BOOTSTRAP CURRENT IN STELLARATOR CONFIGURATIONS

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Neoclassical transport theory predicts the existence of a net toroidal current, the so-called bootstrap current. The presence of this current in stellarators of the next generation (WENDELSTEIN VII X, LHS, etc.) can affect the stability behaviour and the confinement properties of these systems. Therefore it is desirable to reduce its value in order to attain a nearly currentless regime of operation.

The theory of bootstrap currents has been established in several papers [1], [2], [3]. In the present paper a numerical evaluation of the geometrical coefficient C_b characterising the effect of the geometry of magnetic surfaces on the bootstrap current is given for several advanced stellarators with reduced Pfirsch-Schlüter currents.

If the magnetic field $B(\eta, \varsigma)$ on a magnetic surface is given in terms of a Fourier series:

$$B = \sum a_{l,m} \, cos(l\eta - m\varsigma) + b_{l,m} \, (l\eta + m\varsigma)$$

where (η, ς) are the poloidal and toroidal Hamada coordinates, the coefficient C_b depends on the rotational transform ι and the coefficients $a_{l,m}, b_{l,m}$. C_b will be normalized to an axisymmetric configuration with the same aspect ratio and the same rotational transform.

As has been pointed out in [1] the driving term for the bootstrap current is the parallel viscosity $< \mathbf{B} \cdot \nabla \cdot \pi_{>}$ with $\pi_{i,k} \sim (p_{\|} - p_{p\perp})(n_i n_k - \frac{1}{3}\delta_{ik})$, $n_i = B_i/B$. π is the anisotropic pressure tensor in the Chew-Goldberg-Low form.

$$p_{\|} - p_{\perp} \sim \int f_1 (v_{\|}^2 - \frac{1}{2} v_{\perp}^2) d^3\mathrm{v} \tag{1}$$

The relevant term h_1 of the perturbed distribution function f_1 has to be calculated from the drift kinetic equation (see Ref. 4)

$$L\, h_1 =: v_{\|} \frac{\mathbf{B}}{B} \cdot \nabla h_1 - C[h_1] = \frac{(v_{\|}^2 - \frac{1}{2} v_{\perp}^2)}{v_{th}^2} (\frac{\mathbf{V}_j \cdot \nabla B}{B}) f_o \tag{2}$$

f_o = local Maxwellian, C = collision operator, $\mathbf{V}_j$ is the lowest order plasma flow of each particle species j within the magnetic surface.

$$\mathbf{V}_j = [\frac{kT}{q_j}\frac{N_j'}{N_j} + \Phi'(\psi)]\mathbf{V}_o + \Lambda_j\mathbf{B} \tag{3}$$

$N_j(\psi)$ = plasma density, $\Phi(\psi)$ = electric potential, $\mathbf{V}_o$ is a poloidal vector with $\mathbf{V}_o \times \mathbf{B} = \nabla\psi$ and $\nabla \cdot \mathbf{V}_o = 0$. The vector $\mathbf{V}_o$ is proportional to $\mathbf{B}_p$, see in [1].

After evaluating $< \mathbf{B} \cdot \nabla \cdot \pi_j >$ and using eqs. (1), (2) and (3), the geometrical bootstrap factor C_b is:

$$C_b \sim \langle \int (v_\parallel^2 - \frac{1}{2}v_\perp^2)\frac{\mathbf{B}\cdot\nabla B}{B}L^{-1}\{(v_\parallel^2 - \frac{1}{2}v_\perp^2)f_o\frac{\mathbf{V}_o\cdot\nabla B}{B}\}d^3\mathrm{v}\rangle \tag{4}$$

In the collision dominated regime this reduces to:

$$C_b \sim \langle(\frac{\mathbf{B}\cdot\nabla B}{B})(\frac{\mathbf{V}_o\cdot\nabla B}{B})\rangle \tag{5}$$

which can also be obtained from Braginskii's form of the bulk viscosity [5]. In the plateau limit eq. (4) coincides with the equations given by Shaing, Solano [3].

In the long-mean-free path regime the coefficient has been given by Shaing et al. [2]. A numerical investigation of it has been done by Ohkawa ($C_b = (\frac{f_t}{f_c})G_b$) [6].

It can be shown, that the bootstrap current is zero if the Pfirsch-Schlüter currents vanish ($j_\parallel = 0 \rightarrow C_b = 0$) therefore it is expected, that stellarators with low Pfirsch - Schlüter currents also exhibit small bootstrap current.

In Helias configurations [7] the parallel plasma currents $j_\parallel$ are as large as the diamagnetic currents $j_\perp$. A 4-period configuration is shown in Fig. 1. Locally the bootstrap current is not zero, however, integration over a magnetic surface yields nearly zero toroidal current (see table I) In table I the normalized geometrical bootstrap factor C_b (*or* G_b) is given for several Stellarator configurations, beginning with Wendelstein VII-A. $C_b = 1$ corrsponds to the equivalent axisymmetric device.

