Forced Magnetic Reconnection In Tokamaks*
— disruption precursor paradigm? and issues?

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Questions to be addressed: what are the

1) Key issues in $n = 2$ RMP suppression of ELMs in DIII-D?,

2) DIII-D resonant field effects for field errors (FEs), NTMs, RMPs?

Outline:

- **Issues in RMP effects on H-mode pedestals in DIII-D**
- **FMR effects have various manifestations in DIII-D:**

  FE — penetration of $\delta\vec{B}^{3D}$, spontaneous island forms, locked mode grows;

  NTMs — require seed island, then island grows on resistive time scale;

  RMPs — penetrate, tearing-response, transport increases, without islands?
- **Summary — disruption precursors are often initiated by FMR**

*Based in part on J.D. Callen, N.M. Ferraro, C.C. Hegna, R.J. La Haye, R. Nazikian, C. Paz-Soldan, "Effects Of Resonant 3-D Magnetic Fields On Pedestals," poster at 15th Int. workshop on H-mode physics and transport barriers, 19-21 October 2015, Garching, Germany (paper being written to be submitted to Nuclear Fusion), and J.D. Callen, C.C. Hegna and M.T. Beidler, "Forced magnetic reconnection in tokamak plasmas," (paper being written to be submitted to Physics of Plasmas).

Tentative Conclusions Of H-mode Workshop Paper

- **Resonant 3-D field effects due to FEs, NTMs, RMPs can be captured in tokamak forced magnetic reconnection (FMR) model.**

- **Tokamak FMR model provides predictions for 3-D field effects:**

  necessary and sufficient conditions for significant penetration,

  how reconnection effects at rational surface lead to bifurcation,

  conditions for robust island formation and growth,

  the induced n_e and T_e transport, including density pump-out effects, and

  low collisionality conditions for flutter transport model and q_{95} windows.

- **"Back of the envelope" estimates of these predictions compare favorably with DIII-D results for example FEs, NTMs and RMPs.**

- **Bifurcation of pedestal into ELM-suppressed state caused by RMPs is due to an ELM-induced nonlinear 3-D field excitation — like NTMs.**

DIII-D Pedestals Can Bifurcate Into ELM Suppression[1,2]

[1] C. Paz-Soldan et al., "Observation of a Multimode Plasma Response and its Relationship to Density Pumpout and Edge-Localized Mode Suppression," Phys. Rev. Lett. **114**, 105001 (2015).

[2] R. Nazikian et al., "Pedestal Bifurcation and Resonant Field Penetration at the Threshold of Edge-Localized Mode Suppression in the DIII-D Tokamak," Phys. Rev. Lett. **114**, 105002 (2015).

- **When phase between up/down $n = 2$ I-coils causes maximum RMP $|\delta\vec{B}_{\rm pol}|$ at $t \sim 3.7,\ 4.7$ s**

  ELMs are suppressed, and

  density pump-out is largest —

  at these near threshold conditions.

- **Questions:**

  1) What are conditions for bifurcating into the ELM-suppressed state?

  2) Why do RMPs induce density pump-out that increases with $|\delta\vec{B}_{\rm pol}|$?

  3) What other pedestal properties change during these bifurcations?

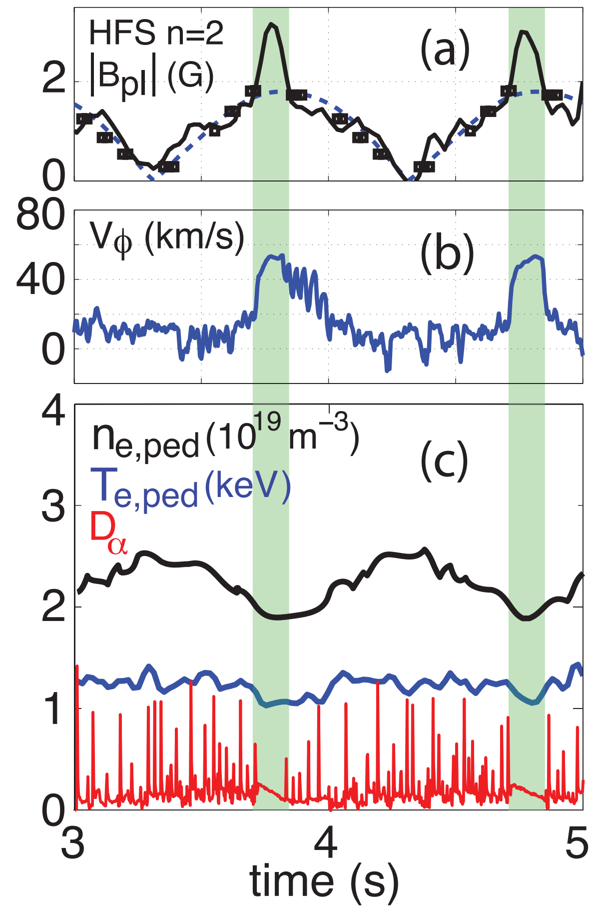

Figure 1: **Evolution as phase $\Delta\phi_{\rm UL}$ changes slowly throughout shot.[1]**

ELM Crashes Precipitate Bifurcation In V_ϕ and $|\delta\vec{B}_{\rm pol}|$

- **At $t \gtrsim 4707$ ms**

  an ELM crash occurs,

  which causes the inner-wall-measured $|\delta\vec{B}_{\rm pol}|$ to increase abruptly ($\sim$ few ms),

  and "simultaneously" the CER-inferred ($\Delta t \simeq 5$ ms) edge toroidal flow increases.

- **Questions:**

  4) why does ELM cause the bifurcation?

  5) why are bifurcations in $|\delta\vec{B}_{\rm pol}|$ and V_ϕ so abrupt? — V_ϕ because electric field E_ρ increases in response to non-ambipolar electron flux caused by increased $\delta\vec{B}_{\rm pol}$.

