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USERS' PERSPECTIVE ON D-Li NEUTRON SOURCES (A-FNS and IFMIF-DONES) FOR DEMO AND BEYOND

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Abstract:
A-FNS and IFMIF-DONES neutron source program in Japan and in the EU, respectively, are advancing targeting on the start of operation in ~2030. These facilities will play a central function in realizing DEMO. This paper will discuss the role of the materials scientists, as the users, in A-FNS and IFMIF-DONES programs in order to encourage them to enhance their commitment to the programs. The past collaborations by the materials scientists and the designers in the IFMIF project are introduced first. Then the roles of the neutron sources in the DEMO-roadmap are discussed, for which materials scientists are requested to take leadership. This paper also emphasizes the need for development of advanced materials and for obtaining fundamental understanding on fusion neutron radiation effects by application of the neutron sources.

Key words:
D-Li neutron sources, A-FNS, IFMIF-DONES, DEMO roadmap

1. Introduction

The development of D-Li neutron sources for irradiation of fusion reactor materials has a long history. Fig. 1 illustrates the major D-Li neutron source programs. FMIT (Fusion Materials Irradiation Test facility, USA) already took the initiative for this concept in the 1970s [1] and was once ready to construct [2], but finally cancelled in 1984, after a high ranking advisory panel recommended 1983 that “the FMIF enterprise, including the associated irradiation program, should be the subject of international collaboration” [3]. The effort was succeeded by ESNIT (Energy Selective Neutron Irradiation Test facility, Japan) in the late 1980s and 1990s, which had a reduced size and a flexibility of energy selectiveness [4]. IFMIF (International Fusion Materials Irradiation Facility) is a relatively high flux large volume neutron source using two deuterium accelerators. This is an international program initially based on an IEA framework, having stages of CDA (Conceptual Design Activity) [5], CDE (Conceptual Design Evaluation) [6], and KEP (Key Element Technology Phase) [7]. This program was extended in 2007 based on BA (Broader Approach), bilateral Japan and EU agreement, with the project name of IFMIF-EVEDA (Engineering Validation and Engineering Design Activities). The IFMIF-EVEDA project is producing extensive achievements in the facility design and R&D for accelerators, lithium targets, test facilities, etc. [8]. The program is continuing to the focus on the completion of the task of accelerator systems [9].

Based on the IFMIF-EVEDA Project and other efforts, the design of compact D-Li neutron sources, A-FNS [10] and IFMIF-DONES [11] in Japan and EU, respectively, are advancing. In these programs, timely construction is being planned for materials qualification, targeting the start of operation in ~2030, which meets the present DEMO development schedule.

Throughout these activities, materials scientists committed themselves largely to design and schedule the neutron sources by defining the requirements of the users, updating the test matrix based on, e.g., SSTT (Small Specimen Test Technology) development, and refining materials development roadmaps, as well as contributing technically to, for example, selection of the constituent materials for the neutron sources and materials interaction with liquid lithium. During the design activity of the neutron sources, users' groups have been organized for communication with the designers, for example:

(1) IEA Implementing Agreement for a Program of Research and Development on Fusion Materials – Annex II,
(2) IEA Working Group on Irradiation Facilities and Testing (W-GIFT), and
(3) IFMIF Specification Working Group.

The users' requirements included neutron flux, flux gradient, fluence, test volume, spectrum (neutron and PKA (Primary Knock-on Atom) energy), temperature control, environments, accessibility (diagnostics, in-situ test capability), etc. Progress in SSTT updated the test matrix and requirements. The users' requirements were included in the past reports [5-8] and published elsewhere [12,13]. The development of neutron sources is an example for a very successful user-design interaction. But, unfortunately, the commitment of the materials scientists at present is seemingly not as great as it was years ago, although A-FNS and IFMIF-DONES programs now have high viability.

This paper will discuss the role of the materials scientists in A-FNS and IFMIF-DONES programs, as the users, encouraging them to enhance their commitment to the programs. In section 2, examples of the past close collaborations between the materials scientists and designers are introduced, which can also be items for collaboration for A-FNS and IFMIF-DONES programs.

In section 3, the roles of A-FNS and IFMIF-DONES in Japanese and European roadmaps toward DEMO, respectively, are discussed. Because the neutron sources are scheduled for acquisition of the necessary irradiation data that will meet the DEMO schedule, the development and construction of the facilities, acquisition of irradiation data, and design qualification and licensing must be closely linked with one another. The materials scientists need to play a key role in these processes.

Section 4 discusses the broader roles of A-FNS and IFMIF-DONES, for development of various fusion reactor materials including those for advanced systems, and for obtaining fundamental understanding on fusion neutron radiation effects. The materials scientists clearly must take key responsibility in the planning and execution.

2. Examples of collaboration between users and designers: temperature control of test samples

It was pointed out by Kiritani et al. [14] that, in fission reactor irradiation, samples are exposed to neutrons at lower temperatures during start-up and shut-down of the reactor, if the temperature is controlled only by nuclear heating. Irradiation tests with improved temperature control using auxiliary electric heaters verified the effects of the temperature transient. In some materials and conditions, large difference was observed between the two cases.

