

PROGRESS OF IFMIF/EVEDA PROJECT AND PROSPECTS FOR A-FNS

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-based D-Li neutron source, in which two 40-MeV Deuteron beams with a total current of 250 mA impact on a liquid Li stream flowing at 15 m/s (Li target). In the IFMIF/EVEDA project under the Broader Approach (BA) agreement, the Li target was continuously operated with the cold trap and satisfied the stability requirement throughout the continuous operation. The linear IFMIF prototype accelerator (LIPAc) is currently under development in Rokkasho, Japan, to demonstrate the 9 MeV/125 mA D-beam acceleration. Recently, the first proton beam was injected into the RFQ with more than 90 % transmission, followed by the first Deuteron beam accelerated at 5 MeV. The superconducting RF linac necessary for the 9-MeV D+ beam is nearing completion of the manufacturing phase and will be assembled in Rokkasho. Based on the results from the IFMIF/EVEDA project, a conceptual design of the Advanced Fusion Neutron Source (AFNS) for its construction in Rokkasho is underway to obtain material irradiation data necessary for a fusion DEMO reactor. The A-FNS is composed of an accelerator with a 40-MeV and 125-mA deuteron beam, a test facility including a liquid Li target system and a post irradiation examination facility, which is designed to be able of multipurpose utilizations for neutron application as well.

INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) aims to provide an accelerator-based, D-Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume for DEMO reactor materials qualification [1]. The IFMIF/EVEDA project, which is part of the Broader Approach (BA) agreement between Japan and EU, has the mission to work on the engineering design of IFMIF and to validate the main technological challenges. The LIPAc being developed in the IFMIF/EVEDA project has the objective to demonstrate 125 mA/CW deuterium ion beam acceleration up to 9 MeV and is composed of 10 major systems as shown in Figure 1. Especially, important main accelerator parts are an injector, a Radio Frequency Quadrupole Linac (RFQ) accelerator, and a first part of superconducting-RF (SRF) Linac.

The LIPAc is under validation. The first accelerator component which allows the production of a 140 mA-100 keV deuteron beam has been already demonstrated the commissioning at Rokkasho showing promising performance. The validation of the second phase (100 keV to 5 MeV), so called

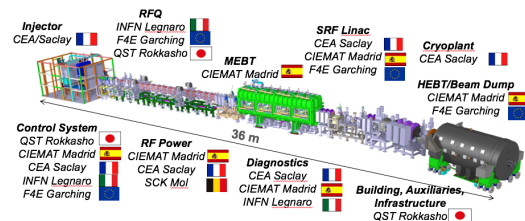


Figure 1: Configuration of a Linear IFMIF prototype accelerator (LIPAc).

RFQ acceleration phase, has been started after the installation of RF system, RFQ, MEBT (Medium Energy Beam Transport), diagnostic plate (D-Plate) and low-power beam dump (LPBD). The third phase, so called final phase, will be the integrated commissioning of the LIPAc up to 9 MeV with its SRF, HEBT (High Energy Beam Transport) and high-power beam dump [2].

On the other hand, Through the review on the experimental results of ITER and JT-60SA, the engineering design of a DEMO fusion reactor and the engineering data, transition judgement for construction of a DEMO fusion reactor is to be done around 2035 in Japanese fusion reactor program. Acquisition of the neutron irradiation data by the fusion neutron source is most critical in the engineering data for a DEMO fusion reactor, because the data is very limited for the neutron energy spectrum. In order to acquire the neutron irradiation data, construction of the Advanced Fusion Neutron Source (A-FNS) is planned as the fusion neutron source [3]. Based on results from the IFMIF/EVEDA project in the Broader Approach (BA) activities, a conceptual design of A-FNS has been carried out until 2020. Consecutively, an engineering design will be conducted from 2020 to 2025. A-FNS will be constructed from 2025 as currently planned, and operated from 2031.

RECENT PROGRESS OF LIPAc

The LIPAc RFQ is the longest one in the world and has 9.8 m length in total. 110 adjust-able tuners were replaced with final tuners and all the test of low power RF was completed 2016.

