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ASYMMETRY CURRENT in ICRF HEATING ITER PLASMAS

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The possibility of creation of a longitudinal asymmetry current in ITER with help of a transverse ion cyclotron resonance heating (ICR) of the plasma minority ions is discussed in this paper. Unlike to the bootstrap current, which is the current of self-generation created by plasma density and temperature gradients in falling magnetic field, the asymmetry current is driven by magnetic field inhomogeneous even in uniform plasma.

In this paper we discuss the asymmetry current drive in ITER taking into account the model description of Grad-Shafranov solution for magnetic surface shapes.

As the source we use the magnetic surface systems from paper [5], developed for High-T model.

For analysis the coordinates in which the *x* axis crosses the points which are defined the maximal size of magnetic boundary are used.

In this case *x* axis cross the magnetic axis of the plasma column and *y* axis passes through the middle between left and right plasma column boundary. In this coordinate system ITER magnetic surfaces are almost symmetric relative *x* axis. In this paper for simplicity we assume that flux surfaces are exactly symmetric relative to the x axes.

The flux function in this case will be

$$\psi = (1 - x^2)(1 + \eta x) - \frac{y^2}{K_{eff}^2}$$

where

$$K_{eff} = \frac{K(1-\delta^2)^{0.2}}{(1+\delta x)^{0.7}\sqrt{1+\eta x}}$$

K is the elongation, δ is the triangularity (in our coordinate system), η is the parameter which is connected with β_j and $l_i/2$

