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X-BAND ACTIVITIES AT INFN-LNF

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Abstract

The EuPRAXIA@SPARC_LAB project, foreseen a 1 GeV Linac based on a X-band booster composed by 16 accelerating structures working at the nominal gradient of 60 MV/m. In this framework, an intense activity has started in the last years in order to prove the reliability and functionality of the X-band technology at very high peak power. The main step of this activity has been the implementation of a X-band test station TEX, based on an RF power source capable to deliver 50 MW RF pulses that are used for accelerating structures and RF components conditioning and testing. This test facility has been successfully commissioned and entered into operation at the end of 2022. Together with the source commissioning different RF components in X-band, necessary for the EuPRAXIA Linac, have been developed and will be tested soon at the nominal peak power in the TEX facility. In this article the status and operation of the TEX facility is reported together with a description of the main activities on the X-band technology performed at INFN-LNF.

INTRODUCTION

In the last years an intense R&D activity has started at the Frascati national laboratories of the INFN, on the X-band radio-frequency technology. This technology has proven to increase the performance of linear accelerators in terms of maximum accelerating gradient (> 100 MV/m) and compactness. For this reason it was chosen as the basic technology for the realization of the Linac booster of the EuPRAXIA@SPARC_LAB project [1, 2]. This project is in a design phase and involves the construction of a linear accelerator that drives a plasma module to create a FEL radiation source. The Linac will generate a 1 GeV high brightness electron beam at 100 Hz, by means of an RF photo-injector in the S-band (2.856 GHz), composed of a 1.6 cells SW RF gun and 4 TW accelerating structures, and a booster consisting of 16, 0.9 m long, accelerating sections, working in the X-band (11.994 GHz) at a nominal gradient of 60 MV/m. Figure 1 reports a sketch of the RF Linac. To increase the FEL performances a future upgrade of the injector with an high repetition rate C-band (5.712 GHz) Gun working at 400 Hz is being studied [3]. The booster RF module consists in a 25 MW klystron based power source feeding two accelerating structures in parallel by means of a BOC type pulse compressor, used to increase the RF power to the level required to reach the nominal gradient in the two sections. 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. Therefore, an X-band test facility, called TEX [4], has been commissioned last year in our laboratory and is currently in operation [5]. In this paper we report the status and future work of the TEX facility, and the progress on the design and testing of the different RF components that realize the X-band module of the Linac, with particular attention to the pulse compressor and the X-band accelerating section prototypes.

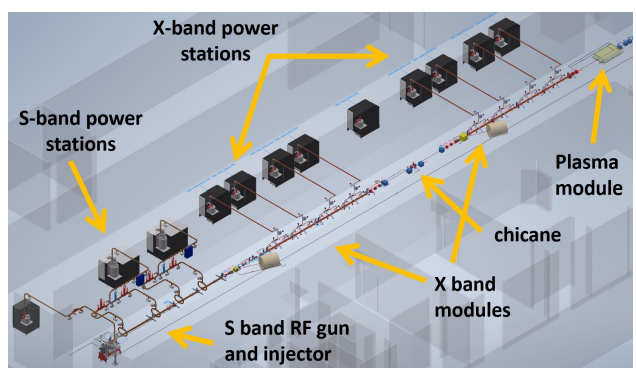

Figure 1: View of the EuPRAXIA@SPARC_LAB Linac.

X-BAND RF MODULE

The basic RF module for the Eupraxia@SPARC_LAB Linac booster involves a 25 MW RF power source, that is connected to a BOC pulse compressor that increase the RF peak power up to 140 MW reducing the pulse length to 130 ns. The connection between the source and the BOC is performed by means of two mode converters and circular waveguide to reduce as much as possible the losses in the 6 meters transmission line. After the pulse compression the power is divided with a 3dB hybrid and sent to two travelling wave X-band accelerating structures terminated on spiral RF loads. The RF signals (forward and reflected) are measured via directional couplers, positioned after the klystron and at the input and output of the sections. In Fig. 2 we report the sketched layout of the single RF module and the details of the components that make up the transmission line up to the accelerating structures. In the following sections we report

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the ongoing R&D and testing activity related to the main components of the RF module.

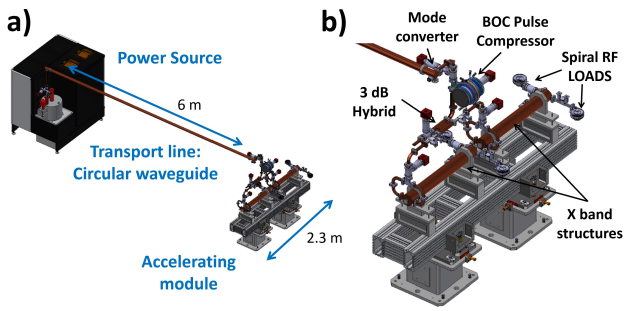

Figure 2: a) Sketch of the RF module. b) Details of the distribution line to the RF structures.

