stellarator news

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New small scale stellarator experiments

Introduction

Many Stellarator configurations have been investigated theoretically. They make use of different type of quasi-symmetry and different optimization concepts. The number of experiments is strongly limited. Only LHD, Heliotron-J, HSX (TJ-II, H-I, WEGA, TJ-K) are operational and Wendelstein7-X (W7-X) will be operational in the near future. The realization of other optimized stellarators experiments like NCSX and QPS is not yet clear. At full performance operation, W7-X it should be possible to test its all optimization criteria at reactor relevant parameters.

Some optimization criteria like the reduction of the Pfirsch-Schlüter currents and β stability have already been tested in the medium size predecessor experiment W7-AS. Neoclassical transport improvement for electrons was also demonstrated on the small scale experiment HSX [1].

Transport investigations of ions, impurities and energetic alpha particles require large machine size and high magnetic fields. The same requirements hold for the ion driven bootstrap current. Experiments on heliotrons can also be used to test neoclassical theory even though they do not make use of the full optimization potential of the non-axisymmetric shaping of stellarators. In a stellarator reactor burning plasma, transport will probably not be determined by neoclassic confinement but by the MHD-driven transport at the MHD stability limit. This is because in contrast to today's fusion plasma experiments, which are externally heated with constant power, in a burning plasma the alpha particle heating strongly increases with $P_\alpha \sim \beta^2$, which overcompensates the characteristic confinement scaling with heating power ($\sim P^{-0.6}$). Therefore, if the temperature is kept constant, which can be achieved by density control, β will rise with the density until MHD-driven transport and alpha particle heating balance each other, finally determining reactor performance. The experimental experience indicates furthermore that the β-limit in stellarators is a soft limit without a disruption-like loss of confinement. Therefore safe reactor operation can be expected at that operation point.

High β values have been already achieved at W7-AS (3.4%) [2] and LHD (5%) [3]. These experiments require highest heating power, but can be performed at moderate magnetic field strength <1 T. For W7-X high-β experiments are also foreseen, but will require a heating power of more than 10 MW. It is clear that under these conditions MHD-stability cannot be tested for many optimization concepts.

But the experimental results at W7-AS had shown that MHD stability can already be tested at plasma parameters, which are below that of a reactor. This is because resistive effects will even degrade stability. In particular the electron temperature was only about 300 eV. The limiting factor reaching higher β at W7-AS was the NBI-heating power and efficiency.

The achievable β scales with the heating power per volume. But one cannot reduce the plasma size since fast ion orbit losses become unacceptable. This is only an issue of

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the heating method, and not of MHD-physics. Therefore a different heating method could enable such an experiment.

Small scale high-β experiment

In this section we investigate how much heating power is needed to test the β limit of a down-scaled stellarator with a HSR4/18-configuration (Helias Stellarator Reactor with 4 periods and 18 m major radius) shown in Fig.1. This configuration was chosen because it was proposed for a Helias type stellarator reactor [4] and because its coil parameters were already available. In principle other configurations could be scaled down to that size. The HSR4/18 configuration is of course already optimized for a high β limit by a reduction of the Pfirsch-Schlüter (PS) currents. We have reduced its dimensions by a factor of 25 and the magnetic field strength by 10. The resultant device is approximately half the size of W7-AS and is a little smaller than HSX. Therefore, any confinement prediction is more an interpolation of experimental data than an extrapolation towards larger size like the prediction for W7-X, which makes it more reliable. Because this experiment is a down-scaled version of HSR4/18, henceforth the working title HSR4/18-DS will be used. The comparative device parameters are listed in Table 1.

