Federal Ministry
of Education
and Research

Position Paper Fusion Research

On the path towards the energy supply of tomorrow

Cover photo: View into the plasma vessel of the Wendelstein 7-X fusion facility. In order to be able to visualise part of the complex magnetic field, an electron beam was sent along a magnetic field line. Throughout the multiple circulations along the field line, it produces a trace. The photo combines this trace with the image points left behind by a fluorescent rod that is swivelled through the image plane.

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Executive Summary

Climate change and the rapidly increasing demand for energy on a global scale have very clearly demonstrated that humanity is dependent on energy sources that can produce clean electricity on a large scale. One promising approach in the search for a solution is fusion energy. Internationally speaking, the race to have the first economical fusion power plant is already in full swing. An increase in private and government involvement worldwide, as well as recent breakthroughs in research, are also helping to raise public awareness of this promising technology and fuel efforts towards achieving a viable power plant.

In early 2022 the Federal Ministry of Education and Research (BMBF) took the first steps to position itself in view of this increasing momentum and explore the possibility of expanding its funding activities in the field of fusion research. Germany is already one of the leading players worldwide in the field of 'magnetic fusion'. But with regard to 'inertial fusion', there are still comparatively few activities both in Germany and throughout Europe as a whole. In order to shed more light on this field and specifically to identify the potential within Germany, the BMBF commissioned an international expert committee at the end of 2022 to perform an analysis and draw up corresponding recommendations. The results are published in a **memorandum** entitled 'Laser Inertial Fusion Energy', which was provided to the Federal Minister of Research on 22 May 2023.

This paper on fusion outlines fields of action and possible, strategically oriented measures in magnetic and laser fusion research, which are to form the basis for a new BMBF funding programme that is to be developed. The main objective of the measures is to accelerate the development of technology with regard to a fusion power plant.

Following the publication of this paper, a **consultation process** has been planned with the German Fusion Community (science and industry) so that opinions from within the community can be taken into account when creating the future BMBF funding programme.

Fields of action

The measures that have been outlined can be divided into **two strands**. Areas to be addressed include, on the one hand, the ongoing further development of technological approaches and, on the other, the **establishment of a fusion ecosystem**. These strands are closely interwoven.

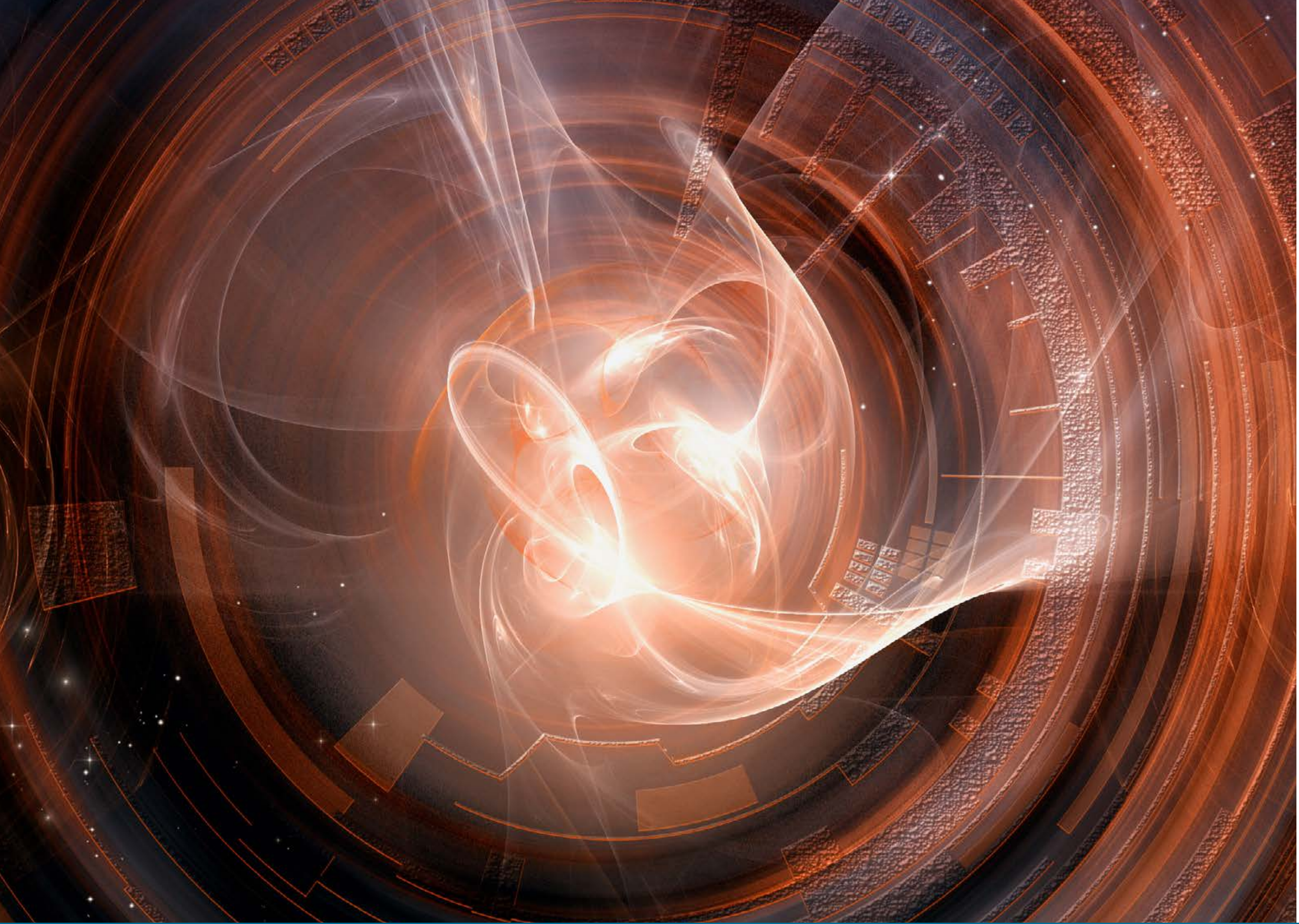
With regard to the **further development of technological approaches**, the stage of maturity of the required technologies is to be increased in a targeted manner together with the involvement of industry (e.g. through collaborative research projects). In order to identify research and development requirements, opportunities and risks inherent in the individual approaches must be continuously evaluated in a manner that remains open to different technologies and subjected to an overall assessment using integrated system studies. The aim is to therefore build on Germany's existing strengths and exploit synergies with other branches of science and industry. The extensive expertise that already exists in terms of magnetic fusion and specifically regarding stellarators is to be further expanded. In the field of laser fusion, a variant within inertial fusion, Germany can draw on skills that are of global importance, particularly with regard to essential system components. This potential needs to be brought together and further developed in a targeted manner.

To ensure the aforementioned goal can be achieved, **a fusion ecosystem needs to be built**. In order to exploit synergies between the existing institutions and to strengthen technology transfer, hubs for individual technologies are to be set up; these will also be open to industry and can be used as test facilities. The aim here is to promote the training and further education of highly qualified experts and to facilitate the networking of national and, within the framework of suitable cooperation, international actors. The chairs and institutes together with their associated infrastructures form an important part of the hubs.

Of key importance for the future use of fusion energy is a dialogue with the public and an open and objective discussion about the opportunities and risks posed by fusion energy.

Adequate legal framework conditions are at the same time required for the construction and operation of fusion power plants. The BMBF will work within the Federal Government to develop these outside of nuclear law at an early stage.

Germany has the opportunity to take on a leading role in realising the energy of the future – fusion energy. The starting point is excellent, but a number of major challenges still remain on the path to energy production using fusion, which can only be overcome through close cooperation between politics, science and industry. This position paper on fusion research is intended to provide guidance and a basis for discussion about this path and lay the foundations for a national programme, open to all technologies, that can promote magnetic and laser fusion.



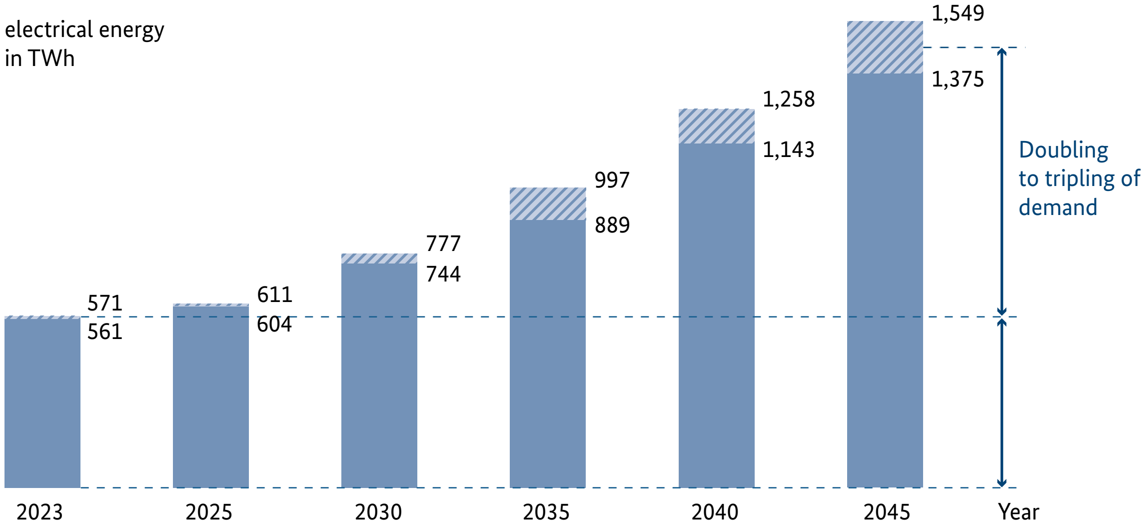
1. Fusion energy as a beacon of hope

Fusion as a future technology for a CO_2-neutral energy source

Humanity is facing huge challenges. While recent studies show that energy demand is rising worldwide and will continue to do so,[1] it can be assumed in particular that the demand for electrical energy will increase sharply by at least a factor of two to three by 2050.[2] Moreover, climate researchers have been highlighting the fact that an energy transition has been urgently needed for decades. The fact is that we need secure, base-load capable, affordable and CO_2-neutral energy sources.

