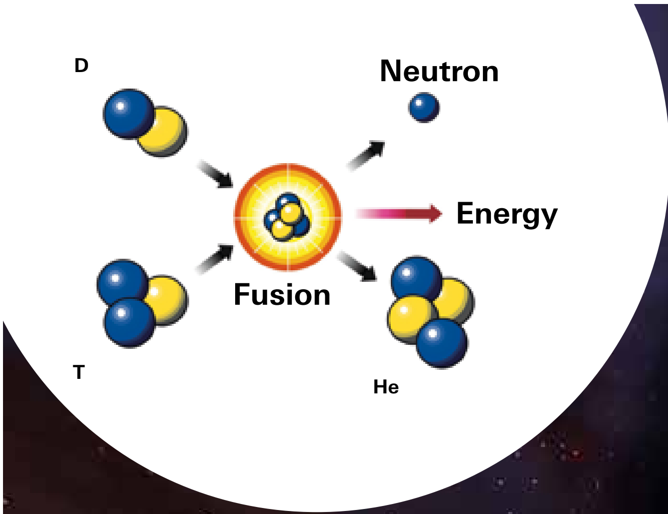

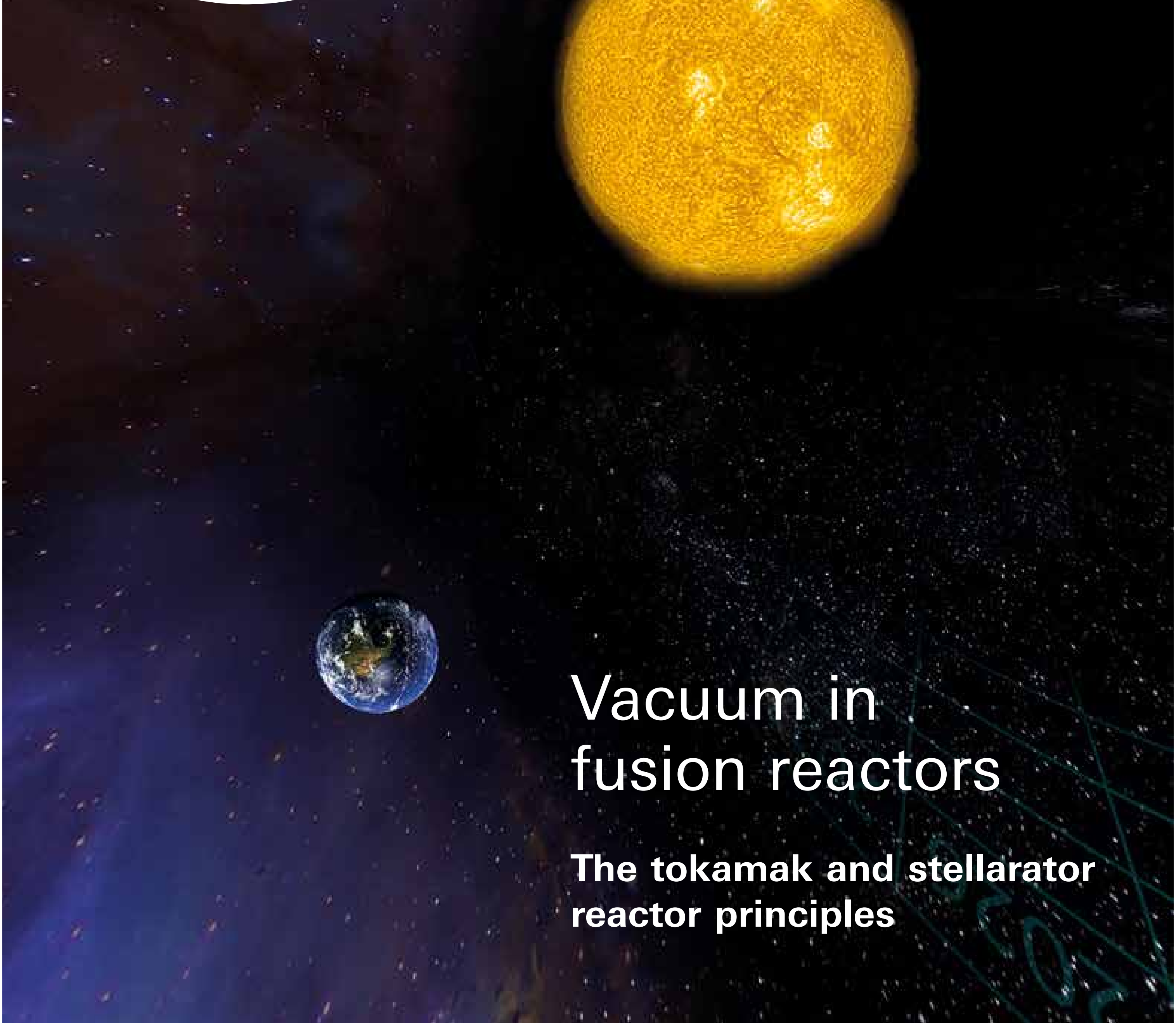

Vacuum in fusion reactors

The tokamak and stellarator