Design Concept, Manufacturing and Performance of Test Structures (6 GHz or C-band) for the Linear Accelerator of the SwissFEL X-ray laser system

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Abstract. The goal of SwissFEL is to provide a source of extremely bright and short X-ray pulses enabling scientific discoveries in a wide range of disciplines, from fundamental research to applied science. To accelerate the electrons to an energy of up to 5.8 GeV a linear accelerator (LINAC) consisting of 104 C-band (5.712 GHz) accelerating structures each of a length of 2m is foreseen. We present the mechanical design of the accelerating structures. High precision manufacturing is applied in order to avoid a tuning step during fabrication. Following this production process several 0.3 m test structures have been produced and tested. First results including RF power tests are presented.

1. Description of linear accelerator (LINAC) of SwissFEL and of its general requirements
The LINAC is used to accelerate an electron bunch to an energy of 5.8 GeV before the lasing process is initiated in the undulator section. One module consists of 4 C-band (5.7 GHz) structures made of copper which are fed by one pulse compressor connected to one modulator and to one klystron (figure 1). 26 modules or 104 C-band structures aligned along a row of 300 m are required to accelerate the electrons up to 5.8 GeV.

To minimize cost and to achieve an economical series production of the C-band accelerating structures fabrication has to meet stringent requirements.

- Precision of one single copper cell is of 1 µm and has a surface roughness $R_a$ of 25 nm.
- Concentricity is 50 µm of a 2m C-band structure before and after vacuum brazing together in one step the J-shaped input and output couplers and the 113 copper cells (table 1).
- No additional mechanical tuning of a 2m long C-band structure is required after brazing since all individual volumes of the 113 copper cells match the specified frequency (5.712 GHz) and the nominal phase advance of 120°.
2. Key Design specifications of a single copper cell and of a 2 m C-band structure

With increasing RF frequency the acceleration efficiency of a LINAC increases but fabrication of the accelerating structures becomes more difficult at the same time. With the availability of high power C-band klystrons the choice of 5.712 GHz seemed to be a manageable compromise. Design and fabrication of prototypes are done in house. Serial production will take place in close collaboration with an industrial partner. To maximize the efficiency of the accelerating structure a double rounded cell design was chosen (figure 2). The diameter of the iris and the cell radius vary from cell to cell to generate a constant acceleration gradient along the structure. The phase advance per cell is $2\pi/3$ (or 120°) (table 1). The design of the copper cell has several round brazing joints to well separate vacuum from water cooling. Air channels allow checking for vacuum tightness after brazing (figure 2). The surface roughness $R_a$ of the RF volume of the copper cell is set to 25 nm based on practical experiences (CERN, CLIC project [1]) of existing 12 GHz design ($R_a=25$ nm, X-band, 100 MV/m). The surface roughness should be much lower than the penetration depth of 0.853 $\mu$m in copper for 6 GHz (skin effect [2]) to prevent additional electrical losses and breakdowns.

| Number of cells | 113 (plus 2 J coupler) |
|-----------------|------------------------|
| Frequency       | 5712 MHz               |
| Phase advance   | $2\pi/3$ (120°)        |
| Iris (mm)       | 7.257 → 5.612          |
| Radius (mm)     | 22.432 → 21.988        |
| Average acceler-| 28 MV/m               |
| rating gradient |                        |

Table 1. Key specifications of 2 m long C-band structure with 113 cells and 2 RF couplers (arrow indicates beam direction).

Figure 1. Overview of C-band module with klystron (top left), pulse compressor and 4 C-band structures on 2 girders (bottom left) and of a 2 m long C-band structure with RF couplers (right).

Figure 2. Double rounded design of a single copper cell and part of the iris design.

Figure 3. FE simulation of temperature distribution in cell (12.7 W, 40°C water cooling).
Electron beam dynamics require a concentricity of 50 $\mu$m per 2m cavity which has to be met after stacking of the cells before and after vacuum brazing of the 2m C-band structure. Along a C-band structure there is an electric field gradient of 28 MV/m operated at 5712 MHz. The repetition rate of electron bunches (10 to 200 pC) is 100 Hz with a rf macro pulse length of 0.35 $\mu$s. The thermal loss per 2m cavity (113 cells plus RF coupling elements) is 3 kW and thus requires water cooling. Finite element calculations are used to verify the design of a single cell to be distortion free with a centre temperature slightly higher than the water cooling of 40°C for an average power of 12.7 W per cell (figure 3).