In 2021 the share of green energies in the global electricity mix did not even reach one third.[3] One reason behind this is that the sun and wind are not always reliable suppliers of energy as a result of fluctuating weather conditions. Short- and long-term storage of green electricity and changes to electricity consumption – turning it into flexible electricity production within a digitally networked energy system – will significantly increase the stability of the electricity system. Nevertheless, we cannot do without conventional power plants at this point in time. For industrialised countries with a particularly high energy consumption, a diversified energy sector will continue to be important in the future. Additional technologies are therefore required: they need to be capable of meeting the base load and of complementing the future electricity mix in a manner that is CO_2-neutral. In addition to electricity from renewable sources and green hydrogen, fusion can also contribute to achieving this.

Figure 1: Modelled development of the demand for electrical energy in Germany until 2045



Source: Fraunhofer ISE, Copernicus Project Ariadne, *ariadneprojekt.de*

Fusion energy provides a beacon of hope

Fusion is the energy source of the sun and all other stars, which therefore makes it the most significant energy source in the universe. At extremely high temperatures of 15 million degrees and a pressure of 100 billion bars, two hydrogen atoms fuse into one helium atom at its centre. The binding energy that is released is so enormous that it far exceeds the energy gain achieved through conventional combustion processes. By way of example, one gram of fusion fuel can produce approximately as much energy as 11 to 13 tonnes of oil or hard coal.

If it is possible in an economically controlled manner to replicate this process on Earth for energy production, it would also be significantly easier to meet the increased demand for electricity in conjunction with renewable energy sources.

Furthermore, there are numerous other advantages to fusion energy:

- **Fusion energy is resource-efficient.** Potential fuels are hydrogen isotopes deuterium and tritium. These are available in almost unlimited quantities since they occur in high levels throughout nature (deuterium is found in seawater, while tritium occurs through breeding in the fusion process itself).
- **Fusion energy is clean.** No fossil fuels are burned with fusion energy. The electricity that is produced would therefore be CO_2-neutral. Moreover, fusion only produces short-lived and low-level radioactive waste that does not require radioactive waste isolation.
- **Fusion energy is safe.** With fusion it is physically impossible for there to be dangerous, uncontrolled chain reactions. An operational failure would immediately stop the reaction.

1 Resources for the Future. Global Energy Outlook 2022: Turning Points and Tension in the Energy Transition. April 2022; *rff.org/publications/reports/global-energy-outlook-2022/*

2 *ise.fraunhofer.de/de/veroeffentlichungen/studien/wege-zu-einem-klimaneutralen-energiesystem.html*

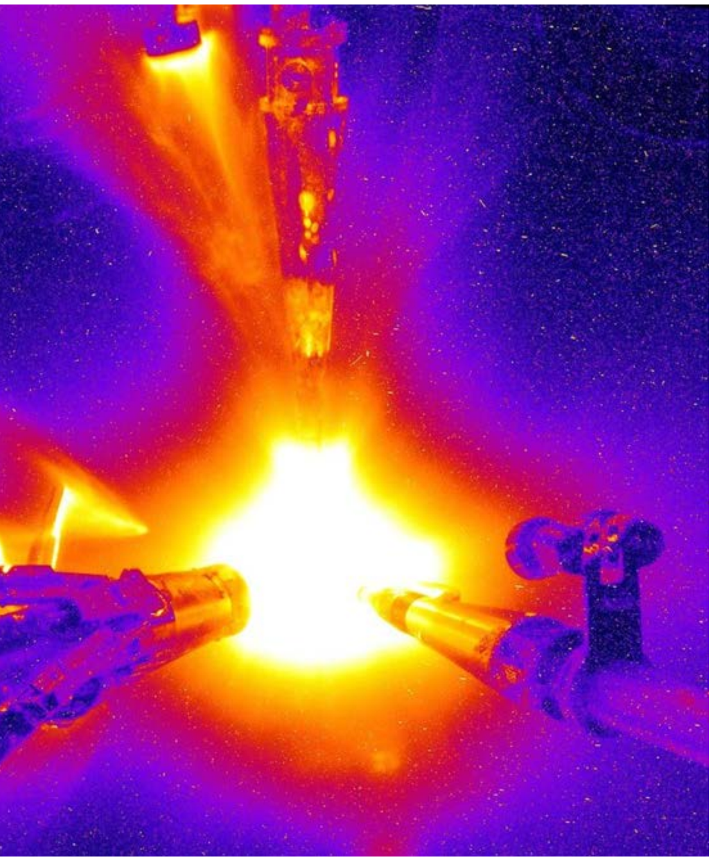
3 Enerdata. Share of renewable energies in generation of power. In: Globales Energie- und Klimastatistik-Jahrbuch 2022; *energiestatistik.enerdata.net/erneuerbare-energien/erneuerbare-anteil-in-strom-produktion.html*

- **Fusion energy is base-load capable.** Unlike the volatile wind power or solar power units, a fusion power plant is able to supply the electricity grid with electrical energy on a continuous basis.

- **Fusion energy is affordable.** According to current calculations, the cost of a kilowatt hour is somewhere in the order of magnitude of today's base-load power.

Advances in fusion research fuel the debate

From a technological point of view, it is incredibly complicated to set fusion processes in motion in laboratories or power plants. Atomic nuclei are subject to strong repulsion because of their positive electrical charge; high pressures and temperatures are required to overcome this. Fusion can therefore only be achieved with the help of extreme magnetic fields, heating systems or very powerful lasers.



Colour photograph of a deuterium-tritium implosion at the National Ignition Facility (NIF)

Recent advances in **laser fusion**, however, are promising. In December 2022 researchers at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California succeeded for the first time in extracting more energy from the fusion reaction (3.15 MJ) than the amount that was irradiated into the target by the laser beams that were used (2.05 MJ). Although this constitutes a considerable scientific milestone in fusion research, the process remains far from being suitable for industrial application in fusion power plants (see Chapter 2.2).

Magnetic fusion is the most advanced approach on an international scale and currently plays a key role in research and industry (see Chapter 2.1). The International Thermonuclear Experimental Reactor (ITER), currently being built in France, will be the world's largest facility for research into magnetic fusion. German research institutions feature among the world leaders in this field.

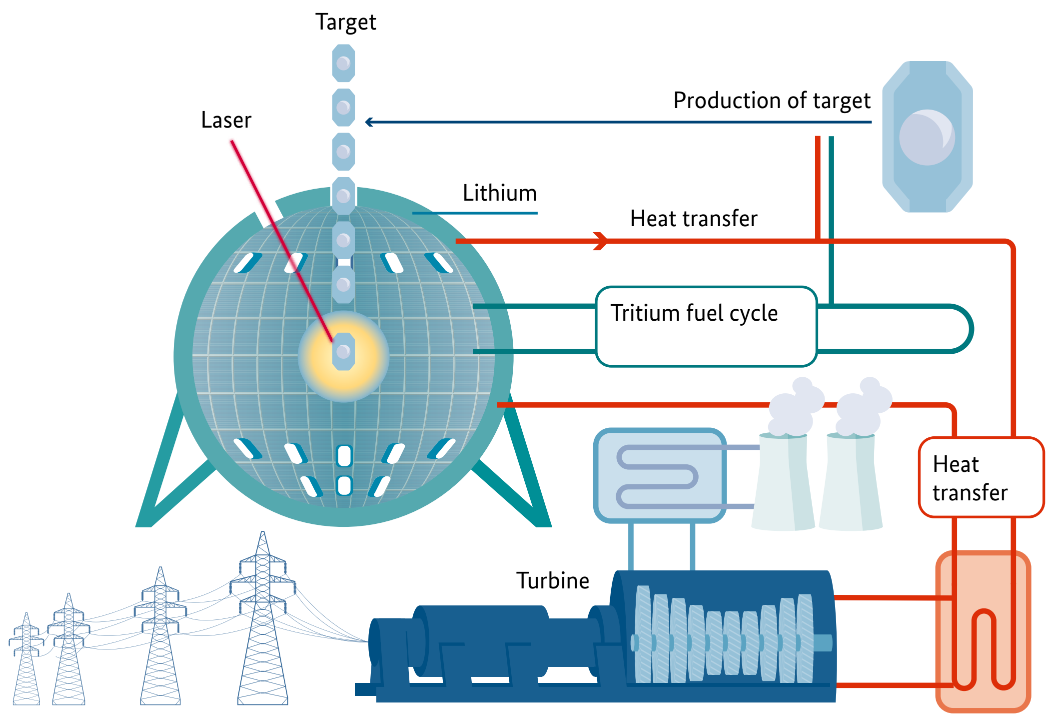
Nevertheless, it is not possible to say with any level of certainty which approach will actually prevail. However, the **sharp increase in private involvement** in the field of fusion research demonstrates that, for a long time now, there has been an international race to achieve the first fusion reactor. In the last two years alone, total private investment worldwide has grown by more than 260 percent to more than USD 4.8 billion today. Only USD 117 million of this came from the public purse (as of July 2022).[4]

