Kinetic modelling of shielding and amplification of RMPs by the tokamak plasma

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Abstract

ELM mitigation by resonant magnetic field perturbations (RMPs) is presently a subject of intensive experimental and theoretical studies. As shown in Ref. [1] and other references, RMPs are strongly shielded by plasma currents if the perpendicular electron fluid velocity $V_{\perp e}$ is finite. As a result, plasma shielding prevents the formation of ergodic layers which were originally thought to be responsible for ELM mitigation. Recently in Ref. [2] it has been found that in one of the successful ELM mitigation experiments on DIII-D, the point $V_{\perp e} = 0$ where the field is not shielded, is located at the top of the pedestal. Based on this finding, in Ref. [3] significant quasilinear effects of RMPs on the pedestal plasma have been demonstrated. On the other hand, in this discharge, not only a $V_{\perp e} = 0$ point but also a reversal point of the radial electric field $E_r = 0$ is present in the pedestal region as shown in Fig. 1 of Ref. [2]. The substantial effect of $E_r = 0$ points on RMP penetration and RMP driven plasma transport is studied in the present contribution.

Kinetic Plasma Response Model

- Linear plasma response model

$$\nabla \times \tilde{\mathbf{E}} = \frac{i\omega}{c}\tilde{\mathbf{B}}, \qquad \nabla \times \tilde{\mathbf{B}} = -\frac{i\omega}{c}\tilde{\mathbf{E}} + \frac{4\pi}{c}\tilde{\mathbf{j}}, \tag{1}$$

- Green's function for linearised kinetic equation

$$i\left[k_\parallel v_\parallel + k_\perp v_{E\perp} - m_\phi \omega_c - \omega\right] G_{\mathbf{m}}(v_\parallel, v'_\parallel) - \hat{L}_{cp} G_{\mathbf{m}}(v_\parallel, v'_\parallel) = \delta(v_\parallel - v'_\parallel). \tag{2}$$

- Energy conserving Ornstein-Uhlenbeck type collision operator

$$\hat{L}_{cp} f_1 = \hat{L}_c f_1 + \hat{L}_{cI} f_1, \qquad \hat{L}_c f_1(v_\perp, v_\parallel) = \nu v_T^2 \frac{\partial}{\partial v_\parallel}\left(\frac{\partial}{\partial v_\parallel} + \frac{v_\parallel}{v_T^2}\right) f_1(v_\perp, v_\parallel) \tag{3}$$

$$\hat{L}_{cI} f_1(v_\perp, v_\parallel) = \frac{\nu}{\sqrt{2\pi} v_T} \exp\left(-\frac{v_\parallel^2}{2v_T^2}\right)\left(\frac{v_\parallel^2}{v_T^2} - 1\right) \int\limits_{-\infty}^{\infty} dv'_\parallel \left(\frac{v_\parallel'^2}{v_T^2} - 1\right) f_1(v_\perp, v'_\parallel). \tag{4}$$

- Perturbed distribution function

$$f_{\mathbf{m}} = -e \int\limits_{-\infty}^{\infty} dv'_\parallel\, G_{\mathbf{m}}(v_\parallel, v'_\parallel) \left[\left(\tilde{\mathbf{E}} + \frac{1}{c}\mathbf{v} \times \tilde{\mathbf{B}}\right) \cdot \frac{\partial f_0}{\partial \mathbf{p}}\right]_{\mathbf{m}}, \tag{5}$$

- finite Larmor radius expansion [1, 4, 5]

$$\tilde{j}^k_{(N)}(r, \vartheta, z) = \frac{1}{r} \sum_{n,n'=0}^{N} (-1)^n \frac{\partial^n}{\partial r^n}\left(r\, \sigma^{kl}_{(n,n')}(r, \mathbf{k}) \frac{\partial^{n'}}{\partial r^{n'}} \tilde{E}_l(r, \vartheta, z)\right). \tag{6}$$

- Quasilinear particle and energy fluxes

$$\Gamma = \frac{1}{2}\mathrm{Re}\sum_{\mathbf{m}} \int d^3p\, a_1 f_{\mathbf{m}}\, v^{r*}_{\mathbf{m}} = -n\left(D_{11}A_1 + D_{12}A_2\right), \tag{7}$$

$$Q = \frac{1}{2}\mathrm{Re}\sum_{\mathbf{m}} \int d^3p\, a_2 f_{\mathbf{m}}\, v^{r*}_{\mathbf{m}} = -nT\left(D_{21}A_1 + D_{22}A_2\right). \tag{8}$$

Here, $a_1 = 1$, $a_2 = m(v_\perp^2 + v_\parallel^2)/(2T)$, and the thermodynamic forces A_1, A_2 are

$$A_1 = \frac{1}{n}\frac{\partial n}{\partial r} - \frac{e}{T}E_r - \frac{3}{2T}\frac{\partial T}{\partial r}, \qquad A_2 = \frac{1}{T}\frac{\partial T}{\partial r}. \tag{9}$$

