INJECTOR SYSTEM OF HIMAC

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Abstract

This paper describes a brief review of a design of an injector system of a synchrotron facility for heavy ion therapy, HIMAC. Some results of rf measurements of an Alvarez type acceleration cavity are also described. Construction of major components of the injector system started in 1987, and will be completed within 1992.

Introduction

As a direct expansion of our long experience with proton, neutron and photon radiotherapy, a heavy ion synchrotron has been adopted for the clinical treatment of tumors at NIRS.[1,2] The superiority of the heavy ion therapy is characterized by excellent dose localization. Another important feature of this type of therapy is a very high value of a linear energy transfer to tumor cells resulting in a low oxygen enhancement factor.

HIMAC is an accelerator facility dedicated to medical use especially for the clinical treatment of tumors. It will be the first heavy ion synchrotron complex in a hospital environment in Japan. The accelerator consists of a 100 MHz injector linac, two separated function type synchrotron rings and a beam delivery system.

The maximum output energy of HIMAC is 800 MeV/u for ions with $q/A = 1/2$. The ion species required for the clinical treatment range from ^{4}He to ^{40}Ar. A beam intensity from the HIMAC synchrotron is determined so that a dose rate as high as 5 Gy/min·ℓ is realized in a 14 (diameter)×10 (depth) cm^2 irradiation volume. The irradiation of heavy ions can be completed within a few minutes, and a set of more than ten times of such irradiation is required through about a one month to treat human cancers.

The facility has three treatment rooms two of which are equipped with vertical beam lines. The horizontal beam will be introduced to the two treatment rooms. The construction of the facility will continue until fiscal year 1993 when the clinical trials are expected to start.

Injector design

The injector system of HIMAC comprises a PIG source for light ions, an ECR source for heavier ions, an RFQ linac of 100 MHz and three Alvarez type linac tanks with the same frequency. A debuncher cavity is to be installed in an output beam transport line in order to reduce a momentum spread. The system has no charge stripper either between or before the linac tanks, and will accept heavy ions with a charge-to-mass ratio as small as 1/7.

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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)
RFQ linac	
Input/Output energy	8 / 800 keV/u
Vane length	7.3 m
Cavity diameter	0.59 m
Max. surface field	205 kV/cm (1.8 Kilpatrick)
Alvarez linac	
Input/Output energy	0.8 / 6.0 MeV/u
Total length	24 m (3 rf cavities)
Cavity diameter	2.20 / 2.18 / 2.16 m
Average axial field	1.8 / 2.1 / 2.1 MV/m
Shunt impedance	31 – 46 MΩ/m (effective)
Max. surface field	130 kV/cm (1.1 Kilpatrick)
Focusing sequence	FODO (6.0 kG/cm Max.)
Output beam emittance	$\leq$ 1.5 πmm·mrad (normalized)
Momentum spread	$\leq \pm 1 \times 10^{-3}$

The specifications and a layout of the overall injector system are presented in Table 1 and Fig. 2, respectively. Expected beam intensities of the injector linac are listed in Table 2 for typical ions.

Ion Source

Two types of ion sources are adopted: one is a hot cathode type PIG source for light ions up to around Ne, and another is an ECR source for heavier ions. Both sources are located independently on high voltage platforms with a maximum voltage of 60 kV.

Beam tests of the PIG source are now under way, and the obtained beam intensities exceed the required values given in Table 2 up to Ne for both DC and pulsed operation.[3] The source is equipped with a bombard electrode and will provide solid ion species.

The 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[4] developed at Grenoble. The microwave frequency and power are 10 GHz and 2 kW at maximum, respectively. The maximum strength of an axial magnetic field is about 1 T with seven solenoid coils excited by 45 kW in total. A transverse field generated by a NdFe permanent sextupole magnet reaches about 0.8 T at the chamber wall.

RFQ Linac

The ions pass through a low energy beam transport line about 7 m long before injection into an RFQ linac.

Table 2
Beam intensity schedule for typical ions.

Ion species	C^{6+}	Ne^{10+}	Ar^{18+}
Output current (eμA)	170	120	69
Transport transmission		0.75	
Stripper efficiency	0.93	0.67	0.18
Alvarez transmission		0.9	
RFQ transmission		0.8	
Transport transmission		0.7	
Source current (eμA)	160	140	340
Ions from source	C^{2+}	Ne^{3+}	Ar^{6+}

A rather low value of 100 MHz is chosen for the linac so as to give sufficient focusing strength. An acceptance of the linac is 0.6 πmm·mrad normalized (145 πmm·mrad unnormalized).

The linac is a conventional four vane type and separated longitudinally into four tanks. The four vanes are precisely set in each tank independently. A longitudinal and a transverse voltage distributions are tuned with about 40 side tuners. The tuners are fixed by welding after the voltage tuning. A vane coupling ring has not been adopted for this linac.