3. Manufacturing process from single copper cells to vacuum brazed test structures

The copper for the C-band cells is oxygen free, high conductivity and forged in three dimensions according to specifications \[1\]. Using the cell design depicted in figure 2 many cells have been manufactured and stacked to short accelerating structures of roughly 0.3m length (13 cells). The RF power is fed to the cell stack through demountable mode launchers.

The manufacturing process of a copper cell can be summarized as follows:

- Raw-cut and pre-turned on a conventional and on a numerical controlled lathe (figure 4).
- Cleaning in several ultrasonic driven aqueous solutions (at 80 kHz), stored in dry nitrogen gas.
- Measuring tolerances (positions) and geometrical shape on co-ordination measuring apparatus.
- Precision turned to 1 $\mu$m on a sturdy and pneumatically stabilized slanted bed lathe (Hembrug) using poly- and mono-crystalline diamond tools.
- Cleaning of precise copper cells in several ultrasonic driven aqueous solutions (at 80 kHz).
- Measuring tolerances (positions) and geometrical shape on coordination measuring apparatus.
- Interferometric probing of the copper surface to measure surface roughness (about $R_a = 25$ nm and $R_z = 80$ nm, figure 5) and microscopic inspection of the surfaces for possible defects.

To build a 0.3 m long test structure we proceed as follows (figure 6):

- Degassing of copper cells and of (commercial) couplers in a vacuum furnace at 200°C.
- Pre-heat (40°C above room temperature) and manually stack one cell on top of the other.
- Braze the stacked column of copper in a vertical vacuum furnace at 850°C peak temperature.
- Check for vacuum tightness after brazing using helium gas.
- RF measurement to check phase advance / geometry of each individual cell.
- RF power tests on the brazed structure to check accelerating properties and for break-downs.
4. Results of cold RF measurements and power test for the first test structure
Cold RF measurements in a clean-room environment (class 6) and power conditioning of the first test structure are described in more detail in [3]. Low power measurements include S-parameter and bead-pulling measurements. The bead-pulling setup is shown in figure 7. In order to determine the phase advances between the cells and evaluate the operating frequency of the structure, the cells are perturbed by means of a ceramic ball (diameter of 3 mm) moving through the structure on a stretched nylon filament (0.12 mm thick).

Low power measurements have produced the following findings:

- The reflection coefficient, as good as -30 dB, confirms the high quality disk production.
- The equivalent frequency in vacuum at nominal conditions for the nominal phase advance \((2\pi/3)\) is \(f = 5712.247\) MHz. The +247 kHz difference to the nominal frequency corresponds to an operating temperature in vacuum of 37.4 °C to have the nominal phase advance.

For the power test the structure was conditioned at 10 Hz up to 35.5 MV/m gradient after first ramping up to the nominal 28 MV/m. Significant results have been obtained.

- The measured breakdown rate of \(8 \times 10^{-7}\) at 33.5 MV/m corresponds to 1 breakdown in 10 hours at 28 MV/m at 100 Hz repetition rate of the SwissFEL main C-band LINAC.
- The surface field enhancement factor (Fowler-Nordheim equation) estimated is \(\beta = 68\).

5. Conclusions
The volumes of the individual cells match the RF volume to the klystron frequency. No mechanical tuning of each individual cell and iteratively measure its frequency is required. After power-testing the first test-structure was wire-cut. All the cavities and the brazing interfaces are clean and show no evidence of breakdowns or of multipacting (figure 8).

6. References
[1] S Döbert et al, “High Power Test of low group velocity X-band accelerator structure for CLIC”, LINAC 2008, Victoria, Canada
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[3] R Zennaro et al, “Design, Construction and Power Conditioning of the first C-band Test Accelerating Structure for SwissFEL”, IPAC 2012, New Orleans, USA