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EXPERIENCE IN EARLY OPERATION AT JSNS OF J-PARC

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ABSTRACT

In May 2008, the JSNS (Japan Spallation Neutron Source) target accepted firstly the proton beams accelerated by LINAC and 3 GeV RCS (Rapid Cycling Synchrotron) accelerators at J-PARC (Japan Proton Accelerator Research Complex). After the adjustment through in-beam commissioning, the MLF (Materials and Life science experimental Facility) with JSNS was opened for users in Dec. 2008. The JSNS is still in early low power operation, accumulating approximately 100 MW-hrs by January 2010. In the paper, the experiences that we have faced so far in low power operation are described; i.e. operations of mercury target system and supercritical hydrogen loop, measurement on diagnostic signals of pressure waves, beam profile measurement, neutronic performance, residual radioactivity around mercury circulation loop, etc. As well, R&Ds to increase the beam power are introduced.

1. Introduction

The J-PARC is the multi-purpose research complex, which consists of three accelerators: 181 MeV LINAC, 3 GeV RCS and 50 GeV synchrotoron, and four major experimental facilities: MLF, Nuclear and Particle Physics Facility (Hadron Facility and Neutrino Facility), and Nuclear Transmutation Experimental Facility [1,2].

In May 2008, the JSNS in the MLF was firstly accepted the proton beam accelerated by the LINAC and 3 GeV RCS accelerators in the MLF. After deliberate adjustment through in-beam commissioning, the MLF was opened for users in Dec. 2008. At present (Feb. 2010), the routine operation is carried out with 120 kW, while the JSNS will be operated at 1 MW proton beam power within about 5 years according to the power upgrade plan. Through early operation stages we could verify the important design values, although we have experienced the unexpected issues: high radiation level in the hot cell even after draining radiactive mercury, a rotor vibration of a hydrogen circulation pump, temperature rising at an upper-flange and an impellor failure in the pump, temperature fluctuation around a He- refrigerator in the cryogenic hydrogen system, etc. Additionally very recently, we had to cancel the user oparation: RUN#30 & #31 in Feb. & Mar. 2010, due to a trouble at an accumulator in the cryogenic hydrogen system. After discussion, we decided to resume the user operation in May without the accumulator, in which the power will be less than 100 kW. The improved accumulator will be installed in the summer shutdown 2010.

As for accelerators, the availability was improved to around 90 % for last a couple of months even with 120 kW beam operation. 300 kW operation was experimentaly performed in Nov. 2009 to confirm the designs of the mercury circulation system and the pressure absorption mechanism in the cryogenic hydrogen system due to beam injection, the neutoronics performances, etc.

R&Ds for the high power facility are carried out: pressure wave mitigation, proton beam flattening, new moderator materials and design, PIE, etc.

In the paper, the recent experiences in the JSNS are described including expected and unexpected results.

2. Outline of J-PARC Spallation Neutoron Source JSNS

The JSNS target station was shown schematically in Fig.1. At the center of the station the mercury target is set, which is designed to accept 1-MW proton beam of 333 μA accelerated to 3 GeV by the RCS with a pulse repetition rate of 25 Hz. The accelerated proton beam was transported through the 3NBT transport line consisting of 108 various magnets and monitors to adjust beam position and profiles at the target. Mercury is selected as a target from the viewpoint of heat removal in the target vessel and neutrons yield efficiency due to its high weight density of 13.6 kg/m^3 at 300 K and high atomic number of 80.

