27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** *(2000) 1012 -1015*

Reduced Aspect Ratio HELIAS Configurations

J. Kißlinger, C.D. Beidler, H. Wobig

Max-Planck-Institut für Plasmaphysik, EURATOM-Ass., D-85748 Garching

Introduction

The configuration currently considered for the Helias reactor [1] is similar to the Wendelstein 7-X configuration and has five field periods and an aspect ratio of 11. A lower aspect ratio would allow one to reduce the major radius of the reactor and/or to enlarge the space between plasma and coils needed for blanket and shield.

Reactor relevant stellarator configurations require not only adequate transport, MHD equilibrium and stability properties, but also satisfactory confinement of highly energetic α particles. The last point calls for some symmetry in the magnetic field spectrum. Axial symmetric and helically symmetric configurations have large bootstrap currents which change the magnetic spectrum and raise the potential for instabilities. The concept of the quasi-omnigeneous stellarator (QOS) confines the fast particles by a reduction of their radial drift so that trapped particles drift poloidally. This poloidal drift must be large compared to the radial drift and is generated by the magnetic well produced mainly by the plasma pressure (diamagnetic currents and Shafranov shift). QOS configurations (WENDELSTEIN 7-X [1] goes in this direction) have only a small bootstrap current but must allow operation at sufficiently high beta to ensure α particle confinement.

The aim of the current investigation is to find a configuration with a lower aspect ratio and good confinement of α particles.

Vacuum field properties

One way to lower the aspect ratio is to reduce the number of field periods. An easy procedure to get a similar configuration to e.g. W7-X is to take the coil description of W7-X in angle co-ordinates, reduce the major radius so that the coil size is unchanged, and arrange the toroidal coil system with the desired number of field periods. The main differences in the magnetic field which one gets in this way are:

- the rotational transform is reduced because it is nearly constant per field period,
- the ratio of the helical field component B_{11} to the axisymmetric component B_{01} is also reduced because the B_{01} component increases with the reduction of the plasma aspect ratio,
- the magnetic well is deepened.

Following this procedure, however, leads to configurations with insufficient α particle confinement. In a further optimization the coil shapes are changed so that:

- In the middle of a field period, where the minimum of the magnetic field strength occurs, a minimum of radial field gradient is attained in the vacuum field. With increasing beta a region with an absolute minimum of |B| grows there and super banana trajectories are not possible; see Figs.1 and 2.
- The ratio of the components B_{11} to B_{01} is increased to values between 1.2 and 1.5, which includes, together with the first optimization aim, an increase of the component B_{1-1} (Fig. 3)
- Higher field harmonics are reduced as much as possible.

These changes in the field structure have consequences for the transport and stability properties. Two configurations with 4 field periods and good α particle confinement are obtained. They differ in the rotational transform ι; HSR-M4a has at the edge ι_a=0.8 and HSR-M4b has ι_a = 1. In Table I the main data of these configurations and the data of the current Helias reactor configuration HSR22B-lsh are listed. Fig. 4 shows one field period of the coil set of HSR-M4a seen from above and Fig. 5 the Poincarè plots of the magnetic surfaces of the configuration HSR-M4a.

TABLE I.

configuration	major rad.	minor rad.	aspect ratio	ι_o	ι_a	B_{max}/B_o	$\langle \lvert j_{\lvert\lvert}/j_\perp \rvert \rangle$
HSR-M4a	18 m	1.95 m	9.2	0.73	4/5	2.2	0.75
HSR-M4b	18 m	1.84 m	9.8	0.87	4/4	2.2	0.63
HSR22B-lsh	22 m	2.05 m	10.7	0.87	5/5	2.1	0.74

