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Threshold Effects for Pellet-Plasma Interaction in Tokamak - MHD Modeling

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The data from the T-10 tokamak [1] provide an evidence of the threshold effect of the pellet size for appearance of the ablation bursts and drops in the pellet injection experiments. The MHD-events initiated by pellets may significantly contribute to faster and deeper penetration of the pellet matter into the plasma.

The computations performed with the 3D non-linear MHD code NFTC [2] demonstrated the possibility of the excitation of the neoclassical tearing modes (NTMs) by the moving cooling front with the increased plasma resistivity due to the pellet penetration into the plasma. The detailed analysis of 3D effects will be given in [3].

The computations of the magnetic field diffusion and current density structure were performed with the 1.5D SPIDER plasma evolution code [4]. At the moving cooling front an existence of the quasi-stationary distribution of the toroidal current density was discovered. The localized changes in the current density and safety factor profiles in tokamak plasma lead to strong increase of the tearing mode growth rates corresponding to the fast magnetic island growth in the nonlinear modeling [5].

The size of magnetic islands with different values of toroidal and poloidal wave numbers m and n are estimated based on the quasi-linear extension of Rutherford equation for the island evolution integrated during the front crossing the rational surface $q = m/n$.

1 Cooling front modeling

Small size of pellet, high conductivity and anisotropy of the diffusion coefficients in high temperature plasma make a full MHD description of the pellet penetration into the plasma quite a complicated task. A model for the pellet – moving low temperature and high resistivity zone, cooling front – was proposed in [5].

The propagation of the axisymmetric cooling front not interacting with magnetic islands is well described by 1.5D quasi-equilibrium plasma evolution, taking into account the magnetic field diffusion. Such a model is implemented in the SPIDER code [4] and the structure of the quasi-stationary perturbation of the current density is studied here under different assumptions about the temperature in the front.

The unperturbed temperature profile is prescribed as a function of the square root of the normalized toroidal flux $a = \sqrt{\Phi/\Phi_b}, \quad 0 \le a \le 1$: $T_0(a) = T_b + (1-a^2)(T_a - T_b)$, where the values at the magnetic axis and the boundary for the T-10 tokamak are chosen: $T_a = 1\ keV$, $T_b = 30\ eV$. The temperature drop at the front $a(t) = a_0 - v_{pellet}t$ moving with the velocity

v_{pellet} in the flux variable a is prescribed as follows:

$$T(a) = T_0(a(t) \pm d) + \left[1 - \left|\frac{a - a(t)}{d}\right|^p\right]^2 \left(T_{pellet} - T_0(a(t) \pm d)\right), \quad a \in [a(t), a(t) \pm d], \quad (1)$$

where d is half-width of the colder zone. The parallel conductivity σ is taken to be proportional to $T^{3/2}$.

In Figure 1 the evolution of the parallel current density, parallel component of the electric field, shear and conductivity are shown. In about 100 μs after an instant drop of the conductivity the perturbation becomes quasi-stationary (initial front position $a_0 = 0.93$, the velocity v_{pellet} corresponds to 400 m/s, the exponent $p = 1$, $d = 5 \times 10^{-3}$ corresponds do the pellet diameter 3 mm in T-10, plasma minor radius 0.3 m, $T_{pellet} = 5$ eV).

