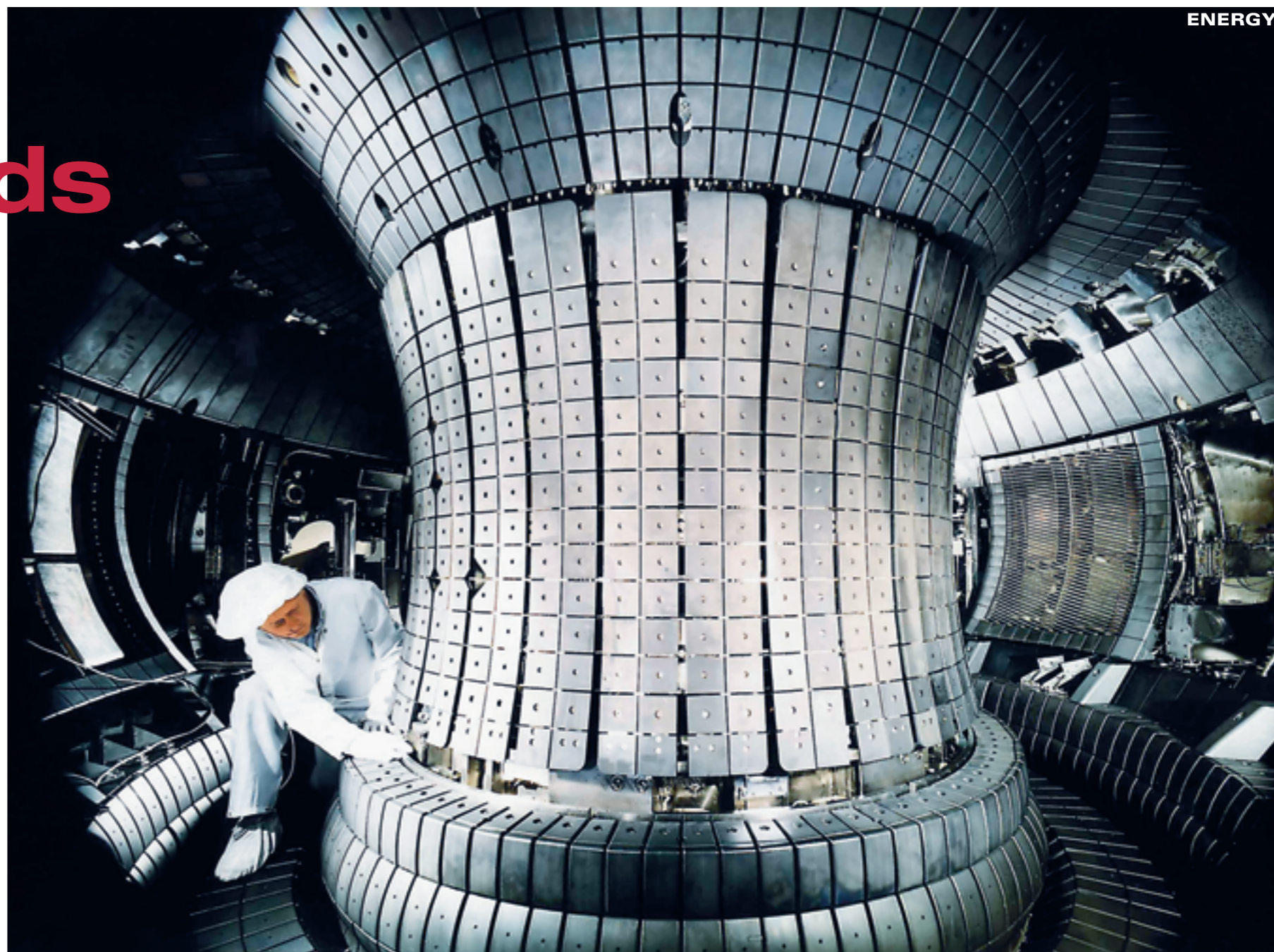


# Magnetic Fields

## Subdue the Elemental Force

*Harnessing the Sun's fiery energy is an age-old dream that scientists at the **MAX PLANCK INSTITUTE OF PLASMA PHYSICS** in Garching are working to make a reality. There, the research of **SIBYLLE GÜNTER**, Director and head of the theory group, and **HARTMUT ZOHM**, who is co-responsible as Director of the ASDEX Upgrade experiment, takes them into an exotic world where temperatures exceed 100 million degrees Celsius. These conditions are supposed to fuse hydrogen nuclei into helium nuclei, thereby releasing usable energy.*



Maintenance work in the plasma vessel of the ASDEX Upgrade fusion device in Garching. The experiment involved temperatures 10 times higher than those in the interior of the Sun.