reactor principles

Image source: ITER

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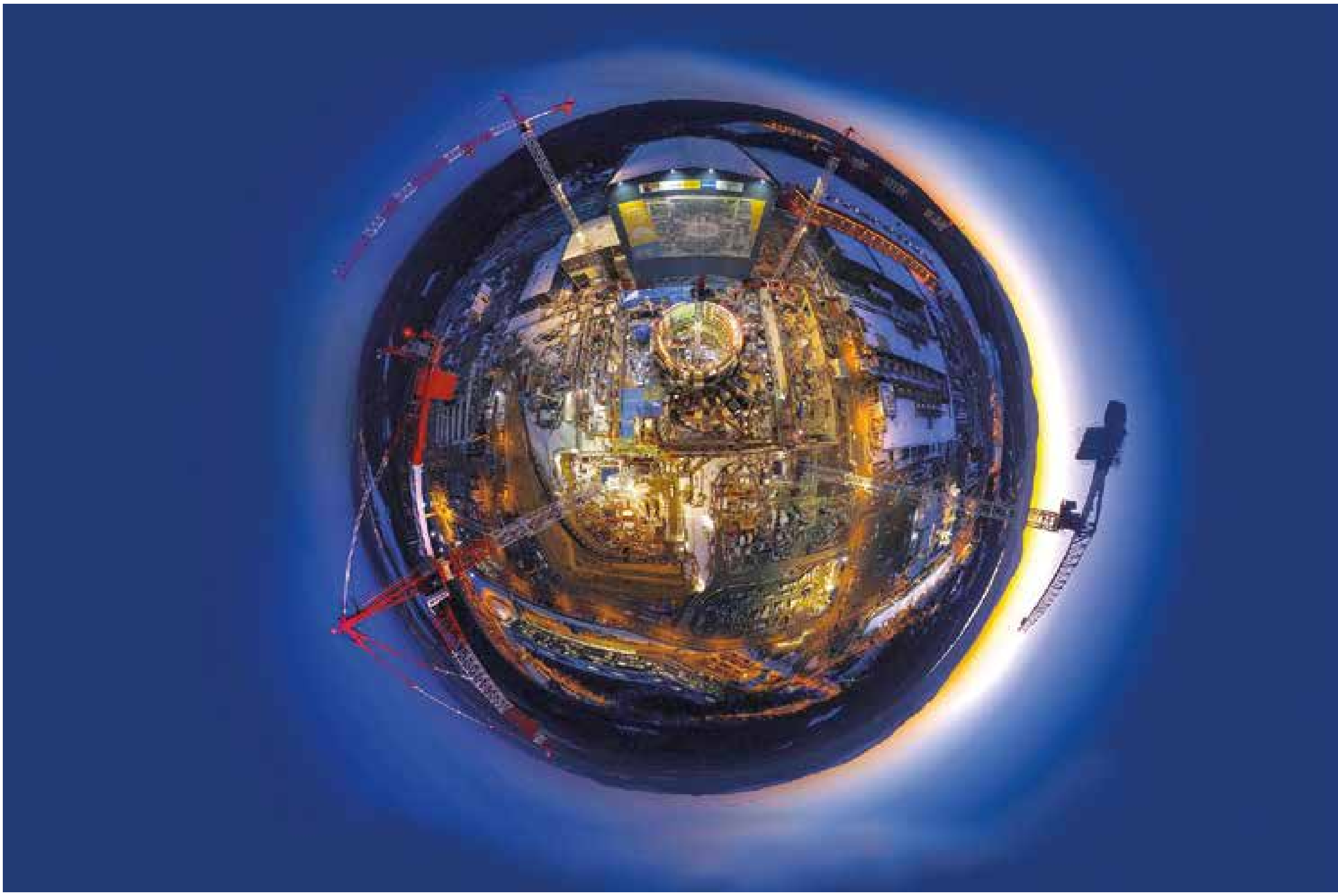


