# Tearing Under Stress — The Collusion of 3D Fields and Resistivity at Low Rotation


by

**R.J. Buttery[1]**

with

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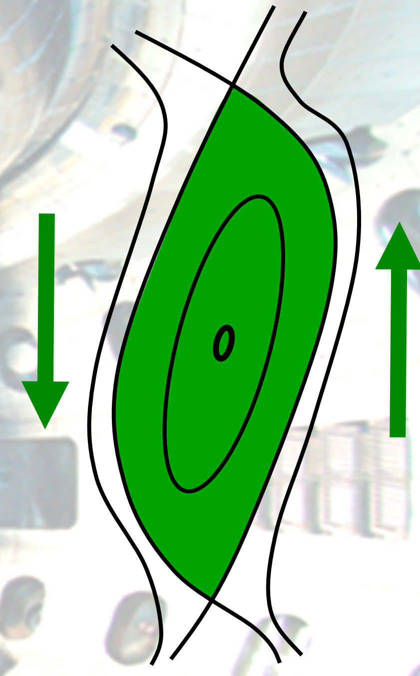
[5]EPFL, Switzerland
[6]UCSD, USA



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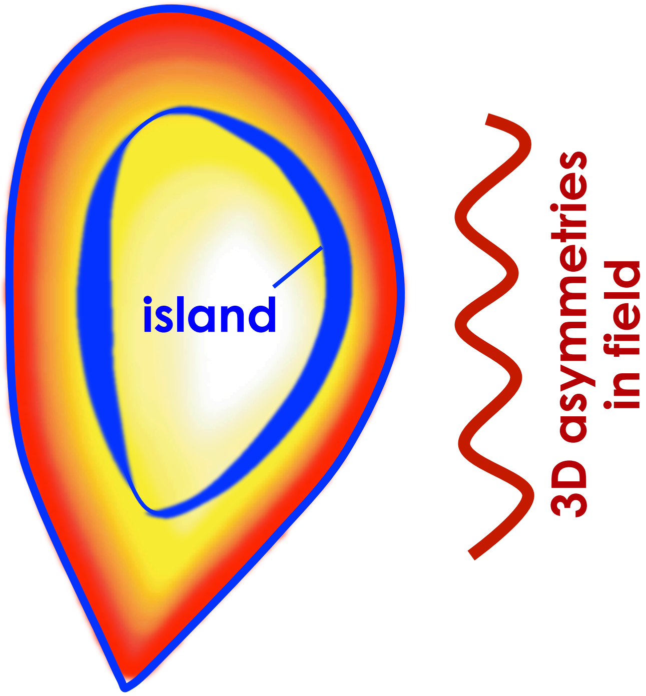

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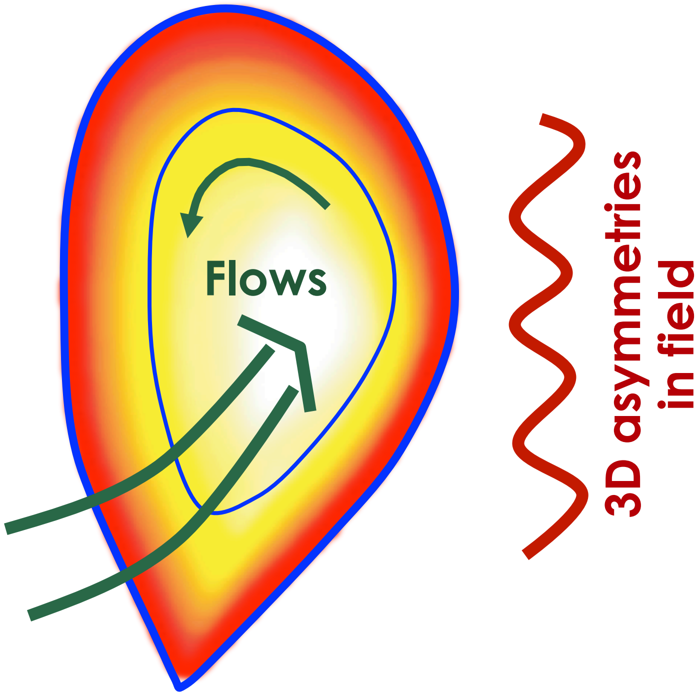

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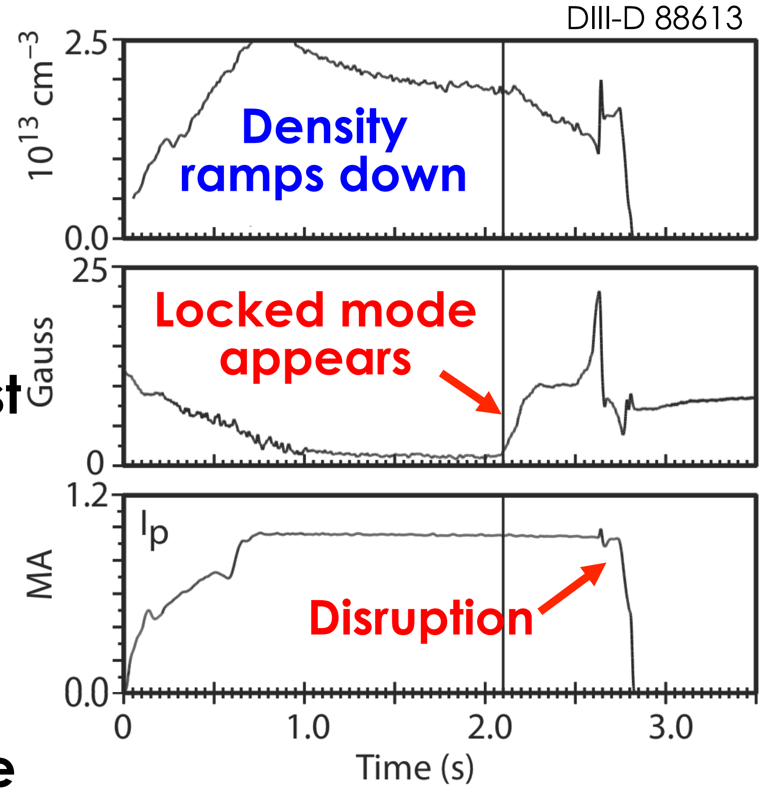
– Fields resonate with rational surface to drive formation of magnetic island

  - **Fields must brake plasma rotation first to stop natural screening currents**
    – Lower density plasmas more readily stopped

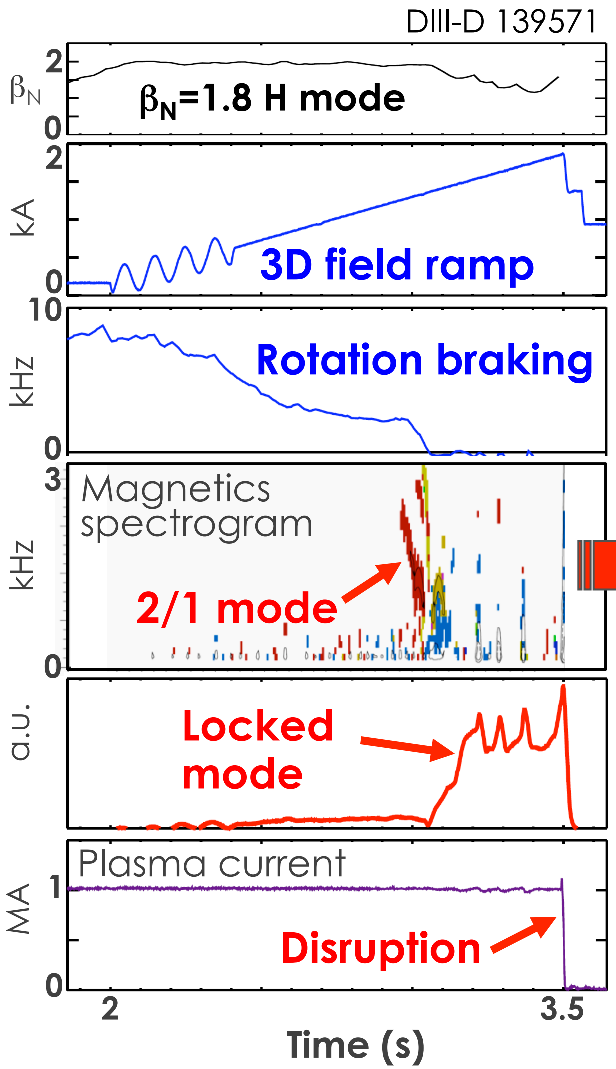
- Basis for error field correction system in ITER
  - 
  – **H mode plasmas expected to be fine**

– High density

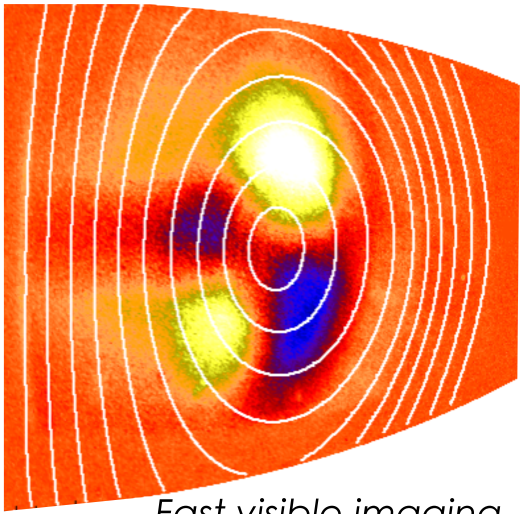



[Scoville, PoP 1992]

# 3D Fields in H Mode Found to Trigger Rotating Modes




- **Less 3D field needed to induce modes than that required in Ohmic plasmas**



*Fast visible imaging (1.8 kHz Fourier decomposed)*

- *How does a static 3D field cause a rotating mode to appear?*
  - *Changes to natural mode stability*
- *Why is H mode so sensitive?*
  - *Answer lies in the plasma response*

***Need to understand how fields interact & what governs mode formation***

[Buttery & Liu, NF 2011]

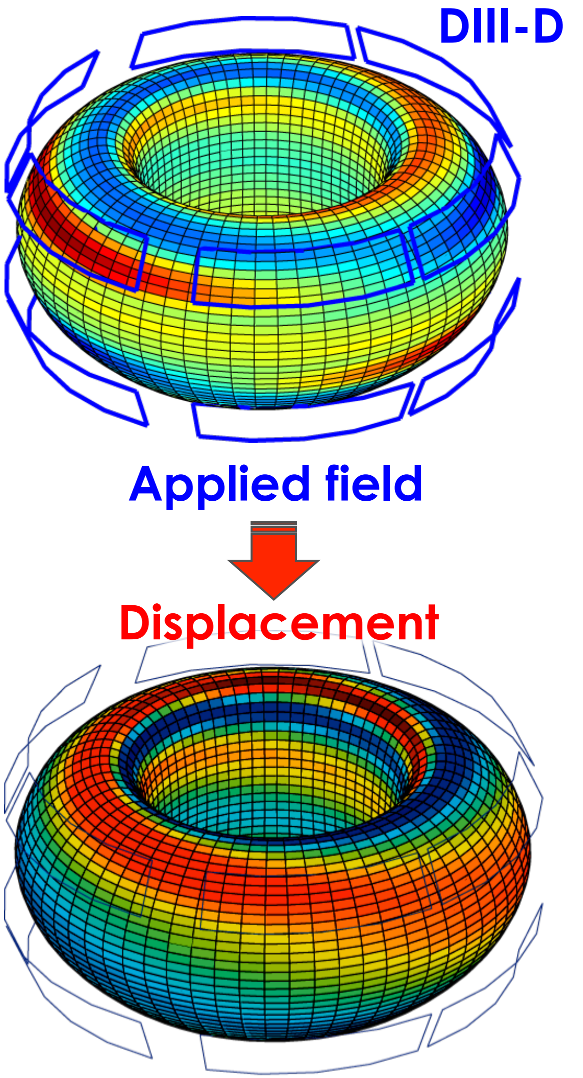
# Contents

- **The plasma response to 3D fields**
  - –Ideal and Resistive MHD
- **Interaction of 3D field with tearing stability**
  - –Braking action of 3D fields is key
- **Reducing the 3D "error" fields in ITER**
  - –Need for more than one mode of correction
- **Conclusion**
  - –3D fields a key concern for H modes

# The Plasma Response to 3D Fields

# The Starting Point to Understand 3D Field Interactions is Through Ideal MHD

- **Plasma displacement transforms internal field**
  - Plasma is an electromagnetically interconnected structure
    - Resists some displacements, accepts others
    - Preferred distortion – least stable ideal mode




[Lanctot & Chu]