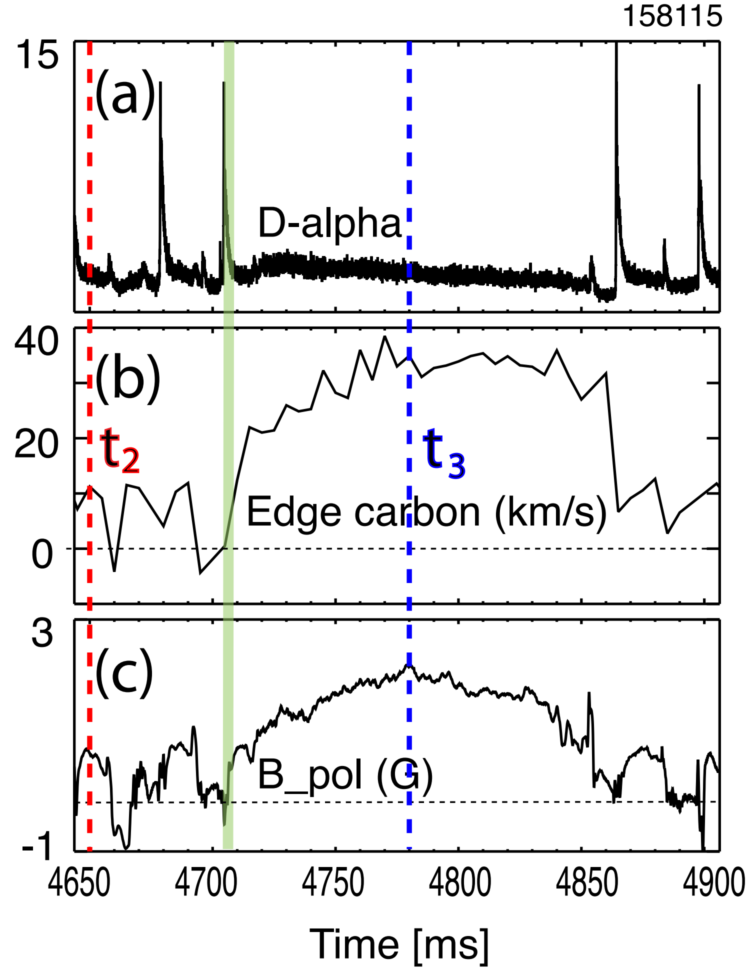

Figure 2: **Finer time scale of bifurcation induced by ELM crash at $t = 4707$ ms at largest $|\delta\vec{B}_{\rm pol}|$.**

3) RMPs Induce Changes In Vicinity Of $q = 8/2 = 4$ Surface

- From before (**t_2**) to long after (**t_3**) RMP-induced bifurcation

  $\omega_{\perp e}$ is reduced to near zero facilitating RMP penetration at $q = 8/2 = 4$,

  and gradients of T_e, n_e at $q \lesssim 4$ are reduced by factors of 7;

  BUT reduced gradients at **t_3** remain larger than large islands or stochasticity would produce.

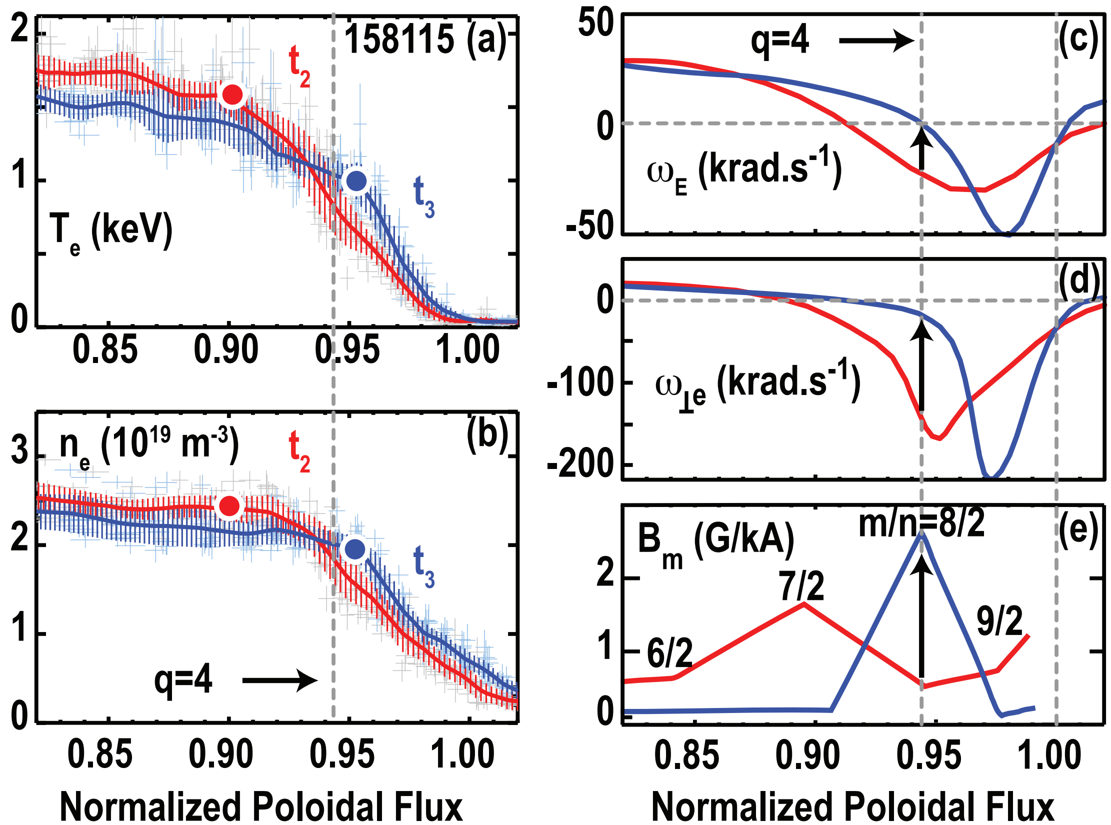

Figure 3: (a)–(d) show RMP-induced changes in profiles from before (**t_2**) to after (**t_3**) bifurcation.[2] (e) shows changes at rational surfaces predicted by resistive (1F) M3D-C1 code.

- A question:

  6) what transport processes reduce gradients?

Resonant $\delta B_{m/n}$ Are Strongly Screened Except $m=8$

- **During ELM suppression at time t_3**

  most B_{mn} are strongly flow-screened at the rational surfaces with $f_{\rm scr} \equiv B_{mn}^{\rm pl}/B_{mn}^{\rm vac} \lesssim 0.1$,

  but 8/2 component is only slightly screened ($f_{\rm scr} \simeq 0.54$) because $|\omega_{\perp e}| \lesssim 15$ krad/s there.

