POLARIZATION CURRENT AND THE NEOCLASSICAL TEARING MODE THRESHOLD IN TOKAMAKS; COMPARISON OF EXPERIMENT WITH THEORY*

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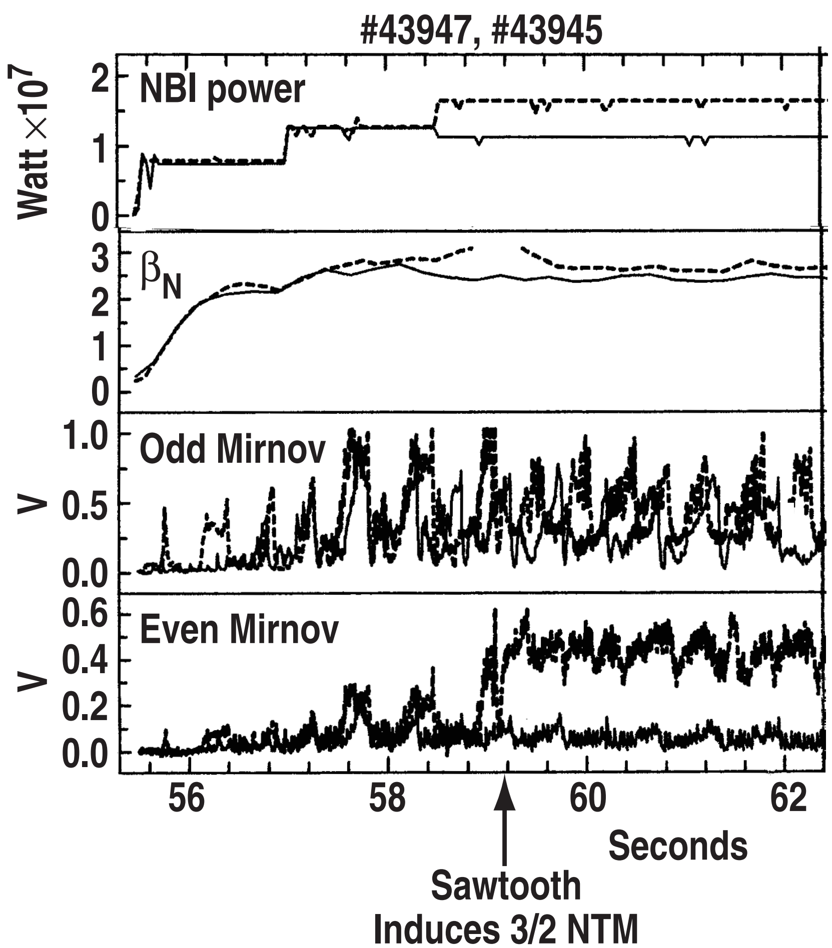
NEOCLASSICAL TEARING MODE ISLANDS CAN REDUCE PERFORMANCE AT HIGHER BETA

- m/n = 3/2 island excited at higher beta
  - Confinement lower with mode
    . . . similar effect observed on ASDEX Upgrade, DIII–D, etc



Also see
Hender, EXP3/02

NUMEROUS EXPERIMENTS HAVE INVOKED THE THRESHOLD FROM POLARIZATION CURRENT (WILSON et al., PHYSICS OF PLASMA 1996, PLASMA. PHYS. CONTROL FUSION 1996) TO EXPLAIN OBSERVED CRITICAL BETA FOR NTMS

- Acceptance of polarization threshold as superior in scaling and magnitude of critical beta in experiments as compared to incomplete pressure flattening threshold (COMPASS–D/Gates, Nuc. Fusion 1997, DIII–D/La Haye, Nuc. Fusion 1998, JET/Huysmans, IAEA 1998, ASDEX Upgrade/Gude, Nuc. Fusion 1998, JT–60U/Isayama, Plasma Phy. Cont. Fusion 1999, TEXTOR/Koslowski, Nuc. Fusion 2000)

- Polarization/inertial threshold questioned theoretically (Waelbroeck and Fitzpatrick, PRL 1997, Mikhailovski et al, Physics of Plasmas 2000)

  ★ Convergence on theory of polarization/inertial threshold (Wilson, Connor and Waelbroeck, Sherwood 2000)

    — Different physics assumptions flip sign of effect

    — Stabilizing threshold for $|\omega_{i*}| > \omega > 0$ in ion direction

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WHY A NEOCLASSICAL TEARING MODE?

