RECENT DEVELOPMENTS OF THE NIRS-CHIBA ISOCHRONOUS CYCLOTRON

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Abstract

Recent developments of the NIRS-Chiba isochronous cyclotron are described. The automatic setting of the magnetic field, a new energy calibration method and a new irradiation equipment for the production of short-lived radionuclides are discussed. An axial injection plan and the preparation for a clinical trial with 90-MeV protons are also presented.

1) Introduction

In 1973, the NIRS-Chiba isochronous cyclotron was installed for the fast-neutron therapy and nuclear medicine using short-lived radionuclides [1]. Proton therapy at 70 MeV and upgrading of the K-number are already reported [2][3]. In 1989, 90 MeV proton therapy is scheduled.

Since 1978, a biomedical study by heavy-ions has been carried out using a self-heated PIG source [1]. It has been found that light heavy-ions have a higher LET and a better dose distribution than that of protons. To make use of these characteristics for radiotherapy, the HIMAC (Heavy Ion Medical Accelerator in Chiba) project has been proposed and is now under construction at NIRS [4]. The first beam will be produced in 1993. As the preparatory works for the heavy-ion therapy by HIMAC, applications of the cyclotron have been extended to both basic and preliminary fields. These involve the research of biological effects by heavy-ions and clinical trials with 90-MeV proton therapy. To meet the above-mentioned extension of applications, the necessary developments of the machine have been made.

An axial injection system has been proposed for installing an external heavy-ion source in order to increase the energy of heavy-ions, to improve the chamber vacuum, to decrease RF-loading, to avoid sputtering by unwanted ions with different e/m in the center region, and to make the source maintenance easier. The system has, basically, been designed in the way to that of CYCLONE in Louvain [5]. NIRS cyclotron and CYCLONE are the twin brothers, type CGR-930. The

first beam axially injected from a compact ECR source will be expected in 1990.

Under typical operation of the NIRS medical cyclotron, a set of ion species, the energy and the beam course are changed at least twice a day. Thus, a computer control system has been introduced for reliability during operation. An automatic pre-tuning of the RF system has already been installed [3]. After that, we extended the automatic control to the setting of the magnetic field, including the beam transport line.

For the study of LET on biological effects using cells, the daily fluctuation of the beam energy should be less than 0.5 %. To verify this and to measure the absolute beam energy, a new TOF method using the phase angle has been developed. This method depends on a pair of cylindrical tube pickups located along the beam line. The flight time is deduced in real time from the phase difference between the second harmonics of the induced signals on two pickups. The accuracy is in inverse proportion to the velocity of ion beams with such a method. We have obtained 0.06 % for β = 0.13 (16-MeV deuterons) in the present system.

The 90-MeV protons are accelerated under pulse operation because of the RF problem. The preliminary test of RF pulsing using 70-MeV protons have already been reported [3]. In this report, an example of the irradiation field by a pulsed 80-MeV proton beam with a wobbler and scatterer is presented.

An irradiation equipment was developed to enable remote exchange of targets for the effective production of short-lived radiopharmaceuticals.

2) Automatic setting of the magnetic field

Two key points regarding the system design are to attain easy operation and to prevent any miss-setting during the frequent changes of the ion species, energies or beam courses. The system consists of a computer, a high-quality DC reference for the main coil, a 16-bit DA-converter for the trim coils and other coils, an interface for the control, a data compiler and a

status monitor (fig.1). Thirty five sets of coil currents are controlled by this system.

The procedure for the setting is as follows. Firstly the main magnetic field is initialized by exciting the main coil from zero to the maximum value for 8 minutes. After the main field is set
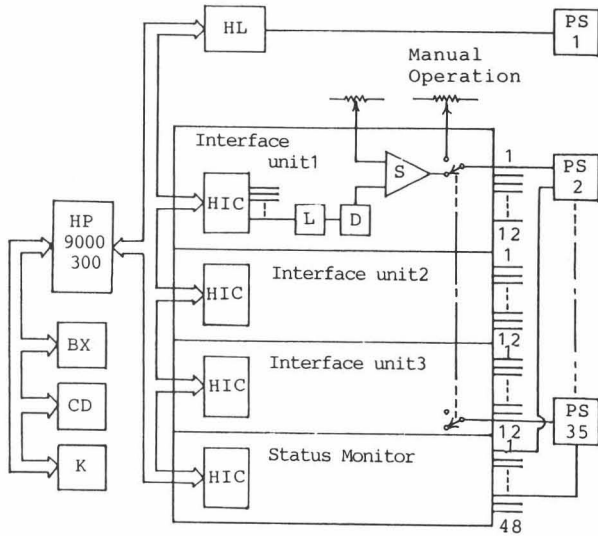
HL. High quality DC refernce; HIC. HPIB Controller;
L. Latch and up-down circuit; D. 16-bit DA-Converter;
S. Sum amplifier; PS. Power supply for magnet;
BX. Button boxes; CD. Control dial module;
K. Rotary Knob.

