DESIGN, CONSTRUCTION AND POWER CONDITIONING OF THE FIRST C-BAND TEST ACCELERATING STRUCTURE FOR SWISSFEL

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Abstract

The SwissFEL C-band linac will consist of 26 RF modules with a total accelerating voltage of 5.4 GV. Each module will be composed of a single 50 MW klystron and its solid-state modulator feeding a pulse compressor and four two-meter long accelerating structures. PSI has launched a vigorous R&D program of development of the accelerating structures including structure design, production and high-power RF tests. The baseline design is based on ultra-precise cup machining to avoid dimple tuning. The first test structure is a constant impedance structure composed of eleven double-rounded cups. We report here on the structure design, production, low-level RF measurements, high-power conditioning and breakdown analysis.

INTRODUCTION

One RF module of the SwissFEL C-band Linac consists of four C-band structures, one pulse compressor cavity, one klystron and one modulator [1]. Accelerating structures and pulse compressor are developed in house for latter industrialization, while klystron and waveguides are procured by commercial companies. The peak power of the klystron is 50 MW with a 3 µs pulse length. Operation requires 33 MW at the klystron output for a 28 MV/m accelerating gradient. The waveguide network is based on an asymmetric design to take into account both phase synchronism and group delay for optimum operation with the pulse compressor. A single accelerating structure consists of 113 cells, including the two coupler cells of the J-type and operates at 5712 MHz with a 2π/3 phase advance and 40 ˚C nominal temperature. The length of each cell is 17.495 mm and the active length of each structure is 1.978 m. The cell shape is double-rounded to increase the quality factor and the iris tips are elliptically shaped and optimized to ensure minimum peak surface electric field. The structure is of the constant-gradient type with linear tapering of iris radius and cell radius. Longitudinal short-range wakefield issues and beam-dynamics requirements fix the average iris radius to 6.436 mm.

DESIGN AND CONSTRUCTION

The R&D program includes the production and test of short structures that can be brazed in the existing vacuum oven, followed by full prototype once the full-scale oven, presently under production, will be operational. In order to test several short structures two removable mode launchers have been designed and produced. The input and output mode launchers are mechanically connected to the structure via two flanges and two RF chokes provide the RF coupling without the needed electrical continuity between the mode launchers and the cavity. The first test structure has constant impedance and is composed by eleven regular cells and two matching cells. The regular cells have the same geometry of the first regular cell of the two-meter structure.

The main parameters of the test structure are summarized in Table 1.

Table 1: Main Parameters of the Test Structure

Structure 1	Parameter
Type	Constant impedance
Number of regular cells	11
Frequency	5.712 GHz
Phase advance/cell	2π/3
Iris aperture/thickness	7.267/2.5 mm
Group velocity	3.1 % c
Q	10400
R/Q	7214 Ohm
Nominal gradient (MV/m)	28 MV/m at 28 MW

Based on RF Simulations a mechanical design for the structure has been developed, Figure 1.

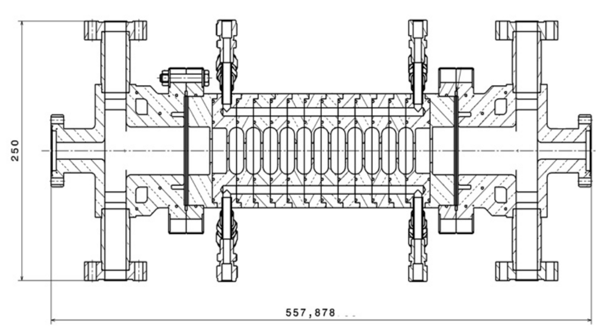

Figure 1: Design of the C-band test cavity.

Each disk of the structure has two half RF-cells and eight integrated cooling channels. Tight dimensional tolerances and high shape accuracy, smaller than 4 µm, are required to avoid dimple tuning of the structure, following the example of KEK [2]. A high precision machining process is used for production of the disks. One of the disks is shown in Figure 2, together with the measurement of its surface roughness.

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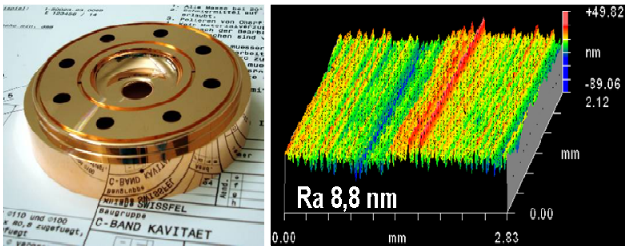

Figure 2: A unit disk (left side) and roughness analysis (right side). The measured average roughness is 8.8 nm, well below the tolerance of 25 nm.

