Neutron Production Measurement in the 125 MA 5 MeV Deuteron Beam Commissioning of Linear IFMIF Prototype Accelerator (LIPAc) RFQ

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NEUTRON PRODUCTION MEASUREMENT IN THE 125 MA 5 MEV DEUTERON BEAM COMMISSIONING OF LINEAR IFMIF PROTOTYPE ACCELERATOR (LIPAC) RFQ

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Abstract

The validation of the Linear IFMIF Prototype Accelerator (LIPAc) is being conducted in Rokkasho Fusion Institute of QST, Aomori, Japan. The beam commissioning of the novel LIPAc RFQ has been progressing significantly, and the acceleration of the world highest current deuteron beam of 125 mA to 5 MeV (1 ms, 1 Hz pulsed beam) was achieved for the 1st time in July 2019. This study is devoted to evaluating the amount of beam loss at the high current acceleration by measuring neutrons generated to verify the accelerator design concept. The foil activation method and the ^{3}He probes were utilized. It turned out that there was no significant trace of the unexpected beam loss at the high energy section of the RFQ and the Medium Energy Beam Transport section. An evidence was obtained with the ^{3}He probes that the beam loss in the RFQ cavity was well controlled as designed. This study concludes that the LIPAc RFQ is working well as predicted by the design calculation, and its concept is successful.

1. INTRODUCTION

In the development of a fusion DEMO reactor, the irradiation test of structural materials with a neutron field simulating the reactor condition is indispensable. The International Fusion Materials Irradiation Facility (IFMIF), which is an accelerator-driven neutron source using deuteron-lithium (d-Li) nuclear reaction, is the most suitable and feasible candidate for the irradiation test- A world-wide research effort has been conducted to validate the required technologies for this type of neutron source. The project is currently in the EVEDA (Engineering Validation and Engineering Design Activities) phase to demonstrate the validity of the engineering design and technology required for IFMIF. One of the key activities in EVEDA is the construction of the Linear IFMIF Prototype Accelerator (LIPAc), which is a prototype of the IFMIF deuteron accelerator aimed to validate the acceleration of deuterons up to 9 MeV with a beam current of 125 mA in continuous wave (CW). LIPAc consists of a deuterium ion source, the Low Energy Beam Transport (LEBT) section, Radio Frequency

Quadrupole accelerator (RFQ), the Medium Energy Beam Transport (MEBT) section, the Superconducting RF (SRF) LINAC, the beam Diagnostics Plate (D-Plate), the High Energy Beam Transport (HEBT) section and the Beam Dump. The biggest challenge of LIPAc is the stable acceleration of the deuteron ion beam at the world highest average current of 125 mA. The accelerator components designed and manufactured by different institutes in EU and Japan has been delivered to Rokkasho Fusion Institute of QST at Aomori, Japan, and the installation, check out and the beam commissioning has been carried out in stages [1]. The installation of the novel RFQ accelerator, the MEBT and the D-Plate was completed in 2017 and the beam commissioning was started in 2018 [2]. The beam commissioning of RFQ and MEBT has been progressing significantly since then, and the acceleration of a deuteron beam of 125-mA peak current up to 5 MeV (1 ms, 1 Hz pulsed beam) was succeeded for the first time on 24th July 2019 [3, 4]. As LIPAc accelerates the very high beam current and since deuterons whose neutron production yield is significantly larger than that of proton, it is highly important to minimize any beam loss at high energy in general to avoid activation or damage on accelerator components. It is the design concept to localize such a loss if it is deemed necessary for control of the quality of the beam or reduce a further loss at downstream. Therefore, in the beam commissioning conducted, it was important not only just to achieve the target current but also to demonstrate that the beam loss was controlled as designed. To this end, the present study aimed to evaluate the amount of beam loss by measuring quantitatively neutrons generated during the deuteron acceleration experiment at high current in order to verify the accelerator design. The details of the measurement method, the analysis calculation and the results are described.

