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2575 SAND HILL RD, MENLO PARK, CA 94025

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

TEX (TEst stand for X-band) at LNF

Claudio Di Giulio

On behalf TEX team:

Scientific Coordinator: F. Cardelli
Technical Coordinator: S. Pioli
D. Alesini, M. Bellaveglia, S. Bini, B. Buonomo, S. Cantarella, G. Catuscelli, M. Ceccarelli, R. Ceccarelli, M. Cianfrini, R. Clementi, E. Di Pasquale, G. Di Raddo, R. Di Raddo, A. Falone , L. Faillace, G. Franzini, A. Gallo, A. Liedl, V. Lollo, G. Piermarini, L. Piersanti, S. Pioli, S. Quaglia, L. A. Rossi, L. Sabbatini, G. Scarselletta, M. Scampati, S. Tocci, R. Zarlenga
With the support of all the LNF Divisions and Services

(National Institute of Nuclear Physics, INFN-LNF, Via Enrico Fermi 54 00044 Frascati, Italy)

Outline

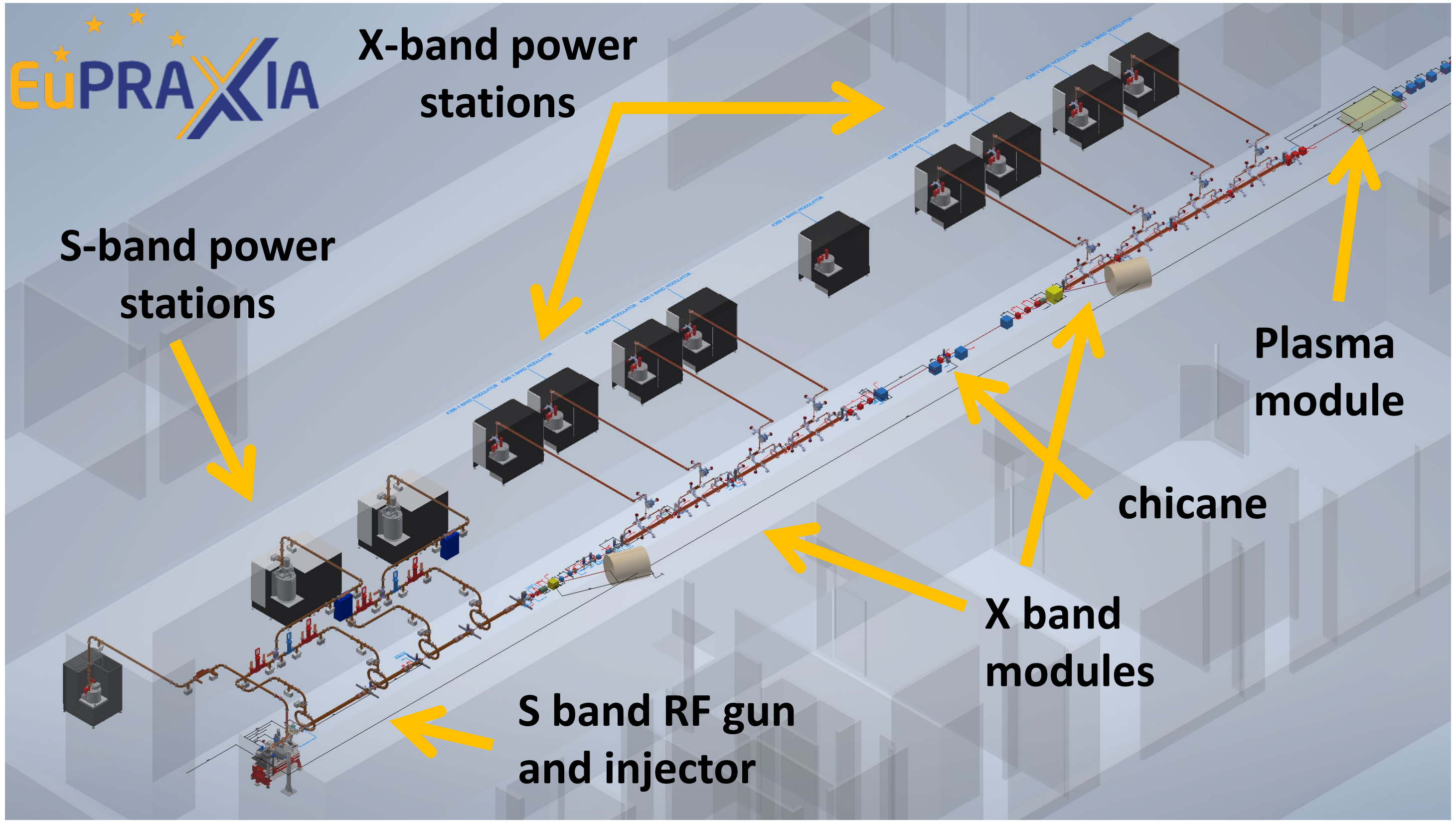
I. **EuPRAXIA@SPARC_LAB project and linac**
II. **TEst stand for X-band**
III. **TEX facility components:**
    a. The RF Source
    b. The LLRF system
    c. The Control system
    d. The building refurbishment
    e. The Safety System
    f. The Vacuum System
    g. The Fluids System
IV. **Conditioning of waveguides and loads**
V. **Current TEX Layout**
VI. **Future TEX Layout**
VII. **Conclusions**

EupraXia@SPARC_LAB project and linac

- The project EuPRAXIA@SPARC_LAB aims at constructing a **FEL radiation source** based on **RF LINear ACcelerator combined with a plasma module** [1,2]
- The project is in a **preparatory phase of the TDR** for this machine
- The project is one of the pillar of the **European Project EUPRAXIA** (coord. R. Assmann, http://www.eupraxia-project.eu/) that has **been included in the ESFRI 2021 Roadmap**
- A **new building**, now under executive design phase will host the new Facility at **LNF**

Overview of the RF LINAC DESIGN

- The RF baseline of the LINAC is the **X-band technology,** and it will be used to produce high brightness electron beams up to 1 GeV.
- The beam will be either injected in the **FEL undulators** or used to drive a **plasma cell** to boost the energy further before the undulators
- **S-band (2.856 GHz) injector** composed by a photocathode RF Gun and 1x 3m TW S-band structure and 3x 2m TW S-band structures
- **X-band (11.994 GHz) booster** composed by **16x TW, 0.9 m accelerating structures** with a nominal gradient of **60MV/m**



[1] Ferrario et al., NIM A 909, (2018) pp.134-138
[2] D. Alesini et al., "EuPRAXIA@SPARC_LAB Conceptual Design Report", *INFN-18-03/LNF.*

TEst stand for X-band

- To investigate and test the reliability of the X-band technology for the realization of this booster, all the components, from the source to the accelerating sections, must be tested at the nominal power and working conditions.
- As first step in Dec. 2017 an agreement with CERN is signed by INFN.
- Therefore, the first step was to install a copy of the CERN X-band station at LNF
- It was be in LNF building #7, very close to the SPARC_LAB area, formerly used for testing and conditioning of the DAFNE RF power plants and cavities
- The X-band test facility, called TEX [3], has been final commissioned last year (2022) in our laboratory and is currently in operation [4]

THE PARTIES AGREE AS FOLLOWS:

1. Project

The Project comprises activities related to the research, development and application of high-gradient, X-Band linac systems in the framework of the CLIC high-gradient, CLEAR and EUPRAXIA@SPARC_LAB projects as described in Annex I.

The main steps was:

- Decommissioning of the old RF Bunker used to test the DAFNE Cavity
- Design and Commissioning of the new bunker, control room, computing room, storage and auxiliary system (logistics, fluids, safety, radioprotection system…)
- Request to the ALL the Authorities the authorizations.

- Modulator k400 procurement and installation of the klystron and components provided by CERN.
- Install RF other components.

