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Current status of 1 MW pulse spallation neutron source (JSNS) of J-PARC

Yujiro Ikeda *

Center for Proton Accelerator Facilities, Japan Atomic Energy Research Institute, 2-4 Shirakata-Shirane, Tokai, Ibaraki 319-1195, Japan

Abstract

Construction of a 1 MW pulse spallation neutron source (JSNS) is in progress under the J-PARC project to provide a vital experimental environment for breakthroughs in neutrons researches with emphasis in materials and life sciences. An overview of the JSNS is given in terms of 1 MW power regime, the mercury spallation target, cryogenic H_2 moderators, and the central station with 23 independent neutron beam shutters. Conventional facility construction and neutron instrumentation scheme are briefly shown along with the technical research and development with emphasis on material issues.

1. Introduction

The J-PARC project has progressed in construction of experimental facilities along with high intensity proton accelerators, which aims at scientific breakthroughs in materials and life sciences, nuclear and elementary physics researches, and technological development of accelerator driven transmutation system [1]. Intense proton pulses (3 GeV, 0.33 mA, 25 Hz, 1 μs width), are to be delivered into a facility called Materials and Life Science Experimental Facility (MLF), in which a 1 MW pulse neutron source (JSNS) and a Muon production target are located and share the proton beam in tandem fashion [2]. The JSNS has missions to provide a vital pulse neutron experimental environment. Neutron beam with high temporal resolution along with high pulse peak intensity in 1 MW regime opens new technologies and advanced sciences of microscopic molecular dynamics, surface physics, magnetism, polymer, biological structure, dynamic visualization technique, many industrial applications, even evolution in cosmology and astrophysics. The design has been finalized and almost all of components have been ordered for manufacturing. The target material and moderator structural components have, however, been identified as critical technological issues, and urgent research and developments (R&D) have been carried out to confirm their specific design life-time estimations. This paper overviews the current status of the JSNS design and construction progress along with R&D efforts.

2. JSNS design concept and major parameters

2.1. Concept

Providing high quality neutrons is the most important primary objective of the facility. The facility is designed with regards to stable beam delivery to users,

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* Tel.: +81 292 82 6006; fax: +81 292 82 5996.
E-mail address: ikeda@cens.tokai.jaeri.go.jp

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insurance of safety, and assurance of comfortable access of users to the facility and providing a good quality experimental environment. From this point of view, design parameters have been optimized through stringent discussion and extensive neutronic analyses. Designs of the JSNS components and the MLF conventional facility building have been almost completed. However, as the design reached the final stage, new technological issues appeared. To realize, in particular, the 1 MW spallation source, we identified difficulties in technologies of high power mercury target, hydrogen moderators with high nuclear heating, high-energy radiation shielding, etc. Fig. 1 shows a conceptual structure of the neutron source. The mercury target is located at the center of the station. A number of neutrons are produced at the mercury target with proton beam injection. Energy of neutrons from the target are moderated by moderators of low temperature hydrogen (liquid or super-critical phases). Neutrons are extracted through neutron beam lines, which are oriented in radial directions from the moderators. Each beam line is specified with the particular moderator type, extraction angle, beam diameter, etc. Moderators are covered with a reflector made of beryllium and stainless steel cooled by heavy water. The target, the moderator, the reflector and the inner shield are installed in a helium vessel. Around the vessel, a heavy radiation shielding structure follows. The final number of the neutron beam lines has been determined by taking account of the above condition as well as shutter gate size, mechanically achievable separation, neutron window size, and so forth. Materials, dimensions, shape, thickness of windows have been optimized by comprehensive thermal and mechanical stress analyses based on nuclear heating data which was given by neutronics calculations. Some design details are given for major components as follows.

