THE STUDY ON RF FIELD OF AN RFQ

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Abstract

Computer simulations are carried out for calculating the RF field distribution and frequency in either 2-D coordinates (by SUPERFISH) or 3-D coordinates (by MAFIA), by which the tunners, the end cells, the coupling cells and other components of the radio-frequency quadrupole (RFQ) are also designed. The designing principle is that the E-field longitudinal distribution and the local quadrupole cut-off frequency should be kept as constant as possible.

1 INTRODUCTION

As a prior option of the energy source for the next generation, the accelerator driven sub-critical nuclear power system (ADS) can use efficiently the uranium and thorium resource, transmute the high-level long-lived radioactive wastes and raise nuclear safety. While the RFQ is best suited for the acceleration of beams with low energy because it can bunch, focus and accelerate charged particles simultaneously by the RF electric fields only. In fact, the four-vane RFQ has become the unique choice of the initial linear accelerator structure that accelerates high-current ion beams to the energy of several MeV.

The 352.2-MHz four-vane RFQ used for our ADS accelerates 50mA pulsed beams from 80keV to 5MeV. The average beam current is 3mA. The RFQ is about 7 meter long, which is 8 times longer than the RF wavelength. For such a long structure, small perturbations would distort the longitudinal field distribution intolerably. A conventional RFQ is obviously not feasible. Therefore, three more than 2-m-long segments are resonantly coupled to form the RFQ. Each segment consists of 2 sections. The resonant coupling is implemented by separating the different segments by coupling plates[1,2]. The coupling plates prevent the magnetic field from continuing from one segment to the next, and a hole at the centre of the plate allows the vane tips to nearly touch. The gap between the vane tips acts as a capacitor, which provides the RF coupling between different segments. The operating mode is the zero mode of the TE_{210} like mode. To produce such a mode, vane undercuts must be machined at both ends of each segment. The magnetic field lines flow around the end of vanes, through the undercuts, into the adjacent quadrants. In our design, the inter-vane voltage is kept constant along the structure. So, as concerns the TE_{210} mode, the local quadrupole cut-off frequency should be kept constant as well. This condition must be satisfied in designing the end cells and the coupling cells. That is to say, the frequency of the end cells and the coupling cells should equal to the cut-off frequency.

2 TUNERS

The number of tuners to be used per quadrant per section is 4, and the frequency variation tuned by the tuners is set to be 1.2MHz. If we do not consider the RF electric fields in the region where the tuners are placed, then the tuners dimension and their penetration inside the RFQ cavity can be easily estimated by the following equation[3]

$$\frac{\Delta\nu}{\nu} \approx -0.5\frac{\Delta V}{V}.$$

Here $\nu = 351$ MHz, is resonant frequency, $\Delta\nu = 1.2$ MHz, $V \approx 5.89\times10^3$ cm^3, is the volume of one quadrant per section, ΔV is the volume occupied by the tuners and its value got from above equation is 40.274 cm^3. Assuming tuners have a cylindrical shape and a diameter of 5cm, then we can get the penetration of the tuners inside the cavity, which is 0.513cm. SUPERFISH simulations could be carried out by considering the tuners as a groove that has the same volume as that of the 4 tuners penetrating inside the wall. The simulation result shows that penetration of tuners should be 0.462cm.

With this penetration value of tuners, 3-dimensional simulation is performed to one quadrant of one RFQ section without end vane undercuts and electrode modulation by using MAFIA code. The reason why we do not simulate the electrode modulation is that enormous number of mesh points is needed to draw the electrode profile with enough accuracy. In the meantime, the modulation does bring small local variation to the capacitance. In the simulation, we use magnetic boundary condition (Newmann condition) for both ends of the section. All meshes are made manually and the mesh density near the vane tip area is largest. But the ratio between the maximum and the minimum mesh step has never exceeded a factor of 10 in three directions. Moreover, in the simulation afterwards, the mesh form is always kept unchanged in transverse section and almost unchanged in the longitudinal direction. The cut-off frequency got by MAFIA is 355.02MHz, which is slightly different from that by SUPERFISH. The difference is due to the limited number of mesh points in 3-D simulation. However, it does not matter, we can just consider that the cut-off frequency got by MAFIA is same as that got by SUPERFISH, and in the 3-D simulation afterwards, the cut-off frequency is considered as 355.02MHz but not

352.2MHz. Figure 1 shows a 3-D picture of one quadrant of one RFQ section. In Figure 2, the distribution of the transverse electric fields along the longitudinal axis is shown. The fields are normalized to the maximum field. From this figure, one can see that, the fields at the sites that the tuners located are lower. This is due to a larger cut-off frequency at these tuner locations. In addition, since the four tuners are not separated equally, the fields where the tuners located are also not same. However, the flatness of the field is 0.431%, which is still well. The flatness is defined as $F = (E_{\max} - E_{\min})/E_{\max}$.

