

C-BAND RF PULSE COMPRESSOR FOR SWISSFEL

R. Zennaro, M. Bopp, A. Citterio, R. Reiser, T. Stapf
 Paul Scherrer Institute, Villigen, Swiss

Abstract

The SwissFEL C-band (5.712 GHz) linac consists of 28 RF modules. Each module is composed of a single 50 MW klystron feeding a pulse compressor and four two meter long accelerating structures. The pulse compressor is based on a single Barrel Open Cavity (BOC). The BOC makes use of a “whispering gallery” mode which has an intrinsically high quality factor and operates in a resonant rotating wave regime; moreover, and contrary to the conventional SLED scheme, a single cavity is sufficient to define the pulse compressor, without the need for two cavities and a 3-dB hybrid. A prototype has been manufactured and successfully tested. A short description of the BOC is presented, together with the prototype design, production, low level RF measurements, and high power test.

INTRODUCTION

In a BOC a generic $TM_{n,1,1}$ mode, where n is the azimuthal index, has a Q value equivalent to r/σ where r is the radius in the middle plane and σ is the skin depth [1]. Therefore the Q value is proportional to the diameter of the cavity and, in our case, the resonant mode $TM_{18,1,1}$ has been selected in order to provide a large enough Q factor while maintaining the size of the BOC reasonable small. In our case the production machines of the mechanical workshop constrain the maximum size. The coupling factor (β) has been defined in order to maximize the energy multiplication factor (M) for a given Q value, pulse length and filling time of the constant gradient accelerating structures [2]. The basic parameters of the BOC are reported in table 1.

Table 1: Main Parameters of BOC

| Pulse compressor | Design parameter |
|--------------------------------------|--------------------|
| Type | Barrel Open cavity |
| Frequency | 5.712 GHz |
| Resonant mode | $TM_{18,1,1}$ |
| Diameter | 492 mm |
| Number of coupling slots | 70 |
| Q | 216000 |
| Coupling factor (β) | 10 |
| Max. input power | 50 MW |
| RF input pulse length | 3 μ s |
| RF compressed pulse length | 330 ns |
| Energy multiplication factor (M) | 2.13 |
| Repetition rate | 100 Hz |

DESIGN AND CONSTRUCTION

The shape of the BOC resonator can be analytically defined in order to provide the required resonant frequency and Q [1]. The configuration and dimensions of the coupling slots and the external circular waveguide require finite element simulations in order to adjust the geometry to the nominal coupling factor (β) and minimize the reflected power. The size of the external waveguide is defined in order to provide phase synchronism with the rotating resonant mode in the inner cavity as shown in Figure 1.

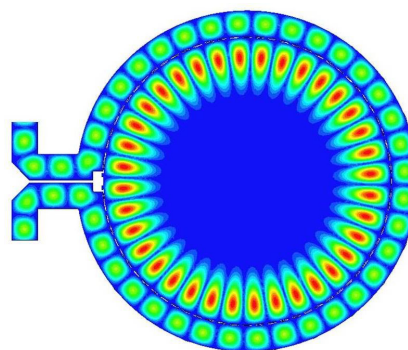


Figure 1: Snapshot of the magnitude of the electric field in an arbitrary colour scale in the middle plane.

The BOC is basically composed of an inner body which fully confines the inner resonator, two stainless steel cooling rings that also provide stiffness to the pulse compressor, an external copper ring to close the circular waveguide, and an input/output coupler. Two CF-300 blind flanges terminate the two extremities and in one of them is mounted the on/off mechanism that allows one to detune the BOC and to operate with uncompressed pulse; a silicon carbide HOM absorber is also mounted on the same flange as shown in Figure 2.

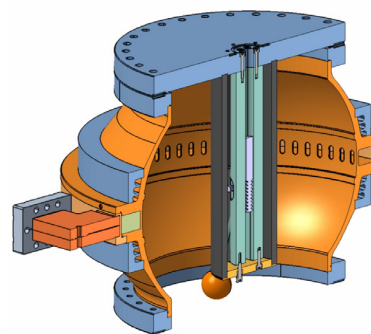


Figure 2: Section view of the assembled BOC.

The most critical geometrical parameter is the thickness of the wall between the inner resonator and the external waveguide. In order to get the required coupling factor this wall must be kept very thin (1.8 mm) and a careful study of the stress and deformation is required. Computations with ANSYS provide the stress during brazing, when the load is equivalent to half of the BOC weight, and during operation, when the load is mainly due to atmospheric pressure (1.25 Tons). The computed values must be compared to the yield stress for copper measured directly at 830 °C, which is the maximum brazing temperature and the measured yield stress of cold copper previously annealed up to 830 °C.

