Recent DIII-D Disruption Mitigation Experimental Results in Support of the ITER Disruption Mitigation System Design

by
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for the
DIII-D Disruption Task Force
(Special thanks to
E. Hollmann & D. Shiraki)

Presented at the
PPPL Theory & Simulation of Disruptions Workshop
Princeton, NJ (USA)

July 11, 2014

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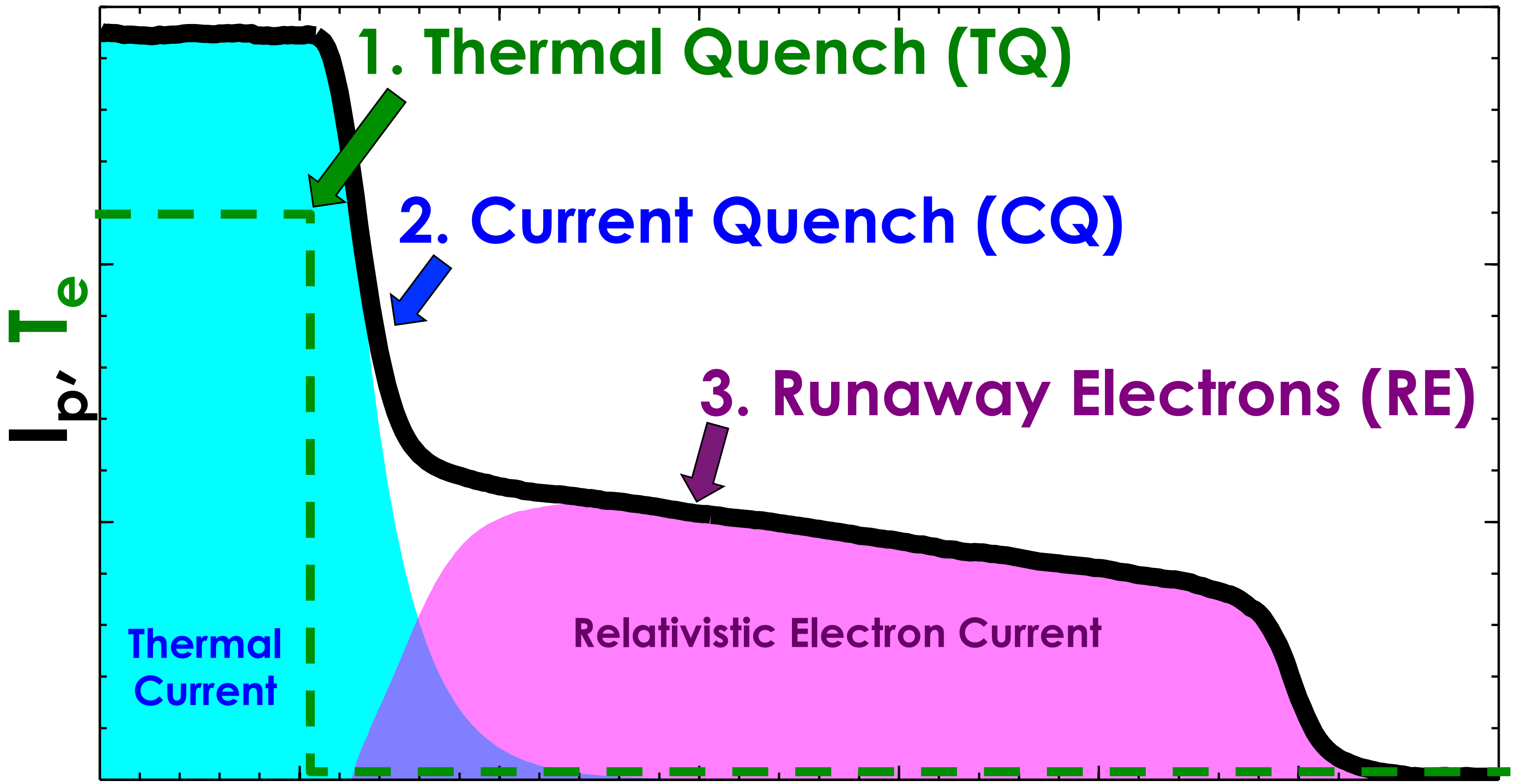
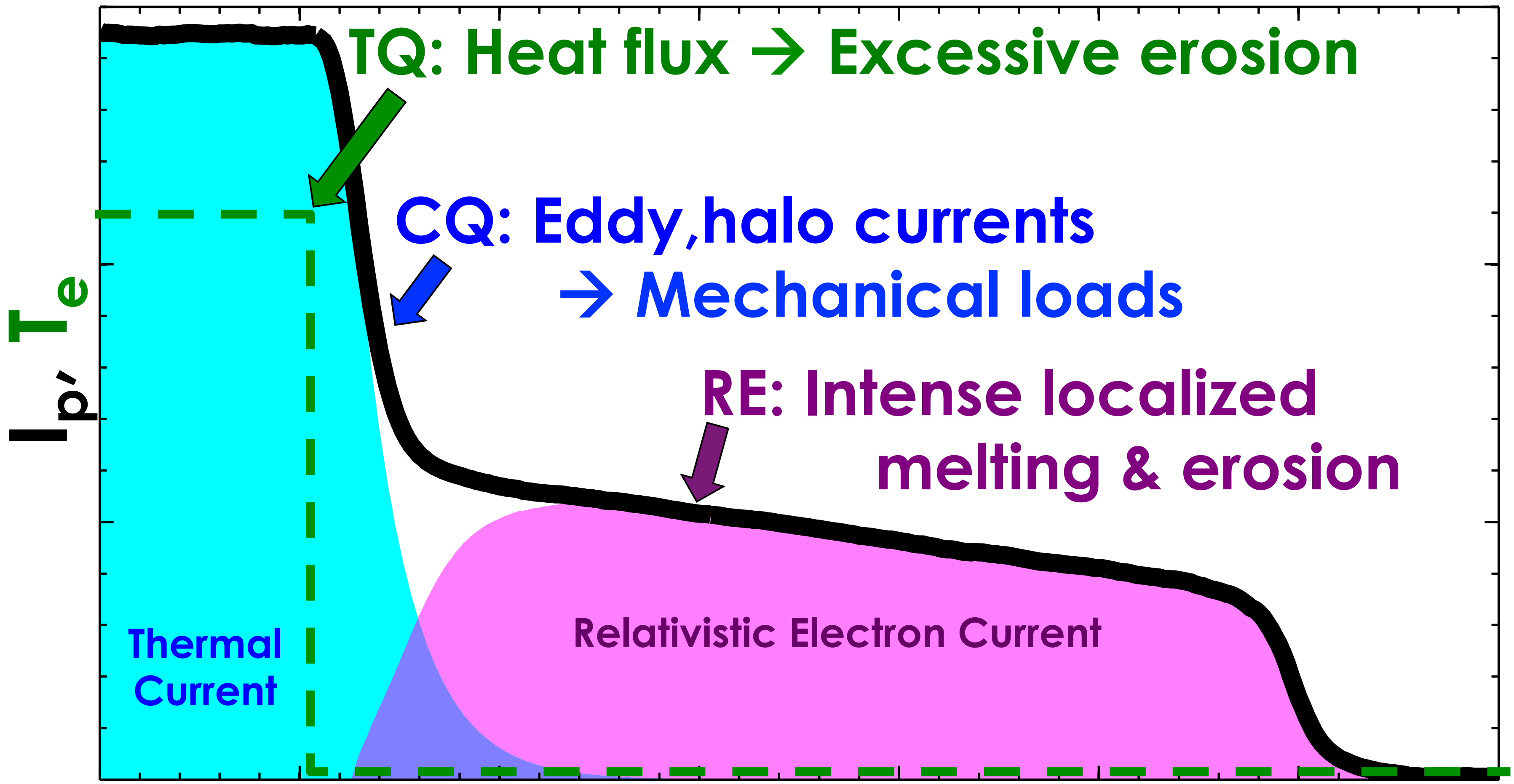
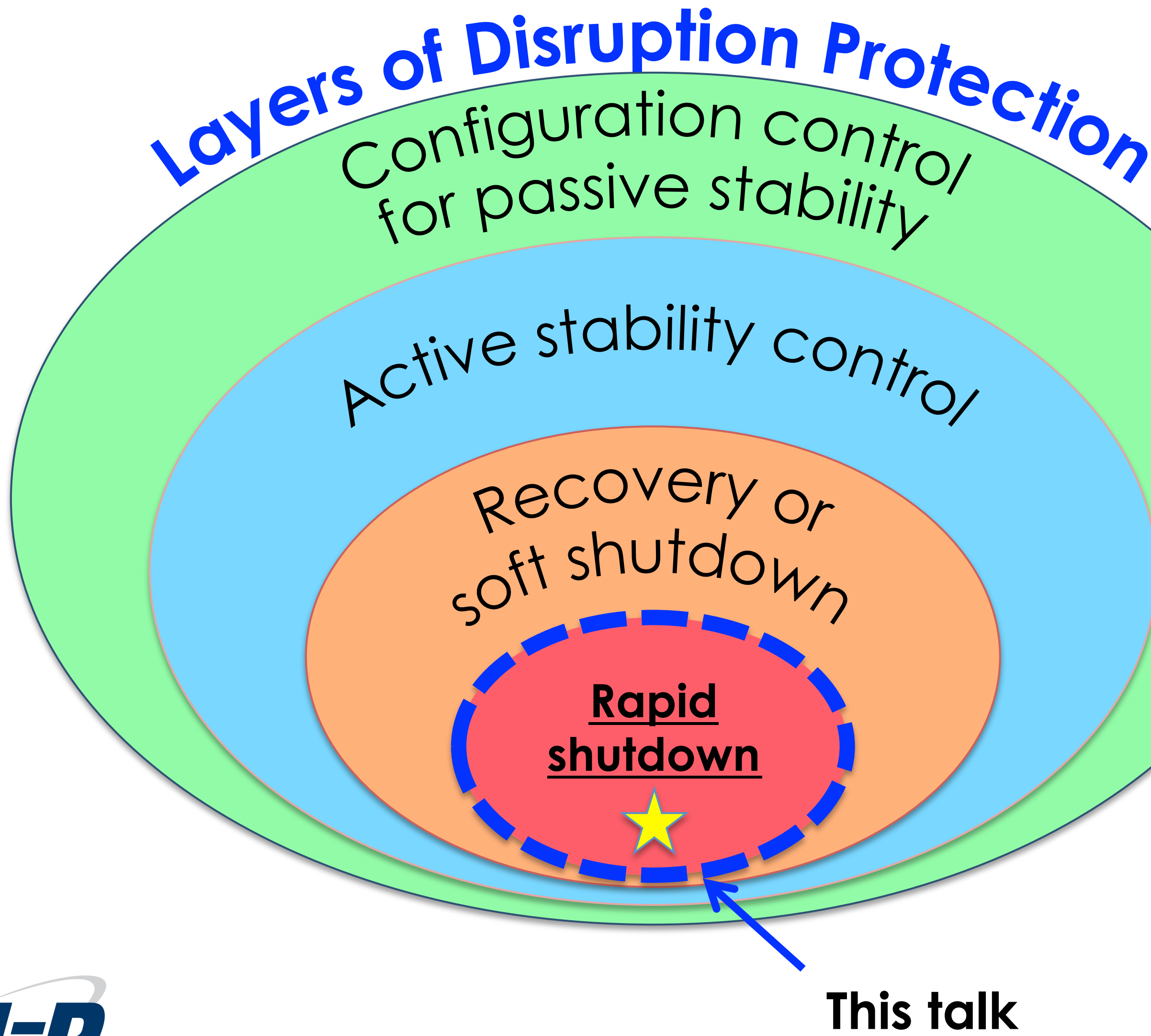
Disruptions Rapidly Release Plasma Thermal & Magnetic Energy, Form Relativistic "Runaway" Electron Beams