Germany as a driving force of fusion research

In order to meet the societal challenges outlined above and to strengthen Germany's sovereignty in technological and energy matters, the BMBF is funding research into all suitable approaches, ensuring there is an **open approach to different technologies.** In addition to those technologies that can already be used to generate electricity without using CO_2 (e.g. wind energy, water energy, solar energy, geothermal energy), fusion is a promising approach to being able to complement the future electricity mix as a CO_2-neutral energy source. All recognised approaches, both in magnetic fusion and in inertial fusion, should therefore be investigated regarding their suitability for achieving fusion power plants.

4 Fusion Industry Association. The global fusion industry in 2022; *fusionindustryassociation.org/about-fusion-industry*

Figure 2: Operating principle behind a laser fusion power plant



Source: In accordance with the Lawrence Livermore National Laboratory

Germany already has diverse and long-standing expertise in both areas (see Chapter 2), but has thus far focused on the promotion of magnetic fusion. Advances in fusion research have now shown that a systematic re-assessment of the situation is necessary. Even before the breakthroughs in California, the BMBF had already discussed the prospects of various fusion technologies in May 2022 with experts from the German science sector and industry. During an expert discussion the different technology paths were highlighted, their potential examined and possible obstacles to their realisation were discussed. The participants additionally determined what needs to be done in terms of research and business so that Germany is well positioned for the future technology of fusion and can thereby profit from it in an optimal manner.

In implementing one of the recommendations from the expert discussion, the BMBF has appointed an **international expert commission**. Between December 2022 and March 2023 they analysed and evaluated various approaches to laser fusion and organised possible implementation concepts into a time schedule. The results of the work of the expert commission are published in a memorandum entitled 'Laser Inertial Fusion Energy' and form a valuable contribution to the BMBF's strategic considerations.

2. Scientific and technological starting position

On a global level fusion research primarily focuses on two technological approaches: magnetic fusion and inertial fusion, of which laser fusion is a variant.

2.1 Magnetic fusion

With **magnetic fusion** (MFE: 'magnetic fusion energy'), a gas mixture of the hydrogen isotopes deuterium and tritium is enclosed in a reactor by a magnetic field so that it cannot touch the reactor walls, and so that particles and energy do not leave the plasma (this is known as magnetic confinement). The enclosed plasma is heated to a temperature of several million degrees Celsius using a very powerful external heater, allowing fusion reactions to take place in a similar way to those in the sun. The **Stellarator** and the **Tokamak** are the two most common magnetic fusion reactor types.

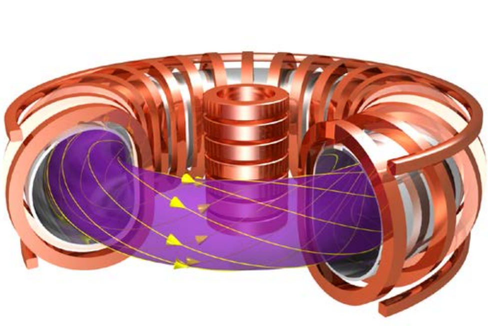
Research in Germany, Europe and worldwide

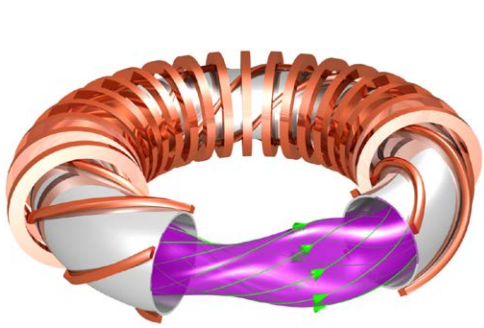
Germany is one of the leading nations in magnetic fusion research. The Max Planck Institute for Plasma Physics (IPP) operates the **ASDEX Upgrade Tokamak** in Garching and the world's largest and most advanced stellarator, **Wendelstein 7-X**, in Greifswald. In addition to the IPP, the Karlsruhe Institute of Technology (KIT) and the Jülich Research Centre (FZJ) are also researching important sub-areas of fusion. In Germany there are therefore outstanding and unique competences, among other things, in research undertaken into the interaction between plasma and the reactor wall, fatigue of materials, high field magnets, the fuel cycle and complex reactor cooling systems. Because of the high potential, the BMBF is currently funding national projects at the above-mentioned institutions to the tune of around EUR 150 million annually (as of: 2023).

Europe is also a major player in magnetic fusion research on a global scale. In the UK the world's largest Tokamak is in operation as part of the **JET** (Joint European Torus) project. It serves as a test environment for numerous technologies and scenarios that are now being applied in the international fusion research facility **ITER**, which is currently being built in Cadarache in southern France. Like JET, ITER is based on the Tokamak principle and is being financed and realised through international research cooperation between the European Union (via EURATOM), China, India, Japan, South Korea, Russia and the USA. ITER aims to demonstrate that magnetic fusion can achieve a positive energy balance. ITER will additionally develop and demonstrate key technological components and processes related to the operation of a fusion power plant. Germany is significantly involved in ITER and makes important contributions to its realisation through sharing expertise, including energy decoupling (plasma-wall interaction), plasma heating (gyrotrons, plasma sources for neutral beam heating), magnetic and cryogenic materials, the fuel cycle, breeding blanket concepts, divertor technology and experiment controls.

Electron photomicrograph of the fracture point of a tungsten fibre composite. Its use in the fusion reactor could help to better absorb thermal stresses and limit fissuring at the prevailing temperatures.

Figure 3: Magnetic confinement



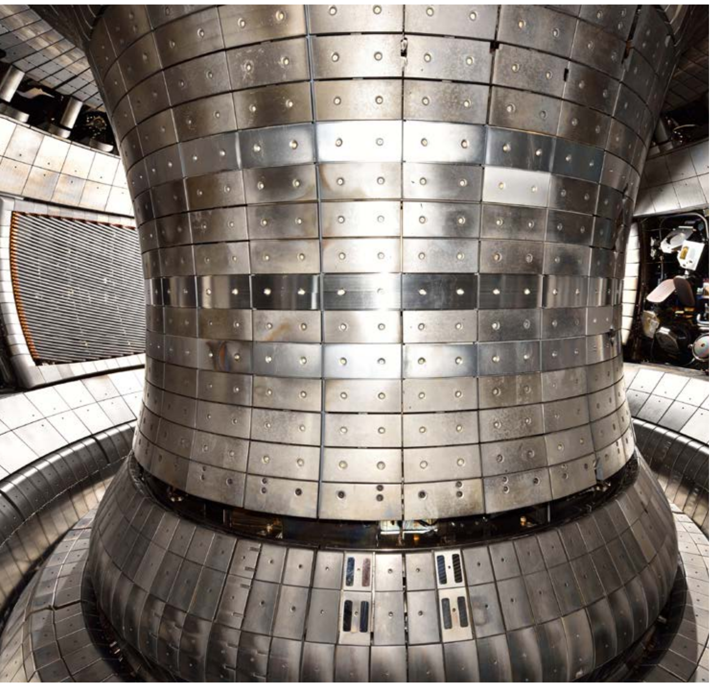


Source: MPI for Plasma Physics

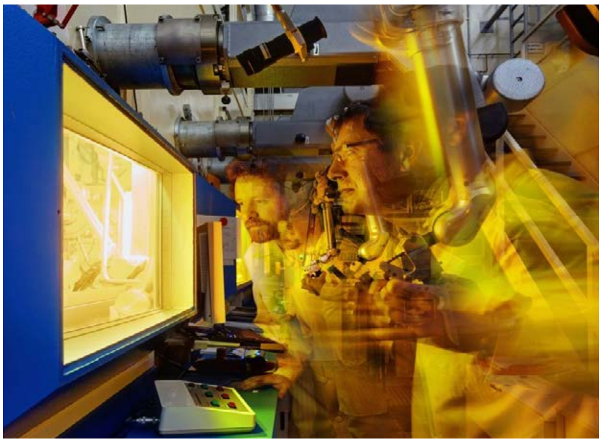
Principle of magnetic confinement: within the Tokamak (left) a current is generated in the plasma (violet) by means of a central solenoid (brown), the magnetic field of which combines with fields of further coils to form the required twisted magnetic field cage. With a stellarator (right) a very complex shape and the arrangement of the outer coils provide the twisted magnetic field.

