[Moonshot Goal 10]

“Realization of a dynamic society in harmony with the global environment and free from resource constraints, through diverse applications of fusion energy, by 2050”
Research and Development Concept

February 2024
Ministry of Education, Culture, Sports, Science and Technology

1. Moonshot Goal

The Ministry of Education, Culture, Sports, Science and Technology, with the Japan Science and Technology Agency (JST) as its national research and development (R&D) agency, is working on R&D in order to achieve the following moonshot goals (decided by the Council for Science, Technology and Innovation on December 26, 2023).

<Moonshot Goal>
“Realization of a dynamic society in harmony with the global environment and free from resource constraints, through diverse applications of fusion energy, by 2050”

<Targets>

- By 2050, to achieve a social system in which fusion energy is put to use in various situations.
- By 2035, to demonstrate the use of fusion energy as a variety of energy sources, not just electric energy.
- By 2035, to demonstrate the application of fusion energy through not only its use as an energy source but also other uses such as the use of particles produced by fusion reactions or multifaceted uses of elemental technologies.

Figure 1. Moonshot goal (fusion energy)

2. Direction of research and development

Based on the final report of the “Study Group on Support for Challenging Nuclear Fusion Research” (October 2023) and the discussions at the “Moonshot Goal 10: International Workshop on Fusion Energy” (held on January 31, 2024) the current direction of R&D is as follows.

(1) Fields and areas in which challenging R&D should be promoted

Based on the Fusion Energy Innovation Strategy (Integrated Innovation Strategy Promotion Council, April 14, 2023), it is important to “strengthen original emerging technology support measures such as potentially game-changing miniaturization and high-performance technologies”, and in order to expand the range of fusion technology, as well as a stage-by-stage forecasting approach from the experimental reactor ITER, which is currently under construction, to a DEMO reactor and then to a commercial reactor, it is necessary to strengthen support for challenging research through a backcasting approach from a future society realized by fusion energy.

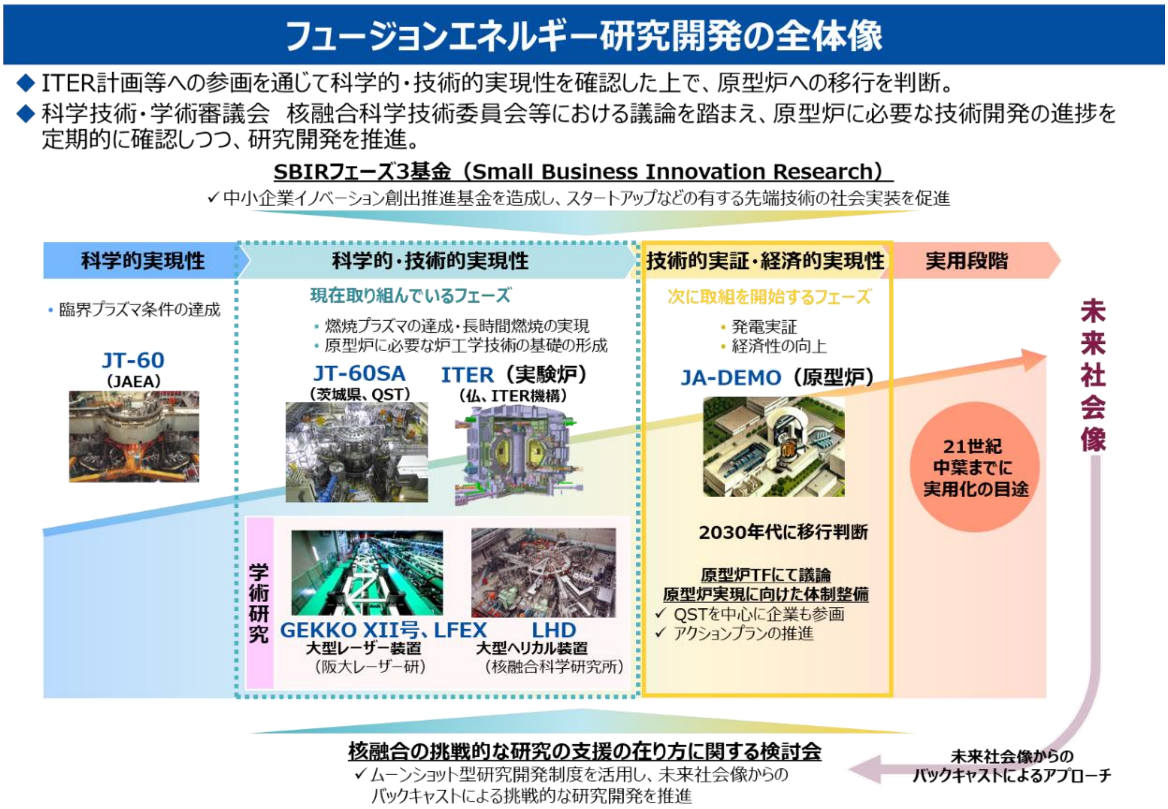

Figure 2. Overall picture of fusion energy research and development

Around the world, the number of startups that are leading private companies in challenging research has rapidly increased to 43, with a cumulative investment of over $6 billion, and two out of three companies expect to make their first electricity transmission in 2035 or even earlier.[1] As well as typical confinement methods (tokamak, helical, and laser), efforts are being promoted on three fronts: innovative confinement methods, innovative elemental technologies, and innovative social implementation. Startups around the world are taking a backcasting approach from market needs other than power generation applications, such as space and marine propulsion systems, off-grid production, hydrogen production, and industrial heat supply, in an effort to pursue miniaturization and sophistication through the use of advanced materials, innovative computing, advanced manufacturing techniques, and industrial components.

