Modeling disruptions caused by NTMs

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CTTS Meeting

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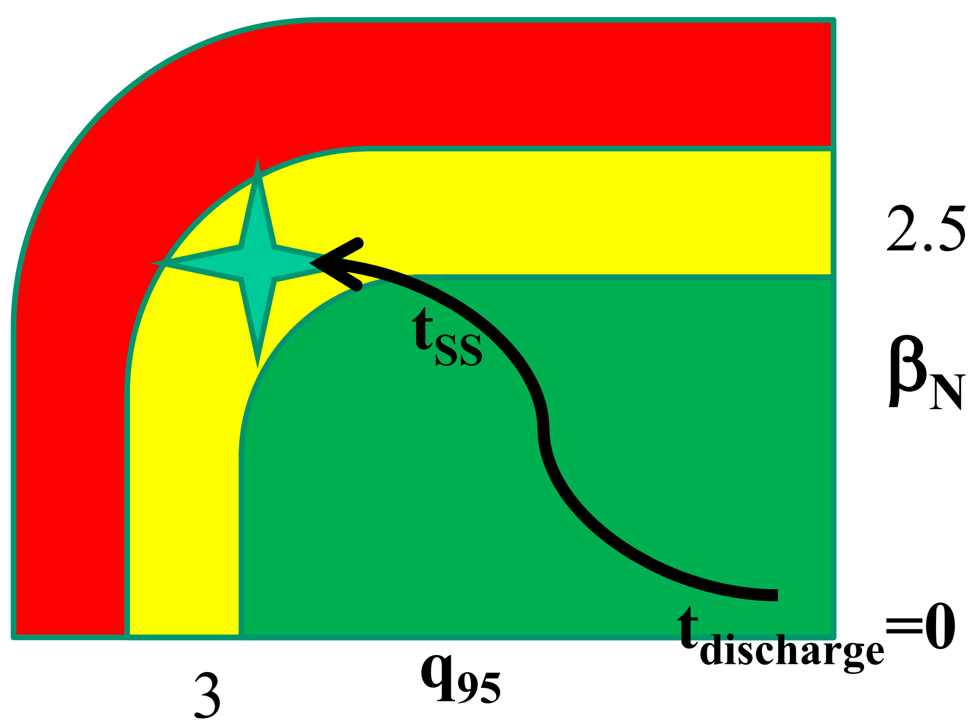
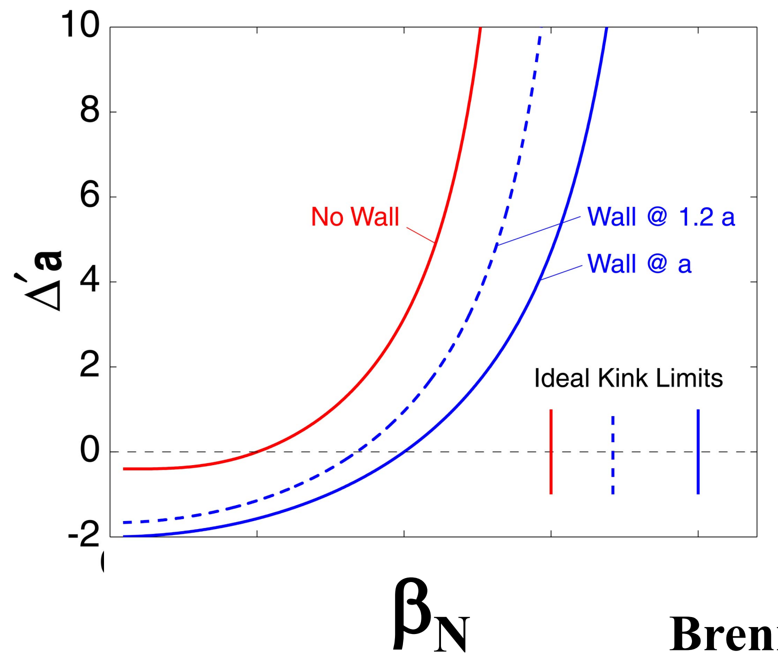
Why are NTMs (and RWMs) of concerns for Burning Plasma Experiments?

