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by

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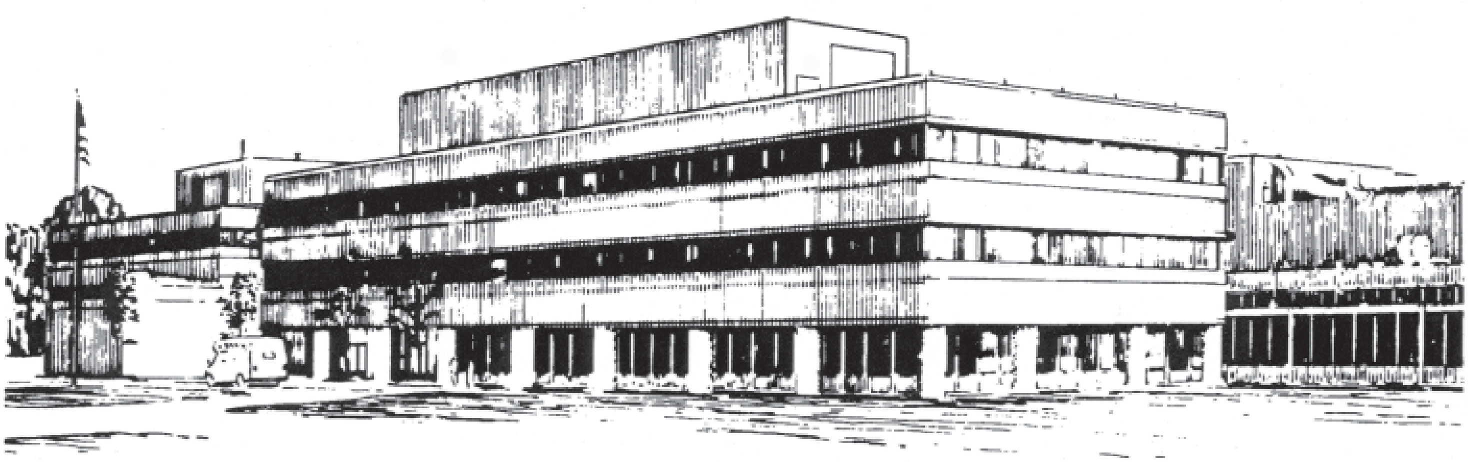

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Stabilization of sawtooth oscillations by the circulating energetic ions

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Abstract

The influence of the well-circulating energetic ions on the ideal kink instability and semi-collisional tearing mode are studied. It is found that the precession of these ions can be a key factor that affects the instability: it can lead to the stabilization of the mentioned instabilities, the effect being weakly dependent on the direction of the injection. The developed theory is consistent with the experimental observations of the stabilization of sawtooth oscillations during the negative-ion-based neutral beam injection in JT-60U (*G.J. Kramer et al., Nuclear Fusion* **40**, *1383 (2000)*).

It is known that trapped energetic ions can stabilize sawtooth oscillations. This was shown in 1988 experimentally on JET, where the trapped energetic ions were produced during the Ion Cyclotron Resonance Heating (ICRH),[1,2] and later theoretically.[3,4] More recently it was found that the circulating ions stabilize sawteeth, too: a considerable extension of the sawtooth-free period has been observed in the JT-60 Upgrade tokamak during the Negative-ion-based Neutral Beam Injection (NNBI).[5,6] This stabilization cannot be attributed to the NNBI-produced change of the plasma pressure profile, $p(r)$ [the change of $p(r)$ affects the MHD potential energy[7]], because the change of the pressure was small.[5] The current generated by NNBI also cannot explain the stabilization because the co-injection, which took place in the mentioned experiment on JT-60U, increases the magnetic shear at the $q = 1$ surface [the increasing shear destabilizes (rather than stabilizes) the sawtooth instability[8,9]]. On the other hand, in the same shot there was no observable effect from the Positive-ion-based Neutral-Beam-Injection (PNBI), although the PNBI power was comparable to the NNBI power. This together with the fact that the particle energy during PNBI was much lower than during NNBI indicate that the nature of the observed stabilization is essentially kinetic (non-MHD) and can be produced only by particles with sufficiently high energy. This conclusion is in agreement with the kinetic theory of Ref.[10] However, recently it was shown that the non-adiabatic contribution found in Ref.[10] is exactly cancelled by the finite-orbit term in the fluid response.[11] Instead, a new fluid term arising from the particles crossing the $q = 1$ surface was obtained in Ref[11]. It was concluded in both mentioned works that the effect of the circulating ions is stabilizing only for the co-injection, the counter-injection was found to be destabilizing. In the present work, we develop a theory, which takes into account the average curvature drift of the circulating particles - the factor, which was ignored in previous theories.

