Frequency chirping of neoclassical tearing modes by energetic ions

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Abstract
The mechanism of rapid frequency chirping for neoclassical tearing modes (NTMs) is studied. Resonance between NTMs and trapped energetic ions can provide an additional torque to change the evolution of frequency. Whether the frequency rises or falls depends on the direction of island propagation. If the island propagates in the direction of ion diamagnetic drift, the frequency will be increased dramatically and rapidly. If the island propagates in the direction of electron diamagnetic drift, the frequency will be reduced to a lower value. The predicted chirping time is consistent with experimental results in DIII-D (Liu et al 2020 Nucl. Fusion 60 112009).

Keywords: neoclassical tearing modes, energetic ions, frequency chirping, magnetic island

(Some figures may appear in colour only in the online journal)

1. Introduction
It is well known that neoclassical tearing modes (NTMs) [1, 2] can significantly reduce the performance of magnetically confined plasmas. When a magnetic island reaches a certain threshold, a perturbed helical bootstrap current, resulting from the pressure flattening across the island, is generated to drive NTMs. These modes can increase the local radial transport, reduce the maximum achievable \( \beta \) (\( \beta = 8 \pi p/B_0^2 \), where \( p \) and \( B_0 \) are the plasma pressure and magnetic field), and lead to plasma disruption if the island is large enough in a high-\( \beta \) plasma [3]. Thus, NTMs are of critical importance in the context of achieving steady-state and highly confined plasmas in present and future tokamak devices [4].

Energetic particles are inevitably produced in burning plasma or during external heating (such as neutral beam injection) in a tokamak. It is evident that energetic particles can interact with plasma instabilities, such as internal kink, Alfvén eigenmodes [5, 6], and tearing modes, including NTMs [7–15]. Stabilization of NTMs by energetic particles and the redistribution or loss of energetic particles due to NTMs in turn have been observed in tokamak experiments [7–9]. Some analytical and simulation studies [10–15] have shown that energetic particles can actually stabilize tearing modes (including NTMs). Furthermore, frequency chirping of tearing modes or NTMs has been observed on TFTR [16], ASDEX-U [17, 18], EAST [19], HL-2A [20], and DIII-D [21]. On TFTR [16], during the evolution of NTMs, frequency chirping of these modes was accompanied by loss of energetic ions. Recently, frequency chirping up and back down of NTMs has also been observed on DIII-D, where the chirping time is a few milliseconds, and has been suggested that trapped energetic ions may be responsible for this [21]. Some efforts [22–24] have been made to theoretically understand the underlying physics. In [22], it was pointed out that resonance between trapped energetic ions and rotating NTMs provides a torque to accelerate the rotation of the NTMs; however, the estimated chirping time is much longer than that observed in the experiments. Two recent articles [23, 24] have described the bursting and chirping of tearing modes on HL-2A. In [23], it was shown that...
resonance between trapped energetic ions and tearing modes can drive a fishbone-like mode. Thus, the physics remains unclear. The experimentally observed frequency chirping of NTMs implies that resonance between NTMs and energetic particles is important. Since the transit frequency of passing energetic ions is much greater than the frequency of NTMs, it is very difficult for the condition for resonance between them to be satisfied. In contrast to the particle model used in [22], a drift kinetic approach is used to give a self-consistent description of resonance between NTMs and trapped energetic ions in the present work. It is thought that this resonance could provide an additional torque and thereby alter the evolution of the rotation frequency of NTMs.

In section 2, the evolution of the rotation frequency of NTMs, including energetic ion resonance effects, is described, and the frequency chirping of NTMs by energetic ions is analyzed and discussed. Finally, conclusions and a discussion are presented in section 3.