- **Kink responses occur**

  inward of the rational surfaces where $q < m/n$,

  and greatly enhance magnitude of B_{mn} there, which is critical for flutter transport $\sim \delta B_{mn}^2$.

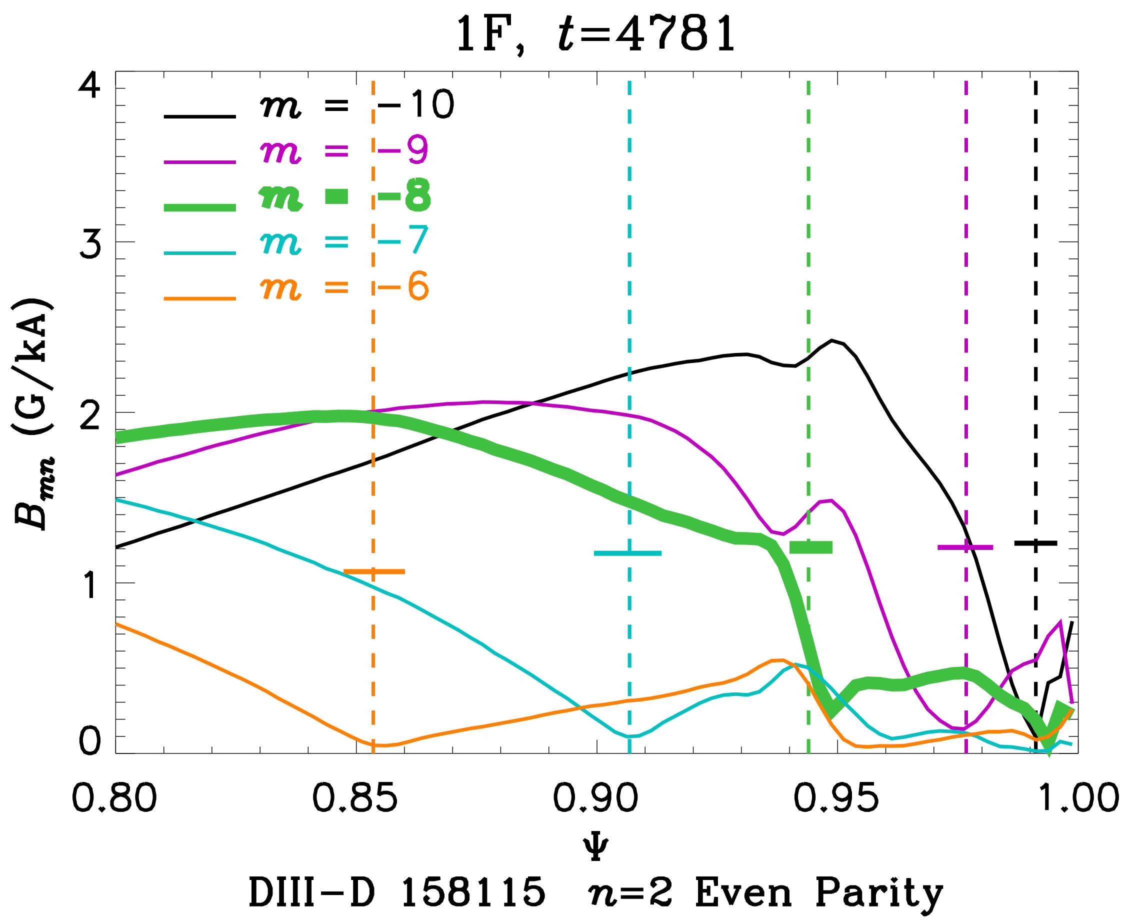

Figure 4: Radial variation of RMP-induced perturbations $B_{mn}(\Psi_N)$ from M3D-C1. Bars show vacuum field strengths at each rational surface.

FMR Theory Of Responses To Resonant Fields Is Evolving

- **Determining the effect of a 2/1 field error on an ohmic tokamak plasma is a classic "forced magnetic reconnection"[3] theory problem.[4]**

- **Field-error-induced effects in a cylindrical model with a flow frequency ω and a dissipative layer (of width δ_η) time τ_δ are[4]**

  1) $\omega\tau_\delta \gg 1$: flow-screening of external $\delta B^{\rm vac}_{\rho\, m/n}$ on $q = m/n$ rational surface,

  2) $\omega\tau_\delta \lesssim 1$: toroidal torque $\propto (\delta B^{\rm vac}_{\rho\, m/n})^2$ in δ_η layer at rational surface, which

  3) can bifurcate plasma rotation to $\omega \to 0$ on a rational surface,

  4) and produce a growing magnetic island "locked mode."

- **We are developing a dynamical FMR theory for tokamaks where**

  $\omega \to \omega_{\perp e}$,[5] δ_η is smaller, geometry and competing ion torques are different.

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[3] T.S. Hahm and R.M. Kulsrud, "Forced magnetic reconnection," Phys. Fluids **28**, 2412 (1985).
[4] R. Fitpatrick, "Interaction of tearing modes with external structures in cylindrical geometry," Nucl. Fusion **33**, 1049 (1993).
[5] F.L. Waelbroeck et al., "Role of singular layers in the plasma response to resonant magnetic perturbations," Nucl. Fusion **52**, 074004 (2012).

Tokamak FMR Theory Involves Five Key Equations

- **Radial component of $\delta\hat{B}_\rho$ obtained from combination of Faraday's law and Ohm's law which provides predictions for**

  singular layer width $\delta_\eta \simeq 2\,\rho_{m/n}/S^{1/3}$ where $S \equiv \tau_R/\tau_A$ is Lundquist number, and necessary condition 1) for penetration[6] $\omega_{\perp e} \lesssim 1/(n\tau_A S^{1/3})$.

- **Parallel flow vorticity equation obtained from $\vec{B}\cdot\vec{\nabla}\times$(plasma momentum balance) provides**

  linear shear-Alfvén wavelength scale effects in determining layer width δ_η, conditions for minimum width of robust islands $\mathrm{w}_{\min} \gtrsim 2\max\{\delta_\eta, \rho, \mathrm{w}_{\mathrm{ib}}, \mathrm{w}_c\}$.

