STATUS OF THE MANUFACTURING PROCESS FOR THE SWISSFEL C-BAND ACCELERATING STRUCTURES

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Abstract

For the SwissFEL project a total of 104 C-band (5,712 GHz) accelerating structures are needed. After developing and radio frequency (RF) testing of several short structures (0.5m), three 2meter prototypes have been produced successfully in-house. Avoiding any RF-tuning after fabrication, a high precision machining of the components is necessary. Special procedures were developed and handling equipment was built in order to maintain the accuracy during stacking and vacuum brazing of the parts for the C-band structures. This paper summarizes the manufacturing techniques and the mechanical test results.

INTRODUCTION AND OVERVIEW

The linear accelerator (LINAC) of the SwissFEL consists of 104 C-band structures each of 2m length. They are aligned along a row of 300m and are used to accelereate an electron bunch to an energy of 5.8 GeV before the lasing process is initiated in the subsequent undulator section.

The manufacturing of C-band structures 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 of one single copper cell of +/- 2 µm with a surface roughness R_a of 25 nm
- After brazing all individual volumes of the 108 copper cells match the specified klystron frequency (5'712 MHz) and the nominal phase advance of 120°
- Perpendicularity of less than 50 µm before and after vacuum brazing of 108 copper cells and of two J-couplers to produce one 2m C-band structure
- Therefore no additional tuning of each individual cell and iteratively measure its frequency would be required after brazing

Encouraged by the results of test structures [1] we have developed, built and improved the equipment necessary to produce the 2m C-band structures to meet the requirements as summarized above. 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. The results of RF and power testing of the first 2m C-band structures are reported in a companion paper of this conference.

MANUFACTURING

The manufacturing process of a copper cell is summarized in [1] when building short test structures. In this paper we describe in more detail how we have proceeded to achieve the precision required to meet the stringent specifications of the C-band LINAC.

Machining

The copper for the C-band cells 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 per cup 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 high-voltage RF fields (28 MV/m at 5'712 MHz).

The raw-cut copper pieces are first pre-turned on a conventional and numerical controlled lathe to a precision of about 10 µm. The finish of the cups to a precision of +/- 2 µm is performed on a sturdy and pneumatically stabilized slanted bed lathe (Hembrug) as depicted in figure 1. 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 lathe.

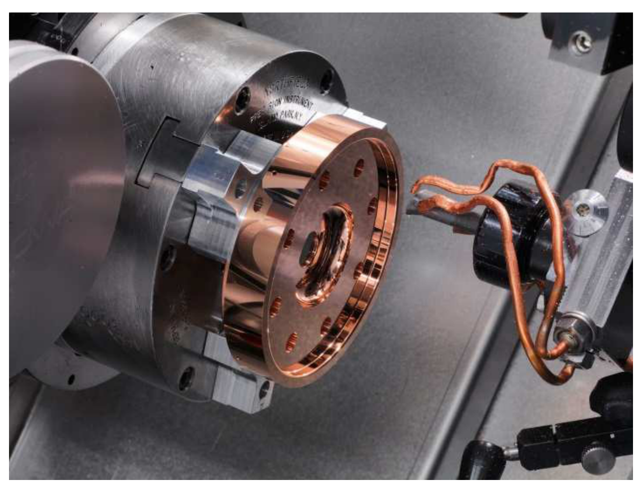

Figure 1: Copper cup in chuck of slant bed lathe after machining with monocrystalline tool.

For this purpose and for the blowing air for machining the copper we use ambient air of the temperature-controlled and air-conditioned room (18.50°C +/- 0.1°C at less than 50% relative humidity and oil-free). With this we finally reach a measured precision of +/- 2 µm on the copper cups. Heat input on the copper cups is mainly caused by the edge of the turning diamond tool. Due to temperature fluctuations during the day while two people

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are working on the lathe (typically 18.5°C to 20.5°C +/- 0.1 °C) and due to the thermal expansion coefficient of copper of 16.8 * 10^{-6} /°C (below 100°C) we expect a +/- 2 µm linear change of length for +/- 1.0°C. For cooling of the machined cooper we use the minimal quantity lubrication system SKF (brand of Hembrug).