2. Frequency chirping of NTMs by energetic ions

Considering a plasma confined in a tokamak with large aspect ratio \( \alpha_d = a/R_0 \ll 1 \) and low \( \beta / (\beta \times c_R^2) \), the magnetic field is written as \( B = \mathbf{m} \nabla \zeta + \nabla \times \nabla (\psi + \delta \psi) \) for NTMs [15, 29], where the toroidal geometry is assumed to be axisymmetric, \( a \) is the minor radius, and \( R_0 \) is the major radius. \( \psi \) and \( \delta \psi \) are the equilibrium and perturbed poloidal magnetic flux, respectively, the magnetic drift and electric drift velocities, respectively, the banana width of trapped energetic ions is smaller than the island width, \( \Delta' \) provides the instability criterion for tearing modes. \( \Delta' \) describes absorption of momentum, \( \Delta_{1,R} \) and \( \Delta_{1,J} \) are the real and imaginary parts of \( \Delta' \), respectively. Here, \( \Delta' \) comes from the resonance between NTMs and energetic ions. Therefore, if there is effective resonance between NTMs and energetic ions, the evolution of the rotation frequency will be modified dramatically.

Based on the quasineutrality equation, the parallel current satisfies

\[
B \cdot \nabla \frac{\Delta J_{||}}{B} + \nabla \cdot \Delta J_{\perp} + \nabla \cdot \Delta J_{\parallel h} = 0. \tag{4}
\]

Here, \( \delta J_{\perp} \) represents the contributions of the background plasma (neoclassical polarization, neoclassical viscosity, etc). \( \delta J_{\parallel h} = cB \times \nabla \cdot \delta p_{h}/B^2 \) represents the contribution of energetic ions, where \( \delta p_h = \frac{\delta J_{\parallel h}}{B} + (\delta p_{h} - \delta p_{\perp h})b_0 \) denotes the perturbation form of the Chew–Goldberger–Low [27] pressure tensor of energetic ions, with \( b_0 \) being the direction of the equilibrium magnetic field. One can make the separation \( \delta J_{1} = \delta J_{||} + \delta J_{\parallel h} \) where \( \delta J_{\perp} \) results from the contribution of the background plasma and satisfies \( B \cdot (\nabla \delta J_{\perp}/B) = - \nabla \cdot \delta J_{\perp} \). Based on equation (4), the perturbed parallel current density of energetic ions \( \Delta J_{\parallel h} \) can be obtained as

\[
B \cdot \nabla \frac{\delta J_{\parallel h}}{B} + \frac{cI}{B^2} \left( \kappa_1 \frac{\Xi}{\Theta} + m \kappa_2 \frac{\partial}{\partial \zeta} - \kappa_1 \frac{\partial}{\partial \zeta} \right) \times (\delta p_{\parallel h} + \delta p_{\perp h}) = 0, \tag{5}
\]

where \( J = (\nabla \psi \times \nabla \theta) \cdot (\nabla \zeta)^{-1} \) is the Jacobian, and \( \kappa_1 \sim - \partial \ln R / \partial \psi \) and \( \kappa_2 \sim - \partial \ln R / \partial \theta \) are the two components of the magnetic curvature. Next, an expression for \( \delta p_h \) needs to be derived.

The nonlinear drift kinetic equation for energetic ions is [6]

\[
\frac{\partial \delta G_h}{\partial t} + \frac{\phi_1}{qR} \left[ \frac{\partial}{\partial \xi} + m \left( 1 - \frac{q}{q_h} \right) \frac{\partial}{\partial \zeta} - m \frac{\delta \psi}{\delta \xi} \frac{\partial}{\partial \zeta} \right] \delta G_h \\
+ \delta \hat{\phi} \frac{\partial \delta G_h}{\partial \theta} + (m \delta \hat{\theta} - n \hat{\zeta}) \frac{\partial \delta G_h}{\partial \zeta} + \frac{\psi}{\delta \hat{\psi}} \frac{\partial \delta G_h}{\partial \psi} \\
+ v_E \cdot \nabla \delta G_h = QF_{h,0} \left( \frac{\psi}{c} \delta A_1 - \delta \phi \right), \tag{6}
\]

