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COMMISSIONING OF CARBON ION TREATMENT ACCELERATOR WITH A SUPERCONDUCTING ROTATING GANTRY

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Abstract

The world's smallest carbon ion treatment facility has been commissioned at Yamagata University. The treatment system consists of an ECR ion source, a linac cascade of 0.6 MeV/u RFQ and 4 MeV/u IH-DTL, a 430 MeV/u slow extraction synchrotron, and irradiation systems of a fixed horizontal beamline and a compact rotating gantry using superconducting combined function magnets. The size of the building is 45 x 45 m, realized by placing the irradiation rooms not on the same level as the synchrotron, but above it, connected by a vertical beam transport.

The most advanced accelerator technology of this machine is to control the beam range up to 300 mm in 0.5 mm steps without any physical block range shifter. To achieve this range step, 600 beam energies were provided in the synchrotron and in the beam transport and tuned to control the beam size in the treatment room. Initial commissioning and daily/monthly quality assurance were performed by interpolation of beam energy and gantry angle.

After tuning the beam size and correcting the beam axis in the treatment rooms, precise dose measurement was performed for clinical irradiation. After the clinical commissioning, the facility started treatment irradiation in February 2021 with a fixed beam port and in March 2022 with a gantry beam port. After March 2023, the gantry angle was operated with a 15-degree step. By March 2024, 1551 patients had been treated.

INTRODUCTION

Radiation therapy is an important application of accelerator today. Electron accelerator-based X-ray therapy is one of the standard therapies for cancer, however, several types of cancers are radioresistive and clinical results of X-ray therapy for these cancers are still not enough. Carbon ion radiotherapy (CIRT), irradiate maximum 430 MeV/u $^{12}C^{6+}$ beam into a human body, is effective to these cancers by its high linear energy transfer (LET). This causes severe damage to deoxyribonucleic acid (DNA) of the cancer cells. Moreover, the dose is extremely concentrated to the target by a Bragg peak and small scattering. Because of these characteristics, CIRT is considered as a potential therapy for following targets: 1) radioresistant cancers: sarcoma (bone and soft tissue cancers) and adenocarcinoma (common in the prostate, uterus, etc.), 2) cancer with huge mass, e.g. huge liver cancer, 3) cancers close to important organs, especially those in head and neck, or pancreas. In these cases, carbon ion radiotherapy is the only treatment option.

After R. R. Wilson proposed proton therapy in 1946 [1], ion therapy started using Bevatron mainly with neon beam in 1974 [2]. Since 1994, carbon ion therapy has been carried out in Heavy Ion Medical Accelerator in Chiba (HIMAC) [3], Japan. Based on the promising clinical results [4], several compact carbon ion therapy facilities have been built in Japan. These facilities use a compact carbon ion accelerator design [5-7] developed by National Institute of Radiological Science (NIRS, reorganized into National Institutes for Quantum Science and Technology (QST) in 2016). By 2023, total 57,498 patients had been treated by CIRT worldwide [8]. CIRT is an essential technology for cancer treatment in today's medicine.

ACCELERATOR AND TREATMENT SYSTEM

The accelerator for carbon ion therapy needs 430 MeV/u for beam range of 30 cm in the human body. As an analogy with light source accelerator, the first generation machine, Bevalac, was a parasiting facility with research accelerator. Second generation, HIMAC, is a dedicated machine for treatment. Third generation machines are optimized for compact facilities or for advanced irradiation systems.