2. EXPERIMENT AND ANALYSIS

2.1. Neutron production mechanism and yield

The configuration of the accelerator components used for the pulsed deuteron beam campaign performed in 2019 is shown in Fig. 1. The deuteron ion beam generated in the ion source was accelerated by RFQ from 100 keV to 5 MeV, transported by the MEBT and passing through the D-Plate down to the water-cooled aluminium Low Power Beam Dump (LPBD) that can only accept pulsed beam up to 625 W, which corresponds to 1 ms/1 Hz pulse at 125 mA. The beam current was measured at several locations as indicated in Fig. 1. When the 125 mA pulsed beam was accelerated, typical measured currents were: LEBT ACCT: 142 mA, MEBT ACCT: 127 mA, D-Plate ACCT: 126 mA, and LPBD: 125 mA [5]. This result meant that about 15 mA beam would be lost somewhere in the RFQ cavity.

During the beam commissioning, neutrons were generated by several different mechanisms as follows:

- The nuclear interaction of deuteron with aluminium cone in LPBD: the neutron production of ^{27}Al with deuteron interaction is exothermic and the reaction Q-value is 9.36 MeV at maximum. Neutrons from this reaction are generated with continuous energy up to approximately 14 MeV, which is the sum of the Q-value and the incident energy [6];
- The interaction with copper in RFQ or other components made of copper (e.g., scrapers in MEBT); the neutron production of ^{63}Cu and ^{65}Cu with deuteron interaction (69.15% and 30.85% nat. abundance, respectively) is exothermic and the reaction Q-value is 6.70 MeV at maximum. Neutrons from this reaction are generated with continuous energy up to approximately 12 MeV;
- The d-D reaction due to the accumulation of deuterium in RFQ walls.

The reaction cross sections in some evaluated libraries available for Cu and Al and the d-D reaction are shown in Fig. 2. Although these reactions are exothermic as mentioned above, the cross sections are very small when the deuteron energy is less than 2 MeV due to the Coulomb potential barrier of nucleus, while the d-D reaction cross section is large enough even if the energy is less than 1 MeV because of a strong resonance. Since the deuteron injected in the target substrate slows down, the actual neutron yield, so-called ‘thick-target yield’, can be obtained by integrating the cross section over energy. The amount of neutron production also depends on the target nucleus number, which is smaller for the d-D reaction. The thick-target yields with 5 MeV deuteron are summarized in Table 1, in which the (d,x)n values are estimated from experimental data available [7] and the d-D values are calculated from the cross section evaluated in the ENDF/B-VII library. The neutron yield with Al is about 8 times larger than Cu for the same current deuteron. Fig. 3 shows the energy dependency of the thick target neutron yield calculated with the evaluated cross sections for d-Cu and d-D reactions on Cu substrate with the assumption that the Cu:D ratio is 1:0.1. The yield increases almost linearly between 1-3 MeV due to the d-D contribution, and the d-Cu contribution is dominant and increases rapidly above 3.5 MeV. Note that the ratio of 1:0.1 assumed for Cu:D is the value at almost fully loaded, thus it requires some time to reach this level, and it also depends on the amount of loss.

TABLE 1. SUMMARY OF THICK TARGET YIELDS FOR AL AND CU WITH 5 MEV DEUTERONS

Substrate	(d,x)n (Estimated from experimental data [7])	d-D with loaded D (Calculated with ENDF/B-VII)
Al	2.61E-04 n/d	7.09E-06 n/d (Al:D=1:0.1)
Cu	3.20E-05 n/d	4.29E-06 n/d (Cu:D=1:0.1)

