A COMPACT H⁻ CYCLOTRON FOR ISOTOPE PRODUCTION

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Abstract

The design of a compact, high intensity H^- cyclotron for isotope production, exploiting the recently developed TRIUMF high brightness multicusp volume H^- ion source, is described. A 5 mA version of this H^- source currently under development, makes possible accelerated beam intensities of up to 500 μA. The cyclotron has a four sector, radial ridge design, with two 45° dees in opposite valleys. Beam extraction is by stripping to H^+ in thin graphite foils. Two foil strippers permit the simultaneous extraction of two beams. By varying the radial position of the stripper the energy of the extracted beams can be varied between 15 MeV and 30 MeV.

1. Introduction

A beam intensity upgrade program for the 500 MeV H^- cyclotron at TRIUMF has led to the development of a dc version of a volume cusp ion source with the capability of producing several milliamperes of low emittance H^- beams. Such a source has applications beyond the immediate development need at TRIUMF, in particular to high intensity H^- cyclotrons for isotope production.

At TRIUMF radioisotopes are produced commercially by Atomic Energy of Canada Radiochemical Co. using a dedicated 42 MeV H^- cyclotron, and parasitically using beams from the 500 MeV TRIUMF cyclotron.[1] Recently AECL has expressed a desire to expand their production capacity with a second dedicated cyclotron. Because of the ion source development, the various cyclotron design skills available at TRIUMF, and a technology transfer policy at TRIUMF, it was decided to cooperate with a commercial partner in the submission of a proposal to AECL to design and construct a cyclotron meeting the AECL requirements.

The basic specifications call for a cyclotron with a maximum proton energy of 30 MeV, an accelerated beam intensity greater than 350 μA, and at least two external beams, each capable of beam currents up to 200 μA and with energy variable from 15 MeV to 30 MeV.

This paper gives an overview of the current cyclotron design.

2. General Description

Because of the ease of extraction, ease of providing multiple external beams, and the extensive experience with H^- cyclotrons at TRIUMF, it is natural that an H^- cyclotron be specified for this application. In this case a four sector compact design with 38.5° radial ridge hills, as illustrated in Fig. 1 is proposed.

The magnet is approximately 2.5 m in diameter, 1.2 m high, and weighs approximately 49 tonnes. It is split near the midplane allowing three jacks installed around the periphery to elevate the upper part for access to the cyclotron interior. Two coils, mounted on the upper and lower poles, with a total of 7.2×10^4 ampere-turns provide the magnet excitation. Power dissipation in the magnet is approximately 29 kW. Because of the fixed field operation, all magnetic field corrections will be made by shimming during the field mapping stage of construction. No trim coils are planned.

To limit cyclotron vault ceiling height requirements while at the same time minimizing injection beam line components, the ion source is mounted directly below the cyclotron. Access to the ion source and other components such as vacuum pumps and the rf drive line which are also located below the cyclotron, is made possible by mounting the cyclotron over a relatively shallow pit.

The H^- beam from the ion source is injected vertically upward along the magnet axis toward the centre where an electrostatic spiral inflector bends it into the horizontal median plane. Acceleration then takes place at four dee gap crossings per orbit.

The two 45° wide dees located in opposite valleys operate in phase at 37 MHz, the second harmonic of the orbit frequency. With the design voltage of 50 kV (peak) on the dees, the energy gain per turn is 140 keV, and approximately 200 turns are therefore required to reach maximum energy. Coaxial stubs to resonate the dees at the operating frequency penetrate the yoke through four 25 cm diameter holes. Rf power is delivered to the dees through a six-inch coaxial transmission line, a variable impedance matching section and a drive loop located near the end of one of the resonator stubs. For ease of maintenance the entire 60 kW rf system is located outside the cyclotron vault.

To maintain four-fold magnetic symmetry there are four additional holes through the yoke in the unoccupied valleys. Two of these in the lower yoke are used as vacuum pump ports in which two 20 cm cryopumps are installed.

The vacuum enclosure for the acceleration region is defined by the upper and lower pole surfaces and an essentially circular cylindrical aluminum shell that is sealed with elastomer gaskets to the outer edge of the poles. With the pumping provided, a pressure of less than 3×10^{-7} torr should be achieved and the beam loss due to gas stripping during acceleration is therefore expected to be less than three per cent.

Basic parameters for the cyclotron are given in Table I.