Building #7

SPARC_LAB

[3] S. Pioli et al.,– doi:10.18429/ JACoW-IPAC2021-WEPAB314.
[4] F. Cardelli et al., -doi:10.18429/JACoW-IPAC2022-TUPOPT061

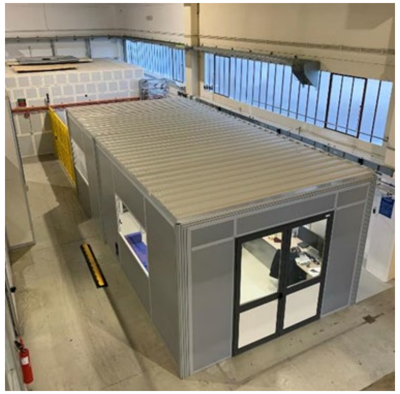
TEX Facility components:

- The **TEst-stand for X-band (TEX)** is 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.**
- **It provide all the challenges to build an accelerator with all the subsystem:**

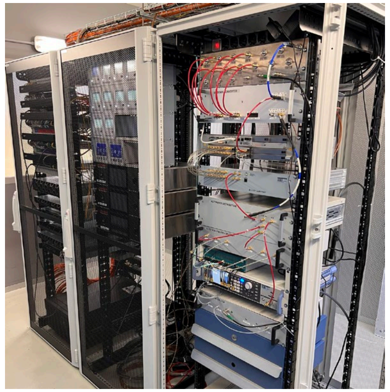
Vacuum system

Safety system

Control system

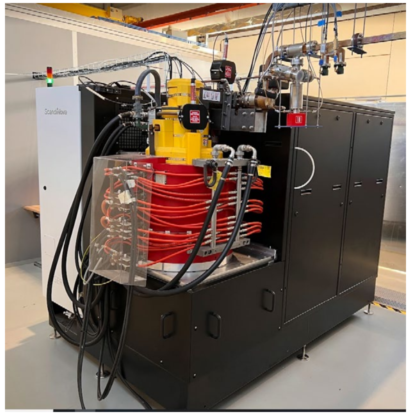


LLRF system



Fluids system

Modulator



Klystron

TEX Facility: the RF source

- The installation and commissioning of the **Modulator and klystron** has been completed in February 2022.
- **The pulse stability is measured at level of 10ppm during the SAT**
- **The klystron curve was verified respect the curve provided by CERN and CPI.**

Pulsed Modulator: to be procured by INFN

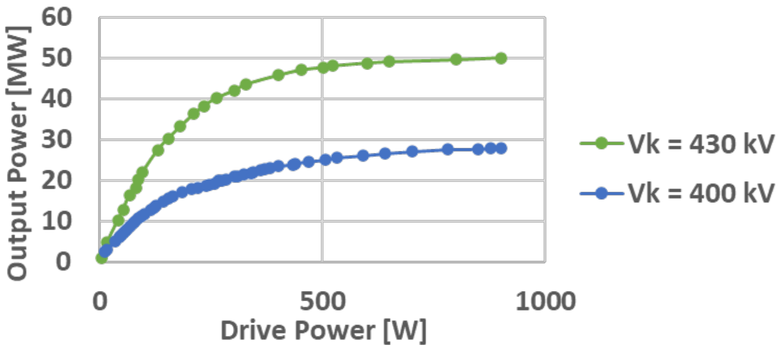
OPERATIONAL PARAMETERS

		Unit	K2-3X	Notes
Pulse Output				
	Peak power to Klystron	MW	150.7	Peak power from Modulator
	Average power to Klystron	kW	17.3	Average power from Modulator
	Klystron Voltage range	kV	450	Nominal 410kV, see fig above
	Klystron Current range	A	335	Nominal 305A, see fig above
	Inverse Klystron Voltage	kV	<30	Reduced by the Solid State technology
	Pulse length	µs	1.5	Top of Klystron Voltage pulse
	Pulse length at 50%	µs	3,4	Of the Voltage Pulse
	RF duty cycle	%	0.0075	
	PRF range	Hz	1 - 50	
	Top flatness (dV)	%	<±0.25	Deviation from nominal voltage within the top of the pulse length
	Amplitude stability	%	<±0.1	
	Trig delay	µs	~1.2	See fig above
	Pulse to pulse jitter	ns	<6	
	Pulse length jitter	ns	<±10	
Filament Output				
	Klystron Max voltage DC	V	30	Nominal 10-30V
	Klystron Max current DC	A	30	Nominal 18-30A
	Kly. Fil. Current stability	%	<±1	
	Pre-heating period	min	60	Filament current is softly ramped to max value during pre-set time

X-band klystron: provided by CERN

Typical Operating Parameters

Item	Value	Units
Beam Voltage	410	kV
Beam Current	310	A
Frequency	11.994	GHz
Peak Power	50	MW
Ave, Power	5	kW
Sat. Gain	48	dB
Efficiency	40	%
Duty	0.009	%



TEX Facility: the LLRF source

- The Low Level RF System The X-band LLRF systems was developed starting by the available on the market S-band system, the Libera LLRF, manufactured by Instrumentation Technologies, whose features and performance have been already reviewed for ELI-NP and SPARC_LAB for a similar architecture[3].
- The systems has been adapted to work at 11.994 GHz by LNF RF team developing:
  - a reference generation and distribution system able to produce coherent 2.856 GHz S-band and 11.994 GHz X-band references;
  - an X-band up/down converter;
  - Promising results have been obtained, with a measured amplitude and phase jitter of the klystron forward output power of 0.04 % and 20.7 fs respectively
  - it does not seem the optimal choice for an X-band based LINAC for various discussed in the reference [3].

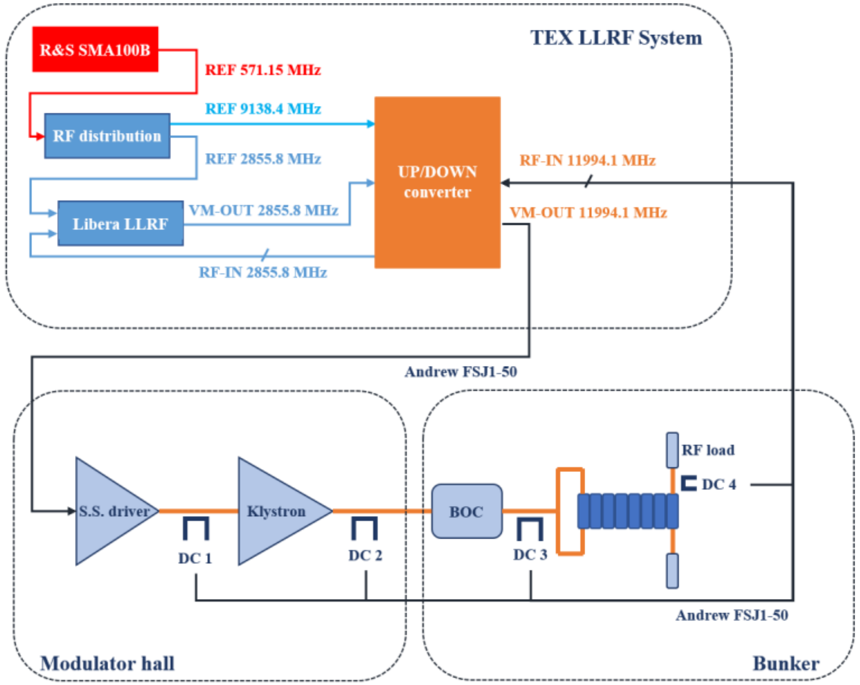


Figure 4. TEX LLRF rack.