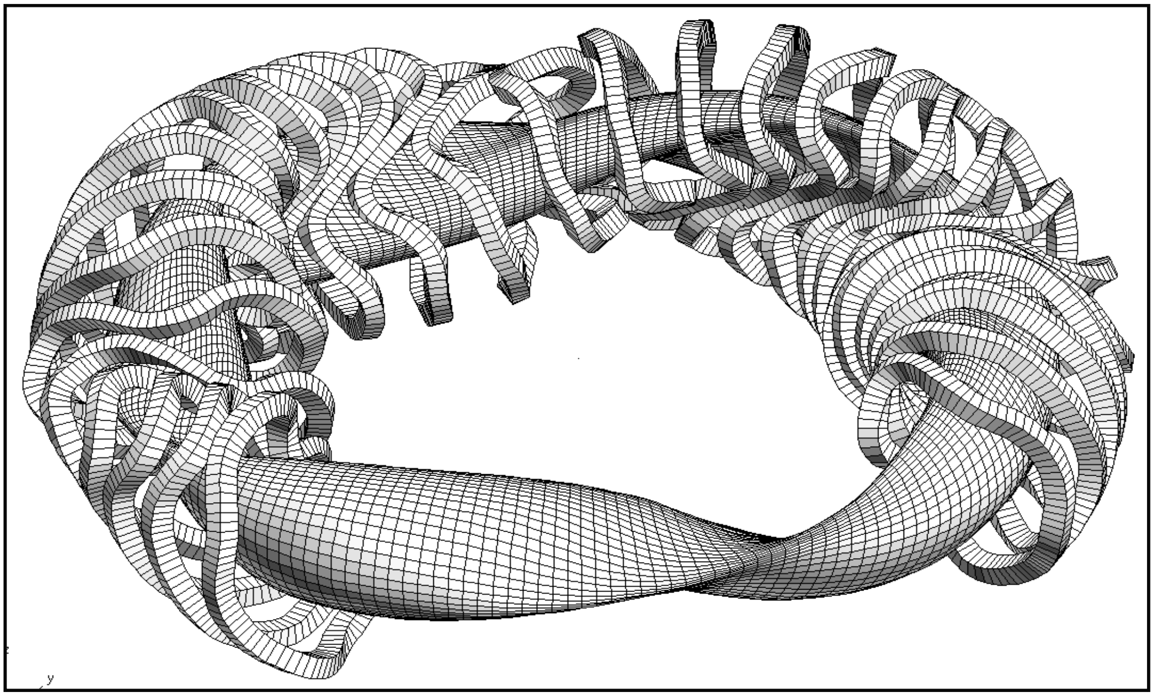

Fig. 1. Magnetic surfaces and modular coils of HSR4/18.

	HSR4/18	Downscaled HSR4/18	W7-AS
Major radius [m]	18	0.72	2.1
Minor radius	2.1	0.084	0.155
Aspect ratio	10.7	10.7	13.5
Iota(0)	0.83	0.83	0.51
Iota(*a*)	1.0	1.0	0.555
$\langle j_{par}/j_{perp}\rangle$	0.74	0.74	1.6
Plasma volume [m^3]	1670	0.106	.996
Magnetic Field [T]	4.4–5	0.44–0.5	0.9T (for high-β experiments)

Table 1. Dimensions and magnetic parameters of HSR, HSR4/18-DS, and W7-AS.

With these numbers we calculated the average β from the confinement scaling making use of

$$\bar{\beta} = \frac{3}{2}\left(\frac{W_{\rm kin}/V}{2\mu_0 B^2}\right) = \frac{3}{2}\left(\frac{\tau_e P/V}{2\mu_0 B^2}\right),$$

where τ_e is the energy confinement time, P the heating power, V the plasma volume and B the magnetic field strength. For comparison we used three different confinement scalings from [4].

The ISS95 with

$$\tau_{\rm ISS95} = 0.25 a^{2.21} R^{0.65} P^{-0.59} n_e^{0.51} B^{0.83} \iota^{0.4}$$

The W7-scaling based only on the data from the W7-A and W7-AS experiments

$$\tau_{\rm W7} = 0.36 a^{2.21} R^{0.74} P^{-0.54} n_e^{0.50} B^{0.73} \iota^{0.43}$$

and the Lackner-Gothardi scaling

$$\tau_{\rm LG} = 0.175(0.25) a^2 R^1 P^{-0.6} n_e^{0.6} B^{0.8} \iota^{0.4}.$$

Stellarators do not have an density limit, based on stability. The achievable density is mainly limited by power balance. For the density we used the empirical formula [5]

$$\bar{n}_{\rm W7\text{-}DL} = 1.46(P/V)^{0.48} B^{0.54}\,[10^{20}\ {\rm m}^{-3}],$$

which was applied to the confinement scaling. It should be noted that this estimation should not give an exact prediction of the expected plasma parameters for HSR4/18-DS, but should show the possibility of such an experiment. The results are shown in Fig.2.

