DESIGN OF A C-BAND 6MeV STANDING-WAVE LINEAR ACCELERATING STRUCTURE *

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Abstract

We design a C-band standing-wave biperiodic on-axis coupled linear accelerating structure for industrial and medical applications. It's less than 300mm long; consists of 3 bunching cells and 9 normal cells. It can accelerate electrons to 6MeV and the pulsed beam current is 100mA. The RF power source is a 2.5MW magnetron. We implement 2D cells geometry optimization by SUPERFISH, beam dynamics study by PARMELA and full scale 3D calculations by MAFIA codes.

INTRODUCTION

The electron accelerator is widely used for industrial and medical applications. Currently, most linear electron accelerators are operated in S-band, which causes great volume. There are also some accelerators which are operated in X-band. Although these accelerators are very small, they are difficult to be manufactured and lack of appropriate RF power. In contrast, C-band linear accelerator has the merits of compact structure, high accelerating efficiency and moderate difficulty of manufacture. Recently, C-band linear accelerator is receiving broad attentions [1, 2, 3].

With 2.2MW input RF power, we design a C-band linear accelerator. It can accelerate electrons to 6MeV and the pulsed beam current is 100mA. We choose the standing-wave biperiodic on-axis coupled structure, which is operated in π/2 mode. The accelerating structure is less than 300mm long.

2D PHYSICS DESIGN

The first part of our design is consists of cell geometry optimization and beam dynamics design. At this stage, it's not necessary to consider the coupling slots and external coupling waveguide. So the whole structure is axis-symmetric and we can use 2D models for the design.

The 2D physics design involves the following four steps:

1. Optimization of the normal cell and basic design of a set of bunching cells by SUPERFISH.
2. Beam dynamics design by PARMELA to decide the number of normal cells and select bunching cells.
3. Optimization of the selected bunching cell.
4. Beam dynamics design of the average electric field strength on axis of each cell.

Because there are many parameters to be adjusted, we write several MATLAB codes to call SUPERFISH and PARMELA. After simulation, MATLAB codes also read the results and extract useful information. This method can greatly improve work efficiency.

Cavity Optimization

The maximum energy an electron can gain from a linear accelerating structure is [4]

$$W = \sqrt{ZPL}\,, \tag{1}$$

where Z is the effective shunt impedance, P is the power loss on the surface, L is the length of the structure. So when Z is enhanced, the accelerating structure can be shorter for particular output beam energy (6MeV in our design). The target of cavity optimization is to enhance the effective shunt impedance.

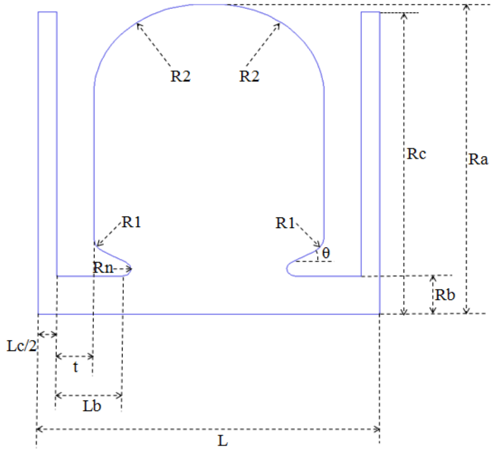

Figure 1: 2D cell model and its parameters.

The 2D model we use in SUPERFISH is shown as Figure 1. There are 11 independent parameters to define this model. Though reducing the length of coupling cell and the wall thickness can improve Z, the cell will be easier to deformation in machining. Reducing the beam hole radius can also improve Z, but it will abase the capture coefficient as many electron will be lost on the wall of the nose. The effective shunt impedance can be also enhanced by reducing the nose radius, but a small nose radius will cause great electric field strength on the nose surface which will make the cell easier to break down. For these reasons, we fix these parameters at compromise values. The coupling cell radius, the nose angle and joint radius have little influence on Z, so we fix them at Rc=20mm, θ=30°, R1=1mm. The length of the normal cell is 26.24mm. By adjusting the accelerating cell radius Ra, the cell top radius R2 and the nose length Lb,

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we finally optimize the normal cell. Some of its parameter characteristics are shown in Table 1.

