THE STUDY ON RF CAVITY TOLERANCE FOR CYCIAE-100*

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Abstract

The tolerances of RF cavity in CYCIAE-100, a high intensity proton cyclotron, are proposed. Two important types of error, manufacture error and dees deformation caused by gravity, exist during the building of the RF cavity. Both analytic treatment and numerical simulation are carried out to give the tolerance of the manufacture error which disturbs the radial and vertical motion of the beam. The dees deformation caused by gravity leads to axial misalignment of the dees and then induces the build-up of coherent axial oscillations. However, our calculated results show that the deformation of our dees is acceptable.

INTRODUCTION

Beijing Radioactive Ion-beam Facility (BRIF) is now in progress in China Institute of Atomic Energy (CIAE). As the driving accelerator of this project, CYCIAE-100, a high intensity proton cyclotron, is designed to provide a 75 MeV~100 MeV, 200 μA~500 μA proton beam[1].

Richardson and Mackenzie et al. studied the influence of asymmetric voltage on beam [2-3]. Craddock and dutto treated the effect of axial misalignment of the dees[4]. Since their analyses were based on 180^o dees of TRIUMF 500MeV cyclotron, the results can't be used in dees with smaller angular widths directly.

In this paper, for dees with unusual angular width, both analytic treatment and numerical simulation have been carried out to give the tolerance of CYCIAE-100. Kinds of error that may exist during manufacture of RF cavity and their influence on beam quality are discussed in detail, then the design requirement is given out. We also research if the dees deformation caused by gravity satisfies the requirement of beam dynamics.

MANUFACTURE ERRORS

The structure of CYCIAE-100 which is composed by two independent RF cavities is shown in Fig.1.

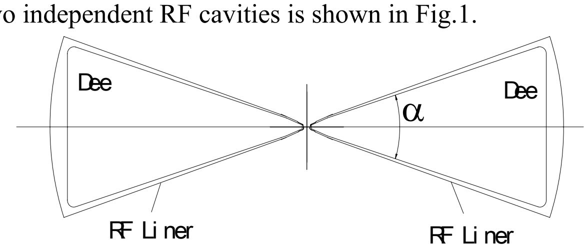

Figure 1: The shape of RF cavity.

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Since each cavity has two accelerating gaps, the particle will be accelerated four times in one turn. The dees, with radius of 1.8m and angle of 36°, are made by red copper.

Types of Errors and induced asymmetric voltage

The two cavities driven by different RF generators have deviation in voltages inevitably. For one cavity, Fig.2 shows the two types of errors during manufacture. First, one dee rotates a small angle with respect to the other, which makes the voltage increase in narrow gap and decrease in wide one. Second, the angle of the dee is a little smaller or larger, which induces higher/lower voltage.

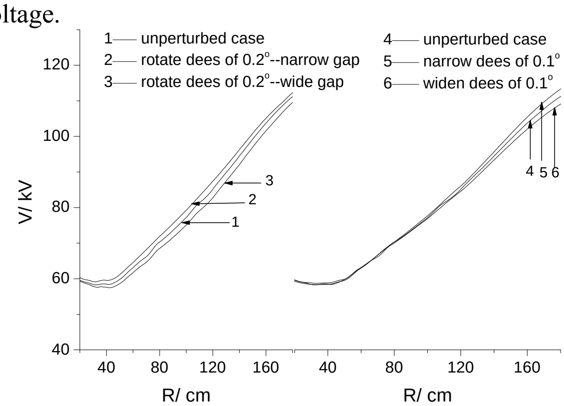

Figure 2: The change in voltage caused by errors during manufacture.

The Effect of Asymmetric Voltage on Beam

The asymmetric voltage of two cavities can be equivalent to the appropriate asymmetry in the magnet field [2]. Fig.3 shows that it is corresponding to weak B in the upper half and strong B in the lower one if the voltage is high in the right half and low in the left one.

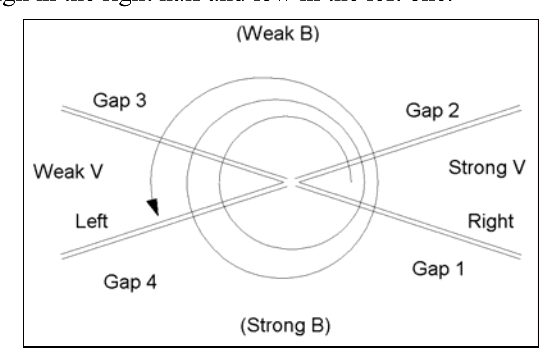

Figure 3: The relationship between asymmetric voltage and asymmetric magnet field.

No matter asymmetric voltage or magnet field could provide a force to move the center towards the left half along the horizontal direction.