Each phase of disruption presents a threat to tokamak vessel components



Rapid shutdown by Disruption Mitigation System (DMS) is ITER's last defense against disruption damage



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Goals of ITER DMS

1. **Radiate plasma thermal energy isotropically to PFC**
    1. 0-D → 3-D

2. **Minimize CQ mechanical loads**

3. **Suppress or benignly dissipate RE**

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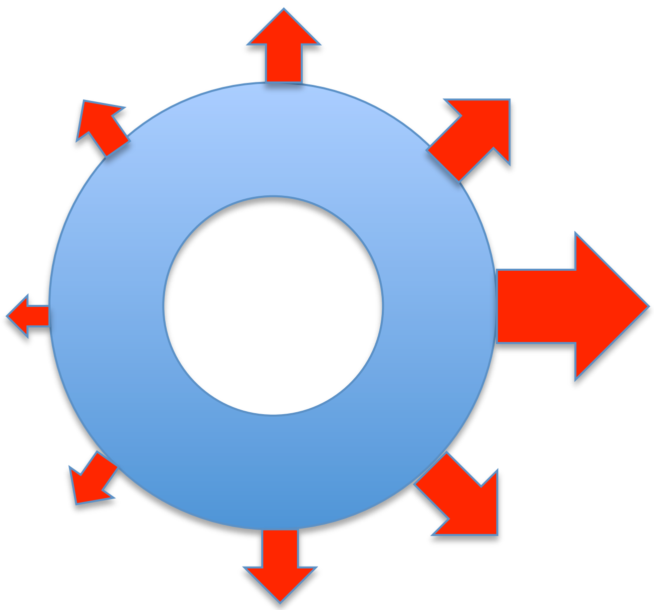
This talk

1. Radiated power asymmetry during MGI

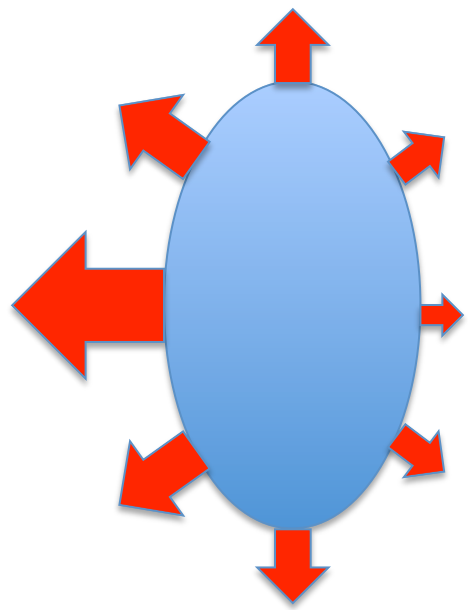
2. Runaway electron dissipation

Radiation peaking during disruption mitigation could cause first wall melting

- **Radiation asymmetries could cause local wall melting even if 100% plasma energy radiated away,**
  - Toroidal/Poloidal Peaking Factor (TPF/PPF) = Max/Mean
  - **Melting limits:** TPF ~ 2, PPF ~4 (assuming 3ms TQ)