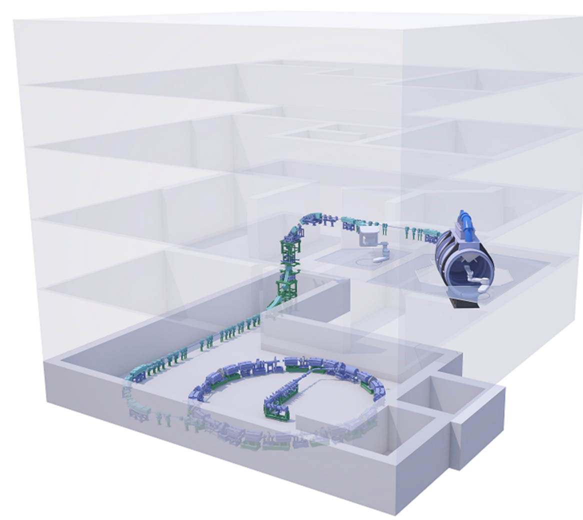

Figure 1: Machine Layout of EJHIC.

East Japan Heavy Ion Center (EJHIC), Faculty of Medicine, Yamagata University is the world's smallest carbon

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ion treatment facility. It corresponds to 3.9th generation, the latest standard model of compact carbon ion treatment facility. Its building area of is 45×45 m as shown in Fig.1, which was considerably smaller than that of former facilities, 65×45 m. The facility uses two new technologies: 600 energy full energy scanning irradiation [9] and superconducting rotating gantry [10]. Both technologies are developed in QST and first implemented in a commercial treatment machine. The treatment machine including the accelerator was manufactured by Toshiba Energy Systems and Solutions. Co. The specifications of the machine are listed in Table 1.

Table 1: Specification of EJHIC Treatment Machine

Ion Source	10 keV/u C^{4+}
	10 GHz ECR w/ permanent magnet
Linac	0.6 MeV/u RFQ (2.5 m) 4 MeV/u IH-DTL (3.5 m)
Synchrotron	55.6 – 430 MeV/u, 600 energy step extended flattop operation
	Circumference: 63 m
	Beam Intensity:3×10^7 - 1×10^9 pps
Gantry	Weight: ~200t
	10 m in length and 6 m in radius
	Superconducting combined function magnets (6 BM / 12 QM) Maximum field: 3.5 T
Irradiation System	# of rooms: 2 (Fixed Horizontal / Rotating Gantry)
	Raster Scanning w/o range shifter
	Field Size: 20×20 cm
	Positioning: Crossed X-ray
	Respiratory Gating system

The ion source of the accelerator is 10 GHz electron cyclotron resonance ion source (ECRIS) [5]. The mirror field and the sextupole field are generated by permanent magnets, the field distribution was optimized to maximize C^{4+} beam current. The ion source generates ~170 μA (max 350 μA) of C^{4+} beam. This model of ECRIS has been used in 5 facilities. At EJHIC. improvements of vacuum pressure at the extraction region, helium gas mixing operation, change to small-radius electrode were applied and it achieved 2 years of maintenance interval, which is longer than the half-year interval of the first model at Gunma University [11].

The injector linac consists of a radiofrequency quadrupole (RFQ) and an alternating-phase-focusing (APF) interdigital H-mode drift tube linac (IH-DTL). Both linacs are operated at 200 MHz, and are driven by a solid state power amplifier (SSPA) up to 150 kW for RFQ, by a tetrode (Thales, RS2042SK) up to 500 kW after an SSPA of 50 kW for IH-DTL. The inner tank surfaces were electropolished to improve the surface condition, which significantly reduced continuous discharge of linac. After the IH-DTL, a charge stripper of 50 μg/cm^2 carbon foil converts the charge state from C^{4+} to C^{6+} for synchrotron acceleration The foil is used 5 years from the start of commissioning.

The synchrotron is 63 m in diameter and has 600 extraction energies which varies from 55.6 MeV/u to 430 MeV/u to achieve 0.5 mm of range steps. It enables a multiple energy extended flattop operation [11], which stops the synchrotron pattern clock at any timing and keeps the flattop for slow extraction using a resonance of $\nu_x = 5/3$ [12] and change to next energy after the irradiation by a certain energy is completed, which is useful technique for respiratory gating irradiation. The gap lengths of bending magnets were reduced compared with former model to save energy consumption. The 600 energies continuous irradiation pattern is shown in Fig. 2.

