Error Field Detection and Mode Locking Avoidance by the Interaction of Applied Rotating 3D Fields with Otherwise Locked Modes

by
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with
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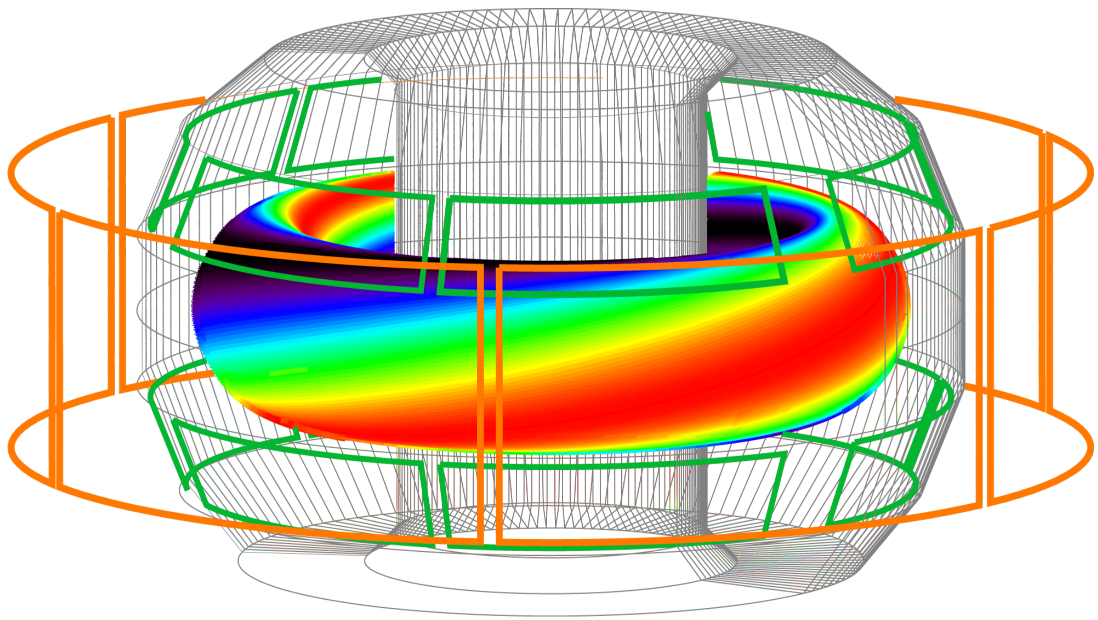

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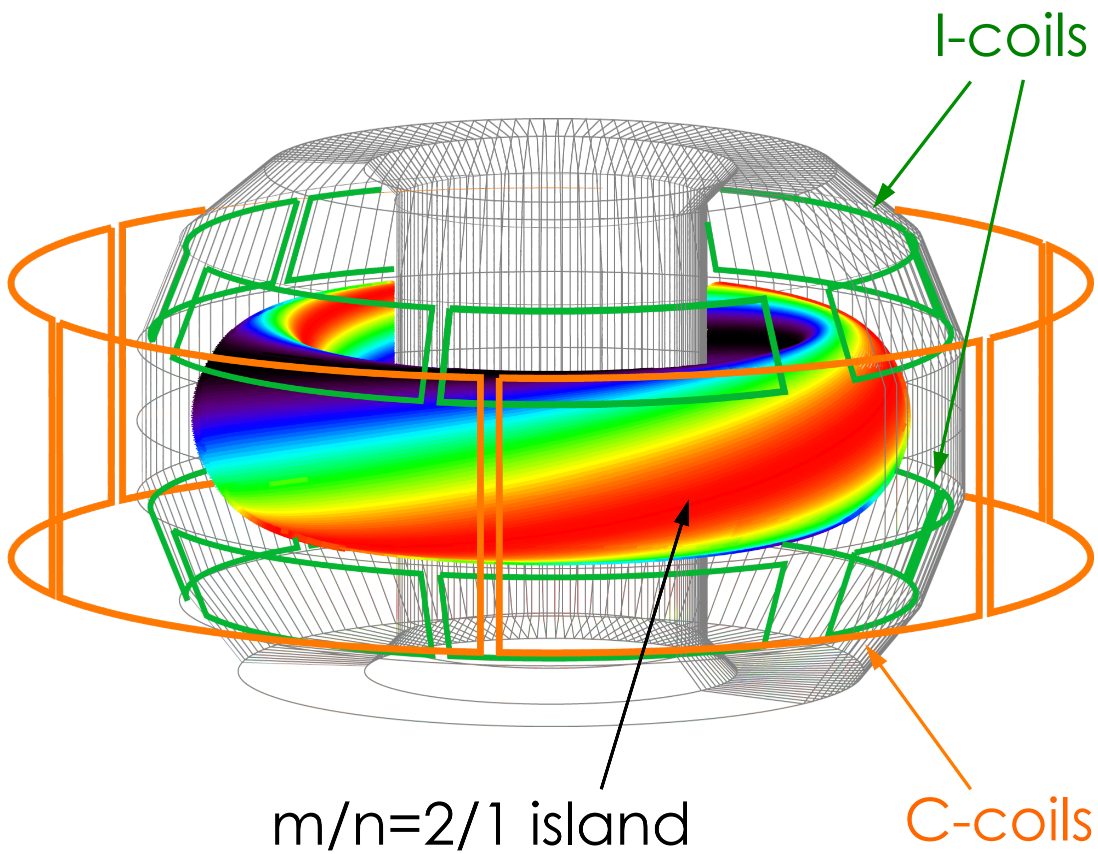
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Resonant interaction with applied 3D fields used for locked mode (LM) control in DIII-D

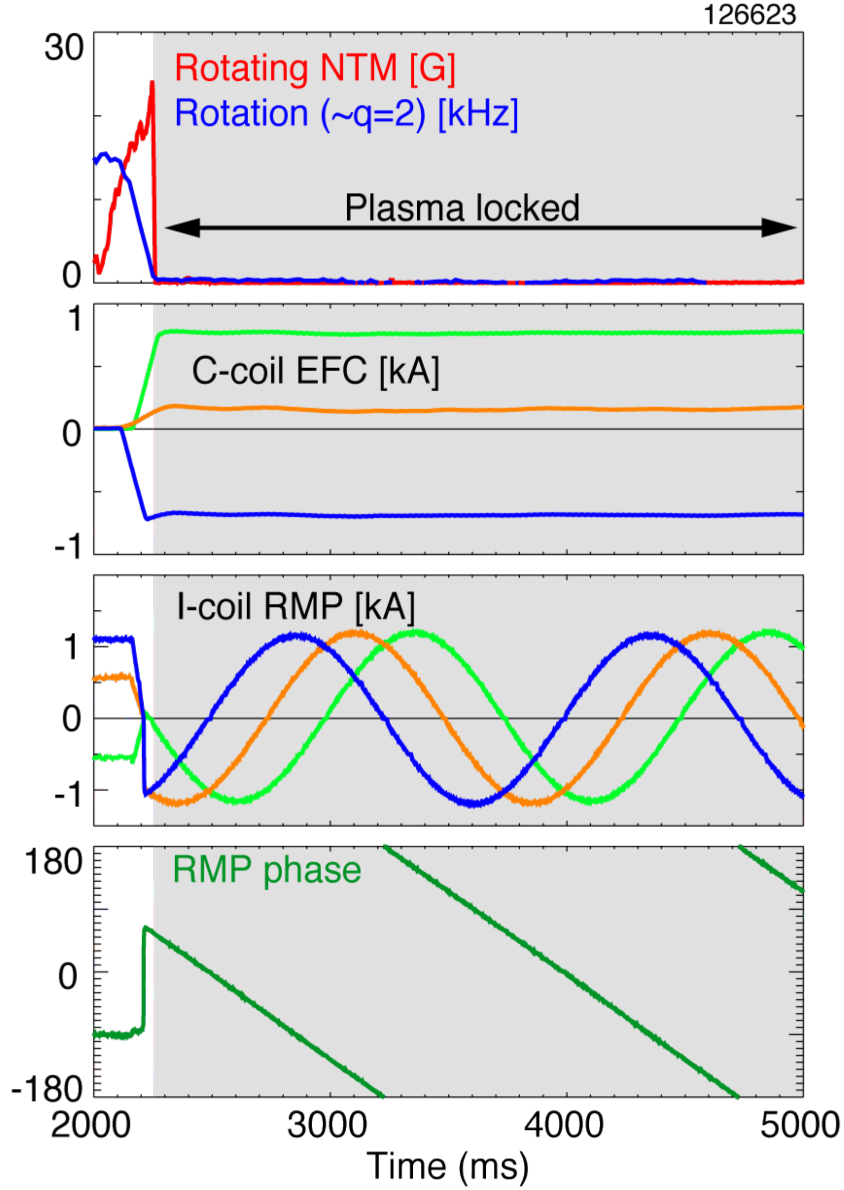
- **I-coil and C-coil n = 1 arrays apply resonant torques on magnetic island**

