ACCELERATED ORBITS FOR INJECTOR CYCLOTRON

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ABSTRACT

Computer programs for the orbit properties of accelerated beams of a ring cyclotron are modified for the analysis of an injector cyclotron. The behavior of the accelerated particles for the accelerated particles for the injector cyclotron, especially the radial and longitudinal coupling, has been studied.

INTRODUCTION

For an injector to a ring cyclotron proposed at RCNP, several types of accelerators was compared.[1] As an injector of a large ring cyclotron, a small ring cyclotron with a preinjector is most preferable but it needs large amount of steel. A compact cyclotron with an external ion source is a candidate in the first phase.[2] The injector cyclotron is commercially available, but it is necessary to modify the central region. A small test magnet was designed to examine the central region of the injector and magnetic fields of the model magnet have been measured.[3]

For the beam transport system between the injector cyclotron and the ring cyclotron, an achromatic transport system has been desinged.[4] By inverting the sign of the energy differences in the beam transport system, the beam energy spreads at the injection of a ring cyclotron can be compensated perfectly in acceleration.

The injector is important to decide the beam qualities at the ring cyclotron. It is necessary to study beam dynamics from axial injection to extraction in the injector cyclotron.

COMPUTER PROGRAMS

Computer programs developed for the design study of the RCNP AVF cyclotron[5] was revised for the study of the ring cyclotron. Original programs for the RCNP AVF cyclotron can be used for the orbit study of the injector cyclotron with some modifications of input routine. However new programs for the ring cyclotron have many options including extensive graphic capabilities.[6,7] Then it is preferable to update the programs for the ring cyclotron to include the capabilities to obtain orbit properties for the injector cyclotron.

The procedures to obtain equilibrium orbits and isochronous field for the injector cyclotron and existing RCNP AVF cyclotron are similar to those for the ring cyclotron. By expanding the field data of the injector cyclotron and existing cyclotron in Fourier series and neglecting higher terms, we can execute the smoothing of data and the reduction of input data. However the magnetic field of the ring cyclotron changes rapidly at pole edges and we cannot neglect the higher terms in Fourier expansion. For the input of field data there are two format: the input of field values at mesh points are used for the ring cyclotron and the input of Fourier coefficients at each radius are used for injector cyclotron.

To obtain isochronous field we must obtain equilibrium orbits at each radius. For the injector cyclotron at first the equilibrium orbit near the magnet center is calculated. Near the magnet center there is no strong flutter and we can assume circular orbit for the first trial of the equilibrium orbit and get the exact orbit by iteration method. For the ring cyclotron the equilibrium orbit at injection energy is not circular and we must assume good initial values for the equilibrium orbit. One solution is to use the analytical formula, but we use the starting point by trial and error. There are two methods to obtain isochronous field, that is, a circular isochronous field and an orbital-shape isochronous. field. For the injector cyclotron we have used a circular isochronization.

In an ordinary orbit analysis we must consider the effects of center and edge fields, but in the present analysis we have used the completely isochronized field and no center and edge fields for simplicity. The effect of center and edge fields will be considered in future analysis.

In the graphic routines of the programs for the ring cyclotron the parameter ranges are not scaled automatically, and these parts have been updated to cover the energy range of the injector cyclotron.

In the existing cyclotron there is a 180° dee, and the phase compression and expanding effect is not considered because of no rf magnetic field. But in the injector cyclotron the harmonic modes of the beam acceleration are 2, 3 and 4, and the dee angles are 60° for example. Dee voltage distribution is not constant in general for this case. Ions are accelerated by radially decreasing rf voltage, and their orbits are bended by the oscillating magnetic field produced by oscillating electric field in the dee gaps. This rf magnetic field effect expands the accelerated beam bunch and produces the phase expansion. We have no data on the dee voltage distribution, and this phase expansion effect is neglected in the present analysis. Computer program includes this phase compression and expansion effect, and this will be considered in the future analysis.

DEE ANGLE AND BEAM BEHAVIOR

The rf frequency range for the ring cyclotron is 20∿33 MHz, and the same frequency range is used for the injector cyclotron. The 4th, 6th, and 8th harmonic modes are used for the light ion acceleration in the ring cyclotron. As mean injection radius of the ring cyclotron is twice of mean extraction radius of the injector cyclotron, the 2nd, 3rd, and 4th harmonic modes are used for the light ion acceleration in the injector cyclotron. For the heavy ion acceleration higher harmonic modes are used.

