STATUS REPORT ON THE NIRS-CHIBA ISOCHRONOUS CYCLOTRON FACILITY

H. Ogawa, T. Yamada, Y. Kumamoto, Y. Sato and T. Hiramoto
National Institute of Radiological Sciences, Anagawa, Chiba, Japan

Summary

A variable energy isochronous cyclotron has been installed for biomedical studies. Since the fall of 1975, the cyclotron has been used for the clinical trial of fast neutron therapy and the production of short-lived radionuclides. To improve the beam stability, a beam-phase stabilizer has been developed. Recently, a heavy ion source of self heated cathode PIG type has been developed and several kinds of ions have been successfully accelerated. The facility and some experiences in the application are also described.

Introduction

The possibility for the National Institute of Radiological Sciences (NIRS) to possess a cyclotron was considered for the first time when significant biomedical features of fast neutrons were presented by MRC Cyclotron Group at Hammersmith Hospital.[1] Thereafter the radiation therapy group in the NIRS studied for several years the feasibility of fast neutron therapy using a 3 MeV VdG generator. The results of clinical trials were very encouraging even though treatment was limited to superficial tumors due to low energy.[2] In 1969, the Japan Atomic Energy Commission recommended that a medical cyclotron should be installed in the NIRS in consideration of the recently expanded interest in fast neutron therapy and in nuclear medicine using cyclotron-produced radionuclides.

The planning of the cyclotron facility was started in 1970. The selection of the size of the cyclotron was the first problem. It was concluded that the machine should be able to accelerate deuterons up to 30 MeV so that the depth dose distribution would be at least as good as that obtained with ^{60}Co (assuming the use of a berrylium target which is the best material from the point of view of accelerator technology). To allow flexibility for other applications, the final specification called for 35 MeV for deuterons and 60 MeV for protons as the maximum energies to be guaranteed. The cyclotron was ordered from Thomson-CSF, France (now CGR-MeV) in February 1971. The construction of the building started in August 1971 and finished in April 1973. The installation of the cyclotron began in September 1972 as soon as the cyclotron vault was completed. The first internal beam was produced in December 1973 and the external beam in January 1974.

Cyclotron and Facility

The design features and general arrangement of the cyclotron are the same as those of the Catholic University of Louvain (Belgium) cyclotron using four sector magnets and 86° dees connected to panel-tuned rf cavities.[3] The frequency range is 11 - 23 MHz. The extraction system consists of a 55° electrostatic deflector followed by a 25° magnetic channel and a gradient corrector. The energy ranges actually achieved are 6 - 70 and 12 - 43 MeV for protons and deuterons, respectively. These ranges are covered by first and second harmonic modes of acceleration. Fig. 1 shows general layout of the facility, the cyclotron and the beam transport. Target stations c_1 and c_2 are used for production of short-lived radio-nuclides. For fast neutron therapy, the beam initially horizontal is directed down by a 90° bending magnet and reaches c_4 vertically under which a patient lies on a bed. c_3 is used for neutron beam production for radiobiological experiments. c_6 and c_7 in the big cave are used for other experiments. For the preliminary study of the proton therapy a new beam course, c_8, is under construction.

The cyclotron has been in operation on a regular schedule of 44 hours/week for clinical trial of fast neutron therapy, radiobiological experiments, radiation dosimetry and production of radionuclides. These experiments always demand high current, and a good extraction efficiency is essential to protect the deflector septum. Extraction efficiencies from 50 to 80%, depending on the energy and ion species, have been routinely achieved. From the start of regular operation in September 1975, several significant troubles have been experienced. The major failure was an occurence of cracks in the movable panels.

