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Equilibrium and Stability Properties of a Helias Reactor

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Helias (Helical Advanced Stellarator) configurations are studied at the IPP Garching with respect to their usefulness for a Helias reactor. In this paper a configuration is investigated with respect to its equilibrium and MHD stability properties up to an averaged volume beta of $\langle\beta\rangle = 5\%$. It is characterized by a major radius of $R_0 = 22$ m, a plasma radius of $a_0 = 2$ m and low shear, that is, the rotational transform value of the vacuum magnetic field amounts to $\iota = 0.875$ on the magnetic axis and $\iota = 5/5$ in the edge region. There, five macroscopic islands surround the last closed magnetic surface (LCMS). The coil system consists of five field periods with ten coils per period which produce a vacuum magnetic field of 5 T on the magnetic axis. In comparison to a previous design [1] the geometry of the coils has been slightly changed in order to reduce the shear and to increase the magnetic mirror. Here the mirror field amounts to approximately 10%.

For the MHD equilibrium and stability computations a system of numerical codes is used. Three-dimensional free-boundary equilibria and the corresponding magnetic fields are computed self-consistently for various pressure profiles and β-values up to $\langle\beta\rangle = 5\%$ by means of the NEMEC, MFBE and GOURDON codes. The NEMEC code [2] computes a free-boundary Helias equilibrium for a given toroidal flux and the MFBE code [3] calculates the magnetic field of this equilibrium on a grid inside and outside the plasma boundary. This magnetic field serves as input to the GOURDON code, which is used to determine the LCMS of this field. If the LCMS does not coincide with the plasma boundary obtained by the NEMEC code, the toroidal flux, which is a free parameter in the NEMEC code, is modified, i.e. the toroidal flux is determined iteratively. Figure 1 shows the magnetic fields for $\langle\beta\rangle = 0$ and 4%. The edge region ergodizes for $\langle\beta\rangle \geq 2\%$. The width of the 5/5 islands increases with β, while the positions of the X- and O-points of these macroscopic islands are almost unchanged. This is a favourable behaviour with respect to divertor operation.

Comparisons of the resulting finite-β magnetic fields with the corresponding vacuum field produced by the external coils yield informations about the variations of the Shafranov shift, the aspect ratio, the magnetic well and ι-profile with increasing plasma beta. Table I contains the values of the rotational transform at the magnetic axis, the

Shafranov shift, the plasma volume, the aspect ratio and the magnetic well in dependence on $\langle\beta\rangle$.

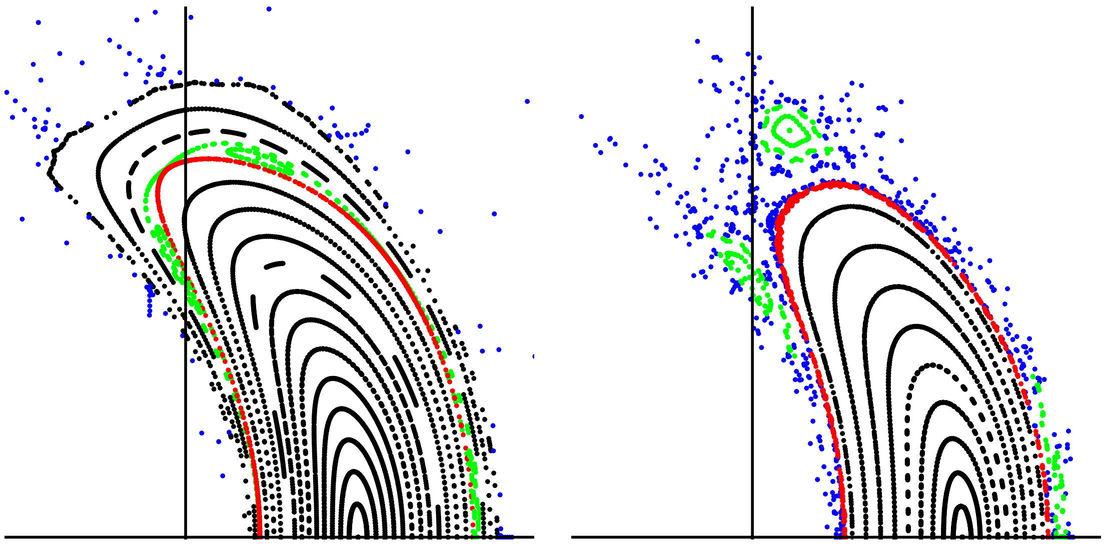

FIG. 1: Upper halves of the Poincaré plots at the symmetric bean-shaped cross-section for the vacuum magnetic field (left figure) and the finite-β magnetic field with $\langle\beta\rangle = 4\%$ (right figure).

