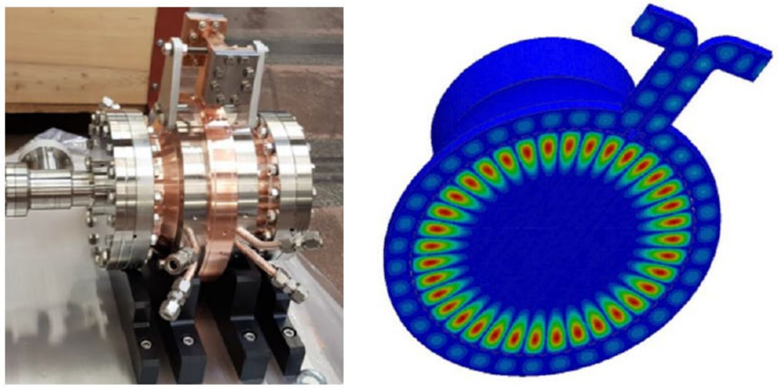

Figure 1.15: picture of the X band BOC (left); electromagnetic field configuration of the BOC operating mode $TM_{18,1,1}$ [**ref_BOC**]

Parameter	Value
Type	Barrel Open Cavity
Frequency	11.9942 GHz
Resonant Mode	$TM_{18,1,1}$
Q_0	150000
Coupling factor β	7.1

Table 1.2: parameters of the BOC-type pulse compressor.

1.6 RF Power source

The X-band power source is based on klystron Canon E37119 and Scandinova K300 modulator, capable of generating 1.5 μs RF pulses of 25 MW with a repetition rate up to 400 Hz (the baseline for the X band linac is 100 Hz). The linac foreseeen eight power sources that feed pairs of structures as illustrated in 1.2. The picture of the power station installed in the TEX facility is given in 1.10. The main klystron and modulator parameters are given in Table 1.3 and 1.4. The input driver will

Parameter	Unit	Value
Frequency	GHz	11.9942
Beam Voltage (V_k)	kV	318
Cathode current (I_k)	A	197
Peak RF output Power	MW	25
Average RF output power	kW	15
RF pulse length	µs	1.5
Repetition rate	Hz	400
Gain	dB	51
Efficiency	%	40
Preveance	μP	1.16

Table 1.3: Parameters of the X band Canon klystron E37119

Parameter	Unit	Value
Peak power	MW	78.2
Average Power	kW	94.4
Voltage range	kV	0-340
Current range	A	0-230
Repetition rate	Hz	0-400
Top Flatness	±% s	1.0
Pulse to pulse stability rms (max)	ppm	20
Rate of rise	kV/µs	<306
Rate of fall	kV/µs	<303
Trig delay	µs	≈ 1.2
Pulse to pulse time jitter	ns	$< \pm 4$
Pulse width time jitter	ns	$< \pm 8$

Table 1.4: Parameters of the k300 Scandinova Modulator

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1.7 Quadrupole and Diagnostics inter-modules

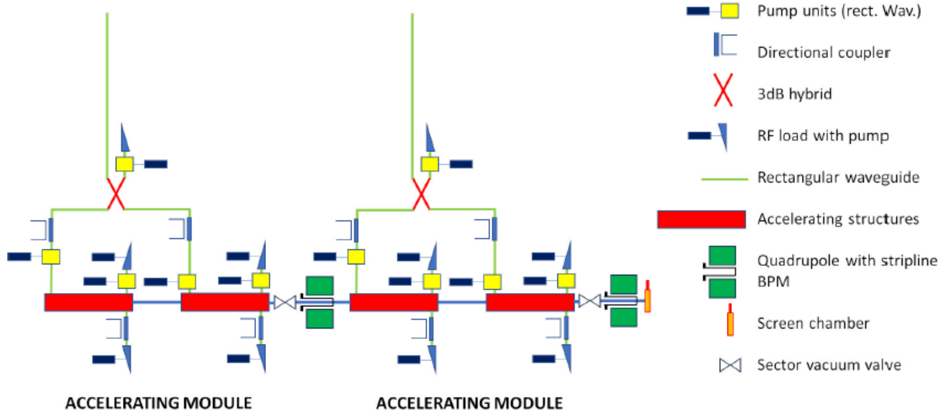


Figure 1.4: Schematic layout of two consecutive modules.

