Analytic Theory of ELM Suppression by Static RMPs

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RMP-Induced ELM Suppression Theory

- Theory of RMP-induced ELM suppression conveniently divided into two parts. 1] Calculate "drive" at given rational surface from given set of RMP coils in given plasma equilibrium. 2] Calculate plasma response to drive at rational surface.
- Calculating drive is straightforward task because it can be accomplished by linear ideal-MHD code.[1]
- Calculating plasma response, which is focus of this talk, is far more difficult task.

[1] J.-K. Park et al. 2018 Nat. Phys. **14** 1223

DIII-D Discharge #158115

- In DIII-D discharge #158115,[2] relative phase of currents in two sets of $n = 2$ RMP coils varied sinusoidally at 1 Hz.
- Plasma exhibits two distinct responses.
- 1] Density pump-out. Reduction in pedestal density, accompanied by much smaller reduction in pedestal temperature, that modulates smoothly with amplitude of edge-resonant RMP harmonics.
- 2] ELM suppression. Occurs suddenly when amplitude of edge-resonant RMP harmonics exceeds critical value. Accompanied by sudden shift in edge ion toroidal rotation. Associated with formation of locked magnetic island chain (can be seen spinning up and decaying away in inverse bifurcation).

[2] R. Nazikian et al. 2015 PRL **114** 105002

Simulating DIII-D Discharge #158115

- To simulate RMP-induced ELM suppression would need to run non-linear, extended-MHD code, in toroidal geometry, for about 10^8 Alfvén times (1 second of experimental time).
- This is completely impossible (present-day codes only run for 10^4 Alfvén times). Need reduced model to make further progress.
- Hypothesis: RMP-induced ELM suppression is direct consequence of mode penetration at top of pedestal. Hypothesis is completely consistent with large body of DIII-D data.
- If hypothesis is true then do not need to model ELMs to model RMP-induced ELM suppression. Just need to model mode penetration. This can be achieved with nonlinear reduced-MHD code in cylindrical geometry.

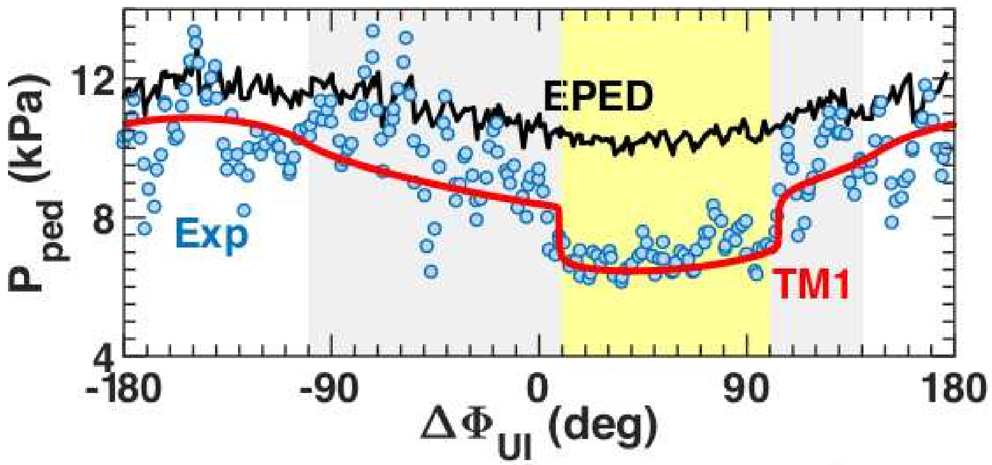
Hu, Nazikian, et al. 2019, submitted to PRL

