A NEWCOMER: THE WENDELSTEIN 7-X STELLARATOR

Thomas Klinger – DOI: http://dx.doi.org/10.1051/epn/2016506
Max-Planck Institute for Plasma Physics, Wendelsteinstraße 1, 17489 Greifswald, Germany

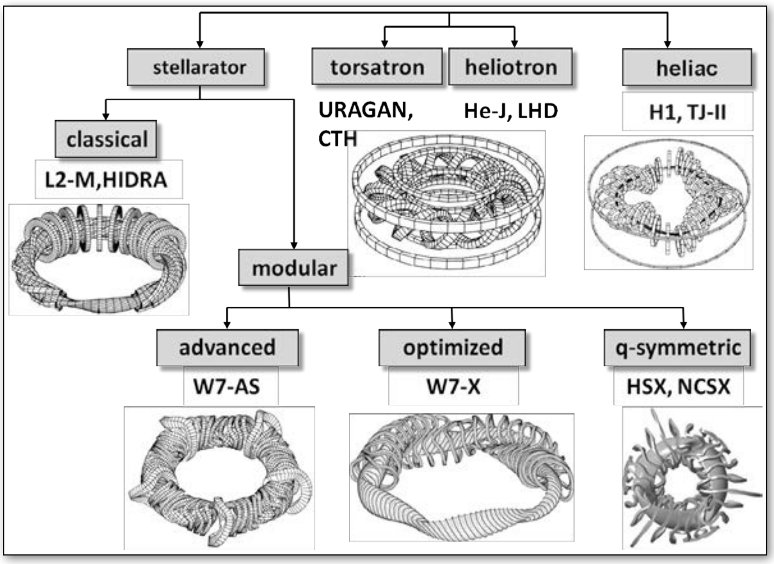
Stellarators ("star generators") belong to the earliest concepts for magnetic confinement of fusion plasmas. In May 1951, a confidential report authored by Lyman Spitzer at the Princeton Plasma Physics Laboratory (PPPL) was issued, in which he proposed the "figure eight" stellarator based on the idea to generate the required rotational transform of magnetic field lines by twisting the torus into a figure-8. The first experimental device based on this idea started operation in early 1953. In the 1950's a series of stellarator experiments were built, most of them at PPPL.

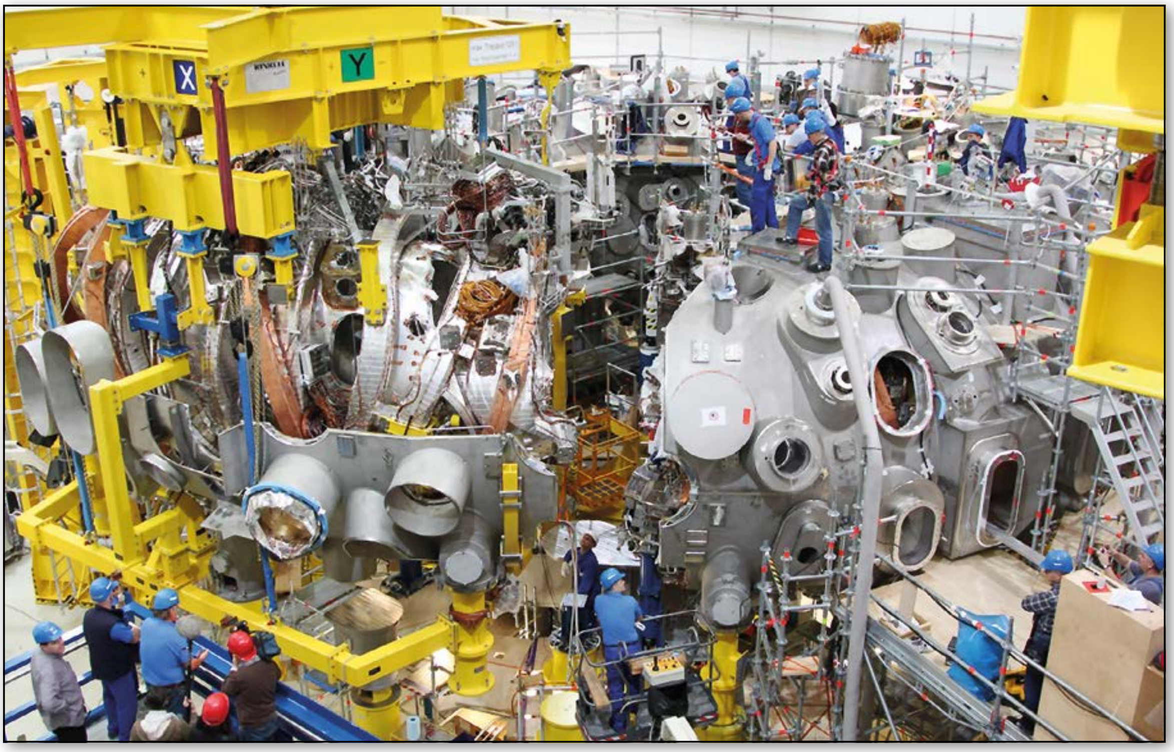
This development has led to the large "Model-C" stellarator, operated at PPPL from 1961-1969 until it was converted into the "Symmetric Tokamak" in 1970, after breakthrough results reported from Russian tokamaks in 1968. The first "Wendelstein" stellarator, the "1-A" went into operation in 1960 at the Max-Planck Institute for Physics and Astrophysics. It was followed by a series of uninterrupted developments until now, when the large, superconducting stellarator "Wendelstein 7-X" (in short W7-X) went into operation. In that sense, stellarators are not "newcomers", but the trust in the concept has undergone a number of ups and downs and W7-X intends to make a major contribution to bring stellarators to maturity.

