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RADIATION MEASUREMENT IN THE 1ST BEAM COMMISSIONING CAMPAIGN OF THE LIPAc RFQ

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Abstract

The 1st proton beam acceleration of the Linear IFMIF Prototype Accelerator (LIPAc) through its novel RFQ was succeeded on 13th June 2018. Addition to plenty of beam diagnostics equipped in the beam line, we prepared some radiation detectors placed around the accelerator in order to acquire supplemental information of the beam, as an indirect measurement. In the first day of the beam injection to the RFQ, the gamma-rays corresponding to certain excited states of Al of the low power beam dump were successfully detected by a LaBr3(Ce) scintillation detector. Some neutrons, which would originate from the interaction of protons with Cu somewhere, were also observed. These results proved that the beam was certainly accelerated up to about 2.5 MeV, and provided us a definitive confidence that the RFQ was working appropriately from the very beginning of the commissioning. Also, the comparison of the radiation yields with the RFQ transmission provided additional information on the beam energy distribution.

INTRODUCTION

The construction of the Linear IFMIF Prototype Accelerator (LIPAc), which is a prototype of the IFMIF (International Fusion Material Irradiation Facility) deuteron accelerator projected to validate the acceleration of deuterons up to 9 MeV with a beam current of 125 mA in CW, is progressing at Rokkasho, Aomori, Japan [1]. The beam commissioning of LIPAc is now in the stage of 'Phase-B', in which we aim to have deuteron beam acceleration up to 5.0 MeV through the novel RFQ [2] and the characterization of the beam in pulsed mode at low duty cycle (0.1% in nominal) [3]. Also, the commissioning of MEBT section with two bunchers [4], as an interface to the SRF Linac, and the functionality test of beam diagnostics are ongoing.

The 1st proton beam acceleration of the LIPAc through the RFQ was succeeded on 13th June 2018 [5]. Addition to plenty of beam diagnostics equipped in the beam line, we prepared some radiation detectors placed around the accelerator in order to acquire supplemental information of the beam, as an indirect measurement. The details of the attempt of this measurement are presented in this paper. The comparison of the radiation yield with the RFQ transmission measurement is discussed as well.

LIPAc PHASE-B CONFIGURATION

Figure 1 shows the accelerator layout of LIPAc in Phase-B. The accelerator consists of the injector with an ECR ion source (H^+ 50 keV/ D^+ 100 keV), LEBT, then the world longest RFQ, MEBT composed of 5 Q magnets, 2 scrapers and 2 bunchers, D-Plate and the low power beam dump (LPBD) that can withstand only low duty cycle operations. LPBD consists of an aluminium alloy cone that is water-cooled, lead gamma shields and polyethylene neutron shields surrounding the cone.

While the final goal of the Phase-B is the demonstration of the 125 mA deuteron acceleration to 5 MeV with pulsed beam of 1 ms, 1 Hz (duty 0.1%), the initial beam commissioning was started with proton beam (2.5 MeV at the exit of RFQ) with a smaller current around 10 mA, which was the achievable minimum with the LIPAc ion source. The pulse width injected to RFQ was set to 300 µs by using a chopper in LEBT. As the beam diagnostics, three ACCTs placed at the entrance of RFQ, the exit of RFQ, on the D-Plate and 7 sets of BPM (4 in MEBT and 3 in D-Plate) [6] were available from the beginning as well as LPBD, whose cone was isolated and used as Faraday Cup.

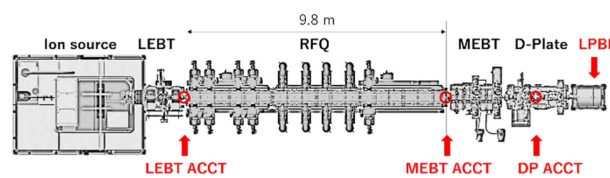

Figure 1: Layout of LIPAc in Phase-B.

RADIATION MEASUREMENT PRINCIPLE

Gamma-rays from LPBD

The threshold energy of the $^{27}Al(p,n)$ reaction is 5.80 MeV, thus no neutrons are produced on LPBD. Several specific gamma rays can be produced from the inelastic scattering of proton on Al. The following three lines are expected to be dominant with the proton beam of 2.5 MeV [7]:

844 keV : $^{27}Al(p,p'\gamma_1)$
1014 keV : $^{27}Al(p,p'\gamma_2)$

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1369 keV : $^{27}Al(p,\alpha\gamma_1)^{24}Mg$
(threshold energy: 1.7 MeV)

In order to detect these gamma-rays, a $LaBr_3(Ce)$ scintillation detector coupled with a PMT was placed at the downstream of LPBD. Since the short beam pulse of 300 μs was used, the response time of the detector should be as fast as possible to obtain a statistically enough number of signals without pile up. $LaBr_3(Ce)$ has the preferred characteristics that the short decay time (typically 20-30 ns) compared to some conventional scintillators like NaI(Tl), whose decay time is almost 10 times larger, and the very good energy resolution.

