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ASYMMETRY CURRENT IN TOROIDAL MAGNETIC TRAPS

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The standard concept of a steady-state tokamak-based fusion reactor needs to use an external current source to produce the toroidal current near magnetic axes of an device. In this context, it is of interest to discuss a new natural mechanism for generating a steady-state longitudinal current near magnetic axes. The origin of this current is the asymmetry of the boundary between transit and trapped particles in phase space. The magnitude of this new current – *asymmetry current* – is proportional to the plasma pressure, and has maximum near the magnetic axes of device [1].

Let us consider the motion of charged particles in a tokamak magnetic field. In this case the trajectories of charge particles in drift approximation may be found from

$$\varepsilon^2 - \varepsilon_s^2 + \sigma_s \varsigma \sqrt{h_s}\sqrt{G + \varepsilon_s \cos\theta_s} = \sigma_v \varsigma \sqrt{h}\sqrt{G + \varepsilon\cos\theta} \qquad (1)$$

where $\varepsilon = r/R$, r is the radial position of a particle, R is the tokamak major radius, θ is the poloidal angle, r_s and θ_s are the coordinates of the point where the particle crosses the magnetic surface, $h = 1 + \varepsilon\cos\theta$, $\varsigma = 2q\rho/R$, q is the safety factor, ρ is the Larmor radius of the particle in the toroidal magnetic field, $\sigma_s = \pm 1$ is the sign of the particle velocity in the point with coordinates r_s, θ_s, $\sigma_v = \pm 1$ is the sign of the particle velocity in the point with coordinates r, θ, $G = 1 - \mu B_0 / E$ is the invariant quantity expressed in terms of the particle magnetic moment μ, toroidal magnetic field value B_0 and the particle energy E. It is important to stress that, in contrast to σ_v, σ_s is an integral of motion. Note that, in

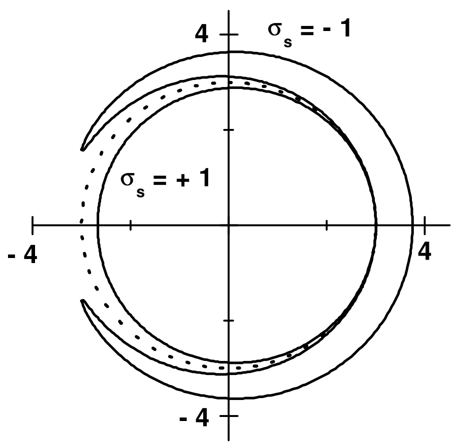

Fig.1. Particle trajectories in the second subrange of **G**

tokamak , a particle with $\sigma_s = +1$ moves in the direction of the ohmic current.

The analysis of Eq.1 shows that the full range of the invariant G changes, $-\varepsilon_s \cos\theta_s \le G \le 1$, may be divided on the three subranges. In the first subrange particles with both values of σ_s are trapped, in the second subrange the particles with $\sigma_s = +1$ are transit and the particles with $\sigma_s = -1$ are trapped (see Fig.1) and in the third subrange both kind of particles are transit. Let us show that it is the second subrange in which the particle motion give rise to a new longitudinal current. If we neglect the precession velocity of the trapped particles, we can see that their mean toroidal velocity is close to zero, so these particles make essentially no contribution to the longitudinal current. In the third subrange the number of particles moving in either direction is the same, so that they also do not contribute to the current. Since the flux of the transit particles only in the second subrange in phase space is not balanced , it drives the longitudinal current.

The longitudinal current in a closed magnetic confinement system can be estimated from the mean toroidal velocity of the transit particles from the second subrange. This velocity can be defined as the ratio of the distance Δz the particle propagates in the toroidal direction during the time interval Δt required for it to complete a revolution in the poloidal direction to this interval (so-called bounce-averaged longitudinal velocity)

$$< v_{II} >= \frac{\oint v_{II} d\tau}{\oint d\tau} \tag{2}$$

where $d\tau = d\theta/\omega$, $\omega = \frac{1}{qR}\left(v_{II} - \frac{\varsigma(v^2 + v_{II}^2)}{4\varepsilon v}\cos\theta \right)$ is the poloidal angular velocity of a particle, $v_{II} = v\sqrt{h}\sqrt{G + \varepsilon\cos\theta}$ is the particle parallel to the toroidal magnetic field velocity. After averaging (2) over magnetic surface we obtain the expression for the longitudinal current calculation

$$< j_A >= e\frac{2\pi}{l_s}\int_0^{\infty} EdE \int_{G+}^{G-} dG \oint \frac{dl_s}{|v_{II}|_s} < v_{II} > f \tag{3}$$

where dl_s is an element of length of poloidal cross-section of the magnetic sutface, $G+$ and $G-$ are the boundary values of G of the second subrange. For calculations we used the following model distribution for transit particles in second subrange

$$f = f_M\left[H(G - G+) - H(G - G-)\right] \tag{4}$$

Here, f_M is a Maxwellian distribution function and the Heavisade step function $H(x)$ is defined to be zero for $x < 0$ and to be unity for $x \geq 0$.