Stellarators and optimisation

The fundamental idea of stellarators is to generate rotational transform – the twist of the magnetic field - to a major extend by external coils [1]. This is different from the tokamak concept, where the poloidal component of the magnetic field is generated by a strong current running in the plasma (see article by T. Donné). This difference has major consequences: The stellarator magnetic field is very much "frozen-in" by the external coils, whereas the tokamak field is strongly defined by the particular plasma scenario with the associated radial current distribution. Furthermore, a current-carrying plasma tends to be less stable than a current-less plasma and steady-state operation is more difficult in a tokamak because of the need for efficient non-inductive current drive. There is a lot of freedom in the choice of external coils for generating a stellarator magnetic field. Consequently, there is a whole "family" of coil configurations [2] with the main lines being (a) stellarators, (b) heliotrons/torsatrons, (c) heliacs (see Fig. 1). Indicated are also the experimental devices, smaller ones for addressing more basic plasma physics questions and bigger ones with direct relevance for reactor extrapolation. The classical stellarator combines planar coils to generate a toroidal magnetic field and sets of helical coils with counter-directed currents to create rotational transform. Torsatrons and heliotrons use helical coils with co-directed currents to produce a twisted toroidal magnetic field. A vertical magnetic field is generated as well and must be compensated with additional vertical field coils. In contrast to stellarators and heliotrons/torsatrons, the magnetic axis in a heliac follows a helical path to form a toroidal helix with twisted magnetic field lines. The vertical positions of the planar toroidal field coils follow the helical path and a central conductor further enhances the twisting of the toroidal magnetic field. Again, vertical magnetic field coils are required for compensation.

▼**FIG. 1:** Overview diagram of helical magnetic confinement concepts and the associated devices. The stellarator line has split up into different branches after the concept of modular coils was introduced.





▸ **FIG. 2:** View into the torus hall during assembly. Tools for stiffening and handling have a yellow colour. Clearly seen on the left is the (last) magnet module that is inserted into the torus.

A different approach is based on modular three-dimensionally shaped magnetic field coils. These coils allow shaping the magnetic field within a wider range, based on specific physics criteria. This iterative process is called "optimization" and the magnetic field of the modular stellarator Wendelstein 7-X was shaped to satisfy the following criteria [3]:

1. nested magnetic flux surfaces with sufficiently small magnetic islands
2. good plasma equilibrium at high average beta ≅ 4%[1]
3. good magnetohydrodynamic stability at average beta ≅ 4%
4. small neoclassical transport in the relevant collisionless regime
5. minimized bootstrap current in the relevant collisionless regime
6. improved confinement of fast particles
7. feasible modular magnetic field coils