- Diffusion coefficients D_{kl} are expressed through the perturbed radial guiding center velocity $v^r_{\mathbf{m}}$

$$D_{kl} = \frac{\pi m^3}{n}\mathrm{Re}\sum_{\mathbf{m}} \int\limits_0^{\infty} dv_\perp v_\perp \int\limits_{-\infty}^{\infty} dv_\parallel \int\limits_{-\infty}^{\infty} dv'_\parallel\, G_{\mathbf{m}}(v_\parallel, v'_\parallel)$$
$$\times\; v^{r*}_{\mathbf{m}}(v_\perp, v_\parallel) v^r_{\mathbf{m}}(v_\perp, v_\parallel) a_k(v_\perp, v_\parallel) a_l(v_\perp, v'_\parallel) f_0(v_\perp, v'_\parallel). \tag{10}$$

$$v^r_{\mathbf{m}} = \frac{v_\parallel}{B_0} B^r_{\mathbf{m}} - \frac{ick_\perp}{B_0}\Phi_{\mathbf{m}} - \frac{ik_\perp v_\perp^2}{2\omega_{c0} B_0} B_{\mathbf{m}\parallel} - \frac{ik_\parallel v_\parallel^2}{\omega_{c0} B_0} B_{\mathbf{m}\perp}, \tag{11}$$

- Torque and force-flux relation

$$T_\varphi = -\frac{e}{c}\sqrt{g} B_0^\vartheta \Gamma, \tag{12}$$

where $\sqrt{g}$ and B_0^ϑ are the unperturbed metric determinant and the contra-variant poloidal magnetic field component.

Plasma Parameters

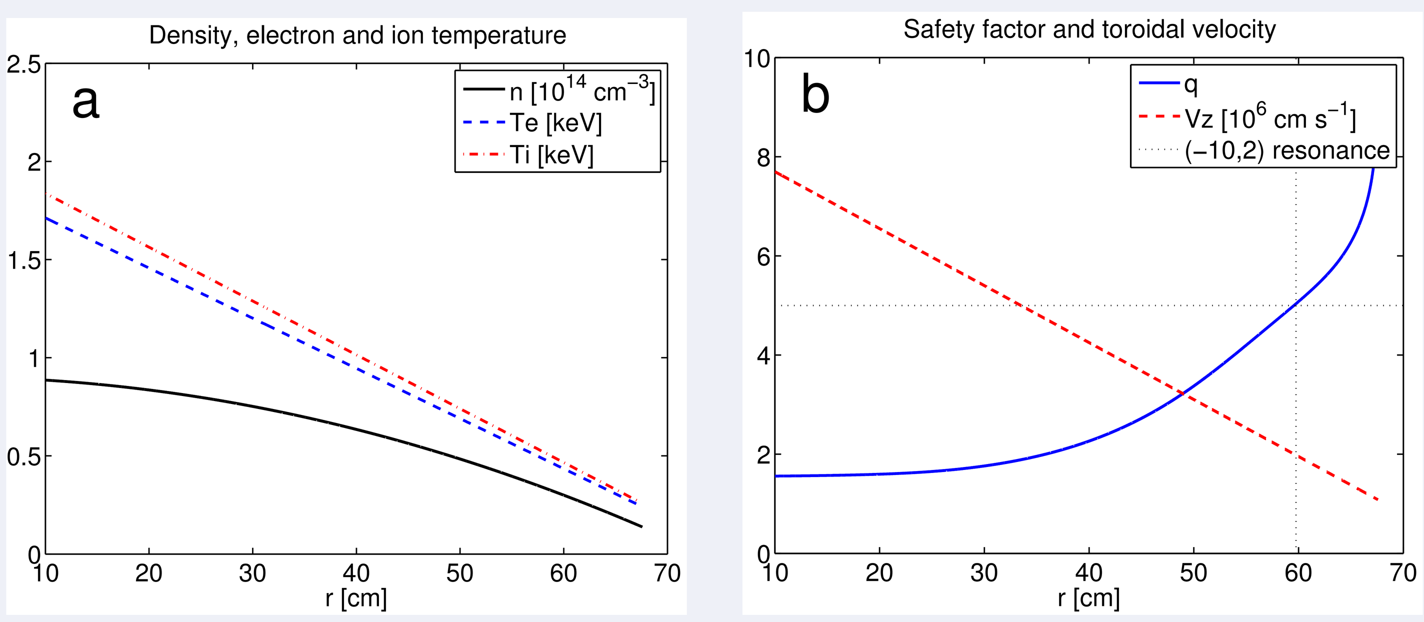

Fig. 1. Plasma parameter profiles and safety factor.