TABLE I: Rotational transform ι_0 on the magnetic axis, Shafranov shift $\Delta R/a_0$ (ΔR = mean shift of the magnetic axis, a_0 = plasma radius), volume V enclosed by the LCMS, aspect ratio A and magnetic well V'' for various $\langle\beta\rangle$.

$\langle\beta\rangle$ [%]	ι_0	$\Delta R/a_0$ [%]	V [m^3]	A	V'' [%]
0	0.875	-	1828.4	10.60	0.68
1	0.867	6.3	1744.3	10.98	2.59
2	0.860	12.3	1681.6	11.20	4.37
3	0.849	18.1	1623.5	11.45	6.00
4	0.837	23.4	1570.5	11.68	7.61
5	0.820	28.9	1521.3	11.91	9.14

One of the main results is the small Shafranov shift. It is in the expected range of a Helias configuration and fulfills the requirement of a fusion reactor. From this point of view a further optimization of Helias configurations is not necessary. Further, equilibria with a sufficient plasma volume exist up to $\langle\beta\rangle = 5\%$. Figure 2 illustrates the behaviour of the ι-profile. The rotational transform decreases with rising plasma pressure leading to the existence of low order rational surfaces in the plasma centre where the onset of MHD instabilities is to be expected. The first surface of this kind is the surface with $\iota = 5/6$, which appears around $\langle\beta\rangle = 4.2\%$ and a peak value of $\beta(0) = 10.3\%$.

Investigations of Mercier and resistive interchange criteria and local ballooning modes, made with the JMC code [4], show stability up to $\langle\beta\rangle = 4\%$. For $\langle\beta\rangle = 5\%$ Mercier and resistive interchange criteria show instability around the 5/6 resonance (see Fig. 3), and local ballooning modes are even unstable for higher mode numbers, e.g. $\iota = 5/6, 6/7, 7/8$ and $8/9$.

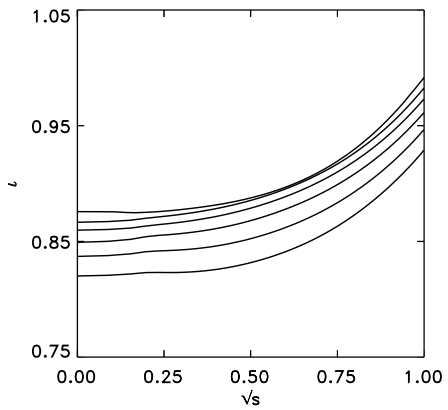

FIG. 2: Rotational transform profiles ι for the vacuum field (upper curve) and the finite-β magnetic fields up to $\langle\beta\rangle = 5\%$ (lower curve) versus $\sqrt{s}$ with s the normalized flux label.

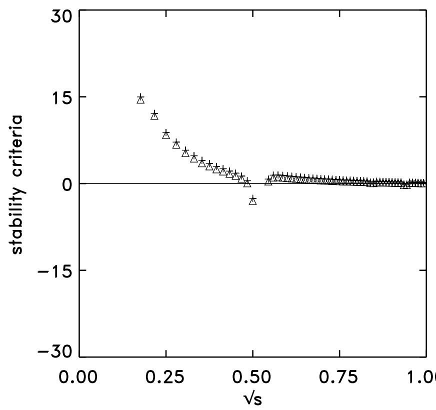

FIG. 3: Mercier (+) and resistive interchange (Δ) criteria versus $\sqrt{s}$ for $\langle\beta\rangle = 5\%$. Instability occurs at $\sqrt{s} \approx 0.5$ for $\iota = 5/6$.