- **Helically perturbed bootstrap current (Qu and Callen 1985)**
  - ★ "Seed" island from another MHD instability
  - ★ O-point and X-point $J_{//bs}$ differ
  - ★ Helically perturbed bootstrap current makes $\tilde{B}_{rmn}$
    - — Reinforces "seed" (q monotonic inc., p monotonic dec.)
    - — A destabilizing effect
  - ★ Neoclassical tearing mode can result even if $\Delta_0' < 0$
    - — Plasma is "metastable"
      . . . must be perturbed beyond a "threshold"
- **Signatures of an NTM include . . .**
  - ★ Higher β, larger bootstrap current $J_{//bs} \propto \varepsilon^{1/2}\beta_\theta/L_p$
    - — Destabilizing
  - ★ Other MHD mode provides "seed" island
    - — Metastable plasma (wo island) must be disturbed above a threshold

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WHY A THRESHOLD?

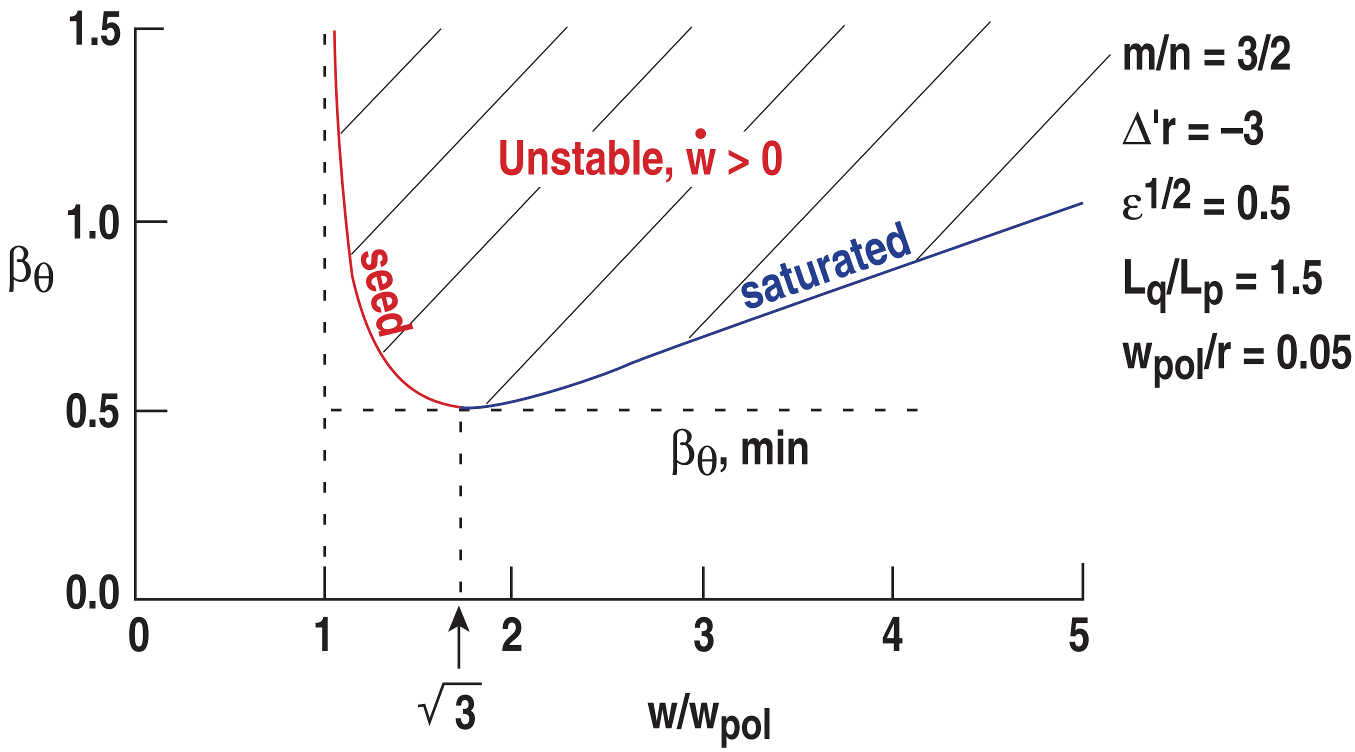
- $\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \varepsilon^{1/2}\left(L_q/L_p\right)\beta_\theta\left(\frac{1}{w} - \frac{w_{pol}^2}{w^3}\right)$, Modified Rutherford Eq.

