UDC 533.951

RF WAY OF IMPURITY FLUXES CONTROL IN TOKAMAKS

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We have studied the influence of the local heating on the impurity flows in tokamaks in the Pfirsch-Schluter regime. If the effect of the thermoforce on the impurity ions is included into consideration, the impurity flux can be reversed by heating the impurities. This concept can be realized in tokamak experiments using RF heating. We describe the scheme of the RF heating of impurities and present estimates of the power required.

Experimentally discovered degrading of plasma parameters due to impurity ions stimulates the search for diverse techniques of plasma cleaning. Passive (divertors) and active methods can possibly be used to act on impurity ions. Active methods, investigated beginning from [1,2], may involve the bulk component puffing (particle source), bulk plasma heating (heat source) and momentum transfer e.g. due to high energy particle injection. But the thermoforce, which affects the impurity ions, was implied small and was not taken into account as in [1,2], so in later papers. This automatically moved beyond the scope the heating of impurities.

To reverse the impurity influx it is necessary to provide the asymmetric (relative to the tokamak equatorial plane) particle, heat or momentum source. The asymmetric particle or momentum source may be established very easy. But there were no any propositions as to asymmetric heat source in tokamak till now. This paper concerns the impurity flux reversal in tokamaks in the Pfirsch-Schluter regime using the RF heating of impurity ions.

Following [1,2], where the heavy impurity behaviour in tokamaks is considered, write the MHD equations
for bulk plasma ions (i) and impurity ions *(I)* in the form

$$\nabla p_i = n_i e(\vec{E} + \vec{v}_i \times \vec{B}) + \vec{R}_\parallel ,$$

$$\nabla p_I = n_I Z_I e(\vec{E} + \vec{v}_I \times \vec{B}) - \vec{R}_\parallel , \qquad (1)$$

where

$$\vec{R}_\parallel = -C_1 \frac{m_i n_i}{\tau_{iI}} \vec{u}_\parallel - C_2 n_i \nabla_\parallel T_i . \qquad (2)$$

Here p_α is the pressure, $\vec{v}_\alpha$ is the velocity, n_α is the particle density, $Z_\alpha e$ is the charge, m_α is the mass, T_α is the temperature of α-species ions ($\alpha = i,I$), τ_{iI} is the time of scattering ions off impurities, $\vec{u}_\parallel = \vec{v}_i - \vec{v}_I$, $\vec{R}_\parallel$ is the friction force. When the sources of heat and particles are present the radial flux of impurity ions, averaged over the tokamak magnetic surface, has the form

$$\Gamma_I == \frac{n_i 2q^2 \rho_i^2}{Z_I \tau_{iI} T_i} \left[\left(C_1 + \frac{C_2^2}{C_3} \right) \left(\frac{1}{n_i} \frac{\partial p_i}{\partial r} - \frac{1}{Z_I n_I} \frac{\partial p_I}{\partial r} \right) - \frac{5C_2}{2C_3} \frac{\partial T_i}{\partial r} \right] - \frac{n_i q^2 \rho_i^2}{Z_I \tau_{iI} T_i} \frac{eB_t R}{cn_i} \left[\left(C_1 + \frac{C_2^2}{C_3} \right) a_{\tau i} - \frac{C_2}{C_3} \frac{a_{Qi}}{T_i} \right] . \qquad (3)$$

