UPGRADING THE UNIVERSITY OF MANITOBA CYCLOTRON

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Summary

A major upgrading of the University of Manitoba cyclotron is nearing completion. The three major areas of improvement are the RF and dee system, the magnetic field, and the unpolarized ion source. The new dee and RF system, now being installed, will operate in the push-pull fundamental mode for H^- and push-push 2nd harmonic mode for D^- acceleration. Two central regions have been designed, one for the H^- and one for the D^- mode of operation. A mapping/shimming program for the magnetic field was carried out during the installation period in order to improve isochronism and vertical focussing. A newly built Ehler's type ion source will complement the existing duoplasmatron source. The cyclotron is expected to accelerate H^- ions by June, 1984. As a result of the upgrading program, a significant improvement in both beam current and quality is anticipated.

Introduction

The University of Manitoba cyclotron is nearing completion of a major machine development program. The main objectives of this program are to increase the transmission of H^-, D^-, and polarized D^- beam through the cyclotron, and to improve the brightness, phase space area and energy resolution of the extracted beam.

Built in the early 1960's(1), this four sector, spiral ridge cyclotron was designed to accelerate primarily H^- ions with a provision for the acceleration of D^- ions. The cyclotron originally operated with an internal ion source which was replaced by an axial injection system in 1976(2,3). At this time D^- ions were successfully accelerated and extracted for the first time. Since then, both unpolarized and polarized H^- and D^- ions have been injected into the machine(4). Polarized D^- ions were successfully accelerated, however, a resonant depolarization of H^- ions prevented the successful acceleration of polarized H^- beams. Prior to the present development program, H^- ions were axially injected at 11 keV and deflected through ninety degrees by an electrostatic mirror. The ions were then accelerated by dees that operated at 28.48 MHz with a peak voltage of 29 kV. D^- ions were injected at 5.5 keV and accelerated at 14.24 MHz with a peak voltage of 14.5 kV. The magnetic field has an average strength of just under 2 Tesla and is trimmed by 64 temperature controlled blocks of Invar under the hills. H^- beam is extracted at energies ranging form 22 to 50 MeV (11 to 19 MeV for D^-) by a stripping foil and is deflected out of the machine by a combination magnet.

Proton beams ranged from a 4 μA average to a peak of about 10 μA at low energies, but fell off rapidly above 42 MeV. The deuteron mode yielded lower beam currents with a maximum energy of 23 MeV.

In 1982, we initiated an upgrading project for the cyclotron to improve the quality and quantity of both H^- and D^- beams as well as giving improved polarized D^- beams. This project included the design and construction of a new RF system, a new dee and central region system, a new unpolarized ion source, as well as a complete mapping and shimming program to improve the magnetic field.

RF/Dee System

RF System

The original dee system was operated in the λ/2 (push-pull) mode with the dees 180 degrees apart in RF phase. The dee system was inductively coupled to a 25 KW RF amplifier by a single coupling loop. The dees were coarsely tuned by a shorting bar which slid along the two dee stems. They could thus be tuned from 14.24 MHz to 28.48 MHz for D^- and H^- operation respectively. In order to change the RF frequency, the cyclotron had to be vented and the dee stem shorting bar moved. The major limitations of this system were the low acceleration voltage on the dees, the need to inject the D^- beam at 5.5 kV, and the need to vent the cyclotron in order to change frequency.

A new RF/dee system, based on a half scale design study, was designed and built in-house (fig.1). The new design includes enclosed λ/4 dee stems, each in a separate coaxial housing, in order to achieve better electrical decoupling. Tuning is accomplished by moving coaxial shorts on each dee stem while the cyclotron is under vacuum.

The RF signal is derived from a frequency synthesizer which drives a power splitter that feeds two 10 W broad-band amplifiers (in phase or 180 degrees out of phase). Each of these signals is, in turn, fed to a 40 W broad-band amplifier that drives a 1 kW tuned amplifier. The final stage for each signal is a power amplifier (25 kW maximum) that is a cathode driven grounded grid, employing one 3CW20000 A7 EIMAC. The output of these two power amplifiers is fed over two equal length, semirigid 41 mm diameter HELIAX cables and is inductively coupled to the dees. Extensive testing was done and 23 kW each were run into dummy loads. The control system design will be finalized only after full power testing of the RF/dee system is complete. RF amplitude is regulated by an analog feed-back system which controls the output of the frequency systhesizer. Controlling the dee phase will be accomplished with the aid of a Rhode and Schwarz vector voltmeter. From this voltmeter, an analog signal, proportional to the phase difference between the dees, will be fed to a phase shifter in one of the amplifier chains.