3. Ion Source

A high intensity, low emittance H^- ion source is the key to achieving high intensity beams from the cyclotron. In this case the ion source to be used is based on the development, at TRIUMF, of the dc multicusp volume plasma source.[2] Figure 2 illustrates the TRIUMF development source with which beam currents of 2.5 mA of H^- ions in a normalized emittance of 0.2π mm-mrad have been demonstrated. For the 30 MeV cyclotron a source with a smaller plasma volume,

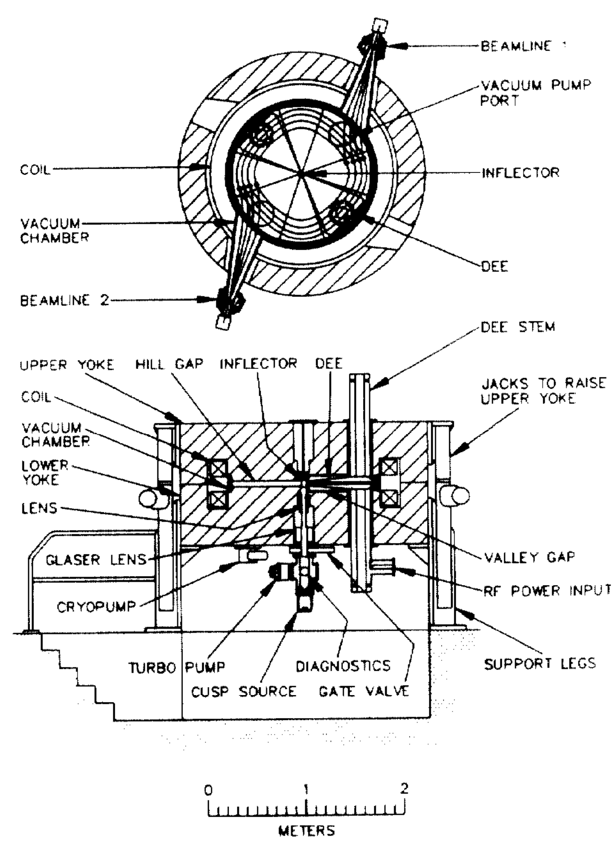

Fig. 1. Cross-sectional and plan views of the cyclotron.

Table I. Principal cyclotron parameters.

Magnet	
Average field	1.2 T
Hill field	1.90 T
Valley field	0.55 T
Hill gap	4 cm
Valley gap	18 cm
Hill angle	38.5°
Iron weight	46 tonnes
Pole radius	76 cm
Height	1.26 m
Diameter	2.62 m
Number of sectors	4
Coil	
Coil power	29 kW
Copper weight	1.9 tonnes
Ampere-turns	7.2×10^4
RF	
Frequency	37 MHz
Dee voltage	50 kV
Electrical width	90°
Harmonic	2
Power	60 kW
Vacuum	
Pressure	3×10^{-7} torr
Pumping	4000 ℓ/s (H_2O), 1500 ℓ/s (air)
Ion source	
Type	H^- cusp
Output current	5 mA
Emittance (normalized)	0.35π mm-mrad
Bias voltage	25 kV
Extraction	
Energy	15–30 MeV
Method	Stripping
External beams	2

and therefore requiring smaller power supplies, is under development. H^- beam currents of up to 5 mA with a normalized emittance of 0.35π mm-mrad are expected from this source.

4. Injection

The transport line from the ion source to the cyclotron consists of a solenoid plus a quadrupole doublet. The optics were optimized by tracking the σ matrix into the axial magnetic field, through the inflector, and into a dipole with a field index chosen to give the correct ν_z value.[3] Since turns are not separated at extraction, betatron phases will mix and only the maximum radial and vertical beam sizes during one betatron oscillation will determine the effective circulating emittance. With ν_z chosen to be 0.2 and a normalized source emittance of 0.35π mm-mrad, optimal radial and vertical normalized circulating emittances were found to be 0.68π mm-mrad and 0.63π mm-mrad, respectively. Because of electric focusing, ν_z and ν_r are actually functions of the rf phase and this further increases the effective emittances. This matching scheme requires that the last quadrupole be located as close as possible to the median plane, which in this design is 15 cm. Initially, an axially symmetric matching system (consisting only of solenoids) was considered, but this was found to give very poor matching: radial and vertical normalized circulating emittances were at best 1.1π mm-mrad and 3.0π mm-mrad, respectively. Moreover compared with the quadrupole scheme, matching was found to be very sensitive to ν_z.