The entire linac tank is 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 the vanes and the tank wall is achieved with silver coated stainless steel spring-rings.

Alvarez Type Linac

The RFQ linac is followed by an Alvarez type linac operated at the same frequency. The linac tank is separated into three independent rf cavities and each cavity is fed with an rf power of 1.4 MW peak. The maximum surface field is chosen to be 128 kV/cm (1.13 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 tanks are made of copper-clad mild steel, and the drift tubes are copper-plated stainless steel. The thicknesses of the clad and plated copper are 8 mm (before machining) and 100 μm, respectively. A photograph of an inside view of the third Alvarez tank is given in Fig. 1. Each drift tube is supported by horizontal and vertical stems, the diameters of which are 3 and 5 cm, respectively. Every second drift tube is equipped with a quadrupole magnet. The magnets have laminated cores and are excited by pulse power sources with a very low flat-top-duty of 0.3% in order to reduce the heavy thermal loads.

RF System

An rf amplifier of the Alvarez linac is designed to deliver more than 1.4 MW and is equipped with a power tube of Siemens's RS 2074 SK. In the two driver stages of the amplifier system, RS 2058 CJ and RS 2032 CL vacuum tubes have been adopted and deliver rf powers of 100 and 5 kW, respectively. Three sets of 1.4 MW amplifiers with a single plate power supply will be used to excite the three Alvarez cavities. The construction of the amplifier for Alvarez tank no.3 is already finished, including high power tests.

In a 300 kW amplifier for the RFQ linac, the Eimac tubes have been adopted: 4CW 100,000 E for the final stage and 4CX 20,000 C for the driver stage. A 30 kW

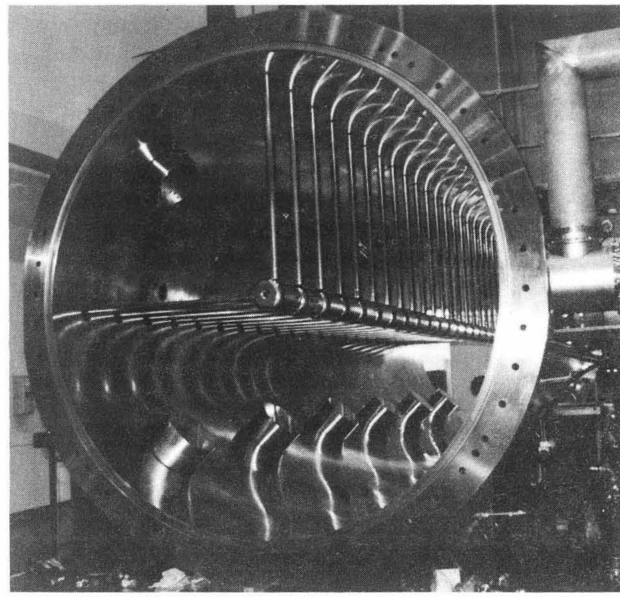

Fig. 1. An inside view of no. 3 Alvarez type linac tank.

amplifier for the debuncher cavity is the same as the driver amplifier.

Charge Stripper and Debuncher

At the output end of the Alvarez linac, a 100 μg/cm^2 carbon stripping foil is installed in order to improve a charge to mass ratio for further acceleration. 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 heavier ions.

A 100 MHz debuncher cavity is introduced in the output beam line to suppress the momentum spread of the accelerated beam. A distance between linac end and the debuncher cavity has been optimized to be about 9 m. 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 $\pm 0.11\%$. Some kind of tuning error of the Alvarez linac, however, tends to increase the energy spread up to more than $\pm 0.2\%$.

Control System

A computer system of the injector consists of three mini-computers: a system control unit (SCU) of μVAX 3500 and two group control units (GCU) of μVAX II. The SCU mainly covers the man-machine interface and controls the injector as a total system, whereas the GCU directly controls a peripheral device through a universal device controller (UDC), which is a 16-bit micro-computer installed within the device.

The SCU is connected to a central computer unit through an ethernet by which other control units for a synchrotron system and a high energy beam transport system etc. communicate with each other. A control computer for medical treatment will also be connected to the network. Another ethernet is used to ensure communication between the SCU and the GCUs. The GCU and a UDC are linked with an optical fiber line.

All devices in the injector system, including a timing unit, are controllable from an operator console with four touch panels and three rotary encoders.