- **Two applications:**
  - Low frequency limit
    - Optimize EF correction currents in a single-discharge
  - High frequency limit
    - Prevent mode locking for disruption avoidance



n = 1 EF detected by slow (0.67 Hz) magnetic steering of LM phase

- **Rotating neoclassical tearing mode (NTM) slows and locks**
- **C-coils do *partial* EF correction (EFC)**
- **I-coils apply slowly rotating resonant magnetic perturbation (RMP)**
- **EF deduced from observed LM dynamics, in a single-discharge**



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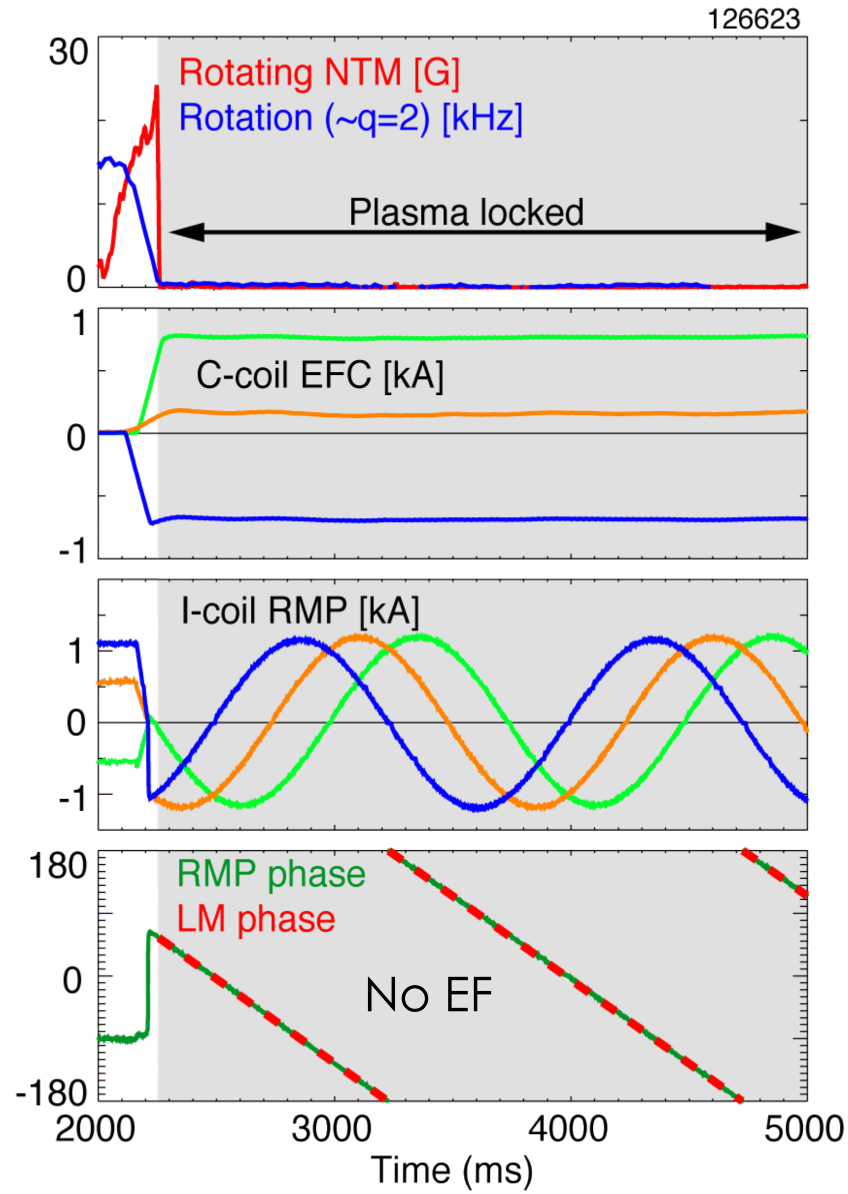

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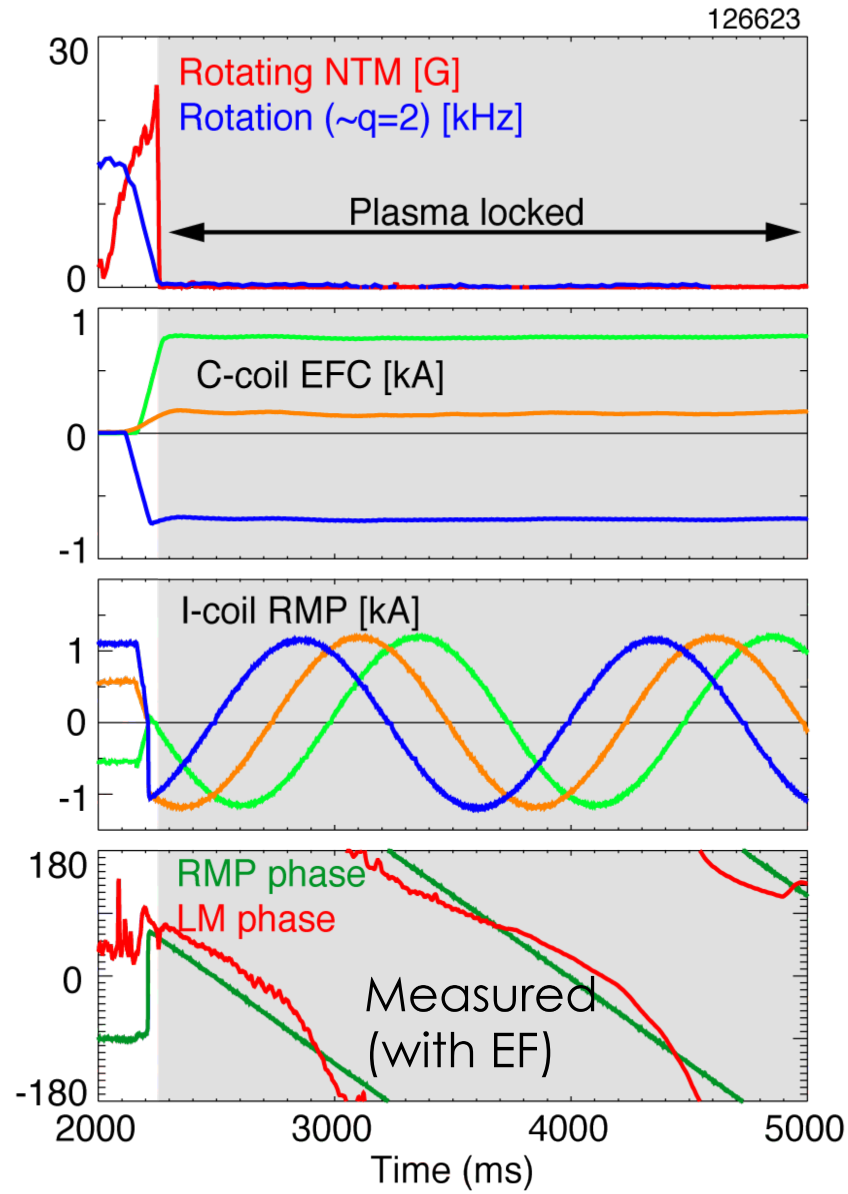

