ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPORI23

HIGH-POWER TESTING RESULTS OF X-BAND RF WINDOW AND 45 DEGREES SPIRAL LOAD

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Abstract

The X-Band test facilities at CERN have been running for some years now qualifying CLIC structure prototypes, but also developing and testing high power general-purpose X-Band components, used in a wide range of applications. Driven by operational needs, several components have been redesigned and tested aiming to optimize the reliability and the compactness of the full system and therefore enhancing the accessibility of this technology inside and outside CERN. To this extent, a new high-power RF-window has been designed and tested aiming to avoid unnecessary venting of high-power sections already conditioned, easing the interventions, and protecting the klystrons. A new spiral load prototype has also been designed, built, and tested, optimizing the compactness, and improving the fabrication process. In these pages, the design and manufacturing for each component will be shortly described, along with the last results on the high-power testing.

INTRODUCTION

High-power RF (HP-RF) windows are crucial components used to isolate different sections of a vacuum line. When designing a RF window, the electric field on the surface of the ceramic window must be minimized, because high electric fields on this region could result in an electrical breakdown (BD) and eventually in the destruction of the ceramic itself. To be able to sustain high-power RF pulses, mixed-mode RF windows are normally used [1,2]. Based on this principle and in order to meet the requirement of the high-power X-Band test stands at CERN, a new design was proposed, optimized to sustain high peak power and high repetition rate.

High-power RF loads are components needed in many accelerator facilities, especially when using traveling wave structures, absorbing the remaining power after de acceleration. In X-band, due to the small size of the structures and the limited available space, new designs have been focused in making them more compact. A new concept of a spiral load has been developed at CERN, fabricated by additive manufacturing techniques out of titanium (3D metal printing) [3]. First prototypes were successfully tested on the high-power X-band test facilities (Xboxes) [4].

Recent designs are moving towards a more efficient fabrication procedure to overcome intrinsic limitations coming from the additive manufacturing process. Previous prototypes of spiral loads were printed at 45 degrees (Fig. 2 left) to avoid the horizontal segments and the associated waste of printed titanium volumes and supports. To improve the procedure of manufacturing, a new spiral load design was proposed [5] with an optimized cross-section and a twisted input waveguide, which allows horizontal 3D printing, with less support posts required and the possibility of stacking them vertically.

In these pages we will present the results obtained during the high-power tests of both components. The high-power tests were carried out at CERN, on the X-Band high-power test stand 3 (Xbox3) which consist of a combination of two 5.5 MW klystrons, feeding two test benches, providing up to 40 MW after pulse compression (50 ns pulse length), with a maximum repetition rate up to 200 Hz per line [6].

X-BAND RF WINDOW

The X-Band HP-RF window was designed to sustain up to 75 MW peak power. The design includes a mode converter from TE_{10} (rectangular) to TE_{01} (circular), which allows higher flexibility in terms of integration, taking advantage of the rotational symmetry of the circular mode. The electric field on the ceramic window was designed to be below 3.4 MV/m. To reduce the peak field, a ceramic disc of 65 mm of diameter was chosen. The thickness of the ceramic was defined as 2,43 mm and the transition, from the circular waveguide diameter to the window diameter was done in two-stages to preserve the required TE_{01} mode purity.

High Power Test

The historic of peak power and average power put into the window is shown in Fig. 1. The component was tested at different pulse length and repetition rate combinations, reaching up to 40 MW peak power at 150 Hz and 1.9 kW average power (35 MW peak at 200 Hz). Table 1 shows a summary of the main parameters measured during the processing. The RF window was tested up to the performance limits of the facility, and no breakdowns were detected.