  — $\beta_{\theta,\,crit} \approx [-\Delta' r/(\varepsilon^{1/2} L_q/L_p] \left(\frac{w_{pol}}{r}\right)\left[\frac{w_{seed}/w_{pol}}{1-(w_{pol}/w_{seed})}{}^2\right]$

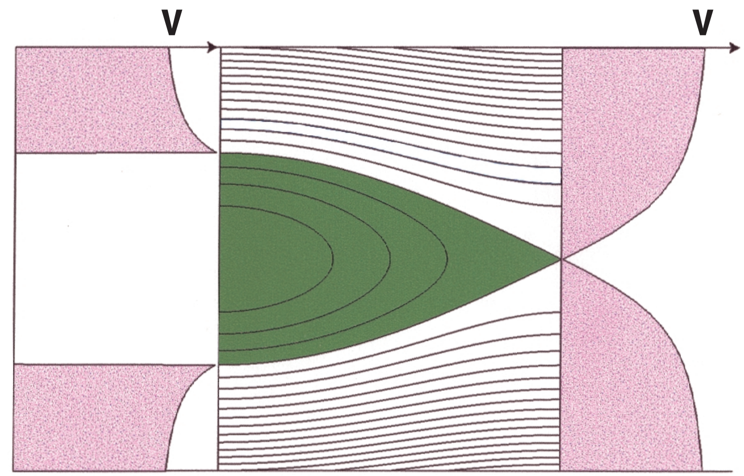
  ★ with $w_{pol} \propto \varepsilon^{1/2}\rho_{\theta i}$ the ion banana width, as suggested by the polarization/inertial theory of Wilson et al. (1996) (to be discussed later)

  — if $w_{seed}/w_{pol} \equiv$ constant > 1

$$\boxed{\therefore\ \beta_{\theta,\,crit} \propto w_{pol}/r \propto \rho_{i*}}$$



POLARIZATION THRESHOLD THEORY (Also see Wilson, TH3/5)



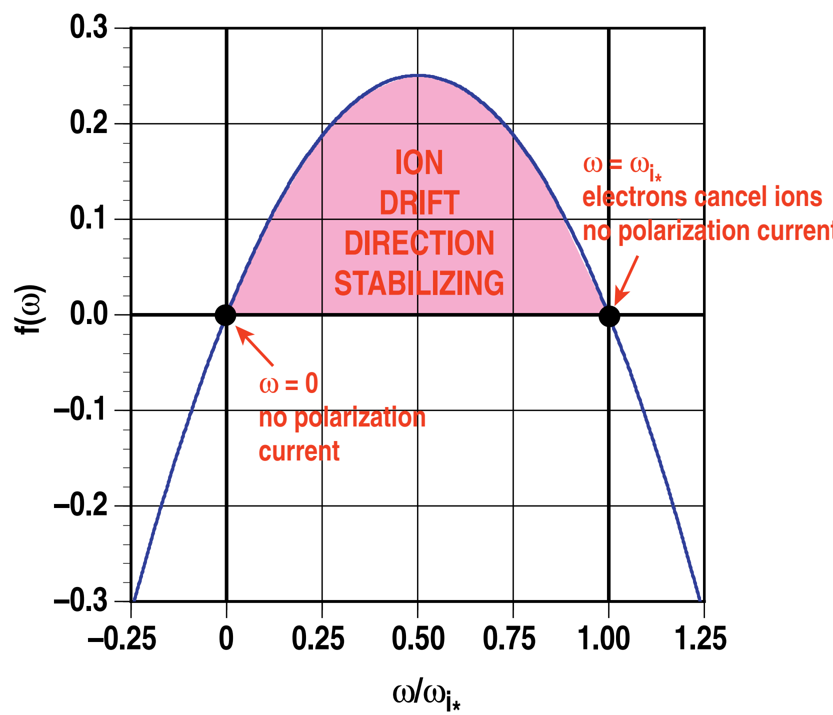
- **Polarization current results from ion inertia**
  - ★ Island streaming through the plasma
    - — polarization drift from ion inertia
    - — quasi – neutrality in $E_r = 0$ frame gives rise to a return current