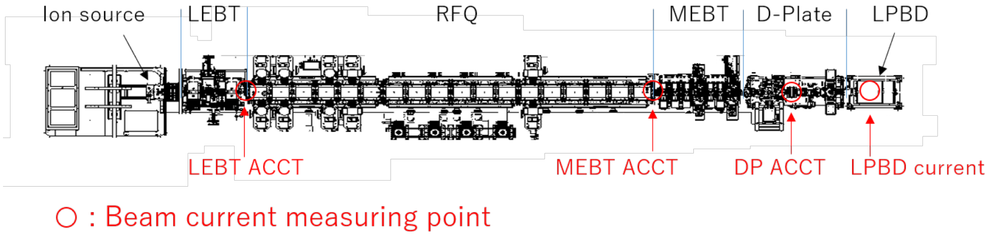

FIG. 1. LIPAc configuration used for the pulsed deuteron beam campaign performed in 2019.

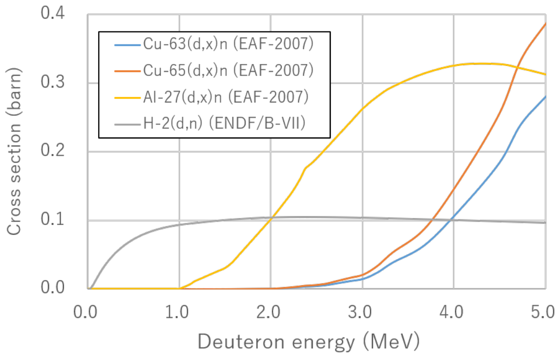

FIG.2. Comparison of neutron production cross sections concerned.

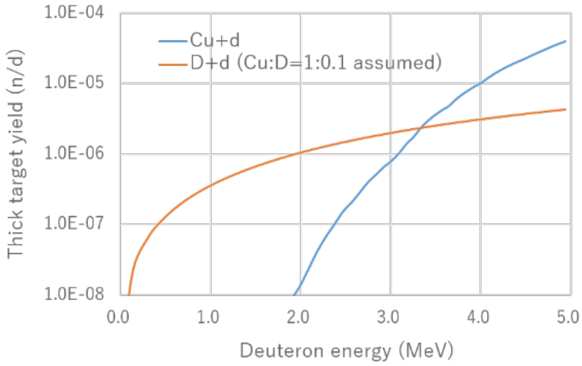

FIG.3. Thick target neutron yield for d-Cu and d-D reaction on Cu substrate (Cu:D=1:0.1 assumed).

2.2. Neutron production measurement

In order to detect neutrons produced, several different methods were utilized. The foil activation method was used to determine the neutron flux distribution along the accelerator. Four different materials having different threshold energies for nuclear reaction, i.e., Nb, Al, Ni and In were used. In this article, we focus on the result of 35 Ni foils (10 mm-ϕ, 1 mm thickness), which were placed in different locations along the accelerator as indicated with orange triangles in Fig. 4. The ^{58}Ni(n,p)$^{58m+g}$Co reaction utilized is sensitive to neutrons with the energy more than about 2 MeV, and the half-life of the product ^{58}Co is 70.86 days, so it is very suitable for long-term irradiation to gain the sensitivity to neutrons at a small production rate. The Ni foils were irradiated in the accelerator vault for about 1 month. After the experiment was over, the induced activity was measured with a HPGe detector. The detection efficiency was determined with a standard source.

Since the Ni foils are sensitive to the wide range of neutrons but it is difficult to detect a trace of small number of neutrons, five ^{3}He proportional counters combined with a polyethylene moderator were placed as indicated in Fig. 4. The accelerator geometry in Fig. 4 is the horizontal cut of the Monte Carlo simulation model used in the analysis and the main neutron source point, LPBD, is placed at the left-hand side contrary to Fig. 1. The probes #1 to #4 were on the low energy section of the RFQ cavity, which includes the bunching section of the RFQ cavity and almost all the loss (about 4% of the incident deuterons) are designed to be occurred in this section before the beam is accelerated to 0.5 MeV [8]. The probe #5 was placed near a scraper of MEBT after the RFQ, where some beam loss is expected according to the simulation since it is designed to cut some unaccelerated (<5 MeV) and halo (5 MeV) particles [9].