Table 1: Measured Parameters on the Flat Regions

	R_1	R_2	R_3	R_4
Power [MW]	35	35	35	40
Average [kW]	1.47	1.9	1.6	1.64
Transmission [dB]	-0.19	0.18	-0.16	-0.15
Pulse Length [ns]	50	50	100	50
Repetition Rate [Hz]	150	200	150	150

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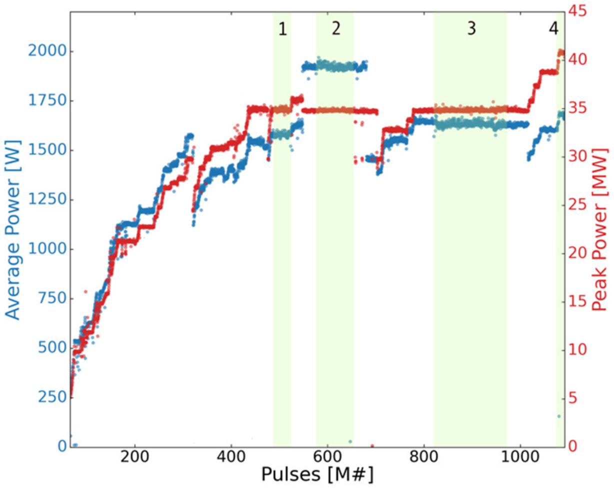

Figure 1: Historic of peak power and average power during the processing of the RF window.

45 DEGREES SPIRAL LOAD

The working principle of the spiral load is based on the "conduction losses" in which the power is absorbed when traveling through a waveguide made with lossy material, in this case titanium. First prototype (Fig. 2 left) was successfully tested on Xbox 3, reaching up to 35.5 MW peak power and 2.1 kW average power [4].

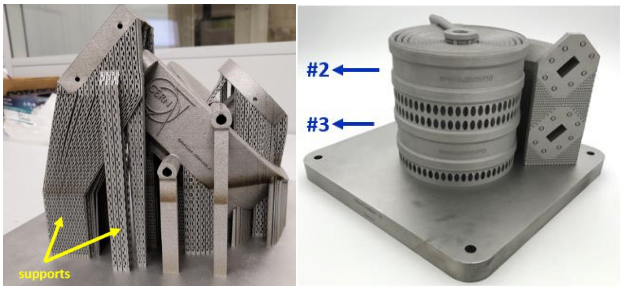

Figure 2: 3D printer loads in titanium; left: spiral load prototype with rectangular cross-section (requires 45 degrees printing); right: two spiral loads with hexagonal cross-section, manufactured in one single printing cycle.

In the new spiral load prototype, the cross-section of the waveguide was redesigned to a hexagonal shape (Fig. 3) and the RF input to the load (transition part in Fig. 4) was elongated and twisted 45 degrees [5]. The new design avoids horizontal segments and optimizes the 3D printing process, allowing to print more than one load in a single printing cycle. Figure 2 right shows the stack of two of these loads after one 3D printing cycle [7].

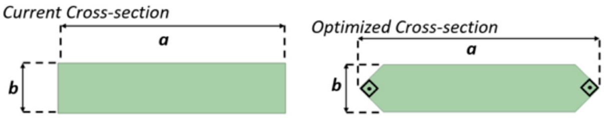

Figure 3: Comparison between the rectangular waveguide (left) and the optimized hexagonal cross-section (right).

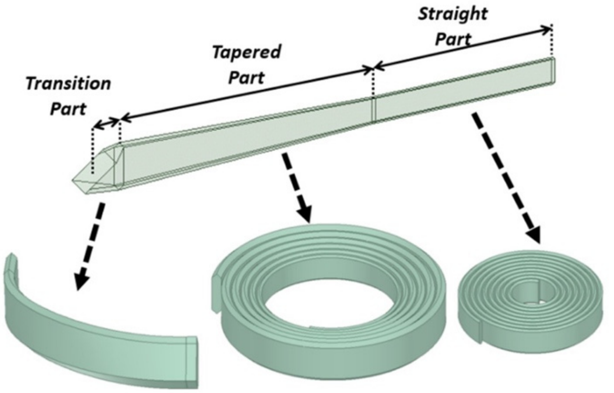

Figure 4: Functional segments used for the spiral load design.

High Power Test

The high-power processing of the spiral load was carried out at Xbox3, aiming to measure its performance at high power and its thermal behaviour. In order to do this, several temperature sensors were place around the spiral load and integrated on the DAQ system.

