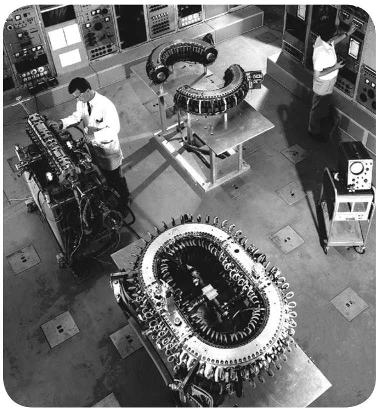
50 years

of research for energy of the future

On 26 July 2010 Max Planck Institute for Plasma Physics (IPP) is celebrating its 50th jubilee – an occasion for sizing up the long stretch already covered on the way to a fusion power plant and determining the laps still to be taken.

The objective of fusion research is to develop a power plant that, like the sun, derives energy from fusion of atomic nuclei. Igniting the fusion fire requires that a low-density plasma composed of the hydrogen isotopes, deuterium and tritium, be confined thermally insulated in magnetic fields and heated to temperatures exceeding 100 million degrees. Whereas research started off a factor of 50,000,000 short of the plasma values needed for ignition, today's large tokamaks are just less than an order of magnitude below the target data, a major contribution to this development having been made by IPP.



Wendelstein 1, IPP's first stellarator, was commissioned in 1960. In the background: right Wendelstein 1-B, left Wendelstein 4.

Photo: IPP

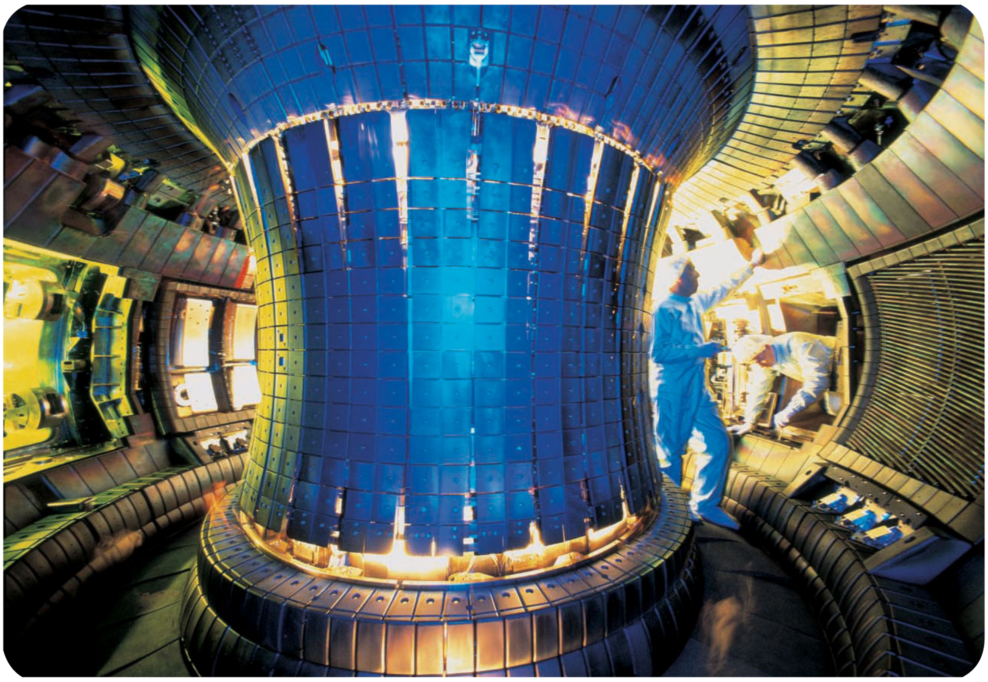
The beginnings | At the end of the 1920s it was presumed by Eddington, Atkinson and Houtermans that fusion of light atoms is the energy source of the sun and stars. In 1938 Bethe and Weizsäcker were able to describe the processes involved. Work aiming at utilising fusion producing energy on earth started at the end of the 1940s, primary in the USA, the Soviet Union and Great Britain.

