THE SWISS FEL S-BAND ACCELERATING STRUCTURE: RF DESIGN

J.-Y. Raguin, PSI, CH-5232 Villigen, Switzerland

Abstract

The Swiss FEL accelerator concept consists of a 330 MeV S-band injector linac at 2998.8 GHz followed by the main linac at the C-band frequency aiming at a final energy of 5.8 GeV. The injector has six four-meter long S-band accelerating structures that shall operate with gradients up to 20 MV/m and with a 100 Hz repetition rate. Each structure has 122 cells, including the two coupler cells and operates with a $2\pi/3$ phase advance. The design presented is such that the average dissipated RF power is constant over the whole length of the structure. The cells consist of cups and the cell irises have an elliptical profile to minimize the peak surface electric field. The coupler cells are of the double-feed type with a racetrack cross-section to cancel the dipolar components of the fields and to minimize its quadrupolar components.

INTRODUCTION

The injector linac foreseen for SwissFEL at the Paul Scherrer Institut (PSI) [1] consists of two boosters, one with two S-band accelerating structures located between the PSI-designed RF gun [2] and the laser heater, the second with four S-band structures positioned between the laser heater and the two X-band structures used to complete the linearization of the longitudinal phase space. These accelerating structures are designed to operate at 40 °C with a pulse repetition frequency of 100 Hz and at 2998.8 MHz, an S-band frequency identical to the design frequency of the RF gun and which has a common sub-harmonic with the C-band main linac.

The presented S-band structure is of the travelling-wave type and operates with a $2\pi/3$ phase advance per cell. With a flange-to-flange length of 4.15 m, it consists of 122 cells - 120 regular cells and two coupler cells. Two cells, located upstream and downstream of the structure, are equipped with an RF pickup for monitoring and controlling the amplitude of the RF fields during operation. Since the energy of the electron bunches accelerated in the RF gun is about 7 MeV, any RF field distortion in the vicinity of the longitudinal axis of the structure may severely deteriorate the bunch emittance. In conventional travelling-wave structures, these field distortions are caused by the breaking of the azimuthal symmetry of the structure due to the topology of RF input and outport ports. The remedies against these field distortions are to equip the coupler cells with symmetrically arranged double feeds and to adopt a racetrack shape of these cells [3]. These two geometrical features are selected for designing the coupler cells.

The peculiarity of the presented S-band structure is the optimized cell-to-cell iris and cell radii to obtain an RF dissipated power per cell *constant* all along the structure. In addition, the cell-to-cell irises have an elliptical cross-section. Such a profile allows to reduce the ratio of the peak surface electric field to the accelerating gradient E_{peak}/E_{acc} and is expected to inhibit the generation of dark current. The accelerating gradient of the structure is 20 MV/m. Table 1 summarizes some main parameters of the designed S-band structure.

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

Parameter	Value
Operating frequency	2998.8 MHz
Phase advance per cell	$2\pi/3$
Total number of cells	122
Accelerating gradient	20 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 a cup-like shape with a curvature radius of 10 mm at the manufacturing temperature (see Fig. 1). The cell-to-cell iris thickness is 5 mm and is constant all along the structure. These irises have all the same elliptical cross-section with an aspect ratio of 1.5:1. Due the difficulty to tune and to match coupler cells with low group velocity, the radius of the last iris of the structure has been chosen to be 9.31 mm. The length of each cell is 33.324 mm at 40 °C to operate the structure in the TM$_{010}$-like mode with a $2\pi/3$ phase advance per cell,
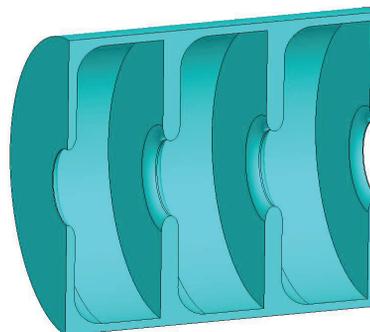

Figure 1: 3D model of the S-band structure cells.