The required straightness for the final two meter structures is ± 50 µm. To maintain the overall straightness of the structure a special stacking technique, based on the use of a small shrink fit smaller than 5 µm, has been developed. The stacking is made possible by a temperature difference ΔT of about 40 °C between the stack itself and the disk which has to be stacked, Figure 3.

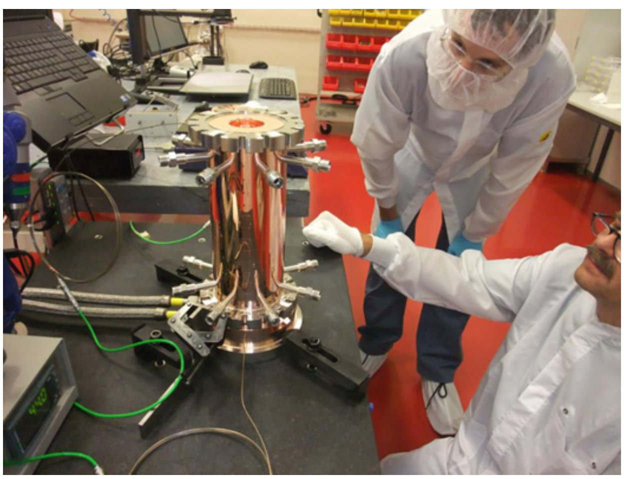

Figure 3: Stacking procedure before brazing of the first C-band test structure.

COLD RF MEASUREMENTS

All the RF cold measurements were done in a clean room with two laminar flow boxes combined (ISO7). Stable operating conditions of measurements in terms of temperature and humidity were obtained by cooling the structure using temperature stabilized water and by filling it with dry nitrogen.

S-parameter and bead-pulling measurements were performed in order to quantify reflections and operating frequency of the structure.

Figure 4 shows the reflection coefficients measured in a 4-port configuration: -29.1 dB and -30.8 dB are obtained, confirming the high quality disk production.

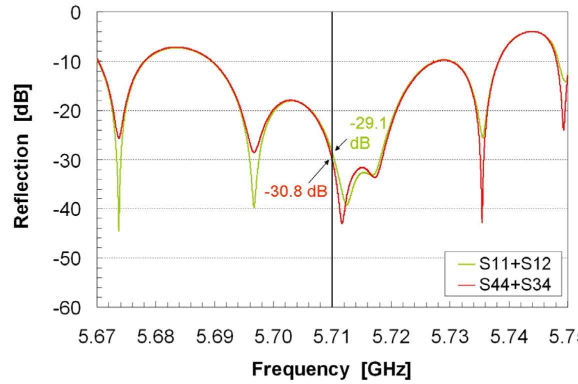

Figure 4: Reflection coefficients of the structure. The 4-port measurement was reduced to an equivalent 2-port measurement: the green (red) curve corresponds to the case of power coming from equivalent port 1 (2).

Several bead-pull measurements were made, perturbing the structure with a ceramic bead (3 mm diameter) running inside the structure on a thin nylon wire (0.12 mm diameter). An example of the field profile obtained is shown in Figure 5.

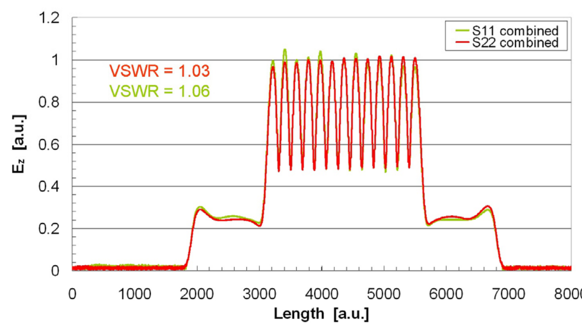

Figure 5: Electric field profiles for the nominal phase advance of 2π/3 feeding the structure from port 1 (green) or from port 2 (red). Their VSWRs are in good agreement with the measured reflection.

The equivalent frequency in vacuum at nominal conditions for the nominal phase advance (2π/3) is f = 5712.247 MHz. The +247 KHz difference to the nominal frequency corresponds to an equivalent operating temperature in vacuum of 37.4 ˚C in order to have the nominal phase advance.