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LM dynamics understood through torque balance model

- **Island torque balance:** $$\underbrace{T(I)+T(C)+T(EF)}_{\text{Resonant}}+\underbrace{T_{NR}}_{\text{Non-resonant}}=\frac{\partial L}{\partial t}$$ **= 0 for LM**

- **Resonant torques estimated from magnetic measurements of island:**

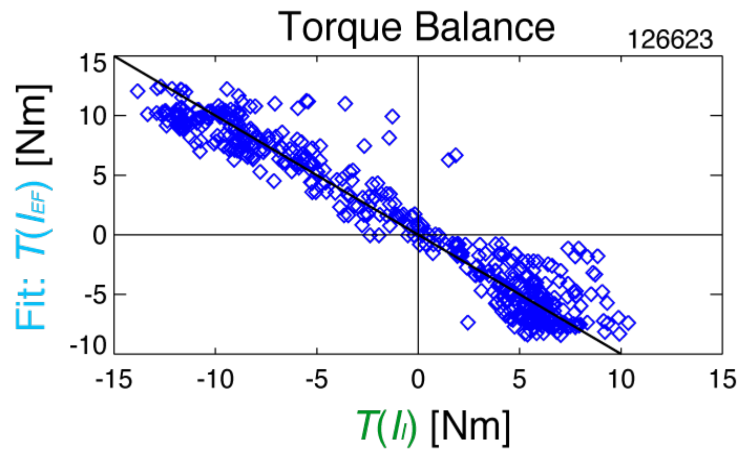
$$T = A\int \vec{j}\times\vec{B}_{vac}dx$$

- **Plasma response modifies poloidal spectrum of applied field, estimated using IPEC code**

- **Can solve for EF, if other torques are calculated**

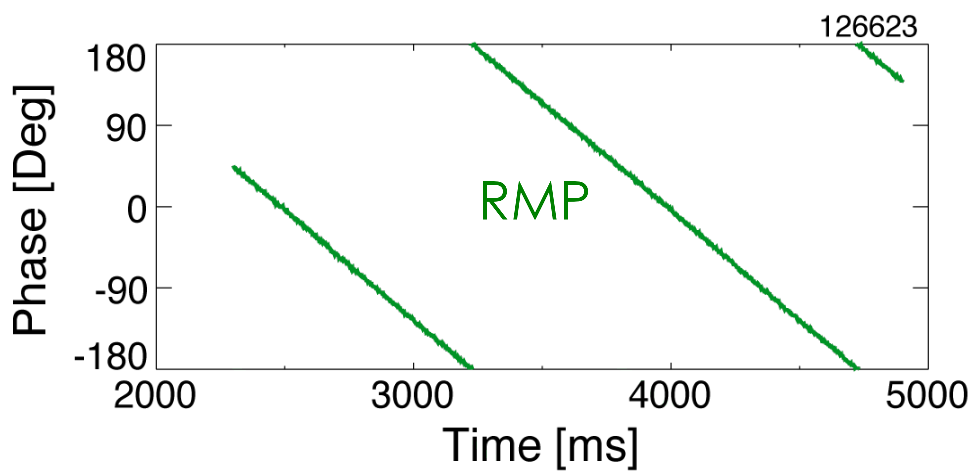
Measured LM dynamics in good agreement with fit to resonant torque balance

- **Fit to: $T(I_I)$ + $T(I_{EF})$ = 0**



- **Resonant torques only:**

  LM phase aligns with total of EF and I-coil RMP



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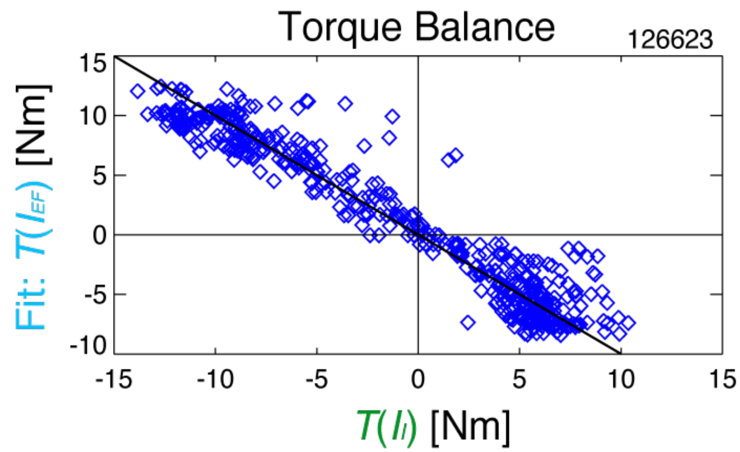

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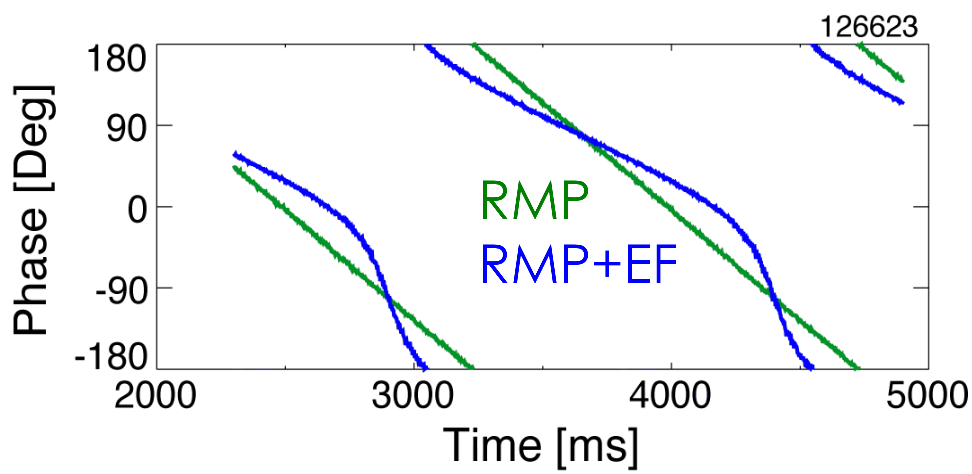

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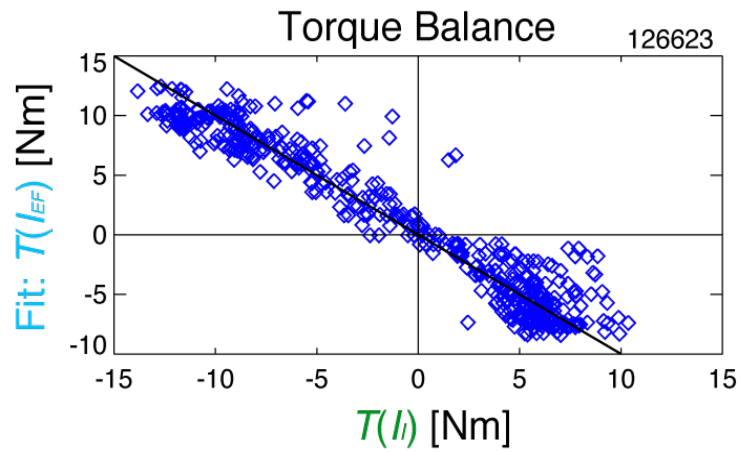