Before to begin a stability analysis we note that the following resonance determines the interaction of the circulating particles and a perturbation:

$$\omega - (m - n\bar{q} + S)\omega_\theta - n\omega_d = 0, \quad (1)$$

where ω is the wave frequency, ω_θ is the frequency of the of the particle motion in the poloidal direction, ω_d is the precession frequency defined by $\omega_d = \langle qv_d^2 \rangle \equiv \oint qv_d^2 dt/\tau_b$, $\mathbf{v_d}$ is the particle drift velocity, the superscript denotes a contra-variant component in Boozer coordinates, τ_b is the particle transit time, $\bar{q} = \oint qd\theta/(2\pi)$ with the integral taken along the particle orbit, q is the safety factor, m and n are the poloidal mode number and toroidal mode number, respectively, S is an integer. Equation (1) is written in the assumption that the perturbation has the form $\widetilde{X} \propto \exp(-i\omega t - in\varphi + im\vartheta)$. In the case of well-circulating particles and $|m - n\bar{q}| \ll |m|$, this resonance condition is reduced to

$$\omega - \left(k_\parallel + \frac{S}{qR}\right) v_\parallel - n\omega_d = 0, \tag{2}$$

where $v_\parallel \approx const$ is the particle velocity along the magnetic field, $k_\parallel = (m - nq)/qR_0$, the bar over q is omitted. In geometry with the shifted circular flux surfaces and large aspect ratio the precession frequency is given by[12]

$$\omega_d = \zeta q \frac{v_\parallel^2}{\Omega_b R_0^2}, \tag{3}$$

$$\zeta = \frac{3}{2} + s\left(\beta_p + \frac{l_i}{2}\right) + \frac{\alpha_p}{2\epsilon q^2} - \frac{1}{q^2} - s\frac{\Delta_b R_0}{r^2}, \tag{4}$$

where Ω_b is the beam ion gyrofrequency, $s = rq'/q$ is the magnetic shear, $l_i = 2/(r^2 B_\theta^2) \int_0^r B_\theta^2 r dr$ is the internal inductance per unit length, $\beta_p = (8\pi/B_\theta^2)(\bar{p} - p)$ with $\bar{p} = (2/r^2) \int_0^r p r dr$ the average pressure, $\alpha_p = -(8\pi p'/B_0^2) R_0 q^2$, $\Delta_b = qv_\parallel/\Omega_b$, and prime denotes the radial derivative. Note that the precessional frequency in Ref.[12] is defined as $\omega_D = -\langle qv_d^2 \rangle$, which explains why ω_d and ω_D have different signs.

The "toroidal circulation" resonance considered in Ref.[10] corresponds to the case of $\omega_d = 0$, $S = 1$. In contrast to this, we take into account that $\omega_d \neq 0$ but neglect the sideband resonances by putting $S = 0$. Then the energetic particle functional, λ_k, can be easily obtained from that of Refs.,[13,14] where ω_d was neglected. We have:[15]

$$\lambda_k = -\frac{\pi}{(B_\theta s)_{r_s}^2} \int_0^{r_s} r h(r) dr, \tag{5}$$