With a just a moderate heating power of 300 kW, the results of W7-AS could be reproduced. With a power of 500 kW a record β of 5% could be achieved. In addition, the density would access the reactor density regime. The main challenge is to develop an efficient heating method, that is able to deposit its power in a small plasma volume at densities of 1–3 $\times 10^{20}$ m^{-3}. An average temperature is expected to be of the order 50–100 eV. But with a localized central heating method, a highly peaked temperature profile with a peaking factor up to 10 is expected.

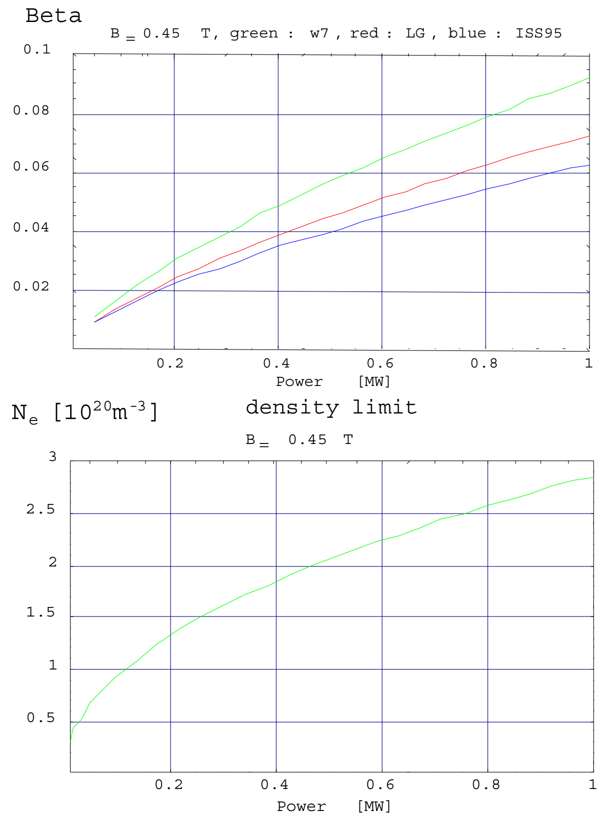

Fig. 2. Expected average β and density as a function of the heating power.

High density electron Bernstein heating.

Electron cyclotron resonant heating (ECRH) has demonstrated highly localized power deposition in high temperature plasmas (T_e > 500 eV) and at moderate densities (>1$\times 10^{19}$ m^{-3}). However, for a magnetic field strength of 0.5 T, the fundamental resonant frequency is only 14 GHz. Therefore the critical density (cutoff) for electromagnetic wave propagation is only 0.25 $\times 10^{19}$ m^{-3}. Even for the second harmonic frequency of 28 GHz the cut-off is 1$\times 10^{19}$ m^{-3}, thus the high-β plasma with $n_e > 1\times 10^{20}$ m^{-3} would be highly over-dense for ECRH using electromagnetic waves. For electrostatic waves, the Bernstein waves (EBW), this propagation limit does not exist. Furthermore they are strongly absorbed at the cyclotron resonance, even at low temperature and a higher harmonic frequency. This makes them to an attractive candidate for high-β plasma heating.