Here $q = rB_t / R_0 B_p$, *a*, R_0 are the small and large radii of the torus B_t and B_p are the toroidal and poloidal components of the confining magnetic field, ρ_i is the ion gyroradius, $a_{Q\,i}$, $a_{\tau i}$ are the amplitudes of the $\sin\vartheta$ components in the Fourier series of heat $Q_i(r,\vartheta)$ and bulk ion $\tau_i(r,\vartheta)$ sources, r, ϑ - radius and poloidal angle at the minor cross-section of the torus (at the low field side $\vartheta=0$). To neutralize the first term in (3) and nullify Γ_I it is necessary that $\mathrm{sgn}(a_{\tau i}) = -\mathrm{sgn}(B_t)$ and $\mathrm{sgn}(a_{Qi}) = \mathrm{sgn}(B_t)$. However, one obtains too large $a_{Q\,i}$ values when heating bulk ions asymmetrically. Therefore in the following consideration we'll take into account the thermoforce which is due to the impurity temperature gradient along the magnetic field lines $R_T^I \propto n_I \left| \nabla_\parallel T_I \right| \frac{\tau_{II}}{\tau_{II} + \tau_{Ii}}$. This friction force is considerably less then the thermoforce due to the temperature gradient of bulk ions $R_T^i \propto n_i \left| \nabla_\parallel T_i \right| \frac{\tau_{ii}}{\tau_{ii} + \tau_{iI}}$ ($\tau_{\alpha\beta}$ is the collision time): R_T^i / R_T^I changes from $Z_I^2 >> 1$ to $Z_I^2 (m_I / m_i)^{1/2}$ on increasing n_I from $n_I \le (m_i / m_I)^{1/2} n_i / Z_I$ to $n_I \ge n_i / Z_I$. Nevertheless the account of R_T^I allows one to include into consideration the heat source acting on impurities. To find $\nabla_\parallel T_{i,I}$ use the expressions for heat fluxes

$$\vec{q}_{\parallel i} = C_2 n_i T_i \vec{u}_\parallel - C_3 \frac{n_i T_i}{m_i} \frac{\tau_{ii} \tau_{iI}}{\tau_{ii} + \tau_{iI}} \nabla_\parallel T_i$$

$$\vec{q}_{\parallel I} = -C_3' \frac{n_I T_I}{m_I} \frac{\tau_{II} \tau_{Ii}}{\tau_{II} + \tau_{Ii}} \nabla_\parallel T_I . \qquad (4)$$

Inserting $\nabla_\parallel T_{i,I}$ from (4) to (2) with account of R_T^I yields

$$\vec{R}_{\parallel I} = \frac{m_I n_I}{\tau_{iI}}\left[\left(\tilde{N}_1 + \frac{\tilde{N}_2^2}{\tilde{N}_3}\right)\vec{u}_{\parallel} + \frac{C_2}{C_3}\frac{\vec{q}_{\parallel i}}{n_i T_i} - \frac{C_2'}{C_3'}\frac{4}{3\sqrt{\pi}}\frac{\vec{q}_{\parallel I}}{n_I T_I}\right]$$

.

Now let us consider the action of the heat source of the type $Q_\alpha = Q_\alpha'(r)\sin\vartheta$ on the impurity flow. Note that other components of the Q_I Fourier series expansions over $\sin(p\vartheta)$, $\cos(p\vartheta)$ do not influence Γ_I in this approximation. From the $div\vec{q}_{\alpha\parallel} = -div\vec{q}_{\alpha\wedge} + Q_\alpha(r,\vartheta)$ (here $\vec{q}_{\alpha\wedge} = \frac{5}{2}\frac{n_\alpha T_\alpha}{e_\alpha B^2}\vec{B}\times\nabla T_\alpha$ is the inclined heat flux) we have

$$\vec{q}_{\parallel\alpha} = -\vec{B}\left(\frac{5n_\alpha T_\alpha}{e_\alpha B_0 B_\vartheta}\frac{\partial T_\alpha}{\partial r}\varepsilon_t + \frac{rQ_\alpha'(r)}{B_\vartheta}\right)\cos\vartheta .$$

After averaging over the magnetic surface one obtains

$$\Gamma_I = -\Gamma_i / Z_I = \frac{n_i 2q^2\rho_i^2}{Z_I\tau_{iI}T_i}\left[\left(C_1 + \frac{C_2^2}{C_3}\right)\left(\frac{1}{n_i}\frac{\partial p_i}{\partial r} - \frac{1}{Z_I n_I}\frac{\partial p_I}{\partial r}\right) - \frac{5C_2}{2C_3}\frac{\partial T_i}{\partial r} + \frac{5C_2'}{2C_3'}\frac{\partial T_I}{\partial r}\right] -$$
$$- \frac{n_i q^2\rho_i^2}{Z_I\tau_{iI}T_i}\frac{eB_t R}{c}\left[\left(C_1 + \frac{C_2^2}{C_3}\right)\frac{a_{\tau i}}{n_i} - \frac{C_2}{C_3}\frac{a_{Qi}}{n_i T_i} + \frac{C_2'}{C_3'}\frac{a_{Q1}}{n_I T_I}\right] \quad (6)$$

Thus, having $B_0 Q_I'(\bar{r}) < 0$, one may reverse the impurity flux using the asymmetric heat source acting on impurities.

