DESIGN OF A C-BAND TRAVELLING-WAVE ACCELERATING STRUCTURE AT IHEP*

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Abstract

A C-band travelling wave accelerating structure has been developed at IHEP. The structure is a constant gradient type and operating with a 3π/4 mode. The total length of the structure is 1.8-meters long with 85 regular cells and two coupler cells. 2D program Superfish is used to optimize the cavity shape and the iris size. The wall cells are rounded for it can improved the Q value for about 10%. The cell irises have an elliptical profile to minimize the peak surface electric fields. In order to compatible with the compact of the short-range wake field on the beam dynamics, the average iris radius is 7.15 mm. The group velocity of the designed structure is from 2.8% to 1.4%. Between the rectangular waveguide and the accelerating structure, magnetic coupling is adopted. The coupled cavity is racetrack type in order to minimize the asymmetry in the coupler. Kyhl's method is used to match the input and output coupler.

INTRODUCTION

The C-band accelerating structures for electron accelerator has been adopted in several linac projects all over the world. Such as Japanese X-ray free electron laser (XFEL) facility at Spring-8 in Japan [1], the Swiss-FEL project at the Paul Scherrer Institute (PSI) in Switzerland [2] , a compact XFEL at Shanghai Institute of Applied Physics (SINAP) in China [3]. Also the energy upgrade of the SPARC photo-injector at LNF-INFN (Italy) has been done by replacing a low gradient S-Band accelerating structure with two C-band structures [4]. Beam dynamics calculation and experimental measurement demonstrated C-band accelerating structures can reach high beam quality and higher gradients. That makes the C-Band technology very appealing. For a compact facility, C-band RF linac technology can supply proper short-rang wake field and various other advantages [5]. From this point of view, C-band accelerating structures have been studied at institute of high energy physics (IHEP), Chinese Academy of Sciences. The structure has been designed to obtain an average accelerating field more than 40 MV/m.

THE REGULAR CAVITY DESIGN

For a C-band accelerating structure, the short-range wake-field is a strong function of the beam aperture (2a). The average iris radius of the structure is more than 7 mm can supply for proper short-rang wake-field on the linac beam dynamics [5]. At the same time, larger beam apertures have other advantages, such as lower peak surface electric field, higher pumping speed, and shorter filling time of the structures thus reducing breakdown probability.

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The Single Cell Design

Since the regular cells that composed the accelerating structure are axisymmetric, the RF design can be performed with the 2D electromagnetic code Superfish [6]. It can calculate travelling-wave fundamental parameters from standing-wave simulations [7]. 3π/4 accelerating mode is selected. For Superfish program is set 20 ^{0}C and the working temperature is 40 ^{0}C, the periodic length is adjusted from 19.682 mm to 19.675 mm. The rounded-wall cavity shape is chosen for the quality factor is 10% higher than the disk-loaded one [8]. The cell irises have an elliptical profile in order to minimize the peak surface electric fields.

Considering the 3π/4 accelerating mode for the elliptical average beam radius 7.15 mm, the shunt impedance and Emax/E_0 have been calculated as a function of the disk thickness t. Fig. 1 shows the calculation results. 4.5 mm of the disk thickness is selected. Fig. 2 shows the peak surface electric field normalized to the average accelerating field as a function of the iris ellipticity for the iris radius 7.15 mm and disk thickness 4.5 mm. 1.8 is the optimal value.

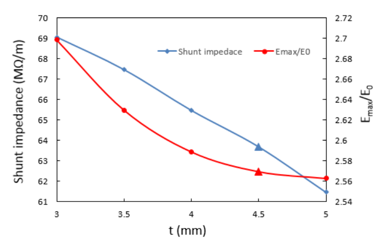

Figure 1: The shunt impedance and Emax/E_0 VS. disk thickness t.

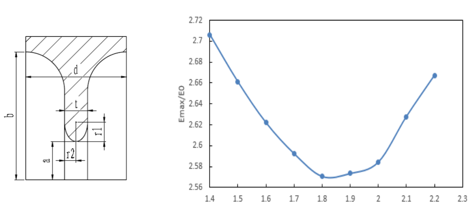

Figure 2: Emax/E_0 as a function of the iris ellipticity.

The working temperature is 40 ^{0}C while the workshop is usually set 20 ^{0}C, so Ansys is used to analyse the frequency shift by temperature variation. Fig. 3 shows the deformation caused by temperature variation and the frequency shift is about 2MHz. The result is consistent with the value from formula $\Delta f = \alpha f_0 \Delta T$, where α is Thermal expansion coefficient. Here it is 1.77E-5.

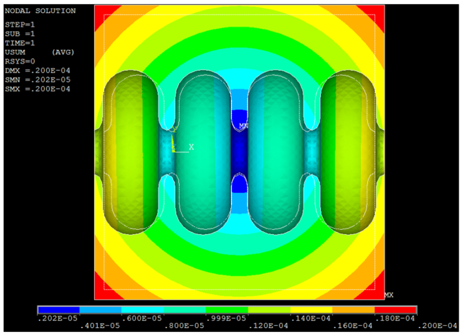

Figure 3: The deformation caused by temperature variation.

