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Conceptual design of proton beam transport system for ADS facilities at J-PARC

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ABSTRACT

To examine the materials issues related to accelerator-driven systems (ADSs), the Japan Proton Accelerator Research Complex (J-PARC) is planning to build the ADS Target Test Facility (TEF-T). The J-PARC also plans to build a Transmutation Physics Experimental Facility (TEF-P), where a subcritical assembly will be located. A fundamental design study for the proton beam transport system to deliver a proton beam to TEF-T and TEF-P has started. A 0.4 GeV proton beam with a relatively high beam power of 0.25 MW is introduced to a lead–bismuth (LBE) target in the TEF-T, where many species of samples are located, for post-irradiation experimental studies of the materials. In contrast, the beam power for the TEF-P is regulated at a level of several watts to ensure the safety of the subcritical assembly. In this study, feasibility studies of beam transport are performed to further the design of the TEF-T system. To introduce the beam to the LBE target, horizontal and vertical beam injection can be considered. To match the geometrical conditions of the TEF-T, perpendicular beam injection, where the beam is introduced from the bottom of the target, is difficult because of the long drift space required in front of the target for beam expansion. Consequently, horizontal beam injection to the TEF-T is chosen. The beam profile at the target is obtained using a simulation. On the basis of the parameters obtained in this study, the beam facilities of the TEF-T and TEF-P will be constructed in the near future.

1. Introduction

In the Japan Proton Accelerator Research Complex (J-PARC) [1], an MW-class pulsed neutron source, the Japan Spallation Neutron Source (JSNS) [2], and the Muon Science facility (MUSE) [3] will be installed in the Materials and Life Science Facility (MLF), as shown in Fig. 1. A 3 GeV proton beam is introduced to the mercury target acting as a neutron source. For both sources, the 3 GeV proton beam is delivered from a rapid-cycling synchrotron (RCS) to the targets by a beam transport system called 3NBT [4–6]. Before injection to the RCS, the proton beam is accelerated to 181 MeV by a LINAC. In the RCS, the proton particles are accumulated in two short bunches having widths of about 200 ns and accelerated to 3 GeV. In November 2008, the JSNS started beam operation for users. Until November 2012, beam operation successfully delivered a cumulative beam power of 1000 kWh with a beam power of 0.3 MW and a quite high availability (as large as 95%). In summer of 2013, a new LINAC with an energy of 400 MeV will be installed at the J-PARC; then, high-power beam operation will start.

To handle the nuclear waste from reactors, many studies have examined transmutation by an accelerator-driven system (ADS). For feasibility studies of the ADS in particular, the status of the target beam window under irradiation by a high-power beam is crucial. For the transmutation of minor actinides, the ADS employs a well-controlled subcritical reactor system. In terms of ADS feasibility, the physics of the neutronics, including the subcritical reactor physics, is also important.

For studies of the ADS, the Target Test Facility (TEF-T) and Transmutation Physics Experimental Facility (TEF-P) are planned at the J-PARC, as shown in Fig. 1. The TEF-T will be used mainly for material examination by using a target of liquid lead–bismuth (LBE), which is a candidate material for the ADS target. For material examination, the TEF-T is designed to receive a high beam power, such as 250 kW of 400 MeV protons with a repetition rate of 25 Hz. Because the proton beam is introduced to a critical assembly made of a fissile material, the TEF-P is, in contrast, required to operate with a low beam power, such as 10 W, and a physical barrier will prevent the introduction of a high-power beam. This paper studies the feasibility of beam transport to the TEF-T, which is related to the material examination facilities for the spallation neutron source and the ADS.

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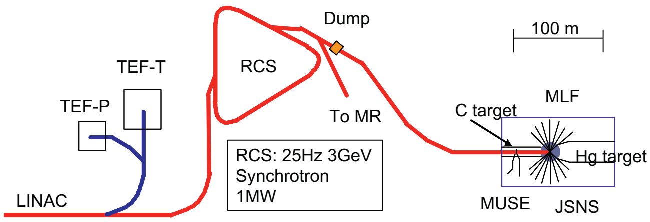

Fig. 1. Schematic drawing of LINAC, MLF, TEF-T, and TEF-P facilities at J-PARC.

1.1. TEF-T and TEF-P

At the J-PARC, to validate the status of the material for the ADS, construction of a new facility called TEF-T is planned. In addition, construction of a new facility called TEF-P is planned for the study of a subcritical reactor driven by the accelerator using the spallation neutrons. Fig. 2 shows a conceptual drawing of the facilities. The beam extracted at the LINAC is bent to the horizontal direction and injected to the target in the TEF-T, which receives most of the beam extracted at the LINAC. Because the LINAC cannot control the beam to deliver a small beam power such as 10 W, a small fraction of the proton beam is extracted to the TEF-P during beam transport to the TEF-T. In this study, the geometrical constraints are considered to examine the feasibility of the TEF-T and TEF-P.