Alongside the **USA** and the **UK, France** with its CEA (Commissariat à l'énergie atomique et aux énergies alternatives) is one of the key players in magnetic fusion research. It operates the IRFM (Institut de Recherche sur la Fusion par confinement Magnétique), which, due to its outstanding expertise, was one of the decisive factors in choosing the ITER site in 2005. France, as the host country, contributes nine percent of the total cost of the ITER project, which is about 20 percent of the European contribution to the costs.

The European consortium **EUROfusion** (consortium leader IPP) is funded by the EU and contributes to the implementation of the research and training programme of the European Atomic Energy Community ('Euratom programme'). The basis for this is the 'European Roadmap to the Realisation of Fusion Energy' developed by EUROfusion.[5] The focus is on preparing the ITER experiments and the concept for DEMO, a future fusion demonstration power plant.



Inside view of ASDEX Upgrade



Materials for the vacuum vessel are investigated in the 'hot cells' of the KIT fusion materials laboratory

Increasing government and private investment

Interest in a fusion reactor based on magnetic fusion is growing worldwide. **China** recently launched a large-scale national catch-up programme. In the new BEST Tokamak plant, the country intends to test all necessary fusion technologies so that they can subsequently build a functioning power plant by 2040. In the USA the latest amount of funding for fusion research was USD 763 million in 2023. An increase to around USD one billion is planned for 2024. Only USD 15 million of this amount has thus far been earmarked for civil laser fusion research. With its comprehensive national public-private partnership programme, the USA intends to invest USD 135 million in 2024 in projects aimed at building, among other things, the first small-scale demonstration fusion power plants for civilian purposes by the end of the 2030s.[6]

The activities under way in the **private sector** are also considerable. In its latest report, the Fusion Industry Association (FIA) predicted that about half of all **fusion companies worldwide** will specialise in magnetic fusion. Larger companies who have investments of over USD 200 million particularly follow this approach. By a large majority the generation of electricity is deemed to be the target market.[7] German start-ups Gauss Fusion and Proxima Fusion have been active in the field of magnetic fusion in Germany since 2022.

5 *euro-fusion.org/eurofusion/roadmap/*

6 *science.osti.gov/fes/About/FES-Budget*

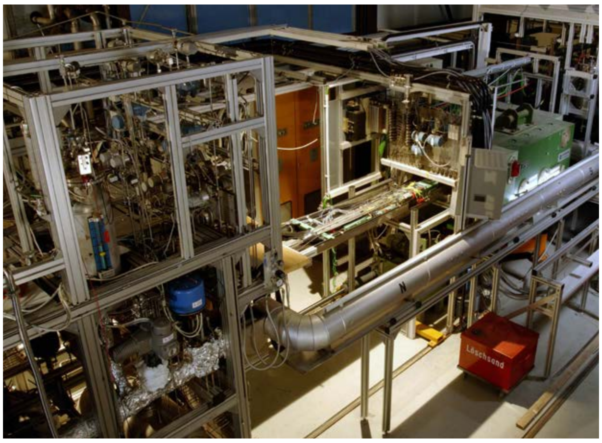
7 Fusion Industry Association. The global fusion industry in 2022; *fusionindustryassociation.org/about-fusion-industry*

Figure 4: Headquarters of private fusion companies worldwide

Source: Fusion Industry Association (as of: April 2023)

2.2 Inertial Fusion

With **inertial fusion** (IFE: 'inertial fusion energy'), a millimetre-sized pellet (known as the target) made from frozen fuel (usually a deuterium-tritium mixture) is bombarded with high-intensity laser radiation in fractions of a second. In this way the pellet reaches a hundred times its density and a temperature of up to 120 million degrees Celsius. This highly compressed state allows fusion reactions to take place before the target is driven apart by the energy that is released.



At the MEKKA-facility (Magnetohydrodynamic Experiments in NaK Karlsruhe) of KIT, liquid metal flows can be studied for fusion applications

Fundamentally, a distinction is made between two processes that exist within laser fusion: indirect drive and direct drive. With **indirect drive** the laser beams pass through small openings into a hollow metal cavity, the hohlraum, inside of which the fuel is located. The laser beams strike the inner wall of the hohlraum, converting the laser radiation into X-rays and uniformly irradiating and thereby heating the target. The plasma expanding from the surface of the fuel pellet creates a recoil that concentrically compresses the remainder. Temperatures that enable the fusion reactions to take place are reached in the centre of the fuel ball. However, this method is associated with additional losses due to the conversion of the radiation.

With **direct drive**, on the other hand, the compression takes place directly via the laser radiation. The hohlraum and conversion into X-rays is thereby avoided.

The fuel ball is only encased in a thin layer of glass or metal. This method requires increased precision, but is significantly more energy-efficient.

For a long time, therefore, direct drive seemed to be the more promising approach for energy generation applications. However, due to the respective specific advantages and disadvantages, experts believe that the race between the two methods is ongoing.

Overview of the status quo of research in Europe and around the world

Most of the research in the field of laser fusion has thus far been motivated by the military: experiments using indirect drive provide important data for the validation of codes to study the processes in hydrogen bombs.

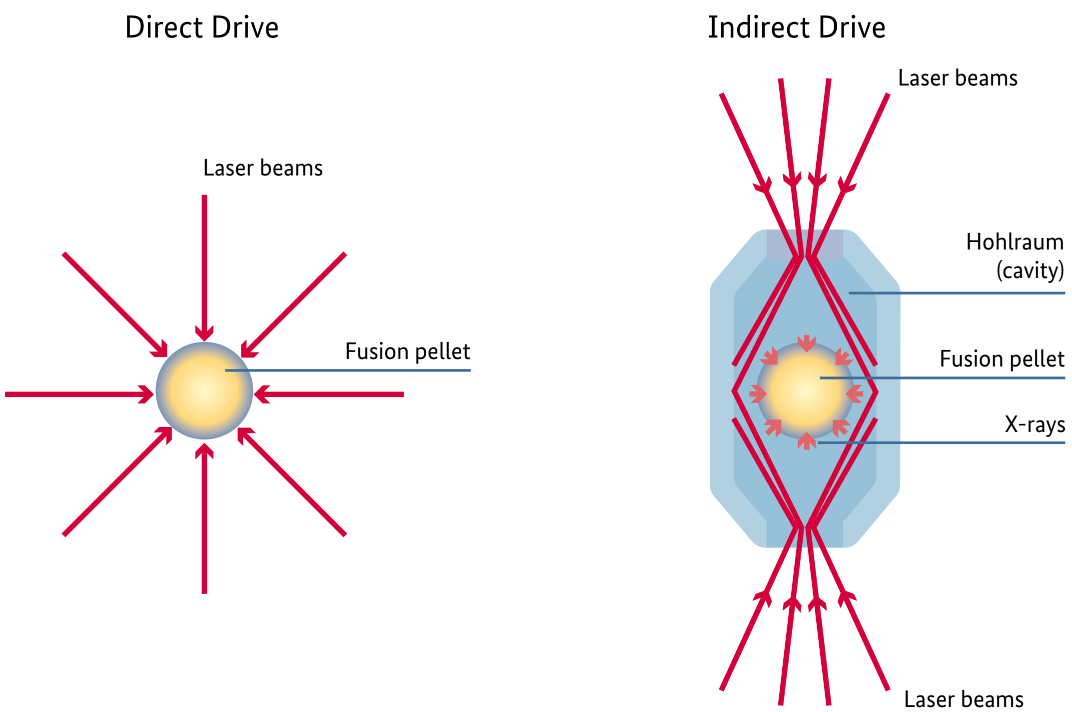
The world leader in the field of laser fusion is the **USA**. After a series of technological breakthroughs, in December 2022 the National Ignition Facility (NIF) succeeded for the first time in using indirect drive to extract a larger amount of energy from the fusion reaction than the amount that was supplied via the lasers ('scientific breakeven'). The energy gain amounted to around 53 percent.

Within **Europe**, France, also against a military background, is particularly active in this field. Other high-energy laser facilities are located in the UK, the Czech Republic and also Germany (see below). For their part, China, Japan and Russia are pushing ahead with laser fusion research.

