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FUSION RESEARCH AND DEVELOPMENT STRATEGY FOR JA DEMO INVESTIGATED IN QST

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Abstract

The paper reports on the recent activities towards JA DEMO at QST in accordance with the "Fusion Energy Innovation Strategy" formulated by the Cabinet Office, Government of Japan in April 2023 and revised in June 2025. In order to realize the strategy vision of commercialization of fusion energy, the revised strategy aims to demonstrate electricity generation in the 2030s and establish the fusion industry ecosystem. QST has been strengthening collaboration with a wide range of industries by establishing fusion technology innovation hub and involving members from industries in the Joint Special Design Team for Fusion DEMO. QST has started to investigate the acceleration scenario of the DEMO program where a phased approach strategy is adopted with ITER size toroidal magnetic field coils. Objective for each phase is defined as demonstration of electricity generation at least net-zero electric power in phase I, demonstration of tritium breeding in phase II and demonstration of steady-state operation with hundred MW level electric power in phase III. As the phase changes, enhancement of the plasma performance and improvement of the blanket are required. QST has also proposed enhancement of facilities and equipment necessary for full-scale DEMO R&D. Recently, Japan has joined the IFMIF-DONES Programme where the fusion neutron source facility DONES will be constructed at Granada, Spain for material development and QST has been designated as the implementing agency. QST will contribute to the construction of DONES based on the results of IFMIF/EVEDA project in BA activities and will obtain the neutron irradiation data up to 10 and 20 dpa for structural materials. For the construction of a DEMO reactor, safety regulation and standardization are important. QST is contributing to the discussion for establishing basic idea on ensuring the safety and standardization activities. QST is also promoting industrialization of fusion technologies through the QST ventures.

1. INTRODUCTION

The potential role of fusion energy has been globally emphasized from the perspective of the transition towards a Net-Zero Society. Research and development activities for realization of fusion energy is being accelerated both in public and private sectors. Considering recent situation regarding fusion energy, the "Fusion Energy Innovation Strategy" was formulated in the Cabinet Office as Japan's first national strategy for fusion energy in April 2023 [1]. The vision for the strategy was defined as commercialization of fusion energy seizing the winning market edge with technological superiority. For realizing this vision, development of the fusion industry is strongly addressed such as visualization of technologies necessary for realizing fusion energy, connections of companies and fostering the industry in addition to the development of fusion technology. In order to promote the strategy, it is required that establishment of framework for conducting R&D by bringing together, centering on National Institutes for Quantum Science and Technology (QST), academia and private companies, namely "fusion technology innovation hub".

The Cabinet Office revised this strategy in June 2025 towards achieving demonstration of electricity generation in the 2030s and establishing a fusion industry ecosystem [2]. For realizing the vision of commercialization of fusion energy, development of the fusion industry is strongly addressed such as collaboration with Japan Fusion Energy Council (J-Fusion) established in March 2024 and ensuring safety that is scientifically appropriate and internationally coordinated. The Cabinet Office established a task force for the discussion about definition of electricity generation demonstration leading to social implementation, evaluation of the Technology Readiness Level (TRL), features of implementing entity and methods for selecting the site. Development of fusion technology and framework for promotion are also addressed including human resource development and environmental development.

QST has been promoting the various activities in accordance with the strategy [3]. The paper reports on the recent activities towards JA DEMO at QST. In section 2, steps for realization of fusion energy in the Japanese fusion program is explained. In section 3, the QST activities for strengthening collaboration with industries are described. The investigation for the acceleration scenario of the DEMO program towards the demonstration of electricity generation in the 2030s and the related activities are presented in sections 4 and 5, respectively. Finally, future prospect is described in section 6.

