H^- Ion injection into the central region of the TRIUMF cyclotron

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ABSTRACT

The usual central region design problems are alleviated in the TRIUMF cyclotron by three main features: (1) injection at relatively high energy (300 keV) from an external ion source; (2) strong magnetic axial focusing; (3) squaring the rf wave with a third harmonic. Numerical studies of the initial orbits in the median plane, based on electric and magnetic fields from model measurements, show that non-linearities in the radial motion are negligible, and that a phase range from −45° to +25° will be centred to within the expected beam width, 0·32 in. For the axial motion, tracking and matching studies using a thick lens approximation to the dee gaps show good acceptance for lagging, but a sharp cut-off at −5° for leading phase ions. This is shifted to −15° by the three-sector narrow pole-gap geometry at the centre which provides phase-independent magnetic focusing of $\nu_z = 0{\cdot}2$. Third harmonic squaring of the rf wave advances the cut-off to −45°, at the same time improving the radial phase acceptance.

1. INTRODUCTION

The phase acceptance and internal beam quality of a cyclotron are determined primarily where the ions are injected and begin acceleration, in the central region. Here the limitations imposed by space-charge effects, by the phase dependence of the strong electrical forces and of orbit centring, and by first-harmonic induced radial oscillations, are well known. However these become less serious the higher the injection energy. In the case of TRIUMF the requirements for an intense H^- ion source, with its associated high gas flow, and yet a good vacuum (<10^{-7} torr) to avoid excessive ion loss by stripping, dictated that the source be located externally. Balancing the above advantages of higher injection energies against the increased difficulties of bunching and

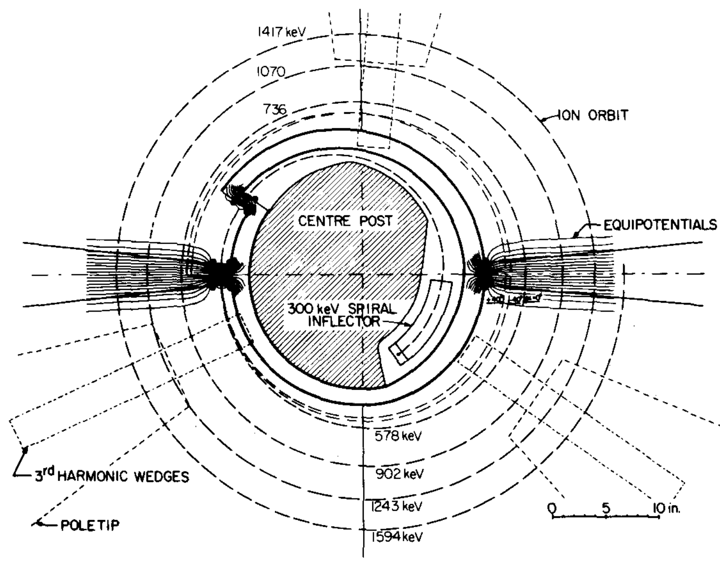

Fig. 1. The central region of the cyclotron. The equipotential curves are derived from an electrolytic tank study

inflection from an axial injection system led to a choice of 300 keV as the optimum energy.

The arrangement in the central region is shown in Fig. 1. H^- ions from an Ehlers arc source are accelerated to 300 keV by a HT set in the ion source room and transported down the axis of the cyclotron to the spiral electrostatic inflector[1,2] (40 kV/cm), which bends them into the median plane. The beam enters the resonator system via an auxiliary 100 kV 'injection gap' which supplements the regular $\Delta T = 400$ keV gain on the first turn, improving clearance of the structural centre post. The fundamental rf is five times the ion orbital frequency, so the injection gap is set at about 36° to the main dee gap.

2. RADIAL MOTION

Median plane ion orbits have been tracked numerically through electric and magnetic fields measured respectively in a 1:2·5 electrolytic tank[3] model of the resonators and a 1:8 central region model magnet.[4] Even with pure fifth harmonic acceleration the dee gap energy gain factors g are high enough (>80%) for ions with phases from −55° to +35° to clear the centre post satisfactorily on their first turn. To obtain good final orbit centring is more limiting, since at lower energies T the orbit centre for phase α must be off machine centre by

$$y_c(T, \alpha) = \frac{1}{4}\Delta\rho(T, 0^\circ) \cos\alpha = \frac{R_c\,\Delta T}{4m_o c^2\,\beta\gamma^3}\, g \cos\alpha$$

where $\Delta\rho$ is the turn separation, R_c the cyclotron radius and β and γ are the usual relativistic factors. Thus for low energies in TRIUMF, y_c(in) $\simeq 0{\cdot}95\, g \cos \alpha/\sqrt{T}$(MeV) = $1{\cdot}73\, g \cos\alpha$ at 300 keV, and a phase spread of ±35° may be expected to have a centre point spread equal to the expected beam width 0·32 in. In fact the phase range found in the orbit studies was –45° to +25°.

