STATUS OF THE NIRS-CHIBA ISOCHRONOUS CYCLOTRON

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Summary

The NIRS-Chiba isochronous cyclotron has been used mainly for the clinical trial of fast neutron therapy and the short-lived radionuclide production since the autumn of 1975. The clinical trial of proton therapy was started in the autumn of 1979. Recently, the machine was upgraded to have a K number of 110 (Q^2/A MeV) for the demand of higher energy particles in the use of biomedical studies. The developments of the machine and the experience on some applications are described.

1. Introduction

During the past twelve years, the maximum energy of particles was increased by two steps. The first augmentation of K number up to 86 from 70 was already reported (1). Since 1979, 70 MeV protons have been used for the clinical trial in which the horizontal beam is scanned over the superficial tumor.

The second augmentation of K number up to 110 was scheduled to extend the application of proton therapy in 1980. Since the magnet and coils were originally designed to have a K number of 110, the corresponding magnetic rigidity is obtained by only the increase in the capability of power supply by 40 %. To determine the parameters for the acceleration of higher energy particles including 90 MeV protons, the magnetic field distribution was measured. The numerical analysis indicated that the axial betatron frequency, νz, was 0.12 for 93 MeV protons at the extraction radius (92 cm). The acceleration of 90 MeV protons has been tested. The resultant parameters through the beam test agree well with the calculated. The construction of the new beam course with a vertical beam of 90 MeV protons was completed last spring. At present, the therapy equipment is being assembled. In near future, the clinical trial will be started.

Since the first beam in 1975, the cyclotron has been regularly operated in a good condition. Major troubles were the growth of cracks on the movable panel in both resonators. The damaged area was replaced and a water cooling was reinforced. Problems to be solved for the stable acceleration and extraction of 90 MeV protons were in the RF system and the deflector. Improvements for the solution of the problems are mainly discussed in this paper.

2. Beam performance

Table-1 lists the present status of the beam performance for high energy particles. The extraction efficiency has been achieved more than 60 % for the most kinds of particles except 90 MeV protons. For 90 Mev protons, the sufficient deflecting voltage could not be applied to the electrode because of frequent discharges. To improve a reliabilty of the deflector, one of three existing deflectors was modified following the design of the IRE (Institute for Radio Elements) machine in Belgium. The material of electrode was changed to copper from stainless steel. The distances between the electrode and both upper and lower ground plates were incresed by a electrode width decrease from 30 to 23 mm. This modification was supported by CGR-MeV. In the preliminary beam test for 90 MeV protons, the extraction efficiency has been improved to 50 %.

Table 1. The beam performance for high energy particles.

Particle	Energy[MeV]	External beam[uA]	η [%]	Application
P	60	5	64	^{123}I
	70	2	74	Therapy
	80	1	80	
	86	1	60	
	90	1	50	Therapy (in future)
D	30	35	80	Neutron therapy
	50	3	65	
$^4He^{2+}$	100	0.1	60	Dosimetry
$^{14}N^{5+}$	157	0.3	90	

3. Development of the RF system

3-1. Coupling loop rotation mechanism

For 90 MeV protons, the tubes must be operated at their almost maximum rating to feed the required power to the resonater. To get easily a good matching between the dee system and the power tube and a good balance of the power between two resonators, a coupling loop rotation mechanism was developed. The detailed analysis of the power tube (TH-120) operation was also made. Although the optimum load impedance is 600 ohm, the imput impedance of the resonator is around 550 ohm at 21.3 MHz. Moreover, the unbalance between two resonators reaches 10 %. This can be corrected by rotating each coupling loop. For one loop, a rotation mechanism was installed and tested. Fig. 1 illustrates a sectional view of this mechanism. It was necessary, so far, to break the vacuum for the rotation of the loop. A remote control system rotates the coupling loop by 30° about a vertical axis to the dee system by keeping a high vacuum. The load impedance varies from 300 to 700 ohm at 21.3 MHz as plotted in fig. 2. Thus this mechanism is useful in obtaining a precise impedance maching during the operation.

