IAEA
International Atomic Energy Agency

IAEA WORLD FUSION OUTLOOK 2023

Fusion Energy: Present and Future

1ST EDITION

IAEA
WORLD
FUSION
OUTLOOK
2023

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I am proud to introduce the first issue of the IAEA World Fusion Outlook, convinced that this publication will become the global reference for authoritative information and updates on a truly fascinating and promising, potentially unlimited, low carbon source of clean energy: fusion energy.

Scientific and technological advances combined with growing demand for clean energy to power economies, mitigate climate change and protect our planet, plus recent significant capital investment in the fusion industry sector, are stimulating international efforts towards achieving the first economically viable energy producing fusion power plant. Private companies have attracted billions of US dollars from venture capital companies, private equity and sovereign funds, and other corporate investors. As the challenges associated with fusion science and technology are formidable, increased private funding combined with State commitment is needed to drive fusion energy forward.

This year has witnessed several new government initiatives that include fusion in response to the climate change urgency, such as UK Industrial Fusion Solutions Ltd, the Fusion Industry Council of Japan, the European Commission's Net-Zero Industry Act, which includes promotion of fusion technology investments, and Germany's Fusion Research Position Paper, as well as the United States Department of Energy's Milestone-Based Fusion Development Program allocation of US $46 million to eight commercial fusion companies. ■

Fuelling the future of fusion

Some of the biggest remaining challenges facing fusion have to do with achieving the conditions for a fusion reaction to sustain itself in a hot, dense ionic gas or plasma, the same sort of reaction that powers the stars. The challenges include extremely high temperatures, exceeding 100 million degrees Celsius; long lasting confinement of the hot plasma inside the chamber core; a fusion machine first wall able to withstand the extreme conditions; closing the fuel cycle; and extracting and harnessing the enormous amount of energy produced. There have been three important advances in 2023 that help surmount these challenges. The first is China's EAST tokamak, which demonstrated a tokamak operation mode that improves energy confinement or long term plasma retention while avoiding accumulation of impurities. The second is the record breaking performance of the most advanced and recently upgraded stellarator W7-X in Germany, which achieved a long plasma discharge with high energy turnover, thus demonstrating the possibility of continuously coupling large amounts of energy in the plasma and removing heat in a controlled way. Finally, NIF in the United States of America achieved even greater scientific energy gain in July 2023 than announced last year. Advancements in a different fusion challenge brought a boost to regulatory certainty for the growing fusion industry with the announcement by the United States Nuclear Regulatory Commission that their national fusion regulatory framework will be different from existing nuclear fission power plant regulation. ■

The IAEA: a hub for fusion research & development

The IAEA has been promoting fusion energy research and development for over 60 years, and it continues to strongly support research and development and future deployment by bringing the fusion community together to create solutions for both scientific and technological challenges. In recent years, the IAEA has increased its fusion activities in a multidisciplinary effort. This includes addressing fusion energy facilities in a holistic manner, integrating best practices and lessons learned from successful fission energy generating plants into efforts to achieve fusion energy production, where applicable. Fusion science research and technology — including plasma and materials sciences, fundamental fusion process data, regulatory frameworks, licensing, nuclear safety, nuclear waste management, nuclear liability issues, and economic aspects of nuclear fusion facilities — span all the IAEA's technical Departments and organizational units. Fusion related programmatic activities in the IAEA are coordinated by its internal cross-cutting Nuclear Fusion Coordination Committee, established in 2019. The International Fusion Research Council and the IAEA's Standing Advisory Groups provide advice on a range of key activities the IAEA conducts to strengthen international cooperation on fusion research and technology development and to enhance the present state of the art. ■

Making fusion energy accessible to all

IAEA support to its Member States in accelerating fusion energy development is delivered using a broad portfolio of tools and processes. This includes providing various fusion related forums such as the biennial Fusion Energy Conference, DEMO

We gratefully acknowledge the following persons for their expert review of this report and constructive suggestions:

A. Becoulet Deputy Director General – Chief Scientist
ITER Organization
France

> “International collaboration is vital in achieving this grand engineering challenge of the 21st century.”
>
> **IAEA Director General**
> **Rafael Mariano Grossi**

Programme Workshops, and periodic consultative and technical meetings and workshops, where experts can exchange knowledge and experience. The IAEA also hosts the Fusion Portal and numerous databases and codes including the Fusion Device Information System; facilitates access to radiation and analytical services through partner organizations and facilities; manages coordinated research projects; delivers education and training activities; and fosters strategic partnerships, often through formal — typically bilateral — cooperation agreements, such as long-standing cooperation with the ITER Organization since its conception and more recently with organizations in the United States of America and China. Last year the IAEA was instrumental in forming Women in Fusion, a non-profit organization aimed at promoting gender parity in the fusion community and establishing a welcoming work environment for everyone. The progress made through these activities is published in IAEA technical documents and publications, in peer reviewed journals, on the Fusion Portal and via social media and outreach channels. ■

Meeting tomorrow’s energy demands

The IAEA is stepping up its support to Member States by accelerating the research and development of fusion energy generation to meet tomorrow’s energy demands and mitigate carbon emissions. International collaboration is vital to achieving this grand engineering challenge of the twenty-first century. As an international organization, the IAEA will continue to work together with countries, other organizations and the fast growing fusion industry across the globe to tackle the scientific and technological challenges and help deliver the talent pipeline, nurture the supply chain, establish best knowledge management practices and engage with the public to make fusion energy a reality. ■

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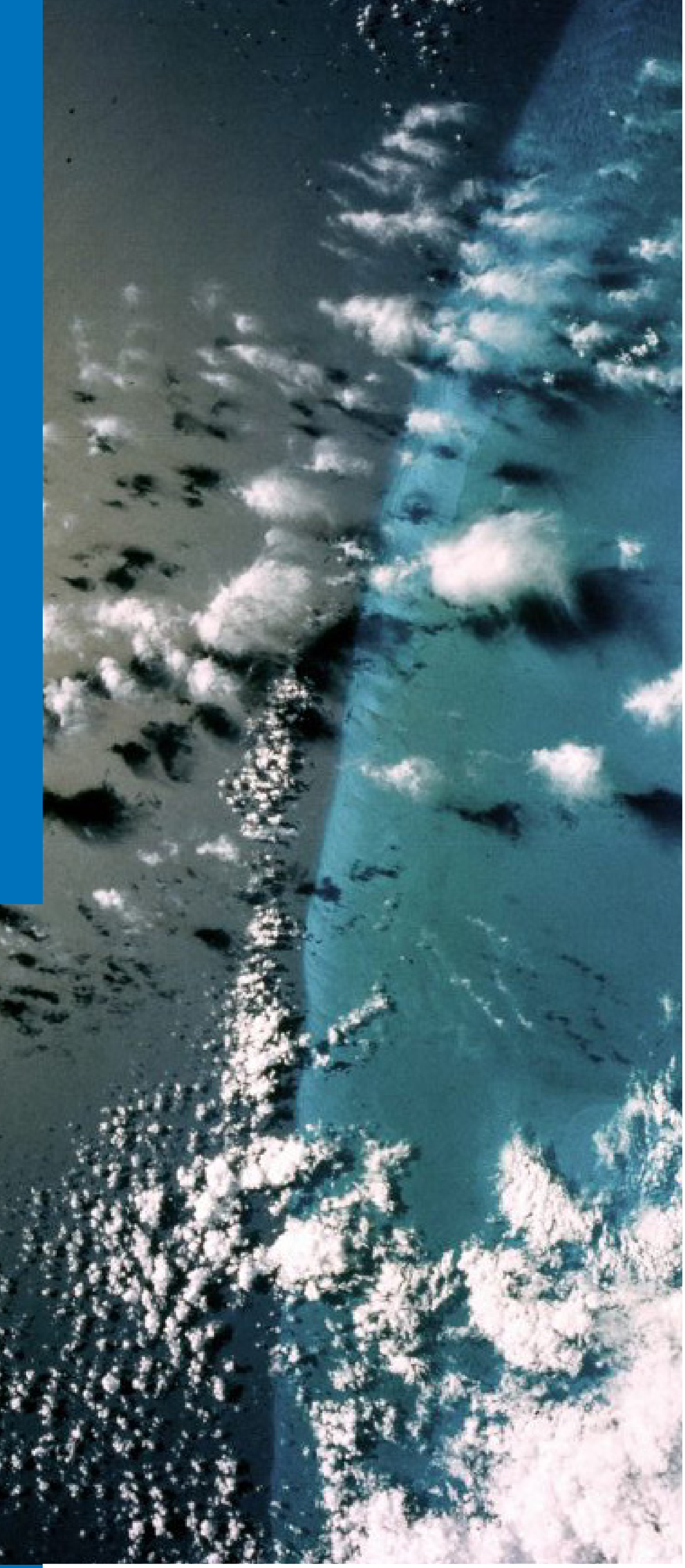
We are closer than ever to making fusion energy generation a reality. The vision of power generation through fusion reactions in a hot dense plasma to provide low carbon energy — without generation of long lived radioactive waste and without the possibility of any nuclear meltdown or runaway reaction, rendering it inherently safe — is sparking much interest. The flagship full scale feasibility project ITER has demonstrated component manufacturing and progress in the construction of the largest fusion experiment in the world with global cooperation, triggering an acceleration of fusion initiatives and trust in fusion feasibility.



Planet Earth.
Courtesy of NASA.

Key factors driving the heightened increasing interest in fusion energy:

- The growing concern over the impact of climate change and security of energy supply;
- Recent scientific and technology breakthroughs towards the goal of achieving safe and sustainable energy through nuclear fusion[1];
- A significant increase of fusion activities and investments in the private sector.

43 **private sector companies in different parts of the world.**

$6.2 **billion invested in fusion companies.**

The world's long term strategy towards net zero[1]

When a reality, fusion will be a source of low carbon energy and can contribute to decarbonization and diversification of energy generation in the long term to meet the mitigation of greenhouse gas emissions and limit increases in the global mean surface temperature, even as electricity needs worldwide continue to grow.

New government initiatives are being launched to respond to the climate change urgency which include fusion energy generation. Canada, in their Mid-century Long-Term Low-Greenhouse Gas Development Strategy [1]; the United Kingdom (UK), in their Net Zero Strategy: Powering Up Britain [2]; and Japan, in The Long-Term Strategy under the Paris Agreement [3], specifically included fusion in their long term strategies[2] towards net zero.

After publishing Towards Fusion Energy: the UK Government's Fusion Strategy, the UK announced the formation of the UK Industrial Fusion Solutions Ltd in February 2023 which is a new delivery body for its fusion programme for low cost, low carbon energy [4, 5][3]. UK Industrial Fusion Solutions Ltd is responsible for the construction of a Spherical Tokamak for Energy Production (STEP) by 2040. The UK announced in September 2023 plans to invest up to £650 million in fusion development until 2027 and was the first to propose fusion specific regulation, outside of nuclear licensing requirements [6, 7]. In the Russian Federation, a decree of the President determined the State Atomic Energy Corporation "Rosatom" as the coordinator of the integrated fusion energy programme [8]. In Japan, the Minister of Foreign Affairs pointed to nuclear fusion for the first time as one of Japan's future directions to address climate change in his country's foreign policy [9]. Japan then detailed a national strategy for fusion energy in April 2023, in which it announced the formation of the Fusion Industry Council of Japan and other fusion accelerants through industry–academia–government collaboration [10]. In the United States of America (USA), the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy, held in March 2022 [11], launched three new initiatives, including a new US Department of Energy (DOE) agency-wide fusion initiative, with a new lead coordinator for fusion energy joining the department's Office of the Under Secretary for Science and Innovation. A common denominator in these initiatives was empowering public–private partnerships to accelerate the research, development, and demonstration of fusion energy. The US Government Accountability Office released a technology assessment report on fusion energy status and opportunities in March 2023, in which policy options are iterated [12]. In January 2023 the US Nuclear Regulatory Commission published Options for Licensing and Regulating Fusion Energy Systems, supporting a hybrid approach, which would introduce decision criteria to license and regulate fusion energy systems under either a by-product material or utilization facility regulatory approach based on an assessment of potential hazards [13]. In March 2023 the European Commission released the Net-Zero Industry Act [14] targeted to create a regulatory framework that supports and accelerates reaching European climate and energy targets by 2030. The new Net-Zero Industry Act specifically lists fusion energy as one of the promotional targets of technology investments. Germany, following the release of Memorandum on Laser Inertial Fusion Energy [15] in May 2023, presented a Fusion Research Position Paper [16] in June 2023, where they announced a new funding scheme for national fusion activities and underpinned the importance of public–private partnerships, building competence for the future, and strengthening supply chains in pursuing both magnetic confinement and inertial programmes. In September 2023 the German Federal Ministry of Education and Research announced more than €1 billion investment in fusion energy development over the next five years [17].

Private companies seeking to fast-track fusion energy [18] have emerged in recent years, nurtured by private capital and a growing supply chain engagement sparked by components manufacturing for and construction of the large fusion experimental reactor ITER, located in the south of France. The private companies assert that they can create a demonstration fusion power plant (DEMO) decades earlier than efforts funded with public funds. Nineteen of thirty companies surveyed by the Fusion Industry Association in 2023 stated they expect fusion power on the grid by 2035 [19]. The Fusion Industry Association found that private fusion sector companies have attracted around US $6.2 billion in investment in total, which is US $1.4 billion more than in 2022. There are 43 such companies located in different parts of the world, namely in Australia, Canada, China, France, Germany, Israel, Italy, Japan, New Zealand, the UK and the USA; over half of these companies are based in the USA. ■

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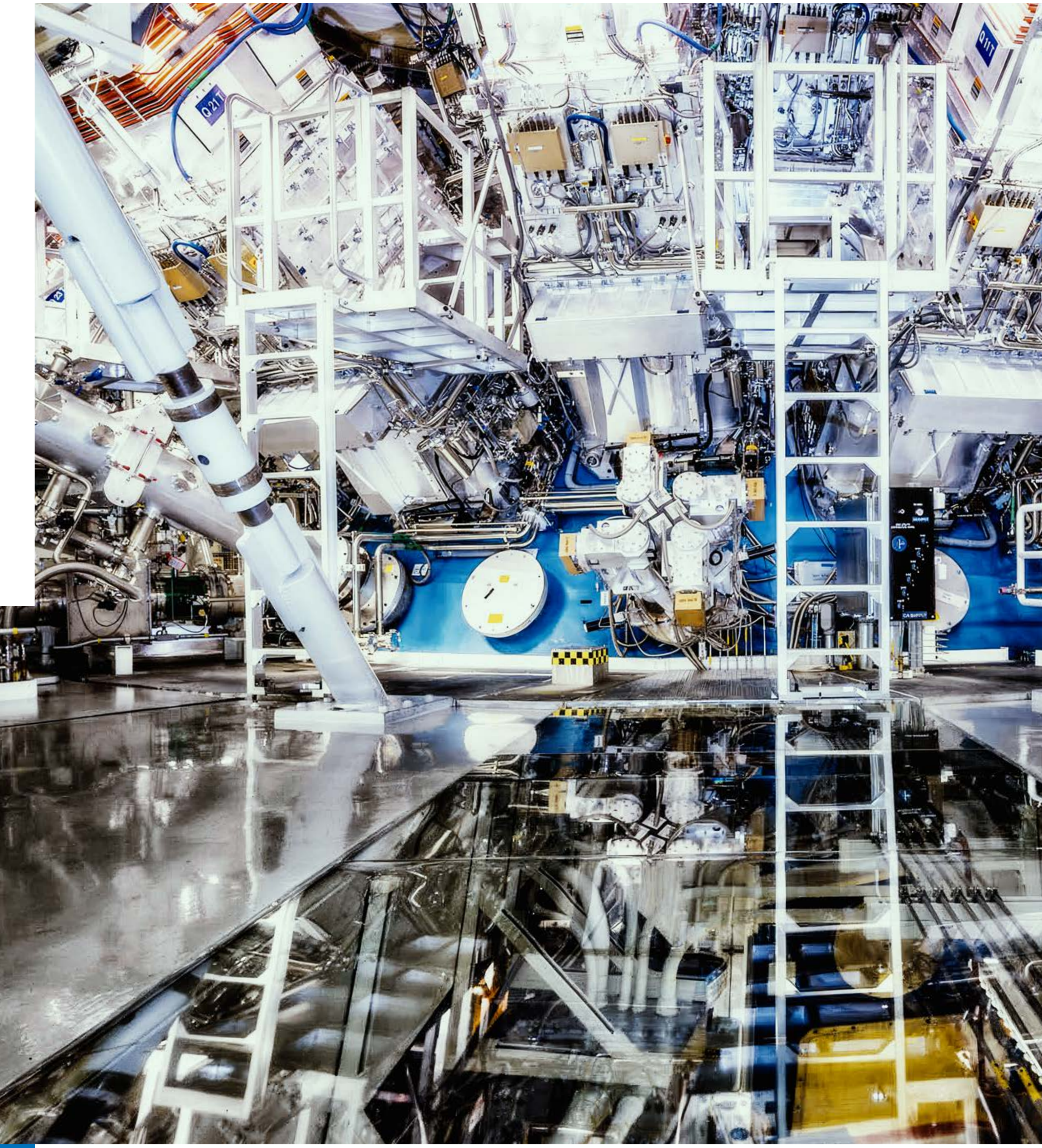
[1] The IAEA hosts a webinar series, Fusion Breakthroughs, which focuses on the latest landmark worldwide achievements announced in fusion energy. The series gives an overview of recent groundbreaking results and puts them in perspective, explaining how such progress brings fusion energy closer to reality.

[2] See: https://unfccc.int/process/the-paris-agreement/long-term-strategies

[3] This places UK regulatory oversight for fusion energy plants with the Environment Agency and Health and Safety Executive, rather than the Office for Nuclear Regulation, see Ref. [5].



3.15 megajoules of fusion energy.

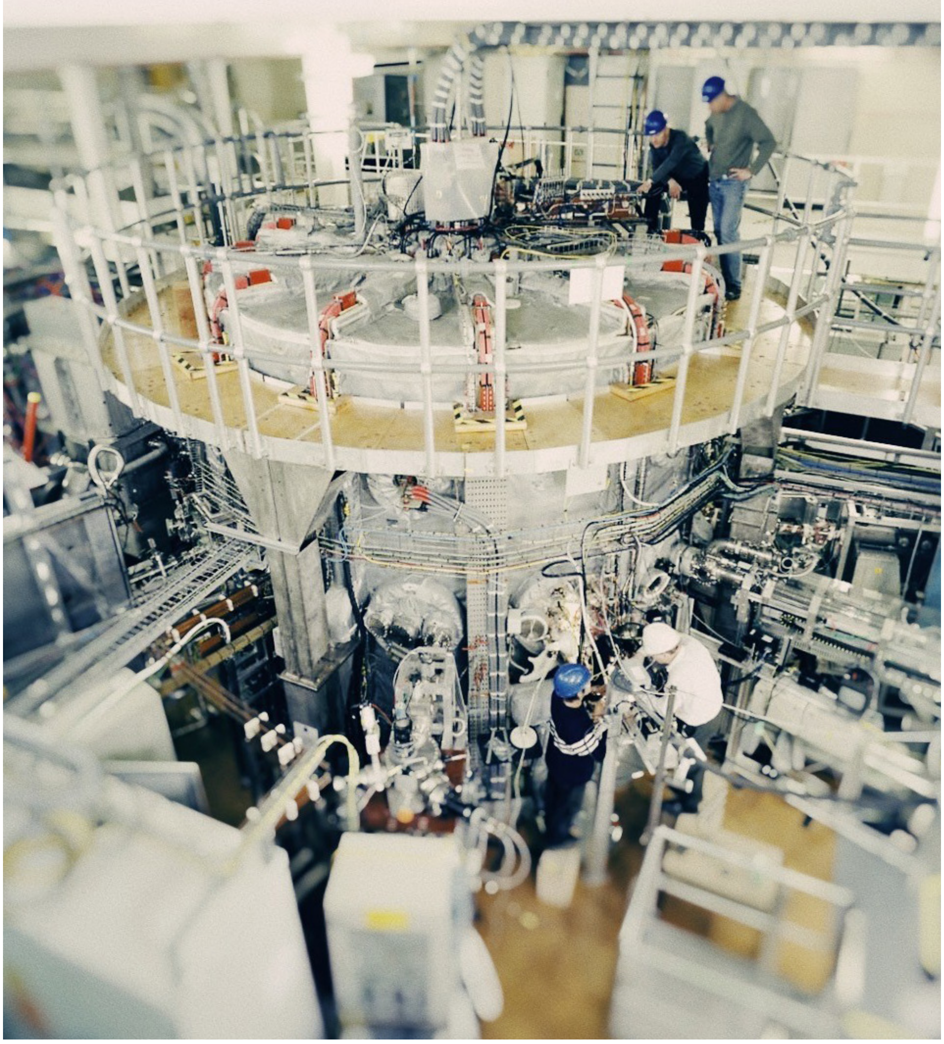
The fusion community has recently witnessed many critical steps towards achieving safe and sustainable energy through nuclear fusion.

Recent fusion highlights

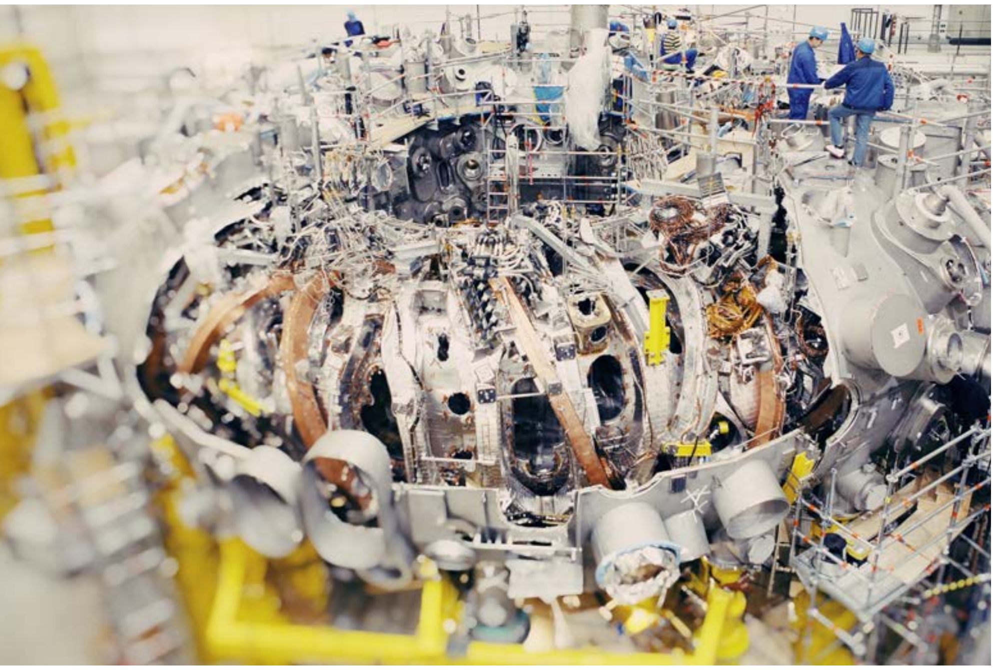
National Ignition Facility achieves first-ever scientific energy gain from fusion at Lawrence Livermore National Laboratory

USA

In August 2021 the National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory in the USA, reached a record breaking 1.3 megajoules of output from 1.9 megajoules laser energy input to a hohlraum encapsulating the deuterium–tritium (D–T) fuel and achieving a burning plasma state or ignition for the first time. On 13 December 2022, the US DOE announced another breakthrough at NIF [20]: 3.15 megajoules of fusion energy was generated from a total of 2.05 megajoules delivered to the fuel provided by 192 laser beams, thus achieving scientific energy gain (Q_{sci}~1.5) for the first time in a fusion experiment. In an experiment in July 2023 NIF achieved even greater scientific energy gain [21]. Courtesy of NIF.



UK
In May 2021 the United Kingdom Atomic Energy Authority's (UKAEA) Mega Amp Spherical Tokamak Upgrade (MAST U) demonstrated the effectiveness of an innovative heat exhaust system, known as a Super-X divertor, which successfully enables around ten times reduction in divertor heat flux. Courtesy of UKAEA.



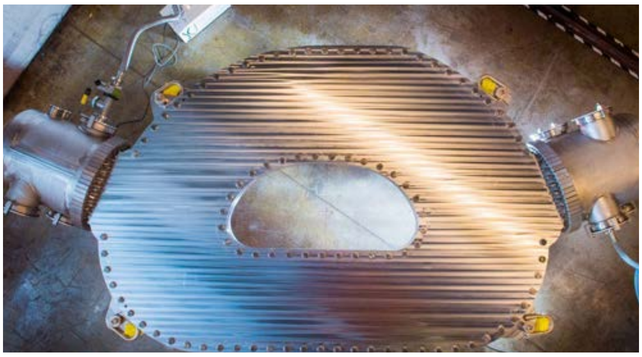
GERMANY
After achieving a number of breakthroughs producing record values for performance in August 2021[4], Wendelstein 7-X (W7-X) — the world's most advanced stellarator in operation since 2015 in Germany — entered its experimental second phase with upgrades that should enable continuous operation and deliver knowledge on particle and heat transport in steady fusion plasmas. In 2023 the W7-X achieved a new record: a plasma discharge for up to 8 minutes resulting in 1.3 gigajoules of energy turnover, which demonstrates the ability to continuously couple large amounts of energy in the plasma and to remove the resulting heat in a controlled way [22]. Following the success of this machine, a new start-up company, Proxima Fusion, announced it had secured €7 million in seed funding in May 2023. Courtesy of EUROfusion.

[4] W7-X has now been fully equipped with a water cooled set of plasma-facing components, allowing discharges for as long as 30 minutes at 10 MW of heating when the device goes back in physics operation in the second half of 2022.

[5] SPARC is presently under construction near Boston, USA. The academia–industry cooperation between the MIT and CFS is a good example of beneficial research and development symbiosis.

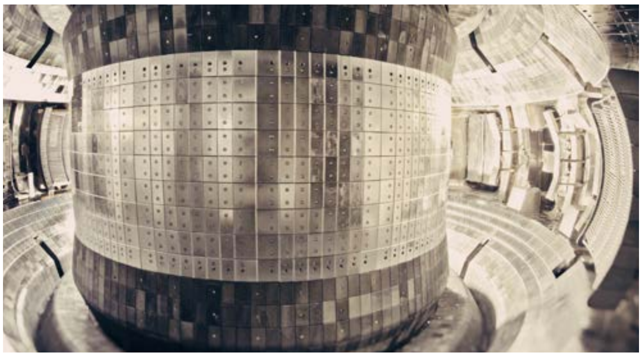
[6] JET's tokamak produced 59 megajoules of energy over a fusion 'pulse' of 5 seconds — more than double the 21.7 megajoules released in 1997 over around 4 seconds. The improvement took 20 years of experimental optimization, as well as hardware upgrades that included replacing the tokamak's inner wall to waste less fuel. JET's latest experiment sustained a $Q_{sci}=0.33$ for 5 seconds (thus $Q_{sci}<1$). JET's record for scientific energy gain remains the result from 1997, with $Q_{sci}=0.67$.

