STELLARATOR RESEARCH AT THE IPP IN GARCHING

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Stellarator experiments at the IPP Garching started in 1965 with small devices until in 1976 the first large device Wendelstein 7-A (major radius 2 m, av. plasma radius 10 cm, magnetic field 3,4 T) went into operation. In 1980 this experiment produced the first plasma without toroidal current. Its successor, Wendelstein 7-A, abandoned the concept of helical windings and generated the stellarator field by a set of modular coils. The same concept is applied to Wendelstein 7-X, (major radius 5,5 m, av. plasma radius 0,5 m, magnetic field 2,5 T), which in addition will be equipped with superconducting modular coils. The paper describes the main experimental results of the Garching stellarators, its future planning and the reactor prospects of the advanced stellarator [1].

1. Introduction

In Mai 1951 Lyman Spitzer, Jr. proposed the stellarator concept as one of the first schemes to confine thermonuclear plasmas [1]. Since then a large variety of stellarator experiments have explored the plasma behaviour using various heating methods. The main argument in favour of stellarators is their potential as a steady state fusion reactor, an argument, which is becoming more and more important in current fusion reactor studies. Steady state in stellarators is achieved by generating the magnetic field by external coils only, the currents in the plasma modify this magnetic field only slightly, and a net toroidal current, which must be maintained by an Ohmic transformer or inductive current drive, does not exist. Therefore, also those instabilities, which in tokamaks are associated with the toroidal current – tearing-modes and disruptive instabilities – do not exist in stellarators.

Stellarator experiments in Germany started 1961 at the MPI für Physik und Astrophysik in Munich, and, after moving to the IPP Garching, stellarator experiments have been carried through since 1965. Wendelstein II-A (Major radius 50 cm, plasma radius 5 cm) was the first stellarator with steady state plasma operation and it demonstrated that plasma confinement in stellarators can be close to classical confinement and is not Bohm-like as was found in the C-stellarator at Princeton. Furthermore, this low shear device already showed how strongly confinement depends on the topology of magnetic surfaces – a feature, which also occurred in the following larger experiments. Wendelstein II-B was similar in size to Wendelstein II-A, however, being equipped with an Ohmic heating transformer, plasma parameters equivalent to those in tokamaks could be achieved. The first large stellarator - Wendelstein 7-A – went into operation in 1976. This device was still a classical stellarator, it was equipped with two pairs of helical windings and toroidal field coils. However, very soon it was recognised that the concept of helical windings is a dead end and cannot be realized in larger devices or in a fusion reactor. This has led to the concept of modular coils where the total confining field is generated by one set of non-planar twisted coils [2]. In 1988 Wendelstein 7-AS went into operation, the first large stellarator with modular coils. Wendelstein 7-AS is an upgraded version of Wendelstein 7-A, which caused some restrictions on the optimisation of the plasma with respect to plasma equilibrium and transport.

[1] This paper is an extended version of the paper by H. Wobig and H. Renner, written on the occasion of the retirement of G. Grieger.

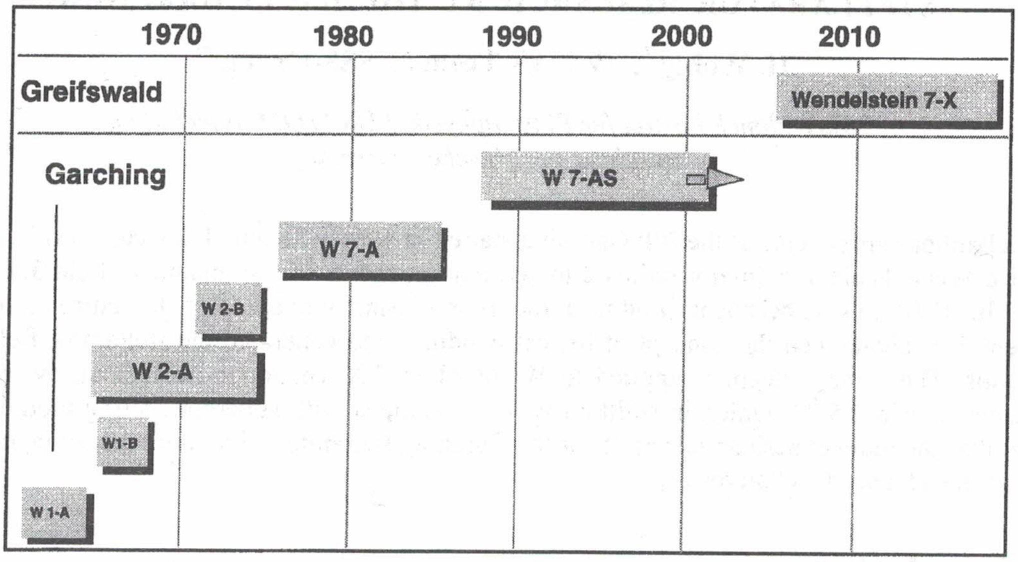


Fig. 1: Time scale of stellarator experiments at the IPP

2. Small stellarators

In Germany stellarator experiments began with a small device called Wendelstein I-A. This device was inspired by the stellarator concept developed in Princeton and it was constructed in the Max-Planck-Institut für Physik und Astrophysik in Munich. At the beginning of 1961 first plasma was created by Ohmic heating. This first device had rather small dimensions but incorporated nearly all features of the Princeton Model-C stellarator. One of the most pronounced results of the Model-C stellarator was the anomalous plasma loss or pump-out, which led to the concept of Bohm diffusion. For this reason, a major goal of the Wendelstein I stellarator was to investigate this phenomenon and to find means to improve the confinement.

Name	Type	R [m]	a [m]	B [T]	Iota
W I-A	Racetrack l=3	0.35	0.02	1	ι(a)=0.2 ι'>0
WI-B	Racetrack l=2	0.35	0.02	1	0 –0.2 ι'>0
WII-A	Circular l=2, m=5	0.5	0.05	0.6	ι(a)=0 – 0.6 shear =0
WII-B	Circular l=2, m=5	0.5	0.05	1.25	ι(a)=.05-0.6

Table 1: List of small stellarators at the IPP

Wendelstein I-A was a racetrack stellarator with l=3 helical windings and the shear of the l=3 magnetic field was considered as a necessary method to ensure MHD-stability. Very soon the Ohmic heating was abandoned and plasma in Wendelstein I-A was produced by contact ionisation of a cesium beam on a hot tantalum ball (4 mm diameter), which was heated to about 2300° K. The density was measured by Langmuir probes and was in the range of $6*10^8$ cm^{-3}. Density contours showed strong vertical elongation indicating strong pumpout losses [3]. Quantitavily the confinement was determined by measurring the particle input flux and comparing this with the total particle number. Since Wendelstein I-A was equipped with l=3 helical windings, the small value of the rotational transform ($\iota \sim r^2$) and the associated increase of Pfirsch-Schlüter current was considered as the reason of the deteriorated confinement.

In order to check this hypothesis the next device, Wendelstein I-B, an upgrade of Wendelstein I-A, was equipped with l=2 helical windings providing nearly constant rotational transform throughout the plasma radius. The tantalum ball (diameter 5 mm), which was suspended at a tungsten wire (diameter 25 µm), was heated by an electron beam. The beam, however, was switched off during the measurements.

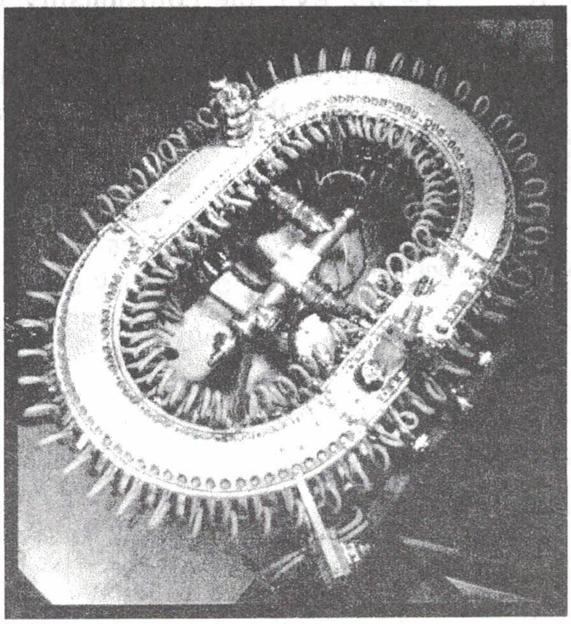


Fig. 2: Wendelstein I-A, racetrack stellarator with *l*=3 helical windings

In Wendelstein I-B classical diffusion was found to be the prevailing loss mechanism [4,5]. The largest plasma losses occurred on the probes, although they were made extremely thin. Alhough the confinement in Wendelstein I-B was considerably improved, a careful adjustment of the magnetic field was necessary to achieve optimum results indicating the vulnerability of the magnetic field arising from field perturbations. In particular, the iron transformer core introduced such a perturbation and only after removing this component, optimum confinement could be achieved. These findings led to the construction of Wendelstein II-A, which had a circular magnetic axis, 5 field periods and l=2 helical windings. The only symmetry-breaking field perturbations were the currents leads to the helical windings.

Wendelstein II-A was operated with a barium plasma produced by contact ionization on a small tantalum ball (3 mm diameter) and heated by CO_2 laser irradiation. Plasma temperature was low in the range of 0.2 eV thus allowing probes to be used as diagnostic tool. However, ion density could also be measured by optical methods using resonance fluorescence. Since the plasma was produced in steady state, the effect of magnetic field structure could be studied by varying the rotational transform during the discharge. Pronounced minima of plasma confinement were observed when the rotational transform was in the range of ι =1/3,1/4,...1/9, while on irrational magnetic surfaces the confinement was close to classical confinement taking the Pfirsch-Schlüter effect into account. Although a quantitative explanation of this effect does not exist it is suspected that magnetic field errors in combination with convective cells are the cause of deteriorated confinement on rational magnetic surfaces. This idea is supported by the fact the convective losses depend on the magnitude of mod B and the background argon pressure. The experimental results cannot be understood on the basis of magnetic islands alone.

