Beam Test of the HIMAC Injector

Takeshi Murakami, Hirotsugu Ogawa, Satoru Yamada, Yukio Sato, Takanobu Yamada, Atsushi Kitagawa,
Jun Yoshizawa, Shinian Fu, Toshiyuki Kohno, Kenji Sato, Akifumi Itano, Masayuki Kumada,
Eiichi Takada, Mitsutaka Kanazawa, Kouji Noda, Michio Sudou, and Yasuo Hirao
National Institute of Radiological Sciences
4-9-1 Anagawa, Inage-ku, Chiba 263, JAPAN

Osamu Morishita and Kenji Sawada
Sumitomo Heavy Industries, Ltd.
5-2 Sobiraki, Niihama, Ehime 792, JAPAN

Abstract

A heavy-ion synchrotron dedicated to medical use is under construction at the National Institute of Radiological Sciences. The injector system, which accelerates heavy ions up to 6 MeV/nucleon, has been completed. An operational test with ^{4}He and ^{40}Ar beams started and the system showed satisfactory performance.

I. INTRODUCTION

A heavy-ion accelerator, HIMAC (Heavy Ion Medical Accelerator in Chiba) [1], is under construction at the National Institute of Radiological Sciences (NIRS), Japan. It comprises an injector system, two identical synchrotron rings, a beam transport system, and devices for treatment.

Since HIMAC is a heavy-ion synchrotron dedicated to medical use, the design is based on the requirements of radiological treatments, referring to the research of biological effectiveness and clinical trials at LBL. Ions with atomic numbers between 2 (helium) and 18 (argon) are accelerated. Maximum energy is 800 MeV/nucleon, corresponding to a range of 30 cm in tissue for silicon, for ions with a charge-to-mass ratio (q/A) of 1/2. Intensity of 2 x 10^{9} pps is required to realize a dose rate of 5 Gy/min. A field size is 22 cm in diameter. Reliability of the whole system is of great importance.

The injector system was completed early 1993. In this report, the results of the first operation of the injector system are briefed.

II. DESIGN OF THE INJECTOR

The injector system [2] comprises two types of ion sources (a PIG source and an ECR source), an RFQ linac and an Alvarez linac of 100 MHz with three tanks. The beams extracted from the ion sources are transported through a low-energy beam transport line (LEBT), 7 m long, and injected into an RFQ linac. The Alvarez linac follows the RFQ linac and an interlinac transport line (LLBT), 1.9m long. The medium-energy beam transport line (MEBT) transports the accelerated beam to the synchrotron. The transport lines also include the beam diagnostic apparatus : Faraday cups, profile monitors, electrostatic pickup electrodes, etc. A 100 MHz debuncher cavity is installed in the MEBT line to suppress the energy spread to ±0.2%.

The linac system accepts heavy ions with a q/A as small as 1/7 and has no charge strippers except for a stripper foil in the MEBT. The specifications of the injector system are summarized in Table 1.

Table 1. Specification of the injector system.

Ion species	^{4}He ~ ^{40}Ar
Charge-to-mass ratio	≥ 1/7
Ion sources	PIG & ECR
Frequency	100 MHz
Repetition rate	3Hz max
Duty factor	0.3% max
Acceptance	0.6π mm·mrad (normalized)
RFQ linac	
Input/Output energy	8 / 800 keV/nucleon
Vane length	7.3 m
Cavity diameter	0.59 m
Max surface field	205 kV/cm (1.8 Kilpatrick)
Peak rf power	260 kW (70% Q)
Alvarez linac	
Input/Output energy	0.8 / 6.0 MeV/nucleon
Total length	24 m (3 rf cavities)
cavity diameter	2.20 / 2.18 / 2.16 m
Average axial field	1.8 / 2.2 / 2.2 MV/m
Max surface field	150 kV/cm (1.3 Kilpatrick)
Peak rf power	840 / 830 / 770 kW (75%Q)
Focusing sequence	FODO (5.1 kG/cm max)
Output beam emittance	≤ 1.5π mm·mrad (normalized)
Momentum spread	≤ ± 1x10^{-3}

III. ION SOURCES

Two types of ion sources (PIG and ECR) were chosen based on their reliability of operation, capability to produce the required intensities, and simple maintenance.

The PIG source is an indirectly heated (hot) cathode type. The performance of the PIG ion source is shown in Table 2. The extraction voltage is 25 kV and the discharge power is 2-3 kW at peak and 1 W on the average. A typical value of the emittance is about 250π mm·mrad for both the x and y directions. The lifetime of the source is about two weeks, due to a low duty factor. The stability is satisfactory and no adjustments of the operation parameters are necessary for 24 hours.

Table 2. Beam intensities (in emA) extracted from the PIG ion source at a test bench. Underlined species have q/A values larger than 1/7. The intensities in parentheses may not be correct due to the mixed beam with the same q/A value.