[7] This result is specifically relevant for demonstrating long-pulse high-performance operation with an ITER-like configuration and heating schemes.

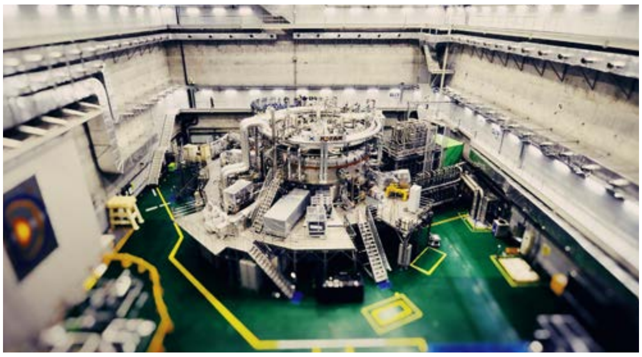


USA
In September 2021 the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center and Commonwealth Fusion Systems (CFS) announced the successful demonstration of a record breaking 20 tesla magnetic field in their first of a kind high temperature superconducting magnet [23], a major breakthrough in the design of their SPARC tokamak project[5]. Courtesy of CFS.

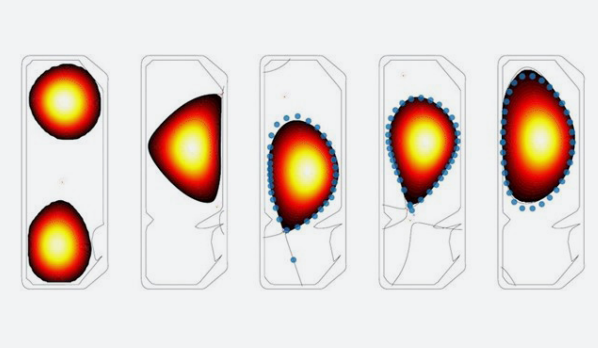
EUROPE
In December 2021 the Joint European Torus (JET) tokamak reached the highest sustained energy pulse ever[6], a record breaking 59 megajoules of sustained fusion energy over a fusion pulse of 5 seconds — more than double the 21.7 megajoules released over around 4 seconds in 1997. Courtesy of EUROfusion.



CHINA
In December 2021 China's experimental advanced superconducting tokamak (known as EAST) achieved the longest steady state high temperature plasma operation (1056 seconds or 17.6 minutes), i.e. long-pulse high-performance operation with an ITER-like configuration and heating schemes[7]. Courtesy of ITER Organization.



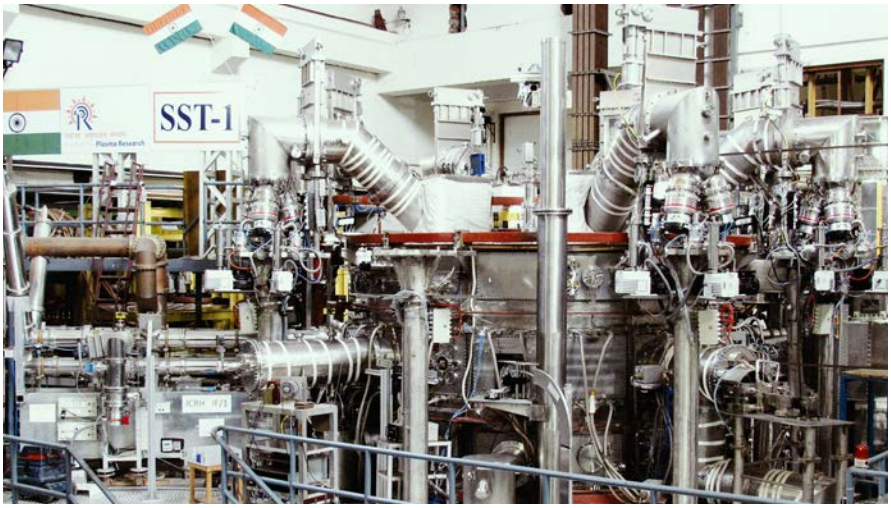
REPUBLIC OF KOREA
A study in September 2022 reported that experiments at the Korea Superconducting Tokamak Advanced Research facility in the Republic of Korea had produced a plasma with a high temperature above 100 million kelvin and sufficient control of instabilities to ensure steady state operation for up to 20 seconds [24]. These results raise confidence in the tokamak design as a promising path towards commercial fusion. Courtesy of ITER Organization.



Artificial intelligence (AI) based modelling of plasma dynamics for real time control of fusion experiments is emerging as state of the art for achieving plasma stability. One example published in 2022 demonstrated AI based systems control to create and maintain a wide range of plasma shapes and configurations in the variable configuration tokamak in Switzerland [25]. The figure shows a range of different plasma shapes and configurations generated with an AI based system controller. From left to right: droplets, negative triangularity, ITER-like shape, snowflake, elongated plasma. Courtesy of DeepMind and the Swiss Federal Institute of Technology Lausanne's Swiss Plasma Center.

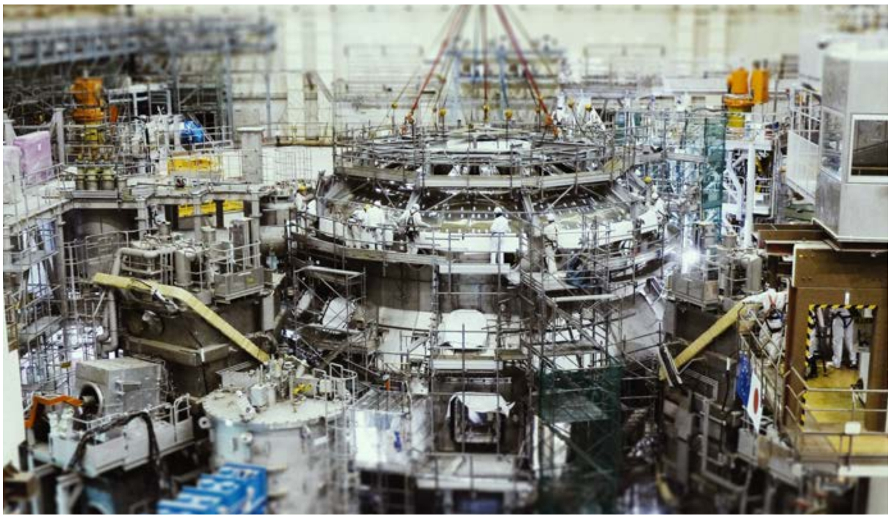
RUSSIAN FEDERATION

In April 2023 the T-15MD tokamak achieved its first stable plasma operation at the Kurchatov Institute in the Russian Federation following an upgrade of the machine concluded in 2021. The research programme on the T-15MD tokamak will be aimed at solving the most pressing problems of ITER. The T-15MD tokamak is water cooled and capable of creating a toroidal magnetic field at the plasma axis of 2 T; it also has powerful quasi-stationary additional heating systems with a total power input into the plasma of up to 20 MW, and modern engineering infrastructure. The current in the plasma should reach 2.0 MA with a duration of 10 s. The T-15MD tokamak was built over ten years and its experimental programme will contribute to the operation of ITER and future power plants.
Courtesy of the Kurchatov Institute.



INDIA

Experiments in the SST-1 tokamak at the Institute for Plasma Research in India demonstrated that the machine could be operated with both fully and partially driven non-inductive plasma current drive — an important feature for achieving long pulses operation. Courtesy of Institute for Plasma Research.



JAPAN

Commissioning of the JT-60SA tokamak at the Naka Fusion Institute in Japan, which started in April 2020, was interrupted because of insufficient voltage insulation capability in one of the magnetic coils. Improvement for isolation capability is ongoing and integrated commissioning is expected to restart before the end of 2023. Also in Japan, physics experiments on plasma turbulence and abrupt instability have provided important insights for developing control methods for turbulence and instability in the Large Helical Device. First experiments are expected to be conducted before the end of 2023. Courtesy of Naka Fusion Institute.

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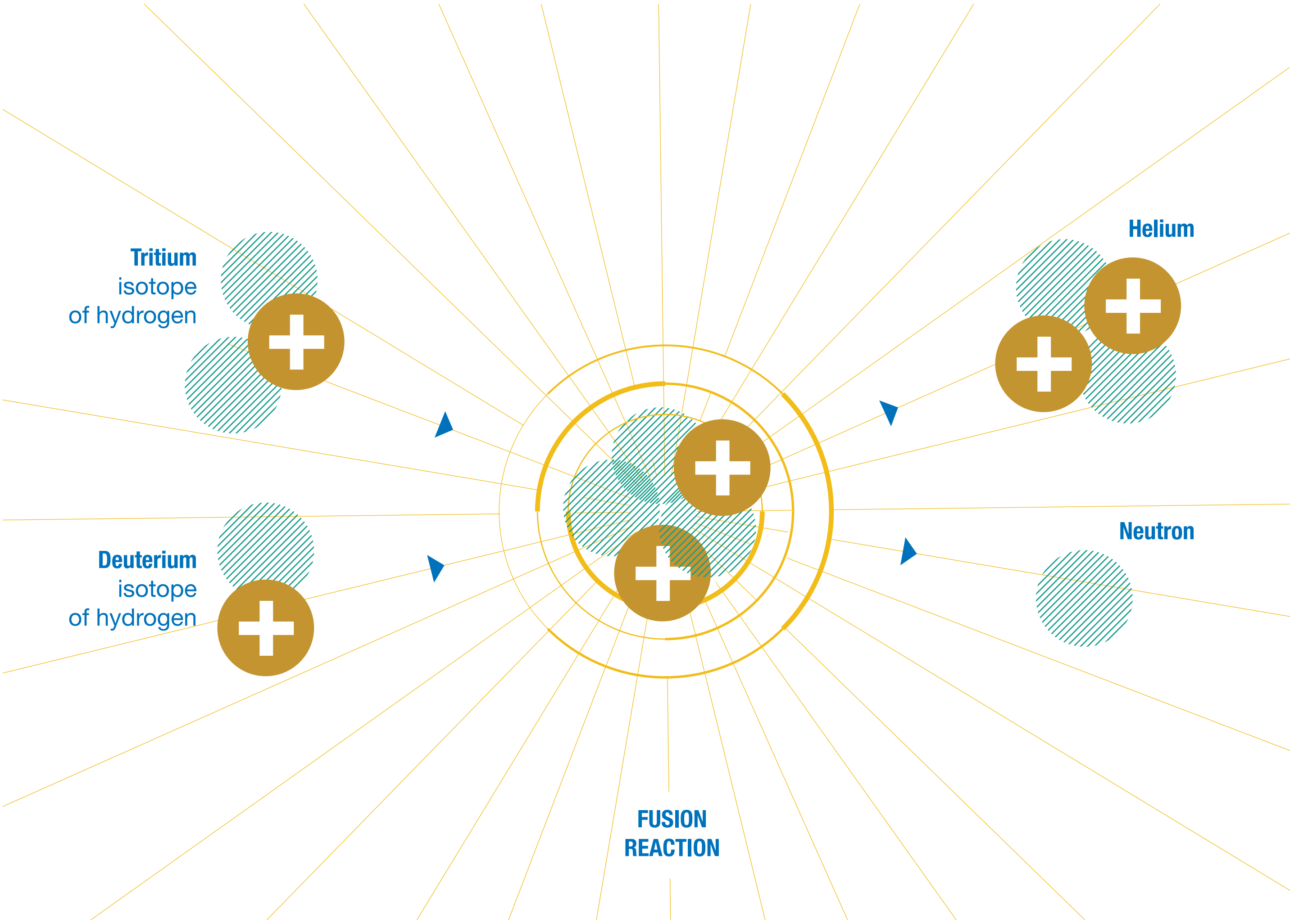
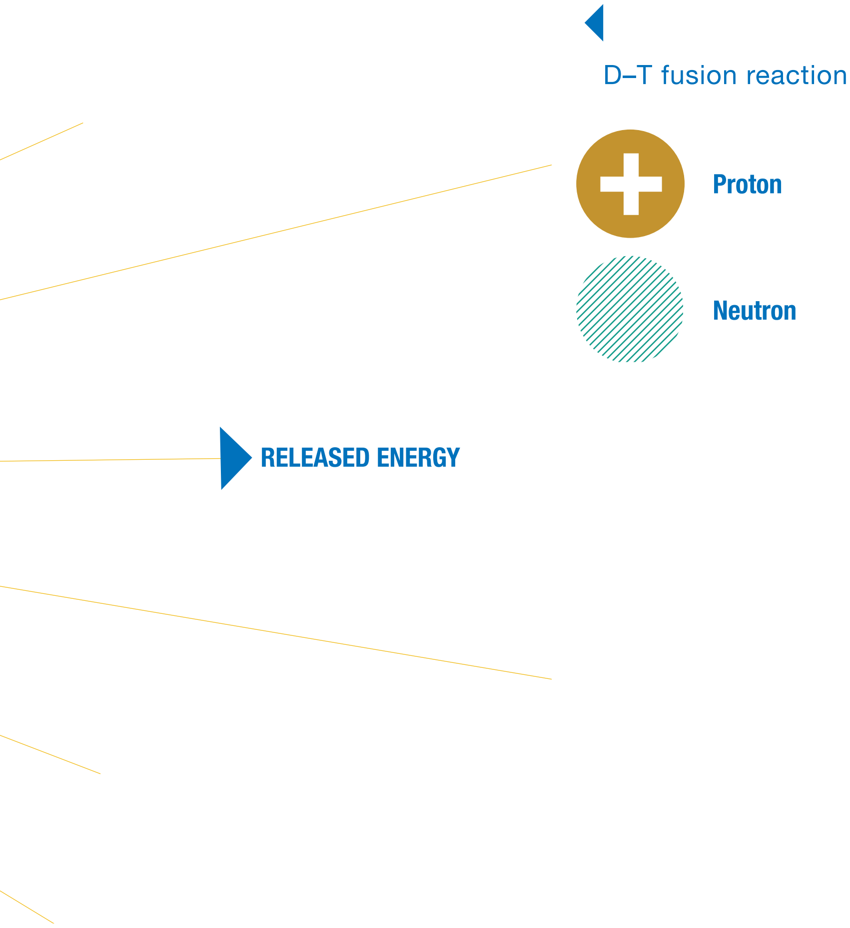
Major issues, research and development needs and technology gaps



Challenges of integrating physics into technologies

The vast majority of past fusion plasma experience is from magnetic confinement in a tokamak design using deuterium–deuterium (D–D) fuel. However, to obtain viable fusion energy, deuterium–tritium (D–T) fuel is the most common choice for future fusion power plants and the majority of fusion development activities continue in variation of this design. The development of commercially viable, controlled fusion power still faces a number of significant technological challenges, some related to successfully generating a high temperature plasma at high density for long times, others related to sustainably securing D–T fuel, to minimizing detrimental effects on materials by fusion reaction by-products, and to ultimately harnessing the immense energy released. ■

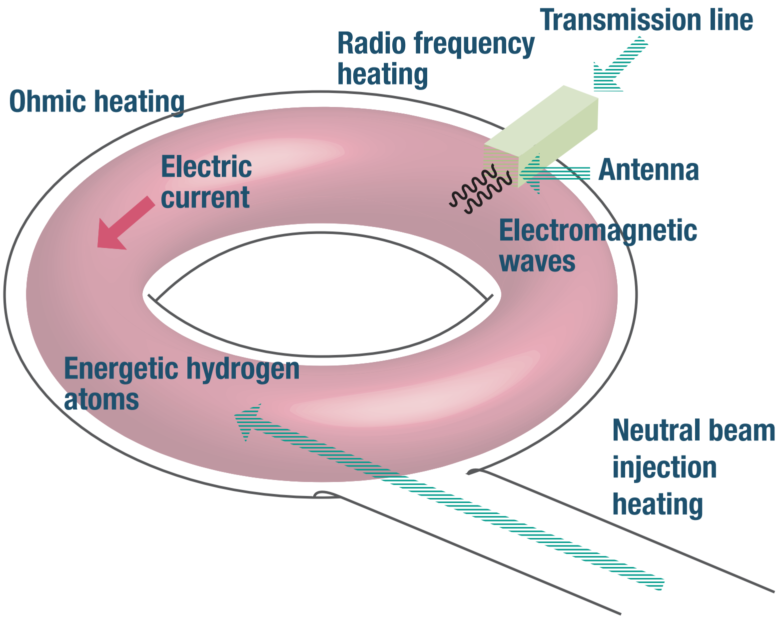


The major challenges are:

- Plasma heating: achieving and sustaining **temperatures in excess of 100 million °C**;
- Plasma confinement: **confining the hot fusion plasma** inside the reactor core;
- Fusion materials: finding the right **materials to withstand the extreme conditions** from which to construct the fusion reactor wall and vessel;
- Fusion fuel: developing the technology to **breed the tritium** component of the fusion fuel using the neutrons released in an ongoing reaction;
- **Energy extraction:** steadily extracting the enormous amount of energy that is produced and converting it into electricity or using it as process heat;
- Maintenance: operating fusion power plants with high availability, which requires novel, **rapid maintenance schemes, including remote handling.**

Heating the plasma

For fusion to occur, a stable, very high temperature plasma (hotter than our sun) of D–T, for example, should first be created. The magnetic field driving the plasma particles creates some of this heating through (non-fusion) collisions. The additional energy required to reach very high temperatures is provided through neutral beam injection and/or high frequency electromagnetic radiation. The electromagnetic radiation is comparable to the heating in a microwave. With neutral beam injection, high speed neutral particles are injected into the plasma, where they become ionized and transfer their energy to the plasma through collisions. Alongside the processes which heat the plasma, impurities can be generated and penetrate the hot plasma core, potentially leading to loss of fusion power through radiative cooling and fuel dilution. A means for removing impurities as well as reaction products from the plasma is another challenge. ■



Fusion materials

The development of suitable materials for the construction of a commercial fusion power plant is a challenge and the subject of ongoing research. Materials design and qualification requires rigorous laboratory quality assurance testing. These are currently performed using ion beam accelerators, high heat flux facilities as well as linear plasma devices and experimental fusion facilities. However, there are currently no facilities available to realistically and entirely simulate fusion power reactor conditions to test such materials. Irradiations in fission reactors are also done but are not prototypical of a fusion reactor, as the neutron energy in a fission reactor is considerably lower than in a fusion reactor. To simulate fusion neutron fluxes, there are phased plans for an International Fusion Materials Irradiation Facility (IFMIF), an accelerator based high energy intense neutron source, to test fusion materials to irradiation dose levels in a DEMO-like device. The Linear IFMIF Prototype Accelerator has been installed in Rokkasho, Japan, while in 2023 the IFMIF–DONES (DEMO Oriented Neutron Source), focused on meeting the most urgent needs of a DEMO project, has already started its construction phase in Granada, Spain.

In general, for a reactor to be viable, plasma-facing materials should have the following properties:

- A high melting point and resilience to damage on exposure to neutron radiation and the high energy plasma particles.
- A low propensity to become activated (become radioactive) through bombardment by the high energy neutrons produced in the D–T fusion reaction as well as resilience to the alpha fusion products.
- A low tendency to absorb tritium to reduce fuel losses and minimize the retention of tritium which would create radioactive waste. Tritiated materials would require special handling when decommissioning the fusion power plant.

The last two properties are related to nuclear safety and waste management. The tendency to absorb tritium has implications for

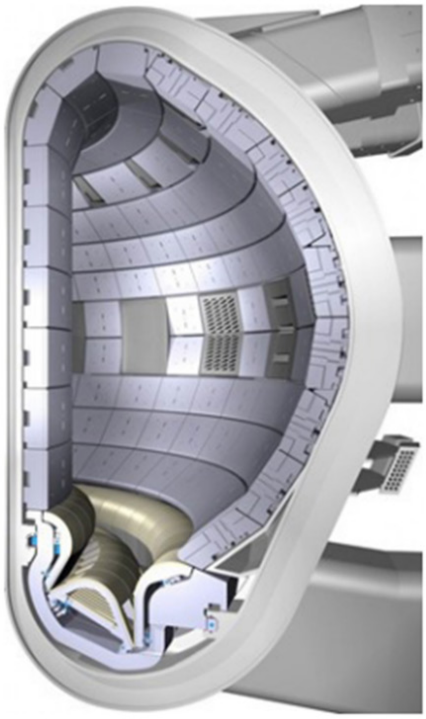
Three external heating sources for a large tokamak fusion reactor. Courtesy of EUROfusion.

Plasma confinement

In a fusion process, the high temperature plasma must be confined for long enough for the fuel nuclei to combine or ‘fuse’. Most concepts for fusion reactors are based on plasma confinement using magnetic fields. In the most common design of a magnetic confinement device — the tokamak — magnetic fields are used to confine the hot plasma around a torus-shaped reaction chamber and keep it from getting too close to the reactor’s first wall. However, plasma confinement is never perfect: turbulence can transport heat and particles to the edge and instabilities can occur periodically that send plumes of hot plasma into the wall, eventually damaging the reactor and reducing its operational lifetime. The reactor components have to survive long enough to make fusion energy production commercially viable. Research is ongoing to better understand, model and mitigate plasma instabilities.

The construction and operation of the large superconducting electromagnets needed to create the plasma confining magnetic fields are expensive, heavy and consume a large amount of energy. They need to be operated at a very low temperature but are positioned near the hot plasma (>100 million °C). This creates the largest known temperature gradient in the entire universe and an obvious technological challenge. Recent private industry efforts (Commonwealth Fusion Systems and a collaboration between General Atomics and Tokamak Energy Ltd [26]) aim to address these challenges in developing and fabricating large scale superconducting magnets which operate at higher temperatures for fusion applications. ■

operational scenarios of a fusion plant as well. For example, avoiding tritium absorption rules out carbon based materials as a plasma-facing component. The initial plans for ITER are to use beryllium in its first wall and tungsten in the divertor, but plans may shift to a non-beryllium first wall design. It is anticipated that the DEMO will employ tungsten as first wall material. In addition, plasma-facing component material solutions, based on liquid metals such as lithium and tin and lithium–tin mixtures, are also being actively studied. The divertor in particular is subject to high heat loads, energetic particles and radiation. During plasma disruptions, the heat load on the divertor can reach levels orders of magnitude higher than during steady state operations. The divertor in a tokamak diverts impurities out of the plasma, including helium reaction products, removes excess heat from the plasma and protects the first wall. ■



Cross-section of the ITER tokamak.
The divertor region is shown in beige. Courtesy of ITER Organization.

Fuelling the plasma

D–T fusion fuel is typically the favoured choice, as it can attain the highest reaction rate at a lower temperature than other fuels. Deuterium can be extracted from seawater, but tritium will have to be made or 'bred' in the fusion facility itself. Tritium (^{3}T) is a radioactive, heavy isotope of hydrogen with a half-life of 12.3 years and is generated naturally in the upper atmosphere in only gram quantities. It has to be bred in a nuclear reaction between the fusion generated neutrons and ^{6}Li, a stable isotope of lithium: $^{6}\text{Li} + \text{n} \rightarrow {}^{3}\text{T} + {}^{4}\text{He}$, a stable isotope of helium, as well as another stable isotope of lithium, ^{7}Li: $^{7}\text{Li} + \text{n} \rightarrow {}^{3}\text{T} + \text{n}' + {}^{4}\text{He}$, where the incident neutron is fast enough. The proposed approach is to surround the reactor with a 'blanket' of a lithium containing material to slow down and capture some of the neutrons produced by the fusion reaction to breed the tritium fuel. The neutron capture reaction in ^{6}Li also releases energy and so can contribute to the reactor's heat output.

A holistic design and tested option for the tritium breeder and associated fuel loops, plant integration plus handling facilities for tritium inventory across a fusion plant does not yet exist. This is a make-or-break point for the future of fusion energy production. One of the goals of ITER is to test various tritium breeder blanket modules surrounding the reactor vessel and ultimately demonstrate technical feasibility of breeding tritium fuel.

TABLE 1. LIST OF THE MOST FAVOURABLE FUSION REACTIONS

Reactants	Reaction products with reaction probability	Available release energy (MeV)
D–T	^{4}He + n	17.60
D–D	T + p (50%)	4.03
	^{3}He + n (50%)	3.27
D–^{3}He	^{4}He + p	18.35
T–T	^{4}He + 2 n	11.33
^{3}He–^{3}He	^{4}He + 2 p	12.86
^{3}He–T	^{4}He + p + n (57%)	12.10
	^{4}He + D (43%)	14.32
D–^{6}Li	2 ^{4}He	22.37
p–^{6}Li	^{4}He + ^{3}He	4.02
^{3}He–^{6}Li	2 ^{4}He + p	16.87
p–^{11}B	3 ^{4}He	8.68

To bypass the breeding and safety/waste challenges posed by D–T fuel, alternative fusion fuels have been proposed, including D–^{3}He and proton–boron-11 (p–^{11}B) (see Table 1). Although these fuels are non-radioactive, do not generate highly energetic neutrons and are readily available so that the need to breed is avoided, they unfortunately require even hotter and denser plasmas for ignition than D–T fuel. ■

Heat conversion to energy

In a D–T fusion reaction, energy is released in the form of high energy neutrons and alpha particles. In a tokamak, a blanket plays an important role; it will be used not only to generate tritium (fuel) but also capture the heat from the energetic neutrons and transfer it to a coolant. The heat from the hot coolant can then be used directly as process heat or for power generation by transferring it to water to generate electricity using steam turbines, for example.

The heat fluxes in the blanket can be extremely high, exceeding the capabilities of conventional heat transfer methods. It is difficult to deal with these high heat fluxes while maintaining the efficient transfer of heat to the coolant. Advanced cooling methods along with compatible materials, which can withstand and remove heat efficiently under these extreme conditions, are needed. It is crucial to manage thermal stress, fatigue and neutron induced damages through appropriate material selection, design and thermal management strategies to ensure the long term reliability of the blanket. Finding the right materials to withstand neutron irradiation and high temperatures is challenging. The high energy neutrons generated in the fusion reaction can cause material damage and lead to embrittlement and changes in material properties, which may affect the thermal performance of the blanket. Rapid heating and cooling cycles can induce mechanical stresses, that may lead to structural damage, cracking and reduced material performance over time. Finding the best blanket is an active area of research and development with some concepts planned to be tested in ITER. ■

Safety, security, safeguards, nuclear law and liability

Nuclear law

Typically with every new nuclear technology comes a need to assess the adequacy and comprehensiveness of existing legal frameworks to ensure safety, security and responsible and peaceful use. Fusion technology is no exception. There is a need to consider whether the current international legal frameworks for the safe, secure and peaceful uses of nuclear technology are applicable and fit for purpose for fusion energy systems. While fission and fusion both produce energy, there are fundamental differences, distinct technological requirements and characteristics which change the hazard potential and key safety issues.