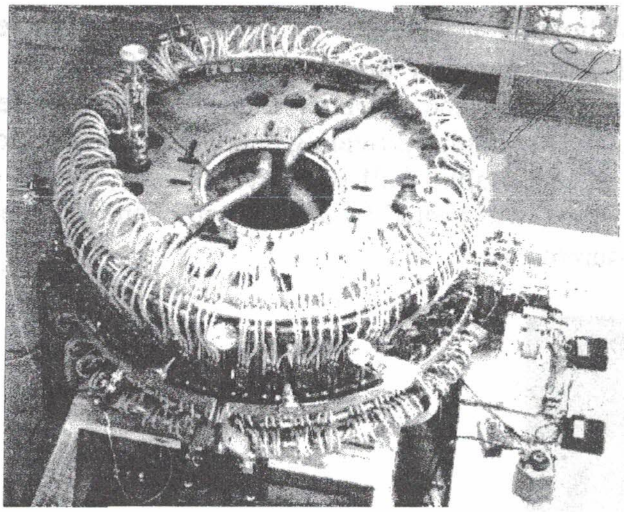


Fig. 3: Wendelstein II-A

Although density and temperature in these experiments were low (n = 5-10*10^{15} m^{-3}, T= 0.2 eV), the collisionality was high enough to bring the plasma into the Pfirsch-Schlüter regime; the mean free path was in the range λ = 0.1 – 1 m.

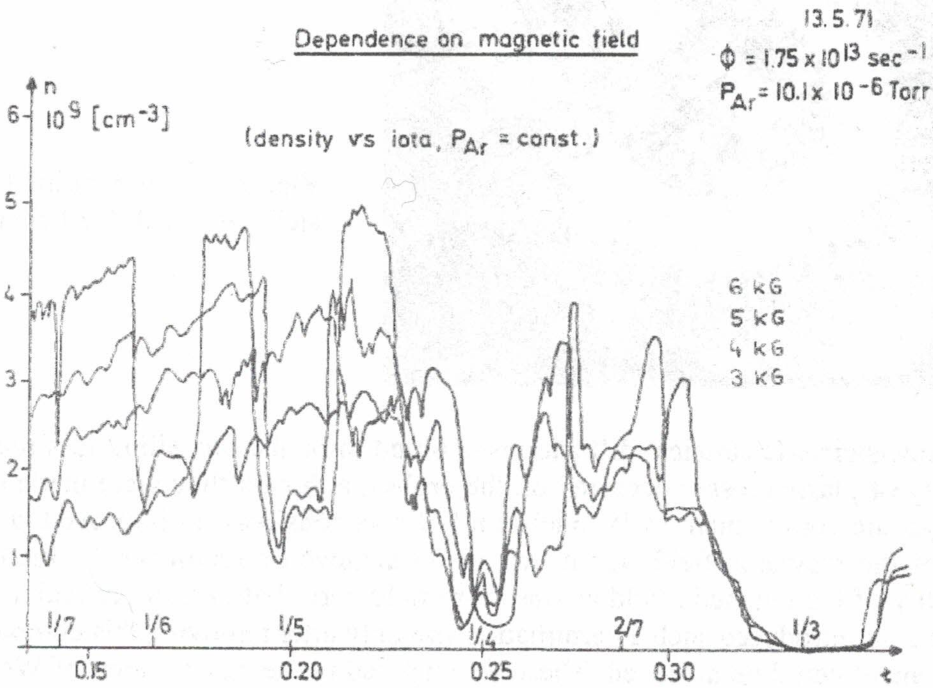
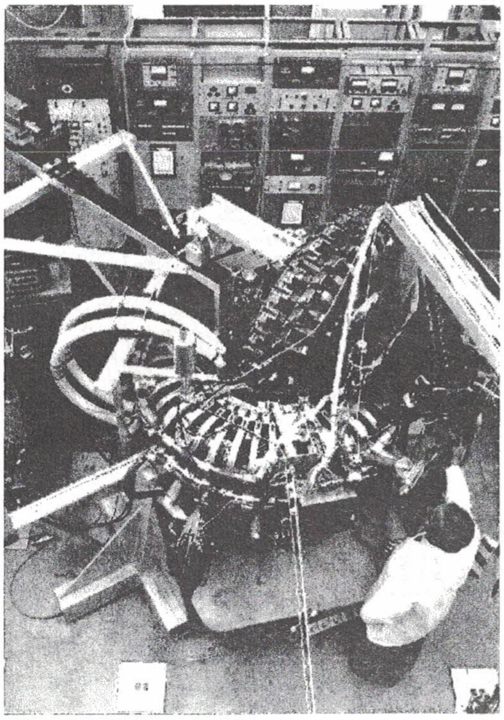


Fig. 4: Wendelstein II-A: Density vs rotational transform at constant particle input.

Although magnetic islands caused by field perturbations were believed to be the primary reason for the collapse of confinement at rational values of iota, various phenomena as the dependence of this collapse on the magnitude of the magnetic field and on the neutral argon background indicated, that plasma equilibrium suffers from bifurcation effects and possibly from convective branches with enhanced losses. In a modified version this effect was determined to occur in all Wendelstein stellarators when operated at low shear.

Wendelstein II-B had the same dimensions as Wendelstein II-A, but since it was equipped with a air core transformer a toroidal current could induced thus leading to an effective heating of the plasma. This combination of toroidal current and stellarator field allowed one to study the influence of stelllarator fields on current induced instabilities [6]. In Wendelstein II-B plasma temperatures up to 300 eV could be achieved by Ohmic heating (I <= 3kA) and it was shown that energy confinement is comparable to that in equivalent tokamaks [7]. The confinement times followed the so-called pseudoclassical scaling, which was also found in ohmically heated tokamaks at that time.



Furthermore, the benificial influence of the external rotational transform on the disruptive instability could be observed for the first time, the disruption did not occur when the external transform was larger than 0.14. However, the confinement deteriorated, when the total rotational transform reached the value of 0.5. Another result of Wendelstein II-B was found in RF-produced plasmas (P = 40 kW, f = 2.4 GHz), were RF-driven currents up to 1 kA could be observed [8].

Fig. 5: Wendelstein II-B, m=5,l=2 stellarator with Ohmic heating

3. Large stellarators

	Wendelstein 7-A	Wendelstein 7-AS	Wendelstein 7-X
Major radius [m]	2	2	5.5
Plasma radius [m]	0.1	0.18	0.55
Magnetic field [T]	≤ 3.4	2.5	3
Rot. transform	0.05 – 0.5	0.3 – 0.6	0.8 – 1.2
Coil type	TF+helical windings	Modular	Modular
Conductor	Normal	Normal	SC (NbTi)
Ohmic heating	≤ 45 kA	≤20 kA	
ECRH	≤200 kW, 70 GHz	≤ 1.2 MW, 140 GHz	10 MW, 140 GHz
NBI	≤ 1.2 MW/27 kV	3 MW/55 kV	20 MW

Table 2: List of large stellarators at the IPP

The first design of Wendelstein 7-A was to build a device capable of true steady state operation, which was only achievable with superconducting coils. Although the performance of a superconducting test coil was excellent, this plan was abandoned and normal conducting coils were designed. Because of the strong forces between helical windings and the main field system the vacuum tube, which also served as the support system for the helical windings, had to be reduced to 0.17 m minor radius, thus leading to a plasma aspect ratio of 20. These issues have led to the development of modular coils where TF coils and helical windings form an integrated system and the vacuum tube is decoupled from the coil system [9].

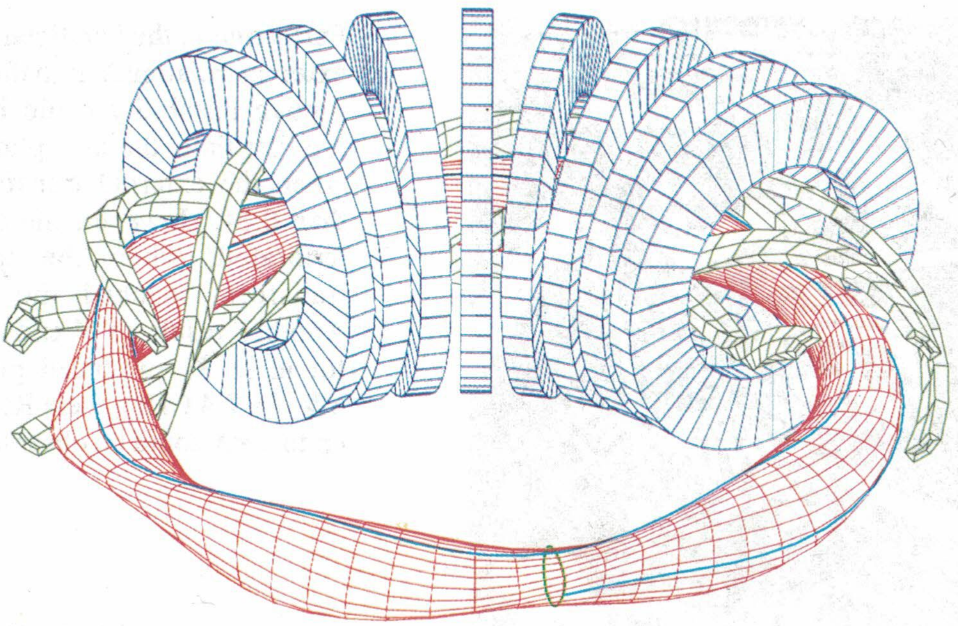


Fig. 6: Scheme of the Wendelstein 7-A stellarator.

The magnetic configuration of Wendelstein 7-A was an *l*=2, m=5 system, no innovative features as reduction of Pfirsch-Schlüter currents were incorporated. However, the next device, Wendelstein 7-AS, was fully based on theoretical results predicting low Shafranov shift and reduced classical and neoclassical transport, if the magnetic surfaces are shaped in such a manner as to reduce the Pfirsch-Schlüter currents. Together with the concept of modular coils the experiment was realized and went into operation in 1988. Since Wendelstein 7-AS has been built in the place of Wendelstein 7-A, many components of Wendelstein 7-A are used in Wendelstein 7-AS, in particular the Ohmic heating transformer allows one to run the experiment in hybrid mode combining tokamak and stellarator physics.

Wendelstein 7-A

In the 10 years from 1976 to 1986, the experiments in Wendelstein 7-A accumulated a large amount of new and interesting results, which renewed world-wide interest in the stellarator line towards fusion and which have led to the construction of new stellarator devices. Three heating methods were available in this experiment: Ohmic heating, electron cyclotron heating and neutral beam heating. In the first years only Ohmic heating was available as a heating method and in particular the effect of the stellarator field on tearing modes [10] and disruptive instabilities [11] could be investigated. A major result was the stabilisation of the disruptive instability by a sufficiently large stellarator field (external rotational transform $\iota >= 0.14$); if the external rotational transform was larger than this number a disruption did not occur [12]. The parameter range of the ohmically heated plasma was: $<n> = 5*10^{18} - 6*10^{19}$ m^{-3}, kT_e = 200 – 900 eV, kT_i = 100 –220 eV, plasma current <= 37 kA. The pulse length of the discharge (<= 200 ms) was determined by the volt seconds available in the Ohmic transformer. Avoiding the disruption resulted in a higher density than in discharges with disruptions, which is displayed in the following Hugill-diagram.

