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Design Features and Operating Characteristics of the MC–50 Cyclotron

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MC-50 싸이클로트론의 설계 특징과 동작 특성

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Abstract

The MC-50 cyclotron at Korea Canter Center Hospital is now operational for neutron therapy and medical radioisotope production. Design features, mechanical structures and operating characteristics of the MC-50 are described in this paper. Optimum operating condition for this cyclotron has been determined by the repetitive running, and the performances of the internal beam have been investigated through the measurements of intensity and spatial distribution of the internal beam as a function of the radius of the cyclotron. Routinely, the 40 μA of 50 MeV protons have been obtained at first Faraday cup with a extraction efficiency of 61%.

요 약

원자력병원에 설치되어 있는 MC-50 싸이클로트론은 중성자 치료와 의학용 동위원소 생산을 위해 가동중에 있다. 본 논문에서는 MC-50의 설계 특징, 기계적 구조, 가동 특성에 대하여 기술하고 있다. 본 싸이클로트론의 최적 가동 조건은 반복적인 운전에 의해 결정되었으며, 내부 빔의 성능은 싸이클로트론 반경의 함수로서 내부 빔의 세기 및 공간 분포 측정을 통해 조사되어졌다. 일상적으로, 인출효율이 61%일 때 40μA 세기의 50 MeV 양성자 빔을 얻었다.

I. Introduction

The MC-50 cyclotron designed by Scanditronix is a spiral-ridge, isochronous cyclotron intended to give intense external beams of 50 MeV protons, 25 MeV deuterons and 50 MeV alpha particles. This cyclotron is a variable energy machine and the first beam was extracted in January, 1986. Neutron therapy was started in October, 1986 after an extensive work to overcome mechanical and electrical problems inherent in the machine. The facility is at present running on a 6 day/week schedule; three 8 hr treatment days, two isotope production days and one maintenance and research day. The efficiency and the quality of the operation have been improved since the first operation.

The present paper gives the results of preliminary measurements on 50 MeV proton beams. A knowledge on the features of the cyclotron is considered to be important for understanding of the beam characteristics, and therefore, they are described first. A view of the cyclotron facility is shown in Fig. 1.

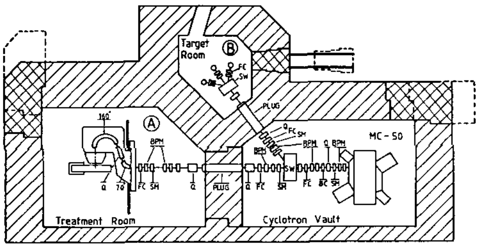

Fig. 1. A View of the Cyclotron Facility.

II. Features of the System

II.1 Magnet

The maximum energy (T) of an accelerating charged particle in a cyclotron can be expressed in terms of charge number, q, and mass number, m, of the particle:

$$T = K\frac{q^2}{m} \text{ (MeV)}$$

The constant K characterizes the magnet, and is given by the average magnetic field (B) and radius (R) of the last particle turn in the cyclotron. In this machine, the K-value is $46.62 \cdot (BR)^2$, where B is in tesla and R is in meter.

The cyclotron magnet which has a total weight of 94 tons is 360 cm long, 155 cm wide, and 236 cm high. The upper, lower, and side yoke pieces are machined from special forgings of low carbon steel. The magnet coils consist of main coil, 10 circular trim coils and 4 sets of harmonic trim coils. The design data for the magnet are summarized in Table 1.

Table 1. Design Values of the MC-50 Magnet.

Pole diameter	143 cm
Min. gap (hill)	11 cm
Max. gap (valley)	19.7 cm
Dimension	3.62m×1.55m×2.36m
No. of sector	3
Spiral angle	max. 55°
Main coil	320 turns, hollow Cu
Circular trim coil	10 pairs
Packing ratio	63 %
Max. current	900 A
Power	126 kW
Max. average field	17.5 kGauss
Min. average field	10.5 kGauss
Max. hill field	20.5 kGauss
Field stability	10^{-5}
Current stability	10^{-5}
Cooling water	90 *l*/min
Water temp. rise	13 ℃
Water pressure drop	4×10^5 Pa
Total weight	94 ton

The 10 concentric trim coils provide the correction required to obtain isochronism for all particles over the whole energy range. A field gradient is added or subtracted from the base field over a radial width corresponding to the width of each coil. The coil No.1 provides correction to the central field shape and the coil No.9 has the special purpose of adjusting the extraction radius of the beam. The coil No.10 adds a field to the internal region from the center to the extraction radius and at the same time, reshapes the fringing field, and therefore it affects the direction of the extracted beam. The harmonic trim coils provide corrections for the first harmonic imperfection components in the magnetic field[1]. Inner 3 harmonic coils serve as a means to centre the internal beam and outermost harmonic coil is used to excite coherent oscillations of the beam, which are required to obtain an efficient extraction. The harmonic coils located in the valleys are wound from round conductors on frames of aluminum. Insulation is provided by a double layer of temperature resistant lacquer and kapton foils, impregnated with radiation resistant Araldite F. Cooling of the harmonic coils is accomplished by the thermal contact to the poles.