[1] The global fusion industry in 2023, Fusion Industry Association

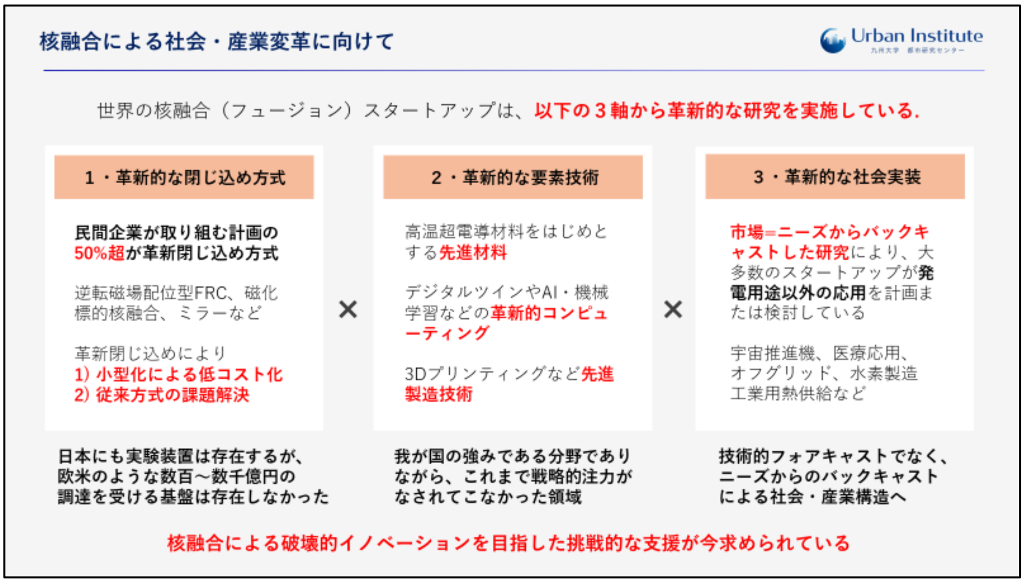

Figure 3. Three fronts: innovative confinement methods, innovative elemental technologies, and innovative social implementation

Even with ITER and the tokamak type, which is the confinement system for the DEMO reactor that is expected to start operating in around 2050, it is essential to work on improving economic efficiency through miniaturization, a high utilization rate, and simplification in order to ensure it becomes a commercial reactor. Specific development elements include, for example, miniaturization by increasing the magnetic field of superconducting coils and improving core plasma performance and controllability; a high utilization rate by increasing the lifespan of the breeding blankets and reducing the time required for remote maintenance; and simplification by simplifying heating systems, fuel systems, etc.

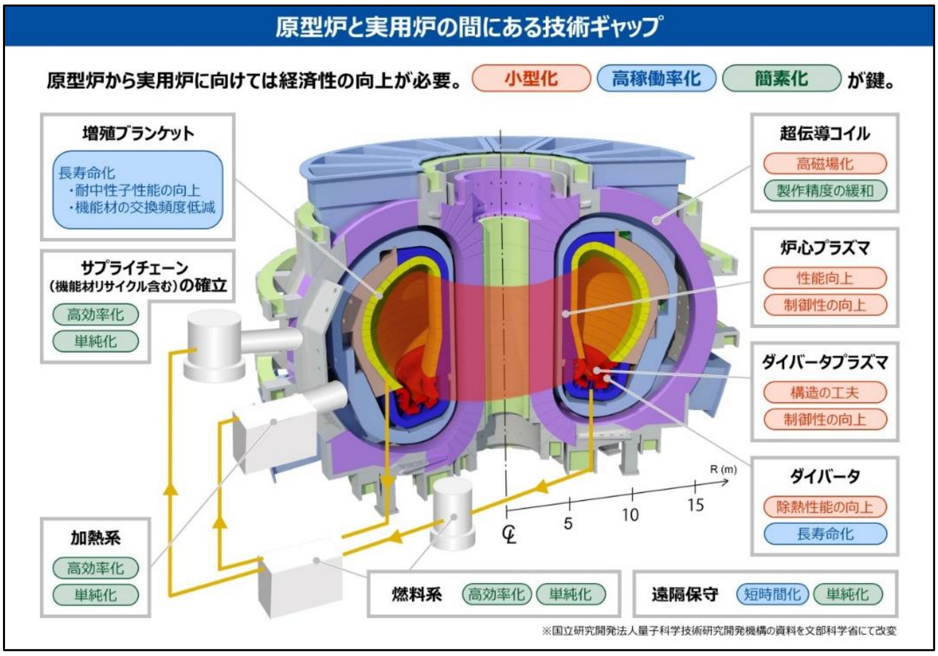

Figure 4. Technology gap between the DEMO reactor and commercial reactor

In Japan, there are multiple devices in operation that use not only typical confinement methods but also innovative confinement methods, ensuring a certain degree of diversity. In addition, although innovative elemental technology is an area of strength for Japan, it is also an area in which Japan has no focused strategy.

We consider these fields and areas of challenging R&D to require promotion, and in order to realize innovative social implementation, we will integrate ideas that are not bound by existing frameworks together with innovative elemental technologies into one system.

(2) Research issues in achieving the goal

The program director (PD) will build a portfolio to achieve the goal while looking at the overall picture of R&D such as the ITER project towards realization of fusion energy. In doing so, we will proactively promote challenging R&D based on Japan's basic research capabilities and the research infrastructure we have developed so far, while allowing for failure.

The envisioned image of the R&D structure is to publicly recruit project managers (PMs) in accordance with the innovative social implementation of Layer 1, and to build a R&D structure that brings together the wisdom of diverse researchers from Japan and abroad under a clear vision and scenario.