- **Ideal MHD limits relatively well-understood**
  β_N<4 ℓ_i relatively robust limit



- **But, near boundaries, resistive instabilities also become more unstable (Δ' goes to infinity at ideal stability limit)**



Brennan 04

Tearing modes, while rotating, cause a *soft* beta limit, until they lock

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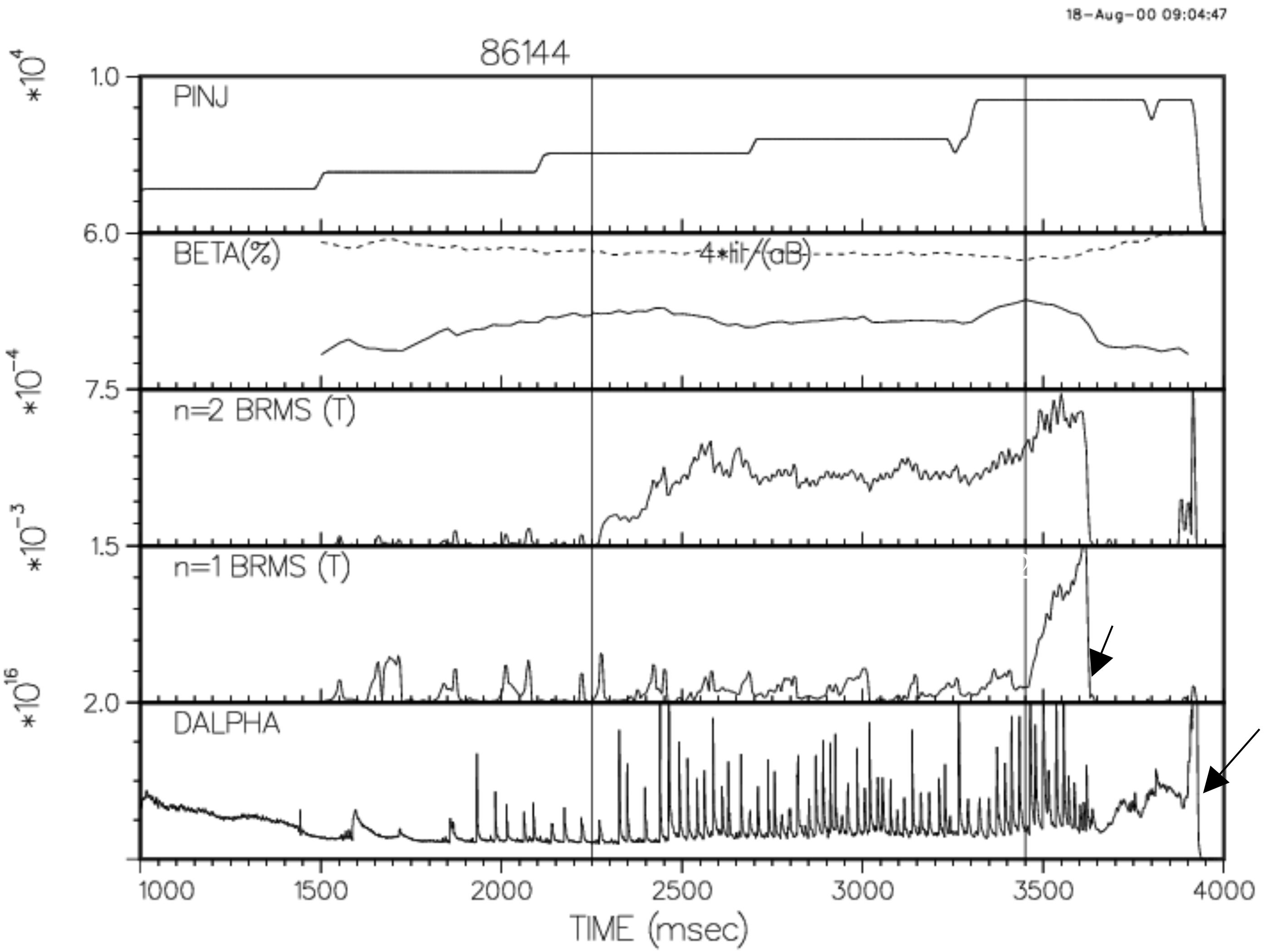