II.2 RF-System

The RF-system extracts the particles from the ion source and accelerates the particles to the final energy in the magnetic field. In order to reach the extraction radius of the cyclotron, the particles must be accelerated for 150~450 turns. The turn number depends on the type of particle to be accelerated. The energy increment per turn of the accelerated particle is given by the following expression:

$$\frac{dE}{dn} = 4eV_{Dee}\cdot \sin(\theta_{Dee}\cdot N/2)$$

where

V_{Dee} : dee voltage
θ_{Dee} : dee angle
N : harmonic number

The RF system comprises two identical acceleration units. These two units are located in the middle of the magnet, and facing each other. Each acceleration unit consists of a resonance cavity energized by an RF power amplifier with associated drive amplifiers. Each of the two RF cavities consists of a quarter wave-length transmission line stem, capacitively loaded by the 90 degree dee at the high voltage end. The stems enter the vacuum chamber via ceramic vacuum feedthroughs. Outside the chamber, each cavity consists of two horizontal coaxial stems with a movable short that provides coarse tuning within the frequency range of 15.5~26.8 MHz.The fine tuning of each system is performed by a motor-controlled capacitor facing the dee[2]. The RF power amplifiers are of a grounded cathode type operating in class AB. Eimac 4CW 50,000E[3] power tubes are used. The RF-power is inductively fed to the cavity via a coupling loop. Table 2 shows the design parameters for the RF-system.

Table 2. Design Values of the RF System.

Dee electrode	2
Dee angle	90°
Dee voltage	40 kV
Min. aperture	2 cm
Frequency range	15.5~26.8 MHz
Mode	push-pull, push-push
Dee voltage stability	10^{-3}
Frequency stability	10^{-6}
Inter dee phase stability	1°
Cooling water	80 l/min
Time for frequency change	4 min
Tuning	resonator, flap
Orbit frequency	7.75~26.8 MHz
Energy gain	113, 160 keV/turn
Total power	120 kW

II.3 Ion Source

The central region of the cyclotron consists of the central parts of the acceleration electrodes (dees), the grounded parts (dummy dees), and the ion source. The characteristics of the ion source and the ion optical properties of the central region entirely determine the possibility of obtaining a beam of high intensity and good quality. These allow an efficient beam extraction. The cyclotron can be operated with two acceleration modes: push-pull (N=1) where the two dees are operated with 180° apart in phase and push-push (N=2) where the two dees are in-phase. In each mode of operation, a constant orbit scheme is employed. This means that the trajectory in the central region is independent of the type of particle and energy setting. No mechanical displacement of the ion source is required when varying the energy and the particle species.

The ions are extracted from the source slit close to the median plane by the RF-electric field from the dee electrodes during part of the RF-period. Two arc columns, with an extraction slit, are provided in the source anode for the two acceleration modes. Fig. 2 shows the median plane view of the central region with the design orbits in the first and second harmonic modes.

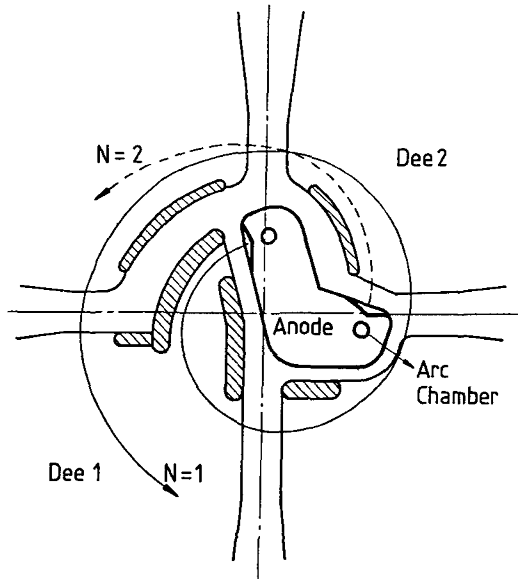

Fig. 2. A Median Plane View of the Central Region.

