DESIGN AND MACHINE FEATURES OF 2.2-M C-BAND ACCELERATING STRUCTURE*

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Abstract

A compact linac system is designed using a longer accelerating column in a C-band linac. It reduces the total number of RF units for the given linac beam energy and results in the cost-effective use of RF powers. For the 10 GeV PAL-XFEL project, a C-band accelerating column of 2.2-m long is investigated, which is 22% longer than 1.8-m for the SACLA at SPring-8. The detailed RF and thermal characteristics are presented by an analytic model.

INTRODUCTION

For the 4th generation light source, there are renewed interests in the X-ray Free Electron Lasers (XFEL). The LCLS at SLAC was completed in 2009, and the SACLA at SPring-8 was also done in 2011. While construction of the Euro-XFEL at DESY will be completed in 2015, The PAL-XFEL is now started in 2011.

Since these XFEL facilities require electron beams of several GeV, the main linac take a large portion of the construction budget and machine length. The LCLS uses 1/3 of the 2-mile SLAC linac with S-band RF, and the Euro-XFEL adopted superconducting L-band RF. The SACLA/SPring-8 developed a new concept in the C-band (5,712 MHz) which has a higher accelerating gradient than that of the S-band (2,856 MHz).

The SACLA/SPring-8 uses 1.8-m C-band accelerating columns [1]. Its nominal accelerating gradient is assumed as 35 MV/m while the maximum accelerating gradient is 42 MV/m, in order to prevent electron loading effects and RF breakdowns [2]. Since the accelerating column is operated at a lower accelerating gradient than its maximum capability for stable operations, there is a certain margin in reducing the accelerating gradient by lengthening the accelerating column. This enables to reduce number of RF modules since the energy gain per column increases.

We propose a 2.2-m long accelerating column. This acclerating column is designed to keep the thermal stability required for XFEL application. Design details with RF and thermal characteristics are presented.

COLUMN DESIGN

In order to achieve RF and thermal stability as well as vacuum performance, the attenuation coefficient should be considered carefully. In general, a larger attenuation coefficient makes a higher accelerating gradient. However, the lower vacuum conductance and RF phase stability under temperature changes, since the iris diameter and RF group velocity are inversely proportional to the attenuation coefficient. Thus, the lower limit of the RF group velocity is defined to be 0.013c (speed of light) and the corresponding iris diameter is 13.5 mm. These values are referred by the 1.8-m C-band accelerating column design [3].

The longitudinal distribution of the attenuation coefficient is determined to make uniform RF power dissipation along the accelerating column, as described in the next section in detail. Then attenuation coefficients α are defined by [4]

$$\alpha(z) = \frac{(1-e^{-2\tau_0})}{2L[1-(z/L)(1-e^{-2\tau_0})]}, \qquad (1)$$

where, z is the longitudinal position, τ_0 is the total attenuation coefficient, and L is the column length. The values of the attenuation coefficient are evaluated using Eq. (1) with the lower limit of the RF group velocity. The other cavity parameters, such as the shunt impedance and Q_0, are calculated by SUPERFISH simulation with the C-band choke-mode cavity of SACLA/SPring-8 [3, 5].

As a result, the accelerating gradient and energy gain per column with length of the column are calculated, as shown in Fig. 1. The input RF power is 25 MW, the RF pulse length is 2.5 μs, and the repetition rate is 60 Hz [6]. The RF power loss is assumed to be 20% on the waveguide surface and by the SLED detuning in practical operations [2]. The column length is determined compromising between accelerating gradients and energy gains per column. The criterion to determine the column length is the accelerating gradient of 35 MV/m, the nominal value of SACLA/SPring-8 [2]. As a result, the accelerating column length is 2.2 m. The detailed parameters are given in Table 1. Fig. 2 and 3 show the longitudinal distribution of iris diameters and RF characteristics.

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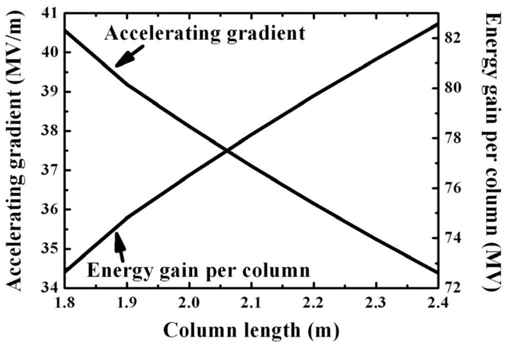
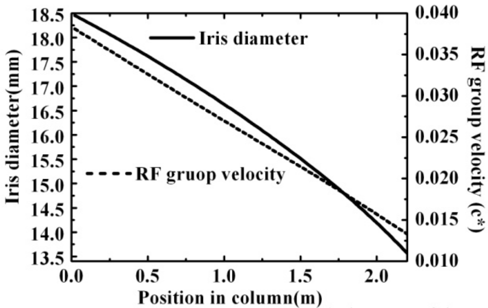


Figure 1: Accelerating gradients and energy gains per column with length of the accelerating column.

Table 1: Characteristics of 2.2-m C-band accelerating column.

Frequency	5712 MHz
Phase advance per cavity	3π/4
Field distribution	Semi – C.G.
Number of cavities	112 cavities
Active length	220 cm
Iris diameter (2a)	13.6 - 18.5 mm
Cavity diameter (2b)	44.0 - 46.3 mm
Disk thickness (t)	4.0 mm
Quality factor (Q)	9879 - 10327
RF group velocity	0.013c - 0.038 c
Shunt impedance	46.6 - 59.0 MΩ/m
Attenuation parameter	0.56
Filling time (t_f)	311.6 ns
Accelerating gradient (E_a)	36.1 MV/m



*c is speed of light

Figure 2: Distribution of iris diameter and RF group velocity along the accelerating column.

