C-BAND LOAD DEVELOPMENT FOR THE HIGH POWER TEST OF THE SWISSFEL PULSE COMPRESSOR

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Abstract

The SwissFEL C-band Linac will have 26 RF modules, each one consisting of a solid-state modulator and a 50 MW klystron that feeds a pulse compressor and four two meters long accelerating structures. The pulse compressor is of the Barrel Open Cavity type (BOC). A first prototype was successfully produced and high-power tested, reaching for full power klystron operation a peak power of 300 MW. For testing this BOC at maximum RF power, a broadband load was designed and built, based on a ridge waveguide design and high permeability stainless steel. Based on the experience gained at CERN for CLIC X-band high power loads, the RF design of the load was optimized to ensure high losses for a quite large range of magnetic steels. Test pieces were realized in three different magnetic steels to choose the best suited material commercially available.

This paper reports about the RF design, material study, production and impressive high power results of this C-band load.

POWER SPECIFICATION AND MATERIAL STUDY

High power loads commercially available in C-band frequency are usually specified to absorb maximum peak power in the range of 25 to 50 MW, according to the technology – dry or water loads – and the adopted RF design. Same loads can support average powers as large as 15 kW.

During the high power test of the BOC prototype performed in 2012 [1], the phase jump operation mode produced, for 50 MW power klystron, a compressed pulse of 300 MW peak power and 12 kW average power. In order to keep the waveguide setting of the high power test as simple as possible, no splitting of the power out of the BOC was carried out, using instead only one load to dissipate this so large peak power. For that a new load was studied to fulfill the power specifications of the C-band pulse compressor of the SwissFEL, having as major constraint high power losses in a compact RF design.

Similar constraints were at the base of the development of a new X-band high power load designed in the context of the R&D CLIC studies [2]. Here a magnetic lossy material such as the stainless steel AISI430 with magnetic permeability $\mu = 6$ h/m, together with a design based on a multiple ridge waveguide, allowed to fabricate a load 0.89 meter long. Because the power losses per unit length in waveguide scale with the frequency f like $f^{1.5}$ [3], assuming for the AISI430 the same permeability at 5712 MHz, a dry load as long as 2.55 m was needed to get the same total power losses in C-band. The problematic machining of such a long piece, together with the unknown μ value of AISI430 at C-band, pushed for the study of a new dry load both in terms of lossy materials and RF design.

Figure 1 shows, before welding, sections of three resonant 5712 MHz standing wave cavity pieces, made of three different magnetic steels with unknown permeability: AISI430, AISI431 and AISI420.

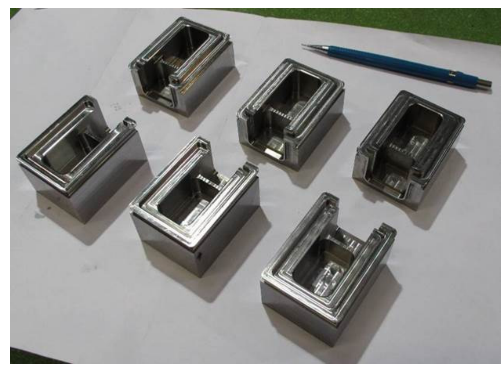

Figure 1: Sections of the cavity test used to determine the best magnetic steel for the load.

Low-power measurements of each cavity allowed to know the β coupling and the unloaded quality factor Q_0 for the three magnetic steels. Then the β and Q_0 measured values were used to obtain the ratios μ/σ between permeability and conductivity by means of the corresponding simulated curves, like in Figure 2.

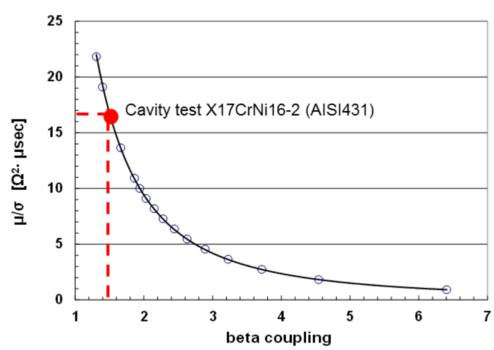

Figure 2: Simulated curve of the ratio μ/σ versus the β coupling. The red circle represents one of the tested material, the magnetic steel AISI431.

