PRESENT STATUS OF THE HIMAC INJECTOR

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Abstract

HIMAC is a heavy ion synchrotron complex dedicated to medical use. The beam acceleration tests of the HIMAC injector have been performed during the first half of the last year with ions of He^{+}, C^{2+}, Ar^{8+} *etc.* The output beam quality including the intensity, emittances and momentum spread are well within the required range. The commissioning study of the remaining parts of the accelerator has been successfully completed until the end of the March using 230 MeV/u He ions. Clinical trials started on June 21 and the whole facility is now in operation.

Introduction

The heavy ion beam has a physical property of the excellent dose localization in a human body and is very much suitable for the treatment of deeply located tumors. The maximum energy of the HIMAC synchrotron is designed to be 800 MeV/u for light ions with $q/A = 1/2$ so that silicon ions reach 30 cm deep in a human body [1], [2]. Ion species of He, C, Ne and Si will be supplied for the clinical treatment. In the facility, there are three treatment rooms which are equipped with a vertical beam line, a horizontal beam line, and both of vertical and horizontal beam lines, respectively.

The design study of HIMAC started in 1984, and it takes about ten years to get the first beam from the HIMAC synchrotron. Construction of the accelerator and buildings lasted during six years. The first clinical trials have been completed for three patients in August. It takes less than 2 minutes for a single irradiation of 290 MeV/u carbon beam, while the precise patient-fixing procedure requires about 20 minuets. Three irradiations per week and total of 18 irradiations for each patient were planned to destroy perfectly tumor cells.

Injector Overview

An injector of HIMAC consists of two types of ion sources (PIG & ECR), an RFQ linac of 100 MHz and Alvarez type linac operated with the same frequency. [3] A charge stripping section and a debuncher cavity are installed in the MEBT line in order to increase the charge to mass ratio and in order to reduce the momentum spread of the accelerated beam. A layout of the injector is shown in Fig. 1.

Ion Source

A PIG type ion source is operated with a very low duty factor, [4] and shows excellent performance as listed in table 1 (a), where underlined values indicate the charge to mass ratio larger than 1/7. The source is an indirectly heated cathode type, and the silicon beam is obtained by sputtering of a silicon block with argon ions. Pulsed operation of the source allows the arc voltage to be high and the peak intensity increases by a factor of five for a short pulse (around 200 μs) of Ar^{6+}.

The output beam intensities of a 10 GHz ECR source are low for light ions, and high for highly charged heavier ions comparing with the PIG source as shown in table 1 (b). The listed intensities are realized after some improvements on the vacuum and cooling system and the magnetic field strength around the extraction hole. [5] The operation of the ECR

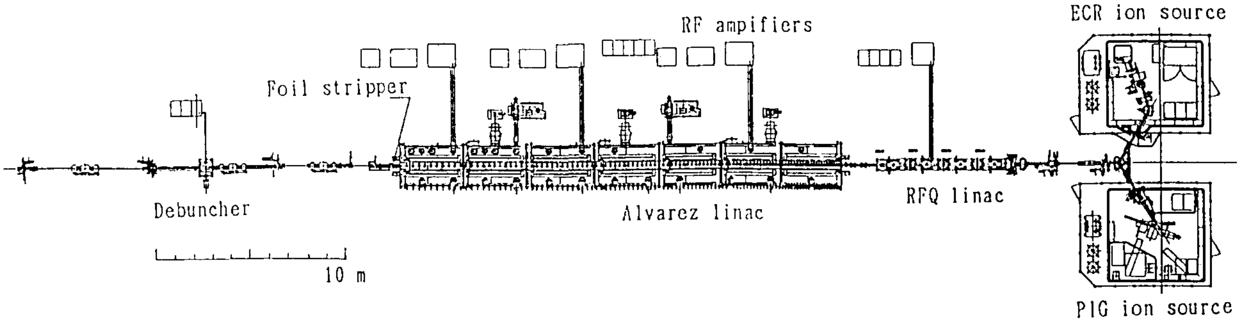

Fig. 1: A layout of the HIMAC injector.

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Table 1: Typical intensities of ion sources (eμA).

