ON BOOTSTRAP CURRENTS IN HELIAS CONFIGURATIONS

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A Introduction. Neoclassical bootstrap currents cause severe problems in stellarators since the profile of the rotational transform is modified with increasing plasma pressure. This effect has been observed in the experiments, particularly in *Wendelstein VII-A* and *Wendelstein VII-AS*, where shear is low and with small changes of the rotational transform low order rational magnetic surfaces arise and confinement tends to deteriorate. Therefore, in future stellarators neoclassical bootstrap currents should be avoided by proper shaping of the magnetic surfaces. As has been shown by Shaing and Callen [1] bootstrap currents in stellarators can be made small by the counteracting effect of toroidal curvature and helical stellarator fields. In quasi-helically symmetric stellarators [2] bootstrap currents flow opposite to those in axisymmetric configurations, however, they are smaller than these. A certain deviation from symmetry seems to be necessary for achieving small bootstrap currents. The present paper discusses analytic theory relating bootstrap currents to neoclassical radial losses and presents some results of numerical calculations based on the DKES-code [3] .

B Analytic theory . Bootstrap currents are the result of parallel momentum balance on every magnetic surface. Particle drifts in the magnetic field lead to a distortion of the distribution function $f(v_{\|})$ and a deviation from the Maxwellian which is balanced by collisions. In the macroscopic picture this leads to tangential forces in the magnetic surface described by the anisotropic part of the pressure tensor. The momentum balance and the resulting flux-friction relations [4] have been widely used in literature to express the bootstrap current in terms of these tangential forces or so-called parallel viscosity. The flux-friction relations also contain radial plasma losses consisting of Pfirsch-Schlüter fluxes and neoclassical fluxes and therefore these equations provide a correlation between bootstrap currents and neoclassical radial losses. Such a relation has already been found by Bickerton et al. [5] for tokamaks. In [6] this proportionality between currents and fluxes has been extended to helically symmetric and quasi-helically symmetric stellarator configurations and yields

$$\eta < B^2 > I'(\psi) = C(\psi)\,(\iota - \gamma_\omega)\{\frac{\Gamma_{neo}}{N} + 0.32\,\frac{q_{e,neo}}{NT_e}\}. \tag{1}$$

$I'(\psi)\,d\psi$ is the differential toroidal current on a magnetic surface $\psi=$ const, $\eta=$ Spitzer resistivity, $\iota=$ rotatitional transform, $\gamma_\omega=$ slope of the invariant direction. $\Gamma_{neo}, q_{e,neo}$

= neoclassical particle flux and electron thermal flux. $C(\psi)$ is a positive constant on the magnetic surface. Tokamak results are obtained by setting $\gamma_\omega = 0$. Equation (1) can be generalized to an arbitrary non-symmetric stellarator, in that case the coefficient $C(\psi)$ can be of either sign and the exact value has to be found from kinetic theory. Details are given in [6] .

C Quasi-helically invariant configurations. These are characterized by the magnetic field being a function of one variable $\theta - \gamma_\omega \phi$ alone (θ, ϕ = poloidal and toroidal magnetic coordinates). Since particle orbits in magnetic coordinates and consequently neoclassical effects are only determined by $B(\theta, \phi)$ and not by the shape of the magnetic surfaces, this implies, that neoclassical tokamak theory can easily be transferred to helically symmetric or quasi-helically symmetric configurations. This isomorphism has been pointed out in [7]. Based on this similarity and Eq.(1) the bootstrap current and the resulting shift of ι are evaluated for helically invariant configurations. The neoclassical fluxes are taken from ref. [8]. In the long-mean-free-path regime, where bootstrap current is largest, this leads to a total current

$$I \approx I_o \, \beta(0) \, (R/a)^2 \sqrt{\epsilon} \frac{0.3}{\iota - \gamma_\omega}. \tag{2}$$

$I_o = 2\pi a^2 B/\mu_o R$ is a reference current with $\iota = 1$, a = av. plasma radius, $\sqrt{\epsilon}$ = number of trapped particles. In extrapolating this to a quasi-helically invariant Helias configuration with R = 6.5 m, a = 0.6 m, B = 2.5 T, $\iota = 0.85$, $\gamma_\omega = 5$ and n(0) = 10^{20}m^{-3} the bootstrap current is 300 kA at $T_e(0) = 8$ keV. The corresponding shift of the rotational transform is $\delta\iota$ = -(0.25 -0.3) depending on the plasma profiles. Eq. (2) says that the bootstrap current in helically invariant stellarators is negative and smaller than the current in a tokamak with the same aspect ratio, the factor is $\iota/(\iota - \gamma_\omega)$.