2. STEPS FOR REALIZATION OF FUSION ENERGY

The Japanese fusion program has three steps for realizing fusion energy, i.e. establishment of physics/engineering basis, fusion energy production and electricity generation as shown in Fig. 1. Current step is fusion energy production. QST is contributing to the ITER project [4] and promoting the Broader Approach (BA) activities in EU-Japan collaboration. There are three projects in the BA activities, these are Satellite Tokamak Programme project JT-60SA [5], IFERC project [6] and IFMIF/EVEDA project [7]. JT-60SA first plasma was achieved in 2023 and the machine enhancement work is now being progressed towards next plasma experiment campaign with heating capability. The IFERC project has three subprojects. These are DEMO design/R&D, Computational Simulation Centre (CSC) and ITER Remote Experimental Centre (REC). In the IFMIF/EVEDA project, Linear IFMIF prototype accelerator is being developed. QST aims at early transition to the next step of electricity generation by integrating the ITER project, the BA activities and the domestic activities. In the next step, construction of JA DEMO is planned, where electric power of >100 MW will be generated. Fusion science and technology committee in MEXT required the three objectives for JA DEMO. These are electric power of several 100 MW, availability sufficient for commercialization and self-sufficiency of fuel. For the construction of JA DEMO, QST thinks that fusion neutron source for material development and full-scale R&D facilities are necessary.

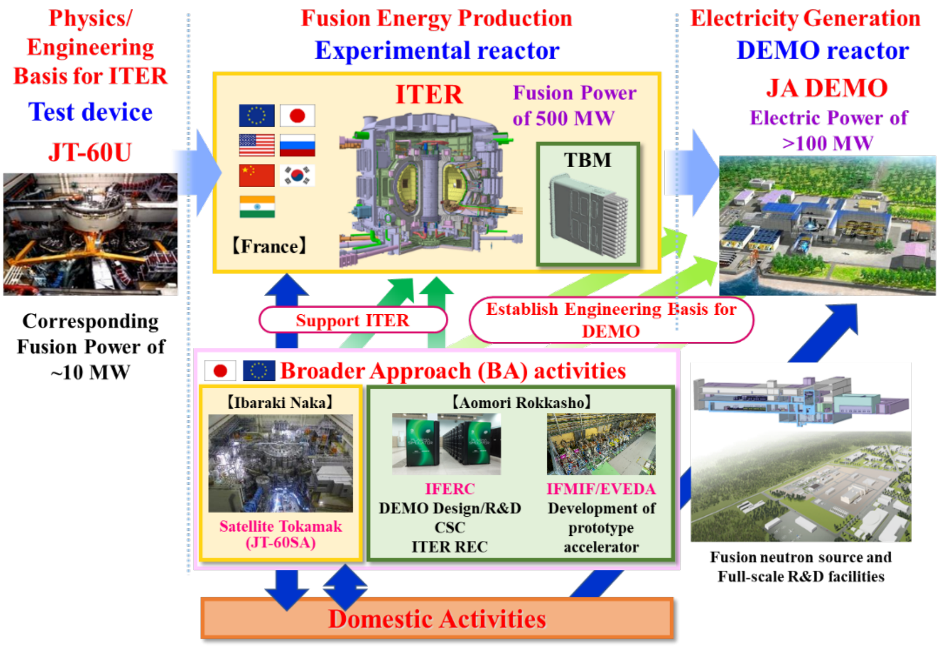

Fig. 1. Three steps for realization of fusion energy.

3. STRENGTHEN OF COLLABORATION WITH INDUSTRIES

3.1. Fusion technology innovation hub

Based on the strategy, QST established "fusion technology innovation hub" where promotion of industrialization and acceleration of DEMO reactor development are centrally implemented in collaboration with private companies and academia as shown in Fig. 2. For industrialization, open innovation for fostering fusion industries is promoted based on joint research, use of facilities and equipment (open flatform), intellectual property strategy etc. Regarding acceleration of DEMO reactor development, fostering young leaders who can lead international research activities on ITER/JT-60SA and plant integration are addressed. Also, in addition to strengthening the basic infrastructure, transfer of technologies, development of new technologies and industrialization, construction of new facilities are aimed in both Rokkasho and Naka institutes. In this framework, QST assigned a technical coordinator and contracted for use of the facilities with private companies through the coordinator.

3.2. Joint Special Design Team for Fusion DEMO

The conceptual design of JA DEMO has been developed based on ITER technologies and industry experiences in the Joint Special Design Team for Fusion DEMO launched from 2015 in the framework of industry-academia collaboration at Rokkasho Institute for Fusion Energy. Recently, the number of members from industry increased to 102 reflecting the formulation of the strategy and the total number reached 219 (67 from universities/institutes and 50 from QST). Figure 3 shows the trend in the number of members. A wide range of industries including not only manufacturing companies and plant companies, but also general conductor companies, infrastructure companies, trading companies and start-up companies join the team.

