Design, Manufacture, and Performance Test of the Injector for Hyogo Hadrontherapy Center

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Abstract

The injector for the Hyogo Hadrontherapy Center, which is mainly composed of two ECR ion sources, an RFQ linac (RFQ), and a drift tube linac (DTL), was manufactured by Sumitomo Heavy Industries, Ltd. The performance tests have been finished successfully for the ion sources, RFQ, and DTL before shipment. For the ion sources, the beam intensities and emittances were measured, and sufficient performance was obtained for each ion. For the RFQ and DTL, the resonant frequencies and the electric fields were tuned with low power RF, and high power RF operation at the design voltage was continued about ten hours. Sufficient performance was obtained in these tests.

1. Introduction

Hyogo Hadrontherapy Center is the cancer therapy facility which is being constructed in Harima Garden City by the Hyogo prefectural government.[1] The facility, which accelerates proton and helium beams up to 230 MeV/nucleon and carbon beam to 320 MeV/nucleon, consists of an injector, a synchrotron, and a beam delivery system. The injector accelerates ion beams of H_2^+, He^{2+}, and C^{4+} to 5 MeV/nucleon. It was manufactured by Sumitomo Heavy Industries, Ltd.(SHI), and has been just installed at the site. This paper describes the design and manufacture of the injector, and also describes the test results performed before shipment.

2. Design and manufacture of the injector

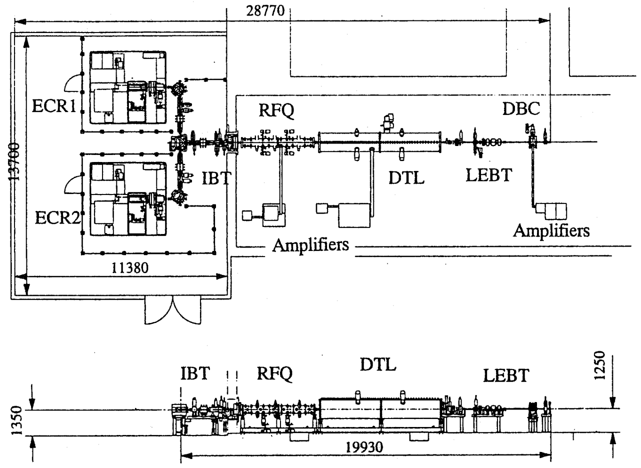

Figure 1 Layout of the injector.

The Injector consists of two ECR ion sources (ECR1,ECR2), an ion source beam transport line(IBT), an RFQ, a DTL, and a low energy beam transport line(LEBT) as shown in fig. 1, and the beam specifications at the end of the injector are listed in Table 1. The beam intensities are required to obtain the dose rate of 2 Gy/min for patients:

Table 1 Beam specifications at the end of the injector

Ion and intensity (μA)	H^+	390
	He^{2+}	290
	C^{6+}	72
Energy (MeV/nucleon)	5.0	
Normalized emittance (mm·mrad)	1 π	
Momentum spread (%)	±0.15	
Maximum repetition rate (Hz)	2	
Beam pulse width (μs)	120	

2.1 *ECR ion source(ECR1,ECR2)*

The injector has two ECR sources to change the ions supplied to the synchrotron as soon as possible, and the sources have entirely the same structure to facilitate operation and maintenance. Hence, it is possible to extract H_2^+, He^{2+}, and C^{4+} beams from both sources.

The ECR ion sources have the same structure as the 10GHz ECR source for HIMAC except for a few improvements on the magnetic field structure. Each source has a single closed ECR zone, and 10GHz microwave power is fed into the cylindrical plasma chamber which is surrounded by two mirror coils, permanent magnets and a return yoke. The mirror coils form an axial mirror field of 1.0T at maximum, and the permanent magnets form a radial sextupole field of 0.88T on the wall surface of the chamber. These values are about 10 % higher than the HIMAC ECR. The microwave power sources, with a maximum output of about 1.8 kW, are operated in both continuous wave (CW) mode and pulsed mode. The extracted beam at 25 kV is focused by a einzel lens mounted with a movable extractor, and is transported to the IBT.

2.2 *Ion beam transport line (IBT)*

The IBT separates the objective ions from the other ions, and injects them to the RFQ satisfying the longitudinal and transverse matching conditions. The beam from the source is accelerated to 35 keV/nucleon at an acceleration gap located downstream of the einzel lens. The objective ion beam is separated by a 90 degree bending magnet (BM) downstream of the acceleration gap, and the beam is bent toward the beam axis of the RFQ by the switching magnet (SWM). Three electrostatic quadrupole triplets are installed to focus and transport the beam, and a solenoid coil is located at the end of the IBT to focus the beam into the RFQ. Four faraday cups and a emittance monitor are also installed on the IBT as beam diagnostics.

2.3 *Radio-frequency quadrupole linac (RFQ)*

The RFQ accelerates the injected beam up to 1 MeV/nucleon, and the main parameters are shown in Table 2. The resonant frequency of 200MHz is selected for each linac in order to make the cavity diameter small, though the frequency is not usually adopted to heavy ion linacs but to proton ones because of the difficulty to obtain enough focusing strength with the quadrupole magnets in the DTLs. This problem is discussed further in the next section.

