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Moderator performance characterization, operational experience, and plans at JSNS

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Abstract. By optimizing 100% para hydrogen, especially for coupled moderator, gave unique volumetric shape, such as large sized cylindrical shape coupled with water premoderator, resulting in the highest neutron intensity per pulse at 300kW. In order to confirm relationship of the measured pulse shape with the para-hydrogen fraction, para-hydrogen fraction was measured directly in the hydrogen circulation loop. The para-hydrogen fraction was almost 99.7% for off- and on- beam operation. We started to fabricate spare moderators and reflector to replace 1st moderators and reflector assembly in 2019 due to lifetime. In spare moderator, invar and Au-In-Cd alloy will be newly installed to improve moderator fabrication and reduce radioactivity.

1. Intorduction

An accelerator-based short-pulsed-spallation-neutron-source was developed to emphasize a neutron science in J-PARC. Three hydrogen moderators (coupled, decoupled and poisoned moderators) based optimization study were installed in JSNS (Japanese Spallation Neutron Source) in J-PARC. In order to characterize short-pulsed source, 100% para hydrogen, Ag-In-Cd decoupler and Cd poison sheet were applied. Especially for coupled moderator, the unique optimization, such as large sized cylindrical para hydrogen shape coupled with optimized water premoderator, gave the higher neutron intensity, which has achieved to provide the highest neutron intensity per pulse in the world at 300kW proton-beam-operation. It's on the way to upgrade the beam power, finally will be up to 1MW in 2016. In order to confirm moderator design and para-hydrogen converter performance, the combination method as a gaseous hydrogen sampling from the hydrogen circulation loop and Laser Raman spectroscopy was applied to enable the direct para hydrogen fraction measurement in the hydrogen circulation loop. On the other hand, the moderator should be replaced in every 6 MWyears due to neutron irradiation. A plan of 2nd moderator fabrication is under way. We modify the design, such as invar use to improve the moderator fabrication and Gold-Indium-Cadmium (Au-In-Cd) alloy for decoupler to reduce radioactivity. In this paper, we report these results.

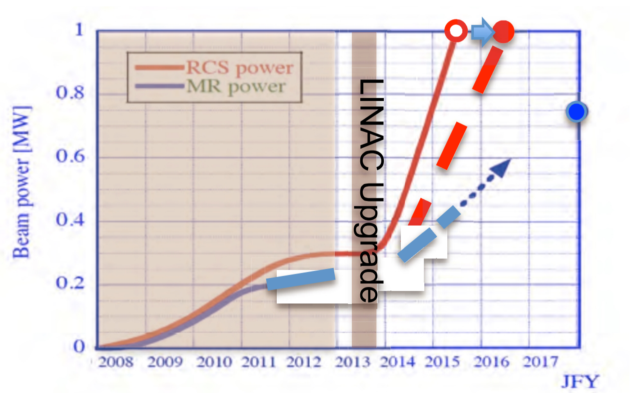

Figure 1. Accelerator rump up schedule. Linac was upgraded from 180MeV to 400MeV in the energy to increase proton beam power in 2013. Protons with 1MW beam power will be injected to JSNS in 2016

2. Moderator development activity in JSNS

Since first neutron production at 2008 in JSNS, the proton beam power gradually went up to 300 kW in 2012. Last year, linac accelerator was upgraded from 180 MeV to 400MeV in the energy to increase the beam power. We will deliver 1 MW proton beam to JSNS within 2016 according to proton beam rump up schedule as shown in Fig. 1. Activity plan of moderator/reflector is shown in Fig. 2. We started to fabricate the

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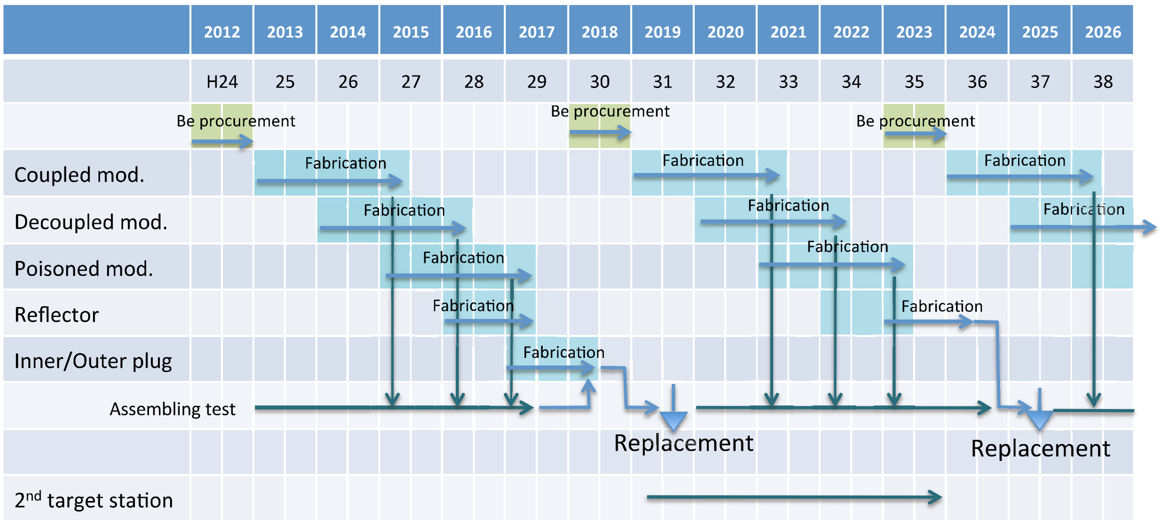

