Disruptive Neoclassical Tearing Mode Seeding in DIII-D with Implications for ITER

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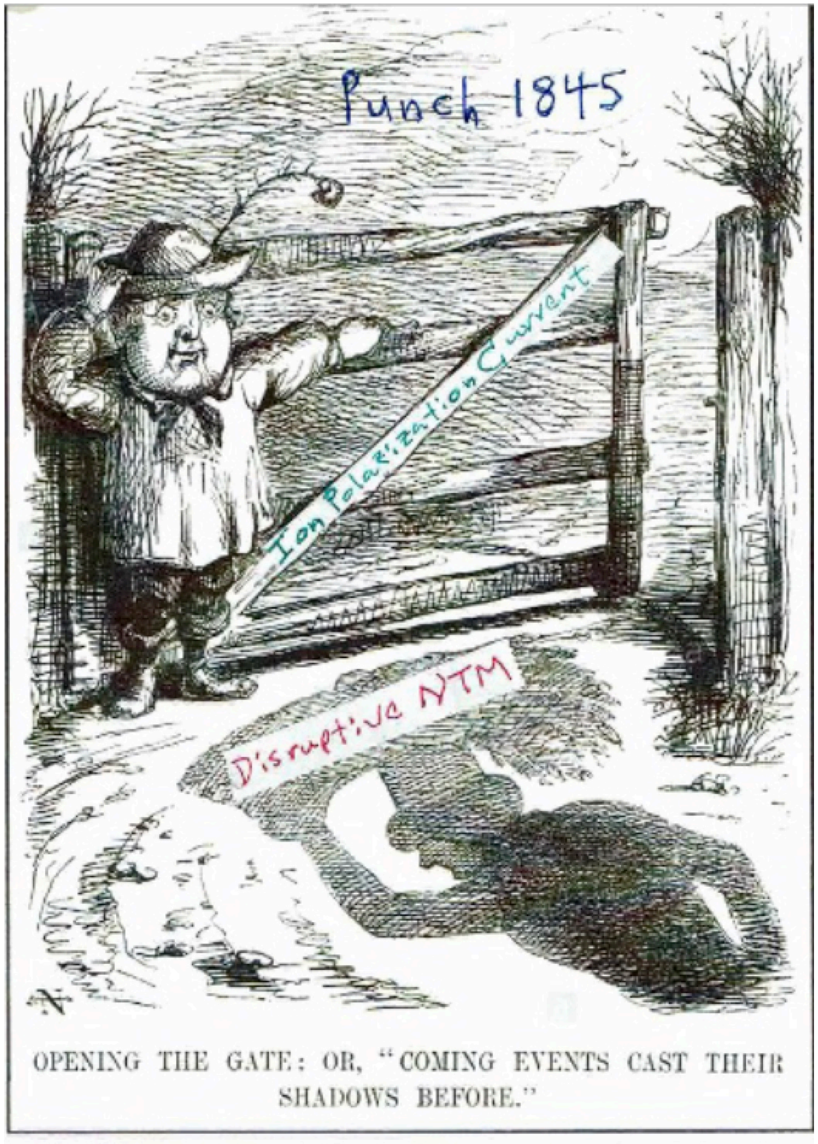
- **Motivation:** a rotating 2/1 tearing mode can robustly grow, lock to the resistive wall, the H-mode is lost, disruption follows
- **This new work:** gives experimental and theoretical insights, as well as novel benchmarked toroidal-theory-based modeling, to a longstanding uncertainty in projecting how NTMs are seeded, for scaling to ITER



GENERAL ATOMICS

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OUTLINE:

- MOTIVATION: [growing NTM slows down, locks to the wall, H-mode is lost, disruption follows: NTMs are a (the) major cause of disruptions]
- DIII-D ITER baseline scenario (IBS) discharges compared to those predicted for ITER (q95~3, β_N~1.8)
- Case studies of an ELM and a sawtooth (ST) that produce robustly growing m/n=2/1 NTMs in the DIII-D IBS
- Physics of NTM stability: Modified Rutherford Equation (MRE) with a coupled rotation relation for the NTM "gate": also NIMROD
- Extrapolating to ITER from the DIII-D IBS
- How ELM control *could*, and ST control *can*, reduce the magnetic perturbations that seed/excite robustly growing NTMs
- Conclusions and future work

GENERAL ATOMICS

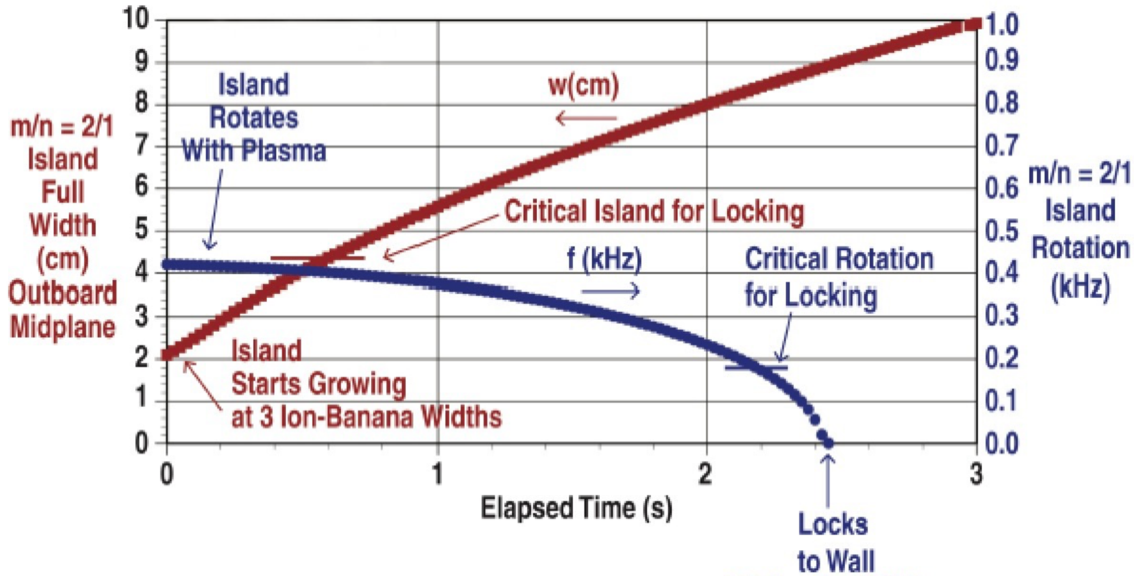
MOTIVATION: Modeling from DIII-D Predicts How Growing m/n=2/1 NTM Islands Will Slow Down and Lock in ITER

- **NTMs that grow and lock are the largest cause of tokamak disruptions (except for human error)**

[P.C. DeVries et. al.,"Survey of disruption causes in JET," Nucl. Fusion 51, 053018 (2010)]

- **Island width w(t) found by integrating MRE benchmarked to DIII-D IBS discharges and with f_m(t) from integrating an equation for rotation with w(t) input**
  - **Initial ITER q = 2 plasma rotation taken here as 420 Hz (A.R. Polevoi, et.al., PPCF 2006)**