For any magnetic surface we have

$$y = \pm K_{eff}\sqrt{(1-x^2)(1+\eta x)-(1-x_s^2)(1+\eta x)}$$

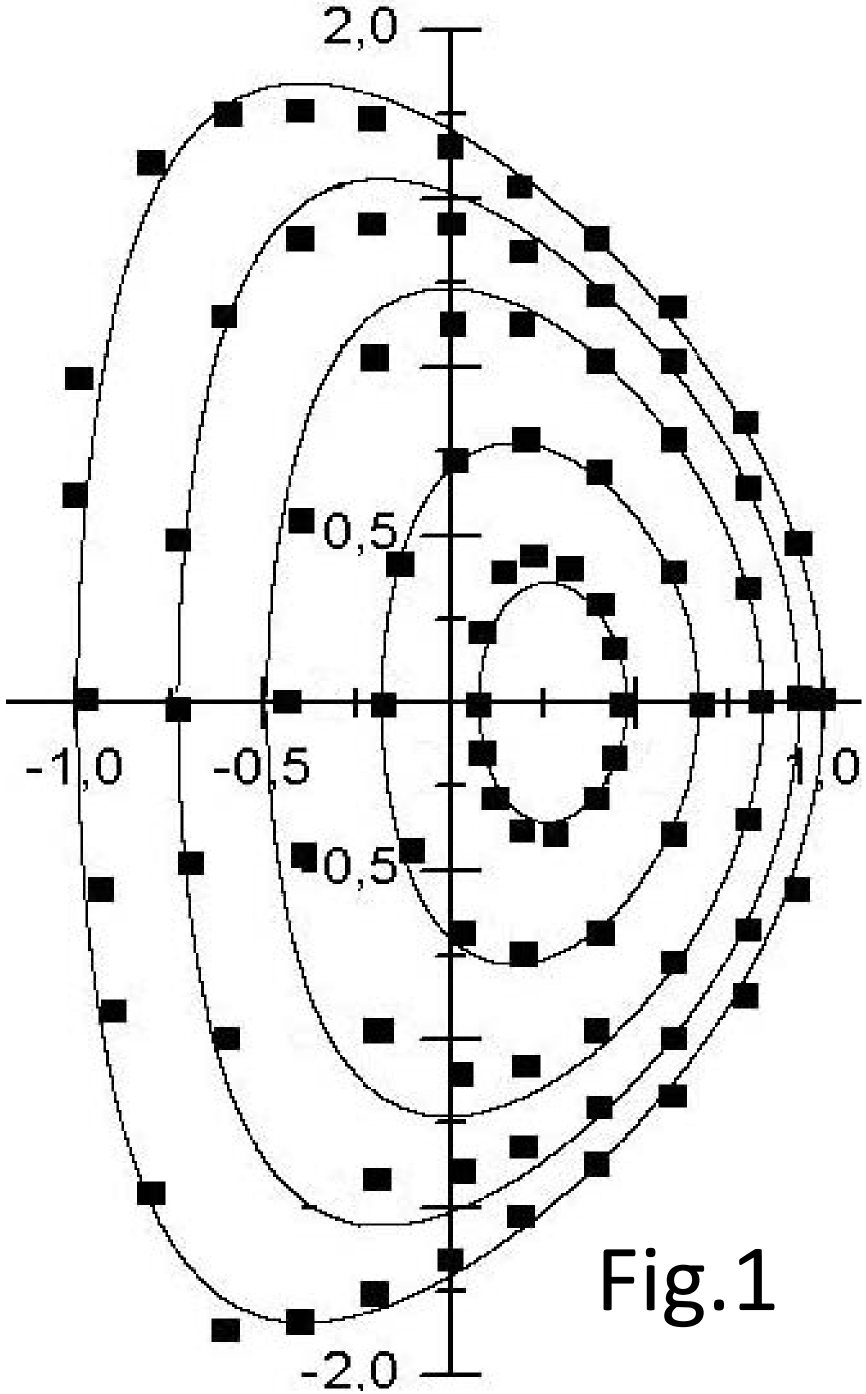

Fig.1

The comparison of the magnetic surface shapes. Solid lines are calculated with help of the formula, points are the data from [5].

If we take into account the real shape of magnetic surfaces and Shafranov shift during transverse ICR heating the orbit equation will be

$$\psi = \psi_s + \sigma_v \zeta_\gamma A^2 v_\parallel \sqrt{h} - \sigma_s \zeta_\gamma A^2 v_\parallel^s \sqrt{h_s}$$

Where ψ_s is ψ value at $x = x_s$, $\sigma_v = \pm 1$ is a sign of particle longitudinal velocity in x point (if $\sigma_v = +1$ the velocity is directed as Ohmic current), $\sigma_s = \pm 1$ is a sign of particle longitudinal velocity in x_s point,

$v_{\|}$ is the module of a particle longitudinal velocity in the *x* point, $v_{\|}^{s}$ is the module of a particle longitudinal velocity in the x_s point,

$$h = 1 + x / A, \;\; h_s = 1 + x_s / A, \;\; \varsigma_{\gamma} = 2\rho q / R,$$

ρ is the Larmor radius, *q* is the safety factor on magnetic axis, $A = R / a$ is the aspect ratio, *R* and *a* are the major and minor tokamak radii.

During transverse ICR heating of the plasma minority when the temperature of the bulk plasma is *T* $(T = mv_{\|}^{2} / 2 + mv_{\perp}^{2} / 2)$ in a resonance point the perpendicular $(v_{\perp})$ and full v velocities rise.

The parallel velocity at the resonance is not affected by the heating.

To describe the heating results let us use the parameter $\gamma^2 = \Delta E_\perp / T$, where $\Delta E_\perp = E_{\perp\gamma} - E_{\perp T}$

In this case the parallel velocities are

$$v_\| = \frac{1}{\sqrt{h}} \sqrt{G - \frac{\gamma(x_s - x)}{A} + \frac{x}{A}}$$

and

$$v_\|^s = \frac{1}{\sqrt{h_s}} \sqrt{G + \frac{x_s}{A}}$$

here $G = 1 - \mu B_0 / E$, $\mu = m v_\perp^2 / 2B$ is the particle magnetic momentum, *m* and *E* are its mass and energy, $B = B_0 / h$ is the magnetic field module value.

