Design and Operation of the HIMAC Injector

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Abstract

A heavy-ion synchrotron dedicated to medical use is under construction at the National Institute of Radiological Sciences, Japan. The injector system, comprising a PIG source, an ECR source, an RFQ linac, and an Alvarez linac of 100 MHz, accelerates heavy ions with a charge-to-mass ratio as small as 1/7, up to 6 MeV/nucleon. First operation of the injector system has shown satisfactory performance.

I. INTRODUCTION

A heavy-ion synchrotron, HIMAC (Heavy Ion Medical Accelerator in Chiba) [1], is under construction at the National Institute of Radiological Sciences (NIRS), Japan. HIMAC is the first heavy-ion accelerator dedicated to medical use in the world. Its 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, and the maximum energy is 800 MeV/nucleon for ions with a charge-to-mass ratio (q/A) of 1/2, corresponding to a range of 30 cm in tissue. The reliability of the accelerator is of great importance.

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.

The injector system has been completed and operation started in March, 1993.

Table 1. Specification of the injector system.

Ion species	$^{4}He \sim {}^{40}Ar$
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	$\leq \pm 1 \times 10^{-3}$

II. 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 sources are placed on platforms to which a high voltage of 60 kV can be applied.

A. PIG Source

The PIG source is an indirectly heated (hot) cathode

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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.

B. ECR Source

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

III. LINACS

A. RFQ Linac

The RFQ linac is a conventional type with four vanes. The cavity is mechanically separated into four tanks. 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.

A rather low frequency of 100 MHz was chosen to obtain a sufficient focusing strength. The calculated transmission efficiency exceeds 90% for a DC beam with a focusing strength of B = 3.8. The longitudinal and transverse voltage distributions are controlled by 40 side-tuners. Those tuners were welded after the voltage distribution was tuned within errors of 4.9% in the longitudinal and 2.6% in the transverse directions.

The transverse phase matching between the RFQ and Alvarez linac is achieved by a quadrupole-magnet quadruplet and steering magnets installed in the LLBT.

B. Alvarez Linac

The 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 RFQ and Alvarez linacs is given in Figure 1.

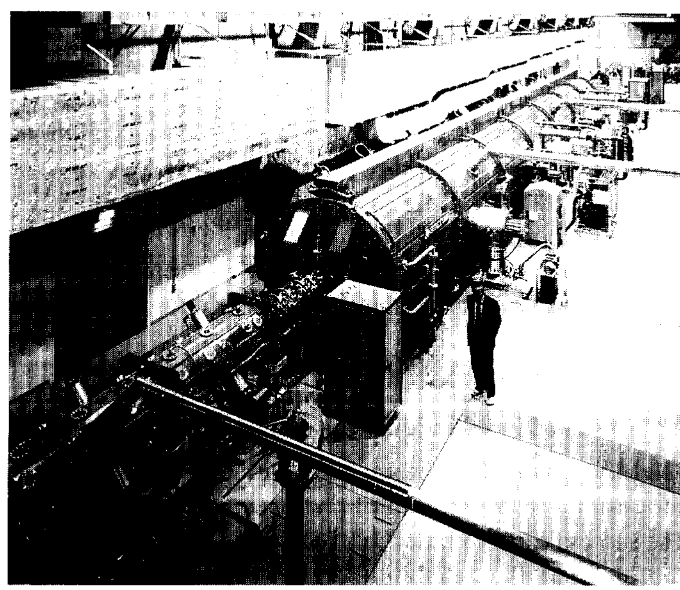

Figure 1. The RFQ and Alvarez linacs.

The number of unit cells is 106 and the gap-to-cell-length ratio is around 0.22. Every second drift tube is equipped with a quadrupole magnet. The Q-magnets have laminated cores and are excited by pulse power sources with a flat-top-duty of 0.3% to reduce the thermal loads. The 54 quadrupole magnets were designed in four categories: 70, 90, 135, and 165 mm in length, and 5.1, 4.0, 2.7, and 2.2 kG/cm in field gradient.

