Predicting Stability Windows in q95 for RMP-Induced ELM Suppression in H-Mode Tokamak Discharges[1]

Richard Fitzpatrick

Institute for Fusion Studies, Department of Physics, University of Texas at Austin

AIP Physics of Plasmas "Features in Plasma Physics" webinar

March 19, 2021

---

[1]R. Fitzpatrick, and A.O. Nelson, PoP **27**, 072501 (2020); R. Fitzpatrick, PoP **27**, 102511 (2020); R. Fitzpatrick, PoP **28**, 022503 (2021).

Suppression of Edge Localized Modes

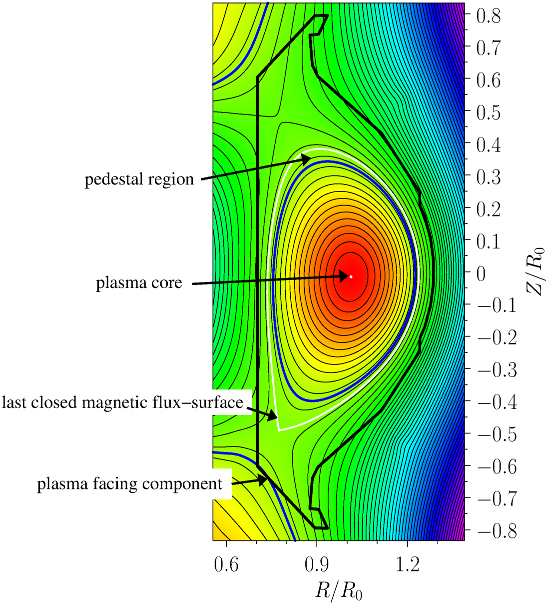
- Magnetically diverted tokamak plasmas operating in so-called *high confinement mode*,[2] a.k.a. "H-mode," characterized by a region of strong pressure and current gradients just inside last closed magnetic flux-surface (LCFS) that is known as a *pedestal*.
- Pressure and current gradients within pedestal act as source of free energy that drives localized instability, known as *edge localized mode*,[3] or ELM, that periodically relaxes gradients.
- ELM causes heat/particle pulse that crosses LCFS and eventually heats plasma facing components (PFCs).
- Estimated that ELM heat pulse in reactor-scale tokamak would cause unacceptable erosion of PFCs.[4]
- Suppression of ELMs of vital importance to tokamak magnetic fusion effort.

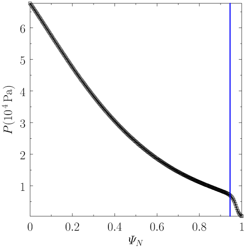
[2] F. Wagner, et al., PRL **49**, 1408 (1982).

[3] H. Zohm, PPCF **38**, 105 (1996).

[4] A. Loarte, et al., J. Nucl. Materials **313–316**, 962 (2003).

Poloidal Cross-Section of Typical Tokamak Plasma





Suppression of ELMs by Resonant Magnetic Perturbations

- Most promising method for suppressing ELMs in H-mode tokamak plasmas is via application of static *resonant magnetic perturbations* (RMPs) generated by external field coils.[5]
- RMPs resonate with equilibrium magnetic field at magnetic flux-surfaces at which $\mathbf{k}\cdot\mathbf{B} = 0$, where $\mathbf{k}$ is RMP wavenumber and $\mathbf{B}$ is equilibrium field.
- To be more exact, if m and n are poloidal and toroidal mode numbers, respectively, then (m, n) harmonic of RMP resonates with magnetic field at flux-surface at which $q = m/n$.
- Here, q is average winding number (no. of toroidal turns per poloidal turn), a.k.a. *safety-factor*, of equilibrium magnetic field.
- (m, n) harmonic of RMP changes topology of nested equilibrium magnetic flux-surfaces by driving *helical magnetic island chain* at associated resonant surface that flattens local pressure profile.[6]

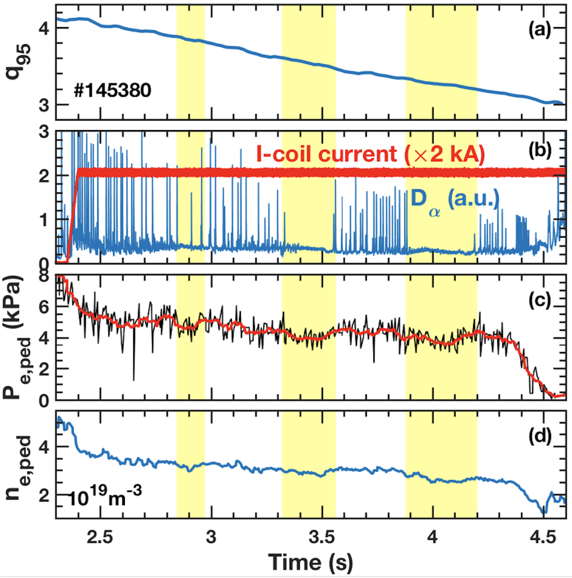
[5] T.E. Evans, et al., PRL **92**, 235003 (2004).