- **FSA of $\delta\hat{B}_\rho$ equation provides modified Rutherford equation (MRE):**

  magnetic island evolution equation applicable for $\mathrm{w} \gg \mathrm{w}_{\min}$.

- **Torque $T_{s\zeta} \equiv R\vec{e}_\zeta\cdot\vec{F}_{\mathrm{orcess}} = -\,RB_{\mathrm{p}}\sum_s q_s\Gamma_s^{\mathrm{na}}$ balance[7] provides:**

  1) sufficient condition for penetration of 3-D field: $D_{et}^{\mathrm{RMP}} \sim |\delta\hat{B}_\rho/B_0|^2 > D_{it}^{\mathrm{sym}}$.

- **Magnetic-flutter-induced n_e and T_e transport fluxes determine**

  2,6) ambipolar E_ρ^{amb} and RMP-induced n_e flux $\Gamma_e^{\mathrm{RMP}}(E_\rho^{\mathrm{amb}}) \rightarrow$ density pump-out.

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[6] Actually $\omega_{\perp e} \rightarrow \Omega_e^\alpha \equiv \omega_{\perp e} + (0.71/e)\,(dT_e/d\rho)$ when T_e gradients are taken into account.

[7] J.D. Callen, A.J. Cole, & C.C. Hegna, "Toroidal flow and radial particle flux in tok. plasmas," Phys. Pl. **16**, 082504 (2009); Errat. **20**, 069901 (2013).

Tokamak FMR Key Equations Are From Two-Fluid MHD

- Radial component of perturbed Faraday's law using Ohm's law:

$$\frac{\partial\,\delta\hat{B}^\rho}{\partial t} - in\Omega_e^\alpha\,\delta\hat{B}^\rho - \frac{\eta}{\mu_0}\overline{\nabla}^2\delta\hat{B}^\rho + \frac{in\langle\vec{B}_0\cdot\vec{\nabla}\cdot\delta\overset{\leftrightarrow}{\pi}_e\rangle}{n_{e0}e\psi_{\rm p}'} \simeq ik_\|(x)\,B_{\rm t0}\,\delta\hat{V}_e^\rho.$$

- Parallel vorticity $\omega_\| \equiv \vec{B}_0\cdot\vec{\nabla}\times\delta\vec{V} \simeq \nabla_\perp^2\delta\phi$ from FSA plasma mom. eq.:

$$\frac{\overline{g}^{\rho\rho}\mu_0\rho_{m0}}{B_{\rm t0}^2}\left(\frac{\partial}{\partial t} - in\,\Omega_E^\alpha\right)\frac{\partial^2\delta\hat{V}_i^\rho}{\partial x^2} \simeq \frac{ik_\|(x)}{B_{\rm t0}}\,\overline{\nabla}^2\delta\hat{B}^\rho + \frac{ik_\theta}{B_{\rm t0}}\,\delta\hat{B}^\rho\frac{d}{d\rho}\left\langle\frac{\mu_0 J_{\|0}}{B_0}\right\rangle - \frac{k_\theta^2}{B_{\rm t0}^2/\mu_0}\frac{\partial\,\delta\hat{P}}{\partial\rho}.$$

- Modified Rutherford equation from FSA of Faraday's law above:

$$\frac{d{\rm w}}{dt} = \overline{g}^{\rho\rho}\frac{\eta_\|^{\rm nc}}{\mu_0}\left[\Delta' + \frac{c_{\rm nc}\,{\rm w}}{{\rm w}^2+{\rm w}_c^2} + \frac{c_{\delta B_\pm}}{{\rm w}^2} - \frac{\delta J_{\rm pol}}{{\rm w}^3}\right].$$

- Plasma toroidal torque balance equation determines $\Omega_{\rm t}$, E_ρ:

$$I_\Omega\,\frac{\partial\,\Omega_{\rm t}}{\partial t} = \textstyle\sum_s T_{s\zeta}(\Omega_{\rm t}) = -\,RB_{\rm p}\sum_s q_s\Gamma_s^{\rm na}(E_\rho) \simeq -\,I_\Omega\,\mu_{et}^{\rm RMP}(\rho_{m/n})\,\Omega_e^\alpha - \,I_\Omega\,\mu_{it}^{\rm sym}(\Omega_{\rm t} - \Omega_{\rm equil}^{\rm sym}).$$

- Flutter-induced electron non-ambipolar density flux (via kinetics):

$$\Gamma_e^{RMP}(E_\rho^{\rm amb}) = -\,n_e D_{et}^{\rm RMP}(\rho_{\rm mid})\left[\frac{d\ln p_e}{d\rho} - \frac{3}{2}\frac{d\ln T_e}{d\rho} + \frac{eE_\rho^{\rm amb}}{T_e}\right] \text{— depends on } E_\rho.$$

Response To Imposed Resonant $\delta\vec{B}^{3\mathrm{D}}$ Is Dynamic

- **3-D magnetic perturbation near a rational surface is governed by**
  $$\frac{\partial\,\delta B_\rho}{\partial t} - i\,\omega_{\perp e}\delta B_\rho + \frac{\eta}{\mu_0}\overline{\nabla}^2\delta B_\rho = ik_\parallel B_0\,\delta V_{e\rho};$$
  sheet current of width δ_η forms at $\rho_{m/n}$, with minimal reconnection if $\omega_{\perp e}$ is large; 1) but if $|\omega_{\perp e}| \lesssim 10^4$/s, after $\tau_{et} \sim$ few ms δB_ρ "penetrates" in resistive layer δ_η.

- **When $\mathrm{w} \equiv 4(\delta B L_S/k_\theta B_0)^{1/2} > \mathrm{w}_{\min}$, the island width w is governed by modified Rutherford eq. (MRE):**
  $$\frac{d\mathrm{w}}{dt} \simeq \frac{\eta}{\mu_0}\left[\Delta' + \frac{c_{\mathrm{nc}}}{\mathrm{w}} + \frac{c_{\delta B}}{\mathrm{w}^2} - \frac{\delta J_{\mathrm{pol}}}{\mathrm{w}^3}\right];$$
  "drives" are $c_{\mathrm{nc}} \sim \sqrt{\epsilon}\,\beta'_{\mathrm{p}}$ for NTMs or $c_{\delta B} \sim (\delta B_\rho/B_0)^2 > 0$ from applied RMPs, but damped by $\Delta' \sim -2m$ and FLR, FBW ion polarization currents (δJ_{pol}).