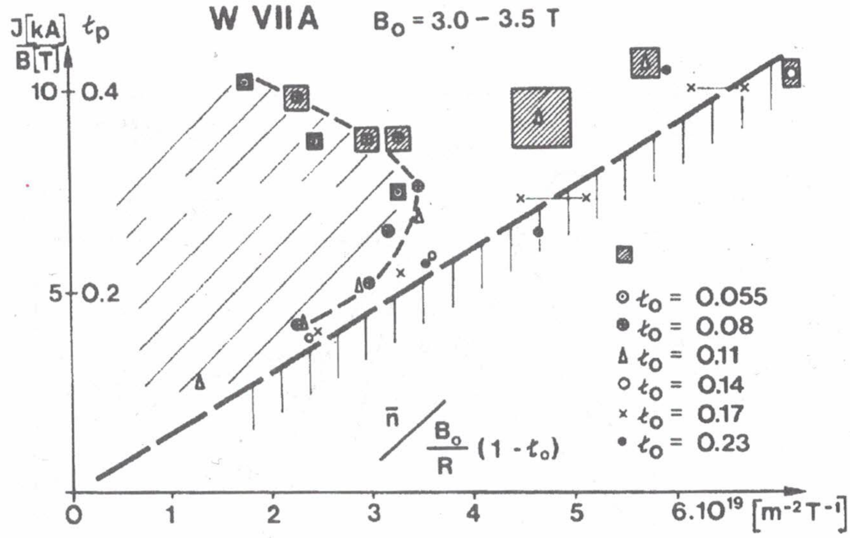


Fig. 7: Hugill – diagram of Ohmic discharges. The figure shows the increase of the density limit due to stabilization of the disruption.

The stabilization of the disruption can be understood as a stabilization of the resistive tearing mode by the external stellarator field. The current profile and the ι-profile are decoupled thus shifting the q=2-surface into a region with low current density gradients.

Due to the stabilization of the disruption Wendelstein 7-A was able to explore the density limit and the impact of impurity radiation on the energy balance [13]. Confinement deteriorated at high density without violent collapse. In helium discharge this behaviour was analysed by additional neon injection showing how the power balance and thus the maximum sustainable density is affected by the radiation. The external rotational transform of the stellarator field has a positive effect on the density limit: The maximum density at $\iota_0 = 0.23$ is two times larger than at $\iota_0 = 0.08$.

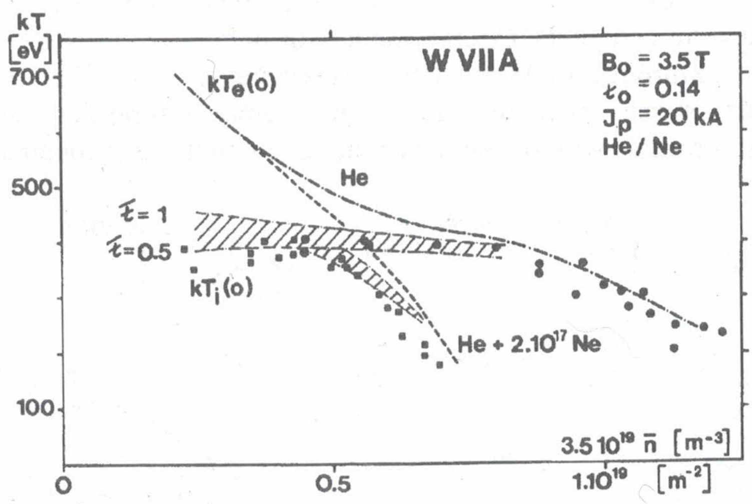


Fig. 8: Ohmically heated helium discharges with additional neon puffing. Enhanced radiation by neon reduces the maximum achievable density.

Energy confinement has been extensively studied in He-discharges, where recycling from the wall can be kept under control. As Fig. 8 shows confinement deteriorates at high density without disruption, which allows one to make a systematic study of the confinement properties. The following figure shows the energy confinement time for various plasma currents.

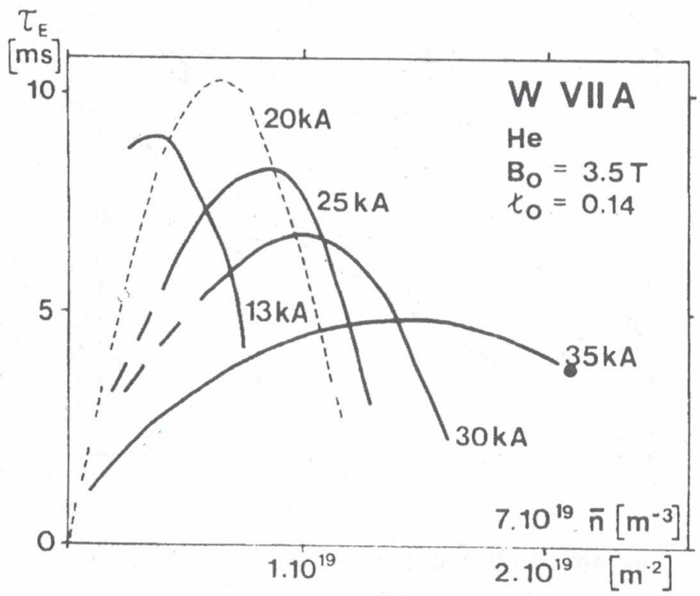


Fig. 9: Energy confinement time in He-discharges. B=3.5 T, ι_0=0.14.

Fig. 9 shows a decrease of confinement time with increasing toroidal current, at the highest current (35 kA, $q_I(a)$=3) the total rotational transform reaches 0.5 at the boundary and 1.0 in the plasma centre. In the high-density regime, confinement time increases with plasma current, which reminds one to tokamak scaling laws. Applying tokamak scaling laws to the 35 kA discharge yields an L-mode confinement time of 4 ms ($<n>=6*10^{19}$ m^{-3}, B=3.5 T, I=35 kA -> τ_{L89} =3.9 ms). According to the Elmy-H-mode scaling law IPB98(y.2) the confinement time is 4.3 ms, which is slightly below the experimental result shown in Fig. 9. At lower plasma current the difference, however, is significant. At 25 kA toroidal current the prediction by tokamak scaling laws are I=25 kA, $<n>=3.3*10^{19}$ m^{-3} -> τ_{L89} =2.8 ms, $\tau_{y.2}$ =2.5 ms, while the experimental result in W 7-A is 7 ms. This clearly demonstrates that in this regime confiment is determined by the external stellarator field.

A major breakthrough of Wendelstein experiments came when 1980 plasma operation without toroidal current could be achieved thus demonstrating that the external stellarator is able to confine a plasma with parameters comparable to those in tokamaks [14].

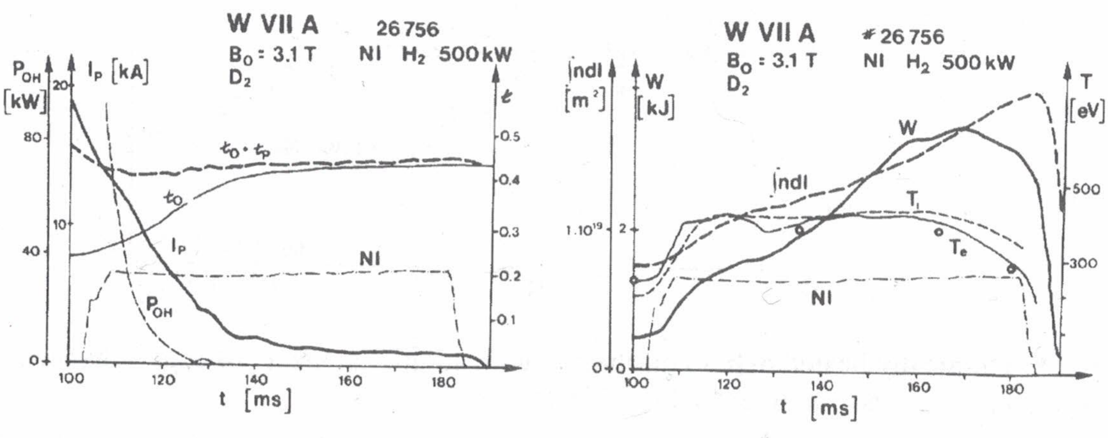


Fig. 10: Left: Transition to currentless operation during during neutral beam injection. By increase of the external transform the total transform is kept fixed. Right: Increase of plasma density and plasma energy during beam heating. Injected power 500 kW. Maximum density $n(0)= 1.5*10^{20}$ m^{-3}.

Starting with an Ohmically heated plasma, transition to a "currentless" state was reached by a careful control of the rotational transform and shear during the discharge. Basically the discharge had to be run with constant rotational transform, which could be maintained by a slow increase of the external transform during the decline phase of the Ohmic current. After ramp-down of the toroidal current the discharge could be maintained by neutral beam heating only. This procedure resulted in spectacular plasma parameters with an ion temperature exceeding 1 keV at line averaged densities of $n=10^{20}\ m^{-3}$. Power balance of the neutral beam heated plasma, however, happened to become a puzzle, since perpendicular injection deposited an appreciable number of particles in lost orbits and the shine-through was also not negligible. Thus the surprisingly high plasma parameters could not be understood on the basis of standard neoclassical theory and the given absorbed beam power. Finally, the build-up of radial electric fields by lost orbits and the associated poloidal rotation, which has led to a significant reduction of ion heat conduction and the improvement of heating efficiency due to an improved confinement of injected particles, was recognised as the solution of this problem. In discharges without net toroidal currents the disruptive instability and tearing mode instability were completely absent.

A main feature of the Wendelstein 7-A stellarator was how plasma confinement depended on the helicity of the magnetic field. As in Wendelstein II-A plasma confinement deteriorated when the rotational transform passed through a low order rational value. In particular, at $\iota=1/3$ and $\iota=1/2$ the confinement was strongly reduced. In contrast to results of W II-A, the ι-regime in W 7-A, however, has been extended to higher values above 0.5. Numerical calculations revealed that at low order rational surfaces magnetic islands exist, which are caused by the current feeders. These islands together with deterioration of plasma equilibrium are considered as the reason for reduced confinement at ι = 1/3,2/5,1/2 and 2/3.