where \( \delta f_h = e \delta \phi \delta F_{h,0}/\partial \psi + \delta G_h \) is the perturbed distribution of energetic ions, \( \hat{\xi} = \hat{m} - n \hat{\zeta} \) is the helical angle, \( \hat{\psi}_d = v_d \cdot \nabla \psi \), \( \hat{\theta}_d = v_d \cdot \nabla \theta \), \( \zeta_d = v_d \cdot \nabla \zeta \), and \( v_E \) are, respectively, the magnetic drift and electric drift velocities, \( QF_{h,0} = e(\delta F_{h,0}/\partial \psi)(\delta \hat{\psi}) - n(\delta \hat{\theta} - \gamma \hat{\zeta})(\delta \hat{\psi})(\delta \hat{\psi}) \), and \( \delta A_1 = - \hat{\psi} / R \). Introducing the coordinate transformation \((\xi, \zeta) \rightarrow (\zeta, \xi)\), one has \( \delta / \delta \xi = \delta / \delta (\zeta - \hat{\psi} / R) \). Considering the ordering \( \omega \sim \omega_d \ll \omega_h \) (where \( \omega_d \) and \( \omega_h \) are the precessional and bounce frequencies, respectively), when the banana width of trapped energetic ions is smaller than the island width, equation (6) can be expanded as

\[
\frac{\partial \delta G_h}{\partial t} + \frac{\phi_1}{qR} \left[ \frac{\partial}{\partial \xi} + m \left( 1 - \frac{q}{q_h} \right) \frac{\partial}{\partial \zeta} - m \frac{\delta \psi}{\delta \xi} \frac{\partial}{\partial \zeta} \right] \delta G_h \\
+ \delta \hat{\phi} \frac{\partial \delta G_h}{\partial \theta} + (m \delta \hat{\theta} - n \hat{\zeta}) \frac{\partial \delta G_h}{\partial \zeta} + \frac{\psi}{\delta \hat{\psi}} \frac{\partial \delta G_h}{\partial \psi} \\
+ v_E \cdot \nabla \delta G_h = QF_{h,0} \left( \frac{\psi}{c} \delta A_1 - \delta \phi \right). \tag{6}
\]
\[
\frac{\partial L_i}{\partial \theta} = 0, \quad (7)
\]

\[
\frac{v_i}{q_R} \frac{\partial G_{i0}}{\partial \vartheta} + \frac{v_i}{q_R} \left[ m \left( 1 - \frac{q}{q_s} \right) - m \frac{\partial \psi}{\partial \xi} - \frac{m \partial \psi}{\partial \psi} \right] \delta G_{i0} \\
+ \left( -\omega + m \theta_d - n \xi \right) \frac{\partial G_{i0}}{\partial \xi} + \psi_d \frac{\partial G_{i0}}{\partial \psi} \\
= Q F_{i0, \psi} \left( \frac{v_i}{c} \delta A_1 - \delta \phi \right). \quad (8)
\]

Here, \( \beta_h \sim \beta_0 \) is assumed, and so \( T_i \ll T_e \), since \( n_b \ll n_i \), where \( T_i \) and \( n_b \) are the temperatures and densities of ions and energetic ions, respectively. A growth rate \( \gamma \ll \omega \) is assumed, which is always the case for NTMs [29]. Then, taking the orbital average \( \langle qR/v_i \rangle \delta \theta \) of equation (8), one obtains

\[
\delta G_{i0} = -\frac{1}{\omega - \omega_d} \left[ Z_{e0} \omega \frac{\partial E}{\partial \xi} + \frac{cm \partial F_{i0}}{rB} \right] \delta \phi, \quad (9)
\]

where \( \omega_d = -\left( mE/rB_0 \right) M(\lambda) \) [28], \( \Omega_i \) is the gyrofrequency of trapped energetic ions, \( \lambda = \mu_0/E \) is the pitch angle, and \( \mu_0 \) is the magnetic moment. Here, we focus on the trapped energetic ions, and only \( \delta p_{i, \lambda} = \int \delta \psi(\psi_i/2) \delta \phi \) is considered next, since \( |\delta p_{i, \lambda}| \ll |\delta p_{i, \mu}| \) due to \( \psi_i^2 \sim \psi_0^2 \) for trapped energetic ions. Here, the velocity space integral is over the trapped region. Then, taking the magnetic flux average \( \frac{\delta J}{\delta \theta} \) of equation (5), one obtains

