First Plasma in the Superconducting Fusion Device Wendelstein 7-X

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January 22, 2016 (STH38, HP104). On 10th of December 2015 the first helium plasma was produced in the Wendelstein 7-X fusion device at the Max Planck Institute for Plasma Physics (IPP) in Greifswald, Germany. After eighteen years of construction work and more than a million assembly hours, the main assembly of the Wendelstein 7-X was completed in April 2014 [1]. The operational preparations have been under way ever since [2]. Each technical system was tested in turn, the vacuum in the vessels, the cooling system, the superconducting coils and the magnetic field they produce, the control system, as well as the plasma heating devices and measuring instruments. On the 10th of December 2015, the operating team in the control room ramped up the magnetic field to 2.5 Tesla and initiated the computer-controlled experiment operation system. It fed about one milligram of gas into the evacuated plasma vessel, switched on the microwave heating for a short 1.3 megawatt pulse – and the first plasma could be observed by the installed cameras and measuring devices. Wendelstein 7-X, the world's largest stellarator-type fusion device, will investigate this particular concept as a candidate for a future fusion power station.

The objective of fusion research is to develop a new primary energy source that is climate neutral and, similar to the sun, uses the fusion of atomic nuclei as fuel [3]. As the fusion burn only ignites at temperatures higher than 100 million degrees, the fuel – a low-density hydrogen plasma – must not come into contact with cold vessel walls. Confined by magnetic fields, it floats virtually free from contact within the interior of a vacuum chamber. For the magnetic cage, two different designs have prevailed – the tokamak and the stellarator.

At present, a tokamak is thought to be capable of producing an energy-supplying plasma. Based on this principle is the international test reactor ITER, which is currently being constructed in Cadarache, France in the frame of a worldwide collaboration.

In a tokamak, the toroidal magnetic field is provided by planar coils. The toroidal field is twisted by the poloidal field generated via a strong electric current in the plasma. The plasma current is induced by the field generated in a central solenoid that is driven with an alternating current. One could say that the plasma acts as the secondary winding of a transformer. The induced electric field is also used for plasma build-up and heating and it is important to note that a tokamak plasma equilibrium is a self-organized state. Tokamaks have a relatively simple geometry and they are toroidally symmetric, which yields a number of conserved physical quantities thereby ensuring good confinement of charged particles. The tokamak concept has proven to be very successful: today's most advanced experiments are based on this principle. However, the ultimate requirement to run a strong current in the plasma is a serious obstacle for stable steady-state operation. Since induction requires pulsed operation, for steady-state operation the plasma current must be driven by other means, e.g. particle beams or plasma waves. In addition – from the thermodynamic point of view – a strong plasma current is a source of free energy, which is often released via plasma instabilities that can lead to a total breakdown of the plasma equilibrium (current disruption).

The stellarator is an alternative concept: The stellarator magnetic field is generated by external coils only. A strong plasma current, and consequently a central solenoid, is not needed. As a consequence, different from a tokamak, the vacuum magnetic field has already confinement properties and the stellarator is intrinsically steady-state capable. The classical stellarator is based on a combination of planar coils and a pair of large, helical coils. These helical coils are critical from the engineering point of view (manufacturing, assembly, and repair). Helical coils can be avoided by combining helical and planar coils to non-planar coils. An important benefit of non-planar coils is that the magnetic field geometry can be shaped via the specific coil geometry. This allows for a physics-based optimization of the magnetic field, which turned out to be extremely beneficial for the development of the stellarator line. The optimization of the magnetic field is, however, computationally expensive and only after the first supercomputers of the late 80's became available, the suite of coupled codes could be run in a reasonable time frame. This also explains why the stellarator concept is somewhat lagging behind the tokamak concept, which is mathematically more accessible. Meanwhile, the stellarator research is moving from mid-size to large-scale experiments.

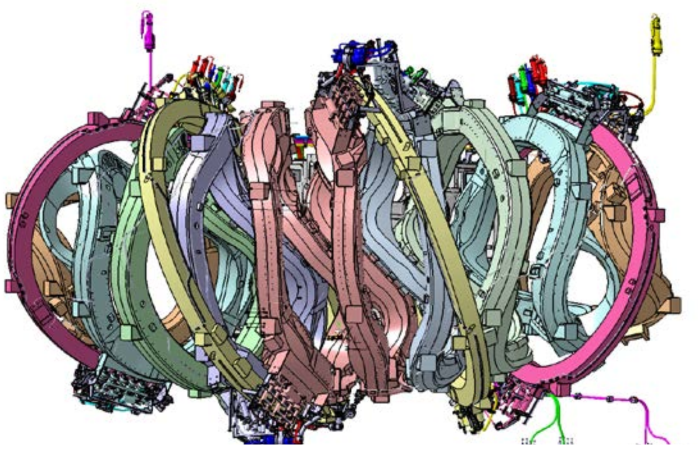

Fig. 1. Superconducting coil system of Wendelstein 7-X (one fifth of it is shown)

The main magnetic field of Wendelstein 7-X is provided by 50 non planar superconducting coils (Figure 1). There are five different coil geometries with ten coils per type each [4]. Each coil type is separately controlled, which yields a range of magnetic configurations. An additional toroidal field is generated by a set of 20 planar superconducting coils, which adds further to the flexibility of the device. It is a major scientific goal of the experiment Wendelstein 7-X to explore the whole range of optimized magnetic geometries with regard to plasma performance and consistency with divertor operation. The non planar coils have dimensions of 3.5 × 2.5 × 1.5 meters and a weight of about 5.5 tons. The planar coils have diameter of about 4 meters and a weight of 3 tons. Coils of each type are connected in series via superconducting bus bars and can be energized up to 18.2 kA independently to provide the above mentioned wide range of operational flexibility. Each of the seven coil groups is connected to a power supply via a pair of HTS current leads [5].

Superconducting coils and bus bars are using the same type of superconductor. It is a forced flow cable-in-conduit conductor using NbTi. It consists of a cable with 243 strands (cabling law of 3×3×3×3×3) enclosed in an aluminum-alloy jacket with a void fraction of 37%. The outer dimensions of the jacket are 16 mm × 16 mm. The inner side is nearly circular with a diameter of 11.7 mm. The design of 3-D coils led to the requirements of bending with a minimum bending radius of 120 mm. Therefore, an aluminum alloy (AlMgSi0.5) was chosen as jacket material. Each strand has a diameter of 0.57 mm and is made of 144 NbTi filaments stabilized by copper with a copper to non copper ratio of 2.6. The specified critical current of the superconductor is 35 kA at 4 K and 6 Tesla background field. This gives a temperature margin of about 1 Kelvin for the coils during operation. The total amount of superconductor produced was about 60 km, made of about 15 000 km of strands.

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