Figure 2. Activity plan of moderator/reflector. Fabrication of spare moderators and reflector is started to replace from 1st moderator and reflector assembly in 2019.

spare moderators and reflector to replace the 1st moderators and reflector assembly due to the lifetime. The lifetime was assumed to be a 20 dpa of neutron irradiation damage of aluminum alloy, which is structural material of moderator and reflector. We will estimate that the accumulated irradiation damage will reach the 20 dpa (30,000 MWhr for 1MW proton beam operation) in 2019 according to proton beam schedule. In the spare moderator, invar and Au-In-Cd alloy will be newly installed to improve the moderator fabrication and reduce the radioactivity. We also just started to consider the second target station for emphasizing the science down to very cold neutron energy region. We also are proceeding with the moderator development focusing on the high ALBEDO material, such as nano-diamonds, to intensify the blow cold neutrons under IAEA collaboration (Project No. F1216).

3. 1st moderator performance characterization in JSNS

3.1 Coupled moderator performance

A liquid hydrogen, which consists of two isomeric forms (ortho- and para- hydrogen), is only available material as the moderator for the MW-class source in terms of radiation damage. The transparent cross section of para-hydrogen, which means rapidly decrease below 14.5 meV in comparison with normal-hydrogen[1] in the total elastic scattering cross section, gives leaky neutrons from the moderator in the slowing down process, but relatively short tail in the neutron beam pulses in the cold-neutron-energy region, however, the low hydrogen density of liquid hydrogen (ca. 1/2 of solid methane) is also a weak point in the neutron moderating process. In the design, we focused on the para to ortho energy conversion in addition the pre-moderator function[2] to improve the neutron intensities in the cold-neutron-energy region for higher neutronic performance such as high peak intensity, narrow width and short tail in the "short-pulsed" neutron beam[3-11]. Especially for coupled moderator, we found the unique volumetric shape, such as large

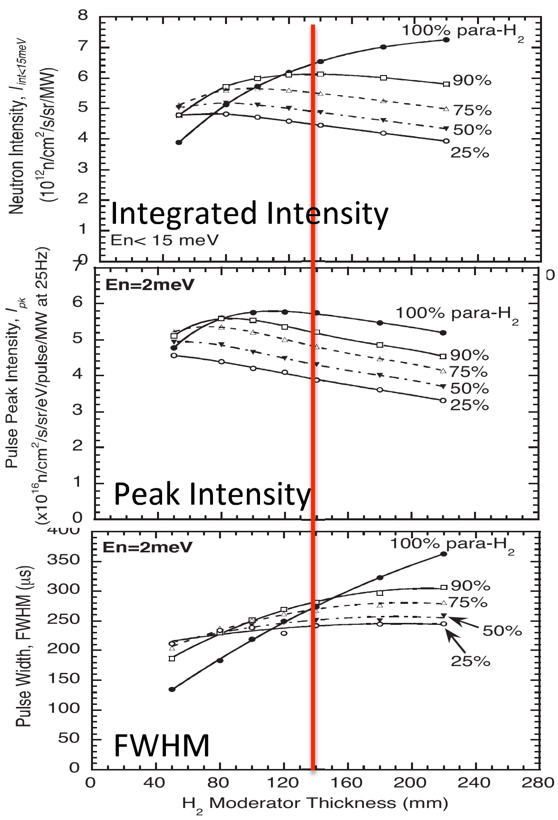

Figure 3. Hydrogen moderator thickness dependence on Pulse width (FWHM)Peak Intensity and Neutron intensity[4]

