VACUUM PERFORMANCE SIMULATION OF C-BAND ACCELERATING STRUCTURES*

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Abstract

A C-band accelerating structure has a higher accelerating gradient than that of the S-band structure. It provides a good advantage of a shorter machine length. In order to effectively use RF power and for cost reduction, the accelerating structure should be as long as possible. We propose a 2.2-m long structure compared to 1.8-m at SACLA (SPring-8 Angstrom Compact free electron LAser). However, a longer accelerating structure has worse vacuum performance than a shorter accelerating structure. Thus, the vacuum conductance of 2.2-m long structure has to be checked. We calculate vacuum performance of the accelerating structure by 1-D analytical method and 3-D finite element method (FEM). It is shown that the vacuum performance for the 2.2-m long accelerating structure is safe enough for the XFEL LINAC.

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.

For main linacs of the XFEL, C-band accelerating structures have a benefit of a shorter machine length. We propose a 2.2-m accelerating column compared with 1.8-m at SACLA/SPring-8 [1]. Extending the column length, the number of RF modules can be reduced. However, a longer accelerating column has a lower vacuum conductance and then there is a high possibility of the RF breakdowns, a shorter beam lifetime and emittance blow-up. For vacuum calculations, there are several methods available: analytically solving the gas flow equation [2], the finite element method (FEM) [3], the equivalent circuit analysis [4], the Monte Carlo [5] and commercial codes [6]. We adopt analytically solving the gas flow equation (1-D) and FEM (3-D) .

VACUUM ANAYSIS

1-D Analysis

In general, the pressure distribution in a vacuum system is determined by the load, flow, and pumping-out of gases. For a simple analysis, we assume that the vacuum pressure is a steady state, and there are no intermolecular collisions in the accelerating column. The relation between the gas throughput Q_V and the vacuum pressure P is given by [2]

$$Q_V = PS + C\Delta P\,, \tag{1}$$

where, S is the pumping speed, C is the vacuum conductance and ΔP is the pressure difference between cavities. Q_V is given by a product of the outgassing rate and the inner surface area of the cavity.

The inner dimension of the C-band cavity is the same as that of SACLA/SPring-8 [7]. The cavity is divided by three parts, as shown in Fig. 1: the main cavity, choke filter, and iris [8]. There are two bottlenecks: one is the iris and the other is the entrance of the choke filter. The vacuum conductance is dominantly determined by the iris, since the entrance of the choke filter is larger enough than the iris. Therefore, in analytic calculations, we simplify the vacuum model as two parts: the main cavity including the choke filter and the iris. The vacuum conductance of iris is calculated by the small cylindrical tube model [2].

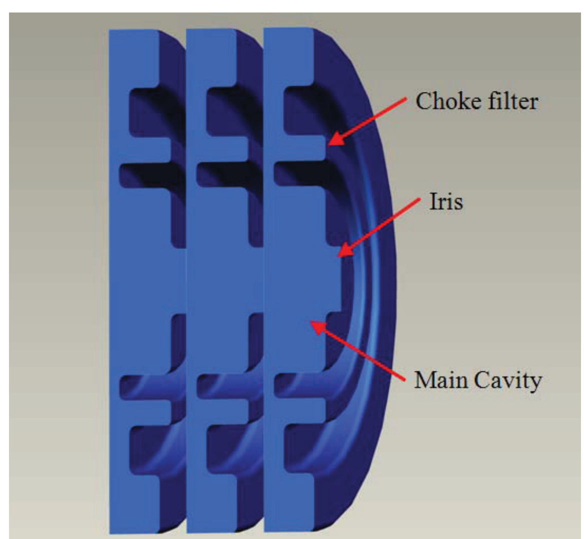

Figure 1: a cross-sectional view of the vacuum volume in the C-band accelerating column.

The out-gassing rate of the inner surface is assumed as 5×10^{-12} Torr·l/s/cm^2, which is referred by the C-band

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accelerating column of SACLA/SPring-8 [7]. The gas molecular mass is assumed as 28, equivalent to nitrogen. Eq. (1) becomes

$$Q_V = P_n S_n + C_{n-1}(P_n - P_{n-1}) + C_{n-1}(P_n - P_{n+1}), \quad (2)$$

where, P_n is the vacuum pressure at the n-th cavity, S_n is the pumping speed at the n-th cavity, C_n is the vacuum conductance between n-th and (n+1)-th cavity. Since the vacuum pumps are connected at the both end of the column, S_n is zero except for the first and last cavity. The coupled equations of Eq. (2) for every cavity are solved by MATLAB [9].

3-D Analysis

The gas flow equation is solved for the 3-D model by the finite element method (FEM). Since the mathematical structure of the gas flow equation is the same as the heat transfer equation [2], we use the thermal analysis module of a commercial FEM code, COMSOL [11].