**A**mid the profound chaos of cables, devices, steps and ducts, a colorful dragon smiles at us. The gaily colored fantasy creature blows his painted stream of fire toward a massive wall of metal belonging to the large vacuum chamber, the heart of ASDEX Upgrade. The experiment is currently on hold, so guests are allowed to enter the inner sanctum.

"Fun is a necessity," says Sibylle Günter, referring to the whimsical mythical creature. The department head at the Max Planck Institute of Plasma Physics (IPP) leads the way

through the labyrinth of the huge plasma facility. "I also enjoy experimenting very much," says the professor of theoretical physics. She is visibly enthusiastic about working on a project that may be one of the boldest undertakings of the 21st century. Plasma physicists want to "harness the Sun's energy," as the media like to portray it. Stars like the Sun obtain a significant portion of their energy from the fusion of hydrogen nuclei into helium nuclei. The physicists want to make this nuclear fusion useful for mankind as a practically

inexhaustible source of energy. Fusion researchers have been pursuing this ambitious goal for a good half-century. Following a euphoric start, however, they have had to swallow some sobering setbacks. Nevertheless, their persistent research appears to be slowly paying off. The progress of the past years allows Sibylle Günter and her colleagues to look toward the future with optimism: it was the physicists in Garching who succeeded in solving a few problems that threatened to barricade the path toward the fusion reactor.

PHOTO: IPP OF PLASMA PHYSICS

Visitors sometimes feel a bit peculiar underneath the large vacuum vessel of ASDEX Upgrade when they consider that, just a few meters above their heads, temperatures have raged up to an incomprehensible 150 million degrees. The interior of the Sun, by contrast, with its 10 million degrees, is a veritable cool spot. However, the temperature comparison also shows that the popular metaphor of bringing the Sun's fire to Earth is not really apt. Inside a future fusion reactor, to which ASDEX Upgrade is a precursor, a different

fusion scenario is envisioned than that in the Sun.

In Sibylle Günter's office, coffee is served at pleasantly earthly temperatures. Seated at our table is Hartmut Zohm, who is in charge of part of the ASDEX Upgrade experiments. Like his colleague, the Max Planck Director is a member of the board of scientific directors of the large institute in Garching. "The fusion processes in the Sun would be a bit too slow to run efficiently in a reactor," says Günter. Thus, the physicists can't simply copy the Sun. That

wouldn't even be possible with facilities like ASDEX Upgrade, as these machines never reach the immense pressure that prevails in the interior of our central luminary.

### NOT SIMPLY A COPY OF THE SUN'S FIRE

"That is also why the density of the Sun's particles – namely, the number of them per cubic meter – is much higher than in our plasmas," explains Zohm. Which is one reason why the Sun can obtain sufficient energy for its fusion fire despite the



A glimpse into the "oven": The ASDEX Upgrade tokamak is the largest fusion experiment in Germany. At the left of the image is the waveguide for heating the system through the application of radio waves.

slow process. In addition, its interior is much better insulated against radiation and heat losses than a comparatively tiny plasma experiment lost in an earthly cold environment.

The physicists' concept relies on substantially lower pressures. "In ASDEX Upgrade, we reach about 1 bar – in other words, normal ambient pressure," says Hartmut Zohm, "and in the fusion reactor of a future power plant, it will be around 4 to 5 bar." Since it will not be fixed walls, but rather pure magnetic fields that have to build up this pressure, this will be an enormous technological challenge.

The reaction itself, too, differs from the solar process. "In the Sun, four protons – that is, nuclei of light hydrogen – fuse in intermediate steps to form a helium nucleus," says Günter. In artificial fusion, on the other hand, the two heavy hydrogen isotopes deuterium and tritium fuse to form a helium nucleus. In doing so, they release a neutron, which plays an important role in creating tritium. In addition, in a future fusion power plant, this neutron will be responsible for transporting the fusion energy to the reactor wall. There, the energy transforms into heat and heats up

water in cooling coils. The steam then powers electricity generators by means of turbines.