1.8 Supports

All the components of the X band module will be supported by the girder shown in Fig. 1.16. The girder is made of iron and equipped with precise rectified rails to host the X band structures. The

four pedestals allow a precise regulation of the height and tilt of the overall module with a precision of better than 0.05 mm in all directions. The detail of the support of the X band structure is given in Fig. 1.17. This support is made of a rectified "V" shaped granite support detailed in Fig. 1.18 that allows to maintain the straightness of the accelerating structure at the level of $\pm 30\mu m$. This granite support is fixed to an aluminum plate that allow a regulation with a precision better than 0.05 mm in all directions.

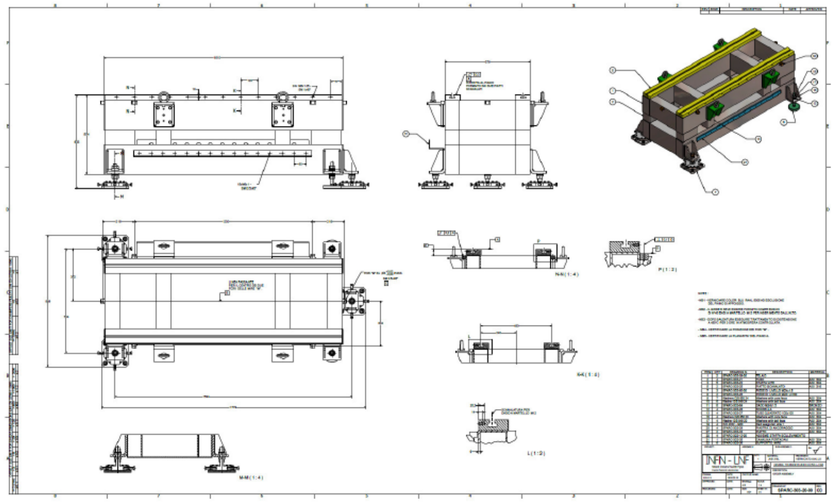


Figure 1.16: girder of the X band module supporting the two X band structures and components

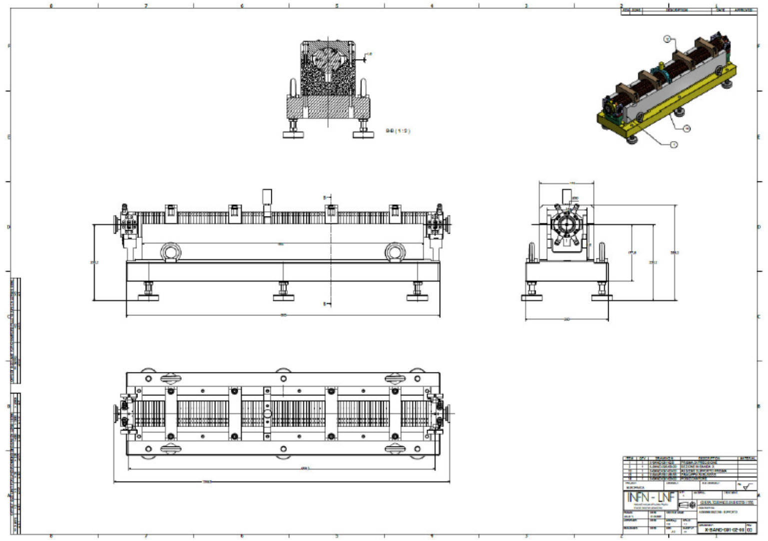
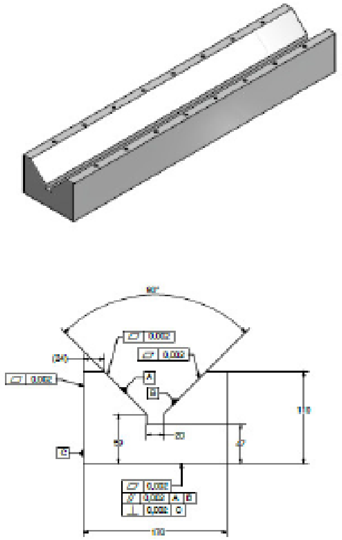