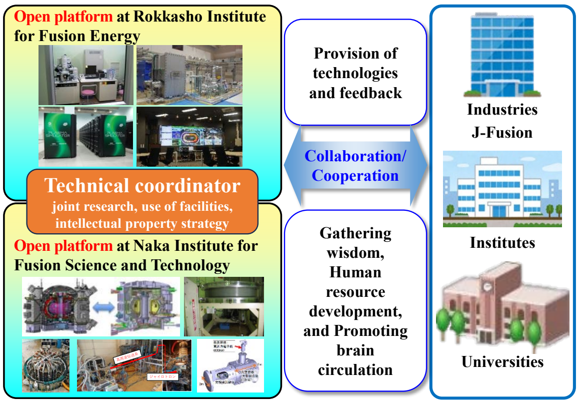

Fig. 2. Fusion technology innovation hub.

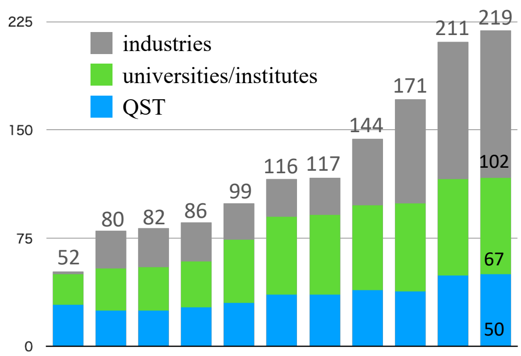

Fig. 3. Trend in number of design team members. Gray, green and blue show the number of members from industries, universities/institutes and QST, respectively.

4. INVESTIGATION FOR ACCELERATION SCENARIO OF DEMO PROGRAM

In order to satisfy the conditions required by fusion science and technology committee in MEXT, original JA DEMO design adopted a major radius of 8.5 m which is 1.4 times larger than ITER, and fusion power of 1.5 GW in steady-state operation. The plasma parameters were set to be normalized beta (β_N) of 3.4, Greenwald density fraction (n_e/n_{GW}) of 1.2 and confinement improvement factor (HH_{98y2}) of 1.3. The cooling water condition in the Pressurized Water Reactor (PWR) was also adopted based on many industry experiences. Gross electric power of 640 MW and net electric power of 250 MW extracting on-site electric power were estimated [8].

Towards achieving the demonstration of electricity generation in the 2030s having a scientifically and technically significance for leading to social implantation as stated in the strategy, QST has started to investigate the acceleration scenario of the DEMO program. By discussing with industries considering the experience of the ITER Toroidal magnetic Field Coil (TFC) manufacturing, QST concluded that the manufacturing of original JA DEMO TFC, which is much larger than the ITER TFC as shown in Fig. 4 (a), needs much time and cost [9]. Therefore, QST newly adopted the TFC that is same size as the ITER TFC. In the case with the ITER size TFC, when the breeding blanket and shielding those are the same thicknesses as those of the original JA DEMO will be installed, plasma volume would be smaller than in ITER where only the shielding blanket will be installed. Figure 4 (b) and (c) show the cross section of ITER and JA DEMO in the case with the ITER size TFC, respectively. Here, the yellow space in Fig. 4 (b) shows the thickness of the shielding blanket ($t_{S\text{-}BLK}$) of 0.45 m in ITER. The yellow and blue spaces in Fig. 4 (c) show the thickness of the breeding blanket ($t_{B\text{-}BLK}$) of 0.5 m and the shielding (t_S) of 0.6 m, respectively, which are the same size as those in the original JA DEMO. The plasma volume is much smaller in Fig, 4 (c) than in Fig. 4 (b). Gross electric power strongly depends on the plasma volume and the plasma performance. The smaller plasma volume will lead to the reduction of fusion output with the same plasma performance. In order to mitigate the risk, QST adopted phased approach as shown in Table 1. Objective of each phase is defined as demonstration of electricity generation at least net-zero electric power in phase I, demonstration of tritium breeding in phase II and demonstration of steady-state operation with hundred MW level electric power in phase III, respectively.