Intentional temperature variation experiments were carried out in HFIR (High Flux Isotope Reactor) to assess the effect of 10% negative excursion of the temperature during irradiation under the Japan-USA Fusion Cooperation Program (JUPITER) [15]. For pure vanadium, large change in microstructure and tensile properties were observed by the temperature variation between 793/633 K. The effect was, however, small for V-4Cr-4Ti-Si [16]. Negative temperature excursion can take place when one of the two beams drops in the case of IFMIF. (Note that IFMIF has two beam lines.)

In the Japanese coordination activity in IFMIF-KEP (2001-2005), the following requirements on the temperature control of the test pieces in HFTM (High Flux Test Module) were raised from the users.

(1) Temperature fluctuation being less than 1 %.

(2) Rapid temperature rise at the beam start-up with minimum overshooting.

(3) Maintaining the temperature and continuing the irradiation test when one of the two beams drops.

These requirements were incorporated into the HFTM design in which temperature control of the test pieces was carried out by gas-cooling and auxiliary electrical plate heaters. The design was carried out based on turbulent models and experimental verifications. The results depended on the module structure and physical parameter of the constituent materials and coolants. Under some assumptions, the following results were reported [17].

(1) Variation of nuclear heating (5±0.5 W/g) caused by the beam fluctuation results in the temperature change of ~4 K, <2 K, and <0.3 K for the test samples, when the variation cycle is 21 s, 5.2 s and 1.3 s, respectively. Thus the temperature fluctuation of the test samples can be maintained within ±2 K if the variation cycle is less than 5 s (Fig. 2).

(2) With the assistance of the plate heaters with 0.3 MW/m^2 when the irradiation starts, the transient time when the sample temperature is below the design is reduced from ~80 s to <30 s (Fig. 3).

(3) Negative temperature excursion when one of the two beams drops can be eliminated if the compensation plate heaters of 0.2 MW/m^2 operate (Fig. 4).

These evaluations clearly showed that the precise temperature control is a trade-off with the available test volumes, because the increase in the heater power results in the increase in the occupied volume by the heaters.

Collaboration on temperature control for the test samples in HFTM was also carried out by the users and the designers in the European community in IFMIF/EVEDA and IFMIF-DONES programs. Their emphases were temperature homogeneity in the specimen capsule and temperature excursions during temperature ramp-ups and beam-power on/off transients. The CFD (Computational Fluid Dynamics) simulation and experiments using HELOKA-LP He loop demonstrated the steady state temperature homogeneity within 3% [18] and the temperature excursion within 10 K [19]. Fig. 5 shows the experimental results of the specimen temperature control with HELOCA-LP in the case of stepwise temperature shift from 523 K to 623 K and a beam-on/off event [19].

3. DEMO development schedule and D-Li neutron sources.

Regarding the Japanese research strategy toward DEMO, “The Action Plan toward DEMO Development (Action Plan)” was produced in 2017 for 15 categories including “Fusion Materials, Standards and Codes” [20]. In 2018 Japanese policy based on the Action Plan was summarized as “A Roadmap toward Fusion DEMO Reactor (DEMO Roadmap)” [21]. In this plan, RAFM (Reduced Activation Ferritic and Martensitic) Steels are defined as the primary candidate for the blanket structural materials.

Fig. 6 summarizes the activity shown in the Action Plan for DEMO Reactor Design, Neutron Source, and Structural Materials. The Action Plan and DEMO Roadmap define First C&R (Check and Review) in 2020 to 2021, Second C&R within a few years from 2025, and Decision of Transition to DEMO (DEMO Decision) after the start of D-T operation of ITER (2030s). The purpose of the First C&R is to redistribute the resources in the programs. The most important decision to be made at the Second C&R is the construction of A-FNS. For the DEMO Decision, the available design database will be reviewed.

In Fig. 7 the irradiation facility development, testing, and design qualification for licensing are selected from Fig. 6, and mutual relations are shown [22]. Irradiation data for the design qualification and licensing of ITER-TBM (Test Blanket Module) will mainly be based on the fission reactor irradiation data. However, according to the expected schedule, it is possible that irradiation with A-FNS will contribute to the TBM.

One of the most important factors influencing the DEMO Decision is the availability of the necessary neutron irradiation data. A set of data to ~20 dpa is expected for the decision. Based on the existing data, it is predicted that significant effect of He will not appear to ~20 dpa [23]. If this prediction is approved by selected irradiations with A-FNS, large fission neutron irradiation database to ~20 dpa can be used for the design qualification and licensing. This is the mission of A-FNS in the early stage of operation. After the DEMO Decision, A-FNS will continue to be used to obtain high fluence irradiation data, e.g. ~100 dpa, for the qualification and licensing of DEMO operation to its full specification. In this stage, He effect is the critical question to be answered. Possibility of upgrading A-FNS to the level of IFMIF-EVEDA design will also be explored for timely data acquisition as schematically shown in Fig. 1.

