I. 13. Study of the Central-Region Orbits of the CYRIC 680 Cyclotron

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Introduction

Orbit calculations in the CYRIC 680 cyclotron central region have been carried out in order to study a possibility of an axial injection method suitable for the cyclotron. As one of the improvements in the orbit calculation procedure is used of a code RELAX3D 1) to calculate the three-dimensional electric field in the central region. In general, orbit calculation of the cyclotron central region requires accurate information about the electric field distribution, because the axial and radial motions of ions are influenced by strong effects of the electric field and its phase dependence in the first few turns. We describe in this paper the electric field studies performed with the existing central region, and some calculation results of the particle trajectory from the internal ion source beam and the axially injected beam.

1. Electric field calculation

The code RELAX3D has been used to compute the potential maps corresponding to the dee’s and the grounded electrodes. This code is an efficient iterative FORTRAN code which solves the Laplace (Poisson) equation for a general 3-dimensional geometry on a regular 3-dimensional mesh. The cuboid mesh, covering a region of 141 mm x 141 mm for 1 mm step in X and Y directions (the X-Y plane at Z = 0 mm is the cyclotron median plane) and of 20 mm in Z direction for 2 mm step has been used. The equipotential lines of the central region are shown in Fig. 1 and Fig. 2 for the slice at Z = 0 and Z = 12 mm, respectively. With the RELAX3D code the potential is computed everywhere and the electric field can be calculated by:

$$\vec{E} = -\text{grad} \, V$$  \hspace{1cm} (1)

The field components $E_x$, $E_y$ and $E_z$ are actually obtained from $V$ along the axis in a third-order Taylor expansion as:

$$E_x(x) = \frac{1}{12H_x} \{ V(x - 2H_x) - 8V(x - H_x) + 8V(x + H_x) - V(x + 2H_x) \}$$
\[ E_y(y) = \frac{1}{12H_y} [V(y - 2H_y) - 8V(y - H_y) + 8V(y + H_y) - V(y + 2H_y)] \]
\[ E_d(z) = \frac{1}{12H_z} [V(z - 2H_z) - 8V(z - H_z) + 8V(z + H_z) - V(z + 2H_z)], \]

where \( H_x, H_y \) and \( H_z \) are the grid spacing and \( x, y \) and \( z \) are assumed to be on a mesh point.

In the outside region, i.e. for radii greater than \( R = 65 \) mm, the electric fields for the standard dee gap geometry are used, which are represented as:

\[ E_t = \frac{1}{\sqrt{2\pi} \sigma} \exp\left(-\frac{1}{2} \frac{(\delta)^2}{\sigma^2}\right), \]
\[ E_z = \frac{\delta}{\sigma^2} \cdot z \cdot E_t. \]

where \( E_t \) and \( E_z \) are longitudinal and vertical field components having the standard deviation \( \sigma = 0.4W + 0.2H \), and \( \delta \) is the longitudinal distance in the dee gap; \( W \) and \( H \) are the width and the aperture of the dee gap, respectively.

2. Orbit Properties

The code \(^2\) used to evaluate the beam dynamics integrates the equation of motion \( \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \) using the cylindrical coordinates system with time as the independent variable. The studies have been performed with two type of test particles, which have different initial velocities at the starting position. One is the particles from the internal ion source, and other is the case of axially injected particles. The cyclotron parameters were set up for the harmonic \( H = 2 \) for proton 20 MeV and the new electric fields calculated as described above were used in the central region. The radial trajectories of six test-particles from the internal ion source are plotted in Fig. 3. They have different initial conditions of \((0, 100)\) and \((1, 0)\) in the \((r, r')\) space in unit of mm and mrad, with the starting RF-phases of 60, 70 and 80 deg.

The betatron oscillations of three particles for the ion source in vertical and horizontal directions are shown in Fig. 4, and axially injected beam which have 10 keV injection energy are in Fig. 5. These simulations show that the axially injected beam indicates large amplitudes of the betatron oscillation in the both directions. In these case, the off-center error at \( R = 30 \) cm is about 2 mm with the RF phase slip of -2 deg. The central field bump and the isochronous field were adjusted carefully for correction of the phase slip. We have also calculated for the other harmonic modes \( H = 3 \) and \( H = 4 \), which are equivalent to proton 12 MeV and 3 MeV, with the same initial conditions. The tendency of the particle motions is similar as for the 2 nd harmonic mode. It is estimated that in an injected beam is accompanied with a larger betatron amplitude in the existing central region.

The results so far obtained indicate that stronger electric focusing forces are required in the central region for a successful acceleration of axially injected beams.
References

1) Kost C. J. and Jones F. W., RELAX3D, TRIUMF, internal report TRI-CD-88-01.
Fig. 1. Equipotential map on the median plane (Z=0 mm) for the central region.

Fig. 2. Similar to Fig. 1 but for the slice plane at Z=12 mm near the dee edge.

Fig. 3. Radial motion of the protons in the 2nd harmonic mode is plotted corresponding to the starting RF-phases of 60, 70 and 80 degrees. Each of the three particles has two different initial conditions (0,100) and (1,0) in the (r,r') space, in units of mm and mrad, at the internal ion source exit.

Fig. 4. Motions of three particles corresponding to (0,0), (0,100) and (1,0) in the phase space at the internal ion source exit are plotted in the both vertical and horizontal planes up to the radius of R=30 cm. The orbit of the reference particle (0,0) coincides with the horizontal axis.

Fig. 5. Similar to Fig. 4 but for the axially injected particles.