Toroidal Asymmetry



Poloidal Asymmetry

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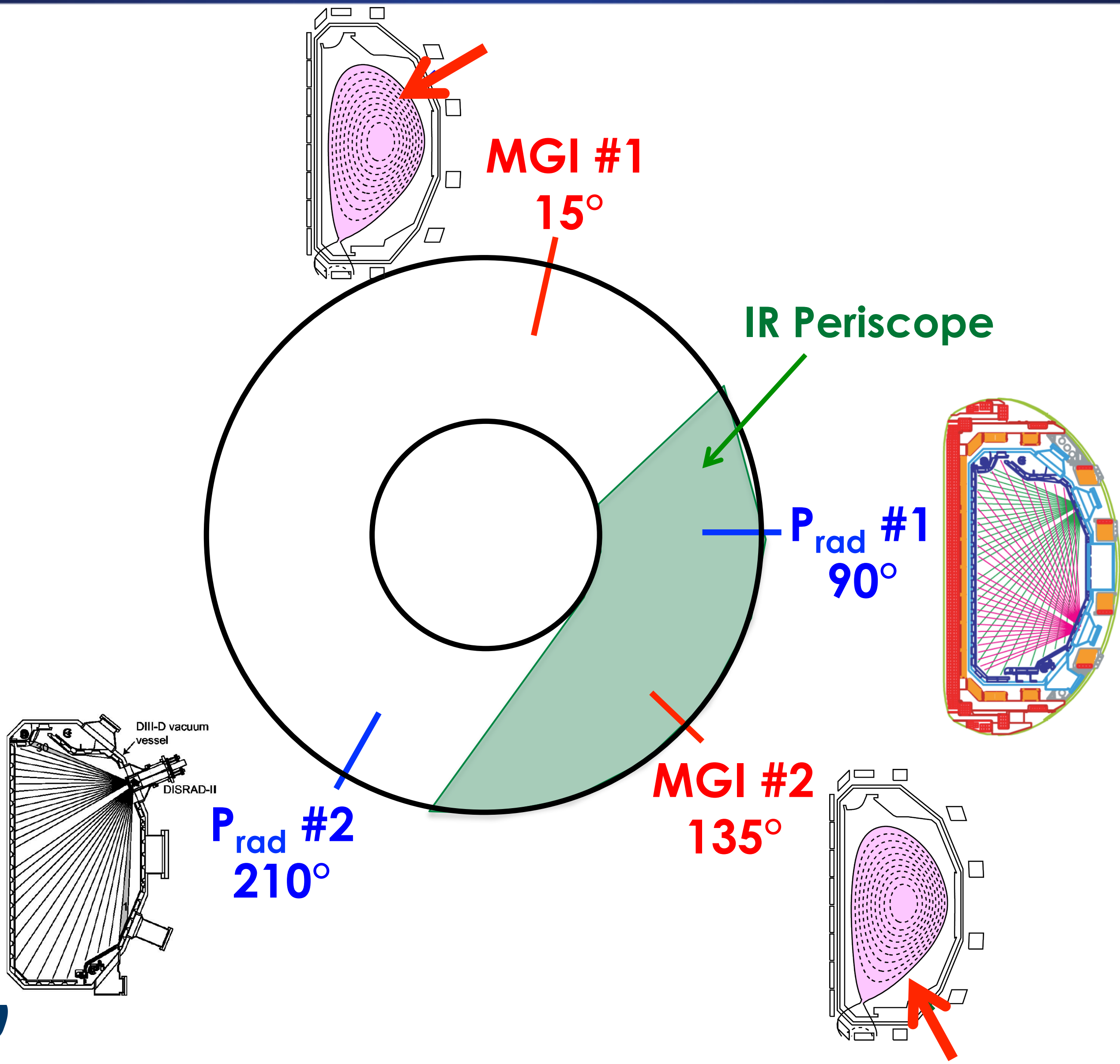
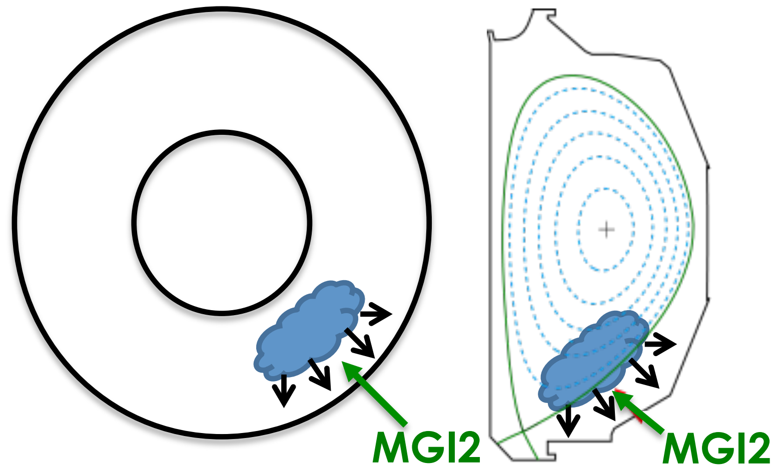
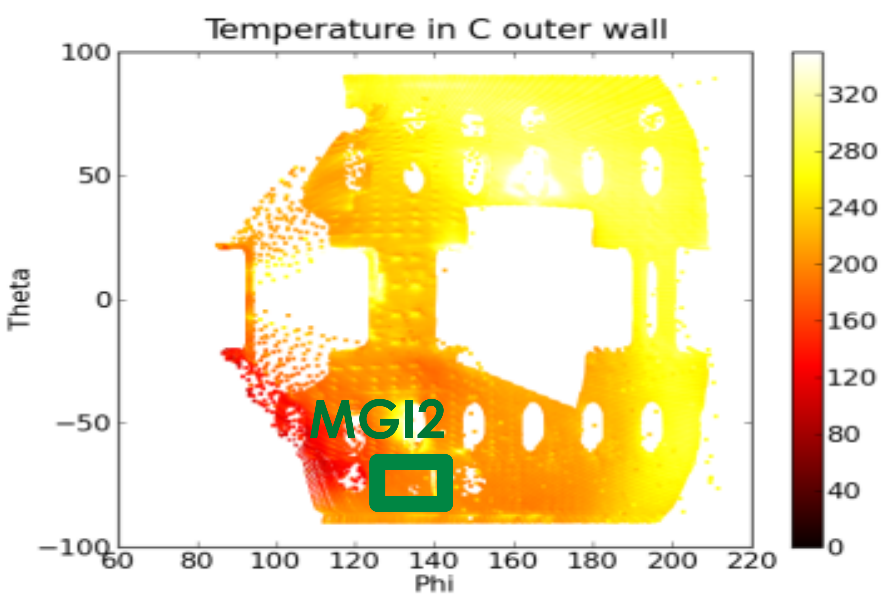
DIII-D experimental setup for radiation asymmetry measurements

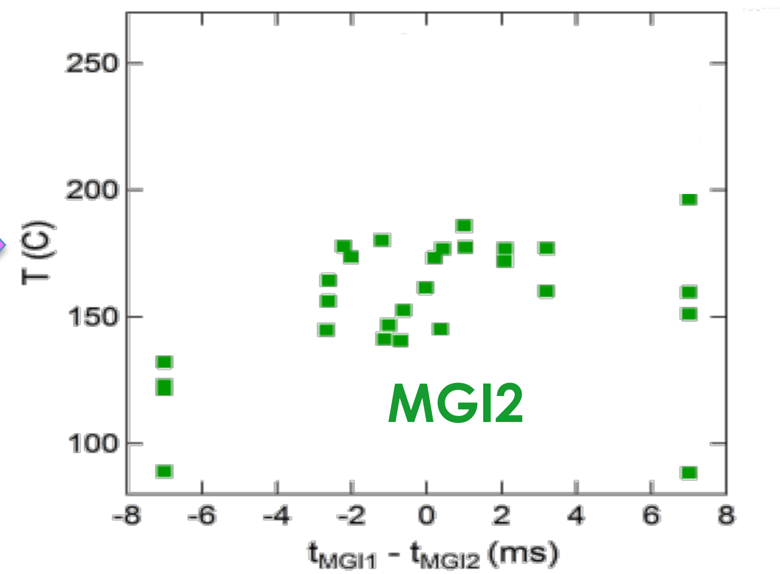


Single Injector Radiation Asymmetry: No preferential heating of the injector port location observed on DIII-D

- **ITER concern:** Extremely concentrated P_{rad} during pre-TQ may cause localized melting of injector port







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Single Injector Radiation Asymmetry: No preferential heating of the injector port location observed on DIII-D