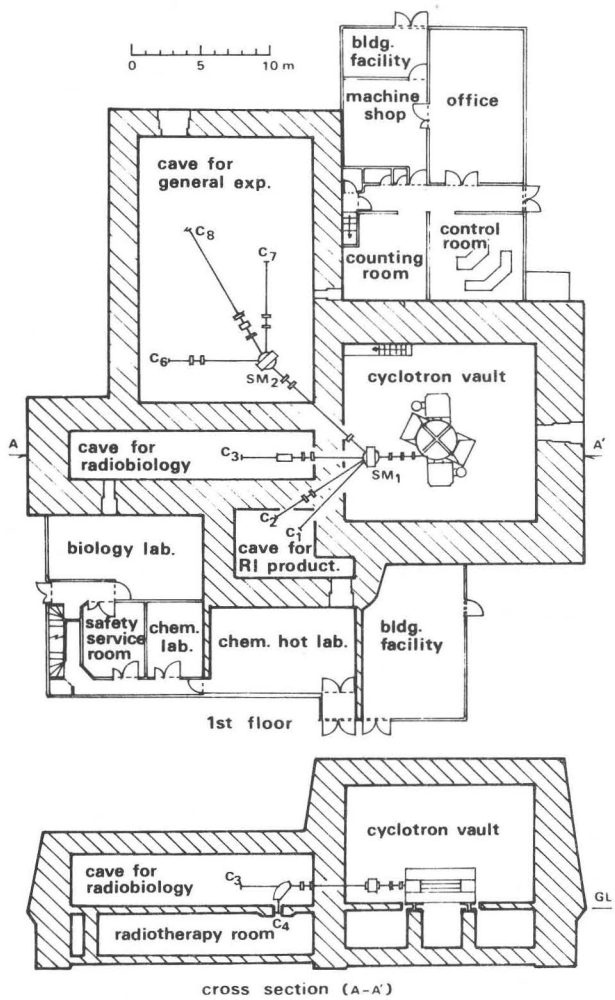

Fig. 1. General layout of the cyclotron facility.

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Machine improvement

External beam-phase stabilization

Several methods to measure the beam-phase relative to the accelerating rf voltage and to stabilize the phase of the external beam have been reported.[4-6] Stimulated by this work, we have developed a relatively simple phase stabilizer, which is designed to improve the beam stability for the fast neutron and proton therapy. In the present system the phase of the second harmonic component of the beam pulse signal is compared with that of the frequency-doubled accelerating rf voltage, and the detected phase difference signal is fed back to the magnetic field of the cyclotron. Fig. 2 shows the schematic of the system.

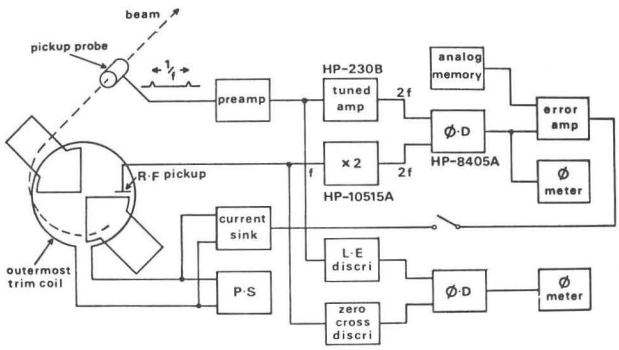

Fig. 2. External beam-phase stabilizer

A capacitive pickup type phase probe (a short cylinder 3 cm in length and 7.5 cm in diameter) is located at 3.2 m from the beam exit of the cyclotron. Positive pulse, representing the beam current, induced on the probe is amplified by a high input impedance preamplifier mounted on the probe housing. The amplified signal is fed to HP-230B tuned amplifier. This amplifier is tuned to the second harmonic frequency of the beam pulse train so that the noise voltage induced by the rf system is effectively rejected. HP-8405A vector meter detects the phase difference between the signal from the tuned amplifier and the frequency-doubled rf which is made by HP-10515A frequency doubler. The phase signal thus produced is routed to an error-amplifier in which the detected phase is compared with the reference phase stored in an analogue memory. When the feed-back circuit is actuated by the operator, the current flowing into the current sink connected in parallel with the outermost trimming coil is controlled by the error signal which represents the beam-phase deviation.

To demonstrate the performance of the system, the beam-phase drift, shown in Fig. 3, was taken a short time after turning on the cyclotron. Without feedback the beam-phase gradually changes due to the initial drift of the main coil power supply. When the feedback loop is closed the beam-phase drift is remarkably reduced. The damping factor is about 40. After the cyclotron reaches its steady state, the phase of the external beam is kept within ±0.2°/hr. This corresponds to a regulation of magnetic field of 2×10^{-6}, assuming the frequency is very stable. This stability is set mainly by the long term phase drift of the tuned amplifier itself. In order to check whether the method gives correct beam-phase, the beam phase was also measured by another method in which the leading edge of the real pulse from the preamplifier was compared with the zero-crossing time of rf. The results of the two methods agree very well as long as the time structure of the beam burst does not change appreciably. The stability of the beam position and intensity on the target have been considerably improved by the use of this system. The minimal current at which the control system can run is 1 μA.