Fig.1. Block diagram of the automatic setting of the magnetic field.

to the operating value from the maximum, all other data are transferred to each latch, then the coil current is set. The settling time for all parameters is about 12 minutes, mostly involving initialization. For fine tuning of the coil currents, the selection of the coil is made individually at a push-button box. The adjustment of the coil current is done using a rotary knob. Each current for the beam transport line is also adjusted by an assigned control dial. A stored parameter file is used for the operation. Any fault of the power supplies can be observed on the status monitor. The system is easily switched over to the previous manual mode by a snap switch. Under practical operation, the best tuning for the internal and external beams is generally obtained by a small adjustment of the outermost trim coil current and harmonic coil current.

3) The axial injection system

The source and the injection line are designed so as to be placed on the upper yoke of the cyclotron. The space is limited, thus requiring a compact source and a simple transport line. The simple system also allows the upper yoke to be easily lifted up for the regular maintenance of the cyclotron.

Recently, a compact ECR source with a higher-order mode discharge (HI-ECRIS) was developed by the T. Hattori group [6]. The design parameters of their work are as follows. The size is 360 mm in length and 530 mm in diameter. A parmanent hexapole magnet has been successfully used. The frequency of micro-wave source is 6.4 GHz. If the transmission from the source to the external beam through the cyclotron becomes 5-10 % using a buncher, their recent performance on HI-ECRIS is satisfactory for biomedical studies. Such a type of source can be employed in the axial injection system with some modifications: RF frequency to 10 GHz and a 30 % increase in the mirror coil current.

The layout of the source and the injection line are shown in fig.2. The design of the spiral inflector and the magnetic focusing elements in the center hole of the yoke has been made based on the design of CYCLONE. The injection line between the buncher and the source has been designed so as to match the above-mentioned devices. At the center of the buncher, a beam waist of 16 mm ϕ (200 π mm·mrad in X and Y) is necessary in order to obtain a good matching at the inflector. This condition comes from both results and experience at CYCLONE. Focusing at the buncher is provided by Einzel lens and a 90° bending magnet with wedge angles of 26.5°, a radius of curvature of 0.4 m (up to 2.5 kG) and a
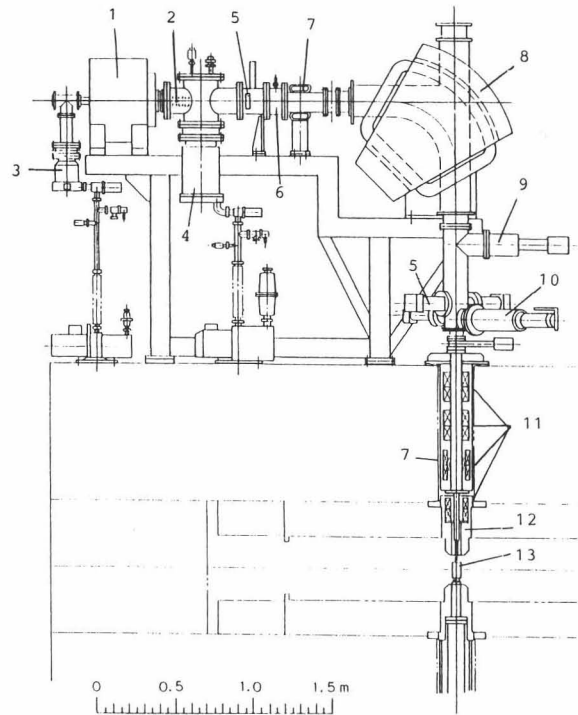
1. HI-ECR; 2. Einzel Lens ; 3,4. Turbo-molecular pump; 5. Slit; 6. Single electical quadrupole Lens ; 7. Magnetic steering; 8. 90°bending magnet; 9. Cryopump; 10. Buncher; 11. Cylindrical Lenses; 12. Plug; 13. Inflector.