[6] R. Fitzpatrick, PoP **2**, 825 (1995).

Typical RMP-Induced ELM Suppression Experiment

- ELMing plasma equilibrium subject to low-n RMP generated by currents flowing in external field-coils.
- Either coil currents or equilibrium parameters (e.g., q_{95}) are varied *slowly* (i.e., over seconds).
- Intervals of ELM suppression occur.
- ELM-suppression intervals only occur when q_{95} (i.e., safety-factor at magnetic flux-surface that encloses 95% of poloidal magnetic flux enclosed by LCFS) lies in certain narrow windows, and RMP coil current exceeds threshold value.
- Pedestal pressure is reduced within ELM-suppression intervals.

RMP-Induced ELM Suppression Experiment on DIII-D[7]



[7] P.B. Synder, et al., PoP **19** 056115 (2012).

Central Hypothesis

- ELM are caused by peeling-ballooning modes/kinetic ballooning modes driven by pedestal pressure and current gradients.[8]
- Externally applied RMPs ($n = 1$, 2, or 3) do not directly interact with ELMs ($n \sim 10 - 15$) in plasma.[9]
- Rather, RMPs drive low-n magnetic island chains in pedestal that reduce pressure gradient, and, thereby, move pedestal further from ELM stability threshold.
- How can we test this hypothesis?

[8] P.B. Snyder, et al., PoP **19**, 056115 (2012).
[9] Q.M. Hu, et al., PRL **125**, 045001 (2020).

Modelling RMP-Induced ELM Suppression

- At a minimum, modelling response of pedestal plasma to RMP requires, toroidal, resistive, two-fluid treatment.
- Furthermore, observed response of pedestal plasma to applied RMP exhibits features (e.g., bifurcations in plasma rotation, hysteresis)[10] that clearly call for *nonlinear*, as opposed to linear, treatment.
- Major challenge to overcome in nonlinear, toroidal, resistive, two-fluid modelling of RMP-included ELM suppression experiments is dealing with long timescales (i.e., seconds) involved.
- Clear that Alfvén time (typically, 10^{-7} s) plays absolutely no role in problem.
- However, Alfvén time is the fundamental timescale in all existing nonlinear, toroidal, resistive, two-fluid simulation codes.

---

[10] R. Nazikian, et al., PRL **114**, 105002 (2015).

Advantage of Asymptotic Matching - I

- According to *asymptotic matching* approach,[11] response of plasma to applied RMP is governed by combination of flux-freezing and perturbed force balance—inaccurately referred to as "marginally-stable ideal-MHD"—everywhere in plasma apart from number of relatively narrow (in radial direction) regions in which applied perturbation resonates with equilibrium magnetic field.
- Magnetic reconnection can take place within resonant regions to produce relatively narrow magnetic island chains.[12]
- Within resonant regions, plasma response governed by linear or nonlinear two-fluid resistive-MHD, depending on whether induced magnetic island widths are smaller or larger, respectively, than corresponding linear layer widths.

[11] H. Furth, et al., PF **6**, 459 (1963).
[12] P.H. Rutherford, PF **16**, 1903 (1973).

Advantage of Asymptotic Matching - II

- Equations of marginally-stable ideal-MHD are solved in so-called *"outer region"* that comprises most of plasma (and surrounding vacuum), equations of linear/nonlinear two-fluid resistive-MHD are solved in various resonant layers that constitute so-called *"inner region"*, and two sets of solutions are then asymptotically matched to one another.
- Magnetic island chains convected by local plasma flow: to be more exact, by local electron fluid according to linear theory,[13] but by local ion fluid according to nonlinear theory.[14]
- Width of island chain driven by RMP at given resonant surface is nonlinear function of island rotation frequency.[15]
- RMPs exert electromagnetic torques on plasma in vicinity of island chains that depend nonlinearly on island widths. Torques modify plasma rotation, and, hence, island rotation frequencies.[14]

---

[13] G. Ara, et al., Ann. Phys. **112**, 443 (1978).