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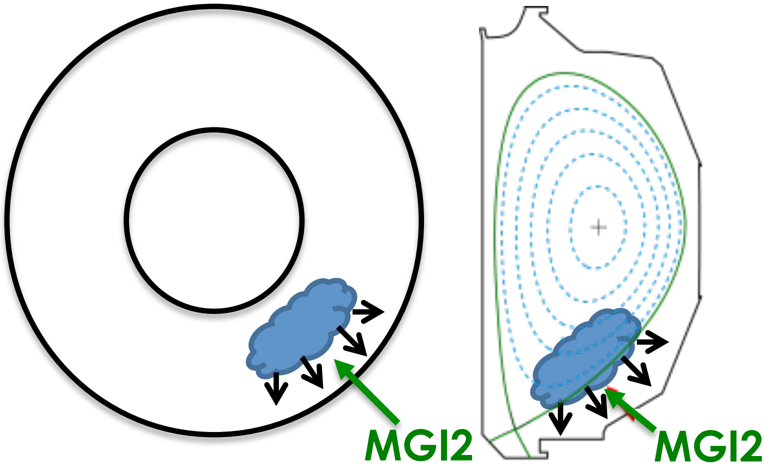
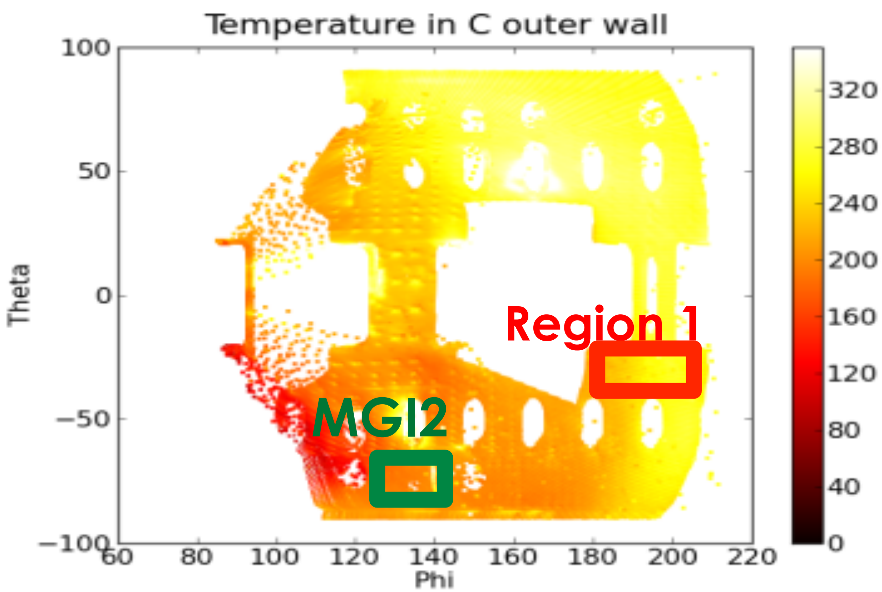
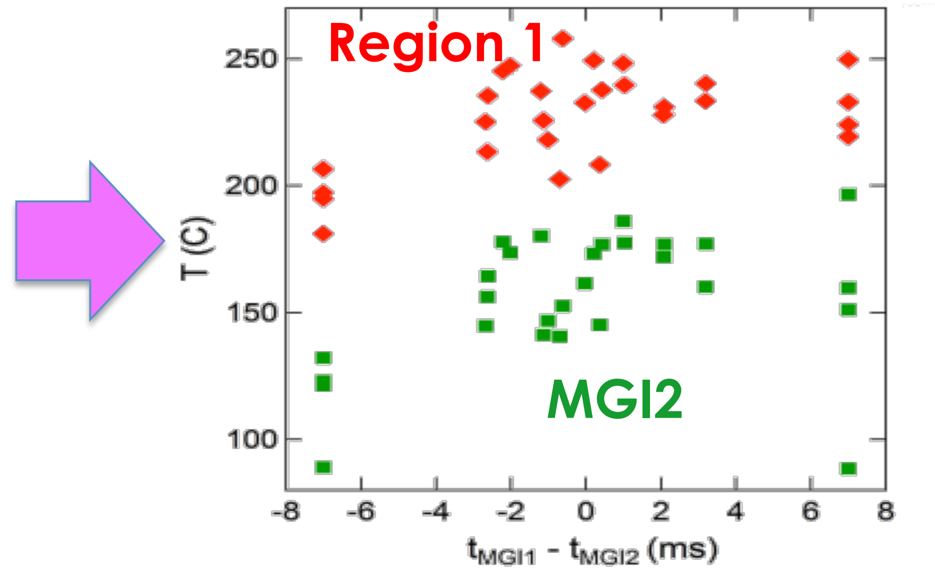
- **DIII-D:** Thermal imaging indicates MGI remains cooler than nearby wall





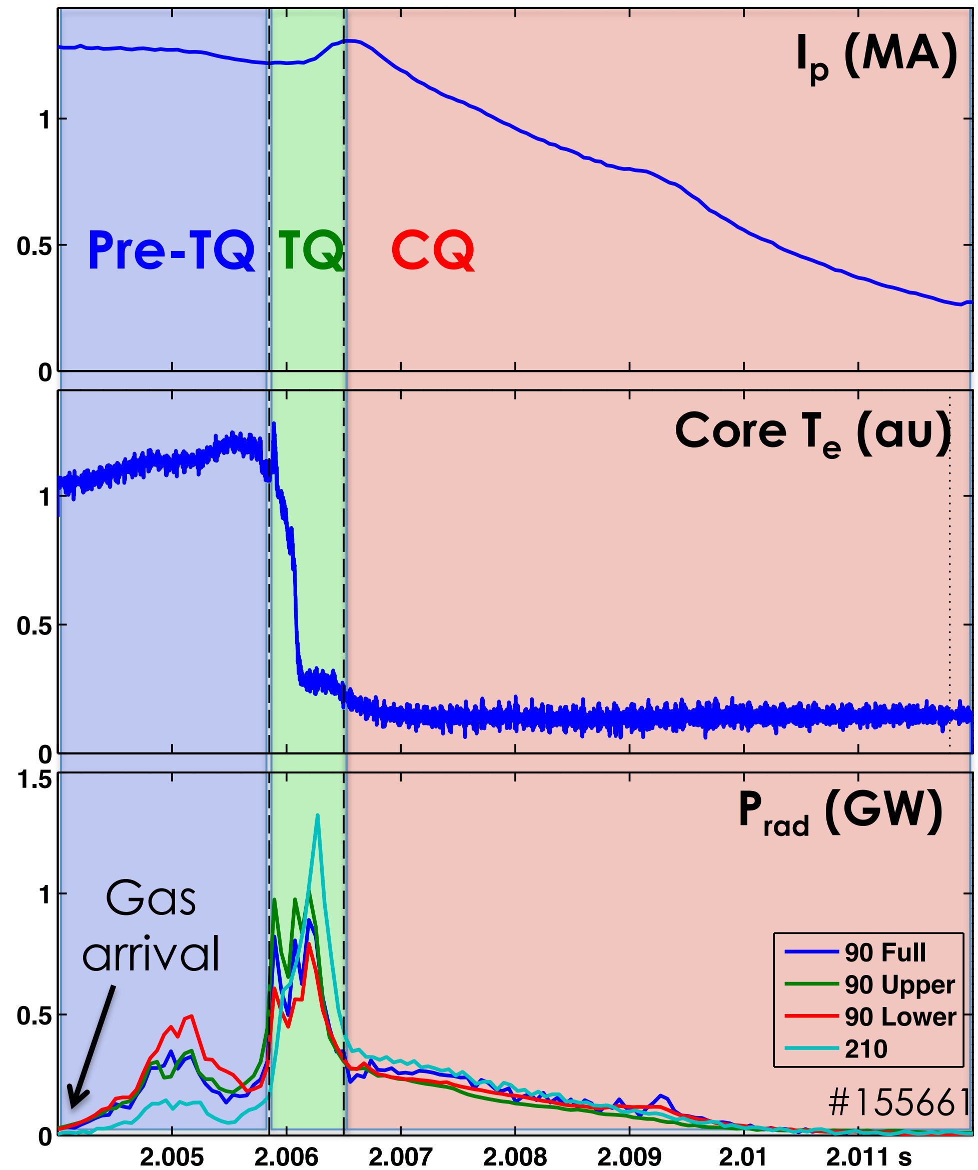


Commaux 2013 APS (PoP in submission)

DIII-D measured dependence of P_{rad} toroidal asymmetry upon MGI spatial distribution