- **Threshold if polarization current opposes island**
  - ★ $w_{pol} \approx 1.64^{1/2} (L_q/L_p)^{1/2} \varepsilon^{1/2} \rho_{\theta i} \times \left[\dfrac{\omega\omega_{i*} - \omega^2}{\omega_{e*}^2}\right]^{1/2}$

    for $(\nu_i/\varepsilon)/\omega \ll 1$

    ~ ion banana width $\times$ function of island rotation $f(\omega)^{1/2}$

    — only a threshold for $\omega_{i*} > \omega > 0$



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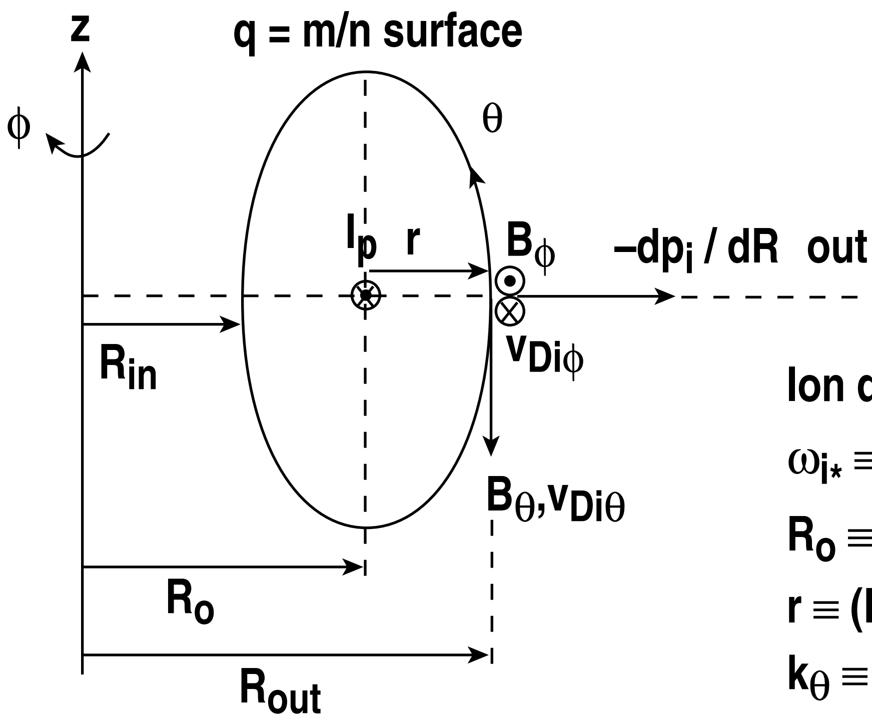
ISLAND PROPAGATION IN $E_r = 0$ QUASI-NEUTRALITY FRAME IS HIDDEN VARIABLE FOR POLARIZATION THRESHOLD

- ω is key for polarization threshold
  . . . must be $\omega_{i*} > \omega > 0$, ion direction



I_p	in
B_ϕ	out
$v_{Di\phi}$	in
$v_{Di\theta}$, B_θ	down

Ion drift frequency

$$\omega_{i*} \equiv \vec{k} \bullet \vec{v}_D = k_\theta v_{Di\theta} + k_\phi v_{Di\phi}$$

$$R_o \equiv (R_{out} + R_{in}) / 2$$

$$r \equiv (R_{out} - R_{in}) / 2$$

$$k_\theta \equiv m/r, \; k_\phi \equiv n/R$$

- ω_{Mirnov} island frequency in laboratory frame

- $$\frac{\omega_{E_r = 0}}{2\pi} = \frac{nE_r}{2\pi R B_\theta} = \frac{-nv_\phi}{2\pi R} + \frac{nv_\theta (B_\phi / B_\theta)}{2\pi R} + \frac{n \nabla p_i}{2\pi Z_i n_i R B_\theta}$$

- $$\frac{\omega_{i*}}{2\pi} = \frac{m}{2\pi r} \frac{(T_i / L_{pi})}{B_\phi} + \frac{n}{2\pi R} \frac{(T_i / L_{pi})}{B_\theta}, \quad \frac{\omega_{e*}}{2\pi} = \frac{-m}{2\pi r} \frac{(T_e / L_{pe})}{B_\phi} - \frac{n}{2\pi R} \frac{(T_e / L_{pe})}{B_\theta}$$