Deuterium and tritium seem rather exotic as fuels, but the ingredients are available nearly everywhere in our environment. Fusion energy would thus effectively ease the global competition for scarce energy resources. "From this standpoint, it would also actively contribute to peace politics," says Günter. The deuterium is obtained from heavy water that is found in low concentrations everywhere in oceans, lakes and streams. The neutrons from the fusion process breed the tritium from lithium, which is the lightest of all metals and is found in many minerals.

**NEARLY UNLIMITED FUEL SUPPLY**

In the fusion reactor, lithium will be a component of the reactor wall. This method offers the advantage that the tritium is first created during operation in the reactor, and is also immediately consumed there. Thus, this radioactive hydrogen – which, with a half-life of a good 12 years, decays fairly quickly – doesn't reach the environment. ASDEX Up-

grade in Garching, however, does not yet use tritium. To date, only two major facilities are equipped for it: the European JET (Joint European Torus) in Abingdon (UK) and the American TFTR (Tokamak Fusion Test Reactor) at Princeton University.

Fusion reactors will get by with astoundingly little fuel. For this reason, the amount of tritium present in the plasma will always be minimal. A fusion reactor would therefore not have the highly radioactive inner life of a nuclear fission reactor. Nuclear fusion provides considerably more energy than any other technically realizable form of energy extraction. Just 0.08 grams of deuterium and 0.2 grams of lithium would suffice to produce the current electricity requirements of one family for one year. This amount of fuel is contained in two liters of water and a few kilos of mineral rock. The reaction produces equally small amounts of fusion ash – helium – which isn't radioactive and which also occurs in nature.

Today, the physicists can say with certainty that a functioning fusion reactor would be an extremely good-natured machine. The temperatures in the ignited plasma are, of course, in-

timidatingly high, but due to its extreme dilution, it contains little energy. In ASDEX Upgrade, the energy stored in the plasma corresponds just barely to that consumed by a light bulb in three hours. If the magnetic field were to collapse, the hot plasma would damage the interior of the vacuum vessel slightly, but the sensitive fusion reaction would immediately be interrupted. "The afterheat would not be sufficient to destroy the structure," says Zohm. "After such an accident, only a couple of components would need to be repaired." A grave catastrophe like the one in Chernobyl can't happen. "A runaway reaction is fundamentally impossible," emphasizes Günter, "because there is no chain reaction like in nuclear fission."

The sensitive plasma must be carefully nurtured. To date, no plasma facility has even achieved the ignition condition required for sustained fusion. All current experiments, like ASDEX Upgrade, serve as preliminary technical studies and basic research on hot plasmas. Physicists describe plasma as a gas whose atoms have separated from their electrons. In our environment, plasmas exist only for a short time, primarily in lightning. "In the cosmos, however, planets like the Earth are the exception," says Zohm. In the solar wind, in stars and in interstellar gas clouds, plasmas are considered a completely normal physical state.

**LYMAN SPITZER'S STAR MACHINE**

The plasma mixture of negatively charged electrons and positively charged atomic nuclei can be elegantly manipulated with magnetic fields. To do this, the physicists use cages made of ornately shaped magnetic fields whose field lines confine the hot plasma, as if behind bars. The fusion researchers have developed two principles for this: the stellarator and the tokamak.

The stellarator gets its name from the Latin word *stella* for star. The American astronomer Lyman Spitzer invented his concept at Princeton

University in 1951. A stellarator generates a twisted magnetic field in its torus-shaped vacuum chamber. With their table-sized stellarators, the physicists in Princeton wanted to quickly reach plasma temperatures of a million degrees. However, they soon had to concede, with disappointment, that their systems didn't work. "With the original three-dimensional shape of the magnetic field, the fastest, and thus hottest, particles didn't remain in the plasma, but flew out," says Sibylle Günter. This robbed the plasma of valuable heat energy. "So the stellarator died an early death."