Looking back from modern fusion experiments into the past shows the beginnings of research to be very modest. With just few litres plasmas were small, magnet and vacuum technologies were not highly developed, experimental experience and theoretical understanding of plasma behaviour were lacking, as also were powerful heating apparatus, measuring facilities for observation and fast computers for calculating the complex plasma behaviour.

It is therefore not surprising that the first assessments of the problem did not come up to scratch: In 1952, the American supervisory authority considered very few years to be sufficient to determine whether nuclear fusion was feasible. But it was not long before huge difficulties cropped up and hopes of a speedy breakthrough had to be abandoned. At the end of the 1950s it was realised that development of fusion called for a long-term programme with intensive fundamental research.

This was when Germany began to consider expanding fusion research: On 28 June 1960 IPP was founded as Institut für Plasmaphysik GmbH by the Max Planck Society and Werner Heisenberg as shareholders. The association agreement concluded with Euratom on 1 January 1961 integrated IPP in the European Fusion Programme. Renamed Max Planck Institute for Plasma Physics in 1971, it now has a staff of some 1,100, making it one of Europe's largest fusion research centres.

When the institute was established, it was completely open-ended how the objective was to be achieved. Work at IPP was therefore first pursued on a very broad basis. The behaviour of plasma was studied both in high-current arc discharges and by various methods of magnetic confinement in linear devices such as mirror machines and pinches as well as in ring-shaped configurations such as stellarators. The foundation year already saw the launching of the first stellarator, Wendelstein 1-A. Compared with today's large devices, the apparatus then was on a small scale; many plasmas occupied vessels scarcely bigger than a neon tube.



Plasma vessel of the ASDEX Upgrade fusion device

Photo: IPP, Peter Ginter

Enhanced know-how and concentration: the 1960s and 1970s | Despite appreciable advances in know-how experimental results during the 1960s throughout the world remained unsatisfactory: Almost all devices suffered from instabilities and much too severe particle loss – dreaded Bohm diffusion. One of the few exceptions was the small Wendelstein stellarator at Garching – the Munich mystery as it was called. With – relatively cold – low-density model plasmas Wendelstein 2-A was able in 1969 to show that the good plasma confinement predicted by theory is actually possible in stellarators.

In 1968 Soviet fusion scientists announced good results with their T3 tokamak. It was to afford much better confinement and stability properties than all previous configurations. This triggered world-wide tokamak fever. New tokamaks emerged everywhere. USA's then stellarator centre at Princeton also revised and converted its unlucky C-stellarator into a tokamak.

In view of its own good results IPP continued its stellarator work. Notwithstanding, planning for the first tokamak was also started in 1970. Pulsator was commissioned in 1973. That same year the group succeeded in controlling the dreaded current disruptions in the plasma for the first time with helical auxiliary fields. Overall from the end of the 1960s smaller experiments were discontinued at IPP. Besides the pinch experiments, which were continued till the end of the 1970s, attention was concentrated on the two types of device, tokamak and stellarator. Since then IPP is the world's only institute pursuing comparative investigations of the two.

Tokamaks produce the magnetic field cage partly with magnetic coils installed outside the plasma vessel, partly by means of a current flowing in the plasma. As the current serves for the initial heating of the plasma, the tokamak principle is rated as particularly effective. Stellarators, on the other hand, confine the plasma by means of magnetic fields exclusively produced by magnet coils outside the plasma area. That is, stellarators work without plasma current, this affording major advantages: This makes them suitable, for example, for continuous operation. Tokamaks, on the other hand, without auxiliary facilities can work only in pulsed mode because the plasma current is supplied pulsewise by a transformer.

