DEVELOPMENT OF NEGATIVE ION CYCLOTRON (CYPRIS-HM18)

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Summary

A 18 Mev H^-, 10 Mev D^- cyclotron and radioisotopes production system (CYPRIS-HM18) for PET (Positron Emission Tomography) diagnosis has been developed in Sumitomo Heavy Industries, Ltd. This system has the following features;

1. Automated functions.
2. High production yield for various labeled compounds synthesis.
3. Economically profitable machine.
4. Easy maintenance.
5. Low electrical power consumption.
6. Flexibility for further development of synthesis system.

This in-house cyclotron which delivers 70 μA of protons and 50 μA of deuterons was already beam tested at the test shop in the factory and shipped to customers site.

Introduction

PET diagnosis has made marked progress developing various labeled radioactive compounds. CYPRIS-HM18 is the system which is used for both clinical use and new labeled compounds development use. The HM18 cyclotron can deliver relatively high energy particles so as to get enough yield of the radioisotopes(C-11,N-13,O-15,F-18). By adopting negative-ion acceleration, operation of the cyclotron becomes simpler and activation of the machine is reduced. D^- acceleration, which is used to generate O-15 gases and water, saves the cost of target gas in comparison with proton machine. Two ports simultaneous irradiation is available for the efficient operation of the system. There are two versions of HM18 cyclotron. One is equipped with an internal ion source described in this paper. The other is equipped with an external ion source which delivers more than 200 μA of protons for industrial use.

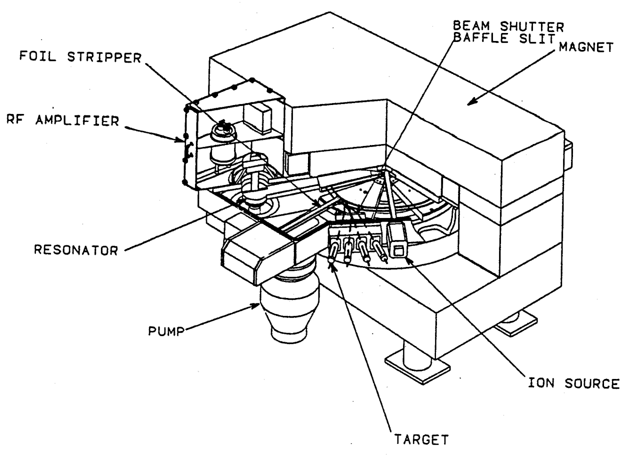

Fig. 1 A bird's-eye view of HM18 cyclotron

Characteristics of the cyclotron

The specifications of the cyclotron are summarized in Table 1.

Electromagnet

The electromagnet is of a frame-type to facilitate maintenance of the cyclotron inside. To reduce electric power consumption of the coils compared with our positive ion cyclotrons, sector gap is reduced to 36 mm and dee electrodes are placed in the valley. Magnetic structure is the same for the internal and the external ion source version except axially injection part. The mean field is chosen to be 1.5 T level so as to locate a spiral inflector and a connection part of the 2-dees, and there is a pair of center plugs to put the inflector or the internal ion source instead of extending the sector shape of the magnet toward the center. So, the center region is mechanically rather

Table 1
Specifications of the cyclotron

Beam		
Particles	H^-	D^-
Energy(MeV)	18	10
Accelerating harmonics	2	4
Beam Current(μA)	70	50
Number of beam ports		max 8
Electromagnet		
Number of sectors		4
Pole diameter(mm)		1080
Hill gap(mm)		36
Valley gap(mm)		154
Mean magnetic field(kG)		14.9
Magnetmotive force(AT)		92000
Electric power of main coil(kW)		24
Number of trimming coils		4
Size(m)		2.2x1.2x1.4
RF		
Number of dees		2
Dee angle(deg)		35
Dee voltage(kV)		35
Frequency(MHz)		45
Power Tube		4CW25000 x 1
RF power(kW) (without beam)		7
Ion source		
Type		PIG
Location		internal
Insertion		horizontal
Filament		no
Adjust		x,y
Extraction		
Type		graphite foil C-shaped flame mounted
Number of foil cassettes		2
Adjust		R, θ, α
Two sides simultaneous beam		yes

complicated. Four-pairs of circular trimming coils are installed on the pole pieces to produce isochronous field of H^- and D^-. The sector shape was determined from 2-dimensional magnetic field calculation and measurements of the field of a model magnet. A field map measured by a hall probe is shown in Fig. 2 and a mean field integrated along constant radius(not along equilibrium orbit) without trimming coil compensation is shown in Fig. 3. Base field is fitted to mass to charge ratio 1.2 so that magnetomotive force of circular trimming coil can be reduced. The mean field at the center is higher than that at R≒150 mm. This is because the shape of equilibrium orbit is distorted gradually from circle at the center toward rounded square shape at accelerating region.