- $\omega \equiv \omega_{Mirnov} - \omega_{E_r = 0}$ island frequency in $E_r = 0$ frame

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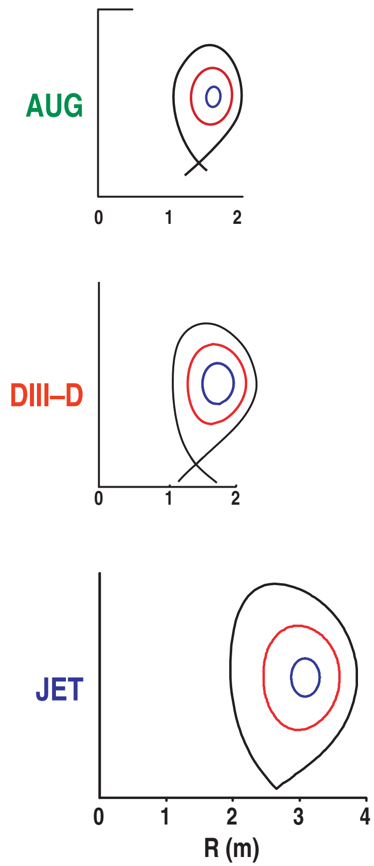
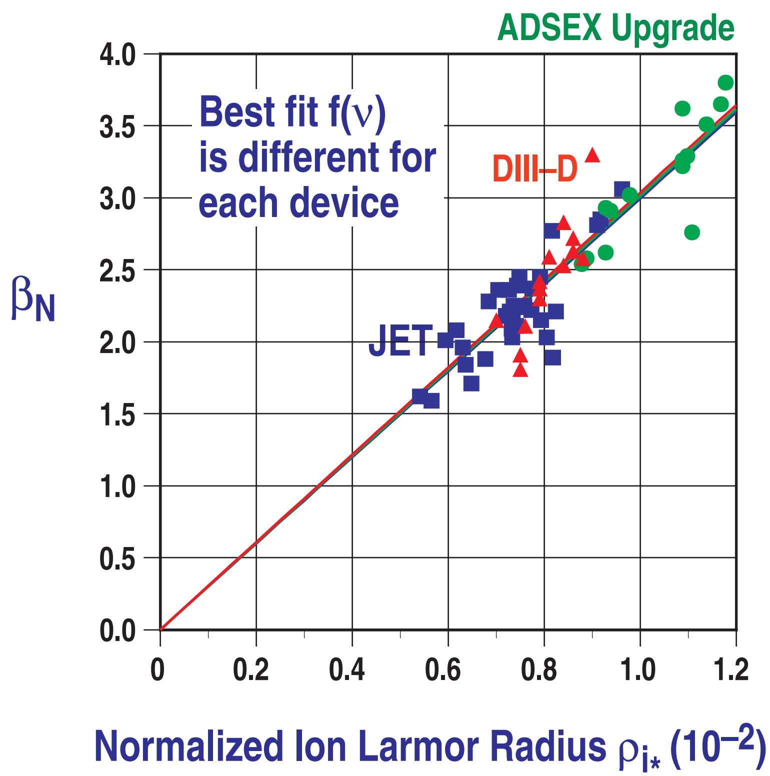
DIMENSIONLESS SCALING OF NTM CRITICAL BETAN = $\beta(\%)/(I/aB_T)$ (CORRECTED FOR COLLISIONALITY VARIATION)

- LSND, ELMing H–mode, q95 ≳ 3
- Sawtooth induced 3/2 NTM database
- $\beta_N \propto \rho_{i*} f(\nu)$ is consistent with polarization threshold