Ion	Gas-flow (cc/min.)	1^+	2^+	3^+	4^+	5^+	6^+	7^+	8^+
^{4}He	20 (He)	3.5	3.0						
^{12}C	0.6 (CO_2)	1.0	3.5	(3.0)	0.6	0.02			
^{14}N	0.6 (N_2)		2.0	2.5	1.2	0.2			
^{16}O	0.6 (CO_2)		2.0	2.3	(3.0)	0.3	0.03		
^{20}Ne	1.1 (Ne)		2.0	2.0	0.8	0.4	0.02		
^{28}Si*	0.3 (Ar)			0.4	0.6	0.3	0.05	0.01	
^{40}Ar	0.2 (Ar)			1.5	1.9	1.8	0.8	0.4	0.2

*Produced by sputtering of a crystal with Ar ions.

The ECR source has a simple single-stage structure with microwaves of 10 GHz and 1.9 kW. The magnetic field for confinement consists of a 1T axial field produced by two solenoidal coils and a 0.8T radial field by a set of permanent sextupole magnets. A typical operational condition is a gas-flow rate of 5 x 10^{-4} Torr·l/sec and a vacuum of about 1 x 10^{-6} inside the plasma chamber. The performance of the ECR source is summarized in Table 3.

Table 3. Beam intensities (in eμA) extracted from the ECR ion source. See captions of Table 2.

Ion	1^+	2^+	3^+	4^+	5^+	6^+	7^+	8^+	9^+
^{1}H	1610								
^{4}He	1290	(440)							
^{14}N	310	350	250	240	160	23			
^{16}O	290	250	180	(180)	120	74			
^{20}Ne	360	210	210	170	(120)	93	19	5	0.2
^{40}Ar	360	170	100	100	(100)	100	100	120	61

IV. LINACS

The RFQ linac is a conventional type with four vanes. The cavity is mechanically separated into four tanks, as shown in Figure 1. The four vanes were placed in each tank independently and the four tanks were aligned precisely. The tanks are made of copper-plated mild steel, whereas the vanes are made of solid copper. The rf contact between the vanes and the tank walls is achieved by spring-rings made of silver coated stainless steel.

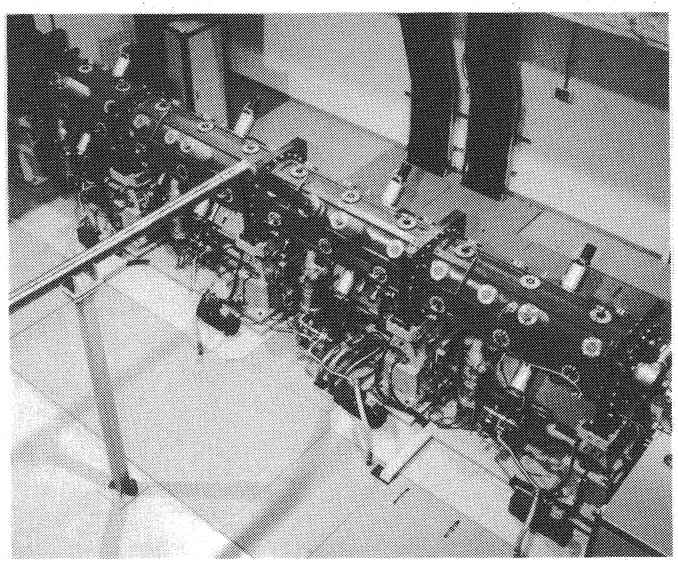

Figure 1. RFQ linac.

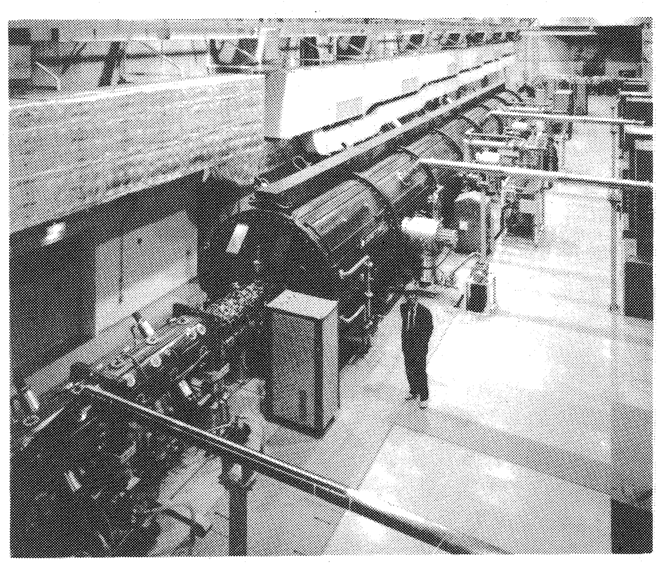

Figure 2. Overview of the Alvarez linac.