\[
\left[ m \left( 1 - \frac{q}{q_s} \right) \frac{\partial}{\partial \xi} - m \frac{\partial \psi}{\partial \xi} \right] \delta j_{i, \lambda/\xi} + \delta K = 0, \quad (10)
\]

\[
\delta K = -\sqrt{2} cm \left( \frac{\partial \psi}{\partial \xi} \right)^{-1} \int_0^{E_{3/2}} dE \int_{\lambda_0}^{\lambda_0} \lambda_0 \lambda_0 K_2 \frac{\partial \delta f_h}{\partial \xi} d\lambda_0, \quad (11)
\]

where \( \lambda_0 B_0 = 1/(1 + \epsilon) \), and \( \lambda_0 B_0 = 1/(1 - \epsilon) \), \( K_2 = \int_0^{\theta_B} \left[ \cos \theta/(1 - \lambda B) \right] d\theta/2\pi \), where \( \theta_B \) denotes the bounce point of trapped energetic ions. In this work, we focus on the evolution of the rotation frequency of the island. For simplicity, the island is assumed to be constant, since the time scale of island evolution is proportional to the resistivity diffusion time [15, 25] and is much longer than the chirping time of the rotation frequency [21]. Therefore, only resonance between NTMs and trapped energetic ions is considered.

To satisfy the resonance condition, on must have \( \omega_d > 0 \). For a monotonic q profile, \( \omega_d < 0 \) is always satisfied [28], i.e. the precession frequency of energetic ions is the same direction as the island magnetic frequency. To proceed further, the slowing down distribution of energetic ions is chosen as

\[
F_{h0} = F_0 \left( \frac{E}{E_c} \right)^{3/2} \left( 1 + \frac{E}{E_c} \right)^{-3} \delta (\lambda - \lambda_0) \Omega(E_0 - E),
\]

where \( F_0 = n_{i, h} / (2\pi) B_0 m_0 k_i \), \( E_c \) is the critical energy, \( m_0 \) is the maximum energy, \( K_0 = \int_0^{E_0} (1 - \lambda B)^{-1} d\theta/(2\pi) \), \( k_i = \int_0^{E_0} \left( E_0^2 + E_c^2 \right) dE_i, E_i = E_i/E_m \), and \( E_m = E_m/E_i \). For trapped particles, the pitch angle \( (1/(1 + \epsilon) \leq \lambda_0 B_0 \leq 1/(1 - \epsilon)) \) should be satisfied. Here, a given pitch angle \( \lambda_0 \) is considered, for simplicity. Substituting the expressions for \( F_{h0} \) and \( \delta f_h \) and equation (9) into equation (11), one obtains the resonant part of \( \delta K \), following Landau’s prescription, as

\[
\delta K_{res} = ig(\omega) \frac{\partial \delta \phi}{\partial \xi}, \quad (12)
\]

\[
g(\omega) = \sqrt{2} cm \left( \frac{\partial \psi}{\partial \xi} \right)^{-1} \pi C_q Z_{e0} e \lambda_0 B_0 K_2 \frac{\omega^3}{\omega_3^3 + E_c^3} \\
\times \left[ H_0(\omega) - \frac{R_0}{L_{m0}(\lambda_0)} \frac{1}{\omega} \left( 1 + K_0 \frac{L_{m0}}{L_{Ec}} \right) \right], \quad (13)
\]

where \( R_0 = \frac{3}{2} \omega_{L} \omega_{3} \left( \omega_{3}^3 + E_c^3 \right) \), \( K_0 = \frac{3}{2} [1 / \ln (1 + E_c^{-3/2}) \left( 1 + E_c^3 \right) ]^{-1} \), \( \omega_{L} = \omega_0 / \omega_{dm} \), \( \omega_{dm} \) is the precessional frequency with maximum energy, \( L_{m0} = (\partial \ln n_0 / \partial r)^{-1} \), and \( L_{Ec} = (\partial \ln E_n / \partial r)^{-1} \).