5. The Central Region

The orbit calculations used to design the central region were preformed using the orbit tracking code CYCLONE.[4] This program can be used to study both radial and vertical motion, and consists of three separate parts. The first part integrates the equations of motion in the region of the first gap using an electric potential map stored in a rectangular grid. In this part the independent variable is the rf time, (τ). In part II the angle is used as the independent variable, and again a rectangular electric potential map is used. In part III a delta function energy gain is used. Typically the first 5 turns are completed in part II and then the program switches to part III. The electric potential grids are calculated using the code RELAX3D,[5,6] which employs the technique of successive over-relaxation. Parallel to the median plane a grid of 201 by 201 points was used, with a spacing of 1.0 mm. In the axial direction 9 points were used with a spacing of 1.25 mm.

In designing the central region we have tried to maintain good centering for a large phase acceptance, while leaving clearance around the median plane posts for the radial phase space. We also felt that it was necessary to achieve the required centering using an inflector with the minimum of tilt to preserve aperture in the inflector. In this design a spiral inflector with an electric bend radius of 2.0 cm and a tilt parameter,[7] $k' = 0.35$ is used. To improve the voltage holding we have maintained a minimum distance between ground and high voltage in the direction perpendicular to the magnetic field of 8 mm

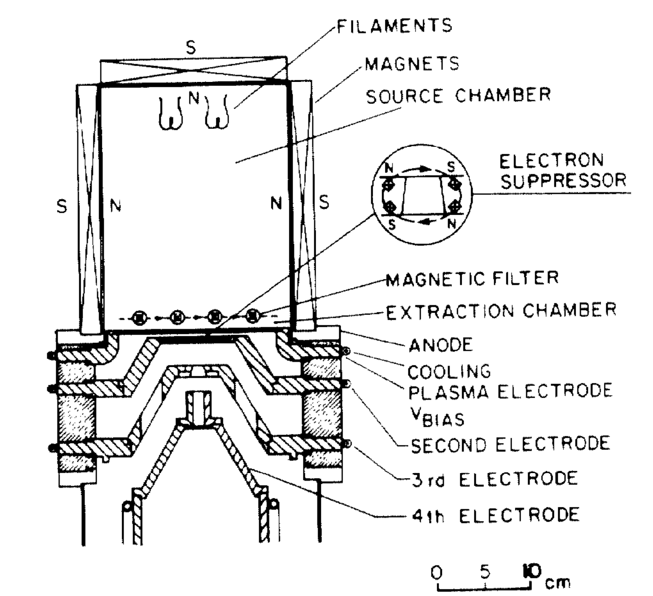

Fig. 2. A cross-sectional schematic drawing of the TRIUMF H^- cusp ion source.

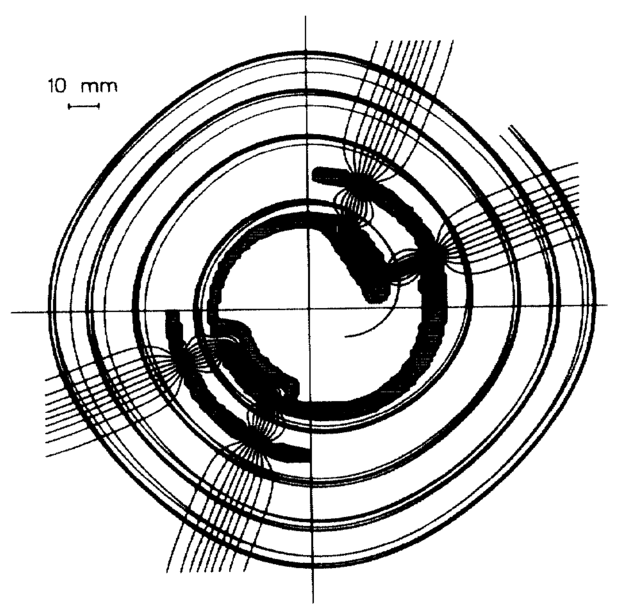

Fig. 3. Orbits of rays with 5 different starting times. Also shown are the central region electrodes in the median plane and the equipotentials of the electric field.