- P_{rad} asymmetry vs Δt between 2 MGI valves measured for pre-TQ, TQ, & CQ

- P_{rad} integrated over each time phase to give W_{rad}



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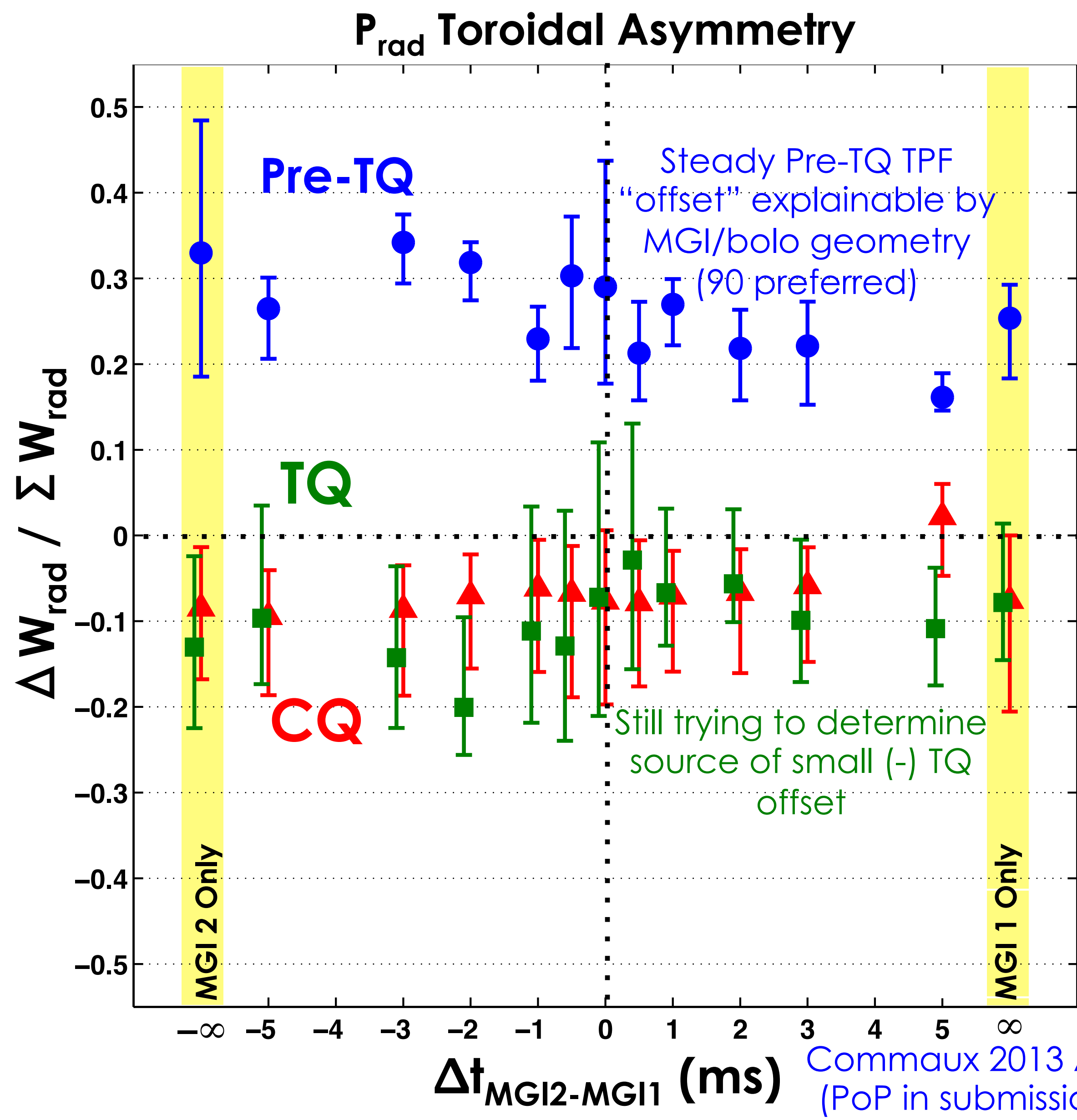
Multiple Injector Radiation Toroidal Asymmetry: Low W_{rad} asymmetry & little variation observed for dual vs single MGI

- TQ & CQ exhibit low toroidal asymmetry
  - TPF = W_{max}/W_{mean}
  - ITER limit: TPF ~ 2
- No significant variation with valve delay



Commaux 2013 APS (PoP in submission)

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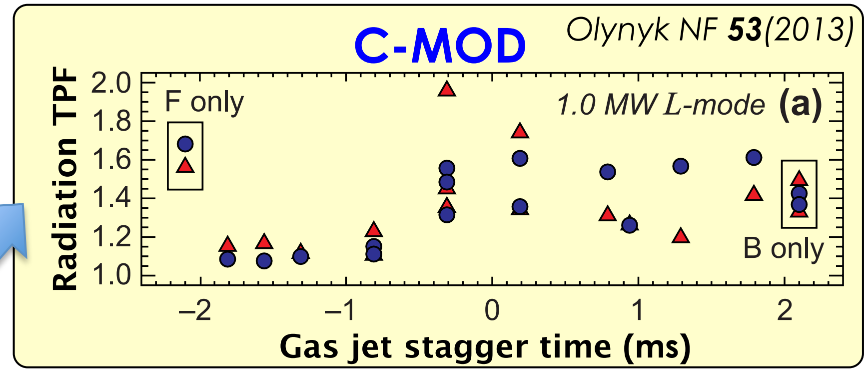
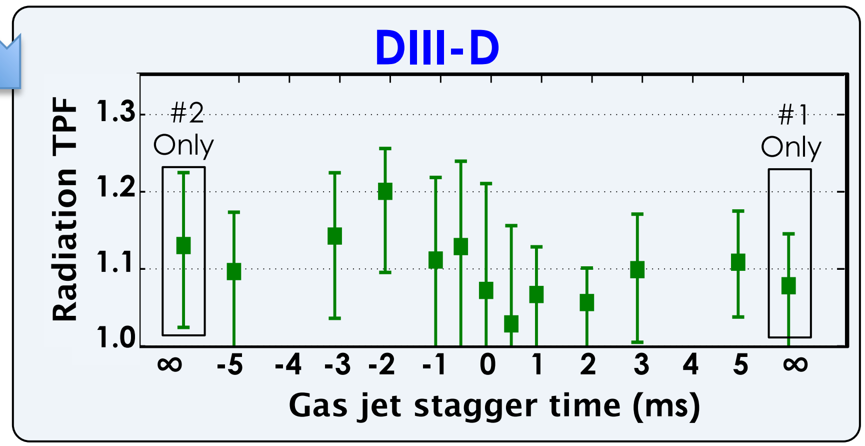
Multiple Injector Radiation Toroidal Asymmetry: Comparison to CMOD data yields mixed results

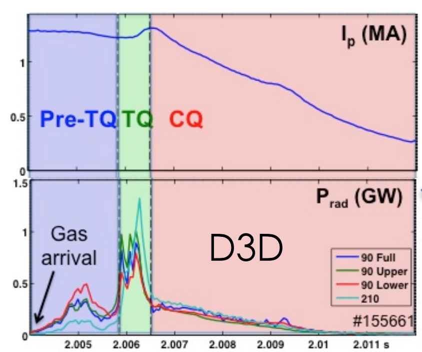
- **C-MOD & DIII-D agree that multiple injectors do not improve TQ P_{rad} toroidal asymmetry…**



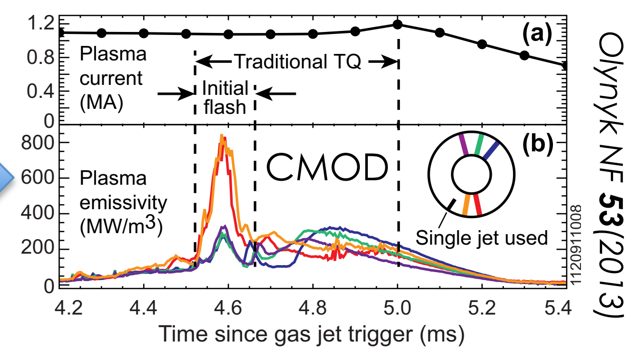
- **…but observed magnitudes differ significantly (C-MOD > DIII-D)**



- **We are trying to determine what may be causing this C-MOD/D3D difference in TQ TPF magnitude**
  - Rotation? Field line pitch? TQ/CQ timing differences?



Why is CMOD CQ timing so delayed?