Heavy ion acceleration

An internal multi-charged heavy ion source has been developed and preliminary test of acceleration began in January 1978. The ion source is of the PIG type with self-heated cathodes and can be installed radially by the use of equipment for the standard source. The section and outside views of the heavy ion source are shown in Fig. 4 and 5. The anode and cathode holders are made of water-cooled copper. The anode has an arc chamber 8 mm in diameter. A tantalum insert provides an extraction slit of 3.5 x 9 mm on the anode chimney. The cathodes are made of tantalum and are inserted in holders. Exchange of cathodes and chimney block takes about 30 minutes. Several shapes of cathode have been tested. The cross sections of these cathodes are shown in Fig. 6. The cathodes of type (a) and (b) have a constricted portion to make thermal conductance poor, and (b) has a shield to prevent thermal radiation. The cathodes of type (a), (b) and (c) are fitted in the holder loosely and (d) tightly. The arc current is controlled by a

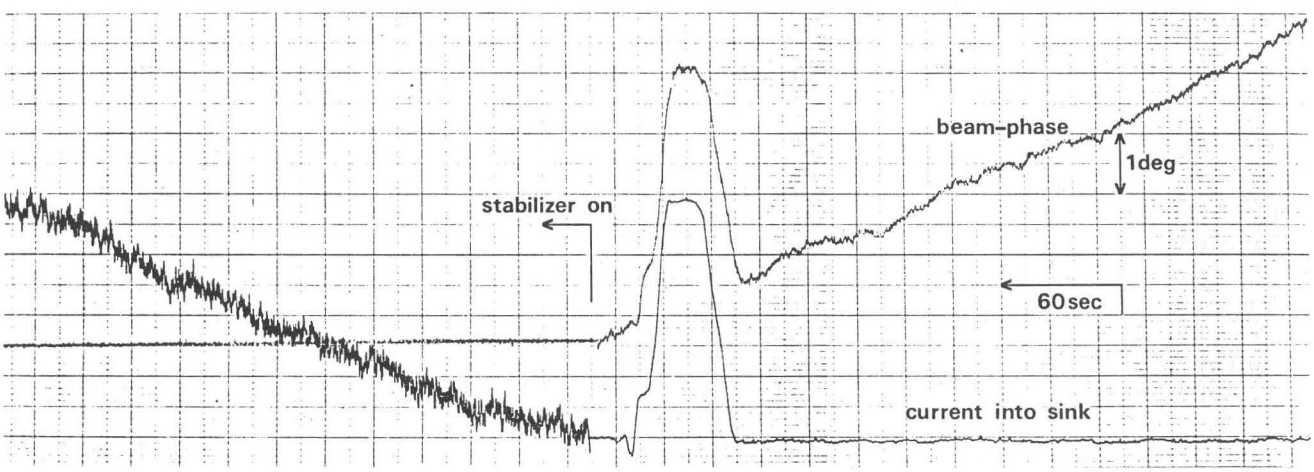

Fig. 3. Performance of the beam-phase stabilizer. The feedback loop is open in the first half and is closed in the second half. Before the loop is closed, current flowing into the current sink is intentionally changed to see the beam-phase shift.

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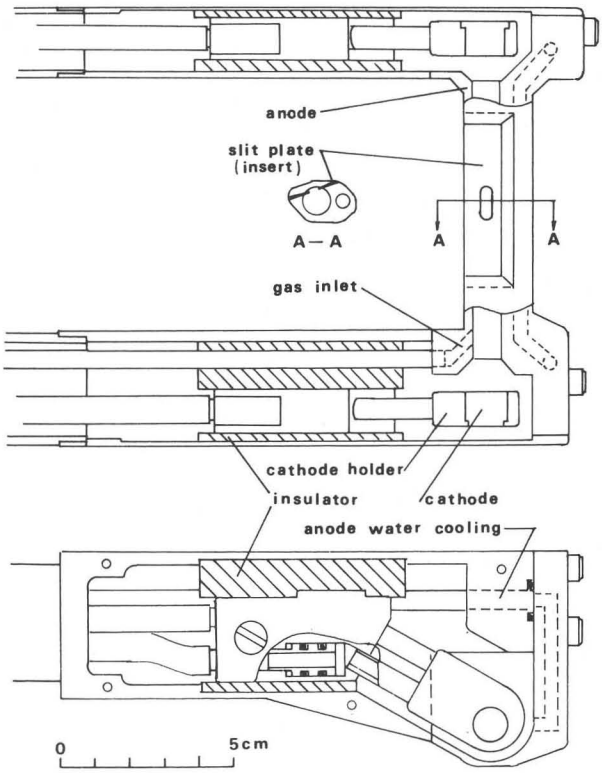

Fig. 4. Section view of the heavy ion source.