The mercury is circulated at a flow rate of 41 m^3/h for heat removal in the target vessel made of 316-type stainless steel. The target system consisting of a heat exchanger, a surge tank and a compact rotated magnetic pump is installed on the target trolley. The main components and valves are replaced using the remote handling system. The target vessel , a so-called cross-flow-type, consists of multi-walled vessels to avoid the mercury leakage

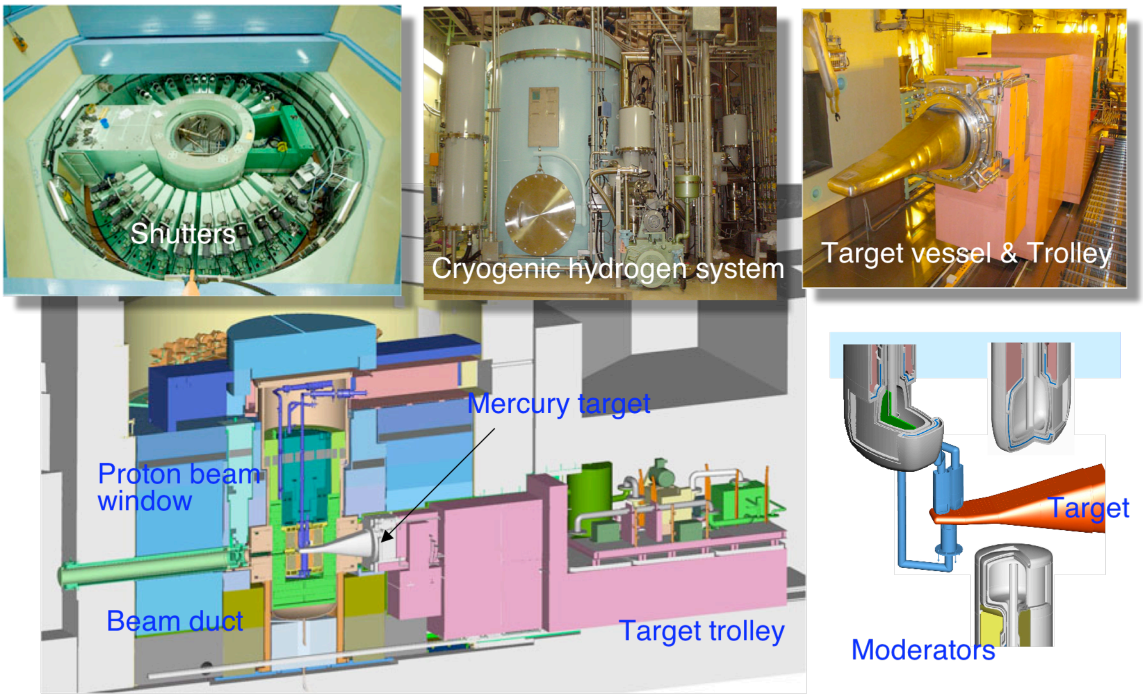


Figure 1 Main components of JSNS at MLF in J-PARC

into the helium vessel in the case of the mercury vessel failure: i.e. the double-walled safety hull encloses the single-walled mercury vessel[3]. Helium gas fills the interspace between the mercury vessel and the safety hull to prevent direct contact between heavy water and mercury, and the helium gas is monitored to detect radio-activated noble gasses that could come from a little mercury leaked from the mercury vessel.

In the JSNS target, an in-situ diagnostic system is installed to evaluate the dynamic response of the mercury target induced by the proton beam injection and the acoustic vibration due to the micro-impact of the cavitation. We can evaluate the macroscopic behavior of the vessel from the dynamic response related to the injected proton beam pulse. A laser beam (Nd-YAG 100 mW) reaches the outer wall of the safety hull, passing through a clearance between one of the moderator pipes and the inner plug. The laser beam reflects on the mirror fixed on the safety hull and the interfered fringe between the injected and reflected beams is obeserved to estimate the vibrational velocity and frequencies[3].

Three moderators in which supercritical hydrogen at 20 K and 1.5 MPa flows are installed around the target to obtain cold neutrons to be suitable for neutron scattering experiments; a coupled moderator (CM) to provide high-intensity neutron pulses, a decoupled moderator (DM) and a poisoned decoupled moderator (PM) to provide narrower pulses but with less intensity, as shown in Fig.1. The silver-indium-cadmium (Ag-In-Cd, AIC) alloy was used in the DM and PM as a neutron absorber[4].