The Whole Accelerating Structure Design

The relatively group velocity v_g is an important parameter of the constant gradient accelerating structures. It is related to efficiency and stability of the structure [9]. The low group velocity will cause high dispersion characteristic, which will lead the stability of the accelerator becomes worse. But the high group velocity will decrease the shunt impedance of the structure. Considering the stability and the efficiency, the relative group velocity is chosen about 1%~3%.

For constant gradient structure, when the beam loading is not considered, the accelerating electric field E_{acc} in the waveguide is constant:

$$E_{acc} = \sqrt{\frac{PR_M(1-e^{-2\tau})}{L}} = \text{const.} \tag{1}$$

where P is the power flow of the cell, R_M is the effective shunt impedance, τ is the attenuation constant defined by $\tau = 2\pi f_0/(2v_g Q)$, and L is the cell length. Between adjacent cavities, the power flow relationship is:

$$P_n = P_{n-1}e^{-2\tau_n L}. \tag{2}$$

Use these equations, the iris diameter 2a and cell diameter 2b are tuned to reach the resonant frequency f_0 and E_{acc}. At the same time, superfish program can give each cell's Q value, shunt impedance, etc. The each cavity's characteristic is reported in Fig. 4-6 as a function of the cell number.

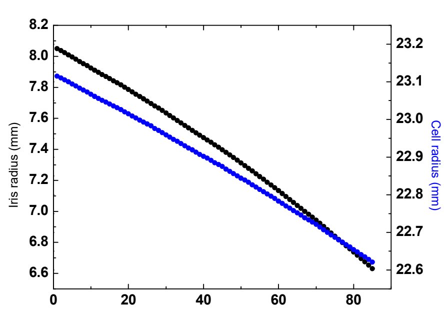

Figure 4: Each cavity's iris and cell radius.

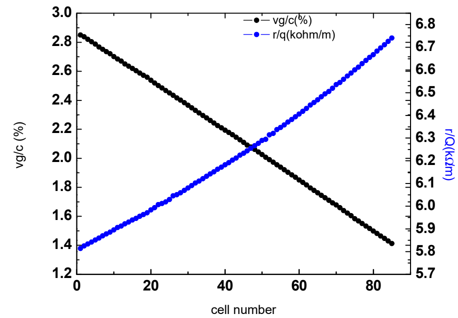

Figure 5: Each cavity's v_g and r/Q.

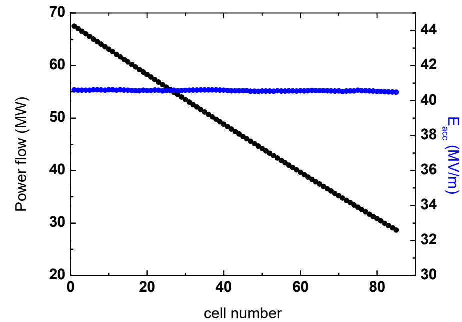

Figure 6: The power flow and E_{acc} along the structure.

Table 1 summarizes the main parameters of the designed C-band structure.

Table 1: Main Parameters of the Structure

Parameters	**value**
Operating frequency (MHz)	5712
Phase advance per cell	3π/4
Total number of cells	85
Length of cell : d (mm)	19.675
Disk thickness: t (mm)	4.5
Shunt impedance : Rs (MΩ/m)	66.0~75.7
Group velocity: Vg/c (%)	2.8~1.4
Filling time : ft (ns)	271
Attenuation factor : τ	0.432

THE COUPLER DESIGN

One important component of any accelerating structure is the fundamental mode input coupler. It must provide a perfect match at the correct frequency between rectangular waveguide and the accelerating structure. Here, a high power compact RF coupler connecting WR90 rectangular waveguide is designed for C-band accelerating structure by 3D electromagnetic codes HFSS. The coupler is a dual-feed racetrack coupler. It is symmetric and free of beam deflecting field components. An efficient magnetic match between the rectangular waveguide power feed and the accelerating structure is adopted.

The compact coupler is divided into two parts. Namely, matching of the splitter used for splitting the input power into two arms and matching of the coupler cavity.

The Splitter

The splitter design should be compact and convenient in processing. There is a λg/4 impedance transformer to match the standard waveguide and the waveguide connect the coupler. Power divider divides power into two parts of equal amplitude and in phase. After optimization, the total VSWR of the splitter at work frequency is -49.9 dB (see Fig. 7). Fig. 8 shows the electromagnetic distribution of the splitter for HFSS simulations. When 68 MW power input, the peak surface electric field is 16.3MV/m.

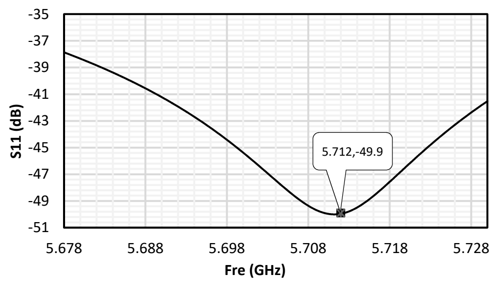

Figure 7: The VSWR of the splitter.

