FIRST BEAM IN A NEW COMPACT INTENSE 30 MeV H^- CYCLOTRON FOR ISOTOPE PRODUCTION

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Abstract

A new high intensity, 30 MeV H^- cyclotron has been constructed for radioisotope production. It is a four-sector radial ridge design with two 45° dees in opposite valleys. An external multi-cusp dc source developed at TRIUMF generates the H^- beam for injection into the cyclotron. Beam extraction is by stripping to H^+ in thin graphite foils. Two multiple foil stripper mechanisms produce two simultaneous external beams, of intensities up to 200 μA. Adjustment of the extraction foil position permits extracted beam energy variation from 15 MeV to 30 MeV. Results of magnet field mapping, vacuum, high power rf and beam tests will be described. A 30 MeV beam of intensity in excess of 250 μA has already been extracted along one beam line. On opposite beam lines two beams, one of 140 μA the other of 164 μA, for a total in excess of 300 μA, were simultaneously produced.

1. Introduction

The 30 MeV cyclotron (TR30) which is being built for isotope production by Ebco Industries Ltd. with the technical and design assistance of TRIUMF achieved first beam on May 9, 1990, within 17 months of project startup date. The basic specifications for the cyclotron [1-3] call for two external beams of current up to 200 μA and energy variable between 15 MeV and 30 MeV, with a total maximum beam intensity of at least 350 μA. More than 300 μA have already been extracted to date.

Figure 1 shows the cyclotron as it was undergoing commissioning tests recently. Design features are more readily apparent in the schematic view given in Fig. 2. The cyclotron 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, so that four hydraulic jacks located at the corners of the yoke can elevate the upper part approximately one metre to allow access to the cyclotron interior. Two coils 37500 A-turn each mounted on the upper and lower poles provide the magnet excitation. Because of the fixed field operation, all magnetic field corrections were made by shimming during field mapping. No trim coils are needed.

Fig. 1. The 30 MeV high intensity compact cyclotron.

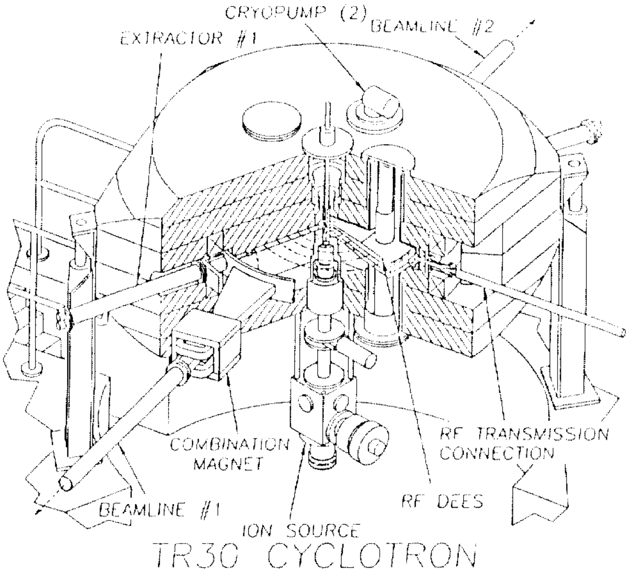

Fig. 2. Schematic view of the cyclotron.

Head room requirements in the cyclotron vault are minimized by installing the external H^- ion source and injection line below the cyclotron. This arrangement has the additional practical advantage of avoiding 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 73 MHz, the fourth harmonic of the orbit frequency. The dees operate in phase.

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 20 cm diameter cryopumps are installed.

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.

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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	73 MHz
Dee voltage	50 kV
Harmonic	4
Vacuum	
Pressure	6×10^{-7} Torr
Pumping	4000 ℓ/s (H_20), 1500 ℓ/s (air)
Ion source	
Type	H^- cusp
Output current	7 mA
Emittance (normalized)	0.34π mm-mrad
Bias voltage	25 kV

In order to test, at an early stage, the design of critical centre region components, a full scale model of the TR30 centre region was also built. A stable beam intensity of 650 μA was measured at the fifth turn (1 MeV). This work is described in another paper presented at this conference [4].

2. Magnet

Initial magnet design calculations were done with the two-dimensional magnet code POISSON and were subsequently refined using the three-dimensional code TOSCA. To avoid the $\nu_r = 2\nu_z$ resonance, the top surface of the hills were sculpted to reduce the flutter slightly and the hill width adjusted to achieve isochronism. The calculations achieved a field that was isochronous to better than 50 G at all points. A template was then prepared according to the calculated hill profile and used to machine the surface of the hills.

The magnet, first energized on August 4, 1989, achieved full field without difficulty. A shuttle coil field mapping system [5], borrowed from Texas A&M University and modified to suit the magnet, was used for the field mapping. Initial data indicated that the magnetic field was within 200 G of isochronism at the worst point, and within 50 G over most of the magnet. In fact the largest discrepancy was at the centre of the machine where four mounting holes, for central region components, had been drilled in the pole tip surfaces. This was rapidly corrected by raising the centre plug pole tips by 1 mm. The field was then within 50 G everywhere. Shimming was accomplished by varying the thickness of plates attached to the hill edges. Initially many small plates screwed onto a larger base plate were used. Once a reasonably isochronous field was achieved, this shape was used to cut a single plate for each hill edge. This procedure turned out to be extremely predictable and reliable. After shimming the magnetic field was isochronous to within ±5° of rf phase. Reproducibility of the average field was better than 2 G after opening and closing the magnet. The tune diagram, calculated from the measured field data shows that the $\nu_r = 2\nu_z$ resonance has actually been avoided. Small imperfection harmonics, generated by small rf liner attachment holes drilled in the pole faces, were overcome by using composite studs in the holes. Custom made studs were designed so that the part of the stud below the hill face was steel and the part above was made of stainless steel. This reduced the first and second harmonic amplitudes to below 4 G everywhere.