We define the relative voltage error and the relative magnetic error as follows:

$$\delta u = \frac{\delta V}{\overline{V}} = \frac{V_r - V_l}{V_r + V_l} \quad , \quad \delta b = \frac{\delta B}{\overline{B}} = \frac{B_d - B_u}{B_d + B_u} .$$

Using the same method as ref [2], the relationship between asymmetric voltage and asymmetric magnet field is:

$$b_1 = -\delta u / \pi / (N + 1/2) \quad (1)$$

where b_1 is the amplitude of the first harmonic derived from δb, and N is the number of turns.

The solution of radial motion in the existence of the first harmonic forcing term is:

$$x = b_1 (\cos\theta - \cos\nu_r\theta)/(\nu_r^2 - 1), \quad (2)$$

where x is the radial displacement from the equilibrium orbit in the units of the orbit radius, and ν_r is the frequency of the free radial oscillations. The oscillation amplitude at the symmetric line of valley is plotted in curve 2 of Fig.4, which indicates that a uniform asymmetric voltage in radius induces oscillation of attenuated amplitude.

Simulations with COMA [3, 5] are carried out to verify the analytic results. First, changing the peak dee voltage used in COMA to obtain a 1% (±0.5%) difference between the left and right, curve 3 is obtained. Second, converting the 1% difference in voltage to the difference in magnet field (i.e. the first harmonic), then adding the first harmonic to COMA, curve 4 is obtained.

Curve 2 is approximately consistent with curve 3 except a little higher for small radii. The difference between curve 2 and 3 is mainly because that the analytic result is a steady state solution where b_1, ν_r are assumed constants. In fact, b_1 is decreasing and ν_r is increasing with radius. Curve 3 is consistent with curve 4 well, thus the compensation of asymmetric voltage could be achieved by adding first harmonic in the proper phase.

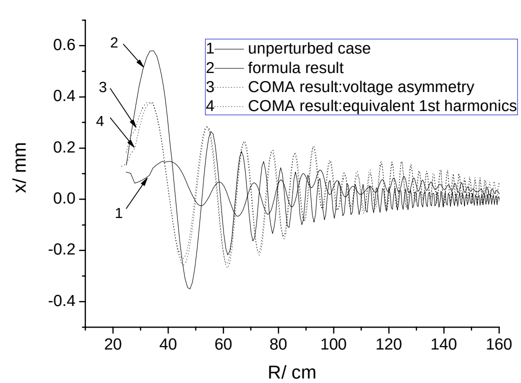

Figure 4: The comparison of analytical result and COMA result.

The phase space distribution with and without asymmetry voltage at different energy is shown in Fig. 5. The 2.5% asymmetry voltage induces radial coherent oscillation and finally causes the increase of the beam size.

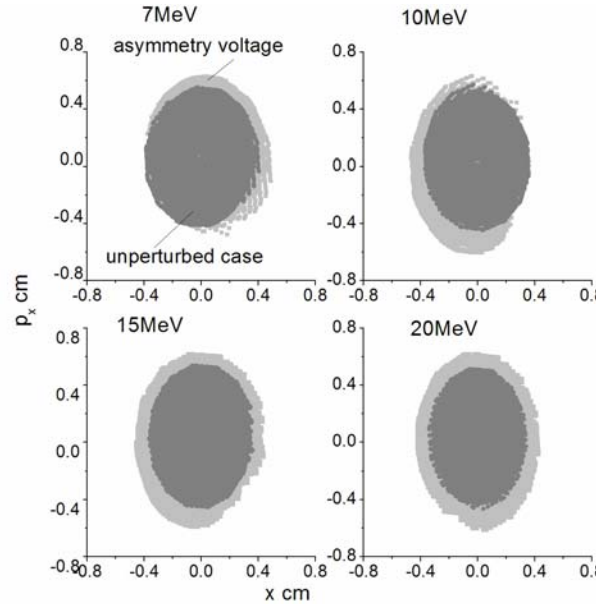

Figure 5: The effect of asymmetry voltage on phase space distribution

In summary, the voltage difference between left and right cavity induces a radial oscillation whose amplitude decays with radius. The amplitude increases about 0.04mm at extraction radii corresponding to 1% voltage difference. To satisfy the requirement of beam dynamics, the radial amplitude growth caused by all possible effects should be restricted to 0.3mm during accelerating. If there are N effects which contribute to the increase of amplitude, then the contribution of asymmetric voltage should be less than 0.3mm/√N. For N=9, the difference in dee voltage should be less than 2.5%.

The dee voltage changes caused by manufacture errors mentioned in Fig. 2 are added to COMA. The changes in betatron amplitude caused by ±0.1 degree width error and by the rotation of one dee of 0.2 degree with respect to the other are about 0.024 to 0.03mm at extraction radii. An error of 0.05 degree, which satisfies the accuracy requirements of beam dynamics, could be achieved during manufacture.