For the base calibration of the lathe we use two calibration rings of hardened steel of a diameter of 100.0 mm and 115.0 mm, respectively and certified to 1 nm. With these rings we calibrate the concentricity and the flapover of the lathe together with the inline measuring system (Renishaw CMP 400, +/- 0.25 µm).

Shape and Position Tolerance

To program the cutting sequence with PCD and MCD tools we start with 4 cups which are measured after PCD and MCD cuts on a precise coordinate measuring machine (Mitutoyo Legex with a base precision of 0.35 µm). Then we do the quality assessment by measuring the form and the position tolerance of the 4 cups.

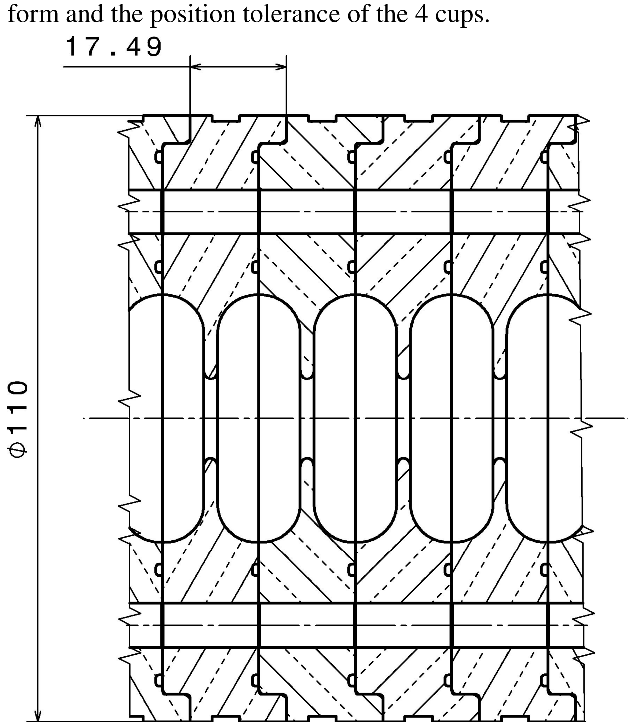

Figure 2: Part of stacked copper cups and diameter and thickness of one cup are indicated.

The cups are rotational symmetric disks with a male and a female side. An overview of cup arrangement as part of the stack is depicted in figure 2. The cups have 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 averaged thickness of the disk and the ledge of the male and of the female plane. For the radio frequency application we need to know the shape of the iris defined by inner diameter, thickness and the distance between two subsequent irises of the cups.

Cleaning

After this verification we machine all the 108 cups required for one 2m-long structure in one sequence and with the same set of PCD and MCD tools. After machining we clean the cups with rubbing alcohol and after 24 hours of acclimatisation we verify with a coordination measuring machine that all 108 cups are within tolerance. After ultrasonic cleaning (with degreasing, de-oxidisation and prevention of re-oxidisation in separate baths) at 80 kHz and 60°C and after flushing with tap and de-ionized water and hot dry air drying we store the cups in a nitrogen filled locker.

Stacking

After heat treatment of the cups at 400°C at 1 hour the two grooves on the female side of the cup are both equipped with a brazing wire so that the inner vacuum part is well separated from the water cooling channels and from the ambient atmosphere. Before stacking all the cups are inspected visually and photographed on both sides for documentation. Then one cup is placed on a plate of a receiving station for reading the bar code, the table is rotated by 180° on the other side and the cup is heated up to 50°C in one minute. After this the robot picker arm grabs the cup and rotates it by 360° above a camera to visually check whether both brazing wires are present or not as depicted in figure 3.