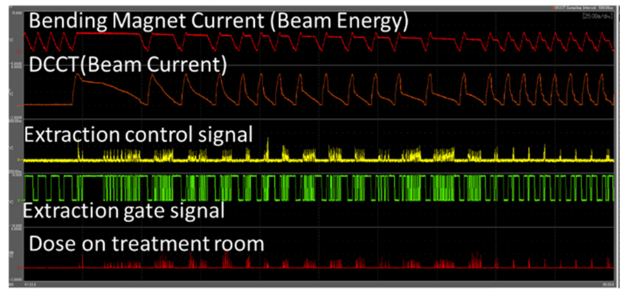

Figure 2: Sample of synchrotron operation of 600 energy continuous irradiation.

Treatment irradiation system is high-speed scanning irradiation with respiratory gating system [13]. The scanning magnet is a newly developed X-Y combined type magnet, which needs the distance of only 3.5 m to form a ±10 cm irradiation field. Irradiation port was composed of ionization chamber dose monitors, a position monitor of multiwire proportional chamber, and a ridge filter which broaden the sharp Bragg peak into 1 mm or 3 mm in 1σ.

The rotating gantry, which is a beam line rotating 360 degree to irradiate from flexible angle to the patient, is world smallest size realized by superconducting combined function magnets. It consists of 6 bending components and 12 quadrupole components with maximum dipole field of 3.5 T [14]. Schematic view of the gantry is shown in Fig. 3. The size and weight of the gantry are 10 m in length and 200 tons, respectively. The gantry allows flexible beam angle, which allows the patients to lie down comfortably with no tilting.

COMMISSIONING OF ACCELERATOR AND SUPERCONDUCTING ROTATING GANTRY

EJHIC has two irradiation rooms, a fixed port irradiation room and a gantry irradiation room. The fixed port room can only use horizontal beams, so it can only treat prostate cancer, which is usually carried out horizontal beams avoiding bladder and rectum. The gantry room has no such limitation for target cancer site, but we need long time for commissioning. Therefore, we at first commissioned the horizontal room and then the gantry.

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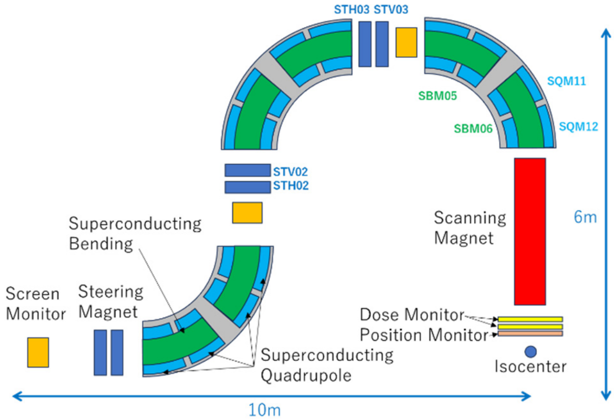

Figure 3: Schematic view of the gantry.

For scanning irradiation commissioning, the tolerance of beam size and position at the isocenter, three-dimensional irradiation center, are ±0.5 mm and ±20% from the reference size, respectively. We use only one synchrotron pattern with 2 seconds of acceleration and 3 seconds of deceleration, and extraction and transport parameter are set for 600 energies. Extraction efficiency, beam size, betatron phase (beam drift) is precisely tuned for 10-30 representing energy and other energies were interpolated. After the parameter tuning, the beam data of the longitudinal and the lateral beam profile used for treatment planning system was measured. The treatment planning system (RayStation 10A, RaySearch Laboratories AB) calculates and optimizes dose distribution based on pencil beam model.

After beam modelling, dose distributions in water were measured using a treatment plan of uniform physical dose of 1 Gy within the irradiation field with various field center depth from 40 to 240 mm and various field size from 3×3 cm to 20×20 cm. The results were acceptable for all conditions with the tolerance, dose difference less than ±3% and field size error less than 2 mm. After this verification, we successfully started the treatment irradiation on 25 February 2021 for prostate cancer in fixed port irradiation room.

