COMMISSIONING STATUS OF THE iBNCT ACCELERATOR

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Abstract

An accelerator-based boron neutron capture therapy (BNCT) has been studied intensively in recent years as one of the new cancer therapies after many clinical research with nuclear reactors. In the iBNCT project, the accelerator configuration consists of an RFQ and a DTL which have proven achievements in J-PARC. Meanwhile, a high duty factor is required to have a sufficient thermal neutron flux needed by BNCT treatments. After a failure of the klystron power supply occurred in Feb. 2019, beam operation was resumed in May 2020. To date, an average current of about 2 mA with the beam repetition rate of 75 Hz has been achieved with stable operation. Irradiation tests with cells and mice are ongoing together with characteristic measurements of the neutron beam. In parallel with that, we have been gradually improving the accelerator cooling-water system for further stability. In this contribution, the present status and prospects of the iBNCT accelerator are reported.

INTRODUCTION

Boron Neutron Capture Therapy (BNCT) has been attracting attention recently as a new type of cancer therapy. It has been originally studied with thermal neutrons generated in a nuclear reactor, but recently many activities have started with accelerator-based neutron generation methods to get rid of many regulations against nuclear reactors. The iBNCT (Ibaraki BNCT) project, which started in 2010, is an industry-academia-government collaborative project organized by High Energy Accelerator Research Organization (KEK), Tsukuba University, and private companies together with support from Ibaraki prefecture in Japan [1].

In the iBNCT project, the linear accelerator consists of an RFQ and Alvarez-type DTL which is the same configuration as the J-PARC linac. The RFQ is the same type as J-PARC RFQ II, and the length of the DTL is reduced to 3 m to have optimized proton kinetic energy. Detailed parameters are found in Ref. [2]. Primary 50-keV protons extracted from a multi-cusp ECR ion source are accelerated by RFQ and DTL up to 3 MeV and 8 MeV, respectively. The proton beam is bombarded onto a three-layer neutron-generation beryllium target [3] to generate neutrons by the ^{9}Be(p, n) reaction. In this reaction, generated neutrons mainly have a kinetic energy of a few MeV, so a moderator is installed after the target to reduce neutron kinetic energy to the epi-thermal region suit for BNCT treatment. In BNCT, a desired epi-thermal neutron flux is formulated by IAEA-TECDOC to be greater than 1×10^9 n/cm^2/sec [4]. To achieve this value with the iBNCT accelerator configuration, averaged proton current must be more than 1 mA. Assuming the peak current of around 30 mA which is presently obtained in the iBNCT ion source, a high duty factor is required compared with J-PARC linac.

Presently, the iBNCT accelerator is operated with a beam width of 920 μs under the repetition of 75 Hz. The resulting averaged beam current is about 2 mA which is sufficient to enable the iBNCT project to proceed with non-clinical studies. In Nov. 2021, non-clinical studies have started and we aim to complete them in the fiscal year 2022. Presently, the iBNCT project is preparing to take safety reviews to start clinical studies in the fiscal year 2023.

FACILITY STATUS

Failure of Klystron High-Voltage Power Supply

In Feb. 2019, a failure of the high-voltage power supply of the klystron occurred during the cavity RF conditioning. High-voltage pulses were not delivered to the klystron due to a breakdown of the high-voltage switching device (HVS) in the power supply. In HVS, gate voltage to the IGBT was not generated due to a failure of the control board of HVS. Since HVS was manufactured by a Korean company, HVS together with its insulation-oil tank was shipped to Korea for repair. Unfortunately, there was no backup of HVS, the beam operation was completely suspended during the period. After repair, HVS was reinstalled at the end of Nov. 2019, however, at the beginning of resuming operation, we could not increase the high-voltage to the rated voltage due to the over-current protection of the power supply. As a result of investigations, we found that the insulation of a high-voltage supply cable between HVS and the klystron was broken. It may be valid that the cable and HVS failure occurred at the same time, though the relationship between them has not been understood yet. Another problem was a malfunction of the RF interlock triggered by the switching noise of HVS. After some measures to the noise, cavity RF conditioning resumed from Feb. 2020 with the repetition of 75 Hz.