[14] R. Fitzpatrick, PoP **25**, 042503 (2018).

[15] R. Fitzpatrick, NF **33**, 1049 (1993).

Advantage of Asymptotic Matching - III

- Net result is a set of highly nonlinear equations that determine widths and rotation frequencies of island chains driven in plasma by applied RMP.
- Island chains driven in pedestal locally flatten pedestal pressure, reducing drive for peeling-ballooning modes (i.e., ELMs).
- Asymptotic matching effectively eliminates Alfvén time from problem. Shortest timescale is rotation time of fastest rotating magnetic island chain (~ 0.1 ms). Longest timescale is that on which RMP coil currents or plasma current ramped (~ 1 s).
- So, simulation of complete plasma discharge can be achieved with about 10^4 (explicit) time-steps. Can do this on an ordinary desktop computer in 1/2 an hour.
- By contrast, if Alfvén time is not effectively eliminated from problem then would need 10^7 (explicit) time-steps. Would need days/weeks on very large supercomputer.

Description of EPEC Code - I

- EPEC (Extended Perturbed Equilibrium Code) code implements asymptotic matching approach.[16]
- Homogeneous toroidal tearing mode dispersion relation calculated by EPEC code using high-q approximation.
- Inhomogeneous components of toroidal tearing mode dispersion relation (which pertain to ideal response of plasma to applied RMP) calculated by GPEC code.[17]
- EPEC takes both poloidal and toroidal plasma rotation into account.
- EPEC incorporates accurate neoclassical model, that includes both impurities and neutrals, in order to determine correct neoclassical poloidal rotation, neoclassical poloidal flow damping rate, and neoclassical resistivity.

---

[16] R. Fitzpatrick, and A.O. Nelson, PoP **27**, 072501 (2020); R. Fitzpatrick, PoP **27**, 102511 (2020); R. Fitzpatrick, PoP **28**, 022503 (2021).

[17] J.-K. Park, and N.C. Logan, PoP **24**, 032505 (2017).

Description of EPEC Code - II

- In inner region, EPEC interpolates smoothly between appropriate linear (semi-collisional)[18] and nonlinear (Rutherford) constant-ψ response regimes.
- EPEC island-induced density and temperature flattening model takes into account fact that parallel transport is *convective* rather than *diffusive* in nature.[19]
- EPEC uses experimental plasma equilibrium (gfile), experimental profiles (pfile), and perpendicular energy/particle/momentum diffusivities determined by TRANSP code.
- EPEC ignores all resonant surfaces beyond $\Psi_N = 0.995$ (because GPEC does not give reliable results beyond this surface).

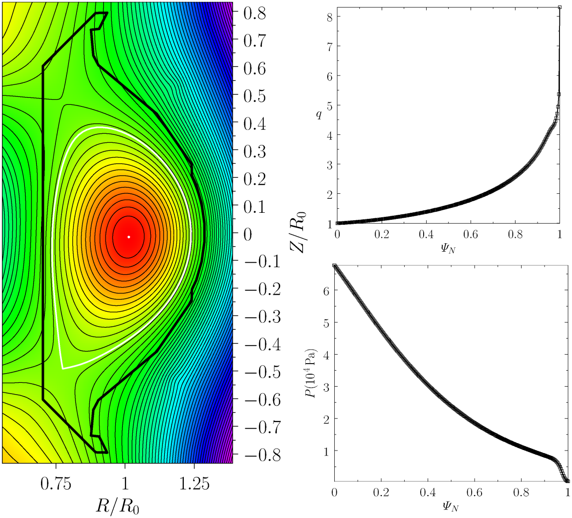
---

[18] A. Cole, and R. Fitzpatrick, PoP **13**, 032503 (2006).

[19] R. Fitzpatrick, PoP **2**, 825 (1995). N.N. Gorelenkov, et al., PoP **3**, 3379 (1996).

