OPERATION AND PERFORMANCE OF A COMPACT, ISOCHRONOUS CYCLOTRON

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Summary

The apparent need for an inexpensive, reliable, and easy-to-operate cyclotron for isotope production, trace element analysis, and nuclear medicine has led to the design and construction of a 30-inch AVF cyclotron. This cyclotron has accelerated very stable beams of protons to 15 MeV, deuterons to 8 MeV, He^{3++} to 20 MeV, and alpha particles to 16 MeV. External beam currents in excess of 50 μA have been obtained for protons and deuterons. The required magnetic field for acceleration of all four particles is attained in a three-sector configuration without the use of profile coils. Two 120° dees provide an energy gain of 100 keV per turn. The ion source, using ion-heated cathodes instead of the usual hot-filament, has allowed internal beams of more than one mA of protons and deuterons to be accelerated to full energy. A 30 μA external beam of 15 MeV protons has also been obtained by accelerating and stripping H^- ions.

Introduction

The rapidly increasing importance to biomedical research of cyclotron-produced isotopes; the need in modern metallurgy for charged-particle activation in the determination of concentration of lighter elements such as carbon, oxygen, and nitrogen; and the requirements of universities for tools with which to train future scientists in both the principles of nuclear structure physics and the use of modern research equipment have led us to design and build this compact, 30-inch cyclotron. It has been engineered for day-to-day use, with minimum maintenance. This machine is self-contained, requiring only standard commercial electric power and tap water for its operation. Automatic frequency control, solid-state stabilized power supplies, and fully interlocked controls assure simple and dependable operation with a minimum of operator training.

The power requirement is only 150 kVA at 480 volts and 25 kVA at 115 volts. Ordinary tap water at a flow rate of 35 gal/min (except in the case of unusually high mineral content) is required for cooling. This machine weighs about 15 tons and occupies a space of 7 x 7 x 9 feet. It has been constructed following a modular design technique (see companion paper No. G-15) which makes it easy to service and reduces the chance of obsolescence. Figure 1 shows the general construction of this cyclotron.

Description

Magnet

The AVF field is produced by three 45° hills which gradually increase in angular width to 60°. No profile coils are used as the proper radial profile is obtained by shaping the hill iron. The radial profile is maintained to an accuracy of about one part in 10^3. A set of three harmonic coils has been installed at about 12.5 inches radius to aid in maximizing extraction efficiency. The power required for these three harmonic coils is only a few hundred watts.

The magnet yoke legs are bolted to the lower yoke piece, but the upper yoke piece is set in place and positioned by dowels. The upper yoke piece, pole tip, and coil can be quickly lifted by hydraulic jacks for access to the accelerating region. Figure 2 shows the machine in its opened position.

The magnet coils each consist of two anodized-aluminum foil pancakes separated by an electrically insulated cooling manifold. The two pancakes are epoxy cast to form a rugged mechanical assembly. The magnet power supply is completely solid-state and provides current regulation to a few parts in 10^5.

Vacuum System

The vacuum tank is a simple aluminum enclosure sandwiched between the magnet pole pieces. Rubber O-ring seals are used. The vacuum pumping system includes a 21 ft^3/min mechanical pump and a 10-inch oil diffusion pump. A room temperature baffle has been included between the diffusion pump and the tank to reduce back-streaming of diffusion pump oil into the vacuum tank. A liquid nitrogen trap is also included to reduce pump-down time after the cyclotron vacuum system has been open to atmosphere.

RF System

The acceleration system uses two 120° dees operating at nominal potential of 30 kV to ground, thus providing approximately 100 keV gain per turn. The RF system operates at fixed frequencies of 24 Mc for protons, 13 Mc for deuterons and alpha particles, and 17 Mc for He^{3++} particles. A movable panel allows these frequencies to be changed over a small range. Frequency is stabilized to one part in 10^5. A detailed description of the RF system is contained in companion paper No. C-15.