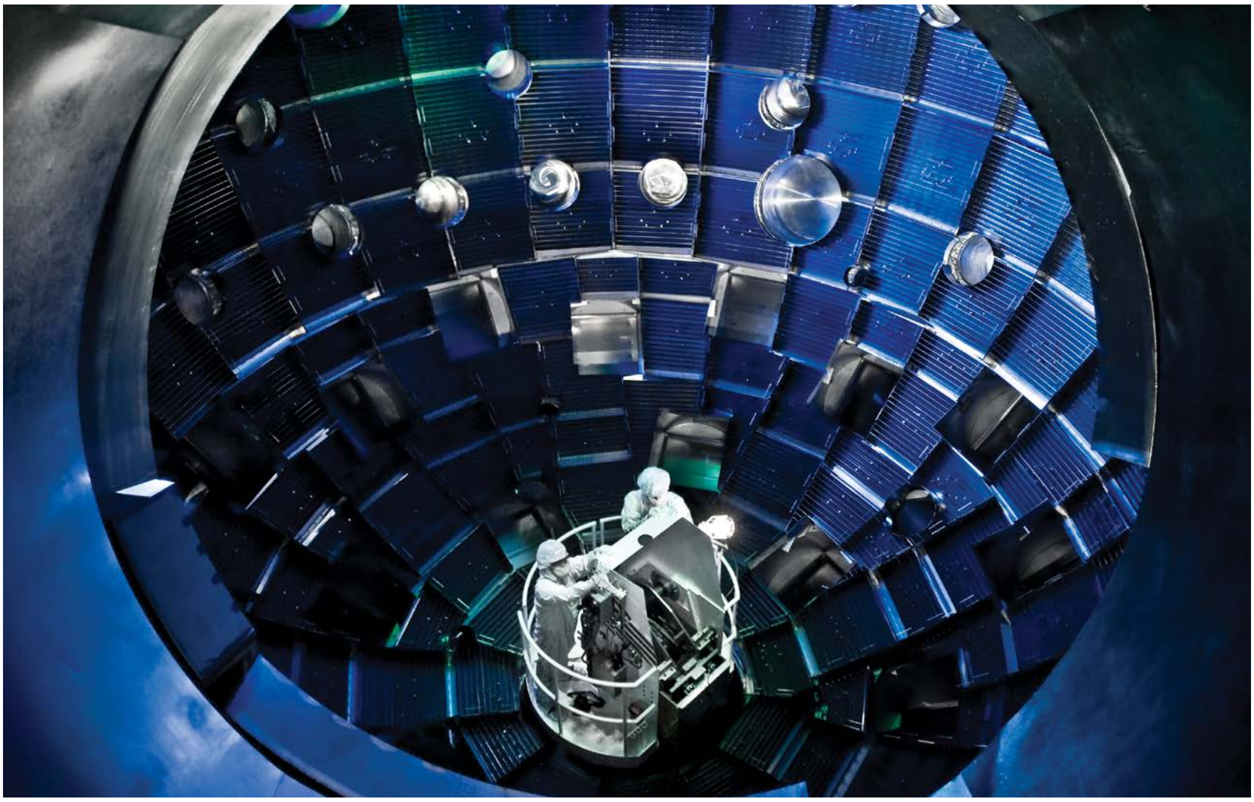
Challenges faced on the way to the goal

While the success at the NIF in the USA is seen as an outstanding milestone, it should not obscure the fact that many **challenges** still need to be overcome, at least with regard to a **fusion reactor** that uses laser fusion. Upon closer inspection, the actual efficiency of the NIF experiment drops to less than one percent as the lasers require 100 times more electrical energy to operate than the amount they transport into the fusion

Figure 5: Firing schematic for laser fusion

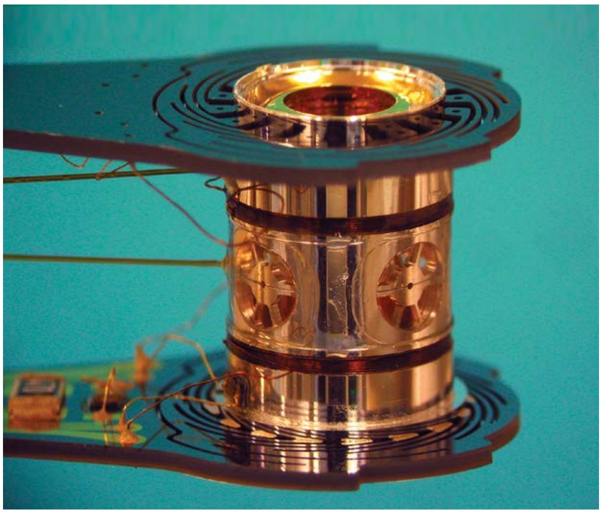


With direct drive (left) the laser beams hit the fuel capsule (pellet) directly from all sides and compress it as evenly as possible. With indirect drive (right) the lasers first enter a cavity (hohlraum) that converts them into X-rays; these then act on the capsule and compress it.



NIF technicians undertaking maintenance work inside the target chamber

chamber in the form of laser energy. In order to be able to generate energy in a fusion reactor, up to ten fuel pellets per second must also be positioned and ignited with a high degree of precision. The required production rate of the targets are still currently unattainable. In addition, the number of shots that can be fired using current laser systems is limited to only one or two per day.

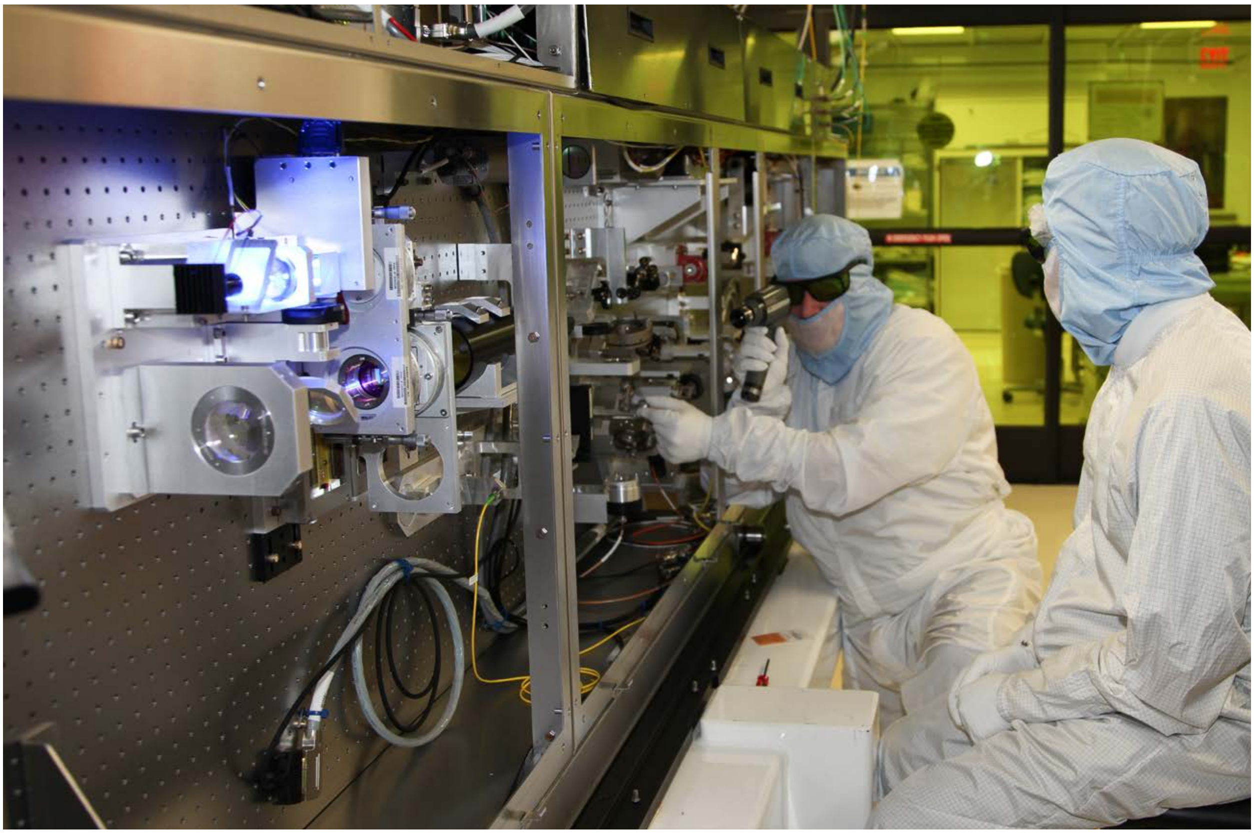


The hohlraum, which measures approximately 1 cm, houses the fuel capsule for the NIF experiments

Inertial fusion research in Germany

Consequently, there is still a long way to go in achieving a usable fusion power plant. Although there are very few activities in the field of laser fusion in **Germany** today, a number of opportunities are opening up in this area. Research entities of the Helmholtz Association, Max Planck Society and Fraunhofer Society have encountered laser-based inertial fusion in the past as a result of their thematic focus. Some of the facilities operate lasers that are significant on an international scale, together with relevant parameters.[8] In addition there are some companies that are world leaders in

8 The lasers PHELIX at GSI Darmstadt; DRACO (and soon PENELOPE) at Helmholtz-Zentrum Dresden-Rossendorf (HZDR); POLARIS at Helmholtz Institute Jena; HIBEF at XFEL/DESY.



For laser fusion the required lasers must be adjusted with great precision

the **manufacture of the targets** and in the **development of optical materials and components used in** the laser systems. For example, the capsules for the NIF's fuel targets come from a spin-off of the Fraunhofer Institute for Applied Solid State Physics (IAF), and their global activities would not be possible without contributions from the German optics industry. At present it is predominantly the two German start-ups Focused Energy and Marvel Fusion that are specifically dedicated to achieving a **fusion reactor** based on laser fusion.

