KOREA HEAVY-ION MEDICAL ACCELERATOR PROJECT

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Abstract

Korea Heavy-ion Medical Accelerator (KHIMA) is the cancer therapy facility located in Busan, South Korea in its construction phase. The accelerator is a synchrotron with multi-ion sources, capable to accelerate carbon ions up to 430 MeV/u and protons, 230 MeV. As for beam delivery systems, 5 treatment lines are provided for clinical applications in 3 treatment rooms; treatment room 1 with a vertical and horizontal line adopting spread out Bragg peak (SOBP) irradiation, room 2 with a vertical and horizontal line adopting scanning irradiation, and room 3 with horizontal scanning line only. Also, for a clinical/non-clinical research and potential extension to a gantry, a research room is prepared with single horizontal line. This report describes the brief history and current status of the KHIMA project.

BRIEF HISTORY

In 2010, the Korea Heavy-ion Medical Accelerator (KHIMA) project started out to develop a superconducting cyclotron to produce carbon-ion beams for cancer treatment. The cyclotron would be the first carbon based clinical machine in the world and the driven clinical facility would be uniquely different from all existing and planned ion-beam facilities in the world.

In 2013, on completion of conceptual design for the accelerator system based on a superconducting cyclotron, there were conducted review programs by world-wide and domestic committees composed of experts in the fields of accelerator physics, medical physics, radiobiology and oncology. The leading opinions of the committees were to switch the accelerator type into a synchrotron. Rationale for a synchrotron is that a cyclotron-based clinical facility will not meet the clinical resources provided by other existing synchrotron-based clinical facilities, and in-house developments of all the clinical resources driven by a cyclotron require more than doubling the budget and manpower.

The amendment to a synchrotron as the accelerator for KHIMA project, thus, was approved by the Ministry of Science, ICT and Future Planning (MSIP, funding government authority) in 2014, and the consequential extension of project period up to the end of 2017 was followed. It's when a lot of efforts have been made with the help of domestic and foreign heavy-ion facility that technical design report (TDR) for the KHIMA synchrotron accelerator was published in early 2015. The project is currently under procurement process considering the system integration schedule.

Regarding conventional facility, the building construction started in 2013 and, after structural alteration due to changing the accelerator type to a synchrotron, is now almost completed (see Fig. 1). The facility with 3 treatment rooms will be mainly devoted to cancer therapy in collaboration with Dongnam Institute of Radiological & Medical Science (DRAMS) located a few minutes distance away by walk. The number of patients will be more than 600 per year. A clinical/non-clinical researches are also carried out utilizing a research room.

Figure 1: Site view of KHIMA treatment facility.

ACCELERATOR OVERVIEW

In the designed KHIMA synchrotron, the proton beam (the carbon ion, $^{12}C^{6+}$, beam) is accelerated from 60 MeV (110 MeV/u) to 230 MeV (430 MeV/u). Those energy ranges correspond to the penetration depth of 3.0 cm to 27.0 cm in body. The main design parameters of KHIMA accelerator system are summarized in Table 1.

Table 1: Main Design Parameters

Particle Species	Proton (p), Carbon 12 (^{12}C)
Types of Ion	H_3^+ for Proton and $^{12}C^{4+}$ for Carbon at ECRIS
Beam Range	3.0 – 27.0 g/cm^2 in Body
Energy Range	60 – 230 MeV for Proton 110 – 430 MeV/u for Carbon
Dose Rate	2 Gy/min/liter
Beam Intensity at Isocenter	$1 \times 10^8 - 1 \times 10^{10}$ Protons/spill $4 \times 10^6 - 4 \times 10^8$ Carbons/spill
Beam Size	4 – 10 mm (FWHM)
Injection	Multi-turn Injection
Field Size	$2 \times 2 - 20 \times 20$ cm^2
Extraction	RF-KO Slow Extraction

At the electron cyclotron resonance ion source (ECRIS), ions with a charge to mass ratio q/m = 1/3, either H_3^+ or $^{12}C^{4+}$, are generated with an energy up to 8.0 keV/u. The ions are accelerated up to 7 MeV/u through radio frequency quadrupole (RFQ) and inter-digital H-mode drift tube Linac (IH-DTL). At the beginning of medium energy beam transport (MEBT), two corresponding ions are stripped and fully ionized to either proton or $^{12}C^{6+}$, and these are finally transported to the synchrotron ring being accelerated up to desired energies. Each ion is injected into the synchrotron through a multi-turn injection mechanism, accelerated by switching the RF system and then extracted into high energy beam transport (HEBT) line by slow resonance extraction scheme. The HEBT lines comprise 6 different transport branches with 4 horizontal and 2 vertical-lines connected to the three medical treatment rooms and one research oriented irradiation room. The schematic layout of the accelerator system is shown in Fig. 2.