It is convenient to transform the coordinates \( (r, \theta, \xi) \) to the island coordinates \( (\Omega, \theta, \xi) \). \( \delta \phi \) can be obtained from the ion continuity equation and the electron momentum balance equation [15, 26] as \( \delta \phi = \delta (\psi/\partial \theta) \omega_{L} \), where \( \omega_{L} = \sigma_3 (\sqrt{\omega E_{F}/4}(\pi/2) [\Omega + 1/(\Omega + 1)] \left( 1/(1 + \Omega) \right)^{-1} \) is determined by the effect of the island on radial transport [29]. Here, \( \sigma_3 \) denotes the sign of \( E \) and \( E_3 = 1/(1 + \Omega) \) is an elliptic function. It should be pointed out here that the form of \( \delta \phi \) in which account is taken of the contribution of energetic ions remains almost unchanged, since \( n_b \ll n_i \) [15].

Then, substituting equation (12) into equation (10), one obtains

\[
\frac{\partial \delta J_{i, \psi|res}}{\partial \theta} = \frac{i \omega B_0^2}{2 \kappa_0} \delta (\omega) \frac{4 \pi}{w^2 \Omega} \left( x - \frac{x}{(1)} \right). \quad (14)
\]

This result from the resonance between NTMs and trapped energetic ions. It should be pointed out that there is no contribution of \( \delta J_{i, \psi|res} \) to the evolution of the island based on equation (2), since \( \delta J_{i, \psi|res} \) is a function of \( \xi \). Substituting equation (14) into equation (3), the rotation frequency of the island can be derived as [26]

\[
\frac{d \omega}{d \Omega} \left[ \omega - \omega_0 \right] = \frac{-6 G_0 \mu_0}{\omega_0} (\omega - \omega_0) + \Delta_{\omega}, \quad (15)
\]

\[
\Delta_{\omega} = \frac{\pi}{2} G_0 \bar{u} \omega^2 \omega \frac{\omega_0}{\omega_{dm}} \mu_0 \mu_0 \mu_0 K_2 \frac{\omega^3}{\omega_3^3 + E_c^3} \\
\times \left[ \frac{\omega_{dm}}{\omega_{sh}} H_0 + \frac{1}{\omega} \left( 1 + K_0 \frac{L_{m0}}{L_{Ec}} \right) \right], \quad (16)
\]

where \( \bar{u} = \omega \lambda_0 \), \( \omega_{dm} \) is the Alfvén frequency, \( \mu_3 \) is the anomalous viscosity, \( \omega_{sh} = k_i E_{F}(\omega_{sh} / L_{sh}) \) is the diamagnetic frequency of the energetic ions, \( \beta_h = 8 \pi p_{ch} / B_0^2 \), \( L_{sh} = \int_0^{E_0} \left( E_0^3 + E_c^3 \right) dE_i, \omega_0 = \omega_{L} / \omega_{dm} (\omega_0) \) is the rotation frequency of the island without energetic ions, and the numerical coefficients \( G_0 \sim 0.82, G_0 \sim 2.31, \) and
Gh ∼ 0.56. In equation (15), the effects of external magnetic fields, such as the error field, are not considered, for simplicity. The first term on the right-hand side of equation (15) results from the effect of viscosity. Without energetic ions, the island rotation would reach a resonance condition which is always the case for a monotonic q profile. Thus, Δsh > 0 can be obtained based on equation (16). The rotation frequency of NTMs will increase. On the other hand, if the rotation frequency of NTMs is the same as the electron diamagnetic frequency, ωd < 0 should be satisfied from the resonance condition, which is always the case for a monotonic q profile. In this case, Δsh < 0, i.e. it plays a damping role. The rotation frequency of NTMs will then decrease.