Then we analyze the possibility of asymmetric heat source managing by means of Alfven resonance heating. We suppose that antenna is placed at the high field side of the torus. The antenna launches wave magnetic field $B_\parallel$, which is parallel to the confining magnetic field. The bulk ions are deuterium. The frequency ω is chosen so, that $\omega = \omega_{cD}(R)$ at the outer side of the torus ($\omega_{cD}(R)$ is cyclotron frequency of deuterium, $R = R_0 + r\cos\vartheta$). As for impurities $Z_I / M_I < 1/2$, so properly changing system parameters we may position the cyclotron resonance of impurity ions at $R \approx R_0$ (Fig.1). Then the Alfven resonance (AR) zone, where $\varepsilon_1(r) = N_\parallel^2(r)$, is located at the inner side of minor cross-section relative to $\omega = \omega_{cD}$ zone. When the plasma density is within the common values $10^{13} \div 10^{14}\,cm^{-3}$, the AR occupies rather narrow region Δa at the plasma periphery. Further we neglect the effect of rotational transform for fast Alfven wave propagation. Assuming $\varepsilon_1/\varepsilon_3 = 0$, we derive from Maxwell equations

$$\frac{\omega^2}{c^2}B_\parallel - rot_\parallel\left[\frac{i\varepsilon_2}{\varepsilon^2 - \varepsilon_2^2}\frac{1}{R}\nabla\left(RB_\parallel\right)\right] + R\,div\left[\frac{\varepsilon_1 - N_\parallel^2}{\varepsilon^2 - \varepsilon_2^2}\frac{1}{R^2}\nabla\left(RB_\parallel\right)\right] = 0, \quad (7)$$

where $N_\parallel = \frac{\tilde{n}l}{\omega R}$, l is toroidal wave number, $\varepsilon_2 = \sum_i \frac{\omega\omega_{pi}^2(r)}{\omega_{ci}(r,\vartheta)\left[\omega_{ci}^2(r,\vartheta) - \omega^2\right]}$.

$\varepsilon = \varepsilon_1 - N_\parallel^2$, $\varepsilon_1 = 1 + \sum_i \frac{\omega_{pi}^2(r)}{\omega_{ci}^2(r,\vartheta) - \omega^2}$,

Using Stox and Gauss theorems we convert (7) into

$$\frac{\partial}{\partial r}\left[R(r,\vartheta)B_\parallel(r,\vartheta)\right] - \frac{i\varepsilon_2(r,\vartheta)}{r\varepsilon(r,\vartheta)}\frac{\partial}{\partial\vartheta}\left[R(r,\vartheta)B_\parallel(r,\vartheta)\right] = -\frac{\varepsilon(r,\vartheta)^2 - \varepsilon_2^2(r,\vartheta)}{\varepsilon(r,\vartheta)\left(N_\parallel^2 - 1\right)}\frac{aR(r,\vartheta)}{rR(a,\vartheta)}\frac{\partial}{\partial a}\left[R(a,\vartheta)B_\parallel(a,\vartheta)\right] -$$
$$-\frac{R(r,\vartheta)}{r}\frac{\varepsilon^2(r,\vartheta) - \varepsilon_2^2(r,\vartheta)}{\varepsilon(r,\vartheta)}\left\{\frac{\omega^2}{c^2}\int_a^r r'B_\parallel(r,\vartheta)dr' + \frac{\partial}{\partial\vartheta}\int_a^r \frac{dr'}{R(r',\vartheta)}\frac{i\varepsilon_2(r',\vartheta)\frac{\partial}{\partial r'}\left[R(r',\vartheta)B_\parallel(r',\vartheta)\right]}{\varepsilon^2(r',\vartheta) - \varepsilon_2^2(r',\vartheta)} + \right.$$
$$\left. + \frac{\partial}{\partial\vartheta}\int_a^r \frac{dr'}{r'R(r',\vartheta)}\frac{\varepsilon(r',\vartheta)\frac{\partial}{\partial\vartheta}\left[R(r',\vartheta)B_\parallel(r',\vartheta)\right]}{\varepsilon^2(r',\vartheta) - \varepsilon_2^2(r',\vartheta)}\right\}. \quad (8)$$