The final results of the three magnetic steels taken into account are summarized in Table 1. All the three tested materials are very similar. Because of the lower Q_0 and larger μ/σ ratio, the first choice was the AISI430, the same material as in [2], but its poor availability in the market led to accept the AISI431 as the magnetic steel for the C-band load.

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Table 1: Beta coupling, quality factor and μ/σ of the three cavities.

Material	β	Q_0	μ/σ [$\Omega^2\cdot\mu s$]
AISI431 (X17CrNi16-2)	1.45	420	16.0
AISI430 (X6Cr17)	1.40	409	17.1
AISI420 (X20Cr13)	1.50	428	15.2

RF DESIGN AND FABRICATION

In order to maximize the power dissipation, the RF design of the load was based on the ridge waveguide concept. Four main parts, shown in Figure 3, compose the design: firstly a taper increasing the WR-187 cut-off frequency, then a second taper matching the ridge waveguide profile to the third section of the constant impedance type, and a final standing wave SW cavity. A transition to the CF vacuum port terminates the load.

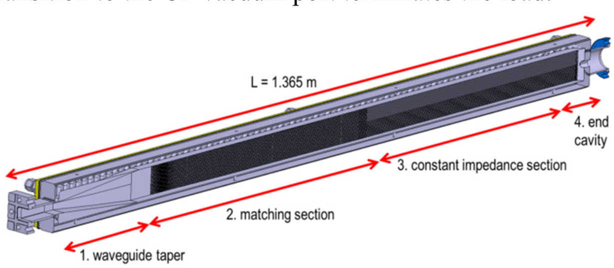

Figure 3: The four waveguide sections which compose the C-band high-power load.

The first taper sets the cut-off frequency f_c equal to 4.654 GHz. Then f_c is further increased, properly choosing the distance D between two opposite ridges of the constant impedance section, as shown in Figures 4 and 5.

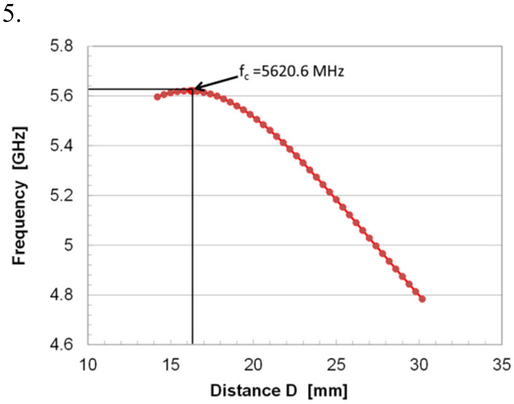

Figure 4: Cut-off frequency varying the distance D between two opposite ridges.

In the constant impedance section a good compromise between dissipated power per unit length and bandwidth was found operating with a cut-off frequency which was roughly 100 MHz below the nominal 5712 MHz. In order to minimize the derivative df_c/dD to be less sensitive to the mechanical errors, f_c was finally fixed equal to 5620.6 MHz, the maximum of the curve in Figure 4.

Figure 5 shows the ridge waveguide profile: a total of 28 ridges, with 2 mm period, forms the waveguide. The maximum electric field E_{max} is concentrated on the ridge extremities, circular noses of 1 mm diameter. For 300 MW input power, E_{max} is of the order of 46 MV/m, less than the maximum surface electric field of 66.4 MV/m experimented by the C-band accelerating structures of the SwissFEL Linac [4].

