A 30 MeV H$^-$ CYCLOTRON FOR ISOTOPE PRODUCTION

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ABSTRACT

Because of an expanding market for radioisotopes there is a need for a new generation of cyclotrons designed specifically for this purpose. TRIUMF is cooperating with a local industrial company in designing and constructing such a cyclotron. It will be a four sector H$^-$ cyclotron, exploiting the newly developed high brightness multicusp ion source. This source with H$^-$ current capability in excess of 5 mA makes feasible accelerated H$^-$ beam intensities of up to 500 μA. Beam extraction is by stripping to H$^+$ in a thin graphite foil. Extraction of two high-intensity beams, with energy variable from 15 to 30 MeV is planned. The use of an external ion source, provision of a good vacuum in the acceleration region, and the careful choice of materials for components in the median plane leads to a cyclotron that will have low activation and can be easily serviced in spite of the very high operating beam intensities.

A design extension to 70 MeV using many of the design features of the 30 MeV cyclotron can be easily made. Such a machine with a good quality variable energy beam is a highly desirable source of protons for isotope production, injection into higher energy high intensity accelerators, and as an irradiation facility for ocular melanomas.

Design of the 30 MeV cyclotron is well advanced and construction is in progress.

1. INTRODUCTION

As part of an applied program at TRIUMF we operate a dedicated 42 MeV H$^-$ cyclotron for Nordion International Inc. (formerly Atomic Energy of Canada Radiochemical Co.) for the commercial production of radioisotopes. Recently Nordion has contracted with Ebco Industries Ltd. to expand the existing facilities and add a second, new generation cyclotron[1,3)] for isotope production. For this endevour, as part of a technology transfer agreement, TRIUMF is providing design assistance to Ebco Industries.

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

2. GENERAL DESCRIPTION

The ease of beam extraction and convenient provision for multiple beams are attractive features of the H$^-$ cyclotron for isotope production. The extensive experience with such cyclotrons at TRIUMF leads naturally therefore to the selection of an H$^-$ design for the present project.

The cyclotron is illustrated in Fig. 1. It is a four sector compact design with radial ridge hills. The magnet is approximately square in shape, 2.3 m flat to flat, 1.26 m high and weighs approximately 46 tonnes. It is split at the midplane, allowing four hydraulic jacks located in the magnet supports at the corners of the yoke to elevate the upper part approximately one metre to allow access to the cyclotron interior. Two 37500 At coils mounted on the upper and lower poles provide the magnet excitation. Because of the fixed field operation all magnetic field corrections will be made by shimming during construction, and field mapping. No trim coils are planned.

Design of the magnet was done with the aid of the 2D magnetic field code POISSON to solve the cylindrical problem using stack factors for the hills and yoke penetrations. This was followed by a series of calculations for azimuthal cuts at various radii together with field calculations for charge sheet analogues of approximately uniformly magnetized segments of the hills and valleys, to give a synthesized 3D field map. Recently these calculations have been augmented with 3D field calculations using the code TOSCA.

Head room requirements in the cyclotron vault are minimized by installing the external H$^-$ ion source and injection line on the bottom of the cyclotron. This arrangement has the additional practical advantage of avoiding

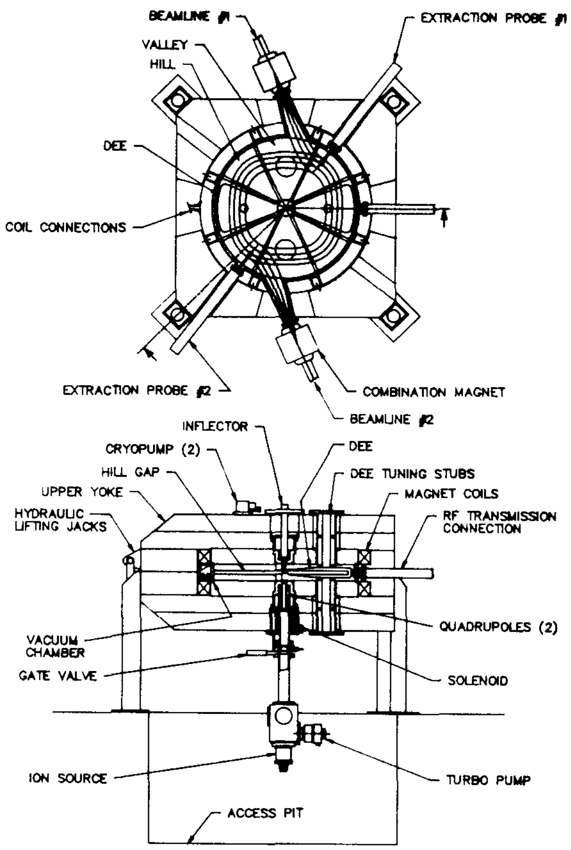

Fig. 1. Cross-sectional and plan views of the cyclotron.