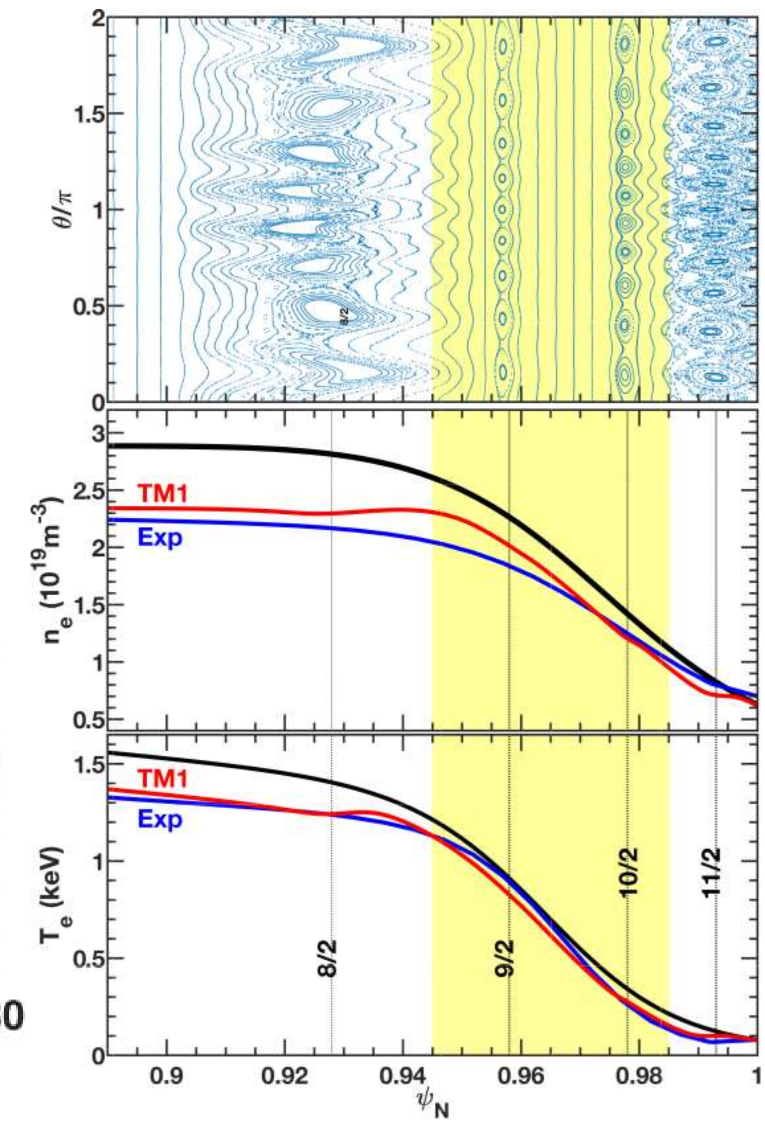
- Hu, Nazikian, et al. have simulated DIII-D discharge #158115 using nonlinear reduced-MHD code in cylindrical geometry (TM1).
- Simulations use experimental profiles, experimental RMP spectrum, and run for equivalent of 2.5 seconds of experimental time.
- Simulations exhibit strong shielding of driven magnetic reconnection in interior of pedestal.
- Simulations show reduction in pedestal density, accompanied by much smaller reduction in temperature, that modulates smoothly with amplitude of edge-resonant harmonics of RMP. This density-pump out phenomenon associated with formation of locked magnetic island chain at base of pedestal, where plasma too cold to effectively shield driven magnetic reconnection.

Hu, Nazikian, et al. 2019, submitted to PRL

- When amplitude of edge-resonant harmonics of RMP rises above critical threshold, simulations exhibit bifurcation in which locked magnetic island chain forms at top of pedestal (where natural frequency of tearing mode particularly small). Bifurcation accompanied by sudden shift in plasma flow. Critical threshold for "ELM suppression" event very similar to experimental value.
- Because of strong shielding of driven magnetic reconnection in interior of pedestal there is no stochastization of pedestal magnetic field.

- Pump out due to 11/2 island at pedestal foot.
- 8/2 mode penetration at pedestal top causes degradation in pedestal pressure.