<u>RF system</u>

Single RF frequency operation adopting 2nd(H^-) and 4th(D^-) acceleration harmonics, makes the system simple. There is no sliding contact in the cavity resonator to get rid of maintenance of contact finger. The cavity resonators are of $\lambda/4$ type and the length of the cavity was determined from full-scale-model cavity test. For saving costs, two dees are connected at the center of the cyclotron and RF power is fed from a single RF amplifier by capacitive coupling. RF power in the cavities without beam load is minimized to 7 kW (3.5 kW each) in the case of 35 kV dee voltage from the reason that capacitance between the dee electrodes and earth plate is very small. Measurement of RF characteristics and RF power test have carried out successfully. Unbalance of RF dee voltage between the two dees was less than 2 % and was negligible for beam acceleration.

<u>Ion source and center region</u>

The internal ion source is a conventionally self-heated PIG type and there is no filament. To generate more negative ions, ion source arc should be heavier and gas pressure inside the source should be higher. To keep gas pressure high inside the ion source and low in the accelerating region, arc space is isolated from accelerating region. To lower the conductance of the ion exiting slit and to get enough beam current, the size of ion extraction slit is optimized to $0.5\ mm^W \times 7\ mm^H$. The anode of the source is made of molybdenum to reduce sputtering caused by bombarding with positive ions and is water cooled. The cathode is made of tantalum. Ion source gas is fed directly to anode center. Ion source position and geometry of center region was determined from 2-dimensional calculations of beam central orbit, beam centering and phase acceptance. Beam orbits for H^- and D^- were calculated by Runge-Kutta-Gill method using measured magnetic field data and calculated RF electric field data. Vertical beam aperture of the dees and the dummy dees at the center is 12 mm for vertical-electric-field focussing. Ion source position is adjustable for acceleration of both H^- and D^-, and for speedy tuning of beam.

<u>Vacuum</u>

Two diffusion pumps (3000 l/sec for H_2) are placed on each side of the chamber. Gas pressure at accelerating region is calculated to be around 5×10^{-6} Torr in the case of 2 cc/min gas flow into internal ion source.

<u>Stripping in accelerating region</u>

Charge stripping of H^- and D^- ions by Lorentz force in the magnetic field is calculated to be negligible. The stripping by gases inside the chamber, however, cannot be neglected for internal ion source version. Ion-source fed gas and outgassing from the chamber wall struck by neutralized ions are assumed to be major factor of stripping loss. To reduce neutral gas load, arc space in the ion source should be isolated from accelerating region by the cylindrical cap except ion exiting slit. Stripping loss is calculated to be around 25%.

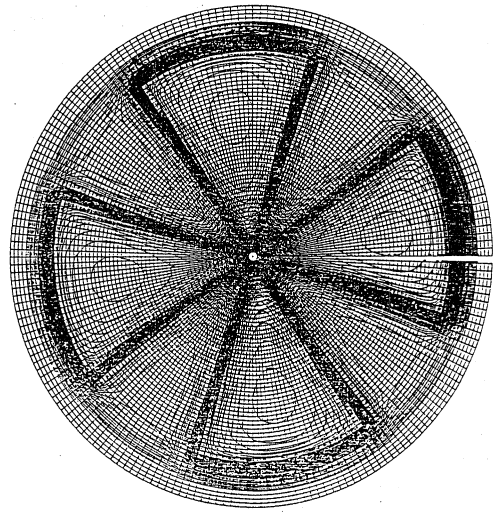

Fig. 2 Magnetic field map with contour interval of 250 Gauss.

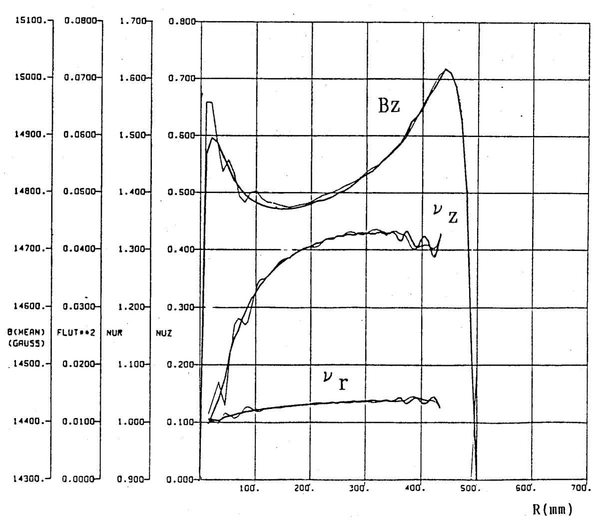

Fig. 3 Base field distribution, ν_r and ν_z. Measured value is shown by thin line and calculated value by thick line.

