A labyrinth of technology: the plasma chamber of Wendelstein 7-X sits deep within a maze of pipework, nozzles, and gangways.

Photo: Jan Michael Hosan/IPP

Solar fire in the **stellarator**

Nuclear fusion aims to recreate the sun's power on Earth and would represent a completely new source of energy. At the Wendelstein 7-X facility, researchers led by **Thomas Klinger**, Director at the **Max Planck Institute for Plasma Physics** in Greifswald, are exploring one approach to this form of energy generation.

TEXT **ROLAND WENGENMAYR**

You can barely make out the torus itself," says Matthias Hirsch as he surveys Wendelstein 7-X. The "torus" that the plasma physicist is referring to is the ring-shaped centerpiece of the gigantic 725-tonne metal object filling the several-story shed in front of us. The ring is hidden within a multitude of over 250 pipe connections and nozzles – a truly bewildering sight for the lay person. In turn, all of this is surrounded by scaffolding made up of staircases, balconies, and access bridges interspersed with pipelines, cable strands, and equipment cupboards.

We're at the Max Planck Institute for Plasma Physics (IPP) in Greifswald, and Hirsch is expertly guiding us through this labyrinth – although there's one piece of equipment whose purpose even he can't fathom. You can't blame him. After all, we're climbing through the external scaffolding of an enormously complex machine that is now used for research by over 200 scientists from across Europe, Australia, Japan, and the U.S. Even for an expert like Hirsch, it's impossible to get to grips with every last detail.

Researchers from Germany – and above all from the Max Planck Society – have taken a leading role in the construction of Wendelstein 7-X. The project aims to support an important scientific objective: harnessing the solar fire as an almost inexhaustible source of energy for applications such as power generation. Deep within the sun, temperatures of 15 million degrees cause hydrogen nuclei – protons – to fuse, forming nuclei of the element helium and releasing vast quantities of energy in the process. Without this furnace running on solar fusion, Earth would be a cold, dead planet.

However, the light hydrogen atoms only fuse when exposed to the crushing gravitational force of the sun. There, they experience unimaginable pressures of some 200 billion atmospheres, which no solid material could even come close to withstanding here on Earth. Exploiting solar energy in this way therefore seemed like an unattainable dream – until ingenious physicists came up with an alternative. In the mid-20th century, they discovered that nuclei of the heavy hydrogen isotope deuterium, which contains a neutron in addition to its proton, and tritium, a superheavy hydrogen isotope with two neutrons, can also fuse to form helium.

NUCLEAR FUSION – A NEW FORM OF ENERGY GENERATION

This fusion reaction takes place in an extremely thin, hot gas, and is easier to implement from a technical perspective due to the low pressures involved. That being said, it also requires temperatures even higher than those present in the sun – well in excess of 100 million degrees. In a high-temperature plasma of this kind, electrons and atomic nuclei are completely separated from one another. As both of them are electrically charged, they can be confined by a strong magnetic field. This acts like a virtual thermos flask and is the trick on which fusion research relies.