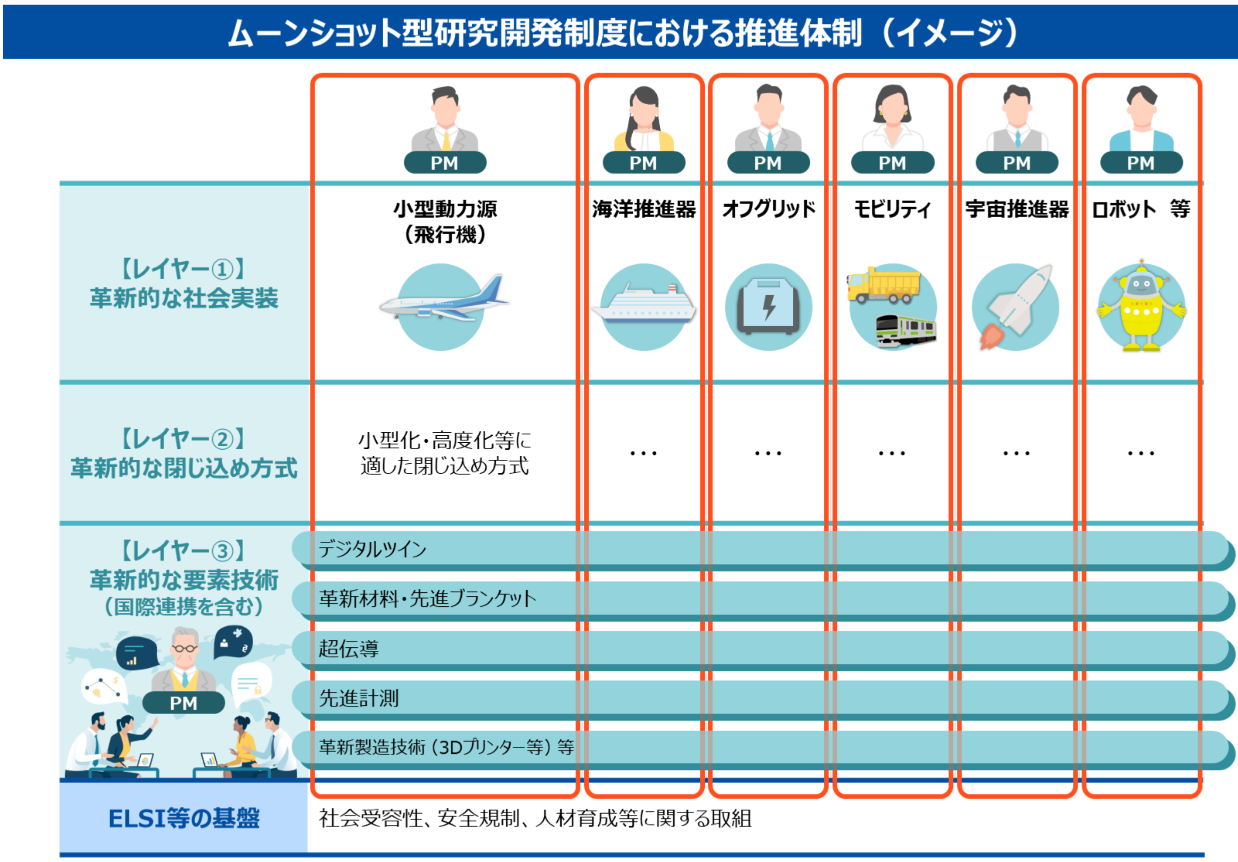

Figure 5. Image of the research and development structure

In addition, of the innovative elemental technologies in Layer 3, we will separately recruit PMs for the common elemental technologies necessary for social implementation and aim to improve the usability of fusion energy by promoting it in an integrated manner through approaches such as higher efficiency, higher functionality, lower costs, and higher intelligence.

When selecting R&D projects, we base the selection on objectivity that allows for clear conclusions to be drawn despite the project constituting a bold challenge, high international academic standards, the validity of methodology, and novelty and innovation that takes into account research trends in other countries. Since it is difficult for institutions only in Japan to carry out all technological development alone, we recommend that proactive efforts be made through international collaboration within the framework of the moonshot R&D structure, while also maintaining technological superiority. In addition, in order to improve the foundations of ELSI (Ethical, Legal, and Social Issues), etc., we recommend initiatives relating to social acceptability, research on social science such as safety regulations, and initiatives relating to human resource development be carried out.

(3) Direction of research and development towards achieving the goal
① Goal to be achieved (milestone)
[2050]
<Milestone>
• Realization of innovative fusion energy systems (systems that integrate confinement methods and elemental technologies based on innovative ideas) that enable innovative social implementation of compact power sources, etc.

<Research and development towards achieving milestones>
• Development of key technologies for implementation in innovative fusion energy systems.
• R&D contributing to resource acquisition and cost reduction enabling mass production of fusion reactors.

<Examples of a ripple effect>
• Application of plant technology to heat sources other than fusion reactors.

[2035]
<Milestone>
• Demonstration of the principle of an innovative fusion energy system for early realization of fusion energy
• Demonstration of uses for diverse social implementation of fusion energy (demonstration of the principle of technologies that are able to foresee new developments such as portable devices and space/marine propulsion systems)
• Multifaceted application of basic innovative technologies that enable challenges and simultaneous construction of an industrial infrastructure

<Research and development towards achieving milestones>
• Strategically build a portfolio and proactively and systematically promote R&D in order to achieve the goals.

<Examples of a ripple effect>
• Medical and environmental technologies that utilize particles generated by nuclear fusion reactions

- Application of high-temperature superconducting technology to superconducting motors, generators, etc. for aircraft propulsion
- Application of materials and structures of high heat removal equipment (divertors) to space and marine fields
- Application of manufacturing technology to aircraft manufacturing, etc.