the possibility of material flaking off the ion source filaments and falling onto any of the high voltage electrodes of the source or inflector. It does however require that the cyclotron be mounted over a 1.4 m deep pit. The H^- beam is injected vertically upward along the magnetic axis toward the centre where an electrostatic spiral inflector bends it into the median plane. Two 45° dees located in opposite valleys then provide acceleration at four gap crossings per orbit. The design voltage for the dees is 50 kV, and the operating frequency is 74 MHz, the fourth harmonic of the orbit frequency. The dees operate in phase.

The rf power is delivered to the dees through a capacitive coupling to the 50 Ω transmission line that passes through a port in the vacuum tank wall. For ease of maintenance the entire rf amplifier system is located outside the cyclotron vault.

Four large holes through the yoke in the dee valleys accommodate the coaxial stubs required to resonate the dees at the operating frequency. For magnetic symmetry there are four identical holes in the unoccupied valleys. Two of these are used as vacuum pump ports in which two 8 inch cryopumps are installed.

The vacuum enclosure is defined by the nickel plated upper and lower pole surfaces and a cylindrical aluminum wall that is sealed to the poles by a double O-ring gasket with a pumped intermediate space. With the pumping provided, a pressure of less than $5\text{x}10^{-7}$ torr is expected and beam loss due to gas stripping during acceleration should be less than 3%.

Beam extraction is by stripping to H^+ in thin graphite foils. Two independent external beams are formed with two extraction probes travelling in opposite hill gaps.

The basic cyclotron parameters are given in Table I.

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
Pole radius	76 cm
Number of sectors	4
Ampere-turns	7.5×10^4
RF	
Frequency	74 MHz
Dee voltage	50 kV
Harmonic	4
Power	< 35 kW
Vacuum	
Pressure	5×10^{-7} Torr
Pumping	4000 ℓ/s (H_20), 1500 ℓ/s (air)
Ion source	
Type	H^- cusp
Output current	5 mA
Emittance (normalized)	0.37π mm-mrad
Bias voltage	25 kV
Extraction	
Energy	15–30 MeV
Method	Stripping
External beams	2

3. ION SOURCE AND INJECTION LINE

A compact version of the TRIUMF dc volume H^- multicusp ion source[2)] has been tested. To reduce arc power the extraction electrode aperture was enlarged (compared to that in Ref.[2)] to 11 mm diameter. The normalized emittance of an extracted 7 mA H^- beam, measured at the 90% contour, 2 m downstream from the source was found to be 0.34π mm-mrad. Arc power in this case was $\simeq 3.7$ kW and the H_2 flow was 10 std cc/min. The current is observed to be stable to $\pm 2\%$ over periods of 6 hours.

A 1.3 metre long injection line transports the beam from the source to the inflector. Beam-line optics along this line consisting of a solenoid and a quadrupole doublet, have been optimized together with the inflector to match the beam to the cyclotron[3,5].

4. THE CENTRAL REGION

In designing the central region we have tried to maintain good centring for a large phase acceptance, while leaving clearance around the median plane posts for the radial phase space. Special attention was paid to obtaining high energy gain on the first turn to reduce space charge effects, while obtaining small phase dependant centring errors to avoid coherent emittance broadening. 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 10 mm except in the injection gap region where it has been cut to 7 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 centre line of the first dee at $\tau = 0°$ ($\phi = 0°$). This corresponds to a starting time of $\tau_0 = 41°$. In Fig. 2 we have shown rays starting at $\tau_0 = 21°, 31°, 41°, 51°$, and $61°$, superimposed on the equipotential plot of the electric field. The central ray has almost no centring error at turn 10 (2 MeV). The maximum centring error for the other phases in the $\pm 20°$ phase band is 1 mm and the centring errors are well grouped together in x, p_x space.

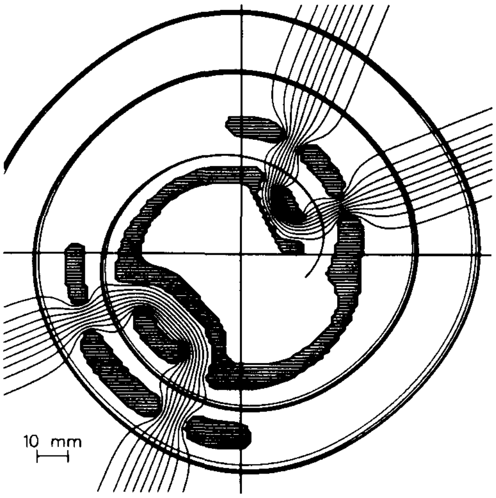

Fig. 2. Orbits of rays with 5 different starting times. Also shown are the central region electrodes in the median plane and the equipotentials of the electric field.