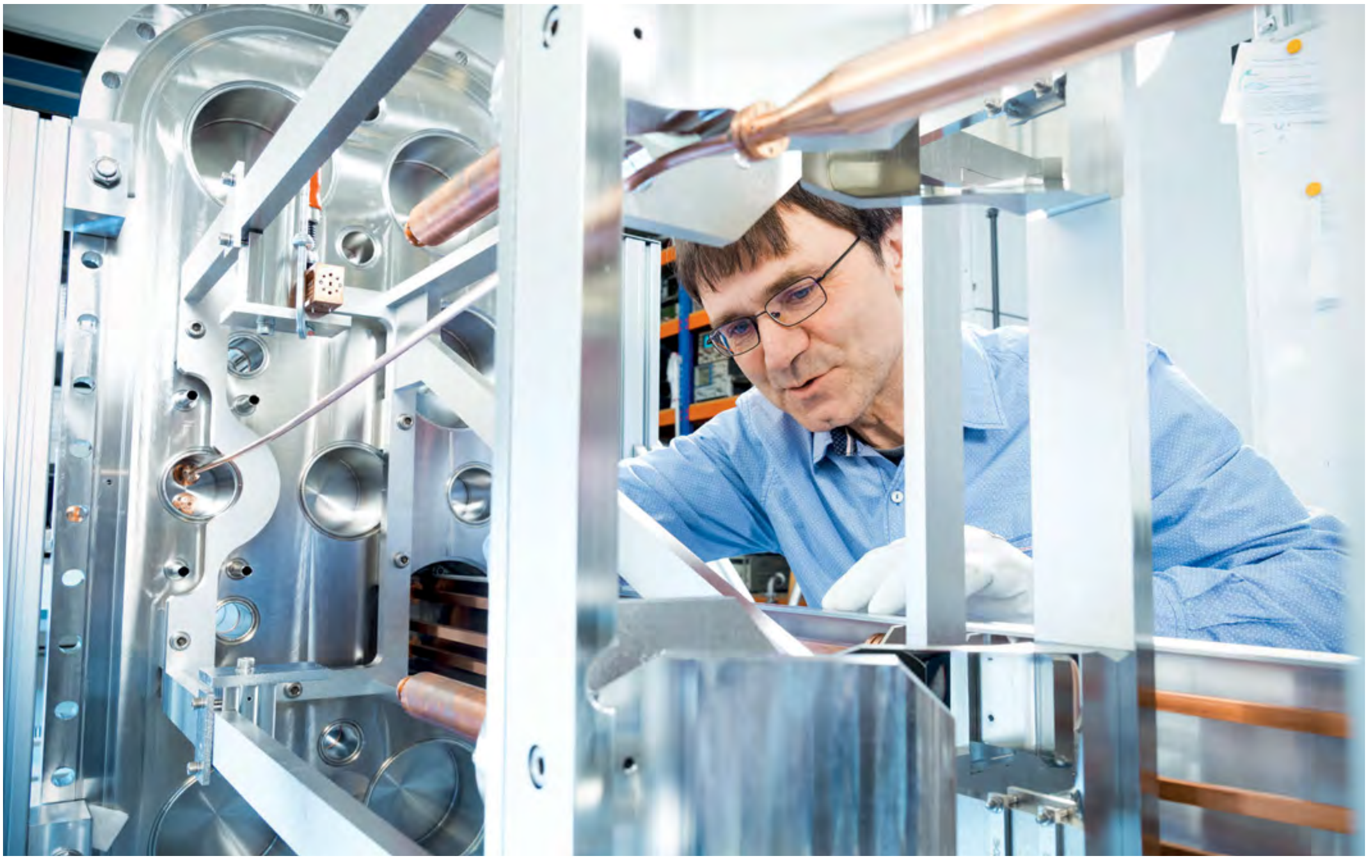
In a future fusion power plant, the plasma vessel would only contain about one gram of the helium/tritium mixture. This almost non-existent quantity of fuel could produce 90,000 kilowatt hours of thermal energy – equivalent to the heat of combustion of 11 tonnes of coal. However, burning that amount of coal would release over 30 tonnes of carbon dioxide into the atmosphere. By contrast, fusion power plants would operate on a carbon-neutral basis. This, together with their extremely low fuel consumption, is what makes them such a promising idea in a century in which our lives will increasingly be shaped by climate change.

The prospect of developing a climate-friendly source of energy may well be the reason why Robert Habeck, co-leader of Alliance 90/The Greens, expressed his positive attitude to the research during a recent visit to Wendelstein 7-X. When the foundation stone for the facility was laid in 1997, his party's supporters protested against it. “Today, we take a less ideological line on nuclear fusion,” Habeck explained. In his view, the basic research is fascinating and should be promoted. “Exploring alternative energy supplies is fundamentally the right thing to do.”

Thomas Klinger points out that fusion energy is the only new form of primary power generation that humanity is currently researching: “It's the last unopened barrel of energy, so to speak.” As if to highlight this statement, a burst of warming sunlight illuminates the office of the Max Plank Director, who leads the Greifswald location of the Max Planck Institute for Plasma Physics. With his wiry build, the physics professor looks as if he might jump up and reach for a wrench at any moment.

