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HIGH POWER CONDITIONING OF X-BAND RF COMPONENTS

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Abstract

As part of the effort to qualify CLIC accelerating structures prototypes, new X-band test facilities have been built and commissioned at CERN in the last years. In this context, a number of RF components have been designed and manufactured aiming at stable operation above 50 MW peak power and several kW of average power. All of them have been tested now in the X-band facility at CERN either as part of the facility or in dedicated tests. Here, we describe shortly the main design and manufacturing steps for each component, the testing and eventual conditioning as well as the final performance they achieved.

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Abstract

As part of the effort to qualify CLIC accelerating structures prototypes, new X-band test facilities have been built and commissioned at CERN in the last years. In this context, a number of RF components have been designed and manufactured aiming at stable operation above 50 MW peak power and several kW of average power. All of them have been tested now in the X-band facility at CERN either as part of the facility or in dedicated tests. Here, we describe shortly the main design and manufacturing steps for each component, the testing and eventual conditioning as well as the final performance they achieved.

INTRODUCTION

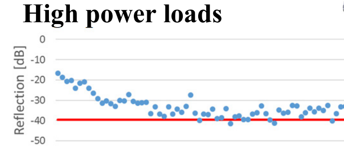
CERN has recently invested in developing X-band technology to test CLIC accelerating structure prototypes. A total of four independent testing facilities with a capacity to test up to six structures simultaneously has been built and is now fully operational [1,2]. The power supplied by these facilities is in the order of tens of megawatts even for very short pulses (ns). Considerable effort has gone into designing, manufacturing and testing X-band components capable of sustaining such high power. The design and manufacture of high-power broadband loads, bi-directional couplers, splitters, hybrids, variable power attenuator and phase shifters can be found in [3]. In this paper, we will report briefly the performance of some of these components in low and high power measurements. A second section will be dedicated to the pulse compressor and the operational results in the X-band testing facilities. The last section is dedicated to recent developments in loads produced by additive manufacturing and their performance at high power.

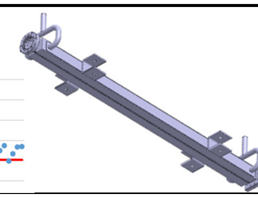
X-BAND COMPONENTS

A number of new X-band components has been designed by the CLIC collaboration and manufactured in industry in small series. They are now in operation in the test facility at CERN or in other collaborating institutes. High power loads and 3dB splitters have been described in [3]. Since a waveguide bi-directional coupler and pumping port have been added to the catalogue of high power X-band components available under the CERN open hardware license [4]. They are made out of milled oxygen-free copper and stainless steel parts joined by brazing. The main RF parameters measured during production are shown in Table 1 together with the maximum power during operation of the test facility. This power value has been reached with a 50 to 200 ns pulse and does not seem to depend on repetition rate. High power loads have reached 31 MW at 50 Hz and 30 MW at 200 Hz depending only on the power and attenuation from the upstream structure. None of these components is currently limiting the power delivered by the facility.

Table 1: Main parameters for each component type as measured during acceptance. Red lines are design values.

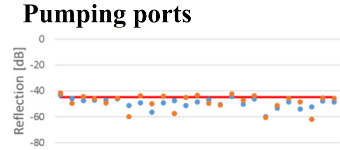
High power loads

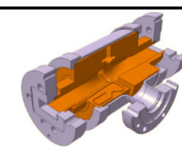




# of units	66
Reflection [dB] *(from later production)*	-36±2.8
P_{ave} in operation [kW]	0.81
P_{max} in operation [MW]	31

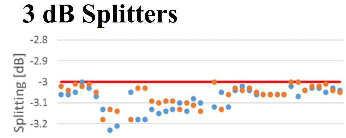
Pumping ports

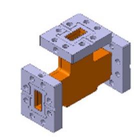




# of units	30
Reflection [dB]	-49±5
Transmission [dB]	(-0.05, -0.08)
P_{max} in operation [MW]	56

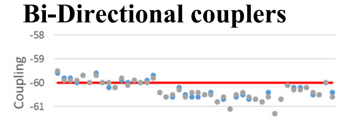
3 dB Splitters

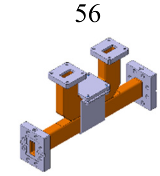




# of units	41
Reflection [dB]	-47±6
Splitting [dB]	-3.02±0.05
P_{max} in operation [MW]	56

Bi-Directional couplers





# of units	67
Coupling [dB]	-60±0.4
Directivity [dB]	-27.9±2.4
P_{max} in operation [MW]	56

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X-BAND SLED PULSE COMPRESSOR

Pulse Compressor

The pulse compressor designed and manufactured for the X-band test facility at CERN consists of two resonant cavities operating at the $H_{0.1.32}$ mode coupled through a double height hybrid [5]. Machining tolerances of the internal cylindrical geometry are on the order of 40 microns. The cavities are machined out of a single cylinder of OFE copper with a groove in the outside face for cooling. A mode converter and a coupling segment are brazed at the entrance of the cavity. A stainless steel jacket and vacuum manifolds are brazed to the outside copper surface. Tuning of each individual cavity is achieved through the manual machining of a fixed piston, which closes the volume of the cavity. After this, a double height hybrid is connected between the cavities which finishes the pulse compressor. Final tuning of the pulse compressor as a whole can be done by changing the temperature of the cooling water.

