RADIAL-LONGITUDINAL COUPLING IN PROPOSED RCNP INJECTOR CYCLOTRON

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Abstract

For an injector cyclotron to a ring cyclotron proposed at RCNP, the second, third and fourth harmonic modes are used for the light ion acceleration. To accelerate ions in these harmonic modes without phase space deformation, it is necessary to investigate the effect of radial-longitudinal coupling. For single, two and three dee configurations, the beam behavior in radial phase space was studied numerically for each harmonic mode and dee angle. In the case of the second and third harmonic accelerations of protons with two dees, dee angles between 60 and 75 degrees are acceptable. The results are compared with 180-degree single dee and 40-degree three dees for the third harmonic mode.

Introduction

The proposed RCNP accelerator complex consists of two ring cyclotrons and an injector cyclotron.[1] The first ring cyclotron has been designed to accelerate protons up to 300 MeV, and an injector cyclotron has been planned to accelerate protons to 26 MeV. The characteristics of the cyclotrons is given in reference [1]. The range of the acceleration frequency for the cyclotrons is 20 to 33 MHz. This accelerator system has been designed to get high quality beams of protons and light ions up to the intermediate energy region. The orbit properties of beams in the first ring cyclotron was studied numerically.[2] For the beam transport system between the injector and the first ring cyclotron, a dispersion matching method was investigated, and an achromatic transport system using new flat-topping method was proposed.[1]

The magnetic field distribution in the central region of the injector cyclotron was studied by using a small test magnet. The orbit analyses have been done with a magnetic field including data from an existent cyclotron.

Radial-Longitudinal Coupling

The injector cyclotron is an AVF cyclotron with four sectors and two dees. The first ring cyclotron is a ring cyclotron with four sector magnets and two RF cavities. The injection radius of the first ring cyclotron is twice as long as the extraction radius of the injector cyclotron. The same RF frequencies are used for two cyclotrons. To accelerate light ions, the second, third and fourth harmonic modes are used for the injector cyclotron, and the fourth, sixth and eighth harmonic modes are used for the ring cyclotron.

If the off-peak acceleration is used, a radial broadening of the beam is observed by the coupling between the radial and the longitudinal motion of ions.[3,4] This effect is expected at higher harmonic-mode acceleration, lower energies and near the $\nu_r = 1$ resonance. For two-dee system with full-dee angle equal to 60 degrees, an off-peak acceleration is necessary for even harmonic modes, and this affects the beam quality by the radial-longitudinal coupling at low energies. But for two-dee system with full-dee angle equal to 90 degrees, a peak acceleration is allowed for the second harmonic mode. It is necessary to study the effect of the radial-longitudinal coupling in the function of dee angle.

Dee Angle and Orbit Properties

The RF frequency ranges from 20 MHz to 33 MHz. The orbital frequency for the acceleration of 25-MeV protons is 15.89 MHz, and the second harmonic mode will be used for an actual acceleration of 25-MeV protons. To study the effect of the radial-longitudinal coupling for the acceleration of 25-MeV protons, numerical calculations have been done with fundamental, the second and third harmonic modes and the full-width dee angles of 60, 70, 75, 80 and 90 degrees.

In an ordinary orbit analysis we must consider the effects of central and outer edge fields, but in the present analysis we have used the isochronized field with no central field bump and outer edge field for simplicity. Next the effect of central field bump has been considered.

After obtaining accelerated equilibrium orbit the particle is decelerated to injection radius (about 3 cm) and injection energy (about 50 keV). The accelerated equilibrium orbit is well centered, and the time of gap crossing is chosen so as to get the same energy gain at each dee gap. The results are shown in Figs. 1 to 3.

In the case of the second harmonic acceleration with 90-degree dee system and the third harmonic acceleration with 60-degree dee system, the coupling between the radial and the longitudinal motion of the particles is small and the beam with good quality can be accelerated. However, in the case of the third harmonic acceleration with 90-degree dee system and the fourth harmonic acceleration with 60-degree dee system, the radial-longitudinal coupling is very strong. This effect is remarkable at the first few turns in the inner region of the cyclotron, and causes nonlinear radial phase-space distortions. Beam quality and extraction efficiency become worse for this distorted beam.

The beam distortion in the radial phase space occurs as follows in the two-dee system. When the dee angle is narrower than that of the peak acceleration, the radial beam width becomes broader at angles inside the dees. When the dee angle is wider than that of the peak acceleration, the radial beam width becomes broader at angles outside the dees.