D Non-symmetric stellarators. The shift of ι in helically invariant stellarators is still too large to be tolerable and therefore a superposition of several helical harmonics, leading to a small deviation from helical symmetry, may be necessary to reduce the bootstrap current further. In realistic Helias configurations (see [9]) the magnetic field

$$B = B_o \{ \sum_{m,n=0} C_{n,m} \cos(n\phi) \cos(m\theta) + S_{n,m} \sin(n\phi) \sin(m\theta) \} \tag{3}$$

not only contains the dominating helical harmonic $C_{1,1}$ and $S_{1,1}$, but also the toroidal term $C_{0,1}$ and higher harmonics. In [9] an example of a five-period Helias configuration and the spectrum of B is given. The geometrical bootstrap factor $G_b \, f_f/f_c$ [10] , which determines the bootstrap factor in the $lmfp$-regime has been computed for various Helias configurations. For comparison, this factor is normalized to an axisymmetric configuration with the same rotational transform and the same aspect ratio. Fig. 1 shows the bootstrap factor for various Helias configurations with the magnetic field generated by coils. The case HS-5-8A is described in [9] . As can be seen, the bootstrap factor ranges between -0.1 and +0.1, which means that the bootstrap current is smaller than $1/10$ of the current in an equivalent tokamak. The dominant terms in $B(\theta, \phi)$ responsible for the bootstrap current are $C_{1,1}, S_{1,1}$ and $C_{0,1}$. The value of $C_{0,1}$ needed to compensate for the current of the helical harmonics $C_{1,1}$ and $S_{1,1}$ is roughly $|C_{0,1}| \approx 0.3 \cdot |S_{1,1}| or |C_{1,1}|$. The case HS-5081 is nearly quasi-helically invariant, symmetry-breaking terms are $C_{0,1}$ and $C_{2,2}$. Here, a toroidal term $|C_{0,1}| \approx 0.18 \cdot |C_{1,1}|$ is sufficient to reduce $G_b\, f_t/f_c$ to -0.1, without these term we find $C_b\, f_t/f_c = -(0.24 - 0.3)$.

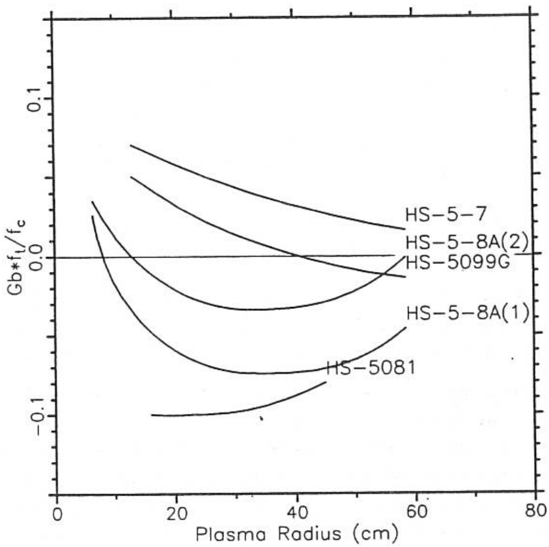

Fig. 1 *Normalized bootstrap factor $G_b\, f_t/f_c$ vs plasma radius for several 5-period Helias configurations. The configuration HS-5-8 is described in ref. [9]*

<u>E Results of numerical calculations.</u> Using the DKES-code [3] the coefficient of the bootstrap current can be calculated for all regimes of collisionality. This code solves the drift-kinetic equation and yields the whole transport matrix D_{ik} with the non-diagonal term D_{31} being the relevant coefficient. Numerical results of Helias configurations show negative bootstrap currents in nearly quasi-helically invariant cases (HS-5081). Fig. 2 shows the result in comparison with the coefficient of the equivalent axisymmetric case. The factor D_{31} is smaller than in the axisymmetric case, however it exhibits a strong dependence on the collisionality ν^* and the radial electric field. In the *lmfp*-regime the coefficient D_{31} changes from negative to positive, this cross-over point, however, depends on the particular magnetic surface and on the radial electric field. This feature complicates the comparison with the *lmfp*-limit G_b. A similar behaviour was also found in the other configurations listed in Fig. 1.

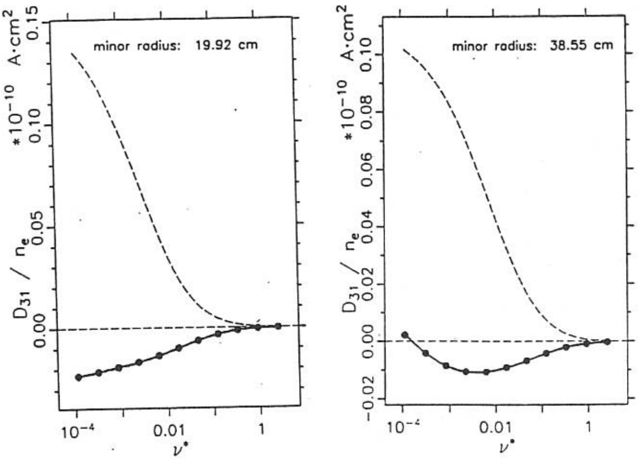

Fig. 2 *Bootstrap coefficient D_{31}/n of the Helias configuration HS-5081 vs collisionality (solid line). Broken line: equivalent axisymmetric configuration. Electric field E=0. Plasma parameter: B=3 T, T_e=2 keV, ι=0.89.*

F Summary and conclusions. Bootstrap currents in optimized Helias configurations have been computed by various methods. In 5-period configurations the current is about a factor 10 smaller than in the equivalent axisymmetric case. This low value may be acceptable in stellarator experiments, however, it is found that bootstrap currents depend sensitively on the Fourier spectrum of the magnetic field and therefore accurate calculations are required. Evaluation of the G_b-factor shows that a toroidal $C_{0,1}$-term of the order $0.3 \cdot |C_{1,1}|$ is needed for sufficiently small bootstrap currents, however, results from the DKES-code show that the size of the current also depends critically on the radial electric field and the collisionality.

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