POWER SOURCES AND TEX FACILITY

For the choice of the final X-band source two main sources are currently under study. The first is based on klystron Canon E37119, capable of generating RF pulses of 25 MW of peak power with a repetition rate of 400 Hz, the second, based on klystron CPI VKX8311 that reaches a peak power of 50 MW at a repetition rate of 100 Hz. Both generate pulses with a maximum length of 1.5 μs. Using the first klystron, we need 8 sources to power the Linac, but has the advantage of a very high repetition rate and having a lower peak power working point for the waveguides and therefore a lower discharge probability. The second would allow to halve the number of sources going to feed 4 structures per source, but doubling the peak working power for the pulse compressor and all RF components of the module. Both the two solutions will be tested at LNF and their performance and reliability compared. Currently a power source based on CPI VKX8311 klystron is in operation in our test facility TEX. This source is able to generate 50 MW RF pulses, with 1.5 μm pulse length at 50 Hz, and will be upgraded in the next years with an high efficiency version of this tube (VKX8311HE) currently under development. A second power source based on the E37119 klystron will be commissioned at the beginning of 2024, doubling the conditioning and testing capability of the facility. The X-band source present at TEX has been completely commissioned and is currently in operation. A conditioning run of the all waveguide distribution terminated on two titanium spiral loads, realized with additive manufacturing, was completed in February 2023. In Fig. 3 is possible to see the loads conditioning history, where the trend of the loads input power (blue), the klystron forward power (yellow) and the RF pulse length (red) are reported. During this conditioning the forward power at the klystron output has been gradually increased with an automatic conditioning routine integrated in the EPICS control system and described in [6]. A final peak power of 42 MW at the klystron output, with a pulse length of 250 ns and 50 Hz of repetition rate, has been reached in 3 weeks of conditioning. This run has been useful also to test all the facility subsystems like the control system, the automatic conditioning routine and the LLRF system. The TEX operation has been interrupted at the end of February by construction work inside the building that houses the facility. In April 2023 an accelerating section of the T24 CLIC type [7], on loan from CERN, has been installed inside the bunker as preparation of the next experimental run. This test will be useful to completely test the conditioning capability of the X-band source of TEX before the conditioning of the first EuPRAXIA@SPARC_LAB accelerating structure prototype. Figure 4 shows the CLIC structure mounted inside the TEX bunker and the current waveguide layout.

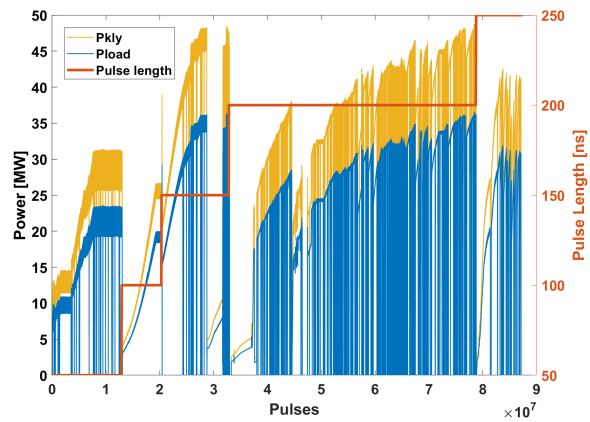

Figure 3: Conditioning history of the two RF spiral loads realized with additive manufacturing. In Yellow is reported the power level at the output of the klystron, while in blue the power at the loads input.

Figure 4: CLIC structure installed inside the TEX bunker.

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BOC PULSE COMPRESSOR AND RF COMPONENTS

For the energy upgrade of the current RF source of the TEX facility, a BOC type pulse compressor will be installed along the line. This X-band BOC is being purchased from the PSI. At the same time, for the future 25 MW station, that will be installed at TEX, another pulse compressor is needed. Therefore, we are working on the design of an X-band BOC to be realized, in-house, without the use of brazing [8], but taking advantage of the clamping technique already widely used and validated for the realization of several SW RF guns at our laboratories [3, 9]. This technique allows to avoid completely any brazing process during the realization of the device thanks to special RF and vacuum gaskets. To allow the use of special gasket, it was necessary to introduce a gap on the edge of the waveguide. This gap does not affect the field distribution of the TE10 mode and enables the insertion of the gasket to seal the cavity with the waveguide that surrounds it. In Table 1 are reported the main design parameters of the BOC. The choice of the resonant azimuthal mode and therefore the quality factor Q_0 and the coupling coefficient β were guided by the optimization performed during the electromagnetic design of the EuPRAXIA accelerating structure and also to keep the size of the BOC reasonable.

