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PRELIMINARY RESULTS ON X-BAND STRUCTURES FOR THE EUPRAXIA@SPARC_LAB PROJECT

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Abstract

The Eupraxia@SPARC_LAB project involves the development of a 1 GeV normal conducting Linac with an S-band injector followed by an X-band booster. To achieve the final energy, the booster consists of 16 traveling wave accelerating structures operating at 11.994 GHz with a minimum working gradient of 60 MV/m. An intensive design activity, prototyping, and testing of these structures is underway at INFN-LNF. This paper comprehensively presents all the work conducted in the design and prototyping, along with preliminary test results obtained from the first RF prototype of the Eupraxia@SPARC_LAB X-band accelerating structure.

INTRODUCTION

In the context of the European project EuPRAXIA, aimed at realizing the world's first high-energy plasma-based accelerator capable of generating an industrial-quality beam for users, the Frascati National Laboratories of INFN aim to carry out the EuPRAXIA@SPARC_LAB project [1,2]. This project involves the development of an FEL source based on the combination of a plasma acceleration module using the beam-driven plasma wakefield acceleration technique and a high-brightness 1 GeV radio-frequency (RF) linear accelerator based on X-band (11994 MHz) technology. This research infrastructure aims to propel accelerator technology towards greater compactness and performances, thereby opening up new avenues for applications and research. The proposed layout for EuPRAXIA@SPARC_LAB's linac includes an S-band (2856 MHz) photocathode RF Gun, four S-band TW structures, and an X-band booster. The design of the booster prioritizes achieving a high accelerating gradient to enhance facility compactness, aligning with EuPRAXIA's objectives. The booster has approximately 25 meters allocated for the accelerating sections, allowing for an active length of around 16 meters after accounting for beam diagnostics, magnetic elements, vacuum equipment, and flanges. Hence, it consists of 16 disc-loaded TW accelerating structures, each 1 meter long, powered in pairs by an RF source of at least 25 MW peak power plus a pulse compressor. In Fig. 1, the basic layout of the X-band RF module of the booster is shown, along with the parameters of the RF pulse in different points of the waveguide network.

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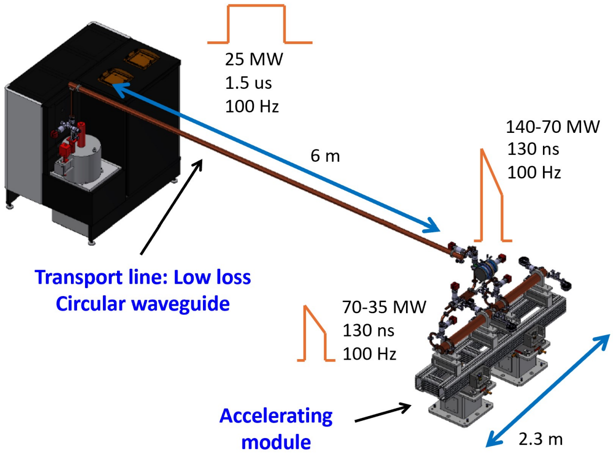

Figure 1: Basic layout of the X-band RF module of the EuPRAXIA@SPARC_LAB booster.

In the following chapters, the design parameters of the X-band accelerating structure are presented, the prototyping phase is described, and the preliminary results obtained from low and high power tests on a 20-cell RF prototype of the structure are reported.

THE X-BAND ACCELERATING STRUCTURE

The electromagnetic design of the X-band structures is detailed in [3,4]. As reported, the average dimensions of the irises have been chosen at 3.5 mm as a compromise between efficiency and beam dynamics requirements. The structures have been designed to be approximately one meter long, operating in the $2\pi/3$ mode at an average gradient of 60 MV/m. This gradient was chosen conservatively both to achieve the desired acceleration within the available space and to control the dark current they generate. The design was carried out for both a constant gradient (CG) and a constant impedance (CI) version of the structure in order to simplify the initial design and mechanical realization of the first prototypes by producing constant impedance structures with identical irises. Subsequently, also a constant gradient version will be realized and tested. The RF system parameters for both the two versions are outlined in Table 1.