3-2. Automatic control

A micro-computer controlled RF system has been developed for a reliability in the operation. The

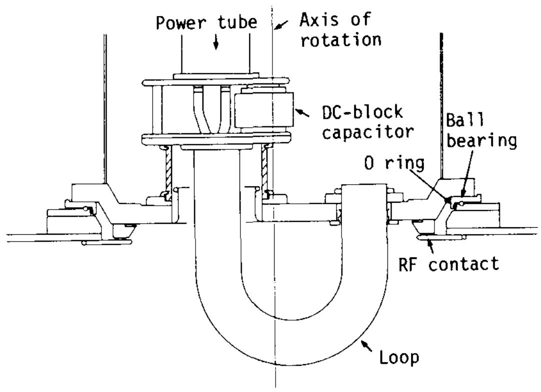

Fig.1 Sectional view of the coupling loop rotation mechanism.

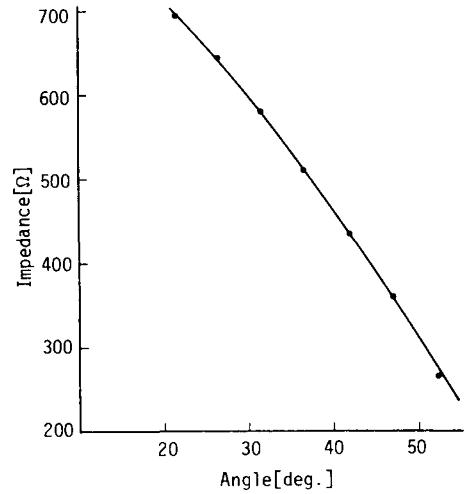

Fig.2 Input impedance versus the angle between loop and dee axis at 21.3 MHz.

automatic pre-tuning systems are already introduced in several facilities. These use an analog technique under the very weak exciting of the resonator (2) (3). We developed a new tuning method in which the resonant frequency was calculated from the resonant curve obtained at a few tens % of the final exciting power in the resonator. Fig. 3 shows the block diagram of the control system. Information of the energy and particle is fed to the computer from a key-board. All of the power supplies are systematically switched on. The resonant frequency of the resonator is preset to match roughly with the operating frequency. The control grid of the tube is excited by 20 % of the final RF power. The frequency synthesizer (master oscillator) is swept around the operating frequency by 100 steps. The sweeping range is selected between 25 and 100 kHz corresponding to the resonator Q-value which depends on RF frequency. During the sweeping, the amplitude of two dee voltages are simultaneously measured by two selective level meters(HP-8568C). The difference of the frequency between the operating and the preset gives the corrected position of the movable panel(tuner). The accuracy of the correction is 0.25-4.0 kHz which corresponds to the phase difference of ± 20° between the anode and grid of the tube. This value is small enough to start a fine tuning by the phase servo loop. After the tuning, the tube is excited by the final RF power. When the dee voltage reaches 95 % of the operating value, the amplitude regulation loop is closed. Then, the phase regulation loop (between two dees) is closed.

To keep a good impedance matching at the grid of power tube, an auto-matching circuit has been developed and tested. The impedance matching adjustment is made by setting the capacitance of the remote controlled variable capacitor. Normally, no trouble due to the mismatching arises at low RF power, but it becomes a severe problem as the power is close to the maximum rating. The control circuit consists of the DC amplifier and the directional RF wattmeters with two plug-in elements. One is to detect the forward power for monitoring, and another the reflected power for feed back to the capacitor. Using this circuit, the reflected power is kept below 2 W. This value is limited by the RF noise. The corresponding VSWR is 1.03 at the maximum input power of 1 kW.