To accelerate ions efficiency in these harmonic modes without exchanging dees, it is impossible to used 90°- or 180°-dees. For 60°- dees off-peak acceleration is necessary for even harmonic modes, and this affects the beam quality. Due to coupling between the longitudinal and radial phase space, a radial broadening of the beam can be expected if off-peak acceleration is used on high harmonic numbers and for low beam energies and near the $\nu_r = 1$ resonance.[8,9,10] In an injector cyclotron of National Accelerator Centre (Republic of South Africa) the beam behavior by using 90°- dees and 80°- dees was investigated.[11] In the case of the 4 MeV proton beam no apparent difference between the phase-space diagrams for 80°- and 90°- dees was observed. In the case of the phase-space diagrams for the 6 MeV $^{12}C^{3+}$ beam, however, a distortion of the phase-space diagram as well as a pronounced broadening of the beam could be seen when 80°- dees were used, but the distortion disappeared after a correction for central particle phase was applied.

The beam behavior in radial phase-space was studied for 90°- and 60°- dees. Fig. 1 (left) shows the RF phase slip for a centered and two off-centered protons with 90°- dees and the 2nd harmonic acceleration. The RF phase is plotted at a dee-gap location. Fig. 1 also shows the beam behavior during acceleration. Phase-space ellipses are not deformed from injection to extraction radius.

Figs. 2-4 show the beam behaviors for protons with 60°-dees and the 2nd harmonic acceleration with different rf phase slips. In the case of 60°-dees

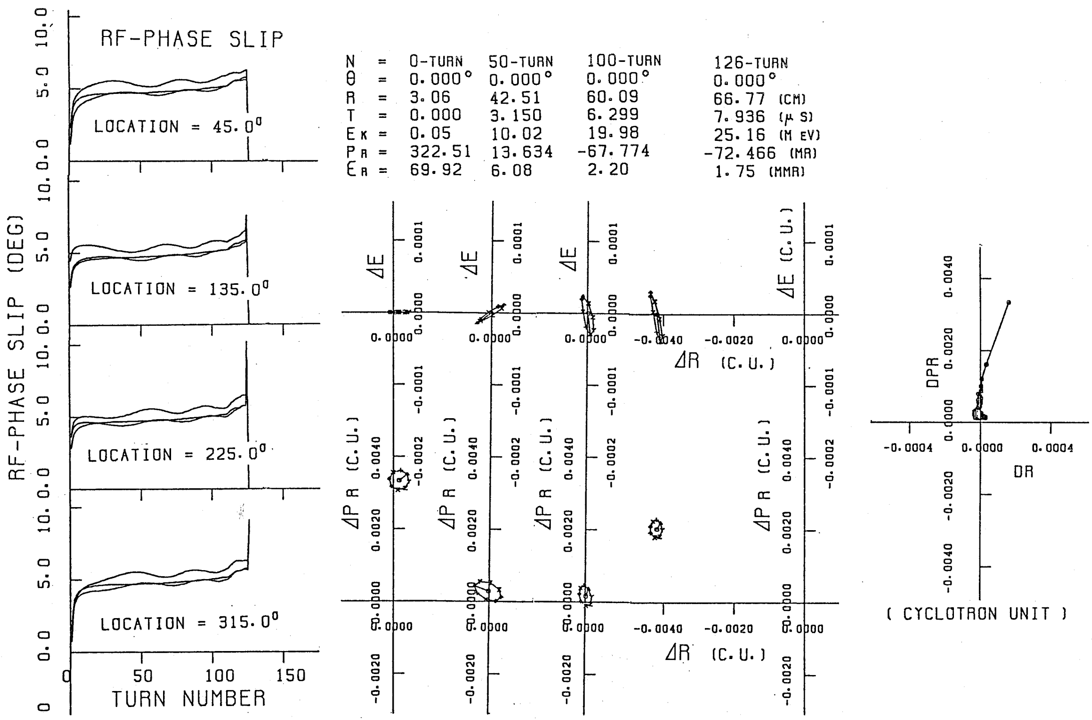

Fig. 1 Beam behavior for protons with 90°-dees and the 2nd harmonic acceleration.