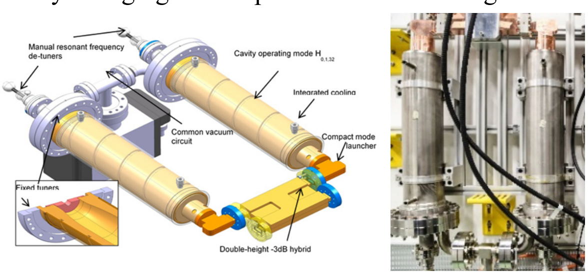

Figure 1: SLED pulse compressor 3D drawing (left) and as installed in the X-band facilities at CERN (right).

Pulse Compressor Commissioning

After tuning, the first pulse compressor was installed in the test facility known as Xbox2. A rectangular pulse is produced by the klystron on the order of 1 µs with a maximum power of 50 MW. During the typical conditioning of a structure, the pulse length to the structure is varied from 50 to 100, 150 and 200 ns by using the pulse compressor. At fixed pulse width, the power and thus gradient is ramped until reaching the nominal values for this structure. Data from Figure 2 are extracted from the successful conditioning of a structure in Xbox2.

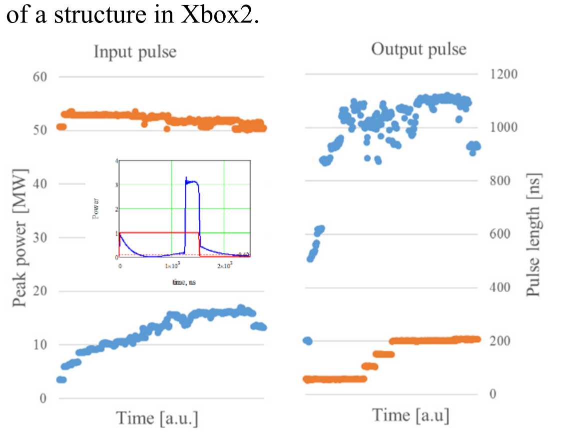

Figure 2: Peak power (blue) and pulse length (orange) before and after the pulse compressor during conditioning of a structure. On the insert, the shape of the incoming pulse (red) and the resulting output pulse (blue).

The compression factor is defined as the ratio between the input and output pulse lengths and it is a parameter of the system. The timing and shape of the phase flip are tuned to get a flat pulse of the required length. The gain, defined as the peak power ratio between compressed and uncompressed pulses, is given by the characteristics of the pulse compressor and ranges from 3 and 4 depending on the compression factor. The net power efficiency of the pulse compressor depends also on the compression factor and gain. As the pulse gets narrower or taller, the area under the $P(t)$ curve before and after the usable pulse becomes more important. For Xbox2, the energy in the compressed pulse is between 15 and 60 % of that in the original pulse and it can be easily calculated as the ratio between gain and compression ratio.

Taking the data from another run, a similar analysis has been done for the data relative to the pulse compressor in the test facility known as Xbox3. In this facility, the klystron pulse is longer and the peak power smaller (12 MW for a maximum pulse length of 2.5 µs). The pulse compressor for both test facilities shares the same design with small variations in the coupling to optimize to the longer input pulse.

Figure 3 shows gain vs. compression factor for both pulse compressors. For Xbox3 pulse compressors, we have chosen to operate at a gain value between 4 and 5 and very large compression factor (13 to 47) to reach peak power values on the order of 45 MW. The price to pay is a reduced power efficiency of between 10 and 25%.

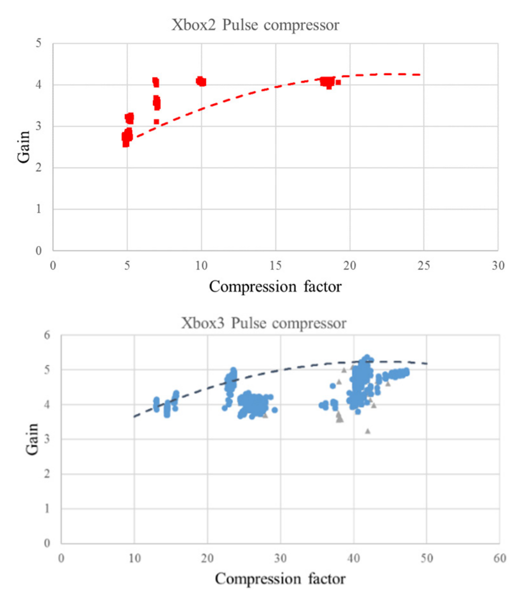

Figure 3: Gain as a function of compression factor for Xbox2 (top, red) and Xbox3 (bottom, blue). The dashed line represents the values calculated from low power measurements.