THE ROAD TO NUCLEAR FUSION

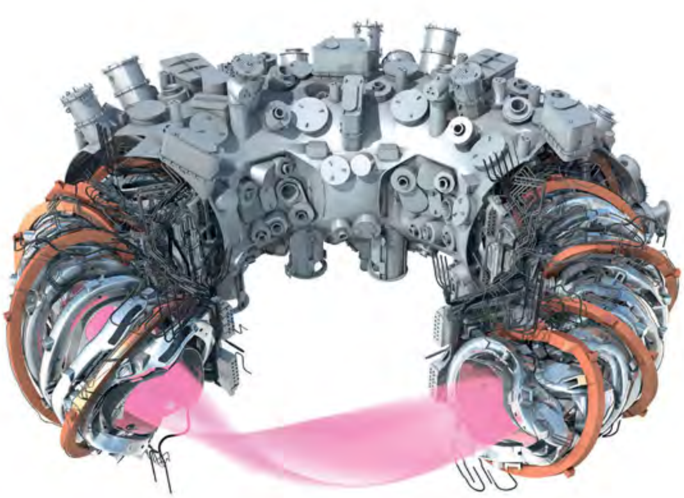
The fusion of deuterium and tritium to form helium ought to be performed in a very thin, hot plasma. Even with a relatively small number of collisions, the heavy hydrogen nuclei release sufficient energy to maintain the fusion reaction. Although any fusion plant of the future will therefore constitute a nuclear facility, it also offers some key advantages over today's nuclear power stations. In the event of an accident, there is no risk of a core meltdown, as the sensitive plasma simply goes out. The radioactive tritium is also bred and consumed directly within the self-contained fusion power plant. Moreover, as only a few grams of fuel are needed, there are none of the disposal problems associated with nuclear power plants. Likewise, fusion doesn't produce tonnes of radioactive waste that then need to be stored for many thousands of years. When a plasma vessel is dismantled at the end of a fusion plant's useful life, only internal components are radioactive. These must then be stored securely for a few decades – a manageable period of time for human civilizations.



Access for researchers: Matthias Hirsch prepares a nozzle through which the sensors of various analytical devices transmit data about the properties of the plasma.

Indeed, the researcher has temporarily found himself in the role of site supervisor – and on a very complex construction site. Little by little, the Greifswald researchers need to forge their way into uncharted technical territory.

But Wendelstein 7-X itself is not a nuclear facility and is not designed for nuclear fusion. Rather, the experiment is an opportunity for physicists to study the behavior of a hot plasma in a stellarator using light hydrogen. A stellarator is one of two types of fusion devices that are currently being researched. As the biggest stellarator experiment to date, the machine in Greifswald is intended to demonstrate that facilities of this kind are fundamentally capable of confining a hot plasma for long enough and with the requisite efficiency. That, in turn, would pave the way for a fusion power plant based on this technical principle.

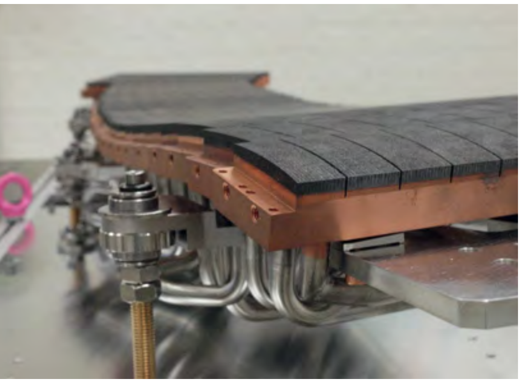


Wendelstein 7-X is currently being adapted for the next series of measurements after completing three previous series, each of which ran for 15 weeks. On 10 December 2015, the first plasma was fired up to a temperature of one million degrees. It consisted of a thousandth of a gram of helium, which was intended to act as a cleaning agent in order to remove contamination from the plasma vessel. This is an important step because hydrogen plasmas are highly sensitive. On 3 February 2016, the researchers in Greifswald then generated a hydrogen plasma for the first time – in the presence of German Chancellor Angela Merkel.

The plasma can be heated using various techniques. The electrons can be set in motion using a beam of microwave radiation – a high temperature simply means that particles are moving

Construction diagram for a magnetic cage: the plasma (pink) is forced to adopt a convoluted path by 70 magnetic coils threaded together around the chamber. Countless openings in the system's casing provide access to the interior.