In the case of the fundamental-mode acceleration with 90-degree dee system and the second harmonic acceleration with 60-degree dee system, there are rather strong radial-longitudinal coupling and the beam width spreads to about three times. But by limiting the phase width of the beam within 10 degrees and adjusting the acceleration voltage in order to minimize the radial beam width at the entrance of the deflector we can extract the beam with good quality. Without the restriction of the phase width and the optimization of the acceleration voltage, the extraction efficiency and the quality of the extracted beam become worse.

In the case of 180-degree dee system, the peak acceleration can be used for the fundamental and the odd harmonic mode, and the effect of the radial-longitudinal coupling is small as shown in Fig. 5. In the cyclotron with three dees and three sector magnets the particles can be accelerated by the third harmonic mode for example. If the full dee angles is less than 60 degrees, the off-peak acceleration is used. However, when the radial betatron frequency is nearly equal to 1, the effect of the radial-longitudinal

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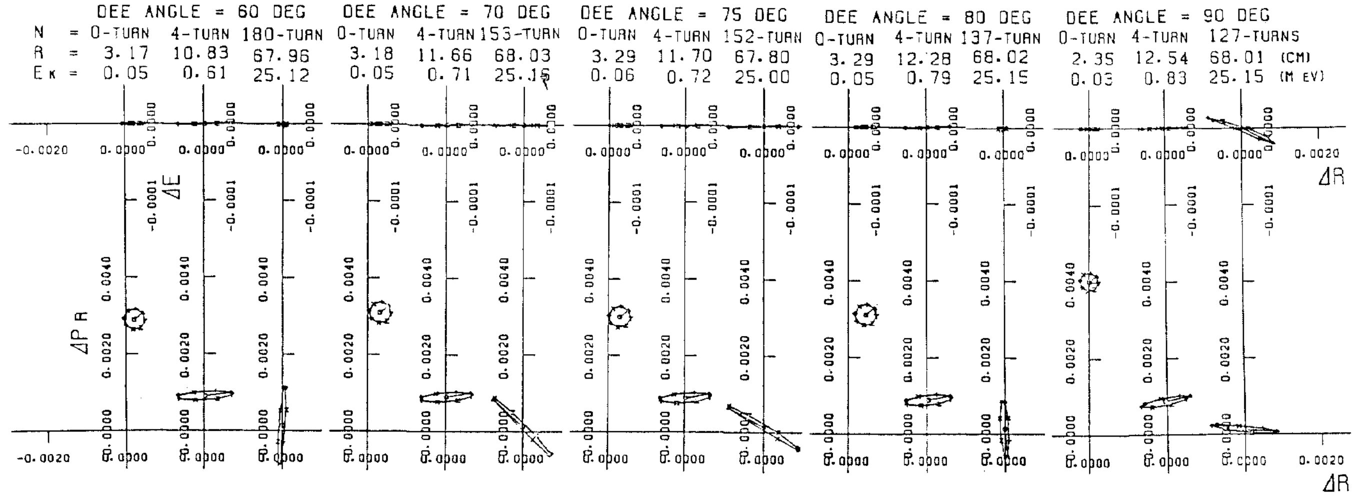

Fig. 1. Beam behavior of protons in the fundamental mode acceleration with four-sector magnet and two-dee system. Δr, ΔPr and ΔE are radius, radial momentum and energy in cyclotron units in respect of a static equilibrium orbit, respectively. The initial radial emittance of the proton beam is 70 mm•mrad.

