THE SwissFEL RF GUN: MANUFACTURING AND PROOF OF PRECISION BY FIELD PROFILE MEASUREMENTS

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Abstract

The high brightness electron source for SwissFEL is an in-house built 2.6 cell normal-conducting RF gun which is scaled to the RF frequency of 2’998.8 MHz. The RF gun is capable of operating at 100 Hz repetition rate and produces electron bunches at the exit of the RF gun of an energy of 7 MeV. Key features of the RF gun are described and how they have been implemented in the manufacturing process. RF field measurements of the RF gun are presented to account for the mechanical precision reached after manufacturing. The RF gun has been thoroughly tested in the SwissFEL injector test facility.

INTRODUCTION AND OVERVIEW

The high brightness electron source that will drive SwissFEL has been completed at PSI and thoroughly tested recently. The photocathode of the gun is illuminated with a short-pulse laser synchronized to the RF frequency, so that electrons are emitted when the RF field on the photocathode reaches an optimum value. It is a dual-feed S-band 2.6 cell standing wave cavity which combines the advantages of two existing electron guns, namely the CTF3 RF gun [1] at CERN and the LCLS gun [2] at SLAC. The SwissFEL gun replaces the CTF3 RF gun which operated in the 250 MeV SwissFEL Injector Test Facility (SITF) until May 2014. The new SwissFEL gun can be characterized hereafter [3]:

- The backplane of the RF gun has a hole where a cathode plug can be inserted through a load-lock system [4]
- The RF field is symmetrically feeded in the middle cell which also has a racetrack design. This suppresses dipole and quadrupole components of the accelerating field in the last cell of the gun.
- A peak-accelerating gradient of 100 MV/m in the cavity leads to a low slice emittance by minimizing space charge effects during the first centimeters.
- Reduced mechanical stress due to heat load reduction is required for 100 Hz operation at a maximum gun gradient of 120 MV/m. The waveguide-to-cell coupling irises are optimized for a coupling coefficient $\beta = 2$ and, because of the pulse-heating, for a maximum temperature rise lower than 50°C.
- Surface electric fields are minimized by the elliptical profile of the cell-to-cell irises. The iris thickness was adjusted to ensure a large mode separation in frequency spectrum.

Figure 1 shows a cross section of the new SwissFEL gun with the symmetric RF connection (splitter).

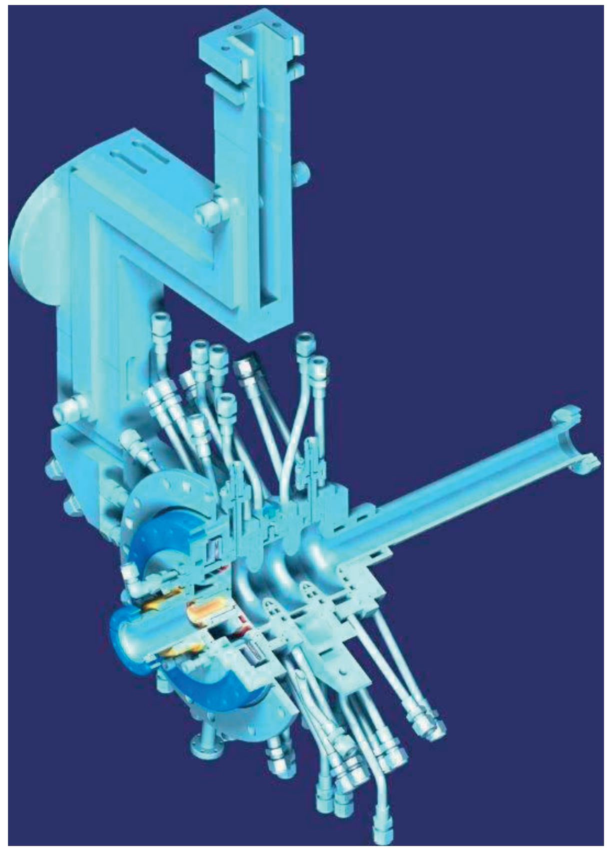

Figure 1: Cross section of 2.6 cell SwissFEL gun and of splitter.

The manufacturing of the new RF gun at PSI has to conform to stringent requirements to achieve a stable process for an economical industrial small series production for one or more guns (if required):

- Target precision of single copper parts of +/- 5 µm with a surface roughness R_a of 25 nm.
- Perpendicularity of less than 50 µm for all parts and for the gun during the whole manufacturing process.
- No mechanical tuning of the three cells of the gun would be required after brazing.
- Tuning operations are anyway possible by acting on the temperature of the cooling water and on the cathode positioning by means of the cathode plug.