Courtesy of R. LaHaye, General Atomics

Rutherford equation provides paradigm for understanding NTM

Π_e $\quad$ $q_e\ q_i$ $\quad$ Π_i $\quad$ Two fluid+ $\Pi e, q_e, \Pi_i, q_i$

$$\frac{\tau_r}{r}\frac{dw}{dt} = r(\Delta' - \alpha w) + r\beta_P\left[a_{bs}\left(\frac{0.65\,w}{w^2 + w_d^2} + \frac{0.35\,w}{w^2 + 28\,w_b^2}\right) - \frac{a_{pol}\ w}{w^4 + w_b^4}\right]$$

classical tearing stability plays significant role…

bootstrap drive

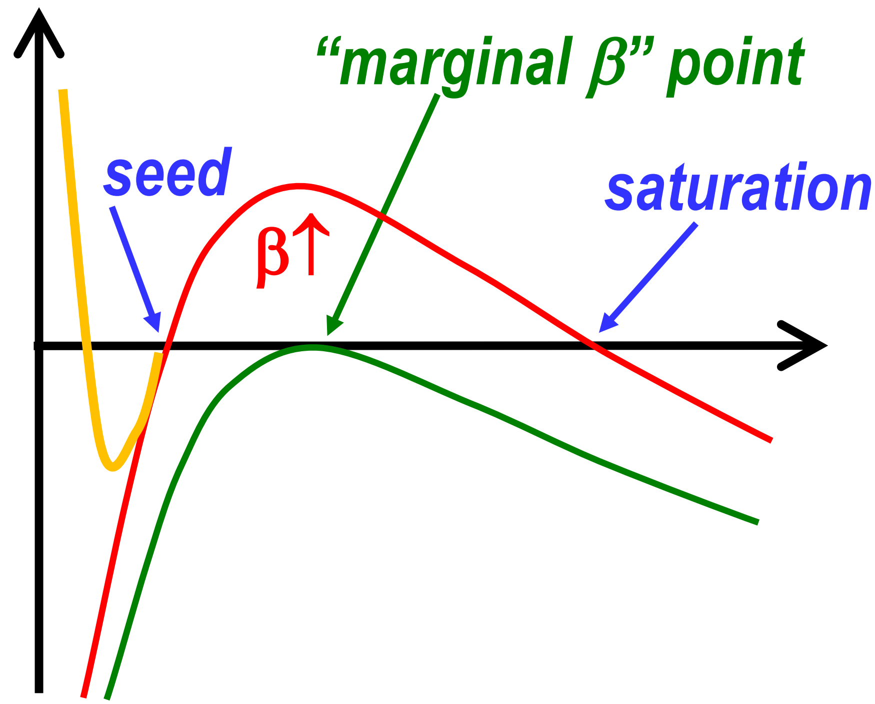
finite island transport

ion banana width

ion polarisation currents

Small island terms are unknown below ion Larmor radius

- At ion Larmor radius, island is nonlinear (> 1mm)
- A 'seed' island *may be* needed
- Seed comes from other MHD
- Island then grows to saturation
- Theory is unable to provide answers between linear regime and ion Larmor radius scale length