The Alvarez linac tank, 24 m long in total, is separated into three independent rf cavities. The tanks are made of copper-clad mild steel, and the drift tubes are copper-plated stainless steel. Each drift tube is supported by horizontal and vertical stems, 3 and 5 cm in diameter, respectively. An overview of the Alvarez linac is given in Figure 2.

Installation of the injector system was completed in February, 1993. The $^{4}He^{+}$ (q/A = 1/4) and $^{40}Ar^{8+}$ beams (q/A = 1/5) were successfully accelerated in the first operation. The maximum current of 400 μA (in $^{4}He^{+}$) was obtained after the Alvarez linac.

The typical parameters and characteristic values for the acceleration of $^{40}Ar^{8+}$ are summarized in Table 4. The observed values of the transmission for the both linacs were satisfactory.

Table 4. Typical parameters and characteristic values for acceleration of $^{40}Ar^{8+}$.

RFQ	
Injected beam intensity	36 - 38 μA
Extracted beam intensity	28 - 30 μA
Transmission of RFQ	~80 %
Rf pulse width	0.4 ms
Rf power	110 kW
Tank vacuum	1.0 x 10^{-7} Torr
Alvarez linac	
Injected beam intensity	28 - 30 μA
Extracted beam intensity	26 - 27.5 μA
Transmission of Alvarez	~90 %
Repetition rate	1 Hz
Rf pulse width	0.4 ms
Rf power	580 / 720 / 670 kW
Tank vacuum	0.7 ~ 1.4 x 10^{-7} Torr

Figure 3 shows the beam pulse shape after the Alvarez linac. The beam intensity was very stable (typically ±3%/2h without any changes in the operational parameters) and this good stability is largely attributed to the automatic phase control system newly developed.

An example of an emittance measurement is displayed in Figure 4. Measured values of emittance for the ^{40}Ar beams are 3.7π and 2.9π mm·mrad (unnormalized) for x and y directions, respectively. The measurements with 0.2 mm steps and the display finish in two minutes in a typical case.

We would like to thank the crew of Accelerator Engineering Corporation of their skillful operation.

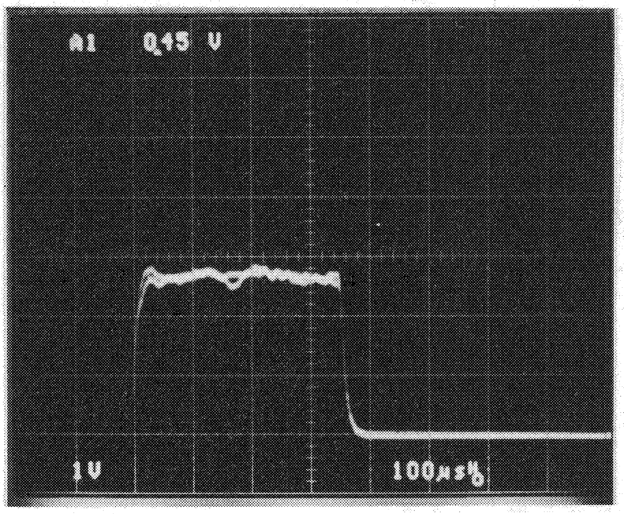

Figure 3. Observed beam pulse (output of a buffered amplifier) after the acceleration by Alvarez linac.

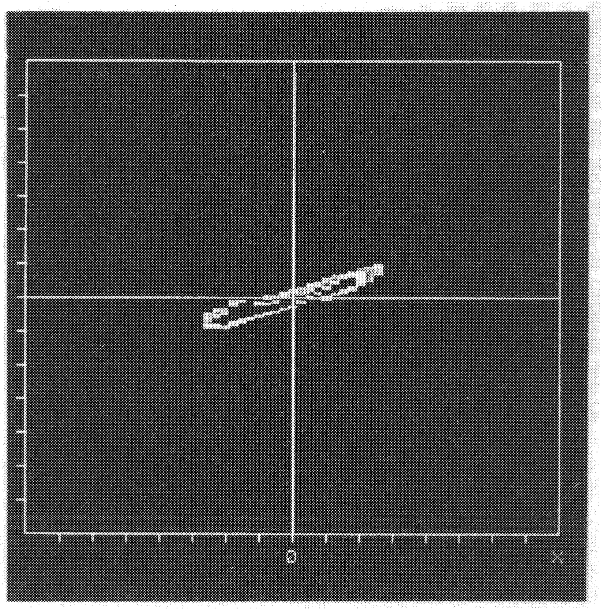

Figure 4. Display of the beam emittance.

V. REFERENCES

[1] Y. Hirao et al., "Heavy ion medical accelerator in Chiba," NIRS-M-89, HIMAC-001, 1 (1992).

[2] S. Yamada et al., "Injector system of HIMAC," Proc. 1990 Linac Conf., Albuquerque, NM, USA, 593 (1990).