Warm and cold tensile tests over 18 samples provided a yield stress respectively of 3 and 18 MPa. ANSYS results give a maximum stress of 0.6 MPa and 12 MPa respectively for the brazing and operating case. Therefore the brazing is not critical in terms of mechanical stress and deformation, instead during operation under vacuum the maximum mechanical stress is only 30% lower than the yield stress although it is very localized as illustrated in Figure 3.

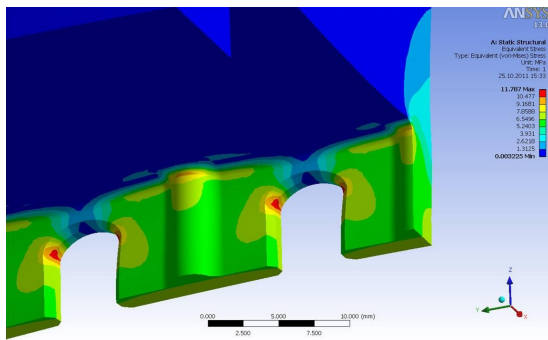


Figure 3: ANSYS computation of the stress due to atmospheric pressure, gravity and thermal load. In red the maximum stress (12 MPa).

A pre-prototype ring, reproducing the final geometry of the equatorial region of the BOC, was manufactured, brazed and successfully tested under equivalent atmospheric pressure and it confirmed the validity of the design. Finally the BOC prototype, shown in Figure 4 has been produced by the company VDL [3].

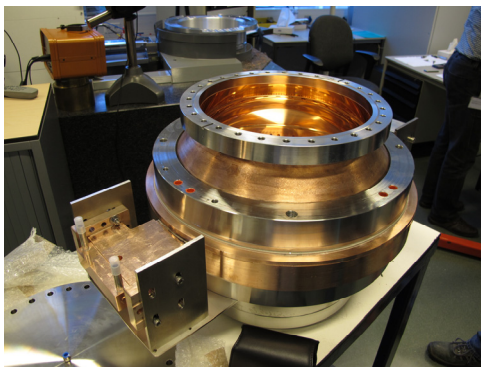


Figure 4: BOC prototype.

TUNING AND RF MEASUREMENTS

The BOC has two tuning rings placed symmetrical 30 mm from the mid plane. The tuning range is ± 8 MHz and is provided by machining these rings. Fine active tuning is also possible during operation by adjusting the cooling water temperature; in this case the tuning range is limited to ± 0.7 MHz. Before tuning the BOC prototype had a resonant frequency of only 1 MHz below the nominal one (5712 MHz+8MHz), consequently it was well inside the tuning range. The tuning procedure consisted of four steps as shown in Figure 5. The final frequency was 5712.08 MHz at the nominal temperature of 40 °C.

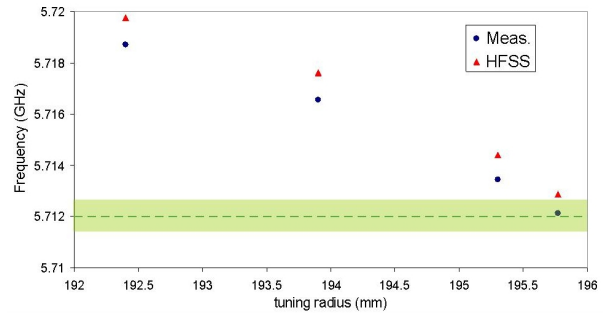


Figure 5: Tuning of the BOC. In blue the measured resonant frequency corrected for the nominal temperature (40 °C). The computed values are in red, the dotted line is the working frequency and the green band is the tuning range provided by regulation of the cooling water temperature.

Figure 6 shows the measurement of the impedance ($Z(f)$) in the complex plane in a 50 kHz range around the resonance. By adding an arbitrary phase the impedance is rotated in the detuned short position and the intercept with the real axis is equivalent to the coupling factor β while the Q is simply $f_2 - f_3 / f_1$ where f_1 is the resonant frequency and for f_2 and f_3 $RZ(f) = \pm IZ(f)$. The measured Q value of the BOC is 214000, only 1% below the computed value and the measured coupling factor is $\beta=10$ as from design.

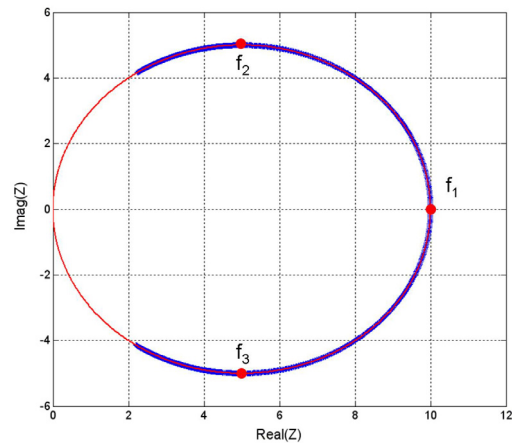


Figure 6: Complex impedance at the resonance and circular fitting.

The reflected power (S11) is measured as to -34 dB at the resonate frequency and is always below -28 dB in a ± 20 MHz range.

In order to study the neighbouring resonances, RF measurements were also performed in a large frequency range (100 MHz) and in three configurations: BOC open, i.e. without CF-300 blind flanges, in order to fully damp the HOM, closed BOC without HOM absorber and closed BOC with HOM absorber. In the first case there is no indication of any resonance while both the measurements with the closed BOC present a resonance 14 MHz below the working mode. This resonance has a very large Q ($Q=152000$), but couples very weakly ($\beta=0.02$). From HFSS computations this resonance corresponds to the $TM_{14,2,1}$ mode and is not damped by the silicone carbide HOM absorber. Because of the very low coupling and the fact that it is outside the klystron bandwidth, this resonance does not represent a problem for the operation.

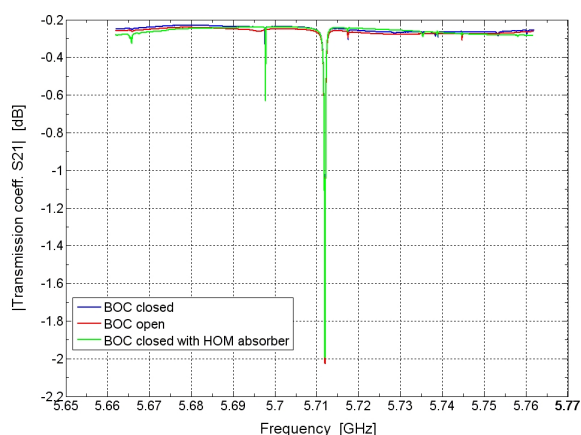


Figure 7: S_{12} measured in 100 MHz range.

CONDITIONING AND POWER TEST

The power test was made in the PSI test stand TRFCB (Test RF for C-Band) equipped with a SCANDINOVA K2-2S solid state modulator and a Toshiba E37210 klystron operating at 50 MW 100 Hz.

To absorb the compressed pulse (up to 300 MW peak and 12 kW average power) a special magnetic steel (AISI 431) load was designed in PSI and produced by the company CINEL [4].

After only two weeks of conditioning without any bake-out the HOM absorber and the on/off mechanism were removed because of the large outgassing of the silicon carbide. The complete conditioning required over 8 weeks (24/7) to reach the maximum available RF power from the klystron i.e. 50 MW for 3 μ s. The main limitations were the outgassing of the load and breakdowns in waveguides and also in the BOC itself. After the long conditioning, a BDR (breakdown rate) equivalent to $5 \cdot 10^{-7}$ was measured for 40 MW, 3 μ s operation. This result is encouraging considering that to provide the nominal gradient of 28.5 MV/m a power of 35 MW is required. The compressed pulse measured in TRFCB fits well with the predictions from the model

assuming the measured Q (214000) and β (10), as shown in Figure 8.

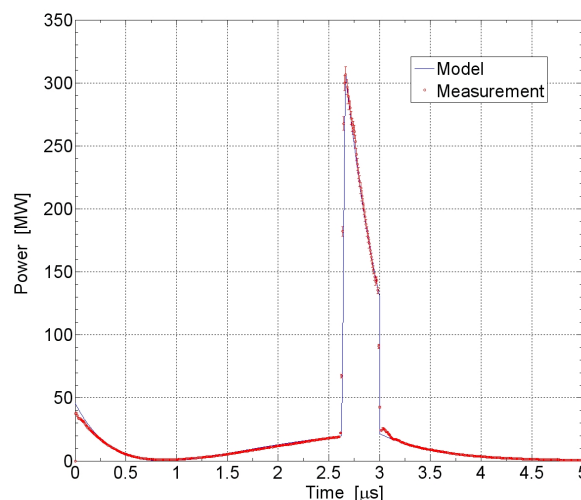


Figure 8: Compression of a 50 MW, 3 μ s rectangular pulse.

CONCLUSIONS

The RF and mechanical design of the BOC resonator have been almost fully qualified for the serial production of 28 units. Only the on/off mechanism needs further power test and the HOM absorber is not required. Test of the BOC with the final cooling station is necessary to investigate the temperature stability.

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