Here we use the concept of “average relative longitudinal velocity”, which is defined as the ratio of the local velocity $v_{||}$ averaged over drift trajectory to thermal velocity v_T

$$\xi = \frac{< v_{||} >}{v_T} = \frac{1}{Lv_T}\left(\int_{L^+} v_{||} dl - \int_{L^-} \left| v_{||} \right| dl \right)$$

here *dl* is the differential drift orbit length and *L* is the full orbit length. The first integral in the parenthesis is taken over the orbit part where $v_{||} > 0$ and the second one is taken over the orbit part where $v_{||} < 0$.

The evolution of the hydrogen ion orbits during perpendicular heating in the resonance layer, passing through the magnetic axes is shown in Fig.2. In this figure *y* axes cross the magnetic axis.

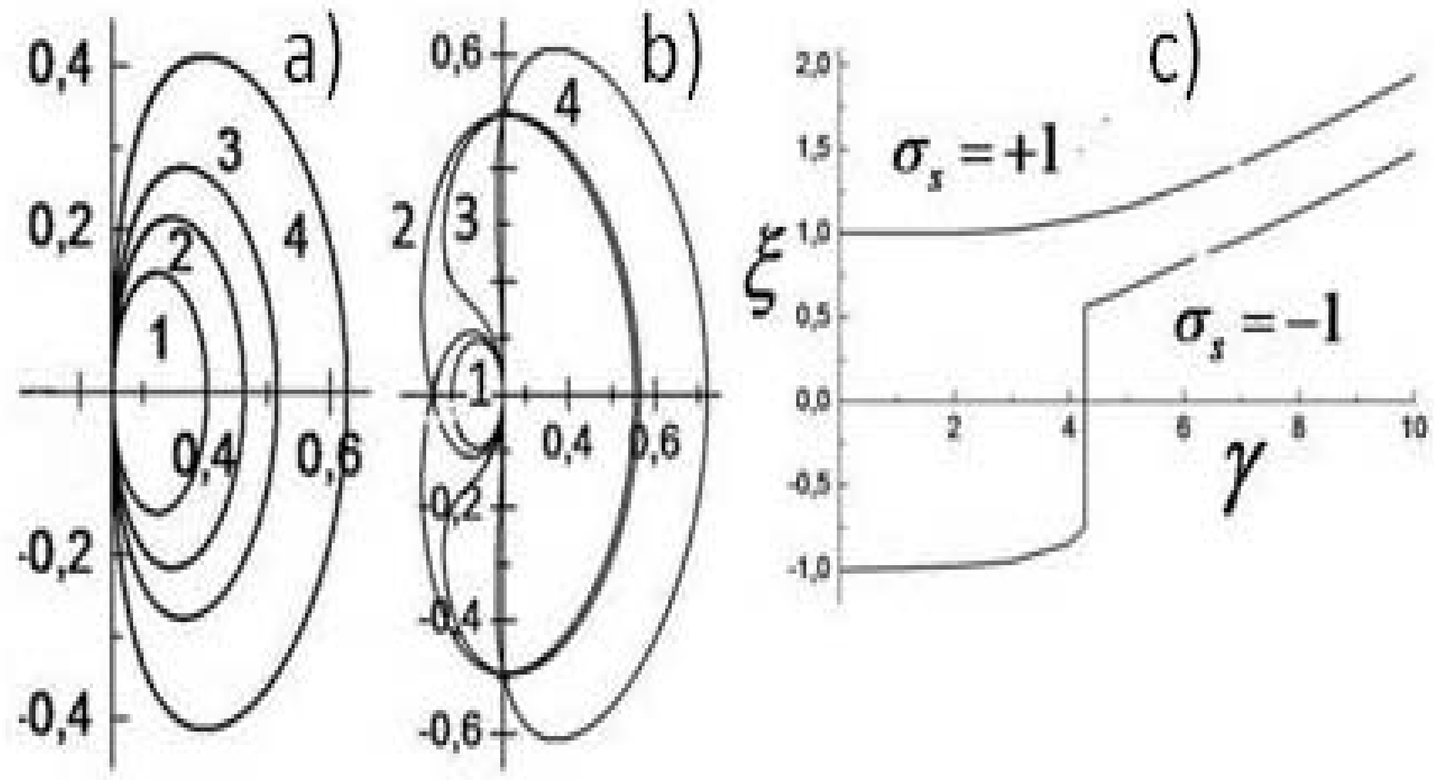

Fig.2

Fig.2

Orbit evolution of the absolutely untrapped particles $(v_{\perp} = 0)$ *and average velocity dependence on* γ .

a). $v_{\parallel} > 0.$ *1 -* $\gamma = 6$, *2 -* $\gamma = 8$, *3 -* $\gamma = 10$,
4 - $\gamma = 15$.

b). $v_{\parallel} < 0$. *1 -* $\gamma = 4$, *2 -* $\gamma = 4.261$,
3 - $\gamma = 5$, *4 -* $\gamma = 15$.

c). Average velocity dependence on γ *for particles with* $\sigma_s = +1$ *and* $\sigma_s = -1$

Orbit evolution of absolutely untrapped particles with $v_{\perp} = 0$ and $v_{\parallel} > 0$ is given in Fig.2a. In this case all particles are untrapped and they are located on the right sight of the magnetic axis. If the $\gamma = 0$ orbit is too small to be seen in Figure.

From this Figure one can see that during heating the orbit size monotonically rise. Throug our analysis we assume that $B_0 = 5.2\ \mathrm{T}$, $T_i(0) = 15\ \mathrm{KeV}$, full toroidal current is equal to $I = 9\ \mathrm{Ma}$