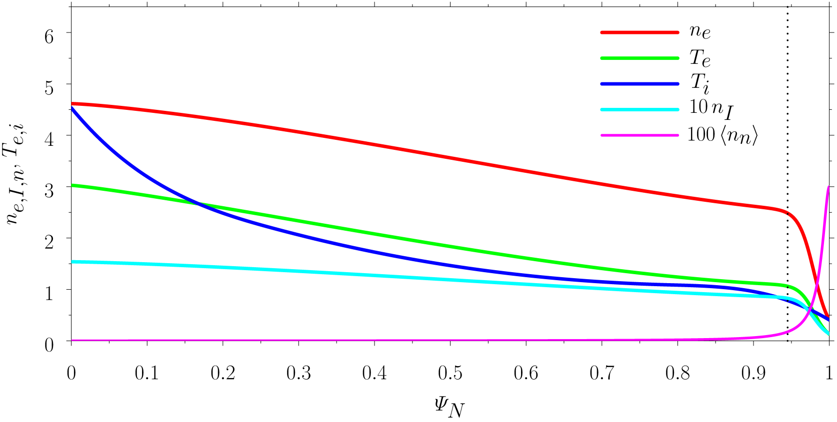
KSTAR Discharge #18594 - Plasma Equilibrium

- In KSTAR H-mode discharge #18594 an $n = 2$ RMP is used to suppress ELMs.[20]

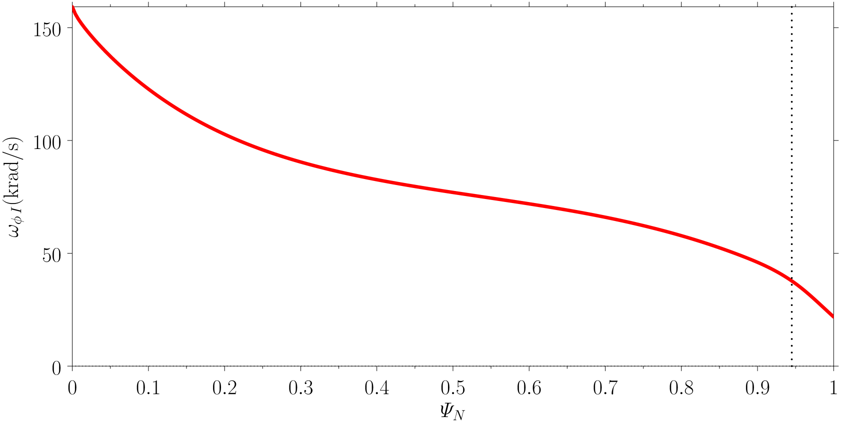


[20] J. Lee, et al., NF **59**, 066033 (2019).

KSTAR Discharge #18594 - Plasma Profiles - I



KSTAR Discharge #18594 - Plasma Profiles - II



KSTAR Discharge #18594 - Plasma Profiles - IV

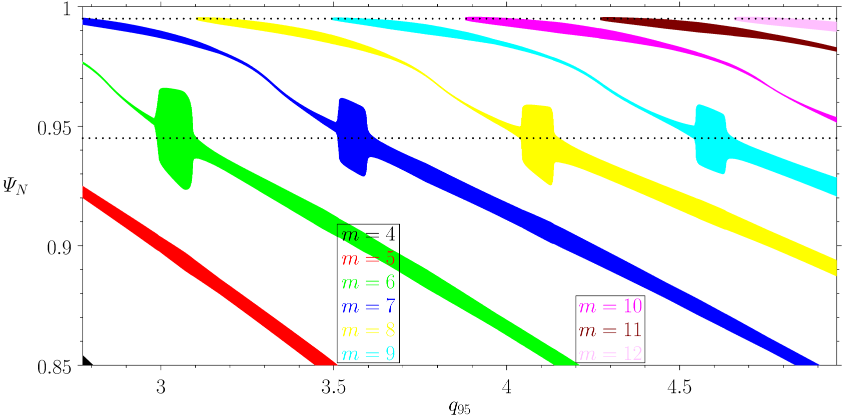
- Impurities are Carbon-VI.
- $Z_{\rm eff}$ assumed to take uniform value 2 across plasma.
- Energy, momentum, and particle diffusivities given plausible values $1\,{\rm m^2/s}$, $1\,{\rm m^2/s}$, $1/3\,{\rm m^2/s}$, respectively.
- Neutral particle density guessed (based on previous DIII-D measurement).[21]
- No useable poloidal rotation data, so $\mathbf{E}\times\mathbf{B}$ profile determined from measured toroidal rotation data combined with neoclassical theory.

[21] P. Monier-Garbet, et al., NF **37**, 403 (1997).