The key element is an efficient excitation of the EBWs. The usual method for this is OXB-mode conversion [6]. Efficient OXB plasma heating has been already demonstrated in tokamaks [7] and stellarators [8], but only as an additional heating method in the presence of ohmic heating and neutral beam injection, respectively. Recently at the WEGA Stellarator an over-dense plasma was achieved with 28-GHz OXB-heating exclusively [9]. WEGA is a classical Stellarator of approximately the same size as HSR4/18-DS. Therefore the demonstration of efficient over-dense operation clearly proves the EBW heating concept for HSR4/18-DS. In the WEGA experiment it was shown, that even with a low ECRH power of 9 kW densities above 1×10^{19} m^{-3} could be achieved. But more important is the fact that the EBWs have been absorbed resonantly in the plasma center, which is shown by the strongly peaked radiation profile in Fig.3. The maximum density was only limited by radiation losses. There should be no limitation reaching a higher density if the heating power would be increased from 9 KW to 500 KW for example. The high electron cyclotron absorption of EBWs enables higher harmonic heating, when the cut-off density of the higher frequency is exceeded [10]. Therefore heating with higher harmonic EBWs should be also possible. For example, 70-GHz gyrotrons can be used for EBW heating at the 4th or 5th harmonic resonance.

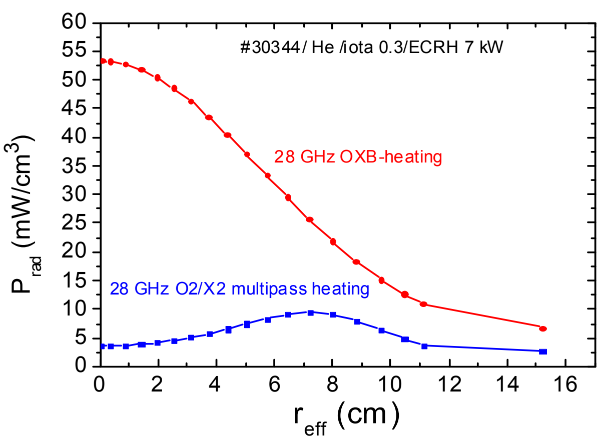

Fig. 3. Radiation profile of over-dense EBW-heated plasma with central total single-pass absorption in comparison with the profile of a low-density plasma with multi-pass O2 heating. The profiles are reconstructed from the signals of a 12-channel bolometer camera.

Technical realization

The relatively small size of the experiment enables to use new and low-cost manufacture methods. The three-dimensional (3D) vacuum vessel could be manufactured by casting, where the lost form is made by rapid prototyping. This vacuum vessel could already incorporate the support structure of the coil winding and the port tubes similar to the report in [11]. The surface should be appropriately treated for sufficiently good vacuum conditions. The four-fold symmetry can be used to divide the torus into four pieces, which then can be rotated in total for simultaneous winding of the ten coils directly on the vessel. Keep in mind that the module size is only about one meter as shown in Fig. 4.

This method would guarantee a sufficiently high positional accuracy of the coils without time-consuming and expensive measurement and adjustment procedures. In addition the parallel coil winding would speed-up the assembly process. Of course, attention must be paid to the precise assembly of the four modules, which would be done by careful welding. Finally standard CF-flanges will be welded on the port tubes. Inside the vacuum vessel there is sufficient space available for a quasioptical ECRH antenna system as shown in Fig. 5, which is by the way, a copy of the antenna system used in the successful WEGA 28 GHz EBW heating experiments. In addition, for higher harmonic heating (3rd at 42GHz, 4th at 56 GHz, at 5th 70 GHz) the optimal launch angle for the OXB mode conversion can also be achieved by a remote steering type antenna. The ports also give sufficient access for diagnostics and vacuum pumping. The current needed to achieve 0.5 T is 47 kA/(winding number). The current density is 5.9 kA/cm^2. In total, an electrical power of 3.25 MW is needed. Of course such an experiment could also be built in the traditional way with individually winded coils and a "classical" vacuum vessel.

Discussion

Several questions should be discussed. The first and of course the most important is:

Does such an experiment contribute to the fusion program?