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MANUFACTURING

Here we report on the procedures of manufacturing to meet the stringent requirements. The results of RF and power testing of the gun are summarized to account for the precision and quality of the design and fabrication [5].

The raw material for the gun parts is oxygen free, high-conductivity OFE-copper. A forging in three-dimensions is used to get a homogenous material with only small pores. An additional annealing is used before ultraprecise machining (UP) to achieve a stress-free state of the material. This is mandatory even if chip formation is less favourably for large grain size of about 400 µm due to the heat treatments. The large grain size could eventually be an advantage in case of breakdowns in high-voltage RF fields (120 MV/m at 2’998.8 MHz).

The gun consists of four parts and of the RF wave-guide which are machined separately (see Fig. 2). They are all made of the OFE-copper as described previously.

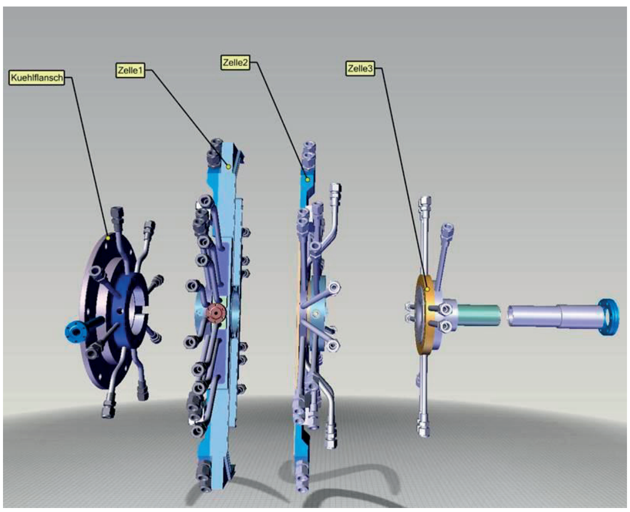

Figure 2: The RF gun consists of the cooling flange, cells 1, 2 and 3 with the copper beam tube (from left to right).

Milling is performed in-house on a CNC machine center with a precision of +/- 20 µm. The RF parts are UP machined with the VDL company in Netherlands within the specified tolerances and surface roughness [6].

After machining we clean the copper parts with rubbing alcohol and after 24 hours of acclimatisation we verify with a coordination measuring machine that the copper parts are within tolerance (Mitutoyo Legex with a base precision of 0.35 µm). Before brazing we use 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 copper parts in a nitrogen filled locker. The last step of cleaning is annealing, degassing and oxygen-free surfaces at 400°C for 2 hours in a vacuum furnace. The brazing is done in a programmable vacuum furnace (Pink, up to 1’200°C and residual pressure below 10^{-6} mbar) with a temperature controlled brazing. Several temperature measurements from the material to be brazed provide an active feedback to control the vacuum furnace during brazing.

The production steps for the RF gun are summarized hereafter:

- For the cooling flange the copper and steel cylinders (N-stabilized, 316-LN or 1:4429) are turned on a conventional lathe and brazed together at 905°C.
- The parts for cell one are milled after annealing to a tolerance of 0.2 mm. Next the water cooling pipes are brazed to it at 860°C. Afterwards the cooling flange and cell one are brazed together at 840°C.
- For cell two and three their copper parts are also milled after annealing to a tolerance of 0.2 mm. Next water cooling pipes are brazed to them at 860°C.
- For all three cells the RF parts are milled precisely to +/- 20 µm and they are mounted on rigid frames for transport to the VDL company in Netherlands.
- The symmetric and L-shaped RF waveguide is milled in two halves to +/- 0.2 mm. The inner waveguide part is then milled +/- 20 µm.
- At the VDL company the RF parts of the three cells are UP milled to +/- 5 µm and to 25 nm.
- Back at PSI (see Fig. 3 and 4) the cells 1, 2 and 3 and a copper beam tube are brazed together at 800°C.
- The RF contacts of the splitter are machined to +/- 20 µm to fit the rectangular contacts of the gun cells.
- The final brazing of the gun cells with the splitter is performed at 770°C.

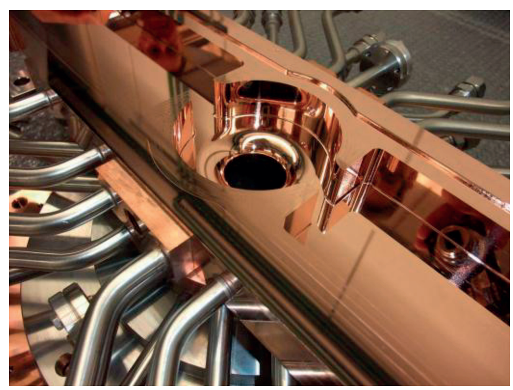

Figure 3: Surface of cell one of the gun before brazing.