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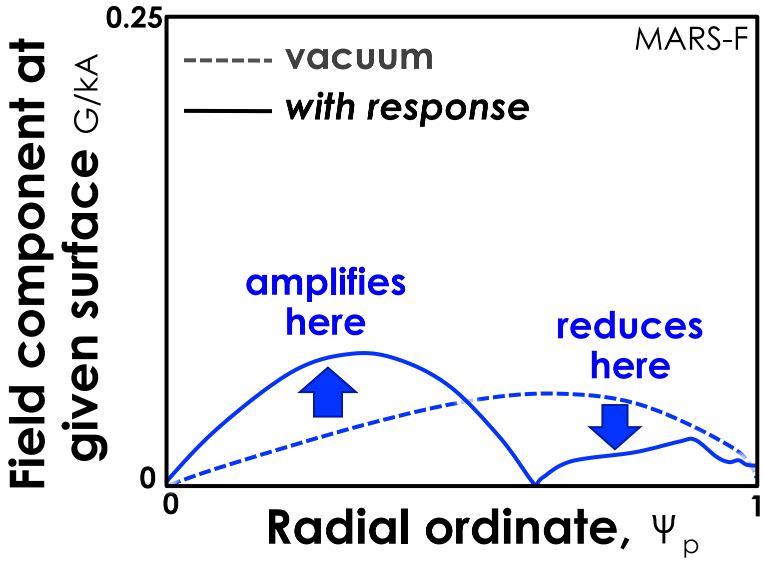
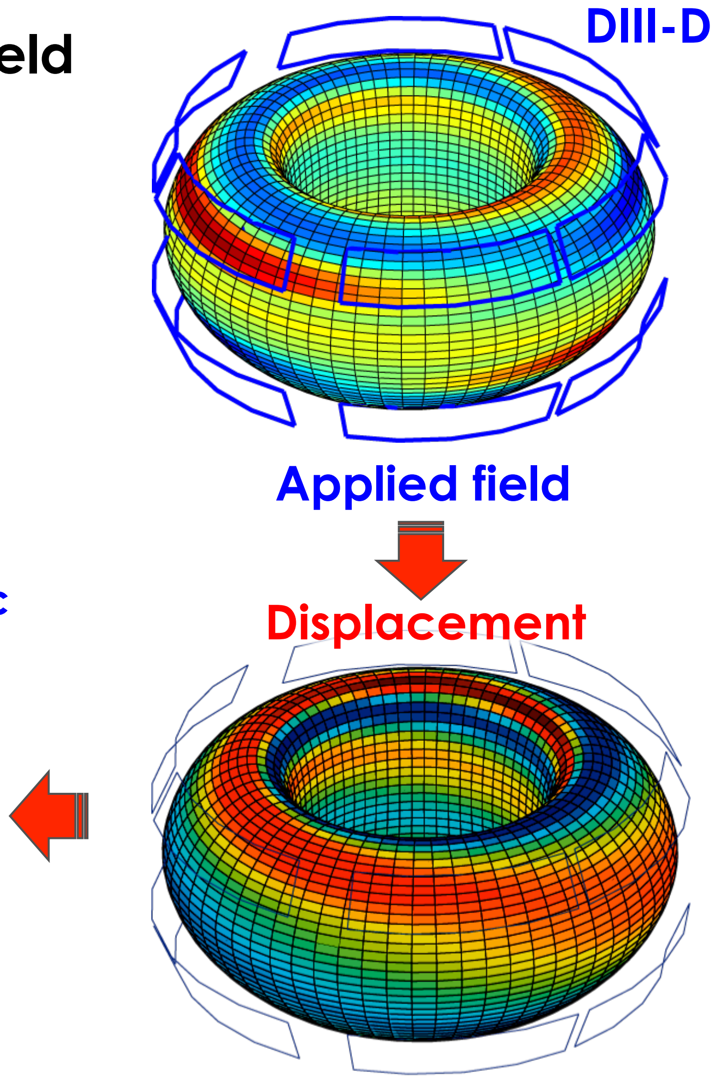



m=2 harmonic

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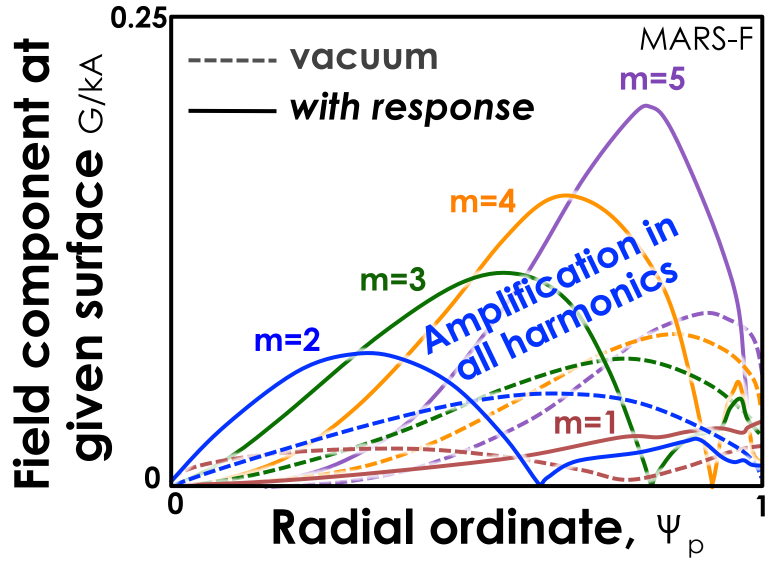


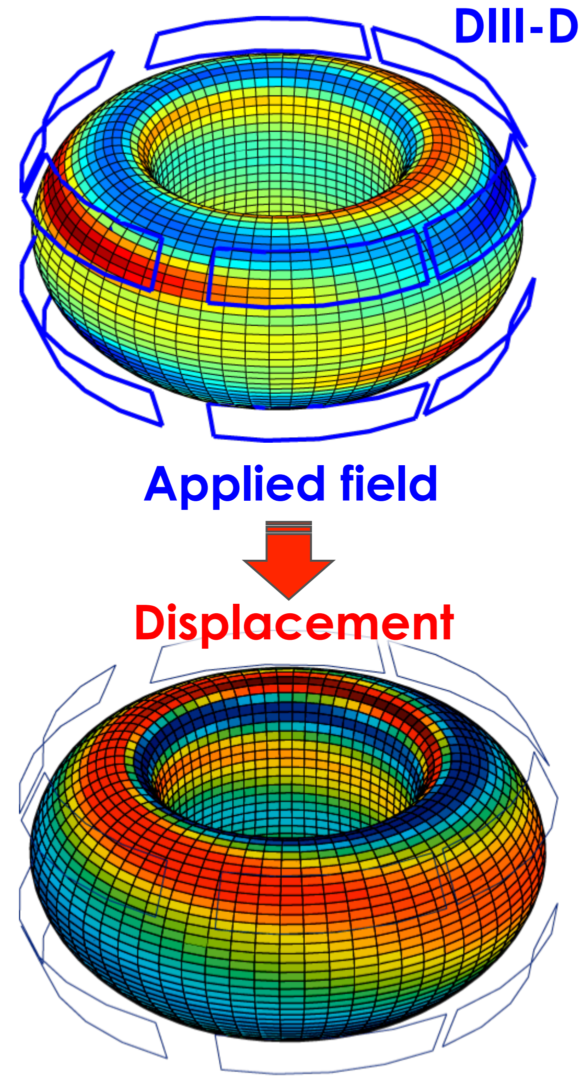

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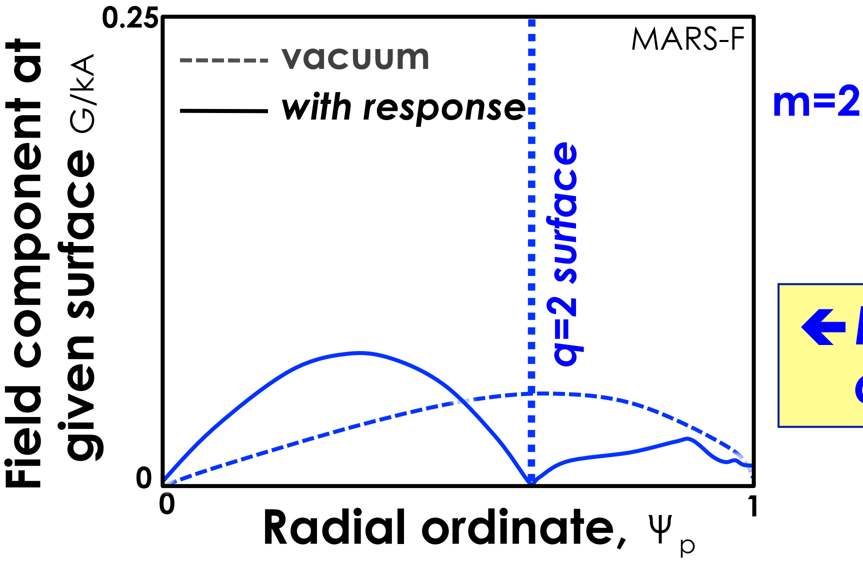


***← Note the field goes to zero at the resonant q surface…***

[Buttery & Liu, NF 2011]

# The Starting Point to Understand 3D Field Interactions is Through Ideal MHD

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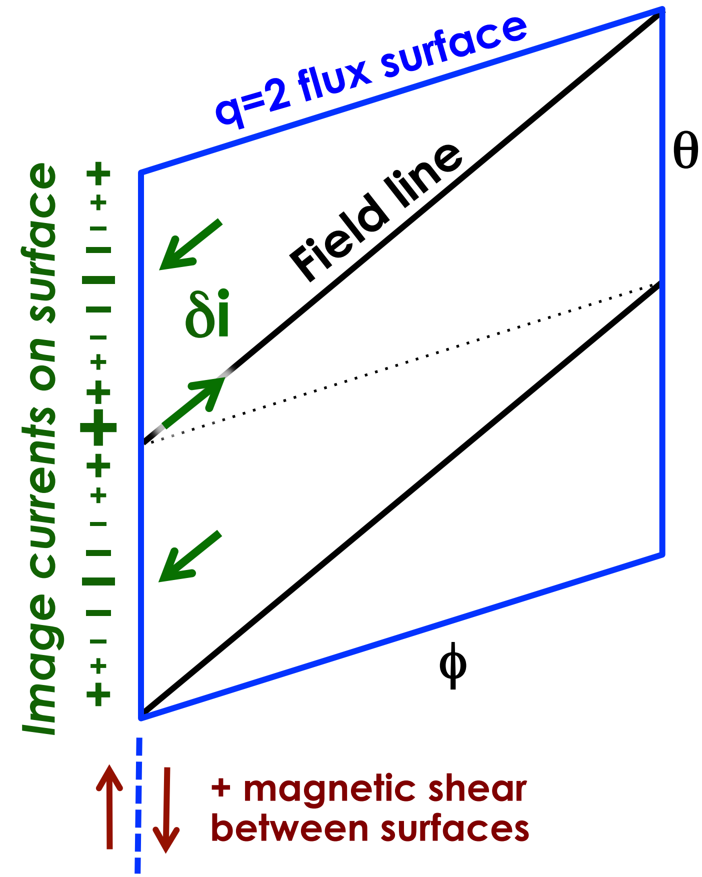
  - Flux conservation: **image currents** driven to prevent tearing of flux surface



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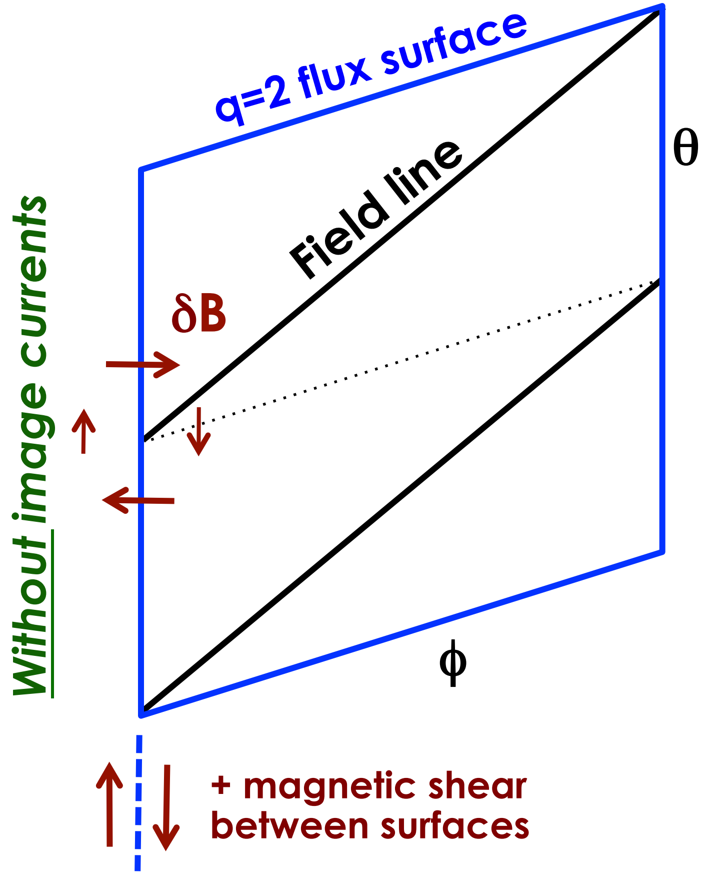