Figure 1.17: support of the X band structure



TEX FACILITY NOW AND UPGRADE

UP TO MAY 24

⇒ 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

⇒ **Currently undergoing an upgrade** with the installation of two new high repetition rate RF sources: a new X-band RF power source and a new C-band RF power source for the test of RF components and a C-band photoinjector.

⇒ These two sources (modulator + klystron) **have been tested at factory** at end of May 2024 (at Scandinova) in diode mode at full power.

⇒ **Have been shipped at the beginning of June**, positioned, and the klystrons installed. The entire waveguide system is also currently being delivered.

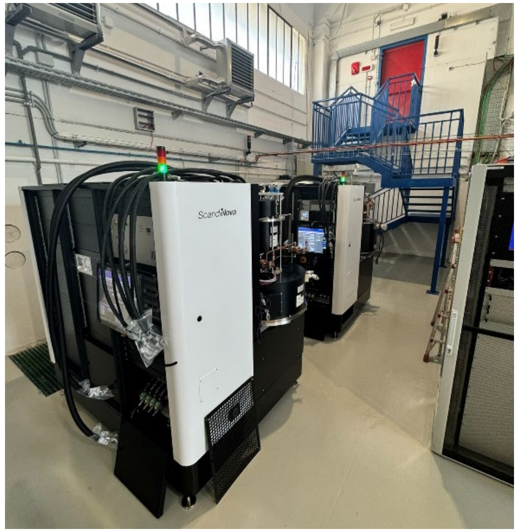
⇒ The **commissioning** of these sources and the waveguide networks is scheduled for **January 2025, after the installation of the cooling and power systems** that will serve these sources.

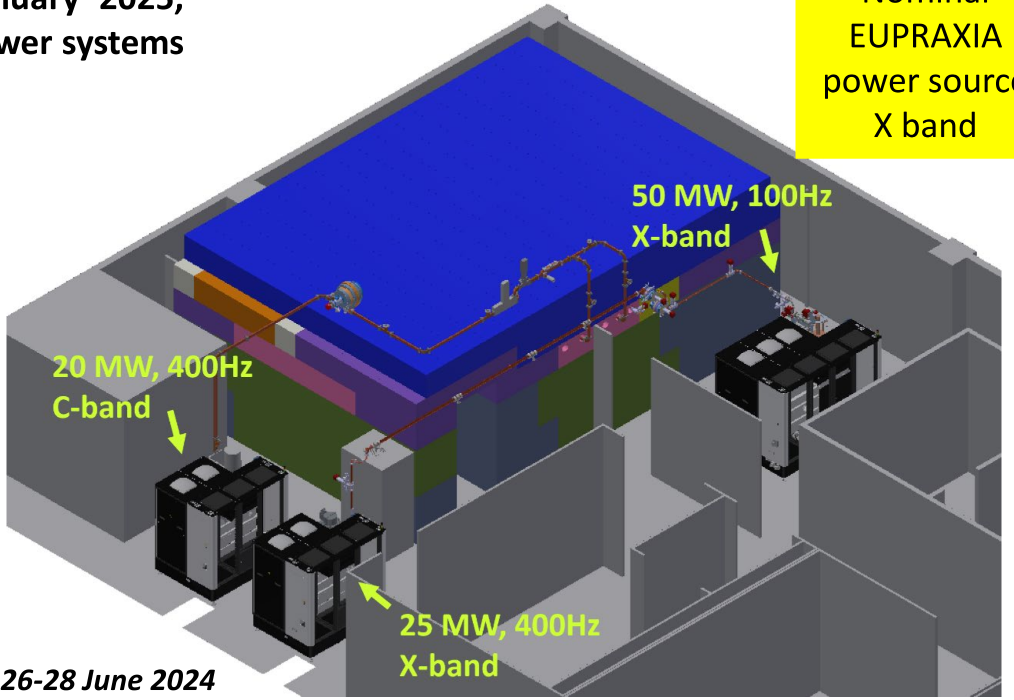
Parameter	Unit	Canon E37217	Canon E37119
Frequency	MHz	5712	11994
Peak RF output Power	MW	20	25
Average RF output power	kW	21	15
Modulator Average power	kW	75,2	75,2
RF pulse length	us	2.5	1.5
Repetition Rate	Hz	400	400
Gain	dB	50	47
Efficiency	%	40	40