Electric Resonance in the Pedestal Region

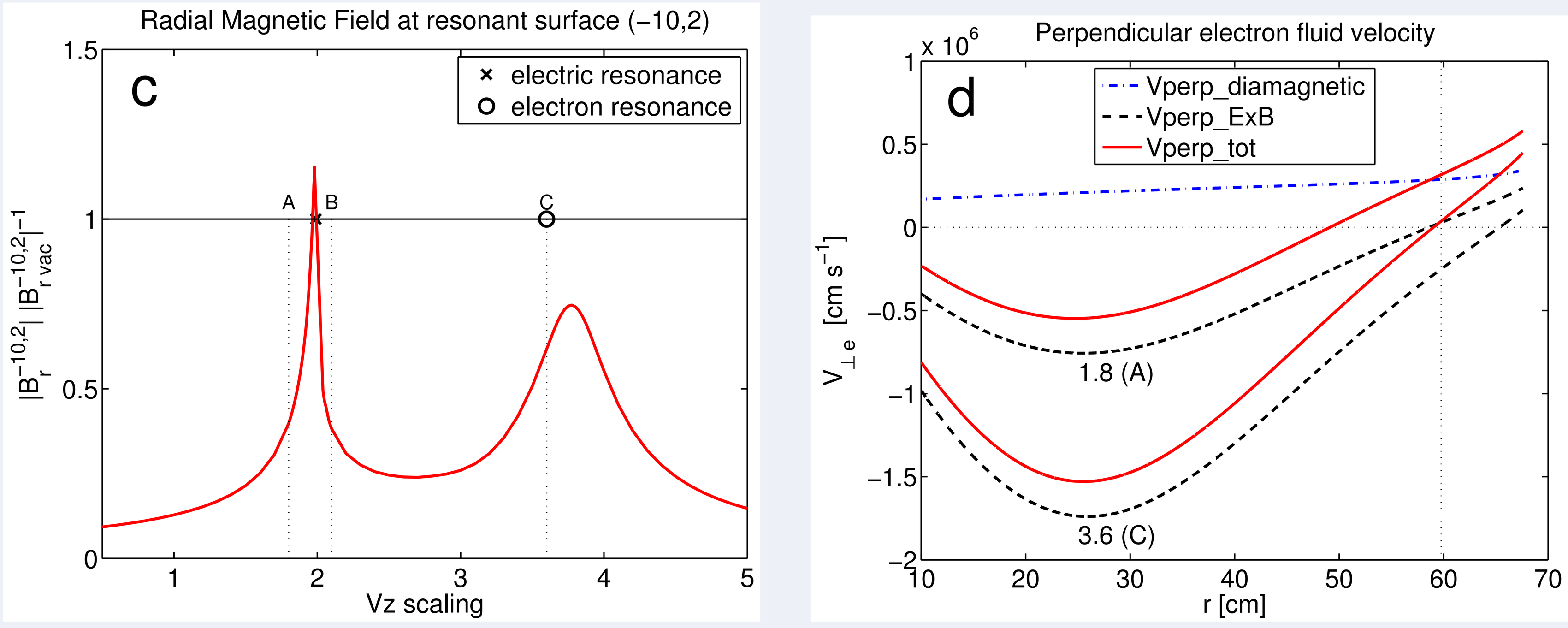

Fig. 2. Scaling with V_z of the radial magnetic field B_r at the resonance surface for mode (-10,2). Electron diamagnetic (blue), electric (black) and total (red) velocity for scaling factors 1.9 and 3.6.