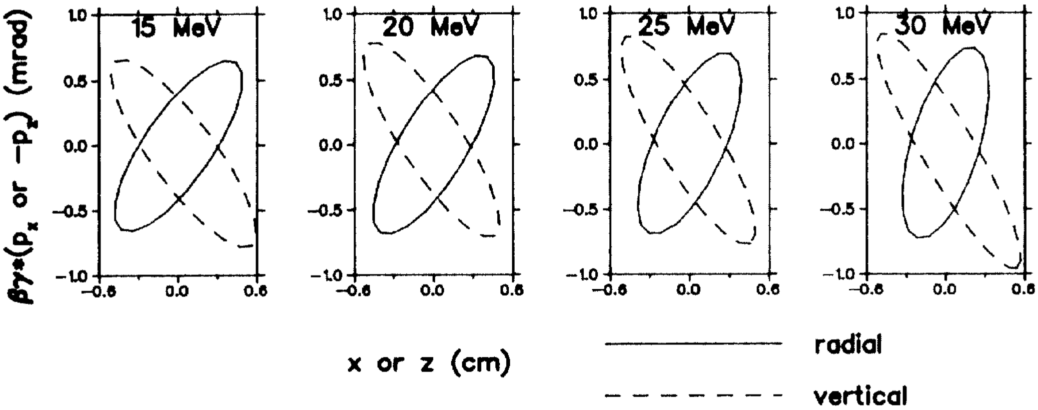

Fig. 5. Transverse emittance plots for various energy beams at the extracted beam cross-over point.

except in the injection gap where it has been cut to 5 mm to reduce the transit time. Finally, we have tried to take advantage of the large ν_z at higher energies, by providing a large vertical acceptance at low energies.

Since we wish to avoid using a field bump, the central ray is that which crosses the center line of the first dee at $\tau = 0°$ ($\phi = 0°$). This corresponds to a starting time of $\tau_0 = 120°$. In Fig. 3 we have shown rays starting at $\tau_0 = 100°, 110°, 120°, 130°$, and $140°$, superimposed on the equipotential plot of the electric field grid used by part II. The central ray has a centering error of 2 mm at turn 20 (orbit radius of 19.8 cm). The maximum centering error for the other phases in the $\pm 20°$ phase band is 3 mm and the centering errors are well grouped together in x, p_x space.

In Fig. 4 the vertical motion is shown for several different phases. In these cases the vertical motion is being treated by CYCLONE in the linear approximation, so one need only track two linearly independent rays. We have chosen to show a ray starting with $p_z = 0$ and another with $z = 0$. The starting values of the conjugate variables have been chosen to show a normalized emittance of 1.0π mm-mrad.

6. Beam Extraction

Extraction is achieved by passing the H^- beam through an appropriately positioned thin graphite foil (approximately 200 μg/cm^2) to strip off the electrons. The resulting H^+ beam then deflects into the exit channel. For an extraction foil locus that is essentially radial and

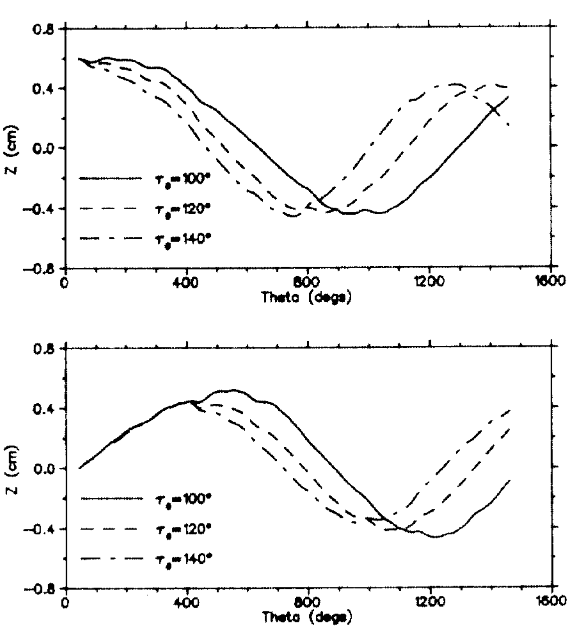

Fig. 4. The vertical motion in the first few turns.

located in a hill gap as shown in Fig. 1, the H^+ trajectories for the 15 MeV to 30 MeV beams exit the cyclotron through a valley, far from the defocusing effects of the hill fringe fields, and come to a common crossover point outside the magnet yoke. A dipole magnet (combination magnet) placed at the crossover then deflects the extracted beam into the external beam line. Results of transverse phase space computations for a range of extracted beam energies, as illustrated in Fig. 5, shows the beams to be well behaved and easily accommodated in a planned 7.5 cm diameter beam pipe. For these calculations the computed magnetic field, including fringe fields were used together with an assumed circulating beam emittance of 2.0π mm-mrad (a factor 6 larger than expected from the ion source). As illustrated in Fig. 1 two extracted beams exiting through diametrically opposite valleys are planned.

7. Present Status

A limited design activity for the cyclotron is progressing while contractual negotiations are proceeding. The major design and construction effort will begin with contract signing. Delivery is scheduled for nineteen months later.

References

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