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Interaction between tuning and phase control will be investigated further. Low power tests indicate that phase stability is very good, with phase shifts of less than 1/4 degree over an 8 hour period (after warm up).

In anticipation of the increased RF heating, extra cooling of the dees and copper liners is employed. The copper liners are constructed of 3 mm O.F.H.C. copper plate and are bolted to the pole-face of the cyclotron, in the valleys in which the dees reside. These liners are cooled by water at 10°C flowing through copper tubing soldered to the copper plate. The dees are also constructed of 3 mm O.F.H.C. copper plate and are similarly cooled.

The increase in the peak dee voltage enticed us to make the dees thinner (z direction) in order to decrease the chance of breakdown from the dee to the liner. This change enabled us to increase the azimuthal width of the dees from 25 to 30 degrees. The dee gap, through which the beam must pass is 20 mm and the total dee thickness is 28 mm (cf. hill gap of 34 mm and valley gap of 100 mm). The maximum dee voltage attainable, may be limited in the long run, by the 3 mm gap between the dee tip and the grounded central region mirror housing.

With these modifications to the dee/RF system, it will be possible to accelerate H^- ions in the push-pull mode using the fundamental harmonic at 28.4 MHz with peak dee voltages of 40 kV. This, combined with the larger azimuthal dee width, results in an increase in the acceleration per turn with a subsequent decrease in the number of turns to extraction energy by 35%. Acceleration of D^- ions will be accomplished in the push-push mode using the second harmonic at about 30 MHz with peak voltages of 40 KV. The improvement is much more dramatic in this case. The number of turns to extraction will be decreased by over 80%.

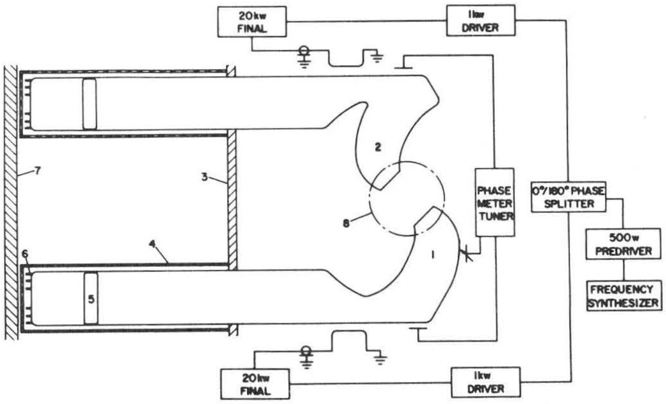

Fig. 1. New Dee System with schematic of RF coupling and power supplies.

Central Region Design Study

The central region of the cyclotron (i.e., up to 12 cm radius) is very important in that it defines the acceptance parameters of the machine and the quality of the beam that is accelerated and ultimately extracted. Therefore, a detailed study was initiated to redesign and analyze the performance of a new central region.

Initial calculations determined a preliminary model of the central region, consisting of the dee tip pair and the ground shield/mirror assembly. The magnetic bump field was derived using data from a field mapping carried out in 1982(5). The RF electric fields were obtained by a computer program which solves Laplace's equation using a succesive over-relaxation method on a grid of 257x129x15 with a mesh size that varied from 4 mm initially to 0.25 mm in the final approximation. Using the magnetic and electric field data, the model was tested by performing a computer simulation of the particle's trajectory, in and out of the median plane. This computer program(6) numerically integrates the three-dimensional equations of motion of a charged particle by the Runge-Kutta method. In the vertical direction, only the paraxial motion of the beam was studied (fig.2).

