VACUUM FIELDS AND PARAMETER RANGE OF A MODULAR HELIAS CONFIGURATION

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INTRODUCTION . At IPP Garching, the stellarator experiment WENDELSTEIN VII-X is being developed. Among stellarators Helias configurations (Helical Advanced Stellarator) offer the prospects of stable plasma operation at $\langle\beta\rangle \approx 5\%$ because of the optimization of confinement, MHD-equilibrium and stability [1]. Considering ballooning modes and resistive interchange instability, Helias configurations with five field periods are preferred [2]. In the present paper the development of a modular coil system for W VII–X is described briefly, and details of the magnetic vacuum fields and the accessible parameter range are given. We concentrate on a data set named HS 5–8 with a major radius of 6.5 m and a coil aspect ratio of 5.4. Each of the 60 coils, considered to be superconducting, carries 1.75 MA at a current density of about 50 MA/m^2. The magnetic field on axis is 3 T and the maximum induction at the coil is 5.8 T . The coil set and an outer flux surface are shown in Fig. 1 .

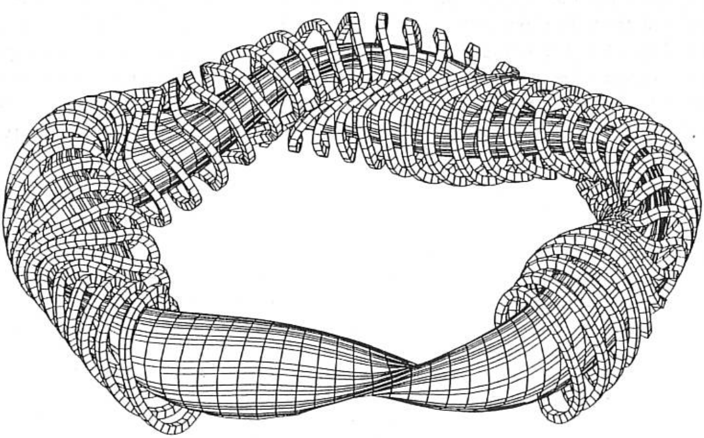

Fig. 1 : Coil set for HS 5–8 (4 of the 5 field periods), and an outer flux surface. The coils have dimensions of lateral 0.18 m and radial 0.20 m.

COIL SYSTEM . Using the NESCOIL code, [3], a system of current filaments is computed on a toroidal surface S_2, which encloses an outer magnetic surface S_1 of a given Helias configuration. Both surfaces are described in Fourier series of two angular co-ordinates. These current filaments are taken as the center lines of finite size coils which are optimized with respect to curvature, maximum distance between coils and between plasma and coils. The number of coils per field period is 12, which minimizes the modular field ripple to about 0.7% at the edge and leaves sufficient space between the coils for access to the plasma. To achieve optimum conditions the Fourier coefficients of S_2 and S_1 are modified, those of S_1 only slightly. At critical positions the coils are smoothed afterwards. This leads to a small deviation from the original Helias configuration which, after comparing it with the vacuum field of the finite coils, is acceptable in the present case. In HS 5–8 three important quantities could be made as large as possible: minimum coil curvature radius 30 cm, minimum lateral distance between coil centers 22 cm, and minimum radial distance of 36 cm between the current surface (coil center) and a flux surface with an aspect ratio of 9 .

VACUUM FIELD PROPERTIES . Up to 5 filaments per coil are used for calculating the vacuum magnetic fields; in most of the cases one or two filaments per coil have be found as sufficient. Fig. 2 shows the Poincaré plots of the vacuum magnetic field for three toroidal positions. The rotational transform is $\iota_0 = 1.02$ along the helical magnetic axis, it increases monotonically to a value of 1.2 at the edge, see Fig. 3 . This figure also shows the value of $V' = \int dl/B$ as function of the averaged radius $\bar{r}$, from which a magnetic well $(V_0' - V')/V_0' =$ -1.5% is calculated. A low neoclassical transport in the plateau regime, small Shafranov-shift and small change of ι and shear with β are expected from the low value of $\langle |j_{||}/j_{\perp}| \rangle = 0.63$. A proper combination and low number of the Fourier components , determining the magnetic field in magnetic co-ordinates, guarantees a small value for the equivalent ripple, which characterizes the neoclassical transport in the $1/\nu$-regime. The equivalent ripple amounts to less than 1% for a similar configuration, HS 5–7, which has a 20% lower value of the rotational

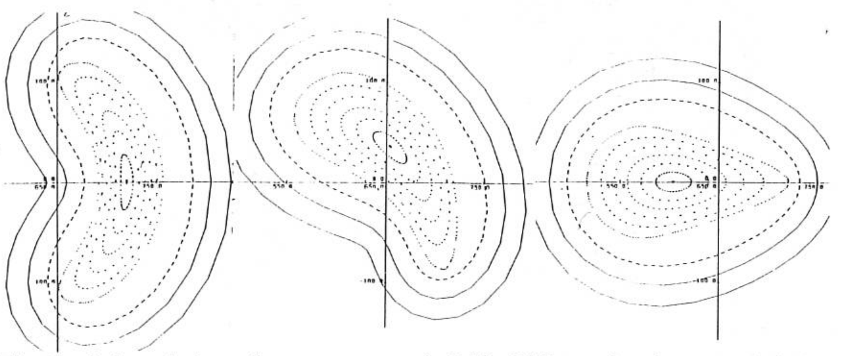

Fig. 2 : Poincaré plots of vacuum magnetic field of HS 5–8 for three toroidal plane with contours of the inner and outer boundaries of the modular coils (solid lines). The dashed line indicates the position of a tentative first wall.