My Research

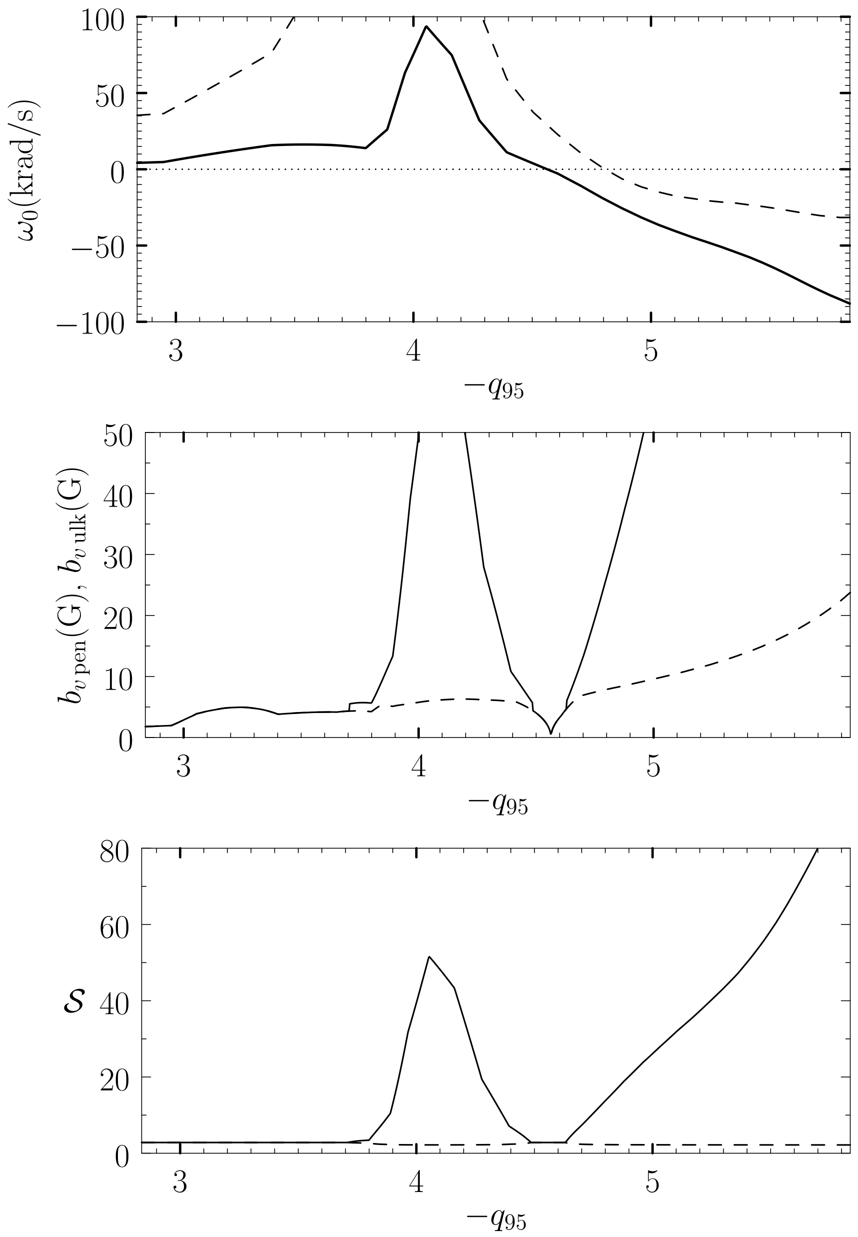
- Simulations of Hu, Nazikian, et al. take few hours of cpu time, corresponding to few days of real time.
- Primary aim of my research[3] is to use analytic theory to produce further reduced model that can perform simulation in matter of minutes of real time.
- Secondary aim is to gain deeper understanding of physics of RMP-induced mode penetration in pedestal regions of tokamak H-mode discharges.