The tolerance of alignment of the Q-magnets was estimated with the program PARMILA. The transverse emittance growth is not serious when the alignment error is ≤0.1 mm in the transverse direction, including the errors of rotation (±1°), tilt (±1°), and excitation (±0.5%). The accuracy was achieved by an alignment telescope and an optical target inside a bore hole of the tube. The tilt of the acceleration field was tuned with side-tuners, which were welded after the tuning, within an error of 2%. The calculation, however, showed that a phase difference larger than ±3° between three tanks had large effects on the beam quality. An automatic phase control system was therefore developed so that the phase stability could be measured to be better than ±0.5°/8h.

Three sets of 1.4 MW amplifiers excite three cavities of the Alvarez linac. Each amplifier consists of a final stage and two driver stages (100 kW and 5 kW), which are equipped with power tubes of Siemens RS2074SK, RS2058CJ, and RS2032CL, respectively.

C. Control System

A control system consists of three hierarchical layers: a system control unit (SCU), a group control unit (GCU), and a universal device controller (UDC). The SCU of μVAX3500 mainly works as a man-machine interface. The GCU, comprising two μVAX II, directly controls the peripheral devices through the UDCs, which are 16-bit micro-computers installed in the devices. The SCU is connected through an ETHERNET to a central computer unit by which it communicates with other systems: a synchrotron system, a high-energy beam transport line, and a treatment control system. Another ETHERNET is installed to connect the SCU and the GCU. The UDCs are linked to the GCU with optical fiber lines. All devices are controlled at an operator console with four touch panels and three rotary encoders.

VI. PERFORMANCE OF THE LINACS

Installation of the injector system was completed in February, 1993. The beams of $^{4}He^{+}$ and $^{40}Ar^{8+}$ were successfully accelerated in the first operation about a month. The success of acceleration in a relatively short term made us confident of the reliability of the system. The typical parameters and characteristic values for the acceleration of $^{4}He^{+}$ (q/A = 1/4) are summarized in Table 4. The observed values of the transmission for the both linacs were satisfactory. Figure 2 shows the beam pulse shape after the Alvarez linac. The beam intensity was stable within ±3%/2h without any changes in the operational parameters.

Table 4. Typical parameters and characteristic values for acceleration of $^{4}He^{+}$ (q/A = 1/4).

RFQ	
Injected beam intensity	190 μA
Extracted beam intensity	167 μA
Transmission of RFQ	88 %
Beam width	1 ms
Rf power	86 kW
Tank vacuum	1.0×10^{-7} Torr
Alvarez linac	
Injected beam intensity	167 μA
Extracted beam intensity	138 μA
Transmission of Alvarez	83 %
Repetition rate	1.3 Hz
Rf pulse width	1.2 ms
Rf power	270 / 390 / 270 kW
Tank vacuum	$0.9 \sim 1.0 \times 10^{-7}$ Torr

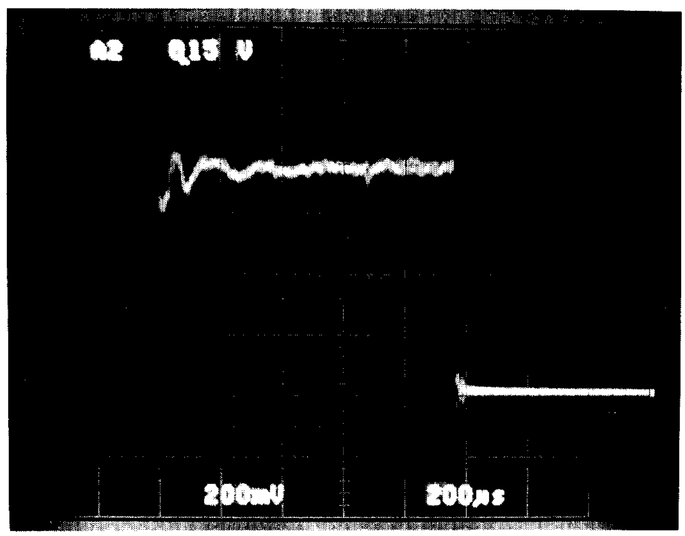

Figure 2. Observed beam pulse (output of a buffered amplifier) after the acceleration by Alvarez linac.

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

V. REFERENCES

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