$$h(r) = -\frac{8}{\pi}\frac{1}{R_0^2}\int d\vec{v}\varepsilon^2 \frac{\partial F_b}{\partial P_\phi}\frac{\Delta_b}{|\Delta_b|}\int_{-\pi}^{\pi}\cos\theta \frac{H(1-|z|)\sqrt{1-z^2}}{\omega - k_\parallel(r_s + z\Delta_b)v_\parallel - \omega_d(r_s)}d\theta, \qquad (6)$$

where $z = [\bar{r}(r,\theta) - r_s]/\Delta_b$, $\bar{r} = r + \Delta_b\cos\theta$, $q(r_s) = 1$, ε is the particle energy, $P_\phi = m_b v_\parallel R + e\psi/c$ is the canonical angular momentum with m_b the particle mass and ψ the poloidal flux, $H(x)$ is the Heavy-side step function. The factor $H(1-|z|)$ in Eq. (6) takes into account that only particles crossing the $q = 1$ surface in the course of their drift motion considerably exchange the energy with the perturbations. For these particles the resonance condition determined by the denominator of Eq. (6) can be written as

$$\omega + s_1\frac{v_\parallel^2 z}{\Omega_b R_0 r_s} - \frac{\zeta_s v_\parallel^2}{\Omega_b R_0^2} = 0. \qquad (7)$$

In order to calculate the integrals in Eq. (6) we have to specify the distribution function of the energetic ions. We take it in the form:[13]

$$F_b = \frac{\sqrt{2}m_b^{3/2}}{\pi\varepsilon_\alpha}p_b(r)H(\varepsilon_\alpha - \varepsilon)\frac{\delta(\mu B_0/\varepsilon)}{\varepsilon_c^{3/2} + \varepsilon^{3/2}}\left[\frac{1}{2}(1-\sigma) + \sigma H(\pm v_\parallel)\right], \qquad (8)$$

where $p_b(r)$ is the beam ion pressure, ε_α is the injection energy, $\varepsilon_c \sim (m_b/m_e)^{1/3}T_e$, T_e is the electron temperature, ($\varepsilon_c \ll \varepsilon_\alpha$ for NNBI), $\sigma = 0$ for the balanced injection, and $\sigma = 1$ in the other cases, the signs "+" and "-" in the argument of the step function correspond to the co-injection and counter-injection, respectively. Combining Eqs. (5)-(8), we obtain:

$$\lambda_k = \frac{2}{3}\frac{r_s}{\pi R_0}\left[\frac{\Delta_b^\alpha}{r_{pb}}\frac{\beta_{b\theta}}{s^3}\right]_{r_s} I(\Omega,\kappa), \qquad (9)$$

where

$$I(\Omega,\kappa) \equiv (1 + 3\Omega^2 + 6\Omega\kappa - \kappa^2)\ln\frac{\Omega+1-\kappa}{\Omega-1-\kappa} + 10\Omega - 2\kappa +$$

$$4\Omega^{3/2}\left[\frac{2\kappa-1}{(\kappa-1)^{1/2}}\ln\frac{\sqrt{\Omega}+\sqrt{\kappa-1}}{\sqrt{\Omega}-\sqrt{\kappa-1}} - \frac{2\kappa+1}{(\kappa+1)^{1/2}}\ln\frac{\sqrt{\Omega}+\sqrt{\kappa+1}}{\sqrt{\Omega}-\sqrt{\kappa+1}}\right], \qquad (10)$$

$\kappa \equiv \zeta_s\epsilon_s/s_1$, $\Omega = \omega/\omega_s$ with $\omega_s \equiv k_\parallel|_{r_s-\Delta_b}v_\parallel = sv_{\parallel\alpha}^2/(\Omega_b R_0 r_s)$, $\beta_{b\theta}$ is the poloidal beta of beam ions, and $r_{pb}^{-1} = -d\ln p_b/dr$. Note that when $\kappa > 1$ (this can be the case in high-β plasmas of spherical tori), I$m\lambda_k \to 0$ and, thus, the "diamagnetic" fishbone branch is stabilized.[15]