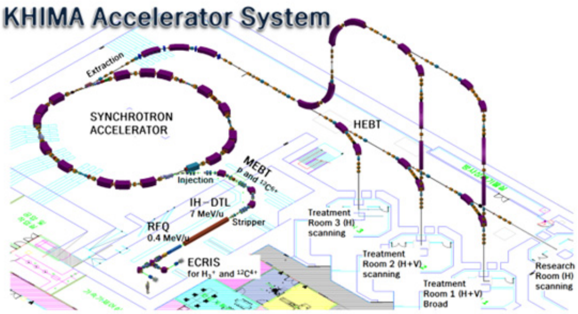


Figure 2: Layout of KHIMA synchrotron system including each treatment and research rooms.

Ion Source

The low energy beam transport (LEBT) line of the KHIMA has two ECRIS's. Considering transmission ratios at each section of KHIMA facility and the required ion intensity at the patient position, $4x10^8$ pps for carbon and $1x10^{10}$ for proton, the output of the ECRIS should cover 122 µA C^{4+} and 328 µA H_3^+ for active scanning method and 285 µA C^{4+} and 765 µA H_3^+ for broad beam method.

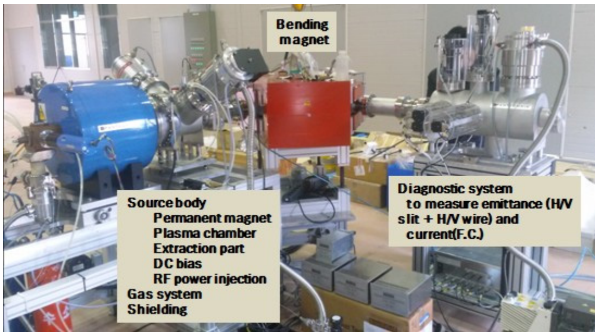


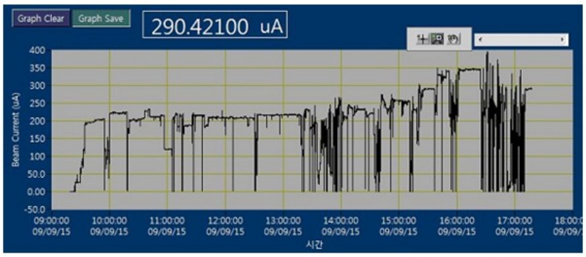
Figure 3: The ECRIS test bench consists of a supernanogun, an analyzing magnet and diagnostics for emittance and current measurement.

The CO_2 gas is usually used as a main gas for supernanogan because of stable output. We have already showed the result for C^{4+} and H_3^+ ion extraction from the supernanogan, which is installed at the test site as shown in Fig. 3, with CO_2 at ICABU 2014 [1]. At that time, the output was 200 µA for C^{4+} and 1 mA for H_3^+. These results mean that the supernanogan with CO_2 gas is applicable for scanning irradiation method but insufficient for carbon ion for the broad beam irradiation method.

We have needed to extract more currents of C^{4+} ion from the ECRIS. The NIRS of Japan, they had developed Kei2 ECRIS which was optimized C^{4+} ion extraction and showed the C^{4+} ion output above 500 µA. The Kei2 source was operated with CH_4 gas as a main gas and was also tested with other various types of gases, such as C_XH_X or C_XD_X . According to their results, the conditions to get more output for C^{4+} ion are like to using CH_4 gas than CO_2, CH_4 without mixing gas, and C_XH_X gas with larger ratio of C to H [2].

In ICABU 2015, we showed the experimental results for C^{4+} output from the supernanogan under operation with applying CH_4 gas [3]. In our case, using CH_4 gas made it easier to extract higher output for C^{4+} ion but its stability became worse as time passed. After about 500 hour operation, we had to stop the extraction test because of a serious contamination problem. In case of CH_4, the maximum extraction intensity of C^{4+} was 400 µA in the condition of an extraction voltage 24 kV, RF frequency 14GHz and RF power 294 W. When we changed the gas to CO_2 again, the output spectrum resulted in the second one of Fig. 4. Because of the gas exchange, initial output was unstable but we could get stable output soon unlike the case of CH_4.

