# Accelerator Facility PATRO for Hadrontherapy at Hyogo Ion Beam Medical Center

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**Abstract**

Hyogo prefecture government has started a design and construction of accelerator facility PATRO (Particle Accelerator for Therapy, Radiology and Oncology) for hadrontherapy (Particle therapy) in 1995. The facility consists of two 10 GHz ECR ion sources, 1 MeV/u RFQ linac, 5 MeV/u Alvarez linac, synchrotron, high-energy beam transport system and patient irradiation system. Beam particles for therapy are proton (230 MeV) and carbon (320 MeV/u). We have 5 treatment rooms including two isocentric proton gantry ports. Beam test finished last year and we have now a full intensity beam which enables a dose rate of about 5 GyE/min. Transverse dose uniformity is obtained by the wobbling method. Ridge filter is used to obtain a spread-out Bragg peak (SOBP). Clinical trial by proton has successfully started this May. Clinical trial by carbon is expected to start after completion of the proton trial.

## 1. Introduction

Hyogo prefecture government had started a construction of the accelerator facility PATRO (Particle Accelerator for Therapy, Radiology and Oncology) for hadrontherapy since 1995 in Harima Science Garden City, which has about 2000 ha surface and is located about 75 km north-west of Kobe city. It is the major accelerator facility in the city together with a synchrotron radiation accelerator facility SPring-8 as shown in Fig. 1. It is also a first hadrontherapy facility in Japan that is constructed by a non-national but a prefecture government level [1-4].

## 2. Specifications of the Facility

Beam particles of the accelerator facility include proton, helium and carbon. Beam energy ranges are 70 - 230 MeV/u (40 – 300 mm range in human tissue) for proton and helium, and 70 - 320 MeV/u (17 – 200 mm range) for carbon. The beam intensities are required to satisfy the dose rate of 5 GyE/min. for treatment volumes of 15 cm field size in diameter and of fully extended spread out Bragg peak (SOBP) over the maximum beam range. The facility consists of injector, synchrotron wit 93.6 m circumference, high-energy beam transport lines and patient irradiation system. Fig. 2 shows a schematic bird's eye view of the accelerator facility with photographs of its components in each system. The injector has two 10 GHz ECR ion sources with 35 keV/u output energy, 1 MeV/u RFQ linac, 5 MeV/u Alvarez linac and debuncher. The Alvarez linac accelerates $H_2^+$, helium (Q/A=1/2) and carbon (Q/A=1/3) up to 5 MeV/u. A stripper located downstream of it makes proton and fully stripped carbon ion. Operation rf frequency of the linacs is 200 MHz. Debuncher then reduces a momentum spread of the beam. Synchrotron ring is of a separated function type with a strong FODO focusing structure and its super periodicity is 6. Maximum rigidity of the ring is 5.58 Tm. The beam is extracted by the third-order resonance scheme. rf knockout extraction is also available to gate the extracting beam by patient's breezing. We have 5 treatment rooms: with Oblique (45-deg) port A, Horizontal and Vertical ports B, Horizontal port with patient seated position C (A-C for carbon and proton) and two isocentric proton gantry ports G1 and G2. Ports in A and B has a large irradiation field (15cmx15cm). Another horizontal port in C has a small irradiation field (10cmϕ ). Gantry ports G1 and G2 have an irradiation field with 15cmϕ. A wobbler beam

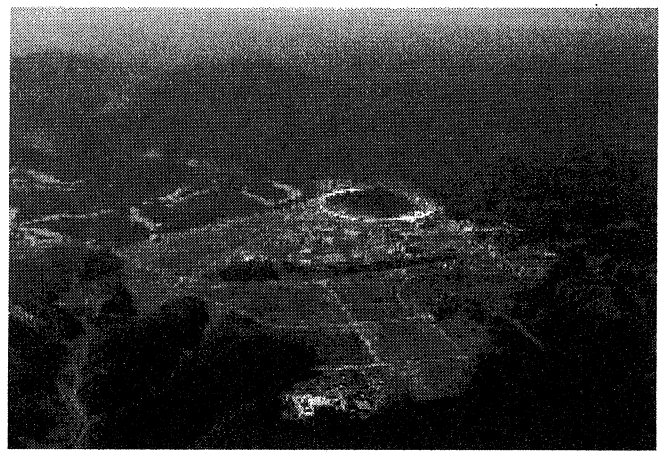
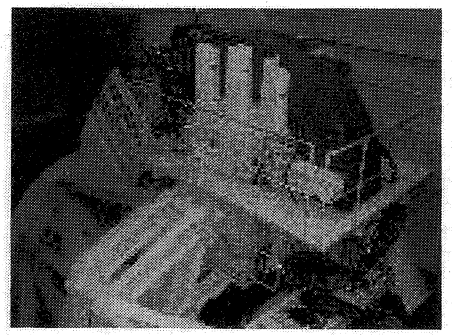
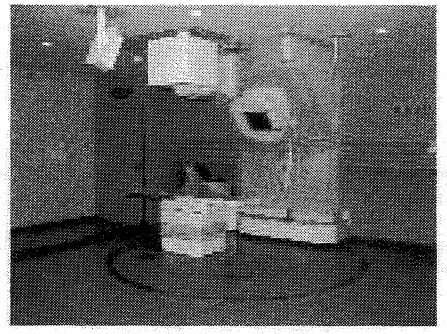