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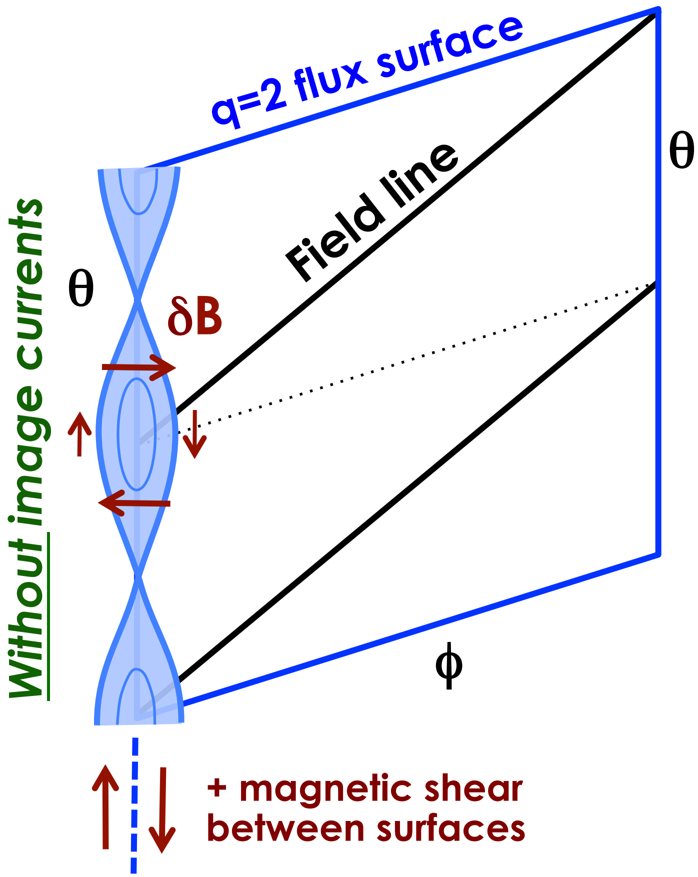

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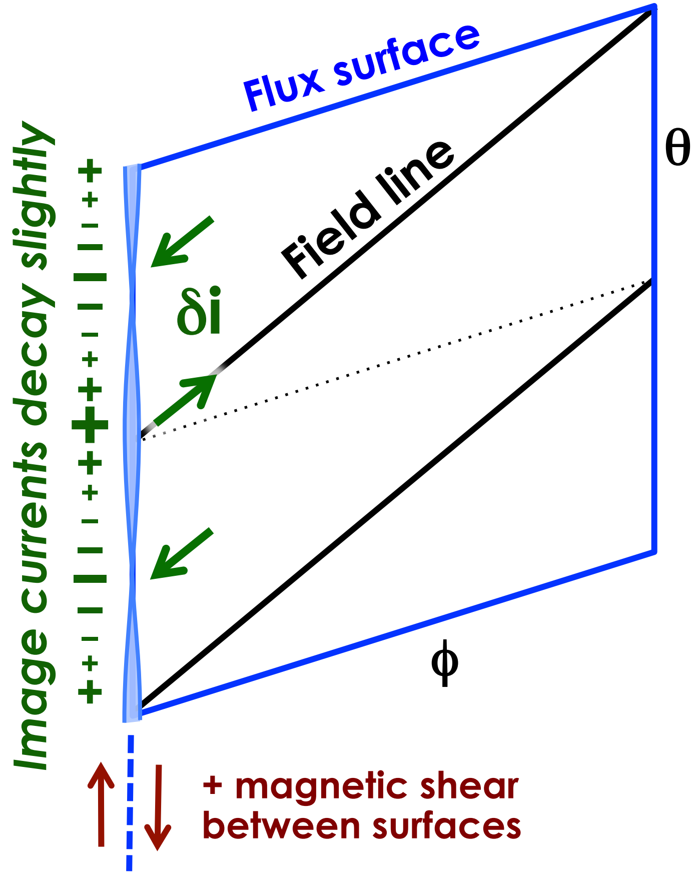
  - Enables formation of small islands ➔



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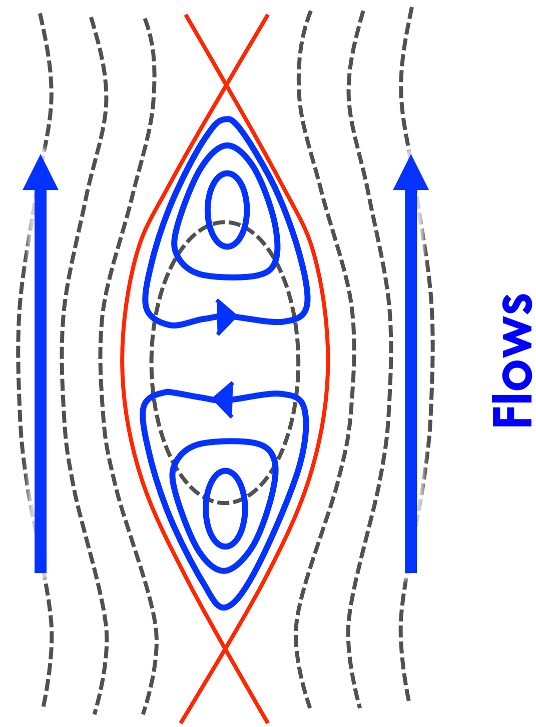


[Fitzpatrick Phys Fluids 1991]

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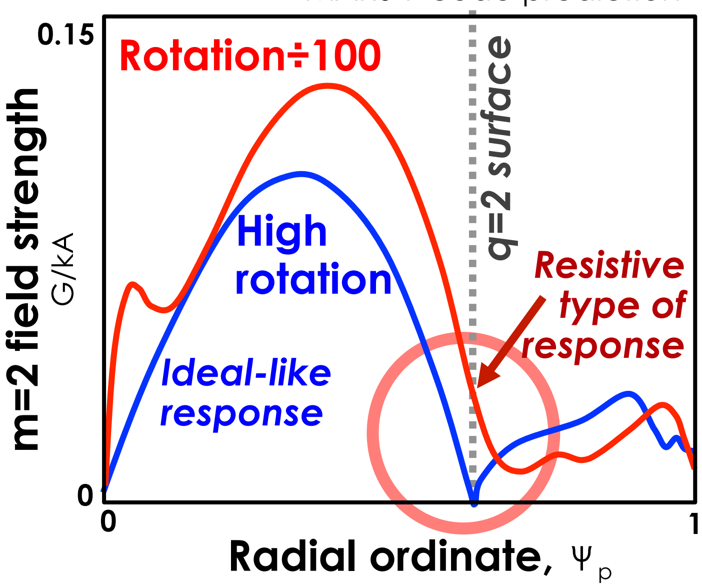
    - Decreasing rotation enables resistive response

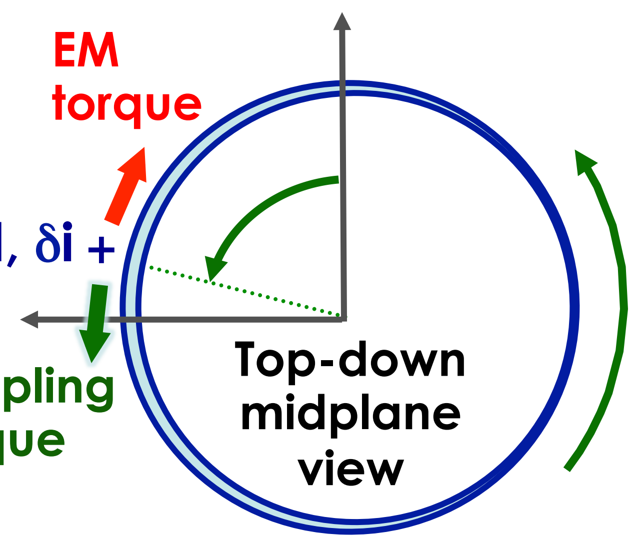
MARS-F code prediction




***Decreasing rotation leads to fall in image currents & more resistive response***

# Resistivity & Rotation Cause a Torque Balance to be Established with the 3D Field

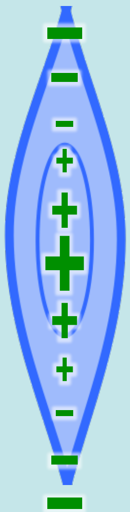
- *Island dragged round by rotating plasma*
- *Island less phase aligned → less driven by 3D field*




- **Torque balance: viscous coupling vs electromagnetic forces**
  - Low field/high rotation: island out of phase, suppressed → plasma slips past
  - High field/low rotation: island aligns to 3D field → grows → stops rotation
- **Resistive response depends on island phase, & so torque balance**
  - Process is highly nonlinear → can bifurcate to a locked state

[Fitzpatrick Phys Fluids 1991]

# Recap — The Plasma Response to 3D Fields



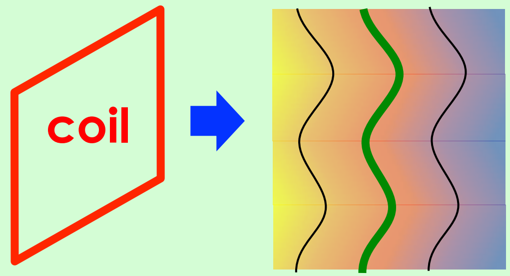
## Degree of Tearing

*depends on*

*amount image currents decay*

**Torque on plasma & modes**

## "Drive" to Tear – amount of imaging current




*Measure by the component of B at edge that induces these currents*

3D field + ideal MHD ➔ imaging currents

## Inclination to Tear

How much plasma tears for given field resonant B

Resistivity + Δ'

## Resilience to Tearing

- Flows inside island renew image currents
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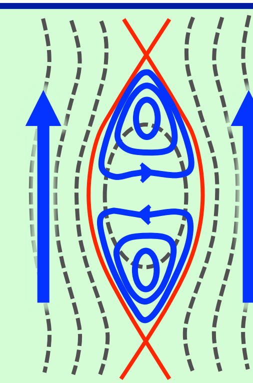
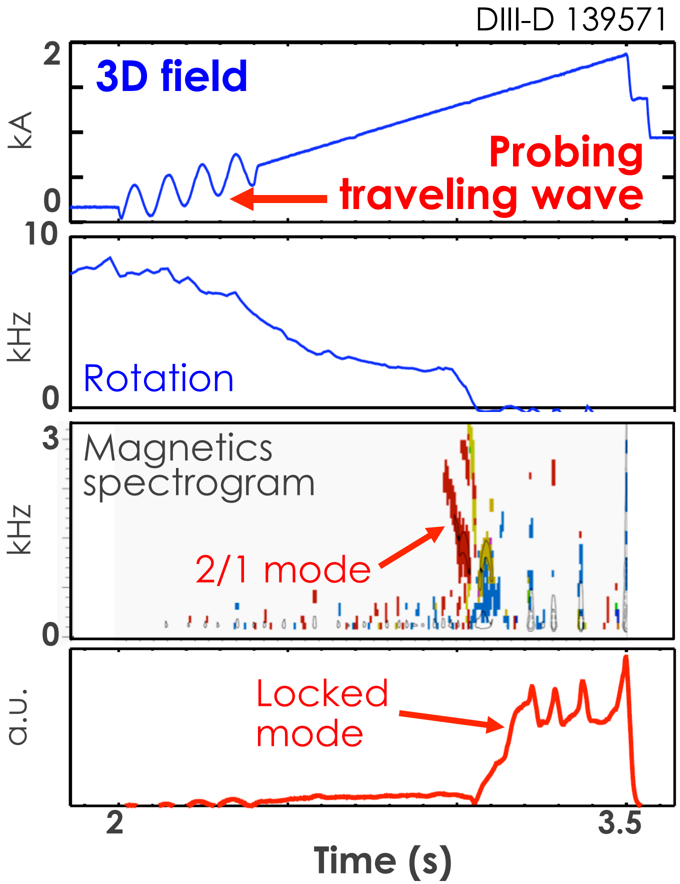


[Park IAEA 2010]

# Measurements of Plasma Magnetic Response Show Ideal and Resistive Components

## Measure response to 3D probing field

– ***Repeat at different beam torques and β's***



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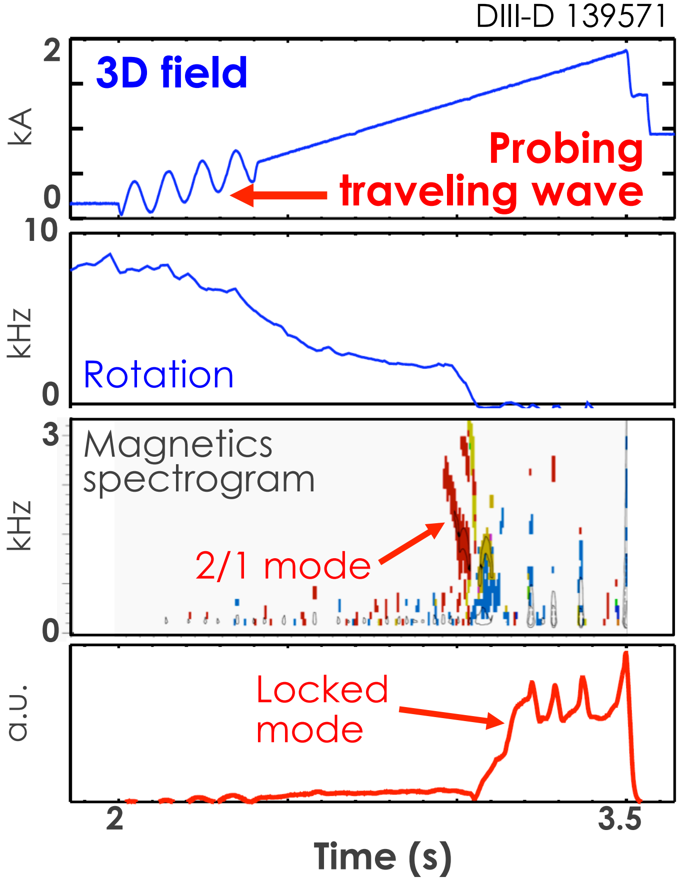
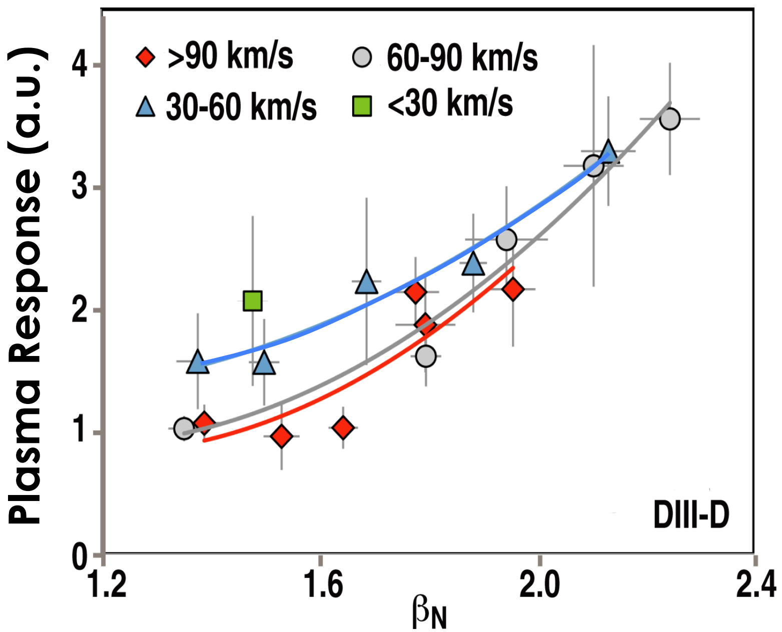