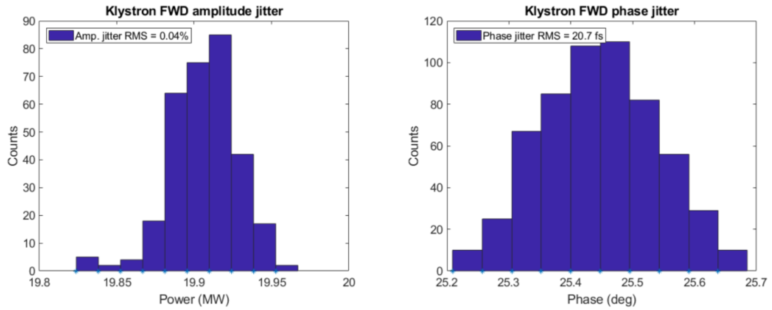


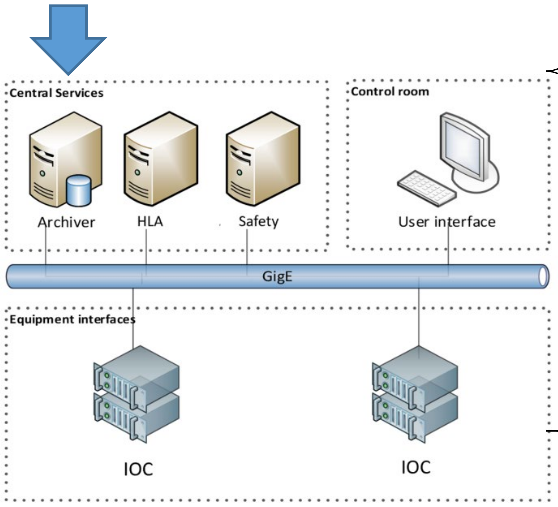
Figure 5. Measured amplitude and phase jitter of klystron output forward power. The measurements refer to 20 MW, 300 ns at 50 Hz repetition rate RF pulses.

[3] L Piersanti *et al* 2023 *J. Phys.: Conf. Ser.* **2420** 012075

TEX Facility: the control system

- TEX has selected a standardized, field-proven controls framework, EPICS, which was originally developed jointly by Argonne and Los Alamos National Laboratories.
- Currently we proceed in the integration of all the hardware equipment present at TEX. IOCs and support modules for any family of device have developed or acquired from repositories, as shown in Table 1.
- An instance of EPICS Archiver Appliance from SLAC to handle the data storage of the facility.
- About User Interfaces (UI) we involved, Table 2, reliable state-of-art graphic interfaces tool to simplify maintenance and improve user experience, Fig. 4 and 5, for TEX operators and users[4].

A SAN for the long-term store - in this storage stage, we store data at a granularity of a month. This stage is physically located at CNAF data center, the INFN European Open Science Cloud (EOSC) pillar of the INFN.



Interface	Solution
Engineering consoles	LabView
Archive Viewer	Grafana [11]
Archiver Data Retrieval	web-based UI
Logbook	ELog
Reference Manual	Confluence
Alarm Notification	Telegram [12]

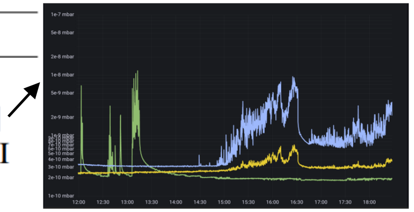
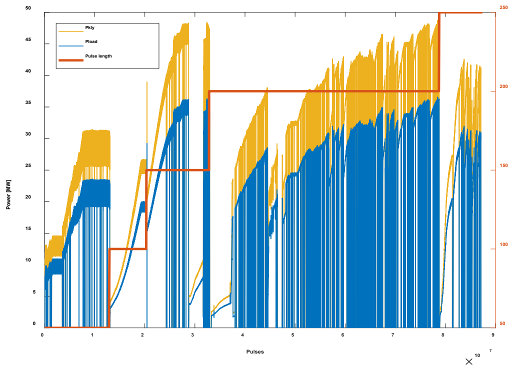


Figure 4: Klystron historical data viewer from Grafana.



Device Family
ScandiNova [6] RF Modulator
LiberaLLRF
Microwave Amps. [7] RF Driver
Pfeiffer Vacuum Gauges
Agilent Vacuum Ion-Pumps
Timing System
RTD sensors
SMC Chiller
Fluid Plant PLC
Faraday Cups
Backhoff Motors
Basler Camera
Magnets
Machine Protection System
Personnel Safety System

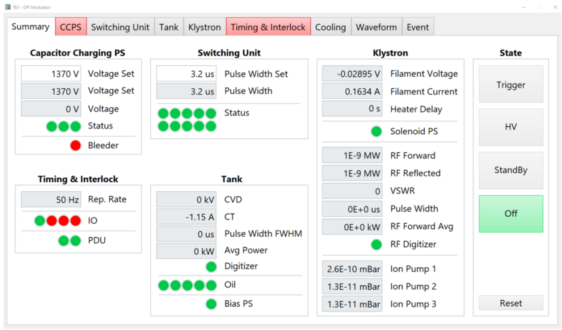
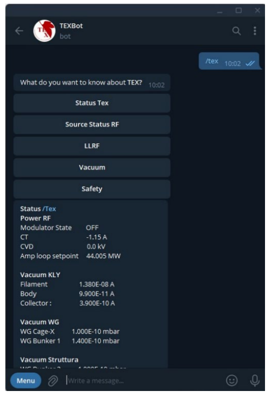


Figure 5: RF Modulator interfaces.



[4] S. Pioli, et al., 13th Int. Particle Accelerator Conf. (IPAC22), Bangkok, Thailand, June 2022, paper MOPOMS047.

TEX Facility: The building refurbishment

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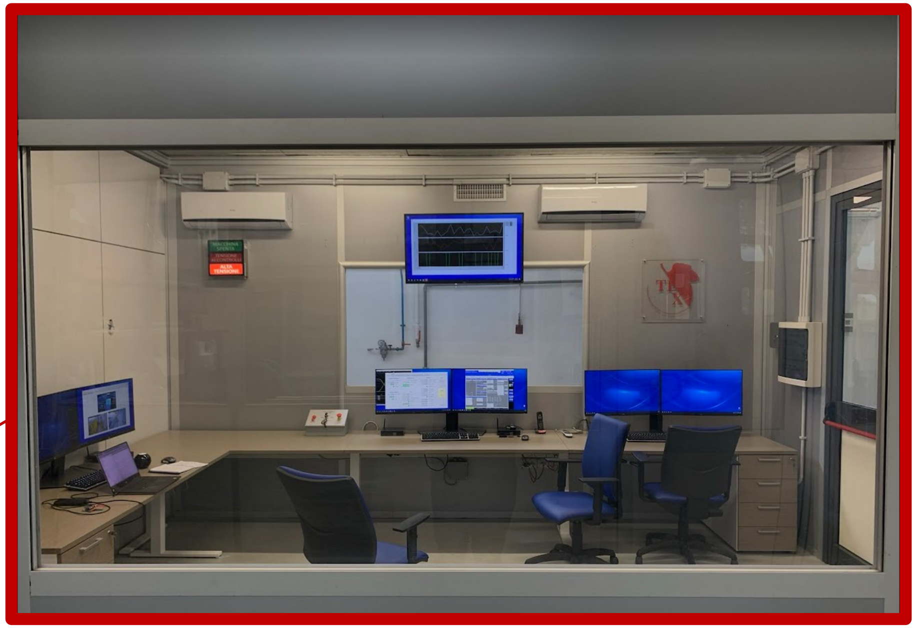
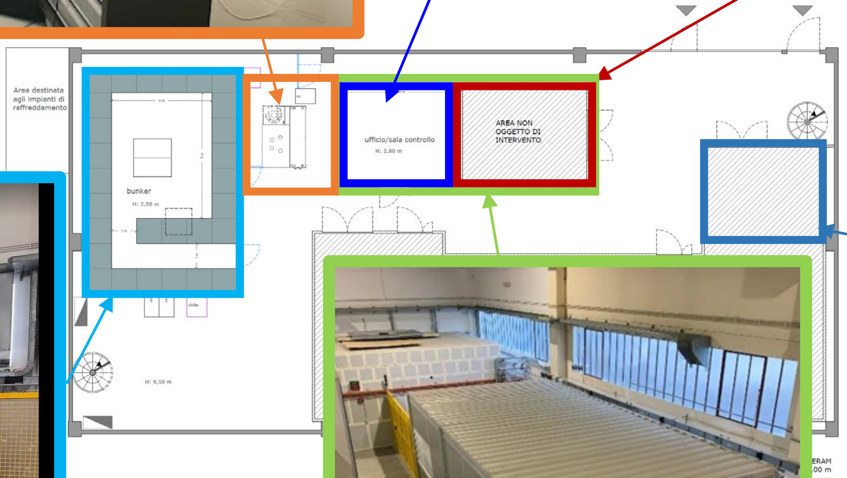
- *A new control room*
- *A new meeting room*
- *A new computing center*
- *A modulator area*
- *A new concrete bunker*





TEX Facility: the safety system

» Safety life-cycle assessment based on statistical methods for risk reduction.