Below we assume that $|\Omega| \to 0$, which is relevant to the sawtooth instability. Then we obtain:

$$\lambda_k(0) = \frac{2}{3}\frac{r_s}{\pi R_0}\left[\frac{\Delta_b^\alpha}{r_{pb}}\frac{\beta_{b\theta}}{s^3}\right]_{r_s}\left\{(1-\kappa^2)\ln\left|\frac{\kappa-1}{\kappa+1}\right| - 2\kappa - i\pi(1-\kappa^2)H(1-\kappa)\right\}, \tag{11}$$

where $\lambda_k(0) = \lambda_k(\Omega = 0)$. It follows from Eq. (11) that $\mathrm{Re}\lambda_k(\Omega = 0, \kappa = 0) = 0$, whereas the presence of the precession ($\kappa \neq 0$) leads to $\mathrm{Re}\lambda_k(0) < 0$. This means that the precession tends to stabilize the internal kink mode. The obtained stabilization by the precession is a consequence of the conservation of the magnetic flux linked through the energetic ion precessional drift orbits, as in the case of the trapped-ion stabilization.[3,4] This non-MHD constraint becomes relevant when precession frequency considerably exceeds the ideal kink growth rate, i.e. when[9]

$$\frac{\omega_d}{\omega_A} \gg \lambda_c, \tag{12}$$

where $\omega_A \equiv v_A/(\sqrt{3}R_0)$ is the Alfvén frequency, λ_c is the negative of the normalized potential energy of the bulk plasma.[7]

Let us evaluate λ_k in the JT-60U experiments, where the sawtooth stabilization by NNBI was observed (during the D $\to$ H co-injection), but there was no influence of the PNBI ions on sawteeth.[5,6] We use the following parameters: $\varepsilon_\alpha \simeq 360$ keV, $s_1 = 0.4$, $r_s \simeq 27$ cm, $R_0 \simeq 3.2$ m, $B_0 = 3.5$ T, $\beta_{ps} \simeq 0.5$, $l_i \simeq 1.41$, $\omega_A \simeq 8 \times 10^6$ s^{-1}. Then we obtain from Eqs. (3), (4) that Eq. (12) is well satisfied for the NNBI ions ($\lambda_c \simeq 7 \times 10^{-4}$,[10] $\omega_d/\omega_A \simeq 3 \times 10^{-3}$). However, Eq. (12), which represents a necessary condition for the stabilization of sawteeth by the energetic ions, is difficult to satisfy for the PNBI ions ($\varepsilon < 90$ keV). Taking $\zeta_s \sim 1$ and $p_b(r) = p_{b0}[1-(r/a)^2]^6$ with $a = 82$ cm, $\beta_{b0} \simeq 0.4\%$, we obtain $\beta_{b\theta}(r_s) \simeq 0.29$, $r_{pb} \simeq 18$ cm, $R_0/\Delta_b^\alpha \simeq 93$, $\kappa \simeq 0.3$. Equation (11) then yields $\mathrm{Re}\lambda_k(0) \simeq -1.8 \times 10^{-2}$. The absolute value of the calculated $\mathrm{Re}\lambda_k(0)$ well exceeds $\lambda_c \simeq 7 \times 10^{-4}$. We conclude from here that the ideal kink instability is suppressed by the NNBI in JT-60U.

However, when $\lambda_c + \lambda_k < 0$, non-ideal instabilities (tearing mode) can arise. One can see that collisionless effects play an important role in this case: with the estimated magnetic