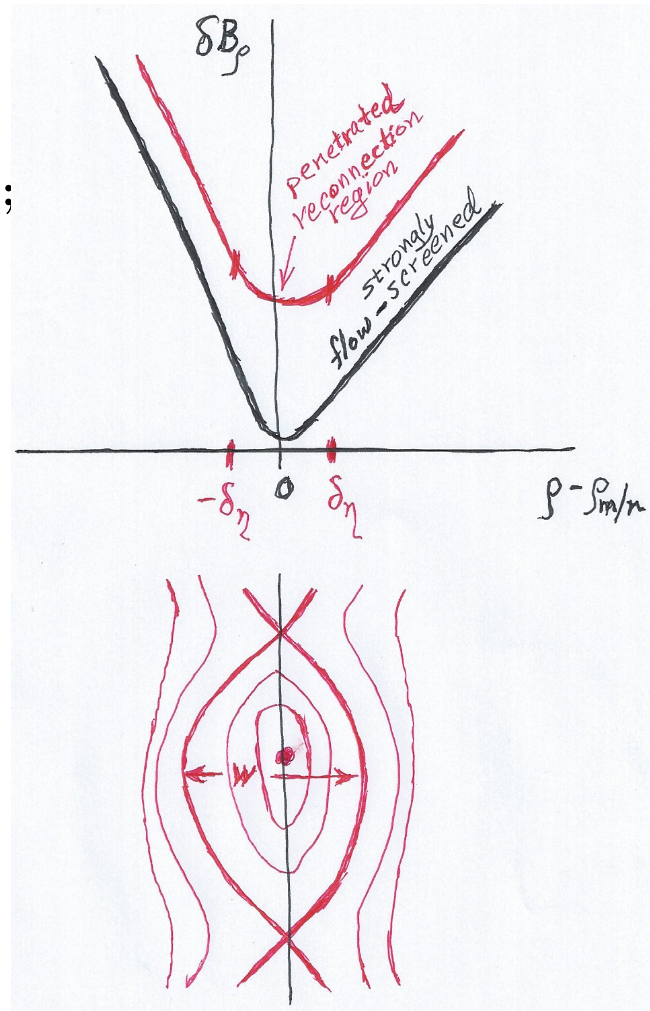

Figure 5: **Schematic of $\delta B^{\mathrm{plasma}}_{\rho\, m/n}$ and field lines in vicinity of rational surface.**

Theory: What Can Happen After 3-D Field Penetration?

- Reconnection: Magnetic field lines in resistive layer[4] $\delta_\eta \simeq 2\,\rho_{m/n}/S^{1/3}$ form a nascent magnetic island of width $\mathrm{w} \sim \delta_\eta$ around $\rho_{m/n}$.

- Does this island grow? There are two possibilities (next viewgraph):

  if δ_η or initial "seed island" of width $\mathrm{w}_{\mathrm{init}} \simeq 4\sqrt{\delta B^{\mathrm{plasma}}_{\rho\, m/n}(\rho_{m/n}) L_S / k_\theta B_{\mathrm{t0}}}$ is larger than $\mathrm{w}_{\mathrm{min}} \simeq \mathrm{w}_{\mathrm{ib}} \equiv \sqrt{\epsilon}\, \varrho_{\theta i}$ (ion banana width), an island can grow, BUT,

  7) if $\delta_\eta < \mathrm{w}_{\mathrm{min}}$, island width is limited to $\sim \delta_\eta$ ($\Delta' < 0$, ion δJ_{pol} currents damp) and $\delta B^{\mathrm{plasma}}_{\rho\, m/n}$ perturbation decays unless it is driven continuously.

- Evolution and transport: Then, m/n magnetic field perturbation $\delta B^{\mathrm{plasma}}_{\rho\, m/n}$ expands radially away from the initial $\sim \delta_\eta$ or $\mathrm{w}_{\mathrm{init}}$ width:

  growing island ($\max\{\delta_\eta, \mathrm{w}_{\mathrm{init}}\} > \mathrm{w}_{\mathrm{min}}$) — width grows on resistive time scale, and radial transport within expanding island region is effectively infinite, which causes the T_e profile to be flat within the island;

  limited island ($\mathrm{w} \sim \delta_\eta < \mathrm{w}_{\mathrm{min}}$) — driven $\delta B^{\mathrm{plasma}}_{\rho\, m/n}$ remains constant at $q = m/n$, but may spread radially from δ_η region, and 6) induce flutter transport.

Island Growth Requires Layer Width δ_η OR Initial Island Width $w_{init} >$ banana width parameter w_{ib}[8,9]

[8] R.J. La Haye, R.J. G.L. Jackson, T.C. Luce, K.E.J. Olofsson, W.M. Solomon and F. Turco, "Insights Into m/n=2/1 Tearing Mode Stability Based on Initial Island Growth Rate in DIII-D ITER Baseline Scenario Discharges," paper O5.134 at 41st EPS Conference Berlin 2014 (to be published).

[9] R.J. La Haye, review paper on "Neoclassical tearing modes and their control," Phys. Plasmas **13**, 055501 (2006).

- **Island growth rate dw/dt**

  is governed by the Modified Rutherford Equation (MRE) $dw/dt = \cdots$, which is

  negative (damping) if island width $w < w_{crit} \simeq 1.3\, w_{ib}$ due to $\Delta' < 0$ and FLR, FBW δJ_{pol} polarization current effects,

  but can be positive (growing) for $\Delta' > 0$ tearing modes or NTMs if $w > w_{crit} \simeq 1.3\, w_{ib}$.

- **Growth of w occurs if**

  layer width $\delta_\eta \gtrsim w_{crit}$ OR

  initial width $w_{init} \gtrsim w_{crit}$.