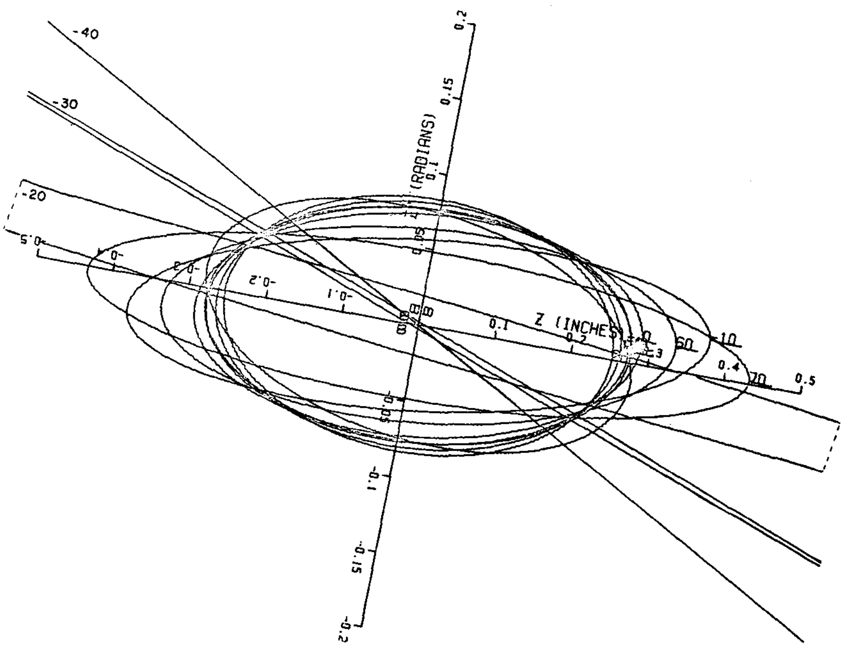

Fig. 2. Axial acceptance ellipses for phases –40° to +70° (ν_z = 0·2, ϵ = 0)

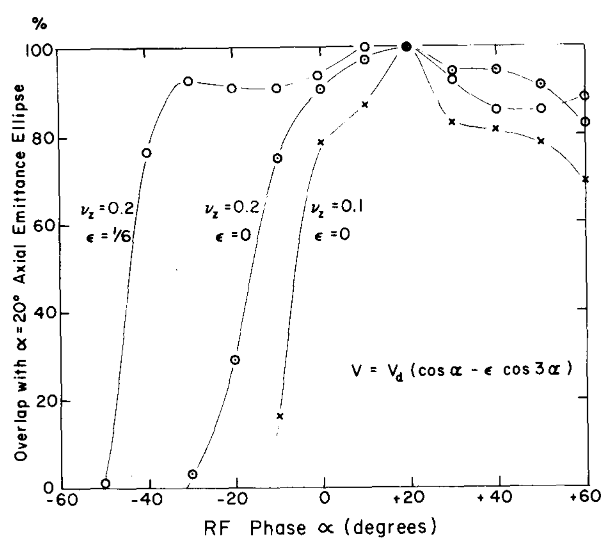

Fig. 3. Percentage overlap of 20° phase axial acceptance ellipse with those for other phases. Curves are labelled by the strength of magnetic focusing (ν_z = 0·1, 0·2) and the fraction of third harmonic (ϵ = 0, 1/6)

The asymmetry here is caused by the injection gap; a slight adjustment in position may effect a cure. Non-linear effects in the radial motion were negligible, so that a beam of the expected cyclotron acceptance[5] (28 π mm mrad [MeV] $^{1/2}$) could be matched at injection to give an internal beam with a uniform 0·16 in radial oscillation amplitude.

3. AXIAL MOTION

Two unusual features of the magnet design[4] maintain the magnetic axial focusing at $\nu_z \simeq 0{\cdot}2$ over the central region, four times stronger than the $\nu_z \simeq 0{\cdot}1$ obtained with the basic six-sector geometry and 20·8 in pole gap; firstly only three of the sectors are brought inside 40 in radius (Fig. 1), and secondly steel 'wedges' within the vacuum tank reduce the pole gap to 10 in locally. Even so the axial electric forces at the dee gaps are relatively strong because of the high dee voltages (V_D = 100 kV) and the fifth harmonic acceleration mode. An initial tracking and matching study of the axial (z) motion has assumed uniform magnetic focusing together with Rose's[6] thick lens approximation for the dee gaps

$$\frac{\Delta z'}{z} = -\frac{N\omega}{v}\frac{qV_D}{E}\sin\alpha - \frac{2f}{\pi b}\left(\frac{qV_D}{E}\right)^2\cos^2\alpha \qquad \frac{\Delta z}{z} = -\frac{qV_D}{E}\cos\alpha$$

where q, v, E, and ω are the ion charge velocity, energy and orbital frequency, respectively, $N\omega$ is the rf and f and b are geometrical factors. If the Δz displacement term is omitted the beam emittance is not conserved. Cohen's improved formulae[7] were also tried but at our energies did not alter the results significantly. Fig. 2 shows, for various phases, the acceptance ellipses at injection which transform to beams of uniform axial width beyond 7·5 MeV, where axial electric effects are assumed to be negligible. In this example the grid posts on the first two gaps were assumed to reduce their effect by a factor four. The percentage overlap of each ellipse with that for +20° phase is plotted in Fig. 3. For lagging (positive) phases the acceptance varies very little with phase. For leading phases, however, there is a sharp cut-off, which is improved from −5° to −15° by raising the magnetic focusing from ν_z = 0·1–0·2. Even more effective is flat-topping of the rf wave[8] with third harmonic; a fraction $\epsilon = 1/6$ advances the cut-off to −45°, and there will be corresponding improvements in the radial phase acceptance.

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