The ion source is of cold cathode PIG type[4]. The source is inserted vertically from below and above through an air lock, which enables anode, cathodes or extraction slits to be inspected or exchanged without venting the vacuum chamber. The entire ion source is adequately water cooled. The positions of the chimneys are adjustable via an eccentric mechanism. The plasma column is approximately 0.35 cm in diameter and 6.2 cm in length, With LaB$_6$ cathodes[5], it operates at about 560 V with currents of about 35 mA. Gas consumption is approximately 3 sccm. Under this operating condition, lifetimes of LaB$_6$ cathode and anode slit for 30 μA proton beams are about 400 hrs and 600 hrs, respectively.

II.4 Extraction System

The internal particle beam is extracted at a radius of about 58 cm by an electrostatic deflector and an electromagnetic channel. To assist the accelerated particles entering the deflector aperature, the precessional extraction has been employed. This method of extraction enhances the turn separation on passing through the radial integer resonance $\nu_r = 1$[6,7]. When the beam enters the deflector, the off-centering is 5~6 mm.

The first extraction channel is electrostatic and has an azimuthal extension of 45°. The maximum voltage used in the electrostatic deflector is 60 kV which corresponds to a maximum field strength of 133 kV/cm. The septum is carefully shaped to avoid beam losses. The position of the deflector is remotely controlled. For proper conditioning[8] of the electrode surface, the deflector is baked at a pressrue of 2×10^{-5} torr. The second extraction channel is electromagnetic and produces a field reduction of 1.7 kGauss over 35 degrees of azimuth.

After leaving the electromagnetic channel, the beam enters the focusing channels, which are located in the fringing field region. These focusing channels is used to counteract radial defocusing of the beam caused by the negative field gradient of the fringing field. These focusing channels are fixed and passive.

II.5 Vacuum System

The pumping system for the vacuum chamber consists of two diffusion pumps each equipped with a water cooled baffle giving a pumping speed of about 8000 *l* /sec. Diffusion pump for group 1 is backed up by a two stage mechanical pump. A fast acting electropneumatic valve protects the diffusion pump in case of sudden rise in tank pressure. Pumping on the beam line is done with a single oil diffusion pump on the switching magnet and the beam line up to the switching magnet. After the switching magnet, the beam lines are divided in two parts with one oil diffusion pump on each part. Each pump group can be insulated by means of gate valves in the beam line. Fig. 3 shows a schematic diagram of the cyclotron vacuum system, which consists of five sub-groups.

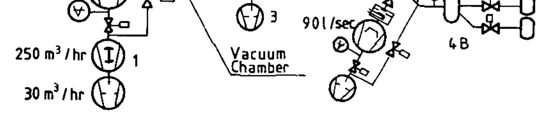

Fig. 3. A Schematic Diagram of the Vacuum System.

The pumping sequences are automatically controlled by a programmable controller and vacuum guards. This system includes monitors for pressure, water flow, temperature etc. The pumping-down time to operation pressure depends on a number of factors. Some of the most important factors are venting time, method of venting, condition of pump oils and dirt and grease from maintenance work. Fig. 4 shows the measured pumping-down curves. The base pressure in the chamber was usually 2.0×10^{-6} torr.

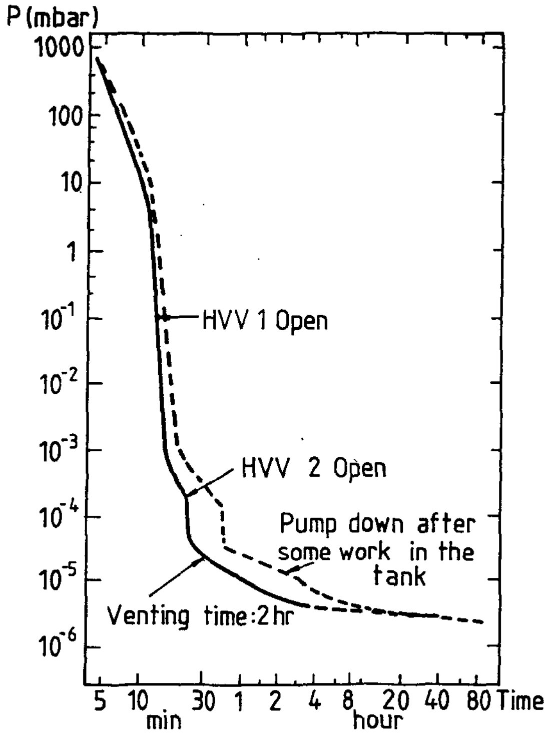

Fig. 4. Pumping Down Curve for the MC–50 Cyclotron.