*Magnetic response from plasma only*

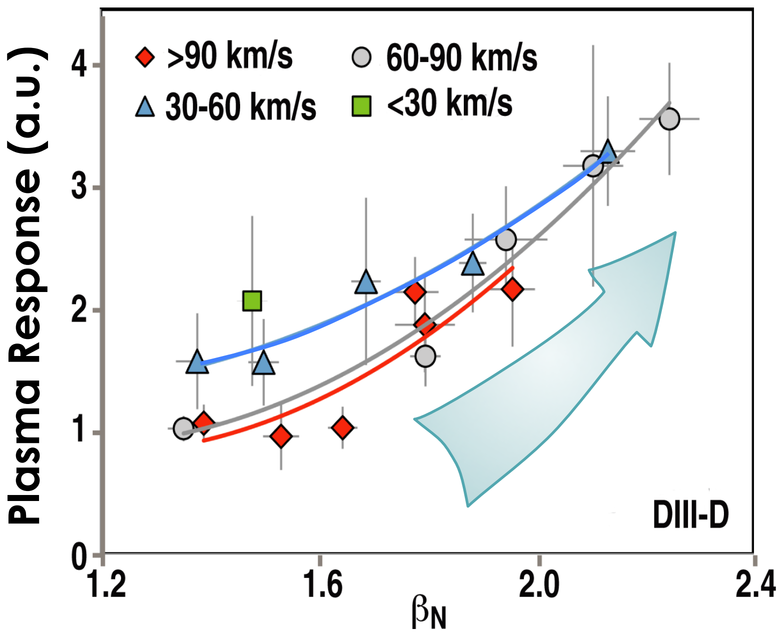
*(excludes applied field)*

# Measurements of Plasma Magnetic Response Show Ideal and Resistive Components

## Measure response to 3D probing field

- *Repeat at different beam torques and $\beta$'s*
- **Clear $\beta_N$ dependence:**
  - ***Characteristic of ideal response***
  - ***Kink mode more readily driven at high $\beta_N$***

*Response to 10 Hz probing field*




[Buttery & Liu, NF 2011]

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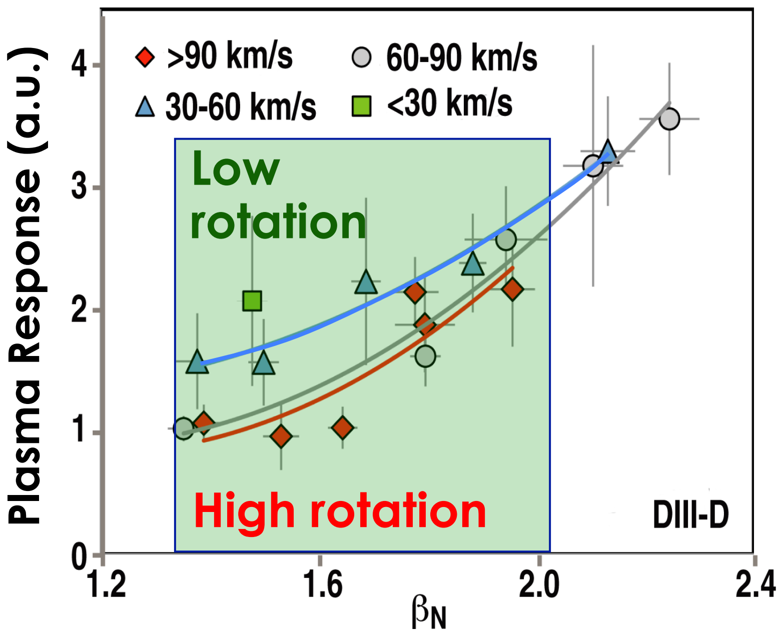
- **Rotation dependence indicative of resistive response**
  - ***An ideal response would maintain shielding, irrespective of rotation***

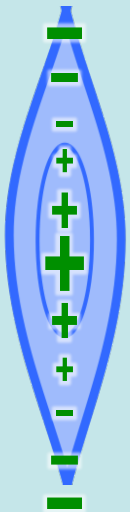
    ➔ ***Developing response indicates breakdown of screening***

*Response to 10 Hz probing field*




- **Resistive response may be an important element of how 3D fields couple to plasma at low torque**

# Need to Focus Further on Resistive Response…



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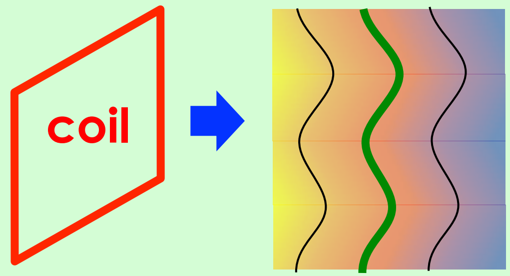


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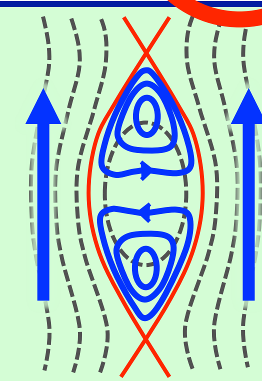


# Need to Focus Further on Resistive Response…

**Inclination to Tear**

How much plasma tears for given field resonant B

Resistivity + Δ'

- **Plasma tearing stability**
  - *Governs response of plasma to applied 3D field*
    - Size of island for given field
  - *Sets threshold for natural tearing mode instability*

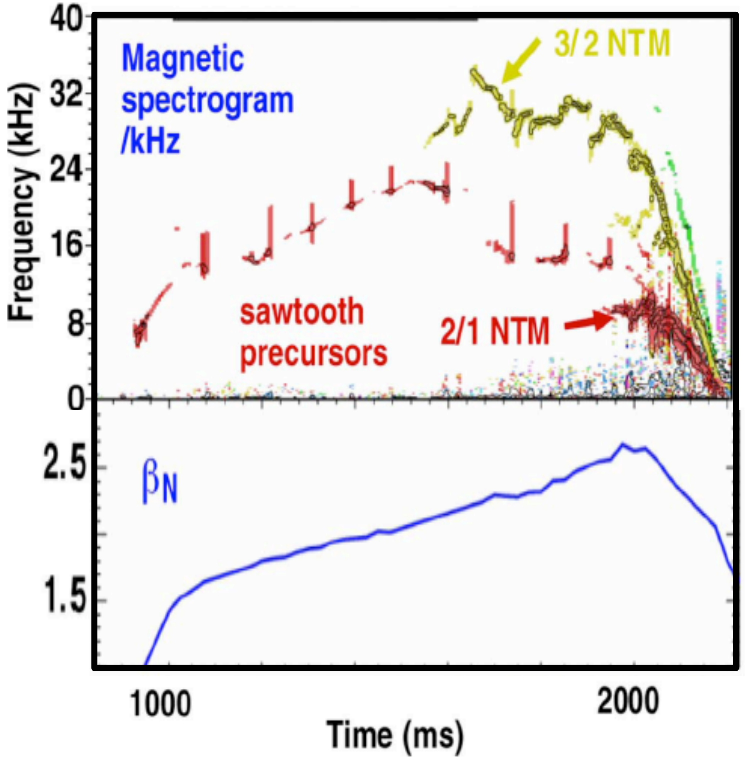
# Interaction of 3D Field with Tearing Stability

- Rotation dependence
- Braking action of fields

➔ 3D field limits in H mode

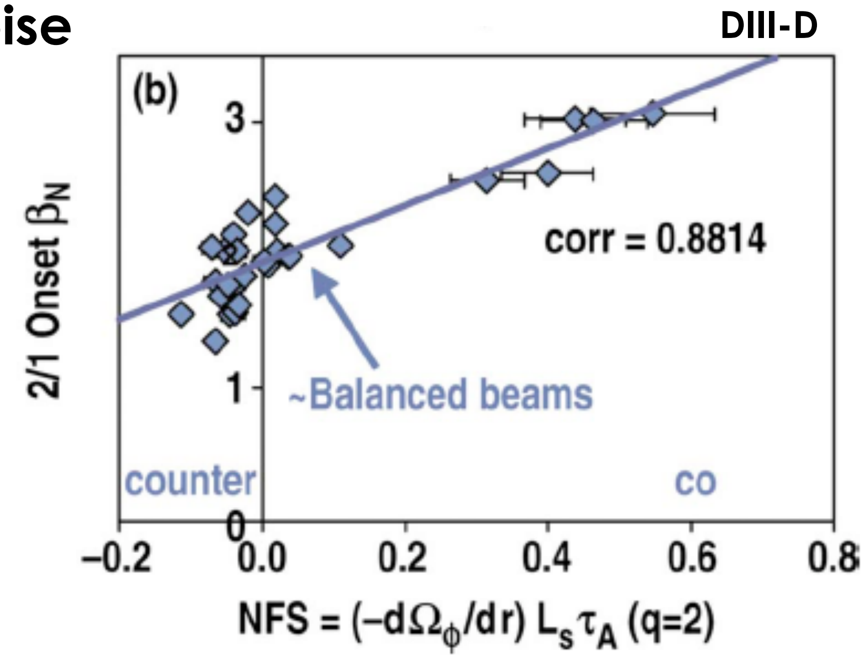
# H Mode Plasmas are Close to Natural Tearing Instability

- **Tearing modes can come out the noise**
  - If β too high or current profile unstable



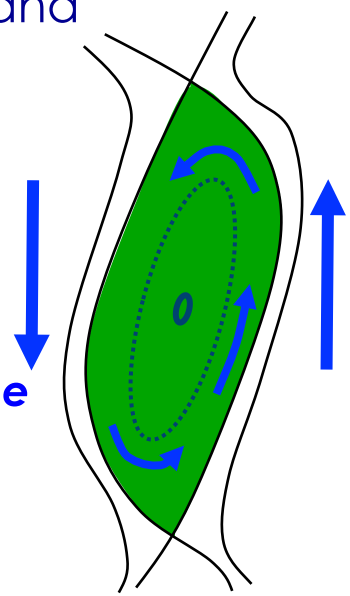
# H Mode Plasmas are Close to Natural Tearing Instability,
## *…which depends on plasma rotation*

- **Tearing modes can come out the noise**
  - If β too high or current profile unstable
  - **Or if rotation too low… ➔**
- **Rotation thought to act through flow shear**
  - Changes field structure and so field line bending and compression energy




***Flow shear***
*normalized to Alfven speed & magnetic shear scale length*

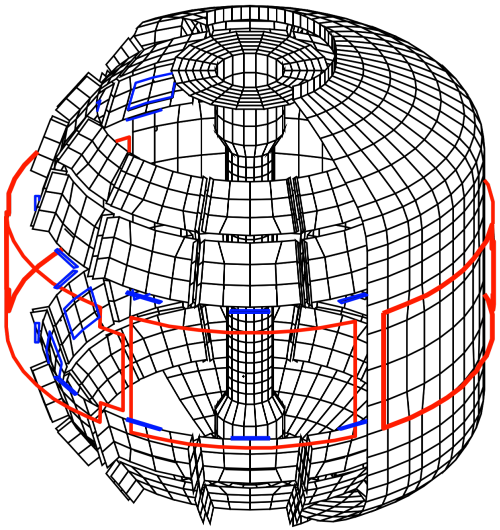
*Flow shear:*
***Viscous forces couple into island to change its structure***