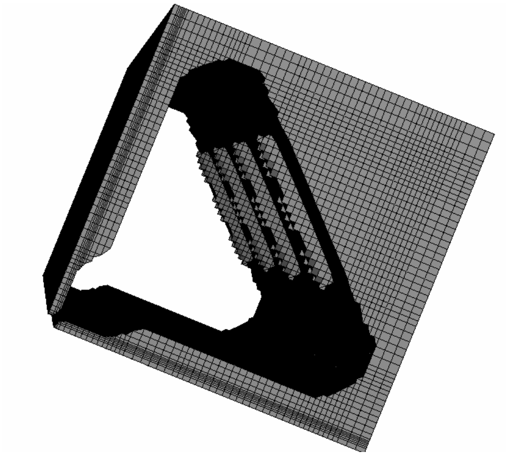

Figure 1: 3-D MAFIA picture of one quadrant of one section without end cells.

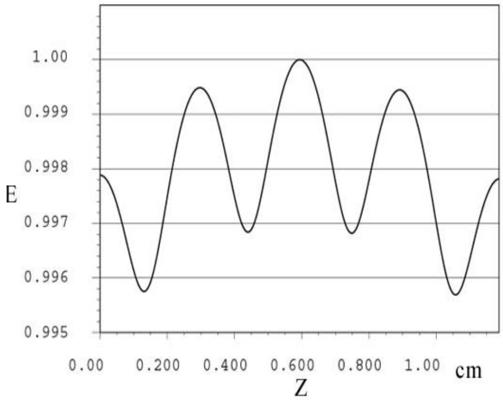

Figure 2: The distribution of the transverse electric fields along the longitudinal axis.

3 THE BEGINNING CELL

In order to design the beginning cell of the RFQ, 3-D simulations are carried out to a quadrant of one RFQ section by MAFIA. The beginning cell of this section is shown in figure 3. The value of the parameters is listed in Table 1. The profile of the matching radial section (MRS) shown in figure 3 is given by the code PARMTEQM[4]. The other end of the section is flush. In simulations, electric boundary condition (Dirichelet condition) and magnetic boundary condition are applied to the beginning end and the other end of the section, respectively. By keeping the slope angle 45^{o} unchanged and adjusting the values of the undercut depth *d* and the height *h*, we simulate the section with different beginning cells many times. When the lowest resonant frequency of the cavity is most near to the criterion frequency 355.02Mhz, we consider that the parameters of the beginning cell are satisfied.

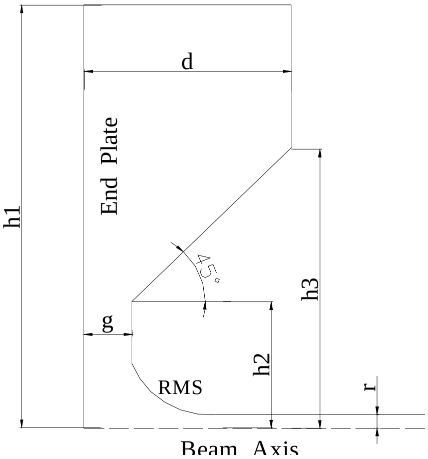

Figure 3: 2-D profile of the beginning cell.

Table 1: The geometrical design parameters of the beginning cell

Parameters	value
h1	91.41 mm
h2	27.38 mm
h3	60.04 mm
d	42.52 mm
r	2.93mm
g	9.86 mm

The distribution of the transverse electric fields along the longitudinal axis in the section is shown in figure 4. The fields decrease rapidly from the vane to the plate and become zero near the plate. Except the fields in the gap region between the vane and the plate, the flatness of the fields is also well, which is about 0.506%.