As shown in table I the bootstrap factor in the Pfirsch-Schlüter regime is negative in most cases and differs appreciably from unity. However, the absolute value of the bootstrap curent is negligible in the collisional regime. In the plateau regime circulating particles carry the bootstrap current. In W VII - A the factor C_b is of the order one, but in the W VII - AS already a smaller C_b arises. In Helias configurations (last three cases in table. I) various cases with large or very small bootstrap factors can be realized.

In the loong-mean-free-path regime (last column in table I.) the three Helias cases show low bootstrap current too.

As has been pointed out by Shaing, Callen [1] the bootstrap current in conventional stellarators or torsatrons can change sign across the plasma radius, thus making the integral bootstrap current very small. The analysis presented here proves the existence of Helias type configurations with vanishing bootstrap current on every magnetic surface.

References

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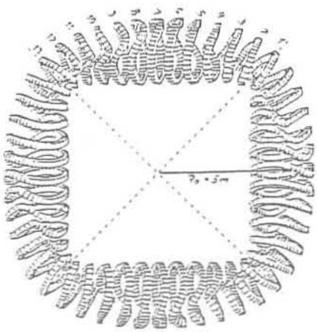
	Regime→ Method→	Pfirsch - direct	Schlüter Fourier	Plateau Ref. 3.	Banana Ref.8.
System	Radius[cm]				
W-VII A	1.1	0.0005 ...	-0.12 ...	1.0	~ 0
	5.6	-0.274	-0.3	0.99	-0.12
	10.1	-0.88	-0.94	0.96	-0.25
W-VII AS	5	2.77	2.05	0.72 ...	-0.03
	10	0.86	0.11	0.6	-0.11
	20	-1.53	-1.78	0.2	-0.2
HC5E1	9	-8.64	-4.6	-2.2 ...	-2.16
	27	-8.65	-4.8	-2.2	-1.1
	45	-8.83	-5.3	-2.4	-3
BSX52	11	7.4	10	0.18 ...	-0.03
	21	8.4	15.3	0.31	-0.15
	30	11.3	23	0.29	-0.06
HELIASK	3	-9.7	-9.1	-1.33 ..	-0.08
	15	-9.3	-8.8	-1.43	-0.11
	31	-7.7	-7.7	-1.30	-0.2
HS4E8	13	-0.1	-0.056 ..	.....	-0.02
	30	-0.1	-0.03	0.	-0.22
	42	-0.15	-0.072		0.1
HSV11	10	-0.056 ...	-0.056 ..	-0.02 ..	-0.04
	27	-0.6	-0.64	-0.03	-0.09
	45	-0.36	-0.85	-0.04	-0.09

TABLE I Bootstrap coefficients C_b *or* G_b of different stellarators.

HELIAS - Configuration HS-4-11

Modular Coil System of HS-4-11



Magnetic Surface of HS-4-11

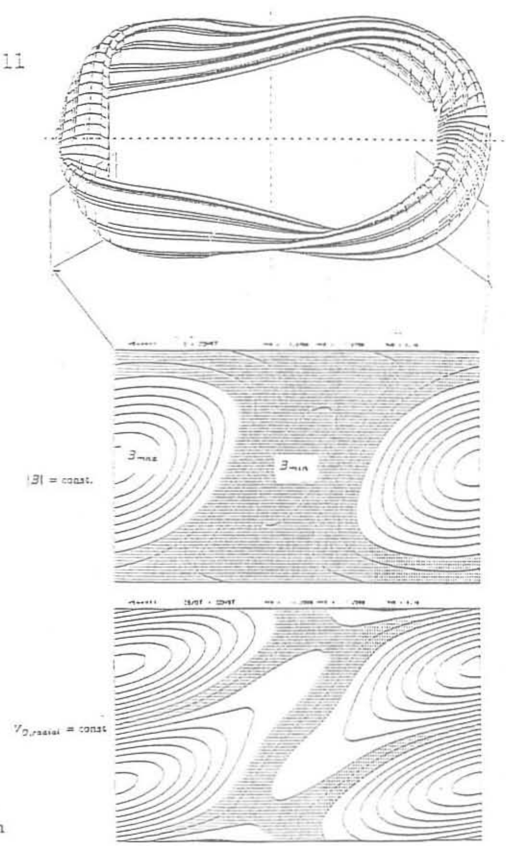


Fig. 1.

This figure shows a magnetic surface of a 4-period Helias configuration with reduced Pfirsch-Schlüter currents. The $|B|$ = const. plot (middle) indicates the region of localistaion for trapped particles. On the last figure the local radial drift velocity is shown, which is particularly small in the region of trapped particles. Small radial drift velocity reduces all neoclassical effects including the bootstrap current too.