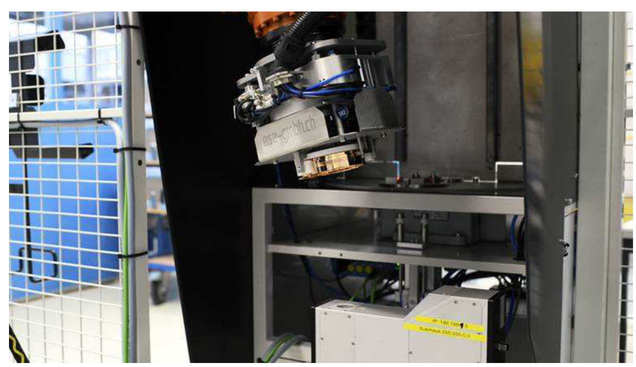

Figure 3: Robot picker arm with a cup at 60°C rotates by 360° above a camera to visually check for presence of both brazing rings.

We use a KUKA robot type KR 30 HA (high accuracy) which has an action radius of about 2 m and a repeat accuracy of 5 µm in (x,y,z). The compensating elements within the grabber are switched to a forceless mode while placing a new cup on top of the stacked cups. In this case small displacements can be compensated since the new cup is only guided by the precise geometry of the former cup on the stack. The new cup is about 30°C warmer than the stack and has an increased inner diameter of 23 µm. In its final self-centering position it makes contact to the stack, cools down to the stack temperature and is thus shrinked. This way we reach a measured perpendicularity of less than 50 µm along the 2m of stacked cups. In addition an inductive measuring system (repeat accuracy of 10 µm) is integrated in the grabber to record

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differences between the final picker arm position for placing a cup and the position of the stacked cups.

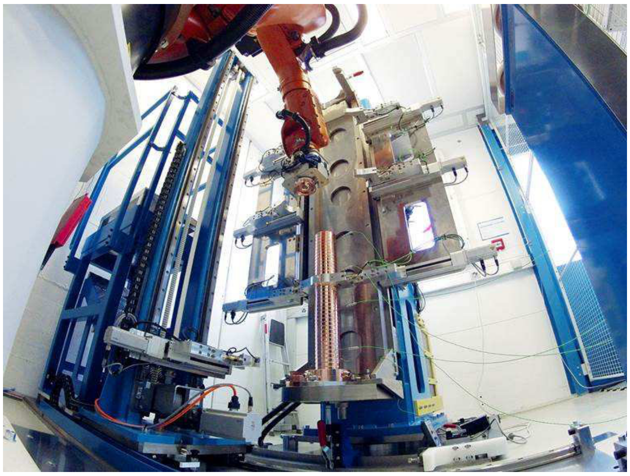

Figure 4: Robot picker arm places a cup on top of a stack of cups. Claws with encoders check for a perpendicularity of the stack to stay below 50 µm.

The input J-coupler (for RF coupling to the waveguide connecting the clystron to the structures) is mounted manually on the base plate and aligned. Then the stacking process of the cups starts using the picker arm of the robot. To prevent heating up of the stack additional cooled copper slabs at 12°C (or 4°C above dew point depending

Figure 5: The frame with the cups and RF couplers is attached to a rotateable bar of a yellow dolly which moves the arangement to a vacuum brazing furnace.

on relative humidity at room temperature) are placed on the stack between two cups. To finish the output J-coupler (for RF coupling to the matched RF load) is heated up to 70°C and manually placed on top of the stack of cups by means of a special hoist device to allow self-centering.

A general overview of the stacking equipment is depicted in figure 4. After one third of the height of the final stack the perpendicularity is checked at that height to stay below 50 µm by means of two claws moving inward and stopping using encoders and glass scales. The same is done at two thirds and near the end of the stack to ensure a perpendicularity of the stack of less than 50 µm along the 2m-height of the stack.