Figure 4: Surface of cell two of the gun before brazing.

COLD MEASUREMENTS

The setup for low power testing in a clean room class 4 is depicted in Fig. 5 for the RF gun with the splitter.

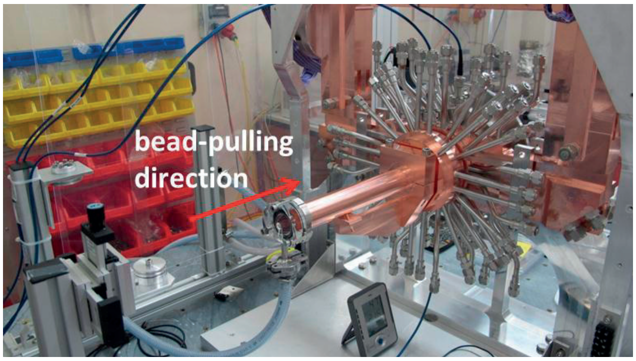

Figure 5: Setup of low power testing for gun and splitter.

The measured frequency is -250 kHz lower than the SwissFEL design value at 40°C in vacuum. So the new operating temperature of the SwissFEL gun will be 35°C (1°C corresponds to 50 kHz for 3 GHz S-band). Coupling β, unloaded quality factor Q_0 and field balance well fit with the design parameters (see Table 1 and Fig. 6).

Table1: RF Field Parameters of new SwissFEL Gun

Parameter	Design 40°C	Measured
Frequency [MHz]	2’998.8	2’998.55
Mode separation [MHz]	16.36	16.20
Quality Factor Q_0	13’631	13’691
Coupling Factor β	1.98	2.02
Field balance	> 98%	> 98%

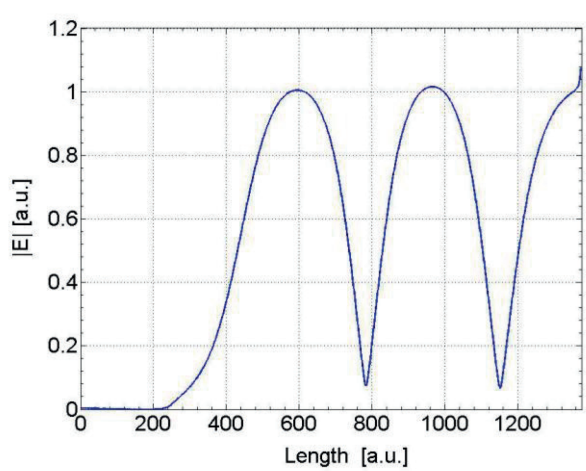

Figure 6: Field balance, measured through bead-pulling, at the operating π-mode frequency of 2’998.55 MHz.

Figure 7 shows the setup for high power testing of the SwissFEL gun at SITF. It is worthwhile to note that the nominal RF power of 18 MW with RF pulse width of 1 µs was reached in the first week of operation [5].

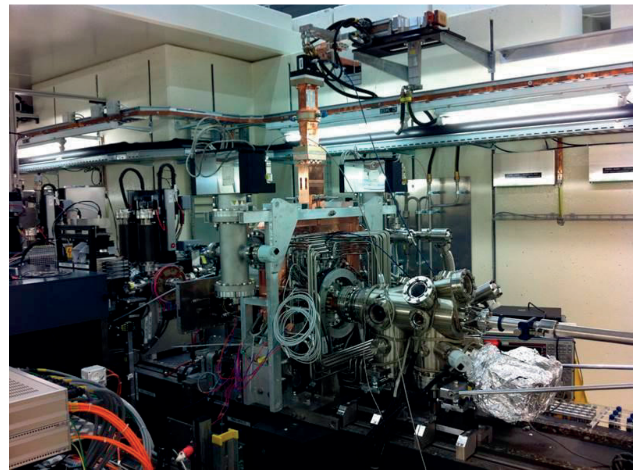

Figure 7: Setup of the RF gun for power testing at the 250 MeV test facility at PSI.

CONCLUSIONS

The characterization of the new 2.6 cells RF electron gun of SwissFEL and its photocathode is in excellent agreement with the design values and there is no need to apply a post-manufacturing tuning. This confirms the quality of design engineering and of manufacturing processes at PSI.

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