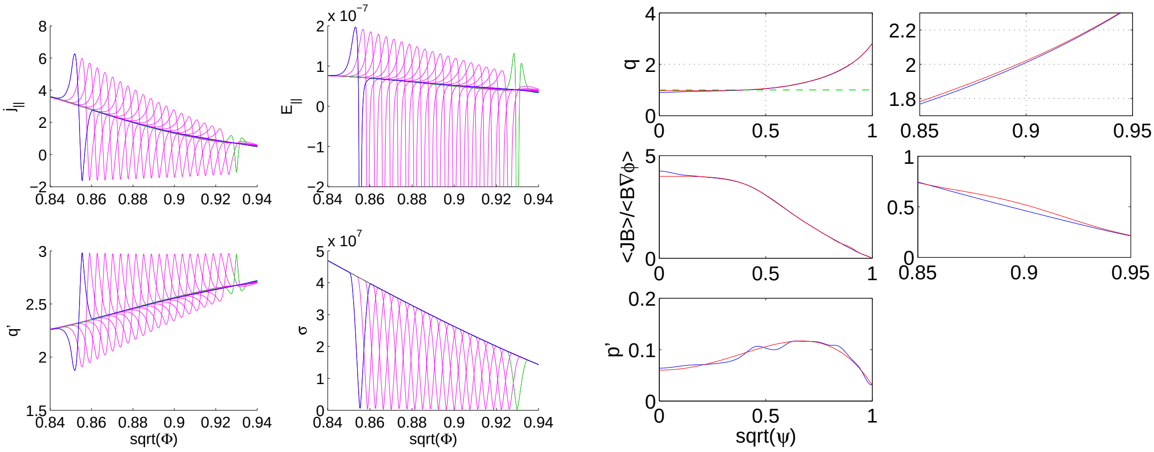

Figure 1. The evolution of the parallel current density, electric field, shear and conductivity in the moving front (left). The original ASTRA and the smoothed profiles for the T-10 shot #42358 (right). The region around the rational flux surface $q = 2/1$ is zoomed for the safety factor and parallel current density plots. Linear tearing modes $m/n = 2/1$ and $3/2$ are stable for smoothed profiles.

The calculations with the SPIDER code (size of the flux grid up to 10000) were performed under variations of the pellet width $d = 5 \times 10^{-4} - 5 \times 10^{-3}$ corresponding to $0.3 - 3$ mm in T-10 and the sharpness of the front when increasing the parameter p in (1). In all cases the current density evolution at the moving cooling front demonstrated an existence of the quasi-stationary distribution: an amplitude of the perturbation at the front is increased with the size of the pellet and the sharpness of the temperature and resistivity profiles; the perturbation dissipates at the trailing edge of the moving high resistivity zone.

2 Magnetic island width estimates

The main mechanism of the tearing mode destabilization in the nonlinear modeling [5] is related to the sharp increase of the Δ' parameter at the resonant surface of the corresponding mode. In turn, the significant increase in the Δ' values is related to the local toroidal current density perturbation propagating with the high resistivity front.

The nonlinear evolution of the magnetic island without neoclassical effects can be described by the extended Rutherford equation [6, 7] for the magnetic island width w:

$$\frac{\tau_R}{r_a}\frac{dw}{dt} = 1.22 r_a (\Delta' - \alpha w), \quad (2)$$

where $\tau_R = \mu_0 r_a^2/\eta$, r_a is the plasma minor radius, η is plasma resistivity; Δ' is the tearing parameter, α is the reduction of this jump when the island is large enough to modify the equilibrium current profile. In cylindrical approximation the value of $\Delta' = \left[\frac{d\ln\psi}{dr}\right]_{r_s}$ is determined by the jump of the logarithmic derivative of the radial magnetic field perturbation ψ at the rational surface $m - nq(r_s) = 0$ [8]:

$$\frac{d}{dr}\left(r\frac{d\psi}{dr}\right) - \frac{m^2}{r}\psi - \frac{d\,j_z/dr}{(B_\theta/r)(1-nq/m)}\psi = 0 \qquad (3)$$

where r is plasma minor radius, $j_z(r)$ is longitudinal current density, B_θ is poloidal equilibrium magnetic field. The function α is related to the saturated width of the island: $\alpha = \Delta'/w_{sat}$. The values of Δ' and w_{sat} are computed with the DELTAPCYL code [9].

The integration of the equation (2) during the time of the pellet passing the rational surface gives an estimate of the attainable island width. In Figure 2 the island width evolution for the modes $m/n = 2/1$ and $m/n = 3/2$ is presented. Due to the existence of the tearing mode unstable zone with $\Delta' > 0$ ahead of the front position r ($r > r_s$, where r_s is the rational surface radius), the island grows there on the regular resistive time scale ($\tau_{R0} = 100$ ms in T-10 plasma center). The island width reaches the saturation level and then goes down due to the Δ' decrease and becoming negative closer to the front. The growth of the island starts again on much faster time scale, when the rational surface enters the high resistivity zone, followed by saturation phase. Eventually the island shrinks due to $\Delta' < 0$ (tearing mode stability) after the cooling front passing the rational surface and leaving just slightly perturbed current density profile behind. Let us note that despite larger current density perturbation near the $q = 3/2$ surface (in particular, due to larger temperature difference between the value at the rational surface position closer to the plasma center and fixed T_{pellet}), the island saturation levels are not much different (~ 1 mm) from the $m/n = 2/1$ case. This is due to the assumption made when deriving the equation (2) that the saturation is observed due to the island sampling a different portion of the exterior solution, giving a quasi-linear decrease of the driving term Δ', modified by internal finite island width [6]. In our case the saturation width corresponds to the exterior solution sampled outside the perturbed current density region. More elaborated models for the island saturation which take into account not only the equilibrium current density profile but also the resistivity variations may be needed to correctly describe the island evolution under impact of the cooling front. Taking into account neo-classical and finite pressure terms incorporated into the modified Rutherford equation [7] could lead to additional effects in the island evolution.

