CONSTRUCTION OF HIMAC INJECTOR

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Abstract

At National Institute of Radiological Sciences (NIRS), the Heavy Ion Medical Accelerator in Chiba (HIMAC) is now under construction. The HIMAC is dedicated to the medical use especially for the clinical treatment of tumor and will be the first heavy ion synchrotron complex in a hospital environment of Japan. This paper describes an outline of the design and construction of the HIMAC injector.

Introduction

Based on the long experience with the proton and neutron radiotherapy with an AVF cyclotron as well as the conventional photon therapy, NIRS has decided to construct the HIMAC[1),2)] for the clinical treatment of tumor. The HIMAC is an accelerator complex which consists of a 100 MHz injector linac, two separated function type synchrotron rings and a beam delivery system. The details of the major components of the accelerator complex are described in other articles submitted to this conference.[3)-5)] The PIG type ion source[6)] and the control system[7)] of the injector are also given in other articles. The construction of the facility started in 1987 and will continue until a fiscal year of 1993 when the clinical treatment is expected to start.

A layout of the injector system is given in Fig. 4 showing that the system consists of two types of ion source, an RFQ linac, three cavities of Alvarez type linac, a debuncher cavity and the beam transport lines between them. The specification of the overall injector system is presented in Table 1.

The ion species required for the clinical treatment range from ^{4}He to ^{40}Ar. The expected intensities will realize a dose rate of as high as 5 Gy/min·ℓ in a 14$\phi\times$ 10 (depth) cm^2 irradiation volume, so that the irradiation of heavy ions will be finished within a few minutes. An intensity schedule to achieve the required values is listed in Table 4 at each acceleration stage.

Ion Sources

Two types of ion sources are adopted: one is a PIG source for light ions, and another is an ECR source for heavier ions. Both sources are located independently on high voltage platforms. The maximum voltage on the platform is about 60 kV to accelerate ions up to 8 keV/u. A beam emittance of the sources is required to be less than 0.6 πmm·mrad normalized. Both sources are operated with pulse mode in which a duty factor is very low ($\leq$ 1%) for the PIG source and high ($\leq$ 50%) for the ECR source. The required pulse width of the ion beam is longer than about 200 μs, because the injection interval to the synchrotron is longer than 150 μs for an effective 20 turns.

The PIG source is a hot cathode type. The typical values for the magnetic field, the pole gap and the extraction voltage are 7 kG, 20 cm and 15 kV, respectively. A beam test of the PIG source is underway, and the obtained beam intensities exceed the required values given in Table 4 for ions up to Ne. Pulse operation of the source is very effective in increasing both intensity and lifetime of the source. The more detailed information is given in ref. 6.

To improve the heavier ion capability of HIMAC, an ECR source is expected to produce heavy ions up to xenon. A compact single stage structure is adopted for the source. The structure is similar to that of Caprice[8)] developed at Grenoble. The microwave ferequency and power are 10 GHz and 2 kW at maximum, respectively. Two solenoid coils with iron return yokes generate a peak axial magnetic field of about 1 T. A mirror ratio is designed to be so large that the second order ECR surface contributes effectively to generate high charge states of heavy ions.

A strong radial sextupole field is produced by NdFe permanent magnet installed outside the plasma chamber. A bore diameter of the multipole magnet is 7.6 cm. The extraction voltage of the source is about 15 kV. The development of the source has been performed in cooperation with INS, University of Tokyo and with RLNR, Tokyo Institute of Technology.

Table 1.
Injector specification.

Ion species	^{4}He to ^{40}Ar
Charge to mass ratio	$\geq 1/7$
Ion source type	PIG & ECR
Frequency	100 MHz
Repetition rate	3 Hz Max.
Duty factor	0.3% Max.
Acceptance	0.6 πmm·mrad (normalized)
Output beam emittance	$\leq$ 1.5 πmm·mrad (normalized)
Momentum spread	$\leq \pm 1 \times 10^{-3}$

Table 2
RFQ linac specification

Operation frequency	100 MHz
Input / Output energy	8 / 800 keV/u
Charge to mass ratio	1/7
Synchronous phase	−90 ~ −30 deg
Transmission efficiency	0.92
Number of unit cells	300
Vane length	725 cm
Cavity diameter	59 cm
Characteristic bore radius	0.54 cm
Minimum bore radius	0.29 cm
Maximum modulation	2.5
Focusing strength	3.8
Acceptance	145 πmm·mrad
Nornalized acceptance	0.6 πmm·mrad
Intervane voltage	81 kV
Maximum field	205 kV/cm (1.8 Kilpatrick)
Peak rf power	260 kW (70% Q)