2.2. Mercury target

The structural concept of the target container made is as follows: (1) mercury flows crossing perpendicular to the incident proton beam, (2) for this purpose, several flow guiding blades are attached in the mercury flowing path, and (3) an outer shroud is attached to the inner target container by welding. Stiffness of the target in terms of liquid metal flow, thermal stress, material integrity, and so on are carefully evaluated by contemporary analysis codes. The conceptual view of the target structure is shown in Fig. 2. SS-316LN stainless steel is the material for the target structure, and the lifetime to exchange is assumed to be 6 months under 1 MW operation taking a safety margin with regard to receiving several dpa (displacement per atom) dose irradiation [3]. As pitting of the inner surface was rather newly observed and identified as a serious lifetime limiter, then, efforts on understanding this phenomenon and developing mitigation process are being extensively made. The target is installed horizontally from downstream of the incident proton beam direction, using a target cart. The circulation system of mercury, e.g., a pump, a heat

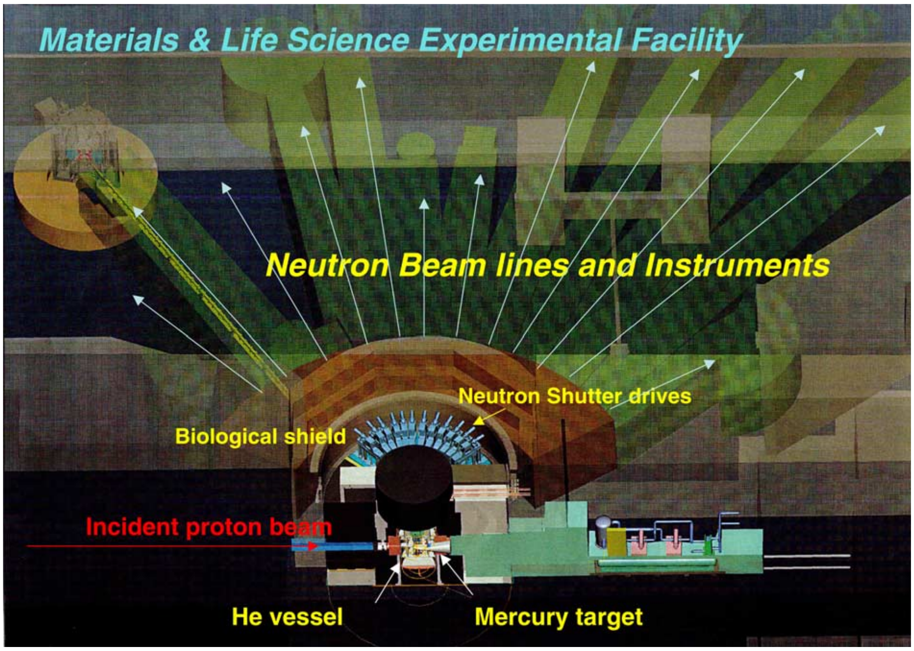

Fig. 1. A three-dimensional CAD image of the 1 MW pulsed spallation neutron source (JSNS).

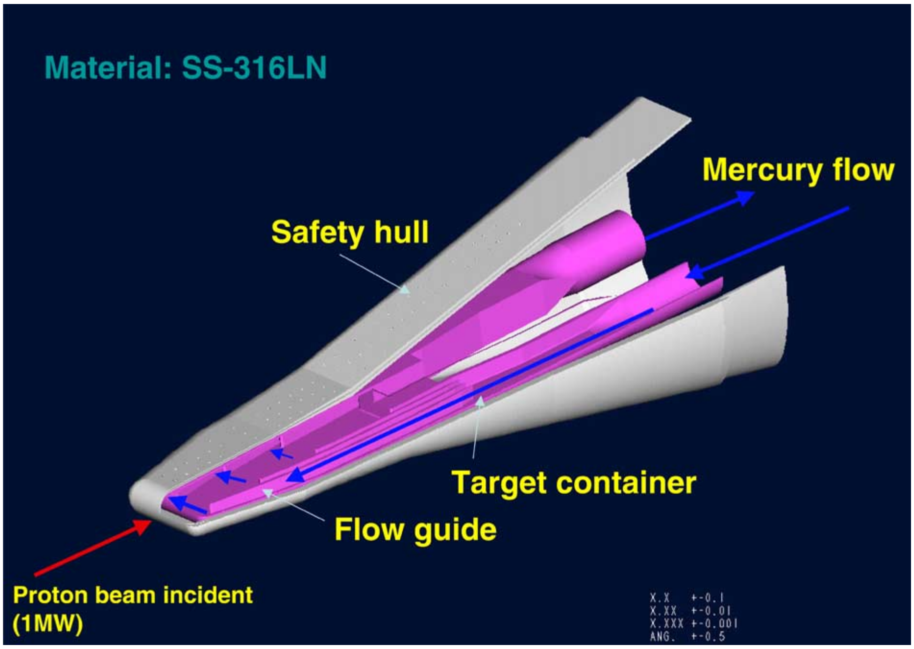

Fig. 2. The conceptual 3-D image of the mercury target structure.

exchanger, a buffer tank, flow meters, diagnostic devises, are placed on the target cart. The target container and the circulation pipes, which penetrate the shielding of the cart, are connected at the front surface of the cart with flange seals. R&D efforts are under way for the seal property.

