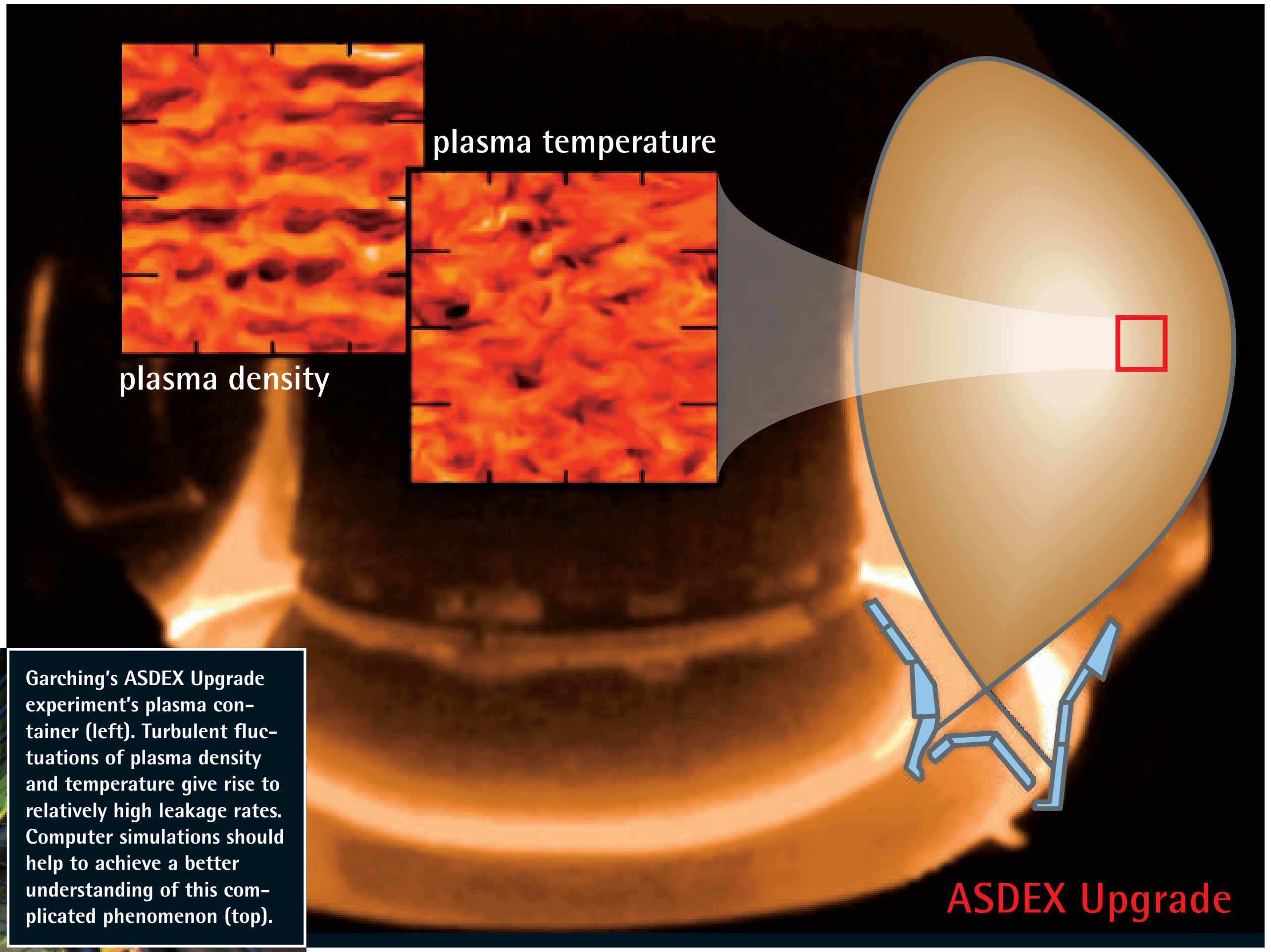