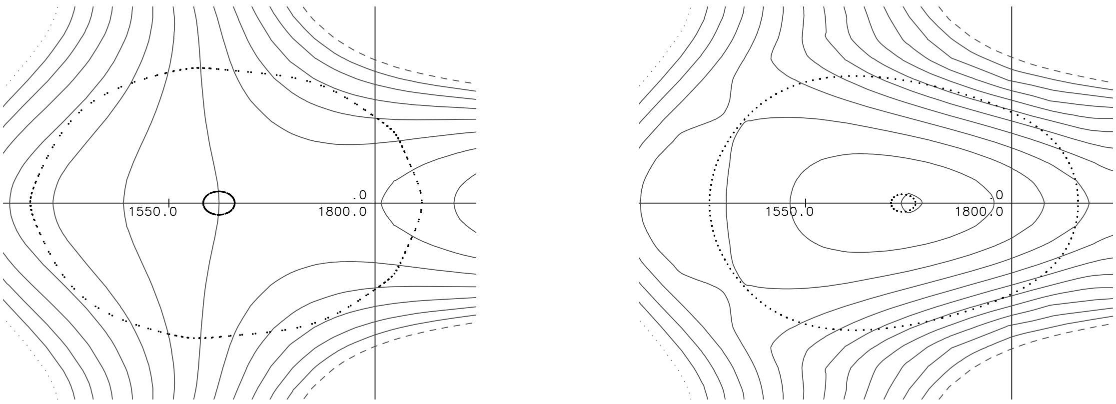

Fig. 1 Contour lines of |B| and Poincarè plots of two magnetic surfaces (near the center and the edge) of the configuration HSR-M4a at the middle of a field period. The left figure shows the vacuum field, the right one the equilibrum field with average β = 4.3%. The minimum of B is at the left side, the maximum of B up and down at the right side of the figures, δB spacing of adjacent contour lines is 1% of the average field on axis.

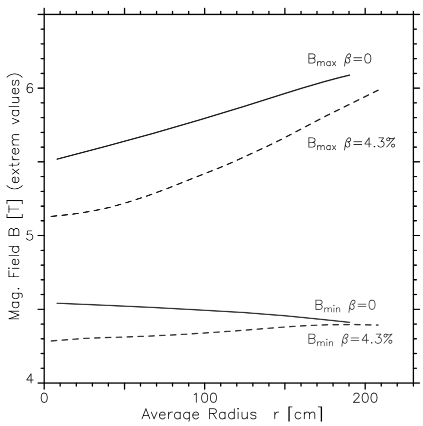

Fig. 2 Extreme values of |B| on the magnetic surfaces vs their average radii for HSR-M4a at $\bar{\beta} = 0$ and $\bar{\beta} = 4.3\%$

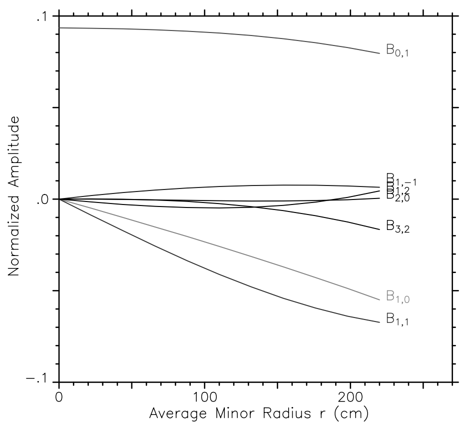

Fig. 3 Main Fourier components of the vacuum magnetic field for HSR-M4a.

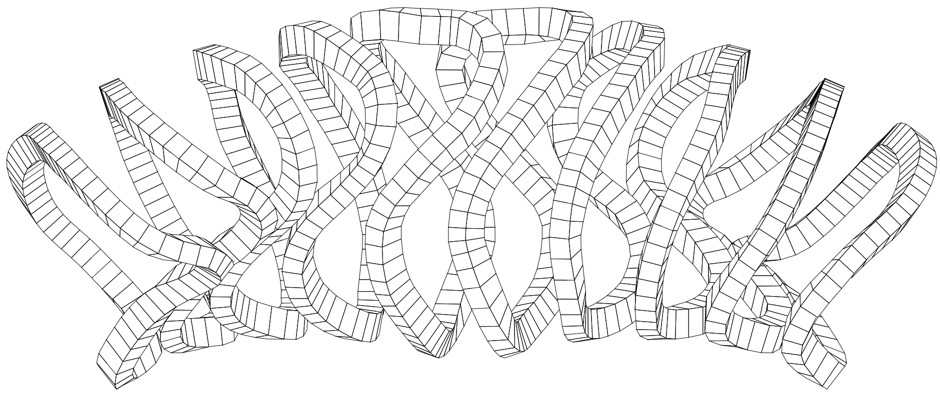

Fig. 4   Top view of one field period of the coil set of HSR-M4a.