III. Experimental Beam Observations

The cyclotron is equipped with two probes to aid in tuning up and operation. The main differential probe covers the range from 16 cm radius to the outermost radius and has a maximum 1 kW power dissipation. The second probe is of single head type, and is located after the deflector. It is used to measure the transmission through the electrostatic channel. Fig. 5 shows the internal beam current on the main probe as a function of the arc current of the ion source. As can be seen, the internal beam current increases with increasing the *arc current.*

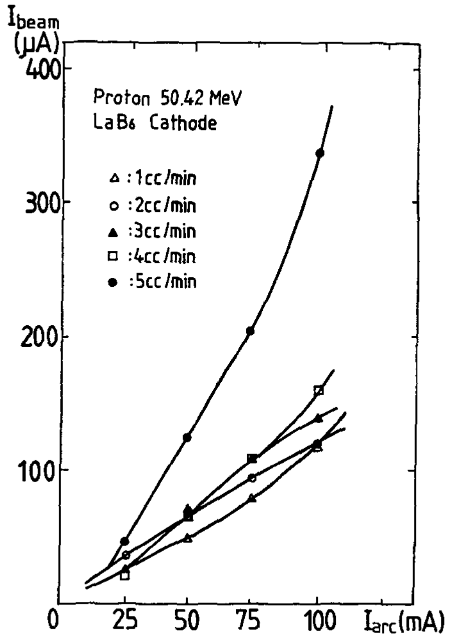

Fig. 5. Beam Current as a Function of are Current at R =20 cm.

The external beam current is limited by overheating of the septum electrode. Normally, *40* µA of 50 MeV proton is obtained stably for 8 hrs without overheating the septum. A plot of beam current vs radius obtained with the main probe is shown in Fig. 6.

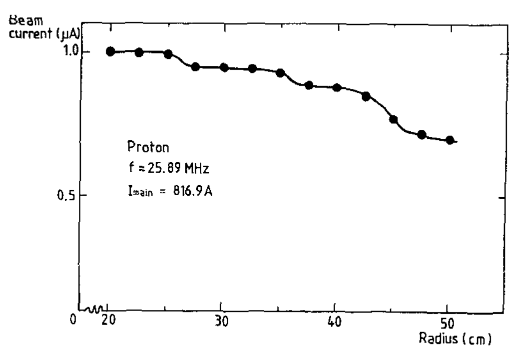

Fig. 6. Beam Current as a Function of Radius.

This attenuation curve is taken after some empirical optimization of main and trim coil currents. This type of curve gives an indication of beam loss at various radii. Also, resonance curves measured at 16.2 cm, 20 cm, 30 cm radii are shown in Fig. 7. As shown by this figure, the main coil current range giving useful beam current decreases with increasing radius. This means that isochronism for the accelerating beam is more and more sensitive as the particle energy increases.

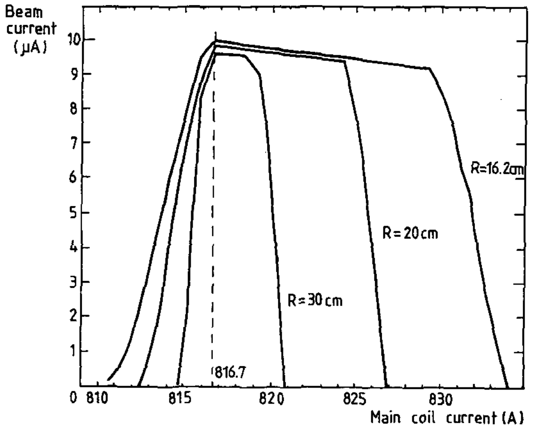

Fig. 7. Resonance Diagram for 50 MeV Protons.

The internal beam distribution inside the vacuum chamber is measured by observing a nylon mesh plate which indicates the burning by the beam. From this measurement, it is confirmed that the vertical extent of the beam is reasonably smaller than the dee and dummy dee apertures, showing adequate vertical focusing. Some runs with the ΔR probe in the MC-50 cyclotron, are shown in Fig. 8.