Orbit evolution of absolutely untrapped particles with $v_{\perp} = 0$ and $v_{\|} < 0$ is given in Fig.2b. In this case when $\gamma < 4.261$ all orbits are untrapped and they are located to the left of the magnetic axis.

When $\gamma \approx 4.261$ the orbit turns into pinch one (curve 2) and when $\gamma > 4.261$ - into banana one. From this Figure one can see that during the further heating (curve 3 - $\gamma = 5.4$, curve 4 - $\gamma = 15$) orbit pursues to potato one.

In Fig.2c one can see the evolution of the particle averaged parallel velocity which are moved along positive $(v_{||} > 0)$ and negative $(v_{||} < 0)$ orbits during ICR heating. From this Figure it is seen that when γ rise velocity of positive particle rise monotonically. As to negative particle its velocity is negative up to γ ≈ 4.261 and then it sharply change its sign, becomes positive and monotonically rise when γ rise.

If heating is fulfilled at different $y_s \neq 0$ the transformation of positive and negative particles qualitatively coincides with evolution of negative particles from Fig.2b but they turns out into pinch one under different values of γ.

In Fig.3 one can see the transformation of the average longitudinal positive and negative particles as function of when heating is fulfilled when . In this case pinch orbit of negative particles arise when $\gamma \approx 2.71$

and pinch orbit of positive particles arise when $\gamma \approx 3.4$.

A further increase in γ leads to a monotonic positive growth rate of both types of particles.

A further increase in γ leads to a monotonic positive growth rate of both types of particles.

During the heating particles with any value of *G* up to high perpendicular energy the transformation of its orbits is the same as it is shown in Fig.2 and Fig.3. So the current slightly depends on *G* and for simplicity we will use $G = 1$.