Reynolds number $S_M \simeq 10^7$, the resistive width of the singular layer $\delta_\eta \equiv r_s/(s_1 S_M)^{1/3} \simeq 1.7$ mm falls below the ion hybrid Larmor radius $\rho_\tau \equiv \rho_i\sqrt{1+T_e/T_i} \simeq 2.6$ mm (we take $T_i \simeq T_e$), but exceeds the inertial skin depth, $d_e \equiv c/\omega_{pe} \simeq 1.2$ mm. Under these conditions and $|\omega/\omega_A| < \rho_\tau/r_s$ the dispersion relation can be written as[16,17]

$$-\frac{\pi}{2}\left(\frac{\omega}{\omega_A}\right)^2 = \frac{\rho_\tau}{r_s}(\lambda_c + \lambda_k(0)) + \left(\frac{i\omega_A}{\omega}\right)^{3/2}\left(\frac{\rho_\tau}{r_s}\right)^2 S_M^{-1/2} s_1^3. \tag{13}$$

In the absence of fast ions we have an estimate $\lambda_c \ll (\pi/2)^{3/7}(\rho_\tau/r_s)^{1/7} S_M^{-2/7} s_1^{12/7}$, and Eq. (13) describes the semi-collisional $m = 1$ tearing mode[17,9] with the growth rate $\gamma_\rho/\omega_A = (2/\pi)^{2/7}(\rho_\tau/r_s)^{4/7} S_M^{-1/7} s_1^{6/7}$. In the presence of fast ions we have $\lambda_c + \mathrm{Re}\lambda_k < 0$, $|\lambda_c + \lambda_k(0)| > \rho_\tau/r_s \gg (\pi/2)^{3/7}(\rho_\tau/r_s)^{1/7} S_M^{-2/7} s_1^{12/7}$. A solution of Eq. (13) in this case is [cf. Eq. (21) of Ref.[15]]:

$$\frac{\omega}{\omega_A} = i\left(\frac{\rho_\tau}{r_s}\right)^{2/3} s_1^2 S_M^{-1/3}(|\lambda_c + \lambda_{kr}| + i|\lambda_{ki}|)^{-2/3}.. \tag{14}$$

where $\lambda_{kr} \equiv \mathrm{Re}\lambda_k$ and $\lambda_{ki} \equiv \mathrm{I}m\lambda_k$. For the parameters given above Eq. (14) yields $|\omega_{*i}/\omega| \simeq 5$, with $|\omega_{*i}| \simeq 10^4$ s^{-1} the bulk ion diamagnetic frequency. This means that the considered non-ideal branch is to be stabilized by the diamagnetic effects: according to Ref.[9], the stabilization takes place when $\omega_{*i}/\gamma_0 \gtrsim 2$, where γ_0 is the growth rate calculated for $\omega_{*i} = 0$, i.e., the growth rate determined by Eq. (14). On the other hand, $|\omega|/\omega_s \simeq 0.02$, which is consistent with our assumption that $|\Omega| \to 0$.

Note that our estimates above were made in the assumption that the plasma cross-section is circular, while the plasma in the considered shot was moderately shaped (with the elongation ~ 1.46 at the edge[6]). Nevertheless, because the condition $|\lambda_{kr}(0)| \gg \lambda_c$ is well satisfied, one can expect that it will be satisfied even with a moderately reduced precession of the energetic ions in shaped geometry.

Now we discuss how the obtained results are related to those in Ref.[11]. The total response of the beam ions crossing the $q = 1$ surface is given by

$$\mathrm{Re}\lambda_{tot} = \frac{r_s}{3R_0}\left(\frac{\Delta_b^\alpha \beta_{b\theta}}{r_{pb} s^2}\right)_{r=r_s}\left\{\frac{2}{\pi s_1}\left[(1-\kappa^2)\ln\frac{1-\kappa}{1+\kappa} - 2\kappa\right] + \sigma_\lambda\right\}, \tag{15}$$

where $\sigma_\lambda = (-1, 0, 1)$ for purely co-injection, balanced injection, and counter-injection, respectively. The second term in Eq. (15) is actually the fluid term found in Ref.[11]. It is less than the first term for the JT-60U parameters used above. In general, when $\kappa \ll 1$, the ratio of the first term to the second one is about $8\zeta_s\epsilon_s/(\pi s_1^2)$, which exceeds unity for $\epsilon_s \sim s_1^2$ and $\zeta_s \sim 1$. In this case, Eq. (15) predicts the stability even for counter-injection. Note that the obtained results imply a stabilizing effect of the circulating α-particles ($\sigma_\lambda = 0$) in fusion reactors.