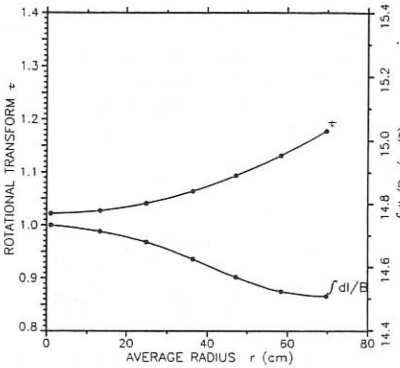

Fig. 3 : Rotational transform ꞓ and the value of $V' = \int dl/B$ as function of the averaged radius $\bar{r}$.

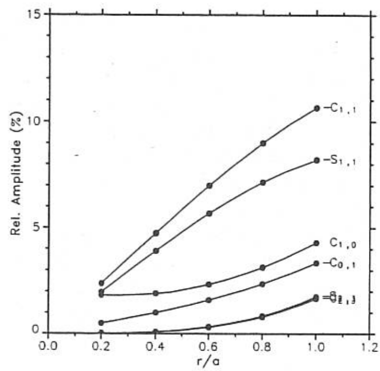

Fig. 4 : Normalized Fourier components of the field strength $|B|$. Coefficients with an edge-value below 1.5% and $C_{0,0} \sim 1$ are omitted.

transform. Fig. 4 shows the normalized Fourier components of the field strength

$$|B| = |B_0|\left(\sum C_{n,m} cos(n\phi)cos(m\theta) + S_{n,m} sin(n\phi)sin(m\theta)\right) \quad ,$$

where ϕ and θ are toroidal (index n) and poloidal (index m) magnetic variables [4], respectively, $B_0 = 3$ T is the average field, and $C_{0,0} \sim 1$. Adjusting in HS 5–8 the helical field components $C_{1,1}$ and $S_{1,1}$ with respect to the coefficients $C_{0,1}$ and $C_{1,0}$ yields a geometrical factor for the bootstrap current, as discussed in [5], of less then 10% of the equivalent tokamak value in the lmfp regime.

At low order rational values of the rotational transform, e. g. ꞓ $= 5/5$, 'natural' magnetic islands usually exist in the system of magnetic surfaces. The position and size of these islands is influenced by the choice of the initial flux surface and of the outer surface used for the NESCOIL input, and by the admitted number of Fourier harmonics determining the current lines. It is also sensitively affected by the smoothing procedure. In HS 5–8 the lowest order rational values of ꞓ $= 5/5$ and $5/4$ are avoided. A method to obtain a small island size, described in [6], is not yet applied. The neighbouring rational values of higher order ꞓ $= 10/9$ and ꞓ $= 15/13$ produce small islands with averaged radial dimensions of 1.5 ... 2 cm. Their average radial positions are 51 and 62 cm, respectively, inside an effective minor radius of about 70 cm.

PARAMETER VARIATION . A necessary prerequisite for an experimental device is a sufficiently broad range of variable magnetic field parameters like rotational transform and axis position. This can be achieved by a set of 4 planar external coils per field period in a helical arrangement as shown in Fig. 5 . Considering individually adjustable currents in the coils A and B allows to introduce toroidal and vertical fields as well. In Fig. 6 the dependences of ꞓ$_0$ on axis, ꞓ$_a$ at the edge, and of the magnetic well V'' are plotted as a function of the current in the planar coils. A current of ± 0.5 MA per planar coil and of 1.75 MA in each modular coil changes the rotational transform by about 20%. In this way configurations with rational values of $\iota = 5/5$ or $\iota = 5/4$ at the boundary are obtained. One can anticipate to use the corresponding island chain for plasma edge control.

Vertical field components, generated by opposite currents of 0.5 MA in the planar coils A and B of Fig. 5 shift the magnetic axis by about 1% of the major radius. The toroidal modulation of the field strength, introduced in this case, can be reduced considerably by using different currents in the modular coils.

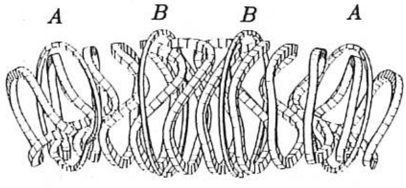

Fig. 5 : One period of HS 5–8 showing the modular coils and the external planar coils A and B for varying the rotational transform and axis position.

SUMMARY AND CONCLUSION

The configuration HS 5–8 with 5 field periods, a major radius of 6.5 m, an averaged field of 3 T, an iota-value between 1.02 and 1.2, is generated by 60 modular coils. The coils are optimized according to technical constraints and appear to be feasible; they leave sufficient access to the plasma and offer space between plasma and wall. The vacuum field properties e. g. low Pfirsch-Schlüter currents, magnetic well, low equivalent ripple, high quality of flux surfaces, are the basis for good plasma confinement and sufficient high stability-β. The adjusted combination of the field components reduces the bootstrap current to a tolerable value. A set of external planar coils allows both, a variation of the rotational transform of 10%, and also a shift of the magnetic axis of 1% of the major radius.

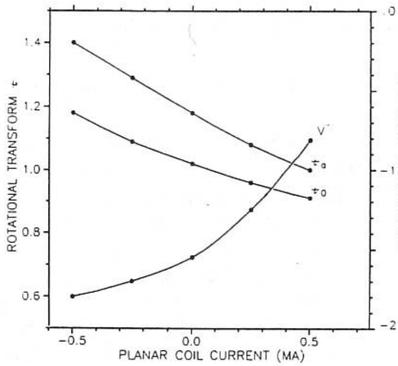

Fig. 6 : Dependences of ι_0 on axis, ι_a at the edge, and of the magnetic well V'' as a function of the current in the planar coils.

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