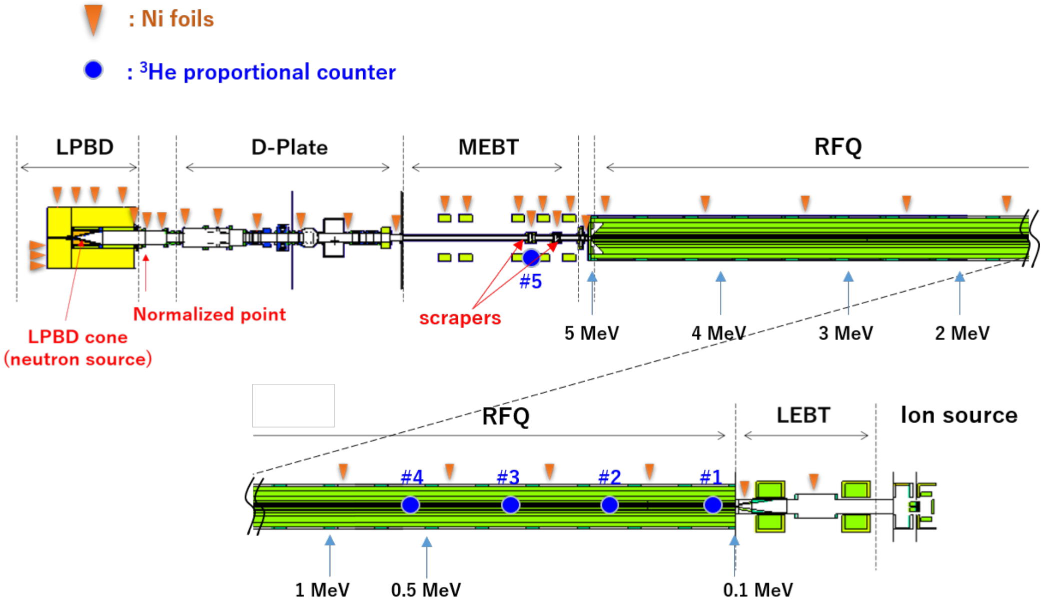

FIG.4. Arrangement of Ni activation foils and ^{3}He counters along the LIPAc accelerator components.

2.3. Analysis

A neutron transport calculation was performed with a 3-dimensional Monte Carlo code MCNP5-1.60 to obtain the neutron distribution coming from LPBD for comparing with the measurement, and the reaction rates of the Ni foils and the count rates of the ^{3}He counters were estimated. In this calculation, only the neutron production on LPBD was considered, and the angle-energy correlated distribution of neutrons emitted from d-Al reaction on LPBD was given based on the experimental data for the double-differential thick target yield measured at Kyushu University, Japan [7]. The 3-dimensional geometry model of the accelerator components as well as LPBD was constructed as shown in Fig. 4. The materials are specified by different colours: yellow for polyethylene, green for copper (or lead for LPBD), orange for water and others for stainless steel (or aluminium for LPBD).

