ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR02

# ADVANCEMENTS IN X-BAND TECHNOLOGY AT THE TEX FACILITY AT INFN-LNF

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*Abstract*

In anticipation of the Eupraxia@SPARC_LAB project at the INFN Frascati National Laboratories, an intensive testing and validation activity for the X-band RF system has commenced at the TEX test facility. The Eupraxia@SPARC_LAB project entails the development of a Free-Electron Laser (FEL) radiation source with a 1 GeV Linac based on plasma acceleration and an X-band radiofrequency (RF) booster. The booster is composed of 16 high-gradient accelerating structures working at 11.994GHz. All radiofrequency components comprising the basic module of the booster, from the power source to the structure, must undergo testing at nominal parameters and power levels to verify their reliability. For this reason, since 2021, several experimental runs have been conducted to test various components in X-band technology at the TEX facility. This paper presents the results obtained thus far from the different experimental runs, and it also outlines the future upgrade of the facility, which will enhance testing capabilities and the future prospects of the facility itself.

## INTRODUCTION

The Eupraxia@SPARC_LAB project is an initiative aimed at developing and constructing an advanced linear accelerator at the National Laboratory of Frascati of the INFN (National Institute of Nuclear Physics) in Italy [1, 2]. This project aims to harness innovative technologies, such as the use of X-band (11.994 GHz) radiofrequency (RF) technology and beam driven plasma wakefield acceleration, for the production of high-brightness electron beams and high-energy particles. Such beam drives a free electron laser for the realization of advanced research experiments in various fields. The linac consists of an S-band (2856 MHz) injector and a booster composed of 16 X-band accelerating sections designed at the Frascati National Laboratories, operating with an average gradient of 60 MV/m to achieve a final beam energy of 1 GeV. We are currently in the phase of drafting the Technical Design Report of the project. To reach this stage, it has been necessary over the past years to undergo an extensive prototyping and testing phase of X-band components and structures, culminating in the testing of all X-band booster module components from the source to the accelerating structures. These tests were conducted at a dedicated test facility built within our laboratory. This article presents a description of the high-power X-band test facility and the results of the tests on RF components and structures conducted up to this point. Furthermore, we are currently in a phase of upgrading this facility to accommodate two new sources, and this aspect will also be addressed.

## THE TEX FACILITY

The TEX (TEst stand for X band) facility [3–5] was born in 2022 out of the need to verify and test the reliability and operation of X-band technology in view of the realization of the X-band Linac for the EuPRAXIA@SPARC_LAB project. This facility has been co-funded by the Lazio Region within the LATINO project to be available to companies and other research institutions as a user test facility. The possibility to have a system replicating the future X-band booster base module of EuPRAXIA@SPARC_LAB has allowed not only to verify its functionality and reliability but also to identify its critical aspects and those of its subsystems (vacuum, controls, safety, diagnostics, LLRF, etc.). Additionally, it has allowed laboratory personnel to train and gain experience in the operation and maintenance of all these systems. Its initial configuration was developed in collaboration with CERN and is based on an X-band source realized with a solid-state pulsed modulator capable of producing high-voltage pulses of 430 kV and 340 A, with a pulse duration of 3 $\mu s$ at 100 Hz. This source feeds a 50 MW peak power X-band klystron from CPI, which is driven by a commercial Low-Level RF system at 3 GHz adapted to X-band through an up/down conversion crate. In Fig. 1 a block diagram of the TEX source overall system is reported.

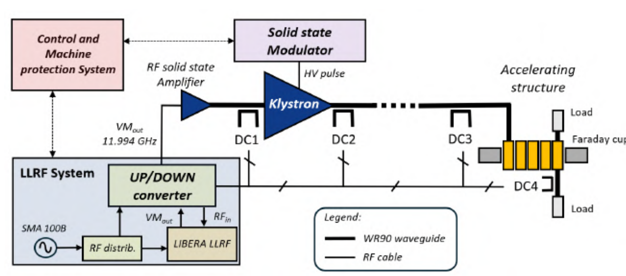


Figure 1: Block diagram of the TEX facility.

A frequency synthesizer generates a 571.15 MHz continuous signal, sub-harmonic of both S-band and X-band references, which is up converted and distributed to the X-band up/down converter and to the LIBERA digital low level RF module. This module generates the RF pulse at 11.994 GHz, which will then be amplified by the driver amplifier and the