The calculations performed for higher tearing mode wave numbers showed that for resonant values of $m/n = 4/2,\ 8/4$ and $m/n = 6/4,\ 9/6$ at the rational surfaces $q = 2$ and $q = 1.5$ the Δ' values in high resistivity zone are comparable to the low wave number cases $m/n = 2/1$ and $m/n = 3/2$ respectively. This is due to domination of the driving term determined by the perturbed equilibrium current density over the stabilizing term proportional to m^2 in the tearing mode equation (3).

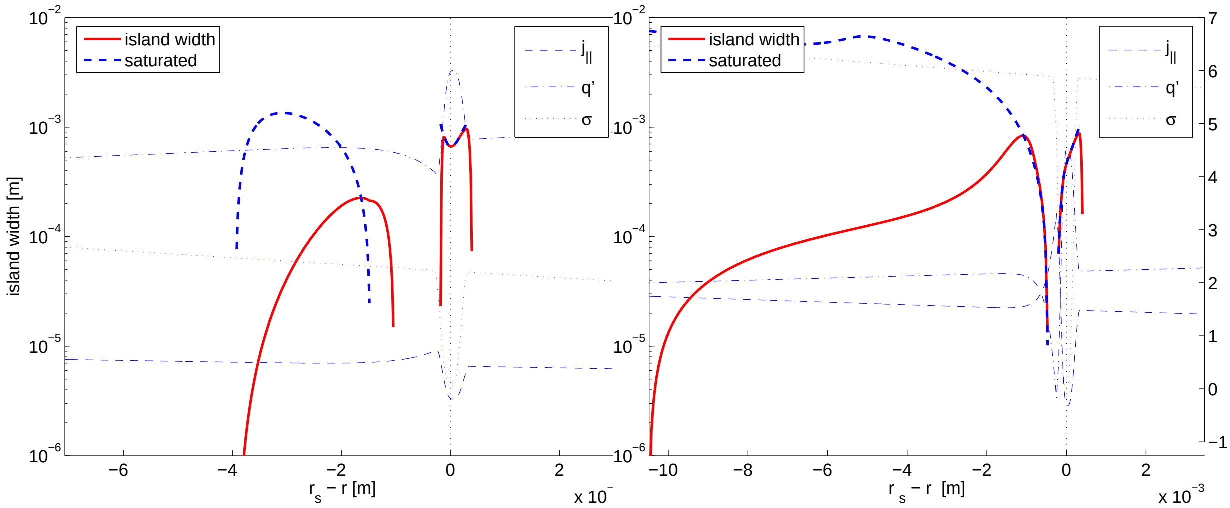

Figure 2. Evolution of the 2/1 island width (left) and 3/2 island width (right) versus the distance from the corresponding resonant surface to the middle of the high resistivity zone. Pellet diameter is 0.6 *mm. The resistive time in the plasma center is* $\tau_{R0} = 100$ *ms.*

3 Conclusions

The quasi-stationary distribution of the toroidal current density at the moving cooling front obtained in the 1.5D equilibrium evolution calculations was employed in the analysis of the magnetic island growth provoked by pellet injection in the T-10 tokamak. The tearing mode stability calculations reveal an existence of tearing unstable $\Delta' > 0$ zone ahead of the front at least for low mode wave numbers $m/n = 2/1, 3/2$. The width of the corresponding island depend on the size of pellet and the steepness of the temperature front. On the contrast, the island evolution inside the high resistivity zone does not demonstrate significant variations under different assumptions about the size of the pellet, the shape of the cooling front and variations of the wave numbers of the resonant mode.

The estimates show that the width of the islands ahead of the cooling front can be comparable to the width of pellet at least in case of large pellet size (0.6 *mm*). It gives a possibility of a seed island generation by large pellets leading to the interaction of the upcoming pellet with the island. Resulting MHD events may explain threshold effect of the pellet size for appearance of the ablation bursts and drops [1].

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