In summary, we have shown that the circulating energetic ions can stabilize the ideal kink mode and semi-collisional tearing mode. The stabilization results from the finite magnitude of the particle precession, which affects the resonance interaction of the perturbations and the particles. The developed theory predicts the stabilization independently on the direction of the circulation and for the balanced injection, although the found stabilizing effect depends on the direction of the circulation [see Eqs. (4), (15)]. As the precession of the circulating particles is rather sensitive to many factors (the plasma shaping, the magnetic shear, the profile of the plasma pressure, etc.[12]), the considered stabilizing mechanism is not so robust as the corresponding mechanism associated with the trapped particles. The developed theory seems to explain the stabilization of the sawtooth instability observed in the experiments with NNBI on JT-60U: the made estimates show that the new mechanism dominates over the mechanism suggested in Ref.[11], although the calculation of the precession frequency with taking into both account the plasma shaping and the magnetic shear is required for the final conclusion. In addition, the developed theory is consistent with the fact that the PNBI had no influence on the sawtooth oscillations in JT-60U.

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REFERENCES

[1] D.J. Campbell *et al.,* Phys. Rev. Lett. **60**, 2148 (1988).

[2] D.J. Campbell *et al.,* Proc. 15th EPS Conf. on Contr. Fusion and Plasma Heating, v. 12B, Part 1, p.377 (1988).

[3] R.B. White, F. Romanelli, M.N. Bussac, Phys. Fluids **B4**, 795 (1990).

[4] F. Porcelli, Plasma Phys. Control. Fusion **33**, 1601 (1991).

[5] K. Tobita, K. Hammatsu, M. Iwase, T. Suzuki, Y. Koide, S. Moriyama, T. Nishitani, Y. Kusama, M. Nemoto, and A. Morioka, in *Proceedings of the 6th IAEA Technical Committee Meeting on Energetic Particles in Magnetic Confinement Systems, 1999, JAERI, Naka, Japan* (Japan Atomic Energy Research Institute, Tokai-mura, Nak-gun, Ibaraki-ken, Japan, 2000), p.73.

[6] G.J. Kramer, M. Iwase, Y. Kusama, A. Morioka, M. Nemoto, T. Nichitani, K. Shinohara, S. Takeji, K. Tobita, T. Ozeki, C.Z. Cheng, G.-Y. Fu, and R. Nazikian, Nucl. Fusion **40**, 1383 (2000).

[7] M.N. Bussac, R. Pellat, D. Edery, and J.L. Soule, Phys. Rev. Lett. **35**, 1638 (1975).

[8] F.M. Levinton, *et al.*, Phys. Rev. Lett. **72**, 2895 (1994).

[9] F. Porcelli, D. Boucher, and M.N. Rosenbluth, Plasma Phys. Control. Fusion **38**, 2163 (1996).

[10] S. Wang, T. Ozeki, and K. Tobita, Phys. Rev. Lett. **88**, 105004 (2002).

[11] J.P. Graves, Phys. Rev. Letters **92** 185003-1 (2004).

[12] Ya.I. Kolesnichenko, R.B. White, and Yu.V. Yakovenko, Phys. Plasmas **10**, 1449 (2003).

[13] R. Betti and J.P. Freidberg, Phys. Rev. Lett. **70**, 3428 (1993).

[14] R. Betti, Plasma Phys. Control. Fusion **35**, 941 (1993).

[15] Ya.I. Kolesnichenko, V.S. Marchenko, and R.B. White, Phys. Plasmas **8**, 3143 (2001).

[16] F. Porcelli, Phys. Rev. Lett. **66**, 425 (1991).

[17] F. Pegoraro, F. Porcelli, and T.J. Schep, Phys. Fluids **B1**, 364 (1989).

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