The predecessor device of Wendelstein 7-X, the Wendelstein 7-AS, was only partially optimized and is denoted as "advanced" in comparison to classical stellarators. Wendelstein 7-AS has already shown improved plasma properties due to physics-based shaping of the magnetic field. Another sub-group are the quasisymmetric stellarators, *i.e.*, non-axisymmetric configurations in which the magnetic field strength depends only on one angular coordinate within the magnetic flux surfaces. Quasisymmetric stellarators meet optimization criteria as well but not necessarily the same as above. The three types of quasi-symmetry are: quasi-helical, quasi-poloidal, and quasi-axisymmetric. It should be emphasized that optimization of the magnetic field is a promising path to bring stellarators to maturity, *i.e.*, to allow for integrated high-performance plasma scenarios that are comparable to those of tokamaks of the same plasma volume.

The construction of Wendelstein 7-X in brief

The project Wendelstein 7-X was officially started in 1996. The initial phase of the project was dominated by design, specification and tendering of the major components of the device, *i.e.* about 60 km length of niobium-titanium superconductor, the 80 m^3 volume and 33 t heavy plasma vessel, the 525 m^3 volume and 170 t heavy outer vessel, the 254 ports, the 72 t heavy central support ring, and the manufacturing of the 20 planar and 50 non-planar superconducting coils. At the same time, the development of 10 gyrotrons with 140 GHz frequency and 1 MW output power for 30 min duration was started. The assembly of the device started in 2004 and was completed 10 years later, with more than one million assembly hours spent. The assembly work was challenging because of (a) three-dimensional geometry and high precision requirements, (b) difficult access situations especially in the cryostat and for the in-vessel components, and (c) the extremely crowded space situation in the torus hall. This leads to unusually high work density and strong sensitivity against perturbations in the work flow. Intense project management on the daily level was required, based on strict industry-proven rules and well defined processes, in particular systematic quality management, change management, and risk management.

[1] <β> is the average ratio of plasma pressure to external magnetic field pressure

The assembly can be described in 17 major assembly steps (roughly in sequence): (1) Assembly of the thermal insulation on a half-module of the plasma vessel, (2) threatening of five non-planar and two planar superconducting coils over the plasma vessel half-module, (3) bolting the coils to a segment of the central support ring, (4) welding of the additional inter-coil support elements, (5) joining two pre-assembled magnet half-modules to a module, (6) installation of the superconducting bus bars and the joints to interconnect the coils, (7) installation and welding of the helium distribution pipework, (8) assembly of the thermal insulation on the inner side of the outer vessel module, (9) insertation of the magnet module into the lower half-shell, (10) installation of the vertical supports and cryo feet, (11) welding of the outer vessel upper half-shell on the lower-half shell, (12) assembly of the thermal insulation on the ports, (13) installation of the 254 ports and their welding on the plasma vessel and the outer vessel, (14) joining the 5 modules by bolting the central ring modules, welding the vessels and connecting the pipes and bus bars, (15) assembly of the 14 current leads, (16) assembly of the in-vessel components, (17) assembly of the device periphery. Fig. 2 shows a view into the torus hall during the installation of the last of the five pre-assembled magnet modules.

The island divertor concept

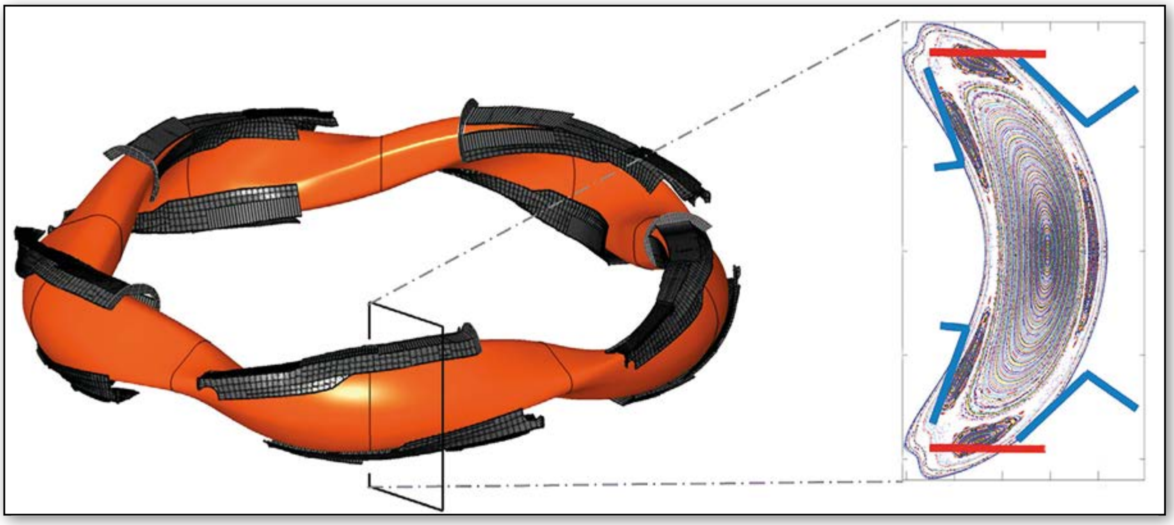
For the development of the stellarator reactor line, it is of utmost importance to qualify a viable divertor concept. Different from a tokamak, the divertor in a stellarator cannot be toroidally symmetric. One approach is a divertor with helical shape as installed in the heliotron "Large Helical Device" in Japan. For the Wendelstein 7-X optimized stellarator a different solution was found, the island divertor (Fig. 3).