The objective of nuclear law is to provide a legal framework for conducting activities related to nuclear energy and ionizing radiation in a manner which adequately protects people, property and the environment. Over the decades, nuclear law has evolved to address the unique challenges of fission based power generation and the Convention on Nuclear Safety (CNS) [27] and other related international legal instruments such as the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) [28], together with IAEA safeguards, have all played an important role, complemented by legally non-binding IAEA safety standards and nuclear security guidance.

The current international legal frameworks for nuclear power establish international principles of safety, radiation protection, radioactive waste management and fundamental principles of physical protection, as well as basic principles of civil liability for nuclear damage. Each State carries the full responsibility for nuclear safety and security. Effective national legal frameworks should establish an effectively independent regulatory body with clear legal authority and sufficient financial and human resources responsible for licensing and regulatory control, such as issuing regulations, licensing, inspection and enforcement. Each licence holder has the primary responsibility for safety and security, such as ensuring safety in the siting, design, construction, commissioning, operation and decommissioning of its nuclear power plant (NPP), and for related activities, like the transport of radioactive material. Together with national legislative and regulatory frameworks, the international fission based legal frameworks provide the foundation for the protection of people and the environment against radiation risks and for the safety and security of NPPs and associated activities that give rise to radiation risks. ■

Legal frameworks and conventions for safety of fusion facilities

The cornerstone of the current international legal framework for nuclear safety is the CNS [27], which establishes fundamental safety principles for the design, construction and operation of nuclear installations, and emphasizes the objective of preventing accidents and mitigating their potential consequences. The IAEA Nuclear Safety and Security Glossary [29] does not include fusion facilities under the category of nuclear installations, however Contracting Parties to the CNS may consider certain fusion power plants as being a nuclear installation (i.e. a land based NPP) for the purpose of the CNS. In doing so, the Contracting Parties should note that a potential limitation arising from the definition of a nuclear installation is that a land based NPP ceases to be a nuclear installation for the purposes of the CNS "when all nuclear fuel elements have been removed permanently from the reactor core" [27]. Currently, nuclear fuel for fission based plants is commonly understood as being fissionable nuclear material in the form of fabricated fuel elements.

Fusion waste is significantly different to radioactive waste from large traditional fission based NPPs. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Joint Convention) [30] combines the safety of spent fuel management and the safety of radioactive waste management into a joint structure. The Joint Convention may be considered as being broad enough to cover fusion facilities and related radioactive waste management activities, both in terms of tritium and in terms of radioactive waste produced by the operation of the reactor.

The peer review process of both the Joint Convention and CNS would appear to provide an effective mechanism for the reporting on the safety of nuclear fusion facilities and the safe management of fusion waste, the extent to which being determined by the Contracting Parties. Indeed, their mechanisms could enable assessment of safety practices and the status of national legislative and regulatory frameworks, the exchange of information, and sharing of best practices and lessons learned, as well as identification of strengths, weaknesses, gaps, and areas for improvement in safety.

The CNS and Joint Convention also address some aspects of emergency preparedness and response (EPR), such as requiring the establishment of on-site and off-site emergency plans. The Early Notification and Assistance Conventions [31, 32] and the associated operational international EPR system, appear broad enough to accommodate potential accidents and emergencies at a fusion facility. ■

Legal frameworks and conventions for nuclear security

The scope of the Convention on the Physical Protection of Nuclear Material (CPPNM) and its amendment [33], which defines the legal obligation of Parties regarding protection of nuclear material and criminalization of offences involving nuclear material, does not apply to a fusion facility, tritium and other associated radioactive material (it does apply to nuclear material in hybrid fusion–fission designs). However, the International Convention for the Suppression of Acts of Nuclear Terrorism (Nuclear Terrorism Convention) [34] adopted under the auspices of the United Nations, has a broader scope than the CPPNM, as it requires Parties to criminalize acts involving radioactive material, which not only includes nuclear material but also other radioactive substances, and hence tritium as a fusion fuel and activated materials from fusion facilities. Consequently, criminalization of certain acts that may have relevance to fusion energy systems are provided for, albeit there is no obligation on the Parties to establish and implement national physical protection regimes for fusion facilities, as provided for in the CPPNM as amended. However, the Nuclear Terrorism Convention does require Parties to make every effort to adopt appropriate measures to ensure the protection of radioactive material, taking into account relevant recommendations and functions of the IAEA. ■

IAEA safeguards agreements

The scope of the IAEA safeguards agreements (e.g. comprehensive safeguards agreements (CSAs), voluntary offer agreements (VOAs), item-specific safeguards agreements) covers nuclear material (source or special fissionable material as defined in Article XX of the IAEA Statute) and fission related technology, including fission reactors and the fission nuclear fuel cycle technologies such as conversion, enrichment, fuel fabrication and reprocessing. Under item-specific agreements, the IAEA also applies safeguards to fission related equipment and non-nuclear material (e.g. heavy water). IAEA safeguards are primarily focused on ensuring the peaceful use of nuclear material and verifying a country's compliance with its nuclear non-proliferation obligations.

A fusion system that does not use, process, produce or otherwise have source and special fissionable material is not subject to IAEA safeguards. Thus, application of safeguards depends on the use of nuclear material in a fusion technology and the type of safeguards agreement. If a fusion system is designed to use, process, produce or to have nuclear material (e.g. depleted uranium shielding), it will be subject to IAEA safeguards under a CSA. It may also be subject to safeguards under a VOA (if included in the list of eligible facilities and selected by the IAEA for the application of safeguards) or an item-specific safeguards agreement (if required to be safeguarded under a transfer agreement or requested by the State). If nuclear material is not involved, the IAEA will not apply safeguards to fusion systems under the existing safeguards agreements.

Under the Model Protocol Additional to the Agreement(s) Between State(s) and the International Atomic Energy Agency for the Application of Safeguards (Additional Protocol) [35] concluded with CSA States, the IAEA may seek access to a fusion plant which is not using nuclear material to assure the absence of undeclared nuclear material and activities at such a plant.

States may use other non-safeguards tools to effectively manage the limited proliferation risks from fusion. Certain components and materials related to fusion (e.g. tritium and tritium systems) are and continue to fall under the existing export control framework ('dual-use' items in alignment with the Nuclear Suppliers Group Part 2 Guidelines [36]), owing to their potential use for nuclear weapons or other nuclear explosive devices. ■

Civil liability for nuclear damage

Fusion facilities are currently not covered by the definition of nuclear installation in all the existing instruments comprising the special regime on civil liability for nuclear damage. Although radioactive waste will be generated, both tritiated and activated material, such materials fall outside the scope of all these instruments. These instruments expressly exclude any radioisotopes outside the nuclear fuel cycle "which have reached the final stage of fabrication so as to be usable for any scientific, medical, agricultural, commercial or industrial purpose" [37].

In the 1960s when the first instruments were adopted, fusion was considered to pose a low level of radiological risk. Even with the modernization of the special nuclear liability regime in the 1990s, in the absence of a near term perspective of commercial use of fusion energy, there was considered no need to bring fusion under the aegis of the regime. Therefore, potential claims related to radiological damage suffered by third parties from fusion activities would have to be dealt with under general tort law, without limitation, and could be brought against the operator and suppliers. ■

Nuclear law and fusion installations

- There is no specific international legal framework for fusion technology.

- The broad principles, obligations, requirements and related mechanisms of the existing international legal instruments for nuclear safety might apply to fusion energy systems.

- The existing key international legal instruments for nuclear security appear not to be applicable to fusion facilities and associated activities, albeit that the Nuclear Terrorism Convention appears applicable.

- While potential questions of civil liability for nuclear damage in the context of fusion energy systems are currently not covered by the existing international legal instruments, they would most likely be addressed under general tort law.

- Fusion energy systems designed not to use or have nuclear material, fall outside the scope of the IAEA safeguards framework and the NPT-based non-proliferation regime.

- Fusion technology appears to present an opportunity to integrate relevant principles and lessons of the existing fission-based legal frameworks, as appropriate, while tailoring them to the specific characteristics and risks associated with fusion. Ultimately, it will be for the Parties to the relevant international legal instruments to interpret their applicability to fusion related facilities and activities and decide what changes, if any, are needed to address fusion technology.

- The applicable legal frameworks should serve to maintain safety, security and environmental protection in a way that is proportionate to the magnitude of the intrinsic hazard and risk of the fusion process.

- These frameworks should ensure public trust and confidence, while also paving the way for investment and development, thereby enabling a smooth transition from fusion research to commercialization.

IAEA Director General, Rafael Mariano Grossi, at the First International Conference on Nuclear Law: The Global Debate.

Safety and security of fusion energy installations

Specific requirements for the design and operation of fusion facilities

Specific Safety Requirements exist for specific nuclear installation types, such as NPPs [38, 39], research reactors [40], fuel cycle facilities [41], and for the disposal of waste [42]. However, unlike NPPs, fusion facilities, except hybrid facilities using fissile materials, do not use fissile materials and have a comparatively smaller amount of radioactive material. Therefore, safety requirements for fusion facilities should be tailored to cover aspects, such as:

- Unique conditions for material degradation, for example, high energy neutron flux;
- Unique equipment conditions, for example, vacuum conditions and the postulated initiating events that can be triggered by this;
- Confinement of radioactive materials, for example, tritium.

Safety of installations

The IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [43], and General Safety Requirements for the protection of people and the environment from harmful effects of ionizing radiation are considered to be generally applicable to fusion facilities; however, neither specific safety requirements for the design and operation of fusion facilities nor specific safety guides for the application of safety requirements to fusion facilities have been developed yet.

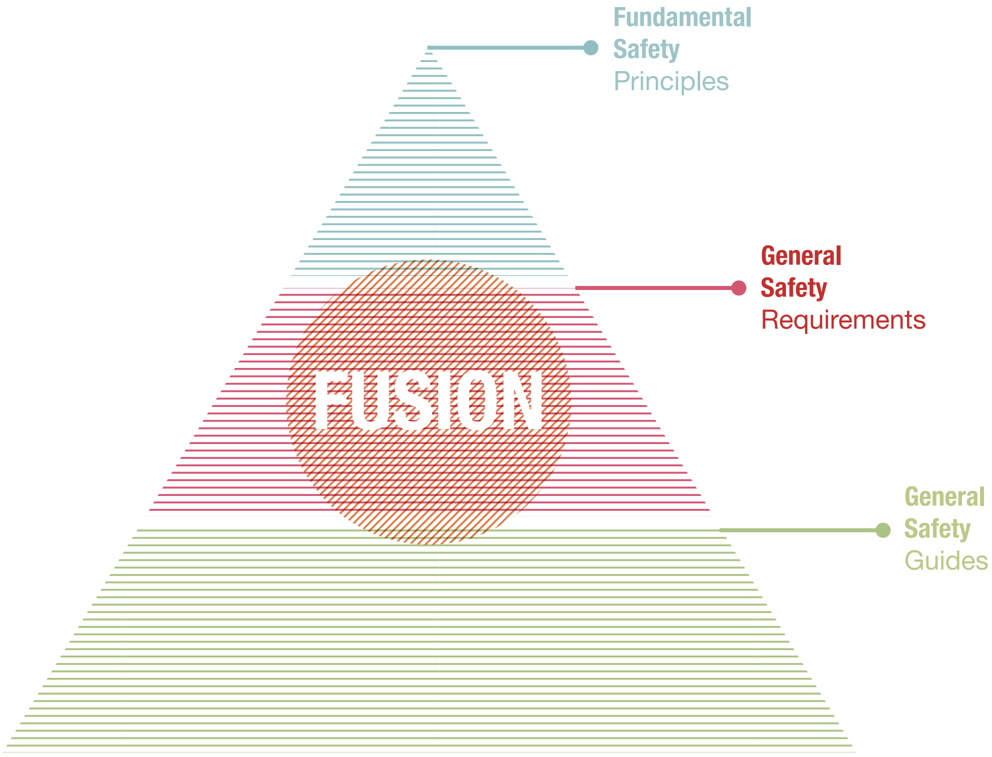
Application of a graded approach

According to Principle 5: Optimization of protection, in No. SF-1 [43], protection must be optimized to provide the highest level of safety that can reasonably be achieved. Radiation risks of fusion facilities and activities must therefore be assessed using a systematic graded approach, taking into particular consideration the magnitude of the possible radiation risks as well as the maturity and complexity of the facility or activity, in line with IAEA Safety Standards Series No. GSR Part 4 (Rev. 1), Safety Assessment for Facilities and Activities [44].

Optimized regulatory framework for fusion facilities

Specific design and operational safety requirements for fusion facilities should be reflected in national regulatory requirements in accordance with a graded approach. Other important issues to be considered include those related to regulatory control, for example:

- Steps for authorization (e.g. siting, design, construction, commissioning, operation, decommissioning);
- Consultation process with developers in compliance with national practices;
- Format of the safety assessment report;
- Requirements for operating organizations to consult with interested parties;
- Frequency and scope of regulatory inspections and enforcement measures.



Inclusion of fusion facilities in the safety standards framework.

The decision making process within the regulatory body should also adopt a graded approach, such as the implementation of public consultation prior to regulatory decisions. The development of regulatory infrastructure should also be based on sufficient capacity of the involved entities (operating organization, regulatory body, etc.) and involve communication and consultation with the public.

Consideration of ongoing progress of technology and international harmonization

Ongoing large scale international fusion projects and government led national projects are driving progress in technology, where new designs or materials are introduced even during the construction stage of the experimental facilities. Recently substantial private sector efforts have emerged in many countries and privately funded companies are engaged in the planning and design of various prototype facilities, suggesting a diversity of future commercial fusion power plant design concepts.

The safety framework for fusion facilities therefore needs to evolve to support rapid progress of technologies, with consideration of the lack of operating experience, as for any first-of-a-kind technology. These issues might be addressed by:

- Setting high-level goal-oriented requirements, rather than prescriptive requirements, to enable the progress of technology;
- Early establishment of approaches to compensate for the lack of operating experience, including a mechanism to enable the regulatory body to have appropriate and timely access to specific information such as detailed research results relating to safety.

In addition, since many States show interest in fusion power and supply chains are likely to be established across the globe, harmonization of safety frameworks for fusion facilities could optimize resources for safety. The earlier such harmonization efforts are made, the easier harmonization will be. ■

Emergency preparedness and response

IAEA safety standards in the area of EPR (IAEA Safety Standards Series No. GSR Part 7, Preparedness and Response for a Nuclear or Radiological Emergency [45]) are technology neutral and thus applicable for nuclear fusion facilities. Appropriate emergency arrangements for fusion facilities need to be decided based on a hazard assessment, provided that this hazard assessment considers:

- Events of very low probability and events not considered in the design, including those triggered by a nuclear security event (e.g. sabotage);
- Events involving a combination of a nuclear or radiological emergency with a conventional emergency that could affect wider areas and/or could impair capabilities to provide support in the emergency response;
- Events at similar facilities located abroad.

States will need to perform a hazard assessment and assign fusion facilities to a specific emergency preparedness category (EPC) defined in table 1 of No. GSR Part 7 [45]. For a given EPC, the relevant requirements will apply, but for the practical application of these requirements for an emergency at fusion facilities further work will be needed. Questions such as the following need to be addressed:

- What are the hazards associated with fusion facilities, including radiation and non-radiation related hazards?
- Can radiological consequences occur on-site and off-site that might result in radiological consequences requiring urgent or early protective actions?
- In which EPC(s) do fusion facilities belong? If fusion facilities are categorized under EPC I or II, what should be the size of the associated emergency planning zone(s) and emergency planning distances?
- What is the timeline of potential emergency scenarios at fusion reactors? How does this relate to the time available for effective decision making and timely implementation of protective actions?
- What non-radiation related consequences (e.g. associated with the use of novel materials and techniques) can be expected on-site and off-site? What will their impact be on the EPR arrangements?
- What mitigatory and protective actions would be effective in addressing the consequences of an emergency at a fusion facility? ■

Safety features impacting radioactive waste management and decommissioning

The decommissioning and waste management processes, responsibilities and safety criteria as described in the IAEA safety standards are fully applicable to fusion facilities. There are some fusion technology specific aspects that need to be considered. The basic features important for understanding safety aspects related to decommissioning and waste management of fusion facilities are:

- There is no chain nuclear fission reaction;
- A small amount of fuel (in the order of grams) circulates in the reaction chamber, which maintains the D–T fusion reaction;
- Plasma-facing components are exposed to tritium at extreme temperatures and high particle fluxes and are also exposed to neutrons (e.g. tritium may accumulate on components surfaces or may transport deeper in the material up to cooling systems, neutrons produce irradiation damage to components materials);
- Hazardous materials may be present depending on a chosen design, e.g. beryllium;
- The main radioactive inventory is generated by neutron activation of reactor components. ■

Inventory and disposal of waste from fusion facilities

Fundamentally, the waste from fusion plants will be very different in composition from that currently generated by fission plants. However, lessons learned in a holistic approach to waste and decommissioning from fission NPPs can be applied to fusion power plants. All fusion wastes will need to have a planned pathway for disposal prior to generation. As fusion waste will have more short-lived radioactive elements, different strategies can be considered, including new waste form standards, criteria with less emphasis on long term waste form stability, and delay and decay strategies to reduce the overall waste volume and activity. Sustainability and equity across generations should be considered, including plans for the estimation of the volume of waste generated and its treatment and disposal. Use of reduced activation construction materials is planned, offering the benefits of less decay heat generation in the waste and rapid radioactive decay overall. Consequently, efforts to recycle and clear are essential for fusion deployment, minimizing the burden associated with radioactive waste for future generations.

Examples of main characteristics of fusion waste from a DEMO sized reactor are:

- Intermediate level waste may be formed during operation, which converts/decays to low level waste post operation;
- Depending on the reactor materials and their quantities used, the volume of waste may be significant, both in terms of actual volume and volume per unit of electricity produced;

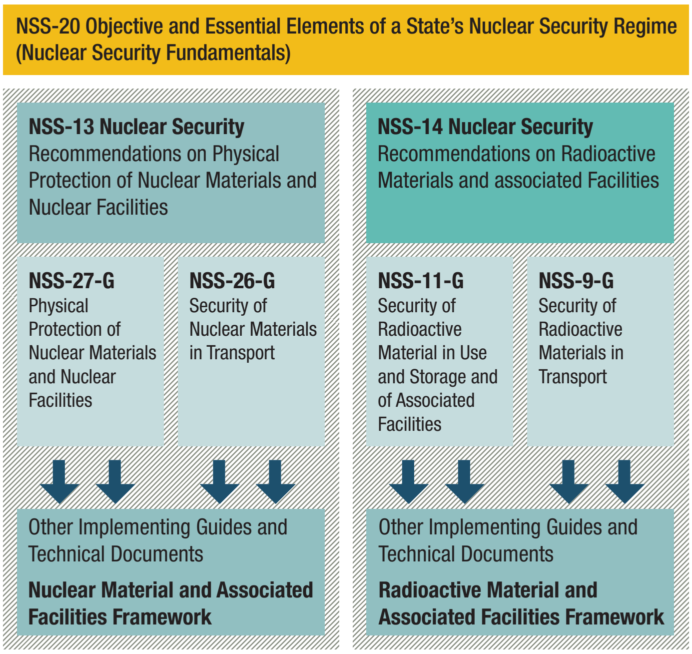
- Fusion power generation will not create high level waste;
- There is a need to detritiate waste, but industrial scale techniques are not yet well established;
- Activation of the biological shield that surrounds the fusion power plant is expected to be very low, so most of the material is expected to be cleared for reuse/recycling in decommissioning.

Depending on the fusion reactor size and design, the amount of intermediate level waste that will be created during operation may necessitate some level of decay storage. The dominant fusion wastes are mainly composed of structural materials (different types of steel) and functional materials (such as materials associated with tritium breeding, manifolds, etc.). States would be encouraged to understand the full inventory of radioactive waste from the fusion reactor design deployed and to plan accordingly to ensure that treatment and disposal options, including capacities, are in place for all wastes.

The disposal of volumetrically tritiated components is especially challenging. The usual scaling methods based on gamma spectrometry (see, for example, Ref. [46]) cannot be used for tritium measurement in fusion waste, as correlation of the amounts of tritium with other activated nuclides might not be possible. This is because tritiated materials result predominantly from permeation into the materials from other sources. Therefore, the assessment of the tritium inventory needs to be based on modelling and specific measurements. Tritium decontamination and recovery techniques that have been developed at the laboratory or pilot scale will need to be demonstrated and commercialized at the process scale. Many low level waste sites, for example, have firm and very low limits on tritium that can be disposed (e.g. 30 ng of T or 10^7 Bq T/gram of waste). For realistic tritium waste management, these levels may have to be revisited to create a safe disposal location or dedicated tritium management options must be created and implemented. ■

Nuclear security

The IAEA Nuclear Security Series provides a comprehensive resource and a solid framework for the security of both nuclear installations and radioactive material associated facilities based on technology neutral principles. The guidance publications developed for radioactive material associated facilities are fully applicable to future fusion power plants. The nuclear facility specific guidance publications are applicable to fusion–fission hybrid power plants, but not directly to fusion power plants. However, a subset of these can be of use to fusion power plant designers, operators and regulators. Until specific fusion power plant security guidance publications are made available, these publications are useful for the security evaluation of fusion power plants when interpreted in a way that is proportionate to the much lower hazardous outcomes from a sabotage or unauthorized removal event at a fusion power plant compared with an equivalent NPP. ■



Categorization of IAEA nuclear security guidance publications with reference to the nuclear material and nuclear facilities framework and to radioactive material and the associated framework.

Nuclear security and security threats

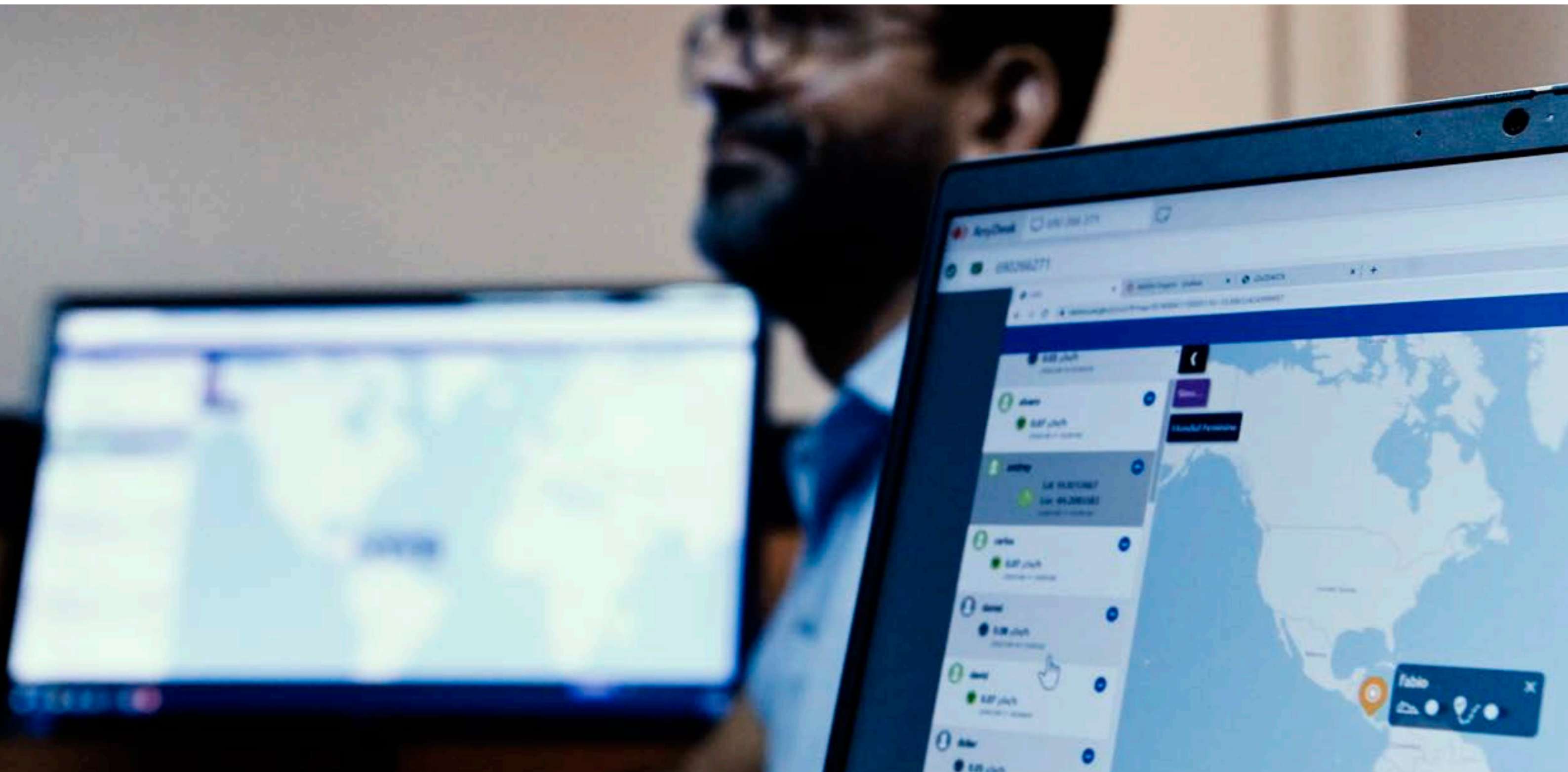
Nuclear security for fusion power plants

Nuclear security is the prevention and detection of, and response to, criminal or intentional unauthorized acts involving or directed at nuclear material, other radioactive material, associated facilities or associated activities. The nuclear security regime of a State comprises the legislative and regulatory framework and administrative measures, the institutions and organizations ensuring the implementation of the framework and nuclear security systems and nuclear security measures.

The risk management approach to be achieved comprises the determination of a credible threat, assessment of potential consequences of unauthorized removal and sabotage, and addressing, through an effective physical protection system, the vulnerabilities of targets within the facility. ■

Security threats

A security threat is a credible description of the capabilities of potential adversaries established by the State based on its national nuclear security threat assessment. The attributes and characteristics of potential insider and/or external adversaries, who might attempt unauthorized removal or sabotage, against which a physical protection system is designed and evaluated. ■



Sabotage targets of fusion technology

Future commercial fusion power plants could be attractive targets for threat actors because:

- The plants will be a part of a Member State's national critical infrastructure; thus, their sabotage will have consequences on energy supply.
- Fusion power plants will contain radioactive material, while hybrid fusion–fission power plants will contain nuclear material as well, which are potential targets for unauthorized removal and subsequent dispersal.
- Sabotage of fusion power plants (especially hybrid fusion–fission power plants) may cause unacceptable radiological consequences in the environment.