3. RESULTS AND DISCUSSIONS

3.1. Activation foils

The results of the measured activity for the Ni foils are shown in Fig. 5 in cyan dots. The error bars given show the statistical error in the measurement. The lower limit of detection in the measurement was determined to be around 0.05 Bq/g, which was roughly estimated to be 0.5-mA constant loss at 5 MeV, and the activities of 15 foils out of 35 were less than the limit (indicated as ‘ND’ in the figure). No significant activation was observed for all the 9 foils placed on the RFQ cavity. In the figure, the orange line is the calculation result. In order to compare the calculated relative distribution with the measured activity, the calculated result was normalized to the point where the highest activity was observed. This point is between LPBD and D-Plate, just upstream of the LPBD cone and thus the calculation depends only on the geometric condition. As one can see in the figure, the overall agreement with the measured and calculated distributions are very well excepts at a few points, namely at two MEBT scrapers and at the last point in LEBT. The good agreement indicates that the activation is only due to the contribution from LPBD and the intentional loss expected on the scrapers, and there are no other significant contributions from unexpected beam loss. The last point in LEBT is close to the Faraday cup that is often inserted to adjust the beam before the injection to RFQ and deuterons were already fully loaded, and thus a large d-D neutron contribution would explain the result. The activity observed at the scrapers are almost twice than the detection limit and hence significant. This result is quite consistent with the beam current measurement, where about 0.5 mA beam loss was observed between the MEBT entrance and D-Plate with the nominal scrapers setting. It proves that the acceleration and bunching in the RFQ cavity and the MEBT transport are working properly as predicted, no significant beam loss take place at the high energy section of RFQ, the MEBT losses are well localized, and the overall behaviour of the beam transport is well predicted by the beam dynamics calculation.

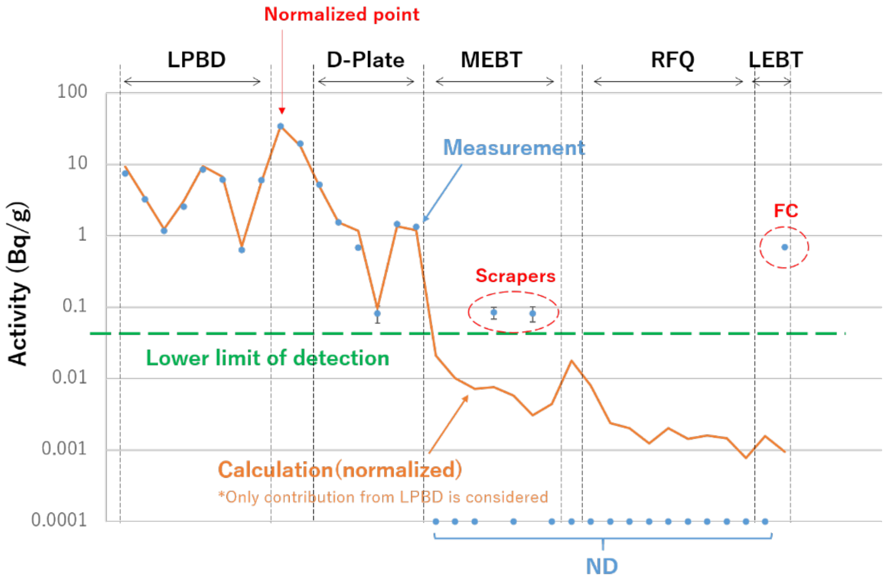

FIG.5. Comparison of the activities measured for the Ni foils and calculation.

3.2. ^{3}He proportional counters

From the result above, it was confirmed that there was no significant beam loss at the high energy section of the RFQ. Hence, the difference of the beam current between LEBT ACCT and MEBT ACCT would be attributed to some loss in the bunching section of the RFQ. Since the deuteron energy in this section is less than 0.5 MeV, it makes sense that the loss cannot be detected with Ni foils unless the amount is very large and deuterons are loaded a lot. The ^{3}He probes are more sensitive and would be possible to detect a trace of d-D neutrons generated at the bunching section. As suggested from the calculation result shown in Fig. 5, the neutrons emitted from LPBD also distribute around all over the RFQ. Although it is difficult to distinguish these two contributions, we investigated the behaviour of the different ^{3}He probes in details.