Nominal EUPRAXIA power source X band

K400 Scandinova

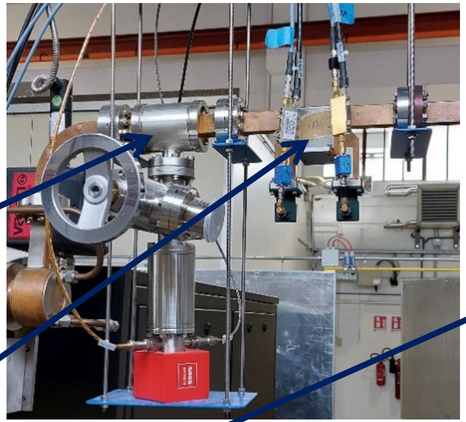
CPI VKX8311A Klystron (50 MW, 50Hz)



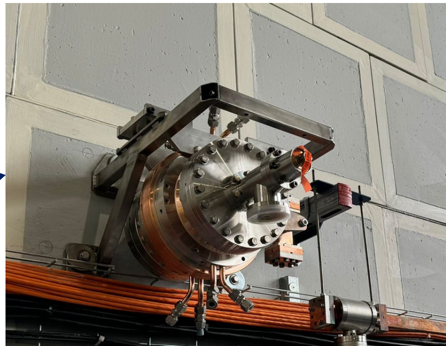


X-BAND WAVEGUIDE COMPONENTS

COMPONENT	DESIGN BY	STATUS	LEVEL OF POWER TO BE TESTED FOR EUPRAXIA MODULE	COMMENTS
Pump units (rect. Wav.)	CERN	Fabricated and installed @ TEX	25 MW 1.5 µs and 70-35 MW 0.13 µs Compressed pulse 100 Hz	Tested up to now to 1 µs, 50 Hz, 33 MW
Directional coupler	CERN	Fabricated and installed @ TEX	25 MW 1.5 µs and 70-35 MW 0.13 µs compressed pulse 100 Hz	Tested up to now to 1 µs, 50 Hz, 33 MW
Splitter	CERN	Fabricated and installed @ TEX	70-35 MW, 0.13 µs Compressed pulse 100 Hz	Tested up to now to 0.6 µs, 50 Hz, 33 MW
RF load	CERN	Fabricated and installed @ TEX	18-9 MW 0.13 µs compressed pulse 100 Hz	Tested up to 0.6 µs, 50 Hz, 16 MW.
Mode converter circular/rectangular	INFN	Fabricated and Installed @ TEX	25 MW 1.5 µs 100 Hz	Tested up 1 µs, 50 Hz, 25 MW
Pump unit (circ. Waveg.)	INFN	Fabricated and Installed @ TEX	25 MW 1.5 µs 100 Hz	Tested up to now to 1 µs, 50 Hz, 25 MW
3dB hybrid	CERN	Delivered	140-70 MW 0.13 µs Compressed pulse 100 Hz	
BOC pulse compressor	PSI	Delivered	140-70 MW 0.13 µs Compressed pulse 100 Hz	