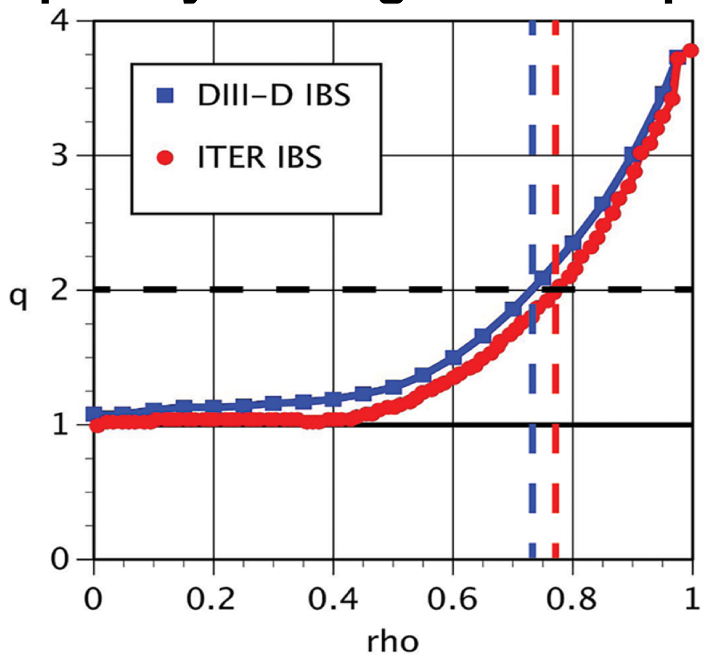
[R.J. La Haye, C. Paz-Soldan and Y.Q. Liu, "Effect of thick blanket modules on neoclassical tearing mode locking in ITER," Nuclear Fusion 57, 01004 (2017]

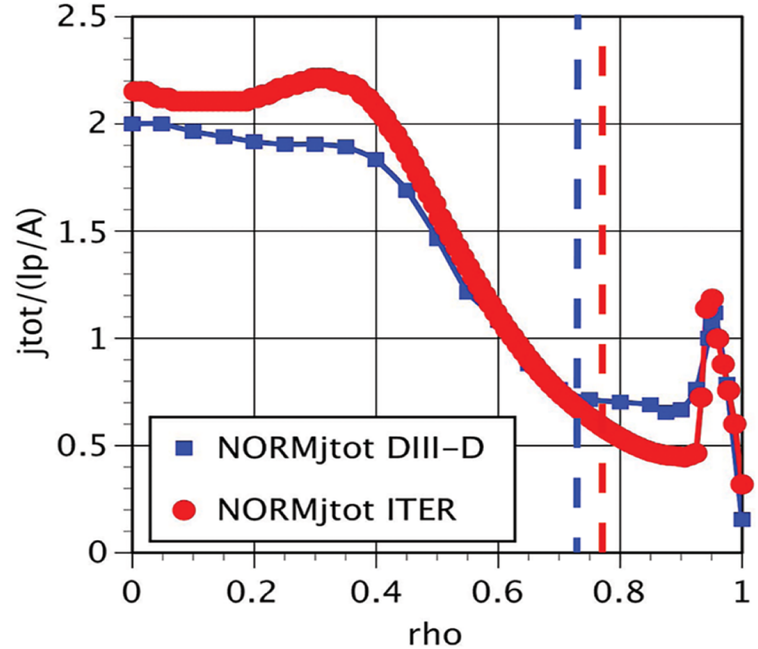


GENERAL ATOMICS

DIII-D IBS & ITER have Similar Current Density j and Safety Factor q profiles (& Classical Stability?)

- $\Delta' r_0$=-0.1 is near marginal classical stability in DIII-D (Thanks to Zhiuri Wang (PPPL) for resistive DCON on kinetic EFIT by Bob Wilcox)
  - assume same for ITER
  - Δ'=-0.002cm^{-1} DIII-D, -0.0005cm^{-1} ITER (negligible effects in both)
- ITER is 3.7X DIII-D IBS in size, 2.65X in field, similar in shape, aspect ratio and ion banana width, lower resistive diffusivity and rotation frequency but higher Lundquist number S= τ_R/τ_A at q=2





GENERAL ATOMICS

NTMs are Classically Stable, Non-linearly Unstable and to Grow Robustly Must be Seeded by a Critical δB From Another MHD Event

- **Critical δB set by induced helical polarization currents J_{pol} that arise from finite island rotation in the plasma ExB rotation frame;**

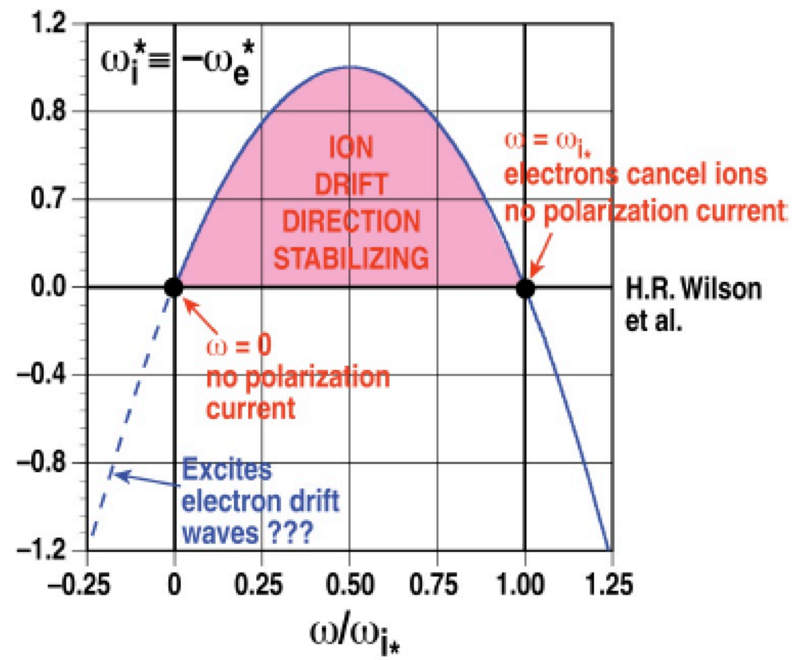
  (not considered here is the transport threshold effect w_d)
  - **helical polarization current from ion inertia and quasi-neutrality sets a critical island width that is sign & rotation dependent**

$$w_{pol} \approx (3L_q/L_{pe})^{1/2}\varepsilon^{1/2}\rho_{\theta i}\ \mathrm{x}2 \left[\frac{\omega\omega_i^* - \omega^2}{\omega_e^{*2}}\right]^{1/2}$$

which is a product of the order of the ion banana width and a function $F(\omega)$ of the rotation (shown on the right)

with $\omega = \omega_{island} - \omega_{ExB}$

- **stabilizing for $\omega_{i*} > \omega > 0$**



n^{th} ELM at 3396 msec in DIII-D Seeds Robustly Growing 2/1 NTM That Has Previously Been "Stalled" After $n\text{-}2^{th}$, $n\text{-}1^{th}$ ELMs at 3335, 3363