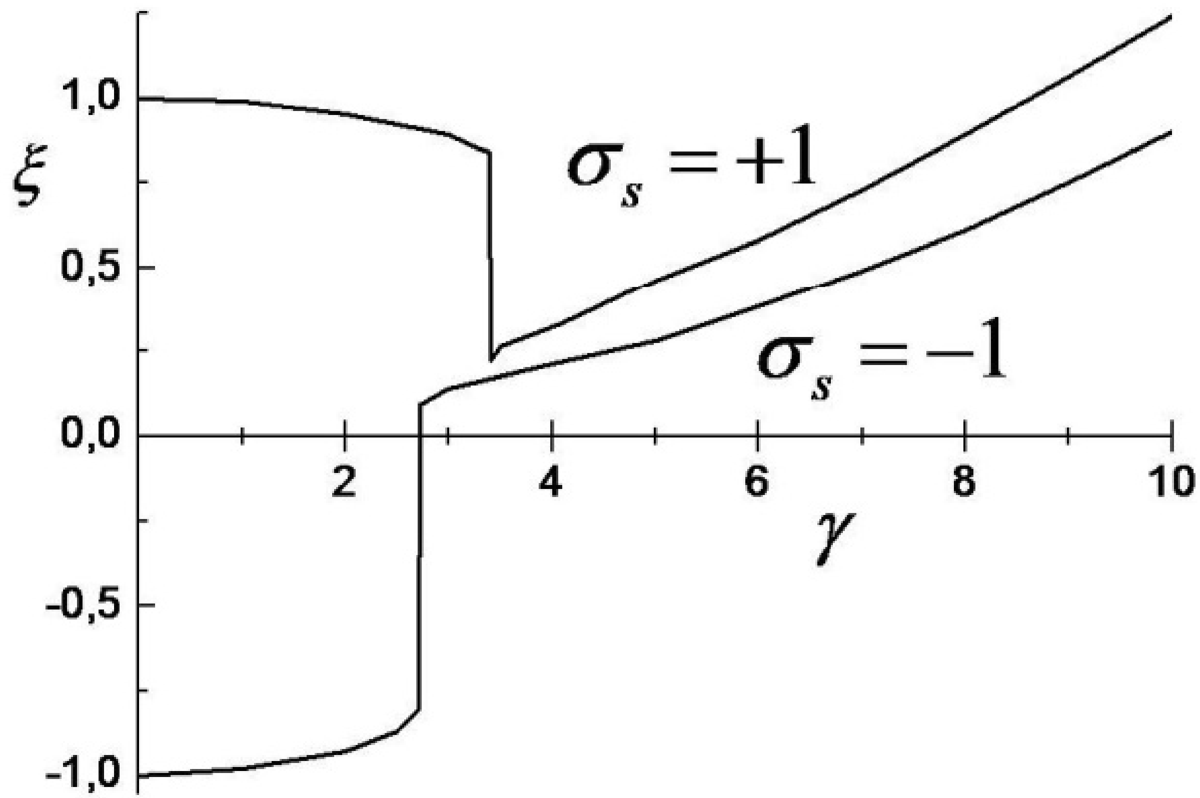

Fig.3. Transformation of longitudinal velocities positive and negative particles as function of γ *when*

$y_s = 0.6$

ESTIMATION OF THE TOROIDAL ASYMMETRY CURRENT DRIVE.

The transverse heating of the plasma does not impact any net momentum to the plasma, and charged particles moving in closed orbits, obtain longitudinal velocity directed in the direction of the ohmic current and which maximum is reached at the minimum of the fields on this trajectory.

At each point in this orbit , which we will choose as a start point, charged particles create the longitudinal current density of which will be estimated using the ratio

$$< j_i(x_s, y_{s,} E, G, \sigma_s) >= en_0 \frac{\int v_{||} F dE dG dl}{\int F dE dG dl}$$

where *F* is a distribution function. Integration over orbit is fulfilled from point with coordinates up to the same point (after detour around the entire closed path).

