MODULAR STELLARATORS WITH IMPROVED CONFINEMENT PROPERTIES

E. Harmeyer, F. Herrnegger, J. Kisslinger, A. Montvai*, F. Rau , and H. Wobig

Max-Planck Institut für Plasmaphysik, D-8046 Garching, FRG, EURATOM-Association.
* Guest from: Central Research Institute for Physics, H-1525 Budapest, Hungary.

Abstract *Vacuum field properties of stellarators with modular coils are compared in order to select the configuration with optimum confinement, small bootstrap current, and prospects to achieve a high beta value.*

In an effort to select an optimized configuration for application to Wendelstein VII-X, the next step of the Garching stellarator program, vacuum field properties of three types of stellarators with modular coils and reduced secondary currents and a modular Heliac system are investigated:

(1) : a system W VII-X-1D with 6 elliptically shaped coils in each of the five field periods, otherwise similar to that of the forthcoming Garching Advanced Stellarator Experiment Wendelstein VII-AS;

(2) : a Bean-shaped Advanced Stellarator configuration BSX derived from item (1), with some indentation of the flux surfaces at particular toroidal positions, realized by 9 elliptical coils per field period and otherwise similar to a system described in /1/;

(3) : several Helias systems with 4 to 6 field periods, HS4, HS5 and HS6, with topologies similar to those published in /2/ or /3/ , realized by 10 to 12 coils per field period;

(4) : a modular Heliac with 5 field periods similar to those published in /4/.

These types of modular stellarator configurations were discussed in a recent 'Workshop on Wendelstein VII-X' /5/. Examples of coil shapes and magnetic vacuum fields are given in the five columns of Fig. 1. The coils of W VII-X-1D and BSX 5-2 are centered along planar curves $R(\varphi) = R_o\,(1 + \delta cos(5\varphi))$, with $R_o = 5\,m$ and $\delta = 0.016$ and 0.075, respectively. The coil bores have elliptical minor cross section. This would ease the maintenance of a future reactor. Indeed, W VII-X-1D is a downgraded version of ASRA6C, the reference configuration of a recent study /6/ of critical issues of Advanced Stellarator reactors. The Helias configurations studied so far require coil contours matched to the shape of outer flux surfaces. In the modular Heliac identical coil shapes should be possible. The coils for the Helias (Heliac) systems are arranged along spatial curves with moderate (large) values for the vertical excursion and coil tilt. Consequently, the magnetic axes follow also spatial curves, whereas W VII-X-1D and BSX have nearly planar magnetic axes.

A typical dependence of the electromagnetic forces in such a coil systems is visualized by the effective force F_{res} shown as arrows in the top part of Fig. 1. These forces are largest near the 'corners' of the coil systems, they point radially outwards in BSX 5-2 at the middle of the field period, and they are spiralling in the Heliac. Other engineering aspects of the four types of stellarators are also investigated, like the support of local electromagnetic forces and the resulting stresses and strains. Reinforcement of the coils is required, by some coil housing and by intercoil structural elements. The stored magnetic energies amount between 0.3 and $1\,GJ$ at a field $B_o = 4\,T$ on axis; the maximum fields at the coils are below $7.5\,T$.