Each ELM lowers n=1 mode frequency f_m *towards* f_E, transiently opening the otherwise stabilizing gate and eventually the gate stays open ($f_m \sim f_E$) at larger mode amplitude (F~1 goes to F~0)

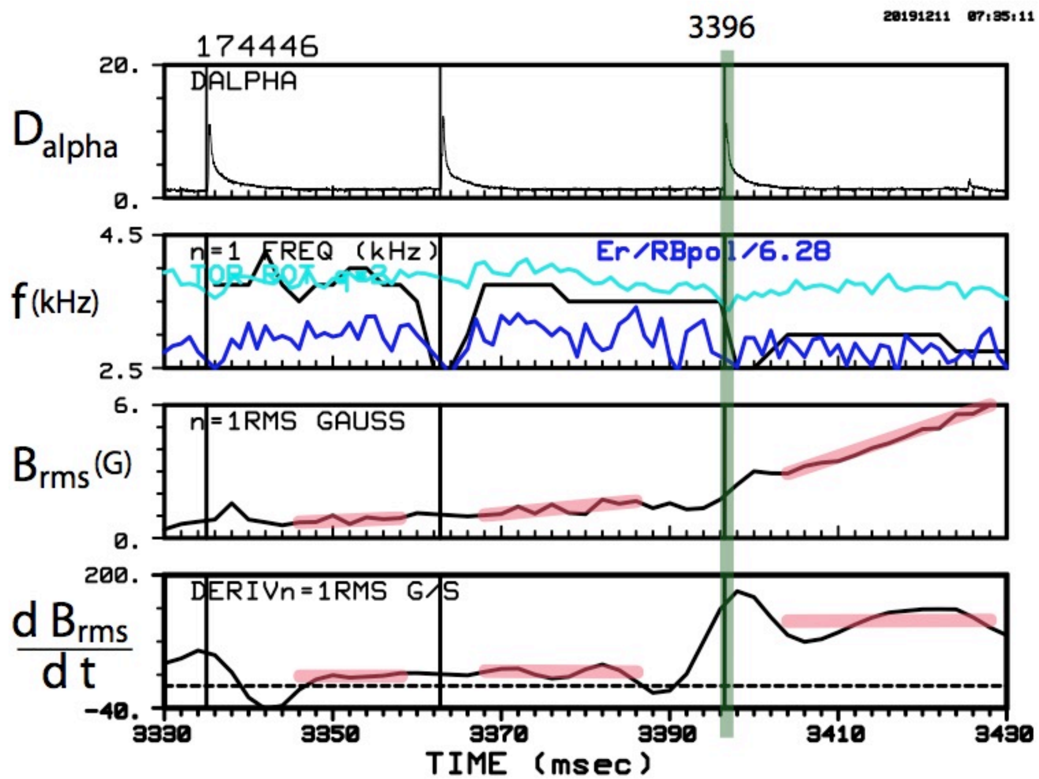
- **Fourier Analysis over running 4 msec interval every 2 msec for f_m, B_{rms}**
- **CER every 1 msec for both toroidal and poloidal rotations for f_E**

ELMs every ~ 30 msec

$f_E = E_r/6.28RB_{pol}$ @ q=2 dips less at ELMs than f_m

Stalled growth at low B_{rms}

2/1 grows robustly from 3396 after $f_m \sim f_E$ and $B_{rms} > 3$ G ($w_0 > 5$ cm)



GENERAL ATOMICS

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n^{th} Sawteeth Crash at 2792 msec in DIII-D Seeds Robustly Growing 2/1 NTM That Has Been Previously "Driven" by 1/1 ST Precursor From 2788

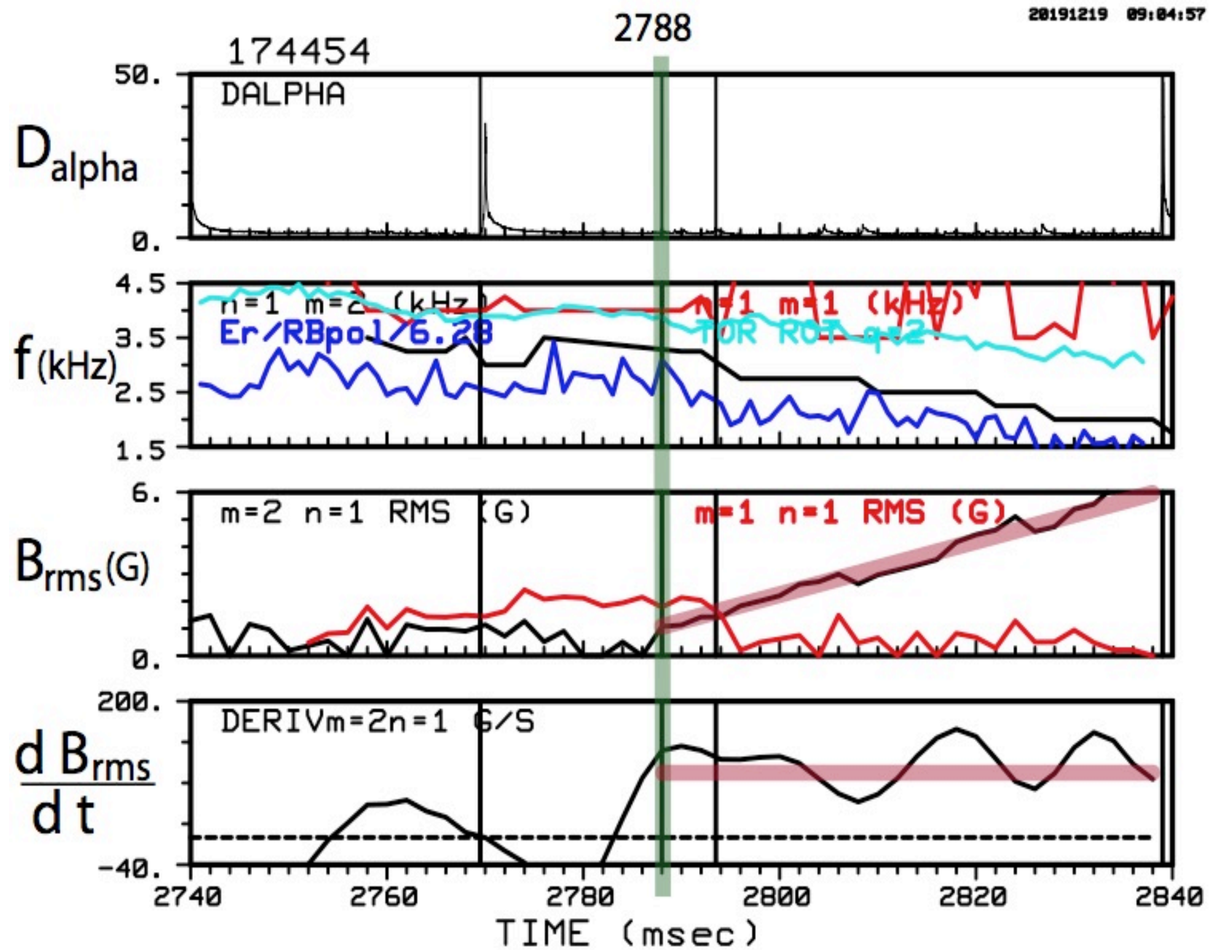
Before crash stabilizing gate is closed (f_t>f_m>f_E), after f_m goes to f_E & gate is opened for mode to grow (F~1 goes to F~0)