Compared with the difficulty in the DTL, it is not so difficult to design the 200MHz RFQ to accelerate the heavy ion beams. Since the RFQ is designed with a low field (1.6 times of Kilpatrick's limit) to achieve stable operation, the vanes are relatively long in spite of the low acceleration voltage of 2.9 MV. The transverse acceptance and the transmission ratio is calculated to be 1.17πmm·mrad and 97 % for the injection current of 0 mA, and we have succeeded in obtaining the satisfactory design performance.

Table 2 Main parameters of the RFQ

Injection energy (keV/nucleon)	35
Ejection energy (MeV/nucleon)	1
Normalized acceptance (mm·mrad)	1.17π
Inside diameter of tank (m)	0.35
Vane length (m)	3.9
Required RF power (kW)	250 at 60% Q

2.4 *Drift tube linac (DTL)*

The DTL accelerates the injected beam up to 5 MeV/nucleon, and the main parameters are shown in Table 3. Each drift tube containing a quadrupole magnet is supported by a stem and aligned to the beam axis within an error of ±0.1mm.

Table 3 Main parameters of the DTL

Injection energy (MeV/nucleon)	1.0
Ejection energy (MeV/nucleon)	5.0
Normalized acceptance (mm·mrad)	6.4π
Inside diameter of tank (m)	1.0
Length of tank (m)	6.45
Average field gradient (MV/m)	2.6
Required RF power (kW)	920 at 70% Q

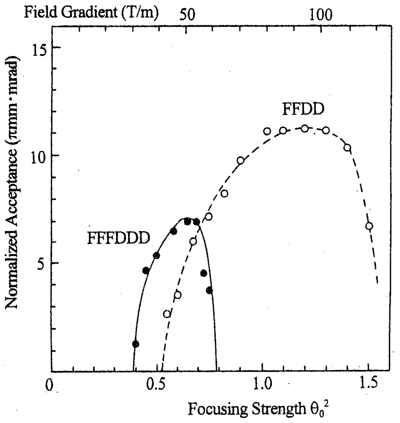

Fig. 2 Relation between normalized acceptance and field gradient in the first cell of the DTL.

As discussed in the RFQ section, the resonant frequency of 200 MHz is not usually adopted to heavy ion linacs, though, we decided to do it in order to make the cavity diameters small. If the focusing magnets are arranged in the polarity grouping of FDFD or FFDD, it is impossible to obtain an enough transverse acceptance with achievable field gradients. Thus, an FFFDDD polarity grouping is chosen and enough normalized acceptance of 6.4 πmm·mrad is obtained with a field gradient of 45 T/m as shown in Fig. 2. Transmission ratio is also calculated to be 100%, then we have succeeded in obtaining the satisfactory design performance.

2.5 *Low energy beam transport line (LEBT)*

The LEBT has two kinds of functions, namely, to fully strip the accelerated ions, and to reduce the momentum spread below the acceptable value for the synchrotron. In order to achieve the first requirement, a carbon foil stripper is installed just downstream of the DTL, and H_2^+ and C^{4+} are transformed to H^+ and C^{6+} through the foil. For the second requirement, a debuncher (DBC) of a re-entrant structure is positioned 5m downstream of the DTL. The momentum spread of ±0.67% decreases to ±0.15% at the gap, and the beam is supplied to the synchrotron.

2.6 *RF system*

The RF system is composed of the three sets of components, which are RF control circuits, a transistor amplifier, and one or two tetrode tube amplifiers, to drive the RFQ, DTL, and DBC, separately. The tube types used in the amplifiers are shown in table 4. 200MHz signal from a signal generator is divided into the three, and the amplified signal through the components is fed to each cavity. The maximum output power is designed to be 1.35MW for the DTL, 310 kW for the RFQ, and 21kW for the DBC, respectively. The RF control circuits are composed of an automatic gain controller (AGC), an automatic phase controller (APC), and an automatic frequency controller (AFC). The AGC and APC work to keep the RF amplitude and the phase in the cavity constant, and AFC keeps the resonant frequency at 200MHz.

Table 4 Tube types used in amplifiers

Cavity	Maximum output power	Tube type
RFQ	310 kW	4CX100KE
	21 kW	4CX12KE
DTL	1.35 MW	8973
	80 kW	RS2058
DBC	21 kW	4CX12KE

Table 5 Computer control system for the injector

Controller	Hardware	OS
Man/machine Controller	Personal computer	Windows-NT
Group controller	VME bus micro-computer unit	Tornado
Device controller	One board micro-computer equipped in each device	-

2.7 *Control and Computer system*

All components are remotely controlled by a computer system, which has a three layer structure of controllers shown in table 5. The group controller receives commands from the man/machine controller, and controls all components via device controllers.