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ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR02



klystron to the operating power. Simultaneously, it receives RF signals taken from various points of the waveguide system to provide feedback on the outgoing pulse and to detect breakdowns in the guides or in the structure under test. A detailed desctription of the LLRF system can be found in [6]. The parameters and interlocks of the Low-Level RF system, the modulator, the vacuum system's vacuum gauges, and the signals read by the Faraday cup are all controlled by the control system and the machine protection system. Through an automatic conditioning routine, the system enables the conditioning and testing of accelerating sections and radio-frequency components autonomously and safely. Following the commissioning phase, the first experimental run of TEX started in January 2023 with the conditioning of the entire waveguide system and two 3D-printed spiral RF loads, designed at CERN [7]. Subsequently, from May to October 2023, a T24 CLIC accelerating structure, designed at PSI, was conditioned. From November to December 2023, the rectangular to circular mode converters and circular waveguide system developed at INFN were tested, and in March 2024, the first prototype of an X-band accelerating structure for the Eupraxia@SPARC_LAB project was installed. In the following chapter, the layout of the basic RF module of the Eupraxia X-band booster will be described, and the results obtained during the high-power test of the circular waveguide system, performed at TEX, will be reported. Finally the future upgrade of the facility will be described.

## X-BAND RF COMPONENTS DESIGN AND TESTS

The basic layout of the X-band RF module of the Eupraxia@SPARC_LAB Linac is shown in the Fig. 2. It consists of a source (not shown in the Figure) capable of generating an RF pulse of at least 25 MW peak power, 1.5$\mu$ s pulse length, and with a repetition rate of 100 Hz. This pulse is transported inside the Linac bunker through a low-attenuation transport line made of overmoded circular waveguide. Then, the pulse is compressed through a BOC pulse compressor down to 130 ns, achieving a peak power of 140 MW, which is divided via a 3 dB hybrid to simultaneously feed two accelerating structures each about one meter long. In Fig. 2 all the components that has been already procured and tested at high power are reported in green, while the BOC and the hybrid are indicated in red because they have been procured but still need to be installed and tested. The accelerating section has been fabricated and installed and is currently undergoing testing, details on the design, prototyping, and preliminary testing of the EuPRAXIA@SPARC_LAB X-band accelerating section are described in detail in [8].

One of the most recent tests conducted at TEX concerned the conditioning of the circular waveguide transport system. It consists of two mode converters at the ends, allowing the conversion of the electromagnetic field from TE10 mode in rectangular waveguide to TE01 mode in circular waveguide. The latter is characterized by low attenuation and enables the transport of X-band radio-frequency power over long distances. Another necessary component for circular waveguide transport is the pumping unit or T-pump unit, which maintains the system in ultra-high vacuum without interfering with the RF signal.

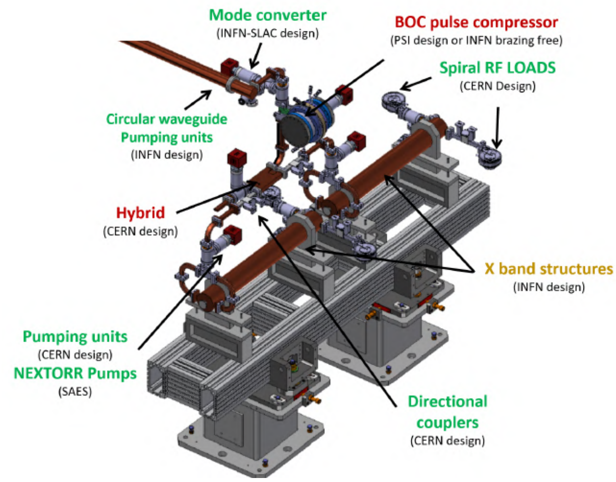


Figure 2: X-band module layout of the EUPRAXIA@SPARC_LAB Linac booster.

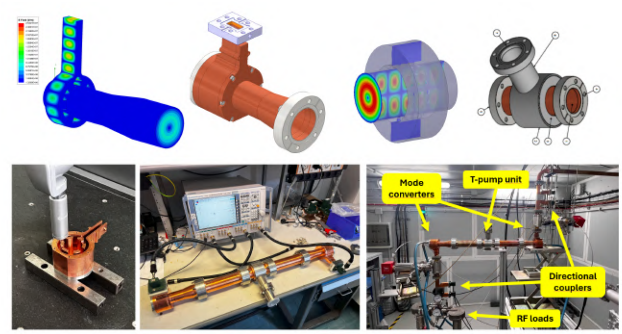


Figure 3: Electric field distribution obtained from the 3D electromagnetic simulations and rendering of the mechanical design for both the mode converter and the T-pumping unit in circular waveguide (Top). Mechanical characterization of the mode converter prototype after machining, low power measurement and high power test layout of the tested circular waveguide transport network (Bottom).