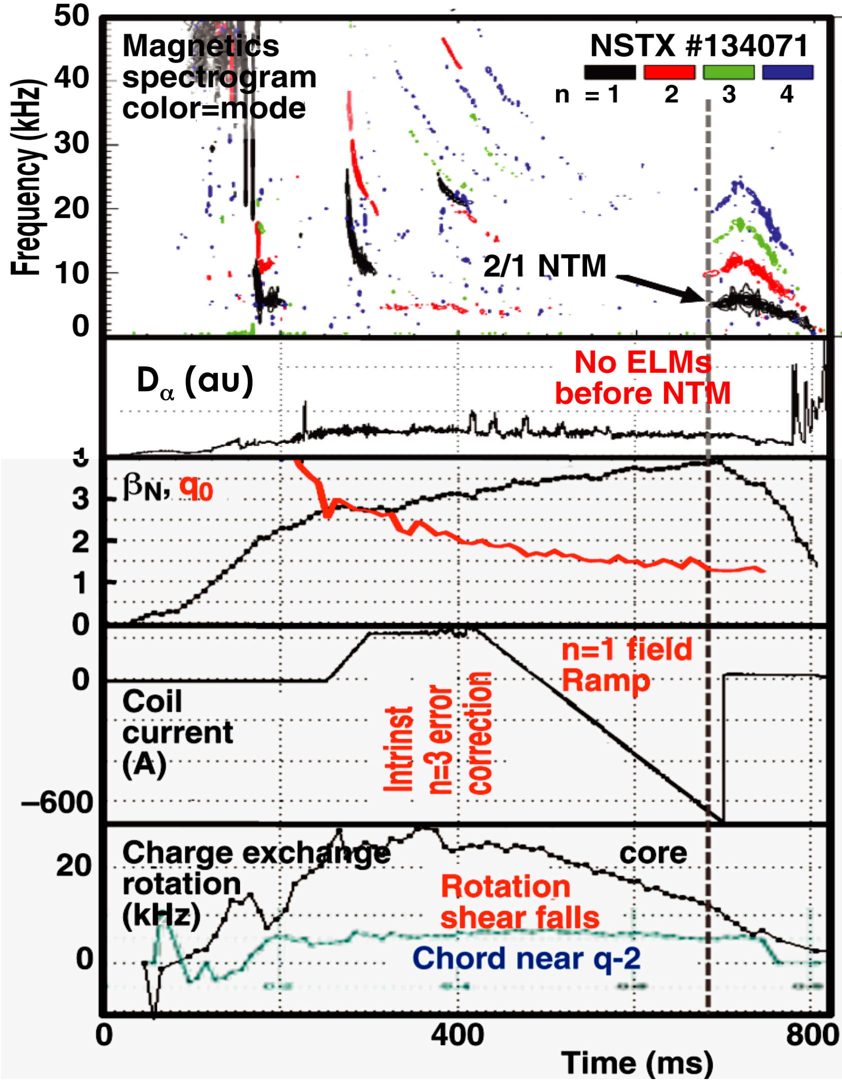

**What is action of 3D Fields?**

# 3D Fields Brake Plasma to Trigger Rotating or Stationary Modes

- **3D field ramps trigger modes in NSTX**

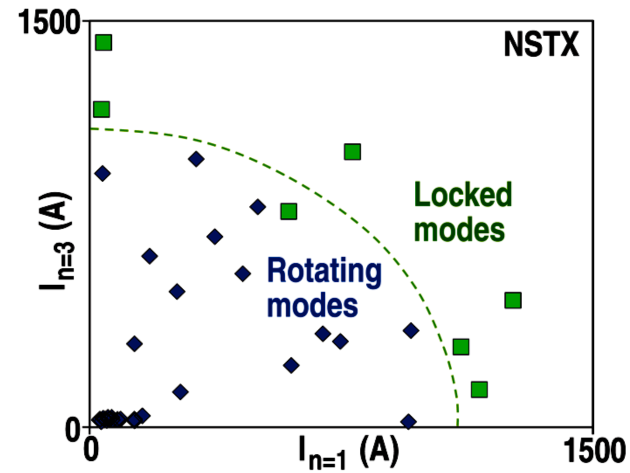


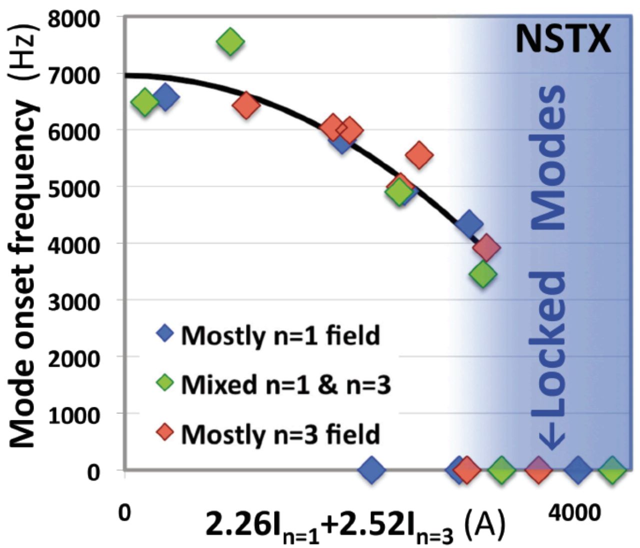
*Midplane field coils on NSTX*



# 3D Fields Brake Plasma to Trigger Rotating or Stationary Modes

- **3D field ramps trigger modes in NSTX**
- **With enough braking, mode born locked**
  - Lower levels of braking → rotating modes
    - Action through inherent stability changes
- **Resonant (n=1) and non-resonant (n=3) fields act similarly on braking & modes**
  - Braking action through NTV?
  - Resonant part of interaction may be weak in these high rotation plasmas



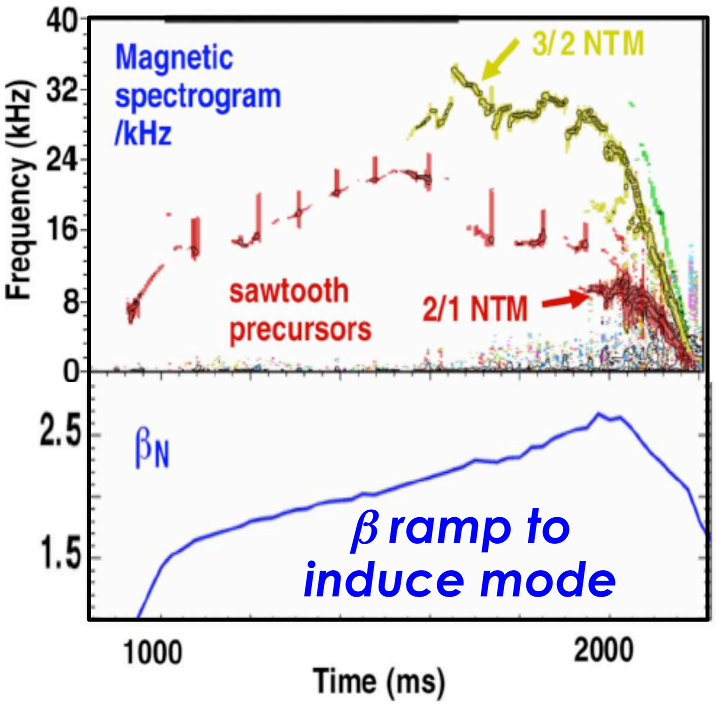

*Combined n=1 + n=3 field*

- **Mode onset is not due to resonant interaction of the 3D field**
  - Mode not directly driven by field
  - **It is an inherent stability change through braking of rotation**

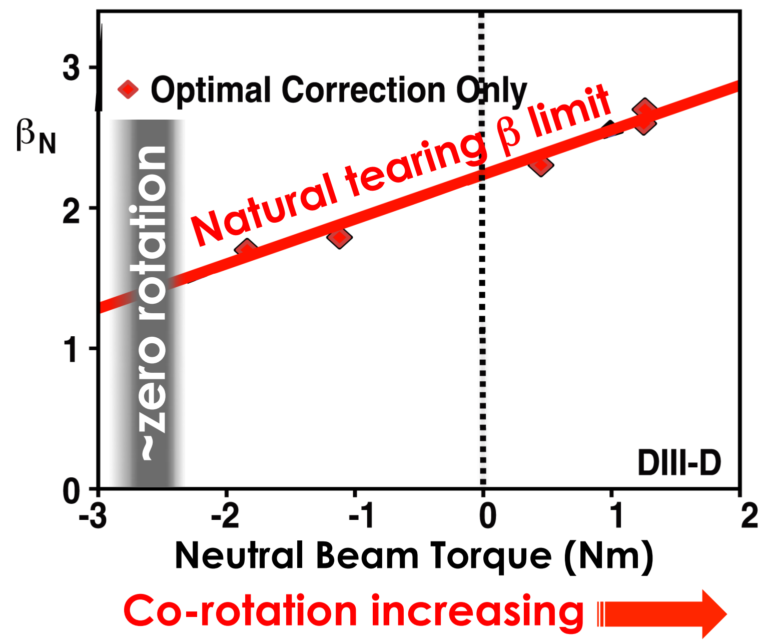
National Spherical Torus Experiment

# At Low Torque 3D Fields Pose Greater Concern

- Consider cases close to tearing instability at low torque in DIII-D




– **Tearing $\beta_N$ limit falls with rotation**
(no 3D field)



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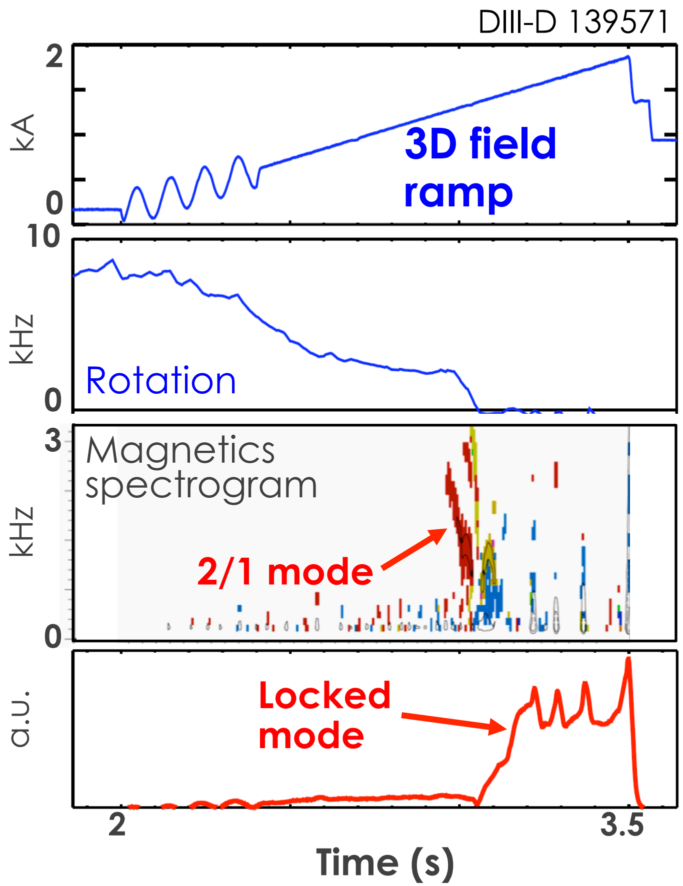
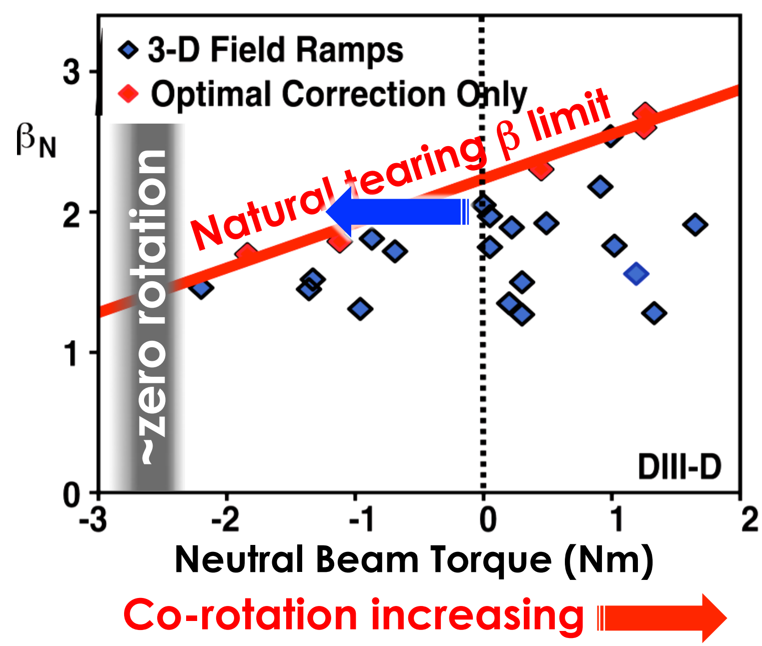
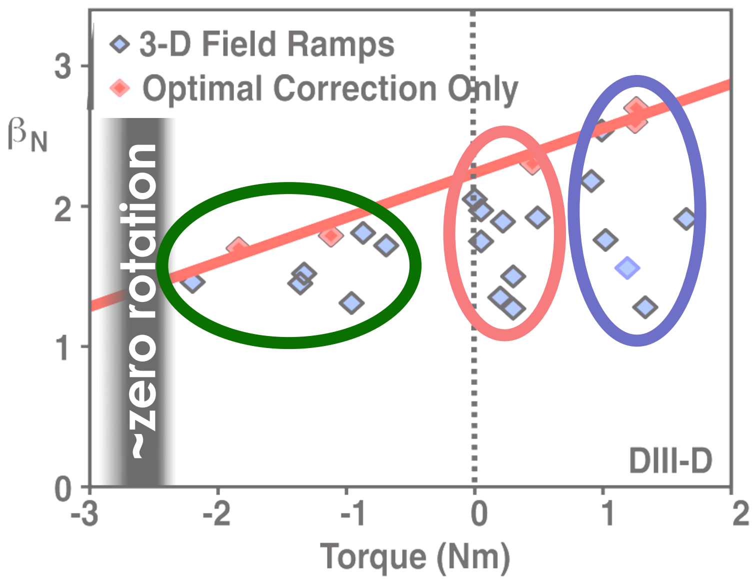