One could argue that experiments of this size can also be justified by the academic interest exclusively. But in our opinion MHD-stability is an important issue for an economic fusion reactor as mentioned in the first section. This experiment can reach the two reactor parameters of density and β. The temperature will be low and thus neoclassical effects will be not as dominant as in a W7-X size machine or in a reactor. But neoclassical effects are less important for MHD-stability except for the bootstrap current, which contributes much to the iota profile and can lower the β limit by neoclassical tearing mode activity, just as in tokamaks. For stellarator concepts with minimized bootstrap current and thus with a stiff iota profile, this does not matter. If a configuration with finite bootstrap current such as NCSX is chosen, the effect of toroidal plasma current could be tested with an additional current driven by an ohmic transformer. One should consider that this kind of experiment would be a continuation of the high-β experiments at W7-AS, which have already brought new insight on β stability in stellarators. In addition the centrally-peaked temperature profile would generate a more realistic reactor pressure profile than a NBI-

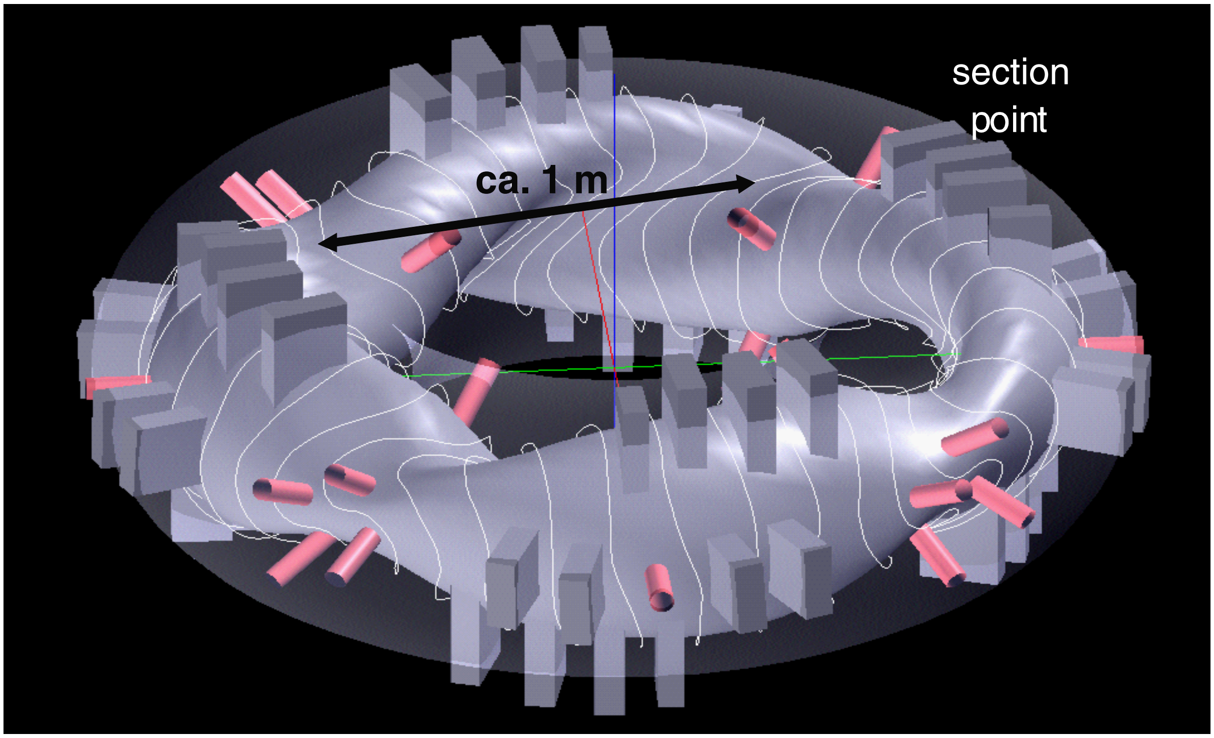

Fig. 4. Vacuum vessel and ports of HSR4/18 DS.(original picture from HSR4/18)