The main sabotage targets would be the main facility structures, systems, and components ensuring the safe and secure operation of the fusion power plant, and storage locations of the fusion fuel materials and radioactive waste on the facility site. The main targets for unauthorized removal from a fusion power plant would be the fuel material present and the radioactive material produced as a result of the fusion reactions. The main materials expected to be used as fusion fuel are D–T. ■

Radiological consequences of sabotage scenarios

An accident based on 1 kg tritium in-vessel inventory and conservative assumptions (see Ref. [47]; 1 kg is without consideration for the tritium in the tritium processing plant associated with the reactor) can cause unacceptable radiological consequences in the case of a successful sabotage, and thus it requires proper security measures to be implemented.

The worst case scenario for a specific hybrid fusion–fission system would be complete destruction of the facility. The radiological consequences of such a scenario would be similar to those for sabotage of a fission NPP. ■

Nuclear security functions

Due consideration should be given to integrating safety aspects along with implemented security measures for safe, economical and secure operation of a fusion facility. Consideration of security measures should start from the design stage. Essential functions of physical protection systems, like deterrence, detection and assessment, delay and response, should be implemented to ensure sufficient delay after detection for timely response. Digital fusion plant control and instrumentation systems need computer and information security measures to ensure confidentiality, integrity and availability. ■

Design principles

Like in the case of fission NPPs, the principles guiding security systems design should offer:

- Defence in depth: several layers of protection measures that the adversary needs to deceive, avoid or defeat in sequence to succeed.
- Balanced protection: a physical protection system, such that the adversary encounters comparably effective measures whenever, wherever or however the malicious act is attempted.
- Robustness: protection with a high probability of operating effectively during a wide range of types of adversary attack. ■

Safeguards considerations

Each non-nuclear-weapon State (NNWS) party to the NPT [28] commits to accepting IAEA safeguards on all nuclear material in all peaceful nuclear activities within its territory, under its jurisdiction, or carried out under its control anywhere. Nuclear material subject to safeguards is defined in the safeguards agreements as source or special fissionable material. To meet the requirements of Article III of the NPT [28], NNWSs party to the NPT also commit to conclude a CSA with the IAEA. In 1971, the IAEA Board of Governors approved The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons [48] and requested the IAEA Director General to use this document as the basis for negotiating safeguards agreements between the IAEA and NNWSs party to the NPT. Currently, CSAs are in force for 181 NNWSs party to the NPT.

Since nuclear material is not involved, the IAEA currently does not apply safeguards nuclear material accountancy to fusion systems under any type of safeguards agreement. Further consideration is needed to ascertain whether the scope of IAEA safeguards under the safeguards agreements (CSAs, VOAs and item-specific safeguards) applies to a fusion energy system, or if IAEA safeguards activities might be conducted at a fusion system location, as more information of such systems becomes available. Cases of a fusion system designed to use, produce or contain nuclear material include fusion–fission hybrid systems; fusion neutron sources for uranium-233 or plutonium-239 breeding; fusion systems for transmutation of radioactive waste containing nuclear material; and fusion systems using depleted uranium in shielding or collimators. These systems, and any other fusion system involving nuclear material, might become subject to IAEA safeguards, depending on the scope of application of the safeguards agreement with the country concerned.

Even in a fusion system that ostensibly does not use, produce or contain nuclear material, there is nevertheless a possibility that nuclear material or other material of safeguards interest (e.g. neptunium/americium) could be (covertly) used or produced, e.g. through the use of irradiation targets containing nuclear material and production of special fissionable material. Under the applicable safeguards agreement with the State, in particular under the Additional Protocol [35], the IAEA can access other relevant locations in the country in order to resolve questions or inconsistencies relating to the correctness and the completeness of the State’s safeguards declarations or to assure the absence of undeclared nuclear material and activities.

Nuclear material subject to safeguards is defined in the safeguards agreements (i.e. source or special fissionable material). Source material and special fissionable material is defined in the IAEA's Statute Article XX. Source material means material containing uranium with a natural occurring mixture of isotopes; uranium depleted in uranium-235; and/or thorium in concentrations above specified amounts. Special fissionable material refers to material containing plutonium-239; uranium-233; and/or uranium enriched in uranium-235 or uranium-233; plus other fissionable material determined by the Board of Governors. Special fissionable material does not include source material. ■

Labelled and weighed bottles at the IAEA's Seibersdorf Laboratories, ready for dispatch to safeguards inspectors.

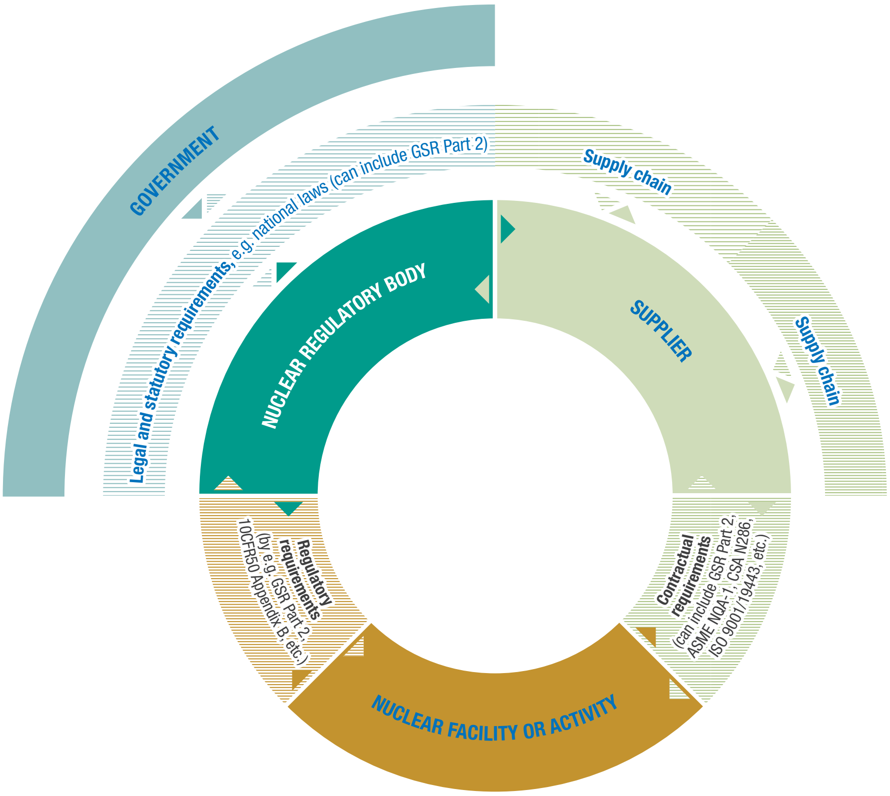

FUSION FOR ENERGY

Additional areas for consideration

Construction works

The construction works of future fusion power plants will not be fundamentally different from that of fission NPPs or other big industries, for which decades of experience is available. Large modules (even 1000 tonnes) have been used in nuclear construction since the 1980s, and traditional stick building still takes place even in fusion projects. In parallel to the construction, and in many cases long before construction starts, manufacturing of structures and long lead components begins. One challenge may be environmental qualification of some of these components to the demanding service conditions. Managing the interfaces to the supply chain brings another dimension of making sure that the specifications (contractual framework, regulatory and owner) are followed. ■

Example of interfaces between nuclear facility construction projects, governmental regulators and suppliers.

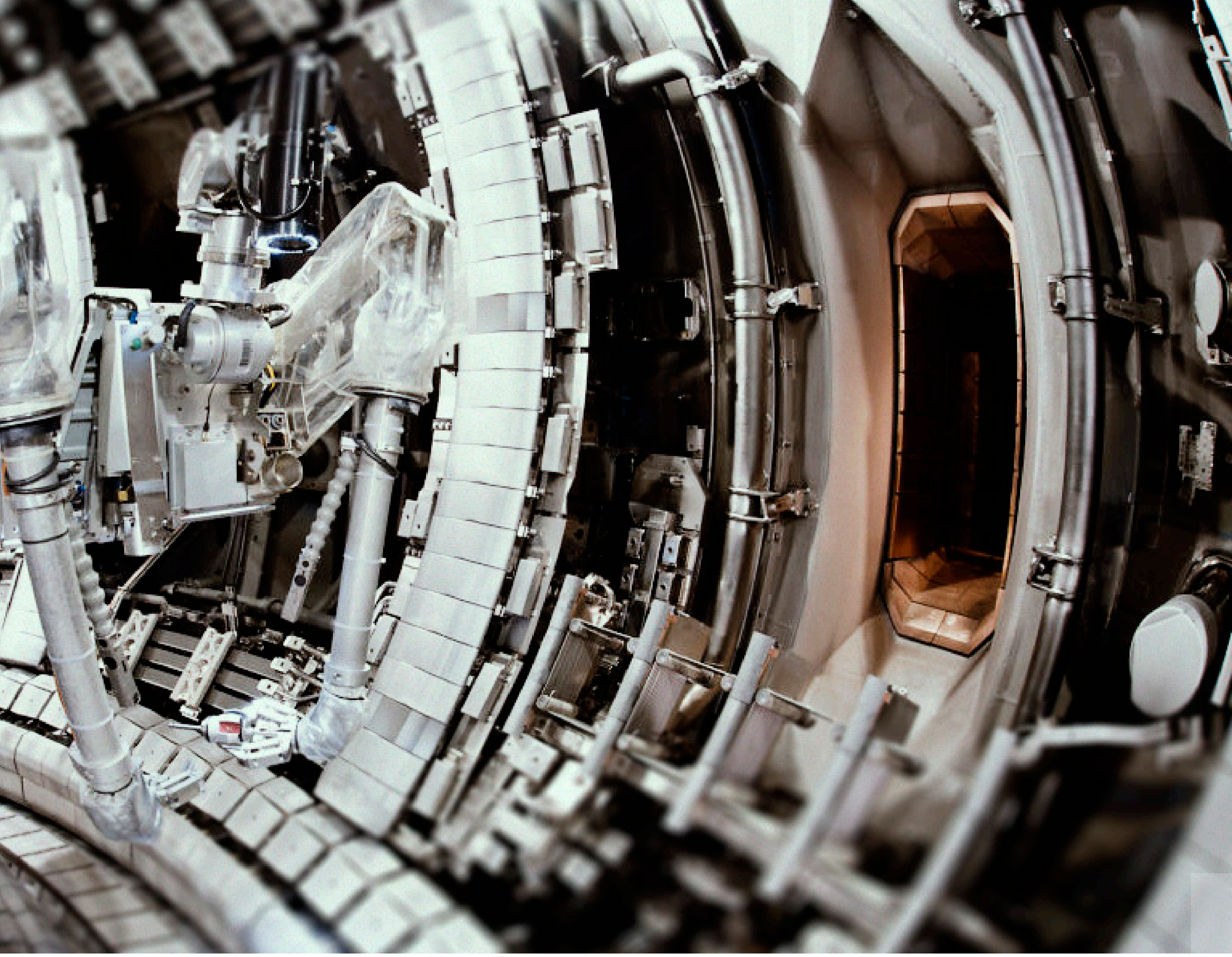


The ITER tokamak. Courtesy of ITER Organization.

MASCOT, a telemanipulator robot system at JET. Remotely operated robotics were used to replace JET's carbon wall with the new tungsten and beryllium wall components. Courtesy of EUROfusion.

Remote maintenance

A fusion plant using D–T as fuel will become activated and the radioactivity and heat inside the torus prohibit direct access; therefore, teleoperation and remote maintenance techniques, including the robotic handling system plus management and operational control, are necessary for interventions and maintenance. The tasks envisioned vary, such that the system(s) have to be extremely variable, maintainable, flexible, radiation tolerant, reconfigurable, etc. Tasks include essential operations such as removal and replacement of blanket and divertor plasma-facing components, and exigent tasks, such as repair or replacement of in-vessel faults. Remote handling tasks necessitate grasping and manipulating, vacuum cleaning capabilities, welding, some with high spatial specification as well as capacity for inspection and monitoring of plasma-facing components, for example, for quantitative in situ determination of fuel and tritium retention. Much experience has been gathered from the remote handling operations at the JET facility in Culham, UK [49]. The ITER experiment will provide additional experience in remote operations, including the challenging task of blanket and divertor module manipulations. These systems are crucial for the future of fusion energy, as they trigger/determine downtimes in operation and energy production. ■



Human resources and knowledge management

As the fusion sector grows rapidly, both public and private projects are finding a shortage of highly skilled scientists, engineers, technicians and other skilled staff. Knowledge development and transfer and the retention of professionals are critical for the success of future fusion power. ■

Public perception

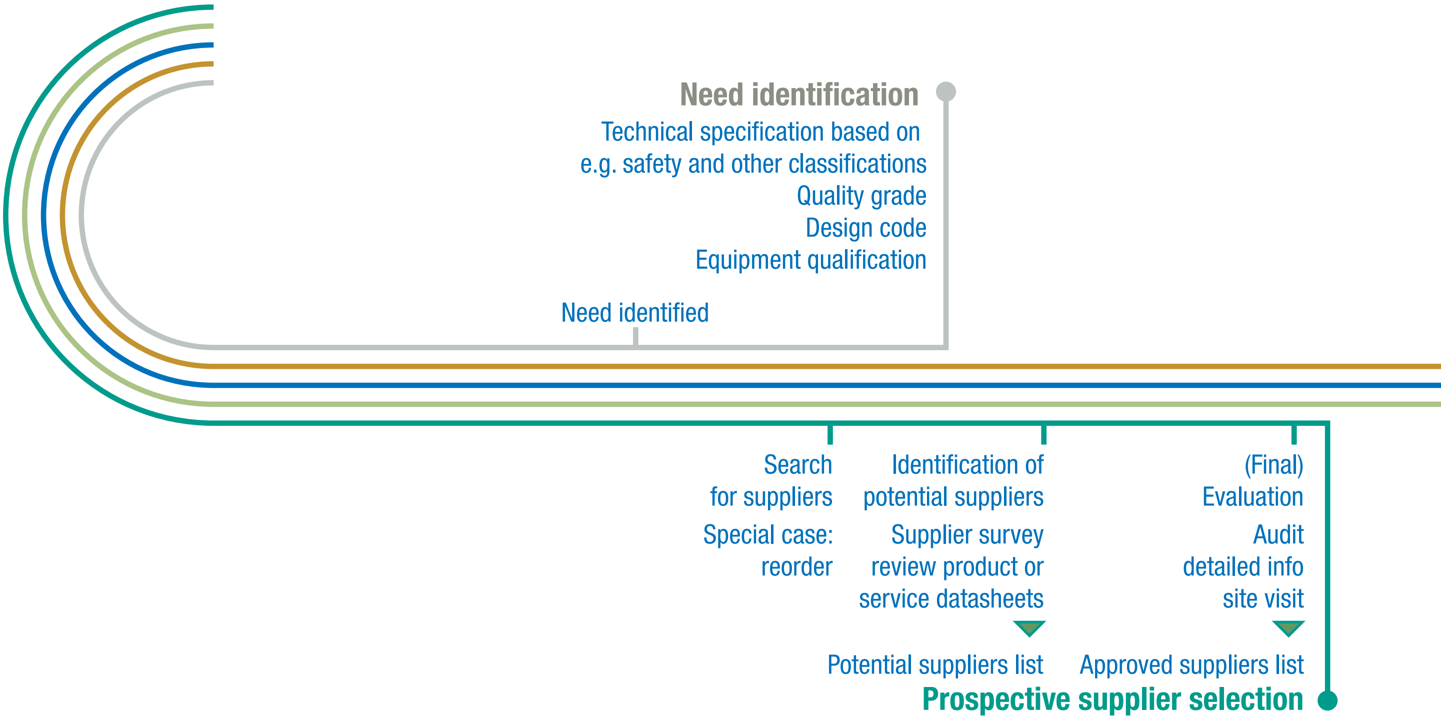
The success of fusion as a future energy source will also depend on public perception. Public education and outreach to increase knowledge and understanding of fusion energy and its benefits as well as associated challenges, such as use of tritium and generated radioactive waste, will contribute to an informed public. The fusion power industry should be transparent, as this will increase public awareness and support. A lesson learned from the fission arena is that lack of transparency can negatively impact public support and perception. ■

Supply chain

The Fusion Industry Association estimates that the value of the fusion supply chain in 2022 was over US $500 million [50]. Furthermore, they predict it will grow to US $7 billion by the time a first commercial fusion power plant is built. The supply chain for fusion energy includes a small number of highly specialized niche manufacturing and services. However, the main bulk of products and services need only to deliver good industrial quality. This means subcontracting and long supply chains will come to play the major role, as in any other high-tech industry. Already, private enterprises that target the fusion industry supply chain have emerged, such as the Japanese Kyoto Fusioneering, which has already attracted capital investments [51]. Such a fusion supply chain dedicated company is driven by the mission to enable net-zero carbon emissions.

It is very important that the fusion customers are well informed and approve suppliers with revaluation in suitable intervals. Having a number of suppliers with varying importance requires a graded approach in evaluation of their suitability to supply. For fusion plant supplies sufficient quality assurance and control is paramount to avoid long project delays, in particular for long lead components and modules. In this respect both fission and fusion supply chains are alike.

Like the supply chain of large NPPs and small modular reactors, that of fusion requires mechanisms that create stability and a clear outlook. These mechanisms include public–private partnerships, equitable risk sharing mechanisms, global and local networks of suppliers to avoid supply bottlenecks, learning from other industries, standardization where possible and transparent regulatory frameworks.



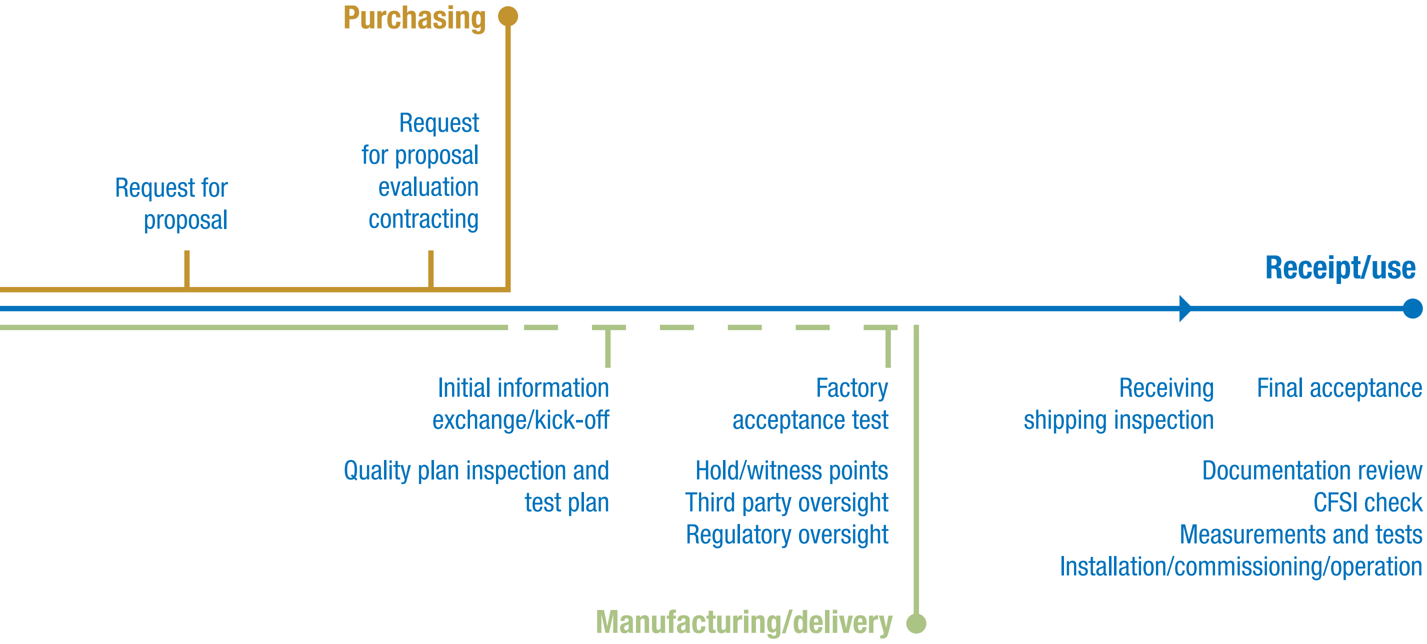
Suppliers need certainty, ways to de-risk the delivery projects and some outlook to the future supply market. Owners/operators need certainty that they can recover the upfront investment during the operation, which may lead to shared risks through collaborative contracting strategies. Supplier networks normally improve security of supply, avoidance of large supply chain disturbances and may help keep costs reasonable; however, supplier networks may lead to difficult tracing. The fusion power industry may need to learn flexible supply chain management, harmonization and standardization from other industries where it makes sense. ■


FUSION
INDUSTRY ASSOCIATION

The Fusion Industry Supply Chain:

Opportunities and challenges

Fusion Industry Association
The Fusion Industry Supply Chain report [52].



Example of the process of procurement and supply in the case of fusion power plant.

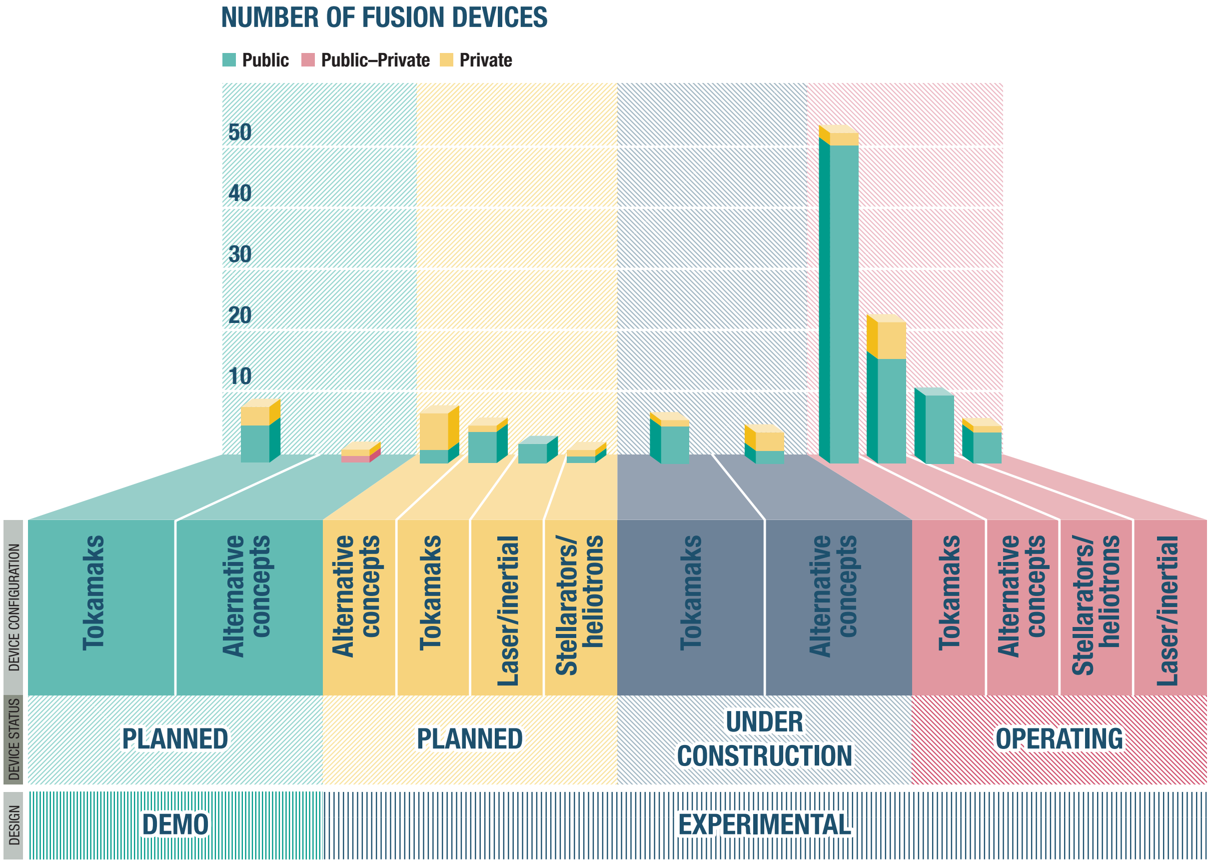
Note: CFSI — counterfeit, fraudulent and suspect items.