RFQ linac

The ions are injected into an RFQ linac through a low energy beam transport line about 7 m long. A rather low value of 100 MHz is chosen for a frequency of the linac so as to give sufficient focusing strength. An acceptance of the injector is 0.6 πmm·mrad normalized (145 πmm·mrad unnormalized). The RFQ linac accelerates an energy range from 8 to 800 keV/u with a vane length of 7.3 m. The maximum surface field of the linac is chosen at a very high value of about 200 kV/cm (1.8 Kilpatrick) so as not to exceed the experimental value obtained with an RFQ cavity with almost the same geometry.[9)] The main parameters of the RFQ linac are given in Table 2.

A low value of 3.8 is chosen for the focusing strength to obtain a high acceleration efficiency. A calculated transmission efficiency exceeds 90% for a DC beam. A number of unit cells in the radial match-

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Table 3.
Alvarez linac specification.

	Tank 1	Tank 2	Tank 3
Synchronous phase (deg)	-30	-25	-25
Ion energy (MeV/u)	0.800 – 2.669	2.669 – 4.385	4.385 – 6.060
velocity (%)	4.127 – 7.526	7.526 – 9.634	9.634 – 11.31
Average axial field (MV/m)	1.808	2.102	2.102
Effective shunt impedance* (MΩ/m)	31.5 – 38.7	41.5 – 42.9	45.2 – 45.6
Transit time factor	0.825 – 0.853	0.869 – 0.867	0.888 – 0.880
Quality factor of cavity*	132,000	141,000	143,000
Tank length (m)	9.768	7.202	6.907
Acceleration rate (MeV/m)	1.34	1.67	1.70
Tank diameter (m)	2.20	2.18	2.16
Drift tube diameter (cm)	16.0	16.0	16.0
Drift tube length (cm)	9.85 – 16.45	17.99 – 21.72	22.90 – 25.73
Bore radius (cm)	1.0	1.5	1.5
Nose corner radius (mm)	20	30	30
Corner radius (mm)	10	10	10
Unit cell length (cm)	12.45 – 22.47	22.67 – 28.77	28.99 – 33.79
Gap to cell length ratio	0.214 – 0.265	0.210 – 0.242	0.213 – 0.236
Number of unit cells	56	28	22
Stem radius (cm)	5 and 3	5 and 3	5 and 3
Shunt impedance* (MΩ/m)	46.29 – 53.16	54.93 – 57.07	57.38 – 58.92
Required rf power* (kW)	870	810	760
Q-magnet sequence	FODO	FODO	FODO
Q-magnet length (cm)	6.0, 8.0	12.0	15.0
Field gradient (kG/cm)	6.0, 4.5	3.0	2.4
Phase advance (deg)	42	49	49
Acceptance (πmm·mrad)	67	—	—
Normalized acceptance (πmm·mrad)	2.8	—	—

* Superfish value including stem losses.

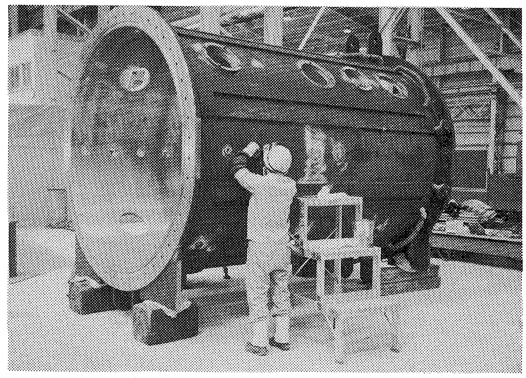


Fig. 1. Alvarez no.3 tank under machining.

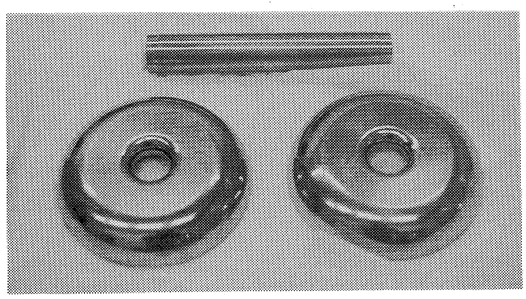
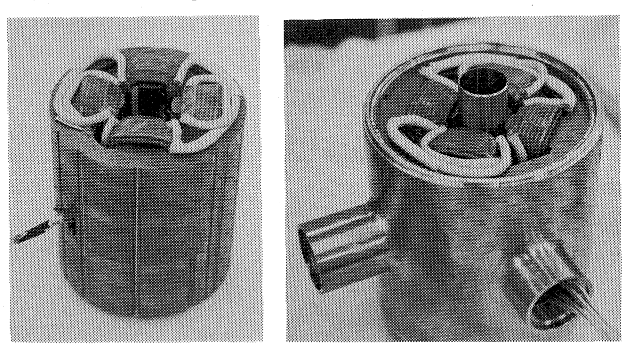


Fig. 2. Drift tube end plates and a bore tube.