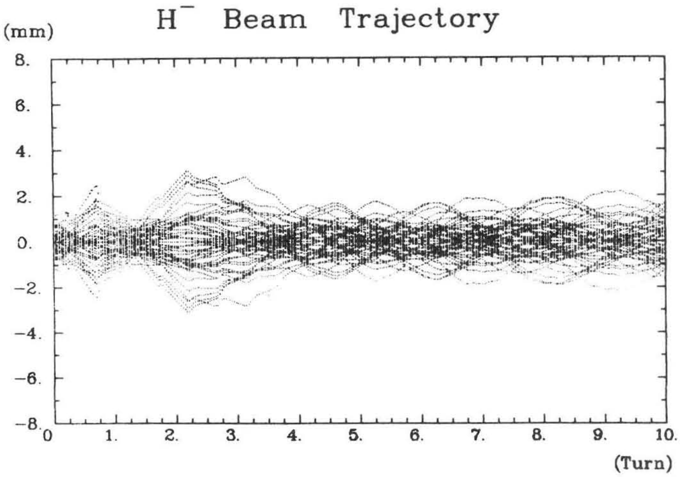

Fig. 2. Vertical motions (paraxial) of 50 sample H^- ions for the first 10 turns of an assumed field (for a reliable study over 300 ions must be traced).

Figures 3 and 4 show the final geometry of the central region for H^- and D^- ions respectively. What is not shown in the diagrams is a set of 6 posts that extend along the leading edge of the North and South dee for both H^- and D^- central regions. The posts act as slits and enhance the electric focussing as the beam passes between them. The two central regions have a common injection point which is off axis by 5.5 mm. The design injection energy is 12 keV for H^- ions and 15 keV for D^- ions.

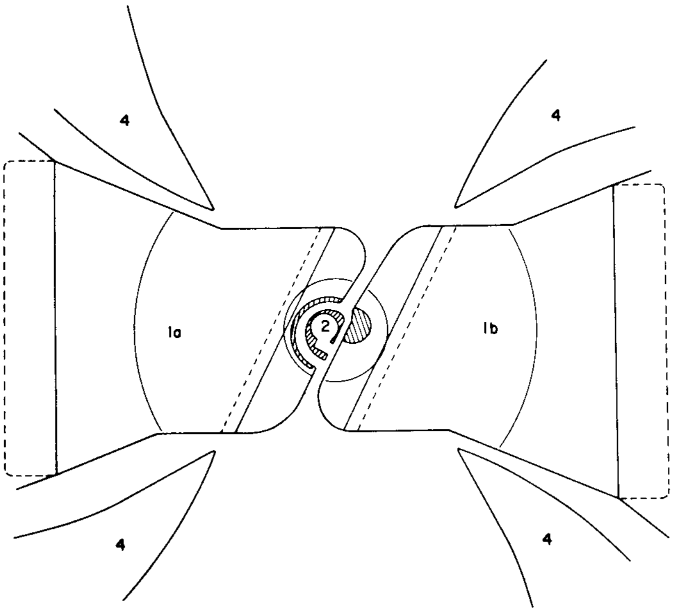

Fig. 3. Central region for H^- ions
1. Dees; 2. Ground Shield; 4. Hills.

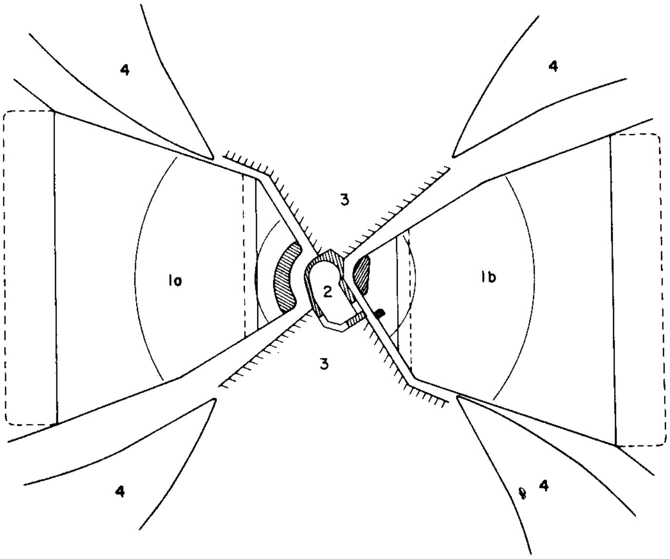

Fig. 4. Central region for D^- ions
1. Dees; 2. Ground shield; 3. Wings at ground potential; 4. Hills.

Unpolarized Ion Source

An "Ehlers" type hot filament source has been constructed. This source will complement the duoplasmatron currently in use and provide a much brighter beam with currents of over 800 μA.