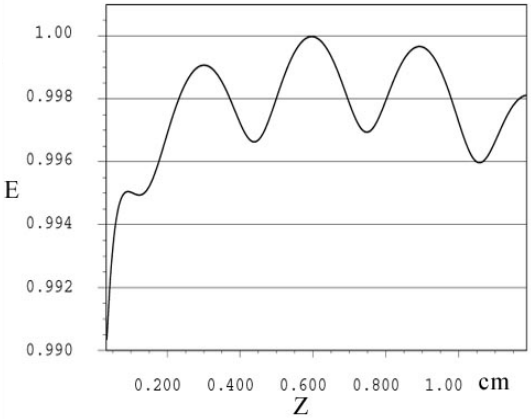

Figure 4: The distribution of the transverse electric fields along the longitudinal axis

4 THE COUPLING CELL

To design the coupling cell, we first determine the shape and size of the undercuts, the size of the plate with a given gap width between the vane tips. Secondly, we determine the width of the gap with the obtained undercuts and plate.

To this end, we first simulate the connecting part of two segments with the coupling cell in the middle. As done above, only one quadrant of the part is simulated and the simulating length is equal to that of one RFQ section. Magnetic boundary condition is used for both ends of the simulating part. Simulations have been performed for various coupling cell configurations. When the frequency of the cavity eigenmode corresponding to the operating mode of the RFQ (zero mode of the TE_{210} like mode) is most near to the criterion frequency 355.02MHz, the required final profile is determined. In figure 5, The 2-D profile of the coupling cell is shown. The corresponding values of the parameters are listed in table 2. Except the sharp decrease in gap, the flatness of the fields is about 0.525%.

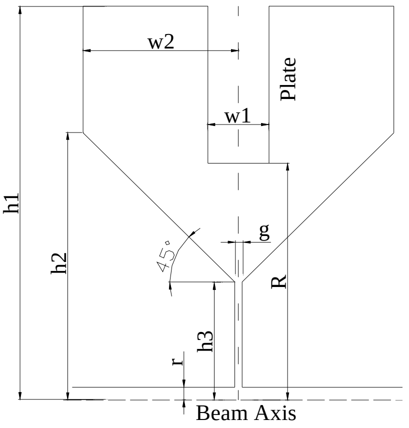

Figure 5: 2-D profile of the coupling cell

Table 2: The geometrical design parameters of the coupling cell

Parameters	Value
h1	91.41 mm
h2	62.03 mm
h3	27.38 mm
w1	14.00 mm
w2	35.52mm
r	2.93mm
R	55.00mm
g	To be calculated

Since the gap acts as capacitor, its width determines the capacitance of the gap and thus the coupling intensity. As known to us, the coupling intensity between the neighbour segments is related with the mode spacing. As concerns our case, the segments are not only the elements for the operating mode (the TE_{210} mode), but also the resonant elements for the coupling mode. The coupling mode is the TE_{211} like mode in each segment. The coupling gaps lower both the frequencies of the TE_{210} and the TE_{211} mode to form the TE_{210} like mode and the TE_{211} like mode, respectively. In both the TE_{210} like mode family and the TE_{211} like mode family, there are three members. They are $-2\pi/3, -\pi/3, 0$ modes of the TE_{210} like mode family and $\pi/3, 2\pi/3, \pi$ modes of the TE_{211} like mode family, respectively. As indicated above, the operating mode is the zero mode of the TE_{210} like mode family. Based on the standard perturbation theory for the eigenvalue problem[5], when the mode spacing between $-\pi/3$ mode and 0 mode is equal to that between 0 mode and $\pi/3$ mode, the structure is most insensitive to perturbation. This is the so-called compensated or stabilized structure[6].

To determine the gap width, we simulate half RFQ with appropriate boundary conditions. Since the longitudinal distribution of the transverse electric fields of $-\pi/3$ mode and $\pi/3$ mode is anti-symmetric about the middle point of the RFQ, the fields of these two modes should be zero at the middle of RFQ. Based on this character, electric boundary condition is used for both ends of the half RFQ in simulations.

Simulations are carried out for different gap width cases. When the gap g is chosen to be 1.74mm, the frequencies of $-\pi/3$ mode and $\pi/3$ mode are 352.65MHz and 357.35MHz, respectively. The mode spacing of the two modes with respect to 0 mode are 2.37MHz and 2.35Mhz respectively, which is very near.

5 OTHER COMPONENTS

Besides above design of tuners, beginning cell and coupling cell, based on the same designing principle, the design of vacuum ports, exit cell and technological model for the exit cell is also made. In order to ensure the flatness of the longitudinal distribution of the transverse electric fields, the vacuum flanges designed penetrate a little into the RFQ cavity.

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