② Goals to be achieved (schedule)

In terms of the schedule for achieving the goals, the PM will proceed with R&D of innovative elemental technologies, etc., with the aim of proof of concept in the first five years regarding visions and scenarios for innovative social implementation. If, as a result of the stage gate evaluation, it is determined that the project will continue beyond five years, support will be provided for up to 10 years, with the aim of proving the principle. In addition, in order to promote the social implementation of R&D results, private sector funds will be introduced for the latter five years, and it is expected that a R&D structure will be established in which universities, research institutes, and private companies, including startups, collaborate.

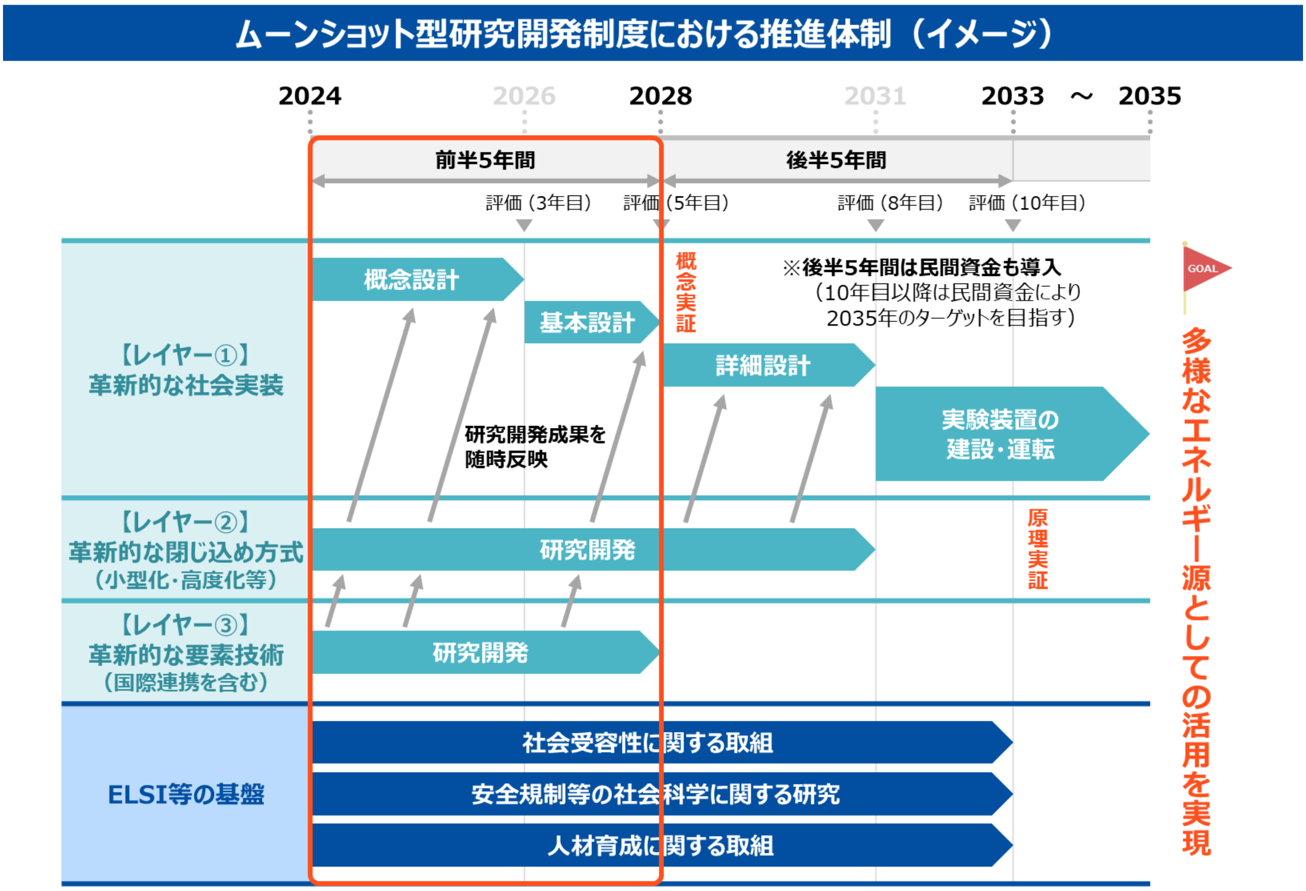

Figure 6. Image of the schedule for achieving goals

ムーンショット型研究開発制度との 協働がない 場合

ITER※／BA／原型炉から発電へと続く道の途中で困難が生じたときに、代替手段がないため、社会実装が遅れる。

ムーンショット型研究開発制度との 協働がある 場合

革新的な社会実装を目指す研究が先回りして成果を創出することで、ITER／BA／原型炉から発電へと続く道をより確実なものにすることが可能。

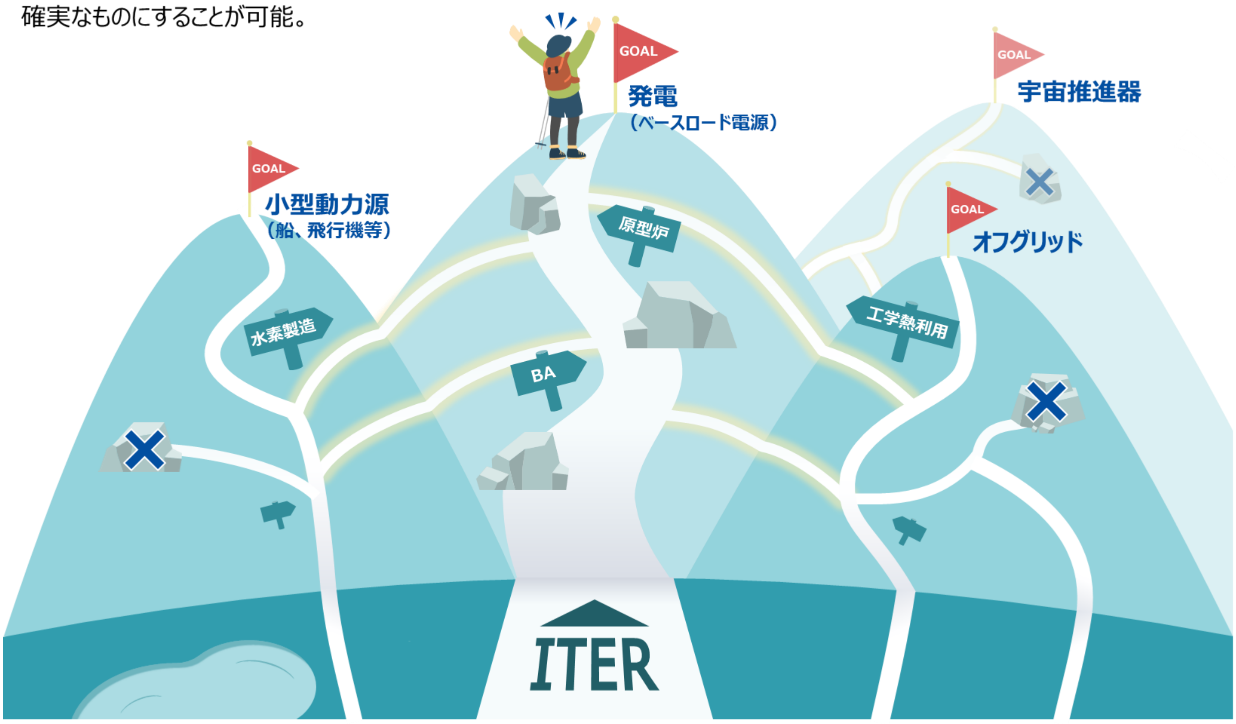