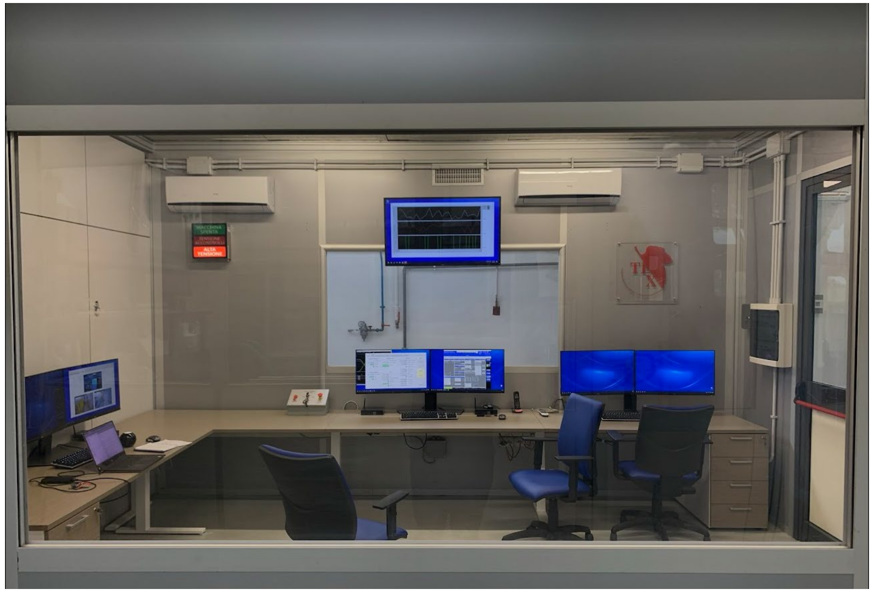
» compliance with:

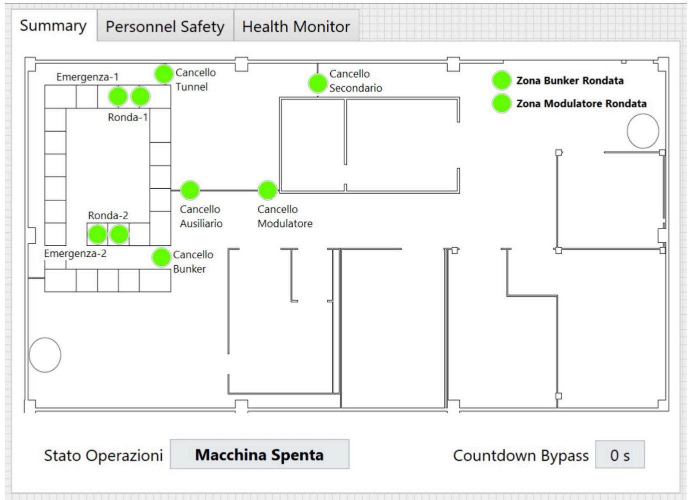
  » • IEC-61508 standard on “Functional Safety”

  » • NCRP reports 88 on “Radiation Alarms and Access Control Systems”

  » • ANSI reports 43.1 on “Radiation Safety for the Design and Operation of Particle Accelerator”

» For these reason we developed Personnel Safety System (PSS) and Machine Protection System (MPS) through FPGA based devices [5, 6] to provide hard-wired, fast and reliable protection to TEX





[5] S. Pioli et al., “Novel FPGA-Based Instrumentation for Personnel Safety Systems in Particle Accelerator Facility,” in 17th International Conference on Accelerator and Large Experimental Physics Control Systems, 2019, doi:10.18429/ JACoW-ICALEPCS2019-THCPR01
[6] S. Pioli, “Expression of Intent Singularity,” Frascati, Italy, Rep. INFN-19-05/LNF.

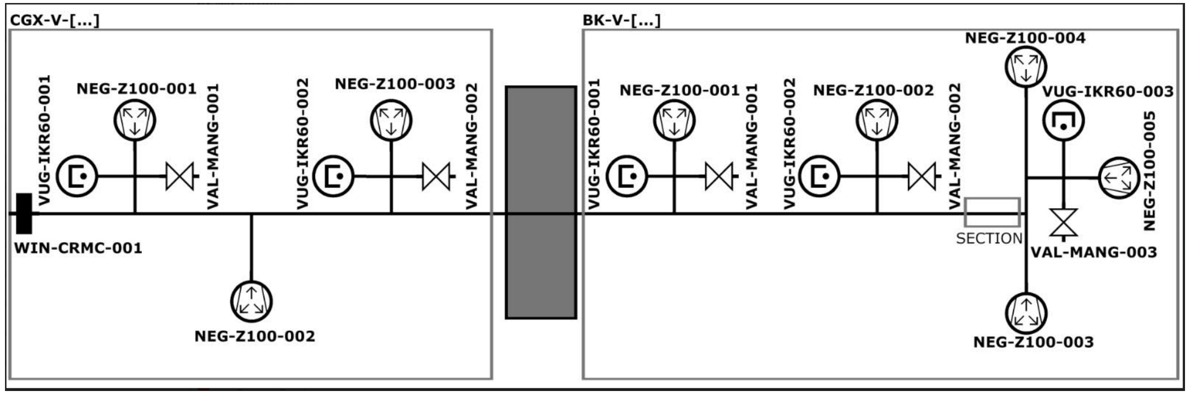
TEX Facility: the vacuum system

- The Vacuum system in TEX was provided by Accelerator Division Vacuum Service with the support of Mechanical Service.
- *Since the Device Under Test could change rapidly in a TEST Facility, a lot of efforts is required to define vacuum operation procedure for the X band components (cleaning, backing……).*
- *In 6 months we pass from a configuration A to configuration B to configuration C.*
- *The control of the vacuum quality is provided by the TEX Control System and the Vacuum Status Control panel is available to the operators as the vacuum gauge value and vacuum level value deducted by the ion pump current.*

A) RF load: leak check.

B) RF Spiral load.