3-3. Pulse operation

In our machine, the maximum power dissipation in the resonator is about 30 kW owing to the limitation in the power loss on the movable panel. The corresponding maximum dee voltage is 35 kV at 21.3 MHz (90 MeV protons). At this dee voltage, however, the radius of the first turn orbit is too small for particles to pass through outside the pillars and the phase slit located in the center region, and many particles are lost. It is very complicated to optimize the tuning of the machine at 35 kV for the routine acceleration of 90 MeV protons. To overcome this difficulty, the RF pulse operation was proposed, which enables us to increase the dee voltage while the power dissipation of resonator is kept within the maximum rating. Since 90 MeV protons are not satisfactorily extracted yet, the preliminary test of RF pulsing was done using 70 MeV

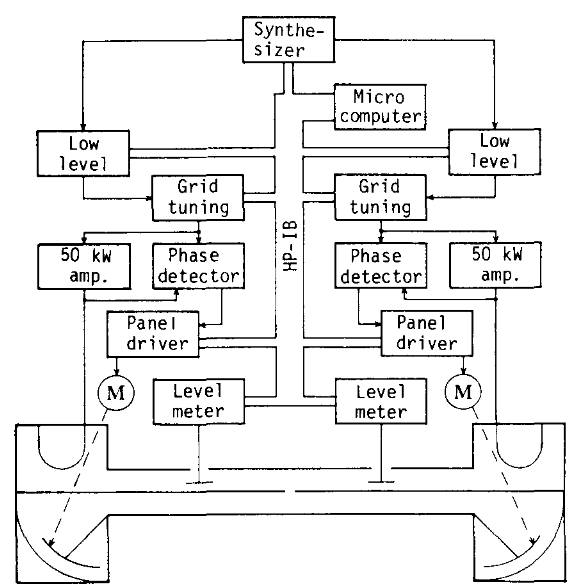

Fig. 3. Schematic of the automatic control system for RF operation.

protons. The first acceleration of 70 MeV protons and the transportation for proton therapy with the pulse operation were made in Feb. in 1986. The 50 % duty operation reduces the beam current to half, however, only a few % increase of the flat top dee voltage can compensate this reduction. The power reduction rate for this case is about 25 %. There was no difference in the extraction efficiency and the transport efficiency between the pulse operation and the continuous operation.

A new low level circuit has been designed for the pulse operation. The circuit consists mainly of commercially obtainable passive 50 ohm devices. Main functions are the amplitude regulation and the phase (between two dees) regulation. Current controlled variable attenuators with an attenuation range of 50 dB, a high quality DC reference (2 ppm/ °C) and 20 dB low noise RF amplifiers are used in the amplitude regulation circuit. The pulse mode is obtained by chopping the reference with an external step pulse. Main characteristics of the circuit at 19 MHz (70 MeV protons) are as follows. Open loop gain is 55 dB at 10 Hz. The small signal unity gain band width is 3 kHz (1 kHz in old system) which is still limited by the response time of 1 kW MARCONI amplifier. To improve the phase stability between two dee voltages, a high speed (1 μs) voltage controlled passive phase shifter is adopted in the phase regulation circuit. The phase shift range is 450° in the control voltage from 0 to 15 V. This value is almost independent of RF frequency. The VSWR at both input and output of the phase shifter is adjusted to be below 1.05. The phase stability was improved to better than ± 0.1° (resolution of the phase meter; HP8405A) from ± 0.5°.

At present, the repetition rate is selected to 30 Hz. Usable repetition range is from 10 to 300 Hz. In the lower rate than 10 Hz, the period for excitation of the resonator approaches the time constant that the resonator reaches thermal equilibrium, then the resonant frequency becomes unstable. The offset dee voltage of 10 kV is necessary to maintain the frequency tuning stably. The rise time and fall time (10 % to 90 %) are 1 ms and 0.1 ms. The dee voltage stability better than 10^{-4} is achieved on the flat top. Fig. 4 gives the envelopes of the dee voltage and the pulsed beam current. In near future, the MARCONI will be replaced by a fast response transistor amplifier to increase the unity gain band width up to more than 10kHz. The maximum repetition rate will also be increased. Fig. 5 shows the block diagram of the low level circuit for the pulse opration.