As a result, very good agreement of the RF field profiles was obtained between the design and the measurement. As the result of measurement, the Q-value was 11000 which was greater than the expected value 9000, and the content of the spurious modes was less than 2 %. After that, the vacuum equipment was assembled, and the baking of the cavity was done. The vacuum system check-out started, and finally the cryopumps were started. The coaxial waveguides were connected and tested with control system to RFQ in 2017 after the completion of the high-power test of the RF modules.

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All preparation for RFQ commissioning was completed in July 2017 as shown in Figure 2.

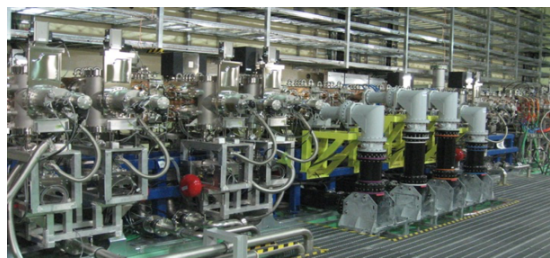


Figure 2: RFQ installation in the beam line.

The RF power system as shown in Figure 3 consists of eight RF chains amplifying RF at 175 MHz up to 200 kW in CW or pulse waveform. The RF output power of individual chain is injected into the single RFQ cavity through RF couplers respectively. Each RF chain synchronizes to the master RF chain through 10 MHz distributed from the White Rabbit to LLRF of the eight chains. The input power to the RFQ cavity (forward power) and reflected power from the cavity are detected from the directional coupler. Using a feedback system, the forward power from seven slave RF chains follow the reference RF power from the master RF chain. This function is essential to the RFQ linac since the RF power into the cavity must be balanced and in-phase. SF system for SRF linac is same configuration as this RF system. RF power per a co-axial line for SRF is 100 kW which is half of RFQ RF system.

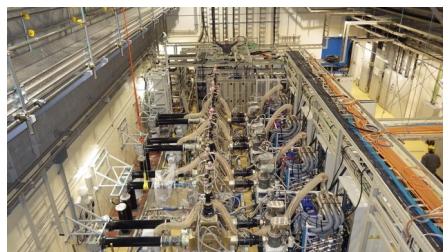


Figure 3: RF system for RFQ and SRF in LIPAc.

The commissioning of the individual RF chains was completed using the dummy load up to 200 kW/CW in July 2017, and the RF conditioning has been started after the coaxial transmission lines were connected to the RFQ. A precise synchronization of the amplifiers phase and amplitude with an active feedback loop is realized by a fully digitalized low level RF control unit combined with the “White Rabbit”. The RF injection with 8 chains synchronization succeeded first time in August 2017 and the RF conditioning activity has been started in October 2017. One of the milestones of the RF conditioning was to obtain the maximum vane voltage in the RFQ cavity 132 kV, which corresponds approximately to the required target value to accelerate D+ beam in the short pulse. This was realized relatively smooth RF conditioning by adopting an automatic rearming system of RF system when RF stops by multipactoring etc. Finally, we could reach the enough cavity voltage for D+ acceler-

ation in March 2019 after very hard longtime conditioning of RFQ.

At the initial beginning of the beam commissioning with 50keV H+ at June 2018, the beam current extracted from ion source was set to 13mA to inject a minimal current <10mA achievable by Plasma Electrode with 6mm diameter aperture, and also duty cycle was set with 0.3ms pulse per 1s repetition, for reducing the possible beam induced damage to the interceptive diagnostic devices. The output energy was measured using time-of-flight method for comparing the 175 MHz bunch signals detected by 3 BPMs installed in D-Plate with fixed drift lengths (0.16 and 1.27m). The results, 2.5 ± 0.02 MeV, showed a good agreement with the design value. The photo and the configuration of the accelerator setup are shown in Figs. 4 and 5. The typical snap shot of oscilloscope to show the beam current signals at four points along the beam line is given in Figure 6. As a result, in this first campaign, the RFQ output current of 26 mA at maximum was observed.