Image source: ITER

The sun as a prototype

The need and demand for clean energy from alternative sources is growing as global warming and climate change continue. Scientists have been trying for many years to replicate the sun here on Earth in order to generate energy according to its example. This would involve hydrogen nuclei being fused to form a helium nucleus – i.e. nuclear fusion would have to take place. The greatest difficulty is replicating the extreme conditions that prevail on the star at the center of our solar system, because the conditions on the sun are completely different to those here on our Earth.

The principle of nuclear fusion

In order to be able to take the principle of nuclear fusion, with which a surface temperature of approximately 6,000 degrees Celsius is reached on the sun, and to use it here on Earth for generating energy, we need to reproduce the reaction of the sun. Vacuum technology plays an important role here, since the sun is surrounded by vacuum.

Large experimental constructions, known as nuclear fusion reactors, are used to recreate solar conditions here on Earth.

The nuclear fusion reactor is a technical plant in which the nuclei of atoms are fused together in a controlled manner in a thermonuclear reaction. The aim of the nuclear fusion process is to generate electricity, since an enormous amount of energy is released when the nuclei of the atoms fuse together. There are currently two common reactor types: tokamak and stellarator. Both reactor types basically work on the same principle. The differences lie in the shape and arrangement of the coils that generate the magnetic field. Both types involve heating hydrogen or hydrogen isotopes to up to 150 million degrees Celsius. To generate such heat, the plasma needs to float freely in a vacuum, since any contact with other particles or walls allows heat to escape. Therefore, a magnetic field with a strength of up to 10 Tesla is often generated with the help of superconducting electromagnets. The plasma is then heated by means of electric heating or electromagnetic waves to cause, in the best case, nuclear fusion.

What tasks does vacuum perform in fusion reactors?

One of the important requirements for operating a fusion reactor is a strong, reliable, and powerful vacuum system.

- **Isolating the free-floating plasma from the walls:** It is essential to prevent the transfer of heat between the up to 150 million degree hot plasma and the chamber walls. Otherwise, the plasma would cool down immediately and the fusion reaction would break down.

- **Removing helium and impurities:** The waste product helium and nuclei from the wall material act as contaminants in the process and must therefore be removed from the plasma by means of magnetic deflection. Once removed from the plasma, the helium and nuclei cool down and are eliminated by the vacuum pumps.

- **Thermal insulation of the cryostat:** In many fusion experiments, superconducting coils are used to create the magnetic field. These coils are cooled with liquid helium. Vacuum pumps are required here to generate the necessary insulation vacuum.

Vacuum system requirements

Low final pressure (< $1\cdot10^{-8}$ hPa in the plasma vessel; < $1\cdot10^{-5}$ hPa in the cryostat)

- The recipient of a fusion reactor must be evacuated to a base pressure of < $1\cdot10^{-8}$ hPa before the process gases are introduced. The process gases are hydrogen, deuterium or tritium. The gas load that develops during operation is often pumped with turbopumps, although the use of cryopumps is also planned. As a general principle, all of the pump technology used must have a high pumping speed for the light process gases.