EU roadmap has a similar role of the neutron source (IFMIF-DONES) in early, middle and long term as shown in Fig. 8, clearly indicating that IFMIF-DONES has a crucial role in the commencement of DEMO [24]. In a recent literature [25], the missions of IFMIF-DONES are defined as (1) generation of materials irradiation data necessary for DEMO design, licensing, construction, and safe operation, (2) generation of database for benchmarking the radiation response of materials hand in hand with computational materials science, and (3) as a possibility, assisting ITER for its nuclear operation phase. The missions are almost identical to those of A-FNS.

It should be noted that for promoting these programs early standardization of materials test technology including SSTT is absolutely mandatory. For many years, the materials scientists made a strong effort toward establishing SSTT. Ongoing IAEA Coordinated Research Project [26] is expected to drive the standardization of SSTT.

4. Broader role of the neutron sources

4.1. Development of various fusion reactor materials including those for advanced systems

Many materials other than those for blanket structural materials also need testing in fusion-relevant irradiation conditions, such as plasma-facing materials, blanket materials, and other functional materials. Early qualification of those materials by the neutron sources can contribute to efficient and robust development of the materials and components.

RAFMs are being developed as the primary candidate blanket structural materials for DEMO. However, in parallel, advanced materials needs to be developed in a long-term view in order to increase the competitiveness of fusion energy relative to other energy options with regard to cost, safety, and environmental benignity.

Vanadium alloys and SiC/SiC composites are among the candidates not only because of their low activation and other advanced materials properties but also of their non-ferromagnetism. Considering that uncertainty still remains regarding the effects of ferromagnetic materials on plasma confinement, development of these materials is also meaningful in terms of risk mitigation by providing backups.

In fact, tests of advanced blankets using the advanced materials are one of the key missions of DEMO operation. This means the targeting materials will be changed from RAFM to the advanced materials in the later stage of the neutron source operation as was schematically shown in Fig. 7 of ref. [22]. The present studies on the advanced materials should be oriented to the qualification by the neutron sources to meet the schedule of the blanket tests in DEMO.

4.2 Enhancing fundamental understanding of the fusion neutron irradiation effects

Because of the limited volume and time available for the irradiation with the neutron sources, and the resulting necessity of the support from the fission neutron irradiation and modeling, it is obvious that fundamental understanding on the materials performance is crucial to obtain the reliability in the prediction on materials performance in DEMO conditions. The neutron sources have much higher accessibility and flexibility than those of fission reactors, and thus can highly contribute to enhancing fundamental understanding.

Recent criticism over the reliability of the prediction based on the surveillance tests data of RPV (Reactor Pressure Vessel), triggered when unexpectedly high DBTT (Ductile-Brittle Transition Temperature) was derived by the tests, is a good example to show that fundamental understanding can still be questioned in the commercial stage of reactors [27,28]. There are various controversies regarding the kinetic model of microstructural evolution and the impact of higher damage rate of the surveillance test pieces relative to RPV, which can jeopardize life extension of the reactors. It should be noted that the data are still insufficient especially at the high-fluence low-flux regime. This means fundamental understanding on the fluence and flux effects of microstructural evolution is still insufficient for RPV. In an overview paper based on the US Light Water Reactor program, it was stated that the effect of dose rate is one of the remaining issues in predicting irradiation embrittlement of RPV, although significant progress in the mechanistic understanding has been made [29].

In most of the set of reactor irradiation data, fluence and flux are not independent, which can be misleading. Fig. 9 shows void swelling of Ni irradiated with D-T fusion neutrons by RTNS-II (Rotating Target Neutron Source-II) and fission neutrons by JOYO (an experimental fast reactor) [30]. Apparently, void swelling is larger by D-T fusion neutrons than by fission neutrons on the dpa (displacement per atom) basis. However, according to the grouping by damage rates (dpa/s) shown in the figure, the relation that low damage rate induces high swelling rate on the dpa basis can be extracted. Rate theory analyses showed that the fraction of vacancies escaping the recombination, which denote the possibility to contribute to the void growth, is a negative function of the damage rate [30]. Thus in this case the damage rate effects dominated over fission-fusion difference.

For fundamental understanding of the fluence effect, change of the fluence by several orders of magnitude is necessary. However, it is very difficult to perform such experiments keeping the flux constant in fission reactor irradiation. Low fluence irradiation is possible by placing the samples in periphery area of the reactors. In this case, however, the flux is also low. One of the rare examples in JMTR (Japan Materials Test Reactor), in which a controlled fluence dependence examination was carried out, showed that voids in Ni were formed already at very low dose, followed by gradual growth [31].

In-situ testing under irradiation is known to be a quite valuable tool both for obtaining fundamental understanding of the materials performance under irradiation and searching for engineering materials in-service performance. For fundamental studies, technological developments have been made such as TEM (Transmission Electron Microscope)-ion beam interface for research into in-situ microstructural evolution and PCT (Pressurized Creep Tube) for creep deformation under irradiation. Push-pull post-irradiation and in-beam fatigue tests for a 12% Cr Steel showed reduced radiation-induced hardening for the in-beam cases [32]. However, in-situ fatigue tests are quite limited. Based on the background, a creep-fatigue test module (CFTM) was designed for MFTM (Medium Flux Test Module) of IFMIF [33]. Unfortunately further examination of the module has not yet been carried out for

IFMIF-DONES. In-situ uniaxial creep tests, in comparison with PCT biaxial irradiation creep tests, can also address key questions with respect to irradiation creep.

