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Necessity for a Korea-Fusion Neutron Source (K-FNS) following Worldwide Development Strategy of Future Fusion Power Plants

Doo-Hee Chang*, Sun-Ho Kim, Dong Won Lee
Nuclear Fusion Technology Development Division, Korea Atomic Energy Research Institute, Daejeon 34057, Korea
**Corresponding author: doochang@kaeri.re.kr*

1. Introduction

The Korean-DEMOnstration reactor (K-DEMO) is being planned and designed [1], which is based on a roadmap of national fusion energy development program in Korea, as a next fusion reactor after the operation of ITER device [2]. Before the construction of K-DEMO, it is necessary to confirm the reliability and stability of breeding blanket, tritium treatment, remote handling technology, neutron-irradiated material test, and so on, with the production of high-flux fusion neutrons from the thermonuclear fusion reaction inside the fusion power plants. So many devices of the various fusion neutron sources (FNSs) are being designed and planed in the major fusion countries (such as USA, Russia, EU, Japan, and China) in the world. The planning worldwide FNSs include the tokamak fusion neutron science facility (FNSF, USA) [3], DEMO-fusion neutron source (DEMO-FNS, Russia) [4], IFMIF-DEMO oriented neutron source (IFMIF-DONES, EU) [5], Advanced-FNS (A-FNS, Japan) [6], and Accelerator/Fusion driven system (ADS/FDS, China) [7], Rotating Tritium Target Holder (RTTH, India) [8]. Based on the worldwide fusion research strategies, it was concluded that the development of Korean-FNS (K-FNS) is required for the reactor-scale approach to the K-DEMO beyond the ITER [9]. In this presentation, the worldwide FNSs as mentioned the above were summarized, and the required FNSs and the plan of K-DEMO and fission application were suggested.

2. Reviews of Worldwide FNS Development

In this section, the development strategy of worldwide FNSs between ITER and DEMO devices are reviewed for the countries globally working toward the fusion energy.

2.1 USA

Under the US accelerated fusion energy development program, developing an understanding of fusion nuclear science in parallel with research on ITER is required to study burning plasmas [10]. A Fusion Nuclear Science Facility (FNSF) in parallel with ITER provides the capability to resolve FNS feasibility issues related to power extraction, tritium fuel sustainability, and reliability, and to begin construction of DEMO. The research aims of FNSF will be to provide the first opportunity to explore the behavior of nuclear components and materials in the fusion nuclear environment and discover new multiple effects/multiple interactions phenomena, and to develop the definitive database essential for both the validation of fusion nuclear science modeling, design and safety codes, and ultimately the demonstration of DEMO-ready in-vessel component operation and reliability. There are two main candidate machine types proposed recently in the US aimed at the FNSF mission: FNSF-AT (Fusion Nuclear Science Facility-Advanced Tokamak) and FNSF-ST (Fusion Nuclear Science Facility-Spherical Torus), as shown in Figure 1 [11]. The FNSF must fill the tremendous gap between ITER and DEMO by providing the break-in to the fusion nuclear regime, as described in Figure 2.

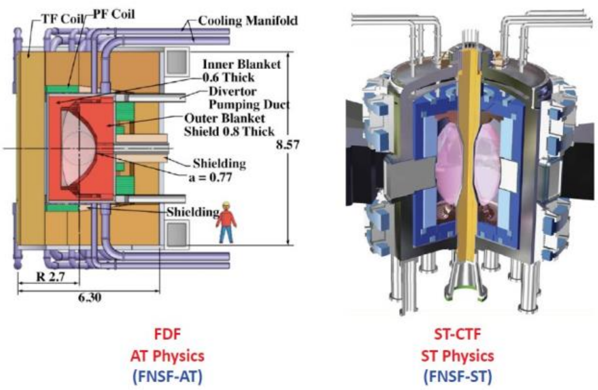


Fig. 1. Two FNSF candidate devices.