Neutrons from Cu-components

There is also a possibility that some amount of beam is lost on Cu, which is used for the RFQ cavity, the MEBT buncher cavities and the MEBT scrapers placed between Q1/Q2 and Q2/Q3. The threshold energy of the ^{63}Cu(p,n) reaction is 4.22 MeV, thus no neutrons are produced from ^{63}Cu, whereas the threshold energy of the ^{65}Cu(p,n)^{65}Zn reaction is 2.17 MeV and thus it's possible to have some neutron productions from ^{65}Cu, whose natural abundance is 30.83%, though the cross section is very small (~ 8 mb) according to the experimental data extracted from the EXFOR database [8] as seen in Fig. 2. The cross section decreases rapidly as the energy decreases from the nominal beam energy of 2.5 MeV (1 order of magnitude smaller at 2.2 MeV), thus the detection of the neutron production is a strong evidence that the beam energy is more than about 2.2 MeV. Since the beam energy of 2.5 MeV is close to the reaction threshold, the energy of the neutron produced is very low: according to the 2-body reaction kinematics, 0.351 MeV at 0 deg. and 0.296 MeV at 180 deg. for 2.5 MeV proton. A He-3 proportional counter was selected and placed near MEBT to detect the low energy neutrons, which are expected to lose the energy by scattering and become detectable with the counter.

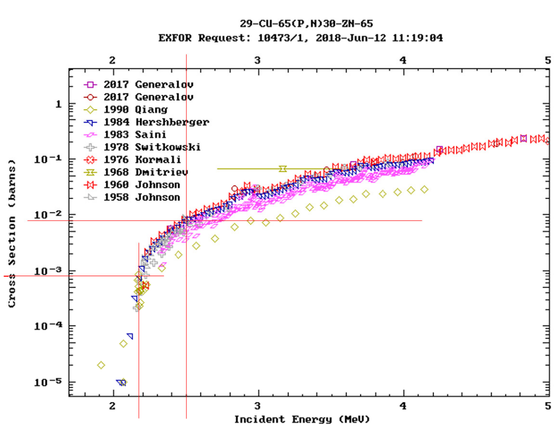

Figure 2: Experimental data of the ^{65}Cu(p,n) reaction cross section extracted from the EXFOR database.

DAY-1 EXPERIMENT

We performed the first proton beam injection to the RFQ in the afternoon of 13th June 2019. However, unfortunately, no any pulse was detected by ACCT after RFQ nor LPBD at the 1st trial, while the beam pulse was observed with the LEBT ACCT. All the radiation detectors were workable at that moment, but also no any traces that the beam reached to LPBD were observed. After a few hours' struggling, when the LEBT solenoids and steerers were manipulated, some beam currents were observed first time on LPBD, although the transmission was still very low (less than 30%). Figure 3 shows the trends of the LEBT ACCT and LPBD currents and the neutron detector count at that time. The LPBD current increased from around 16:45, and at the same time the significant increasing of the neutron production was observed. The count rate was very small, only a few counts per second, probably due to small amount of loss and the small cross section, nevertheless the existence is obvious thanks to the almost-no-natural back ground. As mentioned above, this result suggests that some proton beam accelerated to more than 2.2 MeV was lost on Cu somewhere. At that time, we didn't know where it was, but a few days later we confirmed that it was on the MEBT scrapers, as designed, because the neutron count was disappeared when that was extracted.

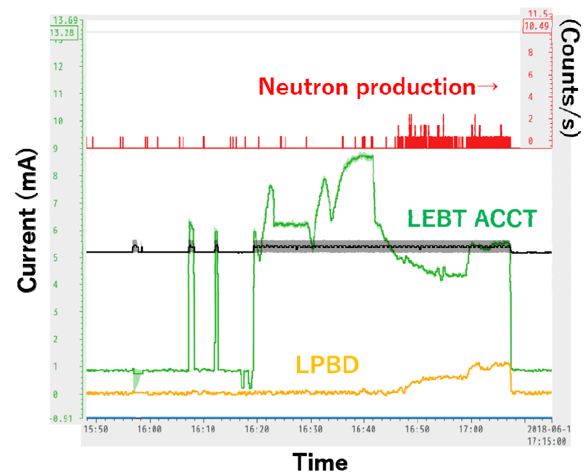

Figure 3: Beam current and neutron production trends when the beam reached to LPBD first time.

The gamma rays were also successfully detected by the $LaBr_3(Ce)$ detector as expected during the day-1 after the beam was reaching to LPBD. The gamma-ray energy spectrum obtained on the day is shown in Fig. 4. The background spectrum is also shown. Each of the foreground and background are normalized by the measurement time, thus the difference of the two spectra is equal to the contribution of the gamma-ray produced by the beam on LPBD. The structure seen in the background at around 700-1000 keV is contribution from natural ^{138}La decay in the $LaBr_3(Ce)$ crystal. The prominent peak at 1461 keV is due to the ^{40}K natural background mainly contributed from the building concrete, and this is the reason why the same contribution is seen in both spectra. The existence of the 1014 keV peak

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is very obvious, and two other peaks are also significant. Considering the threshold energy of the $^{27}Al(p,\alpha\gamma_1)^{24}Mg$ reaction forming the 1369 keV peak was 1.7 MeV, the measurement provided us a rather high confidence that the beam was accelerated to more than around 2.0 MeV.