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Multiple Injector Radiation Toroidal Asymmetry:
Comparison to CMOD data yields mixed results

- C-MO
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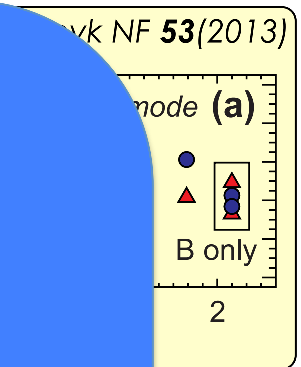
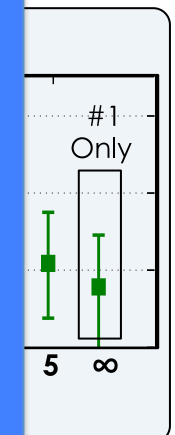
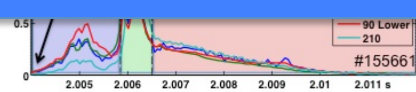
  TQ
- …b
  sig
- We
  ma
  diff
  - –





NIMROD seems to explain results very well…
See Izzo's talk next



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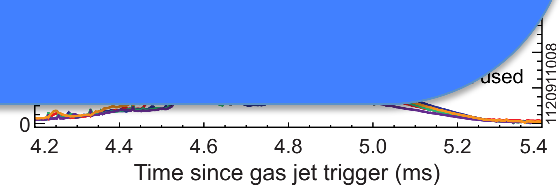
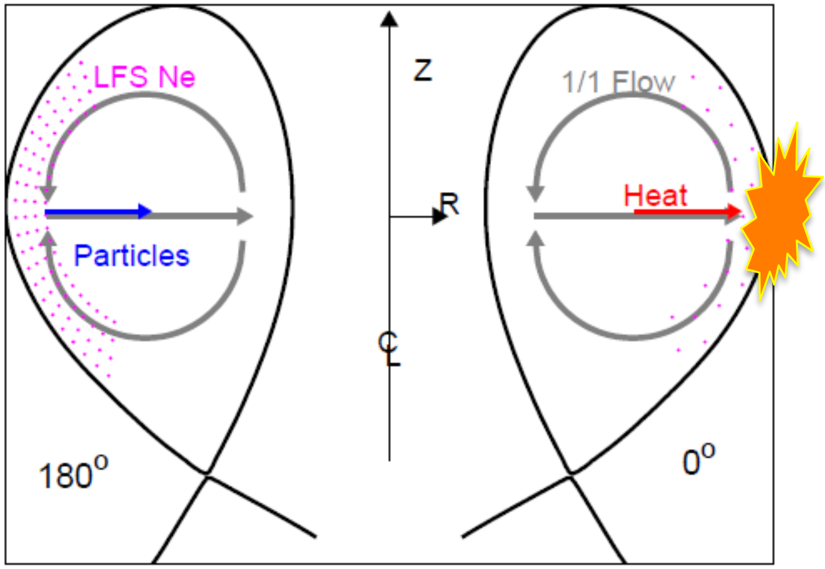


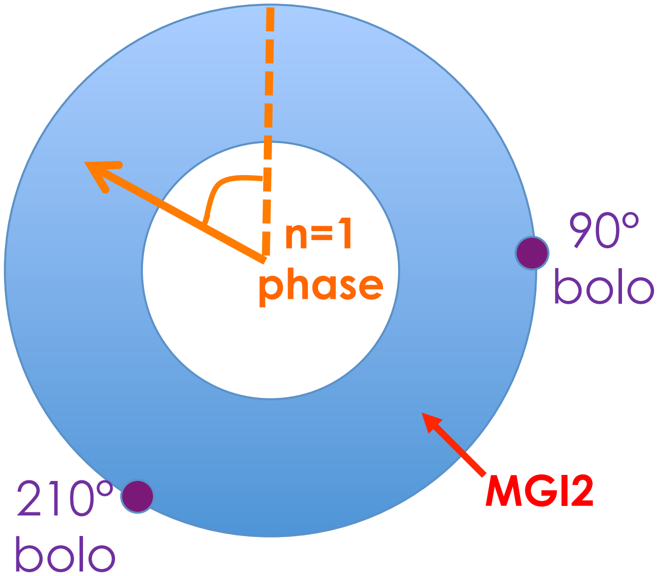
Olynyk NF **53**(2013)

DIII-D exploring effect of MHD upon P_{rad} asymmetry during TQ

- **NIMROD:** **1/1 mode during TQ will cause P_{rad} asymmetry *<u>even if MGI is isotropic</u>*** [Izzo 2012 IAEA]

- **DIII-D Test:** **If MHD causes P_{rad} asymmetry, can P_{rad} phase be altered by locking 1/1 mode at varying phases?**
  – Vary n=1 phase 90° each shot