(a) PIG source

Ion	1+	2+	3+	4+	5+	6+	7+	8+
^{4}He	12,000	3,000						
^{12}C	1,000	5,000		700	20			
^{20}Ne		2,000	3,800	800	400	20		
^{28}Si			400	600	300	50	10	
^{40}Ar			1,500	1,900	1,800	1,300	400	200

(b) ECR source

Ion	1+	2+	3+	4+	5+	6+	7+	8+
^{4}He	3,200	2,100						
^{12}C		470		430	50			
^{20}Ne		622	700	680	600	220	54	10
^{40}Ar				380	340	345	270	235

Table 2: Typical beam performance

Ion (q/A)	C^{4+} (1/3)	He^{+} (1/4)	Ar^{8+} (1/5)	C^{2+} (1/6)
Ion source intensity(eμA)	140	480*	105	300
Trans. of LEBT (%)	93	45	71	80
Trans. of RFQ (%)	92	93	93	92
Trans. of DTL (%)	96	92	86	86
Stripping efficiency (%)	93	100	18	93
(Charge state)	(4→6)	(1→2)	(8→18)	(2→6)
Trans. of MEBT (%)	95	96	81	84
Output intensity (eμA)	152	357	20	445
Emittance X**	0.7	0.6	1.1	-
Emittance Y**	0.7	0.6	0.8	-
Momentum spread (%)	±0.13	±0.14	-	-

* Reduced to 1/3 with a grid type attenuater.

** Normalized value in unit of π mm·mrad.

source is very much stable and easy to tune. In the first series of the clinical trial, therefore, C^{4+} ions from the ECR source is usually accelerated. The PIG source always stands by the ECR as a spare source during the treatment time.

RFQ & DTL

An RFQ linac is a conventional four vane type operated at 100 MHz and covers an energy range from 8 to 800 keV/u. The acceleration vane is 7.3 m long and separated longitudinally into four sections. Up to 300 kW pulsed rf power (for q/A=1/7) is fed through a single loop coupler. A typical width and a repetition rate of the rf pulse are about 0.7 ms and 1 Hz, respectively.

A drift tube linac of Alvarez type is also operated at 100 MHz resulting in the large cavity diameter of about 2m. The DTL accelerates ions from 0.8 to 6.0 MeV/u. More than 100 drift tubes are installed in a 24 m long linac tank and each drift tube is supported with a horizontal and a vertical stems. About 50 tubes are loaded with quadrupole magnets operated in a pulse mode. The rise and flat top pulse length are less than 3 ms and longer than 1 ms, respectively. The DTL is separated into three independent cavities each of which is fed more than 1 MW peak rf power through a single loop coupler. A high power amplifier system is equipped with a power tube of Siemens RS2074SK in its final stage, whereas an Eimac 4CW100,000E is adopted in a final amplifier for the RFQ. Since no charge stripper foil is adopted between the RFQ and the DTL, both RFQ and DTL accept ions with a charge to mass ratio larger than $q/A \geq 1/7$.

Beam Monitor and Control System

A pair of multiwire profile monitors and a Faraday cup monitor are adopted as standard beam monitors of the injector. The profile monitor has 32 tungsten wires for each direction which are 0.1 mmϕ and 1.25 mm apart from each other. As an emittance monitor, a pair of multiwire profile monitors is also used and has a wire pitch of 0.625 mm. The output signals of the monitor are fed into a UDC, which is a 16 bits micro processor, through an ADC unit. The UDC is adopted as an interfacing device between a peripheral device and a control computer. The control computer has two hierarchical layers: a system control unit (SCU) and two group control units (GCU). The SCU mainly plays a role of a man-machine interface, and the GCU directly controls the peripheral devices through the UDCs. All devices including the high power rf system and the ion sources are controllable with the SCU.

Beam tests

The beam acceleration tests of the injector have been performed during the first half of the last year with ions of He^{+}, C^{4+}, Ar^{8+} *etc*. The typical 95% beam emittances are 0.25 and 0.7πmm·mrad in a normalized scale before and after the linacs, respectively. The momentum spread of the linac beam is improved with a 100 MHz debuncher cavity from 0.9% to 0.3% (full width) by a factor of three. The output beam quality including the intensity, emittances and momentum spread are well within the required range. The typical beam performance is summarized in table 2. An example of the momentum spectrum of C^{6+} beam after the debuncher cavity is shown in Fig. 2.

An example of the rf pulses for the RFQ and DTL is shown in Fig. 3 together with an C^{6+} pulse of the injector. In Fig. 4, the beam pulses of C^{4+} from the ECR source and C^{6+} after the DTL are indicated. In these three figures, C^{6+} ions are obtained with a charge stripping foil located downstream of the DTL. A microwave pulse for the ECR source is also indicated in the bottom of the Fig. 4. In the beam pulse of the ECR source, a peak due to the after glow effects is clearly observed. Since the after glow peak is very sharp, a flat part of the beam pulse is used in the next acceleration stage.