With CH_4 gas



With CO_2 gas

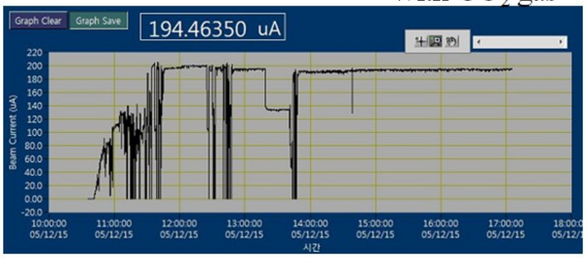


Figure 4: The extraction results for C^{4+} from supernanogan when CH_4 gas and CO_2 gas were used, respectively.

The C^{4+} ion output from the supernanogan was measured adding He gas as a support gas to 0.18 sccm CH_4 gas. Addition of He gas did not cause an increase of C^{4+} ion but the current fluctuation of the ion output beam was conspicuously reduced with above 0.04 sccm of He gas.

Injector

Four-rod RFQ and two IH-DTL structure for the acceleration from 24 keV/u to 7 MeV/u has been studied. RFQ is used for acceleration up to 400 keV/u. It was designed by using PARMTEQ. Two IH-DTL accelerate ion beam up to final energy of 7 MeV/u by using KONUS beam dynamics concept [4]. One double gap buncher and one quadrupole doublet are adopted for the longitudinal and transverse beam matching between RFQ and DTL. At the both ends of the second IH tank (Fig. 5), external quadrupole triplets are located for transverse beam focusing. Main parameters of Linac are described in Table 2.

Table 2: Main Parameters of Injector Linac

A/Q	3	
Input Beam Energy	24	keV/u
Final Beam Energy	7	MeV/u
Operating Frequency	200	MHz
RF Pulse Width	250	μsec
Repetition Rate	4	Hz
Overall Power	1.25	MW (peak)

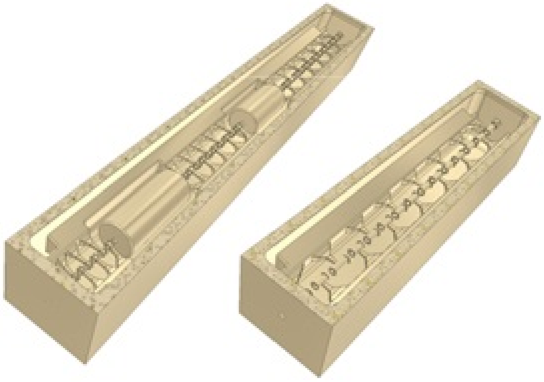


Figure 5: CAD drawing for two IH tanks.

LEBT and MEBT have several functions to fulfil the requirement. Fast electrostatic chopper is adopted in LEBT for the multi-turn injection control and beam intensity control. Debuncher for the beam energy spread control and double achromatic beam line with a waist point for charge selection were considered. The number of quadrupole magnet was optimized for transverse beam parameter tuning during commissioning phase.

In April of 2016, bid process of injector Linac was finalized through Public Procurement Service (PPS). It is expected that manufacturing and beam test of whole injector system will take about two years.

Synchrotron

The circumference of the designed synchrotron is 75 m. The ring diameter is 24 m [5]. The number of bending dipole magnets and quadrupole magnets are 16 and 20, respectively. The magnetic rigidity of maximum energy (430 MeV/u for C^{6+}) is 6.6 T m. The dispersion free region was adopted for the resonance sextupole magnet, RF-cavity, and injection- extraction parts.

The maximum betatron functions for horizontal and vertical space are determined as 16 m and 19 m, respectively. The two dispersion free region of length of 7.2 m were placed, and a super periodicity of the synchrotron lattice is 2. 4 families of sextupole magnet were implemented to adjust a chromaticity. 2 families are horizontally focusing sextupole magnets, and other 2 families are vertically focusing sextupole magnets. Each sextupole magnet is positioned in a way to avoid the third order resonant excitations which are not desired at the cycle of injection and acceleration. After detailed design works, engineering parameters of the entire lattice elements were determined and tested by 3D field tracking simulations.

Diagnostics

In order to secure the patient safety for the particle therapy with high intensity and high energy carbon and proton beams, various beam diagnostics are required to measure the beam specifications such as the beam current, spatial distribution, transverse distribution, beam orbit, spill structure and energy. In total, 17 types of monitors with total number of 88 are taken into account and planned including the related instruments such as slit, stopper, stripper, and so on [6].