C) A **T24 CLIC structure** and spiral loads



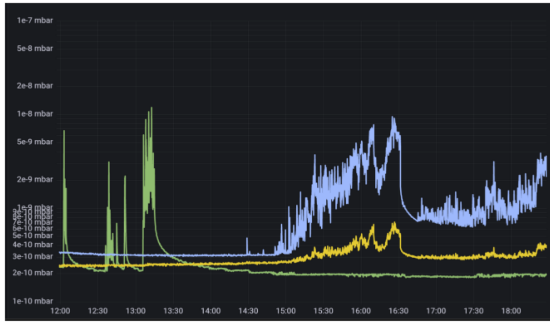
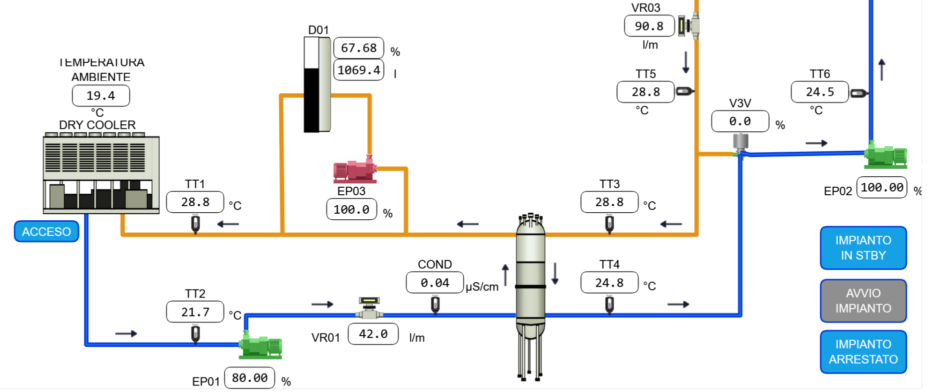
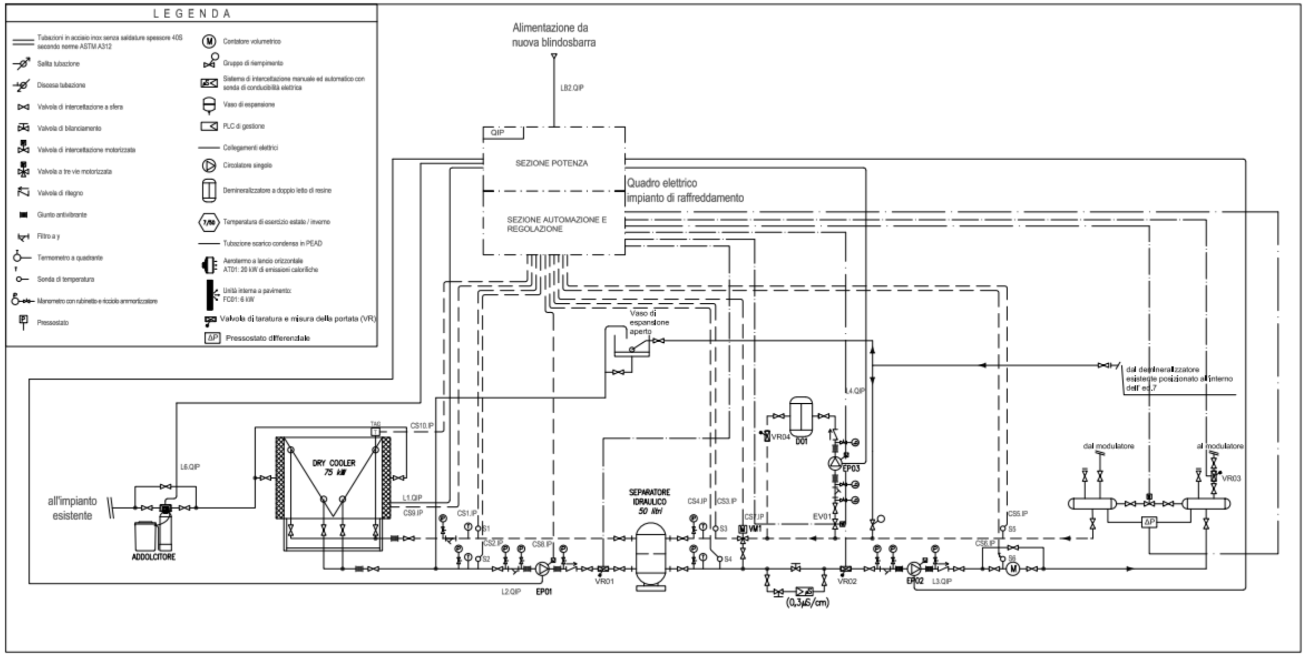


Figure 4: Klystron historical data viewer from Grafana.

TEX Facility: The fluids system

TEX cooling system is based on the EuPRAXIA@SPARC_LAB project guidelines developed by Technical Division at LNF. To reduce the facility opex, the system doesn't use chiller or cooling tower but it's based on adiabatic dry cooler and two independent circuits[*].

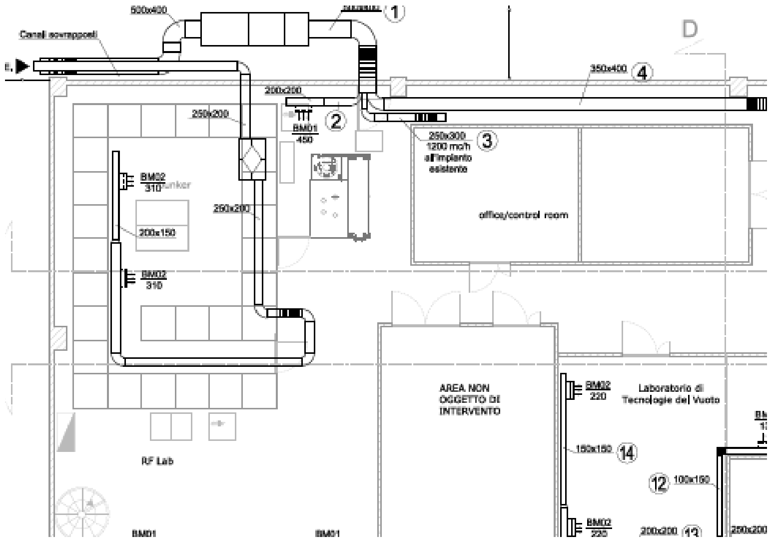




1) The secondary cooling system keeps the modulator temperature setpoint (28°C) mixing cold water from the dry cooler and the modulator exhaust water.
The primary system cools the water through the adiabatic dry cooler with minimization of electrical cost and water consumption.
A demineralization system maintains the water conductivity at the level required by the system components (< 1µS/cm).
The cooling circuit test for the RF components is performed with a Peltier chiller with thermal stability designed better than 0,03°C.

2) A PLC based system controls all the cooling system variables and adjusts parameters actuator to maintain the process variable at the setpoint value. Remote control and operation is allowed by a SCADA system.

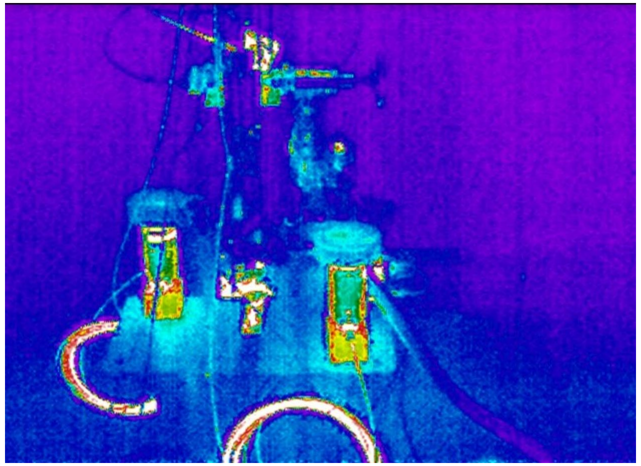
3) The bunker thermalization and ventilation is provided by a AHU installed on the bunker rooftop and will be controlled by the same SCADA as the cooling .