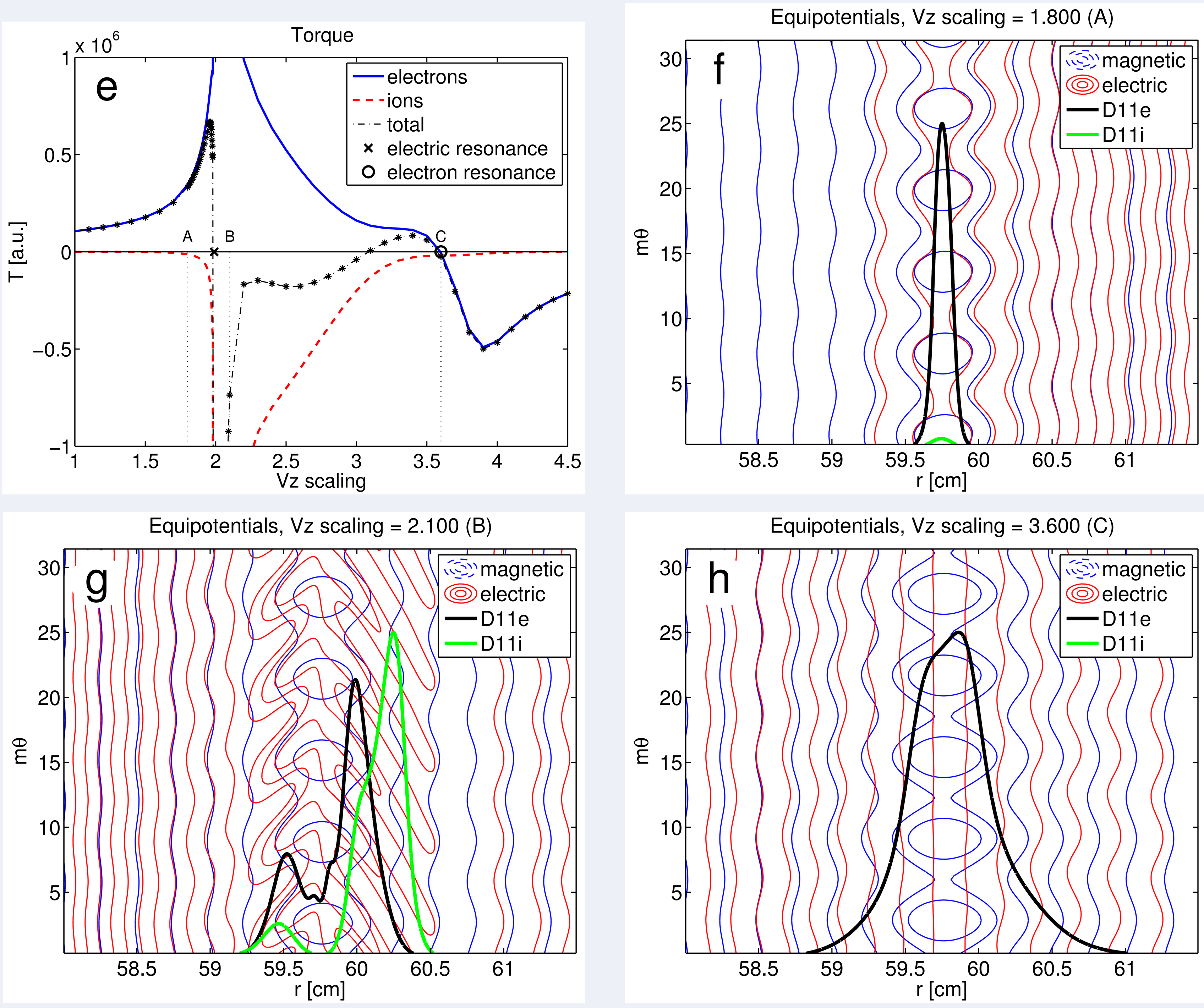

Fig. 3. Torque acting on electrons (blue) and ions (red) and total torque (black) for linear-parabolic tokamak-like profiles. Magnetic and electric equipotential surfaces as well as electron (solid) and ion (dashed) D_{11} diffusion coefficients for different V_z scalings (A), (B) and (C).

Conclusions

- The model is applied to a low temperature discharge in a mid-size tokamak with linear temperature and parabolic density profiles shown in Fig. 1.
- Perturbation mode (m=-10, n=2) is resonant at the plasma edge. Scaling V_z places either the zero of total perpendicular electron fluid velocity $V_{\perp e} = 0$ or the zero of the radial electric field $E_r = 0$ to the resonant surface. In both cases, plasma shielding of the perturbation is highly reduced and the radial component $\tilde{B}_r$ at the resonant surface increases almost to its vacuum value.
- The behaviour of ion and electron torques is different around those resonances (Fig. 3). At the electron fluid velocity zero the electron torque is increased. This follows from the increased perturbation field in a plasma with density and temperature gradients. In this case, the total torque is basically the electron torque and particle fluxes are non-ambipolar. The increase in particle transport is accompanied by a change in the plasma toroidal rotation.
- Near the $E_r = 0$ point both torques increase strongly but balance each other and the total torque stays small. Thus, the increased particle transport is almost ambipolar and the toroidal rotation changes little. The origin of the increased ambipolar transport near $E_r = 0$ is seen from looking at the perturbed magnetic (blue) and perturbed equipotential surfaces (red) in Fig. 3. The unperturbed potential has an extremum at $E_r = 0$ and equipotentials are much more perturbed around this resonance than anywhere else.
- Convective cells are formed due to the ambipolar $\mathbf{E} \times \mathbf{B}$ drift of the plasma along those equipotentials. This leads to a strong increase of the ambipolar particle transport. The increased transport might be responsible for the density pump-out usually observed in ELM mitigation experiments. The $E_r = 0$ resonance region is fairly slim and, therefore, the parameter window where it can affect the pedestal is rather narrow.

References

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