The DC Faraday-cups (FCs) are to be installed at the LEBT and AC FCs are in both LEBT and MEBT line [7]. The AC current transformers (AC CTs) will be installed at the LEBT and MEBT and the DC current transformer (DCCT) be installed at the synchrotron ring. The combination of a slit and wire scanner in the LEBT line or wire grid monitor in MEBT line and the pepper-pot device in the LEBT line are considered for measuring the beam [6]. Two capacitive phase probes are installed in the MEBT line to measure the beam energy and beam phase distribution for precise tuning of RFQ and IH-DTL and monitor the status of the stripper foil by measuring the beam energy changing by the time-of-flight (TOF) method [8]. In the synchrotron, a linear cut beam position monitor, which has the wide linear region, and a strip-line kicker are adopted to measure the Schottky noise and to use as a RF exciter for tune measurement and RF-KO, respectively [9, 10]. The transverse beam profile is measured by using the screen monitor with P43 phosphor scintillation material in the synchrotron and HEBT line [11, 12]. For the interlock, the beam stopper, collimator, and slit are also installed at the each section.

The beam diagnostics such as wire-scanner, Faraday-cup, pepper-pot device, electrostatic chopper, capacitive phase prove, linear-cut BPM, strip-line kicker and scintillation screen monitor are under developing by collaborating with Pohang Accelerator Laboratory (PAL), department of accelerator science at Korea University, Research Center for Nuclear Physics (RCNP) at Osaka University, GSI and KEK. The picture of the developed diagnostics is shown in Fig. 6.

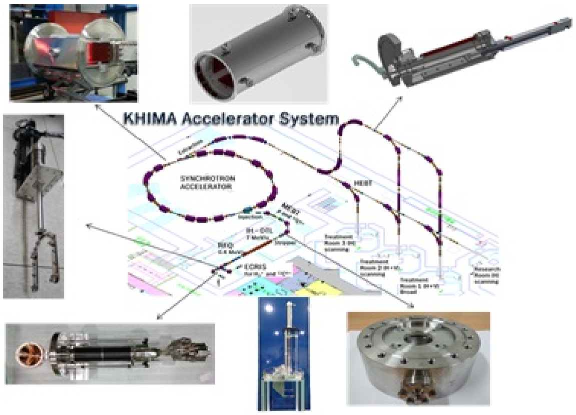


Figure 6: Developed beam diagnostics for KHIMA.

Magnets

Based on the optics design, the lattice was determined and the specifications of each magnet were decided. The detailed magnet design thus has been implemented to optimise the necessary magnetic field quality for the synchrotron main dipole magnet. In the simulation study, the coil specifications were taken into account and the pole profile were optimised [13]. Beside the main dipole on the synchrotron, various other dipole, quadrupole, sextupole and solenoid magnets are under designing and the technical design of the magnets is being reviewed and to be presented in near future. Meanwhile, the specifications for public tender have been finished.

Irradiation System

At the end of the beam transport line, a beam irradiation system is required to deliver an appropriate dose to the patient or target. At this KHIMA project, an active scanning system was selected for the major beam delivery method. The active scanning beam delivery system consists of a beam scanner, beam monitor, energy modulator, and related programs, such as the irradiation control and planning programs.

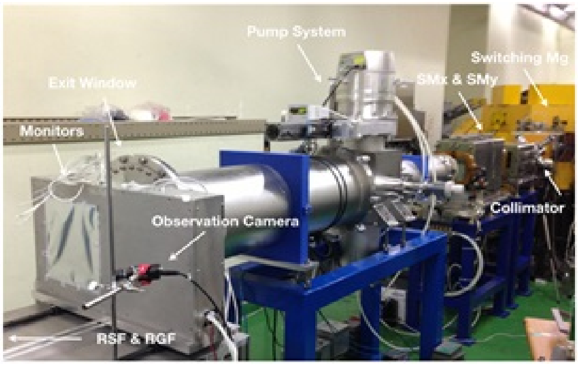


Figure 7: The designed and installed prototype active scanning system at MC-50.

A proposed prototype active scanning system was designed and installed on MC-50 at KIRAMS with a 45 MeV proton beam as shown in Fig. 7 [14]. The laminated magnetic yoke of the scanning magnet supported fast ramping. The beam intensity and the beam profile monitors were designed for measuring the beam's properties. Both the range shifter and the ridge filter modulate the incoming beam energy [15].