The result of the asymmetry current calculations, taking into account the plasma elongation K and triangularity δ, for tokamak can be approximated by the expression

$$< j_A >= \frac{0.55}{(1+0.1\delta)(1+0.1K)} \frac{\varsigma_T nev_T}{\sqrt{\varepsilon_s + \varsigma_T^{2/3}}} \sim \frac{P}{\sqrt{s_s + \varsigma_T^{2/3}}} \tag{5}$$

where the index T shows that parameters are calculated with $v = v_T$ and v_T is a thermal velocity of a particle, and P is plasma pressure.

From Eq.(5) one can see that asymmetry current depends on plasma pressure, in contrast with bootstrap current which depends on plasma pressure gradient. The asymmetry current density has maximal value near magnetic axes of device.

The same asymmetry current must be in stellarator too. Let us a stellarator with a circular magnetic surfaces and the following model magnetic field

$$B = B_0\left[1 - \varepsilon\cos\theta - \varepsilon_h \cos(l\theta + M\varphi)\right] \tag{6}$$

where ε_h is the helical ripple amplitude, l is the multipolarity, M is the number of magnetic field periods, and φ is the toroidal angle. The estimation shows [1] that in this case for the asymmetry current calculations we can use Eq.(5) if we replace safety factor q by $1/\mu_{lM}$, where μ_{lM} is the rotational transform.

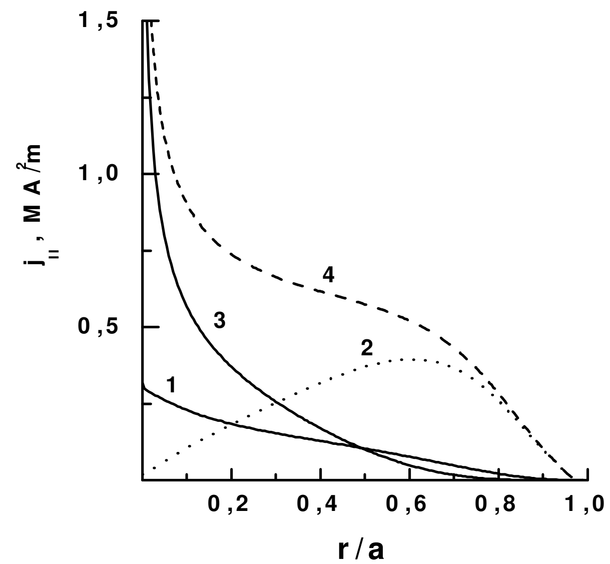

Fig.2. Radial profiles of the noninductive currents in ITER-FEAT tokamak

Our calculations show that the asymmetry current in a stellarator may be of the order of magnitude as that in a tokamak. That is why, that in stellarators without external excited inductive current, the asymmetry current is, presumbly, easier to reveal experimentally than in tokamaks.

In Fig.2 one can see the results of calculations of the radial profiles of the densities of noninductive currents in the ITER-FEAT tokamak. In Fig.2
curve 1 is for the total asymmetry current of plasma electrons and ions, curve 2 is for the bootstrap current, curve 3 is for the asymmetry current of α-particles, and curve 4 is for the total noninductive current. The calculations were carried out for the following radial profiles of plasma density and electron and ion temperatures: $n = 1.05 \times 10^{20} \left[1-(r/a)^2\right]^{0.025}$ m^{-3}, $T_{i,e} = 34\left[1-(r/a)^2\right]^{1.8}$ keV. The remaining parameter values being $K = 1.7$, $\delta = 0.4$, $z_{eff} = 1.65$, $I_p = 15.1$ MA. Under this conditions, the asymmetry current is 1.05 MA, the bootstrap current is 5.1 MA, and the asymmetry current of the α-particles is 1.1 MA. Thus, full noninductive current in these conditions will be 50% of the total plasma current.

In Fig.3 one can see the influence of the asymmetry current on the rotational transform in the stellarator with the same plasma parameters as ones in ITER-FEAT. The profile of the rotational transform from the stellarator winding is presented by the curve 1. The asymmetry current was calculated for the same plasma parameter as in ITER-FEAT. The curve 2 shows the rotational transform in stellarator if asymmetry current is taken into account. It is seen that asymmetry current in a stellarator can dramatically change the conditions of a device operations.

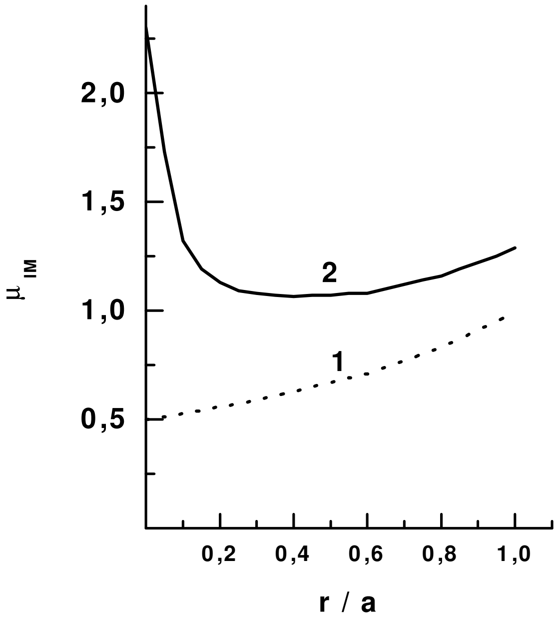

Fig.3. Influence of the asymmetry current on the rotational transform in the ITER-like stellarator

So one can conclude that the asymmetry current may substantially simplify the problem of creating a tokamak reactor.

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