It wasn't until the 1980s that the physicists in Garching managed to revive the concept. "Its rebirth couldn't happen until the magnetic fields could be optimized," explains the Max Planck Director. The stellarator requires a complex magnetic field that doesn't allow the plasma particles whizzing about to escape the hot plasma. It wasn't until recently that modern, powerful computers made it possible to calculate the ideal shape the magnetic coils must have to ensure this.

Thus the Wendelstein-7X experiment was born, which is currently being set up in Greifswald. It is expected to go into operation in 2012. Although its plasma won't reach the ignition temperature for nuclear fusion, Wendelstein-7X is intended to demonstrate that a stellarator can, in principle, achieve it. Success would pay off, as the stellarator has a very impressive property: it can maintain a sustained fusion reaction.

A tokamak reactor, on the other hand, can drive its fusion reaction only in pulses lasting a few hours. But it is easier to build, as the plasma forms a ring. It doesn't require any complicated magnetic fields to confine the hot particles inside itself. The name tokamak is taken from the Russian words *toroidalnaya kamera v magnitnaya katushka*, which mean "toroidal chamber in magnetic coils." The principle of this machine dates back to the two Russian Nobel laure-

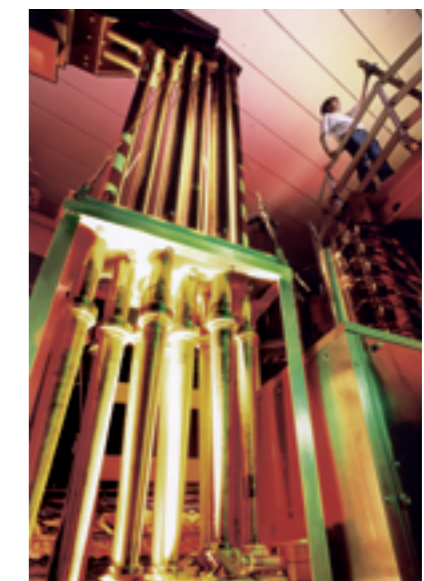
ates Igor Tamm and Andrei Sakharov who developed it in 1952. In 1968, the Russian tokamak T3 became the lifesaver for the frustrated community of plasma physicists. This experiment at the Kurchatov Institute in Moscow was the first to achieve reasonably high plasma temperatures.

**A MAGNETIC TUBE KEEPS THE PLASMA IN CHECK**

Today, nearly all major plasma experiments are tokamaks, including ASDEX Upgrade. Incidentally, ASDEX is an acronym for "axially symmetric divertor experiment" and represents a very successful development of the Garching-based institute. The divertors are magnetic fields that deflect the outer boundary layer of the plasma to collector plates. It is this trick that keeps the inner plasma clean and insulates the hot plasma interior so well that it can reach temperatures of up to 150 million degrees.

In the tokamak, an electrical current must flow through the plasma ring. Its magnetic field holds the plasma together like a tube. "So you have a large transformer, and the vacuum vessel is its secondary winding," explains Zohm. But transform-

The plasma thermometer: The hollow-core conductors direct the cyclotron radiation emitted by the electrons to detectors that then determine the temperature.



PHOTOS: PETER GÜNTER

## ITER ON THE WAY

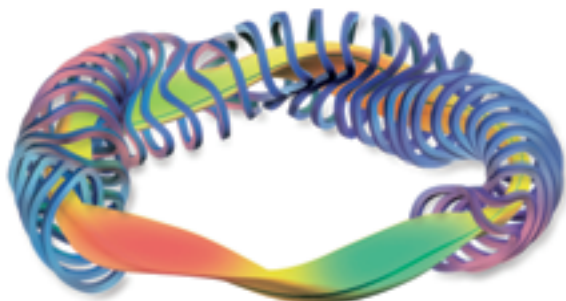
In late May, the representatives of the seven ITER partners met in Brussels to sign the agreement establishing the ITER Organization, which is responsible for the construction and operation of the international fusion test reactor. Before the agreement takes effect, it must still be ratified by the partners' governments – Europe, Japan, Russia, the US, China, India and South Korea – which is expected to take place by year's end.