The RF design of the regular cells is performed with the 2D electromagnetic code SUPERFISH [4]. By modelling three identical cells and by applying the appropriate boundary conditions, one obtains the standing-wave field map and the eigenfrequency from which the travelling-wave fundamental RF mode parameters characterizing the

01 Electron Accelerators and Applications

1D FELs

cell and corresponding to the required $2\pi/3$ phase advance 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 [5] is used for cross-checking the cell design. HFSS can solve for the complex eigenfrequencies of a 3D domain with periodic boundary conditions i.e. with a prescribed phase shift per periodic length. The group velocity and the *effective* shunt impedance per unit length are then computed by postprocessing the modal electromagnetic fields.

To design a tapered travelling-wave structure with a prescribed phase advance requires the modelling of a set of single cells with different iris radii. The radius of these cells is optimized for the desired phase advance at the design frequency. The cell irises are identical. With the RF mode parameters of these sample cells and with fitting and interpolating procedures, a travelling-wave structure with specific electrodynamic properties can be synthesized. This methodology is used here to design a structure for the RF dissipated power per cell to be *constant*.

Let us consider the RF power P_{n-1} flowing *in* the nth cell and the RF power P_{n-1} flowing *out*. Both quantities are related by the equation:

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

where L_{cell} is the cell length and α_n is the attenuation *per unit length* of this cell defined by:

$$\alpha_n = \frac{\omega_0}{2v_{g,n}Q_n}.$$

$v_{g,n}$ and Q_n are the group velocity and the quality factor of the nth cell, respectively. The RF power dissipated in the nth cell $P_{diss,n}$ is defined by the difference between the power flowing in and the power flowing out of the cell. It is then trivial to obtain the condition for which the power $P_{diss,n}$ dissipated in the nth cell is equal to the power $P_{diss,n-1}$ dissipated in the preceding cell. This condition is:

$$e^{2\alpha_{n-1}L_{cell}} = 2 - e^{2\alpha_n L_{cell}}.$$

or:

$$v_{g,n-1}Q_{n-1} = \frac{\omega_0 L_{cell}}{\ln\left(2 - e^{-2\alpha_n L_{cell}}\right)}.$$

A MATLAB-based optimization tool has been written to calculate the cell and iris radii of the 120 regular cells with the above recurrence formula. The highest ratios of the peak surface electric field to the accelerating gradient E_{peak}/E_{acc} are on the structure's first irises. The 1.5:1 aspect ratio of the iris elliptical cross-section minimizes E_{peak}/E_{acc} on the first regular cell irises. In this design, it decreases monotonically from 2.15 for the structure's second iris to 1.81 for the penultimate iris. The filling time of the structure is 840 ns.

Fig 2 shows the accelerating gradient and the *average* power dissipated per cell along the optimized structure for a 3 μs pulse and for a 100 Hz repetition rate. The required RF input power to obtain an overall average gradient of

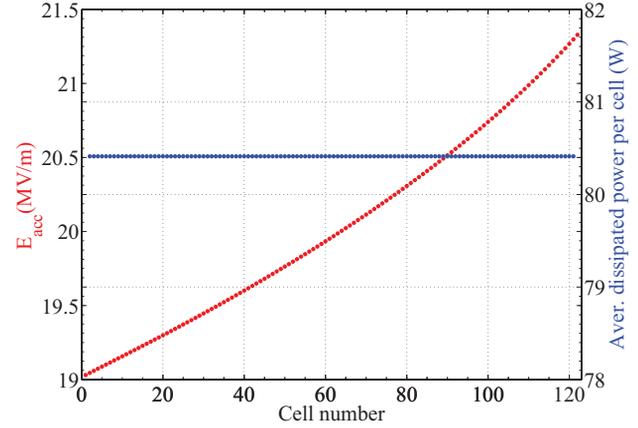20 MV/m is 44 MW. The *average* dissipated power per cell is about 80 W.