For typical tokamaks like DIII-D, the main parameters are B ≈ 2 T, R0 = 1.7 m, a = 0.61 m, n0 = 3.5 × 10^{19} m⁻³, T_i ≈ T_e ≈ 3.5 keV, s = 0.5, L_{Ec} ≈ L_{ni} = −a, L_{nh} = 0.5L_{ni}, the mode numbers m = 3 and n = 2, and the initial frequency ω_0/(2π) = 3 kHz. It is assumed that E_m = 65 keV, the pitch angle λB = 1 for energetic ions, and the viscosity coefficient μ_ν = 1 m² s⁻¹. Then, based on equations (15) and (16), the frequency is plotted versus t in figures 1 and 2 for s = 0.5 and −0.5, respectively. From figure 1, it can be seen that the resonance effects of energetic ions on the island propagation frequency are dramatic when the island propagates in the ion diamagnetic drift direction. When the β_{sh} of trapped energetic ions increases above a critical value, the resonance effect dominates over the viscosity damping effect, and the frequency will chirp up. This is consistent with a DIII-D experiment [21], where frequency chirping was observed when the island propagated in the ion diamagnetic drift direction.

The chirping speed of the frequency increases with the frequency. When the frequency is low, namely, much smaller than the maximal precessional frequency of trapped energetic ions, the chirping increases slowly, since the fraction of resonant energetic ions is small. When the frequency is higher, it chirps up more quickly. In the DIII-D experiment [21], it was shown that the frequency jumps up from the NTM frequency and then chirps down to the NTM frequency again within ∼1 ms. From figure 1, it can be calculated that the times of chirping up to ω/(2π) ∼ 15 kHz are about 1.1 ms, 2.3 ms, and 7.2 ms for β_{sh} = 1.0%, 1.2%, and 1.6%, respectively, which are of the same order as reported in reference [21]. In fact, the chirping found in TFTR [16] and ASDEX-U [18] is also on a millisecond scale. Here, the loss or redistribution of energetic ions is not considered, and so the process of chirping down cannot be shown. If the resonant energetic ions are lost, then the frequency will chirp down to ω_0 quickly owing to the damping effect of viscosity. On the other hand, if the island propagates in the electron diamagnetic drift direction, ω_d > 0 should be satisfied for the resonance condition with reversed magnetic shear. In this case, it can be seen from figure 2 that the resonance effect tends to decrease the frequency. When ω < ω_0 (where ω_0 is the rotation frequency of the NTM without energetic ions), the effect of viscosity tends to enhance the frequency to ω_0. When the effects of resonance and of viscosity balance, the frequency remains constant, as can be seen from figure 2. Hence, frequency chirping of NTMs occurs only when the rotation frequency of NTMs is the same as the ion diamagnetic drift frequency. Actually, in a recent HL-2A experiment [20], it was shown that the phenomenon of frequency chirping only occurs while the rotation direction of the tearing mode changes from that of electron diamagnetic drift to that of ion diamagnetic drift. To confirm the above results, further statistical analysis of experimental results is needed. On the other hand, because the transit frequency of passing energetic ions is much larger than the frequency of NTMs, the resonance contribution from passing energetic ions is thought
to be small and is not considered here. This also needs to be verified by further experiments.

3. Conclusion and discussion

In conclusion, the mechanism of frequency chirping of NTMs has been investigated based on drift kinetic theory. It is found that resonance between trapped energetic ions and NTMs provides an additional torque to alter the rotation frequency of the NTMs. The rise or fall of the rotation frequency depends on the direction of rotation of the NTMs. If this direction is the same as that of ion diamagnetic drift, then the resonance effect will increase the rotation frequency of NTMs rapidly. This is consistent with the experimental results reported in TFTR [16], ASDEX-U [18], DIII-D [21], and HL-2A [20]. If the direction of rotation of NTMs is the same as the electron diamagnetic drift direction, then frequency chirping does not occur. It will be reduced to a lower frequency. It can be concluded that the resonance between the island and trapped energetic ions can change the island rotation frequency dramatically and quickly, in a few milliseconds, when the island propagates in the ion diamagnetic drift direction.

In this work, the effect of the resonance contribution on the evolution of island width has not been considered. In fact, the change in frequency due to resonance will affect the neoclassical polarization, which depends on the island propagation frequency. Thus, the evolution of the island width will be affected by the resonance. This effect will become significant if the island width is small, since the neoclassical polarization then plays an important role. On the other hand, non-resonance effects will also affect the island evolution.

Rapid frequency chirping of NTMs due to energetic ions may have an impact on the dynamics of island locking. It may change the locking state of the island, and may reduce the explosive growth of the island to avoid plasma disruption [4, 30, 31]. It should be pointed out that resonance can also lead to redistribution and loss of energetic ions, which is not considered here. In that case, a chirping down process can occur.