The design of the mode converter and the pumping unit was carried out starting from what is reported in [9], modified, and adapted to our operating frequency. The mechanical machining for the production of a simplified circular transport line was carried out by a private company and all the components have been brazed at our laboratory. In the top part of Fig. 3, the electric field distribution obtained from the 3D electromagnetic simulations and the rendering of the mechanical design are shown for the two components. In the bottom part, the mechanical characterization of the mode converter prototype after fabrication and the simplified setup of the circular waveguide transport system are shown, during the low-power bench test and finally installed in the

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TEX bunker for conditioning and high-power testing. For the high power test the line has been closed on two 3D printed spiral load designed at CERN. The conditioning history of the circular waveguide transport line setup is reported in Fig. 4. At the end of the test, a peak power of 21 MW was achieved at the output of the second mode converter with a $1\mu s$ pulse at a 50 Hz repetition rate, resulting in an average power per RF load of 500 W and a peak power dissipated within the circular waveguide line of less than 100 kW. This is an excellent result to demonstrate the reliability and performance of these components in the X-band and confirm their usability for the EuPRAXIA@SPARC_LAB module.

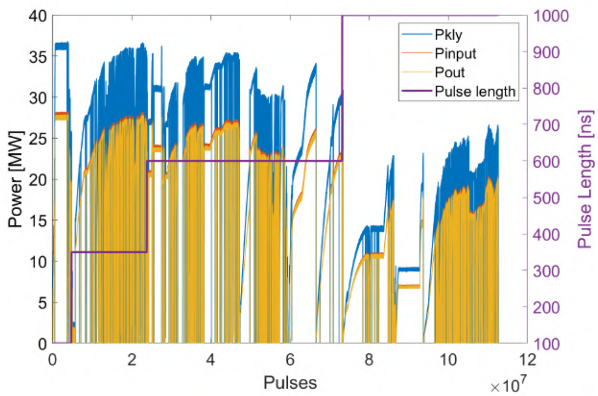


Figure 4: Conditioning plot during the high power test of the mode converters, circular waveguides and circular pumping ports.

## TEX UPGRADE

To enhance the conditioning capabilities of the TEX facility, an upgrade is underway, and by the end of 2024, two new RF sources with high repetition rate will be installed. Their position in the TEX bunker are can be seen in Fig. 5, one source is based on a solid state k300 Scandinova modulator with a Canon X-band klystron capable of generating a pulse of 25 MW peak power, $1.5\mu s$ pulse length, at a repetition rate of 400 Hz. This source will offer a viable alternative for the EuPRAXIA@SPARC_LAB project to the currently installed source at TEX and will enable another high-average-power X-band conditioning station for the facility. The second source is based on a solid state k300 Scandinova modulator with a Canon C-band klystron (5.712 GHz). It will generates a pulse of 20 MW peak power, $1.5\mu s$ pulse length, at a repetition rate of 400 Hz that will allow component testing in the C-band frequency and the test of a high gradient C-band photoinjector [10] at high repetition rate in the TEX bunker.

With the installation of these two new sources, two new waveguide distribution networks will be installed, which are currently in procurement phase. The LLRF system will be renewed by replacing the current Libera system working in S-band with a C-band system accompanied by a new up-down

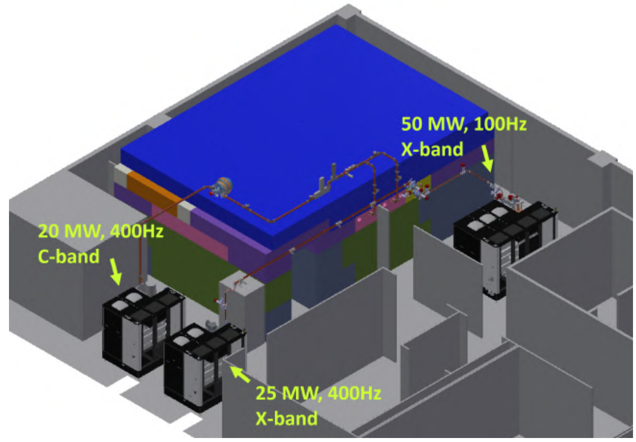


Figure 5: Configuration of the TEX facility area around the bunker, after the upgrade, with the three RF power sources.

conversion crate. Additionally, the control system and the MPS will also be renewed and updated as reported in [11].

## CONCLUSION

Within the EuPRAXIA@SPARC_LAB initiative, aimed at constructing a 1 GeV Linac utilizing X-band technology, a comprehensive R&D effort was initiated at the National Frascati Laboratories of INFN. This initiative resulted in the establishment of an RF power test facility named TEX, currently operational. Soon this facility will accommodate two innovative sources, one X-band and one C-band capable of achieving a repetition rate of 400 Hz. Concurrently, numerous X-band RF components essential for constructing the EuPAXIA@SPARC_LAB base module have been fabricated and tested in order to demonstrate the feasibility and reliability of the Linac X-band booster.

## ACKNOWLEDGEMENTS

This work is supported by NextGeneration EU, Italian National Recovery and Resilience Plan, Mission 4 - Component 2 - Investment 3.1. - Project name: Rome Technopole, CUP: I93C21000150006

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR02



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