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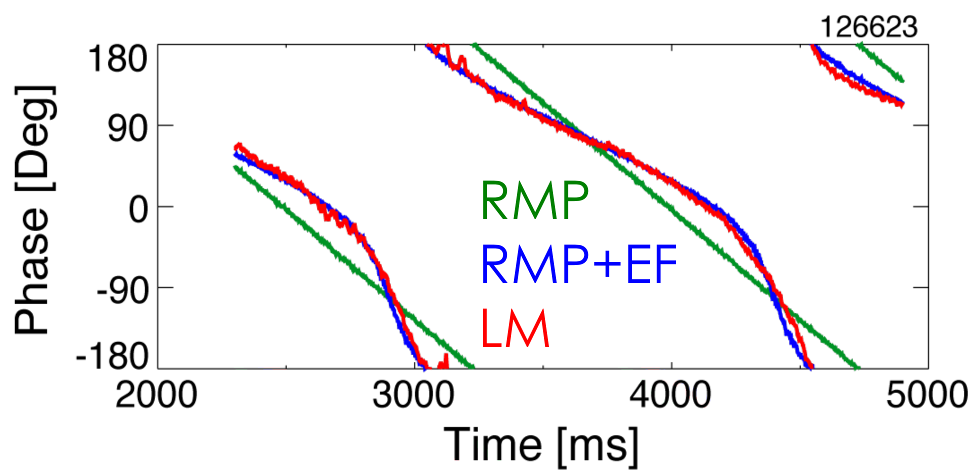
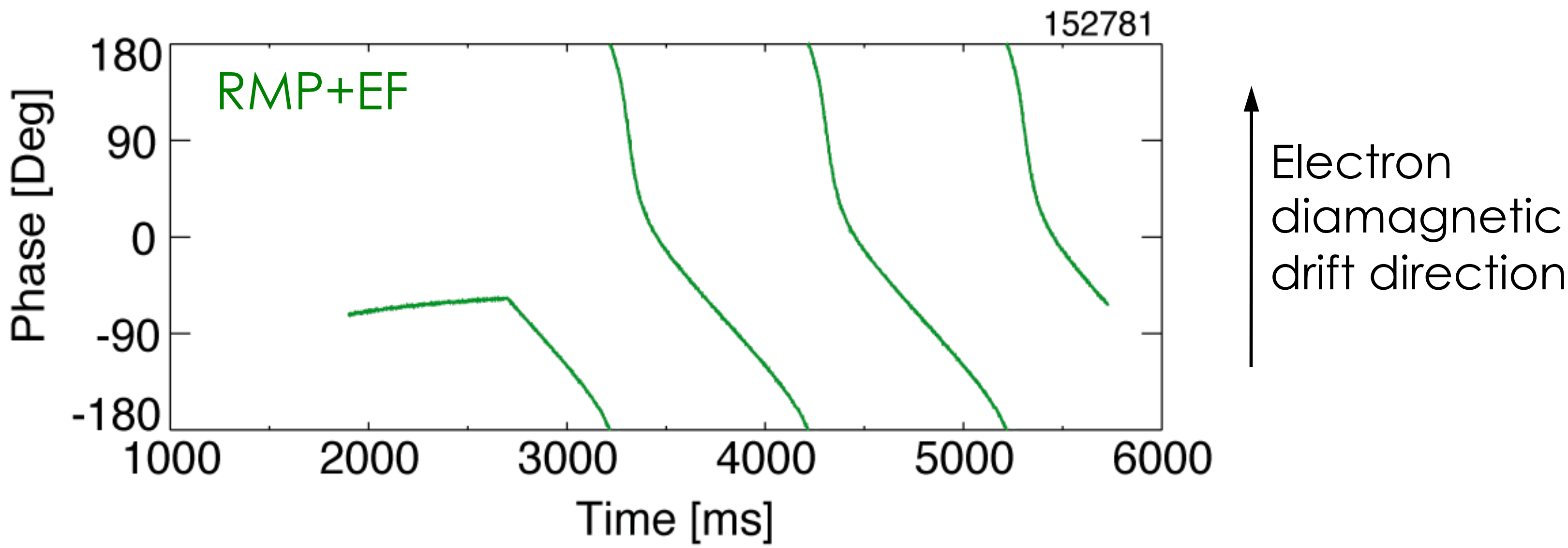


Torque balance model can include non-resonant torque effects

- **More complete model required in Ohmic discharges with EF penetration LMs**
  - Non-resonant torque, $T_{NR} \sim |\delta B|^2$ in electron diamagnetic drift direction



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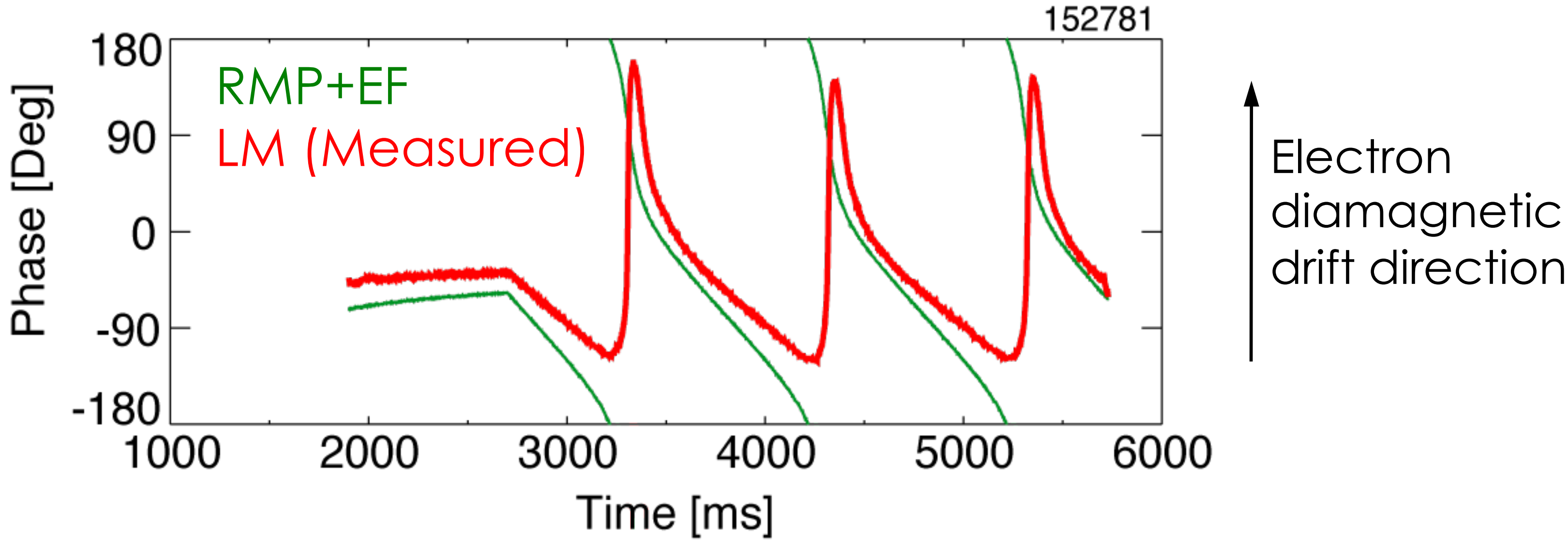