2.3. Moderator and reflector

JSNS incorporates three moderators, namely, a coupled moderator, de-coupled moderator, and a decoupled poisoned moderator. The material of the moderators is hydrogen at a temperature of 20 K, at pressure of less than 1.5 MPa, and with 100% para state hydrogen. The moderators are designed to maximize neutronic performances in terms of pulse peak intensities and pulse time resolutions. Shapes and thickness of the moderator container window of both the coupled and de-coupled were optimized from the extraction angles and neutronic performance points of view. In particular, for the coupled moderator, a cylindrical shape was identified suitable to increase the intensity and availability of the wide-angle extraction. To achieve a high de-coupling energy of 1 eV, a newly investigated de-coupler material made from a silver–indium–cadmium alloy (AIC) was adopted. Beryllium (Be) is adopted as the reflector material. The thickness of Be is adjusted to be 300 mm from the neutronics performance point of view. Be and SS are contained in the reflector container. There are many holes and penetrations, e.g., neutron extraction holes, proton beam injection port, target insertion port, moderator placement ports. Also, as extremely high nuclear heating is expected, there are precise cooling channels inside of these structures. The adequacy of the design of all structures was verified by thermal-hydraulic, thermal stress, mechanical stress analyses. Engineering study is under way to assure the fabrication. Fig. 3 is a three-dimensional CAD image of the reflector plug with moderators and hydrogen transfer lines, which are to be embedded in the helium vessel.

2.4. Biological shield and shutter system

A dose rate 1 μSv/h on the outer surface of the biological shield of the target station is determined as the design guide. To assure this criterion, precise neutronic and shielding analyses have been conducted. We have carefully carried out parametric calculation to optimize the shield thickness and composition. As a result, the thickness of iron has been reduced to 4.5 m and the total weight became 3500 tons. Another outcome is the reduction of the height of the shutter gate by substitution of normal concrete with heavy concrete. In view of the cost effectiveness, SS shield blocks are merely stacked to support the weight of the upper part shield blocks. Accordingly, we have made a significant cost reduction without loosing shielding performance and structural integrity. An aluminum flange with four bolts tightens a window on the core vessel for each neutron beam extraction port. The exchange work is done remotely in the space of the shutter gate. The device for this remote handling is under design. Two shafts suspend the shutter gate,

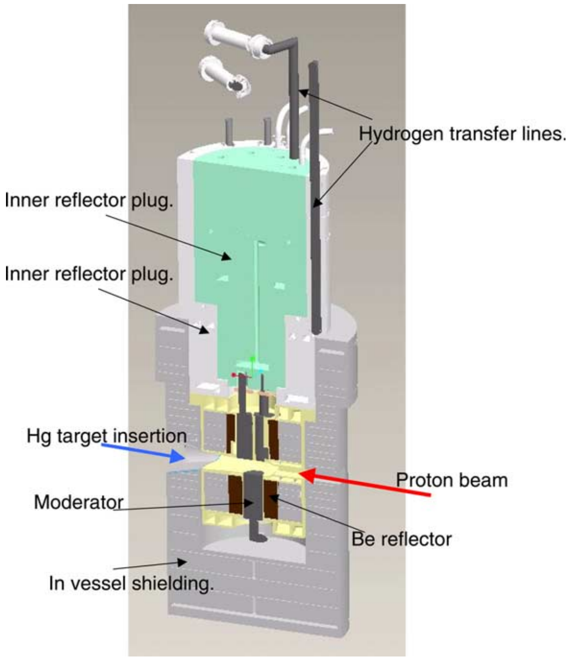

Fig. 3. A three-dimensional CAD image of the reflector plug with moderators and hydrogen transfer lines.

which is moved up and down by an electric motor drive. A total number of 23 independent shutter gates are provided in the design. The neutron flux characteristics derived by using a precise 3-D model, are shown in Fig. 4. It is notable that the neutron spectral intensities from coupled moderators of JSNS at 1 MW and SNS 2 MW are almost identical. This is due to difference in the placement of the coupled moderator between JSNS and SNS. Table 1 summarizes neutron flux level from each moderator, which is used as a reference in designing neutron instruments.