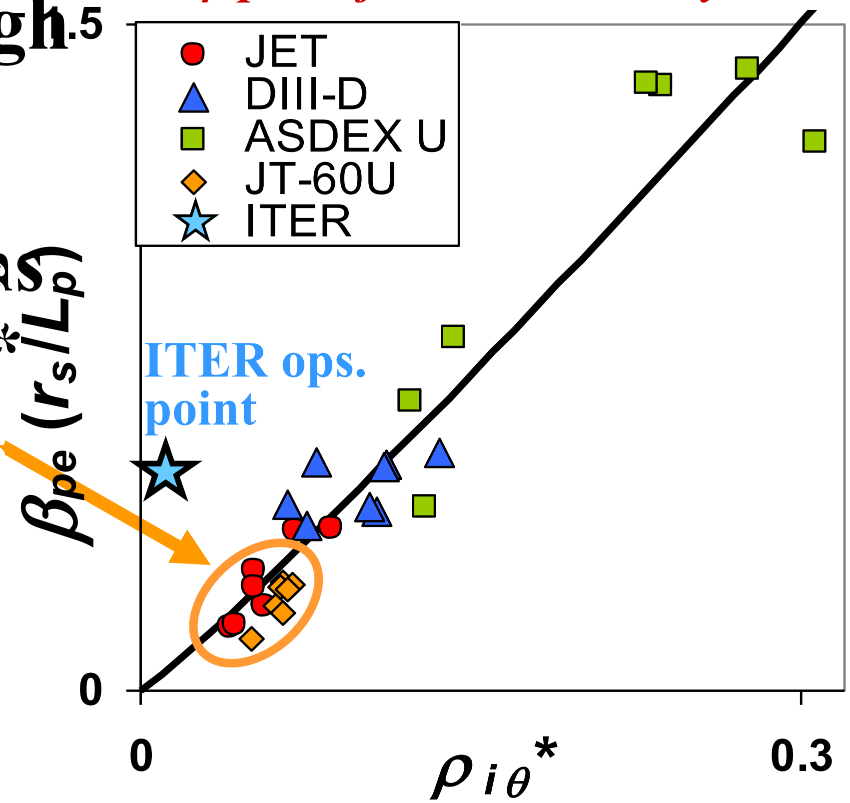
For small island effects: Hegna, Fitzpatric, Waelbrock, Wilson

ITER will operate well above the 'marginal β' where 3/2 NTMs can occur

Ramp down β with a 3/2 NTM present to measure value at which NTM becomes stable:

- **Above this β a large enough seed can trigger the NTM**
- **New JT-60U data confirms reduced stability at low ρ***

Physics parameters at marginal β point for NTM stability



(*reduced plasma shaping likely accounts for slightly lower β values[1]*)

This makes extrapolation of the triggering physics the critical issue…

SEK: But this doesn't really get at onset physics because flow in presence of island is different than onset flow

Buttery, 2008

Experimentally: different types of observed TMs

- **“Generated Tearing Modes”**
  - **Another MHD event (sawtooth, ELM) clearly related temporally to appearance of tearing modes**
  - **Historically: The types of NTMs Z.Y. Chang published for TFTR**
- **“Spontaneous Tearing Modes”**
  - **Little to no other MHD occuring at time of TM appearance**
  - **Typically near ideal MHD Beta limit implying large Δ’**
  - **Seen on all machines**
  - **2/1 modes almost always have near-marginal Δ’ (3/2, 4/3, 5/3 tend to be more triggered)**
- **“Mixed-type Tearing Modes”**
  - **Other MHD activity present, but temporal correlation difficult**
  - **Also typically near ideal MHD beta limit**

D.P. Brennan, S.E. Kruger, T.A. Gianakon, D.D. Schnack
Nuclear Fusion, **45** (2005) B1178

NTMs can be hard to simulate

- **Consider what it takes to simulate self-consistent triggered tearing mode (e.g., sawtooth triggering 4/3)**
  - **No rotation, anisotropic heat flux (Braginskii form), Π_e**
  - **Anisotropic heat flux gives threshold island width**
- **Lutjens:**
  1. **Need $\delta_R < w_D$ => high S (Scaling: FKR, Bondeson, Fitzpatrick)**
  2. **High S => smaller generated island width (Scaling: Hegna)**
  3. **Smaller generated island width => Need smaller w_D**
  4. **Go to #1**