The 1980s: large-scale devices | Worldwide in the 1970s experience gained led to concentration of work fields and to bigger, more powerful experiments. This saw the emergence of the tokamak as the leading type of experiment for investigating the central physical questions, primarily confinement and plasma heating. Heating with plasma current was meanwhile accompanied by powerful external processes, viz. neutral particle heating and high-frequency heating. This, however, soon entailed worldwide an unexpected serious problem: The most important property of magnetic confinement, viz. thermal insulation of the plasma, decreased whenever the plasma temperature was increased by external heating. As the temperature approached the ignition condition, this inevitably entailed a drop in thermal insulation. Under these circumstances it seemed impossible to achieve a burning plasma.

The solution came in 1982 with IPP's ASDEX (Axially Symmetric Divertor Experiment) tokamak, which was commissioned in 1980: Discovery of the High-Confinement Regime, for short H-regime, in ASDEX doubled the thermal insulation attainable. This pioneering achievement was owed to a special magnetic field configuration, called divertor. This diverts the outermost boundary layer of the plasma into annex chambers, where the plasma particles are pumped off. This was to remove impurities from the plasma. However, it also affects the confinement properties: the boundary layer produced by the divertor induces a transport barrier at the plasma edge, creating good thermal insulation.

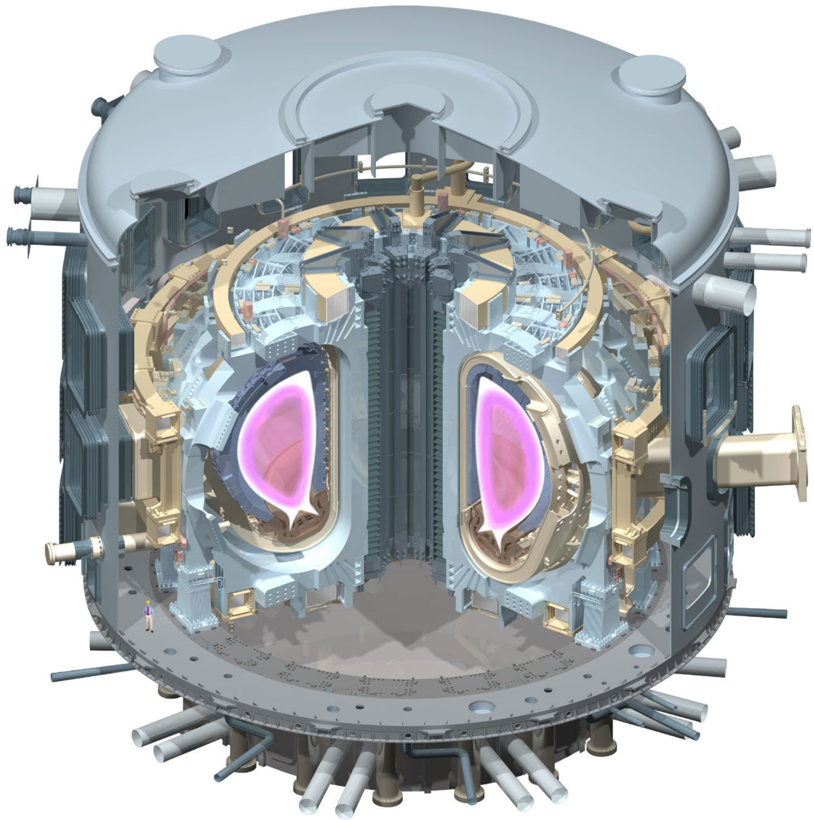
But stellarators also came up with good results. After the severe blow in the 1960s IPP's Wendelstein 7-A experiment brought new impulse to the line. In 1980 the "pure" stellarator principle, i.e. confinement without plasma current, could be demonstrated for the first time with a hot plasma. "Garching shows stellarators may be good after all", stated Physics Today then. "Stellarators appear to be back in business."

On the basis of these successes IPP operated from 1988 the Wendelstein 7-AS advanced stellarator. Previous stellarators had an almost circularly symmetric magnetic field, like tokamaks, in which the circular current in the plasma necessitates circular symmetry of the whole configuration. But stellarators by nature have to enlist non-circularly-symmetric fields. Utilising this property opens up a new, extensive sphere of possible stellarator configurations from which – with considerable theoretical and computative effort – the best, i.e. the most stable and thermally insulating fields, can be selected: "Advanced Stellarators". This work was made possible by the fast computers meanwhile available.

