ASYMMETRY CURRENT DRIVE IN TOKAMAKS
DURING ADDITIONAL PLASMA HEATING.

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1. Introduction. Economically profitable thermonuclear tokamak-reactor can be developed only with stationary operation. For such operating mode ensuring it is necessary to drive the permanent non inductive current both near the magnetic axis and in all plasma volume.

The effective "transvers" method of ICRH non-inductive longitudinal current drive is described in this report. During this ICRH in the resonance point both the perpendicular to the magnetic lines ($V_\perp$) and full (V) velocities rise while as the parallel velocity ($V_\parallel$) in the resonance point is not changed. This non-inductive current which we will named as asymmetry current during auxiliary plasma heating exist even for the uniform distribution of minority ions over the entire plasma cross-section. For the current drive near the magnetic axis potato particles are used [1]. The non-inductive current over the all plasma cross-section is driven by particles on banana orbits which are placed in low magnetic field area.

The calculations of drift orbits of charged particles, which are the base for asymmetry current simulation, were fulfilled taking into account the orbit invariants which are constant along full orbit except the resonance point where the ion absorb the perpendicular energy. Unlike to isotropic heating when the ratio between trapped and untrapped particles is practically not changed during perpendicular heating the biggest part of ions moves along banana orbits and so drive the asymmetry current. All data in this report were calculated for JET tokamak. In these calculations the value of magnetic field was 2.2 T, ion temperature was 5 KeV, and density was 4×10^{18} m^{-3}.

2. Current drive near magnetic axis. The charged particle orbit projection on the poloidal plane can be found with help of expression [1,2]

$$\varepsilon^2 = P_\varphi + \sigma_v \varsigma_T \sqrt{H + \varepsilon \cos\vartheta}\,\sqrt{1 + \varepsilon \sin\vartheta} \qquad (1)$$

where $\varsigma_T = 2q\varrho_T/R$ is parameter which is proportional to the particle Larmor radius ρ_T calculated with help of thermal velocity, q is safety factor, R is the major tokamak radius [3].

To describe the heating results let us introduce the parameter $\gamma = V_\perp / V_T$ which is the ratio of perpendicular to thermal velocity. Near the magnetic axis from expression (1) and taking into account the orbit invariants it is possible to obtain the expression for particle orbit calculation during perpendicular heating [3]

$$\varepsilon^2 = J + \sigma_v \varsigma_T \sqrt{G + (1 + \gamma^2)\varepsilon \cos \vartheta} \qquad (2)$$

Let us named the orbit as positive ($\sigma_s = +1$) if in start point the particle moves in the toroidal current direction and as negative ($\sigma_s = -1$) if in this point the particle moves in opposite direction. In Fig.1 one can see the orbit transformation of the absolutely untrapped particles ($V_\perp = 0$) and changing of its average velocity during parameter γ increasing.
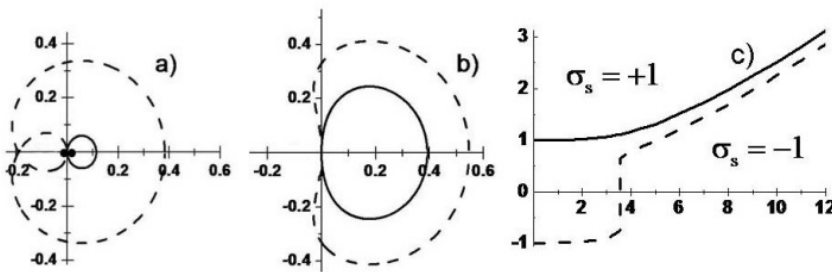

Fig.1 The orbit transformation of the absolutely untrapped particles ($V_\perp = 0$) and changing of its average velocity during parameter γ increasing as function of γ.
a – $\gamma = 3.56$, b - $\gamma = 10$, c – ξ $\xi = <V_\parallel>/V_T$
Solid line – $\sigma_s = +1$, dash line - σ_s - 1

Before heating the orbits of absolutely untrapped particles ($V_\perp = 0$) in this scale are look like points which are located on the left ($\sigma_S < 0$) and on the right ($\sigma_S > 0$) side relative to the magnetic axis. If the heating is relative low (at $\gamma < 3.56$) both particles are untrapped .

At $\sigma_s = +1$ all particles are untrapped and the further increasing of γ to result in orbit extension (Fig.1b). Particle orbit with $\sigma_s = -1$ at $\gamma = 3.56$ is the separatrix and further heating transforms them into banana and after in D-shaped (Fig.1b).

Fig.2. Hydrogen and helium current density as function of γ

For asymmetry current estimation let us use the parameter $\xi = <V_\parallel> / V_T$. The ξ value dependence on γ is presented in Fig.1c.

From this figure one can see that the average velocity of particles with $\sigma_s = +1$ during γ increasing is increasing monotonicaly. The average velocity of particles with $\sigma_s = -1$ up to $\gamma = 3.56$ is negative and at $\gamma > 3.56$ particles are conversed into trapped and its average velocity becomes positive and increases with γ increasing.

In Fig.2 one can see the result of asymmetry current density estimation for monoenergetic particles as function of γ at the JET magnetic axis for hydrogen and helium minorities. During this estimation the return current [4] was taken into account. The minority densities were taken as 10^{18} m^{-3} and q(0)=1 and plasma effective charge is $Z_{eff} = 1.7$. Since for helium $Z_{He} > Z_{eff}$ the current of the helium ions is negative versus hydrogen ions one. This fact give us possibility to adjust the safety factor value at magnetic axis with help of combination of density and heating of minority ions.