Outlook

Existing DEMO and pilot plant plans and public–private strategies for fusion

Major paths to fusion

Nuclear fusion and plasma physics research are carried out in more than 50 countries and fusion reactions have been successfully produced in many experiments, albeit without so far generating useable energy. Experts have come up with different designs and magnet based machines in which fusion takes place, including stellarators and tokamaks, but also approaches that rely on lasers, linear devices and advanced fuels were under consideration. ■



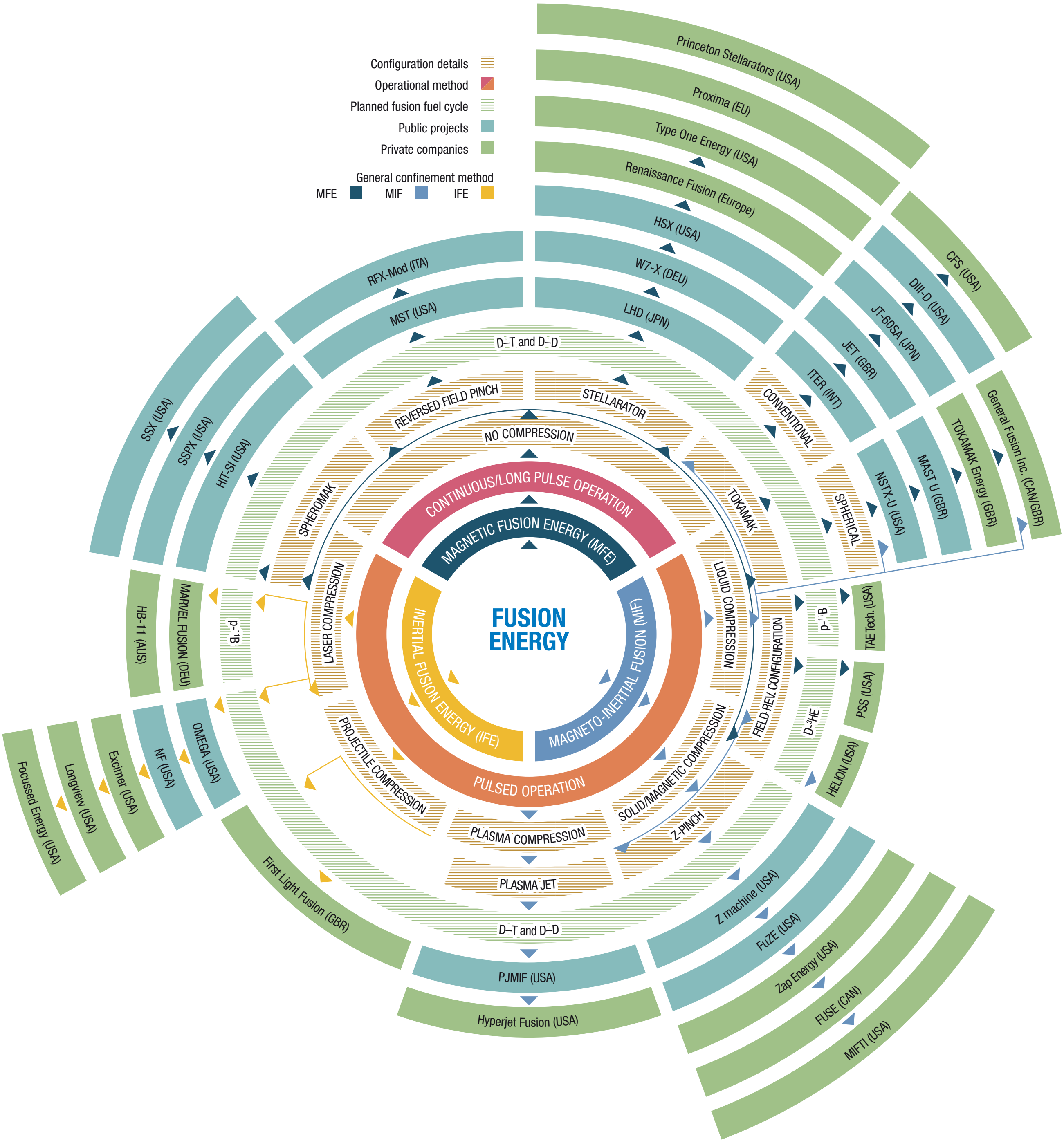
▲

The configuration and status of the more than 140 public and private fusion devices listed in Ref. [52]. Note: Alternative concepts include the following types: dense plasma focus; field reversed configuration; inertial electrostatic fusion; levitated dipole; magnetic mirror machine; magnetized target fusion; pinch; reverse field pinch; simple magnetized torus; space propulsor; and spheromak.

◀ **World Survey of Fusion Devices**

Information on more than 140 fusion devices worldwide, both public and private, either in operation, under construction or being planned, is available in the IAEA Fusion Device Information System (FusDIS). The publication IAEA World Survey of Fusion Devices 2022 [52] is a compilation of the FusDIS information with some additional information for the status ending in 2022.

How long it will take for the successful implementation of fusion energy will depend on how fast the industry is able to develop, validate and qualify emerging fusion technologies as well as establish in parallel the necessary nuclear infrastructure, including relevant requirements, standards and good practices. ■

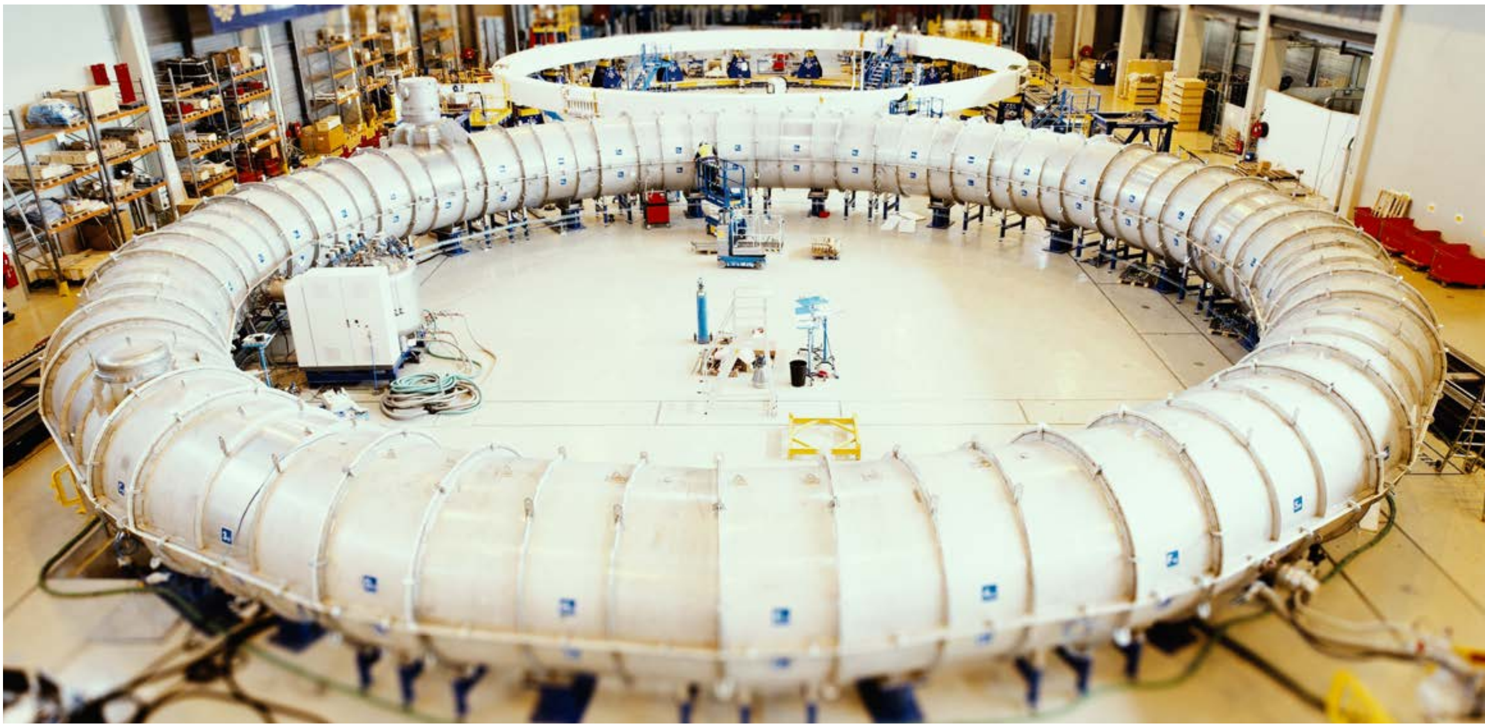


Major paths to fusion currently being developed, their means of confinement, operation mode, configuration, fuel and major source of funding. The list of devices given as examples is not exhaustive and is only representative for the given confinement concept. The figure is based on the original taxonomy created by D.A. Sutherland. Note: AUS – Australia, CAN – Canada, DEU – Germany, GBR – United Kingdom, ITA – Italy, JPN – Japan, RUS – Russian Federation, INT – international, PSS – Princeton Satellite Systems.

“The global surge of interest in fusion energy in recent years, as evidenced by public and private research initiatives, investment, public awareness and stakeholder support, is a most welcome development.
My hope is that these efforts can be channelled into collectively identifying solutions for the remaining science and technology challenges in order to make nuclear fusion an energy source available for future generations.”

Pietro Barabaschi
Director-General of the ITER Organization

Image courtesy of ITER Organization.



Two final ring-shaped poloidal field coils are taking shape in the European Domestic Agency's fabrication workshop on the ITER site. PF4 coil has completed cold testing and will soon re-emerge from a tailor made vacuum chamber (foreground). The resin impregnated superconducting winding pack for PF3 coil (background) is ready for clamps, protection covers and helium inlet pipes. Courtesy of ITER Organization.

Significant fusion programmes

ITER

The world's largest international experimental fusion facility is ITER, located in Cadarache, France. Following ten years of component design, site preparation and construction and manufacturing across the world, the assembly process of ITER started in 2020. ITER is an international experimental project aimed at demonstrating the scientific and technological feasibility of fusion energy production, as well as validating the technology and concepts for future electricity producing demonstration fusion power plants, called DEMOs. Such a DEMO could act as an intermediate step between the experimental fusion reactor ITER and a pilot fusion power plant. ITER members are China, the European Union (EU) (through the European Atomic Energy Community (Euratom)), India, Japan, the Republic of Korea, the Russian Federation and the United States. ITER's current plans are to start conducting first experiments in the second half of this decade and full power experiments commence in 2036. However, at the 32nd ITER Council Meeting in June 2023 discussions focussed on updating financial and schedule baselines for approval in 2024 [53]. Baseline updating is needed due to delays during the COVID-19 pandemic, challenges in first-of-a-kind component fabrication, alignment with the French regulator and enhanced scope, including a proposed change of the first wall material from beryllium to tungsten. ■

ITER
in numbers

TECHNICAL INFORMATION

Device type	**Conventional tokamak**
Status	Under construction
Major radius, R_o	6.2 m
Minor radius, a	2 m
Plasma current, I_p	15 MA
Toroidal field, B_o	5.3 T
Pulse length	Up to 3000 s
Magnetic field configuration	Divertor separatrix
Ownership	Public

ITER is designed to demonstrate the scientific and technological feasibility of fusion energy production. The principal scientific objectives of the ITER project are demonstrating a scientific energy gain $Q_{sci} \geq 10$ for D–T plasma burn for a duration of 300–500 s (inductive ELMy H-mode) and the development of long pulse, non-inductive scenarios aiming at maintaining $Q_{sci} \approx 5$ for periods of up to 3000 s [54]. Courtesy of ITER Organization. ■

The scientific energy gain corresponds to the fusion energy released (heat produced) divided by the energy delivered to the fuel (heating given). This is different from the engineering energy gain (Q_{eng}), which corresponds to the ratio of grid power to recirculating electrical power. ITER is designed to achieve scientific energy gain. DEMO-type devices are designed to achieve net engineering gain ($Q_{eng}>1$). ■

▲
Weight: 23 000 tonnes.
Height: nearly 30 metres.
Site dimensions: 180 hectares.

▲
Plasma volume: 830 m^3
the largest ever built.

▲
Magnet system: 18 toroidal field magnets weighing 310 tonnes each,
6 poloidal field coils, a 13 metre high central solenoid weighing 1000 tonnes,
18 superconducting correction coils, 31 superconducting magnet feeders
and 29 non-superconducting in-vessel coils, weighing more than 9000 tonnes.

Divertor: 54 stainless steel, ten-tonne cassettes. First wall facing material: tungsten, low tritium absorption and highest melting temperature of any natural element.

External heating systems with their maximum capacity:
33 MW neutral beam injection;
20 MW ion cyclotron heating;
20 MW electron cyclotron heating.

Design target: generate 500 MW of fusion power from 50 MW injected power for periods of 300 to 600 seconds.

DEMO and pilot plants

The most advanced DEMOs under development are in the countries that have been involved in ITER.

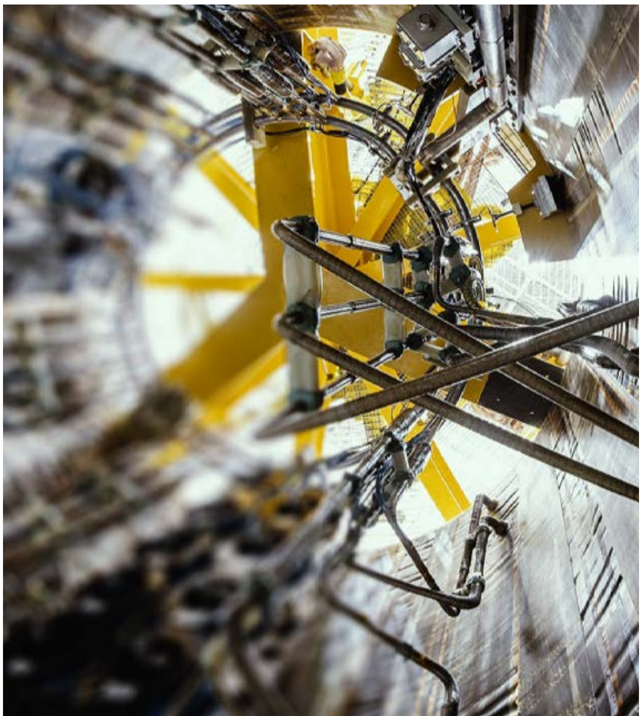
DEMO and pilot plant timelines vary in different countries (see Table 2), but the consensus among experts is that an electricity producing fusion power plant could be built and operating by 2050. A number of privately funded commercial enterprises are also making strides in developing concepts for fusion power plants, some proposing fusion power even sooner, drawing on the know-how generated over years of publicly funded research and development. Some of these private companies are pursuing concepts based on fusion reactions other than the D–T reaction. ■

An employee from ITER's Magnet Section works closely with the contractor team as it carries out the many assembly steps required on module one. Courtesy of ITER Organization.

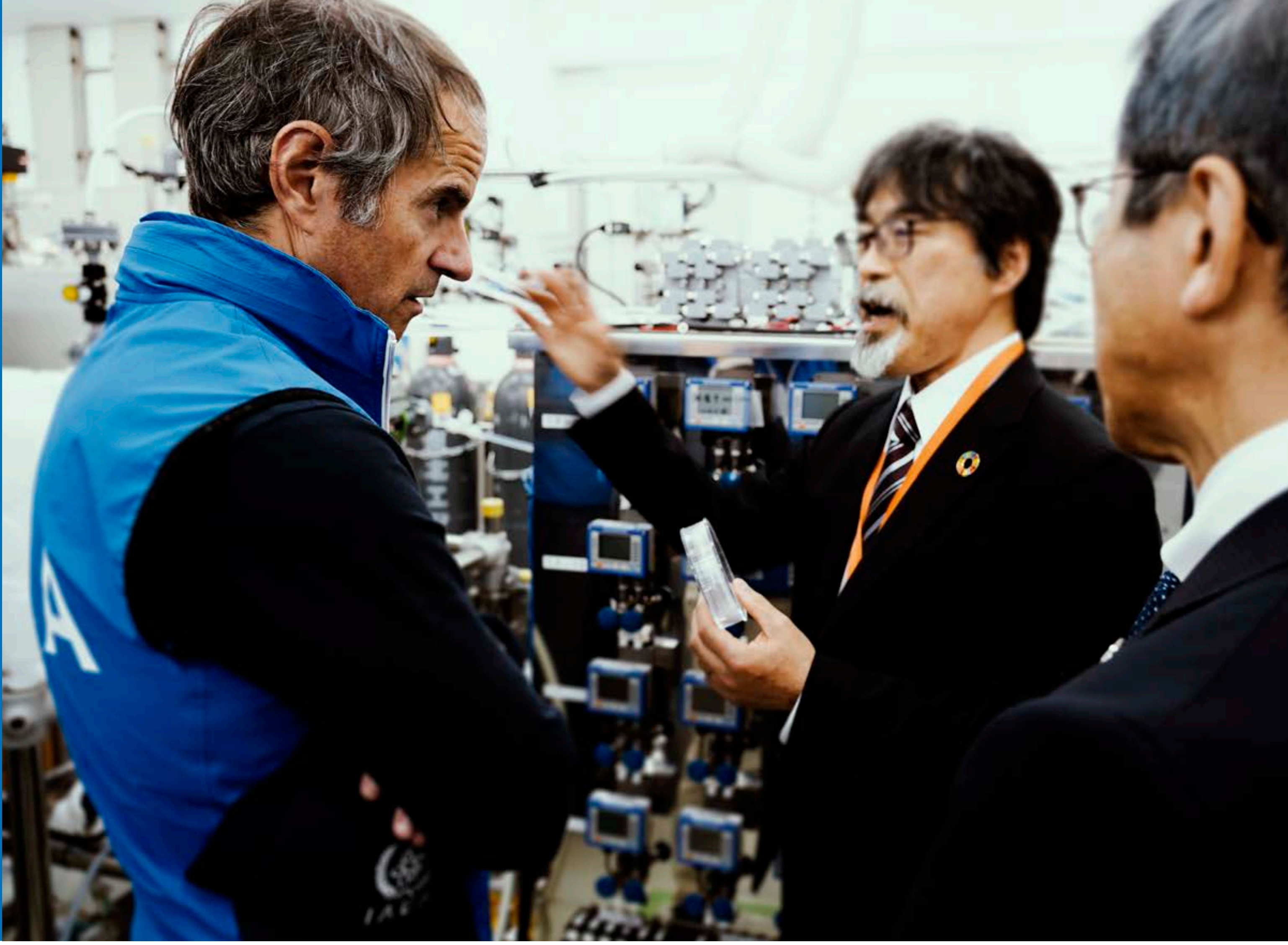
TABLE 2: LIST OF PLANNED DEMO DEVICES

Country	Organization	Name	Type	Ownership
Canada	General Fusion Inc.	FDP	Magnetized target fusion	Public–private
China	Chinese Consortium	CFETR	Conventional tokamak	Public
EU	EUROfusion	EU-DEMO	Conventional tokamak	Public
Japan	Japanese Consortium	JA-DEMO	Conventional tokamak	Public
Republic of Korea	Korea Institute of Fusion Energy	K-DEMO	Conventional tokamak	Public
Russian Federation	Russian Consortium	DEMO-RF	Conventional tokamak	Public
UK	Tokamak Energy	ST-E1	Spherical tokamak	Private
	UKAEA	STEP	Spherical tokamak	Public
USA	Commonwealth Fusion Systems	ARC	Conventional tokamak	Private
	General Atomics	GA FPP	Conventional tokamak	Private
	Longview Fusion Energy Systems, Inc.	Longview Fusion Pilot Plant	Laser/inertial	Private
	TAE Technologies	Da Vinci	Field reversed configuration	Private

The first of six cylindrical superconducting magnets for the central solenoid is positioned on a dedicated assembly platform at ITER. This picture was taken inside the cylinder, among the helium input pipes and electrical connections. Courtesy of ITER Organization.



Plasma-facing units of the ITER divertor outer vertical target prototype have been mounted on a test assembly for high heat flux heating in Japan. The conditions at the bottom of the machine, where waste gas and impurities are exhausted from the reactor, can be described as extreme. Courtesy of ITER Organization.



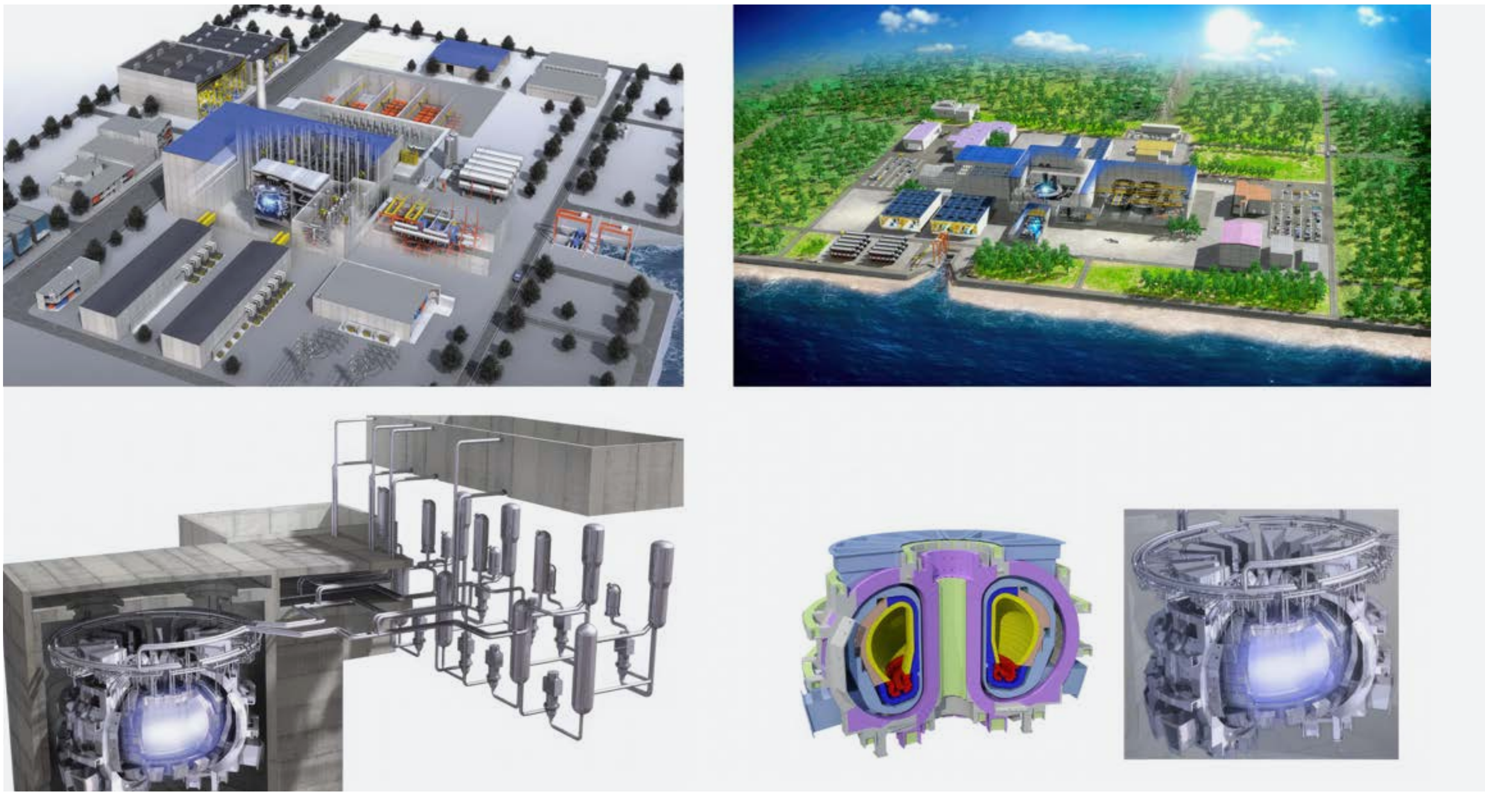
IAEA Director General, Rafael Mariano Grossi, visits the Rokkasho Fusion Institute during his official visit to Japan in July 2023.

Canada

The company General Fusion, with headquarters in Canada, is developing a Fusion Demonstration Plant (FDP) based on magnetized target fusion technology, which aims to be a 70% scaled version of the commercial pilot plant [55]. The magnetized target fusion design uses pneumatic pistons to compress a hot plasma contained within a rotating liquid metal to enable fusion of the fuel. The generated heat from the fusion reaction will be transferred to the liquid metal and, in future commercial power plants, can be extracted to produce steam to drive a turbine producing electricity. The FDP is not fully DEMO-like, as it will not produce electricity. The FDP is expected to be commissioned in 2026 and fully operational by early 2027 [56]. ■

China

China has made significant progress in planning for a device called China Fusion Engineering Test Reactor (CFETR) [57], a DEMO concept based on a conventional tokamak design being developed by a Chinese Consortium. The conceptual design was completed in 2015 and construction of CFETR is expected to be completed by 2040. CFETR is intended to bridge the gaps between ITER and a future fusion power plant, with the aim to demonstrate net engineering gain (Q_{eng}>1). It will be implemented in two phases. During the first phase, efforts will focus on achieving steady state operation and tritium self-sufficiency with power up to 200 MW. This phase will address research and development



The Japanese DEMO concept, JA-DEMO.
Courtesy of National Institutes for Quantum Science and Technology.

issues relevant to burning plasma physics, in order to demonstrate steady state advanced operation. The second phase will focus on validating DEMO-relevant issues with fusion power above 1000 MW. Some of CFETR conceptual features are: major radius of 7.2 m, minor radius of 2.2 m, plasma elongation κ_{95}=2, plasma current of 14 MA, magnetic field on axis of 6.5 T, normalized beta β_N=2.3, and a predicted scientific energy gain Q_{sci}=30. ■

EU

The EU through its EUROfusion Programme follows its Fusion Research Roadmap to Realisation of Fusion Energy, coordinated by the EUROfusion Consortium with financial support from Euratom. The roadmap, published in 2018 [58], has set milestones that include the target of having demonstrated fusion generated grid electricity by the early 2050s in the European DEMO (EU-DEMO) project. EU-DEMO is the facility planned to follow ITER, and currently is in its conceptual design phase; it is expected to start operating by 2050. EU-DEMO aims to demonstrate the technological and economic viability of fusion by producing about 500 MW of net electricity and to achieve tritium self-sufficiency. Several design options are being studied. These options will have an impact on a number of plant technologies, including the divertor configuration and breeding blanket solution, among others. The pre-conceptual design of EU-DEMO tokamak foresees a major radius of ~9 m and a fusion power of ~2000 MW. ■

Japan

The Japanese DEMO (JA-DEMO) concept [59] is a conventional tokamak design being developed in Japan by a Japanese Consortium. Construction of JA-DEMO is expected to be completed by 2050. The aim of JA-DEMO is to demonstrate net engineering gain (Q_{eng}>1) and tritium self-sufficiency, as well as plant availability, thus bridging the gap to commercialization of fusion energy. For reliable electric power generation, a fusion output of

1500 MW or higher is expected to be necessary. For the magnet system of JA-DEMO, superconducting (Nb_3Sn) magnets consisting of a central solenoid, seven poloidal field coils (NbTi), 16 toroidal field coils (Nb_3Sn or Nb_3Al) are being considered. Some of JA-DEMO conceptual features are: major radius of 8.5 m, minor radius of 2.42 m, plasma elongation $\kappa_{95}=1.65$, plasma current of 12.3 MA, magnetic field on axis of 5.94 T, normalized beta $\beta_N=3.4$, current drive power of 83.7 MW, and predicted scientific energy gain $Q_{sci}=17.5$. ■

India

India is the only ITER member that has not formally launched plans for a DEMO plant. India is developing a fusion roadmap for the next 25 years which would revolve around two new machines to be built before launching an Indian DEMO (after 2040): (i) a fusion neutron source based on a spherical tokamak with coils made of copper (toroidal magnetic field of 2 T, major radius of 1.5 m) for fusion research and development, blanket studies and production of rare radioisotopes; and (ii) a conventional tokamak able to operate at steady state and roughly two thirds the size of ITER (toroidal magnetic field larger than 5 T, major radius of 4 m). These machines are envisioned to be built and operated under public–private partnership frameworks with strong industry participation. ■

Republic of Korea

K-DEMO is a DEMO concept based on conventional tokamak design being developed in the Republic of Korea by the Korean Institute of Fusion Energy [60]. Construction of K-DEMO is expected to be completed by 2050. In a first early phase of the project (2037–2050), K-DEMO will be used to develop and test components. In its second phase, after 2050, it is expected to demonstrate net electrical power. K-DEMO is targeted to demonstrate the physics and technology necessary for achieving net engineering gain ($Q_{eng}>1$). The conceptual design of K-DEMO features a major radius of 6.8 m, minor radius of 2.1 m, toroidal field of about 7 T and plasma current larger than 12 MA. K-DEMO is expected to feature a double-null divertor configuration and the divertor X-point inside the vacuum vessel. The K-DEMO blanket sectors are subdivided into 16 inboard and 32 outboard sectors. The upper or lower divertor is also subdivided into 32 modules. The key features of the K-DEMO magnet system include two toroidal field coil winding packs with different conductors, enclosed in the toroidal field case. ■

Russian Federation

DEMO-RF is a DEMO concept based on conventional tokamak design being developed in the Russian Federation by a Russian consortium. Construction of DEMO-RF is expected to be completed by 2055 and is expected to demonstrate net engineering gain ($Q_{eng}>1$). The DEMO-RF conceptual design currently foresees the use of the facility either as a pure fusion energy system or as a fusion–fission hybrid facility with high temperature superconducting magnets, a total magnetic field larger than 8 T, and plasma current of about 5 MA. Liquid metal plasma-facing components are being considered for the first wall and divertor. In addition, the Russian Federation plans to develop a fusion–fission hybrid facility called DEMO fusion neutron source (DEMO–FNS) [61], a reactor that, in addition to generating energy from fusion, should use the fusion produced neutrons to turn non-fissile uranium into fissile nuclear material or destroy/transmute long lived radioactive waste. The DEMO-FNS is planned to be built by 2033 and is part of the Russian Federation's fast track strategy to a fusion power plant by 2050. ■

UK

In the UK, STEP is a compact DEMO concept based on a spherical tokamak design being developed by UKAEA with a target completion date of 2040. The first phase of the programme is to produce a concept design by 2024. STEP is expected to be smaller than ITER, with a tighter aspect ratio torus to improve the efficiency of the magnetic field and potentially minimize the plant's costs. Although not expected to be a commercially operating plant, STEP aims to demonstrate the commercial viability of fusion by producing net engineering gain ($Q_{eng}>1$) alongside establishing an associated supply chain and skills pipeline, in order to further nurture a fusion industry.