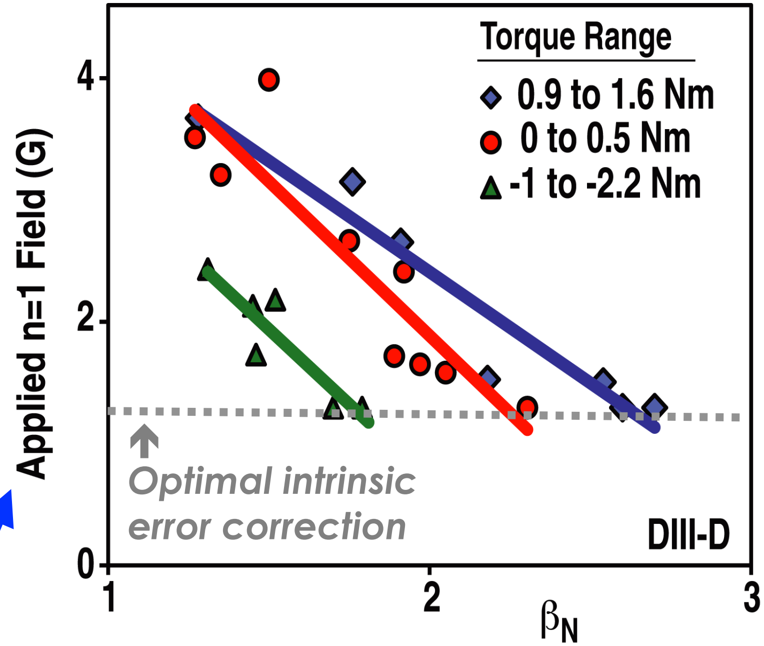

- **Tearing $\beta_N$ limit falls with rotation** (no 3D field)
- **3D field torque brakes plasma, decreasing stability → mode grows & locks**



# A 3D Field Limit is Observed in β and Torque

- **Field thresholds reach optimal intrinsic error correction of 1.3 G as $\beta_N$ rises**
- **Torque dependence observed**



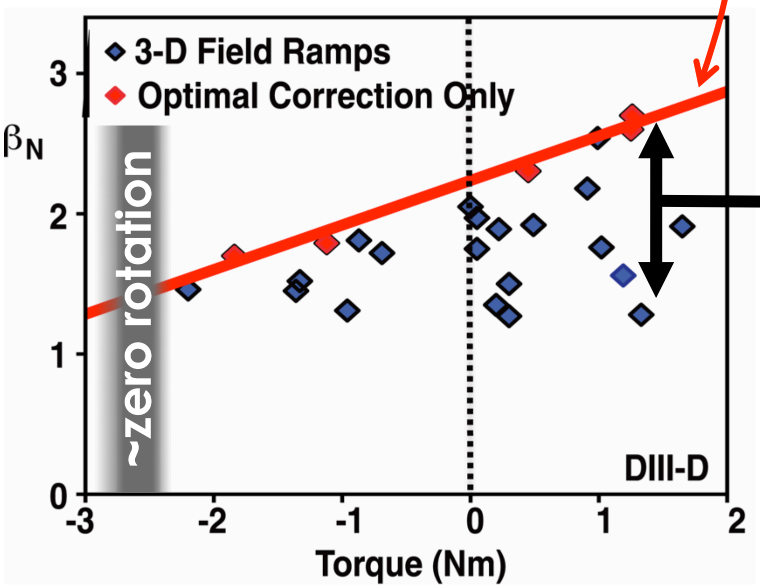




***Component of field at boundary that drives q=2 imaging currents***

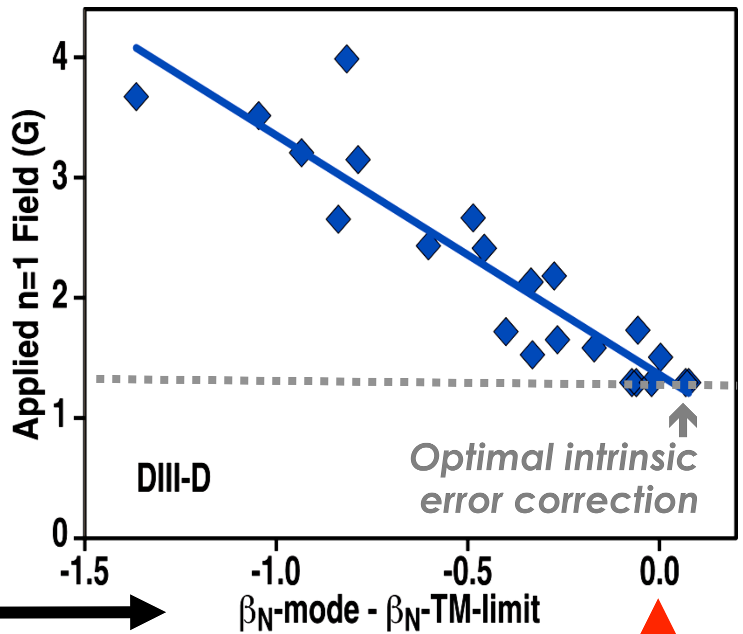
[Buttery & Liu, NF 2011, Park IAEA 2010]

# 3D Field Limit Depends on Proximity to Natural Tearing Limit

- **Field thresholds reach optimal intrinsic error correction of 1.3 G as $\beta_N$ rises**
- **Torque dependence observed**
  - *Explained by proximity to natural tearing β limit*
    - $\beta_{N\text{-TM-limit}} = 2.2 + 0.32\ T_{NBI}$




gap




$\beta_{N\text{-TM-limit}}$=2.2 at zero torque

# ITER Prediction

- **ITER heating systems inject much less torque per MW**
  - Approximate this to zero for a worst case scenario
- **For torque-free plasmas can treat rotation as a “hidden” parameter**
  - Plays an important role…
  - But self generated – a part of the scaling
- **Measure field thresholds to trigger modes in torque free H modes**
  - Extrapolate in $\rho^*$ and $\nu$ by measuring toroidal field and density scaling

***Required precision*** ➡ $$\frac{\delta B}{B_T}$$

# ITER Prediction: 3D Field Limits in H Mode are Even More Stringent than in Ohmic Regimes

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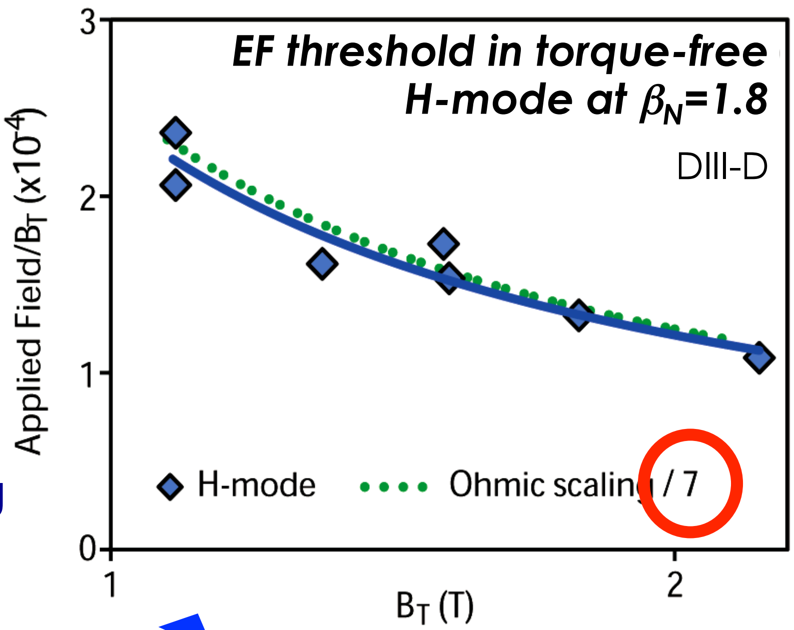



  - Extrapolate in $\rho^*$ and $\nu$ by measuring **toroidal field** and density scaling:

***Required precision*** ➜

$$\frac{\delta B}{B_T} = (1.3 - [\beta_N - 1.8]) \times \frac{\left(n_e/10^{20} m^{-3}\right)\left(R/6.2m\right)^{0.725}\left(q_{95}/3.1\right)^{0.83*}}{\left(B_T/5.3T\right)^{1.02}} \times 10^{-4}$$

  - **Predicts $\delta B/B < 1.3\times10^{-4}$ to avoid modes in ITER Q=10 baseline**
    - 40% lower than Ohmic regime scaling, even though H mode 5x higher density

*Ohmic $q_{95}$ scaling

# Reducing 3D "Error" Fields in ITER

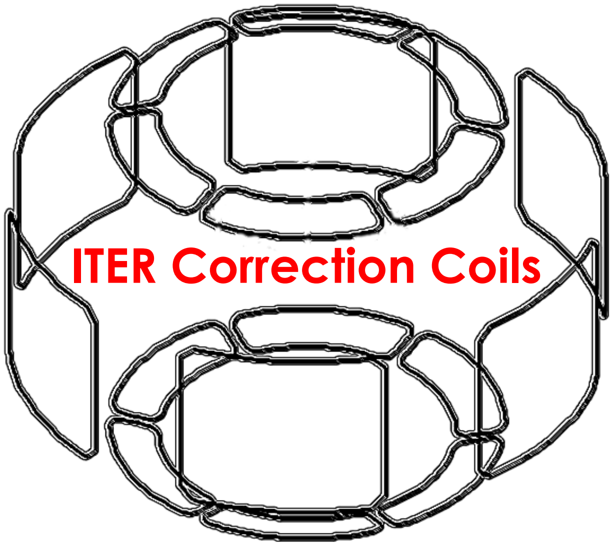
# Updated ITER Error Field Predictions Suggest Significant Error Field Correction Required

- **Monte Carlo analysis of error field sources updated for ideal response formalism** ➡
  - Sum up sources – conservative to allow for lack of magnetic optimization in ITER plans
  - Total possible: **$\delta B/B \sim 2.8 \times 10^{-4}$** cf expected limit of **$1.3 \times 10^{-4}$**

| Source | $\delta B/B/10^{-5}$ |
|---|---|
| TF, CS, PF misalignments | 4.3 |
| TBM | 4.3 |
| Ferromagnetic inserts | 1.5 |
| NBI* | 5.2 |
| TF, CS, PF feeds & joints* | 4.3 |
| Ferromagnetic saturation* | 4.3 |
| Bioshield* | 4.3 |
| Tokamak Complex* | 0.2 |
| **Possible total** | **$2.8 \times 10^{-4}$** |

*scaled vacuum calculation

- **Must remove 55% of error field in ITER baseline, or more for higher β regimes**
  - This task is planned for ITER ➡ error field correction coils



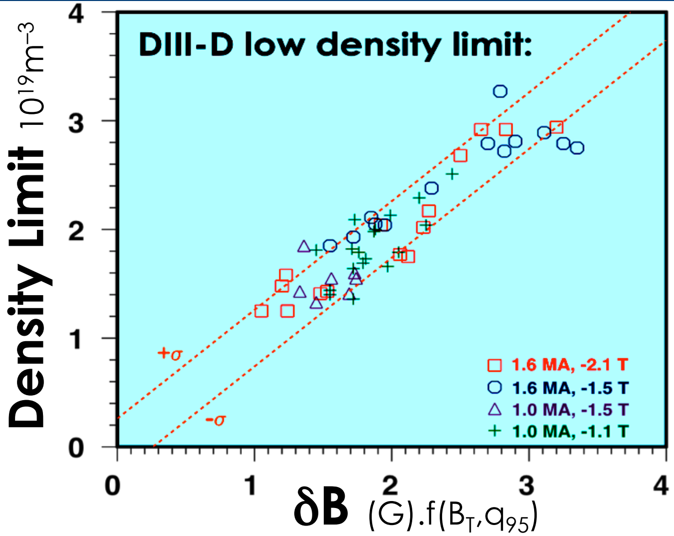

**Can this level of correction be met?**

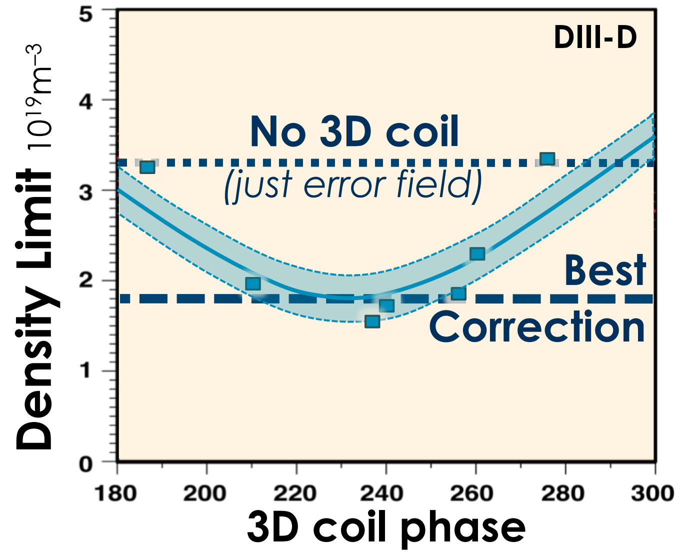
– Assistance needed from internal ELM coils?