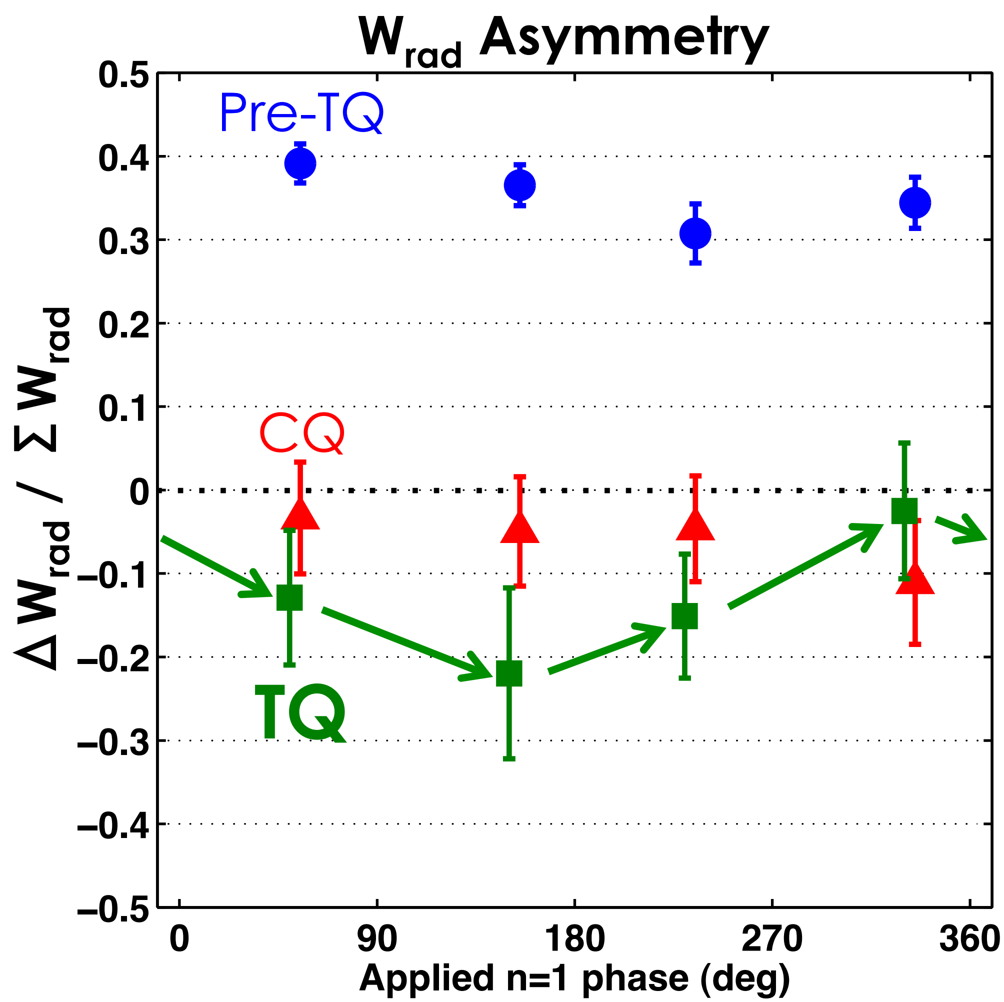




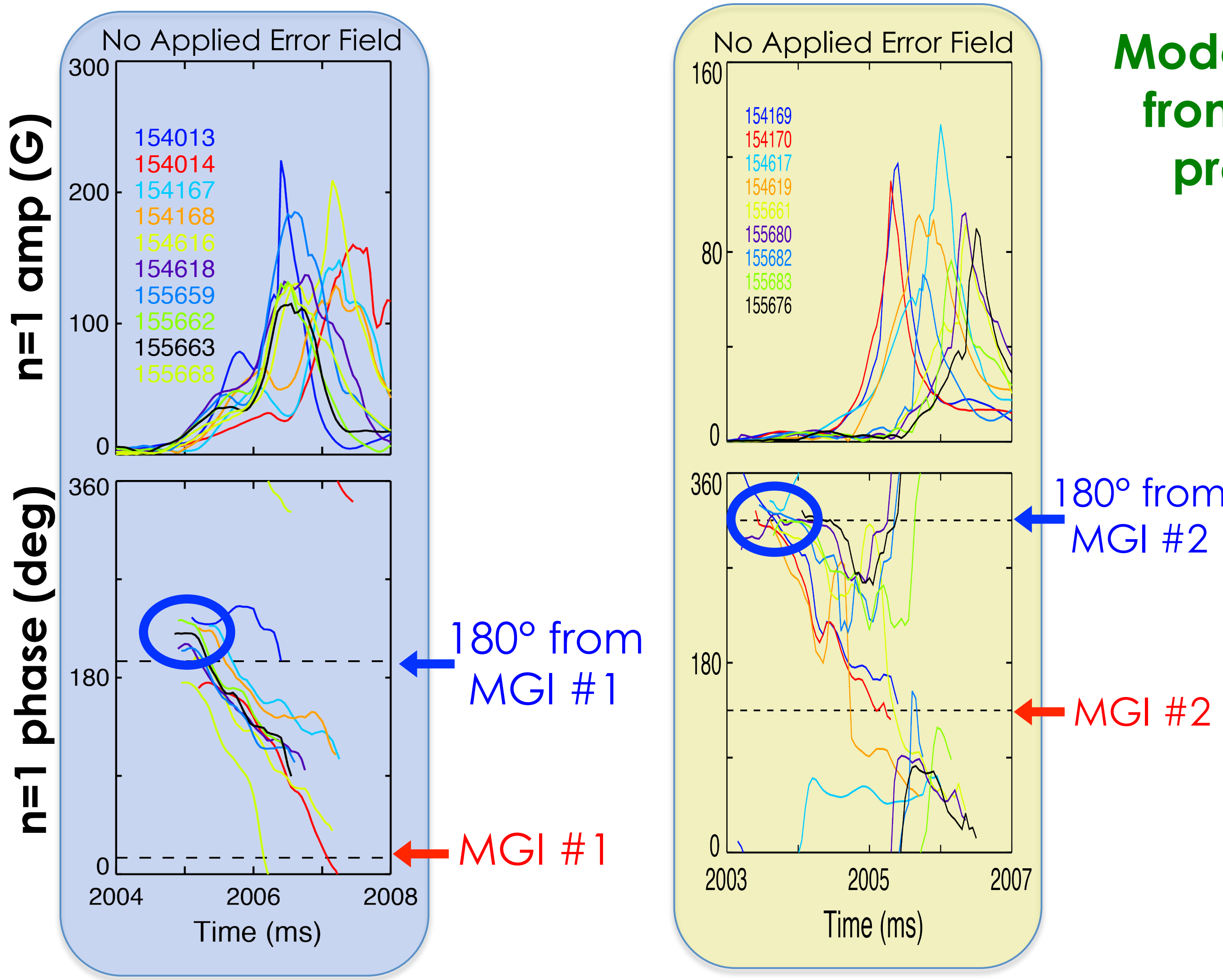
MHD Influence on Toroidal Rad Asym: Phase of TQ P_{rad} asymmetry modified by applied n=1 error field

- **TQ: Systematic variation with applied n=1 field**
  - n=1 character
  - Not observed in preTQ, CQ

- **Consistent with MHD model for TQ P_{rad} asymmetry, although affect is smaller than expected**



MHD Influence on Toroidal Rad Asym: Initial mode phase determined by injection location



Mode begins 180° from injector as predicted by NIMROD!

Izzo NF **20** (2013)

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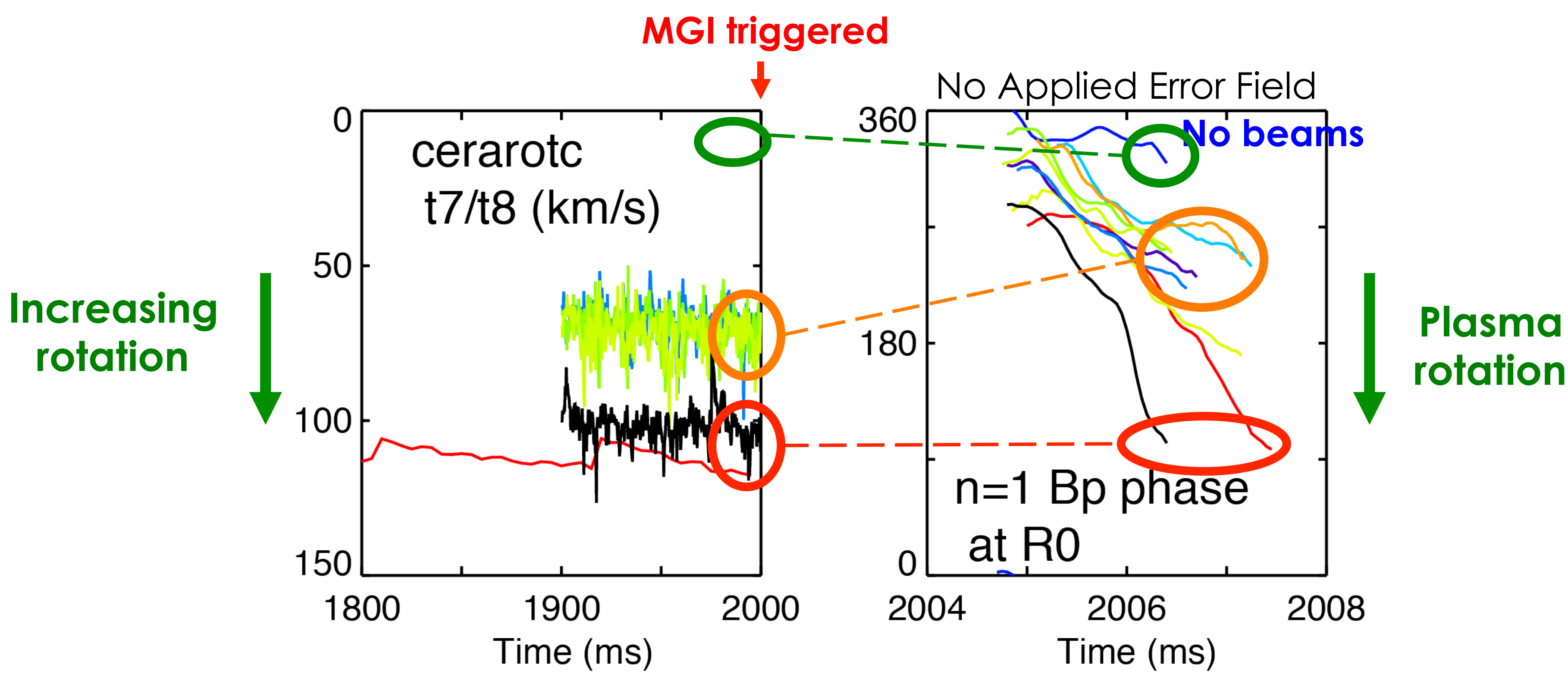
MHD Influence on Toroidal Rad Asym: Mode rotates from initial phase due to pre-MGI plasma rotation



- **Plasma rotation before MGI influences pre-TQ mode rotation**
  - Pre-TQ rotation << pre-MGI rotation
- **Most end near ~250°, due to initial phase plus typical rotation**

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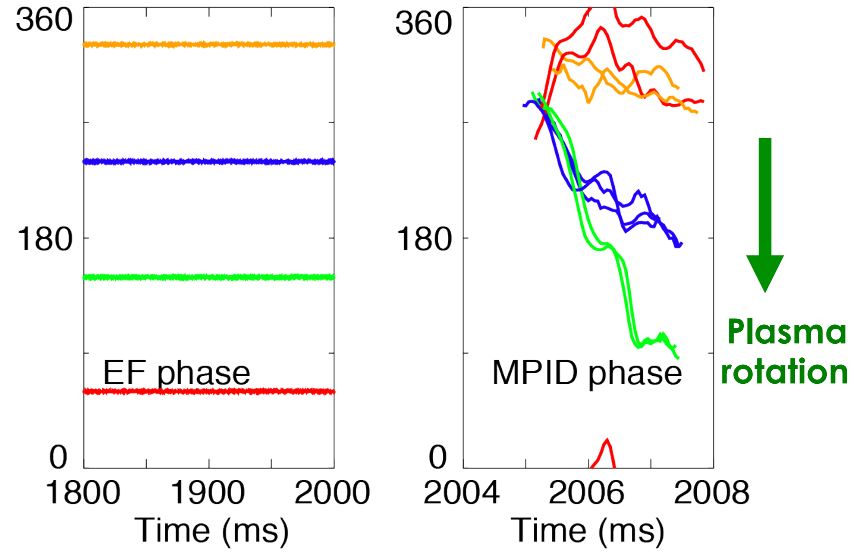
MHD Influence on Toroidal Rad Asym: Error field competes with rotation in determining mode phase

- **Large *n*=1 EF applied using I-coils**
- **Mode rotates from initial phase towards EF**
- **Torque from EF competes against rotation effect**