Figure 2: Variation of the accelerating gradient and the average dissipated power per cell.

The variation of the cell and iris radii along the optimized structure at 20 °C are shown in Fig 3. Fig 4 shows the variation of v_g/c and r/Q. Fig 5 shows the variation of the quality factor Q at 40 °C. These Qs are corrected to 85 % of the values computed with SUPERFISH.
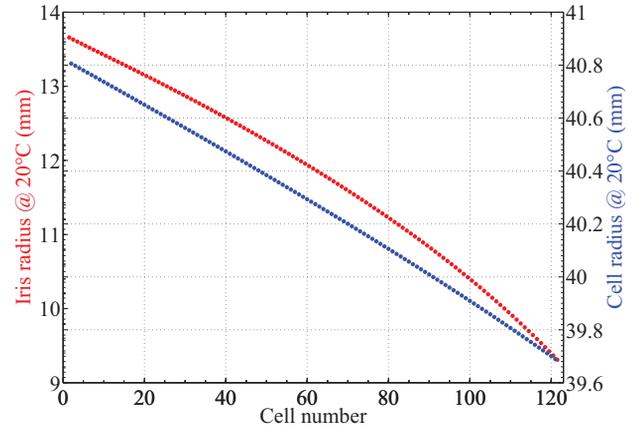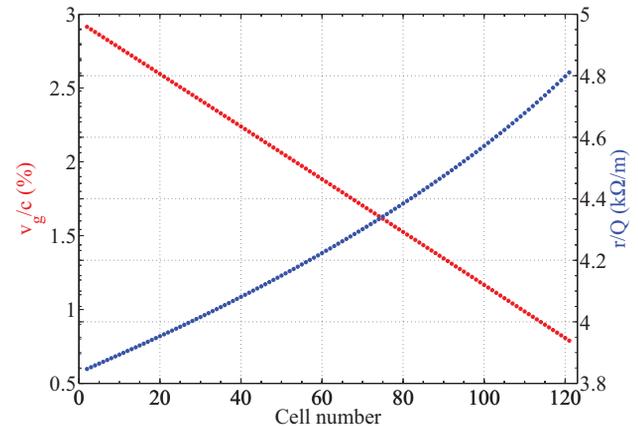

Figure 3: Variation of the iris and cell radii.

Figure 4: Variation of the group velocity and r/Q.

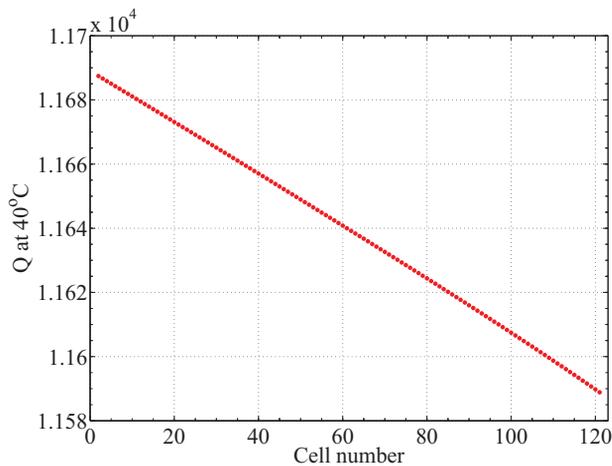The dimensions of the first, middle and last regular cells at 20 °C are given in Table 2. The RF mode parameters -

01 Electron Accelerators and Applications

1D FELs

Figure 5: Variation of the quality factor.

Figure 6: Amplitude of the longitudinal electric field along transverse directions in the middle plane of the output coupler cell.

v_g/c, r/Q and quality factor Q - are presented in Table 3. The Qs are given at 40 °C and are corrected.