The magnetic field of Wendelstein 7-X is five-fold periodic with a strong variation of the cross-section from triangular to bean-shape and exhibits natural magnetic islands at the edge where the rotational transform has a resonance[2] close to unity. On each magnetic field period, one pair of island divertor modules is installed where the cross-section of the magnetic field is predominately bean shaped. The natural magnetic islands intersect the target and partially baffle plates. In this way, a well-defined flow of particles from the plasma edge (outside the confinement volume) to the wall is ensured and the interaction between the plasma and the wall is decoupled from the core plasma region. The target plates of the island divertor have to withstand a heat flux of up to 10 MW/m^2, which is close to the technical limits, especially under steady-state conditions. Wendelstein 7-X follows a staged approach with inertially cooled limiters in the first stage of operation, an inertially cooled divertor in the second stage, and a water-cooled divertor in the third stage. In addition to the divertor and the baffles, the remaining wall surfaces are covered either with water-cooled steel panels (surface area 62 m^2) or with water-cooled graphite heat shields (surface area 47 m^2). The steady-state operation requirements of Wendelstein 7-X imply that there is no uncooled plasma facing component allowed, which means considerable efforts in design, engineering and assembly.

[2] At a resonance the twisting magnetic field line closes upon itself.

First results from Wendelstein 7-X operation

The assembly of Wendelstein 7-X was officially completed on 20th of May 2014. The commissioning process of the device consisted of six major steps, *i.e.*, (1) pump-down of the cryostat volume to high-vacuum conditions, (2) cool-down of the magnet system to 3.4 K, (3) test of all normal-conducting control and trim coils, (4) pump-down of the plasma vessel to ultrahigh-vacuum conditions, (5) ramp-up of the superconducting magnet system to achieve 2.5 T magnetic induction on axis, (6) preparation for plasma operation, in particular plasma vessel baking, wall conditioning, test of gas inlets and device control. After commissioning step (5), the magnetic field geometry was confirmed with an electron-beam mapping technique. Wendelstein 7-X has started operation on the 10th of December 2015 with



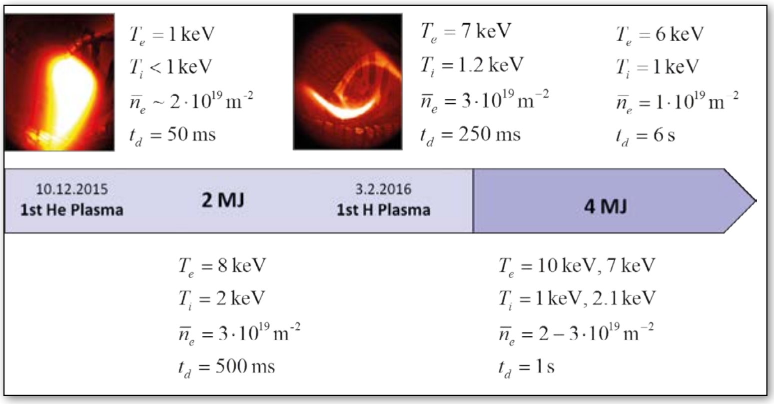
◄ **FIG. 3:** Schematic drawing of the island divertor (left diagram). Ten modules (five top and five bottom) are placed at the toroidal position with bean-shaped cross section. The target plates of the divertor, indicated by red bars, intersect the natural magnetic islands located at the edge (right diagram). The blue bars indicate the baffle plates.

helium as filling gas (Fig. 4). The maximum injected electron cyclotron resonance heating (ECRH) energy was limited to 2 MJ to protect the five inboard limiters from thermal overload. After wall conditioning with repetitive low-power ECRH pulses, the impurity level has dropped to acceptable values and the plasma parameters as well as the pulse duration have significantly improved. The maximum available ECRH power was 4.3 MW.