Table 1: Clamped BOC Main Parameters

Pulse compressor	Parameter
Type	Barrel Open Cavity
Frequency	11.994 GHz
Resonant Mode	$TM_{16,1,1}$
Diameter	171 mm
Q_0	150000
Coupling factor β	7.8

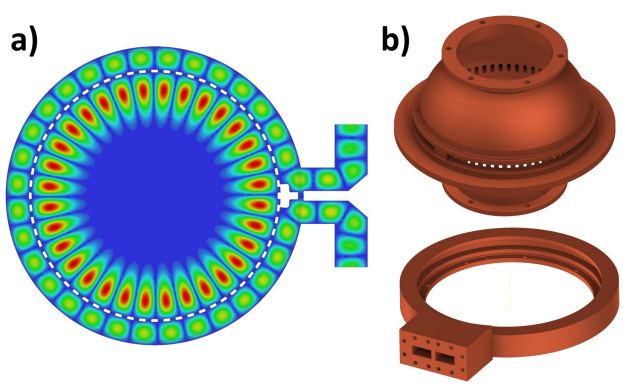

Figure 5: Snapshot of the Magnitude of the Electric Field in Arbitrary Scale (a) and the Mechanical Sketch of Two Machined Components That Are Connected Through The Special Gasket to Realize the BOC Assembly (b).

The electromagnetic and mechanical design of this device have been carried out in parallel. In Fig. 5 are reported the snapshot of the magnitude of the electric field obtained from the EM simulation and the preliminary mechanical layout of the BOC components. The mechanical design still needs to be finalized in order to realize a prototype by the end of this year. Many of the other X-band components that are needed for the EuPRAXIA module are based on designs made at CERN [10], such as directional couplers, splitter and loads, and have already been purchased, manufactured and installed in the current TEX setup. For other necessary components, not finding commercial solutions available, we relied on versions found in the literature and prototypes were designed that will be manufactured and then tested. In particular for the mode converter needed to switch from rectangular WR90 to circular waveguide and the pumping unit in circular waveguide we based our design on the so called "wrap around" mode converter [11]. A prototype of mode converter with circular waveguide pumping unit is in construction and will be soon available for testing. Another component that we are realizing is a modified version of the Titanium spiral loads made by additive manufacturing [12] developed at CERN. The idea is to replace the transverse vacuum pumping holes by cutting the entire load transversely leaving a 1 mm thick gap along the entire length of the waveguide. That allows to increase the pumping speed in the device but also their realization by conventional machining and brazing of the two halves, allowing companies to be able to realize this type of load even without the use of 3D additive manufacturing. Figure 6 shows the mechanical layout of this high power load. A first prototype of this load is being manufactured.

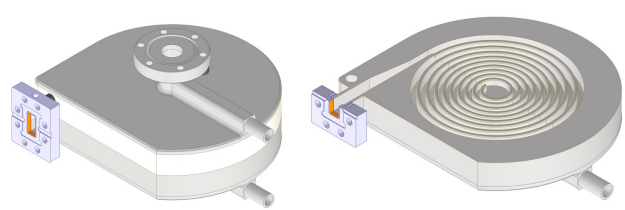

Figure 6: Entire view and section of the modified Spiral Load for machining and brazing.

X-BAND ACCELERATING STRUCTURE

The EuPRAXIA@SPARC_LAB X-band accelerating structure is currently in a prototyping phase. The electromagnetic design of the structure has been completed, it aimed to minimize the modified Poynting vector normalized to the average accelerating gradient and at the same time maximize the effective shunt impedance as function of the iris tapering angle. More details related to the optimization of the accelerating structure can be found in [13]. In Table 2 the main results obtained from the electromagnetic simulation are reported, both for a constant gradient (CG) version of the structure, with a linear tapering of the irises of the cells, and for a constant impedance version (CI). After the electromagnetic design, a thermo-mechanical analysis was performed in order to verify the behaviour of the structure both at 100