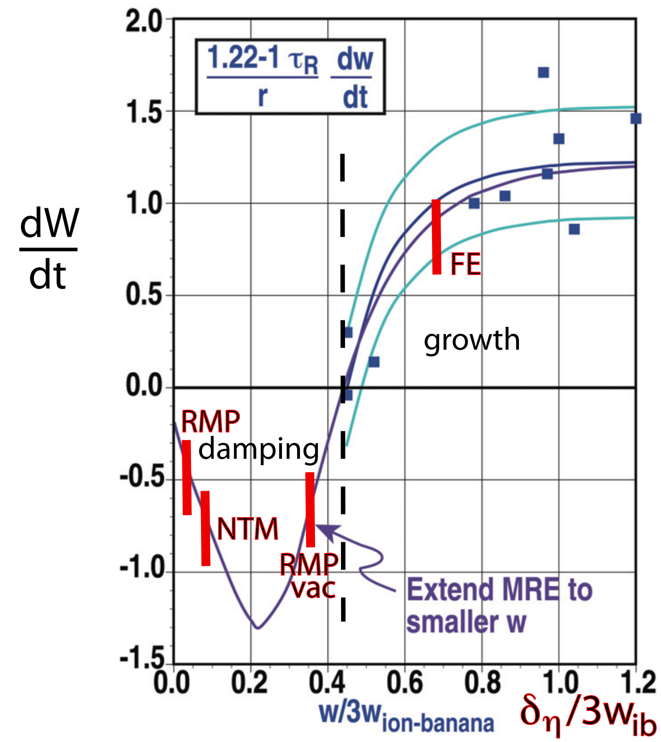

Figure 6: MRE dw/dt indicates island growth for[14] $w \gtrsim w_{crit} \simeq 0.43 \times 3\, w_{ib} \simeq 1.3\, w_{ib}$, otherwise damping. Red bars are normalized layer widths $\delta_\eta / 3\, w_{ib}$ for DIII-D 3-D effects.

Next Few Viewgraphs Discuss FMR Examples In DIII-D

- **Field error (FE)**

- **Neoclassical tearing mode (NTM)**

- **Resonant magnetic perturbation (RMP)**

Table 1: FMR tokamak and plasma parameters for example DIII-D discharges.

Parameters/experiment	FE	NTM	RMP
$\boldsymbol{B_0}$(T), $\boldsymbol{R_0}$(m), $\boldsymbol{a}$(m)	1, 1.67, 0.75	2.08, 1.7, 0.78	1.9, 1.75, 0.78
$\boldsymbol{m/n}$, $\boldsymbol{\rho_{m/n}}$ (m)	2/1, 0.56	2/1, 0.6	8/2, 0.725
$\boldsymbol{\epsilon_M \equiv \Delta B/2B_0}$, $\boldsymbol{\hat{s} \equiv \rho q'/q}$	0.27, 1.6	0.27, 1.5	0.31, 2.2
$\boldsymbol{k_\theta \equiv m/\rho_{m/n}}$ (m^{-1})	3.6	3.3	11
$\boldsymbol{L_{\rm sh} \equiv R_0 q/\hat{s}}$, $\boldsymbol{L_{p_e}}$ (m)	2.2, 0.55	2.3, 0.4	3.2, 0.3
plasma			
$\boldsymbol{n_e({\rm m}^{-3})/10^{19}}$, $\boldsymbol{Z_{\rm eff}}$	0.5, 1.8	5, 2.1	2, 2
$\boldsymbol{T_e({\rm eV})}$, $\boldsymbol{T_i({\rm eV})}$	254, 150	1696, 2035	1100, 2,000
$\boldsymbol{\beta_e \equiv 2\mu_0 n_e T_e/B_0^2}$	0.0005	0.008	0.0024
$\boldsymbol{\nu_e}$(s^{-1}), $\boldsymbol{\lambda_e}$(m)	$\boldsymbol{10^5}$, 85	$\boldsymbol{7.5\times10^4}$, 330	$\boldsymbol{5.5\times10^4}$, 360
$\boldsymbol{\nu_{*e} \equiv R_0 q/[\epsilon_M^{3/2}\lambda_e]}$	0.2	0.02	0.11
$\boldsymbol{\eta_\parallel^{\rm nc}/\mu_0}$ (m^2/s)	0.44	0.014	0.055
bifucration			
$\boldsymbol{\tau_A \equiv L_{\rm sh}/[k_\theta \rho_{m/n} c_A]}$ (s)	$\boldsymbol{1.6\times10^{-7}}$	$\boldsymbol{2.5\times10^{-7}}$	$\boldsymbol{6\times10^{-8}}$
$\boldsymbol{\tau_R \equiv \rho_{m/n}^2/[\eta_\parallel^{\rm nc}/\mu_0]}$ (s)	0.7	26	9.6
$\boldsymbol{S \equiv \tau_R/\tau_A}$	$\boldsymbol{4.4\times10^6}$	$\boldsymbol{10^8}$	$\boldsymbol{1.6\times10^8}$
$\boldsymbol{\delta_\eta \equiv 2\rho_{m/n}/S^{1/3}}$ (m)	0.007	0.0026	0.0027
$\boldsymbol{\Omega_{e\,{\rm crit}}^\alpha}$ (rad/s)	$\boldsymbol{9\times10^3}$	$\boldsymbol{2\times10^3}$	$\boldsymbol{7.5\times10^3}$
$\boldsymbol{\omega_{*e}}$ (rad/s)	$\boldsymbol{3\times10^3}$	$\boldsymbol{6.7\times10^3}$	$\boldsymbol{2\times10^4}$
$\boldsymbol{\delta\hat{B}_\rho^{\rm pl}(\rho_{m/n})}$ (G)	0.2	0.05	0.12 (2.6)
$\boldsymbol{\rho_{S{\rm p}}}$ (m)	0.014	0.017	0.025
$\boldsymbol{D_{\rm et}^{\rm RMP}(\rho_{m/n})}$ (m^2/s)	0.09	0.06	0.13 (67)
$\boldsymbol{\tau_{\rm et}}$ (ms)	2.3	4.8	4.9
island			
$\boldsymbol{\delta_\eta \equiv 2\,\rho_{m/n}/S^{1/3}}$ (cm)	0.7	0.26	0.27
$\boldsymbol{\varrho_i \equiv v_{Ti}/\omega_{ci}}$ (cm)	0.24	0.43	0.47
$\boldsymbol{{\rm w}_{\rm ib}}$ (cm)	NA ($\ll$ **0.8**)	1.45	3.2
$\boldsymbol{{\rm w}_c}$ (cm)	NA (1.2)	0.7	0.47
$\boldsymbol{{\rm w}_{\rm min}}$ (cm)	1.4	1.9	4.2
$\boldsymbol{\delta\hat{B}_\rho^{\rm vac}}$ (G), $\boldsymbol{{\rm w}_{\rm vac}}$ (cm)	0.7, 2.6	NA	4.8, 3.4
$\boldsymbol{f_{\rm scr}}$	0.35	NA	0.025 (0.54)
$\boldsymbol{{\rm w}_{\rm nc}}$ (cm)	0.6	13	6
transport			
$\boldsymbol{\delta_{\parallel{\rm t}}}$ (cm)	2.3	0.6	0.26
$\boldsymbol{\delta\hat{B}_\rho^{\rm pl}(\rho_{\rm mid})}$ (Gauss)	$\gtrsim$ **0.2**	$\gtrsim$ **0.75**	$\gtrsim$ 0.12 (5.2)
$\boldsymbol{D^{\rm RMP}(\rho_{\rm mid})}$ (m^2/s)	$\gtrsim$ **0.001**	0.024	$\gtrsim$ $\boldsymbol{10^{-3}}$ (0.44)