The plans for this source were obtained from TRIUMF and originate from a Cyclotron Corporation design which has been modified by the TRIUMF machine development group(7). This ion source has the potential to deliver beams which exceed the space charge limitations of the cyclotron.

Field Mapping/Shimming Program

Field Mapping Apparatus

The magnetic field mapping apparatus has been used previously in this laboratory(8) and the details of its construction have been described elsewhere(5). However, several improvements have been made in order to improve both the accuracy and precision of the measurements. Absolute measurement of the magnitude of the magnetic field has an accurracy of close to $1/10^4$ where as the precision of the measurements approach $1/10^5$. A detailed report of the improvements will be published in the future.

Magnetic Field

The magnetic field mappings performed in 1982 indicated a sudden loss in vertical focussing at around 10 cm radius for both H^- and D^- ion beams. This is caused by the central region bump field disappearing before the flutter field takes over the vertical focussing. Centre plug positioning and invar temperature adjustments could not adequately compensate for this defocussing.

At 46 cm radius (42 MeV for H^- and 19 MeV for D^-), another severe loss of vertical focussing was encountered. Invar temperature adjustment increased the vertical focussing but introduced a pronounced decrease in isochronism. From the 1982 field mapping data, it was shown that large shims placed in the valleys near the outer edge of the pole face improved the isochronism but caused the effective spiral angle to momentarily turn in the wrong direction. For D^- acceleration, a near isochronous field could not be produced even with maximum Invar settings. This, compounded with the vertical defocussing at 10 cm and 46 cm caused an unacceptable reduction in beam intensity and quality.

In order to improve the magnetic field, a series of successive shim changes and field mappings have been carried out using the field mapping apparatus described above. Typically, a field mapping was carried out over only one quadrant and took about 4 hours. Fast machine shop turn around enabled us to complete a shim change, field mapping, and analysis of the effect of the shim change in one day.

Each field mapping was accompanied by computer calculations of equilibrium orbits from the injection point to 55 cm radius, taking about 1 1/2 hours cpu time on a VAX 750 computer. From these calculations, the isochronism (nu(r)), the vertical focussing (nuz(r)), and the radial focussing (nur(r)) were calculated. These results were then used for the design of the next set of shims.

A total of about 6 weeks were spent for field mapping between January and April 1984, during which the effects of about 30 different shims were investigated. The objective was to obtain isochronism to 55 cm, better vertical and radial focussing, and to increase the maximum useful energy for both H^- and D^- ions. A special effort was made to shift the "nur = 2 nuz" and the "nur = 1" resonances so that H^- beam can be accelerated to 50 MeV without a large reduction in intensity.

Figure 5 shows the isochronism versus radius for H^- ions. A significant improvement has already been made in the three important parameters (nu, nuz, nur). The field shimming program will be completed by the first week in May (1984) at which point the final set of shims will be in place, followed by several 360 degree field mappings.

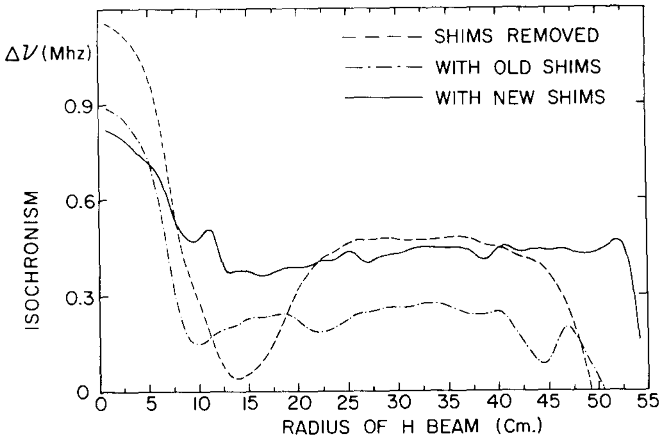

Fig. 5. Isochronism plots for three cases corresponding to the cyclotron configurations:
a) Without any shims (dashed line); b) with previous shims (dash-dot); c) a modified set of shims (solid line).

Conclusion

This upgrading project is now nearing completion with all major components having been constructed and tested as far as possible. Upon completion of the field mapping and insertion of the final shims (May 1, 1984), the new dee and RF system will be installed and tested under full power. The cyclotron should be operational by early summer.

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