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References

[1] Chang Z., Callen J.D., Fredrickson E.D., Budny R.V., Hegna C.C., McGuire K.M. and Zarnstorff M.C. (TFTR Group) 1995 Phys. Rev. Lett. 74 4663
[2] Carrera R., Hazeltine R.D. and Kotschenreuther M. 1986 Phys. Fluids 29 899
[3] Hender T.C., Howell R.D., Buttery R.J., Sauter O., Sartori F., La Haye R.J., Hyatt A.W. and Petty C.C. (JET EFDA contributors and the DIII-D team) 2004 Nucl. Fusion 44 788
[4] Hender T.C. et al 2007 Progress in the ITER physics basis chapter 3: MHD stability, operational limits and disruptions Nucl. Fusion 47 s128–202
[5] Chen L., White R.B. and Rosenbluth M.N. 1984 Phys. Rev. Lett. 52 1122
[6] Chen L. and Zonca F. 2016 Rev. Mod. Phys. 88 015008
[7] Poli E., García-Muñoz M., Fahrbach H.-U. and Günter S. (ASDEX Upgrade Team) 2008 Phys. Plasmas 15 035201
[8] García-Muñoz M., Fahrbach H.-U., Pinches S. D., Bobkov V., Brüdgam M., Gobbin M., Günter S., Igochine V., Lauber Ph. and Mantsinen M. J. (The ASDEX Upgrade Team) 2009 Nucl. Fusion 49 085014
[9] Buttery R.J., La Haye R.J., Gohl P., Jackson G.L., Reimerdes H. and Strait E.J. (The DIII-D Team) 2008 Phys. Plasmas 15 056115
[10] Hegna C.C. and Bhattacharjee A. 1989 Phys. Rev. Lett. 63 2056
[11] Takahashi R., Brennan D.P. and Kim C.C. 2009 Phys. Rev. Lett. 102 135001
[12] Cai H.S., Wang S.J., Xu Y.F., Cao J.T. and Li D. 2011 Phys. Rev. Lett. 106 075002
[13] Cai H. and Fu G. 2012 Phys. Plasmas 19 072506
[14] Liu Y., Haste R.J. and Hender T.C. 2012 Phys. Plasmas 19 092510
[15] Cai H. 2016 Nucl. Fusion 56 126016
[16] Fredrickson E.D. 2002 Phys. Plasmas 9 54859
[17] Gude A., Günter S. and Sesnic S. (ASDEX Upgrade Team) 1999 Nucl. Fusion 39 12731
[18] Sesnic S., Günter S., Gude A. and Marasche M. 2000 Phys. Plasmas 7 9359
[19] Li E. et al 2016 Plasma Phys. Control. Fusion 58 045012
[20] Chen W. et al 2019 Nucl. Fusion 59 096037
[21] Liu D. et al 2020 Nucl. Fusion 60 112009
[22] Marchenko V.S. and Lutsenko V.V. 2001 Phys. Plasmas 8 4834
[23] Zhang X., Gao B., Cai H., Zheng S. and Wang Z.-X. 2020 Plasma Phys. Control. Fusion 62 085010
[24] Zhu X.-L., Chen W., Wang F. and Wang Z.-X. 2020 Nucl. Fusion 60 046023
[25] Rutherford P.H. 1973 Phys. Fluids 16 1903
[26] Smolyakov A.I., Hirose A., Lazzaro E., Re G.B. and Callen J.D. 1995 Phys. Plasmas 2 1581
[27] Chew G.F., Goldberger M.L. and Low F.F. 1956 Proc. R. Soc. A 236 212
[28] Graves J.P. 2013 Plasma Phys. Control. Fusion 55 074009
[29] Wilson H.R., Connor J.W., Hastie R.J. and Hegna C.C. 1996 Phys. Plasmas 3 248
[30] Gerhardt S.P. et al 2013 Nucl. Fusion 53 043020
[31] Fitzpatrick R. 1993 Nucl. Fusion 33 1049