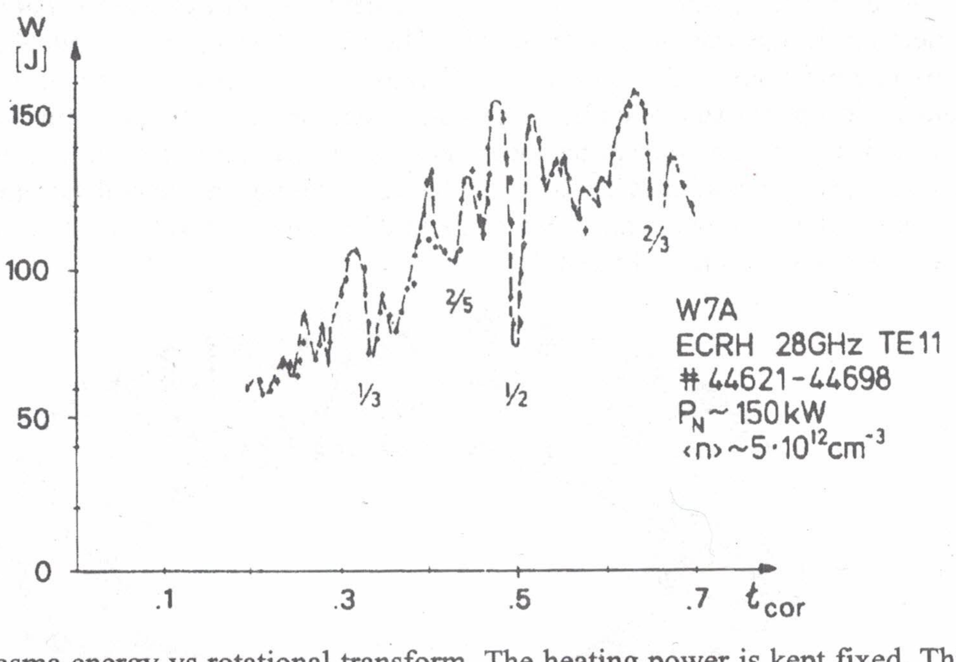


Fig. 11: Plasma energy vs rotational transform. The heating power is kept fixed. This figure represents low-density ECRH-discharges, however, the same phenomenon occurred in NBI-heated discharges.

Good confinement in the very vicinity of the low-order rational surfcaces is one of the most remarkable features of the W 7-A stellarator. A complete explanation is still missing, however this result is believed to be associated with the destruction of magnetic surfaces by error fields. Although the spectrum of magnetic field perturbations is unknown a general feature of magnetic surfaces is, that the very neighbourhood of ι = 1/2, 2/3 etc. is less vulnerable to field errors than other regions. Since in this neighbourhood only high order rational surfaces exist, only small islands can be created [15].

ECRH-experiments in Wendelstein 7-A did not need an Ohmically heated target plasma as required for NBI-heated plasmas. These experiments started 1983 with a 28 GHz Gyrotron (200 kW, 40 ms pulse length, B=1 T) and 19844 a 70 GHz gyrotron (200 kW, 0,1 s pulse length) came into operation [16]. The density in these discharges was limited by the cut-off density and did not exceed $n(0)=6*10^{19}$ m^{-3}. The highest electron ten temperature was T(0) = 2.5 keV, while the ion temperature was below 200 eV. Although the toroidal current was zero in these experiments, confinement turned out to be dominated by anomalous effects. In the plasma centre, however, electron thermal conductivity could by described by neoclassical theory, while in the boundary region the thermal conductivity was more than 2 orders of magnitude higher than neoclassical predicted. This anomalous transport in currentless operation turned out to persist also in the following experiment Wendelstein 7-AS. Electron temperature in these ECR-heated discharges grew with the 2/5 power of the heating power, which is consistent with plateau-scaling or Lackner-Gottardi scaling of the energy confinement time. Toroidal currents up to kA were observed in these ECRH-disccharges, experimental limitations, however, did not allow to distinguish between bootstrap currents and ECR-driven currents. This issue was studied in more detail after Wendelstein 7-AS has come into operation.

Wendelstein 7-AS

Theoretical studies of optimized stellarator configurations already began 1978, a summary of these activities together with a concept of the Wendelstein 7-AS device was presented at the IAEA-conference in Baltimore 1982 [17]. Furthermore, an extended version of physics and engineering design was published in [18]. The idea in designing Wendelstein 7-AS was to incorporate elements of the optimized stellarator as much as possible and to make use of the modular concept of external coils. During the design phase of Wendelstein 7-A the limitations of the helical winding concept has been recognized leading to the discovery of the modular coil system, which combines TF-coils and helical windings in one coil system. Since in such a coil system the rotational transform is fixed additional TF-coils must be superimposed to allow for some experimental flexibility.

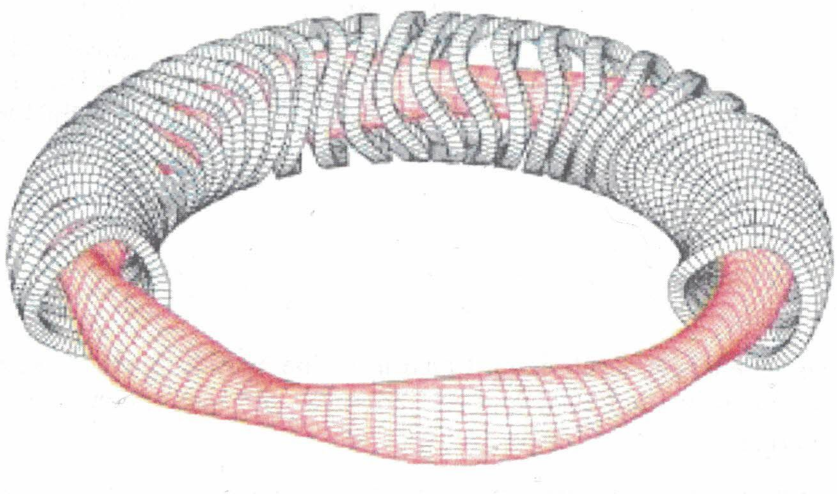


Fig. 12: Modular coil system of a standard l=2, m=5 stellarator

The Wendelstein 7-AS- experiment started in 1988 and is still in operation. A basic feature of this configuration is the reduction of the plasma currents parallel to the magnetic field lines. These so-called Pfirsch-Schlüter currents [19] are the origin of the radial plasma shift with rising plasma pressure, which may become a limiting effect under reactor conditions. In shaping the magnetic surfaces by an appropriate arrangement of the modular coils a special form of the plasma column could be achieved. Later on in the experiment the efficiency of this concept of optimisation has been shown: the radial shift – the Shafranov shift – was found to be a factor 2 smaller than in the Wendelstein 7-A device. Since there is a close relationship between parallel plasma currents and particle orbits – both are strongly affected by the B-variation in magnetic surfaces – a reduction of the Pfirsch-Schlüter currents also helps to reduce the neoclassical diffusion losses. Since due to this procedure magnetic surfaces and drift surfaes of circulating particles tend to coincide more closely the principle is also called drift optimisation. In standard l=2 stellarators the parallel current density is by a factor 2/ι cos θ larger than the diamagnetic current density (θ is the poloidal angle). The reduction achieved in Wendelstein 7-AS is illustrated in the next figure

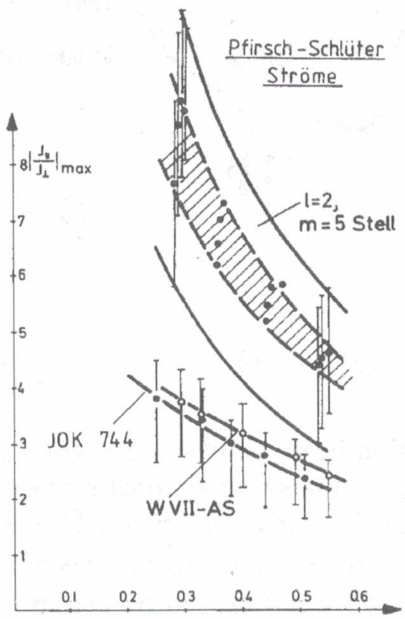


Fig. 13: Ratio of parallel current density to perpendicular current density. The vertical bars indicate the scatter within a field period, dots indicate data on 4 different surfaces.

The magnet system of Wendelstein 7-AS consists of 45 modular coils and 10 planar coils, which allow one to vary the rotational transform between 0.25 and 0.6. Technical details of the magnet system are described in ref. [20]. In October 1988 the experiment started and from the very beginning currentless operation and plasma heating with ECRH at 70 GHz was envisaged.

Operating with 2 gyratrons (power ≤ 400 kW) the following parameters regime could be explored: $n \leq 4*10^{19}$ m^{-3}, $T_e \leq$ 2keV, $T_i \leq$ 0.4 keV. The first results of the experiment were reported at the EPS-conference 1989 in Venezia [21].

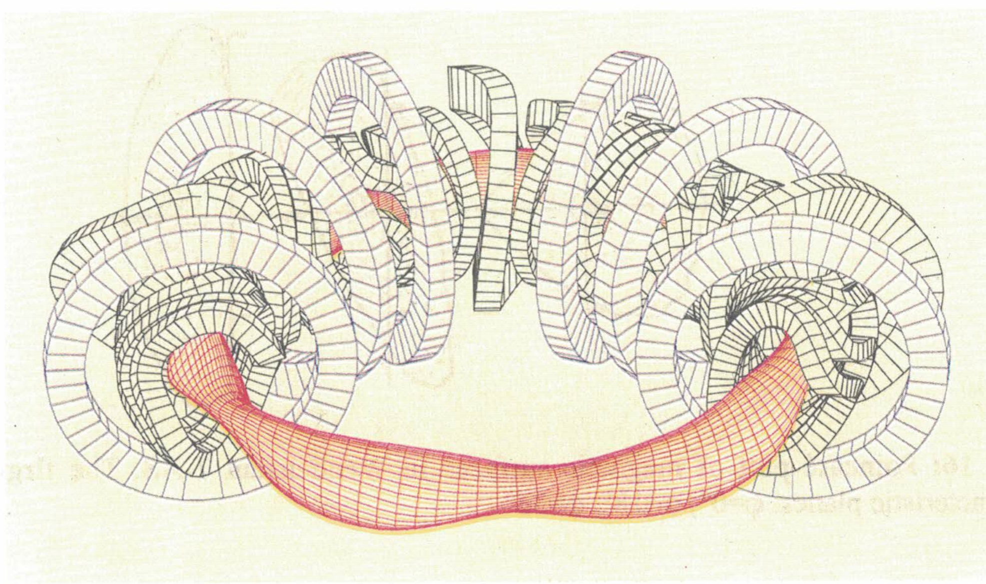


Fig. 14: Coil system and magnetic surface of Wendelstein 7-AS.