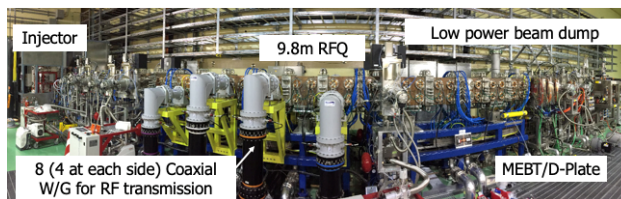


Figure 4: IFMIF prototype accelerator (LIPAc) without SRF.

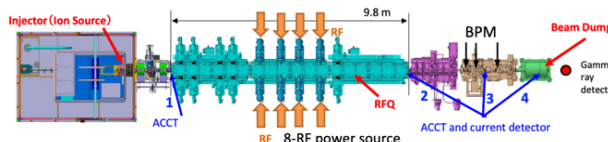


Figure 5: Configuration of the LIPAc.

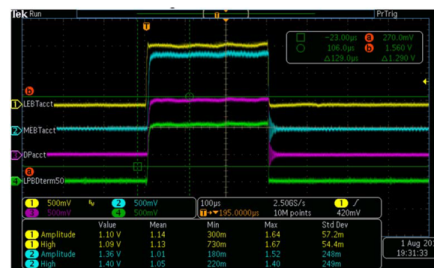


Figure 6: H+ beam Beam current signals measured at four locations of the LIPAC for extracted current 30 mA with 0.3 ms pulse width (yellow: RFQ input, cyan: RFQ output, magenta: middle of D-Plate and green: LPBD).

After the manufacturing studies needed for the licensing of the cavities and the validation of the application form by KHK in March 2016, the manufacturing of the pre-series cavity and the 8 series HWRs have been completed. All the bare cavities have been tested in vertical cryostat and are over the requirements (unloaded quality factor $Q_0 = 5 \times 10^8$ at nominal accelerating field 4.5 MV/m) [4]. Eight cavities have been through the final qualification process. Operational equivalent tests -in a dedicated test stand named SaTHoRi

- were performed on two different accelerating units (i.e. HWR cavity equipped with its tuning system and power coupler). The nominal accelerating field of 4.5 MV/m was achieved with an injected power of 14 kW and the tuning range exceeds the requirement of 50 kHz [5].

The manufacturing of the power couplers ended in April 2017. Four pairs have been successfully conditioned up to 100 kW. The superconducting solenoids are under manufacturing and cryomodule assembly has been just started in March 2019. This assembly takes place at Rokkasho Fusion institute where a clean room is built. The cryomodule and the assembly are shown in Figures 7 and 8.

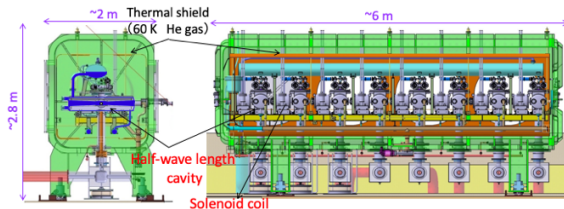


Figure 7: Cryomodule for LIPAc.

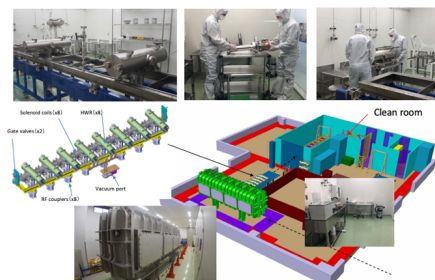


Figure 8: Assembly of the cryomodule in the clean room.

Cryoplant procured by CEA/Saclay is needed for cryogenic cooling of the SRF linac and consists of cryogenic power equipment providing helium refrigeration (He refrigerator, He compressor, oil removal system etc.) and cryogenic transfer lines (including liquid He Dewar, gas He buffer tank, etc.), in addition to the Cryomodule fluid supplying equipment. The plant was installed and commissioned in April 2017 as shown in Figure 9.