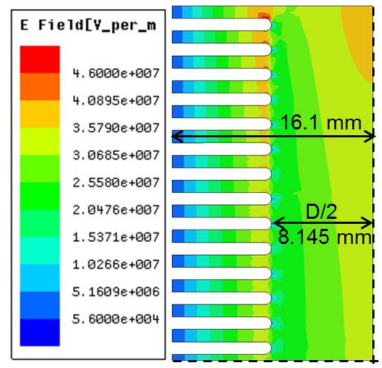

Figure 5: Electric field distribution for 300 MW input power over one quarter of the H-plane of the constant impedance section.

For μ/σ = 16 $\Omega^2\cdot\mu s$, the power attenuation in the constant impedance section is S21 = -50 dB/m.

The matching between the first taper and the constant impedance section is achieved by a second taper, designed such that the impedance Z varies linearly along the taper length. The plot in Figure 6 represents the profile of the ridge distance D varying the impedance of the taper.

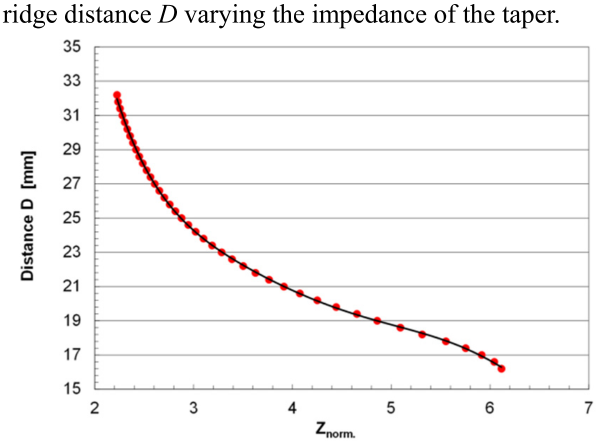

Figure 6: The distance D versus the impedance Z along the matching taper.

The length of this second matching taper was chosen in order to minimize the reflected power. Considering the taper as a 2-ports waveguide, it's possible to study the S11 reflection using the Riccati equation of the transmission lines:

$$\frac{dS11(z)}{dz} = -\frac{d(\ln \bar{Z}(z))}{2dz} + 2\gamma(z)S11(z) \quad (1)$$

where z is the position along the taper, $\bar{Z}$ is the impedance normalized to the initial value, and $\gamma(z)$ is the complex propagation constant, including losses, of the waveguide. Simulating the constant impedance section for different value of $\bar{Z}$, it's possible to obtain the behaviour of the transmitted P_t and dissipated P_l power along z, and so the

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taper attenuation $\alpha(z) = (dP_l/dz)/2P_t$. Because $\gamma(z) = \alpha(z)+2\pi i/\lambda_g(z)$, with λ_g the wavelength along the waveguide, it's possible to solve the Equation (1) iteratively and find the reflected power of the taper for different lengths. The results are shown in Figure 7.

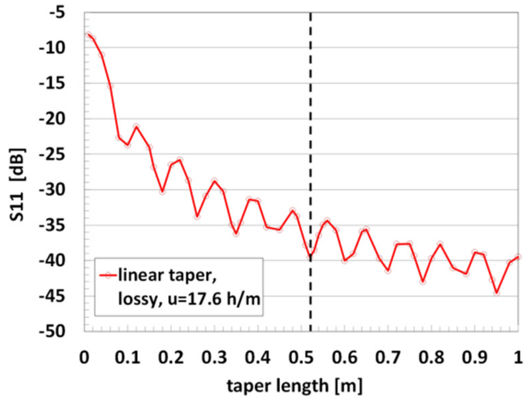

Figure 7: The taper reflection S11 for different lengths.

The length chosen for the taper was 0.52 m, corresponding to a local minimum S11 = -39.5 dB. HFSS simulation of the matching taper gives a reflected power S11 = -37.3 dB, in good agreement with the value provided by the Equation (1), and a transmitted power S21 = -13.5 dB.

With the final SW cavity the total length of the dry load is equal to 1.365 meter. Machining and brazing were performed by the Italian company CINEL [5], and low-power measurements of the load show a reflected power of -28 dB at 5712 MHz, and a bandwidth as large as 1 GHz for S11 < -20 dB. Figure 8 represents the frequency spectrum of the measured and predicted S11.