In the first stage of testing, overheating of the transition waveguide was observed (Fig. 5) the temperature of this region increased proportional to the average power, put into the load. This version of the design didn't include a water jacket around the transition waveguide, which turned out to be necessary. The temperature of the spiral load, embedded inside a water jacket, oscillated around 30 degrees. To keep under control the excess of temperature, a cooling block was installed on the transition region and the repetition rate was limited to 100 Hz. Although the high temperatures achieved of the centre of transition waveguide (around 190 degrees at maximum average power) the spiral load still operated normally.

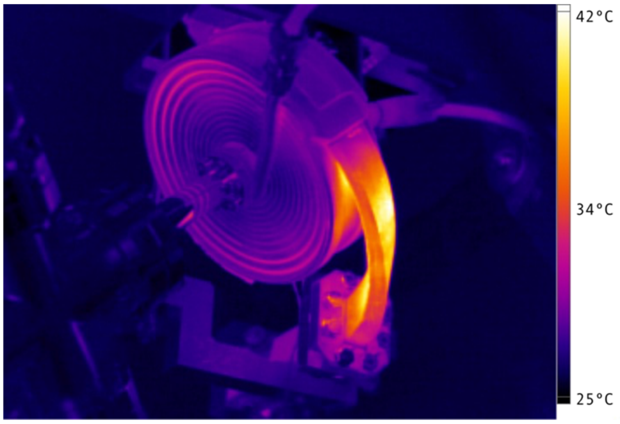

Figure 5: Thermal image of the spiral load.

Figure 6 shows the historic of peak power, average power and pulse length. The testing procedure consisted in raising the average power put into the load by increasing the pulse length and the peak power in separate steps, in order to determine the contribution of these parameters to the conditioning limit.

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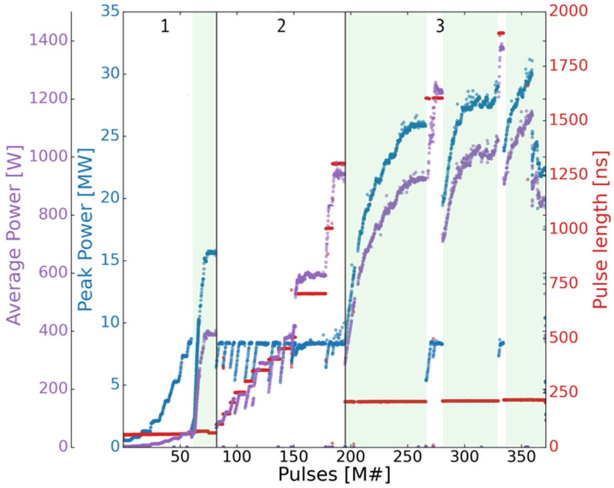

Figure 6: Peak power, average power, and pulse length during the processing of the spiral load. Green regions: pulse compression operation mode

The high-power processing was separated in three stages (Fig. 6). First, peak power was raised up to 15 MW with a 50 ns pulse. Then, with a maximum peak power of 8 MW, the pulse length was enlarged, in steps, up to 1.3 us. Finally, peak power was raised up the 30 MW with a pulse length of 200 ns. In the last stage, long pulses were interleaved to increase even more the average power, which didn't affect the number of BDs. In general, the spiral load operated up to 1.3 kW average power and a maximum peak power of 30 MW. The maximum peak power was limited by the load itself due to the occurrence of BD clusters.

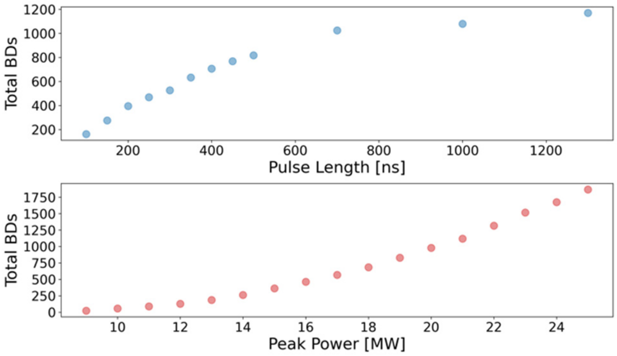

Figure 7: Total BDs accumulated in region 2 (top) and region 3 (bottom), defined in figure 5.