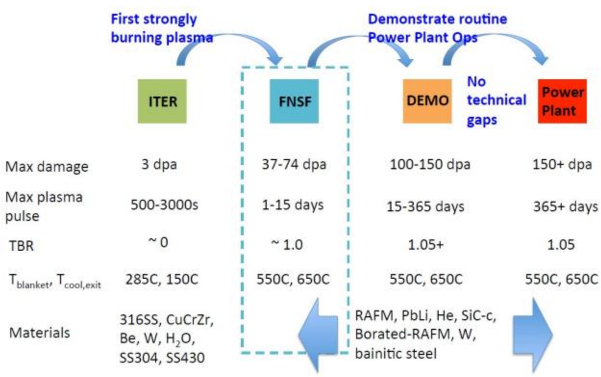
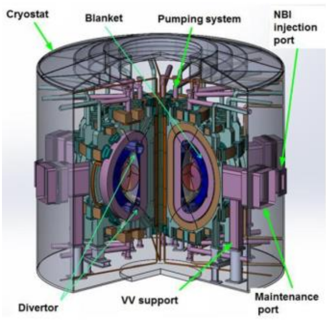


Fig. 2. The FNSF program strategy in USA [3].

2.2 Russia

The development of fusion neutron source DEMO-FNS based on classical tokamaks was launched at the NRC Kurchatov Institute in 2013. Fusion-fission hybrid technologies tested on DEMO-FNS may accelerate implementation of fusion technologies and are capable to get better neutron economy in the global nuclear energy system. Implementation of hybrid technologies should also accelerate the development of atomic energy by reducing the radiotoxicity generated in the nuclear fuel cycle (FC) and the level of pollution by fuel reprocessing. These problems become a matter of interest at the forthcoming transition of nuclear power to a closed nuclear FC. A cutaway view of the DEMO-FNS tokamak is shown in Figure 3 [12].



Major radius,	m	3.2
Minor radius,	m	1.0
Toroidal field,	T	5.0
Plasma current,	MA	5
NBI power,	MW	30
ECRH power,	MW	6
Electron/ion temperature,	keV	11.5/10.7
β_N		2.1
β_p		0.96
Neutron yield	n/s	$>10^{19}$
Consumed/generated electric power,	MW	up to 200
Discharge time,	h	up to 5000
Capacity factor		0.3
Life time,	years	30

Fig. 3. A cutaway view of DEMO-FNS tokamak.

2.3 EU

IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented NEutron Source), as shown in Figure 4, is a IFMIF-based neutron irradiation facility which aims at providing the irradiation data required for the construction of a DEMOnstration fusion power plant (DEMO) [13]. The DONES consists of only one of the IFMIF accelerators (40 MeV and 125 mA), and utilizes only the High Flux Test Module (HFTM) for the irradiation of material specimens. The HFTM is the key component to provide the material irradiation data which fulfill the mission of DONES. The damage dose (quantified in terms of Displacements Per Atom, DPA) for which the DEMO first wall (FW) will be designed is 20 dpa (based on the NRT damage model [3]) in the initial phase and 50 dpa in the second phase. As top level requirements, the DONES HFTM aims at providing a 0.3 litter irradiation volume with 20~30 dpa in <2.5 years, and 0.1 litter volume with 50 dpa in <3 years. The neutron flux is ~10^{14} $cm^{-2}s^{-2}$ with neutron spectrum up to 50 MeV energy.

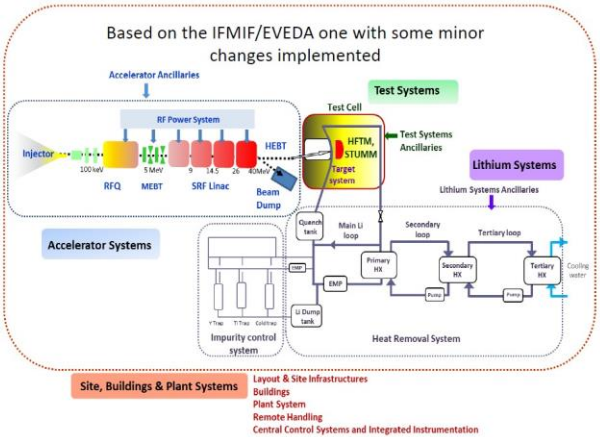
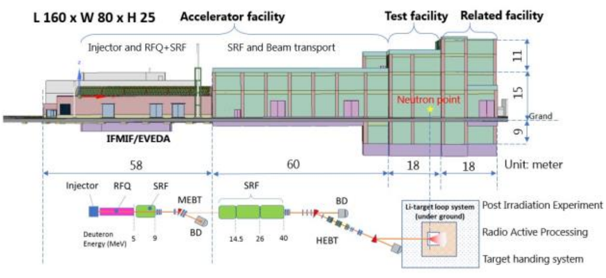
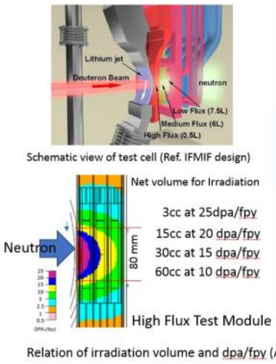


Fig. 4. An IFMIF-DONES plant configuration.