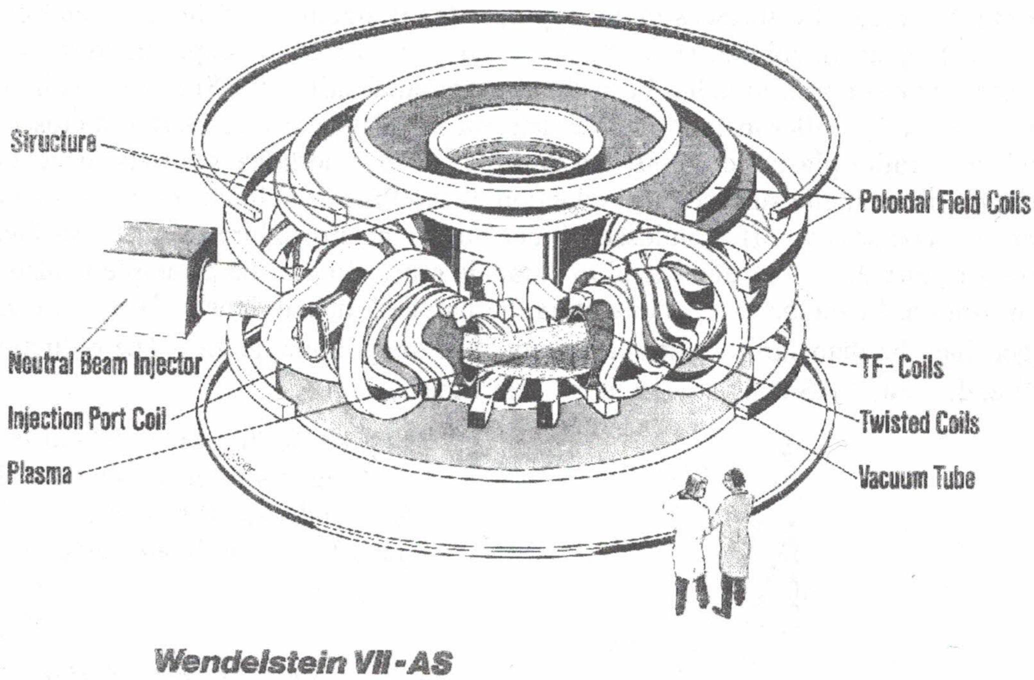


Fig. 15: Modular stellarator Wendelstein 7-AS (an artist's view)

Magnetic surface measurements using an electron beam showed very good coincidence between measurements and computational results. On low-order rational surfaces, however, on the surfaces with ι=1/3, 2/5 and 1/2 magnetic islands were discovered [22]. The islands are created by symmetry-breaking perturbations. Also on the so-called natural resoncances ι=5/9, 5/11, 5/12 these islands exist. These natural islands are not caused by symmetry-breaking error fields, they are an inherent property of the non-axisymmetric configuration. For this reason it was no surprise when the same effects as in Wendelstein 7-A were found: a strong dependence of the confinement on rotational transform, reduced confinement at low-order rational values of ι(a) and good confinement in the close neighbourhood.

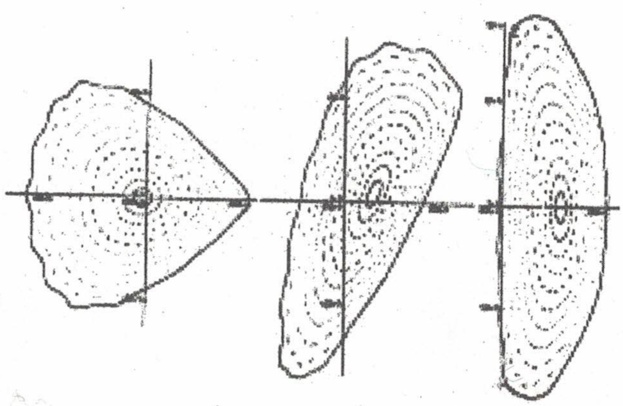


Fig. 16: Poincaré plot of magnetic surfaces in Wendelstein 7-AS. The firgure shows 3 characteristic planes: φ=0°, φ=18°, φ=36°

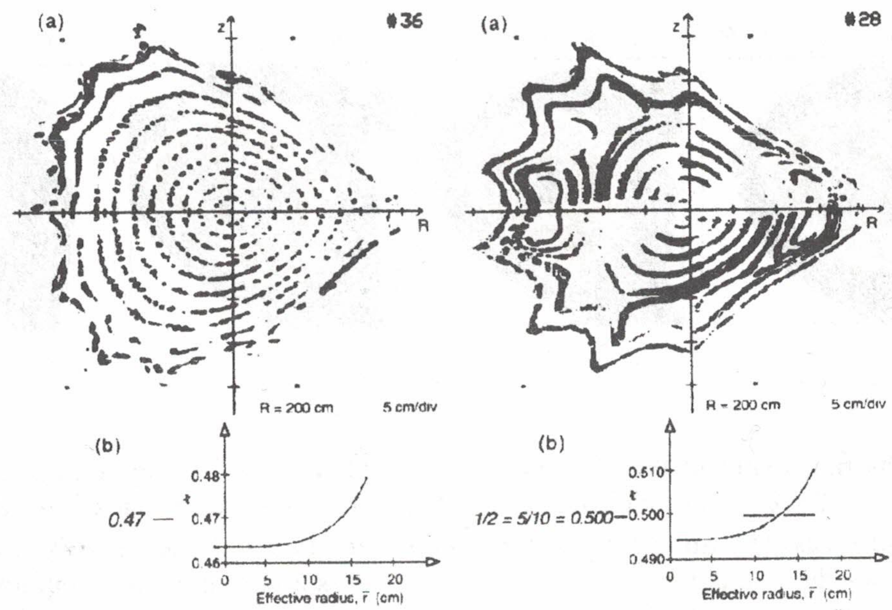


FIG. 17: Left: Magnetic surface in W7-AS, measured by electron beam technique. Right: Perturbed magnetic surface at ι=1/2, superposition of a 5/10- and a 1/2-Fourier harmonic in the error field. The lower part of the figure displays the rotational transform vs radius.

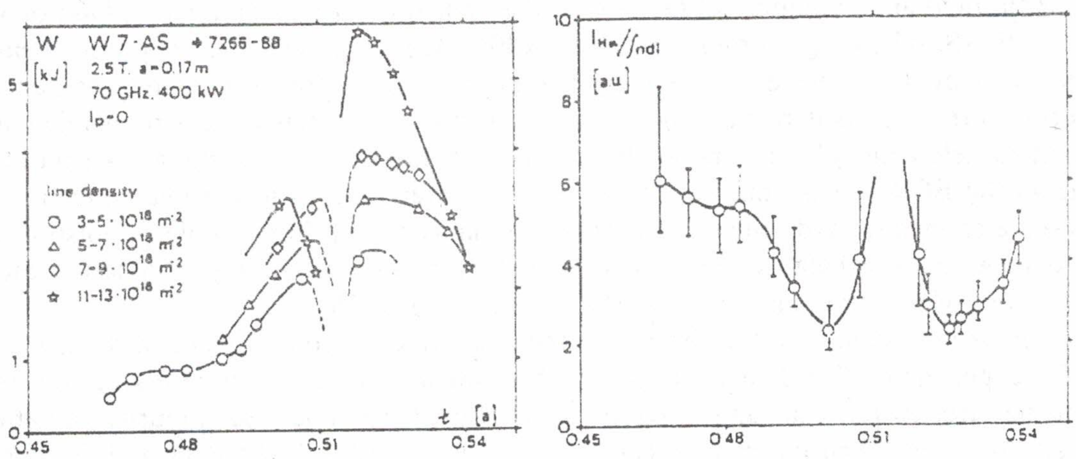


Fig. 18: Left: Plasma energy vs rotational transform. Right: Hα-emission vs transform

Fig 18 exhibits a short section of the ι-scale showing that the confinement is very good in the vicinity of ι=1/2 (there is an offset in the ι-scale), however, when the rational case ι=1/2 is verified the confinement drops significantly. In view of the islands shown in the previous figure, this is to be expected. In regions of good confinement also the H_α-signal decreases indicating that there may be a relation to L-H-mode physics. As will be described lateron, this is the region, where L-H-transitions have been found [23]. This region close to ι=1/2 is also the region of small neoclassical viscosity [24], which in the context of H-mode transition facilitates the generation of poloidal shear flow.

Since the magnetic configuration of Wendelstein 7-AS was designed to reduce Pfirsch-Schlüter currents and Shafranov shift the test of this feature was one of the main goals of the experiment. Using soft-X-ray tomography this task could be successfully managed showing that the Shafranov shift coincides with the theoretical expectations [25]. Compared with a conventional *l*=2 stellarator the Shafranov shift has been reduced by a factor of 2.

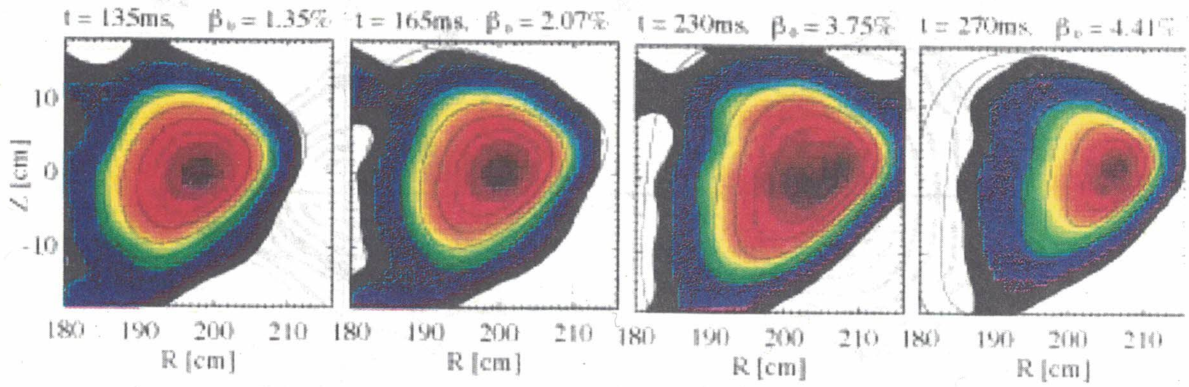


Fig. 19: Shafranov shift in Wendelstein 7-AS measured by soft-X-ray tomography. Left. Low beta ($\beta(0) = 1.35\%$), beta increases from left to right. The solid black lines display the the magnetic surfaces. The finite beta equilibrium is computed with the NEMEC-code. The figure clearly shows the coincidence between measurements and numerical computations (W7-AS #41618, Courtesy of Dr. A. Weller).