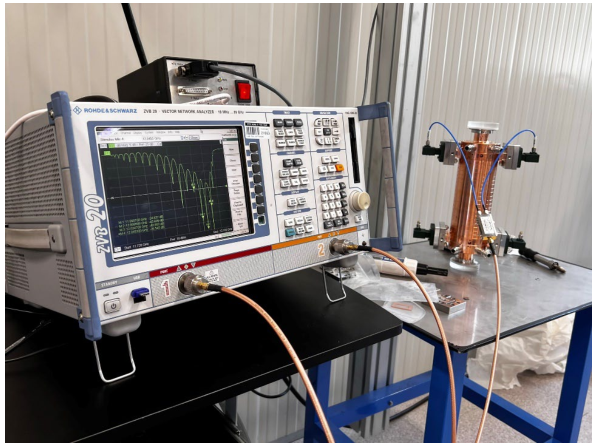


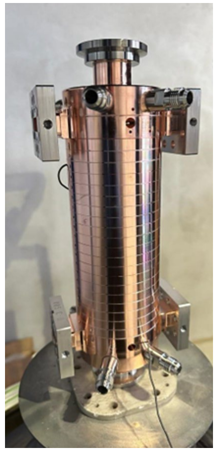


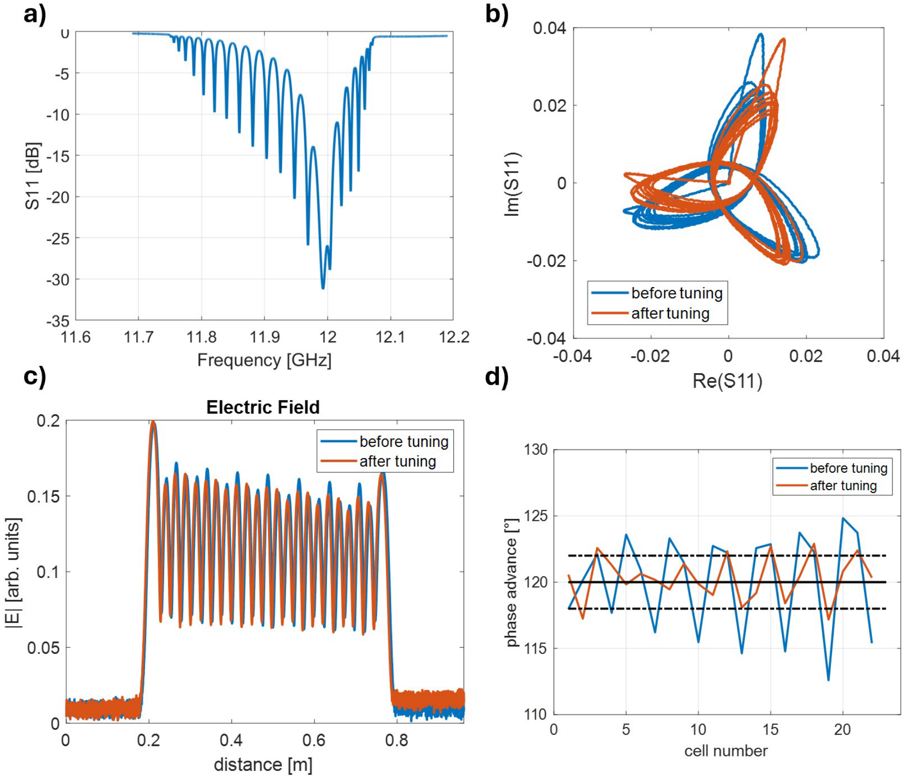
EUPRAXIA X-BAND STRUCTURE RF PROTOTYPE

⇒ A **20 cells RF prototype** has been realized for the high power test.

