MEASUREMENTS AND HIGH POWER TEST OF THE FIRST C-BAND ACCELERATING STRUCTURE FOR SwissFEL

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Abstract

The SwissFEL project is based on a 5.8 GeV C-band Linac which is composed of 104 accelerating structures with a length of 2 m each. Due to the absence of dimple tuning no local frequency correction is possible and hence ultra-precise machining is required. The paper reports on both low level and high power RF test of the first nominal structure produced. The required mechanical precision has been reached and the structure has been successfully power tested to a gradient larger than 50 MV/m, well above the nominal level of 28 MV/m. The measured dark current and break down rates are well in the specifications.

INTRODUCTION

Each of the 104 accelerating structures consists of two RF couplers and of 111 regular cells, the dimensions of which shall ensure operation with a 2π/3 phase advance per cell at 5712 MHz. To reduce the RF power losses, each regular cell has rounded outer walls. The cell-to-cell coupling irises have an elliptical cross-section to minimize the peak surface electric fields. The main feature of the designed structure is the optimization of the cell-to-cell iris and cell radii to produce in each regular cell an *identical* accelerating gradient at the operating frequency. The developed methodology for achieving such RF field characteristics is presented in [1].

The temperature stabilisation of the structure is performed with eight azimuthally distributed water channels integrated into each cell. However, due to a change of the nominal inlet temperature of the water – 30°C instead of 40°C – the dimensions of the cells were updated accordingly. The updated dimensions of the first, middle and last cell at 20°C are given in Table 1. The resulting new numerical RF mode parameters are presented in Table 2. The Qs, given at 30°C, are 94 % of the values computed with SUPERFISH.

Table 1: Dimensions for the first, middle and last cells.

	Av. iris radius (mm)	Cell radius (mm)
First cell	7.232	22.429
Middle cell	6.480	22.197
Last cell	5.458	21.936

Table 2: RF mode parameters for the middle and last cell – Q at 30°C and corrected.

	v_g/c (%)	r/Q (kΩ/m)	Q
First cell	3.08	7.24	10223
Middle cell	2.17	7.84	10183
Last cell	1.21	8.68	10139

The first two meter structure, labelled “L0” is composed by cups and couplers produced by the company VDL; the brazing was performed in PSI [2,3]. It is the first of four structures produced up to now (August 2014), but it is the only one power tested to almost twice the nominal gradient.

COLD RF MEASUREMENTS

The RF measurements of L0 in frequency domain show a very good matching, -30.2 dB for the nominal 120° phase advance at 5711.960 MHz, only 40 kHz below the nominal frequency (5712 MHz). The S_{21} measurement provides an average Q_0 of 10820 in agreement with the value computed with SUPERFISH and without correction. The bead pulling in Figure 1 shows a small standing wave component.

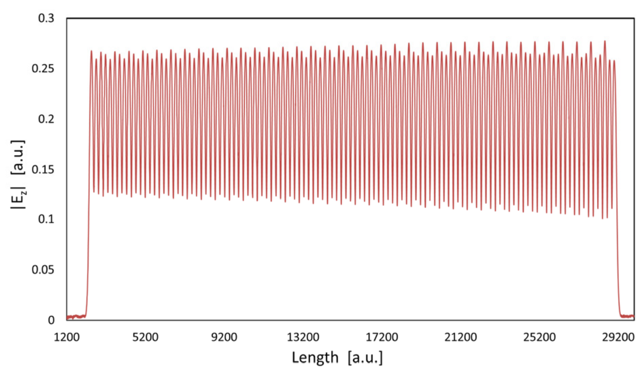

Figure 1: Electric field in the L0 structure.

A special tuning code has been developed at PSI in collaboration with INFN LNF capable to calculate the individual frequency error of each cell, with the exception of the input coupler, from the bead pulling data [4]. The computed error vector for L0 is shown in Figure 2. The output coupler has a frequency error of almost 2 MHz.

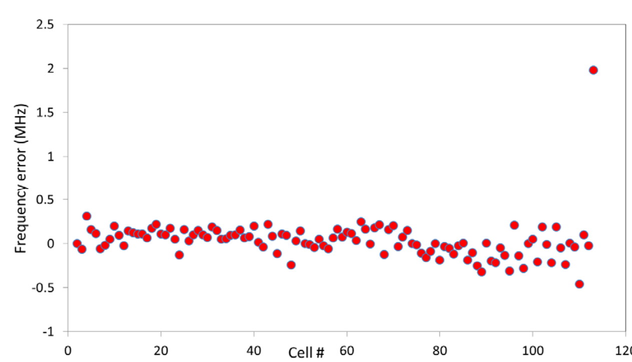

Figure 2: Individual cell frequency error in L0.