- **as in 174446, Fourier Analysis over running 4 msec interval every 2 msec**
- **as in 174446, CER every 1 msec**

1/1 & 2/1 by Fourier frequency bands to isolate modes

1/1 ST precursor starts growing ~2750, crashes at 2792 msec

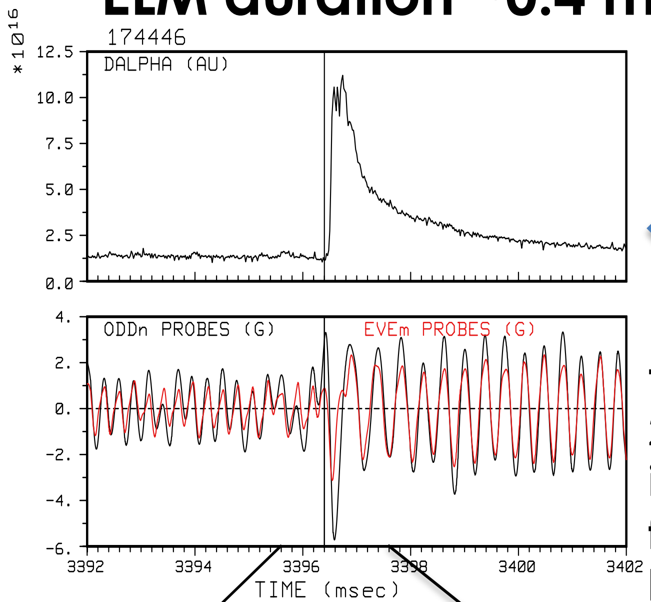
2/1 identified and grows robustly from 2788 msec; crash at 2792 msec

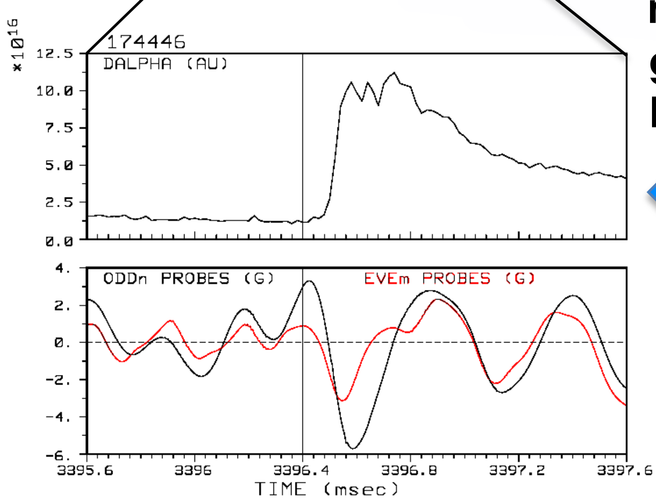


GENERAL ATOMICS

MHD Events That Seed Robustly Growing 2/1 NTMs Have Durations Much Shorter Than Visco-Resistive Tearing Time $\tau_R^{5/6}\,\tau_A^{1/3}\,\tau_V^{-1/6}$ ~36 msec @q=2

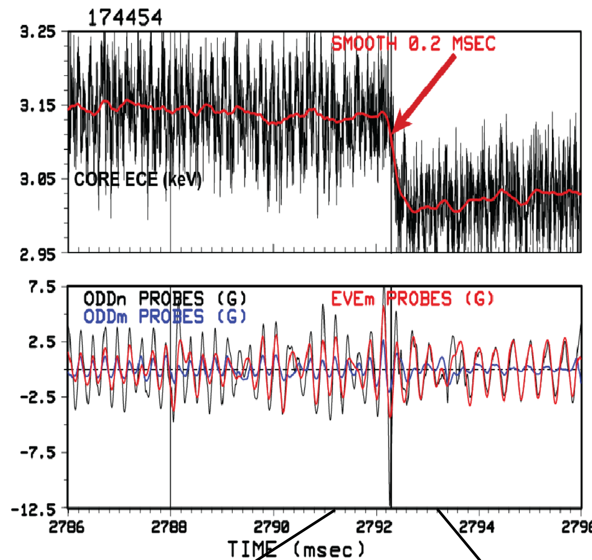
ELM duration ~0.4 msec

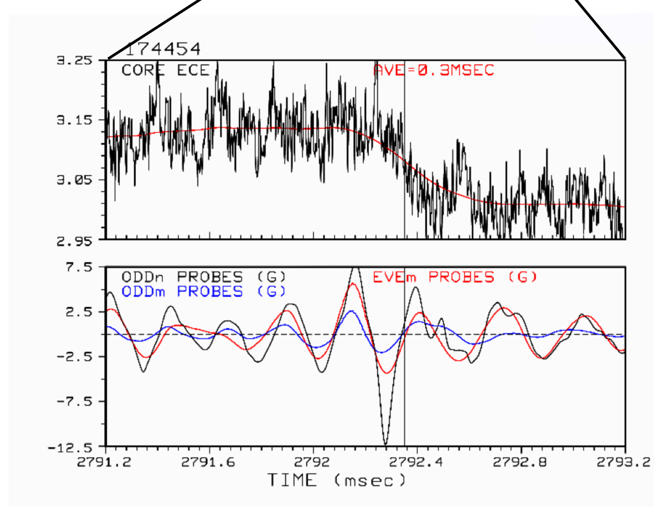




ELM “kink” turns stalled 2/1 mode into lower frequency larger amplitude robustly growing NTM

Sawteeth crash also ~0.4 msec





Sawteeth precursor and crash turns driven 2/1 mode into lower frequency robustly growing NTM

GENERAL ATOMICS

The Modified Rutherford Equation (MRE) has the Physics Elements to Describe the NTM Stability as Functions of Both Island Size and Rotation

