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COMMISSIONIG STATUS OF THE LINAC FOR THE iBNCT PROJECT

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Abstract

For a new type of cancer therapy, the accelerator-based boron neutron capture therapy (BNCT) has been attracted renewed interest. The basic concept of BNCT is to utilize secondary products from a neutron capture reaction on boron medicaments locally-implanted into cancer cells. It has been originally studied with neutrons from nuclear reactors for a long time, meanwhile many activities have been recently projected with accelerator-based neutron generation techniques. In the iBNCT (Ibaraki BNCT) project, the accelerator is consisted with RFQ and Alvarez DTL. We have started the beam commissioning of the accelerator from the end of 2016, and an acceptably-stable operation was achieved with beam repetition of 50 Hz, which is equivalent of the average current of 1.4 mA at the target. This current makes the project possible to proceed to non-clinical bench test toward a first-phase clinical trial study. Further beam commissioning will be performed toward higher beam current. In this paper, a present status of the iBNCT linac and its future prospect will be reported.

INTRODUCTION

An academic-industrial collaborative project for BNCT, Ibaraki-Boron Neutron Capture Therapy (iBNCT) project, has been started in the year of 2010. It is a collaboration with High Energy Accelerator Research Organization (KEK) for an accelerator part, Tsukuba University for a medical part and supportive works by neighbouring companies and Ibaraki prefecture in Japan [1].

BNCT has been originally studied with neutrons generated from a nuclear reactor, but the recently many activities have been started with accelerator-based neutron generation methods. In the iBNCT project, the accelerator is consisted of an RFQ and Alvarez DTL, whose configuration was based on that in J-PARC linac. Primary 50-keV protons extracted from an ECR ion source are accelerated by RFQ and DTL up to 3 MeV and 8 MeV, respectively, and bombarded onto a beryllium target to generate neutrons by the ^{9}Be(p, n) reaction. The most significant difference from J-PARC one is the higher duty factor, more than 5 %, is necessary to have a sufficiently-strong epi-thermal neutron flux for BNCT. Detailed parameters of RFQ and DTL are found in Ref. [2]. One of the features of the iBNCT project is to take aim for BNCT to become a popular cancer therapy not to need specific irradiation facilities. Thus, iBNCT makes compact the whole size of the components to be enable to install inside hospitals.

We have confirmed the first 8-MeV proton beam and neutron generation from the target in 2014 and 2015, respectively. The beam commissioning for higher beam current has been started since 2016. After that, the iBNCT accelerator has been officially certificated as a radiation generator facility since Jan. 2017. In this paper, recent commissioning status will be reported

INSTABILITY OF RFQ AND ITS IMPROVEMENTS

In the former half of 2017, instability of the beam operation caused by an RF interlock followed by a failure in its recovery made difficult to keep the operation for 1 hour which is required for a typical medical-treatment time of BNCT. A discharge inside RFQ frequently occurred and it stopped the RF pulse for the machine protection system of the cavity. In a normal situation, we can quickly re-input RF after the stop (Quick-Recovery) within 1 second. However, a success rate of this Quick-Recovery functionality is not so high due to a problem on RFQ cooling water system described later. Another problem is a pressure in RFQ. A hydrogen gas flow from the ion source increases the pressure in RFQ during the beam operation. It was obviously shortage of the pumping power for the 1-hour operation. Therefore, we first tried to improve these two issues, and details are described in the following sections.

Reinforcement of the Vacuum System

In the beam operation with 50 Hz repetition, due to the hydrogen gas flow from the ion source, the pressure in RFQ gradually increased and sometimes came up to the interlock level. For the beam operation longer than 1 hour, it is necessary that the reinforcement of the vacuum system of RFQ. Originally, 2 cryo-pumps, 10 ion pumps and 2 NEG pumps were equipped to RFQ. We newly installed turbo molecular pumps (TMP). To have enough compulsivity to hydrogen, two TMPs with evacuation

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speed of 800 L/s were installed in tandem configuration. Besides that, fixed tuner ports of RFQ were connected to manifolds to have higher conductance for TMP and cryo pump lines because the top of tuners have slits for the evacuation of RFQ. Furthermore, after the beam parameter tuning, amount of the hydrogen gas flow rate into the ion source was reduced from 6.5 to 3.1 SCCM (Standard cc per minute), and to reduce hydrogen gas flowed into RFQ, TMP at the LEBT was replaced from 300 L/s to 800 L/s. With these improvements, the pressure in RFQ during the beam operation was reduced to 1×10^{-4} Pa, which is about 1/3 of the value before the improvements