After stacking of the cups and the two RF couplers two base plates and three bars are mounted to fix the stacked components for brazing. The material is Inconel 600 (FeNi alloy) which will not distort while brazing. This arrangement is depicted in figure 5. Afterwards the stack is measured with a laser tracker with an accuracy of +/- 1 µm to check the perpendicularity of the stack to be less than 50 µm before brazing.

Figure 6: Stacked cups and couplers are mounted and placed in a rigid frame inside the furnace for brazing.

The frame is attached to a rotateable bar of a yellow dolly. The transport to the vacuum brazing furnace is performed in an upright position. Next to the furnace a slewing crane attached to the wall moves the mount to a hinged position in a tripod frame made of steel inside the open vacuum brazing furnace. The frame with the stacked cups and two RF J-couplers behaves like a pendulum in

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the tripod frame that could move during brazing in case of any distorsion of the tripod frame as depicted in figure 6.

Brazing

The furnace is a full metal construction and operates up to 1250°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 the heating elements. The total height is 8.5 m and the vertial working height inside is 2.8m when the furnace is open.

The brazing is done in vacuum at 820°C. A series of thermocouples measure temperatures along the 2m-long structure while heating up to control the process temperature. Because of the total mass and the brilliant surface finish of the structure the brazing process is slow and takes more than a day.

Testing

After brazing and cooling down under vacuum the furnace is opened. The mount with the 2m-long structure is hanging in a vertical position on the slewing crane while performing a thorough He leak rate measurement on the inner vacuum part and on the water cooling channels (leak rate is < 10^{-10} mbar*l/sec).

Still in the vertical position the wire with the bead for the bead-pull RF measurements is fixed. After this the mount with the 2m-long structure is fixed again on the rotateable bar of the yellow dolly. The dolly with the structure is moved to a transport girder with thee supports where the 2m-long structure is placed after rotating the bar of the dolly by 90° in a horizontal position. This is depicted in figure 7. The transport girder is used to bring the structure into a clean room for bead-pull testing [2]. It does not differ with the support positions from those of the final girder in the LINAC accelerator. The geometry and the positions of the supports have been optimised for optimum balance and support.

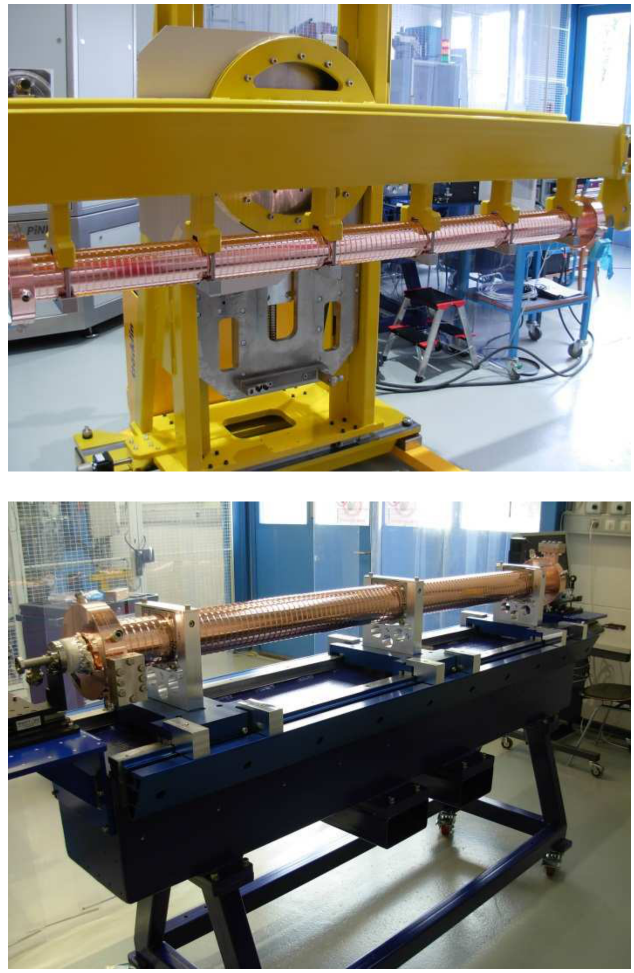

Figure 7: The 2m-long brazed structure is transported with the yellow dolly in a horizontal position (top) to a transport girder (bottom) and mounted on three supports.