Photo: Jan Michael Hosan/IPP (top), graphic: IPP (bottom)



Cooling system and filter: the entire plasma chamber is clad in more or less square-shaped graphite tiles. Much smaller, rectangular graphite plates cover the divertor, which runs through the chamber like a ribbon (large image). Passing through its baffle plates are water pipes (small image) that are intended to carry heat from the plasma to the generators in a fusion power plant. However, the divertor not only cools the plasma but also contains cooling coils in its wall in order to freeze out impurities.

around quickly. As the electron soup in the plasma mixes with the hydrogen nuclei, it also warms them up. In addition, the scientists in Greifswald are testing a second heating method that involves firing fast-moving hydrogen atoms into the plasma. In the future, there are also plans to heat the protons directly using powerful radio waves.

Wendelstein 7-X has already broken a number of records set by other stellarator-type plasma experiments. These include discharges lasting for almost half a minute with a plasma temperature of well over 40 million degrees centigrade. In other low-density discharges, the electrons have reached temperatures of as much as 100 million degrees. This also represented the technical maximum at the current stage of completion, for the walls of the plasma experiment were not yet actively cooled. As a result, the interior of Wendelstein 7-X heated up not only due to radiant heat from the plasma but also due to hot particles escaping from the magnetic cage and colliding with the vessel wall. After longer discharges, the plasma vessel therefore had to cool down for about a quarter of an hour before the next shot. The system is currently out of action for about two years while the team in Greifswald installs an active water-cooling system. This should allow Wendelstein 7-X to cope with plasma discharges lasting for half an hour at very high temperatures. “A water-cooling system may sound trivial,” says Klinger, “but for us it means performing plumbing work to an extremely high standard.” Every part of the plasma vessel that is exposed to heat must be connected to the cooling system, and this work will therefore involve a total of four kilometers of water pipes. “It’s a huge branched-water system,” says Klinger.

THE DIVERTOR DRAWS FUSION HEAT OUT OF THE PLASMA

In this regard, one particular challenge is that a high vacuum must be present in the plasma chamber during operation. What the researchers fear most are tiny leaks in the water pipes, as these are very difficult to detect. A “dripping nose”, as Klinger puts it, could be enough to destroy the vacuum by allowing water to evaporate.

Photos: Bernhard Ludewig/IPP (top), IPP (bottom)

Strict standards therefore apply during the modification work.

However, the greatest technical demands must be met by the divertor. This sits on the inner wall of the ring and consists of a series of consecutive high-tech plates that protrude into the edge of the hot plasma during operation. Accordingly, the plates must be able to withstand extremely high temperatures. In a future power plant, the plan is for similar plates to extract a proportion of the fusion heat from the plasma. This will then drive steam turbines by heating water in a circuit leading out of the vessel.

During operation, the baffle plates of the divertor are exposed to a powerful heat flux of around 10 megawatts per square meter – approximately equivalent to the heat output of 4,000 typical microwave kitchen appliances. "That's about the most that known materials can withstand," explains Klinger. It resembles the conditions experienced by a spacecraft during re-entry into the Earth's atmosphere, which also creates a hot, glowing plasma. The baffle plates of the divertor are therefore made of the same material as the heat shield tiles on the bottom of earlier American space shuttles: a carbon composite material reinforced with carbon fibers.

The carbon fibers not only provide the composite material with mechanical stability but also transport heat toward the vessel wall. Unlike the space shuttle during re-entry, however, these plates need to hold out not just for a few minutes but for almost half an hour. The new divertor – which is currently being installed – must therefore be extremely good at conducting heat between the baffle plates and the water-cooled wall. With this in mind, the Greifswald-based researchers have worked with industry partners to develop a completely new bonding technique.

However, heat dissipation is just one of the divertor's several functions. It is also intended to keep the plasma clean, acting as a vacuum cleaner for impurities arising from unavoidable contact between the plasma's thin outer region and the wall. Charged impurities force plasma electrons to change their trajectories, leading to the emission of X-rays. Moreover, the impurities themselves are excited by the collisions with plasma particles, resulting in greater radiative energy losses from thin plasma, which experiences significant cooling due to these two effects.