Figure 7. Collaboration with the moonshot R&D structure

<Reference: Analysis for goal achievement>

(1) Structure of fields and technology groups relating to the goals

Regarding the positioning of research in the field of nuclear fusion as a science and technology field, e-CSTI[2] analysis shows that the number of papers is not large compared to other fields, and keywords in the field of nuclear fusion (in the figure, magnetic field fusion, superconductivity, etc.) is closer to the engineering domain (green) within the physics domain (light blue), and has a close relationship to clusters containing quantum and materials as keywords.

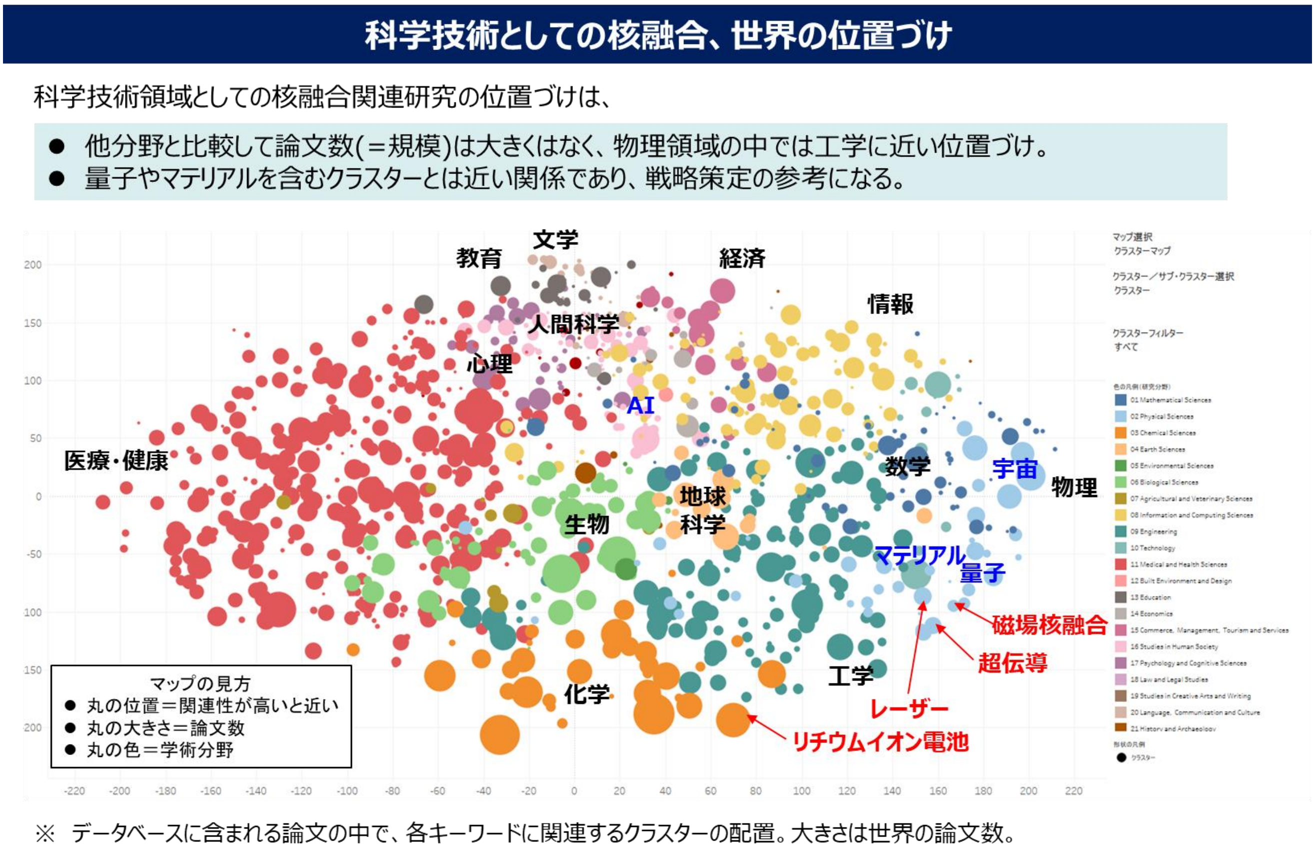

Figure 8. Positioning of research in the field of nuclear fusion

[2] System to collect data relating to science, technology and innovation and to provide data analysis functions based on objective evidence in order to promote the formulation of Japan's science and technology policy and the management of national university corporations, national R&D corporations, etc. Analyzed all papers from 2010 to 2019 in the bibliographic information database.