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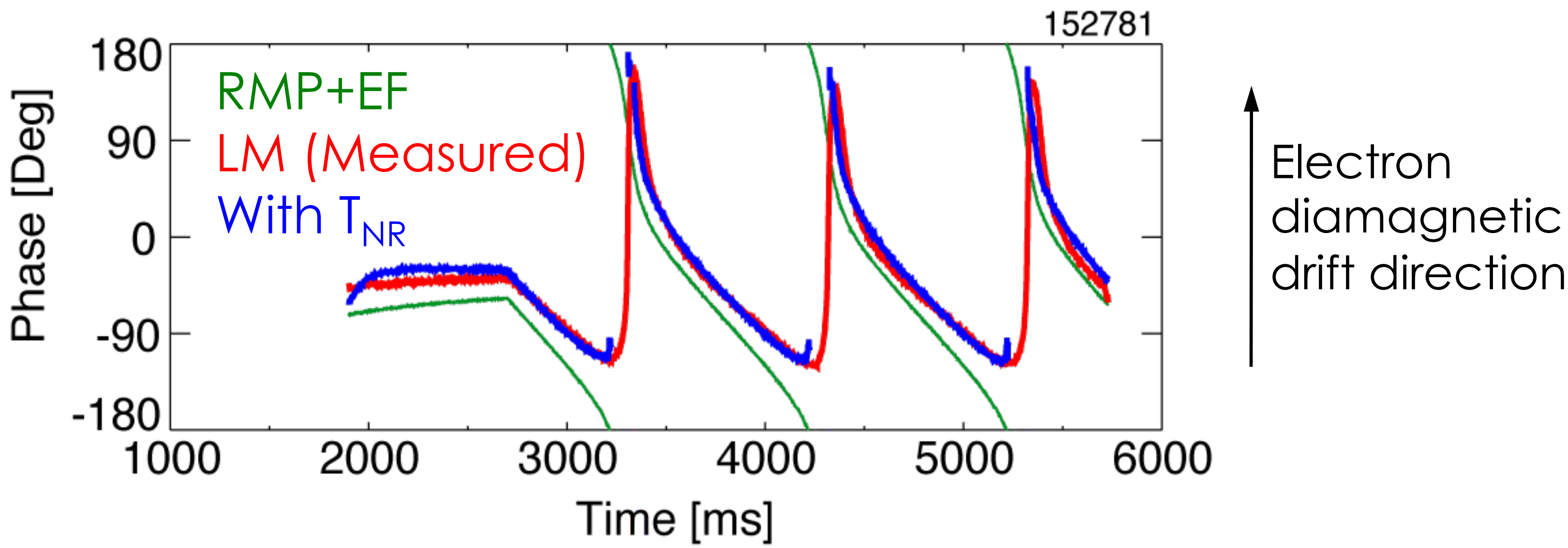
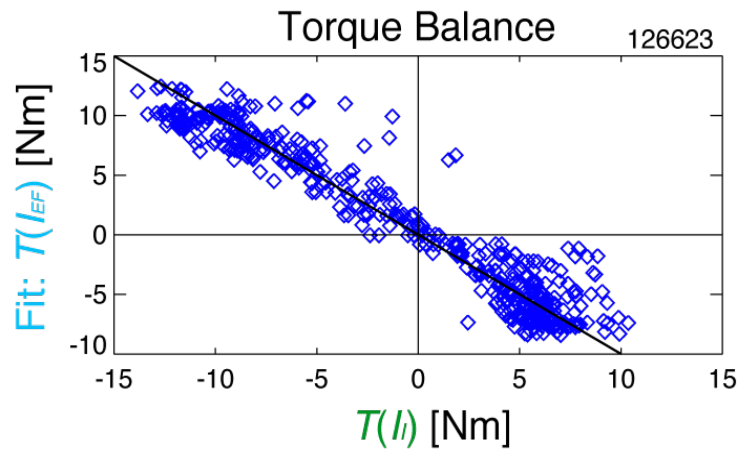


- **LM phase well described by balance of resonant and non-resonant torques**
  - EF can still be fit

Independent coil sets modeled in torque balance

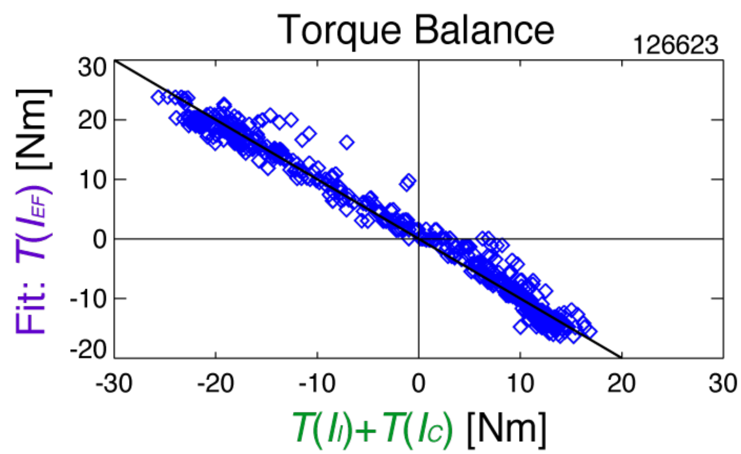
- **"Ignore" C-coil torque:**

$$\underbrace{T(\mathrm{I})}_{\text{RMP}} + \underbrace{T(\mathrm{C}) + T(\mathrm{EF})}_{\text{Residual or proxy EF}} = 0$$



- **Explicitly treat C-coil:**

$$\underbrace{T(\mathrm{I}) + T(\mathrm{C})}_{\text{RMP}} + \underbrace{T(\mathrm{EF})}_{\text{Intrinsic EF}} = 0$$

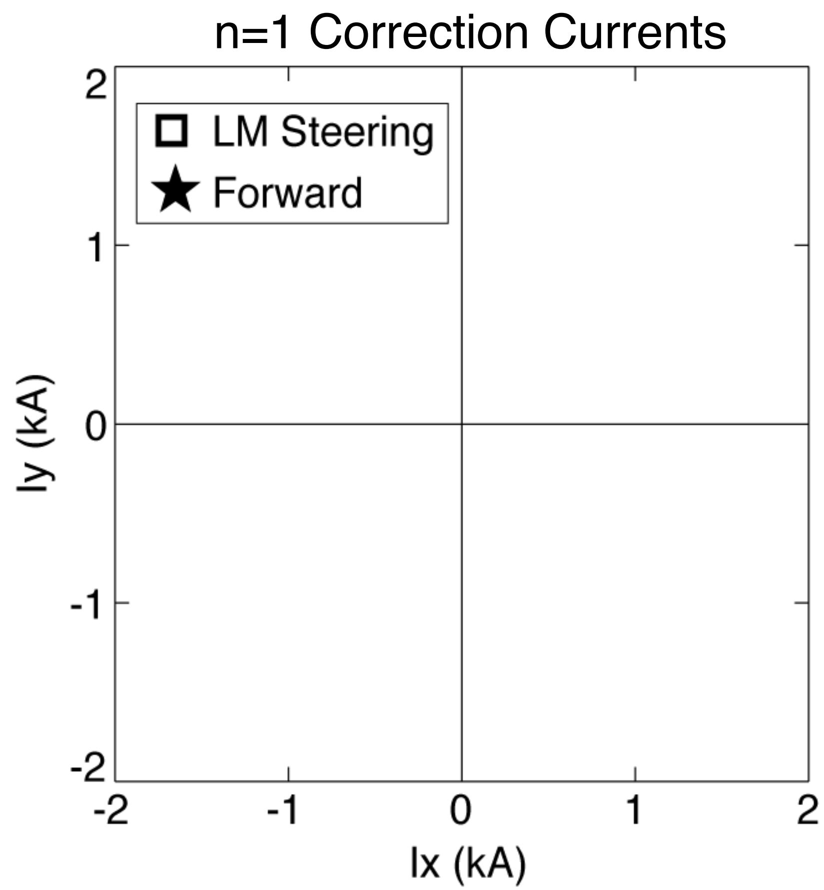


- **Next: intrinsic and/or residual EFs in various DIII-D discharges**

LM steering method for EF detection agrees with other techniques

- **Forward calculation of EFC currents using physical geometry of known intrinsic DIII-D EF**

- **Optimal correction minimizes drive for least-stable kink**
  - See: TI2.00001, C. Paz-Soldan, Thursday 9:30am