For current density estimations which is driving with help of ICRH the experimentally measured on JET tokamak ion distribution function [5] was used. It was found that current density estimated with help of ion distribution function is practically the same as current density estimated with help of average ion energy ($\gamma = 15$). So for the current density estimation it is not necessary to know ion distribution function.
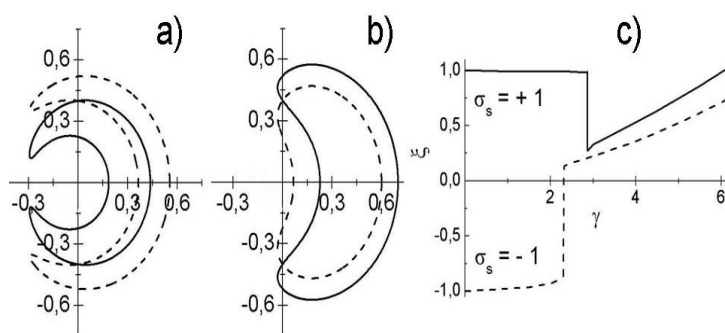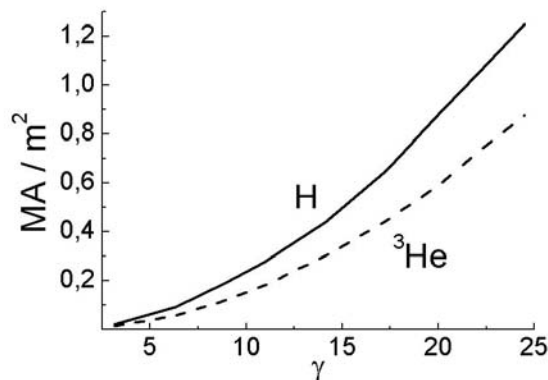

Fig.3. The evolution of the absolutely untrapped particles and changing of its average velocity during parameter γ increasing.
a - $\gamma = 3$, b - $\gamma = 10$, c – velocity changing.
Solid line – $\sigma_s = +1$, dash line - $\sigma_s = -1$

Estimations show that for hydrogen minority density which is equal to 1×10^{18} m^{-3} and helium minority density which is equal to 2.2×10^{18} m^{-3} the safety factor on magnetic axis is q(0) = 2. Let us pay attention to the fact that if q(0) = 4 the biggest part of hydrogen ions with energy equal to 1 MeV will not be confined in JET.

3.   Current drive in plasma volume. Let us assume that the resonance layer is located along the vertical line which is crossed the tokamak magnetic axis that is $B = B_0$.

In Fig.3 the evolution particle orbits with starting point which is located in x = 0 and z = r/a = 0.4 is presented. One can see that orbits of both signs tend to became into D-shape orbits (Fig.3a,b). When $\gamma = 2.87$ the positive and when $\gamma = 2.31$ the negative absolutely untrapped

particles become trapped. The average velocities of all particles with $\gamma > 3$ are positive (Fig.3c).

In Fig.4 one can see the current density distribution of monoenergetic minority in the

Puc.4. Dependence of current density in plasma volume driving by monoenergetic minority ions.

plasma volume ions as function of γ.

It is need to mention that all orbits which is heating inside the resonance band $-0.1 < x < 0.1$ are located in the region of low magnetic field, so the great asymmetry is present (Fig.5a). In Fig.5b the radial distribution of hydrogen and helium minority ions can be seen. From this figure it is possible to see that current radial distribution has maximum near

r/a~0.3. For r/a>0.6 these both distributions practically are the same. Estimations show that if q(0)=2 full asymmetry current in JET tokamak driven by described method may be as big as 2MA.
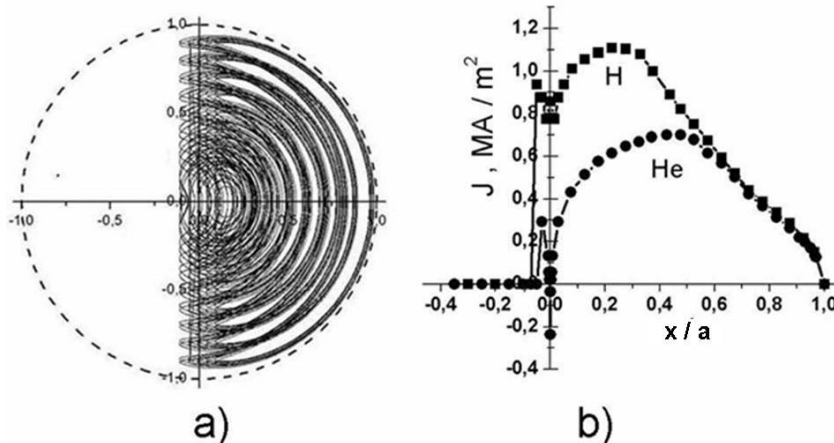

Fig.5. The orbit of heated particles in the plasma cross-section (a) and asymmetry current radial distribution driven be hydrogen and helium minority ions(b).

4. Conclusion.

Until now it was considered that trapped particles do not give contribution into toroidal current. Furthermore it was shown that under perpendicular heating the amount of trapped ions grows and driving effectiveness drops.

In this report it was shown that in reality under perpendicular heating trapped particles can drive the asymmetry current in MA range.

5. **References.** **1.** Eriksson L-G., Porcelli F. Plasma Phys. Controlled Fusion. 2001. V.43. P. R145.
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