⇒ It has been realized **without tuners** on the cells, we just have two tuners on the two couplers

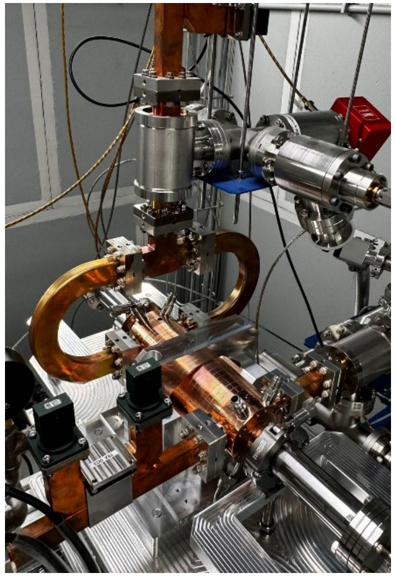


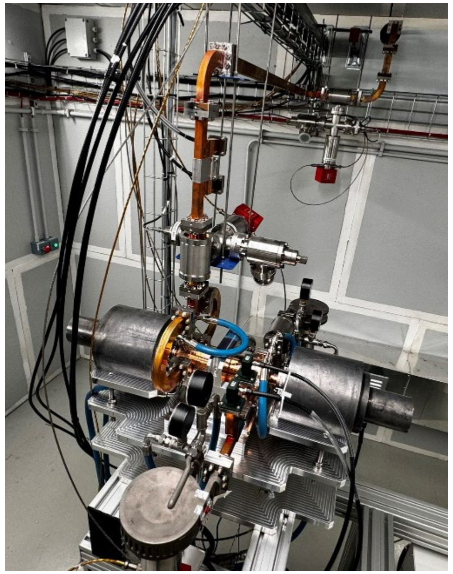


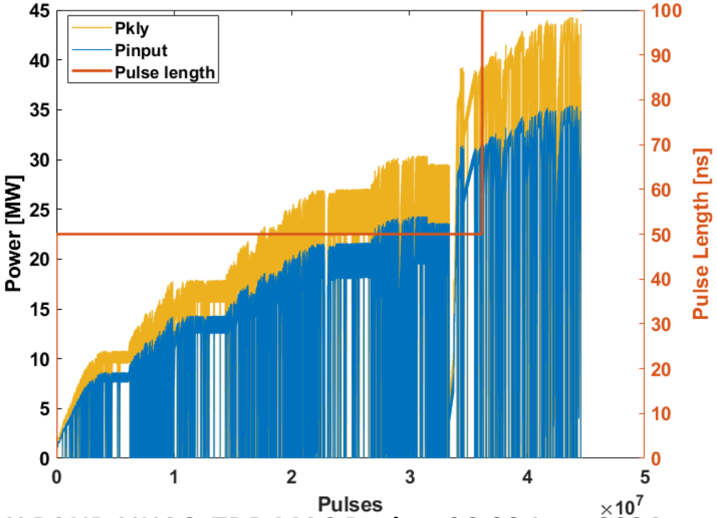


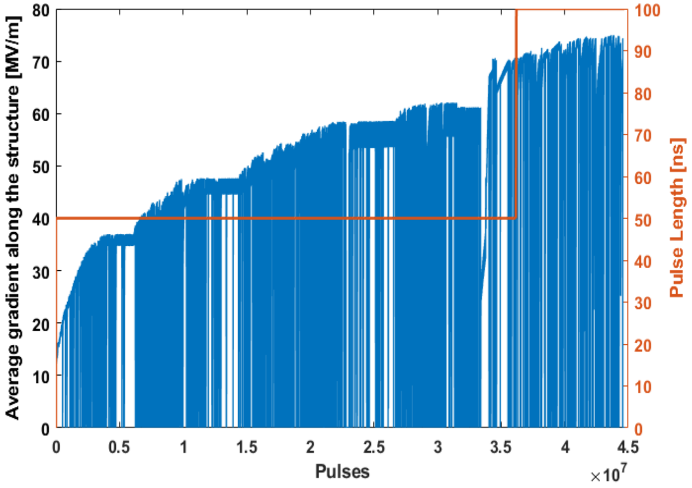
⇒ **In 10 days we reach an input pulse of 35 MW**, 100 ns length at 50 Hz repetition rate, that correspond to an average gradient along the structure equal to **74 MV/m** and a peak gradient at the structure input of 80 MV/m.

⇒ The test will continue, after an initial phase of installations for the TEX upgrade, with the BOC pulse compressor also installed on the line.