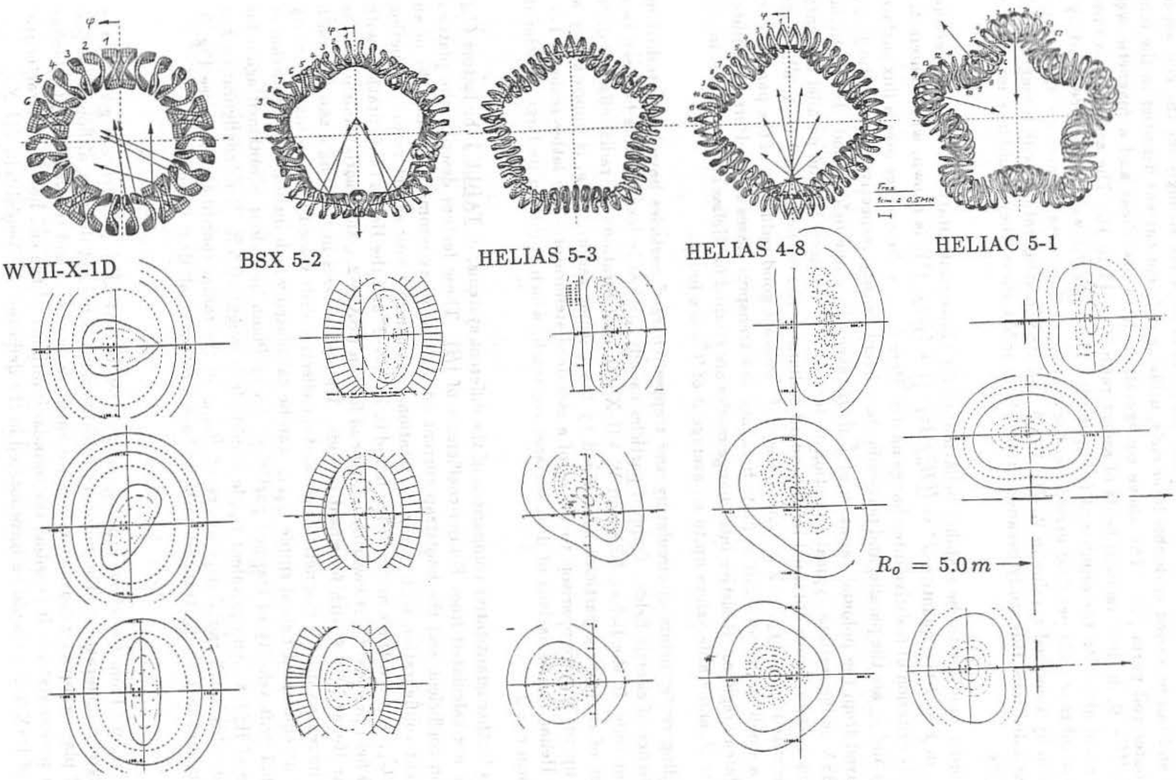

Fig. 1 : Top view on the coil systems, and coil cross sections with magnetic flux surfaces shown at three typical positions along a field period.

The rotational transform ι of modular stellarators depends strongly on the coil aspect ratio and can be varied in double layer coils, utilizing different current densities in the inner and outer coil parts /7/. The above configurations have low shear and a magnetic well, $\Delta V'/V' < 0$, in their vacuum fields of aspect ratio $A = 11$ to 16. The aspect ratio raises with ι and also with the number of field periods. The magnetic well can be deepened by a large number of coils per field period (on the expense of the access between coils, however), and also by a lowered ι-value in W VII–X–1D and BSX. Configurations with a magnetic hill are excluded from this study because, at vanishing or low shear, they would lack interchange stability.

In order to estimate the stability behaviour of the above configurations from their vacuum fields, in Fig. 2 the quantity $J^* = \langle (B_o^2/B^2) \cdot (1 + (j_{\|}/j_{\perp})^2) \rangle$ is shown, which enters the stability criterion of resistive interchange modes. Here $\langle \ldots \rangle$ is the average over a flux surface, and $j_{\|}$ and $j_{\perp}$ are the parallel and perpendicular current density, respectively. The ratio $j_{\|}/j_{\perp}$ is derived from the poloidal variation of $\int dl/B$ taken along one field period. In the Helias and BSX configurations typical reduction factors of ≈ 3 are seen for the parallel currents, as compared to values obtained in a standard stellarator like Wendelstein VII–A, which are characterized by $|j_{\|}/j_{\perp}| \sim 2/\iota$. Low values of J^* indicate good reduction of the parallel currents, a small Shafranov–shift at finite beta, and low transport losses in the Pfirsch–Schlüter and plateau regimes. Resistive interchange modes are studied for Helias configurations in /8/ at finite β, and stable values up to an average β of 9 % are found.

Guiding center orbits of circulating and trapped charged particles have been studied in the absence of electric fields. Trapped particles usually are lost in local mirrors between two adjacent coils. In the Helias, BSX and W VII–X–1D configurations the radial offset of drift surfaces of circulating particles normalized by the Larmor radius, Δ/ρ, is improved by a factor up to 3, in comparison to values of a standard stellarator. The latter scale $\sim 1/\iota$. In the Heliac the deviations of drift surfaces are small, which is due to its large rotational transform $\iota \approx 2$.