2.4 Japan

The international fusion materials irradiation facility, IFMIF, is just due to the candidate material irradiation test with neutron emitted from deuteron-lithium nuclear reaction. The IFMIF/engineering validation and engineering design activities, EVEDA, has implemented as an Japan-EU international collaboration. Based on the results from the IFMIF/EVEDA project, a conceptual design of intense fusion neutron source aiming at obtaining material irradiation data for a fusion DEMO reactor is lunched in Rokkasho site. Japan roadmap and action plan to promote R&D for a fusion DEMO reactor decided in 2017 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 (A-FNS) based on the construction in Rokkasho site, as shown in Figure 5, has been designed at National Institutes for Quantum and Radiological Science and Technology (QST) on the basis of the results from the IFMIF/EVEDA project in the Broader Approach (BA) activities.





Beam	Particle Energy Current Foot print Incident angle Availability	Deuteron 40 MeV 125 mA (CW) 200 x 50 mm^2 Normal 33% at least
Target	Material Temp. Velocity Thickness Window	lithium Liquid target (jet) 200 - 270 ℃ 10-15 m/s at target 25 mm Free surface (no window)
Neutron	Intensity (at back plate) Average flux Helium P. R Displacement HePR/dpa	6.8 x 10^{16} neutron/s 6.0x 10^{14} n/cm^2/s 3.12×10^2 appm/fpy 24.7 dpa/fpy 12.6

fpy: full power year

Fig. 5. Cross-sectional view and basic parameters of an A-FNS.

2.5 China

There are two fusion technology approach processes for the future China-DEMO (C-DEMO) and fusion power plants in China. One is the accelerator-driven subcritical system (ADS) at in Chinese Academy of Science (CAS), and another is the fusion-driven subcritical system (FDS) in CAS. Based on the national demand for the safe disposal of nuclear waste as well as the potential for nuclear fuel breeding and advanced energy generation, the CAS initiated the ADS program in 2011 with a budget of ￥1.78 billion for the first five years under the framework of a Strategic Technology Pilot Project. The ultimate goal for the ADS program is to develop an industrial scale ADS facility for the safe disposal of nuclear waste and advanced fission energy systems, by integrating a high-power superconducting proton accelerator, a heavy metal spallation target and a sub-critical nuclear reactor. In a comparative study, entitled ADS and Fast Reactor (FR) in Advanced Nuclear Fuel Cycles, OECD/NEA drew a conclusion that ADS has the advantage that it can burn pure minor actinides while avoiding a deterioration of the core safety characteristics. The CAS plan to construct demonstration ADS transmutation system ~2030s through three stages, as shown in Figure 6. The definition and design of the multi-functional FDS, which could perform multi-functions such as breeding nuclear fuel, transmuting long lived wastes, producing tritium for fusion fuel cycling, fusion material test, energy production test, and so on as an alternate strategy to utilize fusion energy technology based on the recent progress in hybrid reactor studies in China are being carried out under the support of the CAS. The FDS is proposed as a middle step toward the final application of fusion energy considering available knowledge base of fusion technology and the energy demand in China, as shown in Figure 7.

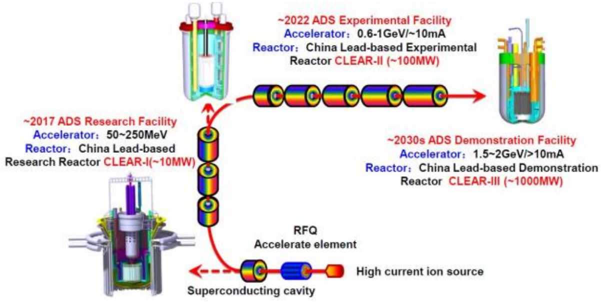


Fig. 6. China LEAd-based Reactor (CLEAR) program as the reference reactor for ADS project and for Lead cooled Fast Reactor (LFR) technology development.

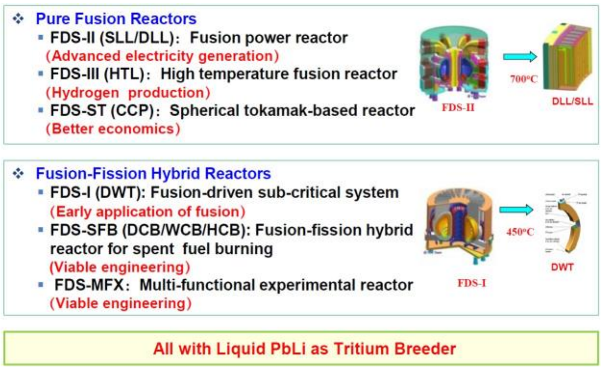


Fig. 7. China Series FDS Reactor Concept Design.