EUPRAXIA X-BAND STRUCTURE RF PROTOTYPE

X-BAND LLRF ACTIVITIES

Courtesy RF group

[1] L. Piersanti et al. "RF power station stabilization techniques and measurements at LNF" In Proc. IPAC24 - TUPR01.
[2] L. Piersanti et al. "Design and test of a klystron intra-pulse phase feedback system for electron linear accelerators" Photonics 2024, 11(5), 413.

Requirements phase jitter (compliant with BD requirements):

- 0.02 deg S band (S-band RF stability state of the art (PSI))
- 0.06 deg X band

⇒ **Scientific collaboration** request with PSI for LLRF system development, update and production declined due to **lack of manpower**;

⇒ **We cannot develop the system in house** because of the complexity, dimension, maintenance for a user facility.

⇒ **2 industrial partners** willing to participate to X-band LLRF R&D (Instrumentation Technologies - solid LLRF experience, Safran - new to high frequency applications);

⇒ The **internal procedures** for the tender for the production of the whole LLRF system should **start by the end of 2024**;

⇒ Detailed **jitter studies on X-band power station carried out at TEX facility in February 2024** [1] (no klystron loop):

1. Driver added jitter: <0.04 deg rms
2. Klystron added jitter: <0.04 deg rms
3. LLRF added jitter (tender spec.): <0.015 deg rms
4. **Estimated RF station jitter: <0.06 deg rms**

⇒ **Dedicated stability measurements** will be carried out at SPARC in S band after the SABINA upgrade.

⇒ We believe also that **with solid state modulator and klystron loops** we can have an additional jitter reduction from new fast intra-pulse phase feedback system [2] to be evaluated for S-band and X-band stations at SPARC and TEX respectively.

⇒ **Jitter compression down to 0.019 deg rms already demonstrated for C-band** station at SPARC in Dec 2023.

Figure 4. TEX LLRF rack.

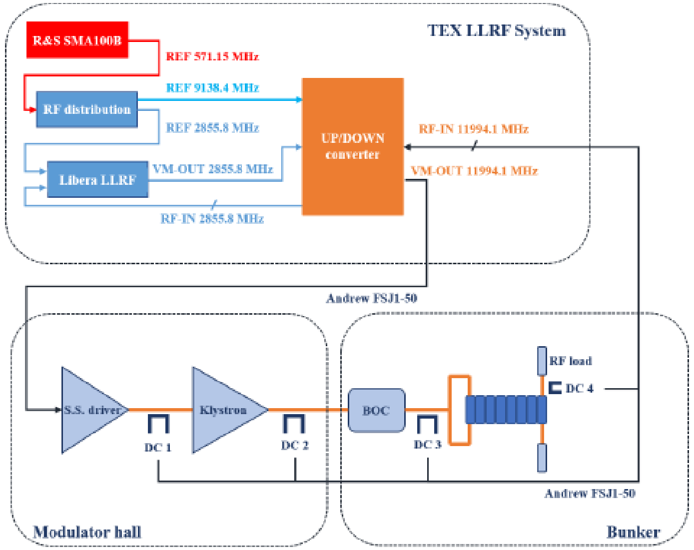


Figure 3: TEX facility RF block diagram.

X BAND LINAC: NEXT STEPS AND CONCLUSIONS

R&D ACTIVITY AND TEST

Test of the 20 cell X RF prototype with BOC (depending on Safety/radioprotection authorizations)

