THE SWISS FEL C-BAND ACCELERATING STRUCTURE: RF DESIGN AND THERMAL ANALYSIS

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Abstract

The Swiss FEL accelerator concept consists of a 330 MeV S-band injector linac followed by the main linac in C-band aiming at a final energy of 5.8 GeV. The two-meter long C-band accelerating structures have 113 cells, including the two coupler cells, and operate with a $2\pi/3$ phase advance. The structure is of the constant-gradient type with rounded wall cells and has an average iris radius of 6.44 mm, a radius compatible with the impact of the short-range wakefields on the whole linac beam dynamics. The cell irises have an elliptical profile to minimize the peak surface electric fields and the coupler cells are of the J-type. We report here on the RF design of the structure, as well as on its thermal analysis, to target operational conditions with an accelerating gradient of about 28 MV/m and a repetition rate of 100 Hz.

INTRODUCTION

The main linac of SwissFEL at the Paul Scherrer Institut (PSI) is designed to consist of 28 RF modules operating at the C-band American frequency 5712 MHz with a pulse repetition frequency of 100 Hz. Each module is composed of one solid-state modulator, one 50-MW klystron, one PSI-designed C-band pulse compressor - a barrel-open cavity (BOC) - and four accelerating structures. Since SwissFEL aims for two-bunch operation with a 28 ns spacing, it is crucial that the acceleration through the structures is identical for *both* bunches. Such a feature can be achieved by performing phase modulation on the klystron drive signal. With a 3 μs, 40 MW klystron RF pulse, and taking into account the RF losses along the waveguide network of the module, the RF pulse, compressed by the BOC to 350 ns, is tailored so that *both* bunches gain an energy per accelerating structure as high as 56 MeV.

A 56 MeV energy gain per structure is achievable with a constant-gradient travelling-wave structure having in total 113 cells - 111 regular cells and two coupler cells. The length of each regular cell is fixed by the imposed $2\pi/3$ phase advance per cell. It can indeed be shown that the resulting energy gain is nearly optimal with such a choice of phase advance and the adopted pulse compression scheme. The accelerating gradient is then about 28 MV/m, a smaller - and safer - gradient than the 35 MV/m gradient corresponding to the state of the art [1].

One peculiarity of the designed C-band structure is the optimized cell-to-cell iris and cell radii theoretically resulting in *identical* accelerating gradient for each regular cell of the structure. In addition, J-type coupler cells [2] are selected since this type is mechanically the least complex to manufacture. Table 1 summarizes some main parameters of the designed C-band structure.

Table 1: Main parameters of the SwissFEL C-band structure

Parameter	Value
Operating frequency	5712.0 MHz
Phase advance per cell	$2\pi/3$
Total number of cells	113
Accelerating gradient	28 MV/m
Maximum pulse repetition frequency	100 Hz
Operating temperature	40 °C

DESIGN OF THE REGULAR CELLS

The regular cells of the designed structure have rounded outer walls to reduce the RF losses. For a defined cell-to-cell iris geometry, the quality factor of such cells is typically 10 % higher than the cells of a disk-loaded structure. At the manufacturing temperature of 20 °C, the length of each cell is 17.489 mm so as to operate the structure at 40 °C on the TM_{010}-like mode with a $2\pi/3$ phase advance per cell. The cell-to-cell iris thickness is 2.5 mm at 20 °C, a compromise between the desired high *effective* shunt impedance and the high mechanical rigidity, and is constant all along the structure. These irises have an elliptical cross-section with an aspect ratio of 1.375:1. Due the impact of the longitudinal short-range wakefields on the whole linac beam dynamics, the average iris radius of the structure is required to be about 6.44 mm.

Since the regular cells that composed the accelerating structure are axisymmetric, their RF design can be performed with the 2D electromagnetic code SUPERFISH [3]. SUPERFISH provides modal standing-wave eigenfrequencies and field maps from which the travelling-wave fundamental RF mode parameters of a cell under design can be calculated: the group velocity v_g, the effective shunt impedance per unit length r and the quality factor Q. The 3D electromagnetic code HFSS [4] is used for cross-checking the cell design.

The design of a tapered structure, such as a constant-gradient type, can be performed by modelling at first a set of single cells with different iris radius, the cell radii being optimized to have the required phase advance at the design frequency. The upstream and downstream iris radii of each of these individual cells are equal. With the mode parameters of these sample cells and with fitting procedures, a *pure* constant-gradient travelling-wave structure can be synthesized with an average iris radius of 6.436 mm at 40 °C.