Full current through this point is the sum of currents which generate by all particles which are moving along the orbits passing this point

$$< j(x_s, y_s) >= \sum_i < j_i(x_s, y_s, E, G, \sigma_s) >$$

It was shown [6] that taking into account the distribution function of accelerated ions theoretically calculated and experimentally measured on tokamak JET [7], it is possible to do calculations for ions with energy averaged with help of this distribution function. To ITER let us assume that this average energy is equal $E_\gamma = 1.5\ \mathrm{MeV}$. In this case the distribution function can be presented as

$$F = n_0 \left(1 - \left(\frac{y_s}{y_{\max}} \right)^2 \right)^p \delta(E - E_\gamma)(G - 1)$$

where y_s is the coordinate of the acceleration point, $y_{\max}$ is the maximal value of y in the resonance layer , n_o is particle density accelerated up to energy E_γ , p = 0.25.

Heat of the bulk plasma will be neglected. Thus, the expression for asymmetry current is reduced to

$$< j_a >= en_0 < \tilde{n}\tilde{v}_{||} >$$

where $\tilde{n} = n / n_0$ $\tilde{v}_{\|} = v_{\|} / v_T$.

In future, the tilde will be omitted.

It should be noted that the current calculated for mono-energetic distribution of accelerated particles allows to calculate the current for any real distribution function. If the longitudinal current is generated by fast ions in the plasma there is a reverse electron current [8], the value of which was taken into account in this report. In this case the full asymmetry current will be

$$j_e = j_a\left[1-\frac{Z_i}{Z_{eff}}(1-G_\varepsilon)\right]$$

where Z_i is the fast ion charge, Z_{eff} is the plasma effective charge, G_ε is the value which is dependent on the trapped electron amount.

G_ε is calculated in the paper [8].

Such as near magnetic axis $G_\varepsilon << 1$, in principle, the possibility to use the heating of minorities with different for safety factor near the magnetic axis and radial current density ajustment.

THE ASYMMETRY CURRENT IN WHOLE PLASMA VOLUME

When radiation with the ion cyclotron frequency or its harmonics is used the heating of ions occurs in the chamber in a vertical strip (resonans layer), in which the magnetic field is constant.

The density current distribution in tokamak when resonance layer cross the magnetic axes one can see in Fig.4. On the horizontal axis in this figure is the value

$$\rho = \sqrt{\frac{\psi_{ax} - \psi}{\psi}}$$

where $\psi_{ax} = (1 - x_{ax}^2)(1 + \eta x_{ax})$

and $\psi = (1 - x^2)(1 + \eta x)$

For calculation it was used the accelerated particles density equal to 10^{18} m^{-3}. In the discussed model the full current is equal to sum of Ohmic one.

