Target test facility for ADS and cross-section experiment in J-PARC

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Abstract. For the development of Accelerator Driven System (ADS), a Transmutation Experimental Facility (TEF) is planned to be built in J-PARC. In this facility, negative hydrogen \((\text{H}^-)\) beam with a power of 250 kW will be delivered to a Lead-Bismuth Eutectic (LBE) target, which is one of the powerful candidates target for the ADS, placed at ADS Target Test Facility (TEF-T). On the beam transport to TEF-T, laser charge exchange (LCE) technique will be utilized to Transmutation Physics Experimental Facility (TEF-P) to deliver a very low-intensity \((10 \text{ W})\) beam with high stability from high-intensity \((\text{H}^-)\) beam. To examine this technique, we carried out the experiment at the RFQ test bench. By using the LCE, very stable short pulse beam extraction has been demonstrated for a long duration. We have started the development of beam monitor for the TEF-T by using heavy ion to give high DPA rate. Some experiments for validation of code and nuclear data are planned in J-PARC to obtain nuclear data for the ADS.

1. introduction

For the development of Accelerator Driven System (ADS) to the mitigate hazard of long-life nuclides produced in a nuclear reactor, especially for minor actinide (MA) such as neptunium and americium, a Transmutation Experimental Facility (TEF) shown in Fig. 1 is planned to be built in J-PARC. In this facility, negative hydrogen \((\text{H}^-)\) beam with a power of 250 kW and repetition rate of 25 Hz, which is accelerated in a 400-MeV LINAC, will be delivered to a Lead-Bismuth Eutectic (LBE) target. The LBE is one of the candidate targets for the ADS, placed at ADS Target Test (TEF-T). In the TEF-T, multi-purpose use of the facility is planned. To perform experiments such as examination of...
semiconductor devices, spallation neutrons produced at the LBE target will be provided to the experimental neutron hall at TEF-T. At the TEF-T, Isotope Separator On-Line (ISOL) is planned to be built as a candidate for multi-purpose use in the second target station. For a study of reactor physics with spallation neutrons, a Transmutation Physics Experimental Facility (TEF-P) is planned to be built in TEF, which is composed of an MA core with effective neutron multiplication factor ($k_{\text{eff}}$) of 0.95.

To transform significant amounts of actinide nuclides, the accelerator with a beam power of 20 MW as a candidate with extremely high reliability is considered in the design of JAEA. For beam injection to TEF-P with a very low intensity such as 10 W from the high-intensity $H^-$ beam (250 kW), a reliable beam extraction system is required. To realize the ADS, further neutronics studies and reaction cross-sections of reaction are required. In this paper, the present status of the design of the TEF and the research and development for TEF and ADS are described.

2. TEF-T and TEF-P
In the Japan Proton Accelerator Research Complex (J-PARC), a MW-class pulsed neutron source, the Japan Spallation Neutron Source (JSNS), and the Muon Science facility (MUSE) were deployed in the Materials and Life Science Experimental Facility (MLF). In the present beam operation, a LINAC provides 400 MeV $H^-$ beam at 25 Hz to a Rapid Cycling Synchrotron (RCS). After upgrade of the LINAC to deliver beam to TEF, the repetition rate will be increased from 25 Hz to 50 Hz. By adding extraction device into the LINAC, an $H^-$ beam of 25 Hz is derived to TEF-T. Preliminary design of the TEF-T has been completed and is described in a Technical design report[1].

3. Research and development for TEF-T and ADS
For TEF-T and ADS, beam extraction system has been developed. To validate the calculation code and the nuclear data used in the neutronics design for ADS, we have carried experiments in J-PARC. In this section, research and development of a beam extraction system based on laser charge exchange and some experiments to obtain cross-section are described.

3.1. Beam extraction based on laser charge exchange
On the beam transport to the TEF-T, the beam extraction technique involves a very low-intensity beam such as 10 W taken from the high-intensity 250-kW $H^-$ beam[2]. One electron of the $H^-$ ions will be detached by photons of Nd-YAG laser to produce neutral hydrogen beam ($H^0$). Following a thin foil, the $H^0$ stripped to $H^+$ so that eventually protons are introduced into the TEF-T. This technique satisfies the requirement for the safety demand for beam separation. It should be noted that the maximum beam power is physically determined. An alternative extraction technique using a thin wire and magnets could produce an unexpected beam power so that these techniques can not be applied at the TEF. Also, an abnormal vacuum level in the accelerator may cause unintentional beam extraction. Therefore, the interaction point is placed in the middle of bending magnet, which prevents unexpected beam extraction by minimizing the straight length in the interaction section.