sized cylindrical para-hydrogen shape coupled with optimized water premoderator. As shown in Fig. 3, we decided the 14 cm of large moderator thickness, which gave the highest peak intensity, but somewhat sacrifice in the FWHM in pulses in the optimization study for "short-pulsed" source[4]. This coupled moderator also gave highest neutron intensity per pulse[13] in the world at 300kW proton-beam-operation in 2012. We also found that brightness area could be seen near premoderator in the spatial distribution on viewed surface of coupled moderator as shown Fig. 4. This calculation results also indicated that there was a room for the further improvement to intensify the neutrons from the different perspective, such as "long-pulsed" source design. ESS (European Spallation Source) group, which is aiming at 5 MW "long-pulsed" source, focus on increasing the brightness area in the design in order to obtain higher neutronic performance. It will be discussed somewhere.

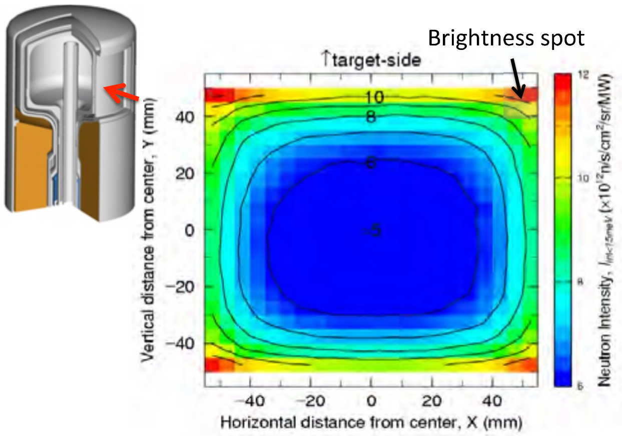

Figure 4. Spatial distribution on viewed surface of coupled moderator. Brightness spot and area can be seen near premoderator[4],

3.2 Para-hydrogen fraction measurement

In order to confirm the relationship of the measured pulse shape with the para-hydrogen fraction, it is an important to measure the para-hydrogen fraction in the hydrogen circulation loop directly. However, it is not easy to measure the para-hydrogen fraction in loop due to high pressure and cold temperature, such as supercritical hydrogen (1.5MPa and 20K) in the high power target facility. It also should be avoidable to break the stable operation of neutron source facility by accident of failure during para-hydrogen measurement process because of the open service. The combination method as gaseous hydrogen sampling from the hydrogen circulation loop and Laser Raman spectroscopy was applied in order to enable the direct para-hydrogen fraction measurement in the loop. The hydrogen sampling line was installed before / after through moderators as shown in Fig. 5. In the loop, the supercritical hydrogen (20K, 1.5MPa) was circulated. The magnetic catalyst, iron oxide hydroxide ($Fe(OH)_3$) was also installed to keep the equilibrium mixture state (99.8% para-hydrogen fraction at 20K) as shown in Fig. 5. In order to sample the gaseous hydrogen, two buffers, which consisted of small (vol.: ca. 20 ml) and large (vol.: ca. 10L) one, were con nected to hydrogen sampling line in series by the manual controlled valves. During hydrogen sampling process, it changed from supercritical state to the gaseous one. The pressure was also reduced to 1/500 (ca. 0.03MPa) by the second introduction to the large buffer. The extracted hydrogen was introduced to the glass-cells by manual valve operation as also shown in Fig. 5. Para-hydrogen fraction was measured by using Laser Raman spectroscopy (JASCO, NRS-5100) with the resolution (1 cm-1) and range (50 to 8000 cm-1) after extracted hydrogen in the glass-cell. We finally measured the para-hydrogen fraction extracted from the hydrogen circulation loop in the 300kW proton beam power. The measured Laser Raman spectrums are shown in Fig. 6 for off- and on- beam operation. The para-hydrogen fraction was almost 99.7% for off- and on- beam operation cases.

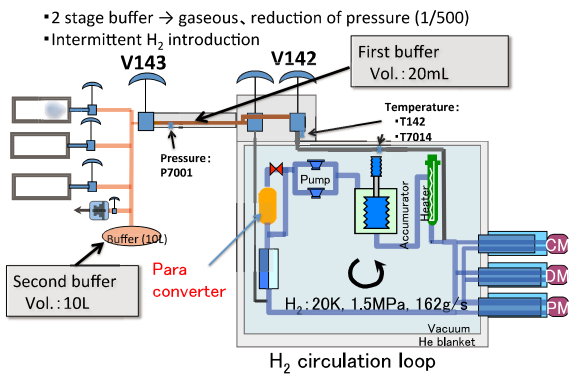

Figure 5. Hydrogen sampling from hydrogen circulation loop to measure para-hydrogen fraction.