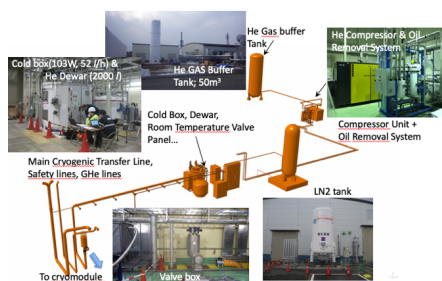


Figure 9: Cryoplant for LIPAc.

A-FNS PROJECT

Based on results from the IFMIF/EVEDA project, a conceptual design of intense Fusion Neutron Source, in

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upgrade plans for existing machines

Rokkasho aiming at obtaining material irradiation data for a fusion DEMO reactor is presented. “Japan’s road map and action plan to promote R&D for a fusion DEMO reactor” decided in 2018 requires that the material irradiation data should be acquired for a decision in the 2030s to start construction of a fusion DEMO reactor. Accordingly, an advanced fusion neutron source based on its construction in Rokkasho, named A-FNS, has been designed at QST on the basis of the results from the IFMIF/EVEDA project in the BA activities.

Table 1: Basic Parameters of A-FNS

| Items | Basic Parameters | Values |
|----------|--------------------|---|
| Ion beam | Particle | Deuteron |
| | Incident energy | 40 MeV |
| | Current | 125 mA |
| Target | Foot print | 200 × 50 mm ² |
| | Material | Lithium (liquid) |
| | Temperature | 523 K |
| Neutron | Thickness | 25 ± 1 mm |
| | Flow velocity | 15 m/sec |
| | Intensity | 6.8 × 10 ¹⁶ /s |
| | Flux | 6.0 × 10 ¹⁴ /sec/cm ² |
| | He production rate | 312 appm/fpy |
| | Displacement | 24.7 dpa/fpy |

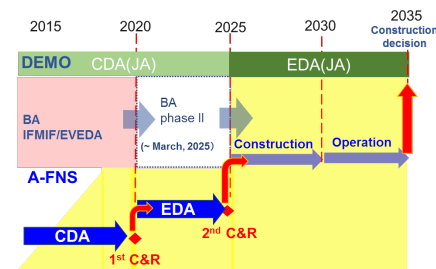


Figure 10: Relation of DEMO design phase and A-FNS design, construction and operation.

Figure 10 shows the schedule relation of JA/DEMO and A-FNS between the conceptual design phase and operation one. The conceptual design phase of DEMO will be implemented until 2025 and then the phase will move into the engineering design phase. The decision of the DEMO construction is set to at 2035. Therefore, the irradiation property data of F82H with A-FNS have to be acquired by 2035. The A-FNS/CDA (Conceptual Design Activity) will be advanced until 2020 and implement the A-FNS/EDA (Engineering Design Activity) until 2025. A-FNS should be constructed at the latest by 2031. For the acquisition of F82H irradiation data, the irradiation period will be for 2-3 years. The A-FNS requires the basic parameters in Table 1.

The A-FNS requires the basic parameters in Table 1. The A-FNS is designed to obtain the material irradiation data up to 20 dpa for a fusion DEMO reactor. It is composed of a deuteron accelerator with one beam line, a liquid lithium

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target test facility in Figure 11 and a post irradiation examination facility in Figure 12.

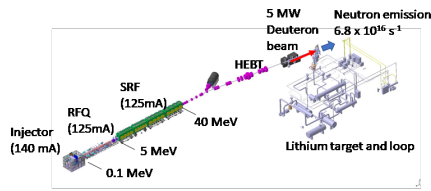


Figure 11: Schematic view of A-FNS components.

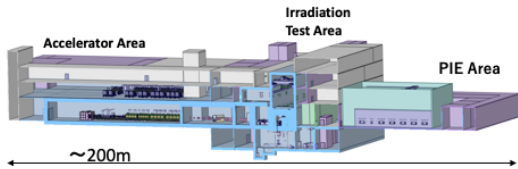


Figure 12: Vertical cross-sectional view of A-FNS building.