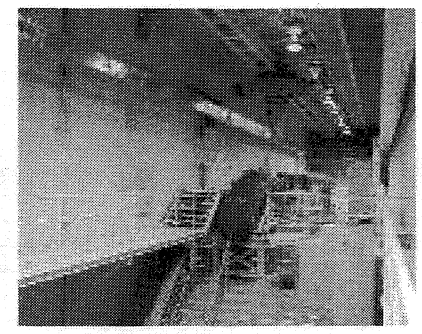
Fig. 1 Hyogo Ion Beam Medical Center and SPring-8 in Harima Science Garden City, Hyogo.



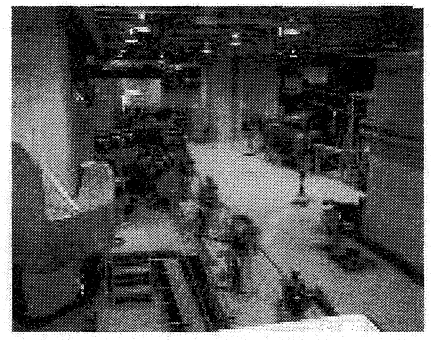
Rotating gantry



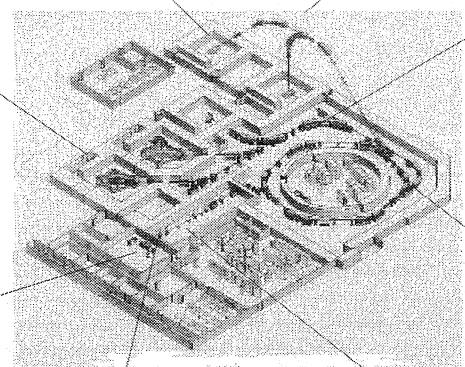
Oblique beam port

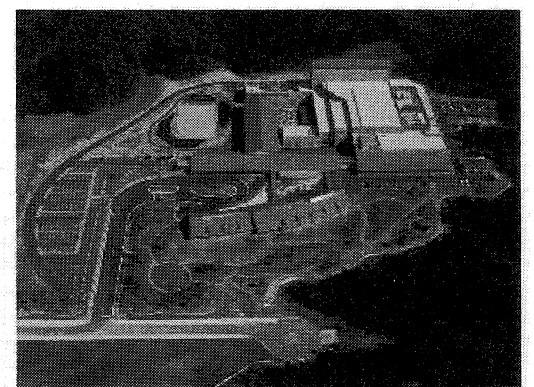


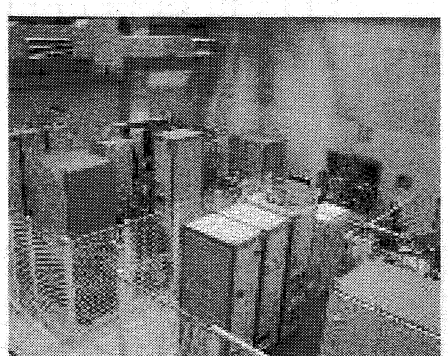
Vertical high energy beam transport line



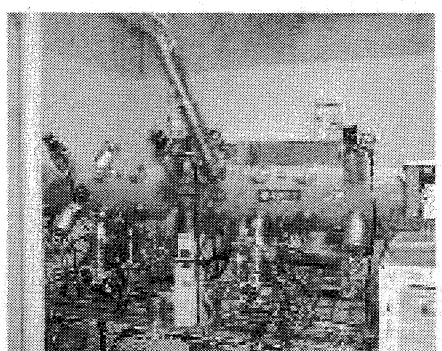
Horizontal high energy beam transport line