- Various sensors are used to measure the total vacuum pressure. In addition to the thermal conductivity vacuum gauges (Pirani), cold cathode gauges are most commonly used. The latter are used to detect high and ultra-high vacuum pressures in the recipient.

- In many cases, high-resolution quadrupole mass spectrometers are installed in fusion reactors for analysis purposes. These instruments are used to detect the ratio of helium and deuterium.

Wendelstein 7-X in March 2014, shortly before completion of the main installation phase (image: IPP, Beate Kemnitz)

Expert Tip

During operation, turbopumps are very sensitive to external magnetic fields. This is due to the eddy currents that occur in magnetic fields. These cause the aluminum rotor to heat up dramatically and can even destroy it in the worst case. This effect is in particular caused by magnetic fields running horizontally to the rotor axis. To enable the turbopumps to operate within a magnetic field despite this effect, Pfeiffer Vacuum offers magnetic shielding for the following turbopumps:

- HiPace 80
- HiPace 300
- HiPace 700

The HiPace 300 H and HiPace 700 H offer very high compression for light gases. They are therefore particularly suitable for use in fusion experiments. The material and wall thickness of the magnetic shield are determined individually. These parameters also determine the strength of the magnetic field to which the turbopump may be exposed.

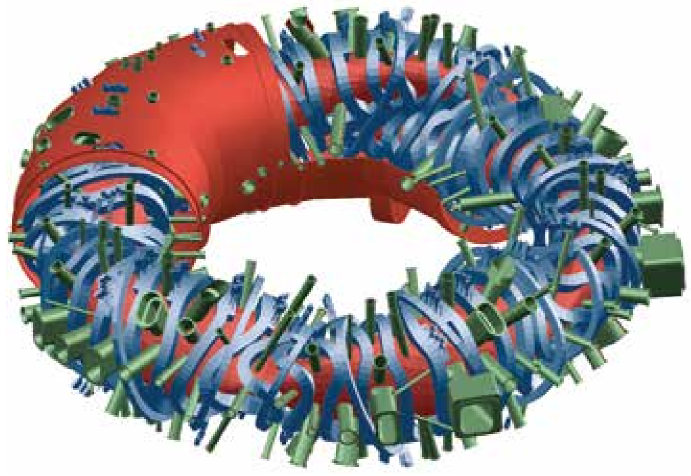
Compatibility with tritium

- In some fusion experiments, tritium is used in addition to hydrogen. Tritium applications are classified according to low, medium and high concentrations, but the materials for the vacuum components are generally clearly specified. No elastomers may be used, for example. And gray cast iron housings for backing pumps are not allowed for reasons relating to tightness.

- The requirements regarding the tightness of vacuum components are particularly high in the case of tritium: $Q < 1 \cdot 10^{-10}$ Pa m^3/s. But even in plants where hydrogen is used, the entire recipient with all its flanges and connecting elements must be checked for leaks, in addition to checking the pumps and measuring devices.

Suitable for use in radioactive environments

For all of the vacuum components used, the general principle applies that the electronics must be installed at a distance from the actual pump or measuring device. This is because modern digital electronics are damaged by radioactivity. The only option available is to separate the control devices and actuators (pumps, measuring devices etc.) with the help of long cables. Often, cable connections made of halogen-free materials are specified with lengths of up to 100 m or more.



Computer graphic: Cryostat, magnetic coils and plasma vessel at Wendelstein 7-X fusion reactor (image: IPP)

Operation in areas of high magnetic field strengths

- The high magnetic field strengths (of several Tesla) that are necessary for operating the fusion reactors can still reach levels of H > 100 mT at the installation locations of the vacuum components. All components must therefore be provided with magnetic shielding. Shielding is particularly important in the case of turbopumps, to prevent the rotor from heating up as a result of eddy currents.