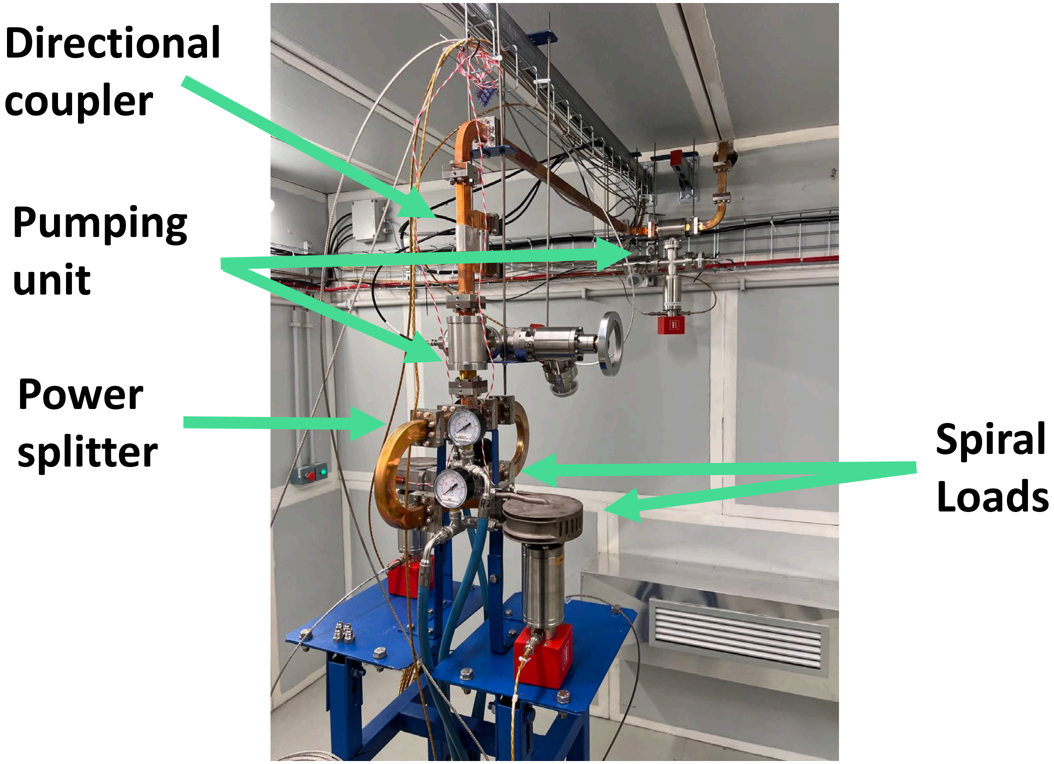


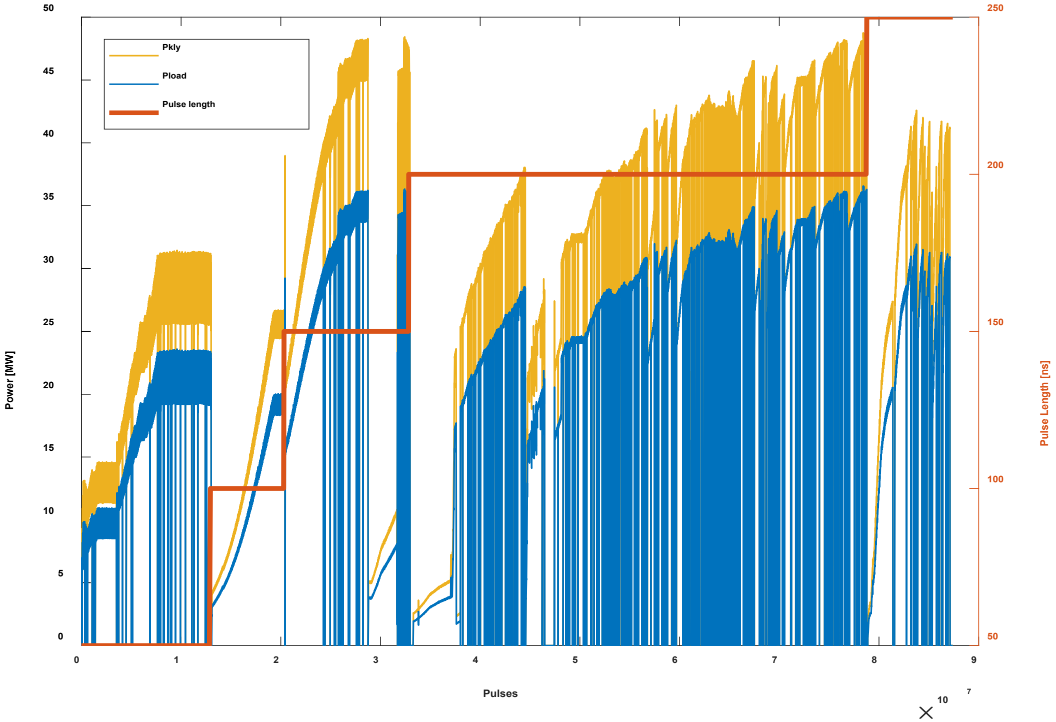
[*] *S. Cantarella et al. Private communication.*

Conditioning of waveguides and Spiral Loads

- A conditioning run of the waveguide distribution line terminated on two **3D printed Titanium Spiral Load** has been completed in February 2022
- A final peak power of **42 MW** with **250 ns** pulse length at **50 Hz** has been reached in **3 weeks**. The test has been interrupted to perform some civil work in the building
- The FWD Klystron power has been gradually increased with an automatic conditioning routine integrated in the control and machine protection system [7]



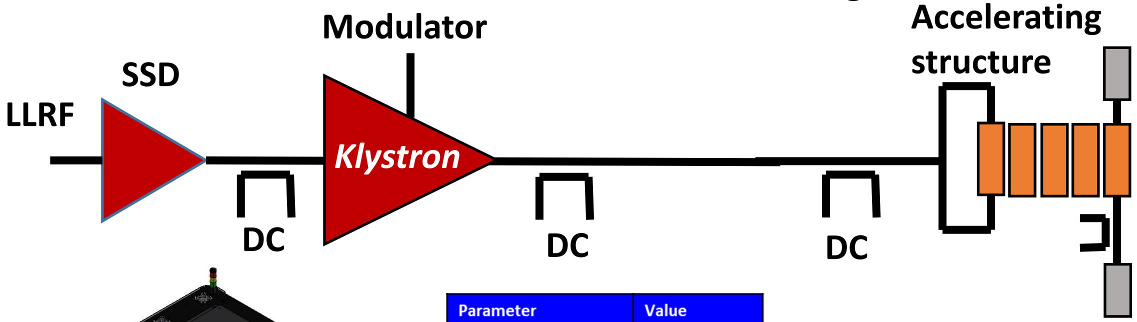


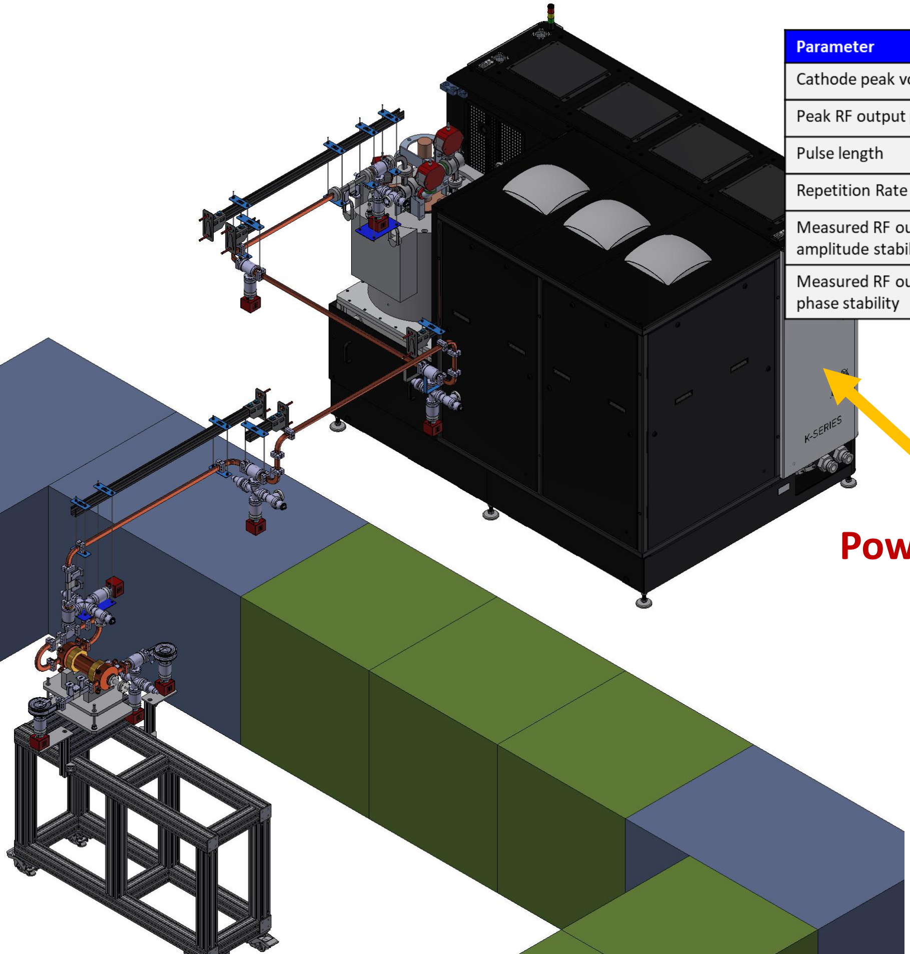


[7] S. Pioli, et al., 13th Int. Particle Accelerator Conf. (IPAC22), Bangkok, Thailand, June 2022, paper MOPOMS047.