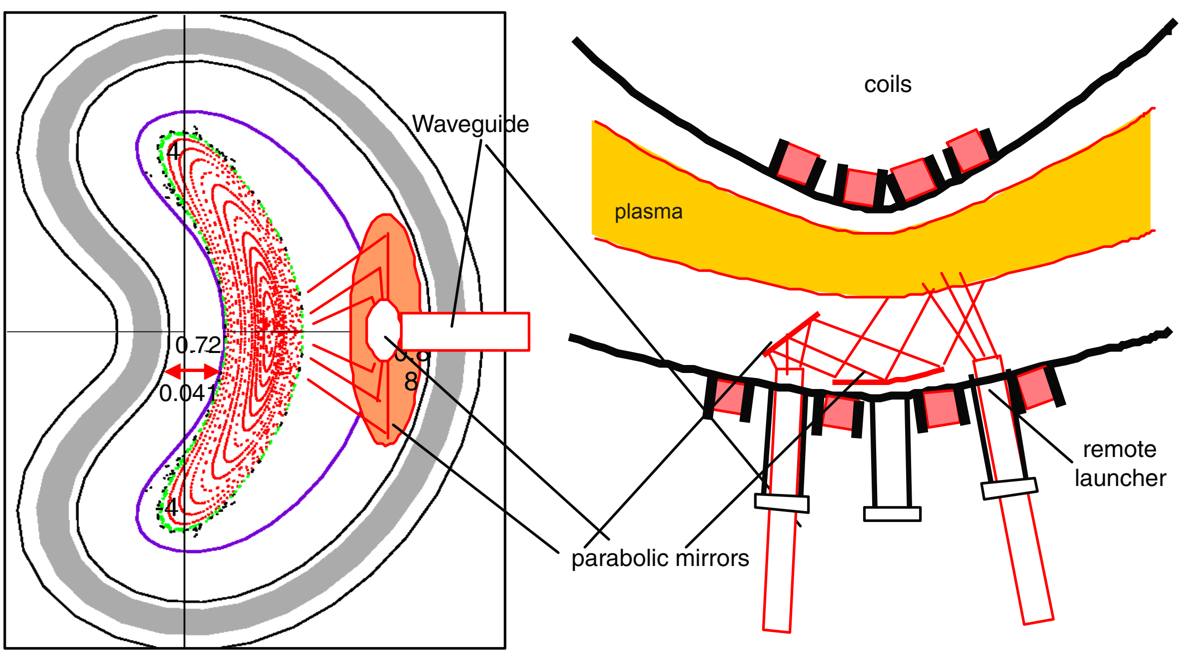

Fig. 4. Scheme of ECRH launching in the poloidal and toroidal crossection.

heated plasma with a broad temperature profile. At this point we come to the second question:

Are the physical predictions given by the scaling laws reliable?

The answer is, that it does not matter much, since in case of a less good confinement, only the heating power must be increased to reach high β. But the plasma parameters of HSR4/18-DS are closer to those of W7-AS than it is the case for W7-X, therefore their scaling should not differ much. On the other hand, due to the small volume to surface ratio, the impurity concentration could be higher than in W7-AS. We should also note that in contrast to previous high β experiments, HSR4/18-DS will be heated by central ECRH and thus a peaked temperature profile is expected. This would generate an edge radiation dominated plasma similar to the HDH-regime of W7-AS [12]. In addition there is experimental evidence that ECRH helps to reduce impurity accumulation. There are of course additional methods to reduce the impurity radiation if needed. For example, lithium coating was recently successfully used for high-density experiments at TJ-II. The vacuum vessel size would also allow use of graphite tiles as a divertor. But the divertor physics in small devices have not yet been investigated. Technically, positioning of the tiles would be straight forward, because the vacuum vessel is a part of the coil system.

Finally we have to discuss the cost and the staff needed to build and to run such an experiment. There are already several experiments of this size operating. Examples are HSX, WEGA, TJ-K, H-I and CTH. But none of them are equipped with a powerful enough ECRH system to reach high β. Only in the Heliotron-DR experiments [13], which were performed 20 years ago, the 28-GHz 200-kW ECRH was sufficiently powerful to demonstrate over-dense plasma operation at moderate β of 0.5%. Unfortunately the ECRH launching system was not optimized for mode conversion.

