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THE PROPOSED UNIVERSITY OF MANITOBA POLARISED AND UNPOLARISED LIGHT ION FACILITY

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Introduction

A variable energy cyclotron with six separated sectors is proposed for the acceleration of polarised and unpolarised light positive (p,d, $^3He^{++}$, $^4He^{++}$, $^6Li^{+++}$, $^7Li^{+++}$ etc.) and light negative (H^- and D^-) charge state ions. The energy range within which these ions are accelerated and extracted is shown in Table 1. Not included in the table is the production of secondary beams of polarised and unpolarised neutrons. In addition H^- and D^- beams can be accelerated and extracted by stripping foils and in this case the lower limit of the energy range will be reduced, (to 10 MeV for H^-). The requirements for beam current and quality are that the accelerator should deliver high level beams ($\gtrsim$200 μA for p and d, several μA for $\vec{p}$ and $\vec{d}$, etc.) with good energy resolution ($\Delta E/E \sim 10^{-3}$). As to the depolarisation of polarised beam during acceleration, it should be negligibly small for all particles. The latter requirement restricts the choice of sector number and magnet angle while the energy resolution and beam current requirement is met by flat topped acceleration. Cost consideration is a very important factor. Because of this, it is proposed to inject the beam from an external ion source at low energy (∿200 keV), rather than incorporate a pre-accelerator. The acceleration of H^- and D^- particles entails losses through collisional electron detachment and electromagnetic stripping inside the cyclotron. The loss from the former is expected to be ∿10% for D^- (at 10^{-7} Torr) while the loss from the latter is estimated to be ∿0.04% for H^-.

TABLE 1

The maximum and minimum particle energy per nucleon for various ions. The corresponding rf harmonid mode and the frequency are also shown.

Particle	rf harmonic	rf MHz	Energy MeV/n
H^+ and H^-	7	26.5	26
	4	30.6	122
D^+, $^4He^{++}$	7	26.5	26
D^-, $^6Li^{+++}$	6	34.3	62
$^3He^{++}$	7	26.5	26
	5	32.9	80
$^7Li^{+++}$	7	26.5	26
	7	34.9	46

The Cyclotron

From the considerations mentioned above a separated sector cyclotron with straight six sector geometry was proposed and this is shown schematically in Fig. 1. The magnet angle (hard edge) is 33° and has a maximum gap field of 1.52 Tesla. The corresponding ν_z and ν_r are calculated as a function of beam energy parameter $\gamma=E/E_o$ using the hard edge approximation formula[1] and the result is shown in Fig. 2. The approximation is valid down to r$\gtrsim$0.4m for the proposed cyclotron. From the beam dynamics point of view both 4 and 6 sectors are acceptable (see, for instance, Ref. 1, 2). However, depolarisation considerations lead to the choice of six sector geometry. The magnet gap is 6.5 cm with 30 radial gradient coils per pole face. An effort will be made to ensure that the field in the valley is very small.

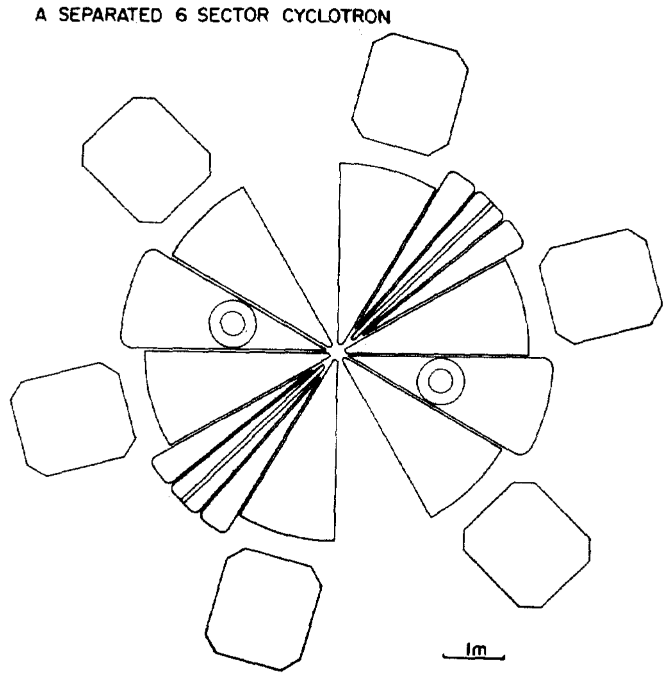

Fig. 1. The proposed University of Manitoba Cyclotron. The central region (r$\lesssim$0.4m) not to scale.