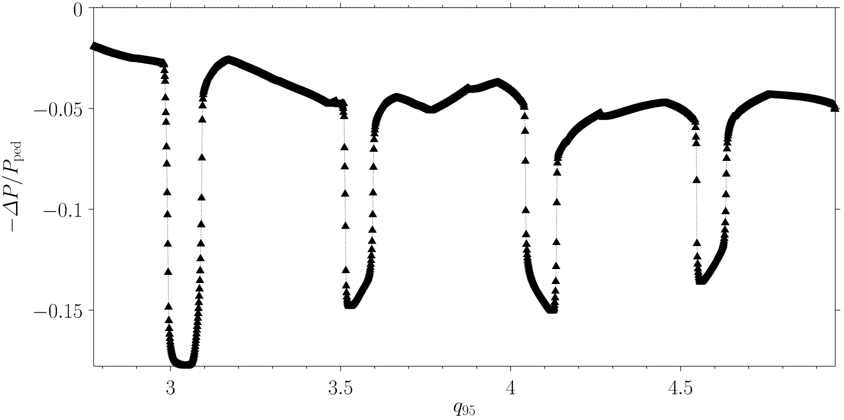
KSTAR Discharge #18594 - Rescaling of Equilibrium

- Rescale experimental equilibrium such that toroidal plasma current is modified while vacuum toroidal field-strength kept constant.
- Rescaling process leads to set of self-similar plasma equilibria with a range of different q_{95} values.
- EPEC performs simulation, based on rescaled equilibria, in which RMP coil current held fixed while q_{95} is scanned over 2 second timescale.

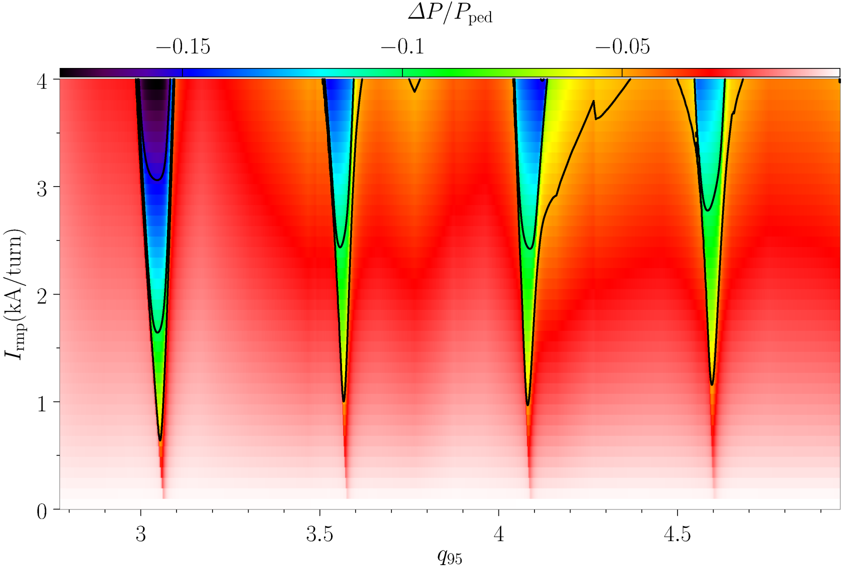
KSTAR EPEC Simulation - Driven Island Widths



KSTAR EPEC Simulation - Pedestal Pressure Decrease



KSTAR EPEC Simulation - q_{95} ELM Suppression Windows



KSTAR EPEC Simulation - Conclusions

- EPEC $n = 2$ ELM suppression windows are shifted upward in q_{95}, compared to those seen experimentally,[22] by 0.2.
- However, KSTAR experiments use "magnetic equilibria" whereas EPEC utilizes "kinetic equilibria" (i.e., equilibria that take strong current and pressures gradients in pedestal into account). q_{95} values from magnetic equilibria are about 0.2 smaller than those from corresponding kinetic equilibria.
- Overall, there is very good agreement between the EPEC simulations of $n = 2$ RMP-induced ELM suppression in KSTAR H-mode discharges and the experimental data.
- EPEC simulations confirm earlier results obtained by TM1 code.[23]

[22] Y. In, et al., NF **59**, 126045 (2019); Y. In, et al., NF **59**, 056009 (2019).
[23] Q. Hu, et al., APS-DPP Invited Talk 2020.

Planned Future Work

- Use EPEC to optimize relative amplitudes and phases of $n = 1$ currents applied to three sets of RMP coils in KSTAR, so as to maximize drive at top of pedestal, and simultaneously minimize drive at $m = 2/n = 1$ resonant surface. Goal is to reliably suppress ELMs in KSTAR H-mode discharges with $n = 1$ RMP without triggering dangerous $m = 2/n = 1$ locked mode.
- Use EPEC to examine RMP-induced ELM suppression in DIII-D discharges with range of different mixes of co- and counter- NBI injection to try to understand why suppression lost at low torques.
- Use EPEC to investigate why RMP-induced ELM suppression failed in MAST and NSTX.