Table 1 shows specifications for each phase currently investigated. Electricity generation will be demonstrated at least net-zero electric power in Phase I with the ITER baseline scenario plasma and the electricity generation and shielding blanket with $t_{E\&S\text{-}BLK}$ of 0.45 m that is the same size as the ITER shielding blanket to secure the large plasma volume. In phase II, tritium breeding will be demonstrated with the original JA DEMO baseline scenario plasma of β_N=3.4 and HH_{98y2}=1.4 and with the original JA DEMO breeding blanket ($t_{B\text{-}BLK}$=0.5 m) and thin shielding (t_s=0.35 m) as shown in Fig. 4 (d). In phase III, steady-state operation will be demonstrated with hundred MW level electric power using high β and high confinement plasma to be developed in JT-60SA operation and with the same blanket and shielding size as those in phase II. As phase changes, enhanced plasma performance and improved blanket/shielding are required. The reduction of the shielding performance would be trade-off with lifetime of the TFC. In phase III, high efficiency heating and current drive is also required for reduction of on-site electric power. For a staged approach strategy, the integration of manufacturing and engineering technology as well as plasma physics to be developed in ITER and JT-60SA will be the key. Further optimization of the specifications should be investigated consierting the entier system including remote maintenance senario in future work. The schematic drawing of the original JA DEMO and the ITER size JA DEMO is shown in Fig. 5.

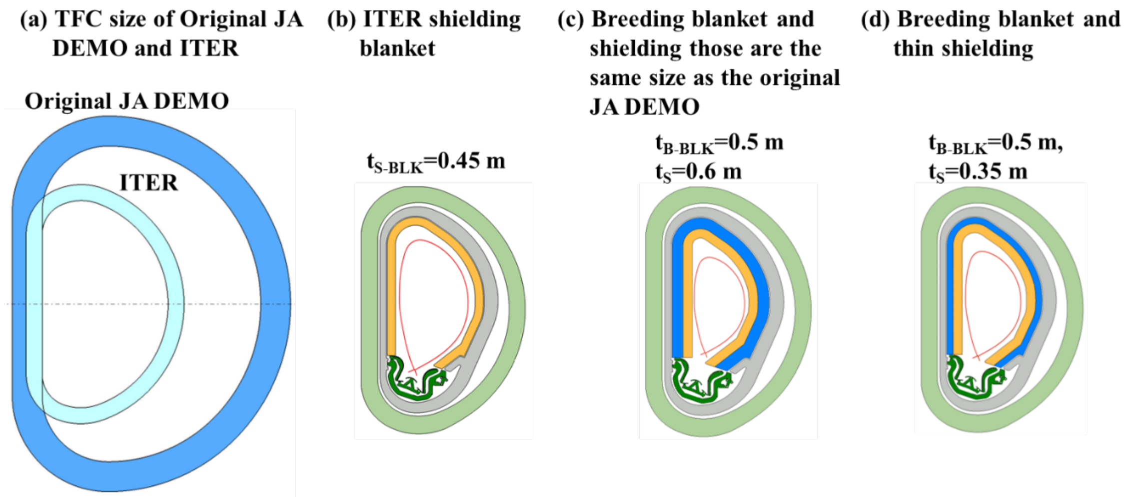

Fig. 4. TFC size and blanket/shielding thicknesses. (a) Blue and light blue show TFC size of original JA DEMO and ITER, respectively. (b) Cross section of ITER where yellow space shows thickness of shielding blanket ($t_{S\text{-}BLK}$=0.45 m). (c) Yellow and blue show thicknesses of breeding blanket ($t_{B\text{-}BLK}$=0.5 m) and shielding (t_S=0.6 m) those are the same size as in original JA DEMO, respectively. (d) Yellow and blue show thicknesses of breeding blanket ($t_{B\text{-}BLK}$=0.5 m) that is the same size as in original JA DEMO and thin shielding (t_S=0.35 m), respectively.