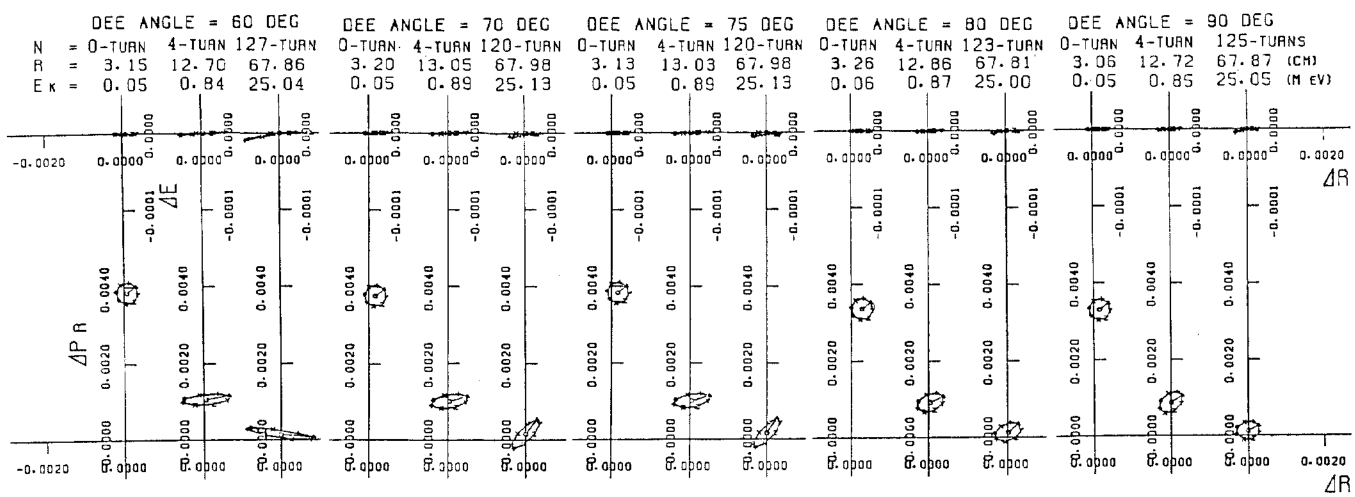

Fig. 2. Beam behavior of protons in the second harmonic mode acceleration with four-sector magnet and two-dee system.

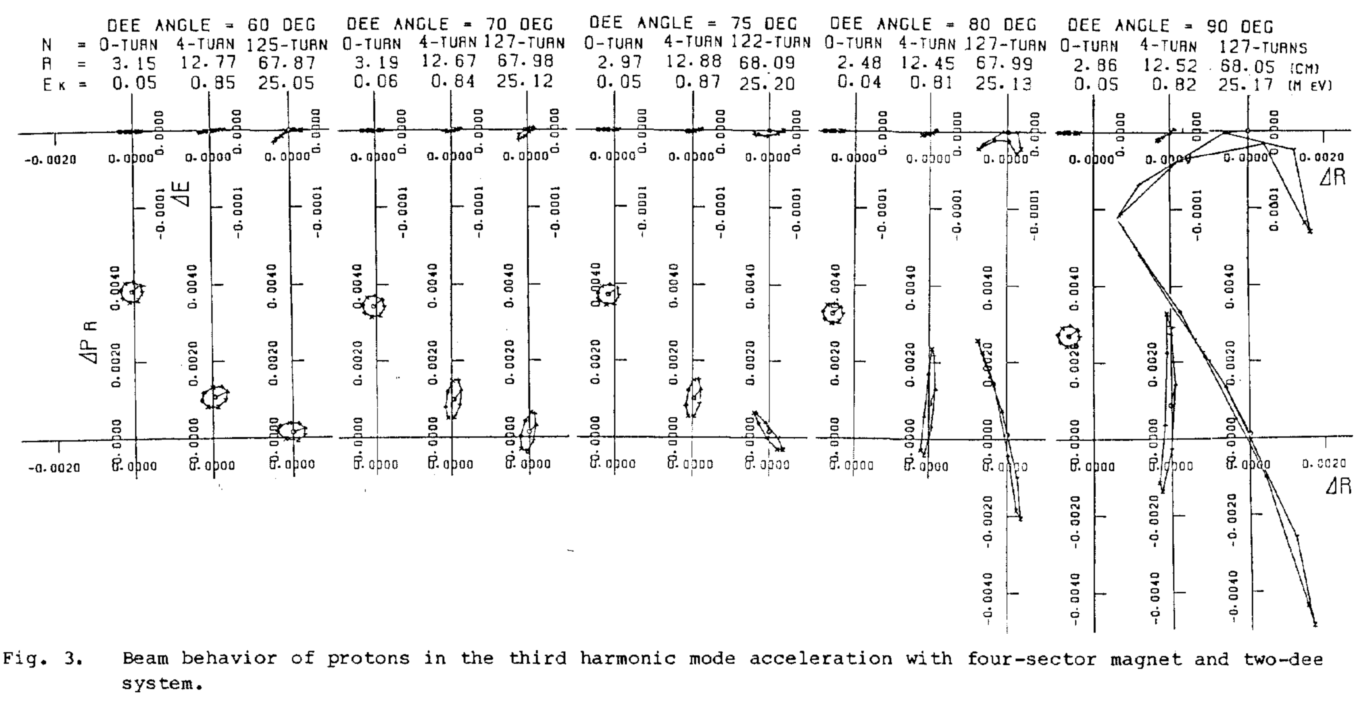

Fig. 3. Beam behavior of protons in the third harmonic mode acceleration with four-sector magnet and two-dee system.

coupling at a dee gap is canceled by the effect at another dee gap almost 180 degrees apart. Results with full dee angle equal to 40 and 60 degrees are shown in Fig. 6.