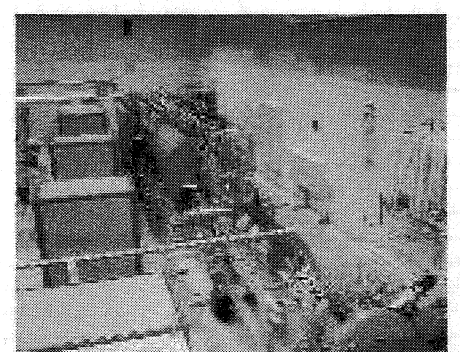




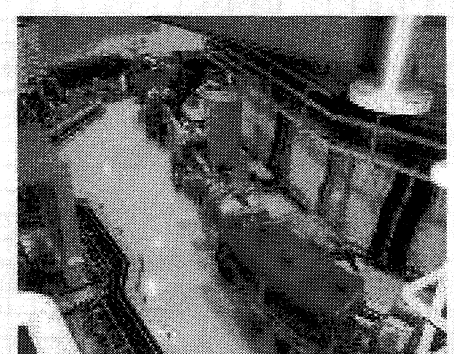
ECR ion source



RFQ linac



Alvarez linac



Synchrotron

Fig. 2 A schematic bird's eye view of the accelerator facility with photographs of its components in each system..
Accelerator building and inpatient clinic (right).

delivery system is used to produce transverse dose field uniformity. Ridge filter is used to obtain a spread out Bragg peak (SOBP). One beam port for physical and/or biological experiments is also constructed. Table 1 summarizes the clinical requirement and physical specifications of the charged particle beams.

Medical center has an inpatient clinic with 50 beds. In Fig. 2, an accelerator building and the clinic of the center are shown.

Table 1
CLINICAL REQUIREMENT and PHYSICAL SPECIFICATIONS of CHARGED PARTICLE BEAM

| | |
|---|---|
| Particles | Proton, Helium and Carbon |
| Energy Range | 70 - 230 MeV/u for p , He |
| | 70 - 320 MeV/u for Carbon |
| Beam Intensity | $7.3 \times 10^{10}$ pps for p |
| | $1.8 \times 10^{10}$ pps for He |
| | $1.2 \times 10^{9}$ pps for Carbon |
| Dose Rate | 5 GyE/min |
| Beam Range | 40 - 300 mm for p and He |
| | 13 - 200 mm for Carbon |
| Field homogeneity | ±2% (over treatment field) |
| Field size | 15cmx15cm for ports A, B |
| | 10cmϕ for port C |
| | 15cmϕ for gantry ports |
| Displacement of beam axis | ± 2mm (from isocenter) |
| Spill length | 400ms |
| Maximum Repetition rate | 0.5 Hz for He and Carbon |
| | 1 Hz for proton |

### 3. Beam Test

Installation of the apparatus started in March 1999. Beam acceleration test of injector linacs started in December 1999. In February 2000, full intensity beams of the linacs were obtained [5,6]. Synchrotron beam test started from end of March. We first started the beam test with He. 1-turn injection, multi-turn injection and rf capture were successively performed. Measurement of rotation frequency of the beam in the ring by a real time spectrum analyzer was very effective to determine the frequency for rf capture.

In acceleration, rf frequency of acceleration cavity is controlled by magnetic field of dipole magnets. At about 0.2 gauss change of reference magnet field, a B-clock pulse is generated to change an output frequency of digital synthesizer, which controls the accelerating cavity. Amplification gain of the electronic circuit to measure the magnetic field was determined using an accelerating beam. If the gain is not well adjusted, the accelerating beam is deviated from central orbit and is finally lost. This was actually observed by COD (Closed orbit distortion) monitor. The amplification gain was changed so as to reduce this deviation of the orbit and finally the beam was accelerated up to the flat top (230 MeV/u). Slow beam extraction was performed with slightly decreasing the current at flattop of focusing quadrupole magnet of the synchrotron ring. Extraction efficiency larger than 80% was obtained. Beam intensity was enough to treat patient with dose rate of 2Gy/min. This was a maximum intensity officially permitted by radiation safety at that moment. Meanwhile beams were successfully transported to the entrance of each treatment room. These results were obtained in about one month from the start of synchrotron beam test, including a period of about 1 week for control software debugging, etc.

The OPF (Operation parameter file) thus obtained by He beam tuning was used without modification to accelerate and extract carbon beam. The beam could be observed at beam transport line although the intensity was about 3 orders of magnitude less than that of He beam (thus about 2 orders of magnitude less than the required intensity for carbon).