NTM Modified Rutherford Equation (MRE) Is Nonlinear

- Lowest order usual MRE incorporating low A toroidal effects is
$$\frac{d\mathrm{w}}{dt} = \overline{D}_\eta \left[\Delta' + \frac{\mathrm{d_{NTM}}}{\mathrm{w}} - \frac{\mathrm{w}_{\mathrm{pol}}^2}{\mathrm{w}^3} F(f_{\mathrm{m}}) \right], \quad \text{in which } \mathrm{w} \equiv 4 \left[\frac{L_{\mathrm{sh}}\, B_{\mathrm{res}}}{k_\theta\, |B_{t0}|} \right]^{1/2} \simeq 3\sqrt{B_{\mathrm{rms}}} \text{ cm.}$$
- Parameters at $q = 2/1$ in DIII-D discharge 174446 at 3390 ms are:
  $\overline{D}_\eta \simeq 1020$ cm^2/s, effective magnetic field diffusivity $\equiv \langle |\vec{\nabla}\rho|^2 \rangle \, \eta_\parallel^{\mathrm{nc}}/\mu_0$,
  $\Delta' \simeq -0.002$ cm^{-1}, classical tearing mode stability parameter (stable, small),
  $\mathrm{d_{NTM}} \simeq 3.1\, j_{\mathrm{boot}}/\langle j_\parallel \rangle \simeq 0.49$, dimensionless and destabilizing NTM drive,
  $\mathrm{w_{pol}} \simeq 2.7$ cm $\simeq 2.1 \times$ ion banana width for polarization current $\mathrm{J_{pol}}$, stabilizing,
  $F(f_{\mathrm{m}}) \leq 1.0$, "gate function" for $\mathrm{J_{pol}}$ effects, depends on 2/1 mode-freq. f_{m}.
- To compare with DIII-D data write MRE in terms of the root-mean-square (rms) $n = 1$ Mirnov magnetic perturbation B_{rms}(G):
$$\frac{dB_{\mathrm{rms}}}{dt} = \frac{2\,\overline{D}_\eta}{\partial \mathrm{w}^2/\partial B_{\mathrm{rms}}} \left[\mathrm{d_{NTM}} - \mathrm{J_{pol}} + \mathrm{w}\Delta' \right], \quad \mathrm{J_{pol}} \equiv \frac{\mathrm{w}_{\mathrm{pol}}^2}{\partial \mathrm{w}^2/\partial B_{\mathrm{rms}}} \frac{F(f_{\mathrm{m}})}{B_{\mathrm{rms}}}$$
$$\Longrightarrow \boxed{\frac{dB_{\mathrm{rms}}}{dt} \simeq \underset{\text{diffusion}}{220} \left[\underset{\text{NTM drive}}{0.5} - \underset{\mathrm{J_{pol}}\text{ gate}}{0.8\,\frac{F(f_{\mathrm{m}})}{B_{\mathrm{rms}}}} - \underset{\text{classical}}{0.006\sqrt{B_{\mathrm{rms}}}} \right] \frac{\mathrm{G}}{\mathrm{s}}}.$$
- Numbers are at 3390 ms in 174446; neglect small $\mathrm{w}\Delta' \sim -0.01$.

GENERAL ATOMICS

Growth Rate of B_{rms} Depends in Part on the Gate Function $F(f_m)$ which in turn Depends on the Island Rotation f_m with Respect to f_E

DIII-D Discharge 174446 MRE Is Analyzed For $B_{\rm rms}$, $\overline{f}_{\rm m}$

- Keeping dominant terms, lowest order MRE neglecting $\Delta', \cdots$ is

$$\boxed{\frac{d\,B_{\rm rms}}{dt}} = 220 \left(\underbrace{\overset{\text{NTM drive}}{0.5}}_{\rm d_{NTM}} - \frac{\overset{\rm J_{pol}\ gate}{0.8}}{B_{\rm rms}} F(f_{\rm m}) \right) \frac{\rm G}{\rm s} \quad \boxed{\begin{array}{ll} <\ 0 & \text{for } B_{\rm rms} < 0.8\,F(f_{\rm m})/{\rm d_{NTM}}, \\ \geq\ 0 & \text{for } B_{\rm rms} \geq 0.8\,F(f_{\rm m})/{\rm d_{NTM}}, \\ \simeq 110 & \text{for } B_{\rm rms} \gg 0.8\,F(f_{\rm m})/{\rm d_{NTM}}. \end{array}}$$

- The $\boxed{\text{“gate function” } F(f_{\rm m}) \leq 1.0}$ for ion polarization $\rm J_{pol}$ effects is

$$F(f_{\rm m}) \equiv -\,4\,\frac{(f_{\rm m} - f_E)\,(f_{\rm m} - f_E - f_{*i})}{f_{*i}^2}, \quad f_{*i} \equiv -\,\frac{\Omega_{*i}}{2\pi} \text{ is diamagnetic mode freq.}$$

- If no MHD transients, the theoretical$^{\rm th}$ equilibrium flux-surface-average (FSA) toroidal $n = -1$ mode frequency $\langle (R^2/R_0^2)\vec{V}_i \cdot \vec{\nabla}\zeta \rangle$ is

$$\overline{f}_{\rm m}^{\rm th} = f_E - f_{*i} + \overline{f}_{\rm pol} \simeq f_{\rm tor}\,(R_{\rm CER}/R_0), \text{ i.e., } \simeq \text{CER-measured toroidal flow.}$$

- $d\overline{f}_{\rm m}/dt$ equation with 2/1 MHD transients (for $\delta t \gtrsim \tau_{\rm MHD} \simeq 0.4$ ms) is

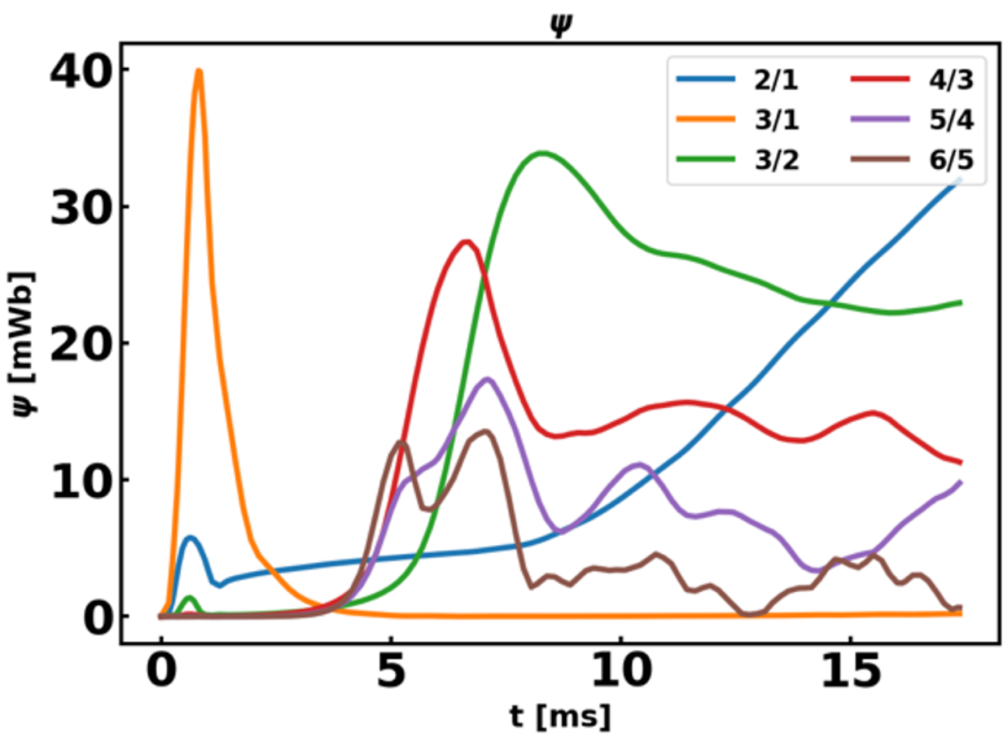
$$\frac{d\overline{f}_{\rm m}}{dt} = -\underbrace{\frac{\overline{f}_{\rm m} - \overline{f}_{\rm tor}}{\tau_\zeta}}_{\substack{\text{NBI-ITG relax-}\\ \text{ation, } \tau_\zeta \sim 0.1\,{\rm s}}} - \underbrace{\frac{|\delta J_\| \,\delta B_{\rm res}|}{R_0\,\rho_m} \left[\frac{\tau_{\rm MHD}}{\delta t}\right]^{1/2}}_{\substack{\text{response } \delta t \text{ after a}\\ \tau_{\rm MHD} \text{ MHD transient}}} - \underbrace{\frac{\overline{f}_{\rm m} - \overline{f}_{\rm offset}}{\tau_{\rm isl}} \frac{\rm w}{r_{2/1}}}_{\substack{\text{island } \| \text{ neo tor.}\\ \text{drag, } \tau_{\rm isl} \sim 0.015\,{\rm s}}} - \underbrace{\left[\frac{\rm w}{a}\right]^4 \frac{C_\#}{(2\pi\tau_{\rm A})^2 \overline{f}_{\rm m} \tau_{\rm V}}}_{\substack{\text{vessel wall drag,}\\ \text{small at seeding}}}.$$