Fig.2. Schematic view of the axial injection line including a compact ECR source.

gap of 0.1 m. To correct any difference in focusing in X and Y, a single electric quadrupole has also been prepared. The charge selection is achieved by a 90˚ bending magnet. The buncher is a two-gap klystron type and is set 1.550 m upstream the median plane of the cyclotron. The source is evacuated by two turbo molecular pumps (1000 l/s and 200 l/s), and the injection line is evacuated by a 700 l/s cryo-pump. The average vacuum pressure in the injection line will be 5 x 10^{-5} Pa, in which the beam loss by charge exchange will be less than 10 %.

For a different harmonic number of the acceleration (h=1,2,3), three kinds of pullers and inflectors have been prepared. For 90-MeV protons (h=1), the allowed maximum dee voltage of 35 kV will be smaller than the required dee voltage of 45 kV. We expect about a 30 % increase in the maxmimum dee voltage by an RF-pulsing technique [3]. The center region has been designed so as to be compatible with the existing sources, which are inserted from the radial direction.

4) Energy measurement by a new TOF method

4-1) Measurement of the absolute energy

The energy is determined from the time difference between the two induced signals on the capacitive pickups located with some given distance. It is difficult to directly measure the flight time with an absolute accuracy of the order of 10^{-3}. To attain this order of accuracy, time is transformed into phase, in which the bunched beam pulse train is considered as " transmitted sinusoidal waves " in a Fourier expansion. Furthermore, we fix our eyes on the second harmonics to prevent from the RF-disturvance. The phase difference, ϕ_2, can be expressed as

$$\phi_2 = 2 \times \omega \times t = 2 \times \omega \times L/v \qquad (1)$$

Here, ω is equivalent to $2\pi f$, where f is the RF frequency, t is the flight time, L is the distance between two pickups, and v the velocity of the beam. The $\delta B/B$ at the optimization of the extraction is 2 x 10^{-4} at most, which does not affect on the energy measurement with an accuracy of the order of 10^{-3}. The energy can be calculated from ϕ_2 using eq. (1).

A block diagram of the experimental setup is given in fig.3. Two pickups are set along the beam transport line at a distance L of 1.2325 m ± 0.25 mm. The distance between adjoining beam bunches is $\pi R \sim$ 2.9 m for h=2 in our cyclotron. R is the average radius at the outmost orbit and R corresponds to a phase angle of 720˚ in the second harmonics, thus, L corresponds to about 306˚. If the delay line is adjusted to 306˚, the reading of the measured value must be indicated around zero. We intend to use the most sensitive range of the phase meter (± 5˚), in which we can obtain the accuracy of ± 0.05˚ (WILTRON-352). In such a technique using phase offset, it is essential to precisely determine the electrical length of the delay line over the cyclotron frequency. The accuracy of phase off-
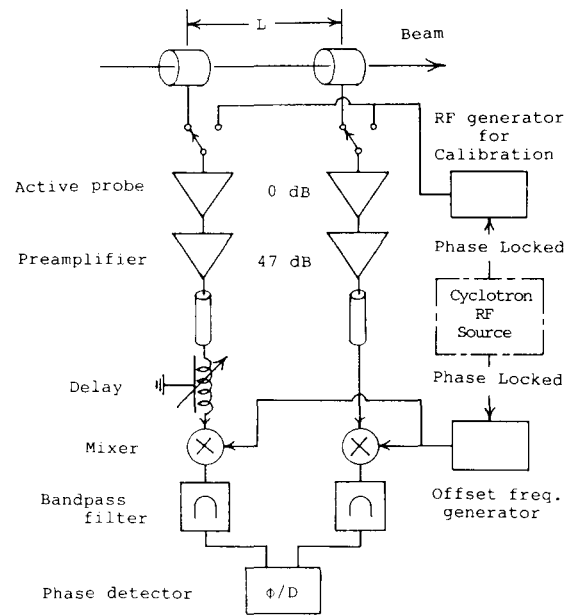

Fig.3. Block diagram of the energy measurement system. Two pickups are located about 13 m downstream the cyclotron.

set in the phase meter is not guaranteed to an order of 10^{-3} (about 1 %). Therefore, a different calibration method is introduced.

One example of the calibration is as follows. When the acceleration frequency is 13.450 MHz (h=2, 16-MeV deuterons in nominal), two active probes are connected to the RF generator with a frequency of 26.900 MHz through an in-phase power divider. Zero control of the phase meter is firstly adjusted so that the reading is zero without the delay line. The variable delay line is independently calibrated as follows. A phase angle of 306˚ in 26.900 MHz corresponds to a time delay of 31.599 ns. In the frequency of 31.647 MHz (T=31.599 ns), the delay line is adjusted by a phase meter (HP-8405A) so that the phase angle is zero, because the phase angle corresponding to a time delay of one period is 360˚ (0˚). The difference in the electrical length of delay line between 26.900 and 31.647 MHz is measured to be 0.2˚. Correcting this value, the absolute accuracy of 0.1˚ in phase and 0.06 % in energy have been obtained. The measured phase, ϕ_2, are 309.1˚ and 301.0˚ for 16-MeV and 22.5-MeV deuterons in nominal. The corresponding energies are 15.69 ±0.01 MeV and 22.99 ±0.02 MeV, respectively.