Supercritical hydrogen is supplied for the three moderators through a cryogenic hydrogen system consisting of two compact hydrogen pumps, a hybrid pressure controller with a heater and an accumulator, a He-refrigerator, etc. [5]

Total 23 neutron beams are extracted from the moderators: 11 from CM, 6 from DM and 6 from PM. The neutron beams are controlled on and off for measurement and sample exchange, respectively, by neutron beam shutters which are equipped independently for each beam line.

Additinally, the muon production target is installed about 30 m upstream of the neutron source in the MLF. Key parameters of the MLF are summarised in Table 1.

Table 1 Key parameters of MLF

Injection energy	**3 GeV**
Repetition rate	**25 Hz**
Neutron source	
Target material	**Mercury**
Number of moderators	**3**
Moderator material	**Supercritical hydrogen**
Moderator temperature/pressure	**20K/ 1.5 MPa**
Number of neutron beam ports	**23**
Muon production target	
Target material	**Graphite**
Number of muon beam extraction ports	**4**
Neutron instruments *	
Open for user program	**7**
Under commissioning/construction	**4/3**
Muon instruments*	
Open for user program	**1**
Under commissioning	**1**

(* as of the beginning of the user program in FY2008.)

3. Beam Condition in Early Operation

The beam operation for user programs started in December 2008 with very limited beam power and the beam power was soon increased to 20 kW. The availability of the beam delivery from the accelerator was not good in early stage of the beam operation mainly due to troubles in the LINAC. Therefore, the RFQ (Radio-Frequency Quadrupole Linac) has been scheduled to be conditioned every 3 or 4 days since May 2009. The availability was improved to around 90 % for last a couple of months even with 120-kW beam operation. The summary of the availabilities is shown in Table 2. The daily beam

Table 2 Availability of the beam delivery from the accelerator

run #	period	nominal beam power(kW)	scheduled run (days)	scheduled beam time (hours)	operated beam time (hours)	availability (%)
24-25	May - Jun	20	25	394	296.07	75.1
26	Oct	20	12	183	154.19	84.3
27	Nov	120	17	270	233.09	86.3
28	Dec	120	17	273	252.90	92.6
29	Jan - Feb	120	20	297	266.32	89.7

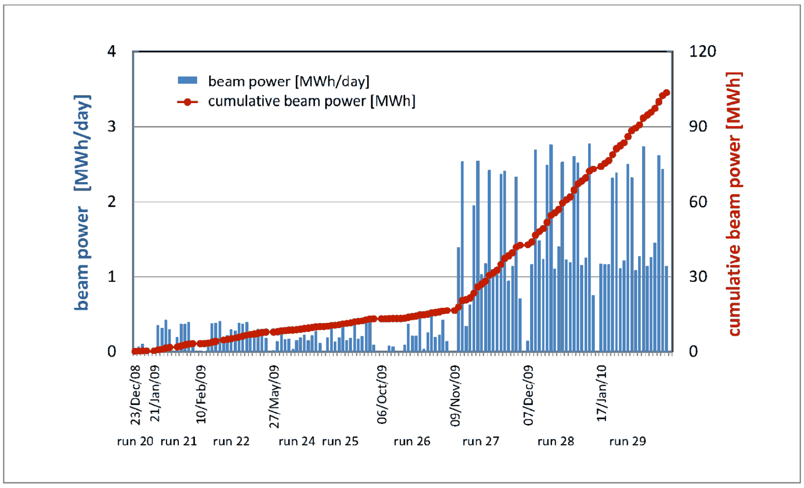


Figure 2 Statictics on proton beam operation
Daily beam powers and cumulative beam powers from beginning of user programs in MLF

powers and the cumulative beam power since the beam operation for user programs started is shown in Fig. 2. The cumulated beam power has been reached 100 MWh by January 2010.

The proton beam transportation from 3-GeV RCS to JSNS has been smooth and no significant beam loss has been observed. The characteristics of the beam optics, such as beam emittance and dispersion, are being studied. The results showed quite good agreement with design values [6]. The proton beam profile at the proton beam window has a Gaussian shape and its FWHM's are ~60 mm in horizontal direction and ~30 mm in vertical direction. The heat density in the mercury target is estimated less than 2 J/cc.