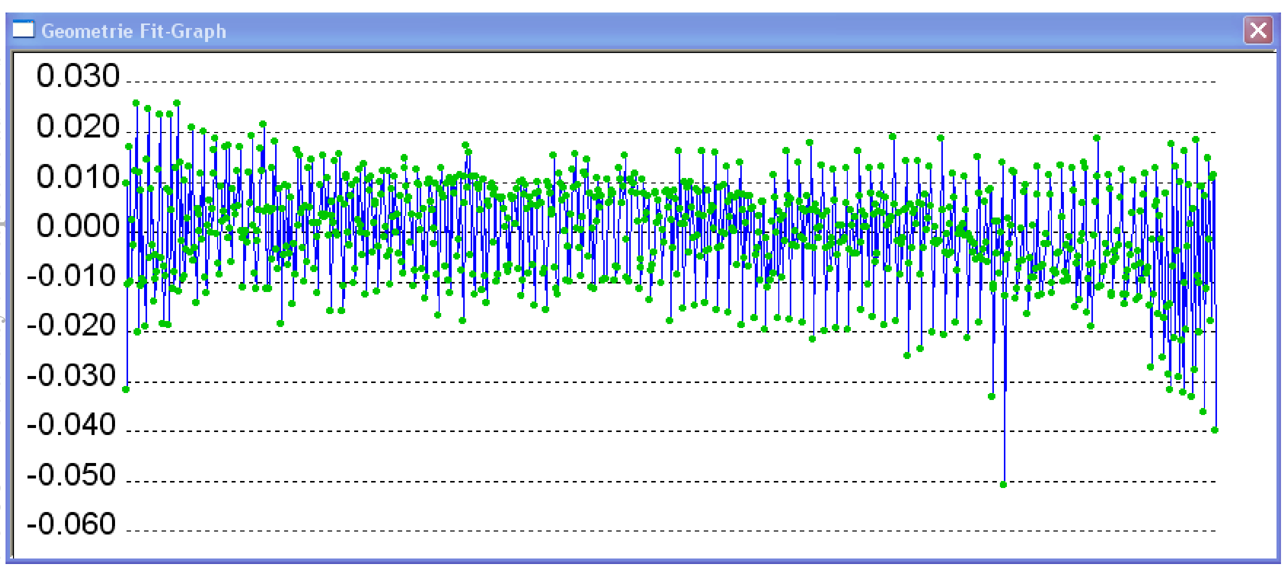

Figure 8: Laser tracker measurements along the 2m-long structure.