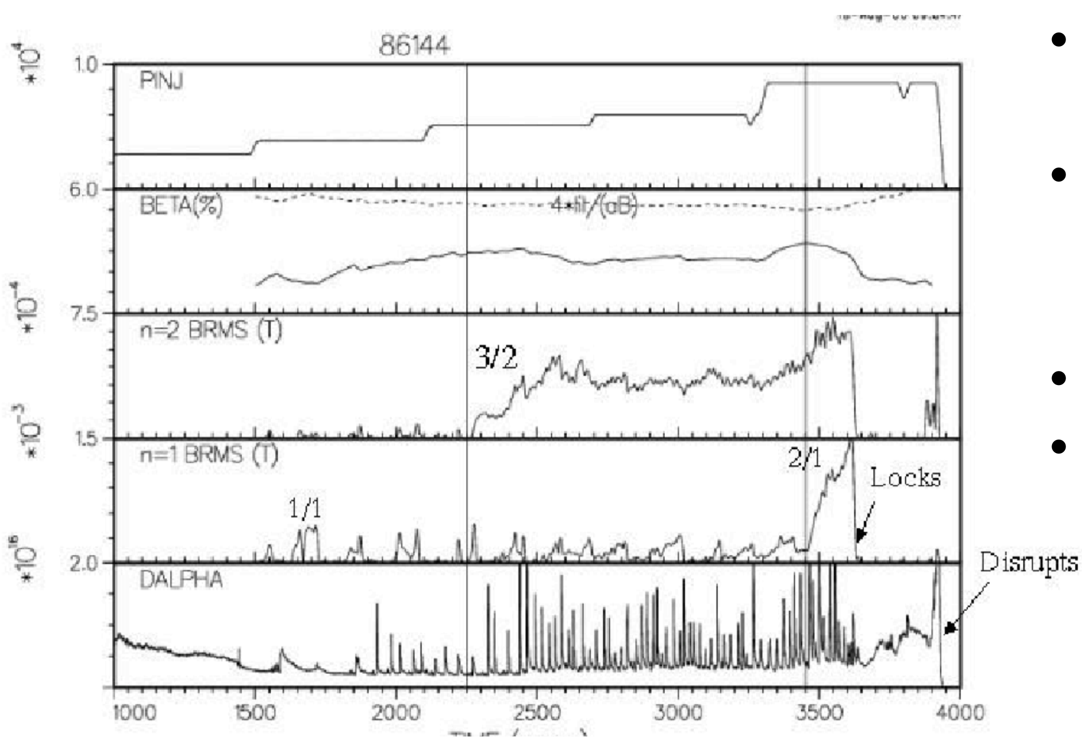
- **To date, no one has done a self-consistent triggered tearing mode**
  - **(Artificial trigger size, non-realistic equilibria, etc.)**
  - **Advanced closures will likely help**

Understanding experimental uncertainties important

- Δ’ drive: $\tilde{B} \bullet \nabla \frac{J_{\parallel 0}}{B_0}$

$$\sim m\tilde{\psi}\frac{\partial^3}{\partial r^3}\psi_0$$

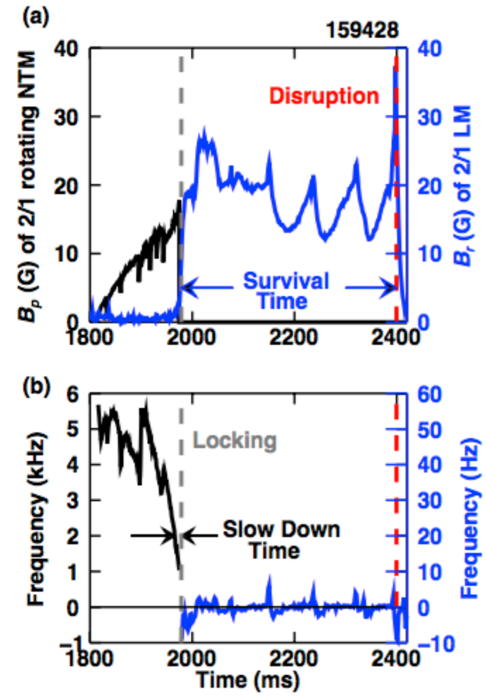
- Stiff problem: Small errors lead to large changes
- Practical matter: good equilibria are hard to find
- Theory is still ignoring a lot (e.g., energetic particles) so experimental comparison can be uncertain