Creating fusion energy requires a group of diverse technologies, from strong magnetic fields to high voltage, from a vacuum to high pressure, etc., and the industry that forms the basis of this is wide-ranging, while it is also expected to have ripple effects in other fields. As an example of a technology map, the following shows the results of organizing the technologies that make up the diverse technology group required to generate fusion energy. The functions necessary for a fusion reactor are listed on the left side of the diagram, and the equipment and components necessary to realize them are listed in order on the right side. On the right side of the diagram, technologies and materials are described in more generalized terms to envision industrial expansion through spin-out to other fields.

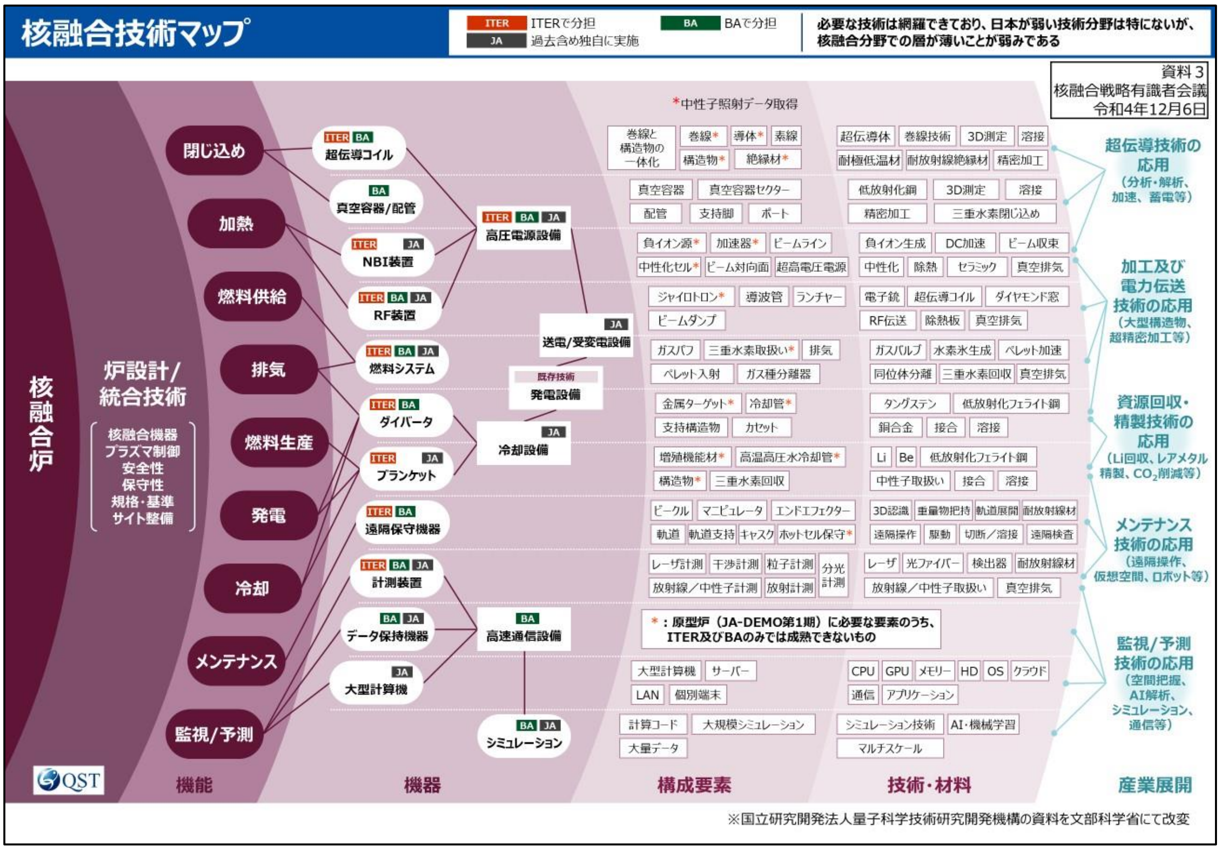

Figure 9. Technology map

(2) Domestic trends in related research and development

Japan is participating in the ITER project and has been working on the technological development of nuclear fusion equipment that is essential to achieve fusion energy, as well as conducting BA activities through international cooperation with Europe and complementing and supporting the ITER project in order to establish the technological foundation necessary for the DEMO reactor. JT-60SA, which is being handled as part of the BA activities, generated plasma for the first time on October 23, 2023, making it the world’s largest tokamak-type superconducting plasma device. In this way, the decision to transition to a DEMO reactor will be made after confirming scientific and technological feasibility through the ITER project and BA activities.

In terms of the Action Plan for DEMO reactor Development (Fusion Science and Technology Committee of the Ministry of Education, Culture, Sports, Science and Technology), the first check and review report were compiled as a follow-up in FY2021, and the items of the first interim check and review were evaluated to have been largely achieved. On the other hand, with regard to the development of a commercial reactor beyond the DEMO reactor, the challenge is to improve economic efficiency through miniaturization, a high utilization rate, and simplification.