Then we started a beam test with proton beam. In one day, beam was extracted with 10% of the required intensity. Soon the full intensity beam was extracted with extraction efficiency about 90%.

Finally we started a beam test with carbon (320MeV/u) in May. In the beginning of June, all beams (p, He and C) were extracted successfully with required intensity (although a limit of 2 GyE/min dose rate was still maintained) and with extraction efficiency 80 - 94%. Meanwhile the beams were introduced into the treatment rooms. Apparatus of irradiation system, including monitors for dosimetry, were tested using beams. Further details of the synchrotron and its beam commissioning is described elsewhere [7].

After the completion of official examination on radiation safety in September, intensive test on irradiation system to form a uniform irradiation fields started. Meanwhile, to investigate the biological dose distribution and the relative biological effectiveness (RBE) of proton and carbon beams,

preclinical biology experiments were performed using human cell lines cultured in vitro as targets from October to December. Skin damage effect was also measured using mice as targets in the same period.

From December, a real simulation test of treatment with the participation of medical staffs started. Software of both treatment control system and accelerator control system was checked and revised.

In April 2001, an operation with full intensity beam, which enables patient treatment with dose rate of 5 GyE/min, was permitted by official radiation safety office.

### 4. Gated Beam Extraction by Patient Breezing

Gated beam extraction by patient's breezing is now indispensable in hadrontherapy to obtain a good dose distribution on cancer target and to reduce a damage of normal tissue [8]. rf knockout method was used for the gated beam extraction [9]. To keep effective beam intensity in gated extraction, it is necessary to choose a cycle length T (sec) of synchrotron pulse properly. If we assume that patient breezing motion is random relative to synchrotron pulse, one can calculate a probability that the gate coincides with flat top of synchrotron pulse as a ratio (T-A)/T, where A is a sum of the times for flat base, acceleration and deceleration. Then an effective beam intensity or effective dose is proportional to 1/T*(T-A)/A. The effective doses are plotted as a function of T in Fig. 3 for proton and carbon. It has a maximum at T around 1.6 sec for proton and at T around 3.3 sec for carbon. Fig. 4 shows a proton beam spill of gated extraction. Circulating beam current increases during acceleration and decreases by extraction. But when gate is off, the beam current keeps its intensity, as the beam is no more extracted. Then it is decreased during deceleration. At about two third of the synchrotron pulses, beam was extracted and irradiated on patient.

### 5. Daily Operation for the Clinical Trial

From May, clinical trials by proton beam started. Every weekday at 5 o'clock in the morning, two operators come to the control room. They start a cooling water system and then patrol the equipments in accelerator room. In 20 to 30 minutes, temperature of the cooling water for linac cavities become stabilized. Then they set the power supplies of accelerator on. In 15 minutes, all power supplies become working. Then they start beam tuning by checking beam

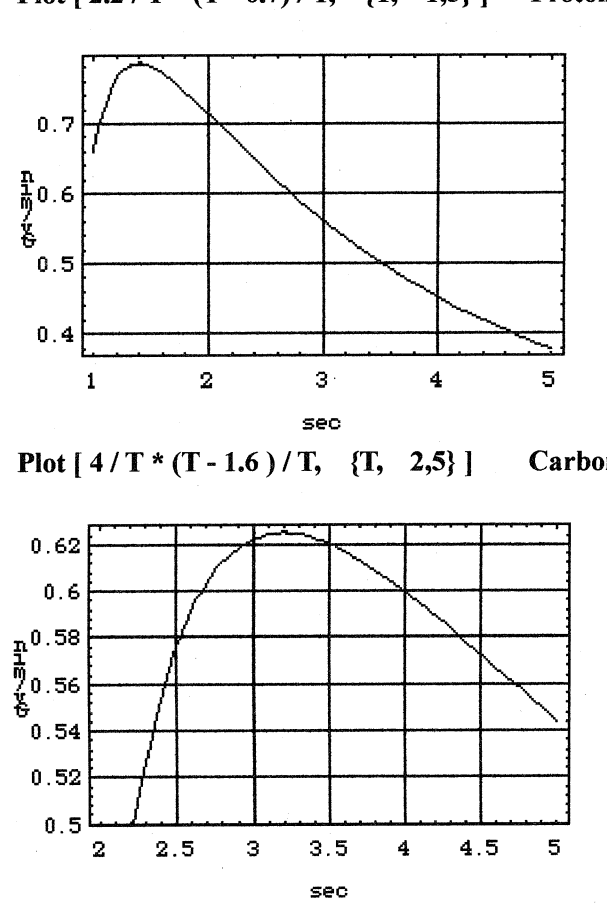



Fig. 3 Effective dose as a function of synchrotron pulse length T (sec).