3. Performance tests of the injector

3.1 ECR ion sources and IBT

The two ion sources and IBT were assembled in the clean shop at SHI, and the performance tests were finished successfully in 1998. Table 6 shows the test results. Beam intensities were measured with the faraday cup at the end of the IBT for both sources, and emittances were measured just upstream of the faraday cup only for the ECR1. Comparing the performance of both sources, almost the same intensities are obtained under similar operation parameters. The required intensities at the IBT end to satisfy the specifications in table 1 are 105 μA for C^{4+}, 500 μA for He^{2+}, and 380 μA for H_2^+. The measured intensities are several times higher than the required values and measured emittances are lower or slightly higher than the specification in table 1. Thus, even if some emittance degradation happens in the linacs, the specifications will be certainly achieved.

Table 6 Result of performance tests for the ECR ion sources. Upper values are for ECR1 and lower for ECR2.

Ion species	C^{4+}	He^{2+}	H_2^+
Beam intensity at the end of IBT (μA)	450 580	1200 1320	1300 1500
Horizontal mormalized emittance (πmm·mrad)	0.52 -	0.96 -	1.00 -
Vertical normalized emittance (πmm·mrad)	0.48 -	0.87 -	1.13 -

3.2 RFQ

After assembling the RFQ, the RF characteristics tests were performed with low power RF as follows. The resonant frequency and the field distribution were tuned by adjusting the projection volume of the cylindrical block tuners inside the cavity. Figure 3 shows the tuned filed distribution, which has axial flatness to within ±2.5% and azimuthal symmetricity to within ±1.2%. The field uniformity is high enough to achieve the design performance for the beam acceleration. The quality factor was measured to be 7900 that is 62.7 % of the value calculated with SUPERFISH, then the RF power of 240 kW is required to excite the cavity at the designed vane voltage.

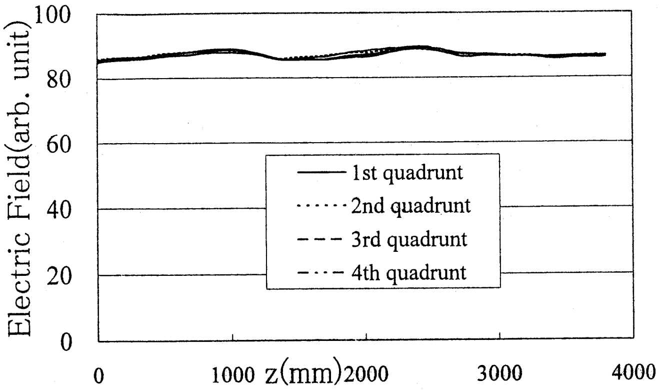

Figure 3 Tuned field distribution of the RFQ.

Following the performance test with low power RF, the RFQ was connected to the RF amplifier system with a 120D coaxial line, and high power RF was fed into the RFQ. After aging operation lasting several days, 6% higher voltage than the design value was applied to the vanes under the operating condition of 0.5 ms RF pulse duration at 4 Hz.

Finally, high power operation at the designed vane voltage was continued for 14 hours, and we finished all performance tests for the RF characteristics successfully.

3.3 DTL

The resonant frequency and the acceleration field were tuned with the same method as for the RFQ. Figure 4 shows the tuned field distribution, which has the axial flatness to within ±3%. The field uniformity is also high enough to achieve the design performance for the beam acceleration. The quality factor was measured to be 60200 that is 78.3 % of the calculation. Thus, the RF power of 820 kW is required to excite the cavity at the designed acceleration voltage.

Following the performance tests with low power RF, aging operation was continued in the manner similar to the RFQ, and 6% higher voltage than the design value was also applied to the drift tubes under the operating condition of 1 ms RF pulse duration at 2 Hz.

Finally, high power operation at the designed acceleration voltage was continued for 8 hours, and we had finished all performance tests for the RF characteristics successfully.

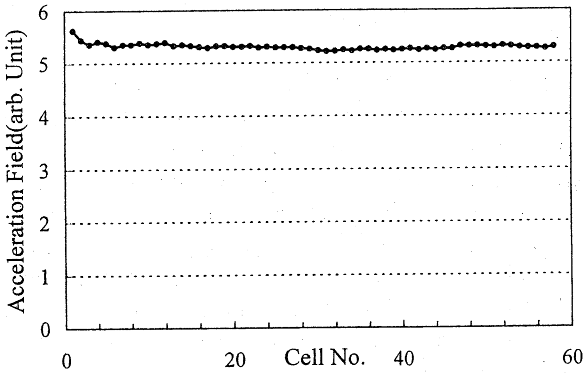

Figure 4 Tuned field distribution of the DTL.

4. Conclusion

The performance tests have been finished successfully for the ECR ion sources, RFQ, and DTL before shipment. For the ion sources, the beam intensities and emittances were measured near the end of the injection beam line of the RFQ, and sufficient performance was obtained for each ion. For the linacs, the resonant frequencies and the electric fields were tuned with low power RF, and high power operation at the design voltage was continued about ten hours. Sufficient performance was obtained in these tests.

References

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