2.6 India

An accelerator-based 14 MeV neutron source is under development to study the fusion neutronics for India fusion programs, as shown in Figure 8. In order to study the neutronics of fusion reactor blankets, a program is underway at the Institute for Plasma Research (IPR) using 14-MeV neutron source. An accelerator-based neutron source is under development in which 30 mA deuterium beam will be accelerated up to 300 keV energy over a 140 Curie tritium target. It will then impinge on a rotating tritium target to producing nearly isotropic 14-MeV neutrons. Being a system handling tritium radioactive material, a recovery system is to be designed to minimize airborne tritium effluent releases to well below the permitted limit. In addition, the system should minimize tritium exposure to staff by maintaining low levels of tritium in the rotating tritium target holder (RTTH). The expected neutron yield is 3~5×10^{12} n/s. The rotating target has been developed for intense neutron source. Total estimated power density on the rotating target is 11.5 kW/cm^2 for a diameter of 10 mm and D^+-beam power of 9 kW with 300 kV/30 mA.

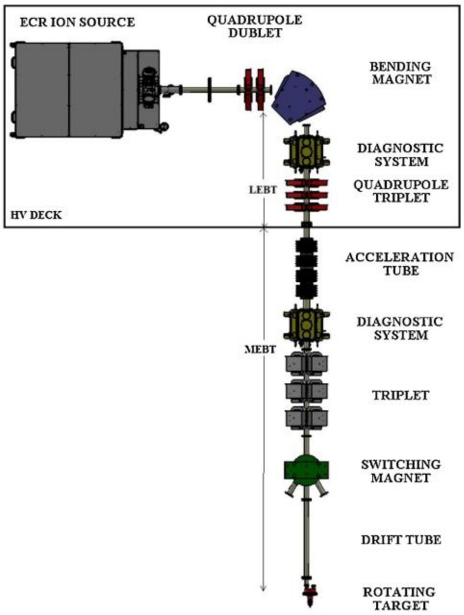


Fig. 8. Schematic diagram of 14-MeV accelerator-based neutron source with a rotating tritium target holder (RTTH) in India.

3. Development Strategy of K-FNS

From the reviewing results, three kinds of FNSs can be considered as the K-FNS candidate;

(i) Compact spherical tokamak (ST)-based volume neutron source (VNS) facility
(ii) Accelerator-based FNS facility
(iii) Fusion-fission hybrid reactor (FFHR)-based VNS facility

The FNSs have been an identified need and research topic in both ITER and DEMO for more than four (or five) decades. Current large international activities are focused on generating the materials design database for the DEMO. The worldwide FNS programs have identified a gap that can be filled with a near term and moderate cost neutron source for materials science studies, and the experimental and modeling & simulation needs have been identified by the essential FNS operation. Considering the national fusion energy R&D roadmap in Korea, an aggressive timeline is suggested and summarized in Figure 9. The K-CVNS, K-AFNS, or K-FFHR could be developed and operated before (or in parallel to) the K-DEMO.

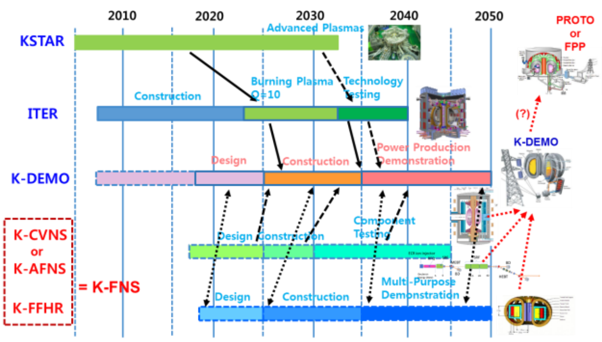


Fig. 9. A proposal of K-FNS operation in the national fusion energy R&D roadmap in Korea.

4. Conclusions

Based on the worldwide fusion research progress toward the future fusion power plants, it is also required the development of K-FNS for the reactor-scale approach to K-DEMO fusion power demonstration plant beyond the ITER device. The national fusion R&D roadmap including the K-FNS development progress in Korea is suggested for the first time.

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