The RF system will operate from 26 to 36 MHz at the 4th to 7th harmonic of the beam revolution frequency. RF voltage will rise toward the outer radii with peak voltages of 250 kV and dee of about 27°. RF power is estimated at 350 kW (500 kW DC input) with 20% maximum beam loading. Third harmonic dees will be filled in the two spare straight sections. Full scale model studies of the central region (see Fig. 4) and half scale studies of the full structure are planned. Considerable work is necessary in order to find the dee stem structure and tuning method that ensures optimum radial voltage variation. Vertical dual λ/4 structures are envisaged for the main dees. The design of the third harmonic dee needs more attention because each dee extends almost a full wavelength radially.

Acceleration of Polarised Beams

The acceleration of polarised ions is an important feature of this cyclotron. Therefore the cyclotron should be demonstrated as free from any major depolarising resonances. The problem has been studied and Fig. 3 summarizes the resonances for the proposed cyclotron. It is seen that for r>0.4m (for r$\lesssim$0.4m the actual ν_z and ν_r will depart from the calculated values) all polarised ions considered in the figure are far away from the intrinsic major depolarising resonances[3,4] i.e. $\gamma(\frac{\omega_i}{\omega_c} - 1) = -6\pm\nu_z$ or $= 6\pm\nu_z$. $\vec{P}$, $\vec{d}$, $\vec{D}^-$, $^6\vec{Li}^{+++}$ and $^7\vec{Li}^{+++}$ are again far away from the intrinsic minor resonances ($= 0\pm\nu_z$, $= 6\pm\nu_z\pm\nu_r$, $= -6\pm\nu_z\pm\nu_r$). $^3\vec{He}^{++}$ is not as far away from one of the

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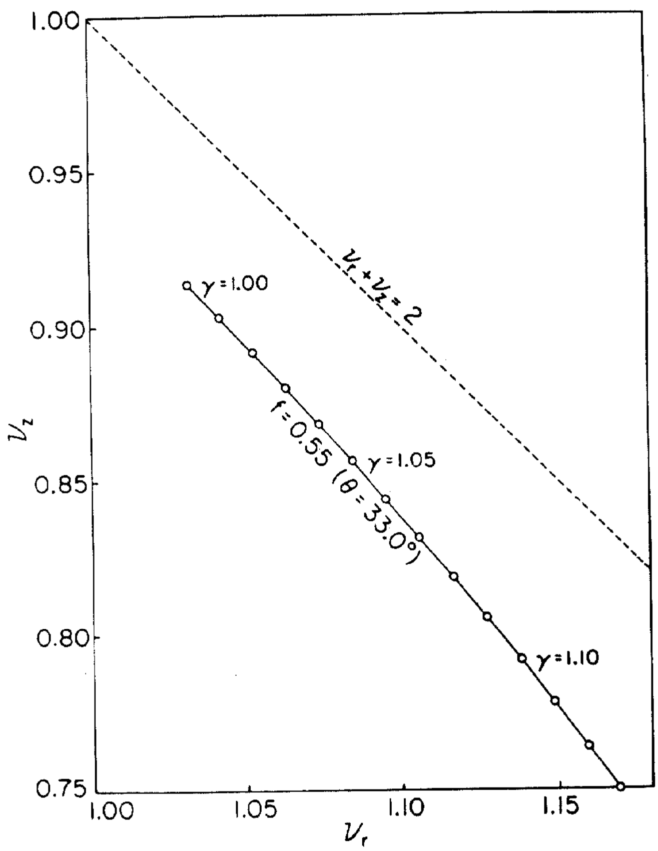

Fig. 2. $\nu_r(\gamma)$ and $\nu_z(\gamma)$ plotted as a function of $\gamma = E/E_o$ as calculated from the hard edge approximation for the proposed cyclotron. The largest γ it can reach is 1.13. This curve does not apply in the central region (r<0.4m).

intrinsic minor resonances ($= -6+\nu_z+\nu_r$) and $\vec{H}^-$ even crosses this line at around 70 MeV. If we assume the vertical and radial betatron oscillation amplitudes to be 2mm and 3mm respectively, the corresponding magnetic field component is estimated to be less than 0.1mT and therefore this depolarisation is expected to be insignificant.