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Hz and 400 Hz. Four cooling channels are integrated into the cell, running longitudinally along the structure, with inlets and outlets on the couplers. By means of this analysis it has been verified that the cooling system is able to compensate the increase of temperature and the consequent detuning of the cavities during the operation for both working points. To evaluate the background radiation generated during the full power operation of this structure, dark current simulations were also performed by means of PIC simulations. The design phase was completed with the mechanical design of the structure, of the individual cells and the couplers. It was conducted in synergy with a preliminary prototyping activity that saw the creation of some samples of the couplers and of single cells. These samples were used for brazing, cells assembly, vacuum sealing and alignment tests and, through some reiterations with the mechanical design and subsequent modification, have led to the final mechanical design. The prototyping activity involves four main steps. The first is the one just described, concerning the creation of small samples of cells to optimize the brazing process and complete the mechanical project. This activity has been also preparatory to train the technical staff of our laboratory in the use of the new vacuum furnace for brazing available in our vacuum laboratory. The second, called full scale mechanical prototype, saw the realization of the complete structure without the precise internal machining of the irises and cells. This was used to test the entire brazing process of the full structure, the achievable cell-to-cell alignment and the vacuum seal at the end of the brazing procedure. To ensure and maintain the alignment of the structure during the assembly of the cells and during the brazing phase, each cell is fixed to the next by means of screws. The cells are assembled together before brazing on an ultra-precise graphite support, inserting the brazing alloy and fixing each cell to the next by means of three screws, which also allowed to simplify the assembly procedure. The structure cell to cell alignment has been characterized before and after the brazing. The final straightness was within ± 15 μm, widely within 30 μm required by beam dynamics requirements. Figure 7 shows the insertion of the assembled structure in the vacuum furnace for brazing and the brazed final prototype. The third prototyping step involves the construction of an RF prototype of 15 cells constant impedance to be power tested in the TEX facility. Currently the cells of this structure are being machined and then will be brazed in our laboratory. The RF power test is expected later this year. Finally, a full-scale RF prototype will be built to be tested at TEX and conditioned at full power.

Table 2: EuPRAXIA@SPARC_LAB X-band Accelerating Structure Main Parameters for both the Constant Gradient (CG) and Constant Impedance (CI) Version

Parameter	Unit	CG	CI
Frequency	GHz	11.994	
Phase advance per cell	degree	120	
Average Acc. Gradient	MV/m	60	
Structure per module		2	
Average Iris radius	mm	3.5	
Tapering Angle	degree	0.04	0
N. of cells		112	
Shunt impedance	$M\Omega/m$	93-107	100
Effective Shunt impedance	$M\Omega/m$	350	347
Average input power	MW	51	
Average dissipated power	kW	1	
P_{out}/P_{in}	%	25	
Peak mod. Poynting Vec.	$W/\mu m^2$	3.6	4.3
Peak Surf. E field	MV/m	160	190
Filling time	ns	130	
Repetition rate	Hz	100	

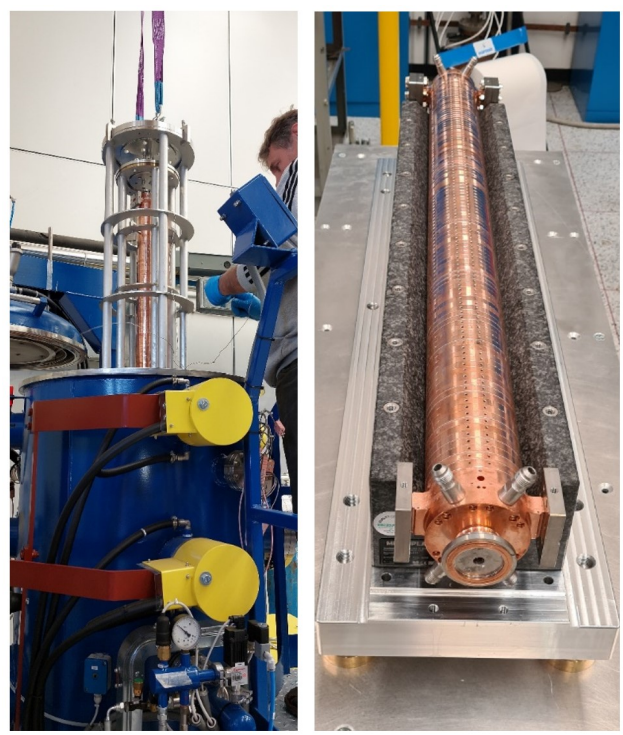

Figure 7: Insertion of the assembled structure in the vacuum furnace for brazing and brazed final prototype.

CONCLUSION

In the framework of the EuPRAXIA@SPARC_LAB project, which involves the construction of a 1 GeV Linac based on X-band technology, an intensive R&D activity began at the National Frascati Laboratories of INFN. This activity has led to the commissioning of an RF power test facility called TEX, which is currently in operation and will soon host another innovative X-band source capable of reaching a repetition rate of 400 Hz. At the same time many X-band RF components needed to build the Eupraxia base module have been manufactured and others are being developed. By the end of the year the first 15 cells RF structure prototype constant impedance for the EuPRAXIA Linac will be realized and tested at full power.

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