(a) (b)

Fig. 3. A quadrupole magnet before (a) and after (b) assembling.

ing section is chosen to be 40 so that the convergence angle of the matched input beam is reduced to be about 60 mrad.

The RFQ linac has a conventional four vane type structure separated longitudinally into four tanks all of which are fed with a 300 kW peak rf power through a single loop coupler. The tank is made of copper plated mild steel, whereas the vanes are solid copper. The rf contact between vanes and the tank wall is achieved with silver coated stainless steel O-rings. The RFQ linac is essentially the same as that constructed at INS including the beam dynamic design parameters.[10)]

Alvarez type linac

The RFQ linac is followed by an Alvarez type linac operated with the same frequency of 100 MHz. The linac tank is separated into three independent rf cavities and each tank is fed with 1.2 MW peak rf power. The maximum surface field is chosen at 150 kV/cm (1.3 Kilpatrick). The linac tank is 24 m long in total, and consists of 106 unit cells. The diameter of the cavity is about 2 m and changes with one tank to the next in order to obtain reasonable values for the transit time factors. The major parameters of the Alvarez type linac is given in Table 3.

The beam dynamic calculations through the Alvarez linac are performed with a standard computor code PARMILA. The effects of the errors in the drift tube alignment and in the Q-magnet field strength and length are taken into accounts in the calculations. The emittance growth due to these errors are not so serious when the alignment error is $\leq \pm 0.1$ mm in the transverse direction together with the rotation error of $\pm 1°$, the tilt error of $\pm 1°$, and the excitation error of $\pm 0.5\%$. The ellipse parameters in the transverse phase diagram of the accelerated beam are almost kept constant against the error. The center of the ellipse, however, moves aroud the oringin and needs a set of steering magnets in the MEBT line to be matched with the optical axis.

The calculations are also made with the errors in the acceleration field including the field tilt and the phase errors. The phase differences between three tanks affects strongly on the output beam quality when they are $\geq \pm 3°$. The effects of the field tilt, however, are not serious even when the tilt is as high as 10%.

The tanks are made of copper-clad mild steel, and the drift tubes are copper-plated mild steel. A photograph of the third Alvarez tank being machined is given in Fig. 1. Figures 2 and 3 show two end caps and a bore tube, and a quadrupole magnet, respectively. Each drift tube is supported by a horizontal and a vertical stems the diameters of which are 3 and 5 cm, respectively. Every second drift tube is equipped with a quadrupole magnet for beam focusing. The magnets have laminated cores and are excited by pulse power sources with a very low flat-top-duty of 0.3% to reduce the heavy thermal loads. The Q-magnet loaded drift tube is cooled with a water jacket directly welded to the inside wall of the tube. The hollow drift tube is also cooled by water directly flowing through the tube. The cooling water is treated and very well regulated in temperature ($\pm 0.1°$) to reduce the duty of the automatic frequency tunner. The water which cools the linac tank is not treated but well regulated. Special care is also taken to the air conditioning system of the accelerator room.

The third Alvarez tank is now its final test stage. The high power tests will begin at early next year.

RF system

An rf amplifier of the Alvarez linac is designed to deliver more than 1.4 MW and is equipped with Siemens's RS 2074 SK which is the same vacuum tube as that adopted by GSI to get more than 1.8 MW peak rf power (25% duty) for 100 MHz Alvarez linac. In the two driver stages of the amplifier system, the vacuum tubes of RS 2058 CJ and RS 2032 CL are used to deliver the rf powers of 100 kW and 5 kW, to the next stages, respectively.