A private DEMO concept in the UK is the ST-E1, based on spherical tokamak design being developed by UK company Tokamak Energy Ltd. ST-E1 is expected to be completed in the early 2030s, following a successful build of a prototype on the UKAEA site. The purpose of ST-E1 is to demonstrate net engineering gain ($Q_{eng}>1$). ST-E1 will be a compact spherical tokamak with high temperature superconducting magnets. ■

IAEA Director General, Rafael Mariano Grossi,
visits the CFS SPARC tokamak in Massachusetts, USA
in September 2023. ▶

USA and privately funded strategies

The report Global Fusion Energy in 2023 [62] by the Fusion Industry Association provides results from surveys of 43 private fusion companies, including information on the status of plans and projects of these companies, the large majority (77%) of which focus on energy production and are based on D–T fuel (65%). The report includes industry profiles, which indicate that, although there are a number of companies with one or two decades of experience, two thirds are recent start-ups and/or were founded since 2018. The numerous private investors in the fusion sector are likely the drivers for this recent surge in industrial fusion activities.

The US plans to deliver DEMOs to date lie in private industry. Very recently, the US DOE announced the allocation of US $46 million to eight commercial companies in their Milestone-Based Fusion Development Program [63]. The eight US enterprises are Commonwealth Fusion Systems, Focused Energy Inc., Princeton Stellarators Inc., Realta Fusion Inc., Tokamak Energy Inc., Type One Energy Group, Xcimer Energy Inc. and Zap Energy Inc.

ARC is a DEMO concept based on a conventional tokamak design being developed by CFS. The purpose of ARC is to demonstrate the commercial viability of fusion with high temperature superconducting magnet technology. ARC will be a compact conventional tokamak with high temperature superconducting magnets able to produce ~200–250 MWe, with a radius of 3.3 m, a minor radius of 1.1 m, and an on-axis magnetic field of 9.2 T. ARC will feature REBCO superconducting toroidal field coils. The coils will have joints to enable disassembly for quick replacements of the vacuum vessel, thus mitigating first wall lifetime issues and enable the possibility of testing various vacuum vessel designs and divertor materials.

ARC will benefit from information derived and lessons learned from the CFS SPARC tokamak, presently under development (construction start was February 2023), expected to become operational in 2025 and planned to generate a net scientific energy gain. CFS have disclosed around US $2.1 billion in fusion funding, which is almost as much as all the other private sector fusion companies combined. The General Atomics Fusion Pilot Plant (GA FPP) is a steady state, compact advanced tokamak design demonstration fusion plant, announced in October 2022 by General Atomics. GA FPP aims to demonstrate the commercial viability of fusion, achieving steady state operation, maximizing efficiency, reducing maintenance costs and increasing the lifetime of the facility. The GA FPP design approach will rely on advanced sensors, control algorithms and high performance computers for controlling the plasma, silicon carbide shielding and microwave heating.

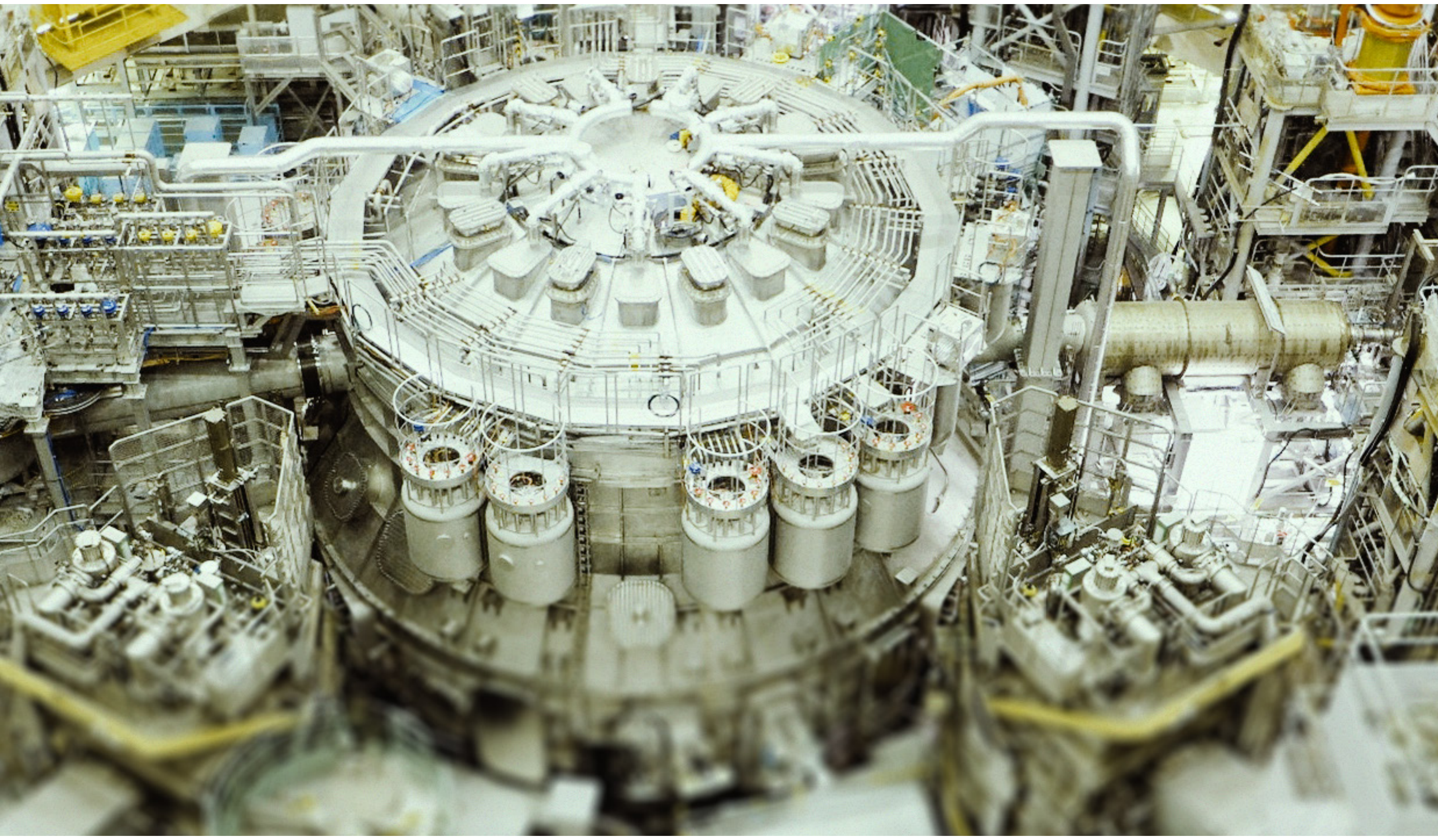
Da Vinci is a DEMO concept based on a field reversed configuration design being developed by TAE Technologies. The purpose of Da Vinci is to demonstrate the commercial viability of fusion in a reversed field configuration via p–^{11}B reactions. Da Vinci will be a field reversed configuration device. ■

Broader approach

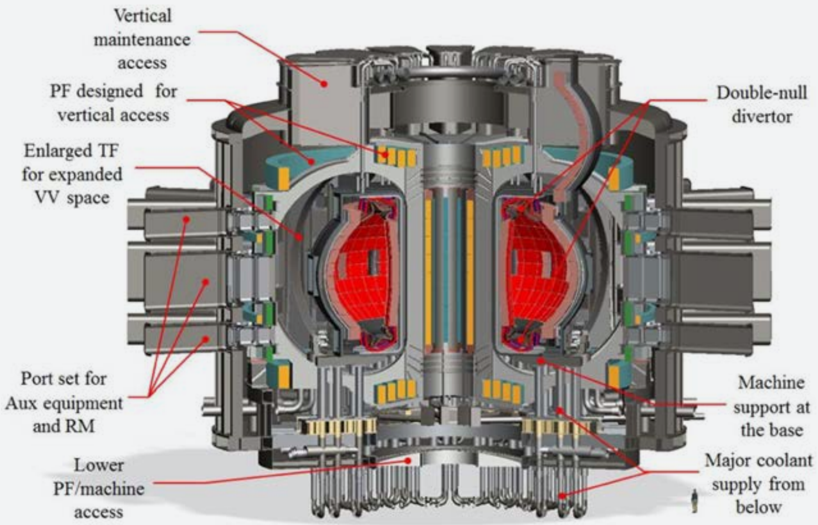
The Broader Approach Agreement established in 2007 between Euratom and Japan strives to accelerate the development of fusion technology. Under the Broader Approach Agreement, the EU and Japan are working together on three fusion-related projects, all located in Japan and complementary to ITER: constructing the joint international fusion experiment, JT-60SA; the Engineering Validation and Engineering Design Activities for the IFMIF (IFMIF/EVEDA); and the International Fusion Energy Research Centre (IFERC).

JT-60SA is currently the largest tokamak in the world and was completed in 2020. Its programme focuses on scenario development and risk mitigation in ITER and DEMOs. Three facilities have been designed and manufactured to validate the IFMIF design in EVEDA: the neutron flux test facility, the lithium target facility and the accelerator facility.

IFERC has coordinated characterization of unique JET samples from tungsten and beryllium-based plasma-facing components of the JET ITER-Like Wall project and from JET operational campaigns with D–T plasmas.



JT-60SA, the joint international fusion experiment between Japan and Euratom. Courtesy of National Institutes for Quantum Science and Technology.



The Republic of Korea’s K-DEMO device. Reproduced from Ref. [60] with permission.

Nascent and emerging fusion programmes

Fusion development should not be wholly limited to the developed part of the world and should involve countries other than ITER members. It is important to inspire a new generation in other parts of the world, leaving no one behind. In this context, the IAEA supports fusion experiments, training personnel in their operation and educating the next generation of fusion scientists.

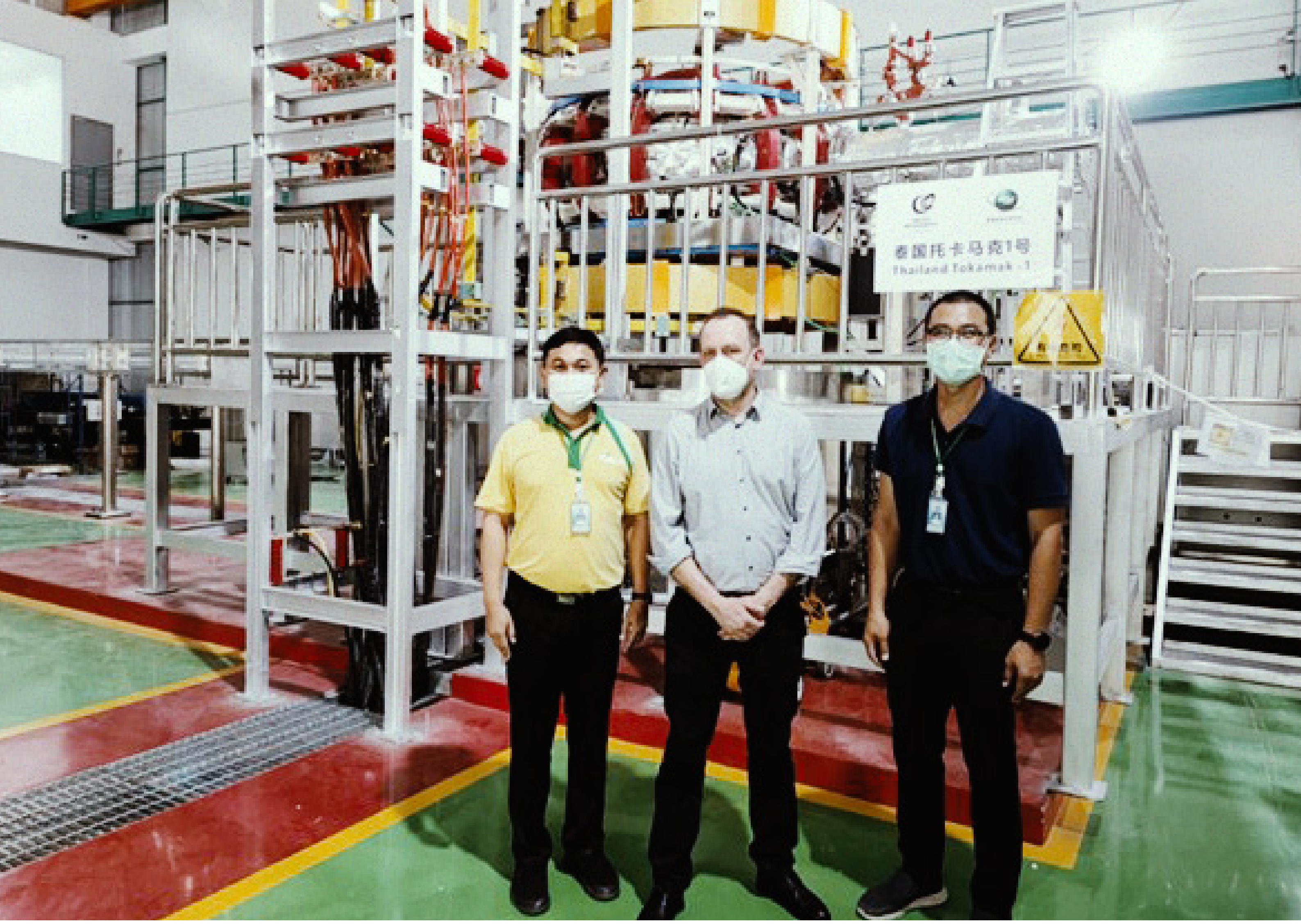
The Association of Southeast Asian Nations (ASEAN) School on Plasma and Nuclear Fusion has been held since 2014, with latest editions in cooperation with the IAEA at the Thailand Institute of Nuclear Technology. These schools helped both Thailand and neighbouring countries to advance fusion research and educate young scientists and students. The experimental tokamak, Thailand Tokamak 1, which is installed in Thailand and commenced operation in 2023, is the central activity in the country's fusion development programme. It is the first fusion device operated by ASEAN and therefore a crucial learning platform for Thai and ASEAN researchers.

Since 2012, many young researchers from developing countries have been able to attend the Joint International Centre for Theoretical Physics (ICTP)–IAEA College on Plasma Physics series, which in its latest edition in 2022, was extended to include fusion applications [64].

The latest editions of ITER International Schools were also organized in cooperation with the IAEA, allowing attendance through grant attributions to participants from developing countries.

To strengthen training and collaboration between research teams in developed and developing countries, the IAEA has led a coordinated research project since 2004 on small and medium size fusion devices.

The IAEA also supports Kazakhstan's KTM Tokamak, central to fusion development in the Commonwealth of Independent States. The IAEA also nurtures fusion activities at the Technology Institute of Costa Rica, which is relatively new to the global fusion scene. ■



Thailand Tokamak 1, a visiting IAEA technical expert (centre) and two experimental officers.

Participants of the 8th ASEAN School on Plasma and Nuclear Fusion 2023, organized in cooperation with the IAEA in Nakhon Nayok, Thailand in May 2023.

Role of the IAEA

Fusion, a cross-cutting IAEA venture

Fusion, a cross-cutting IAEA venture

The IAEA has supported and coordinated development activities in nuclear fusion since as early as 1958. In September of that year, at the Second United Nations Conference on the Peaceful Uses of Atomic Energy held in Geneva, Switzerland, the theme focussed on then recently declassified material on fusion energy. Shortly thereafter, the first IAEA Fusion Energy Conference (FEC) was held in 1961 and this conference series continues to this day. This first FEC meeting marks the start of coordinated international cooperation in fusion research and development. Since 1971, the International Fusion Research Council (IFRC) has been advising the IAEA Director General on the IAEA's fusion programme and its coordinating role in international cooperation in the field. Today, fusion activities in the IAEA have expanded to research, development and demonstration in plasma and fusion science in the fusion programme implemented by the IAEA's Department of Nuclear Sciences and Applications, technological and infrastructure aspects addressed in the IAEA's Department of Nuclear Energy, and safety and regulatory aspects addressed in the IAEA's Department of Nuclear Safety and Security. The activities across the IAEA are coordinated by the internal, cross-cutting Nuclear Fusion Coordination Committee (NFCC), formed in 2019, in a 'one house' approach. The directives of the IAEA's fusion activities are coordinated and strategized by the NFCC with guidance from the IFRC. ■

IAEA fusion science research and development

Research and development activities

The IAEA hosts a variety of fusion related forums, including the biennial FEC, a series of workshops on DEMO concepts, periodic technical meetings and workshops on topics relevant to fusion science and technology, and currently implements five coordinated research projects related to fusion. ■

Network of Small and Medium Size Magnetic Confinement Fusion Devices for Fusion Research

Since 2004, this coordinated research project series has driven a network of currently around 40 small and medium size tokamaks and stellarators operational in 15 IAEA Member States to push fusion research and development forward and develop a pipeline of next generation fusion scientists and personnel. The present project aims specifically:

> “Addressing matters on technology and infrastructure development and deployment cuts across all the IAEA’s technical Departments. This includes qualification of structures, systems and components and their supply chains, regulatory framework, licensing, nuclear safety, nuclear waste management, materials control; as well as human resources development and management, nuclear liability issues and economic aspects associated with the future deployment of nuclear fusion facilities.”
>
> **IAEA Director General**
> **Rafael Mariano Grossi**

IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, later to become known as the second Fusion Energy Conference, Culham, UK, September 1965.

- To develop new computational techniques for modelling plasma processes, in particular for real-time analysis requiring high data volume processing;
- To establish a programme on education and training between participants;
- To develop and model new advanced diagnostics;
- To study the features and the mechanisms of the isotope effect and their relevance to plasma transport;
- To investigate magnetohydrodynamic activity and related fast particle physics;
- To optimize the start-up phase and plasma breakdown;
- To test materials and technologies for liquid metal, high temperature superconductors, functional materials, advanced fuelling, modular vacuum-vessel and complex geometries coil manufacture;
- To improve the coupling of energy transfer by the auxiliary heating systems;
- To investigate edge and core plasma physics, including the coupling between them;
- To study turbulence and transport, including the role of the electric field and possible mechanisms of turbulence self-regulation. ■

Pathways to Energy from Inertial Fusion – Materials Research and Technology Development

This is the fourth in a coordinated research project series targeting development of materials capable of withstanding the extreme conditions in operational fusion, running from 2020 to 2023.

The coordinated research project also has as a goal the establishment of an international network of working groups, addressing both inertial fusion energy and magnetic confinement fusion energy materials challenges. The specific research objectives are:

- To advance the underlying science and develop novel materials for fusion energy;
- To understand key processes in the inertial fusion energy target chamber;
- To assess tritium inventory and its handling;
- To develop next generation targets and diagnostics, thus enhancing knowledge of high gain target materials;
- To develop driver (including materials research) and target fabrication technologies with an emphasis on repetition systems. ■

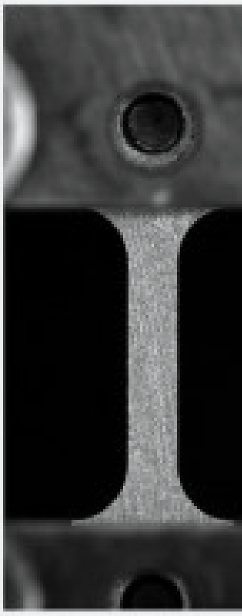
Towards the Standardization of Small Specimen Test Techniques for Fusion Applications

Materials sample testing volume with neutron fluxes in accelerator driven fusion-relevant sources planned for materials development is limited, thus samples will be small. This coordinated research project (2022 to 2026) coordinates the creation of guidelines for the main test techniques for reference structural fusion materials (tensile, creep, low cycle fatigue, fracture toughness, fatigue crack growth rate). The specific research objectives are:

- To produce a comprehensive reference database on fusion structural reference materials (reduced activation ferritic martensitic steels);
- To establish reference guidelines for tensile tests for use of small specimen test technique samples;
- To establish reference guidelines for creep tests, low cycle fatigue tests, fracture toughness tests and fatigue crack growth rate for small specimens of selected materials;
- To define round robin tests;
- To define the small specimen test techniques for characterization of irradiated materials in dedicated fusion neutron sources. ■

Development and Application of Ion Beam Techniques for Materials Irradiation and Characterization Relevant to Fusion Technology

Coordinated research in understanding aspects of ion induced radiation damage in materials relevant to fusion energy over a five year period (2020–2025). The work plan includes experiments to determine original new nuclear data, the development of international standards and protocols for credible measurements and analysis procedures, the selection or production of reference samples for calibration and data analysis purposes and a round robin test to evaluate the performance of ion beam analysis laboratories worldwide. ■



Artificial Intelligence for Fusion Science

A five year coordinated research project running from 2022 to 2027 to develop and test AI models for fusion science at international scale having four work packages to accelerate fusion research and development and community engagement:

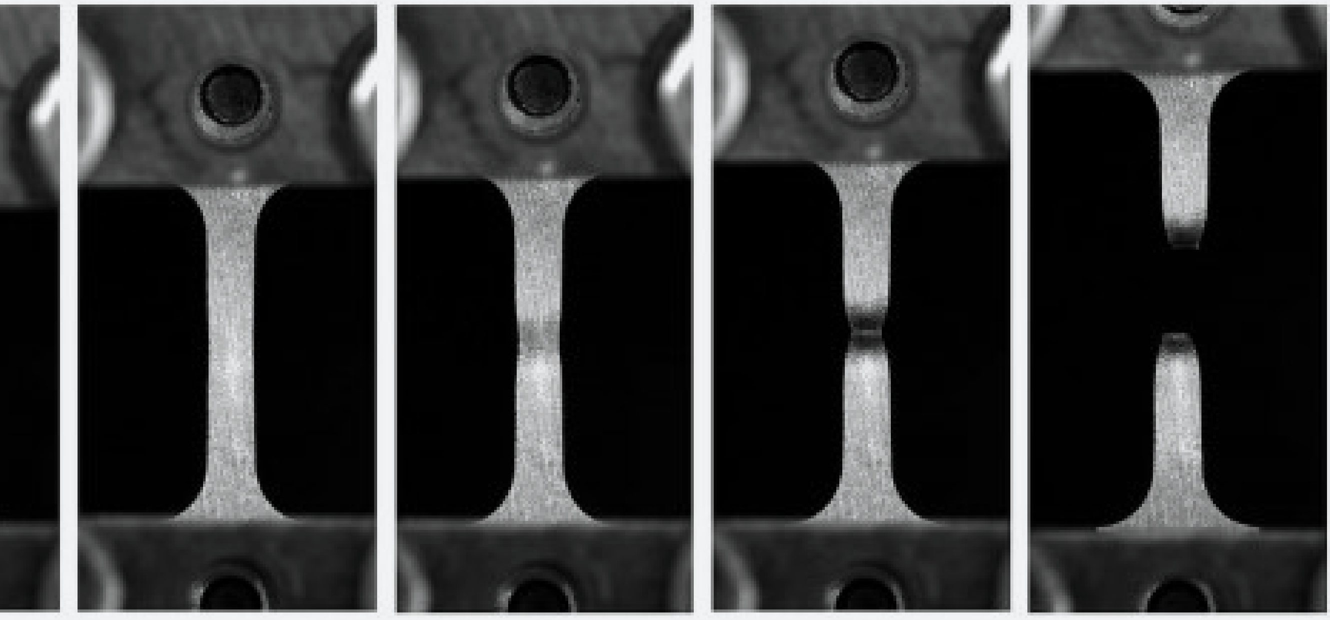
Work package 1 Real time magnetic confinement fusion energy system behaviour prediction, identification and optimization using machine learning (ML)/AI methods. The goal of this work package is to establish a multimachine database of experimental and simulation magnetic fusion energy data (adhering to FAIR/open science principles) for ML/AI driven applications and increase access to knowledge and information of ML/AI methods for magnetic fusion energy.

Work package 2 Inertial fusion energy physics understanding through simulation, theory and experiment using ML/AI methods. The goal of this work package is to establish a database of experimental and simulation inertial fusion energy data (adhering to FAIR/open science principles) for ML/AI driven applications and increase access to knowledge and information of ML/AI methods for inertial fusion energy.

Work package 3 Feasibility of magnetic fusion energy and inertial fusion energy image database. The goal of this work package is to determine the feasibility of an image database from magnetic fusion energy and inertial fusion energy data (adhering to FAIR/open science principles) for ML/AI driven applications.

Work package 4 Community engagement and workforce development. The goal of this work package is to nurture community engagement and capacity building and both create and provide access to knowledge and information in the area of ML/AI methods applied to fusion research and development.

Tensile test performed in a SS-J3 F82H-BA12 specimen.



> “Now is the time to have some positive action to really bring forward the talent that is in all the women scientists and technologists around us.”

Gabriella Saibene
at the Women in Fusion
FEC 2021 side event.

Women in Fusion

A side event was held at the 28th FEC in May 2021 to discuss gender balance, gender equity and the role of women in the nuclear fusion community. The event had great resonance, with over 100 online participants and more than 2200 views of the recording in around one year. Following further discussion and planning, the Women in Fusion (WiF) group was founded by the IAEA, ITER, Fusion for Energy, General Atomics and EUROfusion. The WiF Steering Committee was established and the WiF webpage was launched in July 2022, which heralded the beginning of WiF's efforts.