In conclusion, it is critically important to design controlled irradiation experiments with the neutron sources which can contribute to uncovering fundamental science and constructing fundamental radiation damage models applicable to DEMO and commercial fusion reactors.

5. Summary

Development of D-Li neutron sources for fusion materials development has a long history. Materials scientists, as the users, committed themselves largely to the D-Li neutron source programs. Detailing and updating of users' requirements contributed to advancing the design of the facilities. Among good examples are the users' requirements on the sample temperature control and the designers' effort to fulfil them. Because A-FNS and IFMIF-DONES now have high viability, enhancing the commitment of the materials scientists is even more important than before. For this purpose a related users' community should be reinforced.

In the present Japanese and EU roadmaps to DEMO, acquisition of the necessary irradiation data by A-FNS and IFMIF-DONES is essential for the decision of transition to the DEMO construction phase. Thus careful manipulation of the schedule in the development of the irradiation facilities and the acquisition of irradiation data toward design qualification and licensing for DEMO is necessary. For this purpose, early SSTT standardization is mandatory.

The advanced blanket structural materials need to be developed in parallel with RAFM for exploring advanced fusion reactor options. Testing of advanced blanket segments is one of the key missions of DEMO operation. This means the targeting materials will be changed from RAFM to the advanced materials in the later stage of the neutron source operation, meeting the schedule of the tests in DEMO.

The neutron sources are quite valuable also for efficient and robust development of fusion reactor materials other than blanket structural materials, such as plasma-facing materials and other neutron-interactive functional materials.

Recent controversy in RPV performance clearly shows necessity for fundamental understanding of materials performance under irradiation not only in the design and developmental phase but also in the commercial operation phase. The neutron sources need to have capability for and to place high priority on fundamental researches such as singlevariable experiments for flux and fluence effects and in-situ creep-fatigue property tests, which are difficult by fission reactors.

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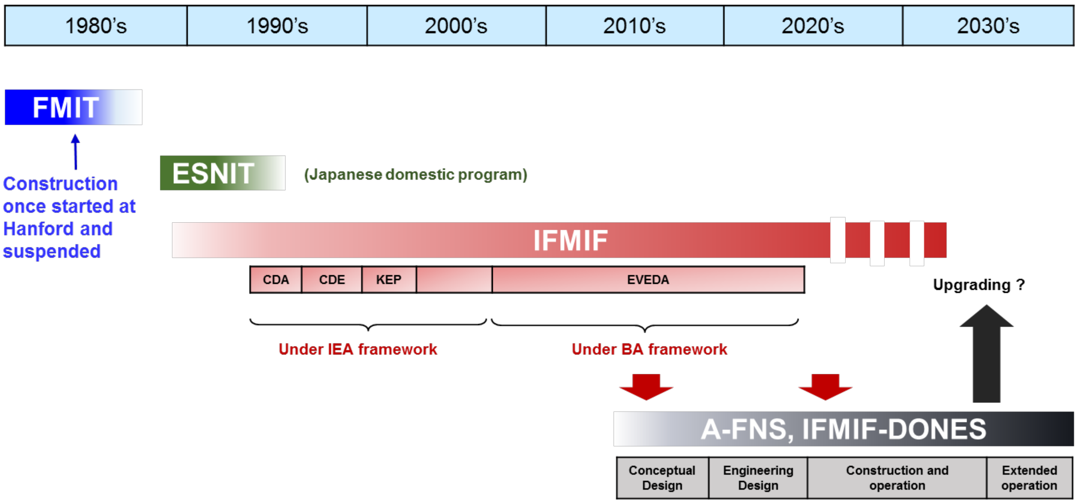

Fig. 1. Summary of the major D-Li neutron source programs.