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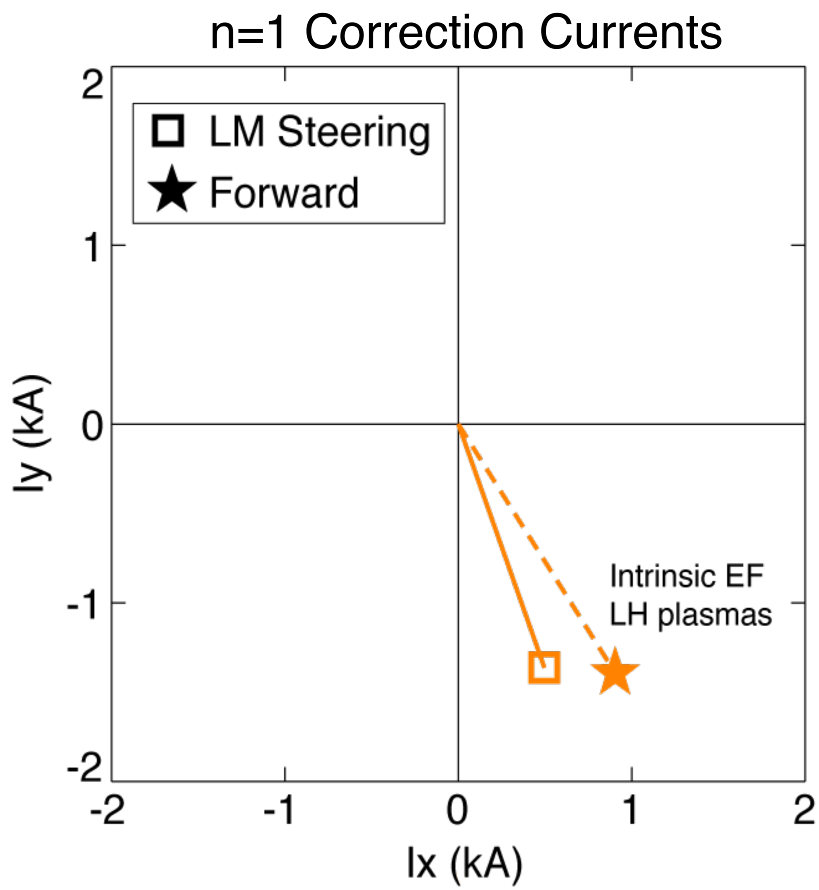

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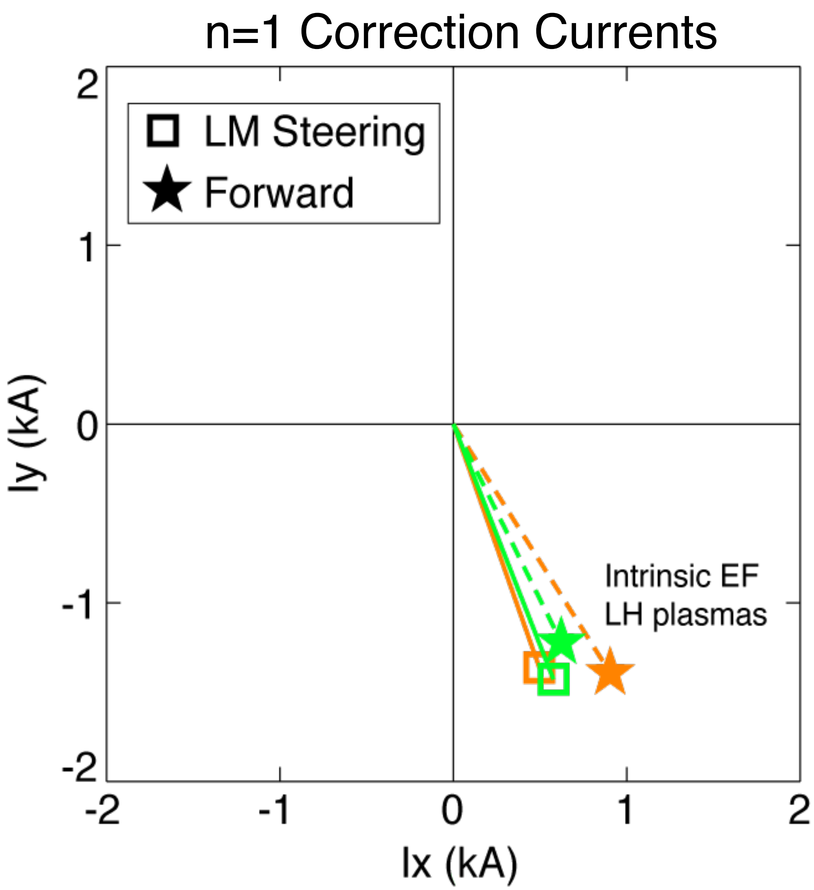

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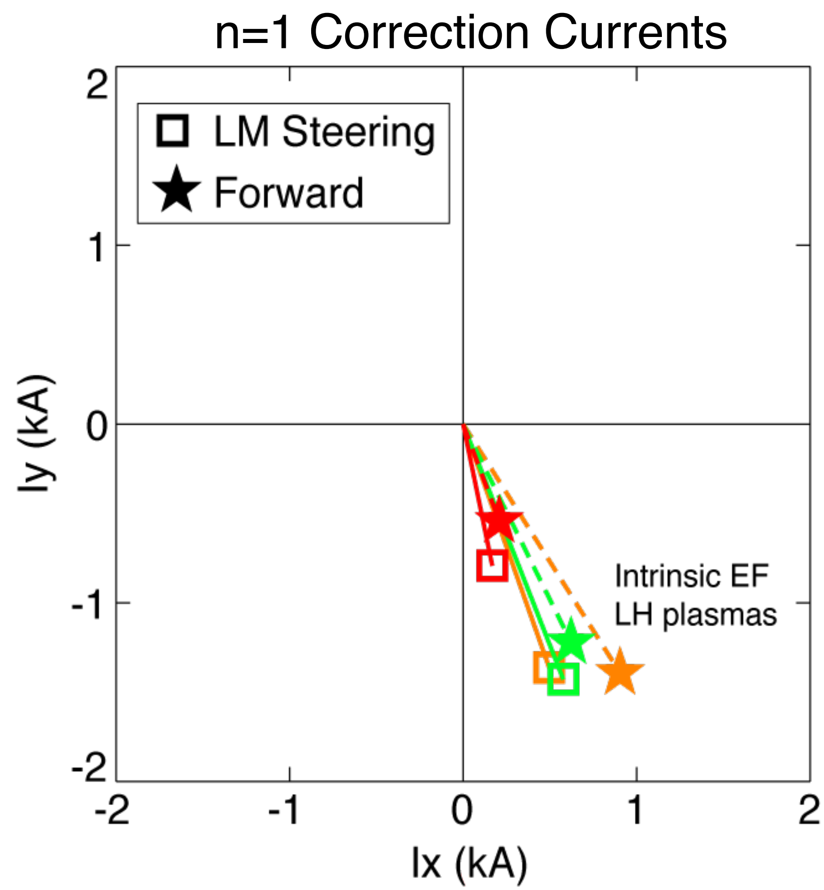