"We are very pleased that the ITER negotiations, which have been in progress since November 2001, have finally reached completion," says Alexander Bradshaw, Scientific Director of the Max Planck Institute of Plasma Physics (IPP) in Garching and Greifswald. "Now the preparations for construction can begin next year. The first plasma can then be expected in about 2017." In the meantime, ITER will mean numerous orders for European and German industry. Likewise, the German fusion research facilities in Garching, Greifswald, Jülich and Karlsruhe might expect to receive some orders.

ITER has been in preparation since 1988, in a global collaboration effort of European, Japanese, Russian and, until 1997, American fusion researchers. In 2003, China and South Korea joined the project, and the US rejoined the collaboration. In 2005, India became the seventh partner. With a fusion power of 500 megawatts, ITER is expected to produce the first burning, energy-yielding plasma. The aim is to achieve an energy gain factor of at least 10. This means that 10 times the energy expended to heat the plasma is to be gained as fusion energy.

Following a construction period of about 10 years, some 600 scientists, engineers and technologists will work at the facility for about 20 years. The construction costs were estimated at around 4.6 billion euros and the operating costs (including reserves for subsequent dismantling) at 265 million euros annually. The host government, Europe, will pick up about 45 percent of the construction costs, and the other six partners will split the remainder. The contributions will be provided primarily in the form of finished components that are manufactured in the respective countries and then transported to the ITER site in Cadarache.

Two principles: In the tokamak (right), the magnetic field confines the plasma, shown in orange here, into a torus. Below: In a modern stellarator such as Wendelstein-7X, the complicated coil arrangement forces the plasma into a twisted pentagon (shown here in lateral view) from which it can't escape.



ers work only as long as the current in a coil changes. Then it likewise induces a current in the second coil, the secondary winding. That is the reason for the pulsed operation of the tokamak. In a power plant, however, this would have the disadvantage that the constant change would severely stress the material. "So we are trying to eliminate this drawback in the tokamak," says Hartmut Zohm.

## CHAOS ON ALL SIZE SCALES

Sibylle Günter's theory group is trying to crack another tough nut: undesired turbulences pervade the plasma. "It's like stirring coffee," explains the scientist: "It moves hot regions toward the outside and cold regions toward the inside." This means that the cold-sensitive plasma interior loses too much valuable heat. This is a serious problem particularly in the boundary layer of the plasma, which is supposed to keep the hot interior well insulated. "There, physics is very sneaky, namely highly nonlinear," says Günter. "After all, turbulence is one of the last problems of classical physics that still awaits its solution."

Turbulent airflows and liquids are so difficult to predict because – to



put it simply – they include a certain chaos on all size scales. A working theoretical model must thus be able to handle an enormous range of scales, from huge current eddies down to the nanoscale of individual molecules. Meteorologists, for example, struggle with this problem in their computer models for forecasting the weather. In the

case of the fusion reactor, Sibylle Günter is pinning her hopes on one peculiarity: it has a smallest scale that limits the calculation effort. "That is the radius of the circular movement of the charged plasma particles in the magnetic field. With today's computers and realistic physics models, we can simulate only small sections of the plasma, but that will improve in just a few computer generations."

The physicists in Garching are so successful with ASDEX Upgrade that their system is a model for the major ITER (Latin for "the way") experiment. ITER will come very close to the ignition conditions and will even breed tritium for the first time. The facility, which will cost some 4.6 billion euros, is now being built in Cadarache, France. Financing is being provided by the EU, Japan, the US, Russia, India, China and Korea. ITER is expected to go into operation in 2017. Later, the first demonstration power plant, called DEMO, will follow. If it works, then – according to the current schedule – the first power plants will go online beginning in 2050.

"A fusion power plant doesn't have fuel rods like a nuclear power plant," says Sibylle Günter, explaining another reason for her commitment to the project. So this technology won't leave future generations with radioactive waste that emits its deadly radiation for thousands of years. But nuclear fusion will have its own price: when such a reactor is shut down, the years of bombardment with neutrons will have made some of its components radioactive. These, however, would emit only weak radiation compared with nuclear fuel elements, and would do so for only a few hundred years. This will greatly simplify their storage. If the fusion researchers are successful, society will have to decide whether it is willing to pay this price to harness the Sun's energy for use on Earth.

ROLAND WENGENMAYR

ILLUSTRATIONS: CHRISTOPH SCHNEIDER, BASED ON ORIGINALS FROM THE MPI OF PLASMA PHYSICS