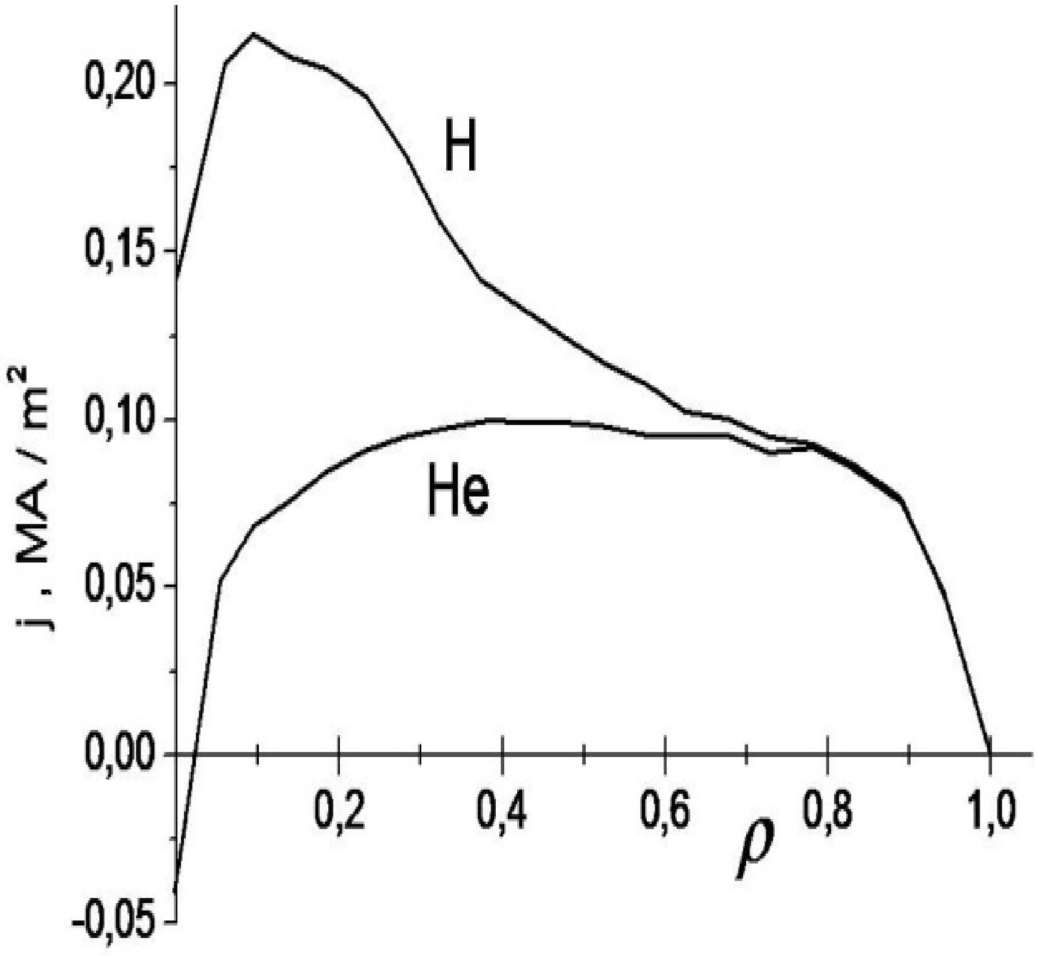

Fig.4. Current density dependence on
$\rho = sqrt(norm.\ toroidal\ flux)$
for H and He ions.

In this model the value of Ohmic current I_{OH} is in the range from -0.8 to -1.9 MA, the bootstrap one is $I_{BS} = 5.4 - 6.6 \text{ MA}$, current drive with help of neutral beam injection is $I_{NB} = 2.3 - 3.15 \text{ MA}$ and with help of low-hybrid radiation is $I_{LH} = 1.15 \text{ MA}$.

At the magnetic axis the current is driven practically only by Ohmic current. Its density is changed from 0.4 up to 0.57 MA/m^2 for different model details.

Let us discuss the possibility to change the I_{NB} by asymmetry current. It is need to take into account the fact that that maximum value of I_{NB} density is located at $\rho \approx 0.35$, while the maximal value of the asymmetry current is located at the magnetic axis. If we assume that $j_{OH} = 0.4 \ \mathrm{MA}$ we will have $q(0) = 3.4$.

Thus if we change the I_{NB} by the asymmetry current we change radial current distribution and the value of $q(0)$.

If we suggest that the effective plasma charge is equal to $Z_{eff} = 1.7$ we will have possibility to compensate the “additional” current at the axis by heating of helium ions.

The calculations show that if we heat 0.35x10^{18} m^{-3} of hydrogen ions and 1.25x10^{18} m^{-3} of helium ions up to energy equal to

$E_\gamma = 1.5\ \text{MeV}$, the full current in this case will be about 3 MA and safety factor at the axis will be $q(0) = 3.4$.

5. CONCLUSION.

In the present work it was shown that during the transversal heating of a minority by ICR radiation in ITER tokamak it is possible to drive asymmetry current which can replace additionally drive currents. In this case the radial distribution of the asymmetry current has maximum near magnetic axis of the tokamak, so that method give us the possibility to drive the seed current which is essential for the steady-state operation in tokamak-reactor.

It has been long recognized that trapped particles cannot carry any current at all and so during ICR driving there is a reduction of current because of trapping effect [9].

Results of the present work show that actually deeply trapped particles, which , can generate the asymmetry current in megampere range.

6. REFERENSES

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