4. Present status in components

4.1 3NBT

The proton beam transport facility [7] has been operated stably. The beam operation has stopped only once due to a trip of one of the magnet power supplies since the operation had started for user programs. This high availability comes from careful facility design for stable operation and regular maintenance work. All the magnet power supplies were overhauled once a year for reliable operation. The interlock systems and the coolant facility were also overhauled once a year.

The beam line tunnel suffered uneven settlement even after the beam commissioning had started. The beam line magnets and the beam monitors were aligned with accuracy better than 0.1 mm during the summer shutdown period every year.

4.2 Mercury target and mercury circulation system

The mercury vessel and mercury circulation system have been operated well so far. The temperatures on the surface of the mercury vessseel were measured at 120 kW and 300 kW proton beam powers. The measured temperatures agreed well with the estimated values in the design, as shown in Fig.3. As the results, we confirmed that the mercury circulation system; electric magnetic mercury pump, heat exchanger, mercury velocity meter, etc., were operated sufficiently as expected in the design.

A laser Doppler vibration measuring system was installed to diagnose the structural integrity of the target vessel relating with pressure waves caused by pulsed-high intense proton beam injection into mercury. The relationship between the traveling time and the beam positon was evaluated [8]. Measurable well from it is the sound velocity in mercury that is very dependent on the mercury condition with cavitation or micro-bubbles, etc. Although the amplitude of vibration was associated with the beam power, the tendency got to be weak little by little. After looking at the surface of the mirror fixed on the target vessel, we admitted corrosion on it. The chemical compositions of gases filled in the He-vessel were measured to be 95 % He and 5 % air approximately. Therefore, the gas circulation system with a molecular sieve was installed in the He vessel to improve the compositions.

In order to evaluate the feasibility of hands-on maintenance after nominal beam operation with 1 MW in the hot cell where a mercury circulation system was installed, gamma dose measurements and gamma spectroscopy analysis were carried out after low power operation during the commissioning period [9]. By analyzing the data, it was found that radioactive spallation products adhered to the inner surface of piping wall of the circulation system and those significantly raised the dose rates in the hot cell, as shown in Fig. 4. In order to discuss about measures for future hot-cell entry, the gamma dose rates after the nominal operation were evaluated based on the measured data obtained in this work. The gamma dose distiributions and the gamma-spectra data behind the mercury circulation system in the hot cell were obtained. Analyzing the data, we found the

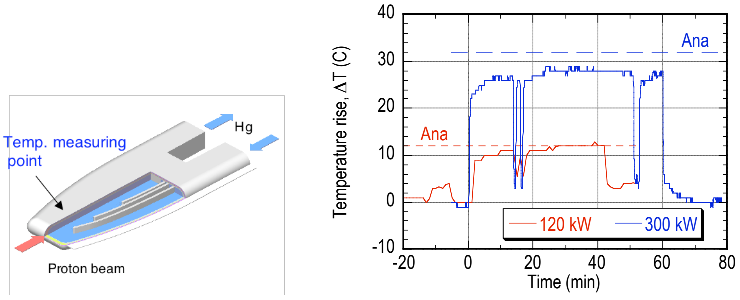


Figure 3 Temperature rising at target vessel by 120 kW and 300 kW operation

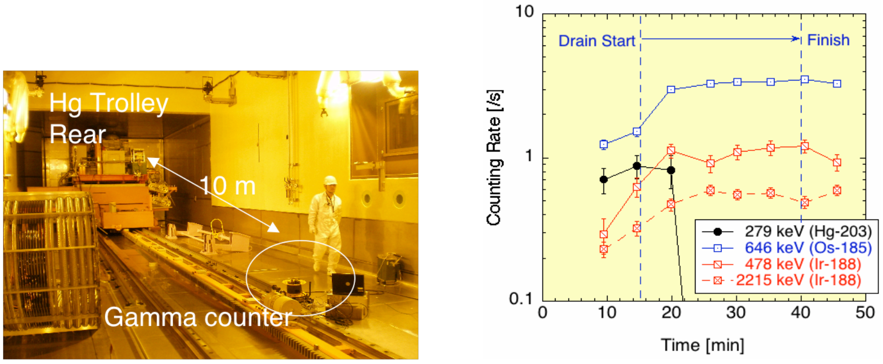


Figure 4 Dose rate in the hot cell during mercury draining: measuring point and results.