# Experience with Error Field Correction Has Shown Limited Benefits

*(see poster for review)*

- **Typically performed in Ohmic plasmas**
- **Benefits measured by density access**
  - Low density limit proportional to error field
  - 3D coil currents optimized to lower limit
- **Single array correction achieves improvements from ~0 to 50%**




[Scoville NF 2003, Buttery NF 2000, Howell APS 2003, Howell NF 2007, Wolfe PoP 2005]

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  - Low density limit proportional to error field
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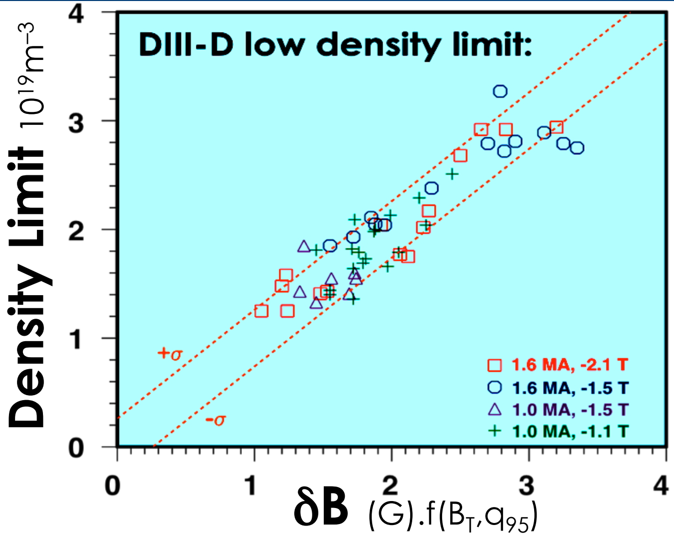
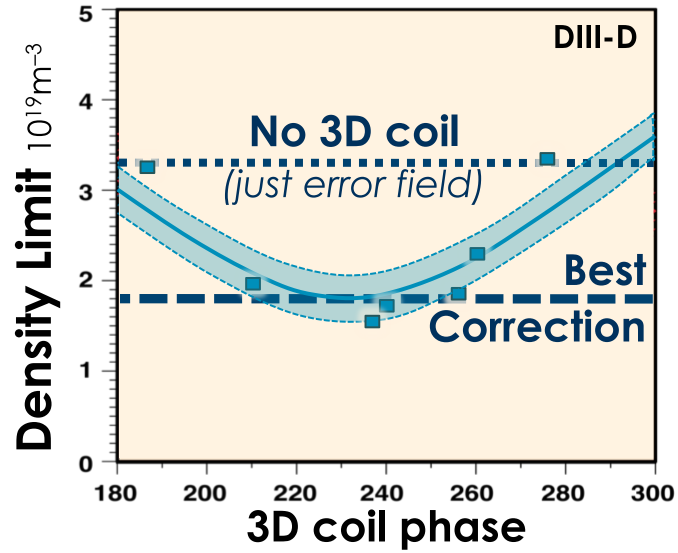
- **Single array correction achieves improvements from ~0 to 50%**
  - Improved with more coils, best ~70%
  - Design of coils matter – some offer little improvement, poloidal pairs do better
    - eg. JET EFCCs seem orthogonal to error field

- **Key questions**
  - ***Do multiple field harmonics play a role?***
  - ***Is plasma response more complex than through a single dominant ideal mode?***
  - ***Is there an inherent stability limit?***

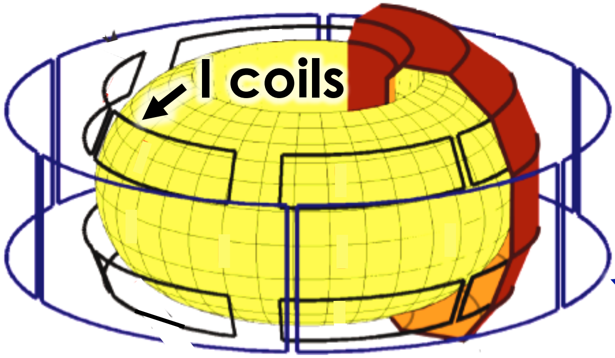


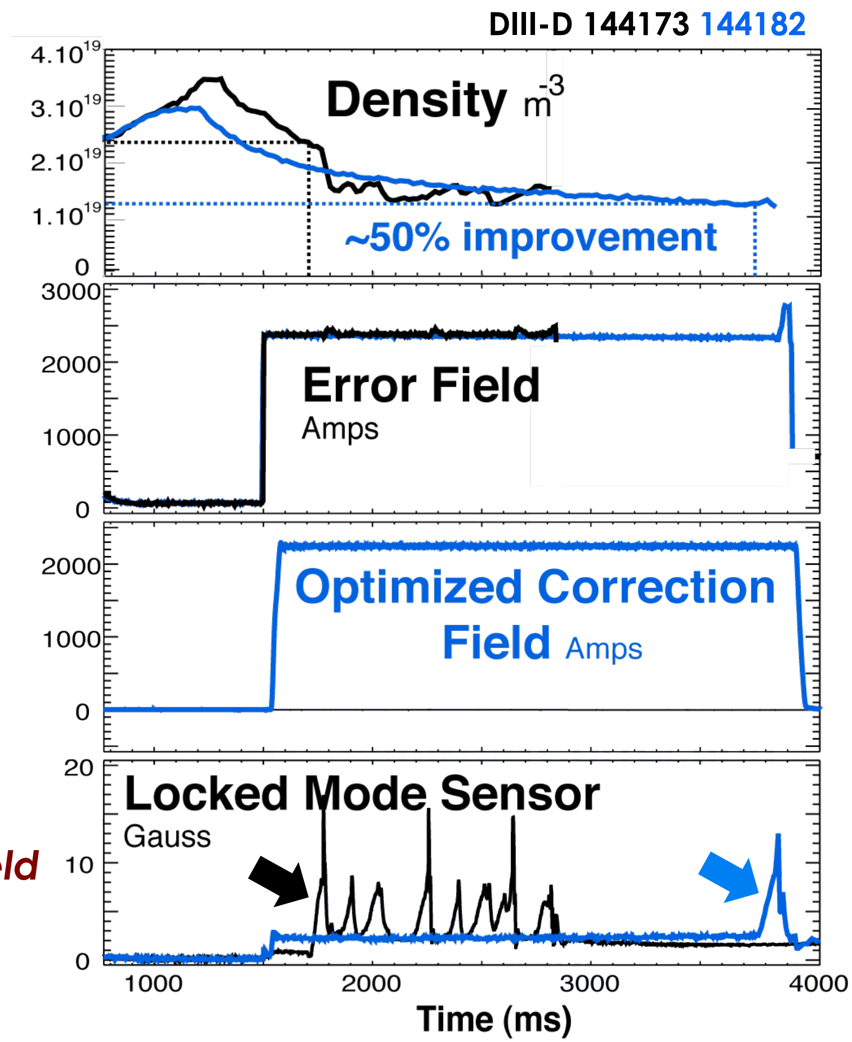

[Scoville NF 2003, Buttery NF 2000, Howell APS 2003, Howell NF 2007, Wolfe PoP 2005]

# Proxy Error Field Study Shows Correction Limits Arise Through Higher Order n=1 Ideal Modes

- **Use DIII-D I coils to correct proxy error field from C coils**
  - Well above usual machine error & density limits
  - Pure n=1 – no n=0,2,3,4
- **Optimal correction yields only 50% improvement in density limit**
  - Confirms correction limits arise from additional components in n=1 field
  - Must couple through more than one ideal MHD mode

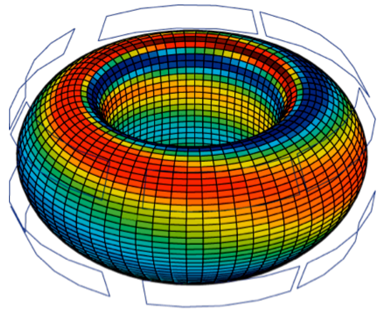



*Coils have very different spectra making large residual field at boundary*

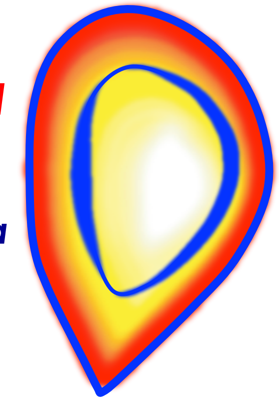


# Interpretation: Error Field Interacts through Multiple Modes and Surfaces, Requiring Multiple Coil Correction

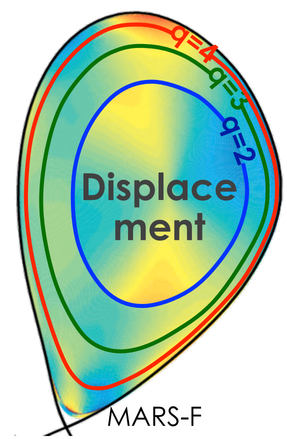
- **With a single ideal mode, perfect correction should be possible**
  - Additional ideal modes enable residual field to pass through to core plasma
- **But if braking is resonant with a single surface, perfect correction is still possible**
  - Braking must be at multiple surfaces
- **Correction must minimize ideal response or minimize internal braking**
  - *Outstanding:* Important to resolve how and where braking manifests in the plasma
- **For ITER 3D field coils must have flexibility to adapt to error field structure and the modes it couples through**
  - Multiple arrays needed (& planned) to push down drives present while not raising others



***Cancel ideal mode drives***
- ***Stops field getting in***



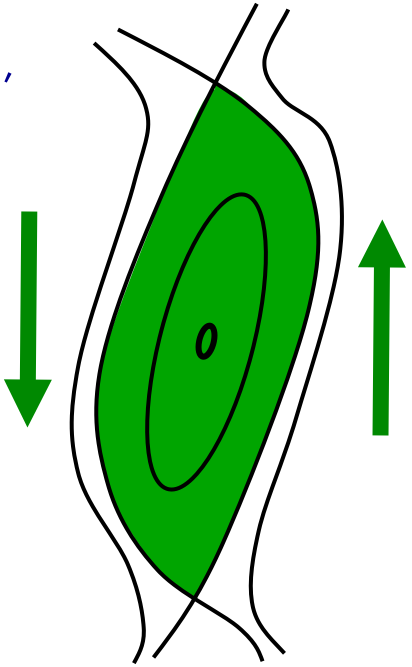
***Cancel internal resonances***
- ***Stop the field braking plasma***




***Cancel field across volume***
- ***Challenging but needed if NTV braking***

# Conclusions

- **3D fields collude with the plasma resistive response at low rotation to cause tearing modes**
  - Flow shear places incipient tearing mode “under stress”, decreasing free energy available to drive the mode
  - 3D fields decrease flow shear to access instability
- **This leads to a limit for tolerable 3D fields in ITER’s baseline low rotation H mode**
  - Scalings obtained, field error predictions updated…
  - Substantial error correction needed
- **Experience with error field correction shows interaction through more than one mode**
  - Multiple coil arrays needed for good correction
    - Planned in ITER; additional internal ELM coils provide important margin



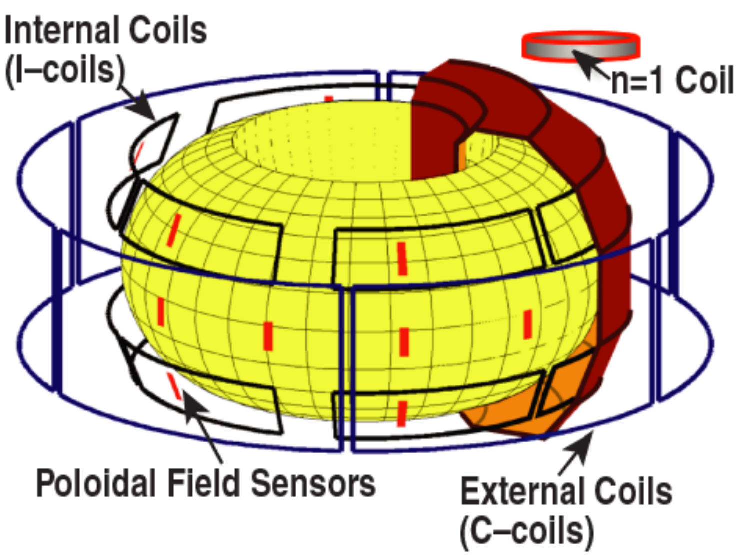

**Understanding the processes of 3D fields and tearing is fascinating physics of crucial importance to resolving development of low rotation regimes**