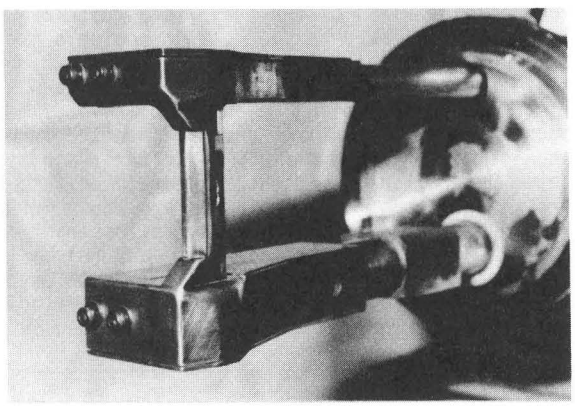

Fig. 5. Outside view of the heavy ion source.

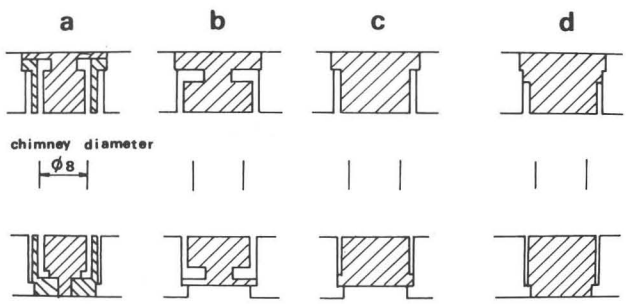

Fig. 6. Cross sections of cathodes tested.

power tetrode (Thomson-CSF TH-120) connected in series with the ion source. The test has been carried out in the dc mode; the pulsed mode of operation will be tried in the near future.

Typical results obtained with the heavy ion source are listed in Table 1. Second harmonic acceleration has been used at the field strength corresponding to k=75.5. Third harmonic acceleration has not yet been tried. In these trials, extraction efficiencies from 60 to 80% were observed. The vacuum in the accelerating chamber was about 2 x 10^{-6} Torr. The cathodes of type (a) and (b) give low arc voltage as expected and their life is longer than 11 hours. They are useful for low charged ions such as $^{12}C^{4+}$, $^{14}N^{4+}$ and $^{20}Ne^{5+}$. Type (c) may be suitable for $^{14}N^{5+}$. $^{12}C^{5+}$, $^{14}N^{6+}$, $^{20}Ne^{7+}$, $^{20}Ne^{8+}$ ions have been successfully accelerated by using the type (d) cathode. This type is effective for highly charged ions although its life is only 1.5 - 3 hours. The arc voltage depends considerably on the shape of the cathode and the condition of cathode fitting. Each type of cathode including cathode fitting must be used properly according to the ion species, charge state of ions and required beam intensity.

At present, the upper limit for heavy ion beams at the NIRS cyclotron is $T_{max} = 90Q^2/A$. Augmentation of k number up to 110 is scheduled in 1980 since the highest possible energy is desirable for radiobiological study.

Table 1 - Typical performance of the heavy ion source.

Ions	Energy (MeV)	Extracted beam curr. (eμA)	Arc volt. (V)	Arc curr. (A)	Gas flow (sccm)	Cathode type
$^{12}C^{4+}$	101	9.0	420	4.4	0.4	a
$^{12}C^{5+}$	157	0.04(0.048)*	600	4.3	1.5	d
$^{14}N^{4+}$	86	8.5**	370	4.5	0.5	a
$^{14}N^{5+}$	135	0.47	410	4.4	1.0	b
		2.0	470	5.3	0.8	c
		3.2(6.5)	610	3.8	1.4	d
$^{14}N^{6+}$	194	0.006(0.012)	670	3.3	1.1	d
$^{16}O^{5+}$	118	4.0(5.2)	520	4.4	1.4	d
$^{16}O^{6+}$	170	0.3(0.46)	630	3.9	1.7	d
$^{20}Ne^{5+}$	98	1.3(1.8)	280	3.0	0.9	b
$^{20}Ne^{6+}$	138	1.1(1.6)	690	3.7	1.1	c***
$^{20}Ne^{7+}$	185	0.01(0.03)	600	4.1	1.0	d
$^{20}Ne^{8+}$	242	0.45nA	530	5.0	1.2	d
$^{22}Ne^{6+}$	124	0.03(0.07)	510	4.1	0.7	d

** Figures in the bracket are maximum values.*
*** With a slit width of 2 mm.*
**** Cathodes fitted tightly.*

Applications

Fast neutron therapy

The clinical trial of fast neutron therapy is the main purpose of the NIRS-Chiba cyclotron. Treatment of patients began on 28 November 1975 after completion of the basic physical and biological evaluation of neutron characteristics. As of 1 August 1978, 352 patients had entered the study.