To get solution of (8) we apply the sharp layer approach. This approach was initially developed in [3] for the case of one dimensional plasma inhomogeneity. Then it was generalized for the case of $(r-\vartheta)$ inhomogeneity in [4]. So we imply that $B_\parallel(a,\vartheta)$ and $\frac{\partial}{\partial a}B_\parallel(a,\vartheta)$ are known at the plasma boundary. Note, that for Δa the inequalities $\Delta a \ll a, a/m, 1/k_\parallel$ are well fulfilled. Taking into consideration that $\frac{\partial\varepsilon}{\partial\vartheta}\Big/\frac{\partial\varepsilon}{\partial r} \sim \frac{\partial\varepsilon_2}{\partial\vartheta}\Big/\frac{\partial\varepsilon_2}{\partial r} \sim \frac{\Delta a}{a} \ll 1$, we expand $B_\parallel$ into the series of small parameter $\Delta a/a$: $B_\parallel = B_{\parallel 0} + B_{\parallel 1} + \ldots$. Then $B_{\parallel 0}$ is defined by

$$\frac{i\varepsilon_2}{r\varepsilon}\frac{\partial\left(RB_{\parallel 0}\right)}{\partial\vartheta} - \frac{\partial\left(RB_{\parallel 0}\right)}{\partial r} = \frac{\varepsilon^2 - \varepsilon_2^2}{\varepsilon\left(N_\parallel^2 - 1\right)}\frac{\partial R(a,\vartheta)B_\parallel(a,\vartheta)}{\partial a}$$

The solution of this equation is found by the method of characteristics

$$R(r,\vartheta)B_{\|0}(r,\vartheta) = R_a B_{\|a} + \delta(RB),$$

$$\delta(RB) = i\frac{\partial}{\partial\vartheta}\left(R_a B_{\|a}\right)\int_a^r \frac{\varepsilon_2(r',\vartheta)}{r'\varepsilon(r',\vartheta)}dr' + \frac{\partial}{\partial a}\left(R_a B_{\|a}\right)\int_a^r \frac{\varepsilon^2(r',\vartheta)-\varepsilon_2^2(r',\vartheta)}{\left(1-N_\|^2\right)\varepsilon(r',\vartheta)}dr'. \quad (9)$$

Here $R(a,\vartheta)B_\|(a,\vartheta) = R_a B_{\|a}$. Thus all features of wave field in the thin layer between the plasma boundary and neighbourhood of the AR are described by these formulas. Using (9) the poloidal flux of RF power is calculated:

$$S_\vartheta = \frac{c^2}{8\pi\omega R}\mathrm{Re}\left\{\frac{B_{\|a}^*}{\varepsilon}\left[\frac{\varepsilon_2}{N_\|^2-1}\frac{\partial}{\partial a}\left(R_a B_{\|a}\right) + \frac{i}{a}\frac{\partial}{\partial\vartheta}\left(R_a B_{\|a}\right)\right]\right\}. \quad (10)$$

Then we analyze (10) supposing that at the plasma boundary $B_\|(a,\vartheta) \sim \exp(im\vartheta)$. The second term is dominant at the vicinity of the boundary and $S_\vartheta \approx \frac{c^2}{8\pi\omega}\frac{m}{a}\frac{|B_{\|a}|^2}{N_\|^2-1}$. The RF power flux is directed clockwise for $m<0$ modes and counter-clockwise for $m>0$ modes. As far the wave penetrates into the plasma, the first term increases. Taking into account $\mathrm{Re}\left[B_{\|a}^*\frac{\partial}{\partial a}\left(R_a B_{\|a}\right)\right] < 0$, the counter-clockwise power flux increases and clockwise power flux decreases. This is the reason of the up-down asymmetric RF power distribution in the plasma minor cross-section. The radial RF power flux is $S_r = S_{r0} + \delta S_r$, where