Resonant Field Error (FE)[10] Can Grow Out Of Noise

- **Low n_e threshold for $\delta B_{\rho\,2/1}$ penetration, $|\Gamma_e^{\rm RMP}(E_\rho)| > |\Gamma_i^{\rm sym}(E_\rho)|$.**
- **2/1 mode "grows out of noise" because $\delta_\eta \simeq 0.7$ cm $\gg$ $\varrho_i \simeq 0.24$ cm.**
- **2/1 locked mode $\delta B_{\rho\,2/1}$ grows on resistive time scale $\tau_{\rm FE} \sim 5.5$ ms.**

[10] R.J. La Haye, C. Paz-Soldan and E.J. Strait, "Lack of dependence on resonant error field of locked mode island size in ohmic plasmas in DIII-D," Nucl. Fusion **55**, 023011 (2015).

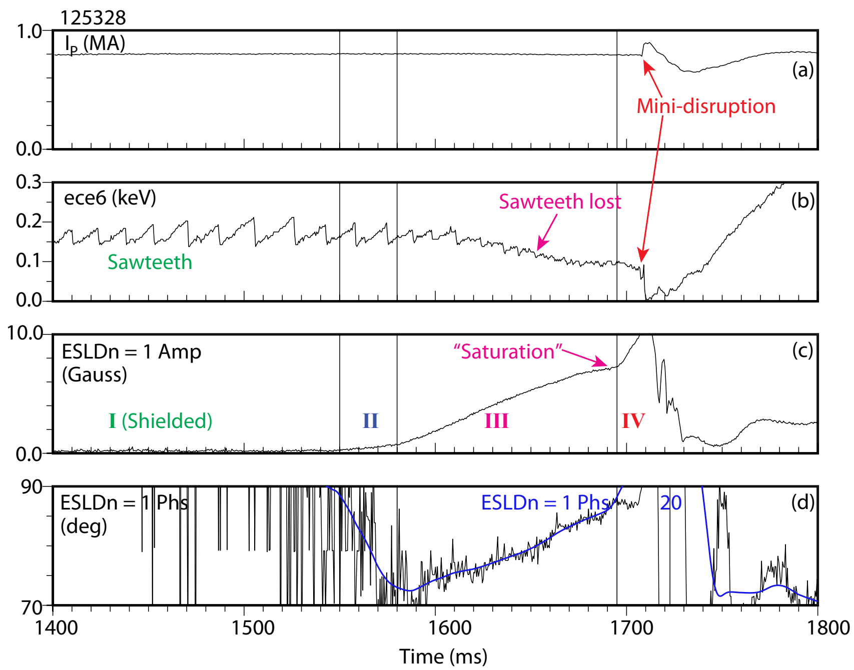

Figure 7: **Locked mode (III: detected by edge saddle loops, ESL) is induced by decreasing n_e etc., grows out of noise spontaneously on resistive time scale.**

Neoclassical Tearing Mode (NTM)[11,9] Needs Big Seed

- **Plasma is metastable; a seed island is required[11,9] to excite NTM.**
- **If seed is too small, it decays because $\delta_\eta \sim 0.26$ cm $\ll$ w$_{\rm min} \sim 1.9$ cm; but if large enough (i.e., w$_{\rm init}$ $>$ w$_{\rm min}$), it induces a growing island.**
- **NTM-island-induced $\delta B_{\rho\,2/1}$ grows on resistive scale $\tau_{\rm NTM} \sim 90$ ms.**

[11] Z. Chang , J.D. Callen, E.D. Fredrickson, R.V. Budny, C.C. Hegna, K.M. McGuire, M.C. Zarnstorff, and TFTR group, "Observation of Nonlinear Pressure-Gradient-Driven Tearing Modes," Phys. Rev. Lett. **74**, 4663 (1995).