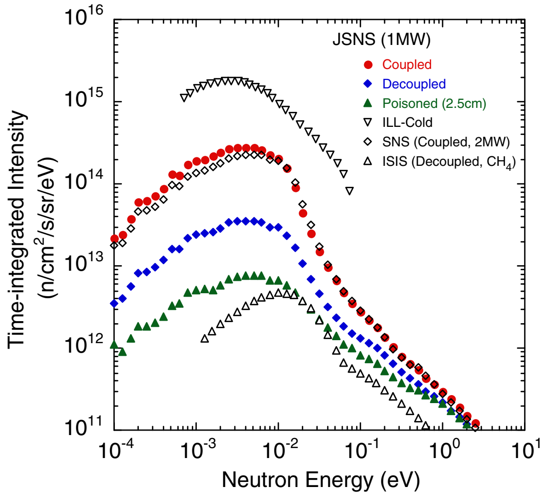

Fig. 4. Neutron characteristics in terms of time-integrated intensity and pulse time structures, derived by calculations with a detailed engineering like model.

2.5. Low temperature hydrogen cryogenic system

In the design of the cryogenic system for operation of the moderators at 20 K, the power estimation is the most important issue. Assuming a temperature increase within 3 K, and an average temperature of 20 K, a power of 6 kW is required for the He refrigerator with regard to the in-leak of the thermal energy through the piping. Considering that cost is proportional to the power, a more precise evaluation of the power is needed to finalize the specification of the system. It is very much possible that we will install a lower power system, say 3 kW, at the early stage due to a cost saving requirement. Transfer pipeline and connection parts are key elements from the down sizing requirement to meet the 3 m diameter of the core vessel. Other components, e.g., a safety box, a cold box, and a refrigerator are under optimization for their layout along with piping rout.

3. Research and development efforts

The importance of the development of high power spallation target technology has been addressed for years. In particular, as mercury was considered to be a potential candidate, an initiative for experiments with a mercury (Hg) target bombarded by intense proton pulses was launched in an international framework among Japan (JAERI and KEK), US (BNL, SNS/ORNL), and EU (Mainly, FZJ, PSI), utilizing a proton pulse environment at AGS/BNL [4]. The program has produced critical data concerning the Hg target, e.g., neutron production, pressure wave, radiation shielding, and induced radio-activity. All results have been taken into account in the design of the 1 MW pulsed neutron source.

Meanwhile, it was observed for the first time that pits were formed on the inner surface of the Hg container when it is pressurized by proton pulse impacts. The pre-investigation gave an explanation that the pits are formed by collapse of cavities, which is induced by negative pressure after a large impact on the mercury. JAERI has developed an electro-magnetic impact device (MIMTM) to simulate the pit formation [5]. With this machine, we have obtained important data for estimating the pitting erosion. Fig. 5 gives a result for the off-line pitting experiment as a function of the impact cycles. Still extensive work is continued to accumulate more substantial experimental data to arrive at accurate lifetime estimation for the target container. In addition to the surface treatment, recent data indicate that the

Table 1
Measures for neutron flux estimation per 1 MW

Type of moderator	Number of beam ports	Time-integrated thermal neutron flux [n/s cm^2][a]	Peak neutron flux at 10 meV [n/eV s cm^2][a]	Pulse width in FWHM at 10 meV [μs]
Coupled moderator	11	4.6×10^8	6.0×10^{12}	92
De-coupled moderator	6	0.95×10^8	3.0×10^{12}	33
Poisoned moderator (thicker side)	3	0.65×10^8	2.4×10^{12}	22
Poisoned moderator (thinner side)	3	0.38×10^8	1.4×10^{12}	14

[a] Values at 10 m from the moderators.