From the experience of the other small machines like HSX the cost for a pure HSR4/18-DS β machine would be of the order one million €. The costs of the auxiliary systems such as power supply, diagnostics and the ECRH would be at least twice that price. But these installations and components are already in existence at many institutes. HSR4/18-DS could also operate as a satellite of a large size stellarator like NCSX, W7-X, LHD for complementary high β studies.

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Three dimensional numerical analysis of edge plasma transport in the Large Helical Device

Divertor optimization in magnetically confined fusion reactors is one of the most critical issues in terms of target power load mitigation, impurity control, and fuel/He ash pumping. Breaking the axisymmetry of the magnetic field configuration as introduced in helical devices as well as in non-axisymmetric tokamaks has imposed the necessity of three dimensional (3D) analyses of the transport properties of the divertor plasma. Optimization of divertor configurations for these 3D machines is, however, not yet fully understood. Numerical codes have been developed to investigate the transport properties, as a tool for interpretation of experiments, as well as for prediction of performance in future devices, e.g., EMC3 [1], E3D [2], FINDIF [3], etc. These codes are nowadays widely used in various devices.

In the Large Helical Device (LHD) [4], EMC3 (which stands for Edge Monte-Carlo 3D) has been implemented for analyzing the plasma transport in the edge stochastic region. LHD has a heliotron type configuration with poloidal winding number of $l = 2$ and toroidal mode number 10 as shown in Fig.1. The major radius and averaged minor radius are 3.9 and ~ 0.6 m, respectively. The edge stochasticity intrinsically appears in this configuration because of breakdown of helical symmetry due to toroidal effects that induce overlapping of magnetic islands. The details of the field line structure of stochastic region is incorporated in the field line-aligned 3D grid of the computations, which then also provides clear separation between parallel and perpendicular transport to field lines.

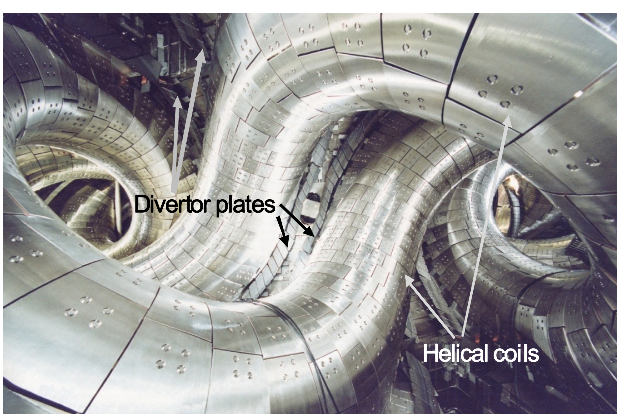

Fig.1. Interior view of LHD. The two superconducting helical coils (poloidal winding number $l = 2$) and the divertor plates are indicated.

Fig. 2(a) shows poloidal cuts of magnetic field connection length (L_C, the distance along field line during travel from one intersection by divertor plate to another) distribution at each 9 degrees of toroidal angle, as reconstructed from the 3D grids. While the flux tubes travel in toroidal direction, they experience compression in the vicinity of helical coils (effect of helical ripple) as well as radial kicks according to the mode spectrum of the coils. The strong magnetic shear at the periphery then squeezes these flux tubes (of different L_Cs), resulting in a stochastic structure. Stretching from the both edges of elliptic shape of the cross sections are divertor legs, which connect the divertor plates situated in-between the helical coils. The stochasticity introduces an extremely long connection length as indicated by the color in the figure, up to an order of several tens kilometers, which is one of the distinct features from the standard X-point divertor tokamak scrape-off layers ($L_C \leq 100$ m). Because of the large ratio of parallel to perpendicular transport, the plasma parameter distribution is strongly influenced by the magnetic field line structure. Plotted in Fig.2 (b) is electron temperature (T_e) distribution in the same planes as Fig.2(a). Since the long flux tubes tend to penetrate deep into the plasma, they deliver hot plasma and thus bring higher T_e as observed in the figure. The calculated T_e profiles are compared with the measurements made by the Thomson scattering system, and they show reasonable agreement each other [5,6], confirming the presence of the stochasticity as well as the validity of the fluid description of plasma transport adopted in the code (at least, for this particular case).