Two waveforms from two pickups are compared on a degital storage oscilloscope and a spectrum analyzer. The results show that the two waveforms are exactly the same. There is no phase error in any harmonics in a Fourier expansion. A heterodyne technique is used in the electronics [7][8]. The intermediate frequency is 1 KHz. We have obtained the SN ratio of 60 dB for a beam current of 1 μA at which the maximum phase in-

stability will be ± 0.06°. To verify the measured flight time and delay time, a digital storage oscilloscope is also used to measure directly the time-of-flight (the accuracy is a few %). The results by two different methods agree well.

4-2) Measurement of the circumference at the outermost orbit

In an isochronous cyclotron with two dees (fan-shaped 90°), ϕ_2 can also be expressed as follows;

$$\phi_2 = 2 \times 2\pi \times h \times L/Lo = 2 \times h \times L/R \quad (2)$$

Here, h is the harmonic number of the acceleration, and Lo the circumference at the outmost orbit ($2\pi R$). The Lo in this equation can not be definitely determined, since the shape of the orbit is not completely circular and the center position of the orbit is not precisely known. However, it is constant as long as the tuning of the magnetic field is maintained. Eq.(2) shows that ϕ_2 depends on Lo and is independent of the energy. As previously mentioned, the adjustment of the delay line to 306° means that R is calibrated to 0.92 m (h=2). We can know a true Lo to an order of 10^{-3} from the measured phase angle.
In the beam test with 16-MeV and 22.5 MeV deuterons in nominal, the measured Lo are 5.723 m and 5.877 m, respectively. We usually adjust the main field strength in 10^{-4} order and the harmonic coil current by 10 - 20 A in order to optimize the extraction, i.e, to give a perturbation to the orbit at the extraction radius and to increase the radius gain per turn, δR, by the 1st harmonics produced by hamonic coils. It has been found that the circumference is considerablly varied with the tuning of the magnetic field.

5) The preparation for 90-MeV proton therapy

For 90-MeV proton therapy, it is necessary to make the extracted beam broad one with a good homogenity in an irradiation field. A pair of X-Y scanning magnets (wobbler), a scatterer and a collimator are used to broaden and to homogenize the beam with a diameter of 17 cm and a dose uniformity of a few %. The coils of the wobbler are excited by a sinusoidal wave current with a phase difference of 90°; the beam then rotates about the Z-axis so that the dose distribution becomes uniform in both the azimuthal and radial directions. These devices are assembled as shown in fig.4.
In the beginning of the pulsed beam test, an overshoot was seen in the time structure [4]. This was because the response of the dee voltage detector was not fast, therefore the dee voltage goes up for the compensation of this lagging in the feed-back loop. After improving this, we obtained the good flatness on the time structure.
The repetition rate of RF pulsing is selected at 18 Hz which is the wobbling frequency (21 Hz) minus 3 Hz, i.e, a fan-shaped stripe rotates with a beat frequency of 3 Hz. The dose
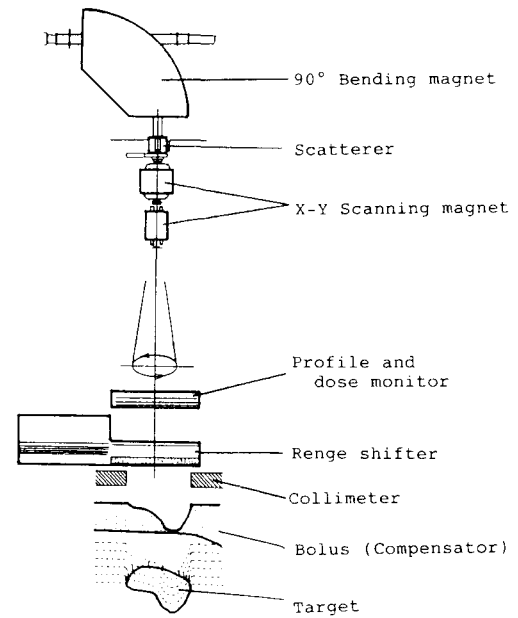