Let us consider the gradient $E_{acc,n}$ in the nth cell and

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the power P_{n-1} flowing in this cell. These quantities are related:

$$E_{acc,n} = \sqrt{\alpha_n r_n P_{n-1}},$$

where r_n and α_n are the *effective* shunt impedance and the attenuation *per unit length* of this cell, respectively. The attenuation α_n is defined by: $\alpha_n = \omega_0/(2v_{g,n}Q_n)$, where $v_{g,n}$ and Q_n are the group velocity and the quality factor of the cell, respectively. The power P_n flowing out the cell is related to the power P_{n-1} flowing in:

$$P_n = P_{n-1}e^{-2\alpha_n L_{cell}},$$

where L_{cell} is the cell length. From these relations, it is straightforward to obtain the recurrence formula for which the accelerating gradient is identical in two consecutive cells, the $(n-1)$th cell and the nth cell:

$$\frac{v_{g,n}}{(r/Q)_n} = \frac{v_{g,n-1}}{(r/Q)_{n-1}}e^{-2\alpha_{n-1}L_{cell}}.$$

A small MATLAB-based optimization tool that makes use of these relations has been written to provide the final cell and iris radii of the 111 regular cells. The aspect ratio of 1.375:1, which characterizes the elliptical cross-section of all the cell-to-cell irises, corresponds to the optimal profile which ensures the lowest ratio of the peak surface electric field to the accelerating gradient E_{peak}/E_{acc} on the structure's *first* iris. The ratio E_{peak}/E_{acc} decreases monotonically from 2.16 for the first iris to 1.89 for the last iris. The filling time of the structure is 330 ns.

Fig 1 shows the accelerating gradient and the power flow along the designed constant-gradient structure. The input power required to obtain a 28 MV/m constant gradient is about 28 MW for a rectangular RF pulse .

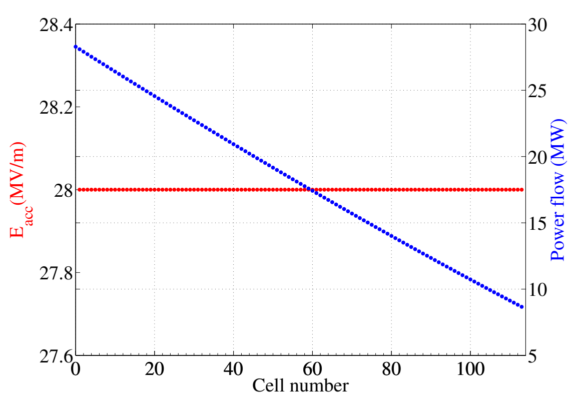

Figure 1: Accelerating gradient and variation of the power flow.

The dimensions of the first, middle and last regular cells at 20 °C are given in Table 2.

Table 2: Dimensions for the first, middle and last cells.

	Av. iris radius (mm)	Cell radius (mm)
First cell	7.244	22.431
Middle cell	6.481	22.194
Last cell	5.436	21.929

Table 3: RF mode parameters for the first, middle and last cell - Q at 40 °C and corrected.

	v_g/c (%)	r/Q (kΩ/m)	Q
First cell	3.10	7.23	10036
Middle cell	2.17	7.84	9995
Last cell	1.19	8.70	9951

The RF mode parameters - group velocity normalized to the speed of light v_g/c, r/Q and quality factor Q - are presented in Table 3. The Qs, given at 40 °C, are 94 % of the values computed with SUPERFISH.

The variation of the cell and iris radii along the structure at 20 °C are shown in Fig 2. The variation of v_g/c and r/Q are shown in Fig 3. Fig 4 shows the corrected Qs at 40 °C.

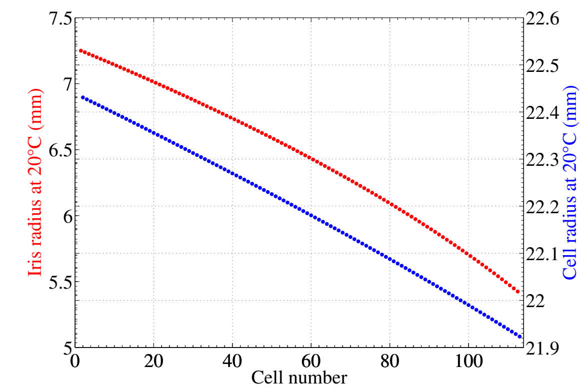

Figure 2: Variation of the iris and cell radii.

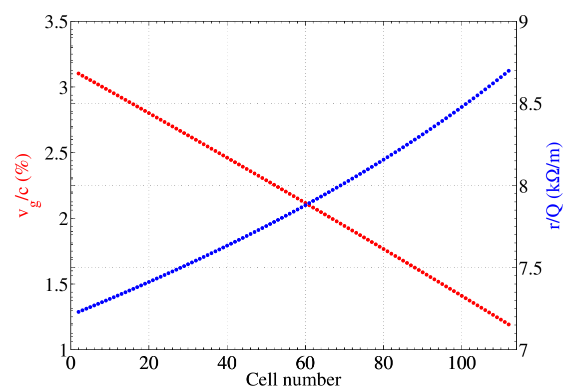

Figure 3: Variation of the group velocity and r/Q.