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JET

ASDEX Upgrade

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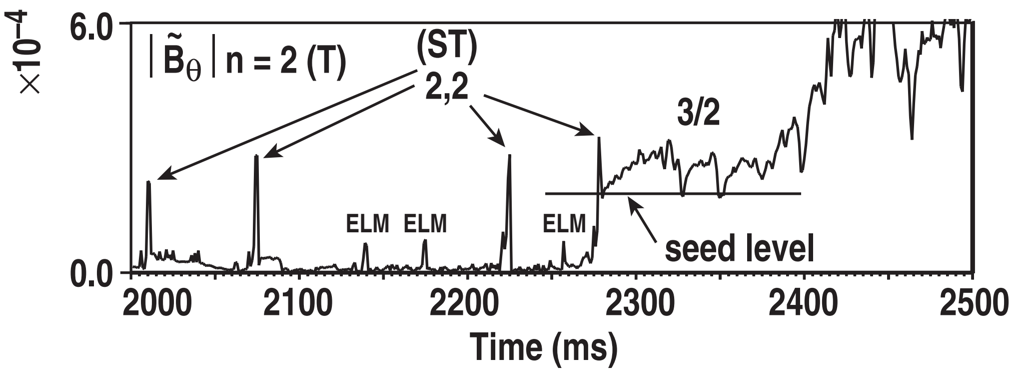
COMPARISON OF UNSTABLE SEED ISLAND TO POLARIZATION THRESHOLD ISLAND

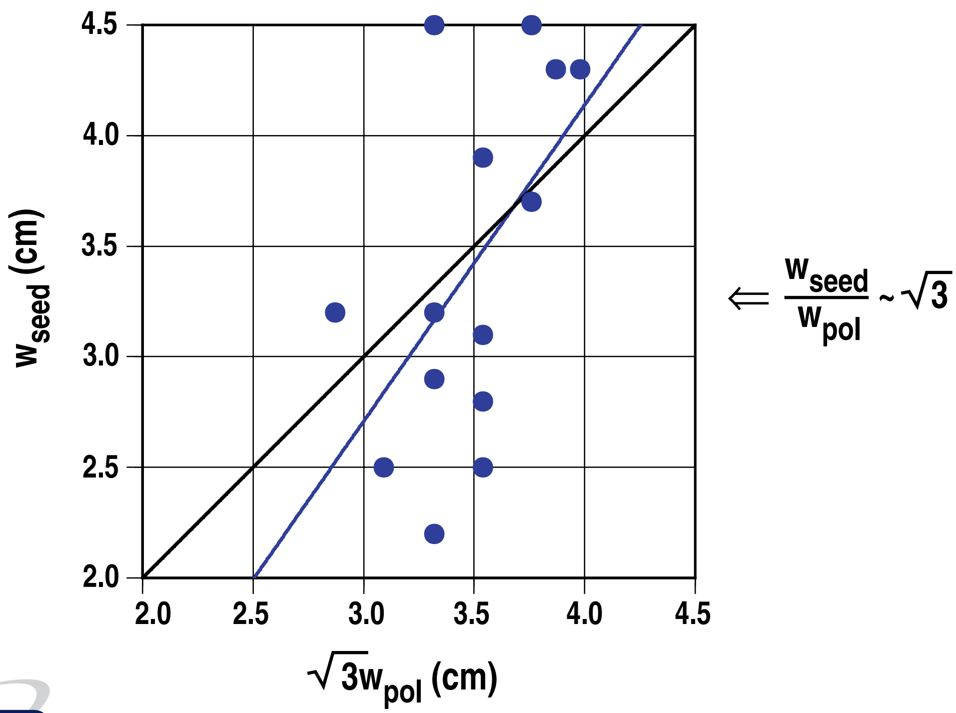
- Islands estimated from m/n = 3/2 Mirnov level upon excitation

  ★ $w_{seed} \approx \left(\frac{16rR\,|\tilde{B}_r|}{3s\,B_T}\right)^{1/2}$ with $|\tilde{B}_r| \approx \frac{1}{2}\left(\frac{b}{r}\right)^4 |\tilde{B}_\theta|_{wall} \times \frac{2}{3}$ calib to ECE radiometer



- Mode grows if $w_{seed}/w_{pol} > 1$, $\beta_\theta > \beta_{\theta,\,min} \propto w_{pol}/r$

  ★ $w_{pol} \approx 1.64^{1/2}\,(L_q/L_p)^{1/2}\,\varepsilon^{1/2}\,\rho_{\theta i}$ for $(\nu_i/\varepsilon)/\omega_{e*} < 0.3$