Besides the improved magnetic field, a technically optimised coil concept was also chosen for Wendelstein 7-AS: The standard helical windings were abandoned, these being unsuitable for a power plant. Instead, the field was produced by means of modular, non-planar single coils. Till operation was terminated in 2002 Wendelstein 7-AS had confirmed every one of the optimisation principles applied and broken all stellarator records in its size category.

However, it was mainly large tokamaks that were built worldwide, in the USA, Japan and primarily Europe, where JET, the Joint European Torus experiment, went into operation in 1983. The objective of this the world's largest fusion device is to investigate plasmas close to ignition, in which self-heating of the plasma by the fast helium particles produced in the deuterium-tritium fusion becomes clearly evident. Contributions to JET came from all European fusion laboratories, including IPP. Very good plasma values were obtained in JET already during its first operation phase – with just current heating without external heating as yet.

By virtue of the encouraging results it was agreed in 1985 in talks between the then Soviet Secretary-General Gorbachev, French President Mitterand and US President Reagan to initiate the ITER project. This device is intended to show that it is possible to derive energy from nuclear fusion and produce a self-heating and energy-supplying plasma for the first time. Essential technical functions of a power plant were also to be tested. From 1988 to 2006 IPP hosted the international ITER planning group.



Layout of the ITER international test reactor

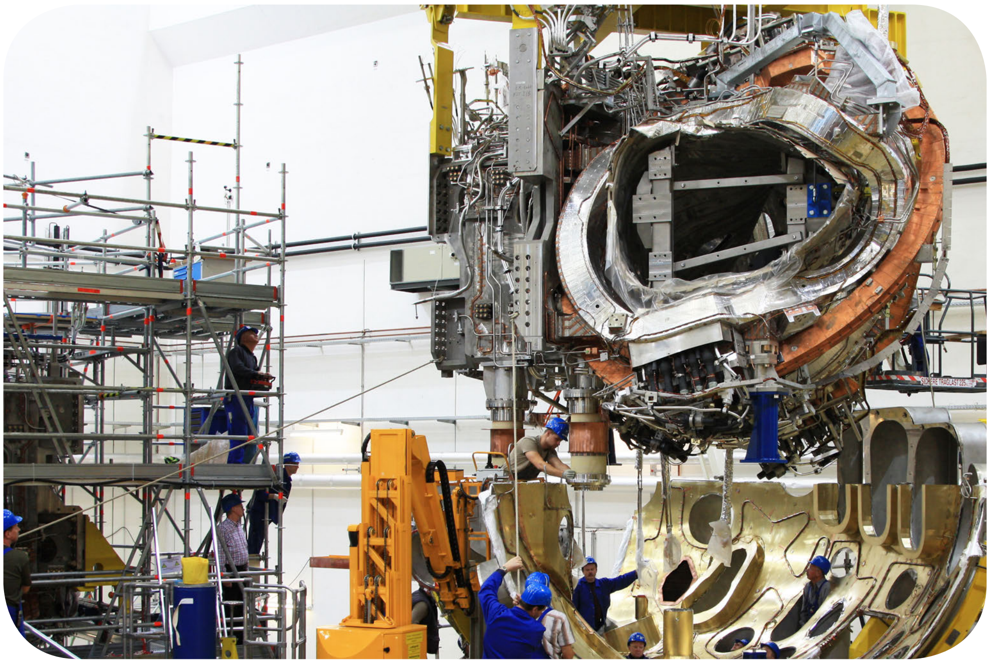
Graphic: ITER

Plasmas suitable for power plants: 1990 till today | For the first time in the history of fusion research the JET tokamak succeeded in 1991 in producing the reaction envisaged in a power plant and in producing noteworthy fusion power: In an as yet "diluted" deuterium plasma more than one megawatt of fusion power was supplied. In 1997 JET then produced 14 megawatts of fusion power for 2 seconds: 65 per cent of the power expended on heating was regained through fusion. The prerequisite for these results was conversion to divertor operation as shown by ASDEX. The H-regime discovered in the latter also served JET in achieving its record results. A future plant will also operate with divertor. ASDEX, however, was successful with a divertor design not directly suitable for a power plant. ASDEX Upgrade, its successor planned at IPP from 1981, was to close this gap and investigate a divertor under power plant conditions.