Alongside the electromagnetic design, thermo-mechanical simulations were carried out for the sizing of the cooling system, simulations of the dark current produced

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Table 1: 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	MΩ/m	93-107	100
Effective Shunt impedance	MΩ/m	350	347
Average input power	MW	51	
Average dissipated power	kW	1	
P_{out}/P_{in}	%	25	
Peak mod. Poynting Vec.	W/μm^2	3.6	4.3
Peak Surf. E field	MV/m	160	190
Filling time	ns	130	
Repetition rate	Hz	100	

by field effects in the structure at nominal gradient, and mechanical design [5].

PROTOTYPING ACTIVITY

The mechanical design was carried out alongside an intensive prototyping campaign. Initially, this involved the production of several 3-cell samples and the coupler to refine the brazing procedure of the structure. All these samples and prototypes were manufactured by private companies and brazed at the vacuum laboratory of INFN-LNF. Subsequently, two mechanical prototypes of nominal dimensions but with simplified internal machining were produced to verify the entire assembly and brazing procedure, vacuum tightness, and straightness achieved after brazing. As reported in [5], a final straightness of the structure within ± 15 μm has been obtained for both the prototypes, widely within 30 μm required by beam dynamics requirements. Hence, these tests demonstrated the correct functioning of the brazing procedure and allowed the technical staff to train and gain experience with the equipment. After the first mechanical prototype, the construction of an RF prototype began, to be tested at high power at the testing station of the Frascati National Laboratories called TEX [6]. Given the small size of the cells in the X-band, it is difficult to incorporate tuners. It was decided to manufacture this structure tuning free and therefore with very stringent mechanical tolerances (on the order of ± 2 μm). So, to simplify the construction of this first RF prototype, it was chosen to create a CI-type structure consisting of just 20 cells. A photo of the 20-cells RF prototype after the final brazing is shown in Fig. 2. Currently, a full scale RF prototype of nominal length (112 cells) is also under construction and should be ready for power testing by the end of 2024.

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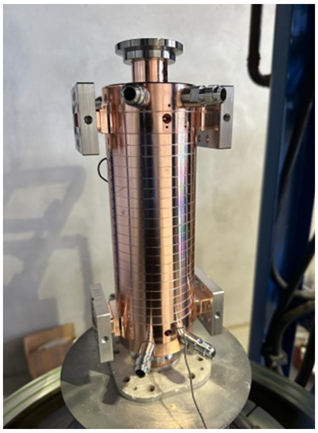

Figure 2: Picture of the 20-cell prototype after brazing.

LOW POWER RF MEASUREMENTS

Before the final brazing of the 20-cell RF prototype, preliminary low-power measurements were conducted to characterize it and verify its operation at the working frequency. This is a significant advantage for a tuning free structure because it allows for identifying any manufacturing errors before proceeding with the brazing of the structure. This was made possible thanks to the technique developed to hold them in place during brazing, which also simplifies assembly by using 3 simple fixing screws placed between one cell and the next. The final brazing was performed by a private company, which also carried out the machining of the cells and couplers.

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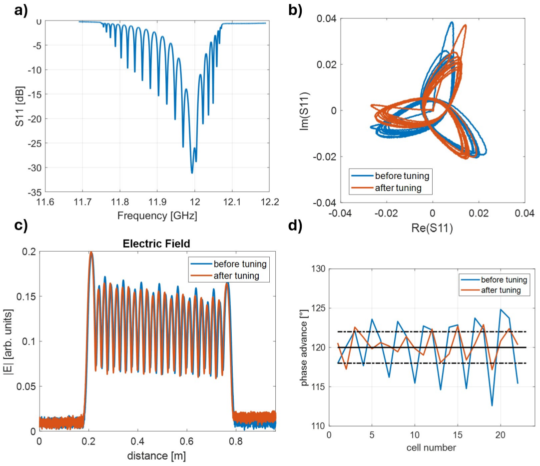

Figure 3: Results of the RF characterization and bead drop measurement before and after the tuning of the 20-cell prototype: a) Reflection coefficient at the structure input after tuning, b) Flower diagram, c) electric field on the structure axis and d) phase advance per cell along the structure.

After the final brazing, bench measurements with Vector analyzer were conducted for RF characterization, and bead-drop measurements were performed to measure the magnitude and phase of the electric field on the axis of the structure, allowing verification of the correct phase advancement between one cell and the next. In Fig. 3 the results of the RF characterization and bead-drop measurements are reported. A slight tuning of the structure was performed using the only tuners available, positioned at the input and output coupler cells. The field and phase advancement measurements revealed an error in the size of the coupling cell of the couplers, compensated by the tuners placed on both of them. Additionally, all cells were found to have a diameter smaller by approximately $2\mu m$. Since this error was common to all cells, it could be easily compensated by operating the structure at a temperature approximately 10 degrees higher than the design temperature.