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

	Iris radius (mm)	Cell radius (mm)
First cell	13.659 upstream	40.806
Middle cell	11.906 average	40.284
Last cell	9.310 downstream	39.689

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	2.91	3.85	11688
Middle cell	1.87	4.23	11640
Last cell	0.79	4.81	11589

DESIGN STUDIES OF THE COUPLER CELLS

The conventional double-feed type coupler, in which two waveguide-to-cell irises are symmetrically arranged [6], is selected as RF input and output ports of the structure. The beneficial impact of the racetrack shaped coupler cells on the RF field amplitudes in the transverse planes is illustrated in Fig 6. For nearly optimized waveguide-to-cell iris width and cell radius of the output coupler, the amplitudes of the longitudinal electric field along the transverse directions of the cell's middle plane are nearly equal over a 2 mm distance from the structure's axis. The length of racetrack straight section, not yet optimized, is 16 mm.

Pulsed surface heating [7] studies on the on-going design of the couplers is performed. For the output coupler, the maximum temperature rise per pulse is below 6 °C with a radius of inner edge of the waveguide-to-cell irises of 3 mm, a 3 µs RF pulse and an overall average accelerating gradient in the structure of 20 MV/m.

CONCLUSIONS

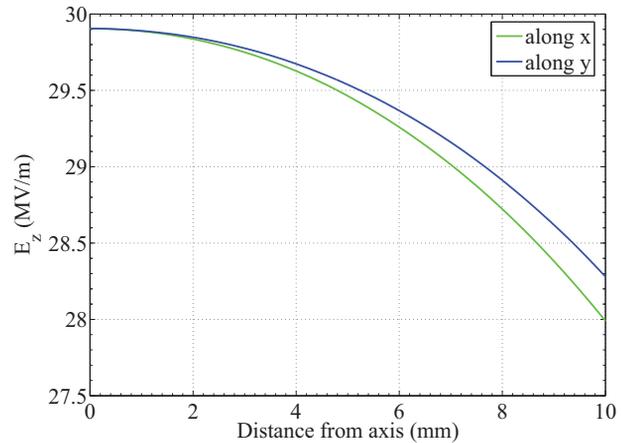The regular cells of a four-meter S-band travelling-wave accelerating structure for the injector linac of SwissFEL, operating at 40 °C with a $2\pi/3$ phase advance per cell, have been designed at the S-band frequency 2998.8 MHz. The structures are expected to run at, or below, an accelerating gradient of 20 MV/m with a pulse repetition frequency of 100 Hz. The RF pulse length shall be long enough to efficiently control the gradient with a dedicated feed-back control system. Since the combination of the high repetition rate and long RF pulse significantly increases the thermal load, the cell and iris radii of the structure are optimized for an RF dissipated power to be constant in each of the 120 regular cells and for a last iris radius of the structure to be 9.31 mm. The two dual-feed input and output coupler cells with a racetrack shape are under study. A model of the transient-state for determining the minimum RF pulse length after which the accelerating gradient has reached a steady-state is also elaborated.

REFERENCES

[1] SwissFEL Conceptual Design Report, PSI Bericht Nr. 10-04, April 2012.

[2] J.-Y. Raguin et al., "The Swiss FEL RF Gun: RF Design and Thermal Analysis", these proceedings, TUPB010, http://www.JACoW.org.

[3] J. Haimson et al., "A Racetrack Geometry to Avoid Undesirable Azimuthal Variations of the Electric Field Gradient in High Power Coupling Cavities for TW Structures", Proc. 7th Workshop on Advanced Accelerator Concepts, Lake Tahoe, 1996, AIP Conf. Proc. 398, pp. 898-911.

[4] J. H. Billen and L. M. Young, "Poisson / Superfish", Los Alamos National Laboratory, LA-UR-96-1834, 1996.

[5] http://www.ansys.com

[6] H. Deruyter et al., "Symmetrical Double Input Coupler Development", Proc. LINAC 1992, pp. 407-409, Ottawa, 1992.

[7] D. P. Pritzkau et al., "Experimental Study of RF Pulsed Heating on Oxygen Free Electronic Copper", Phys. Rev. ST Accel. Beams 5, 112002 (2002)].