Improvement of the Cooling Water System

In the original plan of a cooling water system for the accelerator cavity, a large temperature increase after RF input was allowed up to 10 ˚C by keeping the average of inlet and outlet temperatures constant. This was based on the concept that the iBNCT accelerator should be compact as possible to install whole equipment inside a hospital including cooling water system. However, if RF is suspended by the interlock, temperature immediately decreases and the resonance frequency is largely deviated, and that situation causes a failure to re-input RF quickly. In such a case, we must restart RF from low power level and it takes several minutes to reach the operation power. For BNCT, a stable beam operation is required because an effective time of the boron medicament in cancer is limited. To avoid such a beam suspension, it is essential to minimize the temperature difference (ΔT) between inlet and outlet of the cavity. Due to a limitation of time and cost for the improvement, extensive replacements of the cooling water system were impossible. Thus, we took two measures: One is to increase RFQ cooling water flow by dividing a part of cooling water for DTL (Measure 1). The other is to replace a water-circulation pump (Measure 2). For the former case, this is because the RF interlock is mainly caused by discharges in RFQ. In original, water flow of RFQ and DTL are 100 L/m for each, but we changed them to 160 L/min for RFQ and 40 L/min for DTL, respectively. In this measure, the temperature difference in RFQ was reduced from 1.5 ˚C to 1.2 ˚C with RF repetition of 50 Hz. Meanwhile, that in DTL was increased from 1.5 ˚C to 5.3 ˚C. We accepted this temperature difference because the rate of RF interlock in DTL is extremely low and DTL equips with a variable tuner. In the second measure, we replaced a water-circulation pump to one having twice higher power from 5.5 kW to 11.0 kW. With this replacement, both flows of RFQ and DTL were increased to 220 L/min, respectively. Due to the pressure loss of the cooling pipes just before and after RFQ, the maximum water flow rate for RFQ was limited to be about 260 L/min. We will tune the flow rate between RFQ and DTL after replace and simplify those pipes in the summer maintenance in 2018. We already confirmed that water flow for RFQ was improved to be 330 L/min. Further adjustment of the flow rate will be done in Sept. 2018 after resuming the beam operation. Table 1 is a summary of the measures for cooling water system for cavities. As a result, we can decrease temperature differences about 2/3 of the original values.

Furthermore, the stability of the inlet temperature was improved by changing the PID algorism of the cooling water temperature control. Originally, each PID device was controlled by thier built-in PID. In the new algorism, control of several PID devices were unified in a program. Fine temperature tuning is only done by a local in-line heater attached just before the cavity. Here, the detailed explanation is omitted because of limitation of space.

Table 1: Cavity Temperature Increases and Water Flow

	Original	**Measure 1**	**Measure 2**
		RFQ	
ΔT	1.5 ˚C	1.2 ˚C	1.0 ˚C
Flow rate	100 L/min	160 L/m	220 L/m
		DTL	
ΔT	1.5 ˚C	5.3 ˚C	1.0 ˚C
Flow rate	100 L/min	40 L/min	220 L/min

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Stability of the Beam Operation

After the improvements done for RFQ as mentioned above, the beam operation with 50 Hz repetition and width of 920 μs became very stable to keep more than 1 hour. Since typical medical-treatment time for BNCT is about 1 hour, the iBNCT project aims to start first-phase clinical trial study for melanoma patients by considering the beam stability as a first priority. At the beginning of the commissioning, average beam current was 1 mA at the target. As a result of tuning for the hydrogen gas flow rate, the current of a solenoid magnet of the ion source, an electrostatic lens after an extraction electrode, the beam current was increased up to 1.3 mA. After the retuning of the hydrogen gas flow, the current was increased up to 1.4 mA with the gas flow of 3.1 SCCM. This current is equivalent with an epi-thermal neutron flux to complete clinical treatment to melanoma patients within 1 hour

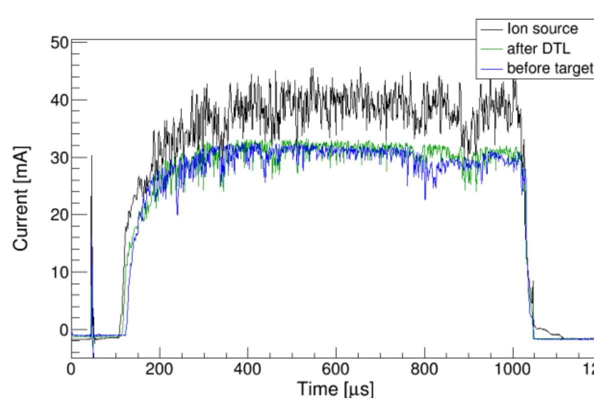

Figure 1: Waveforms taken with CTs installed at the ion source (black), after DTL (green) and before the target (blue), respectively.