In addition to the ITER project being carried out in seven countries around the world and the BA activities being carried out in Japan and Europe, we have also been implementing bilateral international cooperation under the Japan-U.S. Science and Technology Cooperation Agreement, the Japan-Korea Science and Technology Cooperation Agreement, and the Japan-China Science and Technology Cooperation Agreement. Furthermore, we have been carrying out international cooperation through the nuclear fusion experimental device JET with the United Kingdom and ASDEX with Germany.

(3) Japan’s strengths and overseas trends

In the ITER project, Japan will reflect the results of technical and academic integrated science and engineering research conducted in collaboration with industry, academia, and government, and will be in charge of producing the essential main equipment, as well as taking steps necessary for the development of the DEMO reactor through BA activities. Japan has technological superiority and reliability in the manufacturing industry accumulated through past R&D, as well as a basic research foundation and human resource development system to support these, making us a strong partner candidate for other countries.

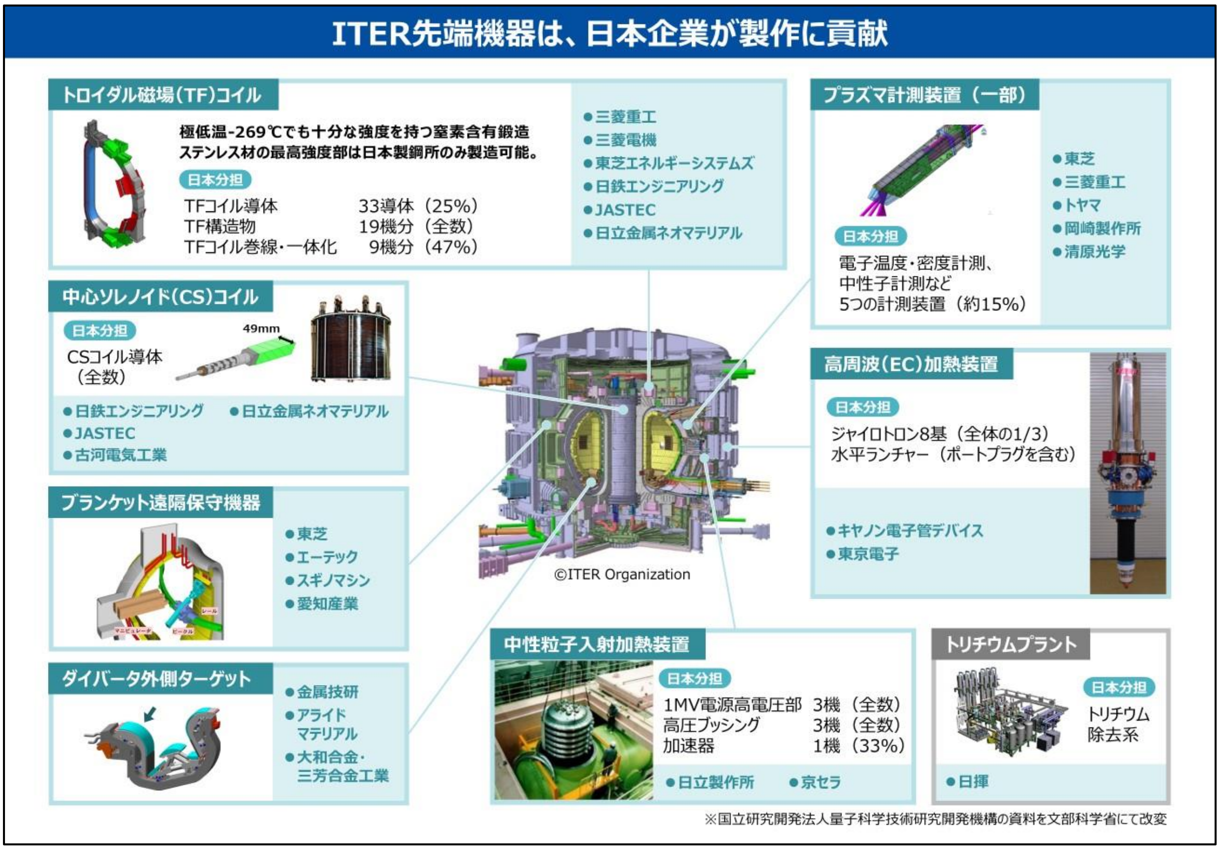

Figure 10. Examples of equipment procured in Japan in the ITER project

The results of a more detailed analysis of related clusters using e-CSTI are shown below. Japan has the top 10% of papers in all subclusters, and there is less bias compared to other countries. In particular, helical types have a large share in materials research. Furthermore, in terms of the country's share of all papers, comparatively, engineering fields such as tokamak design, heating equipment, and DEMO reactors have a relatively high share. A comparison of market share by country shows that countries and regions that have test equipment tend to have a high market share, and the operation of the JT-60SA will provide an advantageous research environment for Japan.