Figures 4 and 5 show a slight difference in the measurements when the structure is powered from the equivalent port 1 or 2. This difference is more evident if the errors in the phase advances between the cells are considered, as shown in Figure 6. Here, the typical periodic behaviour of the curves, which reflects the 2π/3 period of the structure, demonstrates that small standing waves arise inside, mainly because of a detuning of the matching cells, and in particular from equivalent port 2.

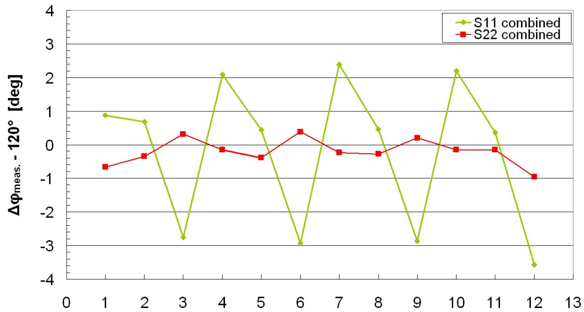

Figure 6: Error in the phase advances.

CONDITIONING AND BREAKDOWN ANALYSIS

The power test was made in TRFCB (Test RF for C-Band) which is the PSI test stand for C-band components. It is presently equipped with a SCANDINOVA K2-2S solid state modulator and a newly developed Toshiba E37210 100 Hz 50 MW klystron; a pulse compressor will be added in the future. The conditioning was made at 10 Hz and after 320 hours operation was started at fixed conditions (33.5 MV/m) to get breakdown rate (BDR) measurements as reported in Figure 7. Due to limited power and, consequently, low BDR it was not possible to get the dependence of the BDR on the gradient.

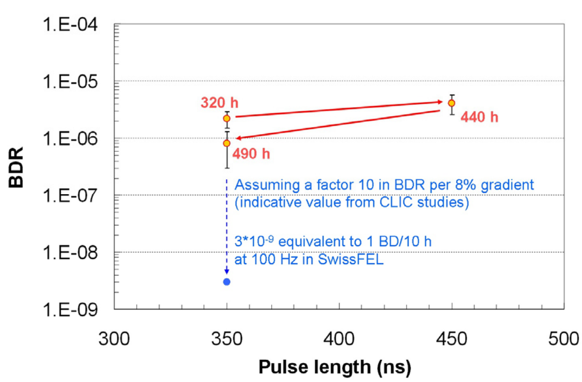

Figure 7: Breakdown rate of the test structure at 33.5 MV/m.

The expected BDR at nominal gradient (28 MV/m) is equivalent to only one breakdown every ten hours operating at 100 Hz in the SwissFEL (104 accelerating structures) assuming a logarithmic dependence of a factor ten in breakdown rate per 8% of gradient [3].

In the experimental setup two Faraday cups were mounted at the input/output beam pipes. In case of breakdown, the relative value of the dark current measurements in the two Faraday cups indicated that the breakdowns were mainly at the input of the cavity. There was no measurable dark current in absence of breakdown even at maximum power level. The estimation of the surface field enhancement factor (β) was possible by using a scintillator mounted transversally to the structure to monitor the x-ray produced during the RF pulse. The integrated signal generated by the scintillator (I_s) has been measured for different gradients. On the assumption that the integrated x-ray signal is proportional to the dark current the estimated β is 68 as shown in Figure 8.

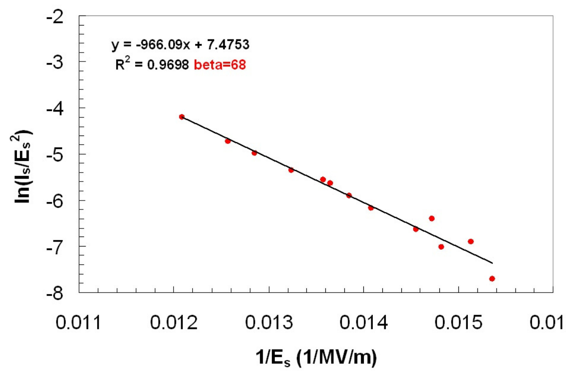

Figure 8: Estimation of the surface field enhancement by extrapolation of β from the Fowler Nordheim formula [4].

CONCLUSIONS

The excellent results in terms of machining, assembly and brazing are very encouraging and the cold RF measurements pave the way to produce structures without tuning. The low breakdown rate is extremely encouraging for the operational feasibility of the C-band Linac.

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