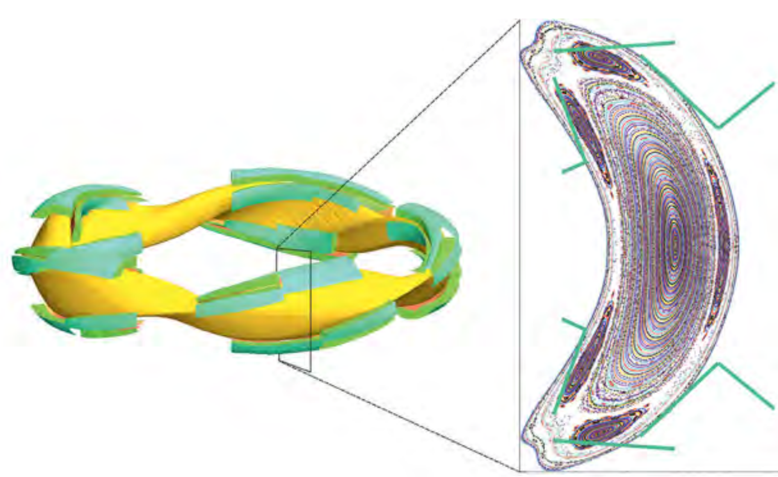
THE CONSTRUCTION PROCESS – A GIGANTIC 3D PUZZLE

Moreover, the divertor helps to keep the number of hydrogen particles under control. For this reason, a cryogenic pump is incorporated into the wall beneath the baffle plates of the divertor. In principle, these "cryopumps" work like a cold beverage can that mists up with condensation when you take it out of the refrigerator in summer – except that the pump in Greifswald is cooled using liquid helium at a temperature of -269 degrees centigrade. "As a result, all of the small particles get stuck there," says Klinger. However, the cryopump requires the team in Greifswald to accommodate additional pipes for liquid helium between the water pipes.

Liquid helium is also used to cool the large superconducting coils, which generate the powerful magnetic field for plasma confinement. In total, 70 of these coils are strung together around the plasma chamber like bracelets on a wrist. Most of the coils have a convoluted geometry and therefore generate a magnetic field with multiple twists and turns. This field acts on the hydrogen nuclei and electrons as they speed past, forcing as many as possible onto magnetic roller coasters that repeatedly hurl them back into the hot plasma. After all, the aim is to minimize the number of hot particles that escape.

The individually shaped coils were just one reason why the construction of Wendelstein 7-X resembled a gigantic three-dimensional puzzle, in which components weighing several tonnes had to be joined together with the utmost precision. First, the team in Greifswald worked with partners to build five 120-tonne modules. Then, the fitters used the shed's overhead cranes to piece these together to form the torus of the plasma vessel. The number of modules depends on the shape of the plasma. "If we could look down from above, we would see a pentagon with rounded corners," Matthias Hirsch explains during his tour.

It is the complex magnetic field that makes the stellarator concept more complicated than the competing tokamak



Anatomy of a plasma: the divertor plates (green) protrude into the convoluted path of the ribbon (yellow). A cross section (right) shows the inner structure of the hot, electrically charged gas.

Graphic: IPP

principle, which is being used to build the large ITER system in Cadarache, France. With their significantly simpler design, tokamaks have already reached a more advanced stage of development. In 1991, the Joint European Torus (Jet) research reactor in the British village of Culham successfully ran the first short, controlled nuclear fusion experiment in a plasma made of deuterium and tritium. For the first time, the fusion experiment at ITER is expected to deliver more power than is needed to heat the plasma. This net gain in energy would represent a preliminary stage in the development of the first demonstration power plant.

THE TWO CONCEPTS OF NUCLEAR FUSION COMPARED

Compared to stellarators, tokamaks have a much more symmetrical, ringlike plasma shape that – besides its technical simplicity – helps to reduce the impact of potential energy-loss mechanisms. However, this must also carry a powerful toroidal current that holds the plasma together within its tubular magnetic field. This toroidal current leads to additional plasma turbulence, which must be kept under control. In addition, a tokamak works like a large transformer, with the plasma representing one of the coils. As the plasma current only arises in response to changes in the coil's current, a voltage is applied to the coil in pulses. Accordingly, a tokamak can only produce pulsed plasma discharges, and so the system is exposed to constantly changing loads.

"We want to avoid the constant cyclical loads on the material and the cyclical forces during startup and shutdown," explains Sibylle Günter, Director at the Max Planck Institute for Plasma Physics. For this reason, international research is underway into con-

Physicists are sometimes also site supervisors: Thomas Klinger is responsible for plasma research in Greifswald and supervised the construction of Wendelstein 7-X.

cepts that can extend these pulses to several hours or even bring about constant – that is, steady-state – operation. In 2016, for example, a team from the IPP in Garching used the site's Asdex Upgrade tokamak to demonstrate that it is possible to do this by driving the plasma flow from the outside. "In the second operating period, ITER is intended to test scenarios such as this with a view to achieving steady-state tokamak operation," says Günter.