Ion Source

The ion source used in this machine is of the P.I.G. type, using ion-heated cathodes. This relatively simple source was chosen both for its small size and for its simple and dependable operation. A complete description of this source can be found in companion paper No. B-6.

Extraction System

The beam is extracted from this cyclotron by means of an electrostatic deflector located between the dee stems (Fig. 3). A tungsten septum, notched to reduce spot heating, is spaced 3/16 inch from an Inconel deflector bar which is operated at a negative potential of 60 kV. This 12-inch-long electrostatic channel is followed by a weak, horizontally focusing magnetic channel. The beam emerges from the cyclotron in a direction normal to the magnet yoke orientation. No remote positioning of this system is required.

Controls

Controls and instrumentation for this machine are contained in a 50-inch-high, three-rack console (Fig. 4). The controls are interlocked to provide almost "foolproof" operation. Metering is provided on the console for all components of the cyclotron.

Operation

This cyclotron has been in day-to-day operation for about four months. It has provided very dependable operation throughout this period with no major component failure. It has been operated for several hours with internal beams of 30 to 50 μA, and beam intensity has been demonstrated to remain steady within a few per cent over this period.

Turn-on of the cyclotron can be accomplished in less than three minutes unless the vacuum system has been open to atmosphere since it was last operated. In this case, it has been found necessary to "bake in" the RF system for about 30 minutes before stable operation is obtained. An automatic cycling system has been provided as part of the cyclotron control system to aid in this "bake-in" process.

Internal beams of all four particles with exceptionally good quality and with intensities of 50 μA or more were obtained within two weeks after final assembly of the machine. Thus, most of the subsequent effort has been devoted to the extraction of the beam from the cyclotron. The original extraction system, which was built into one of the dees and used the RF voltage to aid in extraction, was discarded because the sweeping of the beam by the RF voltage resulted in a larger horizontal width of the beam at the exit port than was desirable. In addition, the RF peak voltages made it difficult to hold sufficient average voltage on the deflector for efficient extraction of a proton beam. The present system, described previously, is isolated from the RF system, and these two difficulties have been eliminated. However, because we do experience considerable defocusing of the beam by the fringe field of the magnet, we have found it necessary to add a horizontally focusing magnetic channel about 16 inches long.

Performance

The 30-inch cyclotron has produced internal beams of over one mA of both protons and deuterons and several hundred μA of He^{3++} and alpha particles at full design energy. All four particles have been extracted from the machine with efficiencies approaching 50 per cent. At present, the external beam has an emittance of 50 mm-mrad vertically and 100 mm-mrad horizontally at the extraction port, and development is continuing to improve this performance.

In addition, an external 30 μA beam of stripped negative ions has been obtained at full energy. The following table lists the guaranteed performance for this cyclotron.