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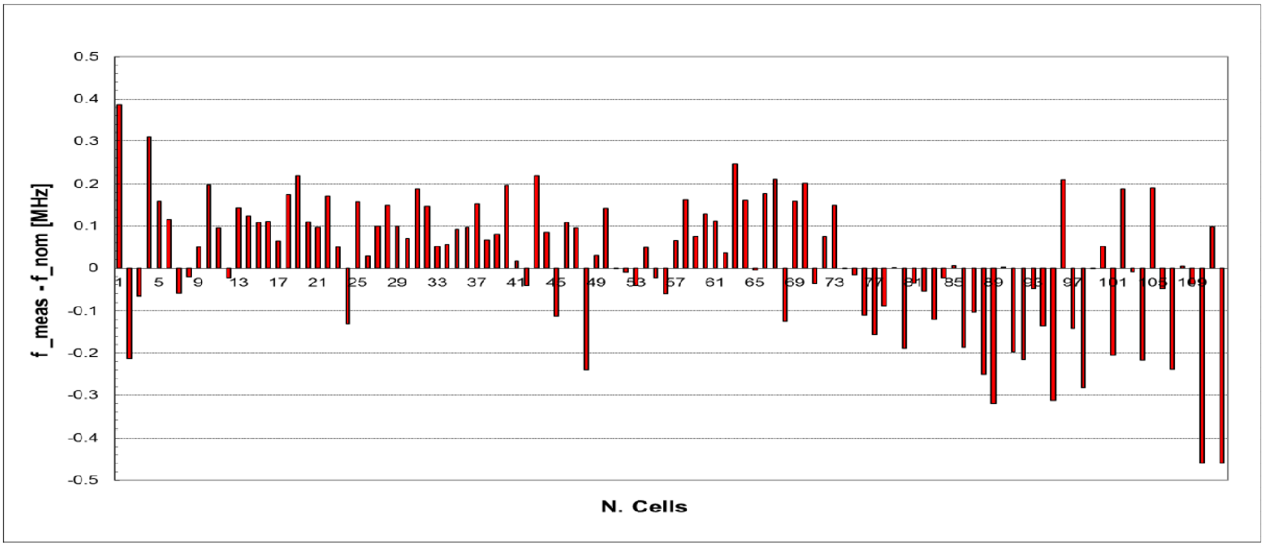

Figure 9: Post-processed data from bead-pulling measurements along the same 2m-long structure. The averaged frequency mismatch from bead pulling testing of Δf = - 40 kHz with respect to f_nom = 5'712 MHz for this structure can be compensated by a - 0.4°C change in temperature.

To check for possible elongation or shrinking and for the perpendicularity along the 2m-long structure we proceed with two independent measurements. First the length and the axial deviations are measured with a laser tracker (+/- 1 µm). Typical results are depicted in figure 8 with an axial deviation between – 30 µm to 20 µm (perpendicularity after averaging < 50 µm). The axial length of the 108 cups measured corresponds well to the reference length of 1'907.819 mm by +/- 0.2 mm. The alleged shrinking or elongation of the stack observed after brazing can be explained by summing up the sum of thicknesses of all cups and the two J-couplers which have been measured individually with the coordinate measuring machine.

The bead pulling (RF cold) measurements check the frequency mismatch of the structure with respect to the nominal frequency f_ nom of 5'712 MHz at the nominal operating conditions. The frequency errors for each cell of the structure are shown in figure 9 as a result of post processing data from bead-pulling energy and phase advance measurements [2]. For practical reasons 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. Because of small back-reflections of end cells and J-couplers the post processing is less precise there for frequency deviations. We summarize the RF cold measurement as follows:

- These values confirm the high precision machining of the cups and the choice to produce structures without implementing mechanical tuning solutions on the cups (push-pull technique).
- At the nominal frequency the reflected power is -30.2 dB and the transmitted power is -4.7 dB. The measured Q factors of the cells agree very well within 1% to the nominal values.
- The frequency mismatch is Δf = - 40 kHz and it can be easily compensated by changing the operating temperature of - 0.4°C.
- The RMS phase advance error is $\Delta\varphi$ = 1.74° which has a negligible effect to the energy gain.

CONCLUSIONS

Up to now 3 prototypes have been manufactured and tested on site. The mechanical results are encouraging (this paper) as well as the RF results with bead-pulling testing and power-testing [2]. A fourth prototype is on its way so that we will soon be able to test a complete module [1]. After this we will start with a zero series of C-band structures to be optimised for series production in industry together with our industrial partner [3].

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REFERENCES

[1] U. Ellenberger et. al, "Design Concept, Manufacturing and Performance of Test Structures (6 GHz or C-band) for the Linear Accelerator of the SwissFEL X-ray laser system", SRI conference, Lyon (France), July 2012, Journal of Physics: Conference Series (online service).

[2] F. Loehl et. al., "Status of the SwissFEL C-band linear acclereator", this conference

[3] TEL Mechatronics Company, Trübbach, Switzerland

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