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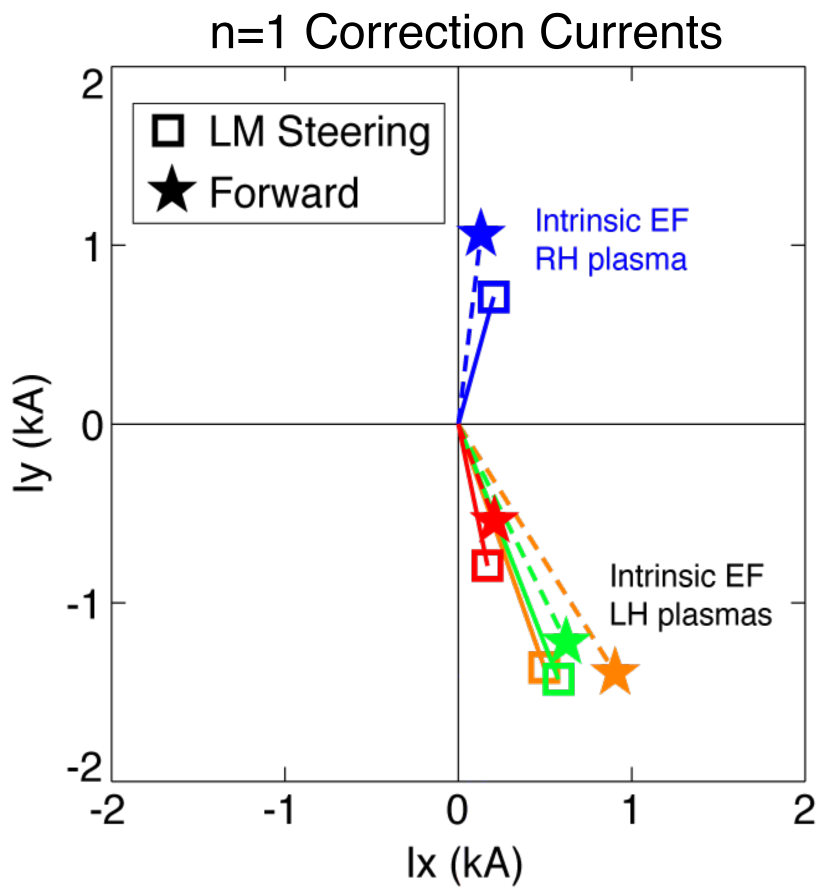

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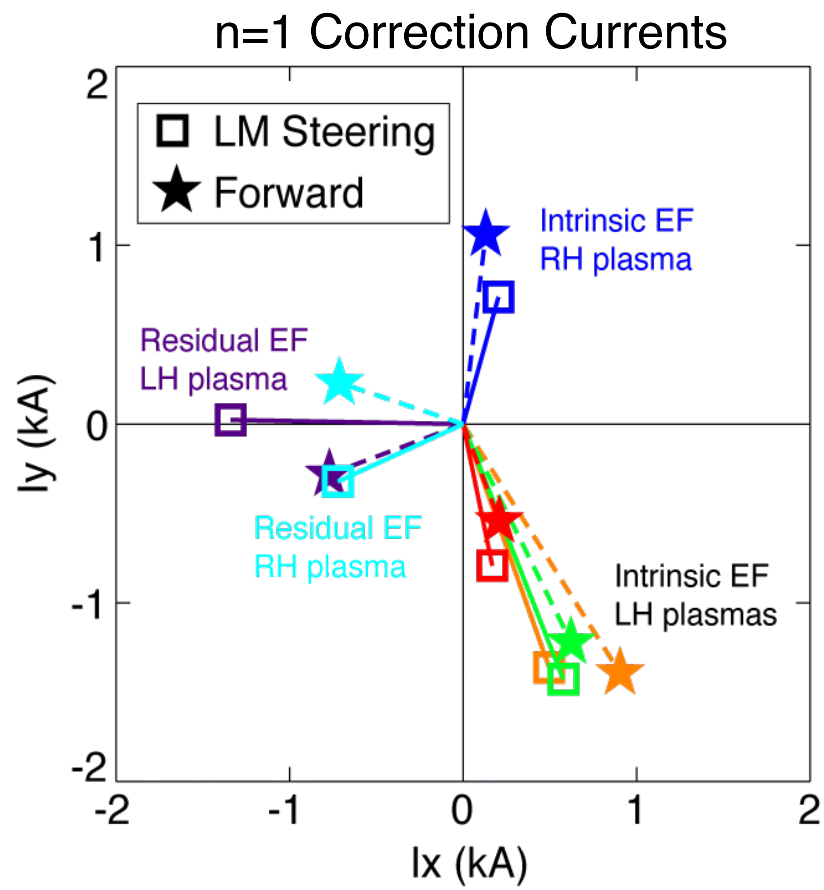

- **Agreement over a variety of discharges with differing EFs (due to coil current changes in EF sources)**

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EF detection by LM steering may be applicable to ITER

- **EFC currents empirically determined in a single discharge**
- **Not restricted to low density discharges**
- **Independent of high beta or rotation**
  - Early operation of ITER lacking full auxiliary power

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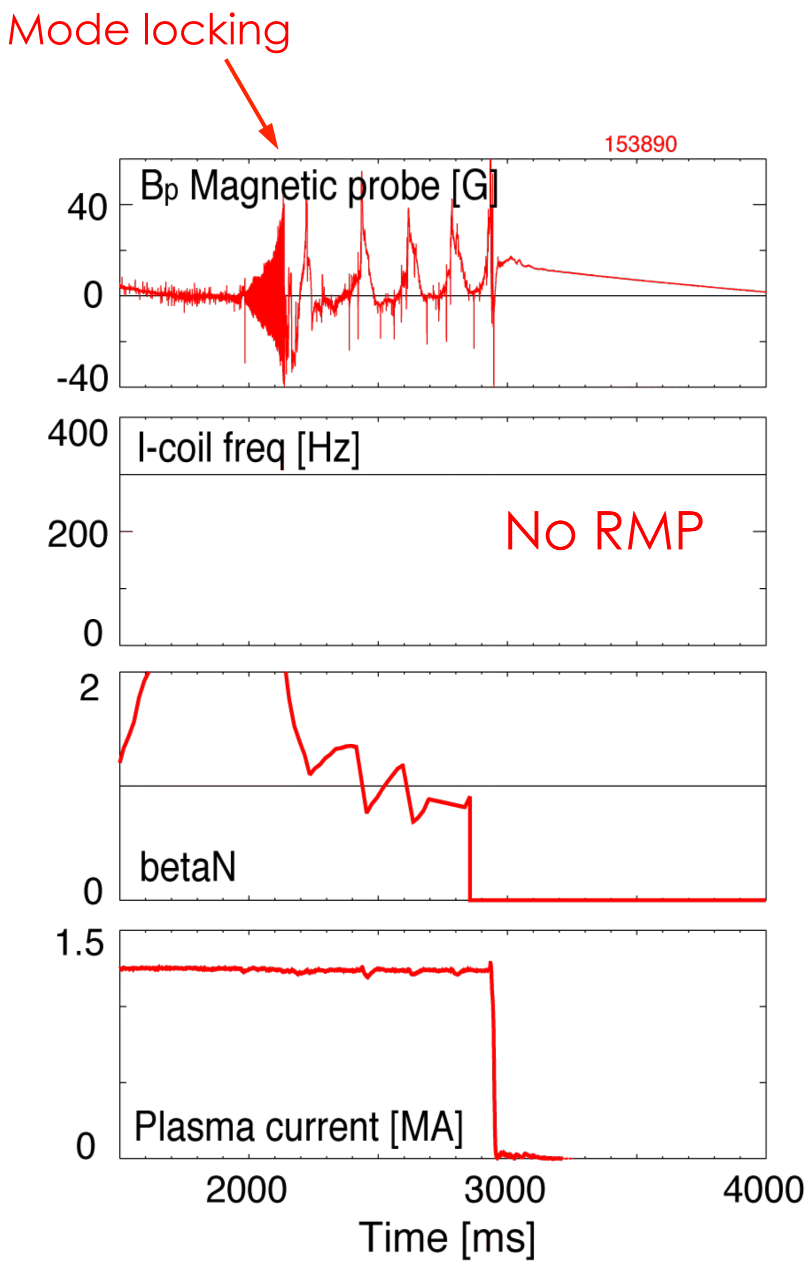
At higher frequencies (300 Hz, $\Omega\tau_w \approx 6$), resonant interaction used to sustain mode rotation