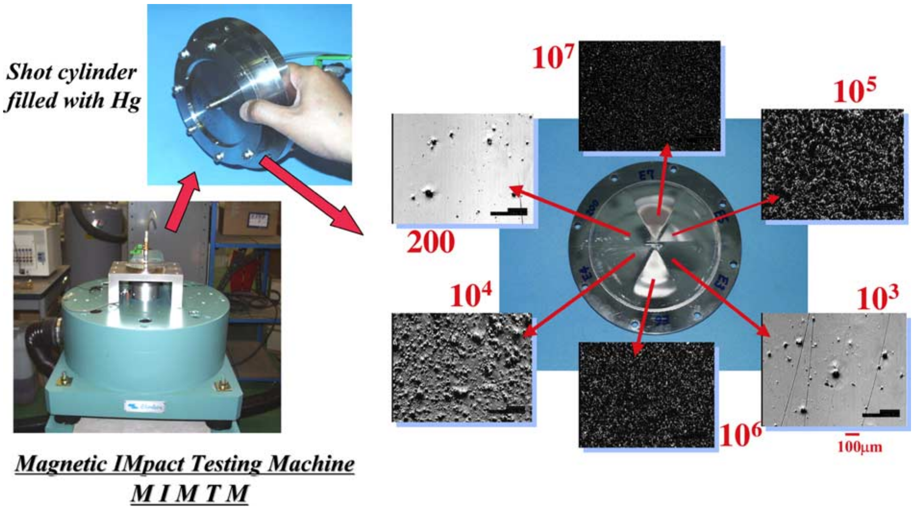

Fig. 5. A result for the off-line pitting experiment with MIMTM as a function of the impact cycles. The cycle numbers are indicated in the picture.

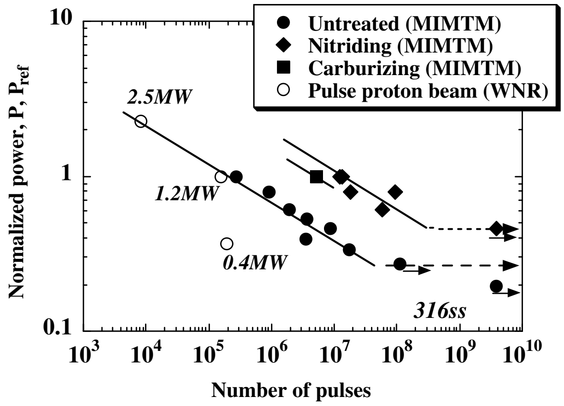

Fig. 6. Acceptable number of pulses in the incubation period. Evaluated using normalized imposed power (equivalent to power density) by 1.2 MW for on-beam WNR, and 560 W for off-line MIMTM. The specimens were prepared from 316ss materials with and without nitriding or carburizing surface-hardening treatment. WNR is the proton accelerator facility at Los Alamos National Laboratory in US.

lifetime and incident proton power density are closely related as shown in Fig. 6. Some important design changes have been made in terms of lowering the incident beam power density in relation to the pitting study, as it helps mitigation.

4. MLF building

The MLF building is 140 m long, 70 m wide, and 32 m high. A bulkhead along the center zone separates the experimental hall into east and west sides with thick walls. In the inside area of the bulkhead, the neutron and muon source are located along the proton incident beam line. The containment with bulkhead mitigates radiological influence during maintenance work with radioactive components, e.g., reflector plug, proton beam window, muon target, etc.

5. Neutron instrumentation

Twenty three neutron user instruments of 23 have been tentatively assigned. Presently, extensive conceptual design work has been in progress through