GENERAL ATOMICS

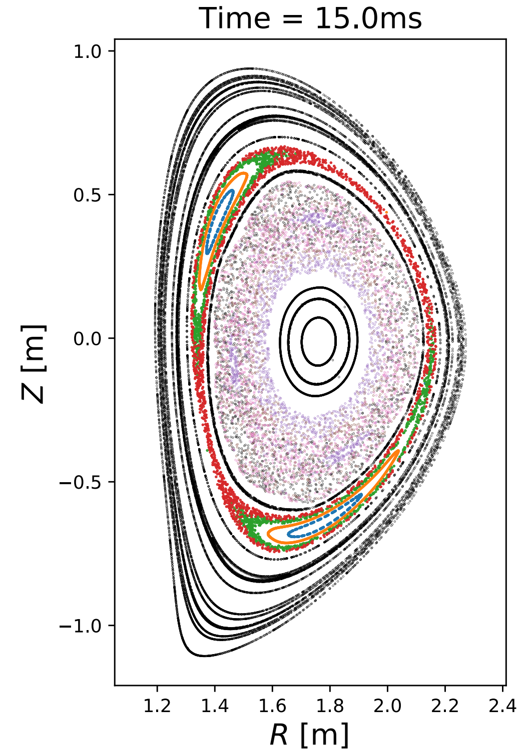
NIMROD Modeling of ELM Induced NTM DIII-D Discharge 174446 Yields Similar Features as MRE, i.e. Linearly Stable, Non-linearly Unstable

- **NIMROD code simulates NTMs seeded by an externally imposed 1 ms MHD magnetic pulse (stable without pulse)**
  - Realistic equilibrium: DIII-D with Lundquist number (q=2) S=2.5E6

    [E. Howell et al., "NIMROD Modeling of Transient-Induced NTM," APS-DPP meeting 2020]



Evolution of helically resonant magnetic fluxes including 1 ms pulse

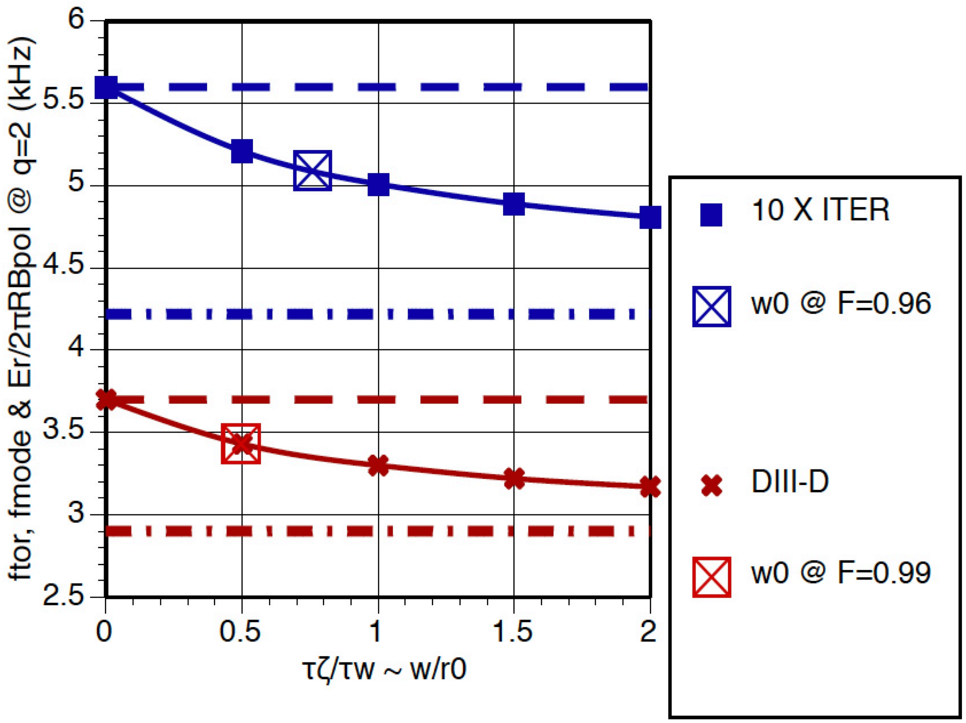


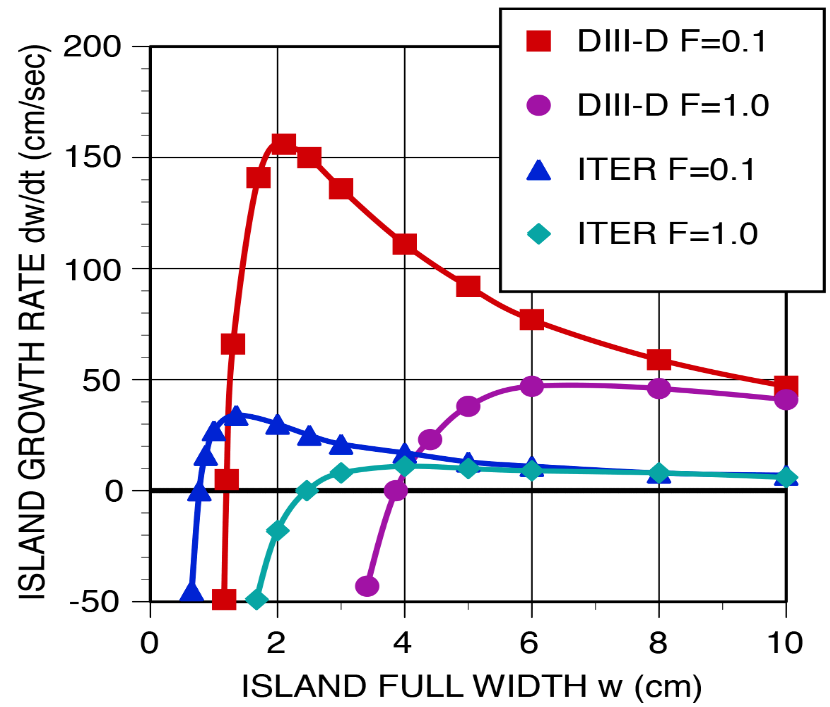
Poincare plot at 15 ms exhibits 2/1 island width of ~10 cm