The arrangement for fast neutron therapy is shown in Fig. 7. Neutrons from a thick berrylium target bom-

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barded with 30 μA of 30 MeV deuterons are used. The average dose rate, as measured in air, at a distance 200 cm from the target is 40 rads/min for 10 x 10 cm field size.[7] The 50% dose occurs about 11 cm below the surface in tissue equivalent materials. Precise and quick patient positioning is realized by virtue of the vertical neutron beam and of a variable field size collimator linked with an x-ray simulator. The total time required to treat a patient is less than ten minutes on average. The machine time for the therapy is scheduled on alternate afternoons. About thirty minutes at the beginning is used for calibration of the monitor chamber and the remaining time for treatment. More than twenty patients can be treated during each session.

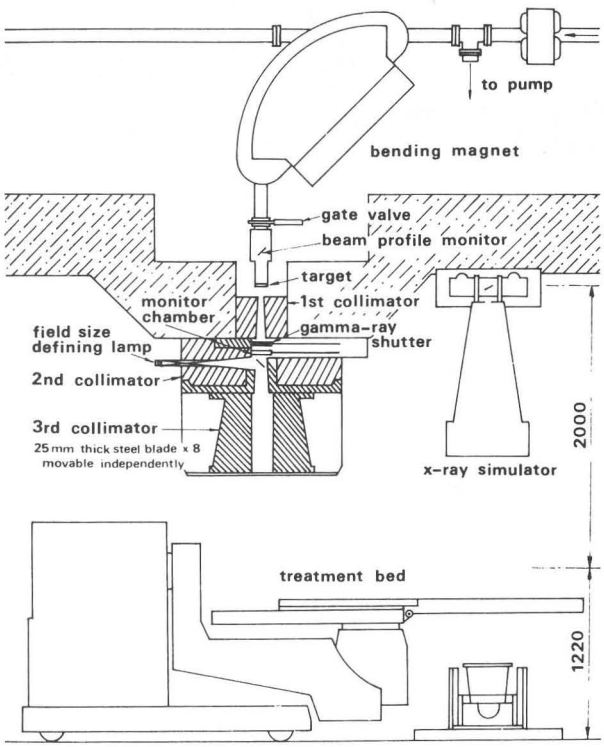

Fig. 7 Arrangement for the fast neutron therapy.

Radionuclide production

Methods of nuclide production and radiopharmacological preparations have been developed, including the construction of target chamber and preparation and control methods. Table 2 shows radiopharmaceuticals of which preparation methods were established. Some of these have been routinely produced and applied to clinical studies.

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Table 2 - Cyclotron production of radiopharmaceuticals.

Chem. form	Target material	Reaction	Incident energy (MeV)	Yield* mCi/μAh	Purity %
^{11}CO	N_2	$^{14}N(p,\alpha)^{11}C$	12	3.5**	99
$^{11}CO_2$	N_2	$^{14}N(p,\alpha)^{11}C$	12	4.0**	99
^{13}N	aq. sol. of NH_3	$^{16}O(p,\alpha)^{11}N$	15	12**	>99.5
$^{13}NH_3$	H_2O	$^{16}O(p,\alpha)^{13}N$	18	20	>99.5
$^{18}F^-$	H_2O	$^{16}O(\alpha,pn)^{18}F$	45	9.4	>99.5
^{43}KCl	Ar	$^{40}Ar(\alpha,p)^{43}K$	27	0.8	~50
$^{45}TiCl_4$	Sc	$^{45}Sc(p,n)^{45}Ti$	12	20	>99
$^{52}FeCl_3$	Mn	$^{55}Mn(p,4n)^{52}Fe$	60	0.3	>99
$^{62}ZnCl_2$	Cu	$^{63}Cu(p,2n)^{62}Zn$	38	6.0	>99
$^{123}I^-$	NaI	$^{127}I(p,5n)^{123}Xe \longrightarrow {}^{123}I$	60	5.8	>99.5

* The value at EOB.
** mCi/10μA·min at a flow rate of 100 ml/min.

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