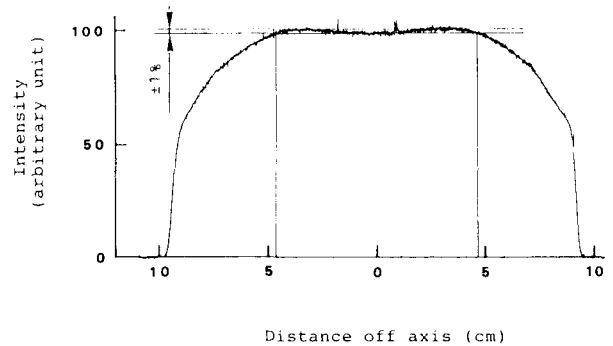Fig.4. Illustration of the beam delivery sytem for the three-dimensional proton therapy.

Fig.5. Lateral dose distribution at the treatment site measured by the image on X-ray film of 80-MeV protons. In the actual treatment, peripharal of the uniform field is blocked by a collimator to define the target volume.

homogenity of the irradiation field was measured on a photo X-ray film. An example is shown in fig.5. The wobbling radius and the thichness of the golden scatterer are adjusted in order to obtain the uniform field (± 1 %) of 10 cm in diameter.

6) Production of Radiopharmaceuticals

In recent 5 years, 1220 GBq of ^{11}C-labelled compounds (flumazepil, methylspiperone, cyanoimipramine, etc.) have been produced at high specific activity and high radiochemical purity using a specially designed automated equipment [9]. 466 GBq of the compounds have been used for in vivo measurement of neuroreceptor and en-
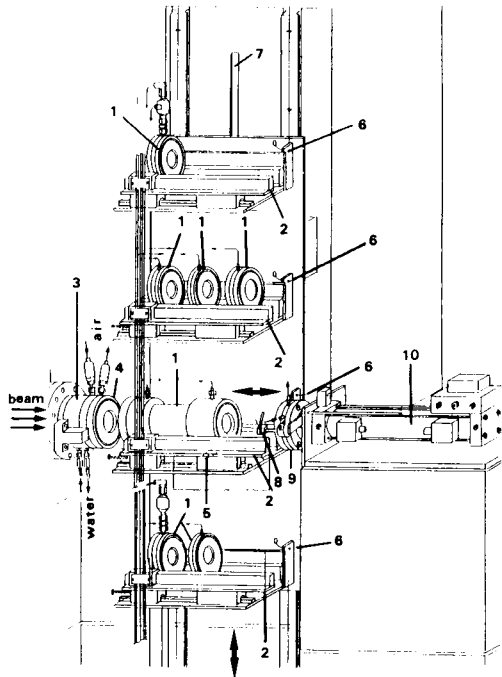
1. Targets; 2. Racks; 3. Collimater; 4. Air-cooling
block; 5. Pin for positioning; 6. Photo-switches
7. Gearing; 8. Terminal for beam monitoring;
9. Water-cooling block; 10. Air cylinder.

Fig.6. Irradiation equipment for the short-
     lived radionuclides.

zyme function in human brain (213 patients and
volunteers) by positron emission tomography (PET)
[10]. 264 human studies have been also carried
out with 588 GBq of ^{13}N-ammonia and 122 GBq of
^{15}O-labelled compounds. Besides, a number of
compounds labelled with ^{11}C, ^{13}N, ^{18}F, ^{52}Fe, ^{77}Br
and ^{123}I have been produced and used for animal
and clinical studies and labelling experiments.
     The PET facility was expanded in 1988 and 3
PET scanners are now in operation. An irradia-
tion equipment and an additional hot cell for
automated equipments were installed to enable
more frequent productions of short-lived radio-
pharmaceuticals in the limited time of cyclotron
operation. As shown in fig.6, the targets
mounted on 4 racks are conveyed vertically by
gearing coupled to a motor and pressed horizon-
tally against the cooling air block and the col-
limater fixed to the beam duct by the water-
cooling block coupled to an air cylinder. It
takes one minute at the longest for their move-
ment. The target position to the beam duct is
determined exactly with the photo-switches and
the air-operated pin for positioning. Beam cur-
rent is monitored through the terminal pressed to
the target surface by the air-operated rotor.
More than two targets can be mounted in series on
each rack. This feature is favorable to produce
different radioisotopes effectively at one time
irradiation using high energy beam.

4 to 6 times productions and clinical uses
of ^{11}C- and ^{13}N- labelled compounds are possible
in one cyclotron operation unit (2.5-3 hr.) using
the equipments described above.

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