Table 1: Some parameter characteristics of the optimized normal cell (without coupling slots)

Normal Cell Characteristics	
Resonant frequency	5712MHz
Efficient shunt impedance	130MOhm/m
Quality factor	11500

Beam Dynamics

In beam dynamics, three characteristics need to be considered particularly. 1. The total power *P* is consists of wall loss *Pw* and beam power *Pb*. It should be less than the input RF power which is 2.2MW. 2. The effective capture coefficient rp. It's the ratio of the number of the output electron whose energy is higher than 6MeV to the number of the injected electron. 3. The root-mean-square beam spot radius Rrms.

The major part of *Pw* is the wall loss of normal cells:

$$P_{normal} = \frac{W^2}{nZ_cL_c} , \qquad (2)$$

W is the output electron energy, n is the number of the normal cells, Z_c and L_c are the effective shunt impedance and length of the normal cells respectively. So n can be 9 or 10, the average electric field strength on axis *Ec* should be 24MV/m to 27MV/m.

After fixing *n* and *Ec*, we need to choose bunching cells and design the average electric field strength on axis of them. We use MATLAB codes to scan these parameters. Some of the preferable results are shown in Table 2. The assembly of three bunching cells and nine normal cells performs well. It has the minimum spot size and its length is less than 300mm. So we choose this assembly as the final dynamics design.

Table 2: Some preferable dynamics design results (the emittance of the electron gun is 60mm·mrad)

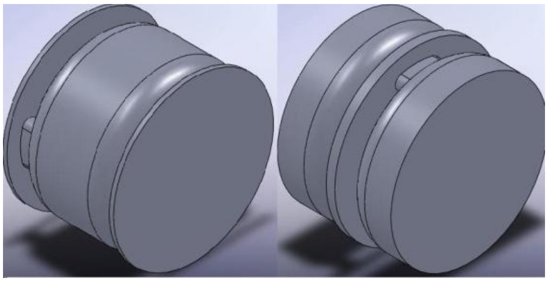
Bunching cells (phase velocity)	n	P (MW)	rp (%)	Rrms (mm)
0.5c, 0.7c	9	2.24	36.47	1.16
0.5c, 0.6c, 0.9c	10	2.03	37.65	0.93
0.5c, 0.6c, 0.75c	9	2.16	32.72	0.71

3D PHYSICS DESIGN

Coupling Slot Calculation

Since the electric coupling is very small due to cell nose, the cells are coupled by magnetic slots on the wall.

The coupling slots between normal cells should be calculated first. The coupling factor should be between 2~3%, providing enough band-width between π/2 mode and its adjacent modes.



(a) (b)

Figure 2: 3D models for coupling slots calculation.

Two 3D models, as shown in Figure 2, are used to simulate the frequency of the accelerating cells and coupling cells [5]. When their z-boundaries are set to perfect H, the electric field will be built up in the middle cell and the filed in the two half-cells will be very weak. So the resonant frequency can be thought of as the eigen-frequency of the middle cell.

After adjusting the frequencies to 5712MHz, we set the z-boundary in model (b) to perfect E. There would be three resonance frequencies, which represent the π mode, the π/2 mode and the 0 mode. The coupling factor k is [6]

$$k = \frac{f_0 - f_\pi}{f_{\pi/2}} , \qquad (3)$$

Then we need to design the coupling slots between bunching cells. The target is adjusting the average electric field strength on axis of each bunching cells to the 2D design result. Because the electric field strength is inversely proportional to the coupling factor, we can adjust the size of slots to achieve the target. Figure 3 shows the electric field distribution on axis after 2D and 3D design.