During its first year, WiF attracted nearly 600 registered members globally, launched a mentoring programme on International Women's Day and organized and took part in several webinars and in-person panel discussions. One highlight was a Congressional Briefing on Capitol Hill, Washington, DC, on Developing a Diverse Fusion Workforce. WiF has been registered as an independent non-profit association since January 2023. ■

▶

Achieve gender parity within the fusion community through network building and promotion of women in science at all educational levels;

▶

Facilitate establishing a friendly work environment for everyone, paying attention to diversity and increasing the visibility of women in fusion;

▶

Acknowledge the many contributions made by women in fusion science, research and technology;

▶

Promote fusion as a clean source of energy in support of the fight against climate change.

◀ In February 2023 the IAEA Chapter of Women in Nuclear organized an inauguration event for WiF at the IAEA. The discussion panel was opened by IAEA Director General, Rafael Mariano Grossi, and was attended by 150 people in-person and remotely.

Explore the Women in Fusion website.

FusDIS

The Fusion Device Information System (FusDIS), developed and maintained by the IAEA, focuses on fusion devices worldwide. FusDIS contains information in the form of a map with selectable filters about public or private fusion devices with experimental and demonstration designs, currently in operation, under construction or being planned, as well as their locations, websites, technical data of these devices and country statistics, including research statistics from the Fusion Energy Conference series. The devices are organized in four main configuration categories:

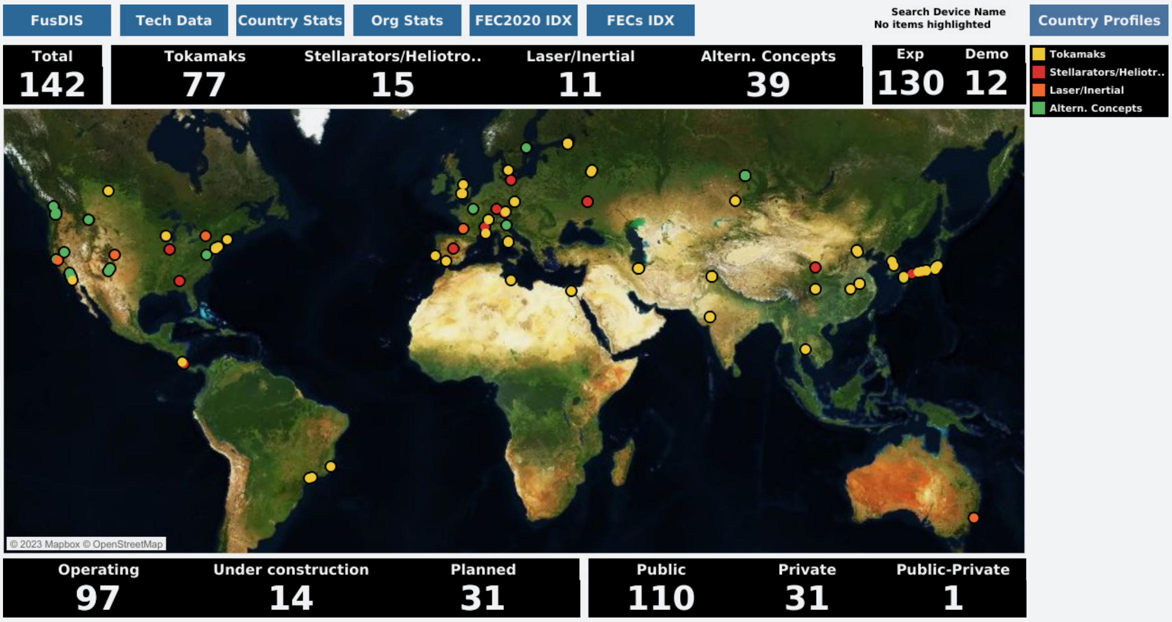
- Tokamaks;
- Stellarators and heliotrons;
- Laser/inertial;
- Alternative concepts, including dense plasma focus; field reversed configuration; inertial electrostatic fusion; levitated dipole; magnetic mirror machine; magnetized target fusion; pinch; reverse field pinch; simple magnetized torus; space propulsor; spheromak.

Through its series of technical meetings, the IAEA acts as a central hub in closing the existing gaps for the realization of a fusion energy source in materials science, fusion physics, technology development, safety, security and waste management, with the objective of encouraging the development of new science and technologies around ITER and beyond.

Explore FusDIS

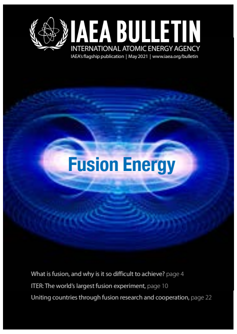
and read the IAEA Bulletin on Fusion Energy.

The IAEA also issues technical and outreach publications on fusion; creates global networks of institutions and scientists to address key issues of common interest; maintains the Fusion Portal and the FusDIS for the fusion community; establishes and maintains numerical databases of fundamental data for fusion energy research; and organizes and supports education and training activities on fusion, including international and regional schools, workshops and seminars in collaboration with ICTP and ITER. ■

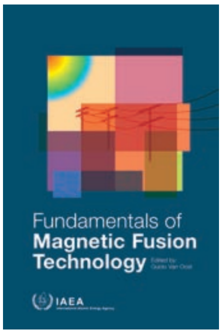


Total 142
Tokamaks 77
Stellarators/Heliotro.. 15
Laser/Inertial 11
Altern. Concepts 39
Exp 130
Demo 12
Operating 97
Under construction 14
Planned 31
Public 110
Private 31
Public-Private 1

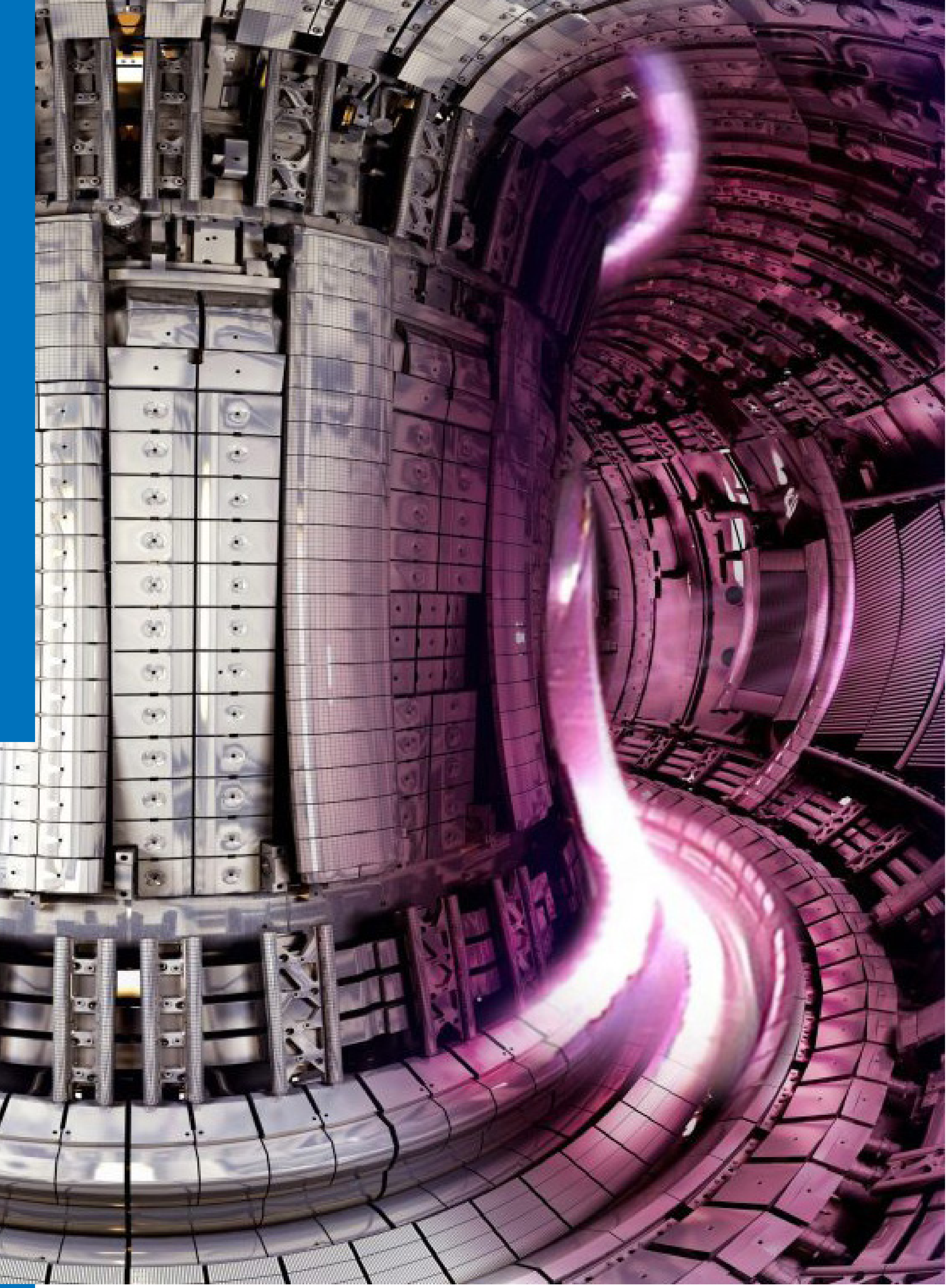
The FusDIS site.



In addition to the Nuclear Fusion Journal, the IAEA publishes technical publications, reporting on the IAEA's fusion related work, as well as other outreach and educational material. One example is the IAEA's flagship quarterly IAEA Bulletin from May 2021 on the topic of Fusion Energy. ■



In September 2023 the IAEA released a high level textbook for graduate students entitled Fundamentals of Magnetic Fusion Technology, which complements another textbook on Fusion Physics, published in 2012. ■



Interior of the JET tokamak vessel.
Courtesy of EUROfusion.

The IAEA’s DEMO Programme Workshops

The IAEA’s DEMO Programme Workshops facilitate the coordination of global efforts for developing devices intermediary to the experimental fusion reactor ITER and a DEMO. Every other year, the DEMO Programme Workshops provide an opportunity to discuss and develop solutions to the main scientific and technical challenges of a DEMO. Although each country may have different priorities and specificities in their DEMO programmes, the objective of the workshops is to coordinate mutually beneficial efforts and facilitate international collaboration, leading to the best possible structured roadmap to future fusion power.

The IAEA has played a crucial role in the evolution of the ITER project since its inception and through the development activities and negotiations held under its auspices. The IAEA Director General is the depositary of the ITER Agreement [65], signed by the Parties in 2006. Collaboration between the IAEA and the ITER Organization is currently formalized through the Practical Arrangements Agreement signed in 2019. The scope of the arrangements includes:

- Promotion and outreach concerning current and future nuclear fusion activities for peaceful purposes;
- Cooperation in educational and training in fusion science, tokamak engineering, and related topics such as construction, licensing, safety aspects, operation and maintenance of magnetic confinement fusion facilities;
- Sharing nuclear safety and radiation protection related experience between the international organization and the IAEA and its Member States, including those who are not ITER members;
- Considerations for the development of nuclear fusion safety requirements and standards;
- Cooperation in the area of human resources and knowledge management;
- Mutual participation in technical meetings, workshops and other activities.

The IAEA and Massachusetts Institute of Technology's Plasma Science and Fusion Center

The MIT Plasma Science and Fusion Center (PSFC) is the first IAEA Collaborating Centre in the field of fusion. The Collaborating Centre agreement was signed by the parties on 22 September 2023 at MIT when IAEA Director General, Rafael Mariano Grossi, was in Massachusetts, USA, to deliver the distinguished 2023 David J. Rose Lecture. David J. Rose was a pioneer in fusion technology. In the summer of 1977, Rose sent a letter to Sigvard Eklund, the IAEA's second Director General, with 'A Proposal to Organize Fusion R&D More Internationally'. Rose's seminal proposal would forever change the way fusion research is coordinated internationally.

The partnership with the PSFC will help the IAEA deliver its fusion research and technology activities for an initial period of four years (2023–2027). Under the agreement, the IAEA will be able to access PSFC expertise in the area of AI applied to fusion and plasma science by bringing together these innovations in an integrated manner, while training a new generation of fusion scientists at the same time.

The PFSC was also a key proposer of the IAEA coordinated research project on AI for Fusion Science, which is focused on developing and benchmarking AI applications in fusion science at an international level. On the same day as the signing, the IAEA launched a crowd-sourcing challenge as part of the coordinated research project with MIT PSFC and the International Telecommunication Union.
The challenge will be open until the end of October 2023.

Take part in the crowdsourcing challenge here.

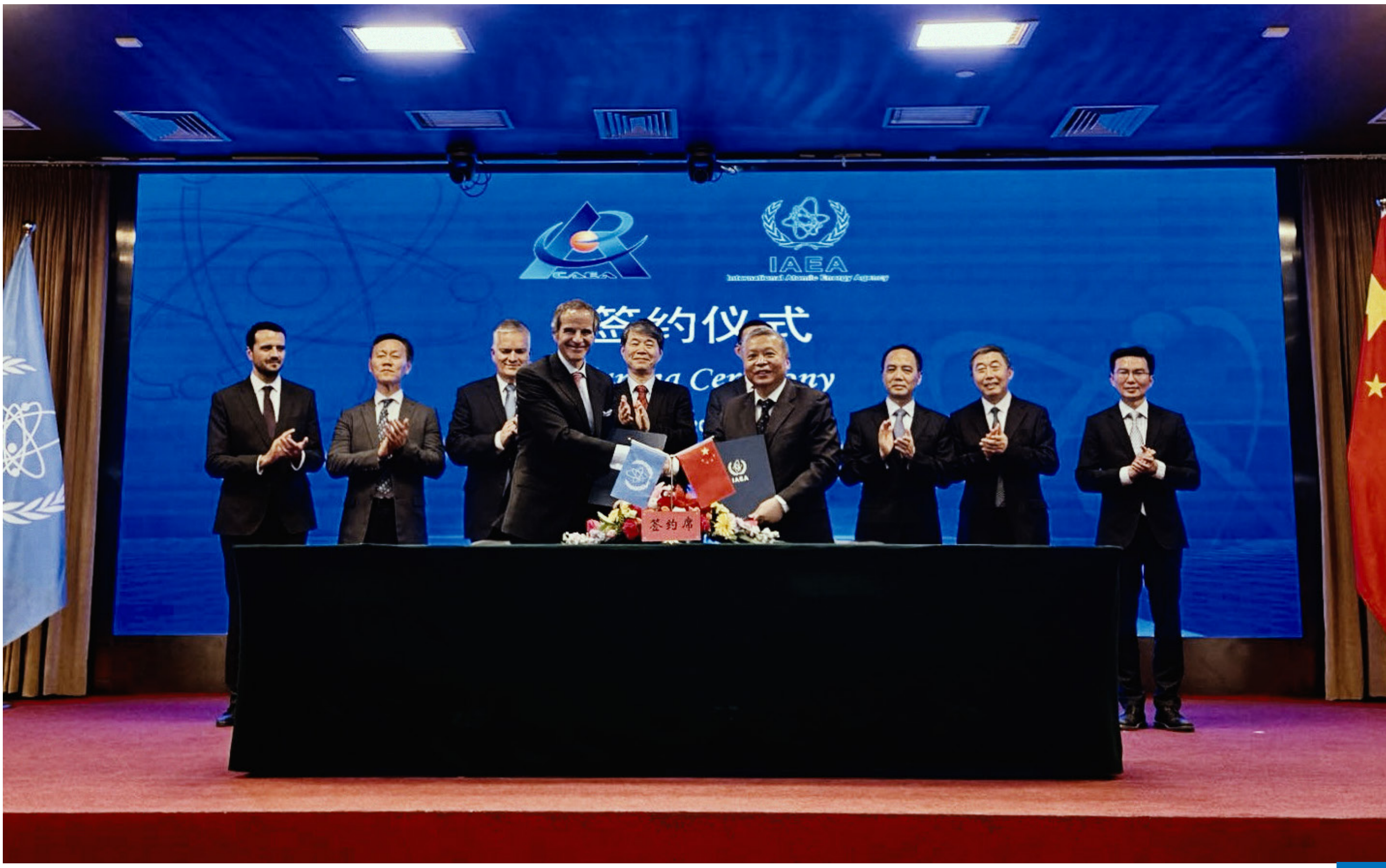
The signing ceremony took place at the MIT PSFC in the presence of IAEA Director General, Rafael Mariano Grossi; MIT PSFC Director, Dennis Whyte; and Cristina Rea, MIT PSFC Research Scientist.

The IAEA and the Princeton Plasma Physics Laboratory

The IAEA and the US DOE’s Princeton Plasma Physics Laboratory have formed a partnership and signed Practical Arrangements in 2022. Together they collaborate to advance fusion science and plasma physics through a combination of interactive workshops, both in person and remotely, as well as by providing fellowships, internships and engaging outreach programmes aimed at inspiring young professionals to explore and pursue careers in fusion energy research. One focus is to strengthen the capabilities in fusion and plasma physics within regions that are either new to or less advanced in the global fusion community, such as Africa, Asia and the Pacific, and Latin America and the Caribbean.

The partnership between the IAEA and the Princeton Plasma Physics Laboratory develops new and uses existing distance learning tools and digital education technologies, such as the laboratory’s Remote Glow Discharge Experiment and Virtual Tokamak.

Signing ceremony of Practical Arrangements between the IAEA and the Princeton Plasma Physics Laboratory, September 2022.



IAEA Director General, Rafael Mariano Grossi, and China Atomic Energy Authority Chairman, Zhang Kejian, at the signing ceremony in May 2023.

The IAEA and the Hefei Institutes of Physical Science

The IAEA and the Hefei Institutes of Physical Science, Chinese Academy of Sciences, an integrated research entity in China comprising seven scientific research units, one of which is the Institute of Plasma Physics, Chinese Academy of Sciences, a fusion research institute, signed Practical Arrangements in May 2023 in the area of physics, technology, training and education in nuclear fusion research. The IAEA and Hefei Institutes of Physical Science have agreed to pursue the following activities:

- Cooperate on joint experiments and joint research activities; such activities may be conducted within the framework of the IAEA's technical meetings and/or coordinated research projects and may include the use of the institute's fusion research and technology infrastructure.
- Cooperate on fellowship and internship programmes in nuclear fusion research.
- Cooperate on organizing conferences, training courses, schools and other events in nuclear fusion research. ■

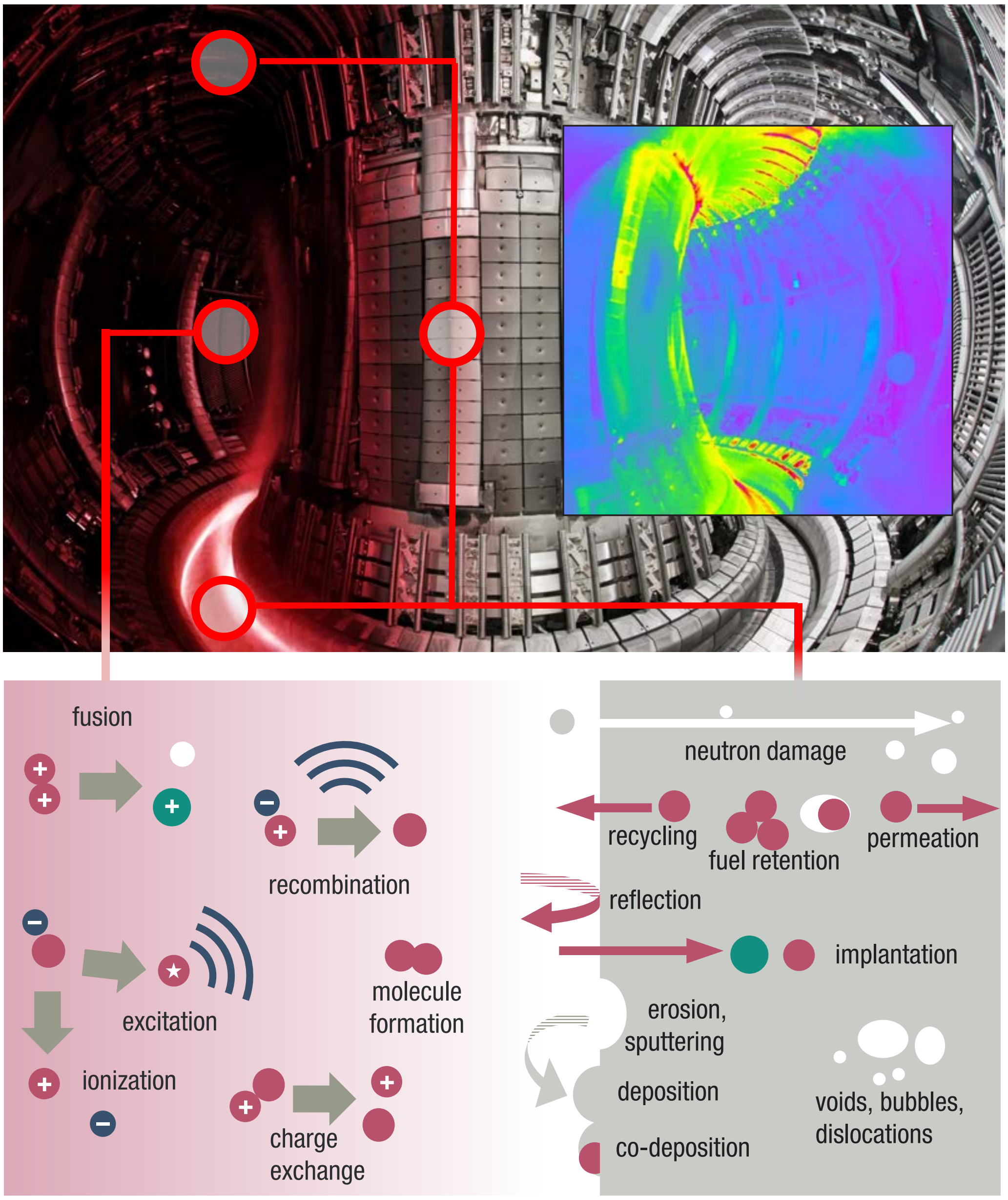
Fundamental scientific fusion data and energy research at the IAEA

The IAEA establishes, curates and maintains internationally recommended databases covering a broad range of fusion energy processes. Databases for fundamental fusion processes in the plasma as well as interactions between the reactor materials and the plasma are needed and extensively used by IAEA Member States and the global fusion energy research and development community. In relation to this, the IAEA coordinates and maintains standards for the classification and interoperable use of collisional and plasma–wall interaction process data. This standardization improves the maintenance of fundamental data and streamlines data sharing. In addition, databases on processes relevant for fusion neutronics — such as neutron transport, neutron reactions and neutron induced material damage as well as transmutation processes in fusion reactor materials and databases for processes involving ion particle interactions and the experimental stopping powers for ions in matter — are maintained by the IAEA.

To implement its fundamental fusion data programme, the IAEA undertakes dedicated coordinated research projects; builds professional networks between national data centres, fusion plasma modellers as well as between plasma theorists and experimentalists providing fusion data; organizes various technical meetings, workshops and schools; and provides global access to and curates evaluated fusion data; databases and libraries originating from these activities. The IAEA also has contractual cooperation agreements, including Practical Arrangements with the Korea Institute of Fusion Energy in the area of atomic, molecular and plasma material interaction data relevant to fusion, and agreements pertaining to international workshops and conferences on plasma theories, plasma–material interactions and plasma fuel properties in reactor materials.

A portion of IAEA activities are dedicated to serve ITER needs. The Fusion Evaluated Nuclear Data Library (FENDL) coordinated by the IAEA provides essential nuclear data for the design of ITER (with FENDL 2.1 being the reference library for the design of ITER) as well as national and regional fusion research facilities. The IAEA's series of Technical Meetings on Tungsten and Hydrogen Properties in Edge Plasmas serves ITER and fusion communities working on tungsten as a first wall and divertor material. Data are needed for simulations for the prediction of fusion operational regimes with best performance and provided in two databases named ALADDIN and CollisionDB. They recently published an application programming interface to access IAEA fusion databases and allows frequent data downloads for professional data power users, such as ITER. ■

The IAEA provides and curates fundamental scientific data for modelling processes in fusion power plants. Left: Fusion reaction in the plasma core and other plasma processes, depending on the temperature and fuel density. Molecular species can form near to the reactor wall, where the plasma is cooler. Centre: Plasma-surface interactions taking place at the reactor first wall. Right: Energetic plasma particles, such as neutrons and ions, may penetrate deep into reactor components, leading to extended materials damage. The interior of the JET vessel superimposed by plasma image is shown at top; the insert shows the temperature footprint. Top image courtesy of EUROfusion.


fusion
recombination
excitation
ionization
molecule formation
charge exchange
neutron damage
recycling
fuel retention
permeation
reflection
implantation
erosion, sputtering
deposition
co-deposition
voids, bubbles, dislocations

Ongoing coordinated research projects cover data related to fusion reactor processes and span from the plasma core up to the structural components’ coolant

Neutral beam injection: Neutral particle beams are used to heat up the plasma through particle collisions, but many of the collision processes require fundamental reaction cross-sections to allow simulations of reliable plasma heating scenarios of a fusion reactor.

Vapour shielding: Interactions between the plasma and the reactor wall may result in formation of a vapour cloud between the incoming plasma and the wall, which could have shielding properties. Simulations of properties as well as the formation of this shielding vapour require fundamental data from the atomistic and spectroscopic communities, particularly for liquid metal components proposed as an alternative future fusion reactor concept.

Hydrogen permeation: Tritium fusion fuel may penetrate the reactor wall and beyond, so theoretical and experimental parameters for multiscale simulations to assess/predict in-vessel and ex-vessel tritium transport and reservoirs are crucial for fusion reactor safety.

Injected impurities: Injecting selected impurities into a fusion plasma can be used for plasma diagnostics and to avoid disruptions in large fusion reactors. Impurity particle processes require validated data in order to improve modelling of reactor plasma operational scenarios.

Coordinated research projects on fusion data.