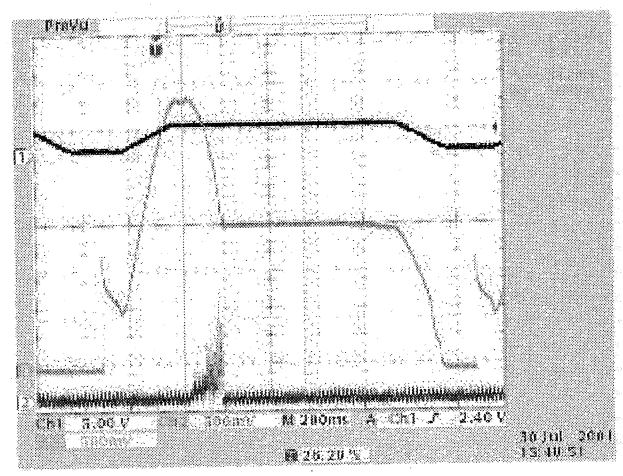


Fig. 4 Gated beam extraction. Magnet current, circulating beam current and beam spill are shown.

profiles and intensity at ECR ion source, linacs, synchrotron and high-energy beam transport line (HEBT) successively. In about 5 minutes, they check beam profile and intensity in front of a neutron shutter at the entrance of one treatment room. Then they introduce a beam into the treatment room

and check the beam profile. They check beam profiles and their central positions in all treatment rooms and for several rotation angles of the gantries for three proton energies every day, i.e., 15-18 beam courses depending on the treatment request of the day (Different rotation angle of gantry is counted as one course.) for 150, 190 and 230 MeV of proton beam. These three energies cover the different beam range in human tissue required by the treatment. Beam profile just upstream of the neutron shutter is stocked in the memory of accelerator control computer. To change the beam course and check the beam profile it takes about 3 - 5 minutes. It takes about 15 minutes to change the beam energy and then check the beam profile in front of one treatment room. All parameter change of the (steering) magnet power supplies after the beam tuning and the resulting beam profile just in front of the neutron shutter are stocked in the memory of accelerator control computer for each beam course. These parameters are set on the request of beam course by medical staff for the treatment and the stocked profile is compared with a beam profile measured at that moment.

In the stage of clinical trial, we check the beam profile in all treatment rooms to take statistical data on the reproducibility of the beam position at isocenter. For the fixed beam, it is ±0.5-1mm. For the gantry, it is ±1mm. Gantry beam position at isocenter seems to have some hysteresis of about ±1mm depending on the direction of the rotation to arrive at the position. So gantry isocenter is reproduced within ±2mm, as is required by specification. We are now studying how to reduce number of OPF (Operation parameter file) to cover all rotation angles of the gantry. 4 OPF seem to suffice (45, 135, 225, 315 deg) to cover within about ±1mm. We will add 4 OPF (0,90, 180, 270 deg). In total 8 OPF will cover all rotation angles of gantry.

From 9 o'clock, we start patient treatments. Intensity of proton beam supplied for the treatment is typically $7\text{-}8\text{x}10^{10}$ ppp with synchrotron pulse length T of 1.6 sec. When there were 14 patients for the treatment in a day as was the case in August, the treatment was finished at about 5 o'clock in the evening. Patient Dosimetry is repeated every day for each patient. It is also measured even in the treatment room with no entry of the patient at that day to take statistical data on stability and reproducibility.

With statistical evidence obtained in the clinical trials, the amount of daily beam tuning in the morning and dosimetry checking procedure will be reduced in future operation.

## 6. Summary

Accelerator facility for hadrontherapy must supply very stable beams for the patient treatment and with high degree of reproducibility when beam course change and/or energy change are required. From the results of daily operations for the clinical trials, it is proved that the accelerator facility at Hyogo Ion Beam Medical Center stands for these requirements. After the completion of clinical trial with proton, clinical trial with carbon is expected to start. Patient treatment with commercial basis is also expected to start next year.

## 7. Acknowledgements

I express my thanks to the colleagues of the hyogo ion beam medical center, guest scientists from institutes and universities, and engineers of Mitsubishi El. Corp. and other companies for their participations to this hadrontherapy project on the stages of design, construction, commissioning and daily operation. My special thanks are for the operation crews of Mitsubishi El. Corp. and Accelerator Engineering Corp.

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