Replacement of the Neutron-Generation Target

After a long shutdown for the repair of the klystron power supply, the neutron-generation beryllium target was

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replaced in May 2020. It had been used from the beginning of the iBNCT project, and the total amount of the irradiated charge onto the target was about 3000 Coulomb [5], whereas no significant reduction of the neutron flux was observed between Nov. 2017 and Feb. 2019 both in measurements by gamma-rays from activated gold wires and an Eu-doped $LiCaAlF_6$ (Eu:LICAF) scintillation counter. After the replacement of the target, leakage of vacuum occurred several times. Those were not caused by the target itself but by an aluminum flange just upstream of the target connection flange. Here, we omit the detail due to the limitation of the pages, but after several trials and errors, the leakage seems to be solved and has not recurred since Sep. 2021.

Reinforcement of Accelerator Cooling Water System

In the original concept of the iBNCT project, a cooling water system for the accelerator cavities was designed to be as minimal as possible in terms of construction costs and installation spaces. However, a small amount of the cooling water causes instabilities of the RFQ especially at the RF interlock since the resonance frequency of RFQ is controlled by cooling-water temperature. When RF is suspended by an RF interlock, cavity temperature immediately decreases and the resonance frequency largely deviates. This situation can be improved by increasing of cooling-water flow. Thus, after the improvement reported in Ref. [6], we have been reinforcing the accelerator cooling-water system focusing mainly on increasing the amount of the cooling-water flow for RFQ by taking various measures. We performed enlarging the cooling-water pipe diameter, changing the flow path inside RFQ and replacing the cooling-water circulation pump with higher output power, and so on. As a result of such measures, the cooling-water flow rate of RFQ was drastically improved from 220 L/min [6] to 770 L/min at present. Then, the resulting input and output temperature differences were reduced from 1.0 ˚C at RF repetition with 50 Hz to 0.35 ˚C at 75 Hz.

COMMISSIONING STATUS

Beam Operation

After recovery of the beam operation in May 2020, the iBNCT accelerator has been operated with a fixed parameter of the repetition of 75 Hz and the beam width of 920 µs which results in the averaged beam current of ~2 mA before the target.

Irradiations for Non-clinical Studies

In the iBNCT project, non-clinical studies have started in Nov. 2021 after many preliminary irradiation studies with cells and mice. In the non-clinical studies, beam irradiations onto a total number of 48 mice were performed in 4 days in Dec. 2021, and 48 mice in 3 days in Feb. 2022. Figure 1 shows a daily trend of averaged beam current at the ion source (blue) and at before the target (green), respectively. The values in the figure represent the scheduled integrated charges in the unit of Coulomb which were obtained online by integration of CT waveform. There are 4 irradiations in the day. The first one is for accelerator check, and the second and fourth ones are irradiations to gold wires to confirm the neutron flux. The third one was onto 12 mice, half with boron drug and the other half without boron drug. All irradiation for non-clinical studies was finished successfully. In this fiscal year, additional non-clinical studies are presently ongoing from Aug. 2022 and aiming to complete by the end of this fiscal year. The iBNCT project is currently preparing to proceed to first-phase clinical studies in the fiscal year 2023.

In Fig. 1, momentary current decreases in third and fourth irradiations were due to a beam stop by a trip of RFQ followed by RF interlock. In the RF quick-recovery function in the LLRF system, the RF pulse is recovered after one or two pulse duration, and the beam operation is resumed within 2 or 3 seconds. This function is based on that in J-PARC linac, but its recovery time is much shortened due to the cavity temperature variation as mentioned before. From the operation results in the beam time in the fiscal year 2021, an averaged RFQ trip rate is about 1.6 times per hour (334 times in a 208-hour beam operation). The trip rate seems to be decreasing year by year. Further statistical investigation will be done in the future.

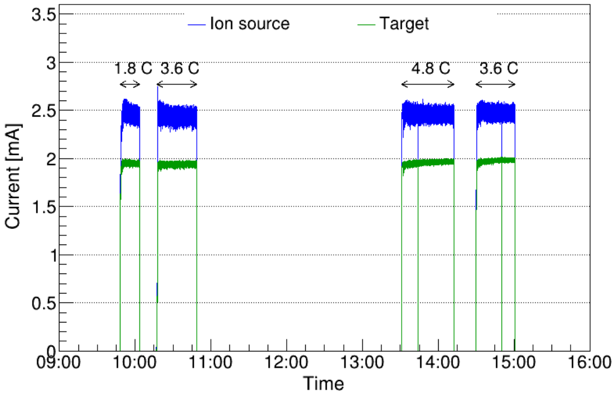

Figure 1: A daily trend of averaged beam current in non-clinical studies held in Feb. 2022. The blue and green lines show the trends at the ion source and the target, respectively.