For the two dee and four-sector magnet system the effect of central field bump was examined. The effect of the radial-longitudinal coupling is similar to that of the isochronous field. In the case of the second and third harmonic acceleration of protons with two dee system, the dee angles between 60 and 75 degrees are acceptable. If the requests on the beam qualities are very severe, there is one solution that the whole dee system of the small injector cyclotron will be exchanged for each harmonic mode.

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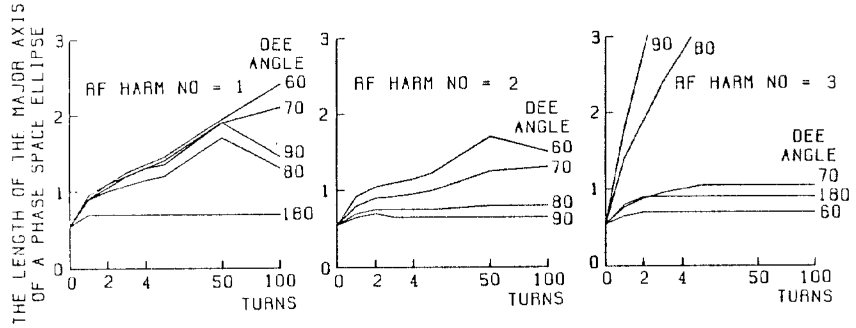

Fig. 4. Distortion of the radial phase-space ellipse.

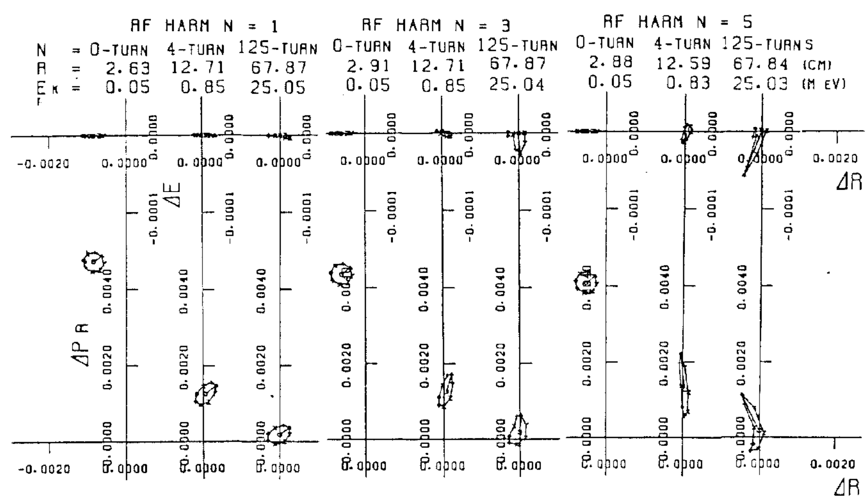

Fig. 5. Beam behavior of protons in the fundamental, third and fifth harmonic mode acceleration with four-sector magnet and 180-degree dee system.

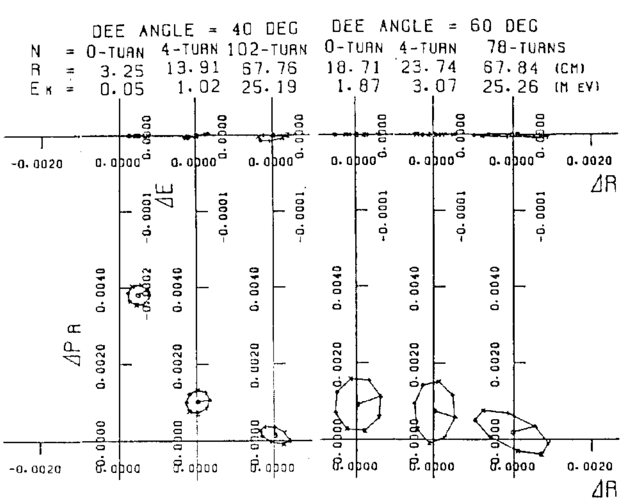

Fig. 6. Beam behavior of protons in the third harmonic mode acceleration with three-sector magnet and three-dee system.