There were many difficulties in the commissioning of the gantry. To keep the beam size against rotation, the horizontal and vertical emittance must be symmetric. It was realized a variable-thickness rotating scatterer in HEBT at β_x~30 m, β_y~0.5 m [15]. The betatron phase between the extraction deflector and the isocenter must be $n\pi$ to cancel the position drift, therefore the tolerance for beta function and phase are small. Moreover, the gantry is composed of combined-function sector magnet, effective length of quadrupole field changes by radial position. Due to the extremely compact design, no screen monitor was placed after the final bend. In principle, the beam size is independent with gantry angle by emittance symmetrisation, actually we need individual optimization for the beam size and beam axis correction for each angle.

The commissioning of gantry was performed in 5 steps. The first step was to make initial experience in a well-established treatment technique: treatment for prostate cancer by 2 angles, achieved on 8 March 2022. The second step involved treating head and neck cancers by 7 angles of 30 degrees steps, with tilting patients slightly. The third step was to enable the beam from all direction with verifying the beam range passing through the patient couch by 12 angles. Until this step, the beam size measurement and automation of beam axis correction was established. The measured beam size for 12 angles and 600 energies are shown in Fig. 4. The fourth step was to use respiratory gating irradiation, which uses high beam intensity and fast spot moving to enable the treatment of lung, liver and pancreas cancers. The fifth step was increasing beam angles from 30-degree step to 15-degree step. In this process, the

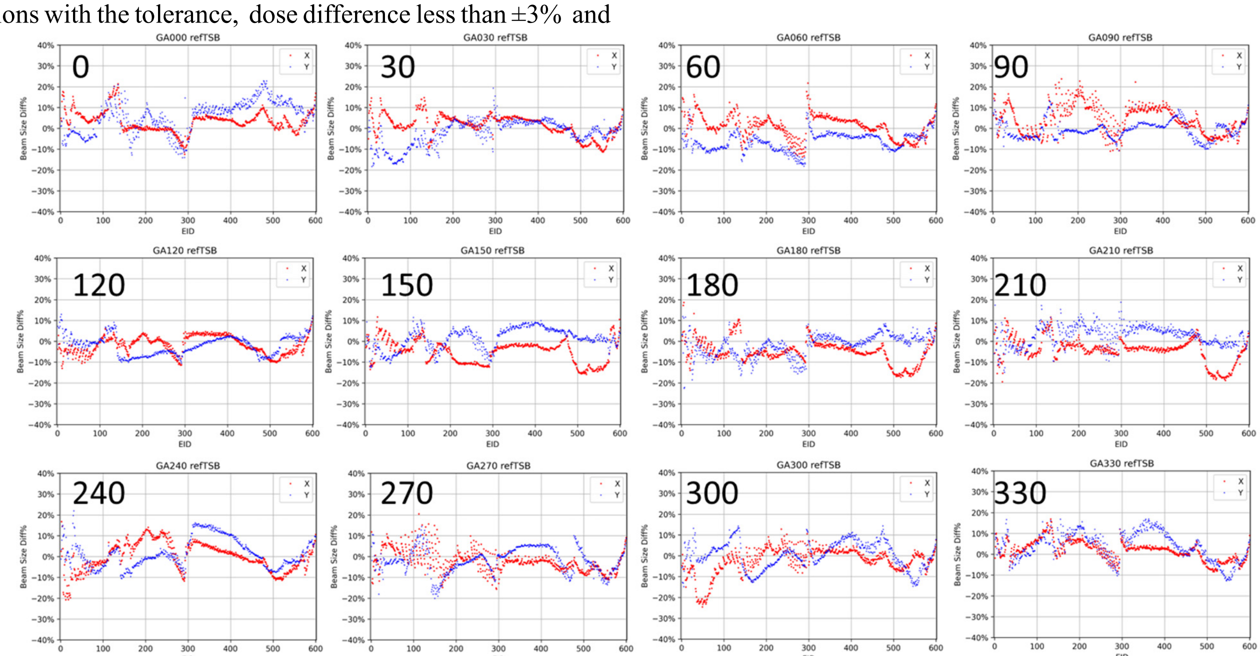

Figure 4: Result of beam size measurement for 12 gantry angles and 600 energies. The beam size was evaluated as the relative difference from reference beam size.