The design of the output coupler was re-optimized to remove the residual standing wave component. The

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diameter of the output coupler cell was increased by 6 µm. The new design was already implemented for the production of the second structure.

The global frequency error and the phase advance per cell standard deviation of the first four structures come directly from the bead pulling data; instead the individual cell frequency standard deviations have been computed with the tuning code. All these values for the four structures built so far are listed in Table 3.

Table 3: global frequency error (Δf), phase adv./ cell rms values and individual cell frequency rms values for the four structures.

Structure #	Δf (kHz)	Phase adv./cell Std (deg)	Individual cell frequency Std (kHz)
1	-40	1.74	142
2	-242	1.4	127
3	-450	0.9	134
4	-150	0.43	88

From Table 3 it is clear that all the four structures have a frequency lower than expected. A similar problem was found also in the four previously produced short test structures [5]. The reason for that is still not clear but to compensate this systematic error, the diameter of all the regular cells has been reduced by 1.2 µm for the serial production.

The individual cell rms frequency values are all reasonably low and basically equivalent in the four structures. During the production there was a clear improvement of the field flatness i.e. a reduction of the phase advance/cell standard deviation. This is due to the reduction of the standing wave component generated by frequency error of the output coupler. A clear correlation between the output coupler frequency and the rms value of the phase advance per cell is shown in Figure 3. The large reduction of the frequency error from structure 1 to structure 2 is due to the optimization of the design.

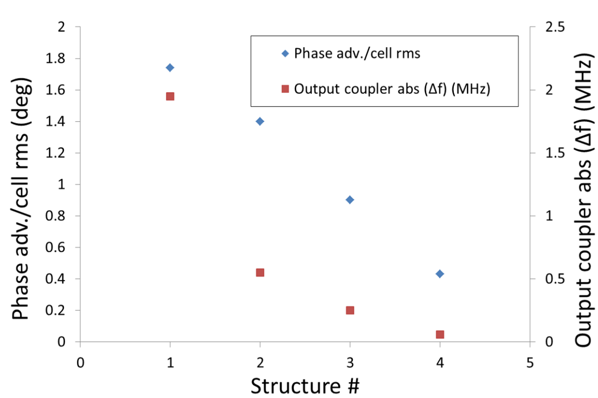

Figure 3: Standard deviation of the phase advance per cell error in the four structures and output coupler absolute frequency error.

CONDITIONING AND POWER TEST

The power test was made in TRFCB01 (Test RF for C-Band) which is the first PSI test stand for C-band components. TRFCB01 at the moment of the L0 power test was equipped with a Scandinova K2-2S solid state modulator and a Toshiba E37212 100 Hz 50 MW klystron. The klystron output was connected to a pulse compressor of the BOC type [6] placed in the bunker below. The L0 structure was directly connected to the BOC output. This configuration allowed to test the L0 structure up to a power level which could be four time larger than in the SwissFEL where each klystron feeds four structures [7].

This configuration was in use only to test the L0 structure; the following power tests in TRFCB01 included always 3 dB splitters at the output of the BOC because of the amount of waveguide components to be tested. For that reasons L0 is the only accelerating structure tested much above the nominal level (28.5 MV/m).

The conditioning was at 100 Hz repetition rate, it took four weeks and consisted in increasing by steps the pulse length up to the nominal 3 µs length.

The BOC operated in two modalities: by applying a 180◦ phase jump towards the end of the RF pulse (phase jump operation) and by modulating the phase in such a way that a flat-top pulse is generated (phase modulation operation). The phase modulation operation is intended to be used in case of two bunch operation [7]. An example of the compressed pulses obtained in the two modalities is shown in Figure 4.