In 1991 the first plasma was achieved in ASDEX Upgrade. How foresighted planning of the device was is shown by comparison with the construction plans for ITER, completed in 2001, which essentially look like an enlarged copy of Garching's device. In particular, the divertor investigations on ASDEX Upgrade were largely incorporated in the conception of the ITER divertor. IPP's experimental tokamak research in conjunction with theory made many contributions to preparation of the test reactor. For example, in 1998 ASDEX Upgrade was able to improve the good thermal insulation of the H-regime in a new plasma state. This improved H-mode might afford a decisive improvement in fusion power and pulse length of future devices. Pioneering work was also pursued in achieving active control of instabilities. The method developed at IPP to get rid of perturbing instabilities is also to be applied in ITER.

In 2007 the inside wall of ASDEX Upgrade's plasma vessel was the first in the world to be completely clad with tungsten, the metal with the highest melting point. By appropriate injection of impurity atoms at the plasma edge and in the divertor it was possible to show that the power extracted could be efficiently distributed over the whole wall without endangering the purity of the core plasma. It was thus possible in ASDEX Upgrade to demonstrate for the first time power-plant-relevant operation with a tungsten wall without unduly contaminating the plasma with tungsten atoms. This is important since tungsten is considered to be the most promising candidate as interior cladding of the vessel wall of a fusion power plant.

In the stellarator line construction of Wendelstein 7-AS was accompanied by intensive continuation of numerical and theoretical stellarator studies. This was because the principles of optimisation were only partially applied in Wendelstein 7-AS: Its successor Wendelstein 7-X, completely optimised by the Stellarator Theory division in ten years of development, is now to show the new stellarator's suitability for a power plant. The device is being built in IPP's branch institute at Greifswald, which was established in 1994 by virtue of the restructuring of German research after reunification. All major components of the device have meanwhile been manufactured and assembly is in full swing. Technical commissioning is expected in 2014. Wendelstein 7-X is then to elevate stellarators to the level of the hitherto preferred tokamaks as a powerful alternative. If this succeeds, the demonstration reactor that is to follow ITER could also be a stellarator.



July 2010: Assembly of Wendelstein 7-X is in full swing.

Photo: IPP

Perspectives | The international ITER organisation, comprising the partners China, Europe, India, Japan, South Korea, Russia and the USA was established in 2007. It is sited at Cadarache in France. The first plasma is expected in 2019. With appropriate success ITER might be able around 2025 to demonstrate a stable self-heating fusion plasma.

Now that the major advances in research make the physical problems of a fusion power plant appear soluble, the importance of technical problems is increasing alongside particularly in the field of materials research. Just as important are questions of safety and the environment. In Europe technological questions are being handled in a separate technology programme, as well as in the international ITER cooperation. Parallel to ITER, work is also progressing in improving the tokamak concept, particularly in respect of continuous operation. To achieve this, the plasma current may no longer be driven by means of the transformer operating in pulsed mode: An important research area of ASDEX Upgrade are therefore so-called Advanced Scenarios: In these discharges with improved confinement the current has already been partly produced by neutral particle heating and pressure-driven internal bootstrap current. How this can be brought into tow with other requirements such as stability, impurity control and energy transport will be one ASDEX Upgrade's prime activities.

This work and the experience with burning plasma gained by ITER will then be incorporated along with the results of stellarator research in the planning of the DEMO demonstration power plant. In view of the construction and operation time needed for ITER and DEMO fusion energy could become economically useful about the middle of the century.

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