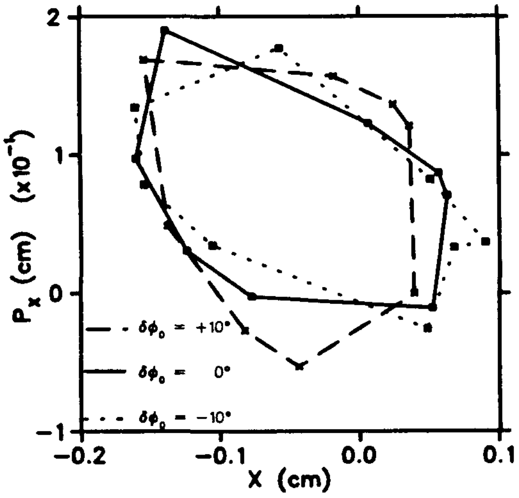

Fig. 3. Horizontal phase space for three phases after ten turns.

Figure 3 shows the horizontal phase space for three phases, after 10 turns. As can be seen, if we start with an emittance of 0.37π mm-mrad there is little distortion of the ellipses, and the phase dependent effects are small. This allows for good horizontal matching of the beam, which in turn reduces the momentum spread. On the first turn the vertical electric forces have a much larger effect than the horizontal ones so the phase dependent effects are much larger in the vertical plane. This makes the vertical match much more difficult. Nevertheless we have found a solution where the global vertical envelope is fairly uniform and the beam is everywhere contained within half the vertical aperture.

5. EXTRACTED BEAMS

The simplicity of extraction is of course the main attraction of H$^-$ cyclotrons. It 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 very nearly linear and 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, shows the beams to be well behaved and easily accommodated in a planned 7.5 cm diameter beam pipe.

As illustrated in Fig. 1, two extraction probes in opposite hill gaps produce two external beams exiting through opposite valleys.

6. PRESENT STATUS

Design of the cyclotron is well advanced. Orders have been placed for a number of major components, including the rf amplifier, magnet power supply, and magnet coils with delivery of all these items expected near the beginning of July 1989. Machining of the magnet steel is in progess. Design of the inflector and central region electrodes is complete and machining of these components will begin soon. A shuttle coil magnetic field mapping system based on the system developed at MSU[4) has been borrowed from Texas A&M and is being adapted to our magnet.

A very tight schedule, calling for two external beams with a total of 250 μA, by mid 1990, has been set for construction and commissioning of the cyclotron. To assist in any development problems, particularly those related to achieving high beam currents, we are building a central region model, since it is the injection optics and central region where limitations to the accelerated beam currents will occur. Fabrication of the magnet for this model is complete, and work is proceeding on the dees and injection line components. First beam measurements on the model are expected in July 1989.

7. DESIGN EXTENSION TO 70 MeV

For some isotope production reactions, as well as for a medical ocular melenoma irradiation facility, higher proton beam energies, say up to 70 MeV are required. As an example, for the production of the strontium/rubidium generators required for PET heart imagining, measurements at TRIUMF and elsewhere have shown that 70 MeV proton irradiation of ^{85}Rb yield .18 mCi of ^{82}Sr per microampere-hour. A cyclotron with a 200 μAbeam would therfore be capable of producing at least one generator every three hours, or easily supplying the current ^{82}Sr demand of 400 mCi per month.[6)

Many of the present 30 MeV H$^-$ cyclotron design features can easily be extended to 70 MeV. To avoid electromagnetic stripping of the H$^-$ beam it is necessary to reduce the average magnetic induction to slightly less than 1 Tesla. For a four sector design with 30° hills, a 60 mm hill gap, and a 200 mm valley gap adequate focusing is achieved without spiral edges on the hills. A preliminary design has a magnet with an outer dimension of 4 metres, a pole diameter of 2.8 metres, and a weight of 125 tonnes. The operating frequency would be 53 MHz, the fourth harmonic of the orbit frequency.

Table II summarizes some of the preliminary design parameters of a 70 MeV H$^-$ cyclotron.

Table II. Preliminary Design Parameters of a 70 MeV Cyclotron.

Magnet	
B_o	.87 T
Bmax	1.6 T
Hill gap	40 mm
Valley gap	390 mm
Pole diameter	2.8 m
Number of sectors	4
Weight	125 tonnes
RF	
Frequency	53 MHz
Harmonic	4
Ion source	
Type	H$^-$ cusp

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