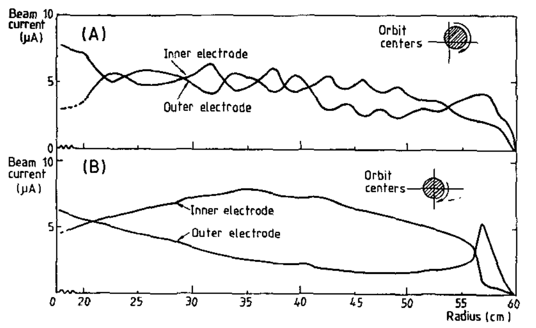

Fig. 8. Beam Current on the Two Electrodes of a ΔR probe

The periodic structure of Fig. 8(a) is an indication of the off-centered beam. Beam centering can be improved with this probe by tuning the trimming coil or harmonic coil. Through the measurement of currents for internal beam at R=40 cm, beam on the first Faraday cup, it is found that the extraction efficiency for the inner beam at the maximum radius is 61 %, and the transmission from exit of the deflector to the first Faraday cup after the first quadrupole triplet is at least 90 %.

The measurement of external beam size is maded by a beam scanner and plastic foil. Beam profile, monitored by a wire scanner[9], showing the beam spot at the first BPM, is shown in Fig. 9. Fig. 10. shows the beam size measured by observing plastic foil being burnt by the beam at the neutron therapy beam line.

IV. Conclusions

This paper has outlined the characteristics for important systems of MC-50 cyclotron and preliminary experimental results. From these experimental results, we can conclude that the beam is well-behaved, and the operation is unusually stable. The 40μ A of 50 MeV protons are obtained without severe difficulty in extraction. The present system shows a good potential for neutron therapy and radioisotope production.

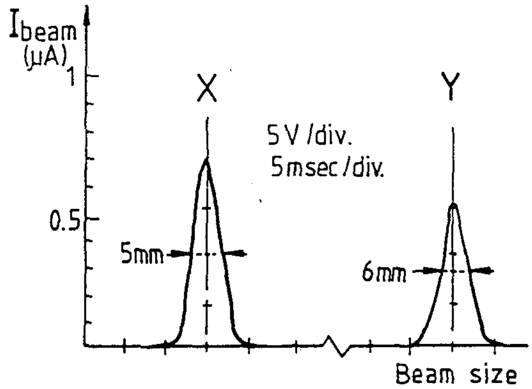

Fig. 9. Beam Profile at the First BPM.

References

1. J.J. Livingood, "Principles of Cyclic Particle Accelerators," D. Van Nostrand, New York (1961).
2. R.S. Livingston and F.T. Howard, Nucl. Instr. and Meth., 6, 1 (1960).
3. Varian Eimac Div. Care and Feeding of Power Grid Tubes (1978).
4. C.B. Mills and C.F. Barnett, Rev. Sci. Inst., 25, 1200 (1954).
5. D.M. Goebel, J.T. Crow, and A.T. Forrester, Rev. Sci. Instr., 49, 469 (1978).
6. M.M. Gordon, Nucl. Instr. and Meth., 6, 221 (1960).
7. M.M. Gordon and W.S. Hudec, Nucl. Instr. and Meth., 18, 243 (1962).
8. L.L. Alston, "High Voltage Technology," p.46, Oxford Univ. Press, London (1968).
9. G. Hortig, Nucl. Instr. and Meth., 30, 355 (1964).

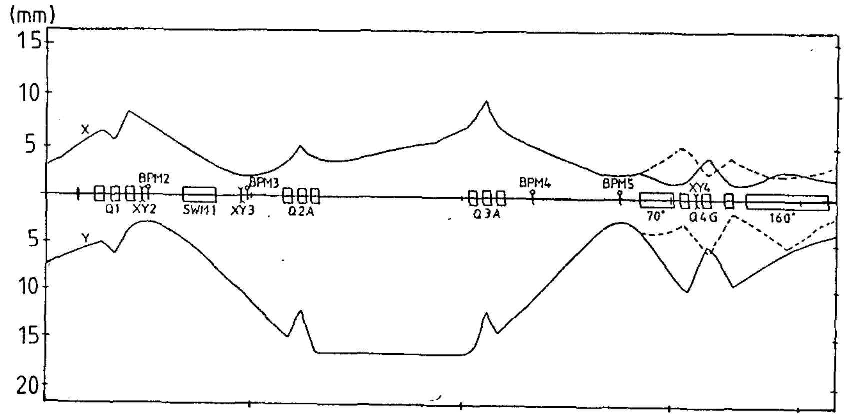

Fig. 10. Beam Size on the Beam Line for Neutron Therapy.