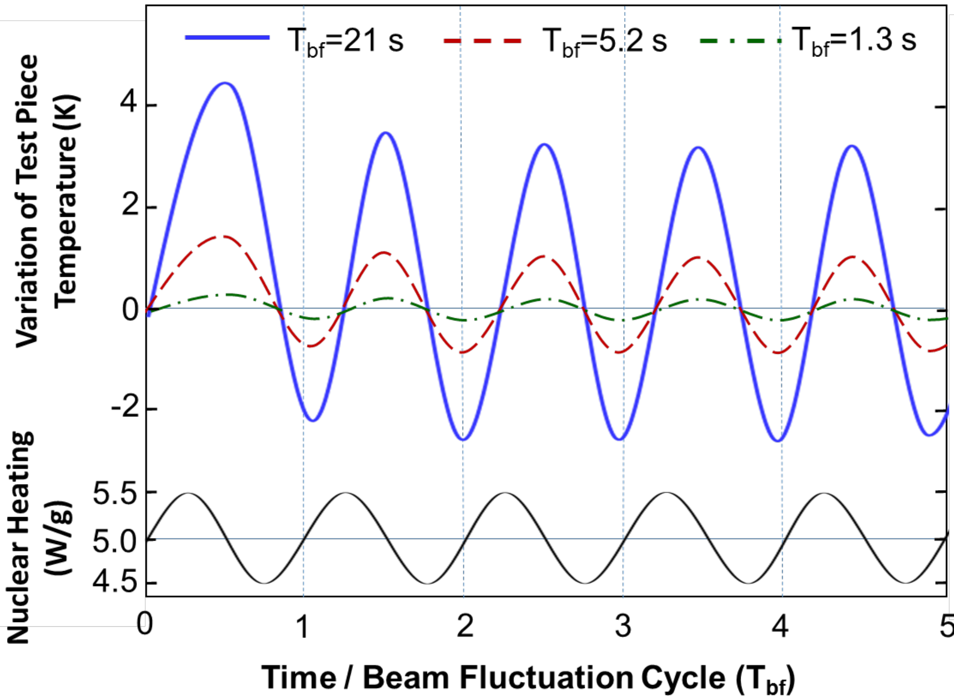

Fig. 2. Effects of variation of nuclear heating (5±0.5 W/g) caused by the beam fluctuation on the temperature change of the test pieces in IFMIF-HFTM for three cases of beam fluctuation cycles (T_{bf}). (Reproduction and minor modification of ref. [17])

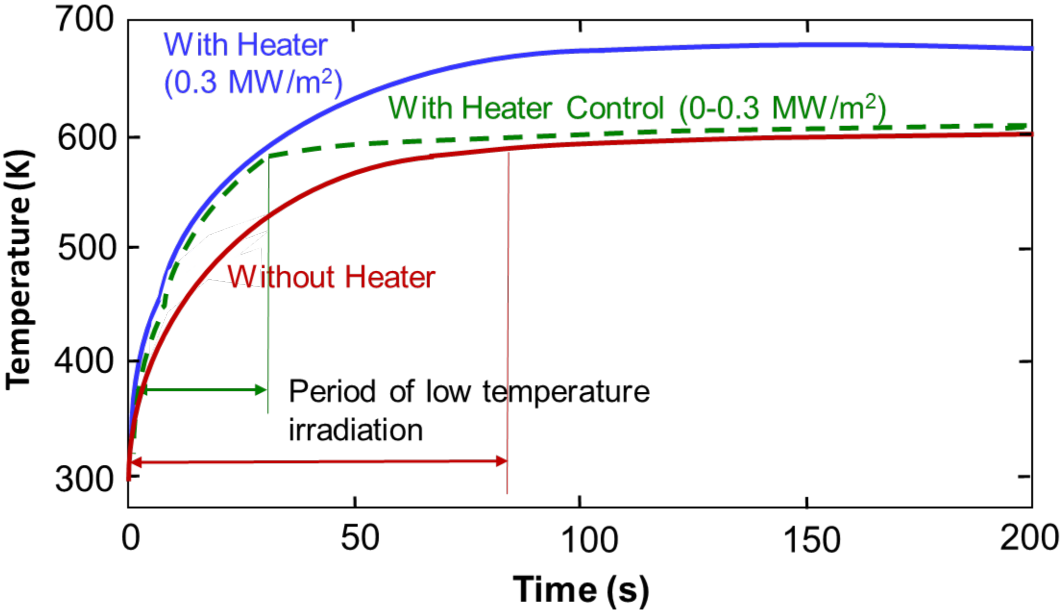

Fig. 3. Temperature transients when irradiation starts for the three cases: (1) nuclear heating only (without heater assistance), (2) with the 0.3 MW/m^2 heating by electric heaters, and (3) with the controlled heating (0-0.3 MW/m^2) for the test pieces in IFMIF-HFTM. (Reproduction and modification of ref. [17])