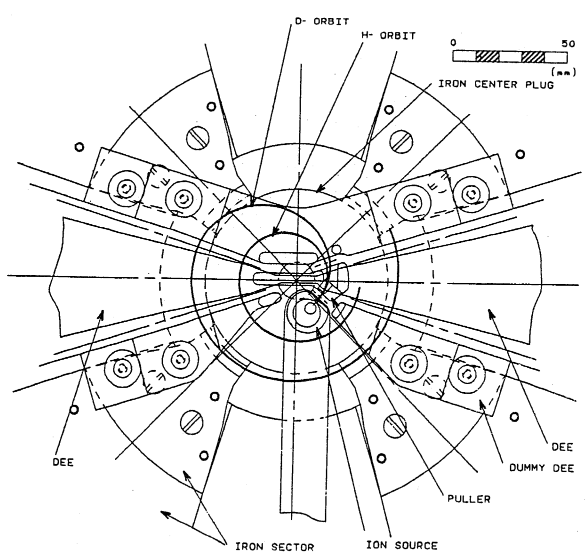

Fig. 4 Center region of the cyclotron.

Extraction

Foil strippers as extractors of accelerated ions are placed between upper and lower iron sectors on both the sides of cyclotron short axis. Because of simple extraction mechanism (polarity change of charge state of accelerated ions by passing through a thin carbon foil), beam position on the target can be directly controlled by adjusting stripper foil position. There is a baffle slit in front of each target, and the stripper foil position is software adjusted by monitoring baffle currents. Tear of a foil during beam extraction is detected by monitoring the current of baffle slit which is located in front of the foil, and in that case, the foil is automatically exchanged.

Beam test

Before negative ion acceleration test, positive ion acceleration test was done. The isochronous field was checked by monitoring the current of a radial integrate-probe and was well established for both the proton and deuteron. Positive ion current level at R=85 mm (6 turns after exiting ion source for proton and 3 turns for deuteron) was 500 μA for H^+ and 800 μA for D^+. These obtained value were high enough comparing with the conventional cyclotron.

After that, negative ion acceleration test started. In early operation, beam transmission from R=85 mm to the extraction radius was measured to be around 60% in the case of 3.5 cc/min gas flow. To reduce ion source gas flow, several types of ion-exiting slits of the source were tested, and finally size of the slit was optimized to 0.5 mm^W x 7 mm^H. Optimum arc position in the source was also searched by changing arc defining slit. Optimization of puller position and shape of puller hole were also carried out. After these trial, transmission between R=85 mm and extraction radius was raised to 70 %. Even though vacuum chamber is made of aluminum, it is important that machine activation by neutralized ions is as low as possible. Further development is planned for lowering machine activation.

Beam extraction test has also been done. Beam size at the bottom of the target measured by alumina monitor was 12 mm^W x 20 mm^H in height. Beam stability is well for routine RI production.

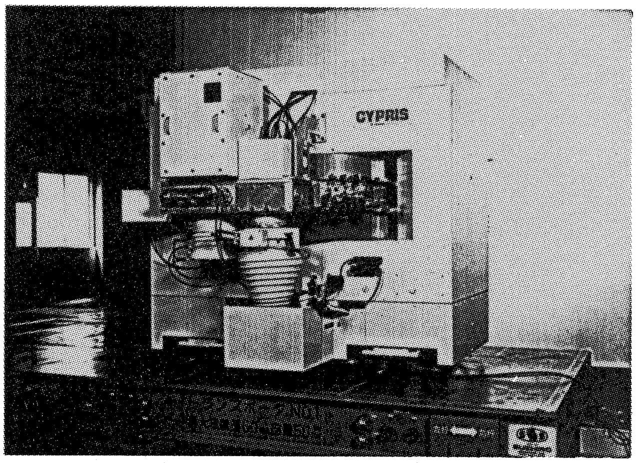

Fig. 5 HM18 cyclotron assembled in the test shop.