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Vertical focusing study in the central region of the CYCIAE-100 cyclotron

YAO Hong-Juan(姚红娟)[1] ZHANG Tian-Jue(张天爵)
GUAN Feng-Ping(管锋平) ZHONG Jun-Qing(钟俊晴)

(China Institute of Atomic Energy, Beijing 102413, China)

Abstract The vertical focusing is one of the primary problems in the central region of cyclotrons. This focusing effect brought about by the magnetic field is inclined to be weak near the center of the machine due to the fact that the flutter is small, while the electric focusing forces incurred from the dee gaps become very strong. Since the electric focusing effect is dependent on the RF phase, we have proceeded to carry out analytical calculations and numerical simulation about the vertical focusing in the central region of CYCIAE-100, including magnetic focusing, electric focusing and the defocusing effect from the space charge effect. All the results have been used for the design of the central region for CYCIAE-100 and a good vertical focusing has been obtained.

Key words vertical focusing, central region, cyclotron

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1 Introduction

An isochronous proton cyclotron, CYCIAE-100[1], is being constructed at CIAE (China Institute of Atomic Energy). The central region of the cyclotron has been designed as shown in Ref. [2]. The problems of the central region concern two aspects, vertical motions and radial motions. The fundamental problem dealing with the vertical motion is that the focusing provided by the magnetic field becomes very small near the center of the machine, while the phase-dependent electric forces incurred from the dee gaps become very strong. So it is critical to find an approach on how to obtain a good vertical focusing and proper phase slip for the vertical motion in the central region. The detailed study of the vertical focusing in the central region of CYCIAE-100 is reported in this paper.

2 Magnetic focusing

For the isochronous cyclotron, the vertical focusing force from the magnetic field is produced by the flutter, which is hard to become large at the machine center. As a result, the magnetic focusing tends to be very weak in the central region. In order to increase the magnetic focusing we have designed a magnetic cone for CYCIAE-100 and a bump field is introduced, as is shown in Fig. 1. The average field is high at the center and falls with radius, thereby producing gradient focusing. The value of the flutter and the vertical tune are calculated by the formula (1) and the plots are given in Fig. 1.

$$
\begin{aligned}
F^2 &= \frac{1}{2\pi}\int_0^{2\pi}\frac{[B(R,\theta)-B(R)]^2}{B^2(R)}\mathrm{d}\theta\,, \\
n &= -(R/B)\cdot(\mathrm{d}B/\mathrm{d}R), \qquad (1) \\
v_z^2 &= n+F^2\,,
\end{aligned}
$$

where $B(R)=\frac{1}{2\pi}\int_0^{2\pi}B(R,\theta)\mathrm{d}\theta$, n is the field index and F is field flutter.

As indicated in Fig. 1, the bump field produces additional vertical magnetic focusing due to the field gradient, and meanwhile the negative effect from this field should be considered, i.e. the phase slip, since

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[1] E-mail: yaohongjuan@gmail.com

the magnetic field is no longer isochronous. Taking these two effects mentioned above into account we have finished the design of magnet cone and the bump field shown in Fig. 1. The phase history from the results of particles tracking is shown in Fig. 2, indicating the phase slip can be controlled within 20°.

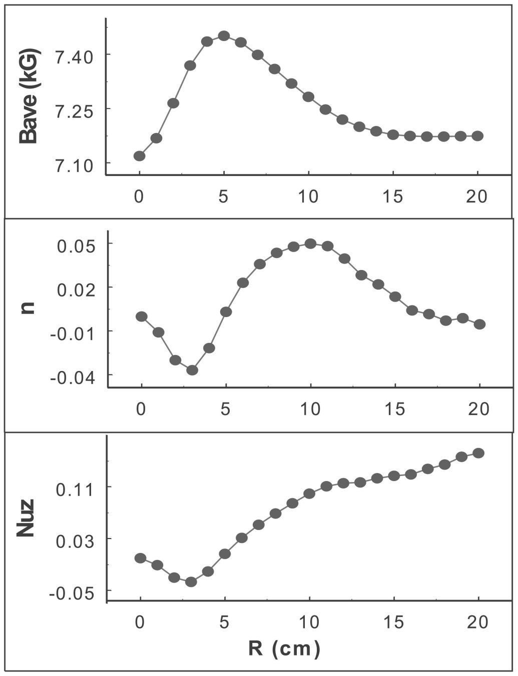

Fig. 1. The average bump field, the field index and vertical focusing frequency produced by magnetic field vs radius.