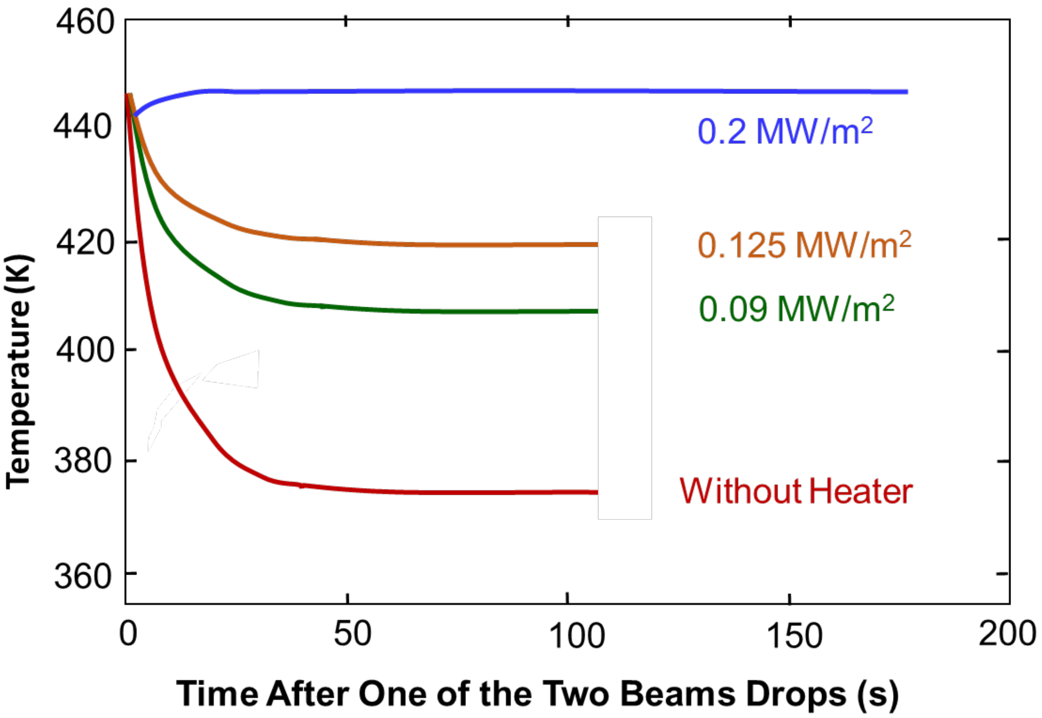

Fig. 4. Temperature change when one of the two beams drops with and without compensation by electric heaters for the test pieces in IFMIF-HFTM. (Reproduction and minor modification of ref. [17])

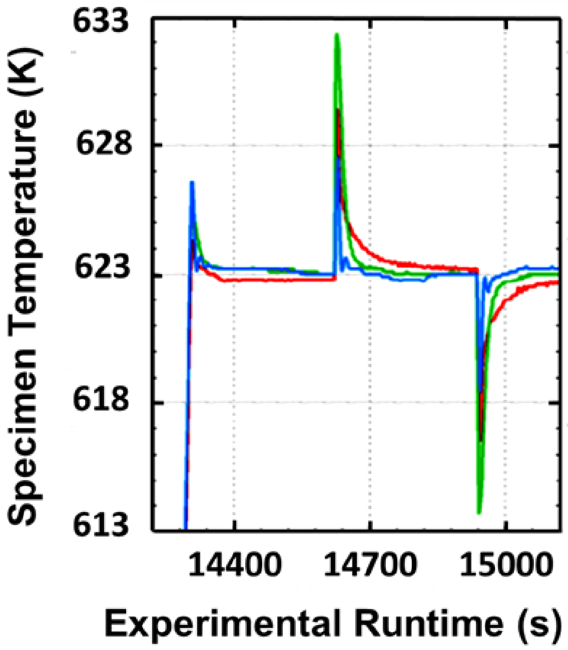

Fig. 5. Excursion of the specimen temperature in the case of stepwise temperature shift from 523 K to 623 K and a beam-on/off event, evaluated experimentally with HELOKA-LP. The blue, green, and red curves show temperatures for top, middle and bottom section of the test piece, respectively. The first peak is the initial overshoot, and the second (positive) and the third (negative) peaks show the response of simulated beam-on (heating) and beam-off (cooling) event, respectively. (Reproduction and minor modification of ref. [19])