In discharges without applied loop voltage any toroidal current – either bootstrap current or ERC-driven current – can be detected. The current found in the early experiments was not larger than 1 kA, it scaled proportional to the plasma energy, it alsso changed sign with the magnetic field and exhibited all features of the bootstrap current. In a later phase of Wendelstein VII-AS, when 4 gyrotrons (70 GHz, 4x400 kW) were available [26], this phenomenon was investgated in more detail showing that neoclassical theory successfuly can explain the toroidal current. This is remarkable since in contrast to this plasma loss perpendicular to the magnetic field cannot be understood by neoclassical theory alone. Using a system of movable mirrors the ECR-waves could be launched at different angles to the magnetic field, which offered a chance to study the current drive mechanism [27]. In particular, bootstrap currents up to 4 kA could be balanced by ECR-driven currents, thus providing a tool to test theoretical predictions of bootstrap currents and ECCD-mechanisms [28].

As in Wendelstein 7-A, the absence of the disruptive instability is one of the main features of the experiment. The density limit, which in tokamaks also leads to disruption, is higher than the Greenwald limit and it seems to be caused by enhanced impurity radiation. The density limit has been the goal of careful investigation [29]. In ECR-heated discharges, the density is constant over the pulse length while in NBI-heated discharges density often increases until enhanced radiation by impurity ions terminates the discharge. The maximum achievable density is determined by radial tranport losses and impurity radiation. The empirical scaling of maximum density is given below.

$$n_c = 1.46\left(\frac{P}{V}\right)^{0.48} B^{0.54}\left[10^{20}\,\mathrm{m}^{-3}\right]\ (\mathrm{m}^3,\mathrm{MW},\mathrm{T}) \qquad \text{Eq. 1}$$

In 1993 H-mode like effects were found also in Wendelstein 7-AS and in this context a strong dependence on the topology of field lines and on the rotational transform has been observed [30]. These H-mode like transitions exist only in 3 narrow gaps on the ι-scale in the neighbourhood of $\iota=1/2$ and close to $\iota=5/9$. They exhibit all signatures of H-modes transitions, which are wellknown from tokamaks: reduction of H_α-emission, improvement of confinement (although this is a 30%-effect only), onset of poloidal rotation and transition to a quiescent phase without ELMS [31]. Profile measurements revealed the existence of a transport barrier in a 4-5 cm wide layer inside the separatrix [32].

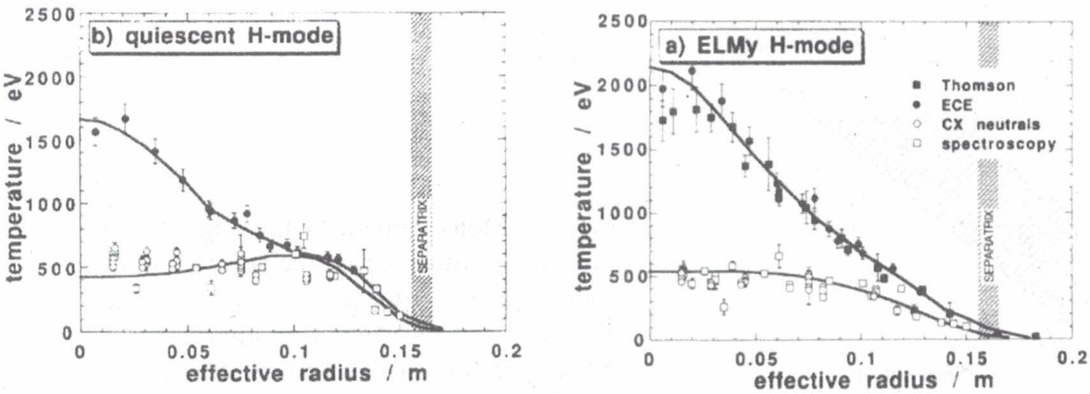


Fig. 20: Temperature profile of electrons and ions in the quiescent H-Mode (left). Right: Before the transition to quiescent H-mode (ref[32]).

A satisfying explanation of the narrow H-mode windows on the ι-scale is still missing, however, there are theoretical arguments that neoclassical plateau viscosity, which at low radial electric field exhibits a strong dependence on the rotational transform may be the key element in this context. Neoclassical viscosity is strong on low-order rational magnetic surfaces thus inhibiting the build-up of a radial electric field and the associated shear flow on low order rational surfaces. However, a model of poloidal shear flow also needs a driving mechanism, viscous damping is only one part of the story. Magnetic islands also play a role in creating the H-mode, since H-mode transitions do not occur if magnetic islands exist in the boundary regions. These islands certainly inhibit the generation of poloidal rotation and shear flow.

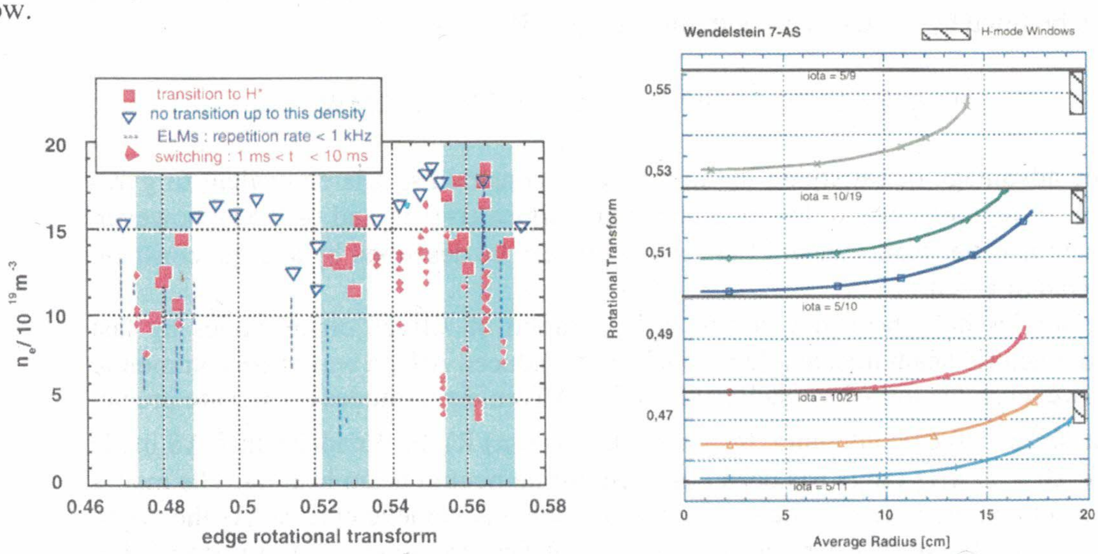


Fig. 21: Left: Operational diagram for H-mode plasmas. The squares indicate the density threshold, where the transition to the quiescent H-mode occurs. Right: profiles rotational transform. The experimentally observed H-modes coincide with those region on the ι-scale where neither in the bulk plasma nor at the boundary low order rational surfaces with islands exist.

Another puzzle is the threshold in density: opposite to tokamak experiments transition to the quiescent H-mode occurs above a density threshold. During the discharge heated by NBI the density slowly increases. After a phase dominated by ELMS, the plasma makes a transition into a quiescent H-mode (ref. [31]).

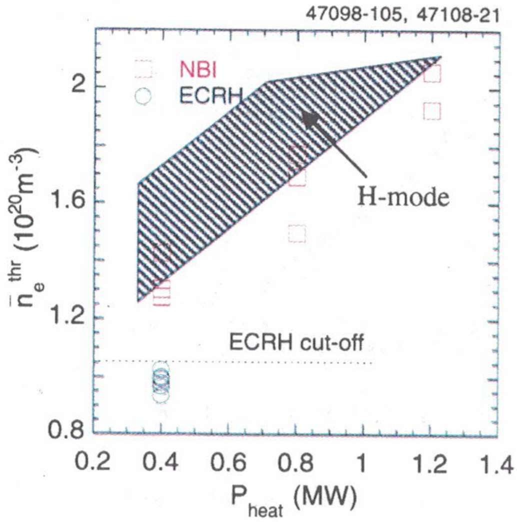


Fig. 22: Measurement of the edge density vs heating power across the separatrix. The transition to a quiescent H-mode occurs above a critical density (squares). The critical density grows with heating power. The hatched region denotes the region of quiescent H-mode.

Plasma transport in Wendelstein 7-AS is dominated by anomalous processes in the boundary region; in the central region of W7-AS neoclassical confinement can be reached [33]. A typical value of the electron thermal conductivity is 1-2 [m^2/s]. Scaling laws of global energy confinement have been investigated by U. Stroth et al. [34]. There it was found that the confinement time is larger than predicted by the so-called ISS scaling. A separate scaling based on W7-AS data only has been derived, the dependence on major radius, however, cannot be deduced from W 7-AS data alone. The global energy confinement in Wendelstein 7-AS also can be fitted by the Lackner-Gottardi scaling [35]

$$\tau_E = 0.175\, Ra^2 B^{0.8} \langle n \rangle^{0.6} P^{-0.6}\, \iota^{0.4}\ [s];\ (m, T, 10^{20}\ m^{-3}, MW)$$

which has the advantage of satisfying the dimensional constraints, it is equivalent to gyro-Bohm scaling. In regions close to low order rational surface (ι=0.34 and ι= 0.52), however, the confinement is better than standard LG-scaling and can be described by a larger constant, C = 0.21, instead of C = 0.175.

Extensive studies have been devoted to the excitation of Alfvén eigen-modes by fast particles during neutral beam injection [36]. Toroidicity induced Alfvén waves are common in tokamaks, however in the low-shear stellarator global Alfvén eigen-modes (GAE) are predicted below the shear Alfvén continuum ($\omega \le k_{||} v_A$, $k_{||} = (m\iota - n)/R$). In Wendelstein 7-AS mode activity in the 20 – 35 kHz range has been observed during neutral beam heating. The modes are very coherent and propagate in the direction of the ion diamagnetic current. As the origin of these modes circulating fast particles could be identified; the modes activity stops after switching off NBI heating. Another type of MHD-activity has been observed in conjunction with high-beta discharges [37]. Maximum beta ($\langle\beta\rangle \le 2\%$) could be achieved in high density discharges at low magnetic field (1.2 T). This number is determined by the lack of further heating power rather than by MHD-instabilities. From soft-X-ray diagnostics low frequency modes in the range of 4-5 kHz were observed, these modes were also accompanied by a small deterioration of the confinement. Global MHD-instabilities were not found in the CAS3D code and is believed that resistive ballooning modes may play a role below the ideal MHD-limit.