A stellarator, on the other hand, operates as a purely magnetic cage without the ring current, and is suitable for continuous operation from the outset. That's what makes stellarators such an interesting idea. However, in the first few decades of research into these devices, the complex shape of their magnetic field represented an insurmountable obstacle: for a long time, the systems simply couldn't confine enough hot plasma particles. That changed in the 1980s, when theoretical scientists from the Max Planck Institute for Plasma Physics in Garching developed the concept of the advanced stellarator, whose modular coils featured complex shapes. Advanced stellarators can now reach the temperatures needed to initiate a nuclear fusion reaction. Part of the reason for this breakthrough was that increased computing power made it possible to calculate the complicated magnetic field geometry accurately for the first time.

Wendelstein 7-X has already produced so much new data in the initial runs that the physicists have plenty of analysis to be getting on with during the modification work. If the experiment with the new water-cooling system succeeds in achieving half-hour plasma discharges, that raises the question of when we might see the first fusion power plant based on the stellarator principle. "Give Wendelstein until the mid-twenties," says Klinger. "Subsequent development will also depend on the results delivered by ITER."

One of the main objectives of ITER is to achieve a net energy gain from fusion, says Sibylle Günter. However, she also raises another key question that ITER is meant to resolve: how will the plasma be affected by the resulting fusion product – that is, by extremely fast-moving helium nuclei? "For example, these fast helium nuclei could also trigger instability in the plasma," she says. "It's a completely new area of physics to explore, and I personally find that very exciting." At any rate, researchers and engineers still have a lot of work to do before fusion energy can be exploited commercially. It remains to be seen whether the stellarator or the tokamak will emerge victorious from this marathon effort, but – even at this early stage – the scientists in Greifswald have made considerable progress with the stellarator concept. ◂

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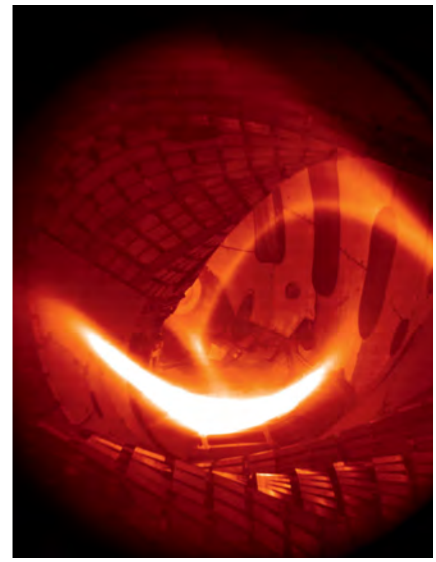

The first hydrogen plasma: ignited by German Chancellor Angela Merkel on 3 February 2016, it burned for a quarter of a second and reached a temperature of 80 million degrees.

SUMMARY

- **Nuclear fusion could offer a completely new way of generating energy in the form of heat or electricity. Researchers at the Max Planck Institute for Plasma Physics are attempting to recreate the intense heat of the sun on Earth using the Wendelstein 7-X stellarator.**
- **Inside the stellarator, hot plasma at a temperature of over 100 million degrees must be permanently confined in a magnetic field cage – the experiment is aiming for half an hour. At the current stage of completion, Wendelstein 7-X has succeeded in generating hot plasmas at temperatures of over 40 million degrees for half a minute at a time.**
- **Unlike the competing tokamak principle, which is easier to implement and has already reached a more advanced stage of development, the stellarator allows continuous operation right from the outset. Its technical exploitation would therefore be more straightforward.**

GLOSSARY

Plasma: A gas whose atoms or molecules are wholly or partially ionized – in other words, they have had some or all of their electrons removed. A plasma is formed at very high temperatures.

Stellarator: In a nuclear fusion facility of this type, a twisted plasma would be confined solely by an external magnetic field with a complex shape. Constructing the coils to generate this field is therefore an extremely challenging task.

Tokamak: In this type of facility, the plasma forms a perfect ring confined by a magnetic field, which is in turn partly generated by a ring current in the plasma itself. Without additional technical measures, which are yet to be fully developed, a tokamak can only be operated on a pulsed basis.