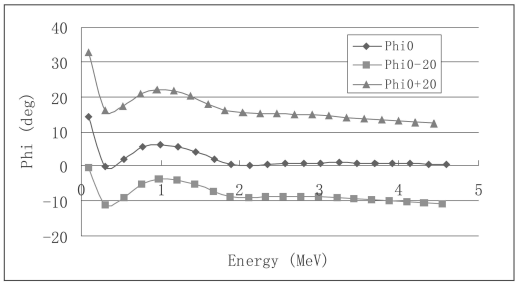

Fig. 2. The phase history as a function of energy at the center line of the first dee, starting with three initial RF phases.

3 Electric focusing

During electric gap-crossings, ions in the beam will experience vertical focusing forces produced by the RF field. The focusing effects are mainly from two aspects. One is produced by the time variation of the dee voltage, i.e. the electric field is changing, and the second focusing effect is from “acceleration”.

The important property of electric focusing is the time dependence, which means the electric focusing for the cyclotron depends on the phase of the injected ions. Fig. 3 gives the results of numerical simulations for CYCIAE-100, and shows the vertical motion for starting condition $(z, Pz) = (1\ \text{mm}, 0)$ at the top, and $(z, Pz) = (0, 1\ \text{mm})$ at the bottom. We observe from the plot the strong dependence of the vertical focusing frequency on the starting phase.

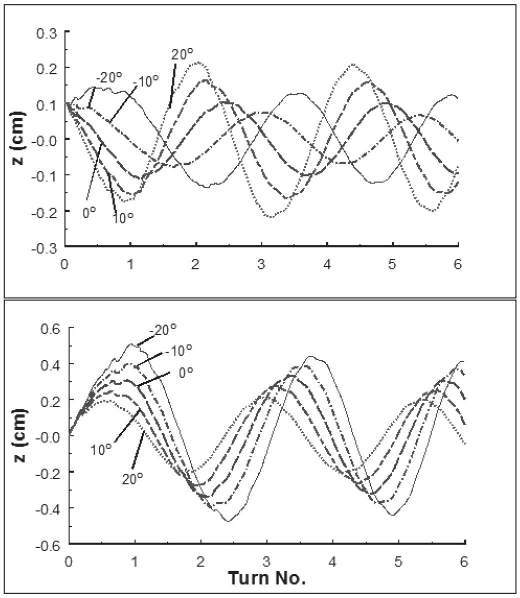

Fig. 3. Numerical results for vertical envelope vs turn number starting various RF phase.

The detailed analysis of the electric focusing during gap-crossing is given in Refs. [3—5]; the vertical focusing frequency from electric field is called Δv_z, expression (23) in Ref. [5] can be written as follows.

$$\Delta v_z^2 = \left(\frac{h}{4\pi n}\right)\sin\phi + \left(\frac{h}{8\pi n}\right)^2 \cdot \\ (\cot^2(hD/2)\cos^2\phi - \sin^2\phi)(\theta_e - D)D\,, \qquad (2)$$

where $\theta_e = 2\pi/N_d$, N_d is the number of dees, h is the harmonic number, n is the turn number, and D is the angular width of a dee.

Using the parameters of the CYCIAE-100 cyclotron we did the plot using different values of the turn number as shown in Fig. 4. We can see the following apparent qualitative features:

1) Positive phases (late ones entering the dee gap) are more useful for vertical focusing than negative phases (early ones entering the dee gap).