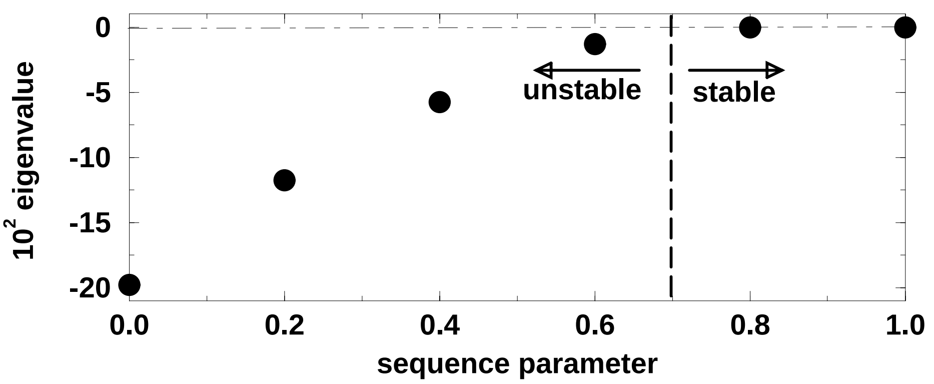

FIG. 4: Result of a global ideal MHD stability study of the $\langle\beta\rangle = 4\%$ equilibrium: CAS3D2 eigenvalues versus an artificially introduced factor which was applied to the main stabilizing term in the MHD energy functional, so that for sequence parameter unity the full MHD energy functional is obtained. The stability limit is reached at approximately 0.7 in the sequence parameter.

In addition, the equilibrium with $\langle\beta\rangle = 4\%$ has been investigated with respect to the global ideal MHD stability by using the CAS3D code [5] in its fixed-boundary version CAS3D2 which uses the incompressibility constraint on the MHD displacement vector. In order to assess the stability of a single equilibrium here a 1-parametric sequence of stability calculations has been generated by artificially varying the amount of the main stabilizing term, such that for vanishing sequence parameter the stabilizing terms are considerably reduced and that for sequence parameter unity the full MHD energy functional is obtained. Various perturbation Fourier tables have been used, especially including both mode families present in a 5-periodic device. The computation parameters have been chosen to be comparable to those used for the investigation of the W7-X stability [6] (64 radial grid point, 115 perturbation Fourier harmonics, N=2 mode family). As an example Fig. 4 shows CAS3D2 eigenvalues as obtained in such series of calculations for N=2 mode family perturbations. The results show that in this sequence a stability limit is obtained for a value of the sequence parameter of approximately 0.7. Similar results have been obtained also for the N=1 mode family, so that it may concluded that this equilibrium is stable with a good safety margin.

Equilibrium and stability properties of the Helias reactor solely depend on the beta profile while confinement and fusion power output depend on the details of the temperature and density profiles. A parameter set which is compatible with the limits listed above is the following (Table II):

TABLE II: Design values of the reactor plasma.

Magnetic field	5	T
Peak temperature $T(0)$	14	keV
Peak density $n(0)$	$2.4 \cdot 10^{20}$	m^{-3}
Average beta $\langle\beta\rangle$	4.25	%
Peak beta $\beta(0)$	10.5	%
Fusion power	2.9	GW
Confinement time	2.1	s

In summary, the present analysis of MHD equilibrium and stability shows that the reduction of the Shafranov shift and the stability limits are sufficiently optimized for the purpose of a Helias reactor.

References

[1] Beidler, C.D., et al., Proc. 16th In. Conf. on Fusion Energy, Montreal 1996, IAEA, Vienna 1997, Vol.3, 407.

[2] Hirshman, S.P., et al., Comput. Phys. Comm. **43** (1986) 143.

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

[4] Nührenberg, J., et al., in Proc. Workshop on Theory of Fusion Plasma, Varenna 1987, Eds. A. Bondesin, E. Sindoni, F. Troyon, 1988, EUR 11336 EN, 3.

[5] Nührenberg, C., Phys. Fluids B **5** (1993) 3195.

[6] Nührenberg, C., Phys. Plasmas **3** (1996) 2401.