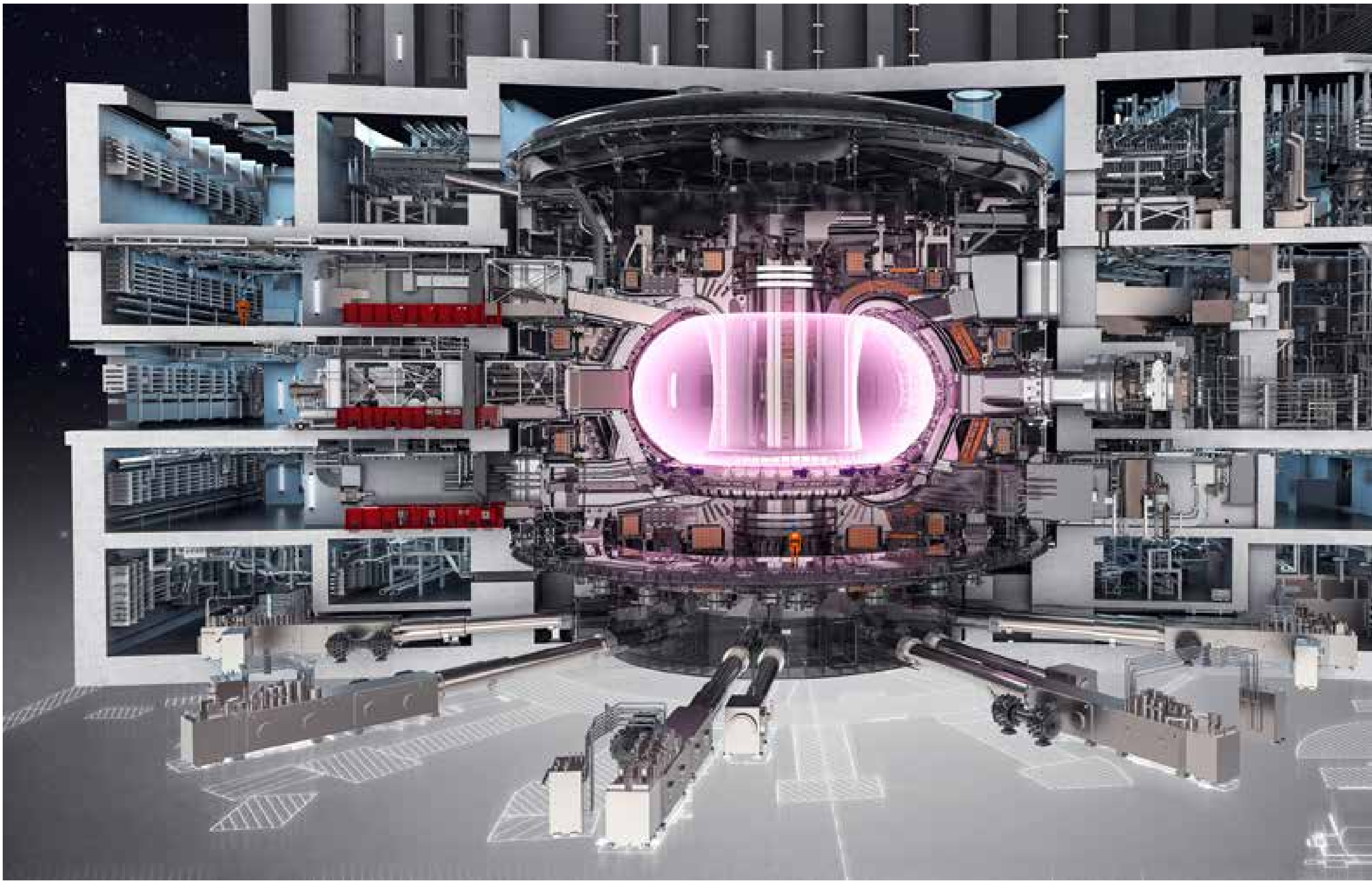


Image source: ITER

- The opposite applies to the material used to manufacture the vacuum recipient. Here, the highest possible magnetic permeability is required. This means that the externally induced magnetic fields should not be deflected and the material should not be heated by eddy currents.