[3] R. Fitzpatrick 2019, http://farside.ph.utexas.edu/Preprints/preprints.html

Major Insights

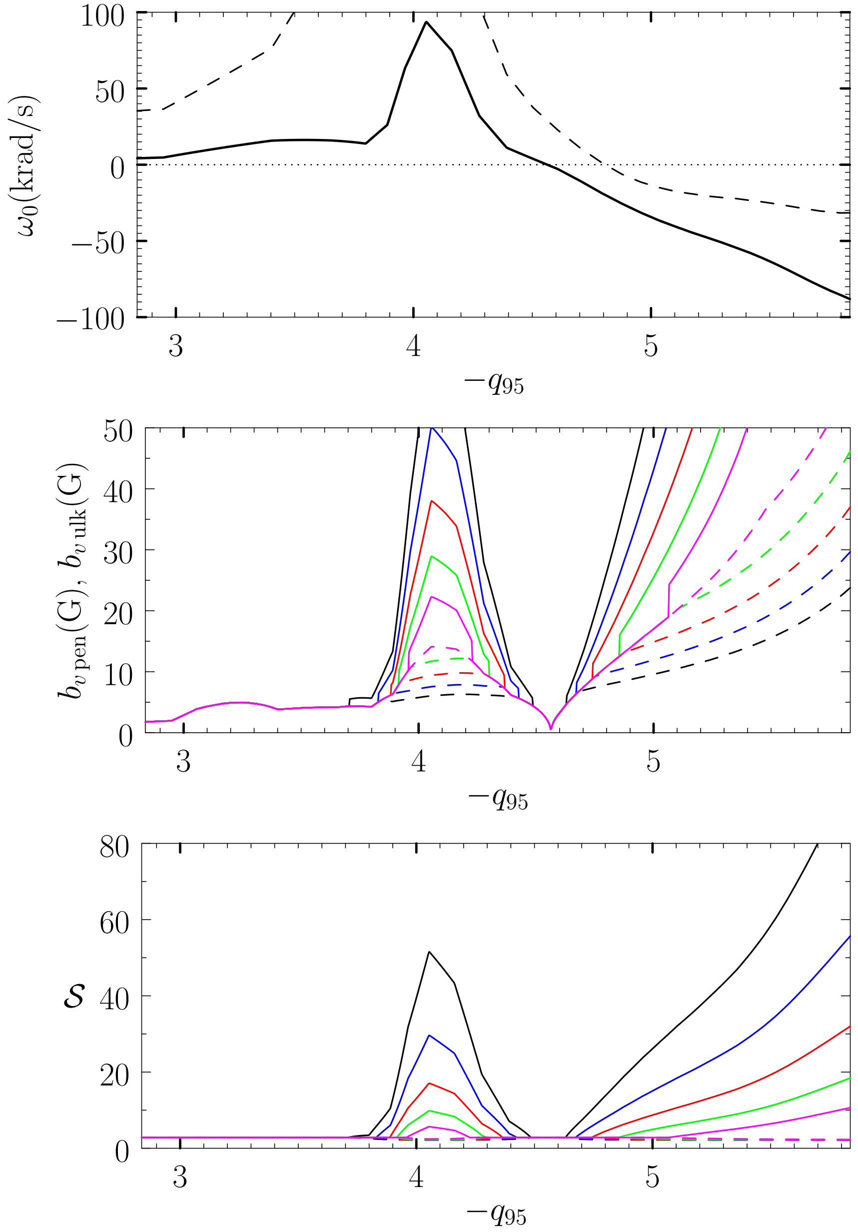
- Response of plasma in vicinity of rational surface to RMP governed by nonlinear magnetic island physics rather than linear layer physics. Driven island widths exceed linear layer widths, even in cases where magnetic reconnection strongly suppressed by plasma flow.
- Natural frequency of nonlinear magnetic island chain offset from local $\mathbf{E} \times \mathbf{B}$ frame in ion diamagnetic direction, rather than electron diamagnetic direction. Degree of offset controlled by neoclassical poloidal rotation.
- Experimental levels of plasma impurities can significantly affect mode penetration because they modify neoclassical poloidal rotation.