THE DEFORMATION OF DEES

The dees deformation caused by gravity and the offset of the whole dees during manufacture cause misalignment in the dee gaps. Fig.6 illustrates the equipotential pattern for axially misaligned dees.

The misaligned dee gap causes an axial electric field E_z in the middle plane which disturbs the axial stable orbit. When the particles pass through the dee gaps, they are kicked in the vertical direction four times one turn because there are four dee gaps.

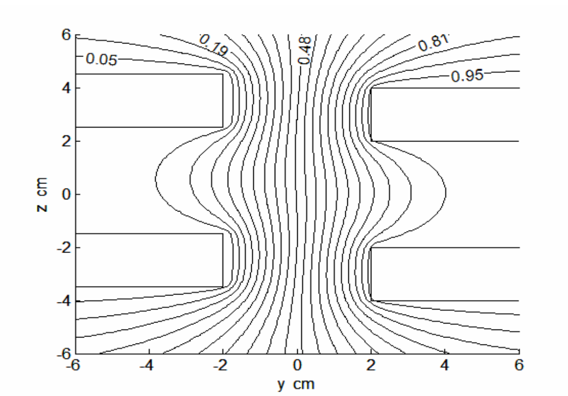

Figure 6: The equipotential pattern of misaligned dee gap. The misalignment is 5mm.

The Electric Field Caused by Misalignment

The electric field component normal to the dee gap is

$$E_y = V(\cos(\pi y / g) + 1) / 2g, \quad (3)$$

where V is the dee voltage, and g is the FWHW of the E_y. Using the axial shift model for the electric field in ref. [4], the change in z-component of momentum caused by Δd

$$\Delta P_z = -\frac{1}{2} q \Delta d \left(\int_{-\infty}^{0} - \int_{0}^{\infty} \right) \frac{\partial E_z}{\partial z} \cos(\omega t + \phi_c) dt, \quad (4)$$

where Φ_c is the particle phase with respect to the RF at y=0.

With $div\ \vec{E} = 0$ and assuming $\partial E_x / \partial x \approx 0$, then

$$\left(\frac{\Delta P_z}{P}\right)_{1,2} = \frac{qV\Delta d}{8gT_{1,2}} \left[\frac{\cos\phi_c + \cos(\phi_c \mp hg / R_{1,2})}{1 - (hg / \pi R_{1,2})^2} \right], \quad (5)$$

where h is the RF harmonic, R_1, T_1 and R_2, T_2 represent the radius of curvature and particle kinetic energy for the left half and the right half of the dee gap respectively.

The effect of misalignment on accelerating orbit

One dee is supported by two fixed stems, as shown in Fig.7. The deformation caused by gravity mainly happens at extraction radii with the maximum of 0.35mm.

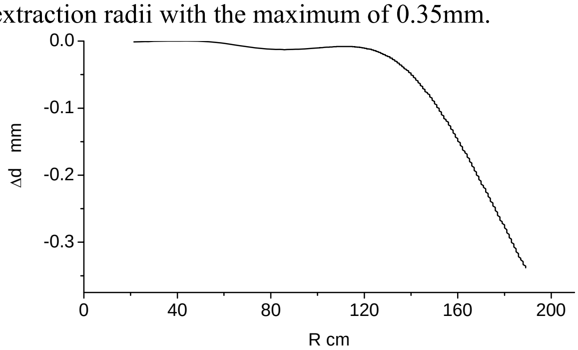

Figure 7: The deformation of one Dee.

The particle enters the dee at θ_1 and exits at $\theta_2 = \theta_1 + D$. Between gap crossing, the vertical oscillation is described by

$$d^2 z / d\theta^2 + \nu^2 z = 0, \quad (6)$$

The boundary condition is

$$dz / d\theta |_{\theta = \theta_j (j=1,2)} = \Delta P_z \, z_j / m\omega \Delta d, \quad (7)$$

The analytic result shows that the amplitude induced by gravitational deformation is 0.003mm. Agreeing with the analytic one, the simulation result obtained by COMA is 0.004mm. The results indicate that the deformation at large radii has little effect on beam. If the whole dees except the central region have an offset of 1mm, the amplitude of ideal particle increases by 0.5mm. To satisfy the demand of beam dynamics, the offset should be limited to 0.2mm.

CONCLUSION

In conclusion, the influences on beam of the voltage difference between left and right cavity and the change in voltage of one cavity because of the error during manufacture have been proposed. Comprehensive analysis is carried out on calculated result and the conclusion is obtained: the tolerance on the voltage difference between left and right is 2.5%; the angle error of one dee during manufacture could achieve 0.05 degree, which satisfies the requirement of beam dynamics.

The deformation of dees with the maximum value of 0.35mm at large radius, which increases the amplitude of axial oscillation by 0.004mm, has little influence on the beam. The offset of the whole dees except central region during manufacture, which may disturb the beam a lot, should be limited to 0.2mm.

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