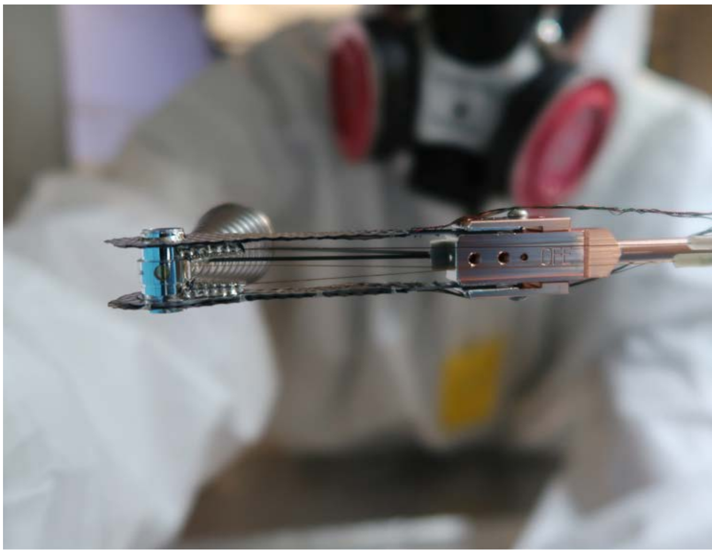
Findings of the 'Laser Inertial Fusion Energy' memorandum

It is clear from the BMBF Expert Commission's memorandum that laser fusion is making rapid progress worldwide and that there is an urgent need for action in Germany with regard to a broader energy portfolio. The expert commission therefore classifies the inclusion of laser fusion in a large-scale and sustainable R&D programme as being essential.

Furthermore, the expert commission characterises the societal and technical challenges as enormous: there is a need for a broad IFE ecosystem that has been grown by a large expert professional community, appropriate infrastructure, a regulated framework for action and public awareness. This is still lacking in Germany. However, the Expert Commission does make reference to infrastructures that already exist in Germany (primarily in magnetic fusion) and to the existing expertise described above (e.g. in laser and target manufacturing) in the field of inertial fusion. This could be built upon to create technology hubs as well as centres of excellence, something that will also benefit start-ups. Their concepts have been based on very special designs and can only be validated and investigated on their own by investing a great deal of time and effort. Furthermore, items such as clear evaluation criteria and milestones required to narrow down approaches at a later stage are still lacking. Germany has proven expertise in system-level integration, which is particularly suitable for international cooperation. Within this context, in addition to the necessary and sometimes considerable technological leaps required to realise a power plant, reference is also made to the need to prioritise a design for a laser fusion power plant, which then subsequently defines the requirements for developments in the relevant sub-technologies.

The memorandum additionally notes an urgent need for early recruitment and training of appropriate skilled personnel. This relates to both the need for researchers from all STEM subjects for the early phases of a programme, as well as engineers and technical staff for transfer and integration activities that take place later on.

Link to the Memorandum on Laser Inertial Fusion Energy



A target with specific apparatus to measure the shock properties of extremely compressed deuterium

3. The road to a fusion power plant

Goals, strategies and milestones

The BMBF's goal is to create the conditions for the construction and operation of fusion power plants as quickly as possible and in the most targeted manner possible. First and foremost this requires extensive research activities. Both inertial fusion as well as magnetic confinement approaches are being pursued in an open mind regarding technology to be used.

The biggest contenders in the race for a commercial fusion reactor outside of Germany are France, China and the USA. What is most noteworthy are the **extensive government funding measures** within the nations, which support ambitious projects in both magnetic and laser fusion research. Although widespread use of fusion power plants is not expected before 2050, increasing investments by other countries and private investors are opening up opportunities for an accelerated pace of realisation. This highlights the need to effectively bring together national strengths in order to keep up with international technology competition. In order to avoid a loss of skills and brain drain, research institutions and companies need to be supported in magnetic and laser fusion, and research infrastructures must be expanded as necessary. The overarching goal of such a funding programme must be the construction of a (demonstration) **power plant**, through which clean electricity can be generated on a large scale and fed into the grid.

Acting with foresight means acting with an openness to technology

The question remains as to which technological approach will prevail in constructing a fusion power plant. The question is not only whether magnetic or inertial fusion will be the approach used in the future, but also which reactor types and processes within the various basic concepts will ultimately lead to success. In order to pursue the most target-oriented approach in achieving a functional power plant, it will be necessary to keep an open mind regarding technology. The different approaches and their chances of success need to be reassessed on an ongoing basis. This was also the conclusion reached by the Expert Commission in its memorandum on laser fusion. Furthermore, it is important to tap into synergies with related high-tech fields, such as lasers, materials development or high-performance computers. On the one hand, developments in these fields can be used for fusion; on the other, the results of fusion research also introduce applications in these fields beyond fusion. In addition to synergies, risks are also present, for example, in terms of dual-use concerns, which must be constantly analysed and evaluated.

Three phases on the way to a power plant

In order to be able to realise a power plant as quickly as possible, it is crucial to rapidly develop the necessary technologies. So that the good starting point can be leveraged in this regard, and to not lose out in comparison with the rest of the world, specific and systematic measures must be taken to expand research into national fusion. It is important to consider the following phases, which cannot be distinctly separated from each other and indeed may even overlap.

1. **Research and development phase (from today until the first half of the 2030s).**
   The **further development technology readiness levels** (TRLs), which currently range from 1 to approx. 4, will initially play a major role. However, magnetic fusion sub-technologies are more advanced than those of laser fusion. ITER, for example, would equal a TRL of 5 to 6. In this phase the focus is still on researching basic principles, interrelationships and materials, as well as developing components and systems. In this regard it is important to establish the necessary structures in the form of hubs. On the one hand this necessitates the strong involvement of research institutions and universities, but on the other the participation of industry at the earliest possible stage. Designs and strategies have to be elicited at this stage by means of comprehensive studies, examining the chances of success and the risks of individual technologies and selecting the pathways to be pursued.

   Supporting businesses, especially SMEs and start-ups, is crucial for this. In order to finance the necessary R&D activities and to accelerate and sustainably strengthen the commercialisation of fusion technologies, financial support should be available though funds provided by state funding agencies as well as

Part of the Wendelstein 7-X plasma vessel during production

View of the Wendelstein 7-X fusion facility in the experimental hall

private risk capital providers (known as venture capital). At the same time, companies need to be provided with regulated access to research infrastructures so they can test and refine systems. Cooperation between research institutions, universities and companies must be strengthened in this phase. Efficient support for the R&D phase is to be the subject of a BMBF funding programme (see Chapter 5).

2. **Transfer phase (first half of the 2030s to the start of the 2040s)**
   During the transfer phase, industry will increasingly take the lead on further development. Private companies will transform the knowledge gained during the R&D phase into initial products using research contributions. The ultimate goal is the **construction of a power plant prototype,** which will correspond to an increase to TRL 7 to 8.

   During this phase an **interdepartmental government programme** is to be put together under the leadership of the BMBF, for which further opportunities for public-private partnerships must also be explored so that greater support can be provided to industry during this phase.

3. **Operational phase (from the 2040s)**
   Lastly, in order to be able to supplement the electricity mix with fusion energy, the **construction and operation** of a large number of fusion power plants must be ensured by the industry. This would require ongoing funding for research and development in order to improve technologies and further develop power plants during this phase.

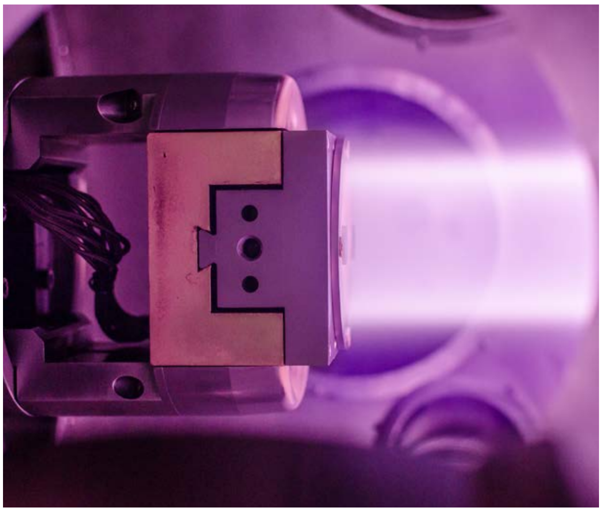
4. Fields of action

Seize opportunities and build on strengths

4.1 Magnetic fusion

The **Wendelstein 7-X** facility is the world's most advanced **stellarator**. In **ASDEX Upgrade (Tokamak)**, Germany has a second important test facility. In the coming years this strength must be maintained, expanded and further developed towards an application orientation. Networking with the private sector should also be promoted on a greater scale.

This supports the transition from fundamental research to industrial applications in the sense of the phases described in Chapter 3, so that additional private capital can be activated for fusion research. Moreover, some sub-technologies are not limited to magnetic fusion, but can provide German companies with interesting second and third applications along the way. This strengthens Germany as a location of industry and reduces the financial risk for taxpayers and companies.