DIII-D #158115 q_{95} Scan



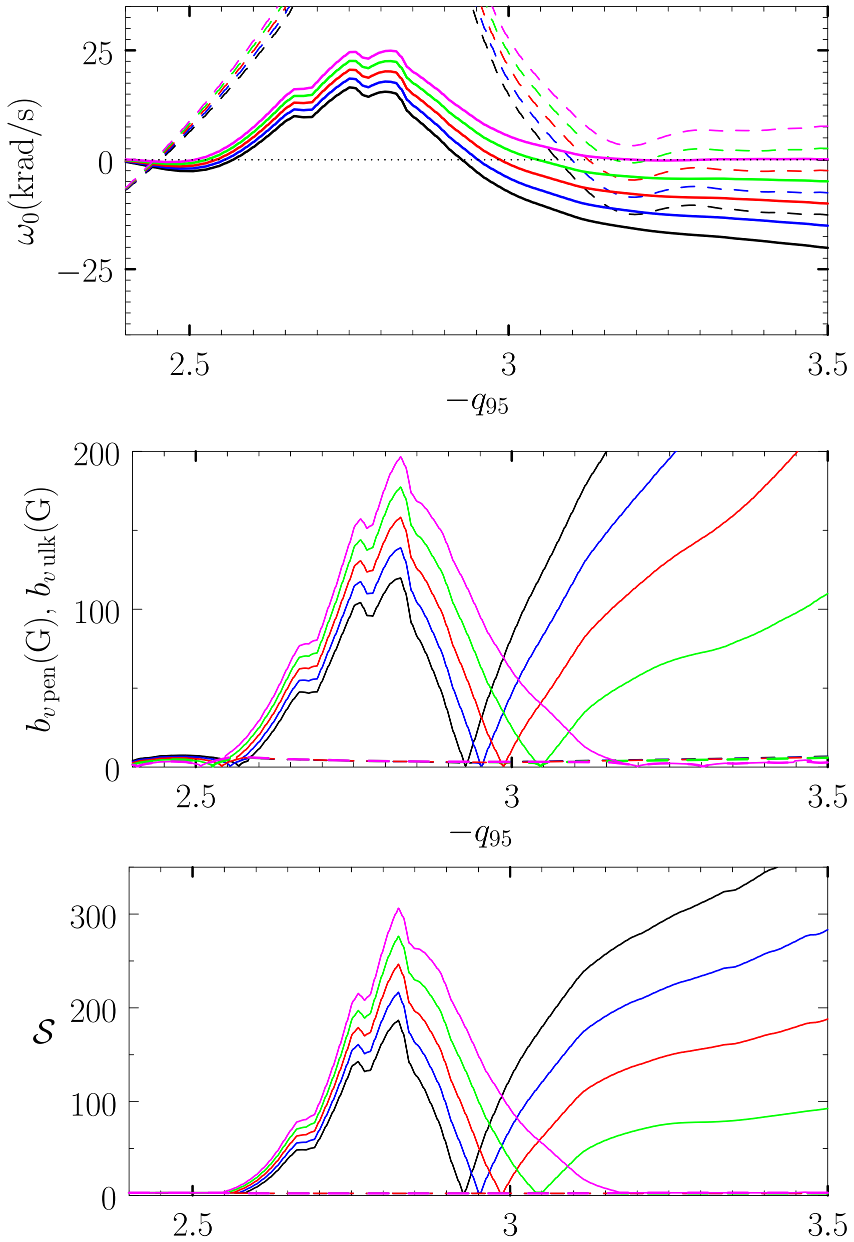
- Response of plasma to $m = 8/n = 2$ RMP harmonic.
- Upper panel: solid/dashed = nonlinear/linear natural freq.
- Middle panel: solid/dashed = mode penetration/unlock threshold.
- Lower panel: solid/dashed = shielding factor before/after mode penetration.
- Max. possible value of 8/2 RMP harmonic = 10 gauss.

DIII-D #158115 q_{95} Scan: Resistivity Dependence



- Black/blue/red/green/magenta = experimental resistivity scaled up by 1/2/4/8/16.
- Increasing resistivity by order of magnitude causes strong shielding in interior of pedestal to completely disappear.
- In absence of strong interior shielding, expect pedestal to be rendered stochastic by applied RMP. In reality, strong interior shielding prevents this.