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which is issued a guideline by IAEA [3]. Figure 1 shows the waveform taken with current transformers (CTs) installed at the ion source, after DTL, and before the target, respectively. The peak currents at the ion source and the target are about 40 and 30 mA, respectively. We consider that further optimization is enable by the increase of the diameter of extraction hole which is presently rather small one of 6 mm in diameter.

With this beam condition, we have finished data taking for basic information on neutron beam, such as intensity and spatial distributions of epi-thermal neutrons. Furthermore, irradiation tests with cells with boron medicaments were performed 3 times in the fiscal year of 2017. An irradiation test with mice was performed in Jan. 2018, which was the first animal irradiation test for iBNCT.

Integrated Charge

Figure 2 shows the integrated charge of the beam commissioning by the end of Jul. 2018. Blue and green lines indicate the charges just after the ion source and at the beam transport line before the beryllium target, respectively. We optimized the solenoid magnet for the ion source at Apr. 2017 to have higher plasma density, and we were keeping beam operation with a fixed repetition rate of 50 Hz since Sept. 2017. At Jul. 2018, the integrated charges are 2500 C at the ion source, and 2000 C before the target. A typical BNCT medical treatment to a melanoma patient needs about 4 C, thus current operational result is equivalent to 500-times medical treatments. Although this remarkably-large charged was irradiated to the target, no deterioration of the neutron yield was observed. Red triangle plots in Fig. 2 show the thermal neutron flux (right scale) measured with a gold-activation method in a water phantom. Values are normalized with a proton average current of 1 mA. Each point has systematic error of 8 % as shown in the leftmost point, and all points are consistent within the systematic error. The irradiation result definitely shows that the stability and usefulness of our beryllium target [4]. We still have an enough margin

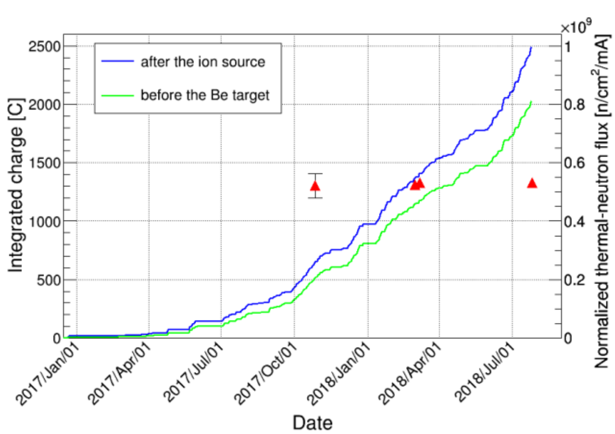

Figure 2: History of the amount of integrated charges after the ion source (blue) and the beam transport line before the target (green), respectively. Triangle plots indicate the thermal-neutron flux normalized the current.

to an estimated lifetime of the target, however, the accurate estimation is fairly difficult. Thus, it is important to check the soundness of the target by an online monitor of the neutron flux with LiCAF ($LiCaAlF_6$ doped rare-earth ion) scintillators and periodical observations of the surface of the beryllium target.

Toward Higher Beam Current

Since the stability of the operation with an average beam current of 1.4 mA was already confirmed, the iBNCT project will start non-clinical bench tests as soon as possible toward the first-stage clinical trial study aiming the realization in the fiscal year of 2019. To achieve higher beam current makes it possible to enlarge the applicable range of cancer and to shorten medical treatment time. A present goal is to achieve the current of 5 mA, and it is necessary to increase the repetition rate up to 150 Hz. We have been ready to start high repetition test from this June. We increase the repetition rate to be 66.7 Hz, and already achieved the average beam current of 1.9 mA with a considerable stability. Toward realization of 5 mA, we keep the beam commissioning with increasing the beam repetition rate up to 150 Hz by a stepwise tuning.

CONCLUSION

In the iBNCT project, instability of RFQ was serious problem for the stable operation at beginning of 2017 after the certification of the radiation generator facility. With improvements of the vacuum and cooling water system of RFQ, we have achieved stable beam operation with an average beam current of 1.4 mA at the repetition of 50 Hz. This beam current enables the iBNCT project to start non-clinical tests necessary for a first-phase clinical trial study aiming at the realization in the fiscal year of 2019. We keep the beam commissioning to achieve more than 5 mA for future extension of the iBNCT project.

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