The analyses have revealed the importance of perpendicular transport in determining the divertor plasma properties, which contributes through the accumulative effect along the long field lines, as well as the enforced strong perpendicular coupling due to the flux tube deformation as mentioned above (compression, shearing). For momentum transport, this leads to a leakage of total pressure from the flux tubes [5,6]. The effects are observed experimentally as weaker compression of divertor plasma, that might degrade pumping efficiency without a closed divertor structure, but on the other hand, that can be advantageous to reach higher edge (core) density before detachment onset. For energy transport, the perpendicular transport provides a supplementary path in addition to the parallel ones, which thereby eases development of parallel temperature gradient. The consequences for the divertor plasma are a somewhat higher temperature as well as a good impurity screening due to the suppressed temperature gradient force (thermal force) [7]. These transport characteristics are common to both LHD and W7-AS [8]. For divertor optimization, the pros and cons of these features are being discussed, and further investigation is ongoing to explore the possibilities of a 3D divertor.

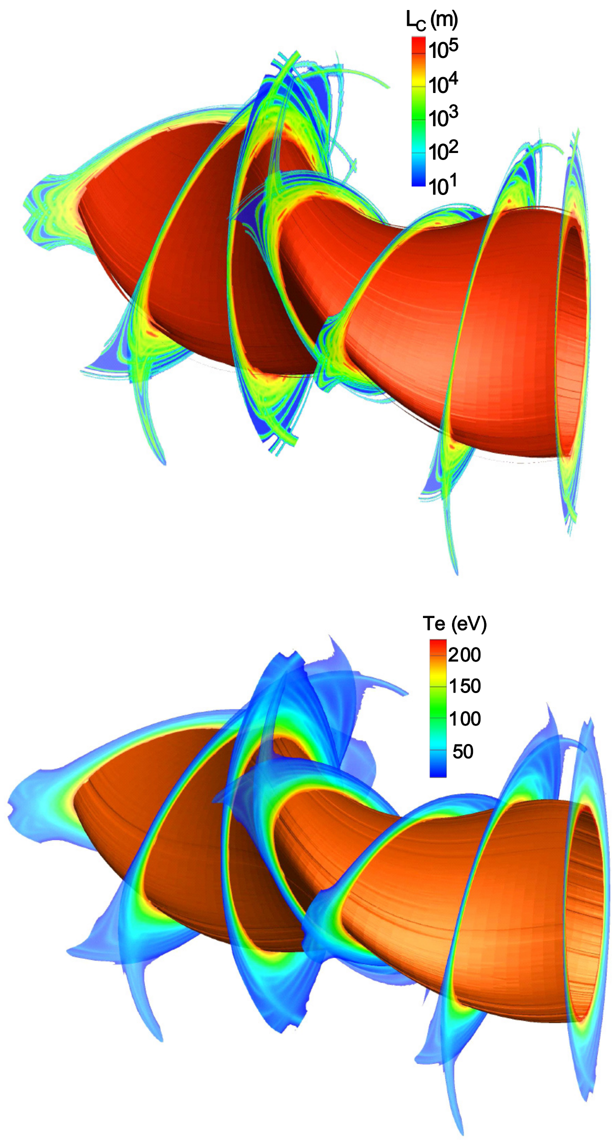

Fig. 2. (a) Connection length (L_C) distribution in the edge region of LHD in poloidal cross sections at each 9 degrees of toroidal angle with iso-surface of $L_C = 10^5$ m (red). The magnetic field structure is reconstructed from the field line aligned 3D grid of EMC3. (b) Electron temperature (T_e) distribution at the same planes as in (a), together with iso-surface of 200 eV (red), obtained by EMC3

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