サブクラスター内での国別シェア（Top10%論文）

核融合関連サブクラスターの中での国別シェアは、

- 我が国は、全てのサブクラスタでTop10%論文を有しており、特に、ヘリカルを筆頭に材料研究、乱流シミュレーション、イオン源、FRCなどの研究でシェアがある。
- 試験装置に紐づいたシェアが見られる一方で、ドイツは全分野で一定のシェアを確保。

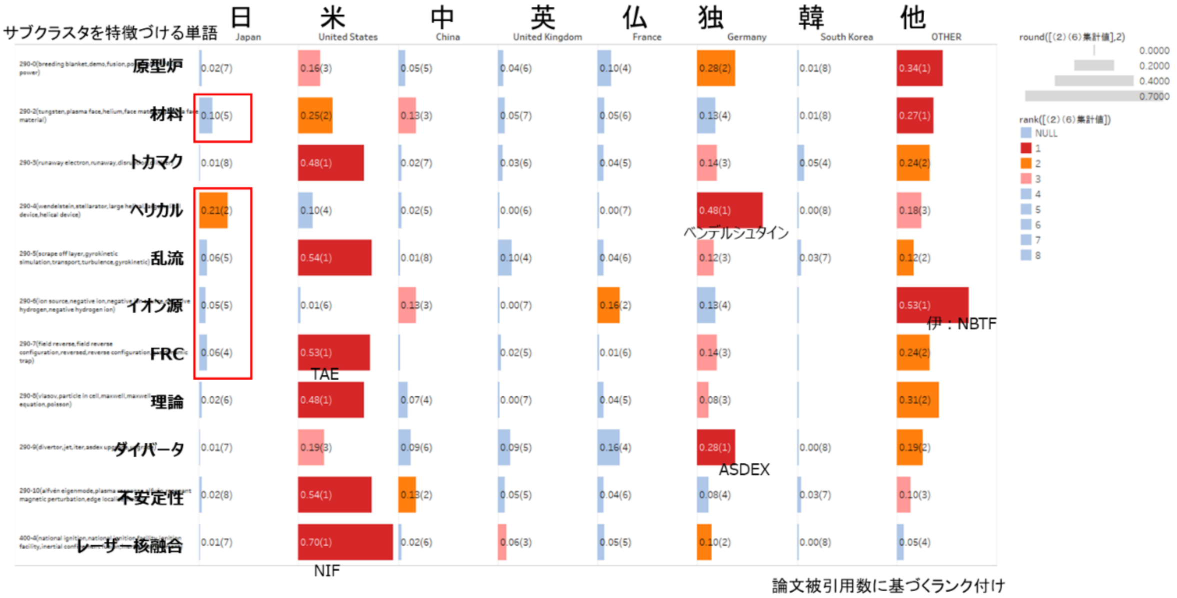

Figure 11. Share by country within fusion-related subclusters (Top 10% papers)

サブクラスター内での国別シェア（全論文）

- 全論文を対象にした場合、我が国では、トカマク設計、加熱装置（イオン源、電子加熱）、原型炉などの比較的工学的な分野で比較的高いシェアが見られる。

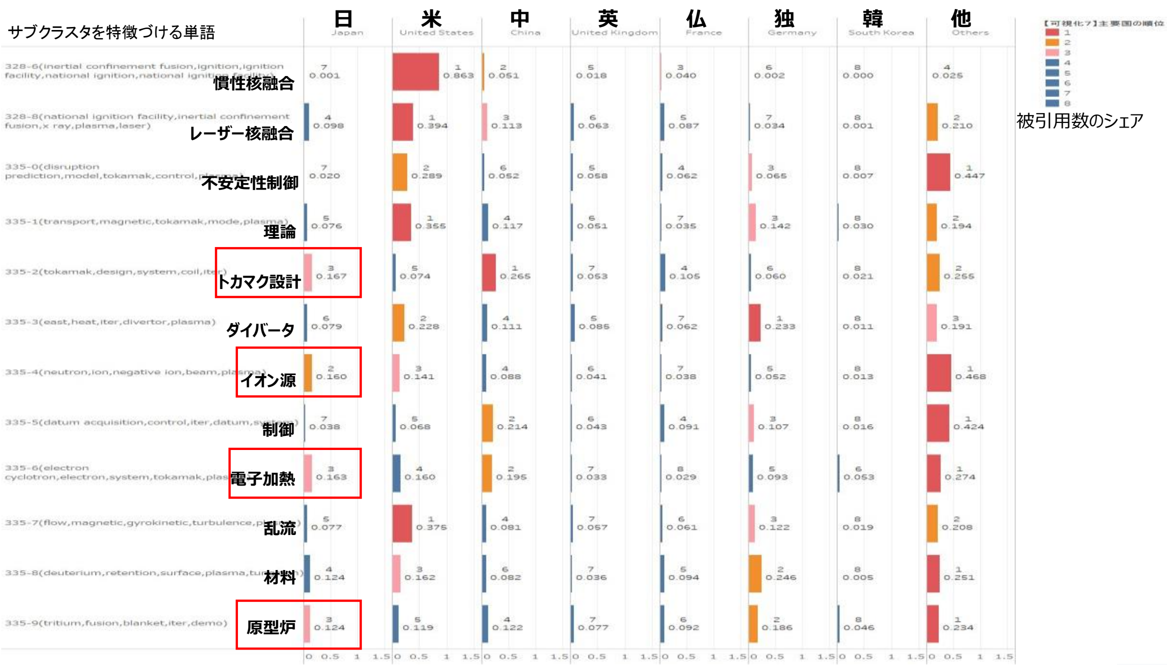

Figure 12. Country share within fusion-related subclusters (all papers)

In terms of the main R&D trends in the world, the United States has a high share in laser fusion and inertial fusion subclusters, and in December 2022, the Lawrence Livermore National Laboratory in the United States succeeded in generating output energy that exceeded input energy for the first time in history through a nuclear fusion reaction using actual fuel.

Amid the global movement towards carbon neutrality, scientific and technological advances are being made under government initiatives, and private investment is increasing in various countries. In response to this booming private investment, fusion startups in the United States, the United Kingdom, and other countries are accelerating their R&D competition, setting ambitious goals for generating power earlier than previous government plans. Furthermore, in China, the government is proactively promoting plans to construct experimental equipment and a DEMO reactor.

Figure 13. Various reactor types aiming to realize nuclear fusion reactions