Improvement of Beam Recovery after RF Stop

In the RF quick-recovery function, there is a limit to the number of attempts to recover for the protection of cavities. If recovery fails, RF is turned off and restarts from low amplitude. Originally, RF restart-up process took nearly 30 minutes to reach rated amplitude because it was necessary to change water temperature slowly according to an increase of the RF amplitude to keep resonance frequency. Meanwhile, since there is a limit to total BNCT treatment time due to drug concentration in cancer cells, the time for beam resume is desired to be shortened as possible. After reinforcement of the cooling-water system, recent trends of the inlet/outlet of RFQ cooling-water temperature, the cavity tank level, and the detuned frequency during RF restart up are shown in Fig. 2. The inlet/output temperature difference both for vane and tank were reduced and inlet temperatures are not needed to change during RF restart up. Inlet temperature fluctuation is controlled within 0.1 ˚C as shown in the figure. Furthermore, RF ramp-up time is reduced roughly to 3 minutes, and after stabilization of detuned frequency, we can resume beam operation with ~8 minutes, which is much improved than before. During the beam operation inlet temperatures are very stable and fluctuation is within ±0.03 ˚C.

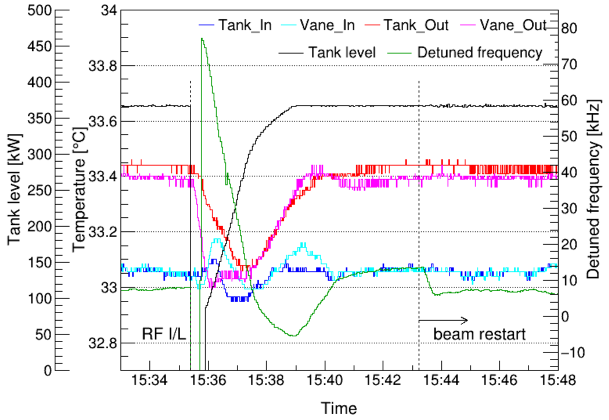

Figure 2: A trend of the RFQ inlet/outlet water temperature together with the cavity tank level and the detuned frequency at RF restart up after stopping by an RF interlock. Beam operation was resumed after 8-minute later from the RF interlock.

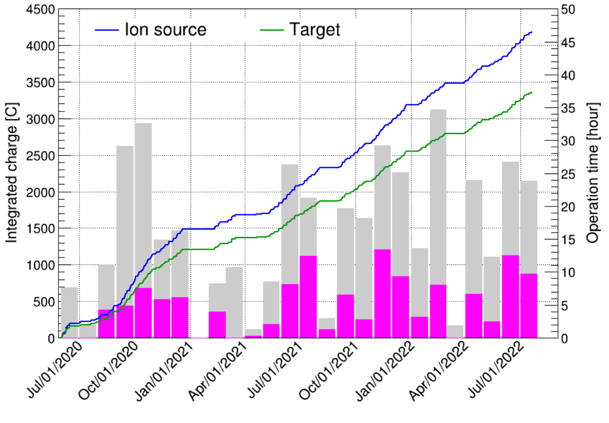

Figure 3: A history of integrated amounts of charge after the target replacement. Blue and green lines show the values at the ion source and the target, respectively. Gray and magenta bar graphs represent operational time per month on the right axis for total beam and irradiation tests.

Beam Operation History

Figure 3 shows a history of the integrated charges after the replacement of the beryllium target. Blue and green lines represent the total integrated charges at the ion source and before the target, respectively. The integrated charge on the second beryllium target is more than 3400 Coulomb as of the end of Jul. 2022, which is already above that in the first beryllium target. We continue to confirm the soundness of the beryllium target by periodic measurements of the thermal neutron flux.

Bar graphs in the same figure represent monthly beam operation time in total (grey) and for irradiation tests (magenta), respectively. Not only the non-clinical studies but many irradiation tests for cells and mice have also been performed together with characteristic measurements of the neutron beam.

SUMMARY

In the iBNCT project, stable operation with the averaged beam current of ~ 2 mA has been achieved with the beam width of 920 μs under a repetition of 75 Hz, with gradual improvements to the accelerator cooling-water system. The iBNCT project started non-clinical studies in Nov. 2021 and will be completed in the fiscal year 2022. The first-phase clinical study will be started in the fiscal year 2023.

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