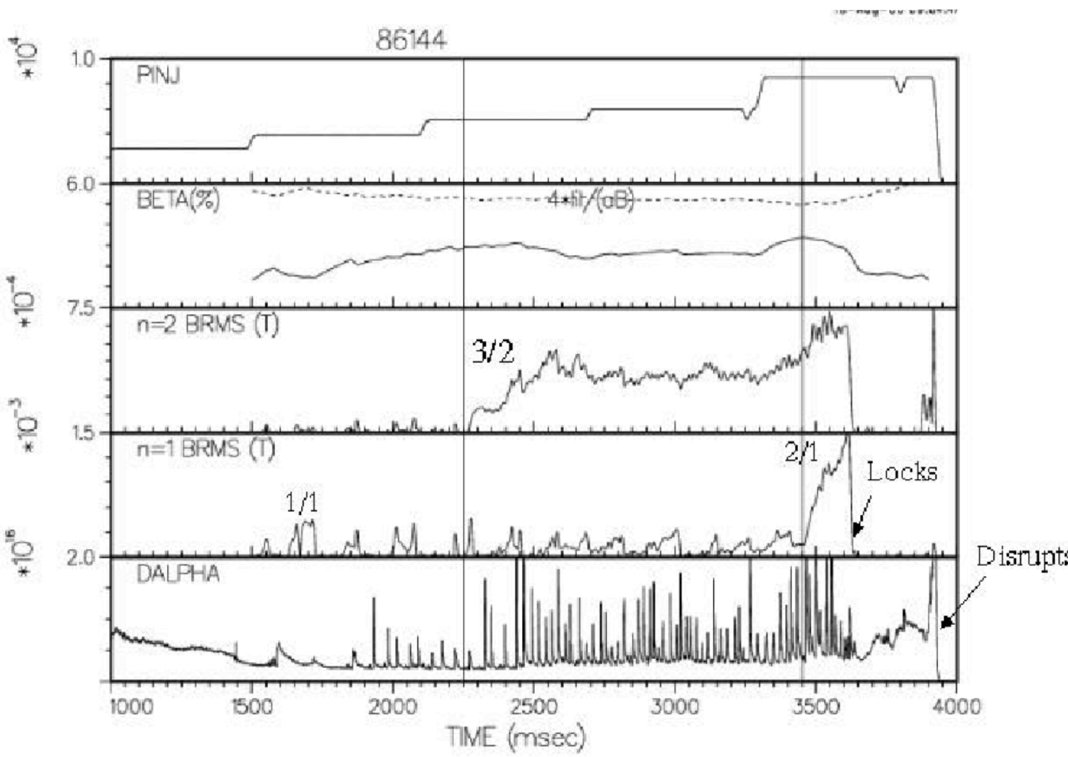


- *Other things to make you miserable:*
- Realistic NTM => realistic time scales (100s of msec)
- Computationally expensive *and* need to worry about transport time scale interactions
- Rotation is really critical
- No quick evaluation with linear codes like ideal MHD (Resistive DCON?)

So what to do?

- Birth
  - As a practical matter, we will *always* study this, but cheating can be useful
  - Explain shear flow trend? (see next slide)
- Life
  - Models for Π_e, q_e critical: Basic science validation (island saturation)
- Locking
  - Π_i, q_i (NTV)
  - RWM, field errors
  - Impact: How easy is it to lock an isla
- Death/Disruption
  - Why do locked modes lead to disruption?
  - Likely interaction with transport





From the proposal

Project objective: Develop increased understanding and improved predictive capability for locked mode disruptions and how best to avoid them.

- Model NTM growth and saturation using the DKE closures to compute the temperature equilibration about an island and the perturbation to the bootstrap current.
- Understand the locking of NTMs from NTV and Maxwell torques from field errors and the drag on the resistive wall and the scaling of these torques to burning plasma conditions.
- Investigate hypotheses on how locked modes grow and cause disruptions.