The subcritical reactor assembly, which has a spallation neutron target at the center, will be located in the TEF-P. Because of the difference in radiation control regulations, the TEF-P, which is treated as a reactor, will be physically separated from the other facilities. For safety reasons, the TEF-P has to be limited to receiving beams with powers of less than 10 W. To fulfill the requirements, a new beam extraction technique is developed on the basis of charge exchange driven by a laser [7], which is described in Section 1.2.

1.2. Beam extraction system driven by the laser

Fig. 3 illustrates the concept of the laser-driven beam extraction system. Photons from the laser convert H^- ions to H^0 ions by electron stripping caused by the interaction between the electrons in H^- and the photons from the laser. By using a commercial YAG laser having a pulse power of a few Joules, the electrons in the H^- ions can be stripped with a high efficiency, e.g., 90%. For radiation safety at the TEF-T, the control of electron stripping is quite important. If the vacuum deteriorates in the beam duct, the electrons in the H^- beam are stripped owing to interactions with the gas. Consequently, a large amount of the beam may be introduced to the TEF-P target. To prevent this event, an electron stripper system is placed at the center of the bending magnet to minimize the straight length of the charge exchanger. By using this scheme, the amount of the H^0 beam introduced to the TEF-P target because of stripping by the gas in the vacuum duct can be kept small. After drift due to the bending magnet, the H^0 beam is separated from the H^- ions and introduced to the stripping foil. After passing the foil, the H^0 ions are converted to H^+ ions and then delivered to the TEF-P target. A material with a low melting temperature will be used as the stripping foil to avoid high-power beam injection to the TEF-P target.

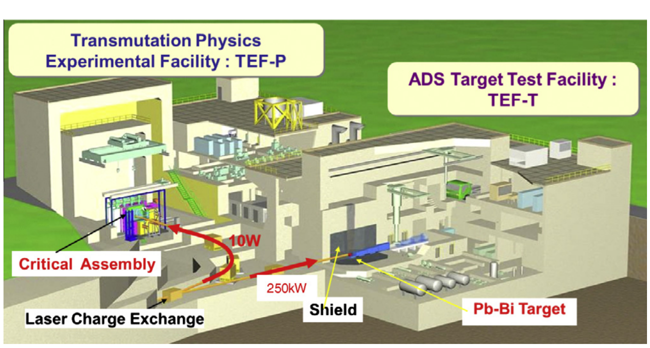

Fig. 2. Conceptual drawing of TEF-T and TEF-P at J-PARC.

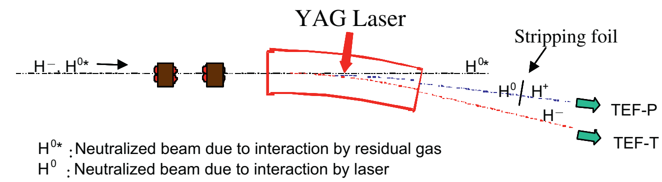

Fig. 3. Concept of laser-driven beam extraction system.

2. Requirements for TEF-T and TEF-P

For beam delivery to the ADS facilities, a pulse-bending magnet is required at the LINAC. After extraction, the beam is transported to the TEF-T and TEF-P. In this section, the requirements for the TEF-T and TEF-P are discussed.

2.1. Beam requirement at TEF-T target

The design parameters of the TEF-T and TEF-P are shown in Table 1. To perform experiments under various irradiation conditions at the TEF-T, various beam conditions can be selected, in particular the beam size. In the design of the TEF-T, a beam profile having a peak current density of 20 μA/cm^2 is planned as the basis of a design for receiving a high DPA at the target window, which is important for material studies at the ADS facility. The beam profile of the LINAC is well known to be characterized well by a Gaussian function. To achieve a peak density of 20 μA/cm^2 at the target, the beam is shaped to have a root mean square (RMS) width of 22 mm. For the study of the actual ADS using a high current of beam, the beam current density must have a higher value such as 60 μA/cm^2 m to achieve a high DPA at the material. A smaller beam size can generally be achieved easily at the LINAC because the transverse emittance of the beam will be as small as 0.3 π mm mrad, which is much smaller than, e.g., a synchrotron beam. On the other hand, expansion of the beam is rather difficult because of the requirement of a long drift space in front of the target under the given geometrical conditions. In this study, a wide beam is considered.

In an earlier design of the spallation neutron source (JSNS) target at the J-PARC, a peak current density of 10 μA/cm^2 was originally planned. However, owing to the quite extensive damage to the mercury target vessel related to pitting erosion, the beam density must be kept smaller than 7 μA/cm^2. This fact demonstrates the importance of the margin of the beam profile and the variation

Table 1
Design parameters of TEF-T and TEF-P.

	TEF-T	TEF-P
Injected particles	H^-	H^+
Energy (MeV)	400	400
Maximum beam power (W)	2.5×10^3	~10
Average beam current (A)	6.25×10^{-4}	$\sim 2.5 \times 10^{-8}$
Pulse length (s)	5×10^{-3}	1×10^{-9}–5×10^{-3}
Repetition rate (Hz)	25	Variable
Beam height from sea level (m)	6.8	~20
Magnetic field for beam transport (T)	0.5	No limit