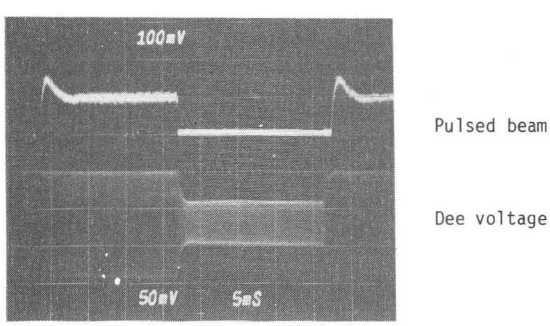

Fig. 4 Envelopes of the beam and the dee voltage under pulse operation at 30 Hz.

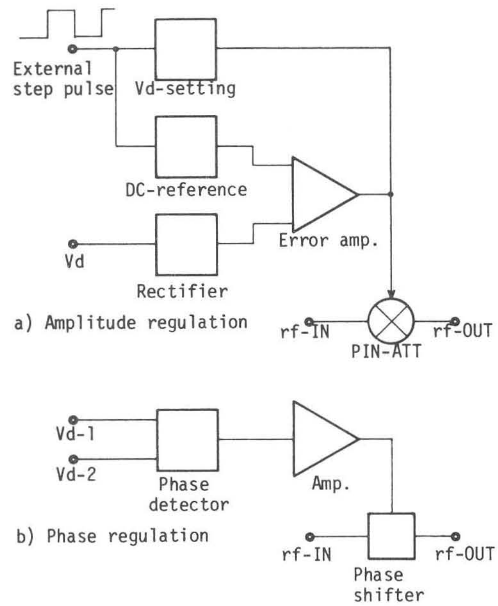

Fig.5 Schematic of the low level circuit for the pulse operation.

4. Applications

Among some applications (4), the status of fast neutron and proton therapy and the recent developments in the production of radiopharmaceuticals are briefly presented.

4-1. Fast neutron and proton therapy

The clinical trial of fast neutron and proton therapy is one of main applications in our cyclotron. Three afternoons for neutron therapy and one morning for proton therapy are weekly scheduled in the regular machine time. Fast neutrons are produced by bombarding a 4 mm thick water cooled beryllium target with 30 MeV deuterons. By March 1986, 1305 patients were treated with fast neutron. Protons have a property of good dose localization. To make use full of this characteristic, a spot beam scanning method on the horizontal beam course using 70 MeV protons was developed (5). This method realized an uniform dose distribution over the field of 180 x 180 mm^2. For a typical treatment, the spot beam current is 0.1 nA in the area of 10 x 10 mm^2. This beam current corresponds to a dose rate of about 1 Gy/s. It takes about 3 minutes to scan the field of 100 x 100 mm^2 with a dose rate of 2 Gy/s. By March 1986, 33 patients were treated with protons.

Fig. 6 illustrates the overall sketch of the new beam course including the therapy equipment. The beam is vertically deflected downward by a 90° bending magnet. To produce a broad beam for treatment, the equipment is designed so that both the spot scanning and the wobbler scanning are applicable. A pair of deflecting magnets are used in the wobbler scanning. At present, the biophysical experiments with 90 MeV protons are in preparation. The treatment of patients will be scheduled after those experiments.

4-2. Production of radiopharmaceuticals

Up to now, short-lived radiopharmaceuticals labeled with ^{11}C(T1/2=20.4 m), ^{13}N(9.96 m), ^{15}O(122