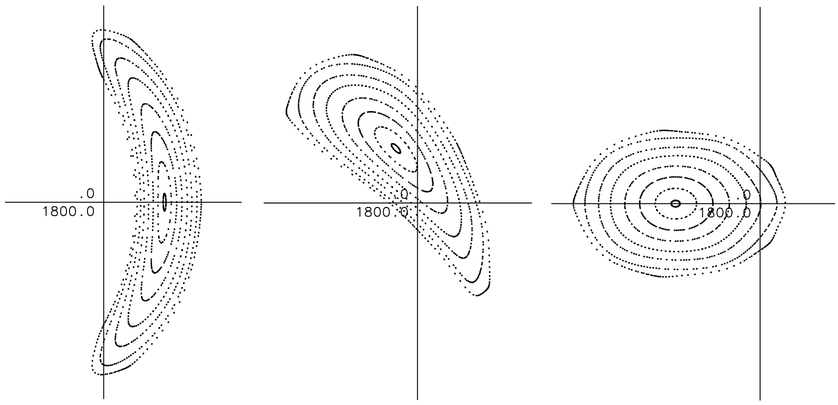

Fig. 5   Poincarè plots of magnetic surfaces of the HSR-M4a vacuum field at the beginning (left), 1/4 (middle) and 1/2 (right) of a field period.

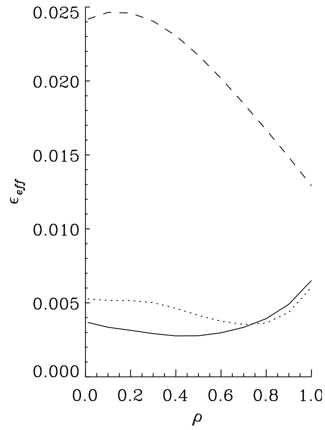

Fig. 6 ϵ_{eff} vs the normalized radius ρ of HSR-M4a (solid line), HSR-M4b (dotted line) and of hsr22b-lsh.

Calculations of the neoclassical transport coefficient ϵ_{eff} show for the two cases with 4 periods values of about 0.5% in the core region and an increase to about 0.7% towards the edge in the vacuum field. These very low values are significantly reduced compared with the coefficient for the current five period configuration; see Fig. 6. With increasing β a further reduction of the coefficient by a factor of two occurs in the core region. The increase of ϵ_{eff} towards the edge has the advantage of counteracting the formation of hollow density profiles. With the improvement of neoclassical confinement the loss of fast α-particles is considerably reduced. At a β value of 4.3% the energy loss due to fast α-particles is 2.5% and 2.9% for the 2 configurations; see Table II. The estimation of the bootstrap current yields relative values of 5% (HSR-M4a) and 3% (HSR-M4b) of an equivalent toroidal symmetric configuration.

A disadvantage of the low aspect ratio configurations is the larger ratio B_{max}/B_0, the magnetic field strength on the coils to the average field strength on the magnetic axis, due to the lower coil aspect ratio. This ratio is increased for the 4-period configurations to 2.2 compared with 2.1 for the 5 period case.