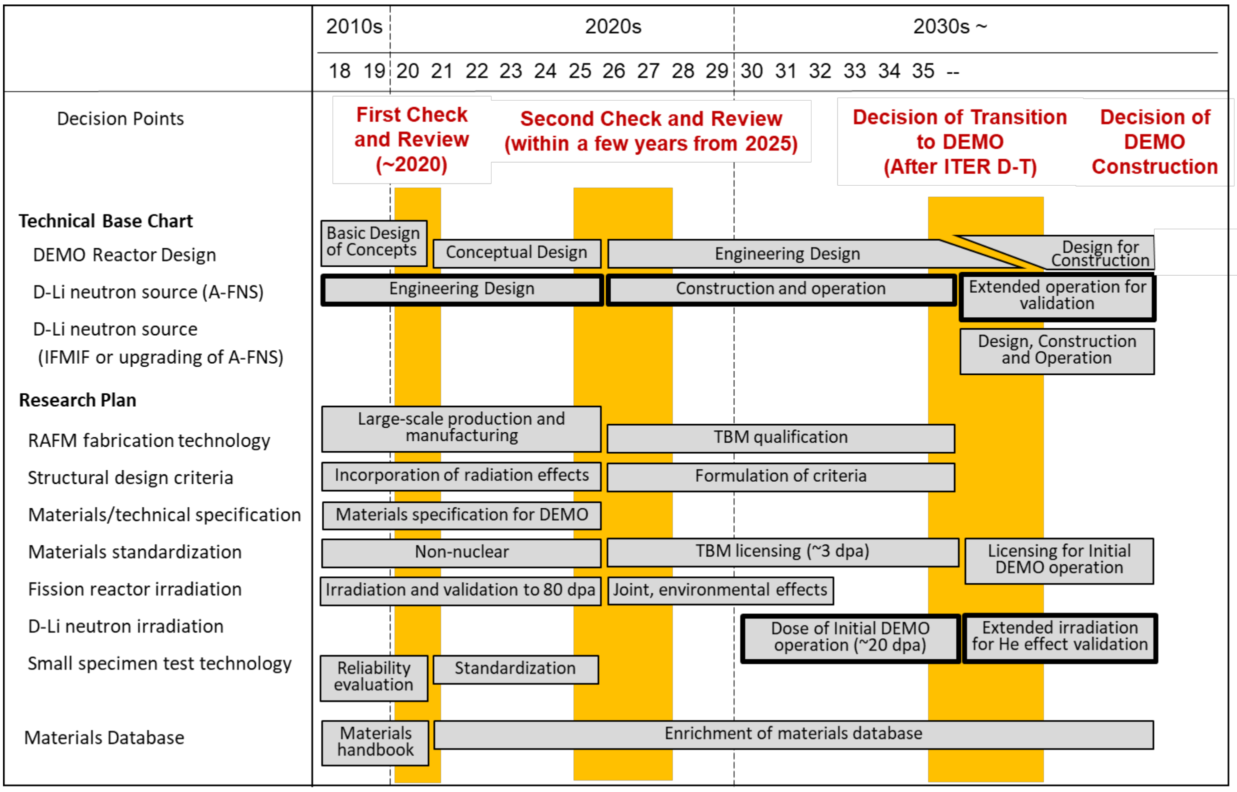

Fig. 6. The activity shown in the Japanese Action Plan for DEMO Reactor Design, Neutron Source, and Structural Materials. (Rearrangement of ref. [20])

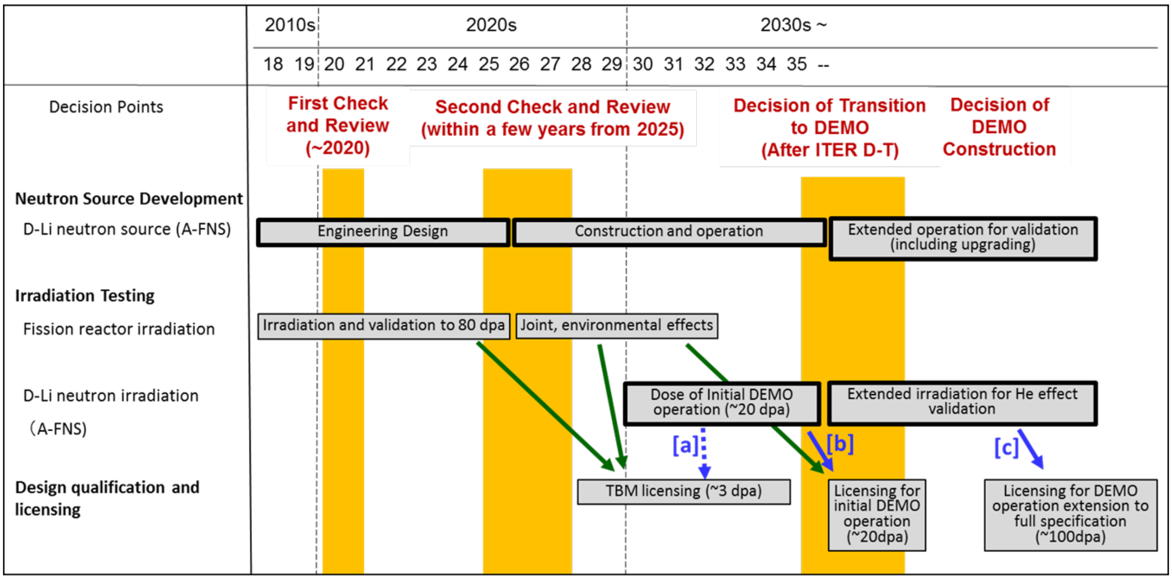

Fig. 7. The selected activity of Fig. 6 for correlating design, construction and operation of A-FNS, fission neutron irradiation, and design qualification and licensing. The contribution of A-FNS in early [a], middle [b], and long term [c] are shown. (Rearrangement of ref. [22])