In November, He^{+} ions of 6 MeV/u were injected into the synchrotron for the commissioning of the accelerator system in whole. The beam tests have been carried out during four months and completed with the satisfactory results. A beam transmission efficiency at each acceleration stage exceeds a design value, and almost all components work perfectly as expected. The accelerator complex is now in use of clinical trials of tumor treatments after biological and physical experiments of three months.

Daily Operation

Until September, all magnets, cavities, ion sources, cooling water *etc.* are scheduled to be powered off around 8:00 pm. Only the control system, the ion source gas and the vacuum system continue to work. At next 9:00 am, all system including the synchrotron magnets, the HEBT magnets *etc.* are powered on. The beam tuning of the ion source and whole injector requires about 30 and 60 minutes, respectively. The aging procedure of the linac cavities is not required because a field level for C^{4+} ions is rather low and 3/7 of the maximum design value.

At the output end of the injector, more than 150 eμA of C^{6+} is stably obtained. After reducing the beam intensity to about 50 eμA with an attenuater made of tungsten wire grid, the ions are injected into the synchrotron. It takes about 1.5 hours for tuning of the synchrotron and HEBT lines. Finally the user obtains 290 MeV/u carbon beam of 1.8×10^9 pps around noon. The very short time for the beam tuning can be realized only with a stable and reliable accelerator system.

In a short time, the operation time will be extended to 24 hours per day except for Sunday and Monday.

Schedule Hereafter

In the coming October, the synchrotron beam will become available not only for the clinical trials but also for the basic experiments including biophysics, nuclear physics, surface physics *etc.* The users are expected to come from both inside and outside NIRS. The linac beam will be also available in parasite experiments.

In order to improve the beam capability in the medium energy experimental room, the time sharing acceleration will be introduced in the injector system. The development of 18 GHz ECR source is also underway in collaboration with INS, University of Tokyo. The newly developed ion source will make it possible to accelerate heavier ions, such as Kr, with the synchrotron.

References

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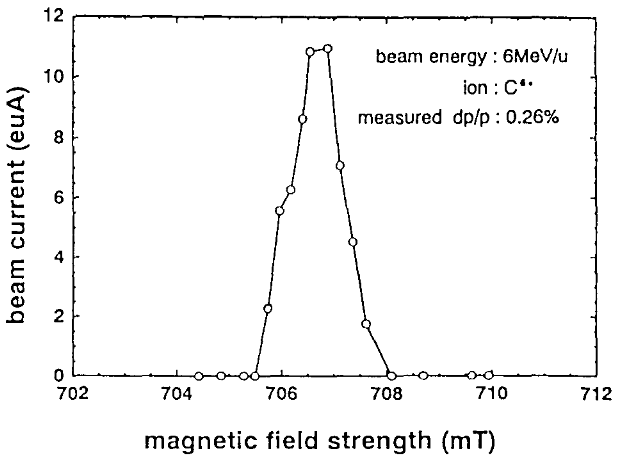

Fig. 2: An example of the measured momentum spectrum of C^{6+} beam after the debuncher.

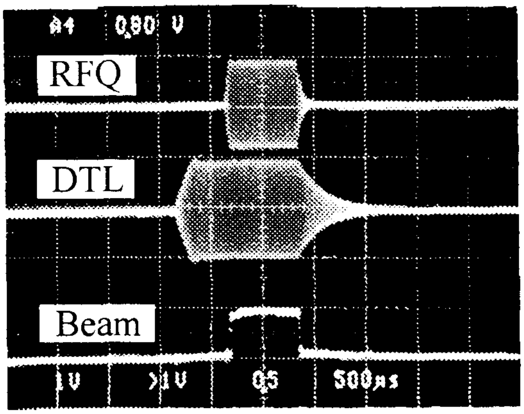

Fig. 3: Rf pulses for the RFQ and the DTL together with the output C^{6+} beam.

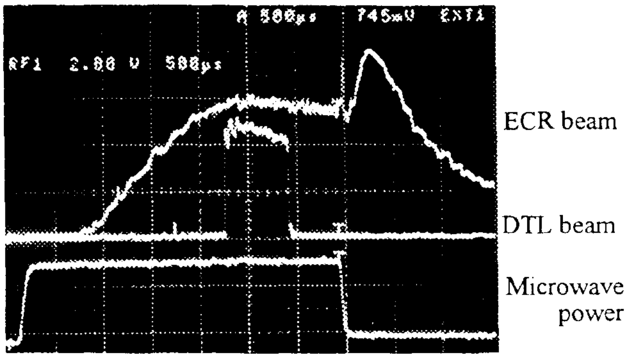

Fig. 4: Beam pulses of the ECR and the DTL. A microwave pulse for the ECR source is also indicated in the bottom of the figure.