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beam orbit correction tool to interpolate the measured beam position of 143 energies into 600 energies [16] was developed. This tool reduced the time for 1 iteration of correction from 30 minutes to 6 minutes, final orbit correction was finished in 2 or 3 hours, greatly contributing to the 15-degree step operation. On 28 March 2023, 15-degree step operation was started. Figure 5 shows a result of quality assurance measurement of 13-angle beam irradiation (starshot) into a cylindrical scintillator. The beam position of the isocenter was kept within ±1 mm.

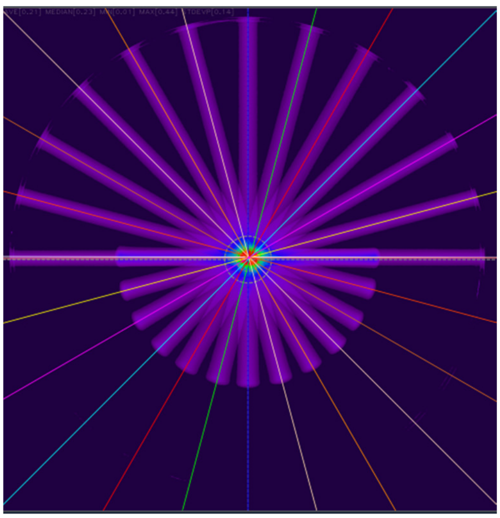

Figure 5: Image of 13-angle beam irradiation (starshot) into a cylindrical scintillator.

For medical accelerator, quality assurance is an essential attempt to keep patient safety. In the early stage of gantry operation, monthly full measurement of beam size and position for all gantry angles and 600 energies had been carried out. Figure 6 shows the trend of beam position measurement of the 296.37 MeV/u, which was kept within ±1 mm. After available angle increased, we gradually reduced the measurement conditions and frequency for items which is well stable in the former experience.

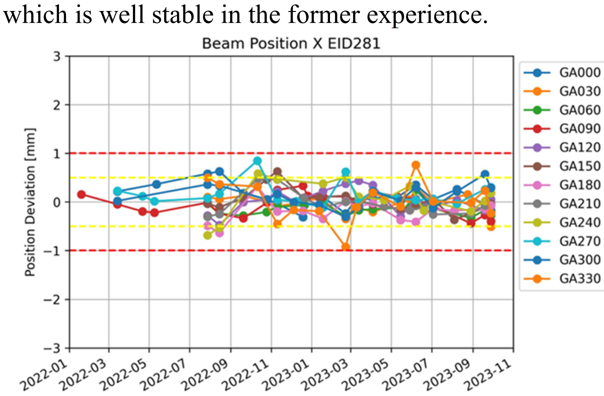

Figure 6: trend of beam position measurement of the 296.37 MeV/u.

OPERATION STATUS

By March 2024, 1551 patients had been treated in EJHIC. In JFY2023, 662 patients were treated, exceeding the original target of 600 patients/year. About 70% of the patients were prostate cancer were treated in fixed port irradiation room, and other cancers (head and neck, liver, pancreas, bone and soft tissue, etc.) were treated in gantry irradiation room. The energy distribution for all treatment irradiation is shown in Fig. 7, the most common maximum energy for each patient was 358.2 MeV/u, which was because many prostate cancers were irradiated. The maximum beam energy ever used by March 2024 was 411.8 MeV/u. whereas the minimum beam energy of 55.6 MeV/u was used frequently for the target close to the skin.