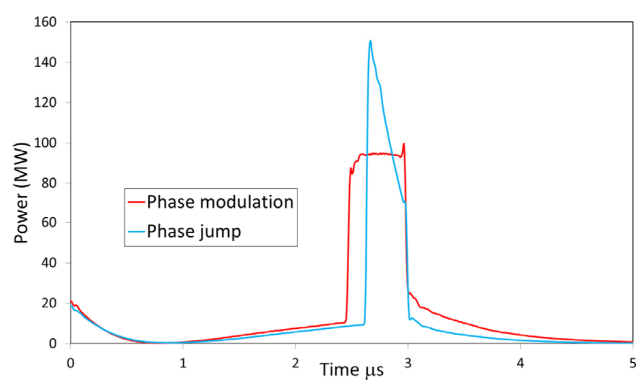

Figure 4: Example of compressed pulse in phase modulation operation (blue line) and in phase jump operation (red line). In both cases the equivalent accelerating gradient was 52 MV/m

During conditioning the vacuum was always in the 10^{-8} mbar range or lower; the larger pressure was at the structure output because of degassing of the silicon carbide of the dry load. After four weeks of condition the vacuum was anyway in the10^{-9} mbar range in the full vacuum system and at every power level. The measurements were made between 46 and 52 MV/m in order to get good statistics as shown in Figure 5.

The structure performed very well and the measurements shown in Figure 5 indicate that the BDR for the nominal gradient (28.5 MV/m) is well below the accepted value (10^{-8} breakdowns per pulse).

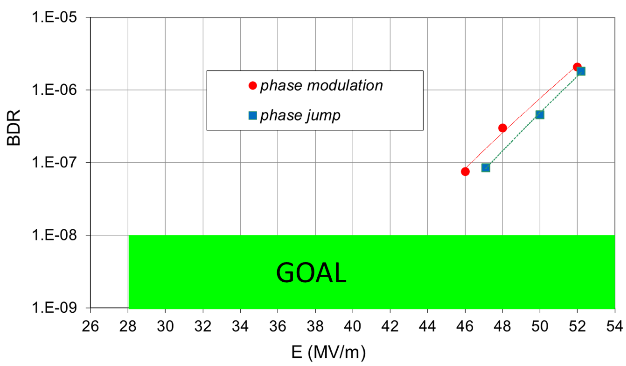

Figure 5: Breakdown rate (BDR) for the L0 structure.

DARK CURRENT MEASUREMENTS

The power test gave the possibility to monitor the dark current produced by the structure. The measurements were done by using two faraday cups placed at the input/output of L0.

The signals from the two faraday cups were filtered by a 10 MΩ low pass filter with 10 seconds time constant and red by two voltmeters. Operating at 100 Hz the final resolution of the system was much below 1 pC per pulse.

The dark current at the input coupler was always around 10% of the value at the output coupler. The dark current was measured at different power level as presented in Figure 6.

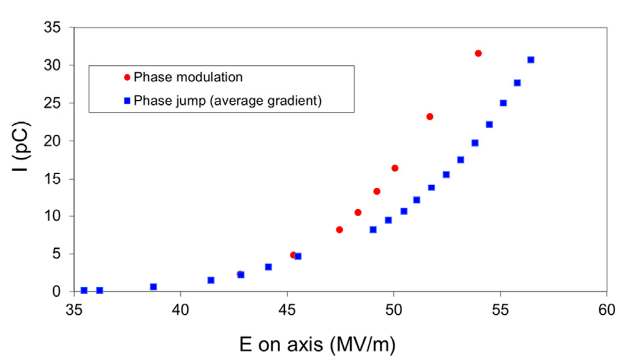

Figure 6: Measurements of dark current at the output coupler in both phase jump and phase modulation operation for different gradient levels. The values are in pC/pulse.

At the nominal value of 28.5 MV/m the dark current is always below 0.2 pC per pulse at the output coupler, this value is negligible for the SwissFEL operation.

The surface field enhancement (β) was extrapolated from the dark current measurements by means of the Fowler Nordheim formula [8]; the average value is β=71; this vale is in good agreement with the field enhancement values of the short test structures measured by means of a scintillator [5].

CONCLUSIONS AND OUTLOOKS

The L0 and the following three structures fully demonstrated the feasibility and the quality of the design. L0 gave the possibility to optimize to the micron level the geometry of the output coupler in order to remove the small residual standing wave component. The improvement in the field configuration was confirmed by the cold RF measurements on the three following structures. The results in terms of machining and assembly were always excellent. During the power test L0 performed very well and the breakdown rate was largely inside specifications. The dark current was small and not critical for the operation of the SwissFEL. The test of the entire module will be the next main milestone.

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