followings; 1) some of the spallation products selectively adhere to the pipe walls in the mercury circulation system, 2) the drain of mercury doses not work for reducing the dose rate in the hot cell due to the adhered products, 3) addtional shield is required for the hands-on maintenance work in the hot cell.

4.3 Cryogenic hydrogen system

The cryogenic hygrogen system had been operated as solving several troubles up to the end of January 2010, as follows;

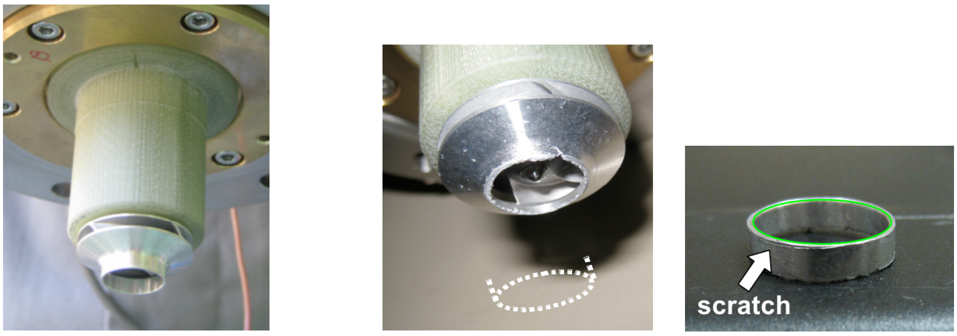
1) An impeller in one of the hydrogen circulation pumps was broken in February 2009 probably due to a foreign particle lodging in the pump, as illustrated in Fig. 5. There has been no such trouble after considerable flushing in the hydrogen loop.

2) Rotors of the hydrogen circulation pumps vibrated sometimes up to 100 μm though it was just in a moment. The vibrated rotor is self-recovered after a few 0.1 s without any damage on the pump. An FFT vibration analysis system was installed to watch the vibration and to understand the phenomenon in more detail.

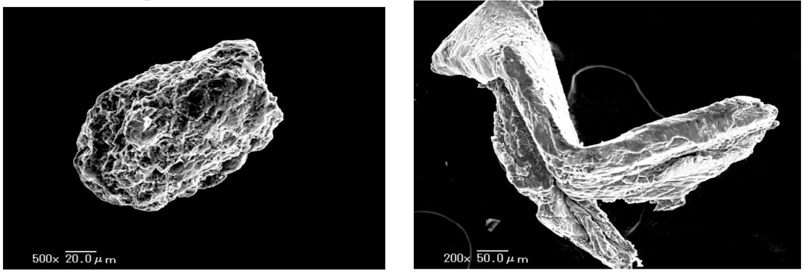
3) The heat exchanger in the He-refrigerator of the cryogenic hydrogen system lost gradually its efficiency in 10-20 days operation. The reason was attributed to impurities in the helium. A purification process of the helium gas is now adopted in starting up the cryogenic hydrogen system to solve the problem.

In December 10, 2010, a high-power operation at 300 kW was conducted. A hydrogen temperature rise due to nuclear heating was 0.7 K which was close to the design value of 0.9 K. A pressure rise of the closed hydrogen loop at 14.8 MPa was suppressed to only 0.014 MPa as expected due to the hybrid pressure control system. The pressure rise was also very close to the design value of 0.015 MPa.

In February 2010, however, a trouble causing a long shutdown occurred at the accumulater in the cryogenic hydrogen system, which can absorb the pressure fluctuation due to thermal load imposed on hydrogen in the moderators by high intense proton beam injection. A leackage was found at the boundary between He/H gases in the accumulater.