Three sets of the 1.4 MW amplifier system will be used to excite three Alvarez cavities. The high voltage power supply for the amplifiers, however, is not separated into three independent power supplies

Table 4.
Beam intensity schedule for typical ions

Ion species	He^{2+}	C^{6+}	Ne^{10+}	Si^{14+}	Ar^{18+}
Extracted intensity (pps)	1.2×10^{10}	2.0×10^{9}	8.5×10^{8}	4.5×10^{8}	2.7×10^{8}
Injected ion intensity (pps)	1.1×10^{15}	1.8×10^{14}	7.8×10^{13}	4.1×10^{13}	2.4×10^{13}
Injected ion current (eμA)	340	170	120	91	69
Beam transport transmission			0.75		
Stripper efficiency	1.0	0.93	0.67	0.52	0.18
(Charge states)	(1+ → 2+)	(2+ → 6+)	(3+ → 10+)	(4+ → 14+)	(6+ → 18+)
Alvarez linac transmission			0.9		
RFQ linac transmission			0.8		
Beam transport transmission			0.7		
Source electrical current (eμA)	630	160	140	130	340
Ions from source	He^{1+}	C^{2+}	Ne^{3+}	Si^{4+}	Ar^{6+}

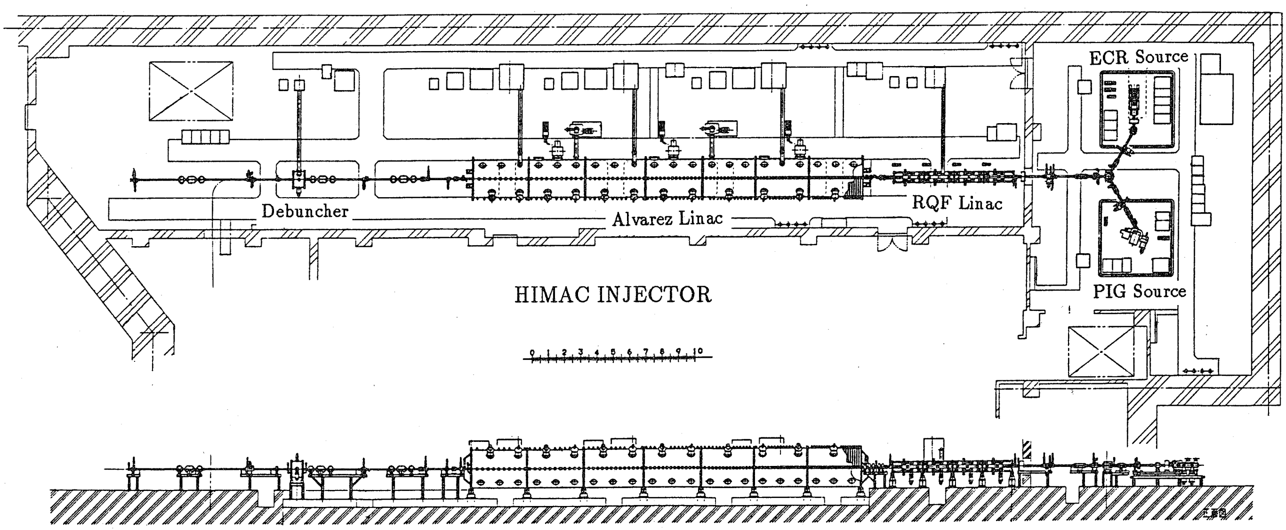


Fig. 4. A layout of the HIMAC injector.

but a unified one having a large condensor bank. The construction of the amplifier system for Alvarez tank no.3 is already finished including the dummy load tests.

In a 300 kW amplifier for the RFQ linac, the Eimac tubes are adopted: 4CW 100,000 E for the final stage and 4CX 20,000 C for the driver stage. The 4CX 20,000 C tube is also used as a final tube for the debuncher cavity which requires 30 kW peak rf power.

Charge stripper & debuncher

At the output end of the Alvarez linac, an automatic changer for carbon stripping foils is installed. Only one stripping section is used at a relatively high ion energy because of the reliability of the system and of future expansion to the acceleration of the heavier ions.

After the foil, the fully stripped ions are obtained more than 18% up to Ar. The charge to mass acceptance of the medium energy beam transport (MEBT) line is designed to be $q/A \geq 1/4$ in order to ensure the heavier ion capability of the HIMAC.

A 100 MHz debuncher cavity is introduced in the MEBT line to suppress the momentum spread of the accelerated beam. A distance between linac end and the debuncher cavity is optimized to be about 9 m. The maximum phase spread at the acceleration gap in the debuncher cavity is estimated to be ±45° from the PARMILA calculations. An rf voltage of 300 kV (for $q/A = 1/4$) rotates the beam bunch in longitudinal phase space, and reduces the energy spread of the linac beam from $\Delta W/W = \pm 1.2\%$ to a satisfactorily good value of ±0.11%. Some kind of tuning error of the Alvarez linac, however, tends to increase the energy spread up to more than ±0.2%.

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