Basic validation

NTM slowing down

Locked modes

From the proposal: Timeline

Year 1	Identify suitable for NTM/locked mode disruptions on DIII-D for modeling
	Implement Ramos-form of DKE closures into NIMROD and M3D-C1.
	Investigate Maxwell torques induced by error fields in the presence of tearing modes
Year 2	Benchmark M3D-C1 and NIMROD with DKE closure about fixed magnetic island geometry
	Work with Δ'>0 cases to produce a saturated TM as an initial state for DKE NTM calculations
	Use Δ'>0 case to study growth of non-rotating magnetic island in presence of a resistive wall
	Investigate resistive-wall torques induced by error fields in the presence of tearing modes
Year 3	Model NTM evolution using DKE closures inc. temp equilib. and perturbation to BS current
	Study side-band induced stochasticity and edge effects in island in presence of resistive wall
	Investigate NTV torques with DKE closures on the mode from field errors
Ys 4-5	Understand the locking of NTMs from NTV, field errors and the drag on the resistive wall
	Investigate hypotheses on how locked modes grow and cause disruptions

Extra Slides

Code development tasks

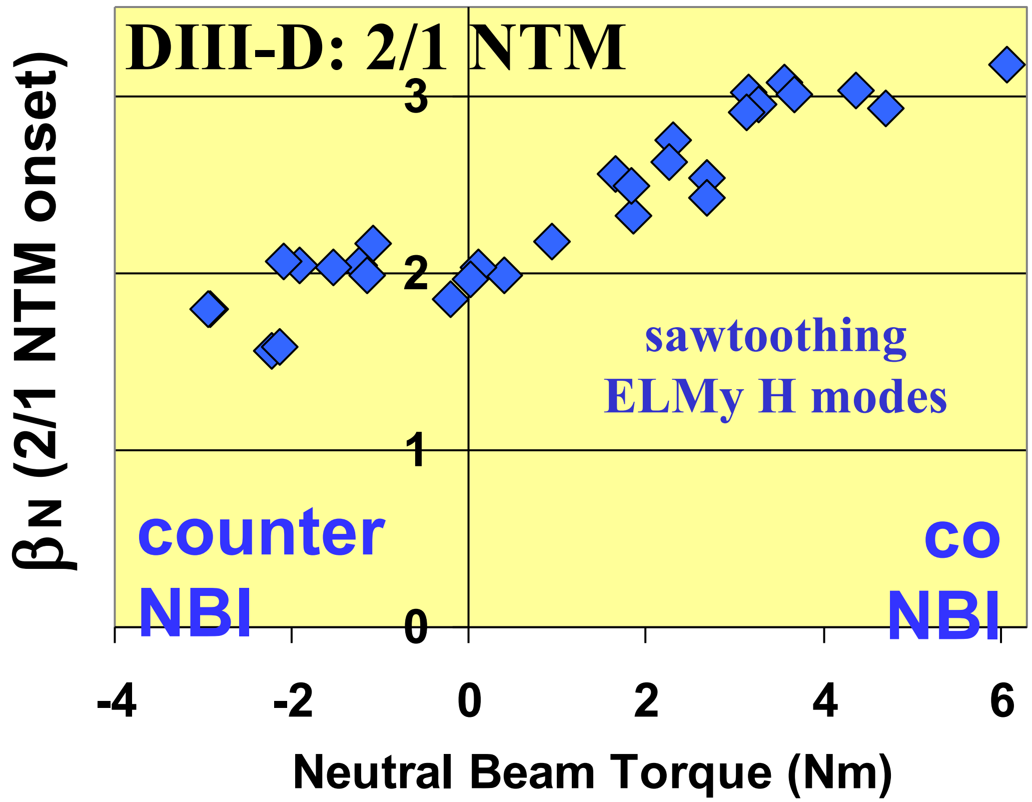
- $\mathbf{\Pi_e}$
  - Braginskii, Heuristic (including NTV?), DKE
  - Important for all stages
- $\mathbf{q_e}$
  - Braginskii, DKE
  - DKE makes things easier
  - Important for all stages
- $\mathbf{q_i}$, $\mathbf{\Pi_i}$
  - Braginskii (with heat flux corrections?), DKE
  - Necessary for locking
- Hot particles may be important in cases
- Getting mode rotation right requires two-fluid
- Validation
  - What cases? s

Headline: NTM β limits may fall as ITER-like parameters approached

- **NTM thresholds are found to fall as co- injected torque falls, on a rang[e]**

  ... a concern for low rotation devices such as ITER

  ... exacerbated by an underlying decrease in NTM stability with ρ^*



Buttery, 2008