To demonstrate this technique, we carried out an experiment by using a 3-MeV RFQ placed on the test bench of the LINAC building by using experimental setup [3] shown in Fig. 2. The interaction point of the laser was put in the center of the dipole magnet, which bends the $H^-$ beam by 23°. Consequently, the charged exchanged beam by the laser is delivered at 11.5°, which is the half angle of bending magnet. At 11.5° direction, we placed a thin foil to strip the remaining electron from the $H^0$ ions and also deployed a beam position monitor (BPM), a slow current transformer (SCT), and a Faraday cup (FC) to observe the extracted beam position and power. The length between the laser oscillator, which is Nd-YAG with 1.6 J/shot at 25 Hz
Figure 2. Laser charge exchange experiment using 3-MeV H\(^-\) beam at test-stand RFQ.

Utilizing a laser light time structure having a length of 6 ns (\(\sigma\)), and the interaction point is chosen to be similar to the TEF-T condition.

At the extraction channel, an H\(^+\) beam was observed as expected, which showed an efficiency of the charge exchange as 100% during the laser injection. These signals show, the laser light time structure having 6 ns in \(\sigma\) and the signals of Faraday cup, the BPM and the SCT. From the signal of the SC, the extracted beam power was 35 mW at 3MeV. A stable beam extraction with a fluctuation of intensity less than 2% was demonstrated for a duration longer than 7 days. At the TEF-T, 400 MeV will be utilized so that the extracted power was interpreted to be 7.7 W, which satisfied the requirements of the TEF-T. It should be noted that the present successful result means that one of the significant milestones for the TEF construction is achieved.

The current experimental result showed the capability of a small pulse in a macro pulse with the length of 0.5 ms. Using the LCE with a long length laser loop, which makes many interaction events in the macro pulse, many bunches of the beam with short pulse length about several ns with relative high repetition can be created. Those pulses may be used for a spallation neutron source with high repetition rate with short pulse length by introducing an additional target placed in the TEF-T. For the development of the ADS, neutron data around 1 MeV, which has a peak in fission and spallation neutron production, are required. Therefore, the repetition rate of the laser applies to 1 MHz, which gives the length of laser loop 300 m. Consequently, the beam power will be 700 W. Owing to the short flight path of the neutrons to the experimental hall, a relatively high-intensity neutron beam can be obtained. By using a Time-of-flight (TOF) technique, neutron experiments with high energy resolution can be performed to obtain cross section for the ADS.

3.2. Beam profile monitor

During beam operation, the observation of the beam profile on the target is essential for stable beam operation. As a candidate for the beam profile monitor, luminescence monitor is considered. Since the peak current density of the TEF-T is 6 times higher than that of MLF\(^4\), TEF requires a profile monitor that will stand the high-intensity beam. To observe the degradation of the luminescence of chrome doped Al\(_2\)O\(_3\), the experiment was performed using an Ar\(^{+15}\) (150 MeV) beam at the cyclotron in Takasaki Ion Accelerator for Advanced Radiation Application (TIARA).

The result of the degradation light is shown in Fig. 3, which shows 20 % degradation of light yield for 160 h beam operation in the MLF. Similar results were obtained at Spallation Neutron Source (SNS) in Oak Ridge National Laboratory (ORNL)\(^5\). A new material with less degradation will be developed and confirmed.
with the Ar beam irradiation.

3.3. Measurements cross section for TEF-T and ADS
To obtain cross section, we had begun activation cross-section measurements of target and window materials at the beam dump line of the beam dump placed near the extraction channel of the RCS [6]. Since gasses at the LBE loop are continuously purged to prevent erosion on the surface of the target, the gas production cross section is important, especially for rare gas because the rare gas can not be reduced in the off-gas system. Because of its particularly long half lifetime (32 days), an accuracy of estimation of $^{127}$Xe is important. In Fig. 4, a cumulative cross section of Pb(p,x)$^{127}$Xe is shown, which is normalized for the beam power. The yield of spallation neutrons is roughly constant to the beam power irrespective of the proton energy. The cross-section is shown in Fig. 4 and may give the optimum energy for the ADS to reduce the inventory of hazardous nuclides. However, the experimental data is scattered in the energy range between 1 to 2 GeV so that we will carry out further measurements for validation. In Fig. 4, comparison of various calculation using PHITS[7, 8] is also shown, and this drastically underestimates the experiment. In future, modifications will be applied to PHITS.

4. Summary
To evaluate the performance of the LCE, we carried out an experiment by using a 3-MeV RFQ placed on the test bench of the LINAC building. It was found that very stable beam with power of 8 W at 400 MeV can be extracted for a long duration. By using the LCE, a very short pulse length can be created. By using the LCE with long length loop, very short pulse spallation neutron source can be set up at the TEF-T for measurement of cross-sections for the ADS. We had started some experiments for the TEF-T and ADS.

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