(a) Normal status of impeller (b) Failured impeller



(c) Foreign particles found in hydrogen loop during flashing.

Figure 5 Failured impeller in cryonic hydrogen pump

In order to urgently resume the facility operation for users, we decide to operate at ca. 100 kW without the accumulater system, and will replace it with the improved accumulator in this summer shutdown.

4.4 Moderator performance

We have studied neutronic performance of the JSNS to know whether users can utilize neutron beams as designed or not, and also to confirm the adequacy of neutronics design of the JSNS. Neutron spectral intensity, time structure of neutron pulses, intensity distributions of the neutron beam cross-section, a luminosity distribution on a viewed surface of the moderator and so on were measured. The calculated neutron spectral intensity agreed within ±20% with the measured one. General agreements were confirmed for the other quantities. These results suggest that the design calculations are reasonable. It was demonstrated through characteristics measurements at 120 kW and 300 kW that neutronic performance at the JSNS could be the world's highest level in terms of resolution and flux intensity which is brought by the unique and advanced design of the target-moderator-reflector assembly and the neutron instrument, as shown in Table 3.

Table 3 Comparison of neutron intensity integrated below 0.4 eV among world's intense pulsed spallation neutron sources. Numbers in { } indicate values under the rated power operation to be achieved in the future.

Facility & Moderator	Operating power [kW]	Repetition rate [Hz]	Viewed surface [mm]	(a) Neutron intensity*1 [n/(cm^2·s·sr)]	(b) Neutron intensity*2 [n/(cm^2·sr·pulse)]	(c) Neutron intensity*3 [n/(sr·pulse)]
JSNS / J-PARC / Japan						
coupled hydrogen*4	300 {1,000}	25	100w×100h	1.3×10^{12} {4.5×10^{12}}	5.1×10^{10} {18.0×10^{10}}	5.1×10^{12} {18.0×10^{12}}
SNS / ORNL / US						
coupled hydrogen (top-downstream)	1,000 {1,400}	60	120w×100h	2.1×10^{12} {3.0×10^{12}}	3.5×10^{10} {4.9×10^{10}}	4.2×10^{12} {5.9×10^{12}}
ISIS-TS2 / RAL / UK						
hydrogen/methane composite, grooved face	48	10	83w×30h	0.5×10^{12}	5.4×10^{10}	1.3×10^{12}
hydrogen/methane composite, hydrogen face	48	10	120w×110h	0.3×10^{12}	3.0×10^{10}	4.0×10^{12}

4.5 Auxiliary system

The cooling system supplies pure water to the components in the neutron source and some neutron beam line instruments. It has been working well, except for the line to the moderators and the proton beam window. The pressure drop in one of the moderators is much higher than its design and it is very painful to balance their flow rates properly. The water path of the moderator is to be repaired sometime this year. The tritium concentrations in the circulating water line are several thousand Bq/cm^3 at the beginning of February 2010.

The power manipulator in the hot cell was taught the precise position data of possible objects to be accessed in the hot cell and their safe access routes before the beam commissioning had started. The power manipulator and the master-slave manipulators were extensively used for the maintenance work of the target and the target trolley. Although the power manipulator was operated manually in most cases so far, the automatic positioning system worked well once when mercury sensors were examined.

The cutting device has been installed in the hot cell and tested using dummy moderators. They managed to be cut to pieces to some extent. It was difficult to hold the moderators balanced well during cut process. It was concluded that the cutting device wouldn't work well for real moderators and had to be modified. The cutting device is being re-designed for possible modifications.

5. R&Ds for High Power Facility

5.1 Mercury target

In the mercury target for pulsed spallation neutron source, cavitation damage caused by pressure waves due to proton beam injection is the most crucial issue to realize the high power facility. Microbubble injection into mercury is one of the prospective technologies to mitigate the pressure waves, and the mitigation effects by microbubbles have been investigated experimentally and numerically[10,11]. The injected microbubbles are expected to absorb thermal expansion of the mercury at the heat source location, and attenuate the pressure wave during the propagation process.