Load test of a material sample in the plasma source PSI-2

Examples of this include:

- Medical technology (e.g. through new types of high-field magnets, superconductors)
- Materials for extreme operating conditions (e.g. special mechanical engineering, aviation, space)
- Accelerator technologies (superconducting [HTS] magnets)
- Telecommunications (gyrotrons)
- Robotics
- High-precision measuring techniques (e.g. for magnetic fields)

Possible priorities and research topics in magnetic fusion are:

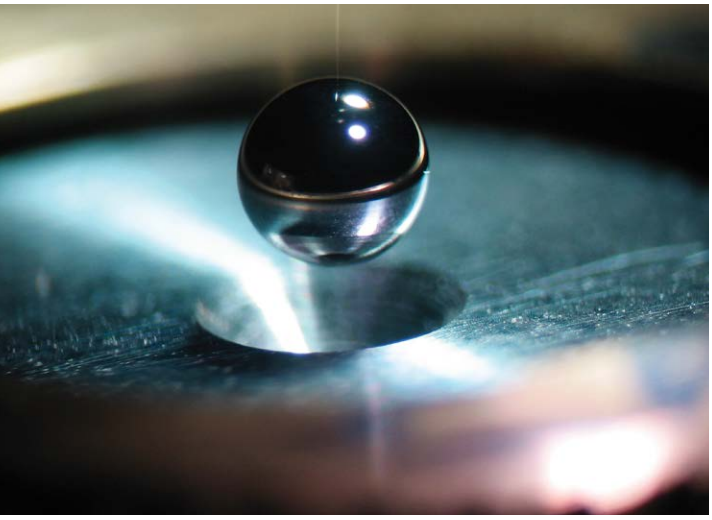
- Research on Wendelstein 7-X as a model facility for plasma physics and operating framework conditions of a stellarator-type fusion power plant
- Research on ASDEX Upgrade as a model facility for Tokamaks; most importantly in this respect is the clarification of plasma physics issues in the construction of ITER
- High-field magnetic coils, if necessary using high temperature superconductors
- Plasma-wall interaction and materials research for the first wall
- Resistant and low activation divertor materials
- Tritium cycle including concepts for tritium breeding blankets
- Rapid, high-precision diagnostic systems for operating magnetic fusion systems. These include magnetic diagnostics, bolometric systems for plasma measurement, microwave diagnostics, interferometry and spectroscopy instruments for the characterisation of plasma core and edge regions, in addition to infrared imaging systems
- Better understanding of fundamental plasma physics, which can also be achieved through improved simulation tools and in perspective, possibly through quantum computers and new simulation codes
- Development of remote handling systems for critical parts of a power plant, as well as the complex geometry of stellarators

4.2 Inertial Fusion

Unlike in magnetic fusion, there is currently no comparable research landscape in Germany in inertial fusion and specifically in **laser fusion**. Nevertheless, Germany can **start from an excellent point** as it has research centres active in the field of fundamental research with high-energy lasers. Looking at the industrial landscape, Germany is one of the leading nations in relevant branches of technology and required system components (laser technology, optical components, specialised sensor technology). This creates **opportunities** for laser fusion in Germany. The existing locational advantages are to be maintained and expanded through a new funding programme **(strengthening our strengths)**.

Possible priorities and research topics in laser fusion are:

- High-energy lasers (concepts and materials: cooling, decoupling, efficiency, diode-pumped laser systems, high bandwidth for ‘direct drive’ investigations)
- Target concepts (manufacturing, handling, cryogenics, codes for target physics)



The NIF fuel capsules are approx. 2 mm polished hollow spheres made from plastic, diamond or beryllium, which are filled with frozen hydrogen

- Optical components (large apertures, reinforcing materials, lenses, coatings, electro-optical materials)
- UV- and radiation-resistant components
- Diagnostics adapted to the needs of IFE, including radiation-resistant systems and refined diagnostics for validating codes and models (e.g. target compression)
- Materials for first wall and blanket, including cleaning concepts, material characterisation and material data
- Analysis of the advantages and disadvantages of direct and indirect drive
- General reactor concepts ('system codes', working closely with international partners and the simultaneous development of common standards)

The development of certain components is often interdependent. This is the case, for example, when developing target concepts and reactor designs. On the one hand sufficient infrastructural capacities are required so that concepts can be examined as comprehensively and as holistically as possible. Today, for example, facilities specialise in a single target technology. The result is that the investigation of variants is associated with a great deal of effort and might not even take place at all. Flexible testbeds in conjunction with the hubs could result in significant progress in this respect.

On the other hand systematic studies will be needed to examine the interdependencies and design a route along which a goal-oriented overall concept can be developed so that limited resources can be used as purposefully as possible.

From this, interfaces for cooperation with other countries and partners (such as ELI) can also be identified.

4.3 Cross-cutting issues

With both approaches (magnetic and laser fusion), there are a number of cross-cutting and overarching issues that need to be addressed as the next point of action.

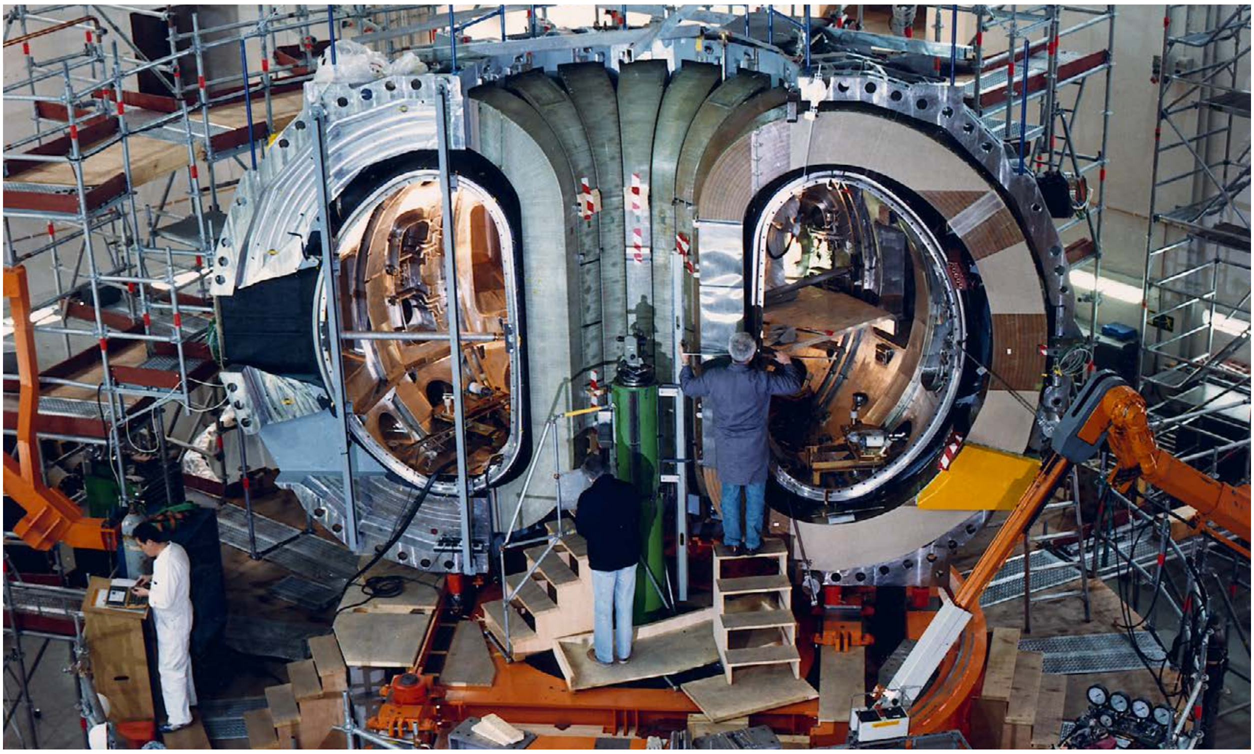
A key priority topic, both in terms of time and content, is the actioning of **design studies** for possible fusion reactor concepts. These are a prerequisite for prioritising suitable sub-technologies and the R&D work required for them. Moreover, it is only on the basis of a design for a complete fusion power plant that a decision can be made in a timely fashion on realising demonstration power plants.

When it comes to **technology development**, the choice of **material for the innermost reactor wall** is extremely important in view of intensive neutron irradiation when using deuterium and tritium as fuel. Research into materials requires (novel) neutron sources such as IFMIF-DONES, in which Germany is seeking to participate.

For both approaches, the generation and handling of tritium will also be important. There is an additional overlap when it comes to **simulation codes** and the **modelling** of the processes. For this, access to 'High Performance Computing (HPC)' centres is needed.

The fundamental goal is to make optimal use of synergies between different technological approaches in terms of cross-cutting issues.

One overarching field of action, as already mentioned above, is the early **education and training of skilled workers.** In-depth study modules, internships as well as specific courses of study are all ways to attract young talent and provide training so they can become highly qualified professionals. Due to new dynamics within



The ASDEX Upgrade fusion plant during assembly

fusion, research and teaching capacities must be built up, leading to the recruitment and training of additional staff. This mainly concerns high-energy laser and plasma physics, and materials research, but also relates to specialised personnel in computer science, engineering and technology.

The **networking** of the excellent research landscape **with industry** is particularly important for focusing research towards application or a power plant. The fusion industry can be mobilised and strengthened through direct (including international) research cooperation, as well as through the transfer of skilled labour and intellectual property (IP). Other peripheral industries can also benefit from this (laser technology, metrology, medical technology, etc.).

Since there are currently no relevant and suitable **regulations** in Germany on the construction, operation and dismantling of fusion power plants (including demonstration plants), adequate regulations outside of nuclear law must be created or existing regulations will need to be adapted at an early stage. Limit values, classifications, etc., must be laid down in a binding manner. This creates planning security for companies.