On the 3rd of February 2016 the operation with hydrogen as filling gas had started. The heat loads on the limiters allowed to double the maximum injected ECRH energy up to 4 MJ. This has improved the plasma performance considerably and both higher-power 1 s duration and lower-power 6 s duration discharges could be operated routinely. During the 10 weeks of operation about 1000 experiments could be conducted with the about 30 diagnostic systems in operation. The first operation stage of Wendelstein 7-X has exceeded all expectations with regard to reliability and availability of the device, plasma performance parameters, and validity of the obtained data. Already a large variety of physics programs could be conducted, including the investigation of the central electron root [6], plasma rotation, influence of external trim coils on wall loads, and first impurity transport studies. The analysis of the data is in progress and valuable experience for the next operation stage has been gained. Also the formation of the scientific and the operation team was successful, in particular the international cooperation in the framework of the EUROfusion consortium (see article by T. Donné) and a strong cooperation with U.S. American research laboratories and universities.

The path to steady-state operation of fusion relevant plasmas

Steady state operation of plasmas with fusion-relevant parameters is one of the grand challenges in fusion research. The fusion triple product $n{\cdot}T{\cdot}\tau_E$ usually deteriorates for longer plasma discharges, either due to lack of long-pulse heating and current drive performance or heat load limits of plasma facing components. The stellarator concept without net plasma current is inherently steady-state. However, a large number of measures must be taken to make a fusion device – including stellarators – steady-state capable: (a) The magnet system must be superconducting. (b) A steady-state heating system must be developed for the operation of the experimental devices. Here ECRH is a most promising path, since the gyrotron development has made enormous progress during the past 10 years. The 1 MW 140 GHz gyrotrons for Wendelstein 7-X have proven 30 min of operation without any loss of performance. Using water-cooled mirrors and diamond windows, the ECRH beam can be quasi-optically directed into the plasma. (c) All plasma-facing components must be actively (water) cooled. (d) Plasma diagnostic systems must be prepared to cope with steady-state conditions. (e) The requirements on control and data acquisition of a steady-state fusion device are much higher than for any short-pulse machine. The sheer amount of data, the necessity of highly-available systems, and continuous control of the plasma make dedicated developments indispensable. In summary, a steady-state device with fusion-relevant plasma parameters is not only a physics program (predominately aspects of plasma-wall interaction) but requires also a dedicated engineering and development program and Wendelstein 7-X will make a serious contribution.



▾FIG. 4: Overview over the plasma parameters achieved during the first operation campaign of Wendelstein 7-X. The doubling of the injected ECRH energy from 2 MJ to 4 MJ has considerably improved the plasma performance.

Reactor concepts for stellarators – the way forward

Wendelstein 7-X is clearly the key device for the qualification of optimized modular stellarators as possible candidates for a fusion power plant. A burning-plasma power plant study based on stellarator optimization using non-planar coils is the HELIAS 5-B (helical-axis advanced stellarator) with the following design parameters [4]: plasma volume 1400 m^{-3}, number of non-planar coils 50, major radius 22 m, overall diameter 60 m, average magnetic induction on axis 5.9 T, magnetic energy 160 GJ. To go directly from Wendelstein 7-X to such a device would be too large a step and an intermediate device is most likely needed to study the physics of a burning stellarator plasma and to develop the related technologies, in particular blanket modules that match the stellarator geometry and the associated remote handling technologies. Prior to that step, Wendelstein 7-X has to fulfill its missions to demonstrate: (1) constructability, (2) plasma performance, (3) divertor operation, (4) steady-state operation. The forthcoming two operation phases, that extend until mid 2025, will be decisive for making major progress towards achievement of these milestones. ■

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