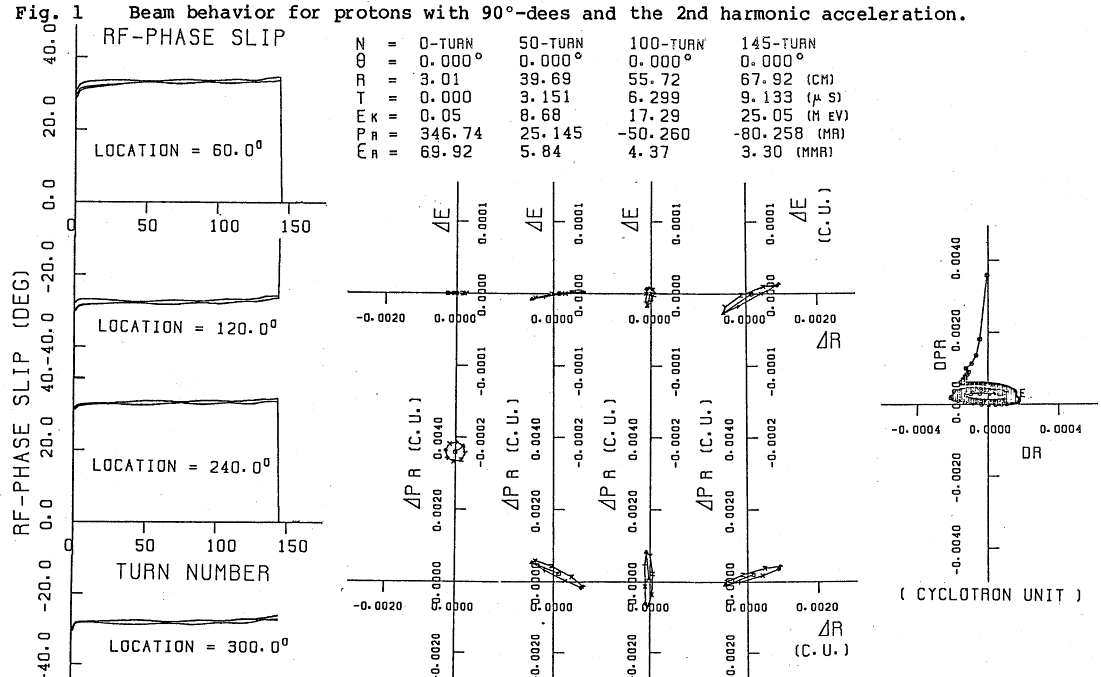

Fig. 2 Beam behavior for protons with 60°-dees and the 2nd harmonic acceleration. RF phase slip at the dee gap of θ=60° is same as that at the dee gap of θ=120°.

phase-space ellipses deform strongly in the low energy region, and for the rf slip of Fig. 4 the energy resolution is low at the extraction radius. More extensive investigation is necessary including heavy ion acceleration with high harmonic modes.

Fig. 5 shows the results starting from 0.45 MeV for 90°-dees and the second harmonic acceleration, and the energy resolution at the extraction radius is better than that in Fig. 1. This result indicates that the initial values of relative phase slip for each point are inadequate at small radius, and they do not satisfy the central position phase matching.

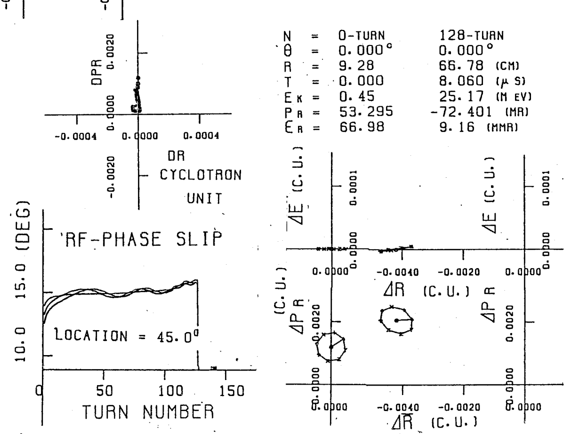

Fig. 5 Beam behavior for protons with 90°-dees and the 2nd harmonic acceleration.