Current TEX layout

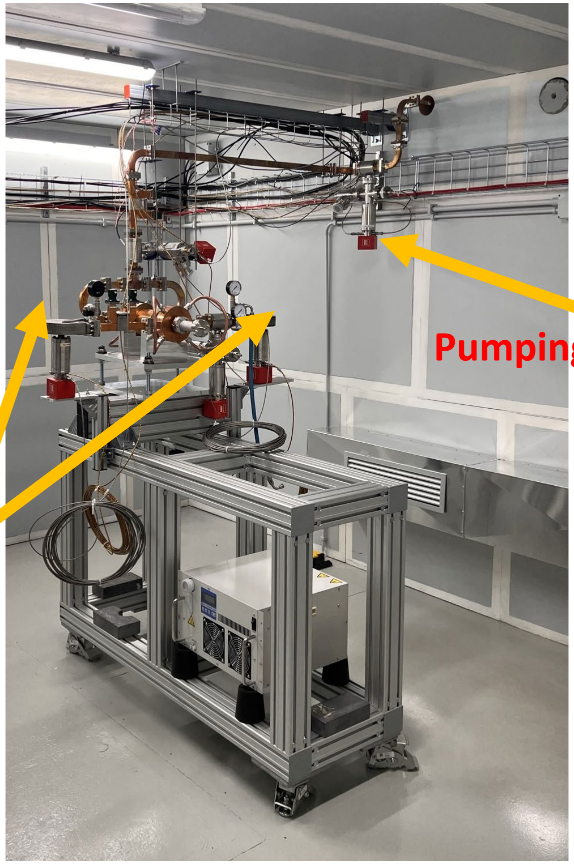
- In April 2023 we installed inside the bunker a CERN accelerating section of the **T24 CLIC** type. The complete setup is being implemented in these weeks