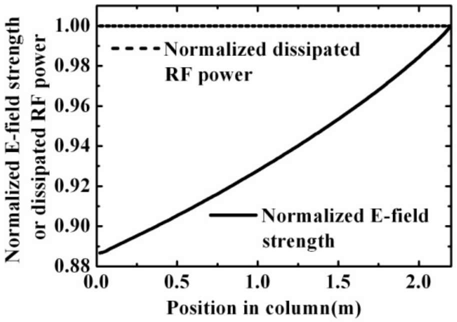


Figure 3: Distribution of dissipated RF power and E-filed strength along the accelerating column. Distribution of dissipated RF power is uniform within 0.01%.

THERMAL STABILITY

The cooling configuration of C-band choke mode cavity is described in Ref. [7]. The choke filter structure causes the temperature difference between the inner surface, interacting with electromagnetic fields, and the outer surface, interacting with coolants. This temperature difference depends on geometries of the choke filter and dissipated RF power in cavity. Their relation is defined by

$$T_{inner} - T_{outer} = bW_n, \tag{2}$$

where, T_{inner} is the temperature of the inner surface of cavity, T_{outer} is the temperature of the outer surface of the cavity, W_n is RF power dissipation of the n-th cavity, and b is a coefficient determined by the thermal resistivity and geometry. b is a constant for every cavity, since the geometry of the choke filter is almost identical. That value is

$$b = 8.3\times10^{-2}\ \mathrm{K}/W, \tag{3}$$

calculated by ANSYS simulation [7].

For the RF phase stability, T_{inner} should be uniform per cavity. Adopting bi-directional cooling, commonly used in accelerating structures, T_{outer} is almost uniform. Thus, RF power dissipation, W_n in Eq. (2), should be uniform for every cavity. The iris diameters in Fig. 2 are determined in this condition.

Actually, T_{outer} is not exactly uniform, and it is not T_{inner}. The temperatures of cavities are calculated by a 1-D model. Heat generated in the cavity is transferred to the neighbouring cavities by conduction and to coolant by forced convection [8, 9]. The heat transfer coefficient for forced convection is calculated using the Dittus-Boelter equation [9].

The equilibrium condition forms 3N-dimensional simultaneous equation. By solving the equation using MATLAB, T_{outer} is calculated. Then, T_{inner} is calculated using Eqs. (2) and (3).

There are 8 cooling channels with a hydraulic diameter of 9.4 mm [7]. The dissipated RF power is 22.5 W per each cavity. It is assumed that the accumulated phase shift at the end of the column is zero by the feedback control. With a flow rate of 24 *l*/min per column, the temperature distribution along the column and RF phase shifts due to the temperature deviation is shown in Fig. 4.

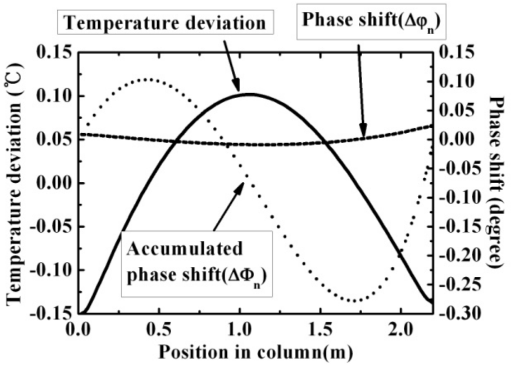


Figure 4: Temperature deviations, RF phase shifts of each cavity, and accumulated RF phase shifts along the column at a flow rate of 24 *l*/min per column.

RMS of the accumulated phase shift, equivalent to the phase shift seen by the electron beam, is shown in Fig. 5. Since heat transfer coefficient h, calculated by Dittus-Boelter equation, has an error of 25% [9], results in errors of ±30% on h shown together. As shown in Fig. 5, the phase shift is lower than 0.2°, which is equivalent to 8% of the phase shift caused by machining error in case of 1.8-m column of SACLA/SPring-8 [10]. The energy loss due to that phase shift is lower than 0.016%.

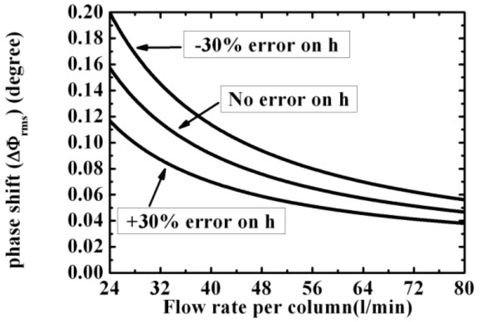


Figure 5: RMS of the accumulated phase shift.

SUMMARY

The C-band accelerating column for the XFEL application is designed with the length of 2.2 m. The maximum accelerating gradient is 36 MV/m. It is comparable to the nominal accelerating gradient of 1.8-m C-band accelerating column of SACLA/SPring-8. There are 8 cooling channels with the hydraulic diameter of 9.4 mm. When the flow rate is higher than 24 *l*/min, the RF phase shift is lower than 0.2°. The energy loss due to the phase shift is lower than 0.016%. In addition, the vacuum pressure of the column is expected to be low 10^{-7} Torr with a 30 *l*/s pumping rate per column [11].

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