Table 1. Phased approach strategy for acceleration scenario of JA DEMO program

	Phase I Demonstration of electricity generation	Phase II Demonstration of tritium breeding	Phase III Demonstration of steady-state operation
Obj.	・Short pulse (several min.) ・P_{gross} > ~180 MW ・P_{net} ~ 0	・Long pulse (several hours) ・P_{net} ~0 ・Self-sufficiency of fuel	・Steady-state operation ・P_{net} > 0 (~100MW) ・Self-sufficiency of fuel
Spec.	・ITER baseline scenario ✓ Fusion output: 500 MW ✓ Q value: 10 ✓ Pulse length: ~400 s ・Electricity generation and shielding blanket ✓ Same size as ITER shielding blanket ($t_{E\&S\text{-}BLK}$=0.45 m)	・Original JA DEMO baseline scenario ✓ Fusion output: >500 MW ✓ Q value: 10 ✓ High β_N: 3.4 ✓ High HH_{98y2}:1.41 ・Tritium breeding blanket ✓ Original JA DEMO breeding blanket ($t_{B\text{-}BLK}$=0.5 m) ✓ Thin shielding (t_S=0.35 m)	・JT-60SA scenario (High β & High confinement) ✓ Fusion output ~1 GW ✓ High efficiency heating and current drive ・Tritium breeding blanket ✓ Original JA DEMO breeding blanket ($t_{B\text{-}BLK}$=0.5 m) ✓ Thin shielding (t_S=0.35 m)

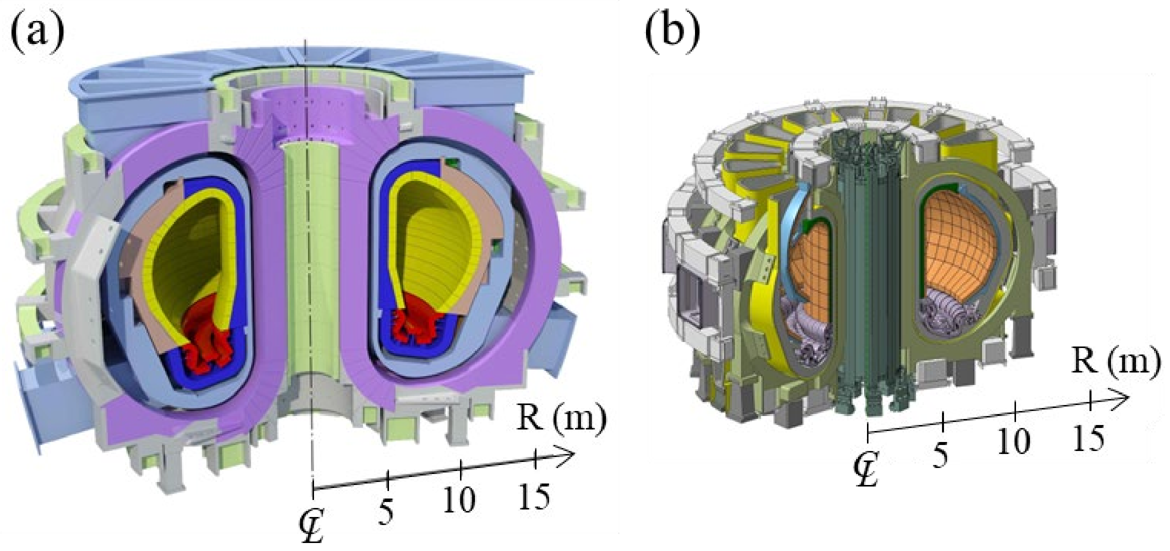

Fig. 5. Schematic drawing of (a) original JA DEMO and (b) ITER size JA DEMO.

5. RELATED ACTIVITIES TOWARDS JA DEMO

5.1. Enhancement of facilities

In order to utilize key technologies acquired through the ITER project and the BA activities for the acceleration of the DEMO program, QST has proposed to enhance facilities and equipment in Rokkasho and Naka Institutes as shown in Fig. 6 such as fuel cycle safety test facility, blanket development facility, neutron source facility, superconducting magnet facility, plasma heating test facility. These facilities can be opened for use by industries and academia as platform and contribute to establishment of the industry ecosystem. We have already started detailed design of new facilities for fuel cycle safety test.