Figure 7 shows the total number of BDs accumulated by changing, independently, pulse length and peak power. The maximum average power considered in both cases was 900W. It can be observed that the number of BDs tended to stabilize when the pulse length is extended, but it kept growing as the peak power is raised. This shows the limited effect of the pulse length on the conditioning process which is mostly dominated by the peak power. In consequence, if the temperature of the load is controlled and after conditioning with peak power, the average power can be raised (increasing the pulse length or repetition rate) without requiring long stages of conditioning.

The performance of the spiral load at different temperatures, measured at the centre of the load, was also studied. To do this, the water cooling was stopped, and the operation was done at constant power and changing the repetition rate. Figure 8 shows that the reflected power ratio remained constant, independently of the temperature of the load, in a range from 35 to 98 degrees. This means that the spiral load can be operated at any of these temperatures with the same performance. Considering the amount of power that is absorbed on the spiral load, the possibility of operating them at high temperature, makes this component suitable to be part of a heat recovery system for a large accelerators facility [8,9], allowing to transfer the waste heat to other places, with the corresponding reduction on general power consumption.

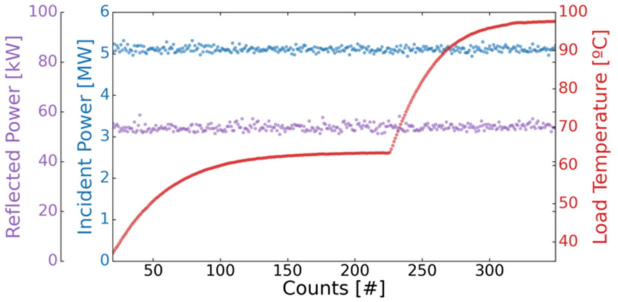

Figure 8: Spiral load performance at different temperatures.

CONCLUSION

Driven by operational needs of the X-band high-power test stands, two key components have been redesigned, manufactured and tested at CERN. The results on the RF window high-power test have shown its capability to sustain high-power and high repetition rate pulses, reaching up to 40 MW peak power at 150 Hz and 1.9 kW average power. The spiral load design has been optimized to improve the additive production procedure. The high-power conditioning has proven the stable operation up to 30 MW peak power, although the high temperature achieved on the transition waveguide. The studies performed have shown the limited effect of the pulse length on the conditioning process which is mostly dominated by the peak-power. Moreover, the spiral load performance has been proven stable in a wide range of temperatures, making it suitable to be part of a heat recovery system for a large accelerators facility.

REFERENCES

[1] S. Tokumoto *et al.*, "High power testing results of the X-band mixed-mode RF windows for linear colliders", in *Proc. 10th Int. Linac Conf. (LINAC2000)*, Monterey, California, USA, 2000, paper THA02.

[2] S. Yu. Kazakov, "A new traveling-wave mixed-mode RF window with a low electric field in ceramic-metal brazing area", KEK preprint 98-140, Aug 1998

[3] G. L. D'Alessandro, "Development of X-Band High Power RF Load for CLIC Applications Using Additive Manuf. Techniques", BSc. thesis, CERN, Geneva, Switzerland, 2015

[4] N. Catalan-Lasheras et al. "High power conditioning of X-band RF components" in *Proc. 9th Int. Particle Accelerator Conference (IPAC2018),* Vancouver, Canada, 2018 `doi: 10.18429/JACoW-IPAC2018-WEPMF074`

[5] H. Bursali *et al*. "X-band spiral load optimization for additive manufacturing mass production" in *Proc. 12th Int. Particle Accelerator Conference (IPAC2021),* Campinas, Brazil, 2021 `doi: 10.18429/JACoW-IPAC2021-MOPAB370`

[6] B. J. Woolley, "High-power X-band RF test stand development and high-power testing of the CLIC Crab cavity", PhD. thesis, CERN, Geneva, Switzerland, 2015

[7] H. Bursali, "Study of novel devices for compact accelerating structure", PhD. thesis, CERN, Geneva, Switzerland, 2022

[8] M. Seidel "Improving the energy efficiency of accelerator facilities", in *Proc. 6th Int. Particle Accelerator Conference (IPAC2015)*

[9] Johanna Torbernstsson "Heat recovery at European accelerator-based facilities – Possibilities and Opportunities", Master thesis 2014*,* Lund Institute of Technology, Lund, Sweden