The even minor intrinsic resonances ($= 0\pm\nu_z\pm\nu_r$) cross the $^6Li^{+++}$ resonance line and lie very close to the D^+ resonance line at low energy (these are not shown in Fig. 3). However the depolarisation is expected to be extremely small because ω_i/ω_c is small and the amplitude of the B_h component for this resonance is also very small.

Apart from these intrinsic resonances there are the imperfection resonances. These are $\gamma(\omega_i/\omega_c - 1) = N$ (for all N) or $= \pm N\pm\nu_z$ or $= \pm N\pm\nu_z + \nu_r$ ($N \neq 6$ or 0). It is seen in Fig. 3 that some of the polarised ions pass through such resonances. These resonances arise from imperfections in the field. Among these the resonance $\gamma(\omega_i/\omega_c - 1) = \pm N = \pm$ sector number, is the only serious one for the light ions considered. There are so many factors that can contribute significantly to this component in practice (such as the median plane of the hills being higher than that of the valleys or each magnet sags symmetrically about the mid-line of the hill) that the only way of removing this depolarisation entirely would be to have a perfect median plane throughout the cyclotron. In the proposed cyclotron this is avoided by choosing 6 sector geometry for which none of the ions can be seen to cross this resonance (H^- would cross this resonance at around 60 MeV for a 4 sector machine). The N = 0 imperfection resonance is of no concern because there is no crossing or near close crossing. H^- and H^+ passes through the N = 4 and N = 2, resonance respectively (and $1+\nu_z$, $-3-\nu_z$, $-5+\nu_z$). However, by keeping the proper rotating (horizontal) component of these harmonics, $_hB_{-4}$ and $_hB_2$ etc., to less than 0.6mT the depolarisation can be kept down to less than 0.1%. The other imperfection field components are usually small in comparison to the sixth