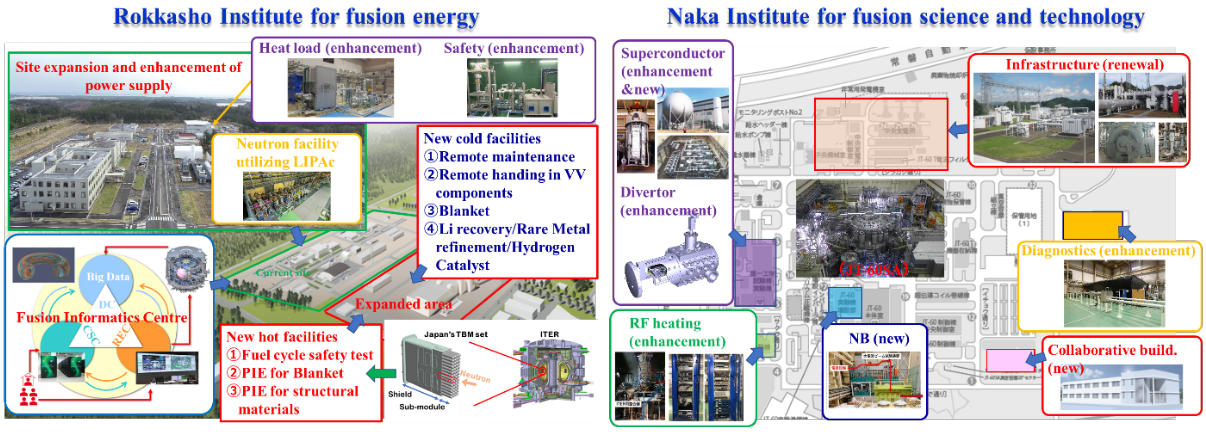

Fig. 6. Proposed enhancement of facilities and equipment.

In order to develop JA DEMO, it is necessary to investigate in advance the effects of neutrons irradiation on functional materials. A large flux neutron source that can produce neutrons with similar energy as DT fusion reaction is required. In the BA activities of the IFMIF/EVEDA project, the development of a neutron source that combines an accelerator and a liquid lithium loop is being advanced through cooperation between EU and Japan. The testing of the prototype accelerator is being carried out at Rokkasho institute. Recently, Japan has joined the IFMIF-DONES Programme [8] which will construct the neutron source based on the IFMIF/EVEDA project at Granada, Spain. QST has been designated as the implementing agency. QST will contribute to the construction of DONES based on the results of IFMIF/EVEDA project in the BA activities and will obtain the neutron irradiation data up to 10 and 20 dpa for structural materials.

5.2. Ensuring safety

For the construction of JA DEMO, safety regulation is important. QST contributed to publishing the initial recommendations from Agile Nations working group on fusion energy regulation [11]. QST provided technical advice as an expert and analyses results for accident events such as an Ex-Vacuum Vessel Loss Of Coolant Accident (Ex-VV LOCA) [12]. The Working group recommended the development of a regulatory framework for fusion energy that maintains appropriate protections for people and the environment, proportionate to the hazards of fusion energy while remaining transparent and pro-innovation. QST also led the discussion of ideas on ensuring safety with academic societies such as the Atomic Energy Society of Japan. Progress of the discussion was informed to the task force established to formulate basic ideas on ensuring safety for fusion energy in the Cabinet Office.

QST also contributed to the task force for formulating basic ideas on ensuring safety for fusion energy [12]. The safety principles were defined as prevention of radiation hazards for the public and workers as well as evaluation and management of radiation risks to the environment. For a scientific and reasonable approach, application of agile regulations that can respond to new findings and technological advancements in addition to the graded approach (regulation according to the magnitude of specific risks) were mentioned. The task force reported as issues to be considered in future that it is appropriate to regulate fusion devices as subjects of the RadioIsotope (RI) Law within the scope of the risks currently anticipated as a regal framework. The task force also reported that platforms for the government and business operators to continuously share information and engage in dialogue should be established. Based on this idea, Nuclear Regulation Authority (NRA) accepted to start the dialogue with business operators such as QST and fusion start-ups.