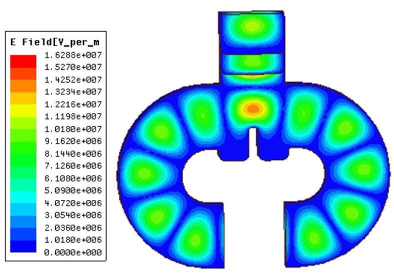

Figure 8: The electromagnetic distribution of the splitter.

Matching and Tuning of the Coupler Cavity

To preserve low emittance in multi-bunch beams, RF field and phase must be made symmetric across the coupling cavity to avoid transverse deflections. Dual feed racetrack coupled cavity is designed use Kyhl method [10]. It is used to evaluate coupling vs. tuning based on reflected phase at three frequencies calculated for the π/2 mode and the designed 3π/4 mode [11].

Fig. 7 is the design results of the input coupler, and the output coupler is designed use the same method. Fig 9 (a) is the model to check the kyhl method design results. Fig. 9 (b) shows the phase along the axis of the model. During one period, the phase advance per cell is about 133^{0}. Fig 9 (c) shows the electromagnetic field distribution along the axis.

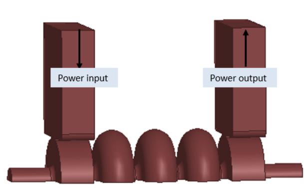

Figure 9 (a): The simulation model of the coupler.

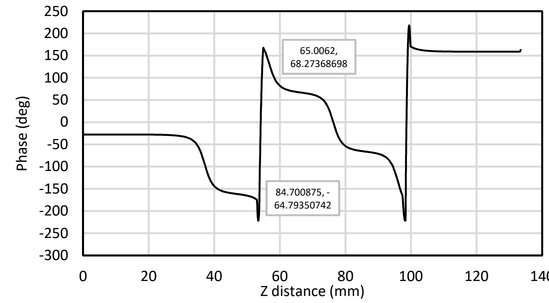

Figure 9 (b): The phase along the axis of the model.

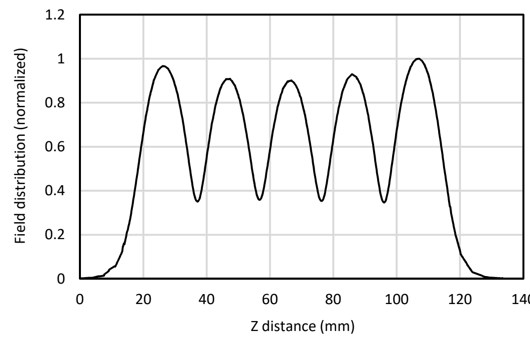

Figure 9 (c): The field distribution along axis.

Pulsed Heating in the Coupler

Pulsed heating due to surface magnetic field causes a temperature rise ΔT on the metal at each RF pulse. It is given by:

$$\Delta T = \frac{\left|H_{||}\right|^2 \sqrt{t_p}}{\sigma\delta\sqrt{\pi\rho c k}}. \tag{3}$$

Where t_p is the pulse length, σ is the electrical conductivity, δ the skin depth, ρ the density, c the specific heat, and k the thermal conductivity of the metal.

The subsequent cooling between pulses causes surface fatigue. This cyclic stress will cause micro cracks which may decrease the heat conductivity and in some conditions cause RF breakdown.

For copper, Eq. (3) can be simplified as:

$$\Delta T[^{0}C]=127\left|H_{||}[MA/m]\right|^2 \sqrt{f.[GHz].t_p[uS]}\,. \tag{4}$$

The RF power enters the structure through the coupler window. The maximum of the magnetic field is at the place of window edges. They are designed round to reduce the pulsed heating.

When the input power is 68 MW, there will be 34 MW power flows the edges. In HFSS simulation, the peak surface magnetic is 157 kA/m (see Fig. 10). When the pulse length is 0.3 us, the temperature rise per pulse is 4 ^{0}C. As a general experimental rule, if this pulsed heating below 50 ^{0}C the couplers can avoided to be damaged.

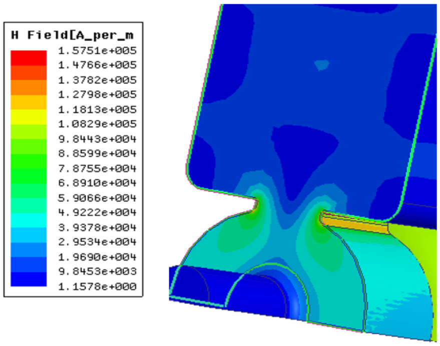

Figure 10: The peak magnetic field at the coupler windows.

SUMMARY

A 1.8-m long C-band constant gradient accelerating structure has been designed. The operation mode is 3π/4. The design goal is accelerating gradient greater than 40 MV/m. The cavity shape is optimized to get higher shunt impedance and higher gradient. Single cell deformation caused by temperature is simulated. It causes 2MHz frequency shift from 20^0C to 40^0C. The input and output coupler cells are of racetrack dual feed type. The whole structure design is finished and the designed accelerating structure is being manufactured.

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