The effect of external stellarator fields on current driven instabilities was also studied in Wendelstein 7-AS. However, unlike the favourable results of Wendelstein 7-A no threshold in the rotational transform for stabilising the disruption was found. On the other hand, the disruption is significantly mitigated by the external field since the external stellarator field inhibits the strong displacement of the plasma after a current quench. The difference to the former Wendelstein 7-A results is explained by the role of stronger bootstrap currents, which lead to steeper current density gradients in the boundary region.

Wendelstein 7-AS has demonstrated the viability of the modular coil concept; the experience accumulated with the fabrication and operation of this novel magnet system has prepared the ground for larger stellarator experiments and has increased confidence that even stellarator reactors can utilise this concept. Wendelstein 7-AS is still in operation, the schedule is to focus mainly on divertor studies for better understanding of the plasma physics at the edge.

The principles of stellarator optimisation

The effort to extrapolate the stellarator to a viable reactor has led to the Helias concept [38] (Helias = Helical advanced stellarator). The expected beta-limit in the Wendelstein 7-AS stellarator is around 2%. In a fusion reactor, however, this value is too low for economic reasons and it is therefore necessary to proceed further in optimising stellarator configurations. These efforts finally resulted in the Wendelstein 7-X concept.

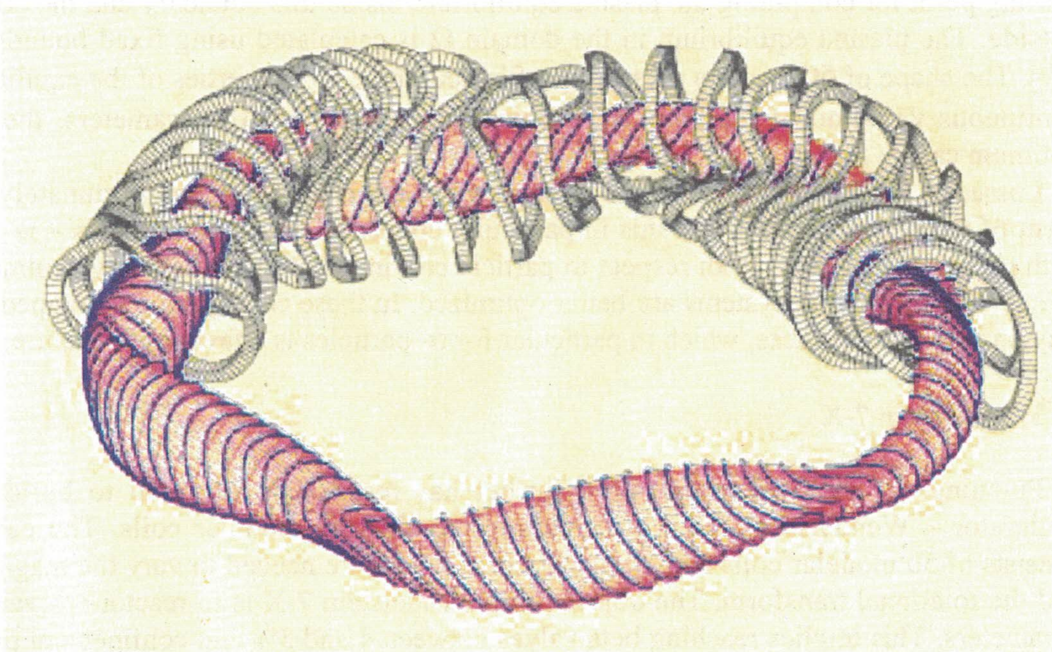


Fig. 23: Magnetic surface and modular coil system of Wendelstein 7-X. Solid lines are the current lines on the magnetic surface. In some regions the current lines are nearly perpendicular to the field lines.

By proper choice of the magnetic field configuration the currents flowing in the plasma can be reduced to a low level where the Pfirsch-Schlüter currents are smaller than the diamagnetic currents (see Fig. 23). As a consequence the radial shift of the plasma column with rising plasma pressure — the Shafranov shift — is strongly reduced and the MHD-stability limit is raised to values around $<\beta> \sim 5\%$. In essence the conditions for an optimized reactor configuration are

- Good magnetic surfaces of the vacuum field without large islands and stochastic regions in the bulk plasma. Islands or stochasticity in the boundary region may be utilized for divertor action.

- Low Shafranov shift and a stiff equilibrium configuration up to $<\beta> = 5\%$. The rotational transform should depend only weakly on the plasma pressure.
- MHD-stability up to $<\beta> \sim 5\%$.
- Sufficiently small neoclassical plasma losses so that the ignition condition is satisfied.
- Sufficiently small bootstrap currents so that the magnetic field is not modified by this effect.
- Good confinement of α-particles.
- Good technical feasibility of the coil system and sufficiently large space between coils and plasma for blanket and shield.

To fulfill one or two of these requirements is not difficult, the important result, however, is that all conditions can be met simultaneously in one configuration. The geometrical form of the Helias configuration, the number of periods, rotational transform etc. are consequences of these optimization criteria. The method used to find an optimized Helias configuration differs essentially from the standard method, which starts from a given coil system and calculates the plasma behaviour afterwards. In the Helias approach a fixed plasma boundary $\delta\Omega$ is the starting point for computing the plasma equilibrium inside this boundary and the coil system outside. The plasma equilibrium in the domain Ω is calculated using fixed boundary codes [39]. The shape of $\delta\Omega$ and the pressure profile determine all properties of the equilibrium; by continuous variation of the boundary, which is described by 10 parameters, the required optimum can be found.

Losses of localized particles are a weak point in the Helias concept. Fortunately confinement of trapped particles – and this in particular concerns fast alpha-particles – is improved with rising plasma beta. With respect to particle confinement quasi-helically symmetric [40] or quasi-axisymmetric systems are better optimized. In these configurations trapped particles stay on magnetic surfaces, which in particular for α–particles is a favourable feature.

Wendelstein 7-X

Pursuing the path of optimisation further has resulted in the plan to build a larger stellarator – Wendelstein 7-X - utilising superconducting modular coils. The coil system consists of 50 modular coils and 20 planar coils, which are needed to vary the magnetic field and the rotational transform. The objective of Wendelstein 7-X is to reactor-relevant plasma parameters. This implies reaching beta values between 4 and 5% and confinement properties, which allow one to make reliable extrapolations towards the reactor regime. The conceptual design of the new experiments began 1981, final approval to the project was given in 1996. This Wendelstein 7-X device is presently under construction in the city of Greifswald located in the north-east of Germany and it is scheduled to begin operation in 2006. Steady-state operation for more than 30 s will demonstrate the reactor potential of this stellarator line and the envisaged heating power of 10 MW ECRH and 20 MW neutral beam injection will ensure that plasma temperatures up to 10 keV can be reached. Since plasma wall interaction will become an important issue in fusion reactors, this topic will be intensively studied in the new experiment. Specially designed divertor target plates will be located at the plasma periphery and will make use of the island geometry in this region.

A large R&D program has been initiated to prepare the technical basis of the device. This implies the development of a NbTi superconducting cable and the construction of a superconducting test coil, which has been tested successfully at the Forschungszentrum Karlsruhe. Prototype components of the divertor, in particular the target elements designed for a power load of 12 MW/m^2 have already been fabricated and have been successfully tested. The envisaged electron cyclotron heating with 10 MW has initiated the development of 140 GHz gyratrons. Using these heating methods plasma temperatures up to 10 keV can be expected in this experiment.

It is scheduled to start the experiment in 2006 and the main aim is to demonstrate the reactor potential of this advanced stellarator line. This implies to demonstrate favourable confinement properties which provide a reliable extrapolation towards the reactor reactor regime and to reach a beta value between 4 and 5%, which is needed to make the reactor economically attractive. According to present knowledge about confinement properties in stellarators, this goal can achieved with 20 MW heating power and a low magnetic field of 1.2 –1.4 T.

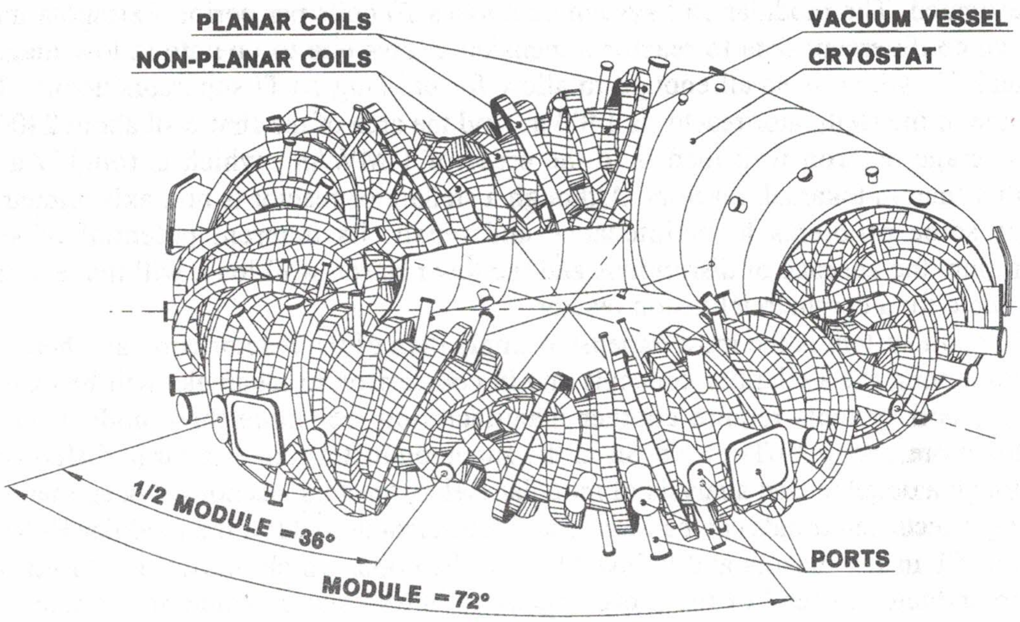


Fig. 24: Wendelstein 7-X: Coil system, portholes and part of the cryostat.