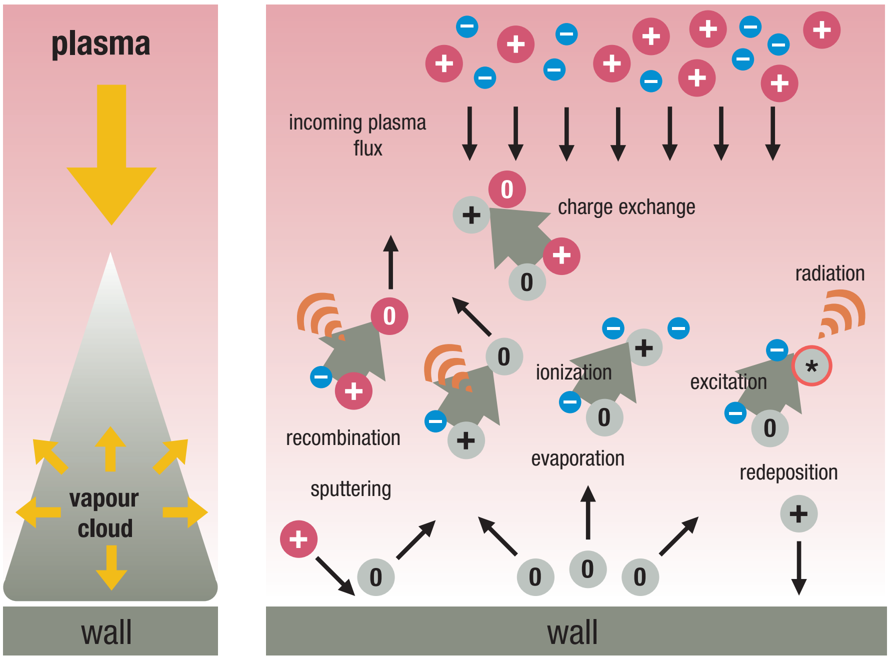
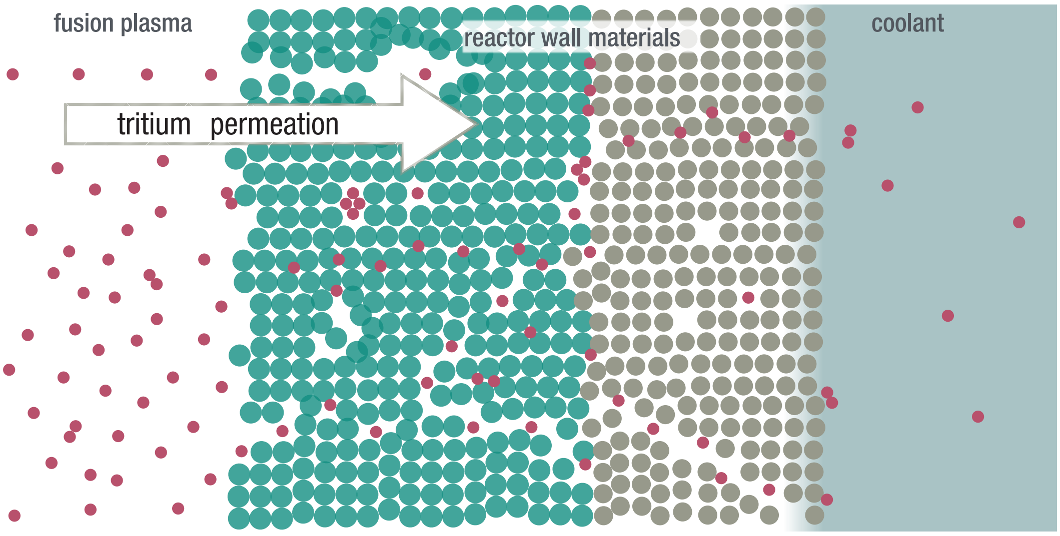


Illustration of the interactions between incoming ions and neutrals ejected from the wall in a plasma vapour shield.

Plasma–wall interactions and neutrons produced from the fusion reactions create atomic cavities in the reactor's wall materials, in which tritium can get trapped or permeate through if not recycled back to the plasma.



IAEA databases for fusion research and development

The IAEA numerical and bibliographical databases for fusion are globally used by the fusion communities with several thousand monthly pageviews. ■

AMBDAS: A bibliographic database of peer reviewed articles presenting fusion data on atomic, molecular and plasma–wall interactions. There are currently 51 339 references and the database is jointly maintained with Korea Institute of Fusion Energy through Practical Arrangements.

ALADDIN: A numerical database only for recommended and evaluated data on atomic and molecular collisional and radiative properties (cross-sections, spectroscopic data), plasma–wall interactions processes (e.g. physical sputtering, erosion) and bulk material properties (e.g. thermomechanical properties, particle diffusion, retention) for materials relevant for fusion research and development.

CollisionDB: A numerical database for atomic and molecular collisional radiative properties for fusion processes in the core and edge plasmas. It currently contains over 120 000 data sets.

CascadesDB: A numerical database for classical molecular dynamics simulations of neutron induced damage in fusion reactor materials, particularly suited for ML applications. There are currently data originating from over 14 000 simulations covering all fusion relevant energies and temperatures.

DefectDB: A numerical database for quantum mechanical calculations (density functional theory) of primary radiation damage of fusion materials. DefectDB stores atomistic geometries and energy landscapes needed for multiscale and multiphysics calculations of fusion plasma–wall processes. The structure of this database is well suited for ML applications. ■

IAEA nuclear libraries for fusion research and development

The IAEA hosts various libraries with experimental and evaluated nuclear data. Evaluated data are derived from collections of experimental data by a careful assessment of experimental setups. ■

Fusion Evaluated Nuclear Data Library (FENDL):
Nuclear cross-section data for incident neutrons, protons and deuterons for particle transport and nuclide inventory calculations. FENDL addresses the evolving needs of fusion research, such as an extension of incident neutron energy to serve the needs of the IFMIF testing facility for fusion materials. TENDL-2017 has been adopted as the recommended activation library in the most recent version of FENDL (3.2b).

TALYS-based Evaluated Nuclear Data Library (TENDL):
Cross-sections and related data for incident neutrons, protons, deuterons, tritons, helium-3, alpha, and gammas for about 2800 isotopes, a fission yield and thermal scattering sub-library. Broad coverage achieved by interfacing to nuclear models code TALYS. For essential isotopes with lack of or insufficient predictive power, such as resonances, TENDL adopts data from the national nuclear library projects. The latest release is TENDL-2021.

Engineers in Japan test a prototype of the control system for the ITER blanket remote handling system. On the left screen is a virtual reality model; on the right is the view from the camera. Look closely to see the manipulator on the other side of the window. Courtesy of ITER Organization.

International Reactor Dosimetry and Fusion File (IRDFF-II): Nuclear data for fission and fusion neutron metrology applications up to 60 MeV neutron energy.

EXFOR Library: The most comprehensive compilation of experimental nuclear reaction data world-wide for cross-sections and related quantities for incident neutrons, charged particles and photons. The compilation and inclusion of new data is undertaken by the International Network of Nuclear Reaction Data Centres under the auspices of the IAEA.

Ion Beam Analysis Nuclear Data Library (IBANDL): Provides experimental cross-sections relevant to ion beam analysis techniques, such as elastic backscattering spectroscopy, nuclear reaction analysis and particle induced gamma-ray emission spectroscopy, and is widely used within the fusion materials communities.

Electronic Stopping Power Tables: Used for the predictions of plasma ion-induced damage in fusion reactor materials in simulations of plasma–material interactions by high and low energy ions from the plasma. ■

CHALLENGES
Heating
Stability
Confinement

Economics
Stakeholder involvement
Design safety, safety analysis and regulation
Coolants
Power conversion systems
Structural materials
Operation and maintenance
Fusion–fission hybrid energy system
Infrastructure
Tritium technology
Construction and missioning
Decommissioning
Manufacturing and supply chain
Remote handling
Waste technology
Safeguards
Modelling and simulations
Nuclear data
Fuel cycle
Scenarios for future energy systems
Knowledge management
Human resources

IAEA contribution to fusion technologies

Synergies in technology development between nuclear fission and fusion for energy production

In 2021 the IAEA launched a new initiative promoting the transfer of lessons learned and knowledge from fission to fusion. The main objective is to identify and analyse, with an international perspective toward industrial deployment of fusion energy facilities, all the possible synergies in technology development and deployment between nuclear fission and fusion and also gaps to plan further specific focused activities. The project will cumulate in a publication analysing the synergies in technology development in the two areas.

Coolant options for fusion can benefit from shared insight from advanced fission and fusion facilities. The IAEA has started associated activities, tackling the issue of compatibility between coolants and materials, through Technical Meetings covering these main areas:

- Experiments and modelling on coolant–material interaction;
- Irradiation effects in cooling environments;
- Coolant quality control and chemistry;
- Thermal-hydraulics, magnetic field, and other effects on material behaviour;
- Tools for characterization of materials behaviour;
- Additive manufacturing materials behaviour and characterization in harsh environments.

From the analysis, the strongest synergy was found in the development of materials designed to withstand extreme conditions. In all six fission Generation IV reactor designs, accelerator driven systems and fusion facilities, construction and component materials will experience extreme conditions, including high temperatures with steep gradients, high radiation doses, and compatibility issues between coolants and materials. Consequently, materials research and development for all these systems benefit from increased cross-cutting collaboration and knowledge transfer.

Another synergy identified is in radioactive waste management and decommissioning. As official standards and guidelines specific for fusion were lacking, established standards from fission NPPs were adopted for facilities like ITER, taking into account significant differences in structures, systems and components, and risks associated with the technologies.

Further synergies between fusion and fission power plant development lie in the areas of computational tools, design and safety analysis codes, choice of coolant, balance of plant, energy conversion systems, and facilities for materials testing and irradiation. Within the fuel cycle, only the link with tritium generation and detritiation systems from fission power plants, such as Canada deuterium–uranium (CANDU) reactors, is relevant. Finally, remote handling and in-service inspection also offer opportunities for collaboration between the fusion and fission sectors. ■

Fusion pre-feasibility study modules

The IAEA has started to lay the groundwork for a pre-feasibility study for fusion DEMO facilities, the aim of which is to create thematically defined modules that contain relevant information for Member States considering developing and deploying future fusion programmes.

This is an approach that leans on work already done by the IAEA for fission NPPs and related infrastructure, gathering the results from technical meetings and workshops, technical documents, consultations with external experts, and other expertise and tools available in the IAEA. ■

The present modules planned are:

Fusion facilities safety and security

Nuclear safety

The IAEA assists its Member States and has a coordinating role to play in addressing challenges associated with fusion safety, with the aim to explore the benefits of increased regulatory collaboration, to establish common positions on technical and policy issues, and to pave the way to greater harmonization. As a mid-term target, the IAEA will develop a set of principles for design safety, safety assessment and regulation of fusion facilities in the future and is currently laying down a critical foundation for these principles. The IAEA is in the process of drafting two publications on experiences on design safety and safety assessment for fusion facilities, and international experience in the regulation of fusion facilities. Member States' responses to questionnaires on the status of these areas were evaluated by fusion experts in a series of consultancy meetings and will be reflected in the publications.

- Regulatory frameworks and safety assessments;
- General design criteria for the development and deployment of a fusion power plant;
- Fusion power plant applicable codes and standards;
- Fusion technologies and fuel cycles;
- Economies and financial analysis;
- Fusion modelling and simulation;
- Materials and structures;
- Fusion project risk management;
- Fusion project development and deployment;
- Fusion systems integration and construction;
- Staffing and training requirements;
- Operations and maintenance requirements;
- Fusion power plant capacity and integration with grid.

TABLE 3. FORTHCOMING IAEA PUBLICATIONS IN FUSION FACILITIES SAFETY AND SECURITY

International experience in the regulation of fusion facilities	Summary of current national practices: ‣ Current and planned regulatory framework of fusion facilities; ‣ Technical capability of regulatory body. Common regulatory issues; Common regulatory approaches; Suggested areas of focus in the development and updating of the regulatory framework for future fusion facilities.
Experiences on design safety and safety assessment for fusion facilities	Design safety (principal technical requirements, general plant design, design of specific plant systems, etc.); Safety assessment (specific aspects to fusion facilities).

A key activity for the development of the set of safety principles for fusion facilities is a Technical Meeting on Fusion Design Safety and Regulation to be held in October 2023, where experts in fusion safety will further discuss the challenges associated with design safety, safety assessment and regulation of future fusion power plants and early stage fusion facilities on the path towards fusion power plants, such as demonstration, pilot and prototype facilities. The meeting will provide essential input to develop principles and key concepts for safety and regulation for a planned publication.

The ultimate objective of these IAEA efforts is to develop a safety standard for fusion safety and regulation, commensurate with the pace of development of this technology and the needs of the Member States. ■

Emergency preparedness and response

The IAEA's Incident and Emergency Centre (IEC) is the global focal point for international emergency preparedness, communication and response to nuclear and radiological incidents and emergencies, regardless of whether they arise from an accident, negligence, or a deliberate act. As such, the IEC will be the international focal point for a radiological incident related to a future fusion power plant. ■

Waste and decommissioning and safety

The decommissioning and waste management processes, responsibilities and safety criteria, as described in the IAEA safety standards, are fully applicable to fusion facilities. Aspects that are technology specific are mainly to be addressed in informational publications. Some technology specific aspects pertaining to fusion waste and decommissioning that the IAEA is addressing include:

- Exchange of experiences on characterization prior to decommissioning, which provides the key input to decommissioning planning, safety assessment and waste management planning;
- Worker protection during dismantling;
- Management of waste containing tritium, including applicability of clearance levels;
- Specific guidance for estimating waste production volumes and radionuclide inventory for each physical category of waste;
- Adjustments potentially needed to address the specificities of regulatory and legal framework for fusion facilities.

The IAEA has published, together with other experts, a treatise on disposal, recycling and clearance of radioactive waste generated from fusion plants [66]. The publication further provides a comparison of estimated fusion radioactive inventory to fission and information on the relevant existing regulatory frameworks in Europe, Japan and the USA and a list of other related IAEA publications. ■

Nuclear security

The IAEA establishes and maintains the IAEA Nuclear Security Series as part of its central role in providing nuclear security related international support and coordination. The IAEA, on the request of a Member State, can develop specific nuclear security guidance publications for future fusion power plants to cover security related issues, as currently there is no IAEA publication that is related specifically to the security of fusion power plants. ■

Institutional and legal frameworks for fusion

INPRO Fusion Study

Legal and Institutional Issues of Prospective Deployment of Fusion Facilities is the topic of an International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Collaborative Project (INPRO Fusion Study) started in 2022. It aims to support the fusion community in accelerating the development and implementation of fusion powered facilities and integrated fusion–fission hybrid systems over the next decades. This task includes early identification of possible gaps in long term sustainability and needed capabilities using INPRO assessments and analyses; review and critical analysis of previous experience in developing national legislation and infrastructure; engagement with pioneering new fusion concepts; and identification of appropriate policy options at the global and regional levels in different scenarios.

The INPRO Fusion Study has raised much interest from IAEA Member States, with more than 20 international experts from six countries and one international organization (ITER) joining this study.

The INPRO Fusion Study will culminate in a publication, with an envisaged publication date of 2024. The publication will cover results from expert discussions and input on:

- Long term sustainability issues beyond fusion technical aspects;
- Fusion's role in the adaptation to climate change;
- Fusion fuel cycle;
- Resource availability;
- Legal issues and challenges;
- Safety issues;
- Civil liability;
- Nuclear security;
- Regulatory classification;
- Safeguards and non-proliferation;
- Key export/import issues;
- Fusion potential for nuclear waste transmutation;
- Gigafactory/mass production of fusion facilities and licensing timelines;
- Human capacity building;
- Project and quality management systems for fusion deployment.

IAEA Office of Legal Affairs activities related to fusion

The IAEA General Conference has encouraged the Secretariat to study and consider the legal, institutional, safety and regulatory aspects of fusion. The IAEA Director General is depository for the 11 multilateral instruments adopted under IAEA auspices on nuclear safety, security and liability. The IAEA also serves as the Secretariat to the meetings of the Contracting Parties to the CNS [27] and Joint Convention [30]. As concerns the international legal instruments, it will ultimately be for the Parties to interpret their applicability to fusion related facilities and activities and decide what changes, if any, are needed to address fusion. In the future, the Contracting Parties to the CNS and Joint Convention could even decide to tailor aspects of national reporting on their implementation of the conventions' obligations to the specifics of fusion facilities and related activities. The IAEA can be expected to support the Parties in such efforts, on request.

Over the years, the IAEA's International Expert Group on Nuclear Liability (INLEX) has held several discussions on fusion and the international nuclear liability instruments. For now, INLEX considers that the nature of the low risks by fusion facilities, the limited potential transboundary damage and the status of the development of the technology still do not fully justify the inclusion of fusion installations within the scope of the international liability regime. INLEX continues to discuss the application of the nuclear liability conventions in respect of fusion facilities.

During the IAEA's First International Conference on Nuclear Law, held in April 2022, the IAEA organized a technical session entitled Legal Framework for New Nuclear Technologies: Fusion. With the potential future availability of commercial-scale fusion power plants, experts from different Member States and organizations discussed potential legal and regulatory challenges associated with this new technology and the applicability of international nuclear law instruments and of IAEA safety standards and nuclear security guidance, as well as specific national approaches. ■

Nuclear Fusion journal

The Nuclear Fusion journal was launched by the IAEA in 1960 to provide an international and impartial publishing forum for research in pursuit of controlled fusion for energy generation. Its scope includes all relevant aspects of physics and technology. In 2023 the original aims of the journal are maintained: internationalism, impartiality and quality. Quality is ensured through double peer review of submitted manuscripts, with strong involvement of the journal's Board of Editors, a geographically and thematically diverse team of leaders in fusion. The journal's topical coverage, however, has evolved from plasma physics through the experimental regimes on generations of complex machines to aspects of materials, technology and engineering critical for future devices. The online journal includes an archive of 63 years of full text published articles.

Since 2002 Nuclear Fusion has been co-published with Institute of Physics Publishing, which handles all post-acceptance work: production, promotion and dissemination of journal content. This arrangement is subject to periodic review and an open tendering process and is managed by the IAEA's Publishing Section in the Division of Conference and Document Services, Department of Management, which also coordinates the peer review process. Nuclear Fusion is self-funding and switched from being primarily subscription-based to fully open access in January 2023, now funded solely from article publishing charges. Discounts and waivers are available for authors from institutes in financial difficulty.

Nuclear Fusion has published over 12 000 articles and many major advances in fusion have been reported as part of its regular content. The journal collaborates with the FEC, organized by the IAEA, to publish results presented at each conference. Since 2006 exceptional work published in the journal is recognized by an annual prize and announced at the FEC. Support for this prize was provided initially by the Japan Atomic Energy Agency and now by the journal co-publisher, Institute of Physics

Impact factor (2021)	Downloads (2022)	Citations (2022)	Mentions (2022)
4.215	745 637	14 846	434

News	Blog	Policies	Patents	Twitter	Facebook	Wikipedia	Reddit	Q&A
144	8	3	64	186	2	24	2	1

Two most downloaded articles in 2022

DIII-D research advancing the physics basis for optimizing the tokamak approach to fusion energy — IOPscience

Overview of the SPARC physics basis towards the exploration of burning-plasma regimes in high-field, compact tokamaks — IOPscience

Publishing. In addition, Nuclear Fusion review articles and collections have become valued reference works, for example its ITER Physics Basis issues, and the most highly cited journal review paper. ■

Plasma–material interactions in current tokamaks and their implications for next step fusion reactors — IOPscience

Nuclear Fusion is the foremost academic journal in the field, with between 400 and 500 articles published annually. In 2022 submissions were received from 30 countries. The geographical spread of the published papers in 2022 indicates that China is the IAEA Member State contributing the most content, followed by the USA.

Nuclear Fusion is consistently highly ranked in citation reports, meaning that articles published in the journal are typically cited more frequently than those published in other journals in the field. Other metrics, such as downloads and mentions on social media, in news stories, patents and policy documents, are also indicative of usage.

In 2024 the journal will publish a special issue as a collection of review articles. Entitled ‘On the path to Burning Plasma Operation’, the issue will feature contributions from International Tokamak Physics Activity topical groups. ■

These most popular articles reflect the interest of the user community influenced by, among other things, the demonstration of ignition at NIF and current work on novel devices.

Two journal articles most widely mentioned in 2022:

Reaching 30% energy coupling efficiency for a high-density-carbon capsule in a gold rugby hohlraum on NIF — IOPscience

Fusion nuclear science facilities and pilot plants based on the spherical tokamak — IOPscience

> “Nuclear fusion promises the possibility of abundant, low carbon, clean energy.”

IAEA Director General
Rafael Mariano Grossi

IAEA Director General, Rafael Mariano Grossi, holding a piece of high temperature superconducting tape, the key part of the MIT–CFS toroidal field magnet that successfully attained 20 tesla magnetic field strength [23].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List of abbreviations

AI	artificial intelligence
ASEAN	Association of Southeast Asian Nations
CANDU	Canada deuterium–uranium
CFETR	China Fusion Engineering Test Reactor
CFS	Commonwealth Fusion Systems
CNS	Convention on Nuclear Safety
CPPNM	Convention on the Physical Protection of Nuclear Material
CSA	comprehensive safeguards agreement
D–D	deuterium–deuterium
D–T	deuterium–tritium
DEMO	demonstration fusion power plant
DOE	Department of Energy
DONES	DEMO Oriented Neutron Source
EAST	Experimental Advanced Superconducting Tokamak
EPC	emergency preparedness category
EPR	emergency preparedness and response
EU	European Union
Euratom	European Atomic Energy Community
EVEDA	Engineering Validation and Engineering Design Activities
FDP	fusion demonstration plant
FEC	Fusion Energy Conference
FENDL	Fusion Evaluated Nuclear Data Library
FNS	fusion neutron source
FusDIS	Fusion Device Information System
GA FPP	General Atomics Fusion Pilot Plant
IBANDL	Ion Beam Analysis Nuclear Data Library
ICTP	International Centre for Theoretical Physics
IEC	Incident and Emergency Centre
IFERC	International Fusion Energy Research Centre
IFMIF	International Fusion Materials Irradiation Facility
IFRC	International Fusion Research Council
INFCIRC	Information Circular
INLEX	International Expert Group on Nuclear Liability
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IOPP	Institute of Physics Publishing
IRDFF	International Reactor Dosimetry and Fusion File
JET	Joint European Torus
MAST U	Mega Amp Spherical Tokamak Upgrade
MIT	Massachusetts Institute of Technology
ML	machine learning
NFCC	Nuclear Fusion Coordination Committee
NIF	National Ignition Facility
NNWS	non-nuclear-weapon State
NPP	nuclear power plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
PSFC	Plasma Science and Fusion Center
STEP	Spherical Tokamak for Energy Production
TENDL	TALYS-based Evaluated Nuclear Data Library
UKAEA	United Kingdom Atomic Energy Authority
VOA	voluntary offer agreement

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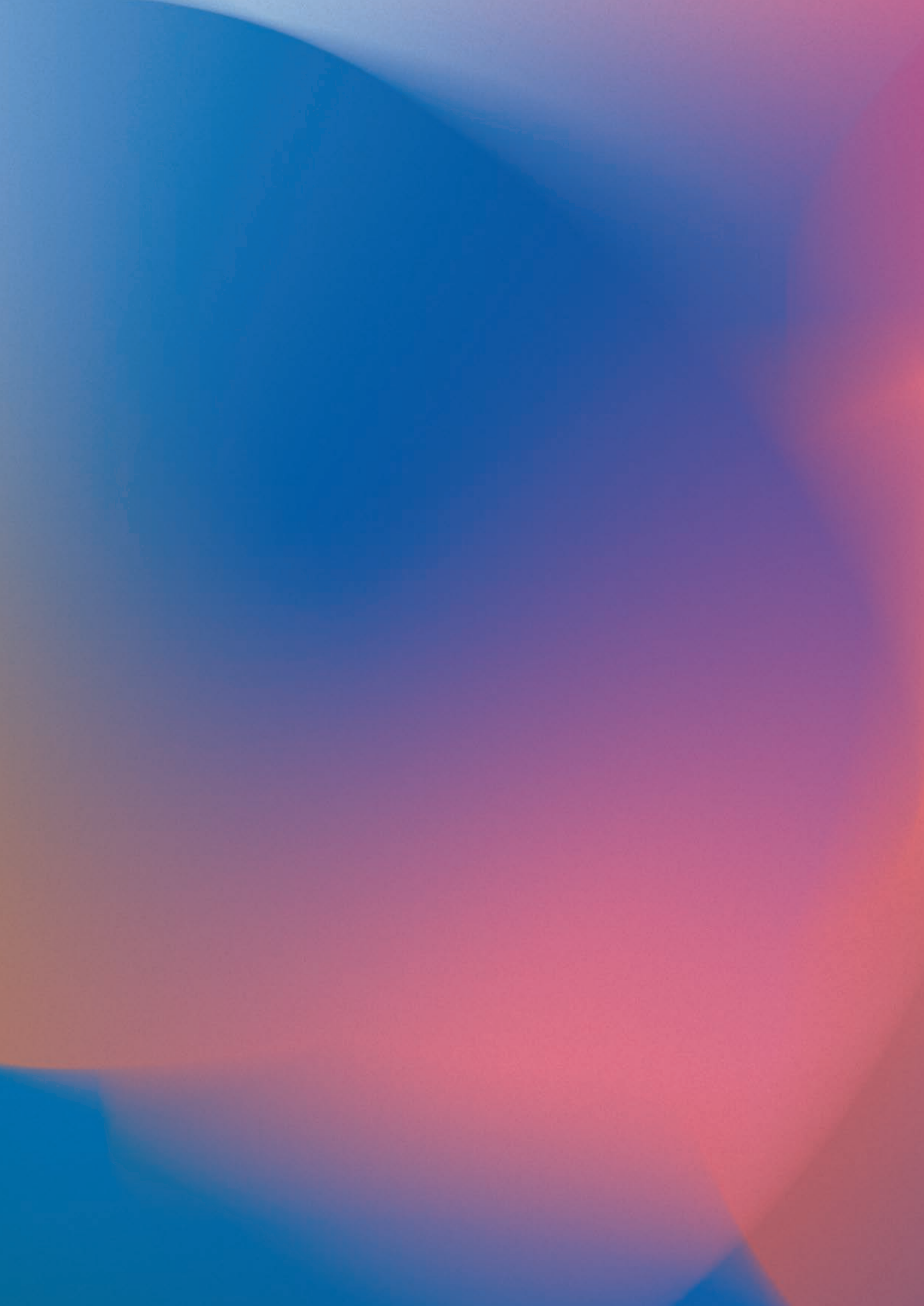
Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/publications

Printed by the IAEA in Austria
October 2023
IAEA/PAT/001

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: IAEA world fusion outlook 2023 / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2023. | Includes bibliographical references.
Identifiers: IAEAL 23-01624
Subjects: LCSH: | Nuclear fusion. | Nuclear fusion — Research. | Nuclear fusion —
International cooperation.
Classification: UDC 539.17 | IAEA/PAT/001



23-04119E

> “International collaboration is vital in achieving this grand engineering challenge of the 21st century.”
>
> **IAEA Director General**
> **Rafael Mariano Grossi**

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OCTOBER 2023
INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA