THE SWISSFEL C-BAND RF PULSE COMPRESSOR: MANUFACTURING AND PROOF OF PRECISION BY RF MEASUREMENTS

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Abstract

A pulse compressor is required to compress the RF power distributed to the four accelerating structures of a single C-band (5.712 GHz) module of the SwissFEL. The pulse compressor is of the barrel open cavity (BOC) type. A total of 26 BOC devices are necessary to operate the linear accelerator (26 modules or 104 C-band structures) of SwissFEL X-ray laser. The C-band BOC combines the advantages of compactness and large RF efficiency i.e. large compression factor. Key features of the BOC are described and how they have been implemented in the manufacturing and tuning processes. RF measurements of the BOC are presented to account for the mechanical precision reached by manufacturing. So far 4 BOCs have been manufactured in-house and one has been high power tested in a RF test stand to simulate the operation in SwissFEL.

INTRODUCTION AND OVERVIEW

The linear accelerator (LINAC) of the SwissFEL consists of 26 C-band modules each of 4 pieces of 2m long C-band structures made of copper discs and supported on two granite girders. The waveguide system of each module is fed through a pulse compressor made of the barrel open cavity (BOC) type [1]. It is mounted on top of one end of the module as depicted in Fig. 1.

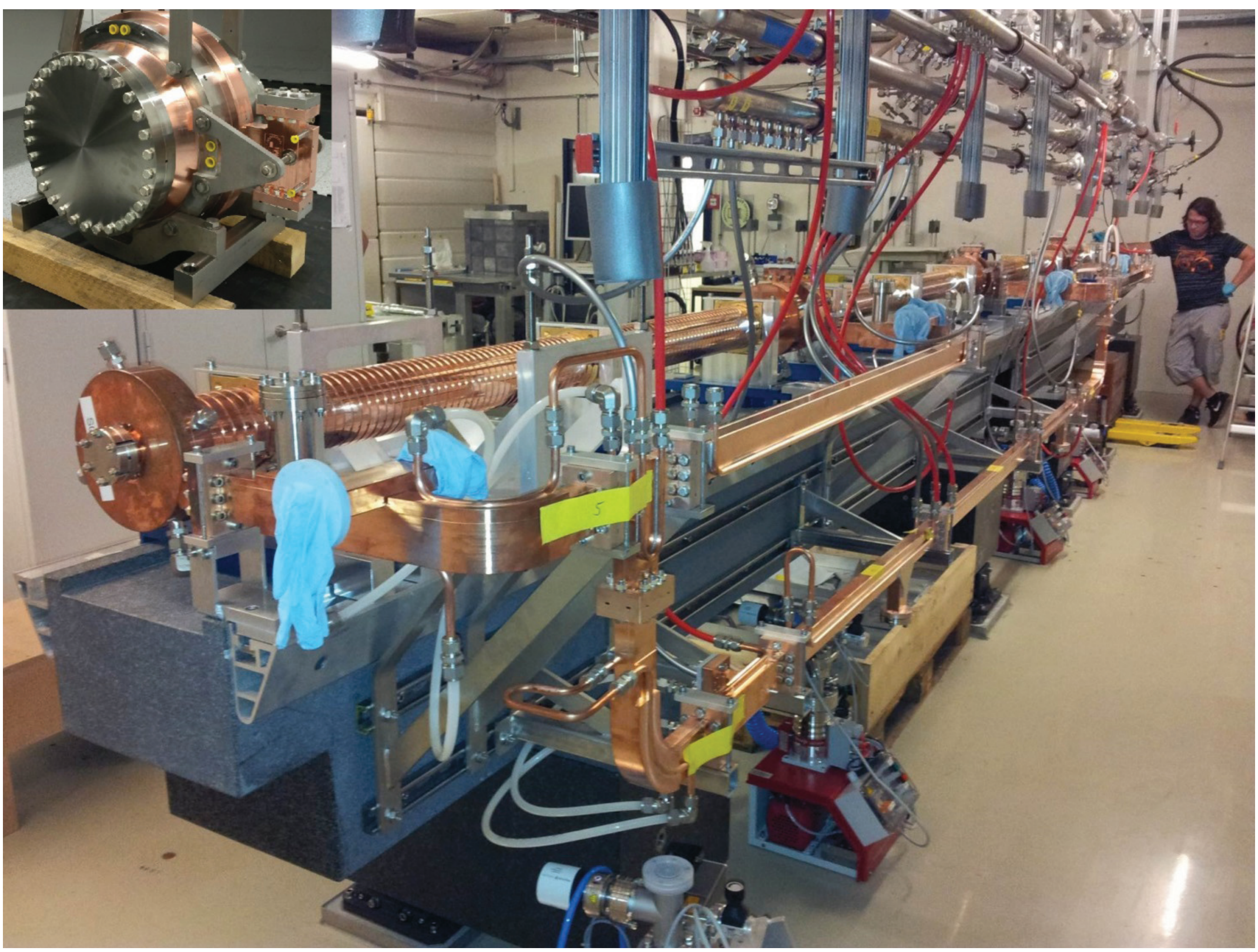

Figure 1: One C-Band module consists of 4 C-band structures made of copper discs and supported on two granite girders. The waveguide system is attached laterally on the girders. On the top left side of the module the pulse compressor BOC will be mounted (note inset photography on top, left).

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The design and construction have been thoroughly tested on a prototype BOC made by VDL company in Netherlands. As a result the RF and the mechanical design of the BOC resonator have been qualified for the series production of at least 26 units. An on/off mechanism and an absorber inside the prototype BOC have been removed because they were unessential during testing and because of outgassing problems of silicon carbide parts [2].

The BOC for the SwissFEL is of a new design and uses the whispering gallery resonant mode TE18,1,1. The RF efficiency is determined by the quality factor Q (the ratio of stored energy and power loss in a pulse compressor) and by the coupling factor β (between RF field of external waveguide and of resonance body of compressor). The β value has been optimized to maximize the multiplication factor M for a given klystron pulse length, Q_0 value and filling time of the accelerating structures [2]. For the main design parameters see Table 1.

Table 1: Main Parameters of BOC

Pulse Compressor	Design Parameter
Frequency	5.712 GHz
Quality Factor Q	216'000
Coupling Factor β	10
Energy Multiplication Factor M	2.13

The mechanical setup of the BOC is depicted in Fig. 2:

- The inner copper ring (large copper body of diameter 492 mm and height 290 mm) fully confines the resonator with 72 coupling slits.
- The outer copper ring composes part of the waveguide coupled to the inner cavity.
- Two stainless steel rings provide the water cooling to the cavity and make the body stiffer.
- One T-shaped copper piece for input and output RF signal and 2 C flanges close the inner copper ring.

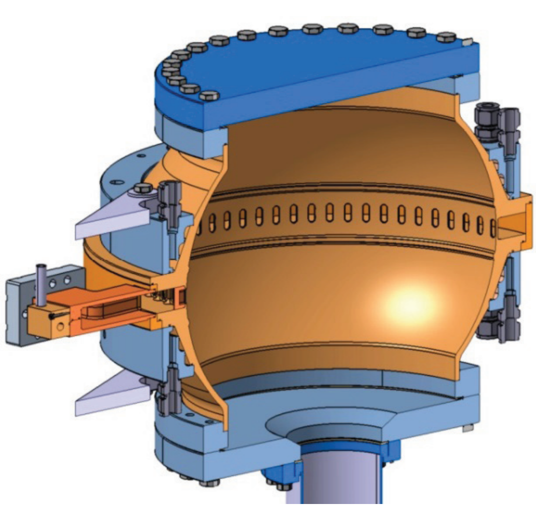

Figure 2: Cross section through the BOC and its parts.

The BOC is mounted on a frame on top of the C-band module. The total weight is about 80 kg. It has a very small impedance for vacuum which allows one vacuum pump to be directly connected to the bottom of the cavity.

MANUFACTURING

The manufacturing of C-band RF pulse compressors BOC has to conform to stringent requirements to minimize cost and to achieve a stable process for an economical industrial series production over years:

- Target precision on the inside of the copper body of +/- 10 µm with a surface roughness R_a of 0.2 µm
- After milling and final brazing the resonant frequency of the BOC (in whispering gallery mode) match the specified klystron frequency (5.712 GHz)
- The tuning range is +/- 7 MHz and is provided by machining two tuning rings placed symmetrical from the mid plane while measuring the resonant frequency achieved through a network analyzer.
- Each month a complete C-band module with one BOC has to be manufactured until spring 2016.

Encouraged by the results of a test BOC [2] we have developed, built and improved the equipment necessary to produce in-house the 26 units of BOC's and to meet the requirements as summarized above. Whenever possible we use pre-machined components to start with and work in parallel when appropriate. In this paper we report on the procedures and handling equipment of the manufacturing process and on the mechanical test results to meet the stringent requirements.

Manufacturing Process

The copper for the BOC pulse compressor is oxygen free, high-conductivity and forged in three-dimensions. Because of the forging-process we have a homogenous distribution of only small pores (not detectable with ultrasonic probes), a stress-free and inherently stable material due to the additional heat-treatment (forging) with a rather large grain size of about 400 µm. To achieve the precision required for the inner and for the outer copper ring the stress-free material is mandatory even if chip formation is less favourably for large grain size. On the other hand this is related to large grain boundaries which are less prone to breakdowns in high-voltage RF fields (from the klystron, i.e. 50 MW for 3 µs at 100 Hz).

The BOC production steps are summarized as follows:

- Pre-turning, annealing and cleaning of inner copper ring and stainless steel rings and flanges
- Precise turning after annealing of the outer surface of the inner copper ring and of the stainless steel rings and flanges to fit the contour of the inner copper ring
- In-house turning, milling and cleaning of the outer copper ring, copper pieces and stainless steel plates for the T-shaped RF coupler
- Brazing of the inner copper ring with stainless steel rings and flanges (vacuum furnace, 850°C)

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- Brazing of the copper and stainless steel parts to the T-shaped RF coupler (vacuum furnace, 850°C)
- Precise milling and turning of the inner surface of the inner copper ring and of the coupling slits (with a wall thickness of only 3 mm)
- Cleaning and final brazing the BOC body with the outer copper ring and with the T-shaped RF coupler in a vacuum furnace at 780°C.
- Tuning by turning the two tuning rings (symmetrically located above and below the mid-plane of the inner copper ring) to match the target frequency of 5.712 GHz
- Final cleaning, annealing and mounting on a frame ready for installation on a C-band module

Equipment used for Manufacturing

For the precise milling and turning of the copper we use a sturdy 5-axis CNC machining center (Hermle C42 U MT) with an actively driven swivelling rotary table as depicted in Fig. 3.

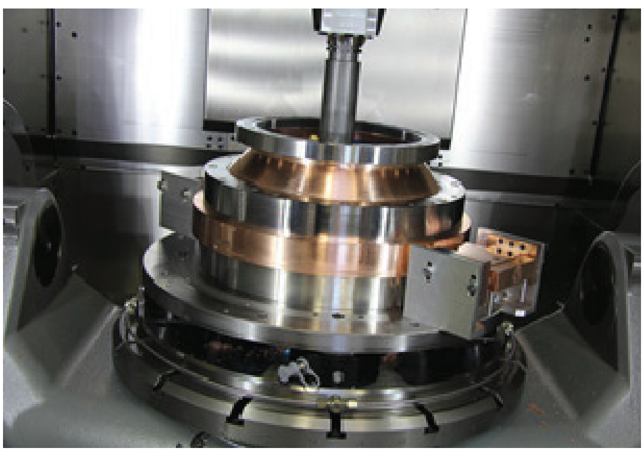

Figure 3: Pulse compressor BOC mounted in a zero-point clamping system on the swivelling rotary table of the CNC machining center Hermle C42 U MT.

The milling is based on a gantry construction type. The turning tools were adapted to fully reach the inner surface of the inner copper ring. A defined sequence of cuts (each cut prepares the next one) with poly- and mono-crystalline diamond (PCD, MCD) tools is required in a temperature and humidity controlled machining compartment of the milling-machine. With this we finally reach a measured precision of +/- 10 µm on the inner copper surface with an estimated surface roughness of R_a of 0.2 µm.

For quality control of shape and position tolerance we use a precise coordinate measuring machine Mitutoyo Legex with a base precision of 0.35 µm. The BOC has a reference plane and a lateral surface area. The quality assurance is performed always related to the same reference plane. For the brazing fit we need to know the shapes of the inner and outer copper rings, of the flanges and of the stainless steel cooling rings and of the T-shaped RF coupler. For the radio frequency application of the BOC we need to know the inner surface shape of the inner copper ring (equal to two displaced spheres) and position and shape of the tuning rings.

We use ultrasonic cleaning (with degreasing, de-oxidisation and prevention of re-oxidisation in separate baths) at 80 kHz and 60°C (see Fig. 4). After flushing with tap and de-ionized water and hot dry air drying the copper and stainless steel parts are stored in dry nitrogen gas or the BOC is filled with dry nitrogen gas and closed.

Figure 4: Ultrasonic cleaning of a BOC pulse compressor in one of the aqueous chemical liquids.

Figure 5: For the first brazing at 850°C three BOC pulse compressors in their solder gauges are arranged in a frame (total weight 640 kg) which is on a stationary table.

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For heat treatment (annealing for stress relief at 250°C for 2 hours) and brazing we use a vacuum brazing furnace. The furnace is a full metal construction and operates up to 1'250°C in UHV vacuum (< 10^{-6} mbar). It has been custom made by the PINK company (Germany). It has a rigid platform and a vertical movable dome with 9 programable heating elements. The total height is 8.5 m and the working height inside is 2.8m when the furnace is open. The usable working diameter is 0.8 m. The resulting working volume can accommodate up to three BOC's fixed in solder gauges and placed in a frame on top of each other (see Fig. 5). A series of thermocouples measures process temperatures along the copper bodies while operating the vacuum furnace for brazing. Because of the total mass and the brilliant surface finish of the copper the brazing process is rather slow (18 h).

For adequate handling of the BOC and its parts we have constructed and built a number of tools in-house. Among others the most important are:

- Zero-point clamping system for the BOC body to ensure reproducible setups within 10 µm
- Special lathe tool (280 mm long) to fix diamond tools and to allow turning of the full inside surface of the inner copper ring of the BOC
- Round supports with three-point bearings for levelling the BOC on the coordinate measuring machine to ensure proper measurements with respect to the reference plane of the BOC
- Positioner with a controlled center of rotation for crane operation to allow a defined and safe rotation of the BOC by 90° to its final mounting position

TUNING

The RF (cold) measurements check the frequency mismatch of the structure with respect to the nominal frequency f_ nom of 5.712 GHz at the nominal operating conditions after turning a defined sequence of the two tuning rings (see Fig. 6).

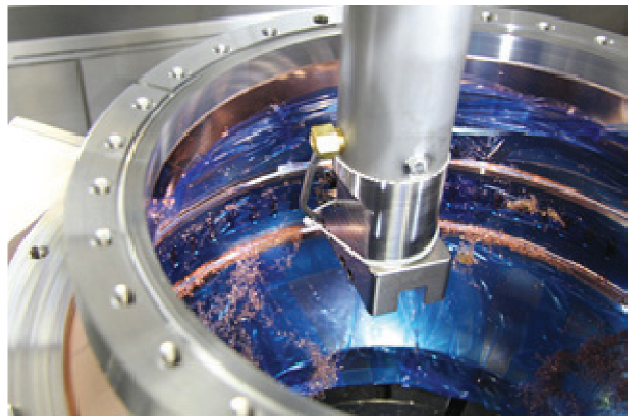

Figure 6: Turning on tuning rings with diamond tool.