2) The electric focusing tends to be weak with the increase of the particles’ energy.

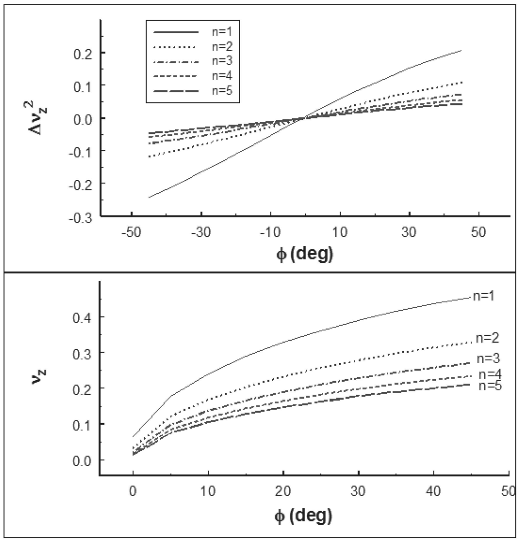

Fig. 4. The vertical electric focusing frequency calculated by Formula (2).

4 Space charge effect

In the central region of CYCIAE-100, the space charge effect is produced by the force on an ion of a bunch given by other ions within this bunch and the force by ions in other bunches. Most of the effects are from the force on an ion produced by other ions in the bunch, so an approximate formula can be used to express the vertical frequency produced by the space charge effect[6]:

$$(v_z^2)_{\mathrm{sc}} = -\frac{q}{4\varepsilon_0 m\omega^2}\frac{G}{z_m^2}\frac{I}{\Delta\phi}\frac{1}{v}\,, \tag{3}$$

where I is the average current, v is the velocity, z_m and $\Delta\phi$ are the height and length of the bunch respectively, ε_0 is the permittivity of free space, and G is a factor which depends on the height-to-width ratio of beam bunch.

In the case of CYCIAE-100, the phase acceptance is 40°, and various beam currents (200 μA, 400 μA and 500 μA) were used. Fig. 5 shows the relation between the vertical frequency produced by the space charge effect and ion energy for different values of $I/\Delta\phi$ and z_m.

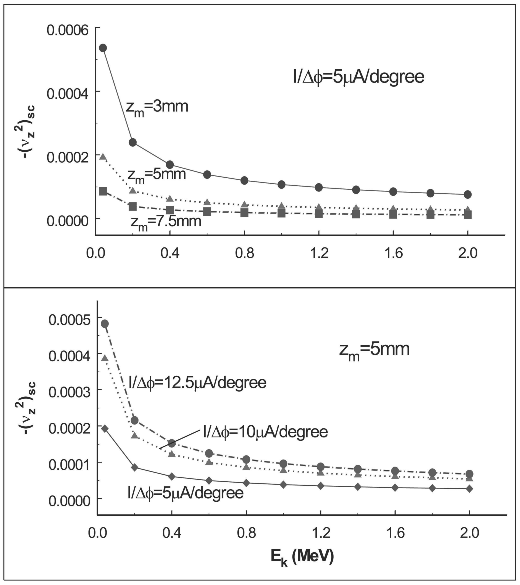

Fig. 5. The vertical focusing frequency produced by space charge effect vs the energy for various currents and beam heights.

5 Conclusions

From the numerical simulations of the vertical envelope for CYCIAE-100, we observe the time dependence of the electric focusing during the gap-crossing. And the analytic calculations describe some features of the vertical focusing. For CYCIAE-100, the positive phases are more useful for the vertical focusing than the negative phases.

The results studied in this paper have been applied to the design of the central region for CYCIAE-100, and a good vertical focusing has been obtained. In addition, the bump field has two functions, one is used to strengthen the magnetic focusing, and the other one is used to set phase slip. The positive starting phase is selected to avoid the electric defocusing effect, then the phase will slip to negative value by the bump field to satisfy the request of the radial motion.

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