Fig. 6 shows the time evolution of the neutron production rates measured by the ^{3}He probes during a 100-mA pulsed deuteron beam acceleration test. The count rate of 4 probes on RFQ (#1 - #4) were slightly different, while the simulation with the LPBD source predicted almost the same count (within 10% difference). When the cavity voltage (Vcav) of RFQ was decreased from the nominal one of 132 kV for deuteron acceleration, a very interesting trend was observed. The LPBD current was decreasing, nevertheless the neutron production measured with the probe #4 was gradually increasing, and then the probe #3 was also increasing. At that time, the difference of the input current (LEBT ACCT) and the output current of RFQ (MEBT ACCT), which corresponded to the loss in RFQincreased. This result suggests that most probably the increase of the probes #3 and #4 counts are attributed to the increasing beam loss in the bunching section of the RFQ cavity when the cavity voltage was decreasing. The behaviour is in accordance with the prediction by the beam dynamics simulation that the beam loss mainly occurs at this section and its amount and point of loss shall increase and move to upstream side when Vcav is lowered. When the cavity voltage was very much decreased below 110 kV, the LPBD current decreased and the difference between MEBT ACCT and LPBD was significant. This means that the beam was lost somewhere within the output of the RFQ and the LPBD. At that time, the count rate of the probe #5 increased. This behaviour can be explained as follows: when the cavity voltage is very low, some input particles cannot be accelerated to the nominal energy of 5 MeV by RFQ, cannot be passing through MEBT, and lost on the scraper. The result is also consistent with the prediction of the beam dynamics simulation.

The present result proves that those probes are a very powerful tool to investigate the behaviour of the RFQ cavity from the beam dynamics point of view. It is complicated to predict the measured count rates quantitatively since there are several different neutron sources without information of their strengths, but a comparison with the beam dynamics simulation would reveal the neutron production behaviour in the bunching section as well.

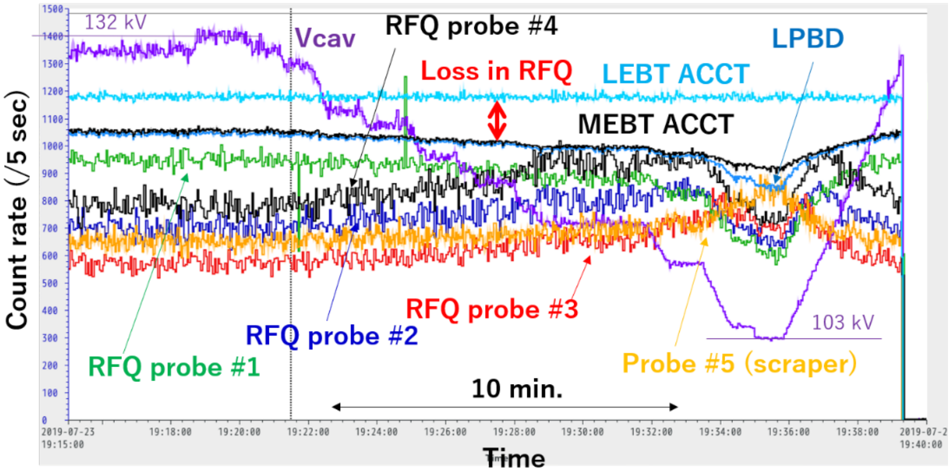

FIG.6. Time evolution of the ^{3}He probes counts and the beam currents when the cavity voltage was changed.

4. CONCLUSION

The accumulated neutron production and the relative production rates during the 125-mA pulsed deuteron beam acceleration campaign in LIPAc were measured with the foil activation method and the ^{3}He proportional counters, respectively. The comparison of the measured activity with the foil activation method and the calculation suggests that unpredicted beam loss is not significant after the beam is accelerated to 5 MeV. No trace of the beam loss at the high energy section of the LIPAc RFQ was observed, while only the loss at the MEBT scrapers were clearly identified as expected. From the measurement with ^{3}He probes, an evidence was obtained that the difference between the RFQ input and output was made at the bunching section as designed and the beam loss was well controlled. This study concludes that the LIPAc RFQ and MEBT are working very well as predicted by the design calculation, and their concept is successful.

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