ITER q_{95} Scan

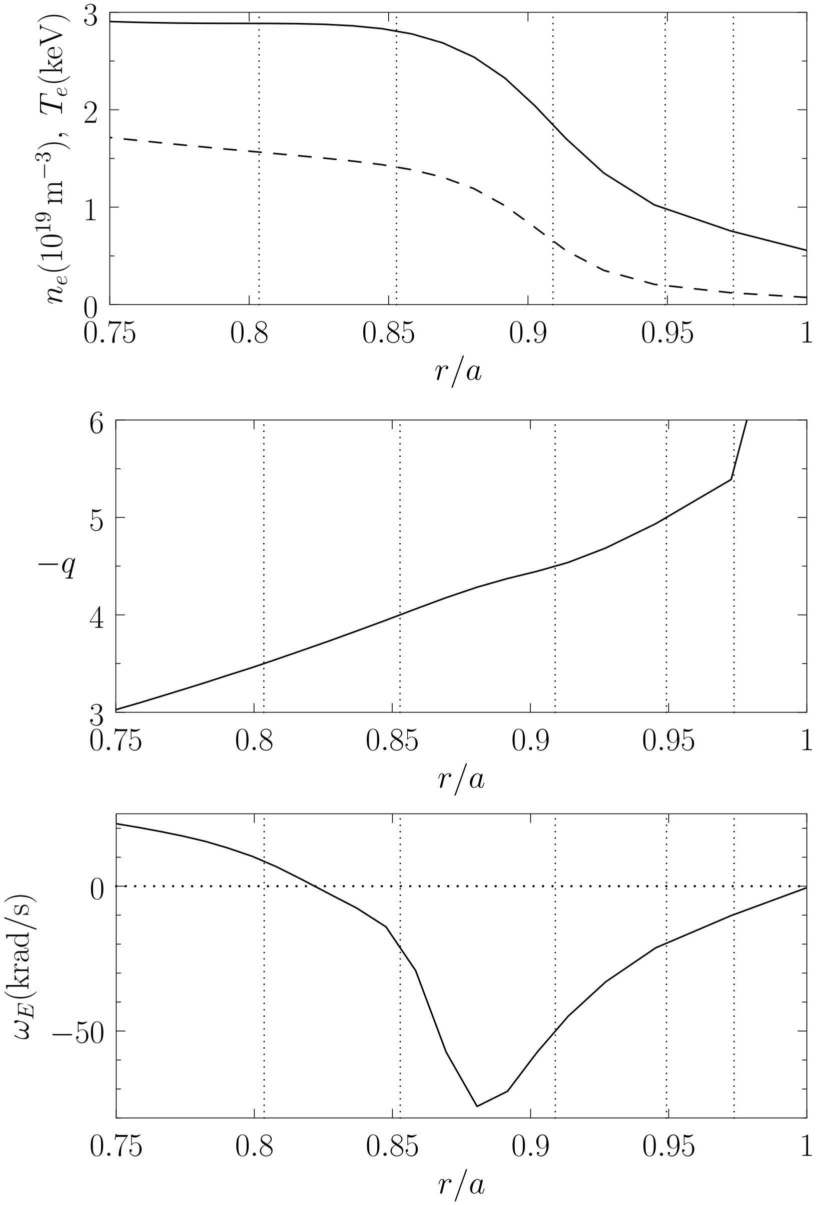


- Response to 9/3 RMP.
- Maximum possible value of 9/3 RMP harmonic = 60 gauss.
- Black/blue/red/green/magneta curves correspond to 20/15/10/5/0 krad/s core plasma rotation. 20 krad/s rotation = 17 MW NBI.
- Without core rotation, no shielding in core.
- 20 krad/s q_{95} window width slightly smaller than in DIII-D.