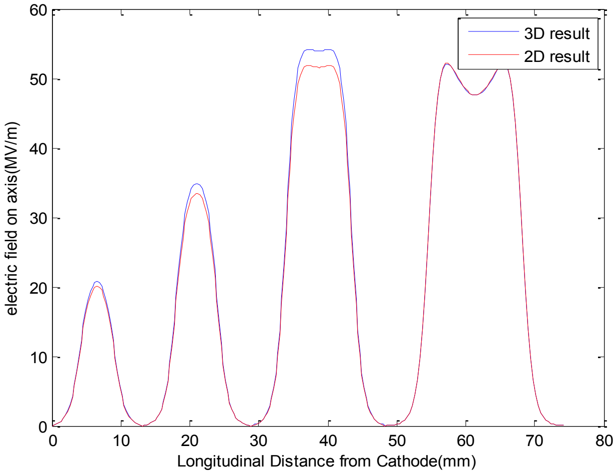


Figure 3: The electric field distribution on axis (the first four cells).

External Coupling Calculation

The accelerating structure is not isolated; it's coupled with the waveguide through the coupling window.

The external coupling can be defined as

$$\beta = \frac{Q_0}{Q_e}\ , \tag{4}$$

where Q_0 is the unloaded quality factor and Q_e is the external quality factor. When the beam is ignored, the optimum coupling is 1, which means that the RF power can be fed into the accelerating structure without any reflex. When the beam loading is taken into account, the optimum coupling is

$$\beta = [\frac{I}{2}\sqrt{\frac{ZL}{P_0}} + \sqrt{1+\frac{I^2 ZL}{4P_0}}]^2\ , \tag{5}$$

where I is the beam current and P_0 is the input power. Z and L are respectively the effective shunt impedance and the length of the structure. In our design, $I \approx$ 130mA and P_0 is 2.2WM, so the optimum external coupling is about 1.6.

Because the accelerating structure is consists of 12 cells, simulation of the whole structure will be a time-consuming job. Instead of simulating the whole structure, we use a model consists only the waveguide-connected cell [7]. We set the z-boundary perfect H. As the accelerator is operated at π/2 mode, this model can represent the whole structure. The external quality factor of this cell is

$$Q_{e,s} = \frac{U_s}{U} Q_e = \frac{U_s}{U}\frac{Q_0}{\beta} \tag{6}$$

where Us and U are respectively the stored energy over one RF period in the single cell and the whole structure. So the optimum external quality factor of the waveguide-connected cell is about 670.

COLD TEST

At present, all the cells have been machined, as Figure 4 shows.

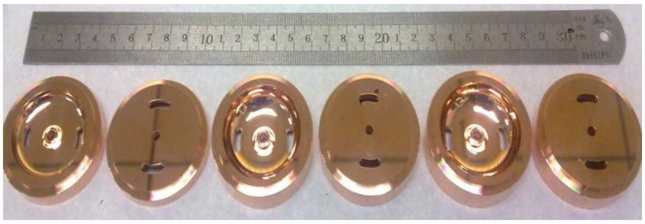


Figure 4: the machined cells

The machined cells have been measured in cold test. Some of the results are shown in Table 3.It shows that the result of simulation is in good agreement with the test.

Table 3: The Cold Test Results of the Machined Cells*

	Simulation	Cold test
$fa1$	5738.8MHz	5745.5MHz
$fc1$	5725.0MHz	5733.6MHz
$fa3$	5738.6MHz	5743.5MHz
$fc3$	5724.7MHz	5731.1MHz
fan	5718.3MHz	5720.4MHz
fcn	5725.1MHz	5729.4MHz
kn	2.44%	2.46%

* The radius of each cell in machining is smaller than the design value.

CONCLUSION

We design a 6MeV C-band standing-wave biperiodic on-axis coupled linear accelerating structure. The cells have been machined and are under cold test. The cold test result shows that the simulation has good accuracy. High power test will be carried out at the end of this year.

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