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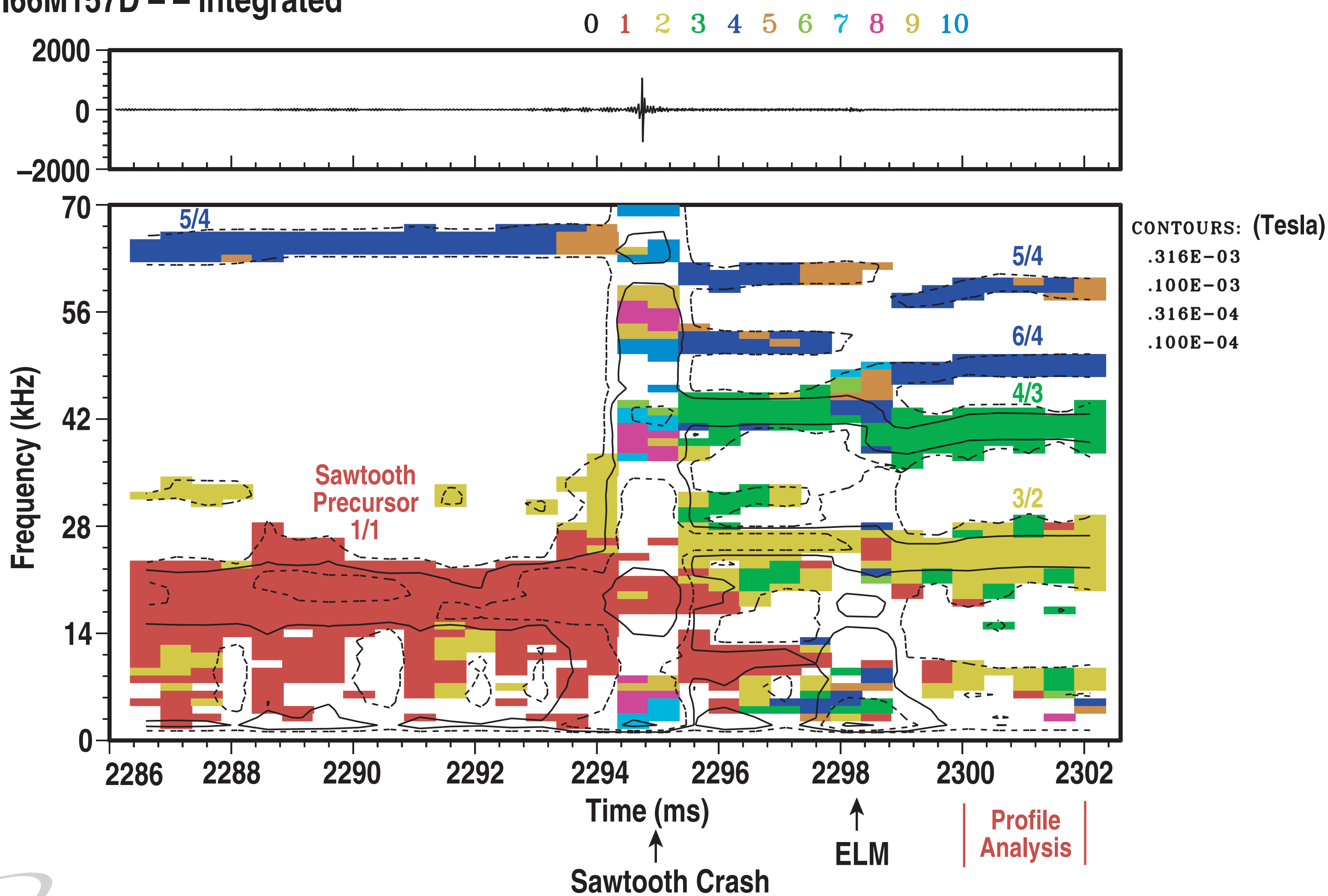
MIRNOV ACTIVITY ACROSS A SAWTOOTH INSTABILITY THAT TRIGGERS NTMS

- m/n = 3/2 and 4/3 tearing modes produced, 5/4 pre-existing
  - ★ Sawtooth on 97835 with 50% beam step up at 2500 ms also produces m/n = 2/1 mode

MPI66M137D – – integrated modes 0 to 17 2.000 kHz smoothing (3 PTS) 1.0 ms intervals