5.3. Standardization

For the construction of JA DEMO, standardization is also important. QST has also started the activities for standardization and globalization in the fusion energy system using the BRIDGE Program promoted by the Cabinet Office in collaboration with industries and academic societies such as the Japan Society of Mechanical Engineers (JSME) and the Japan Society of Maintenology. The BRIDGE program is to begin first three-year ramp-up for the purpose of promotion of standardization and globalization, development of young human resources, and development of R&D facilities environment required for standardization and globalization as shown in Fig. 7. JSME and the American Society of Mechanical Engineers (ASME) collaboration is being organized for standardization and globalization.

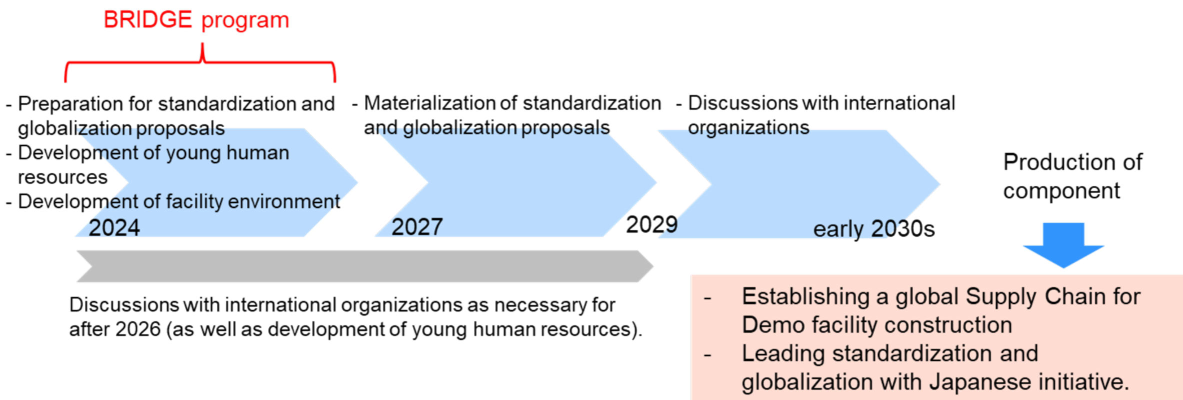

Fig. 7. Timeline of BRIDGE program for standardization and globalization in the fusion energy system.

5.4. Industrialization

Some of the fusion technologies developed in QST have been already attempted to be industrialized. Start-up companies MiRESSO and LiSTie have been established in 2023 as a QST venture based on the refining technology of beryllium using the low energy consumption process with alkali and RF power and the recovery technology of lithium using ionic conductors, respectively. These technologies are developed for securing resources for blanket functional materials. QST supports these start-up companies by secondments to the companies, collaborative research, preferential use of facilities and priority licensing of intellectual properties. QST is investing in LiSTie by acquiring shares as compensation for the licensing of the intellectual properties.

QST is aiming for a fusion technology spin-off through these start-up companies and feedback of these technologies matured in the market to the DEMO project.

6. FUTURE PROSPECT

The task force towards promoting social implementation will discuss the definition of electricity generation demonstration leading to social implementation and carry out hearing from QST and fusion start-ups. The Cabinet Office and MEXT (and related ministries) will objectively and cross-sectionally evaluate TRL of the DEMO reactor project and/or the electricity generation project proposed by start-ups considering the progress of the ITER project and the challenging goals set by various countries. A roadmap will be developed based on back-casting from the electricity generation demonstration leading to social implementation in the 2030s. The NRA will have a meeting for opinion exchange with business operators promoting R&D for fusion devices. As information gathering for future considerations, the NRA will carry out hearing from start-ups about the development status, safety assurance concepts, future outlook etc. QST will proceed with the conceptual design of the ITER size JA DEMO considering the status of the discussion described above.

QST envisions contributing to a future society considering the realization of our basic philosophy "Creation of Harmonious Diversity" through construction of JA DEMO and establishment of new industries utilizing related fusion technologies as shown in Fig. 8.

Fig. 8. Fusion Industry and Future Society.

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