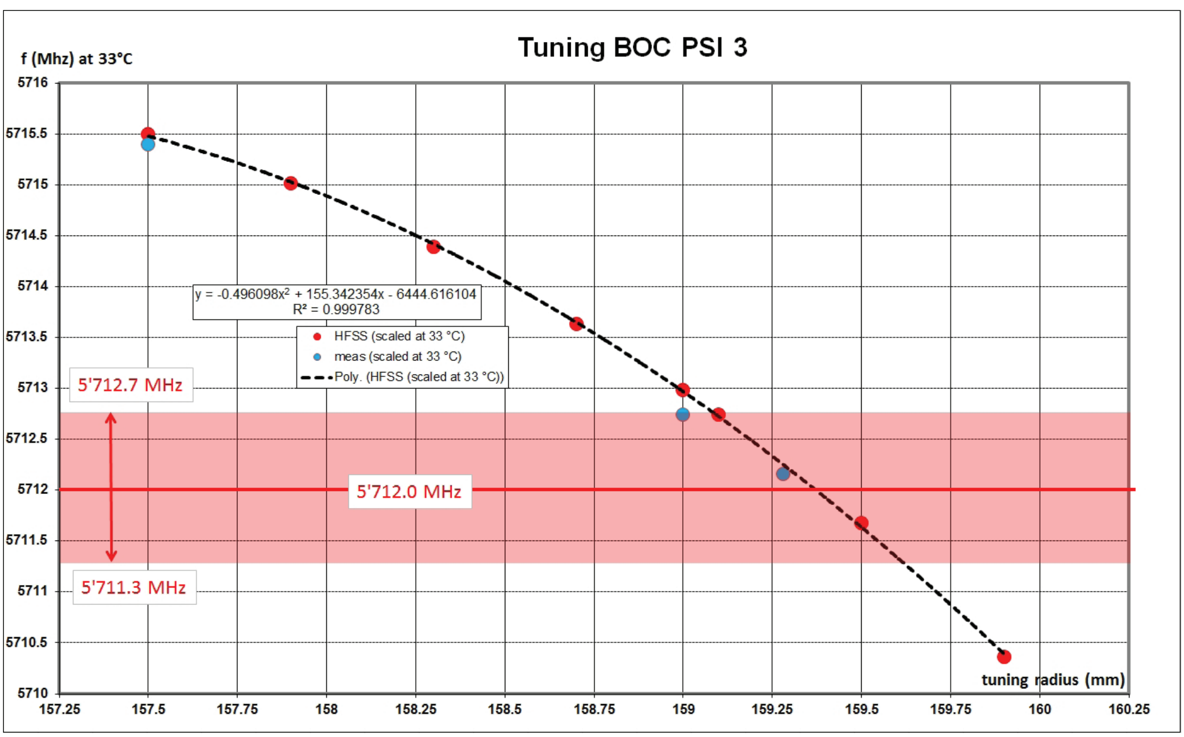

Figure 7: Measured tuning radius and resonant frequencies of BOC (blue dots) and calculated tuning radius and resonant frequencies (red dots). The range of tuning accessible through water cooling of the BOC (corresponds to 5'712 MHz +/- 0.7 MHz) is dashed in red and needs no further turning of the tuning rings.

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#	Maker	Tuning steps	f (MHz)	Q_0	Power test	Breakdown rate [1])
0	VDL	4	5711.952	219000±4000	✓	$3 \cdot 10^{-8}$ (35 MW; phase jump) (1) $2{*}10^{-8}$ (40 MW phase modulation) (1)
1	PSI	4	5712.061	226000±4000	✓	$1{*}10^{-7}$ (40 MW phase jump) (2)
2	PSI	3	5711.944	225000±4000	-	-
3	PSI	2	5712.159	218000±4000	-	-
4	PSI	0	5711.979	217000±4000	Next test	No tuning
5-8	PSI	0	Under production			
9-30	PSI	0	Series production			

Figure 8: Measured parameters of resonance frequencies, quality factor Q_0 and power test with breakdown rates.

Referring to Fig. 7 this is expressed by increasing the radius of the tuning rings as a measure of increasing volume of the inner copper ring. The measurements are plotted against simulated data (code HFSS in ANSYS) to determine the next sequence of milling until the resulting frequency is sufficiently close to f_nom. In this case, quality factor Q_0 and coupling factor β are determined as well as the resulting frequency f_meas by the network analyzer. In practice no mechanical tuning can be performed for f_meas – f_nom < 0.2 MHz since this corresponds to a dimensional change of < 34 µm or equivalent to a 2°C change.

The RF cold measurements are given below (Fig. 8):

- The values for Q_0 and β agree well within 1% to the designed values. This confirms the high precision machining and brazing of BOC pulse compressors.
- The frequency mismatch can be easily compensated by changing the operating temperature within +/- 7°C (corresponds to +/- 0.7 MHz or to +/- 50 µm).
- Starting with BOC number 4we have verified that the manufacturing is precise enough that no extra mechanical tuning (turning of tuning rings) is necessary. The tuning to resonance frequency f_nom (5.712 GHz) is performed by adjusting the cooling temperature within +/- 7°C.

Referring to Fig. 9 for power testing of the BOC pulse compressor the input power from the modulator is 15 kW at 5.712 GHz. Peak power at the output of the BOC is 53 MW for 3 µs at 100 Hz. We have observed breakdown rates of $3 \cdot 10^{-8}$ at 100Hz (1 breakdown in 93 h).

CONCLUSIONS

Up to now 4 BOC pulse compressors have been manufactured and tested on site one of which has no tuning rings. This makes the manufacturing process shorter and less risky for possible break-downs (no chips and no additional cleaning after chip production due to tuning). The mechanical precision required as well as the very good results of RF and power-testing are very well accomplished through the manufacturing processes. The next power test with a complete C-band module and with BOC number 4 is planned in spring 2015 when a new modulator becomes available.

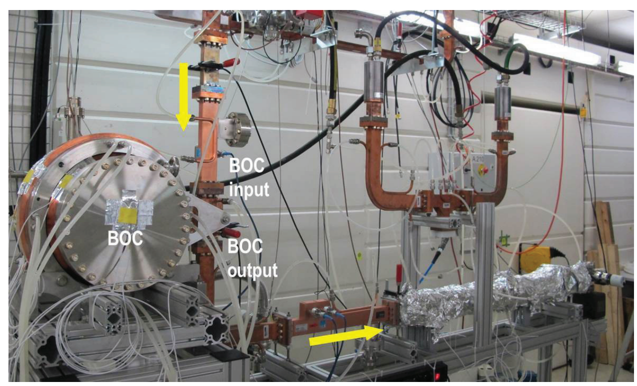

Figure 9: Setup for power testing of the BOC.

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