Major radius	5.5 m
Average plasma radius	0.53 m
Magnetic field on axis	3.0 T
Magnetic field on coils	5.8 T
Number of field periods	5
Magnetic energy	0.6 GJ
Current density in coil	48 MA/m^2
Superconductor	NbTi
Rotational transform on axis	0.84
Rotational transform on boundary	0.99
Variation of iota	±0.2
Variation of shear	±0.1
Pfirsch-Schlüter currents $\langle j_{II}^2/j_{dia}^2 \rangle$	0.5
Magnetic well depth	0.01
MHD-stability limit $\langle \beta \rangle_{st}$	0.043
Ratio of bootstrap currents I_{st}/I_{tok}	≤ 0.1

The stellarator reactor

Intensive reactor studies have analysed the basic properties of a stellarator reactor based on the Wendelstein 7-X or Helias concept. The size of such a reactor is determined by the need to accommodate a breeding blanket and a shield, by the need to ensure ignition and by the envisaged fusion power of 3000 MW. As a guideline blanket calculations made for tokamaks were taken as the basis. Confinement times were computed according to present scaling laws, mainly Lackner-Gottardi scaling. The main data of this reactor are: major radius 22 m, and average plasma radius 1.8 m. Smaller versions with major radius of 18 m have also been investigated. The modular coil system comprises 10 coils per period Extrapolating presently known confinement data to reactor dimension allows one to operate at low magnetic fields around 5T, which is small enough to allow for utilising NbTi superconductors. The plasma volume of the stellarator reactor is 1400 m^3 and the area of the first wall about 2400 m^2, hence the average neutron wall load is in the order of 1 MW/m^2, which is roughly a factor two smaller than in tokamak reactors. Although a stellarator reactor is non-axisymmetric and thus poses some problems to maintenance and repair, its inherent potential of steady state operation, the absence of disruptions and the low neutron wall load, will make it an attractive candidate for a commercial fusion reactor.

The coil system is the most expensive single item of the reactor core, and here some differences among the stellarator concepts and in comparison to tokamaks will be expected. Continuous coil systems require another manufacturing technique than modular coil systems. Furthermore, using NbTi or Nb_3Sn in the superconductor makes a large difference in costs. Although a detailed cost analysis of modular Helias reactors has not yet been made, some cost saving effects and trends can be identified. The magnetic field of the modular Helias reactor is kept at 5T in the plasma and below 11 T on the coils, which allows one to utilize a NbTi-superconductor instead of the more expensive Nb_3Sn superconductor. Another cost saving factor is to reduce the major radius of the reactor while keeping the plasma volume constant and the magnetic field at 5T. The result of these efforts is a 4-period Helias reactor with 18 m major radius, HSR4/18 [41]. This implies that the capital cost will be reduced by about 20% in comparison to the reference reactor HSR5/22. On the other hand in a more compact device neutron wall loading will be slightly larger and the lifetime of plasma facing components will be reduced. The neutron wall loading depends on the fusion power and the geometry of the first wall. In a Helias reactor with 3000 MW fusion power the specific neutron wall load is not more than 2 MWm^{-2}, which, at a maximum permissible neutron fluence of 15 MWy/m^2, yields a lifetime of 7.5 years of full power.

TABLE I: Main parameters of HSR4/18 and HSR5/22

	HSR4/18	HSR5/22
Major radius [m]	18	22
Av. minor radius [m]	2.1	1.8
Plasma volume [m^3]	1567	1407
Iota(0)	0.83	0.84
Iota(a)	0.96	1.00
Av. magnetic field on axis [T]	5.0	5.0
Max. magnetic field on coils [T]	10.3	10.5
Number of coils	40	50
Magnetic energy [GJ]	98	100

As in any toroidal fusion device the purpose of the blanket is to provide sufficient breeding of tritium and to shield the superconducting coils against neutrons. Since atomic processes determine the size of the blanket, its radial width is an absolute figure and any fusion device has to provide enough space to accomodate a blanket with about 1.3 m radial build. In contrast to tokamaks the stellarator, however, requires a 3-dimensional design of the blanket, which must conform to the 3-dimensional shape of the plasma. Blanket segments must be small enough to be replacable through the portholes. For this reason a stellarator needs a large variety of different modules, which in case of the Helias reactor HSR5/22 is 250 comprising 25 different shapes. The various blanket concepts, which have been studied for tokamak reactors [42], also fit into stellarators.

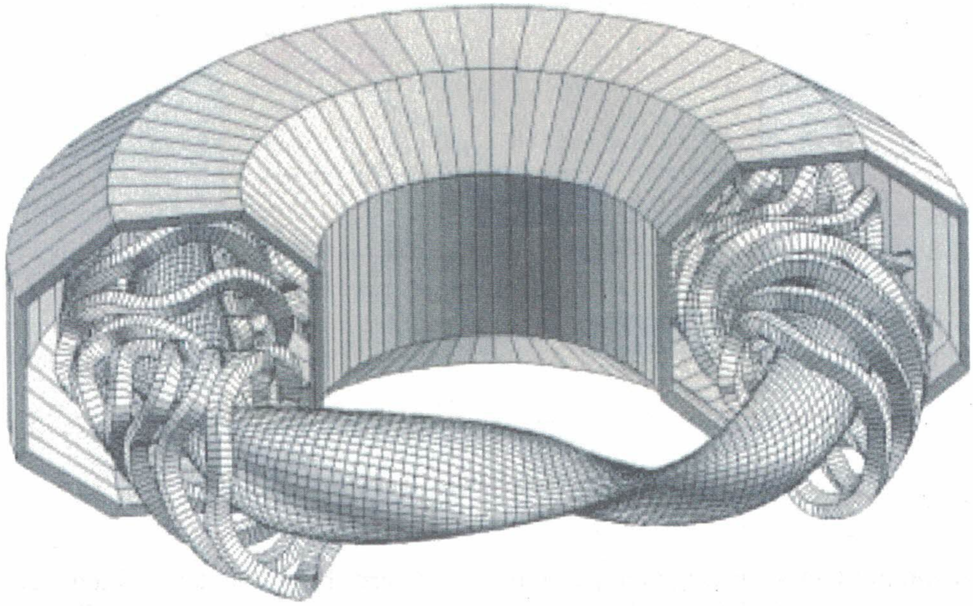


Fig. 25: Scheme of a 4-period Helias reactor. Main components: Cryostat, modular coils and plasma. Blanket and vacuum vessel are not shown here.

Conclusions

For 40 years stellarator experiments have been performed at the Max-Planck-Institut, first in Munich, and after the foundation of the IPP in Garching. A series of small devices have prepared the path for the first large stellarator Wendelstein 7-A. For the first time this experiment could realize net current-free operation with significant plasma parameters. The experiments of Wendelstein 7-A and Wendelstein 7-AS also clearly show the positive effect of the stellarator field on current-driven instabilities and the suppression of disruptions. This eliminates the need and the provisions for disruption control, which must not fail under reactor conditions. Plasma confinement in stellarator experiments is anomalous, however the empirical scaling laws derived from these experiments are not in contradiction with the requirements of a self-sustained burning phase in a stellarator reactor. Plasma density in Wendelstein 7-AS can be driven as high as $3\text{-}4 \cdot 10^{20}\ m^{-3}$, which is sufficient for reactor application. The maximum density is determined by the impurity content. A large amount of data has been collected concerning MHD-activity in both devices. In W 7-AS one expects the MHD-stability limit in the range of $\langle\beta\rangle = 2\%$. The plasma behaviour at the beta-limit, however, is still an unresolved issue. At least it can be stated that a hard onset of MHD-instabilities does not occur.

A stellarator reactor requires stable operation at beta values up to 4-5%, which is needed to deliver sufficient fusion power. There exist many theoretical investigations, which ensure the existence of such Helias configurations. In present experiments this number cannot be achieved since the heating power is too low. The design of Wendelstein 7-X, however, is layed out to overcome this barrier. The energy confinement found in stellarator experiments is anomalous, the empirical scaling laws, however, are compatible with the requirements of self-sustained burn. In terms of the fusion product the step from todays experiments to a stellarator reactor is more than three orders of magnitude, experimental and theoretical results, however, provide enough justification to continue research on advanced stellarators.

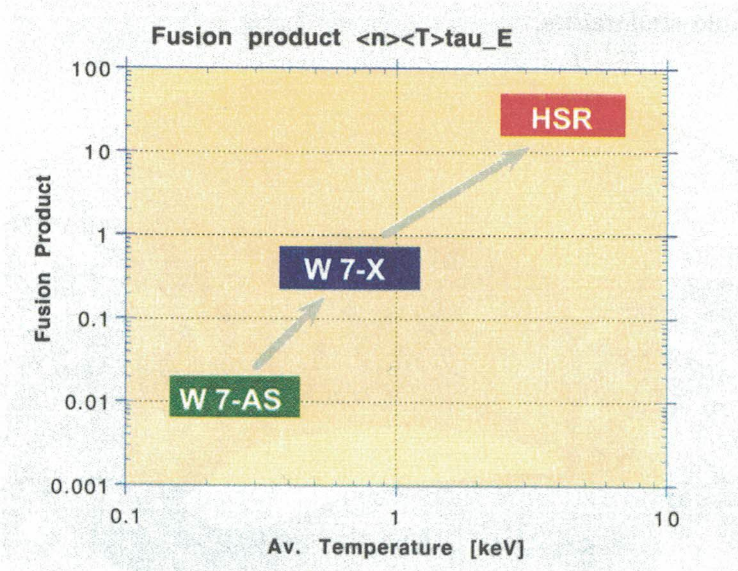


Fig. 26: Fusion product vs average temperature. The figure shows the data, which have been reached in Wendelstein 7-AS and those, which are expected in Wendelstein 7-X and the Helias reactor (HSR). The extrapolations are made on the basis of empirical scaling laws derived in current stellarator experiments.

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СТЕЛАРАТОРНІ ДОСЛІДЖЕННЯ В ІНСТИТУТІ ФІЗИКИ ПЛАЗМИ У М. ҐАРХІНҐ

Г. Вобіг, W7-AS-Група, SSS-Група

Експерименти на стелараторах в Інституті фізики плазми Макса Планка у м. Ґархінґ розпочалися в 1965 р. на малих пристроях. У 1976 р. було запущено в дію перший великий стеларатор Вендельштайн 7-А (радіус тора 2 м, радіус плазми 10 см, магнітне поле 3,4 Тл). У 1980 р. на цьому стелараторі було отримано першу плазму без тороїдального струму. У наступному стелараторі, "Вендельштайн" 7-AS, вже відмовилися від концепції гвинтової обмотки і генерували поле стеларатора за допомогою модульних котушок. Така ж концепція була застосована й до стеларатора Вендельштайн 7-X (великий радіус 3,5 м, середній радіус плазми 0,5 м, магнітне поле 2,5 Тл), який до того ж буде обладнано надпровідними модульними котушками. У роботі подано основні експериментальні результати на стелараторах у м. Ґархінґ, обговорюються плани на майбутнє, а також перспективи створення термоядерного реактора на базі оптимізованих стелараторів.