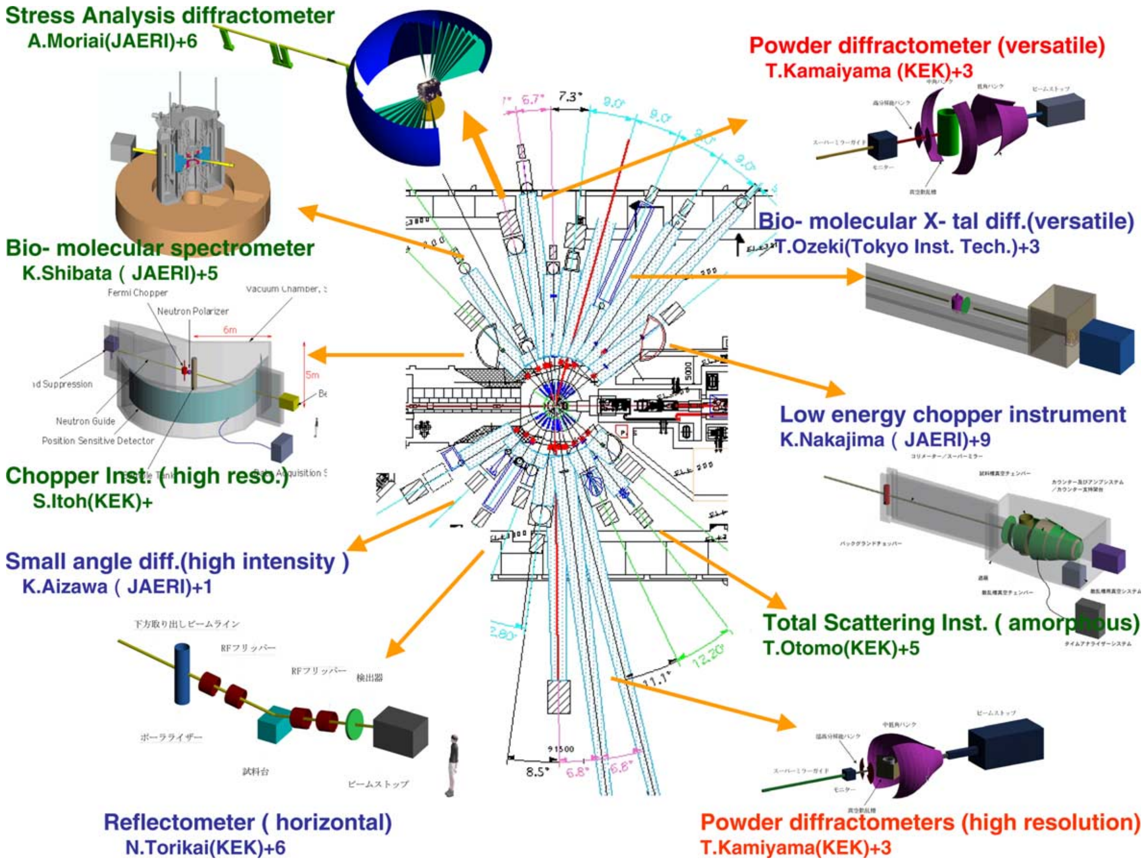

Fig. 7. Conceptual drawings of important instruments proposed by the project team, and corresponding locations with respect to the neutron source. Due to space limitation, only locations are indicated eliminating image drawings for SANS and Inela.

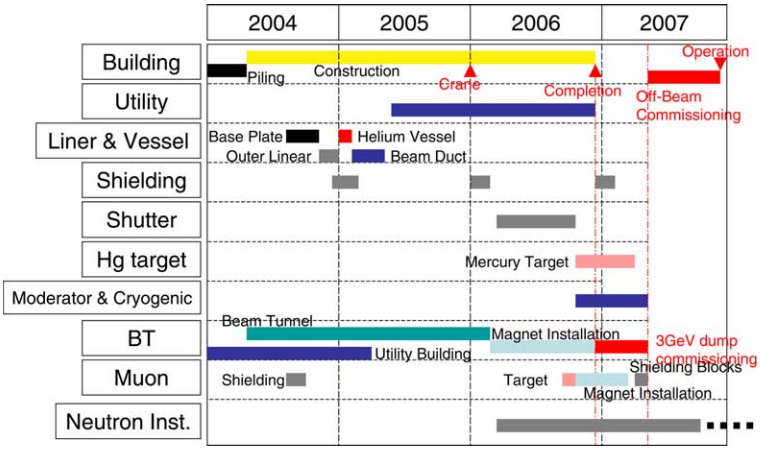

Fig. 8. Time schedule of the MLF construction.

dialogs with potential users in viewing the importance of the science to be realized. Fig. 7 illustrates conceptual drawings of important instruments with high priority in the project, and corresponding locations with respect to the neutron source. The call for LOI (Letter of Intent) was sent out in 2002 to potential users in Japan as well as foreign countries.

6. Summary

Our primary goal and mission is to construct a 1 MW pulse neutron source and a muon source as the materials and life science experimental facility. Currently the completion of the facility is expected to be by the end of 2007 FY. Fig. 8 shows the corresponding construction schedule of the MLF. Although, overall construction is in progress to fulfill all requirements to meet the design principal, there are still needs of several critical R&D efforts, in particular, for materials of the most important components, e.g., target, moderator, proton beam window and reflector. We sincerely expect a wide variety of new research, applications and technologies from the environment.

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