Figure 13 shows a schematic view of SRF accelerator for A-FNS from 5 MeV to 40 MeV. It is presently based on the design of the LIPAc. The SRF-LINAC is composed of four cryomodules, and deuterons are increasingly accelerated to 9, 14.5, 26 and 40 MeV by each cryomodule.

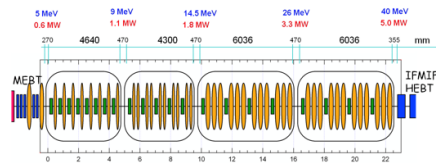


Figure 13: Cryomodules for A-FNS.

In QST, the A-FNS main building and related buildings are planning to construct at Rokkasho. Figure 14 is shown the image of location. As the related building and facility, electric power receiving and water supply equipment, lithium facility and storage facility for the activation will be needed. Therefore, its total area needs 300 m × 450 m (13.5 hectares).

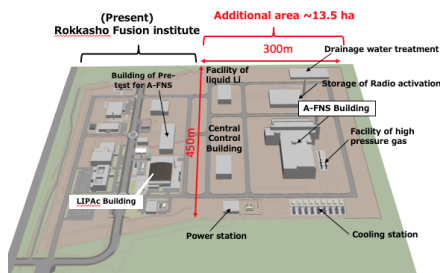


Figure 14: Site layout of A-FNS.

One of the features of neutrons generated in the A-FNS is its angular dependency which is caused by d-Li reaction. Especially, high energy neutrons which have an energy peak around 14 MeV has a strong dependency in the forward direction. Compared with other neutron sources, these high

energy neutrons are peculiar to the A-FNS. Considering effective use of the neutrons in the application, irradiation samples are to be placed in the forward direction of the lithium target in the radio isotope (RI) production by using (n,2n) reaction, (n,p) reaction, etc [6]. It is noted that this means the irradiation location for the RI production is the same for that for the test modules of the fusion reactor materials. Another is the big footprint size in which deuteron beam is injected. The size is 20 cm in width × 5 cm in height. Neutron generation source with an acceleratorbased system usually corresponds to a point source, because the beam size is enough small. In this case, an area of the sample is to be very small in order to utilize neutrons which have the dependency in the forward direction. The A-FNS has an advantage of usage of samples which have large irradiation areas. On the other hand, the neutrons which have an energy peak around 1 MeV generate isotropically. Relatively strong neutron fluxes can be achieved in 90 degree direction, because there are no test module for fusion reactor materials and no big structure for the target and test modules. These neutrons in the 90 degree direction are also valuable for the neutron application.

SUMMARY

The results of the activities on the Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA) project under the framework of the Broader Approach agreement was overviewed. The first step to demonstrate the 100 keV deuteron and 50 keV proton beams from the LIPAc injector was completed by satisfying the target value of beam emittance at the beam current of 140 mA and 70 mA for deuteron and proton, respectively. The important milestones are verifying the design of 175 MHz RFQ with the RF power system and acceleration of deuteron to 5 MeV. And the associated beam transport line to the beam from RFQ into the superconducting RF linear accelerator, has been started and 100 mA deuteron beam was obtained with the beam transmission, about 90% at this moment.

In other hand, on “Japan’s roadmap and action plan to promote R&D for a fusion DEMO reactor”, the design activity of fusion neutron source of A-FNS has been implemented in QST Based on the results of IFMIF/EVEDA project. The first mission of A-FNS is to complete the irradiation data acquisition of F82H by 2035. For the mission achievement, the A-FNS/EDA will be implement from 2020 after the conceptual design activity toward the neutron operation around 2030. The site is planning to A-FNS at Rokkasho-mura, Aomori in Japan. It is also planning to implement blanket irradiation test and irradiation durability test for DEMO in A-FNS.

As current design activities, the designs of material test specimen module, lithium target, remote handling, neutron monitor have proceeded. Furthermore, the wide application of A-FNS is being investigated.

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