Close and ongoing **public involvement** in further research into fusion is of key importance so that comprehensive information about the opportunities and risks of this technology can be ensured. This is necessary so that the search for sites and the commissioning of the first plants can succeed supported by a broad social consensus, while the technology is also recognised and understood as being an important contribution to the energy transition.

5. Outlook and measures of the BMBF

With a view to the ambitious goal of a rapid realisation of fusion power plants, the BMBF's research funding is to be expanded, provided with an even stronger programmatic orientation and focused on strategic (sub-)goals. This includes both institutional funding (the HGF 'Fusion' programme) and the specific new project funding to be established together with mutual networking.

A key pillar of future funding for fusion research is a new BMBF funding programme, which is to be published before the end of 2023. In addition to specific project funding, other measures relate to the structuring of the research environment in Germany and the establishment of a fusion ecosystem that involves the public. In parallel the establishment of an adequate legal framework is being driven forward.

The funding programme

Following the publication of this position paper, the German fusion community (science and industry) will be given the opportunity to submit comments as part of a consultation process. If necessary, the BMBF will provide an invitation to further expert discussions to clarify specific questions. On this basis a BMBF funding programme for fusion research is to be created by the end of 2023. This will supplement the existing institutional funding for the technology with project funding, provide the framework for the first phase of 'research and development' outlined in Chapter 3, as well as formulating appropriate priorities in relation to this.

The BMBF programme on fusion research is to be designed as a learning programme. Although research into fusion has been taking place for more than 50 years, the technological developments of recent years and the rapid global increase in (financial) commitments have meant that scientific findings and breakthroughs are to be expected, something which can strongly impact the choice of suitable technology paths and the suggested time scales for achieving a fusion power plant. The latest developments suggest that, in the best case scenario, the realisation of a fusion power plant could be significantly accelerated and, contrary to earlier forecasts, the construction of a demonstrator power plant with a feed-in to the electricity grid could be achieved before the year 2045.

Application-oriented collaborative research as a form of **public-private partnership** (PPP) is one focus of the programme. This represents the logical next step in order to consistently use the expertise derived from fundamental research. In this respect projects on specific sub-technologies are to be carried out as part of cooperative projects between research institutions, universities and industry. This type of research funding has already proven successful in other fields of technology. This allows new findings from research to be taken up at an early stage and expertise to be transferred into the domestic industry for further utilisation. In addition to the networking idea and the financial incentives for industry, this type of funding also provides a secure legal framework for cooperation (as well as between companies), which is particularly important for SMEs and start-ups. Open innovation concepts are also to be encouraged on suitable individual topics.

The BMBF will additionally strive to promote international cooperation and networks in coordination with partner countries and the measures put in place by the EU Commission. This includes the use of such research facilities as the Extreme Light Infrastructure (ELI).[9]

In order to comprehensively investigate any sub-technologies and thereby bring together existing expertise in Germany, the networking of sciences with each other and with industry will be promoted through the establishment of **hubs**. Within this framework, test facilities can be constructed that can also be used by industry ('signature facilities').

The temporary funding of **junior research groups** at universities is intended to provide an additional incentive for building research capacity and know-how, as well as piquing the interest of students in the topic at an early stage.

Preservation and expansion of key infrastructures

Germany continues to support the construction of **ITER** in Cadarache. ITER will provide valuable practical knowledge on the operation of a highly complex fusion facility, which will in any case be relevant for the construction of future fusion power plants.

The further design and financial support of **HGF's 'Fusion' programme** (with which the IPP is associated) will be the subject of talks that are due to take place soon between the funding agencies (federal and state governments) and the HGF about research policy goals for the fifth period of the HGF's programme-oriented funding (PoF V). Within this context the continued operation of essential infrastructures (e.g. tritium cycle at KIT, HML at FZJ, HiBEF at HZDR) must also be ensured.

9 *eli-laser.eu/*

New instruments within the framework of disruptive innovation funding As part of the dynamic environment of a rapidly developing technology, new opportunities for cooperation will also be explored. One initial example is the Federal Agency for Disruptive Innovation (SPRIND GmbH).

From the viewpoint of SPRIND GmbH, fusion research also has potential for the future. In order to accelerate fusion research, SPRIND intends to establish the subsidiary 'Pulsed Light Technologies GmbH'[10], through which SPRIND intends to invest up to EUR 90 million from BMBF funds in fusion research over the next five years. In cooperation with the private sector, Pulsed Light Technologies will focus on the development of infrastructure for laser-driven fusion.

New **research infrastructures** for researching or demonstrating technologies for a fusion power plant should only be planned and actioned with the close involvement of industry.

International cooperation

Fusion research is already an extremely international area. Examples of this are EUROfusion, which is a coalition of European fusion research institutions, and the numerous international contributions and users at Wendelstein 7-X. In this way, research can be accelerated for the benefit of all partners involved. The BMBF will continue to explore opportunities for bilateral cooperation (e.g. with the USA, UK or France) and provide funding where appropriate.

Public participation

One of the BMBF's priorities is involving the public and increasing society's level of knowledge about fusion research. The aim is to encourage a positive approach to fusion as an energy technology through raising awareness and highlighting its potential contribution to the energy transition. The goal is to engage the general public in the following ways, among others:

- Informative websites
- Outreach concepts
- Explainer videos and the use of social media, involving suitable science influencers where appropriate
- Events with public involvement
- InnoTruck:[11] mobile information and dialogue initiative by the BMBF to promote understanding and dialogue on important technologies of the future

Pupils and students can be directly addressed through measures such as technology days, academies or learning materials for physics lessons. These will continue throughout the entire duration of the programme.

Regulation and legal framework

The topic of a legal framework (see Chapter 4) is already being intensively discussed within the fusion community and by various governments. Studies have already looked at this issue in the past. The federal government will actively pursue the creation of a legal framework from the outset.

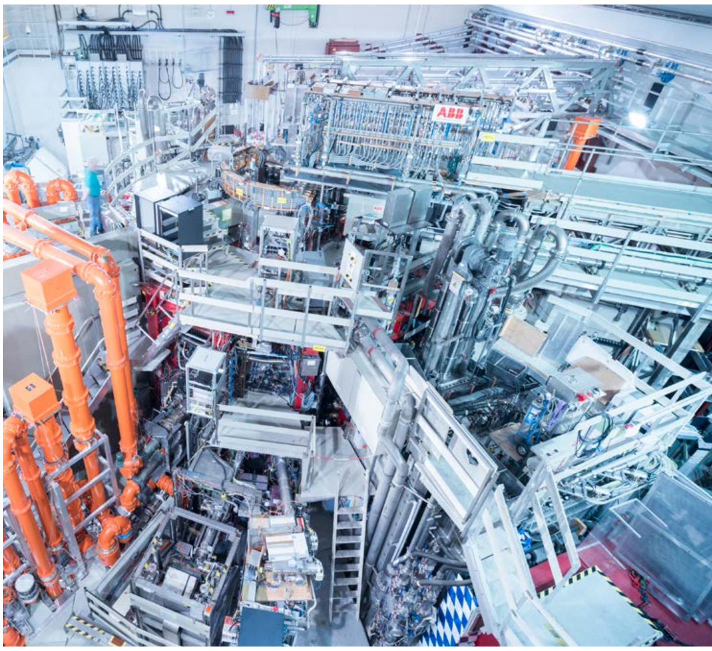
A clear framework that provides legal and planning security for interested companies needs to be put in place in relation to the construction and operation of fusion power plants.

10 *sprind.org/en/articles/pulsed-light-technologies/*

11 *innotruck.de*

In the United Kingdom the decision was made to use existing occupational health and safety regulations pertaining to ionising radiation environments; in this way there is no need for a new legal framework because of the low risk of radiation.[12] A similar approach is employed in the USA.[13] By adopting this same approach in application to the German legal system, one solution could be to adapt the Radiation Protection Act. In order to create a legally secure framework and, in particular, to exclude any contradictions with applicable law, the federal government will need to very carefully look into this in consultation with the professional community.

A discussion of the issue should also be sought within the wider EU context. A uniform legal framework for fusion in European countries could simplify and accelerate the pace of law making within European member states. With this, for example, the existing directive on nuclear safety[14] could be expanded. By involving technical safety organisations, such as the IAEA, a directive like this could be initiated by the EU Commission.



The ASDEX Upgrade fusion plant in Garching

Conclusion

Thanks to the considerable progress in fusion research in recent years, the world has reached a point where this technology is no longer just a hypothetical promise for the future, but seems to be a concrete possibility. Strategic action and a clear positioning from the federal government are therefore urgently needed in order to make decisive use of existing opportunities. Through the planned funding programme and other measures, the BMBF will approach the fields of action outlined above in a manner that is open to different technologies, providing support and networking for German key players in industry and science. This will create the conditions for using fusion as a future CO_2-neutral energy source.

12 *gov.uk/government/consultations/towards-fusion-energy-proposals-for-a-regulatory-framework*

13 *nrc.gov/cdn/doc-collection-news/2023/23-029.pdf*

14 *op.europa.eu/en/publication-detail/-/publication/e1579af9-8d44-11ec-8c40-01aa75ed71a1/language-en*

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