- **Without control:** growing 2/1 NTM locks, causing beta collapse and major disruption



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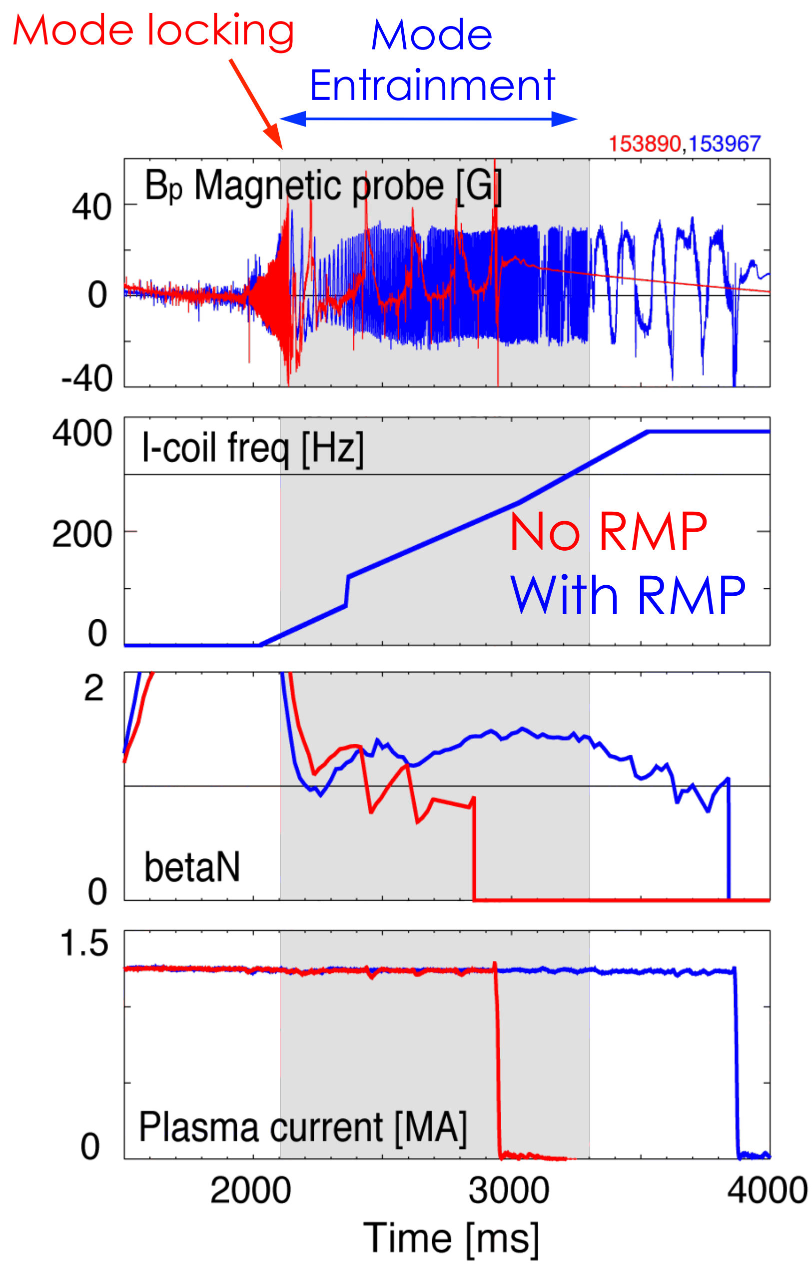
At higher frequencies (300 Hz, $\Omega\tau_w \approx 6$), resonant interaction used to sustain mode rotation

- **Without control: growing 2/1 NTM locks, causing beta collapse and major disruption**
- **Rotating n=1 I-coil field "entrains" slowing island**
- **Entrainment up to 300 Hz ($\Omega\tau_w \approx 6$) demonstrated**
- **Modest improvement in confinement observed**



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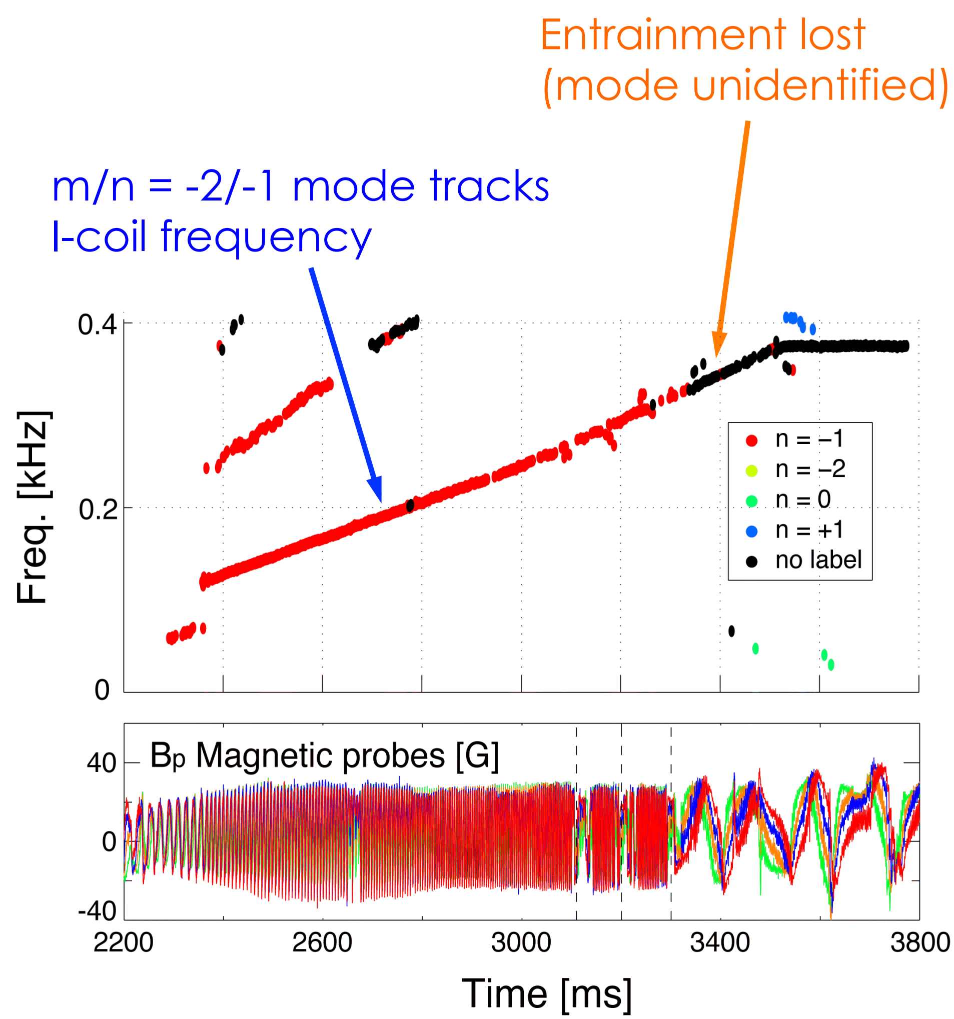
Modal analysis of magnetics arrays confirms entrainment and spin-up of 2/1 mode

- **Magnetics arrays analyzed for modal shapes (eigspec code)**
- **Verifies entrainment of m/n=-2/-1 island**
- **Periods of entrainment loss, under study**
- **Similar approach investigated with feedback control of mode rotation**
  - See: BP8.00112, M. Okabayashi



Summary: Resonant interaction with applied 3D fields successfully used for LM control in DIII-D

- **Optimize EF correction currents in a single discharge**
  - Not restricted to low density, and independent of auxiliary heating sources

- **Prevent mode-locking for disruption avoidance**
  - Entrainment up to 300 Hz ($\Omega\tau_w \approx 6$) demonstrated