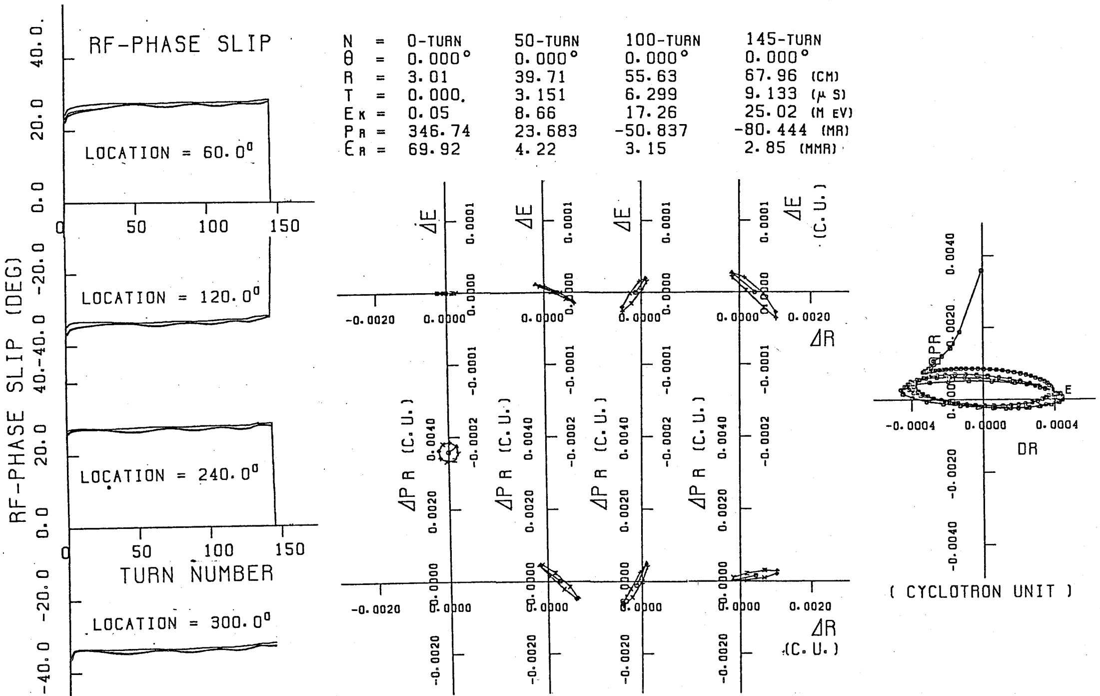

Fig. 3 Beam behavior for protons with 60°-dees and the 2nd harmonic acceleration. Rf phase slip at the dee pag of θ=60° is smaller than that at the dee gap of θ=120°.

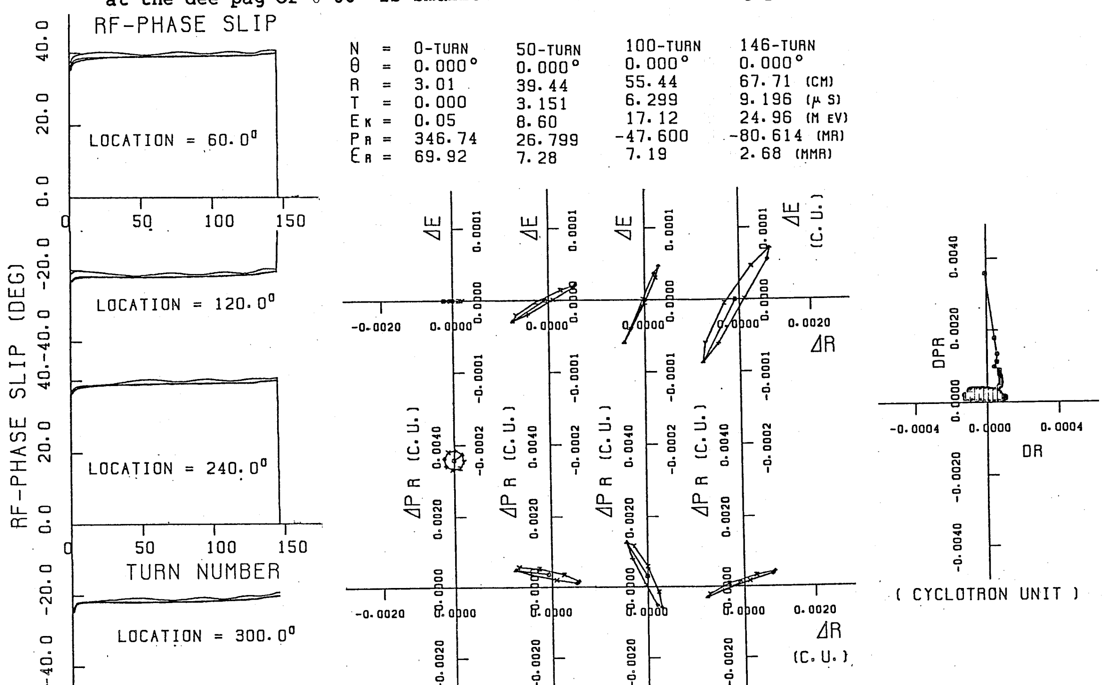

Fig. 4 Beam behavior for protons with 60°-dees and the 2nd harmonic acceleration. Rf phase slip at the dee gap of θ=60° is larger than that at the dee gap of θ=120°.

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