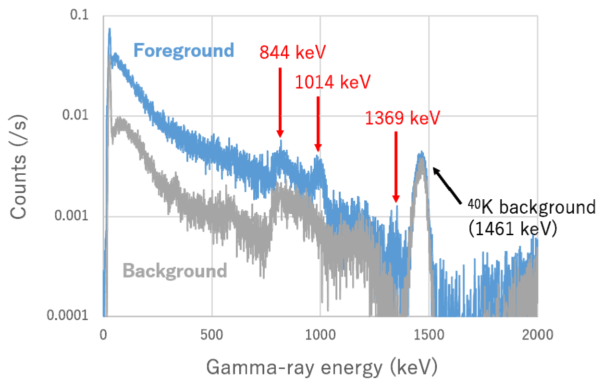

Figure 4: Gamma-ray spectrum observed at LPBD with $LaBr_3(Ce)$ detector in the day-1 experiment.

The accurate measurement of the beam energy was performed later by using the time-of-flight technique with BPMs, and the energy was confirmed to be equal to 2.5 MeV [5].

In this campaign, we were facing a difficulty due to the unexpected behaviour of the machine requiring a quite strong steering to achieve the good transmission through the RFQ [5]. However, the results of the radiation measurement provided us from the very beginning of the commissioning the confidence that RFQ was working properly and the beam was accelerated to the nominal value as designed, and therefore the problem would exist elsewhere. In the second beam commissioning campaign started on 20th February 2019, it was finally confirmed that the issue was coming from the LEBT. After having solved the issue, the maximum transmission was achieved without using the steering.

RFQ TRANSMISSION AND RADIATION

When the RFQ transmission was measured by changing the RFQ cavity voltage, an interesting relationship was observed between the transmission and the radiation yields. Figure 5 shows the evolution of the neutron and gamma count rates and the LPBD current as the RFQ cavity voltage was modified. Note that the gamma count rate is just a sum of a peak region, and the Compton continuum was not subtracted. In the beginning, the cavity voltage was set to the nominal value of 66 kV for proton acceleration [2]. After that, the voltage was decreased gradually step by step. When the voltage was downed to less than 83 % of the nominal, the LPBD current was getting a bit smaller, which means the transmission was decreasing, and consequently the gamma production and the neutron production were also decreasing. When the voltage was downed further to less than 75 % of the nominal, the gamma production was suddenly dropped to almost zero, while still more than 50% of the beam transmitted to LPBD. There was also no neutron production observed. This result implies that the beam energy profile would be affected, and the mean energy was decreased.

More quantitative analysis to deduce the beam energy information from the gamma-ray measurement is underway. The comparison with the beam dynamics simulation is also necessary and under investigation.

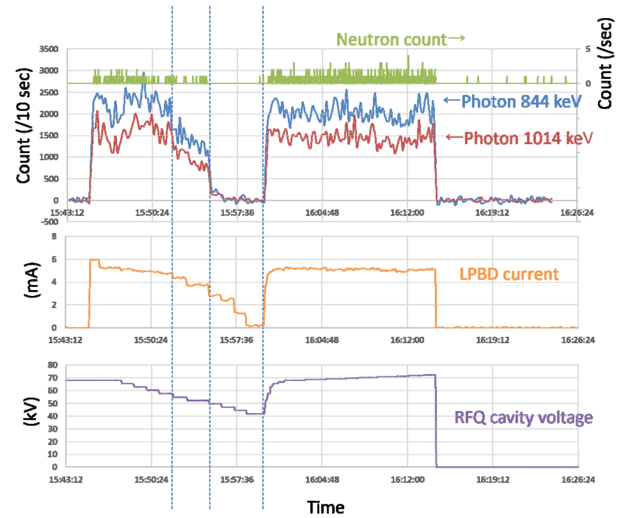

Figure 5: Relationship between the neutron/gamma count rates and the LPBD current and the RFQ cavity voltage.

SUMMARY

By means of indirect measurement of the proton beam in the first beam commissioning of the LIPAc RFQ, some radiation measurements were utilized. In this commissioning stage, from the first day of the campaign, the instrument was working properly and gave us very useful information. It also turned out that such an instrument is an important tool to be used for the validation of the RFQ design, for which the beam dynamics simulation has been intensively used. This tool would make it possible to conduct the optimization of beam transport using the proton beam efficiently and enhance the understanding of the machine characteristics before proceeding to the deuteron beam commissioning, where beam loss must be avoided as much as possible.

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