Mercury loop tests using a mockup model of the target vessel were carried out to investigate the bubble distirbution in the cross-flow-type mercury target with bubbling system. This experiment was carried out under the collaboration with the Oak Ridge National Laboratory (ORNL) using the Target Test Facility (TTF), which is the actual-scale mercury loop constructed for the mercury target development at ORNL. The swirl type bubbler that was developed by JAEA was installed at the mercury inlet in the target vessel. The performance of the swirl type bubbler was evaluated in the water and mercury loop tests in JAEA, and it could generate microbubbles with ca. 50 μm in radius. Based on the results, we will improve the position of bubbler and flow guids in the target vessel.

The components tests on the gas suppling system were carried out in water and mercury loops to investigate gas injection condition at the bubbler for constant formation of bubbles in flowing mercury. The design will be fixed in FY 2010 and the fabrication and installation are scheduled in summer 2011.

5.2 Moderator materials & design

Spare moderators is planned to be procured by the end of FY 2014. R&Ds for the procurement have progressed. One of motivation for the R&D is simplifying their structure to improve the manufacturability, to reduce cost by the simple structure and also by encouraging general competitive bedding, and to enhance reliability of the moderators which have rather complicated structure. There are three main items for simplifying.

1) A vacuum insulation layer between inlet and outlet hydrogen tubes is eliminated to modify the sextuplex coaxial tube structure to the quintuplex one. Detailed design for the coupled moderator was conducted in FY 2009.

2) The material of the hydrogen transfer tubes is changed from SS316 to Inver to largely reduce shrinkage of the tubes, 20 mm and 2 mm, respectively, when they are cooled down from the room temperature to 20 K. Some test pieces of friction welding between aluminum-alloy and Inver, and also SS316 and Inver were produced. Mechanical strength testing at the room and the cryogenic temperature are under way. Welding and bending tests of Inver tubes are under planning.

3) Some coaxial tubes are combined into a single piece for facilitating positioning of individual tubes in fabrication.

Another motivation is to reduce radioactive inventory. Although the decoupler made of the Ag-In-Cd alloy improves neutronic performance significantly, it has a demerit in its high residual radioactivity mainly due to products from Ag. Use of the Ag-In-Cd alloy imposes difficulties in handling used moderators and reflector, and future storage as retained waste. A new alloy replacing Ag with Au, i.e., Au-In-Cd alloy, is a candidate as a low activation decoupler material. An experimental apparatus for producing small amount of the alloy has been prepared.

5.3 Flattening on Proton Beam Profile

One of the essential factors to mitigate pressure wave in the mercury target is the current density of the proton beam. [12] The profile monitors in the proton beam window assembly showed that the proton beam distributed normally. The proton current density at 1-MW beam operation won't be reduced sufficiently only by broadening the beam profile.

The proton beam optics is being studied to flatten the beam profile with help of octapole magnets in the beam transport line. They turned out to be effective for this purpose. The proton beam profile may have a sharp peak, on the other hand, once the center of the beam profile shifts from the ideal beam orbit. Beam monitors and online beam control system are also essential to be developed in this system.

6. Summary

After the proton beam injected into the target in May 2008, we have learned many lessons through expected and unexpected experiences. As for the expected results, the design values of each component were verified in particular through 120 kW and 300 kW operations: nuetronics performance, mercury circulation system including target vessel, pressure absorbing mechanism in the cryogenic hydrogen system, etc. As for unexpected ones, many difficulties realized in the cryogenetic hydrogen system: temperature risig and rotor vibration at the hydrogen pumps, temperature fluctuation at the He-refrigerator and the accumulator trouble causing unscheduled shutdown, and higher radiation dose in mercury circulation system after draining radioactive mercury than estimated value, etc. R&Ds still are needed to solve a sort of issues relating to unexpected results and increase the power.

7. Acknowledgements

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