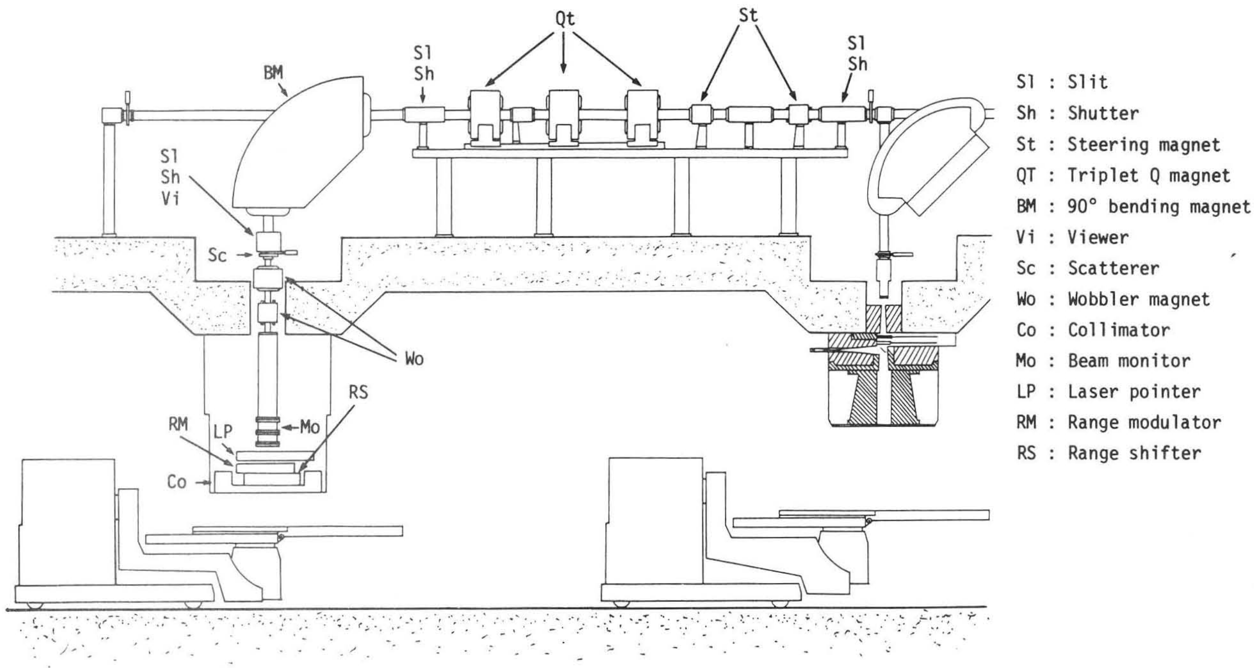

Fig. 6 New beam course for 90 MeV proton therapy.

sec), ^{18}F(109.8 m), ^{52}Fe(8.27 h), ^{123}I(13.0 h) and so on have been produced for medical use. For in vivo study of neuroreceptor and enzyme function in human brain, about 1 GBq of ^{11}C-Ro 15-1788 (benzo-diazepine receptor antagonist) and ^{11}C-DMPEA were synthesized automatically with >99 % radiochemical purity and 37-150 GBq/umol specific activity (6). Taking advantage of high energy characteristics of our cyclotron, ^{52}Fe and ^{123}I were produced as follows : 1) ^{52}Fe: reaction; ^{55}Mn (p,4n) ^{52}Fe, target; sintered manganese disk, Ep; 73-39 MeV, yield; 0.025 GBq/uAh, purity; 99 % (7), 2) ^{123}I: reaction; ^{127}I(p,5n) $^{123}Xe \rightarrow {}^{123}I$, target; 60% aqueous solution of NaI, Ep; 60-43 MeV, yield; 0.27GBq/uAh, purity; 99.7 %. ^{123}I yield could be increased up to 0.44 GBq/uAh with a target solution of I_2(50 %) + NaI(25 %) + H_2O(25 %).

In the preparation of radiopharmaceuticals for medical purpose, automatization and quick response to change of interest in radiopharmaceuticals are quite important. A central system was constructed to meet above requirements (8). Characteristics of the system are 1) control of many components, corresponding to those of more than 10 standard equipments, ($^{13}NH_3$, ^{18}FDG, etc.), 2) parallel control of maximally five equipments, 3) easy programming procedure (in tabular form). An automated equipment can be easily constructed by connecting components such as electric valves, flow controllers to the system. 11 GBq of ^{11}C-Ro 15-1788 and 7.4 GBq of $^{13}NH_3$ ready for i.v. injection could be produced simultaneously with simple equipments coupled to the central system.

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