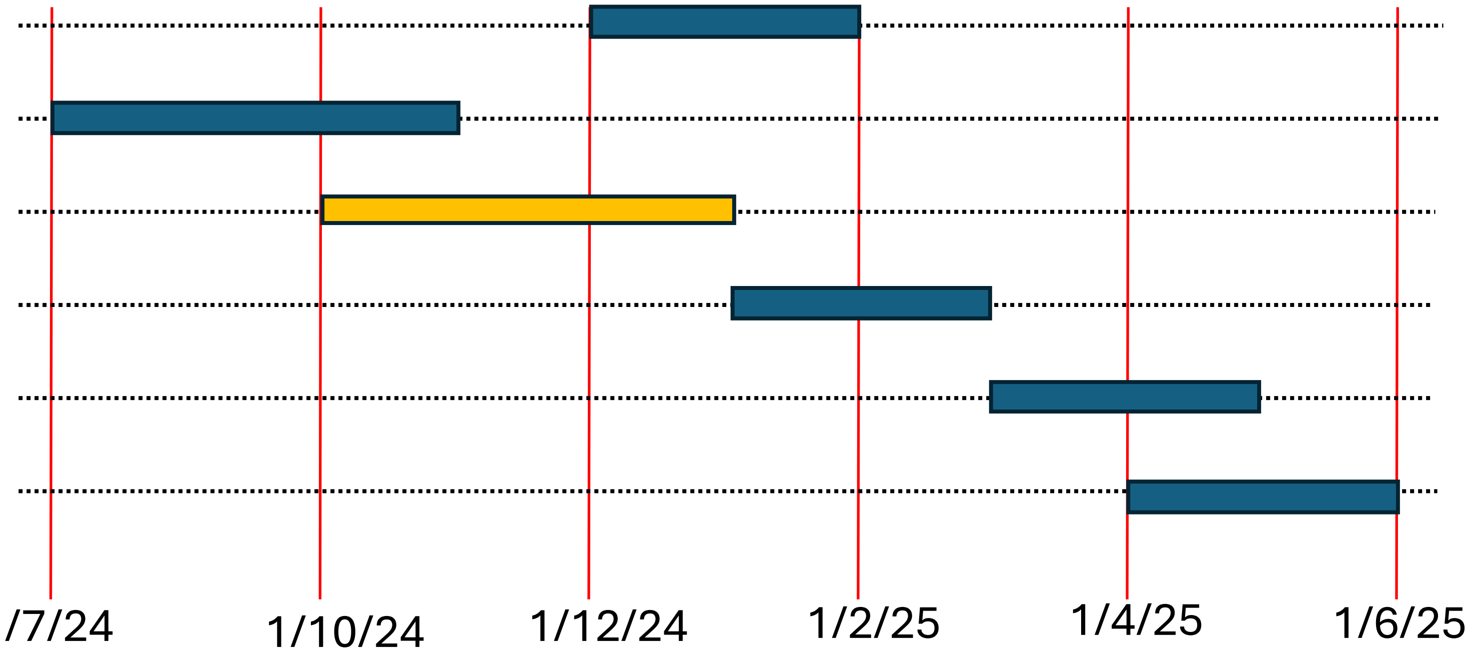
Realization of the full scale RF prototype (CI)

Cooling/power works@ TEX

X-band power sources (25 MW CANON) and new WG networks commissioning

Test of the full scale RF prototype

Test of the 3dB Hybrid in combination with RF structure and BOC



TDR WRITING

⇒ LLRF paragraph: short recap of the RF system Chapter: October 2024
⇒ X band structure support final definition: October 2024
⇒ Quadrupole/stripline within RF modules

Aknowledgements:

INFN-LNF: *F. Cardelli, S. Pioli, S. Bini, B. Buonomo, S. Cantarella, R. Clementi, M. Diomede, L. Faillace, A. Gallo, L. Giuliano, C. Di Giulio, E. Di Pasquale, G. Di Raddo, R. Di Raddo, G. Latini, A. Liedl, L. Spallino, V. Lollo, L. Piersanti, M. Bellaveglia, R. Ricci, B. Serenellini, M. Zottola, P. Chimenti, B. Spataro, M. Cianfrini, G. Luminati, G. Catuscelli, A. Iungo, A. Esposito, F. Chiarelli, R. Donghia, D. Chiti, M. Ferrario*

CERN: *W. Wuensh, N. Catalan-Lasheras, A. Grudiev, G. McMonagle on behalf of the CLIC and XBOX group*

SLAC: *V. A. Dolgashev*