TABLE I

Guaranteed Performance

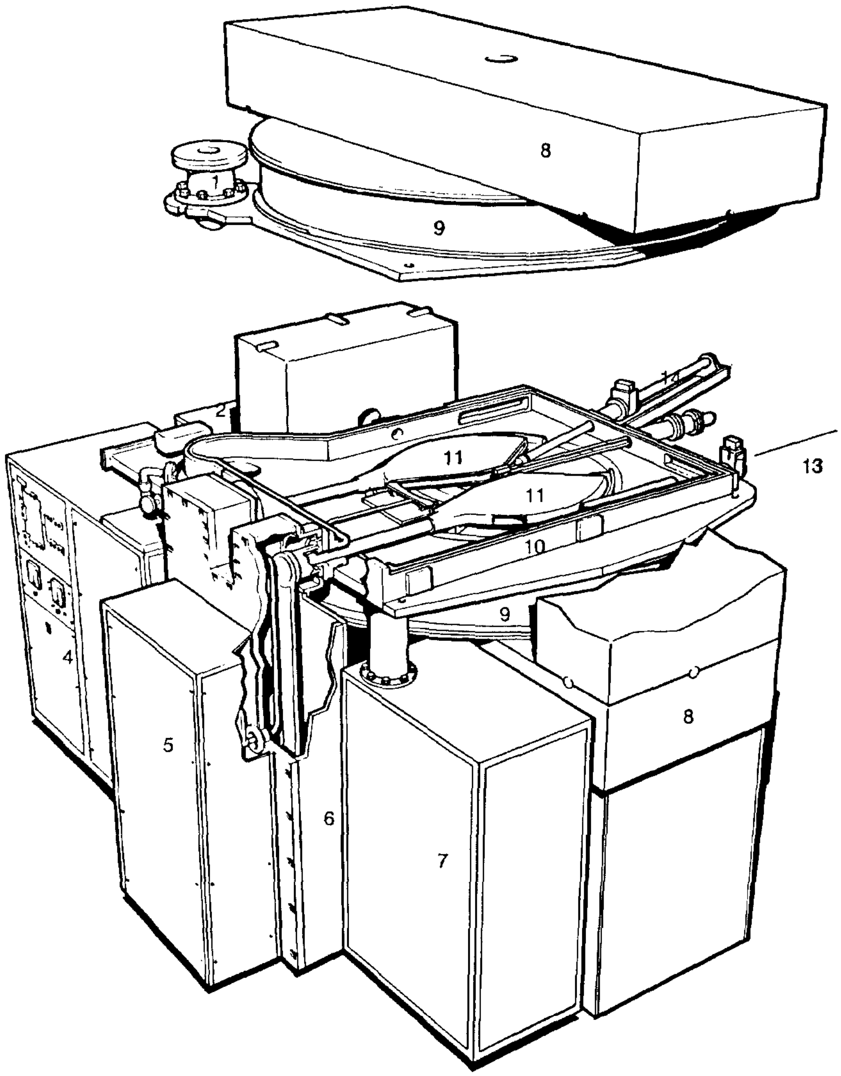
Beam Energy	Protons	15 MeV
	Deuterons	8 MeV
	Helium-3	20 MeV
Beam Energy Resolution	1% FWHM	
External Beam Intensity	50 μA	
Beam Diameter at Exit Port	0.5"	
Beam Divergence	50 mrad	

Actual performance normally exceeds these guaranteed ratings. In addition, helium-4 ions may be accelerated to about 15 MeV.

Conclusion

This cyclotron will be installed at the Sloan-Kettering Institute for Cancer Research located in New York, New York, and will be used to produce short-lived isotopes for use in cancer research. Present plans call for the shipment of this machine to Sloan-Kettering in April of this year and full operation of their facility within three months of that time.

A second machine will be installed at Duke University in Durham, North Carolina, and is now nearing completion. This machine will be modified from the one described here by the addition of an external ion source and an axial injection system. This cyclotron will provide an extracted beam of negative hydrogen ions at 15 MeV and will be used by Duke University as an injector for a two-stage model FN tandem Van de Graaff. The combination of the fixed-energy cyclotron and the tandem accelerator is expected to yield protons with an energy range between 3 and 30 MeV with an energy resolution of 0.1 per cent.



1 Liquid Nitrogen Trap
2 Helium-3 Recovery System
3 Radial Ion Source
4 Vacuum System
5 Oscillator
6 Resonator Tank
7 Extraction Power Supply
8 Magnet Yoke
9 Magnet Coil
10 Vacuum Tank
11 Dee
12 Beam Exit Port
13 Beam Line
14 Beam Probe

Fig. 1. Cyclotron Assembly.