4. Spare moderator fabrication

4.1 Introduction of invar material

In the first design, in order to make the moderator vessel and the hydrogen transfer line, as a material combination, aluminum alloy (A6061-T6) and stainless steel (SS316L) were adopted[14, 15]. However, some troubles such as welding leak, deformation and contact with other pipes, etc, were occurred in the actual fabrication process[16] due to the thermal shrinkage measure in the hydrogen transfer line. We had a plan to adopt the invar alloy to make the 2nd moderator fabrication because of very low thermal expansion. The thermal expansion of invar is one order of magnitude lower than that of aluminum alloy or stainless steel. It is also used for many specific applications, especially in cryogenic application, such as LNG (liquefied natural gas) carriers, transfer pipes, etc.

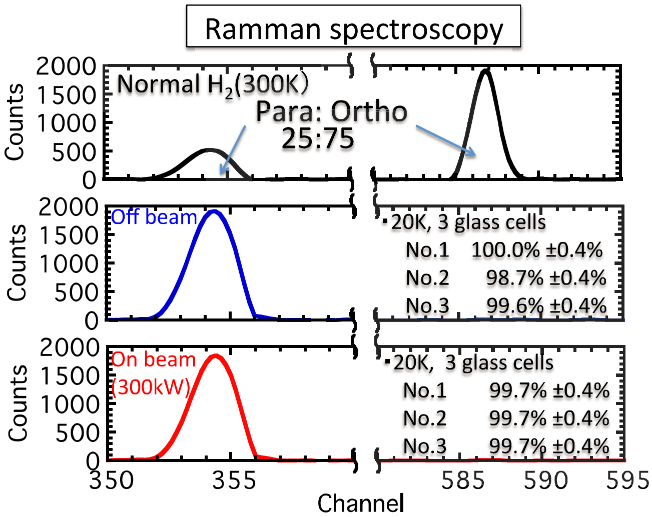

Figure 6. Measured Ramman spectroscopy for off- and on- beam operation. For the reference, normal hydrogen case is shown in upper.

Recently, it was also utilized to make the H_2 transfer line in SNS Ornl[17]. It will give more easily manufacture in the moderator fabrication process. We developed the invar-joints for the conversion of invar alloy to aluminum alloy and stainless steel and evaluated the mechanical strength of invar-joints[18, 19], which was also requirement for the Japanese High Pressure Gas Safety Law. These results were reflected the hydrogen transfer line design. Figure 7 shows the drawing of hydrogen transfer line, which is including the invar and invar joint. The thermal shrinkage could be reduced from 20 mm to 2 mm, resulting in no need asymmetrical setting in fabrication. Just now, we are starting to fabricate the spare coupled moderator based on this drawing.