The heat transfer equation in case of both conduction and convection is given by [10]

$$Q_H = hA(T - T_{ex}) + k\frac{A}{d}\Delta T, \quad (3)$$

where, Q_H is the heat, k is the thermal conductivity of the material, A is the cross-sectional area, d is the distance, ΔT is the temperature difference between two points, and h is the heat transfer coefficient. T_{ex} is the external temperature where the forced convection source, such as the coolant, is positioned. Comparing Eq. (3) with Eq. (1), one can find that physical quantities of the vacuum system correspond to that of the thermal system, as described in Table 1. T_{ex} should be zero in order to keep the correspondence. As a result of the COMSOL simulation, we obtained the pressure distribution along the accelerating column, as shown in Fig. 2.

Table 1: Relationship between the vacuum and thermal system.

Quantity of vacuum system	Symbol Unit	Quantity of thermal system	Symbol Unit
Pressure	P Torr	Temperature	T K
Gas flow rate	Q_V Torr·l/s	Heat	Q_H W
Vacuum conductance	C_V l/s	Heat conductance	C_V(=A·k/d) W/K
Pumping speed	S l/s	Heat transfer coefficient · area	h·A W/K
Outgassing rate	R_V Torr·l/s/cm^2	Boundary heat source	Q_b W/m^2

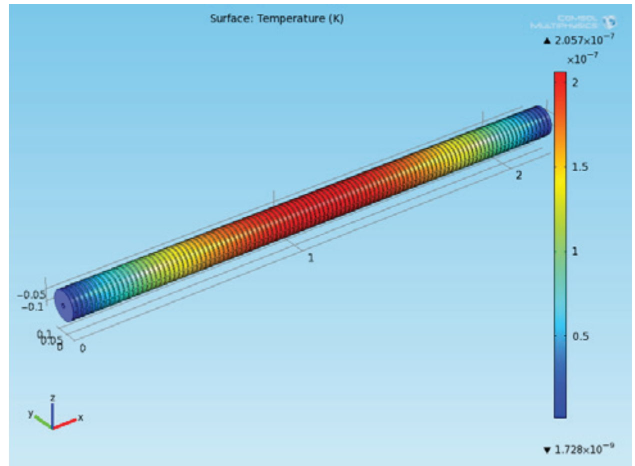

Figure 2: Vacuum simulation model using thermal analogy calculated by COMSOL

CALCULATION RESULT

The vacuum pressure along the accelerating column is shown in Fig. 3. In comparison with that of 1.8 m, the pressure is 50% higher in the 2.2-m column. The maximum pressure is almost 2×10^{-7} Torr in the middle of the column. In Fig. 3, there are no significant differences between results of the 1-D and 3-D analysis. The pumping speed is 60 *l*/s

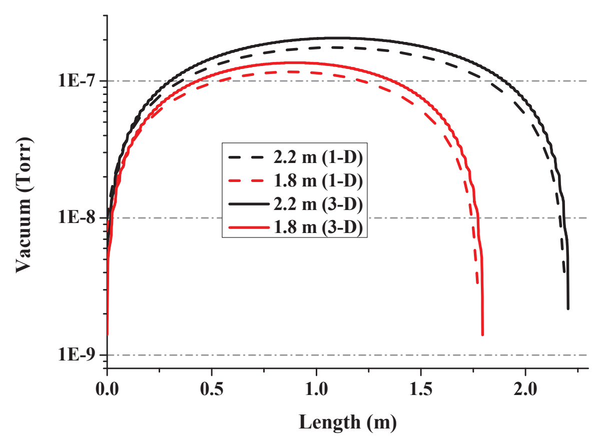

Figure 3: Distribution of the on-axis vacuum pressures along the accelerating column.

The pressure profiles are not changed significantly by the pumping speeds, as shown in Fig. 4. The reason is that the effective pumping speed S_{eff}, which is defined by

$$\frac{1}{S_{eff}} = \frac{1}{S_0} + \frac{1}{C}, \quad (4)$$

where, S_0 is the pumping speed and C is the vacuum conductance, is limited by C although S_0 becomes higher.

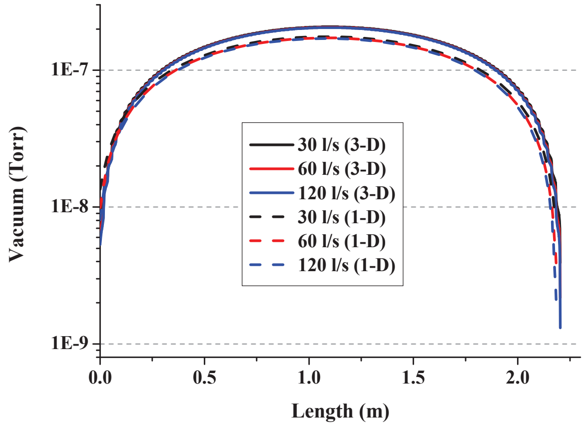

Figure 4: Vacuum pressures with pumping speeds.

SUMMARY

The vacuum pressure is calculated for the 2.2-m C-band accelerating column. By the 1-D analytical and 3-D FEM analysis, the vacuum pressure of the 2.2-m column is 50% higher than 1.8-m one. However, the maximum pressure is 2×10^{-7} Torr with the pumping speed of 60 *l*/s and it is safe enough to be used in the proposed XFEL linacs. The vacuum pressure dominantly depends on the vacuum conductance not the pumping speed.

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