3. RF System

The rf power is delivered to the dees through a motor tunable capacitor coupled to the 50 Ω transmission line that passes through a port in the vacuum tank wall. A tuning capacitor, located at the back of the dees and having actuators that pass through ports in the vacuum tank wall, provide a tuning range of 200 kHz for dee voltage balancing and resonance control. For ease of maintenance the entire rf amplifier system, which will consist of two combined 25 kW FM transmitters modified for operation at 73 MHz, is located outside the cyclotron vault.

Figure 3 shows the two dees being installed in the magnet. All copper surfaces of the dees, resonator stubs, and valley liners are water cooled to assure stable rf operation. Cooling water lines enter from the lower resonator so magnet opening is possible without disturbing the cooling circuits. The measured Q of the dee-resonator system is 5200, and the rf power necessary to establish the specified 50 kV dee voltage is 19 kW.

4. Ion Source and Injection Line

A compact version of the TRIUMF dc volume H^- multicusp ion source [6] has been tested. To reduce arc power the extraction electrode aperture was enlarged 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 ±2% over periods of 6 h.

A 1.3 m 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 [7]. Because of the intense bright beam available from the source no bunching is required.

5. Extraction and Diagnostic Probes

The simplicity of extraction is of course the main attraction of H^- cyclotrons. It is achieved by passing the H^- beam

Fig. 3. View of the dees in opposite magnet valleys.

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 port. For an extraction foil locus that is very nearly linear and located in a hill gap, 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 at the combination magnet location outside the magnet yoke.

Two diametrically opposite extraction probes, each carrying a five foil carousel of graphite foils, pass through 15 cm diameter holes in the magnet yoke and vacuum tank port, into the respective hill gaps. The probes are remotely adjustable in radial and transverse direction for energy variation and steering into the extraction beamline.

For magnetic symmetry there are two additional 15 cm holes opposite the two other hills. One of these is used to accommodate a water cooled radial diagnostic probe. As an injection diagnostic a pop-up probe to intercept the fifth turn is installed in a valley.

6. Control System

The control system, which is totally automatic and computer controlled, is based on an Allen Bradley PLC for monitoring and controlling individual power supplies and switches. These are connected by means of a proprietary communications network to two 20386 PCs with a 60 megabyte hard disc and running at a clock speed of 25 MHz.

Operator interaction is achieved by using a modular software program called Control View supplied by the same company. It controls all screen (mouse) and keyboard input/output and manages the multitasking operating system. It also maintains a current value database and is capable of interacting with up to 10,000 I/O points in the system.

Two 14 in. high-resolution color monitors are used to display a series of graphic screens on which the operating values of all of the power supplies, the states of switches and valves, and the readings of all relevant water flows, vacuum pressures, and temperatures in the system can be viewed.

Separate crates containing PLCs are used for the safety systems, target monitoring, and ion source control units. The latter, which is at a potential of 25 kV with respect to ground, is accessed through a fibre optical cable serial data link. The control program includes an RS 232 driver system and is thus capable of communicating with serial devices.

The system is easy to program and operate, and it is not difficult to write macro routines to simplify control and tuning procedures. As well as the built-in application packages other application routines have been written using the C-toolkit provided with the software. Microsoft C can also be used to create routines that will run in the multitasking environment.

7. Commissioning

Commissioning of the TR30 cyclotron has proceeded rapidly as components have been completed. The vacuum system has achieved a base pressure of 8×10^{-8} Torr and typical operating pressure with beam is 6×10^{-7} Torr. Initial tests began with beam blockers at 1 MeV. Quite quickly an injection line tune was demonstrated that gave 200 μA at 1 MeV. The measured transmission efficiency from the ion source up to 1 MeV is 8% for a dee voltage of 49 kV and increases to 12% for a dee voltage of 51 kV. The beam blockers were then removed and 1 μA of beam was accelerated to full radius. Checks performed with a radial probe showed that there was better than 95% transmission between 1 MeV and 32 MeV.

Following these tests we installed the two stripping foil mechanisms. By performing shadow measurements with the two strippers and the diagnostic probe, we verified that the beam was centered to within 4 mm. This also verifies that the maximum energy is greater than 30 MeV. As soon as a target became available we began extracting 30 MeV and in a matter of hours we had beam current in excess of 100 μA on the target. On June 6 a 30 MeV beam of intensity in excess of 250 μA was extracted from the machine (with 230 μA reaching the production target system), a major milestone in a tight 18 months design and construction schedule. On June 7 two beams of 164 μA and 140 μA were simultaneously extracted on opposite beam lines, with a total beam intensity in excess of 300 μA being accelerated. For these tests only one of the two transmitters was used, powered to 28 kW. The losses in the cyclotron were very low and small losses in the beam line were mainly at the protection slits which had been deliberately set to form a tight restriction for setup purposes. The commissioning team was pleased to find that most settings lie very near the calculated values. The rf system, the vacuum system, the extraction stripper and the control system have behaved extremely well so far. Overall component stability is very good.

Future commissioning work will aim at reliable high intensity operation with minimal operator intervention and extraction at several combinations of energies. It is expected that Nordion International who contracted the cyclotron and its building as a turn-key facility to Ebco, will be able to start isotope production on or before August 1, as originally planned.

Acknowledgement

This isotope production cyclotron is the first cyclotron produced by Ebco and is an important example of technology transfer for TRIUMF. TRIUMF and Ebco would like to thank all those who have contributed to this 18 month endeavour with ideas, suggestions, hard work or support. A particular thanks goes to those colleagues from the international community who have given useful advice during design and construction.

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