Rf Characteristics of Alvarez No.3 Tank

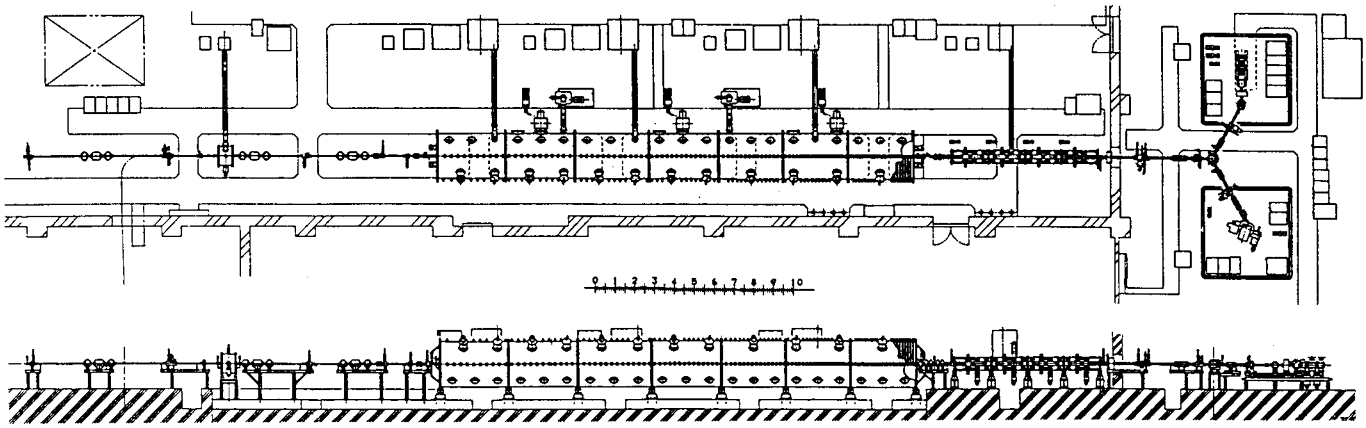

Fig. 2. A layout of the HIMAC injector.

An inside diameter of the tank was machined within an error of ±0.3 mm. After that, the copper surface was treated with a orbital sander to a surface roughness of 0.4a (1.2s). An alignment accuracy of better than ±0.1 mm has been achieved for the transverse position of a drift tube with an alignment telescope and an optical target inside a bore hole of the tube. The bore hole was machined with an accuracy of ±10μm after measurements of a center position of the quadrupole field. A longitudinal positioning error of the drift tube was measured to be better than ±0.2 mm.

Low Power Tests

A resonant frequency of the cavity exists very close to a desired value with calculated positions of a frequency tuner. The frequency is about 1 MHz apart from the nearest neighboring mode of TM_{011} (Q_0 is about 50,000). An unloaded Q-value, Q_0, of the fundamental TM_{010} mode was measured to be 88,000 for a virgin tank and about 70% of a calculated value including stem losses.

A tilt of the acceleration field was tuned with six side tuners within an error of 2%. The positions of the tuners were fixed after the low power measurements by welding. A small jump (about 2%) in the acceleration field appears at the end of the tank where a unit cell volume is a little bit reduced with a 2.5 cm thick copper wall separating the cavity from the next one.

Field and frequency measurements were carried out in order to obtain dependencies on a longitudinal position and a radius of an end drift tube. All efforts, however, resulted in little effects on the compensation of the field jump at the end cell.

A field distribution in the acceleration gaps was also measured with a bead pull method. The results were very well reproduced by the calculated values.

The resonant frequency changes with the cavity temperature by 1.2~1.4 kHz/deg and the value agrees well with a calculated one.

High Power Tests

A full design power was successfully injected into the virgin cavity after conditioning of about one whole day. There was no visible damage to the coupling loop and any other components. A maximum surface field of 150 kV/cm (1.3 Kilpatrick) is stably obtained.

A length of a coaxial line between the amplifier and the cavity is optimized with a trombone tuner so that coupling between the amplifier and the cavity takes its minimum value. A rise time (0 to 90% value) of the field level is about 500 μs without any feed back loop, and about 50% longer than a simply predicted value of 320 μs. The rise time, however, is reduced to about 400 μs with an automatic gain control loop. A flatness better than $\pm 1 \times 10^{-3}$ is obtained in the duration of more than 700 μs for an rf pulse width of 1.2 ms.

Phase stability was measured to be better than ±0.5°/8hr with an automatic phase controller, and well within the acceptable range. After a long run test of 24 hr, the unloaded Q-value of the cavity was improved to 102,000 (79% of Superfish value).

Construction Schedule

Mechanical construction of a debuncher cavity is already finished and rf measurements are now under way. Major part of the RFQ linac is machined and the fabrication will be finished soon. Machining of the Alvarez no.1 and 2 tanks has already started and will be completed early next year. Tests of parallel operation of the three Alvarez cavities is scheduled in the middle of the next year.

After characteristic measurements, all components will be carried into NIRS during the last part of 1991. The first beam from the synchrotron will be obtained in 1993.

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