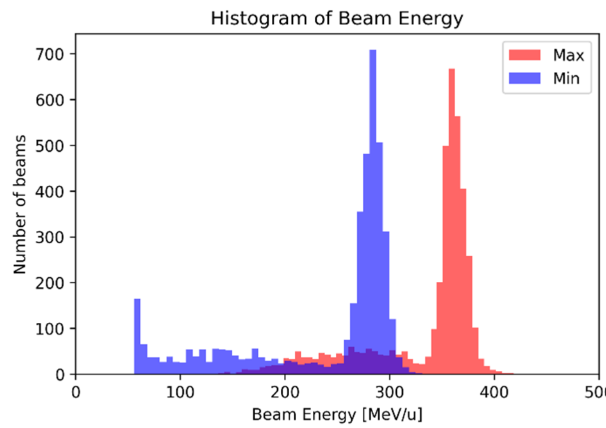

Figure 7: The energy distribution for all treatment irradiation.

Machine availability is important for medical accelerators. Each patient receive total 4 – 20 irradiations, but if the treatment is interrupted for several days by machine trouble, repopulation of cancer cell will affect the clinical result. Usually 4 irradiations/week/patient is planned, and even in case of machine trouble, 6 irradiations/2week/patient was kept. The machine availability for the treatment, R_{treat} is calculated as

$$R_{\mathrm{treat}} = 1 - \frac{T_{\mathrm{delay}}}{T_{\mathrm{treat}} + T_{\mathrm{delay}}}$$

where T_{treat} and T_{delay} are planned treatment operation time and downtime, respectively. The trend of monthly machine availability is shown in Fig. 8. Total machine availability since Feb. 2021 is 95.8%.

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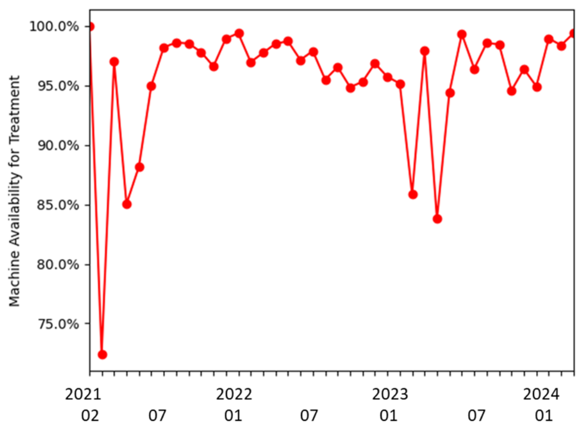

Figure 8: Trend of monthly machine availability concerning the treatment.

FUTURE DEVELOPMENT

CIRT has been stably operated and treated many patients, but its technology has a room for further improvement. One is a downsized facility which can be installed into the small hospital. For this purpose, superconducting synchrotron is now under construction in QST. Its diameter is 8.6 m, less than half of that of current machine, 20 m [17]. The second approach is to increase LET for radioresistant cancer. QST started multiple-ion irradiation to increase minimum LET in the tumor volume using oxygen or neon beam combined with carbon or helium beam. Better clinical outcome for bone & soft tissue cancer, and head & neck cancer are expected by this technology. The third approach is to improve positioning precision. Current positioning relies on bone structure matching by orthogonal 2-dimensional X-ray image, but a 3-dimensional positioning using computed tomography which can detect the position and the shape of the tumor is preferable. EJHIC is now developing such advanced positioning system for more adaptive therapy for each patient.

SUMMARY

Carbon ion radiotherapy is an effective radiotherapy to cure radioresistant cancer using high LET and tumor close to important organ by sharp dose distribution. In Yamagata University, 430 MeV/u synchrotron with 600 variable energy operation realized 0.5 mm step range control was successfully commissioned and started the treatment on Feb. 2021. For gantry commissioning, emittance compensation and beam size optimization considering the perturbation of focusing force due to orbit change was the key technologies. The challenging machine achieved successful operation for 3-years to treat more than 1500 patients.

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