The LabVIEW-based beam-irradiation-control program operates the system in a sequential operation manner for use with the MC-50 cyclotron. In addition, an in-house-coded irradiation-planning program generates an optimal irradiation path. A scanning experiment was successfully completed to print the logo of the KHIMA on GaF film as shown in Fig. 8. Moreover, the beam's position accuracy was measured as 0.62 mm in the x-direction and as 0.83 mm in the y-direction.

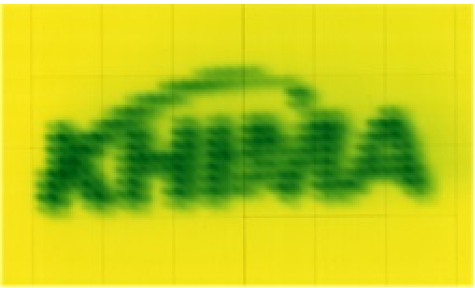


Figure 8: The obtained GaF film image obtained by using the prototype active scanning system.

SUMMARY

Changed to a synchrotron from a superconducting cyclotron as the accelerator for KHIMA project, a lot of efforts have been made with the help of domestic and foreign heavy-ion facility. A technical design report (TDR) for the KHIMA synchrotron accelerator was published in early 2015. ECRIS, already generating more than targeting current for both scanning and broad beam irradiations needs to be operated with long-term stability by research of a mixture of various gases. A bidding process for the injector was completed. Instruments for diagnostics, mainly in-house products are under performance test. A prototype of active scanning system was developed and evaluated the performance to give a reasonable result. Most of the accelerator components including magnets, power supply, vacuum system and utilities are currently under procurement process considering the system integration schedule.

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REFERENCES

[1] Won Taek Hwang, Tae Keun Yang, Jeong Hwan Kim, Dong Wook Park, Hong Suk Chang, Chang Hyeuk Kim, Kun Uk Kang, Min Yong Lee, In Su Jung, Hwa Ryun Lee, Hee Joong Yim, Geun-Beom Kim, Multi-charged particle extraction with supernanogan, The 18th International Conference on Accelerators and Beam Utilization, AP-18 (2014).

[2] A. G. Drentje, M. Muramatsu, A. Kitagawa, Optimizing C4+ and C5+ beams of the Kei2 electron cyclotron resonance ion source using a special gas-mixing technique, Rev. Sci. Instrum. 77, 03B701 (2006).

[3] Won Taek Hwang, Jeong Hwan Kim, Dong Wook Park, Hong Suk Chang, Kun Uk Kang, and Tae Keun Yang, C4+ ion extraction from supernanogan using CH4 gas, The 19th International Conference on Accelerators and Beam Utilization, PA-84 (2015).

[4] Y. Lee, E. Kim, Z. Li and G. Hahn, “IH-DTL design with KONUS beam dynamics for KHIMA project”, *NIM.A*, vol. 801, Page 51-57, Nov. 2015.

[5] Springer http://link.springer.com/article/10.3938%2Fjkps.67.1364.

[6] TK. Yang et al., Status of Beam Diagnostics at KHIMA Facility, in *Proc. IBIC2015*, Melbourne, Australia, Sep. 2015, paper MOPB38.

[7] J.-G. Hwang et al., Proceedings of IPAC’16, Busan, Rep. of Korea, MOPMR009 (2016).

[8] J.-G. Hwang et al., Proceedings of IBIC2015, Melbourne, Australia, MOPB037 (2015).

[9] J.-G. Hwang et al., Proceedings of IBIC2015, Melbourne, Australia, TUPB041 (2015).

[10] J.-G. Hwang et al., Proceedings of IPAC’15, Richmond, USA, MOPTY030 (2015).

[11] S.Y. Noh et al., Proceedings of IBIC2015, Melbourne, Australia, TUPB043 (2015).

[12] G. Hahn et al., Proceedings of IPAC’16, Busan, Rep. of Korea, MOPMR005 (2016).

[13] H. W. Kim, B. H. Hong, and J. Kang, “Design Study of Main Dipole Magnets for Korea Heavy Ion Medical Accelerator Synchrotron”, IEEE Trans. On Appl. Superconductivity, vol. 26, Issue 4, 4401404, Feb. 2016.

[14] C.H. Kim et al., Preliminary results, obtained by using a proton beam, for an active scanning system to installed on the KHIMA, Journal of the Korean Physical Society, Vol. 67, No. 3, August 2015, pp. 581-589.

[15] C.H. Kim et al., Ridge filter design for a particle therapy line, Journal of the Korean Physical Society, Vol. 64, No. 9, May 2014, pp. 1308-1313.

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