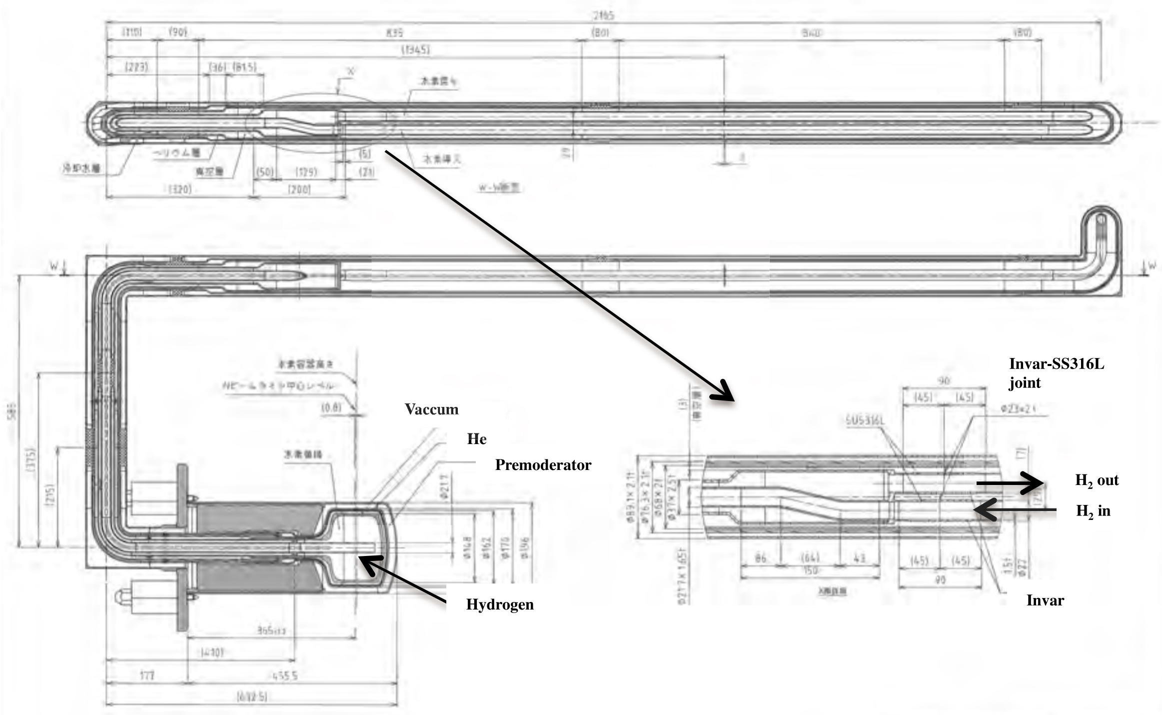

Figure 7. Drawing of coupled moderator

4.2 Au-In-Cd alloy for decoupled moderator

A thermal-neutron-absorber, called decoupler, is adopted to obtain a neutron beam pulse with narrow width and fast decay (short tail) for the decoupled and poisoned moderator. The higher cut-off energy (decoupling energy) gives shorter tail in the beam pulse. For the first moderator, we developed a Ag-In-Cd decoupler which uses a combination of the resonance absorption cross sections [20-24], resulting in reaching 1 eV of decoupling energy effectively. However, the Ag-In-Cd decoupler has a disadvantage in view of high residual radioactivity, for example, owing to ^{108m}Ag (half life of 418 years).

We have focused on the development of a low activated decoupler for the next generation decoupled moderator. A combination of Au, In and Cd was selected as the candidate decoupler material, resulting in the low induced residual radioactivity in comparison with Ag-In-Cd decoupler by three orders of magnitude without sacrificing the neutronic performance in the pulse shape. In order to utilize the Au-In-Cd decoupler, it is necessary to develop the alloying of Au-In-Cd and to make the bonding between Au-In-Cd and aluminum alloy (A5083) in terms of the heat removal and thermal stress. The required design bonding strength due to the thermal stress was estimated over 30 MPa. A Hot Isostatic Pressing (HIP) technique is applied to obtain the bonding the Au-In-Cd alloy to the A5083. This technique is also available for the bonding to unique shape, such as curved shape. In case of manufacturing of Au-In-Cd, we have already succeeded to make a homogeneous ternary Au-In-Cd alloy [25]. We also found the HIPing condision (Temp: 535℃, Holding time: 1hr) to obtain the required bonding strength between Au-In-Cd and A5083 for small sized sample[26]. We are going to next step to utilize the Au-In-Cd alloy to the actual moderator fabrication. As shown in Fig. 8, Au-In-Cd alloy ingot (Weight: C.A 1kg) is just prepared by ourselves for the actual sized HIPing test.

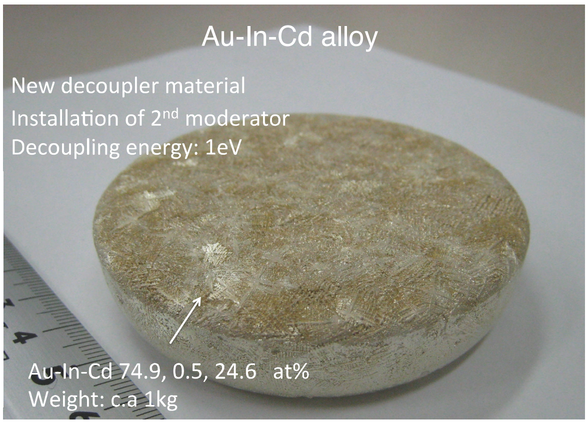

Figure 8. Au-In-Cd alloy ingot. We prepared Au-In-Cd alloy ingot for HIPing test for Au-In-Cd alloy and A5083.

5. Summery

Activity plan of moderator / reflector is described. We started to fabricate the spare moderators and reflector to replace the 1st moderators and reflector assembly in 2019 due to the lifetime. In the spare moderator, invar and Au-In-Cd alloy will be newly installed to improve the moderator fabrication and reduce the radioactivity. We also just started to consider the second target station for emphasizing the science down to very cold neutron energy region. We also are proceeding with the moderator development focusing on the high ALBEDO material, such as nano-diamonds, to intensify below cold neutrons under IAEA collaboration. By optimizing 100% para hydrogen, especially for the coupled moderator, gave the unique volumetric shape, such as large sized cylindrical shape coupled with water premoderator, resulting in the highest neutron intensity per pulse at 300kW.

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