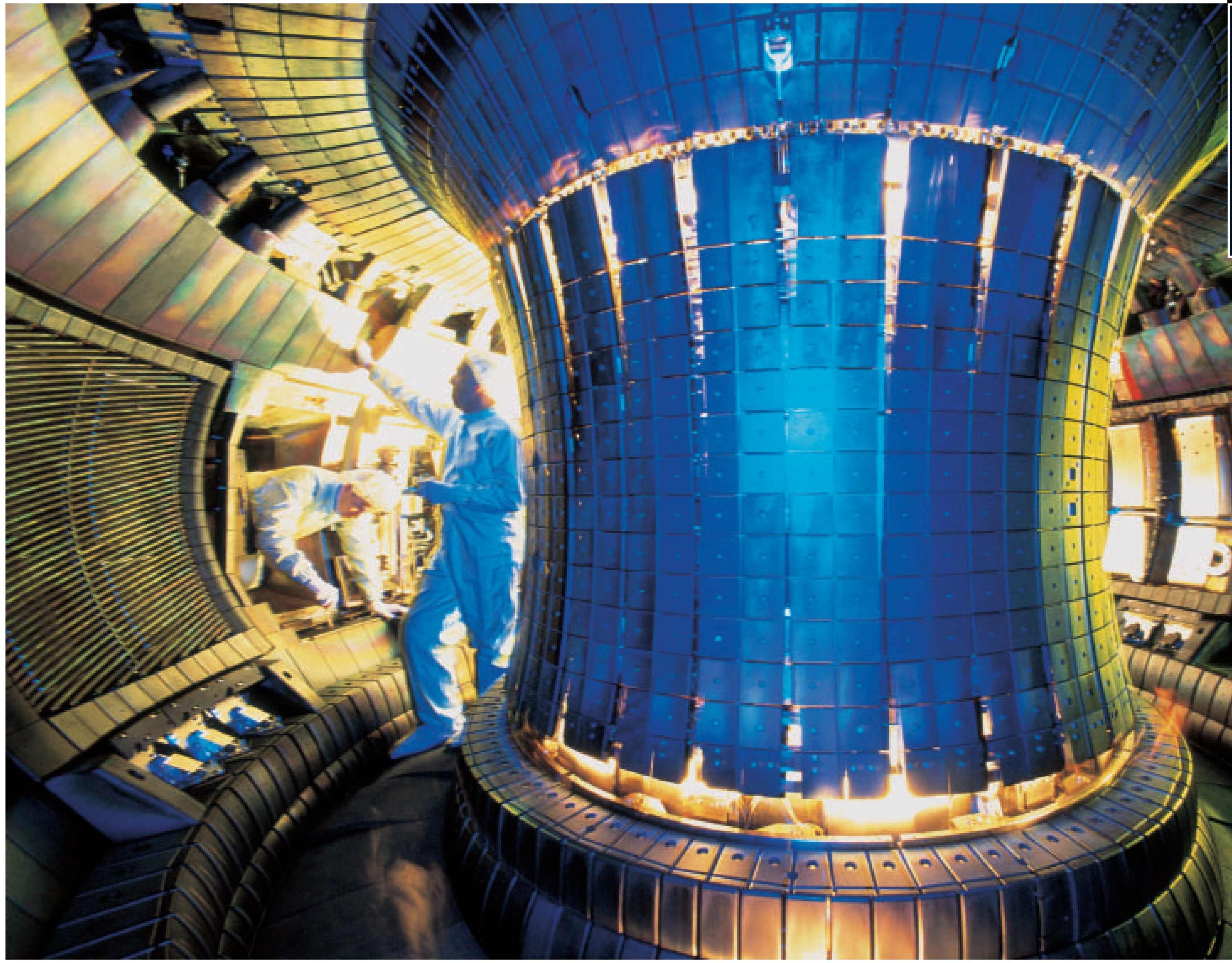
The Lord of the Vortices