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

Power Source

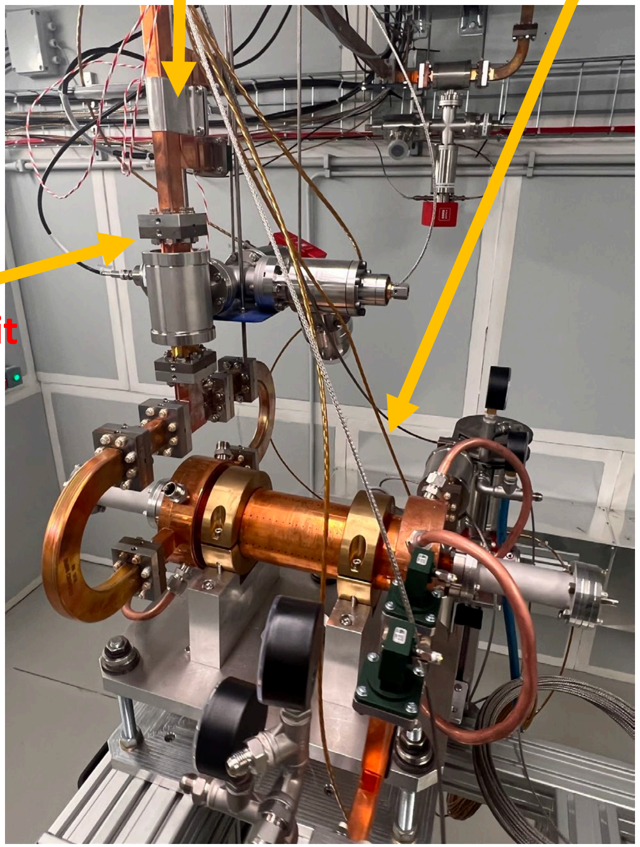


Spiral Load

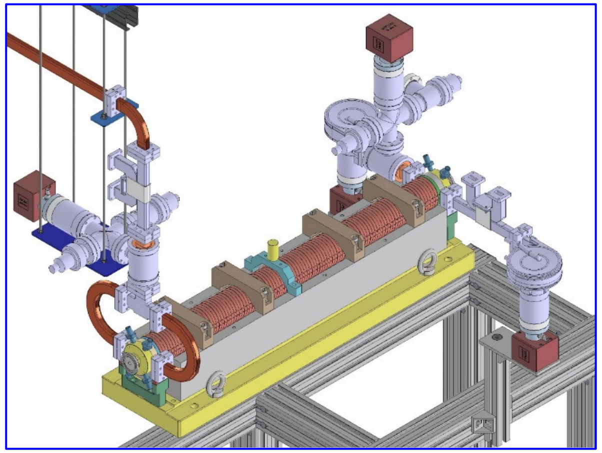
Pumping unit

Directional coupler

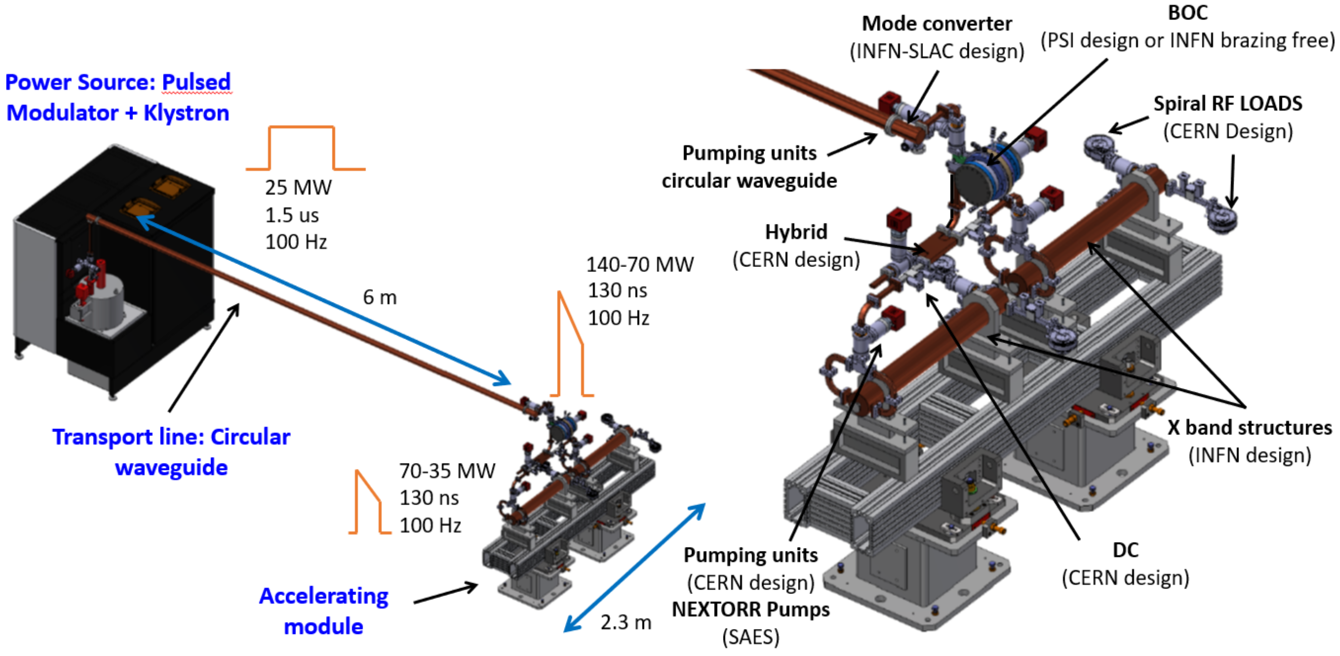
Accelerating structure

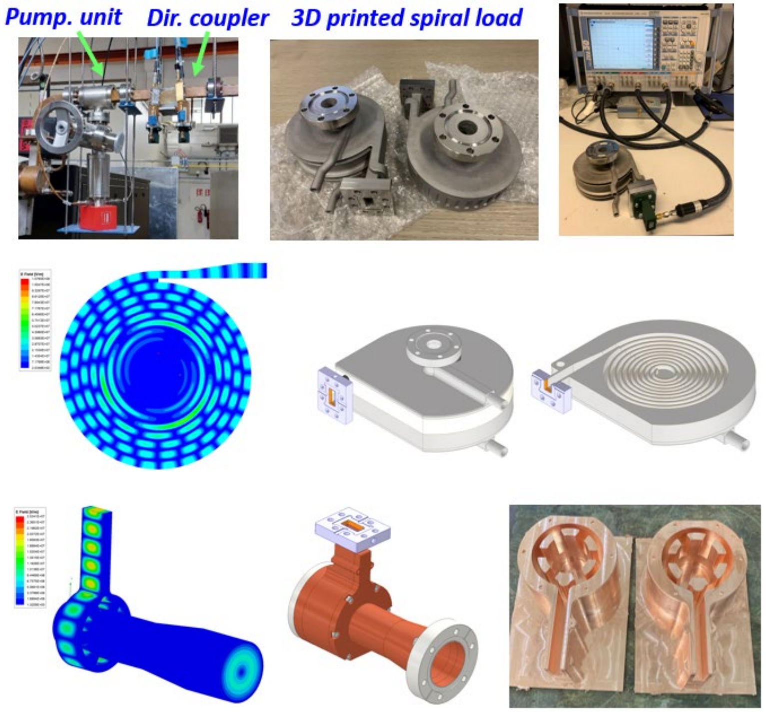


Next TEX activities:



- A **BOC pulse compressor** will be integrated in the layout in order to increase the available power provided by PSI.
- Study of design on Pump. Unit, Dir Coupler, Loads, Mode Converter, BOC and section is ongoing.
- All the elements of the baseline design of the X band module of the **EuPRAXIA@SPARC_LAB** will be procured by in house or in outsourcing and it will be tested at TEX in the next years [8-10].



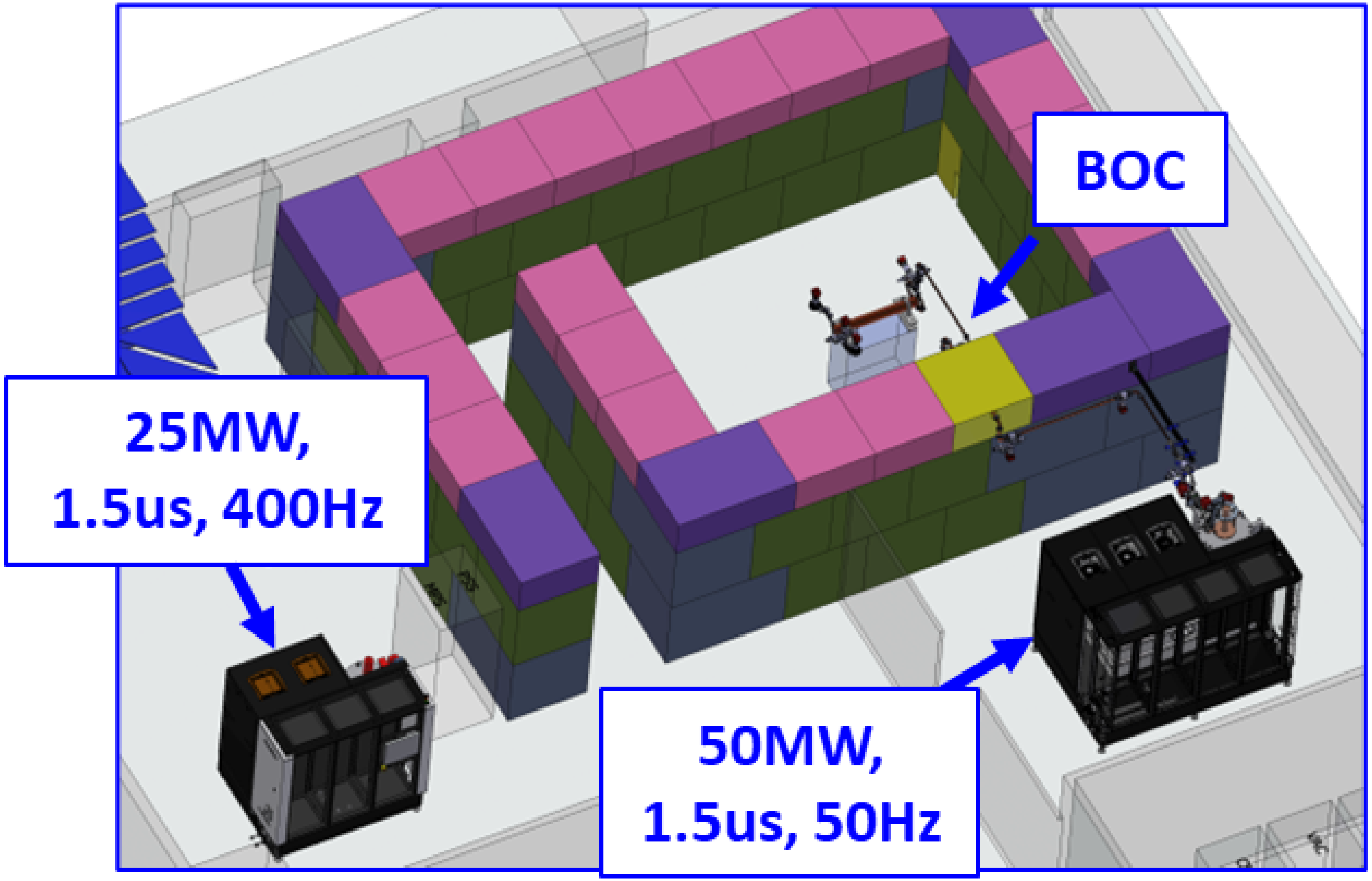


[8] F. Cardelli IPAC2023 X Band Activities at INFN-LNF (MOOG1)
[9] N. Catalan-Lasheras, et al., 9th Int. Particle Accelerator Conf. (IPAC18), Vancouver, BC, Canada, May 2018, paper WEPMF074.
[10] S. Tantawi, et all. (2000). Reviews of Modern Physics – doi: 10.1103/PhysRevSTAB.3.082001

Next TEX layout and RF Sources:

- A new Modulator for the CANON E37119 (nominal value 25MW 400 Hz) is scheduled to be installed in 2024.
- A new HE Klystron CPI VKX8311HE it's ordered, and it will be tested at TEX.

Parameter	Unit	Canon E37119	CPI VKX8311HE
Frequency	MHz	11994	
Vk beam voltage	kV	318	415
Ik cathode current	A	197	201
Peak drive power	W	500	
Peak RF output Power	MW	25	50
Average RF output power	kW	15	7,5
Modulator Average power	kW	75,2	25
RF pulse length	us	1,5	
Repetition Rate	Hz	400	100
Gain	dB	47	50
Efficiency	%	40	55



Conclusions and Acknowledgements

- **EuPRAXIA@SPARC_LAB** is the next INFN-LNF project.
- **TEX (Frascati Test stand for X-band)**: is the facility to test all RF components and X band prototypes at the nominal power/gradient. It has been commissioned and in operation.
- A **T24 CLIC structure** test is started yesterday.
- A design and procurement of **X-band RF components** of for EuPRAXIA RF module have been purchased and will be tested at TEX.
- An upgrade program of the facility is ongoing.

Aknowledgements:

INFN-LNF: *D. Alesini, S. Bini, B. Buonomo, S. Cantarella, R. Clementi, A. Gallo, C. Di Giulio, E. Di Pasquale, G. Di Raddo, A. Liedl, V. Lollo, L. Piersanti, S. Pioli, R. Ricci, A. Vannozzi on behalf of the TEX and EuPRAXIA technical team, INFN-LNF Accelerator Division, Technical Division and all the Laboratory Administrative and Safety Services staff.*
CERN: *W. Wuensh, N. Catalan-Lasheras, A. Grudiev, G. McMonagle on behalf of the CLIC and XBOX group*

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