HIGH POWER TEST

After the low-power characterization, the structure was mounted in the bunker of the test facility, TEX, and connected via a waveguide distribution system to the source for high-power testing. A photo of the prototype mounted in the TEX bunker and the setup used for high-power testing is shown in Fig. 4.

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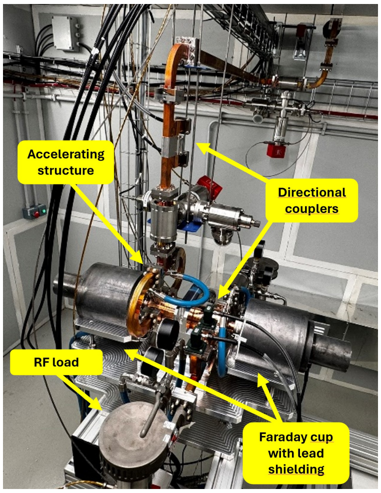

Figure 4: 20-cell X-band RF prototype installed in the TEX bunker for the high power test.

The forward and reflected power at the structure input and output was monitored by directional couplers connected to the TEX LLRF and two faraday cups with lead shielding were mounted at the input and output of the structure's beam tube. These Faraday cups allow for detecting the dark current produced by the structure under high field but also for generating a fast interlock to stop the pulsing from the source in case of internal discharge, detected by a peak in the dark current.

In Fig. 5, the output power trend of the klystron and the input power to the prototype are shown as a function of the number of pulses from the source, along with the increase in the RF pulse length. Meanwhile, in Fig. 6, the increase in the average accelerating gradient inside the structure is depicted. After approximately two weeks of conditioning, a peak power at the entrance of the structure of 35 MW was achieved with a 100 ns pulse, at 50 Hz, generating an average gradient in the structure of approximately 74 MV/m and a pek gradient at the structure input of 80 MV/m.

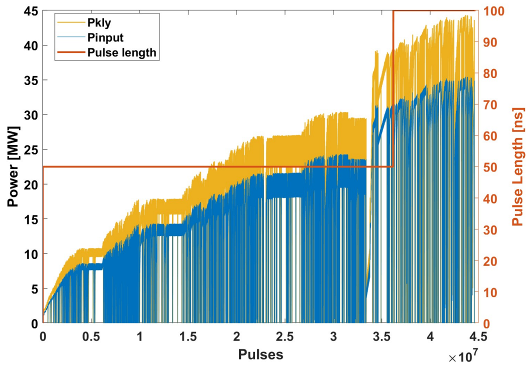

Figure 5: Conditioning story of the 20-cell X-band RF prototype. In yellow is reported the peak power at the klystron output, in blue the peak power at the structure input and in red the pulse length during the conditioning.

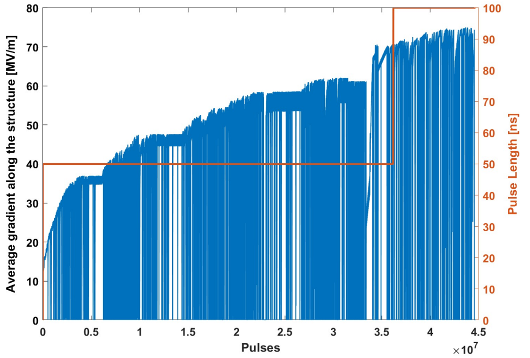

Figure 6: Trend of the average accelerating gradient within the 20-cells prototype as a function of the number of pulses.

CONCLUSION

The initial mechanical prototypes and the preliminary RF tests conducted at both low and high power on the first RF prototype of the X-band accelerating structure for the EuPRAXIA@SPARC_LAB linac booster have shown excellent results, both in terms of the manufacturing process and performances, demonstrating the ability to achieve the nominal accelerating gradient. In the following months, testing activities will continue, aiming to complete high-power testing and reduce the breakdown rate. Simultaneously, an RF prototype with the nominal number of cells is under construction and will be tested at high power in 2025 to demonstrate its full functionality and reliability.

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