At the **Max Planck Institute for Plasma Physics (IPP)** *in Garching near Munich,* **Dr. Frank Jenko** *is conducting computer simulations of turbulent flows in the plasma vessel of a fusion reactor. The scientist's aim is to track down the 'leaks' through which the hot gas, which has a temperature of 100 million degrees, loses its energy.*





Garching's ASDEX Upgrade experiment's plasma container (left). Turbulent fluctuations of plasma density and temperature give rise to relatively high leakage rates. Computer simulations should help to achieve a better understanding of this complicated phenomenon (top).

Photograph / Fig.: Max Planck Institute for Plasma Physics

Frank Jenko spends over half his working time in a queue. However, it is not he personally who stands in line but his programme: it is one of the biggest jobs currently running at the computer centre in Garching. If the programme were to run without interruption from beginning to end, the most powerful super computer in Garching, a Cray T3E – which is capable of making 470 billion arithmetic operations per second –, would do nothing else for many days and nights. However, since Jenko is not the only user of the facility, he is allocated six hours on the computer each time he has a turn on it, after which he has to return to the back of the queue.

The gigantic computations serve a high purpose: to help construct a working fusion power station which can provide power by means of fusing deuterium and tritium. This is the same mechanism that enables the sun to glow, and if it were possible to tame it, it may provide an important contribution to the globe's energy supply. For decades now, scientists around the world have been toiling to achieve this goal. In huge facilities they heat hydrogen gas to millions of degrees. They try to confine the plasma this creates (a mixture of atomic nuclei and electrons) in magnetic fields: this is the only way of keeping the hot plasma off the cold walls of a container. ►

Frank Jenko at his monitor, on which turbulent flows can be seen.

PHOTO: STEFANIE GRAUL

So far the most successful fusion facilities have been those run on the so-called Tokamak principle: the plasma is captured in a torus – a shape somewhere between an inflated tyre and a savarin mould – and is then heated by a circulating current and electromagnetic waves. Temperatures of more than 200 million centigrades have been achieved in this way, as for instance at the large JET facility in Culham (UK), where scientists have succeeded in enclosing the plasma for a few seconds. The Max Planck Institute for Plasma Physics in Garching also has a Tokamak, the ASDEX-Upgrade. This is where Frank Jenko works.

ENERGY IS VOLATILE

The principle underlying the idea of using such facilities to gain energy is that hot plasma with sufficient density is kept together for long enough periods to allow a sufficient number of hydrogen nuclei within it to collide and fuse to form helium. In every such fusion process a fast neutron is produced and emitted into the surroundings. If it is slowed down in a container made of suitable material, its energy can be turned into heat and technically used. Therefore, the essential function of a fusion power plant is to maintain a very high temperature in the plasma for as long a period as possible.

It is a regrettable fact that the plasma cools down at a rate which is up to one thousand times faster than originally expected. “These anomalous energy losses are one of the greatest problems for the development of fusion power plants”, says Jenko, “because the increased losses can only be compensated by building larger and correspondingly more expensive facilities”. For example, ASDEX-Upgrade is the largest fusion facility in Germany; it is nine metres tall and contains 14 cubic metres of plasma. The International Experimental Reactor (ITER) currently being planned will be even larger and will enclose more than 800 cubic metres of plasma (MaxPlanck-Forschung 3/2000, p. 83). A successful reduction of energy losses would be of tremendous benefit.

For this reason, experimentalists and theoreticians are attempting to understand how the capricious plasma behaves inside the cage of magnetic fields. It is known from classical physics that the charged particles take spiralling trajectories as they circle around the lines of force of the magnetic field, and it is possible to calculate the frequency with which they will collide. These collisions are partly responsible for the – unwelcome – transverse breaking away of matter and energy from the lines of force.