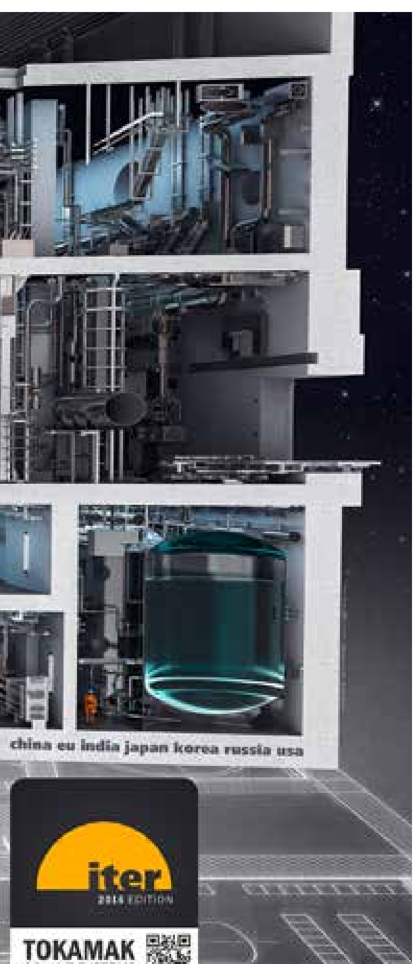
References
For many years, Pfeiffer Vacuum has been a globally well-established and highly competent partner for fusion experiments. It is especially important for us to work out a solution in close cooperation with the user. The most essential part of the process is determining the best possible product combination or solution for the respective application. The following customer reference projects are outlined here as examples:

Wendelstein 7-X (Stellarator)
- 47 x HiPace 2300 C turbopump
- HiCube Eco pumping stations
- ModulLine vacuum gauges (with remote electronics)
- ASM 310 leak detector
- HPA 220 mass spectrometer

ITER (Tokamak)
- Tritium compatible Roots pump, patented and exclusively available from Pfeiffer Vacuum
- Mobile residual gas analysis systems
- Mobile leak detectors

Tritium compatible Roots pump Okta 1500 GM with highest compression for hydrogen

Special leak detector for a very wide range of applications. All gases from H_2 to Xe can be detected within a wide pressure



Pfeiffer Vacuum products and their advantages at a glance

HiPace turbopumps
- High pumping speed
- High compression for light gases
- Variations for high external magnetic fields
- External drive electronics up to 100 m from the pump
- On-site maintenance possible

ACP multi-stage Roots pumps
- External drive electronics
- No wear thanks to frictionless operation
- No reflux of hydrocarbons
- Generates a very clean vacuum
- Contactless pump module
- Particle-free vacuum
- Fluorine-free version available

Roots pumps
- Made of stainless steel; patented
- Tritium compatible
- Pumping speeds: 250 to 25000 m^3/h
- Magnetic coupling – excellent sealing and a long service life
- High compression, also for light gases

Chambers and components
- Large dimensions
- Customizable
- Versatile components

Vacuum gauges

- Magnetic shielding up to 70 mT (ModulLine)
- Cable length up to 500 m
- Profibus connection

Mass spectrometer

- Residual gas analysis and leak tests
- High resolution mass spectrometer, also for detecting helium and deuterium
- Variations for multiple applications

Leak detectors

- Lowest detection rate up to $1 \cdot 10^{-13}$ Pa m^3/s
- Easy to use
- Dry backing pumps up to 40 m^3/h are possible

VACUUM SOLUTIONS FROM A SINGLE SOURCE

Pfeiffer Vacuum stands for innovative and custom vacuum solutions worldwide, technological perfection, competent advice and reliable service.

COMPLETE RANGE OF PRODUCTS

From a single component to complex systems:
We are the only supplier of vacuum technology that provides a complete product portfolio.

COMPETENCE IN THEORY AND PRACTICE

Benefit from our know-how and our portfolio of training opportunities!
We support you with your plant layout and provide first-class on-site service worldwide.

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