For a further quantitative comparison of the different systems, in TABLE I the factors C_{pl} and C_b are calculated from Fourier-coefficients of $|B|$. These factors describe the plateau diffusion coefficient and the bootstrap current normalized to axisymmetric values /9/ of an equivalent configuration with the same rotational transform ι and aspect ratio. Reduction factors C_{pl} between three and four are found in BSX 5–2 and the Helias configurations with 4 and 5 field periods; C_b is lower by a factor of four in BSX 5–2 , and nearly vanishes in the modular Helias HS4–8 with four field periods. Transport losses in the long mean free path regime increase with the magnetic ripple and the effective drift velocity. Following the theory of /10/ an equivalent helical ripple $\epsilon_{equiv.}$ can be calculated which includes the reduction of the radial drift velocity of trapped particles. An optimum behaviour is obtained again for the case of HS4–8. An equivalent ripple amplitude is roughly 0.5 %. This configuration has a considerably small radial dependence of B_{min} on the radial coordinate r_{eff}, see Fig. 3, which implies that deeply trapped particles have a rather small drift velocity.

Conclusion : From the above studies, summarized in TABLE I, preference is given to the Helias type configurations. The number of field periods is not yet definite, although the low coil and plasma aspect ratios, as well as the small value of C_{pl} and the vanishing C_b favour the four period system. If possible, the toroidal invariance of the coil bores, a characteristic feature of BSX 5–2 , should be incorporated in the definition of Wendelstein VII–X.

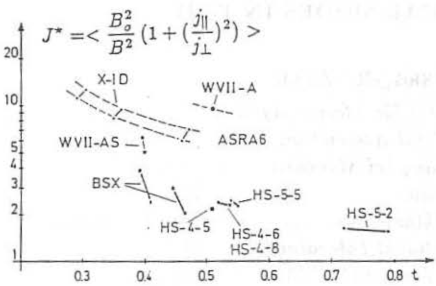

Fig. 2 : Dependence of J^* on the rotational transform ι for modular systems with reduced secondary currents.

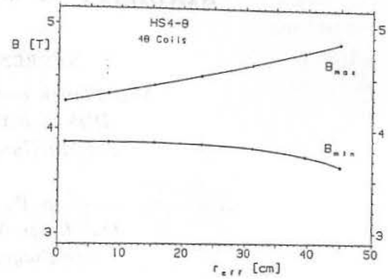

Fig. 3 : Dependence of minimum and maximum induction B_{min}, B_{max} on the effective minor radius for HS4–8.

TABLE I: Characteristics of different WVII-X approaches.
Major radius $R_o = 5.0\,m$, magnetic induction $B_o = 4.0\,T$

	$r_p[m]$	$r_c[m]$	ι_o	$\Delta V'/V'[\%]$	J^*	Δ/ρ	C_{pl}	C_b
WVII-X-1D	0.45	1.22	0.45	-1.7	7.	1.7-2.4	0.75	0.55
BSX 5-1	0.40	0.90	0.41	-0.1	3.			
BSX 5-2	0.30 +)	0.89	0.49	-0.1	2.3	0.3-0.9	0.22-0.3	-0.25
HELIAS 4-1	0.44			-1.0	2.6	0.3-1.0		
HELIAS 4-5	0.44	0.80	0.51	-0.4	2.2			
HELIAS 4-8	0.45	0.90	0.55	-0.7	2.4		0.27-0.3	≈ 0
HELIAS 5-3	0.38	0.72	0.72	-0.4	1.6	< 0.6	0.3-0.35	-1.2
HELIAS 6-1	0.34		1.03	-0.1	1.3	< 0.4	0.61-0.8	-2.8
HELIAC 5-1	0.45	0.85	1.99	-0.1	2.5	0.2-1.0	2.4-2.5	-3.3

+) determined by preliminary vacuum tank, separatrix $r_s = 0.38\,m$
r_p , r_c : minor plasma and coil radius, respectively; ι_o: rotational transform on axis

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