MPI66M157D – – integrated



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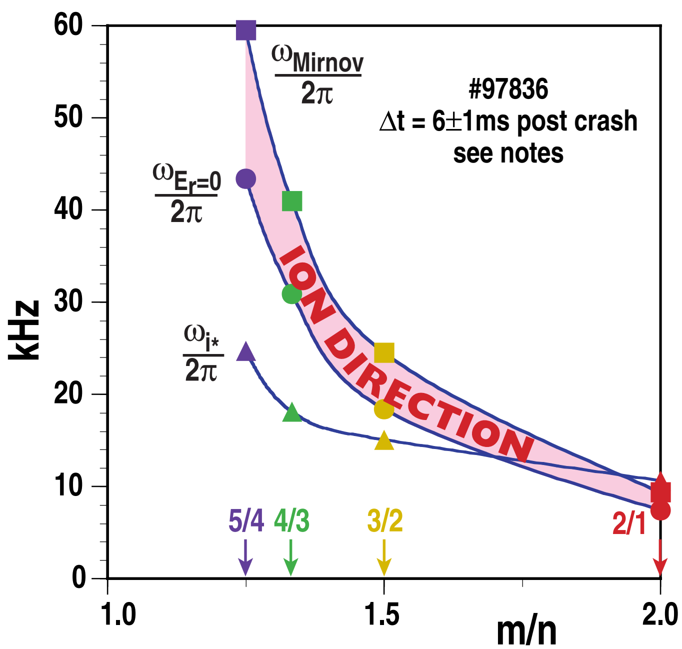
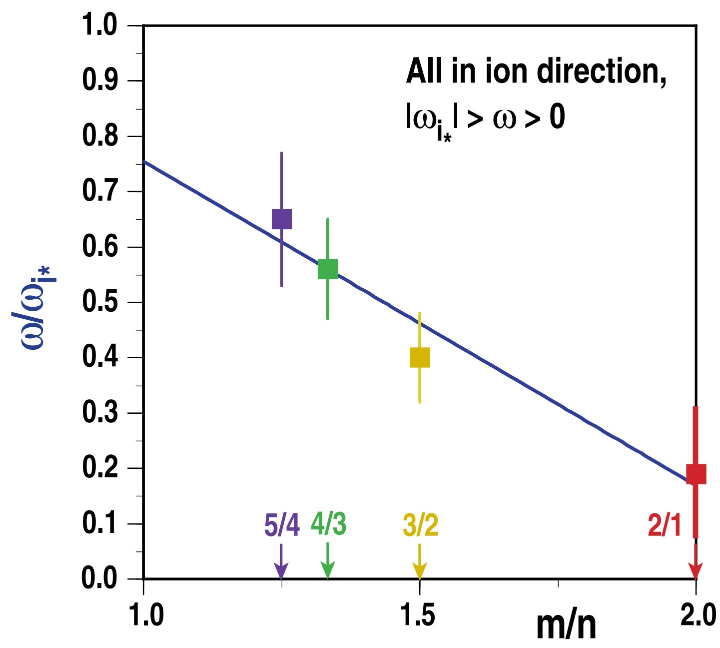
ALL ISLANDS OBSERVED PROPAGATE IN ION DRIFT DIRECTION IN LOCAL E_r = 0 FRAME

- q = m/n location from EFIT with 35 channel MSE profile
  - q good to ± 3%
- E_r at q = m/n from CER includes v_ϕ, v_θ and ∇p_i terms
  - Resolution to 0.5 ms
- Consistent with a polarization threshold
  - ★ $|\omega_{i*}| > \omega > 0$
- Relative propagation decreases at larger minor radius
  - ★ Higher collisionality, smaller $\eta_i = L_{ne}/L_{Ti}$





Notes: (1) 5/4 exists both pre and post sawtooth crash

(2) 2/1 is from #97835 with 50% more beam power after 2500 ms and is 9±5 ms from sawtooth crash

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CONCLUSIONS ON COMPARISON OF EXPERIMENTAL NTM THRESHOLD TO POLARIZATION THEORY

- **Consistency with polarization threshold?**

  ★ **Linear critical beta ρ_{i*}, i.e. $\rho_{\theta i}/r$ (worrisome for future devices)**

  ★ **Seed island of order of ion banana width**

  ★ **Island propagation $|\omega_{i*}| > \omega > 0$ in ion drift direction in $E_r = 0$ frame**

  • • • **Co-injected beams and upon island initiation**

  — **Stabilizing polarization current predicted**