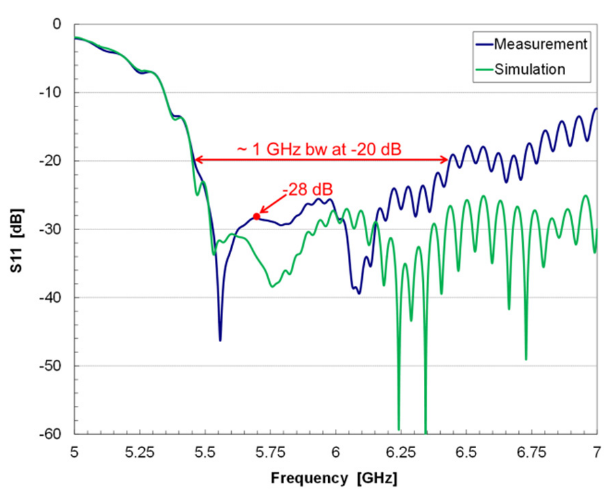

Figure 8: S11 frequency spectrum from cold measurement (blue line) e from analytical computation (green line).

The predicted S11 in Figure 8 is a result of HFSS simulations and post-processing analysis. Firstly the global S-matrix of the first three sections of the load was obtained from the product of the corresponding T-matrices. Then this S-matrix was combined with the reflection Γ of the SW end-cavity to get:

$$S11_{load} = S_{11} + \frac{S_{12}S_{21}\Gamma}{1 - S_{22}\Gamma} \qquad (2)$$

Taking into account the large frequency spectrum studied, the so computed reflected power can be considered a good estimation of the measured one.

HIGH POWER LOAD PERFORMANCE

The dry load was built for the high-power test of the BOC prototype, performed in the first four months of 2012 [1]. Before the installation in the test-stand, shown in Figure 9, the load was baked out up to 140 °C. After 8 weeks of BOC conditioning, operating in phase jump mode, 40 MW and 3 µs pulse from the klystron, at 100 Hz repetition rate, the load showed a breakdown rate BDR = $1.5\cdot10^{-7}$. In these conditions, the load was able to absorb 256 MW peak power. The maximum peak power dissipated by the load was 300 MW, produced by the BOC when the klystron operates at the full 50 MW power.

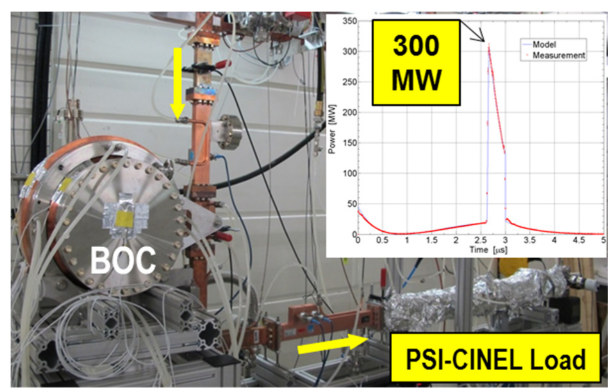

Figure 9: High-power test of the BOC prototype. The dry load absorbs up to 300 MW peak power produced by the pulse compressor in phase jump operation. In the plot the compressed pulse of the BOC.

Two vacuum pumps were located at the input and output of the load. In absence of breakdown events the vacuum levels in the load were stable around 10^{-9} mbar, but when a breakdown occurred, vacuum peaks larger than 10^{-8} mbar could be reached.

CONCLUSIONS

The fruitful collaboration with company CINEL allowed to successfully realize, in the frame of the high power test of the BOC prototype for SwissFEL, a C-band load based on ridge waveguide design and special magnetic steel. The load is characterized by a compact RF design, a very large bandwidth in term of reflected power – S11 < -20 dB in ~1 GHz frequency range – and it was able to absorb compressed pulses of the BOC as large as 300 MW of peak power.

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