GENERAL ATOMICS

DIII-D and ITER are in similar regimes for island rotation f_m wrt plasma toroidal f_t and $f_E = E_r/2\pi R B_{pol}$ rotations at q=2

- **Solving $df_m/dt = 0$ of Slide 10, absent the transient torque from an MHD perturbation, the island rotations both fall within the stabilizing frequency band with gate function F~ 1, i.e. closed, at critical island width w_0 for onset**
- **Predicted island growth rate (for gate nearly open or for closed) in ITER is slower than DIII-D due to its much smaller magnetic field diffusivity but shifted to smaller w_0 and very much smaller (0.17X) relative size w_0/r_0**

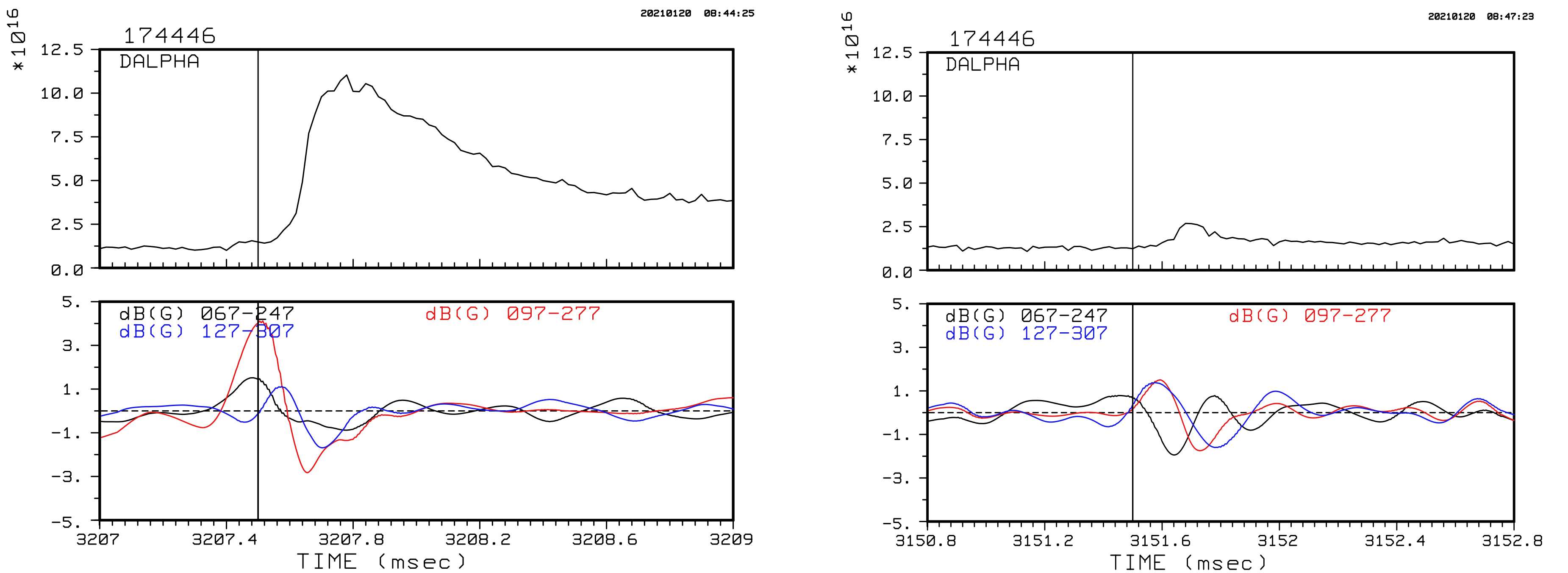




GENERAL ATOMICS

ELM Control in ITER Could Reduce the Seeding Magnetic Perturbations so as to be Below the Critical Level for Robust Growth?

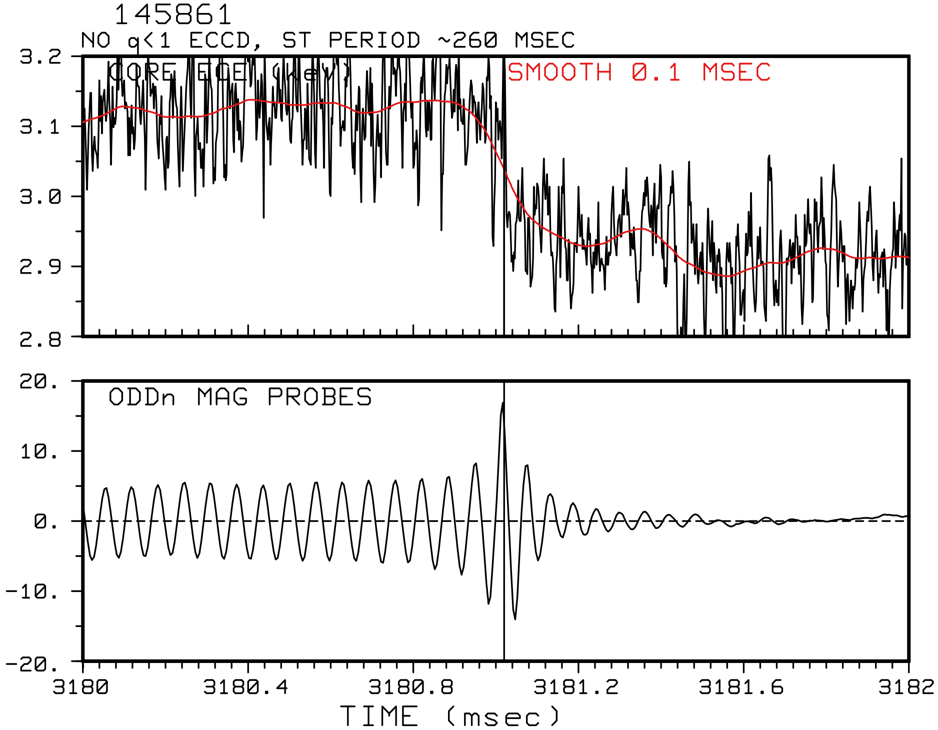
- **ELM control by Resonant Magnetic Perturbations (RMP) in the low torque low q_{95} DIII-D IBS awaits full success; instead we contrast a major ELM and an in-between minor ELM for the size of the n=1 magnetic perturbations (neither of these excites the NTM)**
  - **Two-point scaling of peak odd n (here 3 pairs) is δB~1.4$(\delta D_\alpha/D_\alpha)^{1/2}$ and all else being equal, $w_{seed} \sim (\delta B)^{1/2} \sim (\delta D_\alpha/D_\alpha)^{1/4}$ so a factor of two smaller seed island requires a factor of 1/16 in $\delta D_\alpha/D_\alpha$**