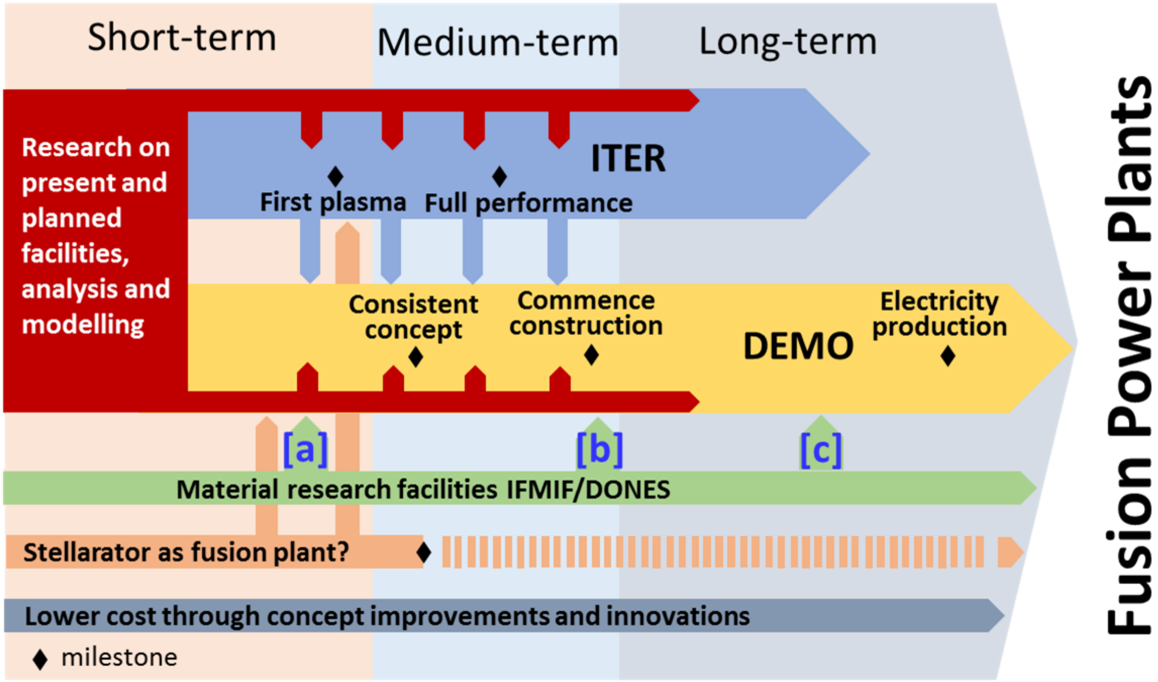

Fig. 8. EU roadmap toward DEMO, showing contribution of IFMIF-DONES in early [a], middle [b], and long term [c]. (Reproduction and minor modification of ref. [24].)

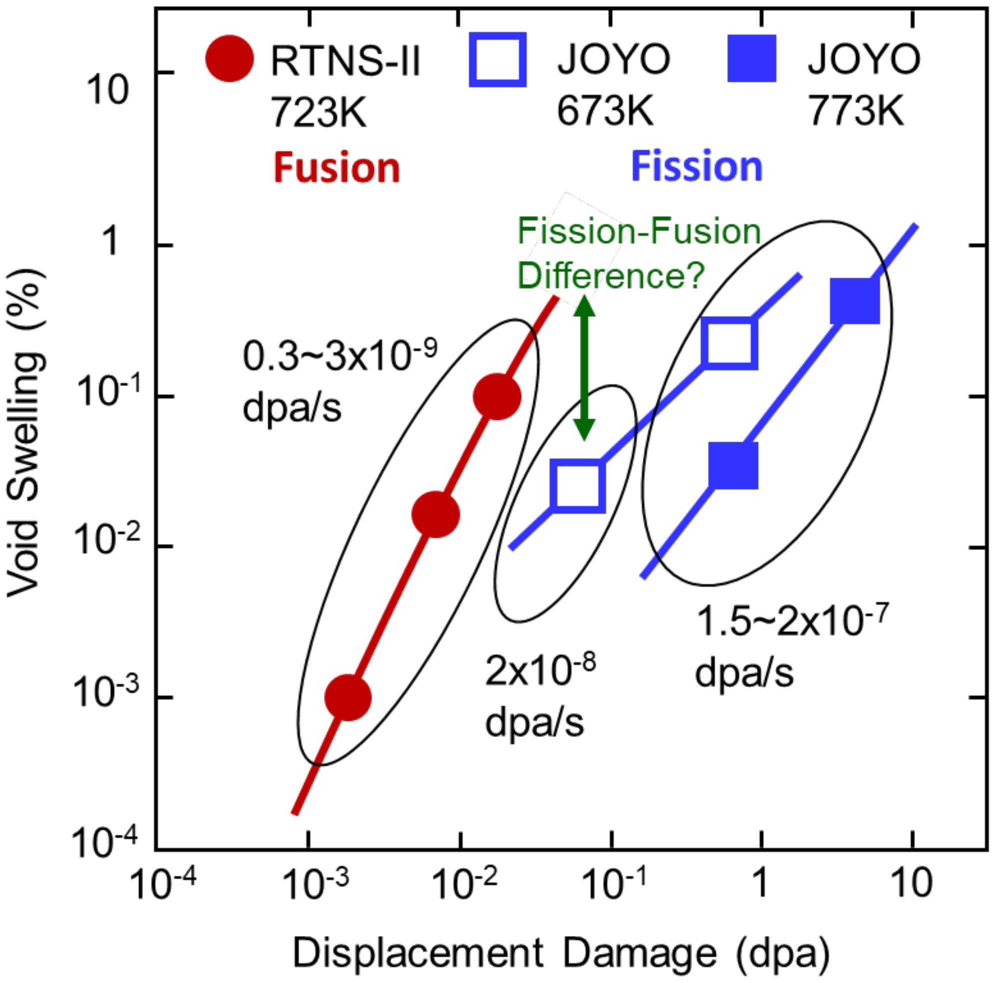

Fig. 9. Dose dependence of void swelling in Ni by D-T fusion neutron irradiation with RTNS-II and fission neutron irradiation by JOYO. Approximate damage rates (dpa/s) are shown for interpretation. (Reproduction and minor modification of ref. [30])