Equilibrium and Stability

The NEMEC code [2] was used for equilibrium calculation, the MFBE code [3] to calculate the magnetic field outside the plasma boundary and the JMC code [4] for the stability investigations. Fig. 7 shows Poincarè plots of an equilibrium with average beta of 4.3% (nearly bell shaped pressure profile) of HSR-M4a. Compared with the vacuum field (Fig. 5) noticeable is the small

Shafranov shift, which is even smaller in HSR-M4b with the higher rotational transform. Not observable in the figure is the reduction of the rotational transform. This reduction is larger in the core region but shifts also the rational $\iota_a = 4/4$ value radially outwards, so that the plasma radius increases with increasing β. The configuration HSR-M4b does not show a decreasing central rotational transform with increasing beta, but shows an increase of the plasma radius. The study of the MHD stability properties with respect to the Mercier and resistive interchange criteria shows localized, but finite MHD unstable regions around the low order resonant ι values (HSR-M4a $\iota = 8/11$). Table II contains results of equilibrium calculations for 3 configurations at $\bar{\beta} = 4.3\%$. The larger Shafranov shift in the HSR-M4a case is caused by the lower rotational transform of this configuration.

TABLE II. Rotational transform ι_o, Shafranov shift $\Delta R/a$ ($\Delta R =$ mean shift of the magnetic axis, $a =$ plasma radius), magnetic well $V'' = \delta V'/V'_o$ and energy loss of fast α-particles.

conf.	ι_o	$\Delta R/a$	aspect ratio	mag. well [%]	energy loss [%]
HSR-M4a	0.70	0.19	8.2	7.3	2.9
HSR-M4b	0.87	0.14	9.0	7.5	2.5
HSR22B-lsh	0.837	0.23	11.7	7.6	1.9

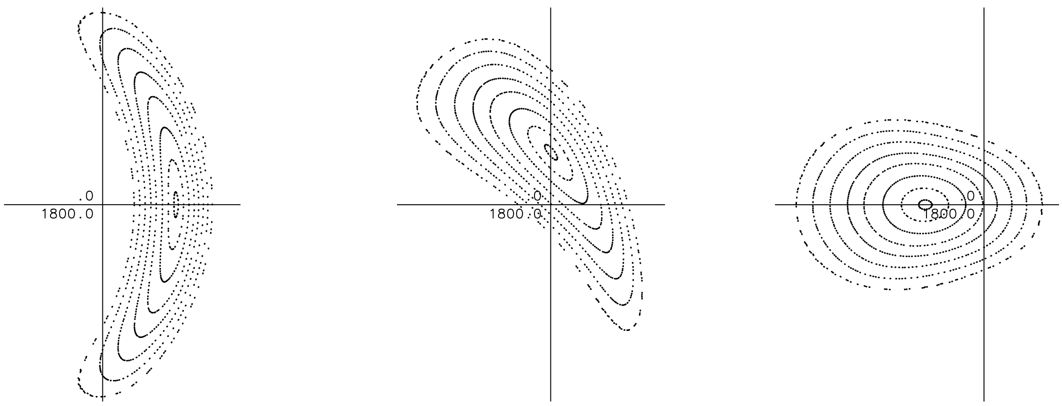

Fig. 7 Poincarè plots of magnetic surfaces of the HSR-M4a equilibrium field with $\bar{\beta} = 4.3\%$ at the beginning (left), 1/4 (middle) and 1/2 (right) of a field period.

Summary

The derived configurations with 4 field periods allow the reduction of the major radius to 18 m. The shapes of the coils are similar to that of the current Helias reactor. The neoclassical transport coefficient, the bootstrap current and the loss of fast α-particles are very low. Equilibrium calculations show that the Shafranov shift and the reduction of the central rotational transform are small at reactor-relevant β values. A further optimization of the configurations with 4 field periods is possible with respect to the stability limits. For a burn experiment, where high power output and a breeding factor > 1 is not necessary a device with $R \approx 15m$ seems to be possible.

Referenzes

[1] Kißlinger, J., et al., Proc. 17^{th} Int. Conf. on Fusion Energy, Yokohama (1998), 1239.

[2] Hirshman, S.P., van Rij, W.I., Merkel, P., Comput. Phys. Comm. 43 (1986) 143.

[3] Strumberger, E., Nuclear Fusion 37 (1997) 19.

[4] Nührenberg, J., Zille, R., in Proc. Workshop on Theory of Fusion Plasma, Varenna 1987, (1988), Eur 11336 EN, 3.