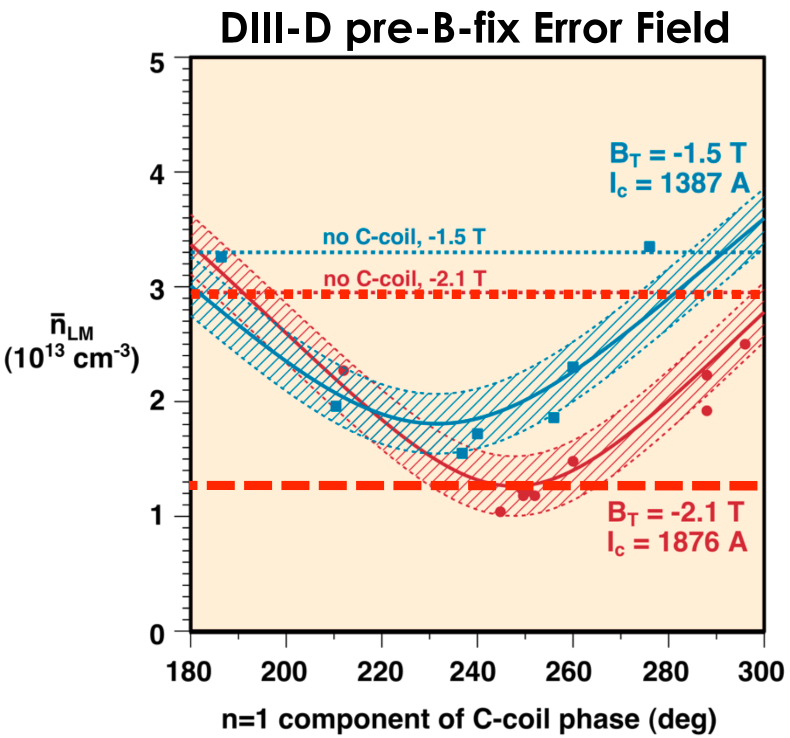
For Poster:

# Survey of Experience with Error Correction across the world

# Experiments Suggest More to Plasma Response Than Coupling Through a Single Ideal Mode

- **DIII-D C-Coils access lower density**
  - But correction imperfect: ~50%




[Scoville, APS 2003]

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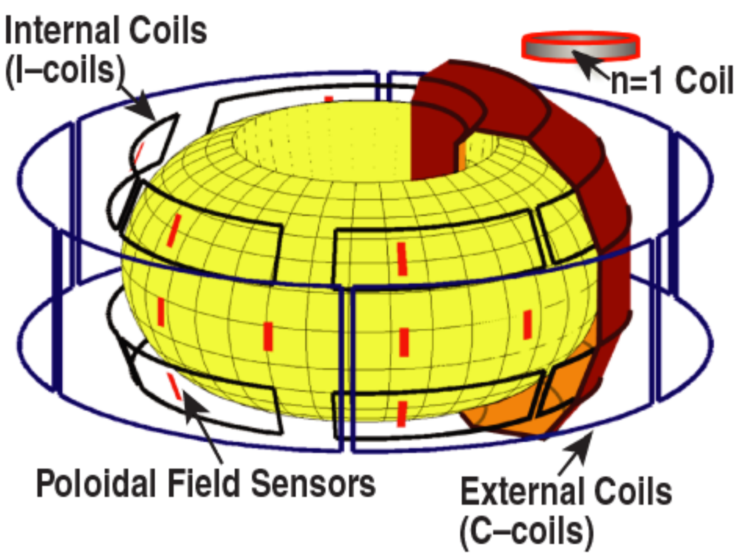


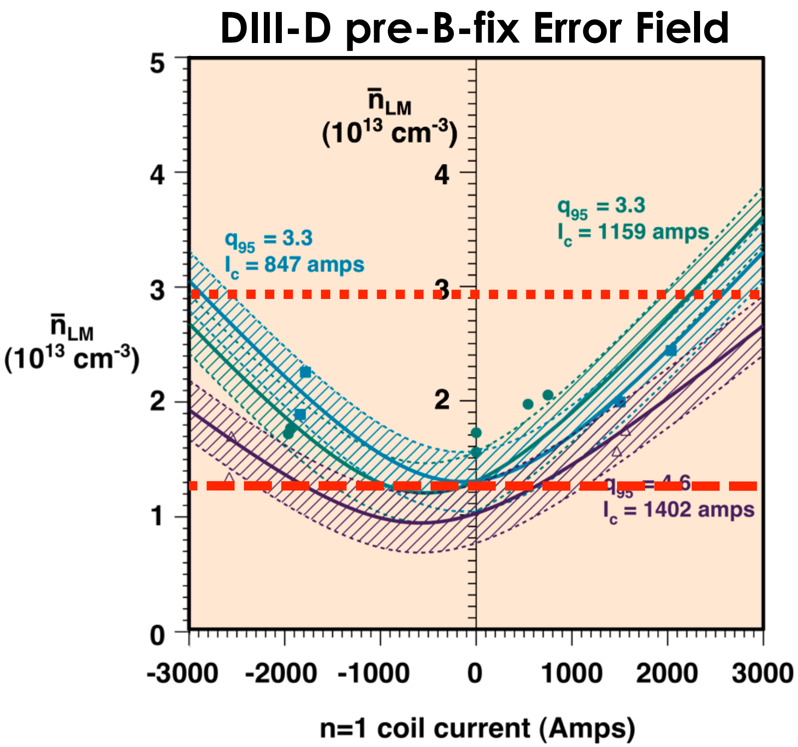


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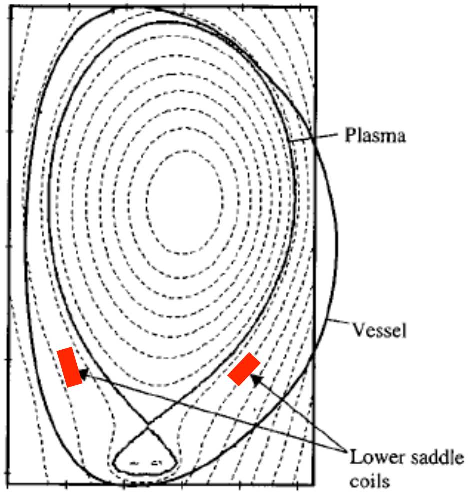
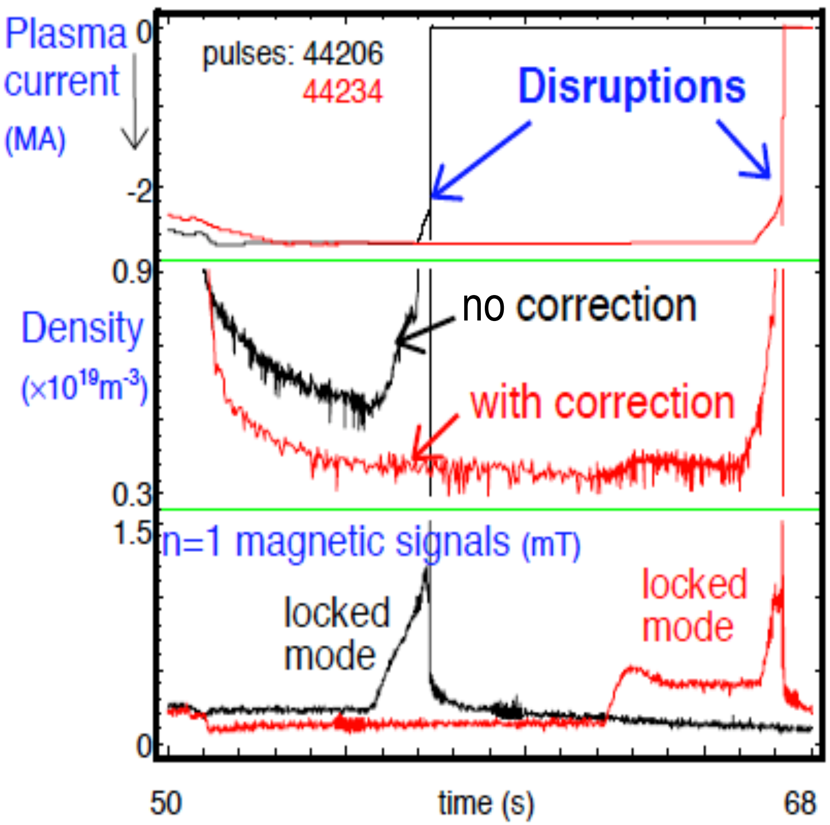
- **JET saddle coils measure 1.2 G error***
  - **Correction → 35% lower density**

**JET saddles**




**JET**




***vacuum 2/1 measure**

[Buttery, NF 2000]

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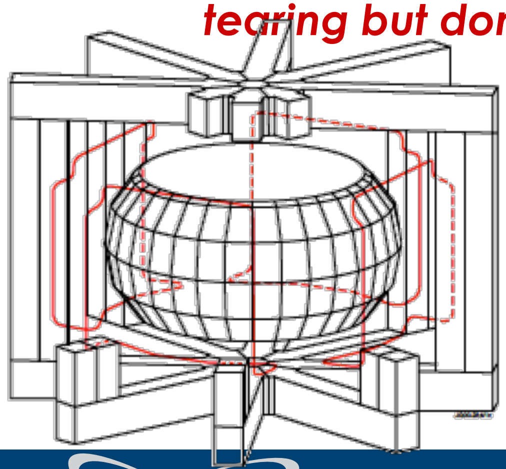
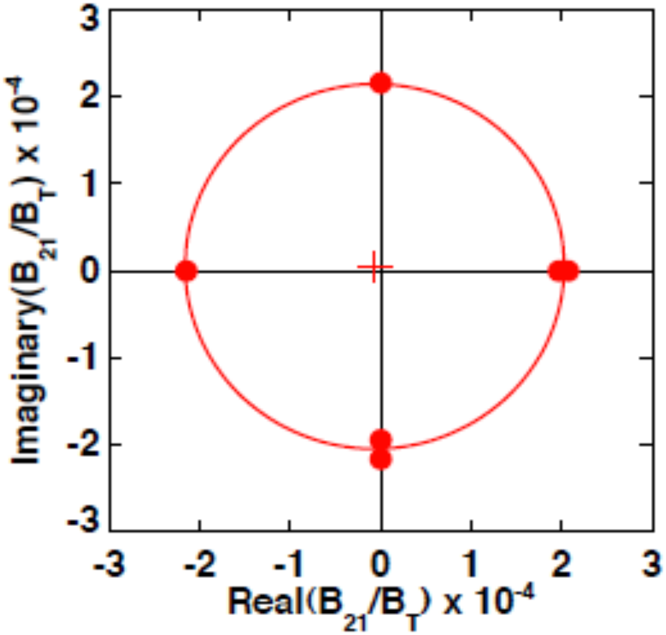
    - ***Do couple to plasma to induce tearing but don't "see" intrinsic error***



JET EFCCs

**JET EFCC measurement of intrinsic error*:**

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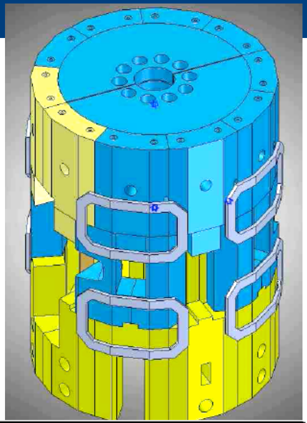
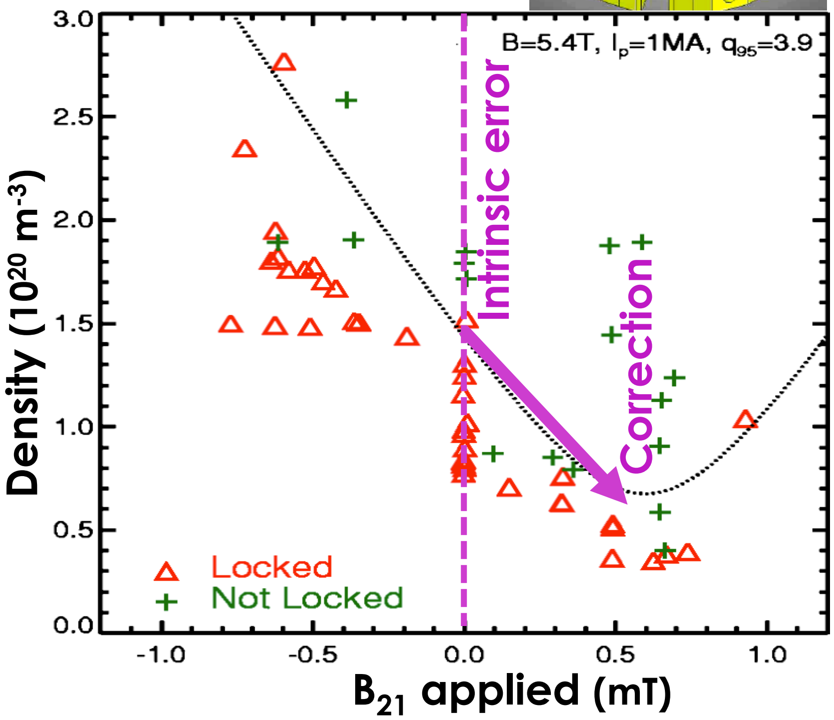
**C-Mod**
**A coils**






[Wolfe, PoP 2005]

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**<u>Observations</u>**

- **Correction benefits depend on shape of EF <u>and</u> coils**
- **More coils improve correction**
- **Internal twin arrays have been most effective**
- **Coils can couple orthogonally to machine error**

➢ **Is this intrinsic instability?**

➢ **Is this all through n=1?**

➢ **Where does error field couple to plasma to cause braking?**