However, another mechanism seems to be much more important: there is a suspicion that small vortices – physicists speak of turbulence – are responsible for the rapid loss of the energy that has been put into the plasma. After only a few tenths of a second it becomes necessary to reheat the plasma – an expensive and, from the point of view of physics, disappointing undertaking. Therefore, it would mean a lot to plasma physicists if they could find out how these turbulence are created and how they develop: if successful, they could try to suppress, or at least attenuate, the vortices and their disagreeable consequences.

If a stream slowly flows into a valley, its current will exhibit few irregularities. Physicists call this well-known phenomenon a ‘laminar’ flow. If a stone is placed in the water, the stream will flow around it smoothly. If the slope is greater and the stream flows faster, whirlpools appear behind the stone. These are relatively stable and tend to stay in the same place. However, as the speed of the stream’s flow increases, these whirlpools detach themselves and are carried downstream. In extreme cases the water becomes a throng of constantly changing and intermingling swirling eddies: the stream has become ‘turbulent’, and the movement of any one area of water appears to have become utterly unpredictable and random – the stream now represents a wholly chaotic system.

There are many areas where this kind of chaos prevails: in boiling water, in the flow of lava rolling down a volcano, but above all in the swirling air masses of the atmosphere that control our climate. And just as these air vortices make it extremely difficult to predict the weather, so too the plasma turbulence impede the prognosis of behaviour inside a Tokamak.

Jenko investigates plasma vortices by simulating them on the computer. This is a huge challenge: the famous Nobel Prize winner Richard Feynman described the understanding of turbulence as “the most important unsolved problem of classical physics”. And the British physicist Sir Horace Lamb, author of a standard textbook on hydrodynamics, wrote in 1932: “I am an old man now, and when I die and go to Heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am really rather optimistic.”

In the meantime the tremendous speed at which modern super-computers are becoming ever more powerful is helping to come closer to the challenging goal. Hence, Frank Jenko can divide virtual plasma into around a billion tiny cells and calculate the flow conditions for each individual cell in close succession – approximately ten million times for a single second of plasma life. This creates structures that have the appearance of “tiny weather”, with highs and lows, storms and calm periods, all scaled down to millimetres. The calculations need to be correspondingly lavish because the plasma and the electromagnetic fields in each cell obey complicated equations, and each cell is coupled with all its adjacent cells and influences them in turn.

512 PROCESSORS OPERATE IN PARALLEL TO EACH OTHER

Special programmes require special strategies: “It has become practically impossible to work on problems of this order of complexity in a sequential order”, says Hermann Lederer of the computer centre in Garching, “for this reason we help physicists change their algorithms to so-called parallel processing”. The idea behind this is that the more a programme is precisely adapted to a computer’s structure, the more efficiently it will be able to make use of it. The Cray T3E computer, for instance, has 512 processors that can operate in parallel to each other. This is how Frank Jenko’s programme was handled. Lederer, who is responsible for application support, points out: “We naturally don’t get involved in the physics or the arithmetic.” One of his colleagues spent months painstakingly working on Jenko’s Fortran programme to increase the speed of its parallel processing. When speaking of this process, experts describe it as ‘performance tuning’: like pit stop mechanics, specialists work to squeeze as much speed out of the algorithm as possible. This tuning process was so successful when it was applied to Jenko’s programme that it immediately created new aspirations. “As calculation times were shortened, the physicists naturally became hungry for more, and so the original programme was continuously changed and enlarged”, explains Lederer.

In his calculations Jenko is less concerned with the formation phase of the vortices than with the analysis of “fully developed turbulence” and the computation of its statistical properties. The hope is that this will provide hints for setting the Tokamak’s experimental parameters in such a way that will minimise the turbulent transport. According to Jenko the intention is, “one day, to simulate not only plasma turbulence but also a whole Tokamak”. Then it would be possible to optimise a facility, including the plasma, before it was even constructed. However, the power of computers will have to increase by several orders of magnitude before this can be achieved.

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