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3D PRINTED LOADS

In order to benefit from the recent advances in 3D printing technology, RF loads have been designed to be produced by additive manufacturing. This technology is not presently suited for copper but can be used on other conductive materials like aluminium, titanium or stainless steel. Titanium produces accuracy and roughness of around ±50 µm which makes it unsuitable for other components. Two kind of dry RF loads have been designed and manufactured and were recently tested in the CERN X-band facility.

Compact Load

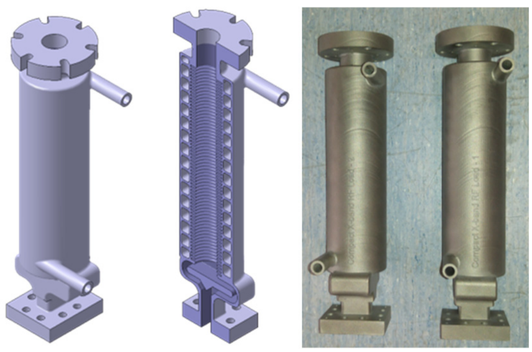

Figure 4: Compact load mechanical design and finished product printed from titanium at CERN.

The first load is a compact all-metal RF load based on a corrugated waveguide [6]. After some unsuccessful trials in industry, one example of this type was printed out of Titanium at CERN. The load was vacuum tight and the measured reflection was considered acceptable. It was installed in Xbox3 for dedicated high power tests. We observed that, unlike an accelerating structure, a breakdown in the load is only visible through vacuum activity as no significant reflected power is measured from the load. We did reach the maximum power under the condition of having a maximum vacuum level of 10^{-8} mbar in the load by increasing both pulse length and repetition rate. We observe that the power in the load is limited by a combination of peak power and average power (cf. Figure 5). The load can be used at relatively high peak power by keeping the average power low or at a considerable average power by keeping the peak power low. From the two points above the curve taken at a vacuum of $5 \cdot 10^{-8}$ mbar, we see that working at a higher vacuum level will shift the curve to higher power.

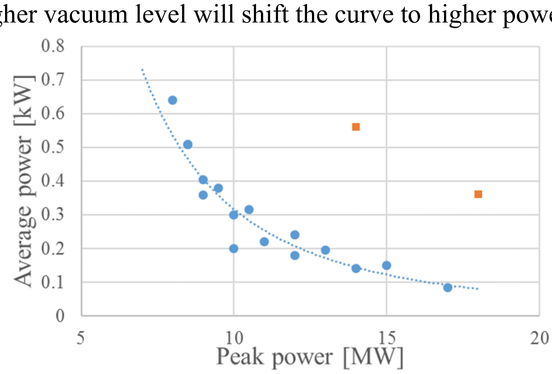

Figure 5: Power parameter space for the operation of the compact load measured at a vacuum level of 10^{-8} mbar. The two points in orange were measured allowing the vacuum in the load to degrade to $5 \cdot 10^{-8}$ mbar.

Spiral Load

A radically different design for a 3D printed load can be seen in Figure 6. This load is a tapered waveguide spiralling inwards for compactness. Vacuum pumping holes and water cooling are integrated in the spiral [7].

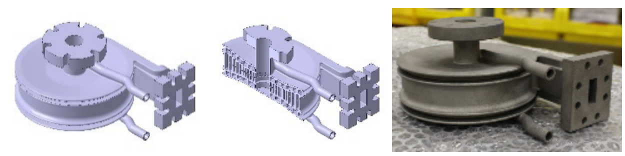

Figure 6: Spiral load RF and mechanical design and the final item manufactured out of Titanium at CERN.

A first load was manufactured in stainless steel and showed very high reflection during RF low power tests. The load was cut longitudinally by EDM and traces of material were seen inside the load traversing the waveguide. After mechanically removing this material, the two halves were mechanically clamped and RF tests showed a net improvement on the reflection, albeit not to the required value. A second unit has since been produced in a company and a third at CERN both made of titanium. This last load was installed in Xbox3 for a dedicated test of the performance. Breakdowns in this load are clearly visible through reflected power and the vacuum levels were good after a short time. We operated the load at pulse length of 50-200 ns and up to 200 Hz repetition rate. The load does not seem to have an intrinsic limitation. We tested up to the maximum available power in the line which was 35.5 MW peak power for 50 ns and 25 MW for 200 ns pulses always at 200 Hz. The maximum average power put into the load was 2.1 kW. A test of the second unit plus an improved version of the load is still pending.

CONCLUSION

The experience of testing CLIC prototypes has allowed the development of RF X-band components capable to perform in high power. They have now been validated through routine operation at high gradient and are available for use and manufacture under the terms of the open hardware license at CERN [4]. Besides the ones described in this paper, variable power splitters and phase shifters are currently under test and will be reported in the future.

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