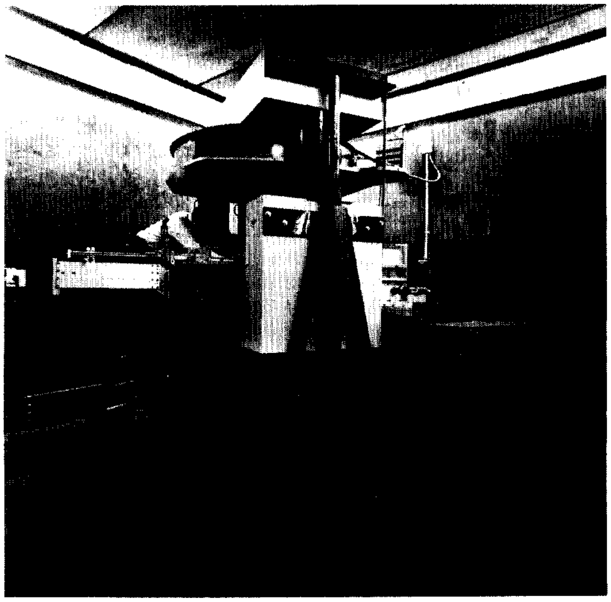


Fig. 2. Cyclotron in Open Position.

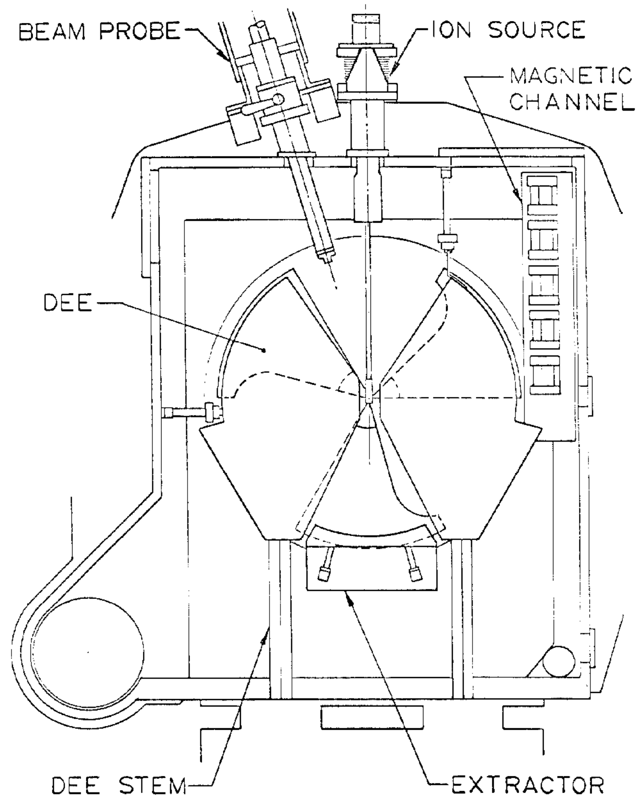


Fig. 3. Sketch of Extraction System.

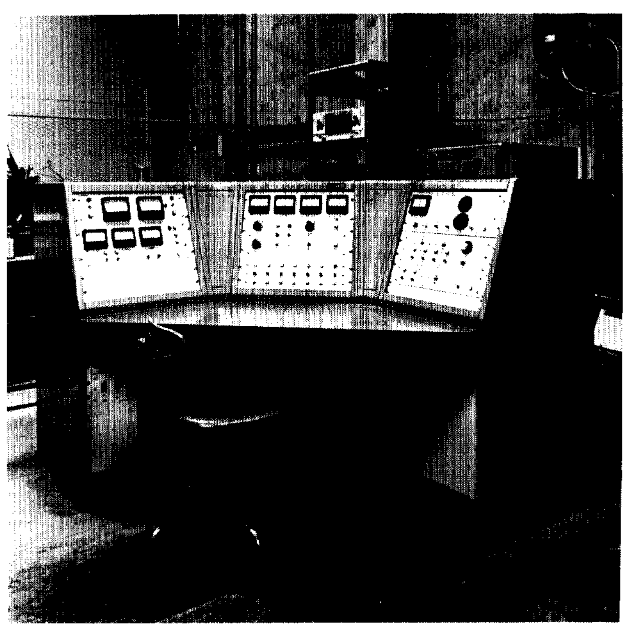


Fig. 4. Control Console.