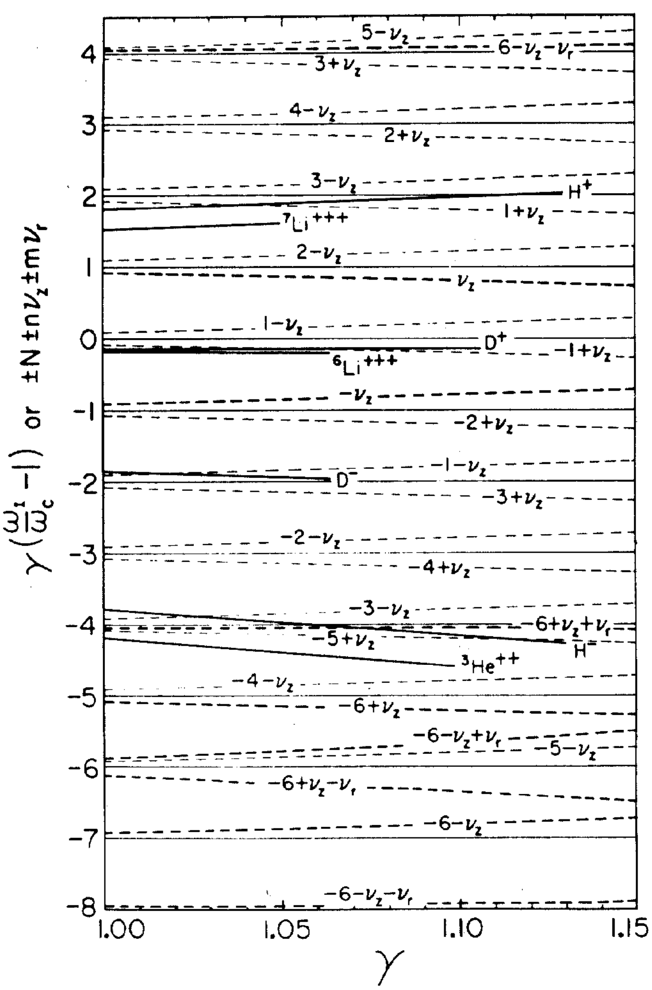

Fig. 3. The depolarising resonance curves for various polarised ions. The abscissa is $\gamma = E/E_o$ and the ordinate is either $\gamma(\frac{g_i me}{2m_p q} - 1) \equiv \gamma(\omega_i/\omega_c - 1)$ (thick solid curve) for the ions or $\pm N\pm n\nu_z\pm m\nu_r$ for the cyclotron. Here ω_i is the spin Larmer frequency and ω_c is the cyclotron frequency.

harmonic and are expected to be corrected by additional coil windings. A computer study of the effect of these crossings is under study as an additional check of this estimate.

Injection and Central Region

The central region of the magnet is the subject of a separate study. The proposed sector magnet has to extend to within $r \approx 14$ cm from the centre axis. Therefore, to keep the hard edge boundary approximately at a constant angle the real edge of the magnet has to deviate from a straight line in the central region and at the same time extensive shimming is required. The spacing between two adjacent magnets at r = 14 cm would be only 6 cm and this raises some engineering problems. The flutter component is expected to drop down substantially and the average field deviate from isochronism considerably in this region. To overcome these problems it is proposed that two pairs of small dees be placed in the four free spaces between the magnets as is shown in Fig. 4. These pairs of dees are driven by separate RF supplies at the same frequency as the main dees but phase adjustable to each other and with respect to the main dees and extend radially only for two orbits. With 50 kV on each dee the 200 KeV beam injected into it is accelerated to 1 MeV by the time it enters the main dee. The particles are injected slightly ahead of the main RF phase to compensate for the lack of isochronism. Non-linearity in the field level in this central region means a different amount of phase lag for different types of ions. This can be accommodated by adjusting the injection and the RF phases of the two pairs of small dees. Much lower RF voltage to the small dees reduces the gap required between these dees and the ground shield and therefore reduces transit time. A likely crossing of $\nu_r = 2\nu_z$ as a result of drop in ν_z in this region is expected to be rapid enough for the particles.

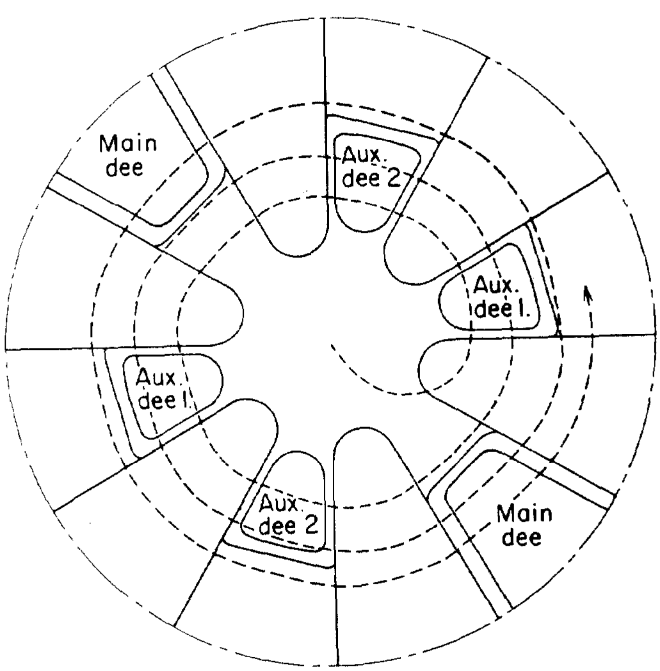

Fig. 4. The central region of the proposed cyclotron. It is only schematic and not to scale.

The engineering problems concerned with beam injection will be solved in studies using a full scale model of the central region.

Conclusion

The proposed separated six sector cyclotron will be free from any major depolarising resonances for light ions and is expected to suffer little depolarisation from others.

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