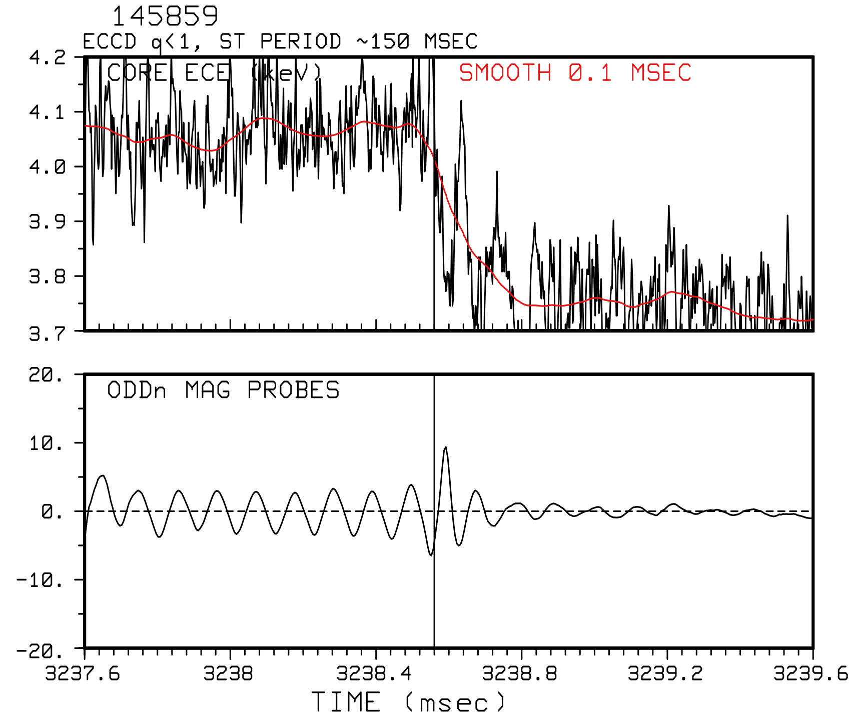


GENERAL ATOMICS

Sawteeth Control by ECCD inside q=1 in ITER Could Reduce Magnetic Seeding Perturbations so as to Be Below the Critical Level?

- **Co-ECCD inside q=1 can destabilize sawteeth making them occur more frequently** **[I.T. Chapman, et al., "Sawtooth control using electron cyclotron current drive in ITER demonstration plasmas in DIII-D," Nucl. Fusion 52 (2012) 063006]**
  – As shown below $j_{eccd}/j_{tot} \sim 0.2$ at $\rho \sim 0.2$ in DIII-D halves the ST period T as well as the peak n=1 magnetic perturbation at the crash
  – Scaling of peak odd n is $\delta B \sim T$ and $w_{seed} \sim (\delta B)^{1/2} \sim T^{1/2}$ all else being equal; factor of 4 reduction in T needed for seed island width a factor of 2

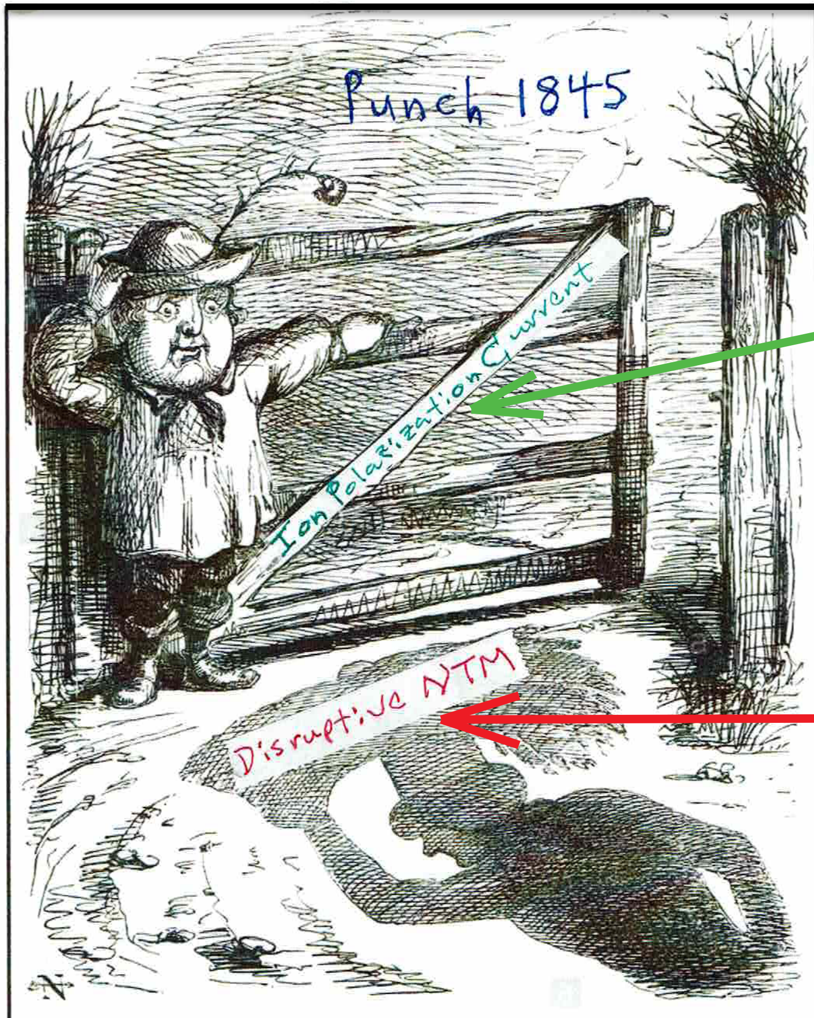




Conclusions, Questions and Future Work: ITER is predicted to be more sensitive to seeding of disruptive NTMs than DIII-D by a factor of 1/6 in w_0/r_0 (F=1); δB~0.1 G which will make early detection problematic

- **MHD transients in ITER are much more likely than in DIII-D to destabilize the most problematic, robustly growing 2/1 NTMs that ultimately lead to locked modes and disruptions**
  - **ELMs and sawtooth (ST) crashes identified as causes**
- **How much *and for how long* will the transient torque $\delta j_{11}\delta B_{res}$ during an ELM or ST crash drive down the mode rotation in ITER?**
  - **recovery (gate opens & closes) or not (gate stays open)**
- **Will ELM suppression by RMP *and* ST control by ECCD reduce the transient magnetic perturbations enough so seeds are too small for tearing mode excitation?**
  - **DIII-D data suggests these techniques can be effective**
    - **How to scale to ITER? Can NIMROD test?**

Robustly Growing 2/1 NTMs Lead to Disruptions, Particularly at low q95; MHD Transients Open J_{pol} Gate to Growing 2/1 NTMs



OPENING THE GATE: OR, "COMING EVENTS CAST THEIR SHADOWS BEFORE."

ION POLARIZATION CURRENT GATE

DISRUPTIVE 2/1 NTM ROBUST GROWTH

COMING EVENTS CAST THEIR SHADOW

Acknowledgements

Acknowledgement: This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award(s) DE-FC02-04ER54698, DE-FG02-86ER53218, DE-AC05-00OR22725, DE-AC02-09CH11466 and DE-SC0018313.