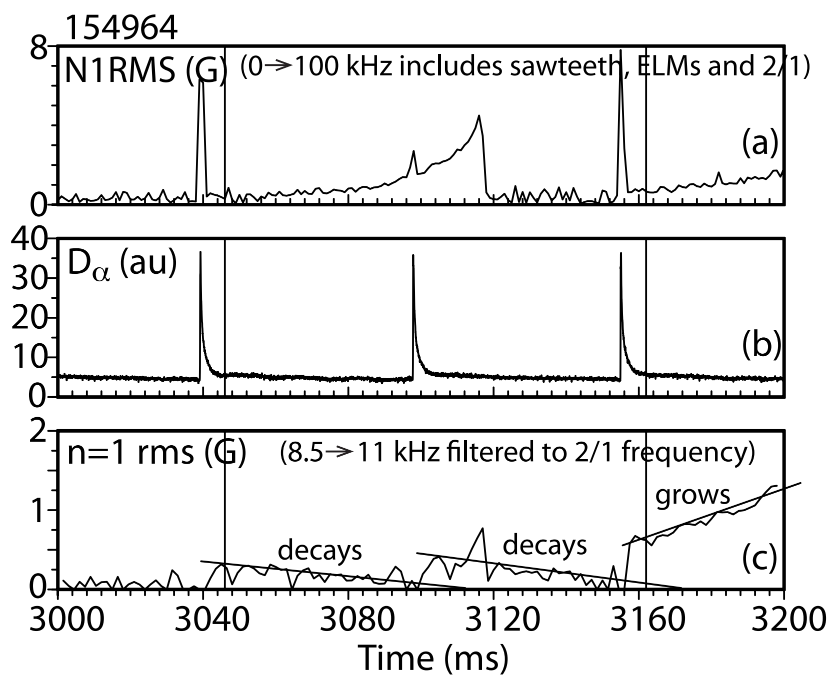

Figure 8: **First two ELM seeds are too small, last one causes growing NTM.**

Summary Of Interpretation Of Resonant 3-D Field Effects

- Field lines reconnect in thin δ_η layers at rational surfaces, and 2) lead to density pump-out throughout pedestal $\propto (\delta B^{\text{plasma}}_{\rho,m/n})^2$.
- 1) Strong reconnection occurs for large $\delta B^{\text{vac}}_{\rho\, m/n}$, small $\omega_{\perp e}$ at $q = m/n$, and 4) for NTMs, RMPs is induced by effects of ELM crashes.
- 5) Bifurcation by ELMs to penetrated state occurs in $\tau^{\text{3D}}_{e\zeta} \gtrsim$ ms.
- Induced nascent magnetic island can be unstable and grow if

  $\delta_\eta \gtrsim \mathrm{w}_{\min} \simeq \varrho_i$ or $1.3\, \mathrm{w}_{\text{ib}}$ — large enough resistive layer width, or

  $\mathrm{w}_{\text{init}} \gtrsim \mathrm{w}_{\min} \simeq 1.3\, \mathrm{w}_{\text{ib}}$ — large enough seed island,

  BUT, if $\mathrm{w}_{\text{init}} < \mathrm{w}_{\min}$, steady RMPs drive fuzzy islands in $|\Delta\rho| \simeq \delta_\eta$ to w_{init}.
- Region affected can expand radially away from δ_η, w_{init} at $q = m/n$

  with growing $\delta B^{\text{plasma}}_{\rho\, m/n} \propto \mathrm{w}(t)^2$ if island is growing, but

  with $\sim$ constant $\delta B^{\text{plasma}}_{\rho\, m/n}$ on rational surface if driven $\max\{\mathrm{w}\} \sim \delta_\eta$.
- Radial plasma transport in possibly radially expanding region is

  effectively infinite within growing island region which causes flat T_e profile, but

  3,6) if $\max\{\mathrm{w}\} \sim \delta_\eta$ it can be caused by δB_ρ flutter-induced n_e, T_e transport.

FMR Studies Are More Complicated In Tokamak Plasmas

ANALYTIC THEORY:

- **Dynamical theory is needed to address temporal development and dynamical accessibility — not just time-asymptotic states.[3–5]**
- **Both electron and ion diamagnetic equilibrium flows are needed.**
- **Full tokamak geometry is needed, particularly in edge pedestal region where resonant magnetic perturbations (RMPs) are applied.**
- **Singular resistive reconnection layer widths δ_η are much smaller.**
- **Toroidal torques competing with resonant field induced torques are different at edge — ion orbit and c-x losses, different transport.**

EXTENDED MHD CODE MODELING:

- **M3D-C^1 and NIMROD mainly calculate linear response $\delta B^\rho_{\mathrm{n}}$ now.**
- **FMR needs toroidal and poloidal flows, nonlinear evolution.**

FMR Is Important Process For Tokamak Plasmas

- **Major programmatic thrust is disruption control, which requires understanding forced magnetic reconnection (FMR) processes that lead to locked modes via field errors (FEs), NTMs, and ELM suppression via RMPs.**

- **Analytic-based theory is being developed; it needs to be tested and work with M3D-C^1 and NIMROD studies of FMR processes.**

- **FMR studies are logical next steps for extended MHD codes:**

  study evolution from linear δB^ρ studies into nonlinear island states,

  begin coping with poloidal and toroidal flow evolution,

  figure out how to couple extended MHD, kinetic, transport for 3-D effects,

  provide a target case for unified extended MHD, kinetic, transport models.

Field Errors And RMPs Are Good Paradigm Problems

- **$m/n = 2/1$ field errors (FEs) are good focus for initial FMR studies:**

  low T_e ($\sim$ 250 eV) ohmic (OH) plasmas where $S \lesssim 10^7$ which causes δ_η to be larger than FLR, FBW effects and modes can grow out of noise, and

  since 2/1 modes are often resonant at about the half radius, the mode coupling effects are likely to be small,

  plasma pressure is small for OH plasmas so finite β effects are likely small and

  plasma response to slowly increasing δB^ρ (or decreasing n_e) is a good test.

- **Ultimate tests will be provided by pedestal responses to RMPs:**

  due to significant geometry effects in pedestal near separatrix,

  finite mode coupling and β_p' effects,

  significant FLR and FBW effects,

  multiple m resonant modes present simultaneously,

  toroidal plasma rotation that varies strongly in radius,

  challenge of predicting why ELMs induce bifurcations to tearing state, and

  challenge of predicting δB_ρ and q_{95} needed for ELM suppression and why no significant magnetic islands are produced.

Some Developments Are Needed For Extended MHD

- **General:**

  identify good cylindrical code case for benchmarking M3D-C^1 and NIMROD,

  identify experiment-based test case and compare to FE experimental results,

  begin exploring developments needed for modeling RMP effects, and

  figure out how ELMs induce bifurcations in metastable NTMs and to tearing responses to RMPs.

- **Analytic theory:**

  finish developing theory for single resonant magnetic perturbation,

  and compare analytic formulas with NIMROD and M3D-C1 modeling.

- **M3D-C^1 and NIMROD:**

  begin cylindrical benchmarking case,

  begin including neoclassical closures, poloidal and toroidal flow effects,

  explore how to couple extended MHD, kinetic and transport effects,

  longer term — couple in drift-kinetic modeling for closures in extended MHD.