Summary

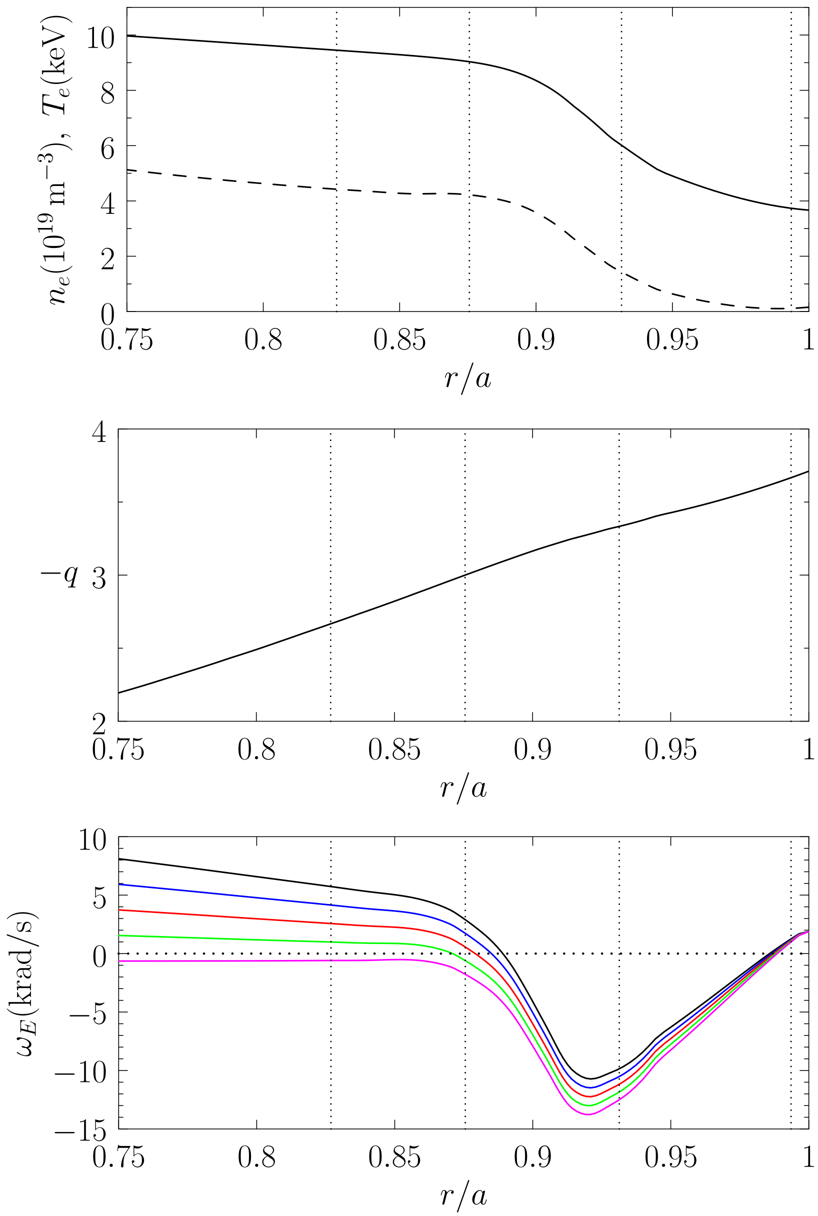
- Have developed reduced analytic model of RMP-induced ELM suppression, based on plausible simplifying hypothesis.
- Model can be used to locate q_{95} windows in which RMP-induced ELM suppression is possible.
- Assuming 20 krad/s core rotation (17 MW NBI), RMP-induced ELM suppression in ITER is predicted to be only slightly more difficult than in DIII-D. Without core rotation, no core shielding.
- Information required by model: q profile; density and temperature profiles; rotation profile; B_ϕ, R_0, a, $Z_{\rm eff}$, $M_{\rm majority}$, $M_{\rm impurity}$, $\chi_\perp$.

Profiles: DIII-D Discharge #158115, t = 3399 ms



$B_\phi = 1.94$ T, $R_0 = 1.75$ m, $a = 0.93$ m, $Z_{\rm eff} = 2.5$, $M_{\rm majority} = 2$, $M_{\rm impurity} = 12.001$ (carbon), $\chi_\perp = 1\,{\rm m}^{\,2}/{\rm s}$.

Profiles: ITER



$B_\phi = 5.15$ T, $R_0 = 6.38$ m, $a = 1.98$ m, $Z_{\rm eff} = 1.6$, $M_{\rm majority} = 2$, $M_{\rm impurity} = 9.1004$ (beryllium), $\chi_\perp = 1\,{\rm m}^2/{\rm s}$.