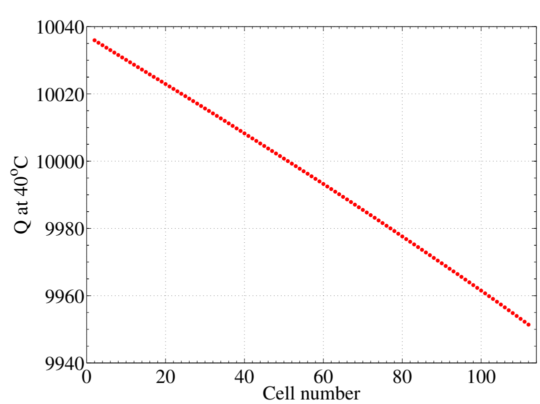

Figure 4: Variation of the quality factor.

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DESIGN OF THE COUPLER CELLS

Comparative studies of several types of coupler cell revealed that the J-type, its topology and design methodology having been described in [2], provides satisfying RF characteristics to feed the C-band structure. The width of the two symmetrically arranged waveguide-to-cell irises is moderately small to avoid detrimental field distortions in the vicinity of the structure longitudinal axis when the coupler is properly matched and tuned. In addition, its intrinsic mechanical simplicity makes it suitable for reliable mass production. Such a coupler is then selected for the RF input and output ports of the structure. The length of both coupler cells is 14.8 mm at 20 ^{o}C. Fig 5 shows a 3D computer model of the input coupler.

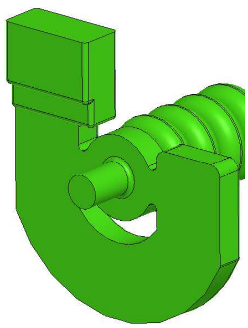

Figure 5: 3D computer model of the J-type coupler.

The determination of the optimal waveguide-to-cell iris widths and cell radii for both couplers is performed with the module Optimetrics of the 3D code HFSS [4]. For the input coupler, the optimal cell radius and the width of the irises are 20.342 mm and 16.170 mm, respectively, with inner and outer edge radii of the irises of 2.5 mm. For the output coupler, the optimal cell radius is 20.372 mm and the width of the irises is 13.289 mm with edge radii of 2.0 mm.

An estimation of the dynamic stress induced by pulsed surface heating is provided by calculating the maximum temperature rise per pulse on the critical areas [5]. The highest amplitudes of the magnetic field on the structure inner surface are located at the inner edge of the waveguide-to-cell irises of the coupler cells. Assuming a 350 ns *rectangular* RF pulse and an accelerating gradient of 28 MV/m, the maximum temperature rise per pulse, about 4 ^{o}C, is negligibly small, a consequence of the chosen fairly large inner edge radii of the irises.

THERMAL ANALYSIS

The temperature stabilization of a C-band accelerating structure is achieved by water flowing through eight azimuthally distributed channels integrated in each disk of the structure and running all along it. The design pressure of these 8 mm-diameter channels is 6 bar and the foreseen water speed is around 1 m/s. The nominal inlet temperature of the water is 40 ^{o}C for each of the four accelerating structure of an RF module and shall be stabilized within $\pm$0.01 ^{o}C. With a 3 μs long klystron RF pulse and a 100 Hz repetition rate, the average thermal load per disk is expected to be around 13 W. Fig 6 shows a typical temperature distribution in one of the copper disks that composed the structure with such thermal load.

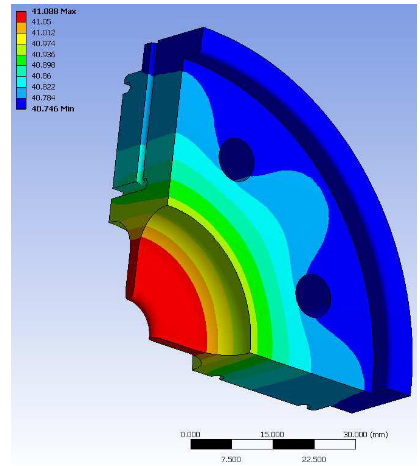

Figure 6: Temperature distribution in a disk of the C-band structure for a 40 ^{o}C inlet water temperature.

A global tuning of the four accelerating structures of an RF module can be performed by varying the inlet temperature of the water within $\pm$5 ^{o}C of the nominal temperature.

CONCLUSIONS

A two-meter long C-band travelling-wave accelerating structure operating at 40 ^{o}C with a $2\pi/3$ phase advance per cell has been designed at the C-band frequency 5712 MHz for the main linac of SwissFEL. The structures are expected to run at a peak accelerating gradient of 28 MV/m with a compressed RF pulse of 350 ns. The cell and iris radii are optimized for a constant gradient in each of the 111 regular cells and for the averaged iris radius of the structure to be about 6.44 mm during operation. The two coupler cells are of the J-type. The eight integrated water cooling channels running along the structure allow one to maintain the structure at the nominal temperature with a pulse repetition frequency of 100 Hz. The manufacturing at PSI of some prototype short C-band structures and their successful high-power tests are presented in [6].

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