$$S_{r0} = \frac{c^2}{8\pi\omega R}\mathrm{Im}\left[\frac{B_{\|a}^*}{N_\|^2-1}\frac{\partial}{\partial a}\left(R_a B_{\|a}\right)\right] \text{ and}$$

$$\delta S_r = \frac{c^2\omega}{4R^2}\left(\left.\frac{d\omega_{pi}^2}{dr}\right|_{r=a}\right)^{-1}\varepsilon_t(1-\cos\vartheta)\left|\frac{\omega}{\omega_{ci}}\frac{\partial}{\partial a}\left(R_a B_{\|a}\right) - \frac{m}{a}R_a B_{\|a}\right|^2. \quad (11)$$

Here δS_r is the "absorbed" at the AR power. As it follows from (11) too, absorbed in the down part of the torus RF power exceeds the RF power, absorbed in the upper part of the torus. In the vicinity of the AR the fast Alfven wave is converted into the small scale kinetic wave (KW). Since the AR is placed at the plasma periphery the input of ions $(\sim k_\perp^2\rho_{Li}^2)$ in the KW dispersion is negligible for nowadays tokamak parameters at $z_e<<1$ and at $z_e>>1$ ($z_e = \omega/\sqrt{2}k_\| v_{Te}$) too. The KW propagates along the confining magnetic field lines to the inner part of the torus, undergoing small deviation to the low density side. Those KW, which started in the $-\pi/2 < \vartheta < \pi/2$ region, intersect the ion cyclotron resonance of impurity ions. Thus the asymmetric heating of impurity ions can be provided with a proper sign of $B_0 Q_I'(\bar{r})$. The portion of "useful" KW is $\kappa_u = (\pi-2)/(\pi+2)$. To stop the impurity influx, the total RF power $P_{tot} = 2\pi Ra\Delta r\kappa_u Q_I'$ is necessary. Here Δr is the radial size of region, where RF field is absorbed by impurity ions.. For estimations $\Delta r \sim \Delta a$ was adopted. Then for the tokamak of middle size *(a=50 cm, R_0=150 cm)* we get $P_{tot} \approx 100\ kW$.

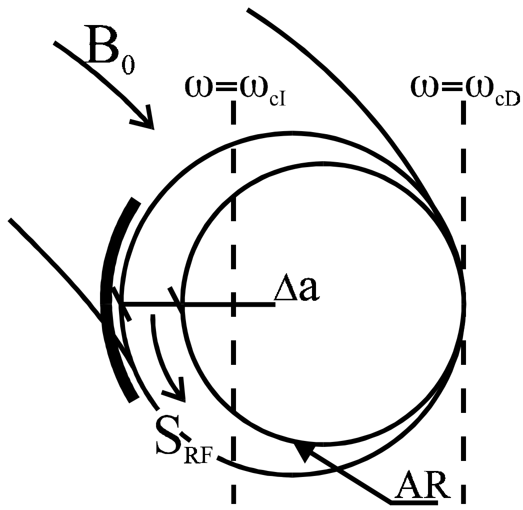

Fig. 1

Thus it is shown in this paper that there exists an effective RF method for reversing the flux of heavy impurities in tokamaks.

References

1. P.H.Rutherford. Impurity transport in the Pfirsch-Schluter regime // *The Physics of Fluids*, 1974, **17**, №9, c.1782-1784.

2. K.T.Burrell. Effect of particle and heat sources on impurity transport in tokamak plasmas // *The Physics of Fluids*, 1976, **19**, №3, c.401-405.

3. K.N.Stepanov. To the influence of plasma resonance on the propagation of the surface waves in inhomogeneous plasma // Journal of technical physics, 1965, **35**, в.6, c.1002-1014 (in Rus.).

4. S.V.Kasilov. *Theory of ion cyclotron resonance in plasma in an inhomogeneous magnetic field in tokamaks and open traps.* Ph. D. thesis. Kharkov, 1989, 21 p. (in Rus.).