EF on at 1400 ms



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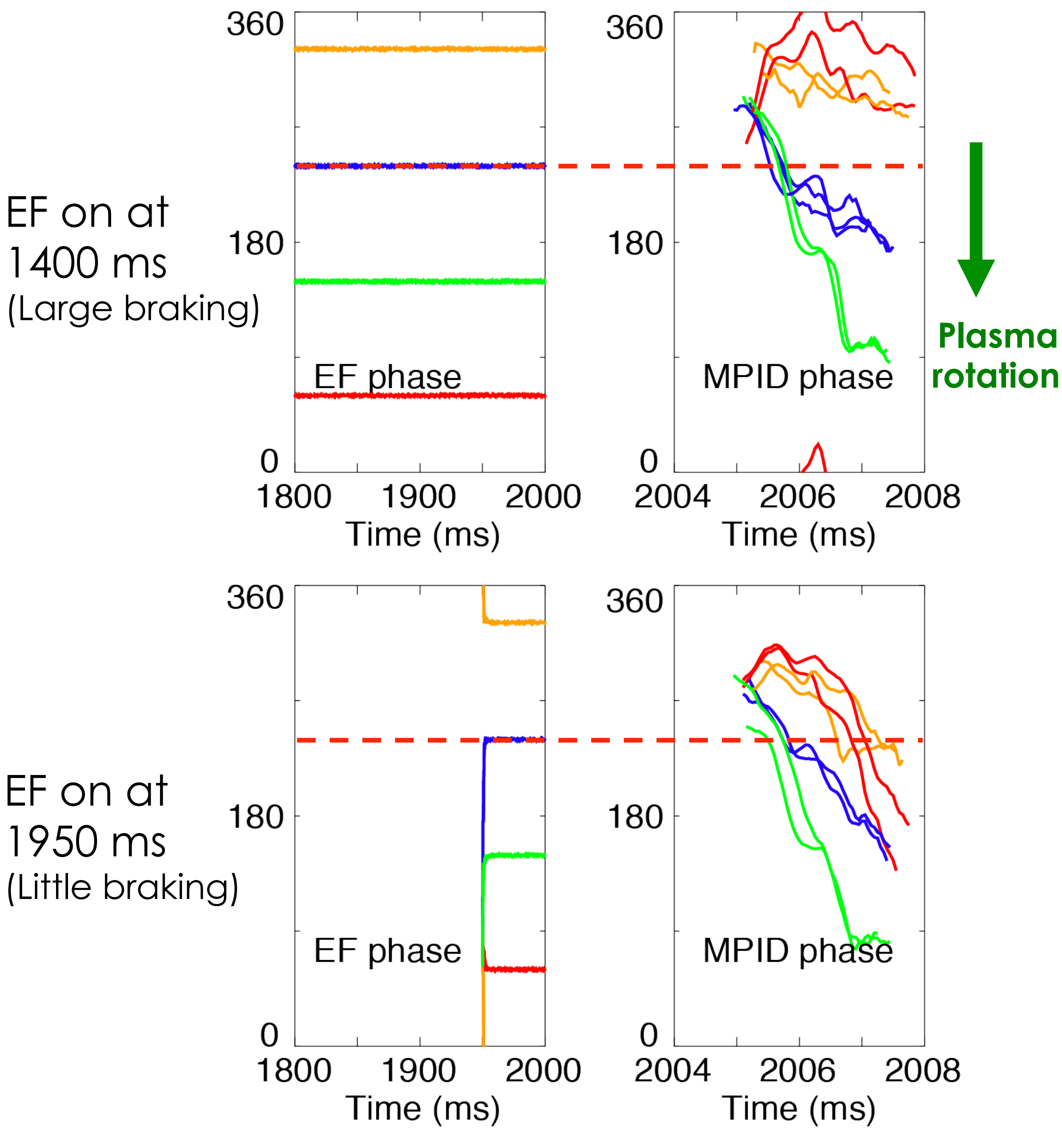
- **Torque from EF competes against rotation effect**
  - Red case is like inverted pendulum



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Radiation Asymmetry: To Do List

1. **Verify relationship between toroidal asymmetry and n=1 mode** (planned end of July)
   - Avoid "blind spots"
   - Remove rotation
   - Flip helicity (see Izzo talk next)

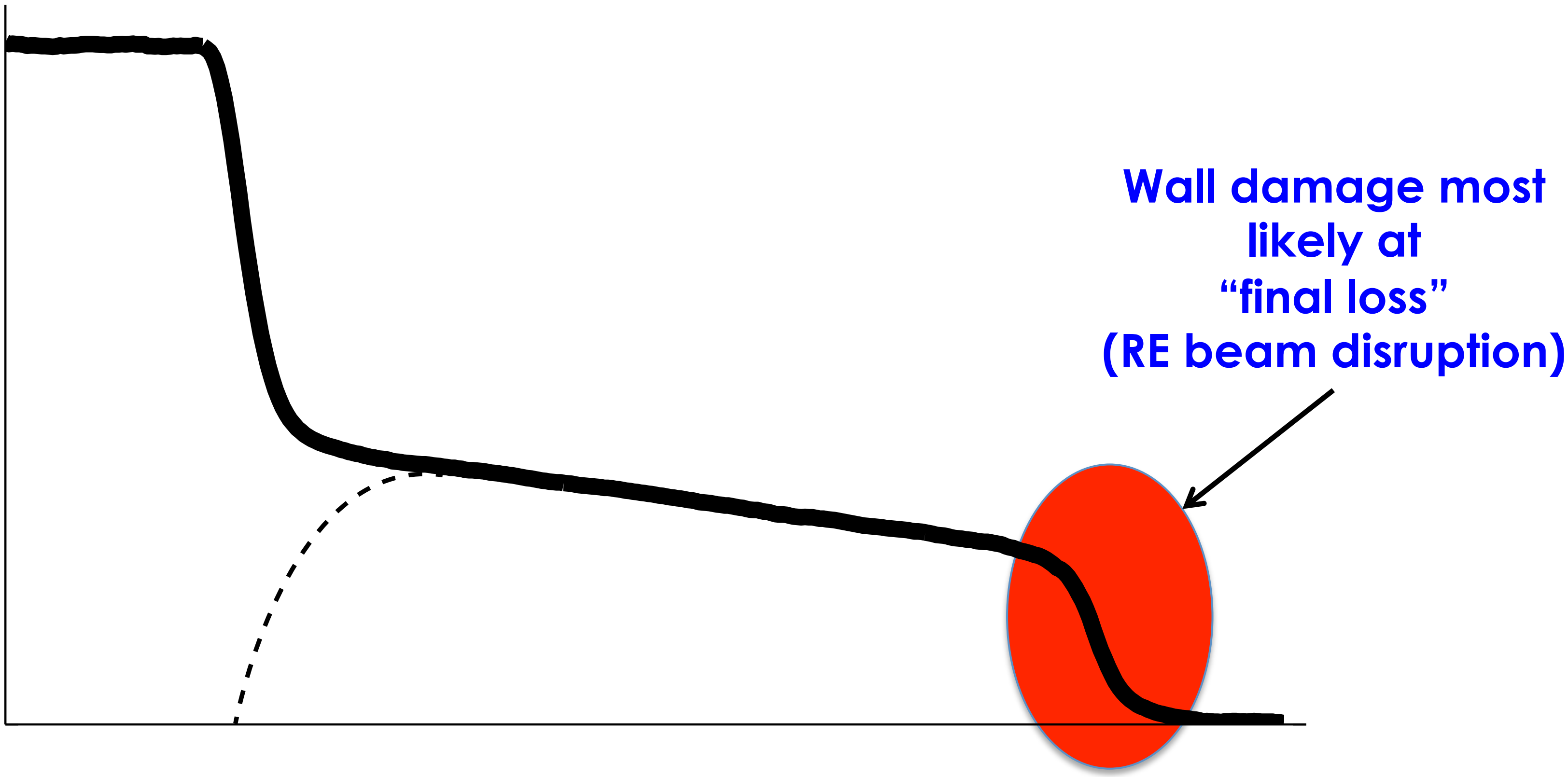
2. **Measure / predict effect of multiple injectors on poloidal asymmetry** (in progress)
   - Likely more important than toroidal asymmetry

3. **Characterize radiation asymmetry using shattered pellet injection (SPI)**

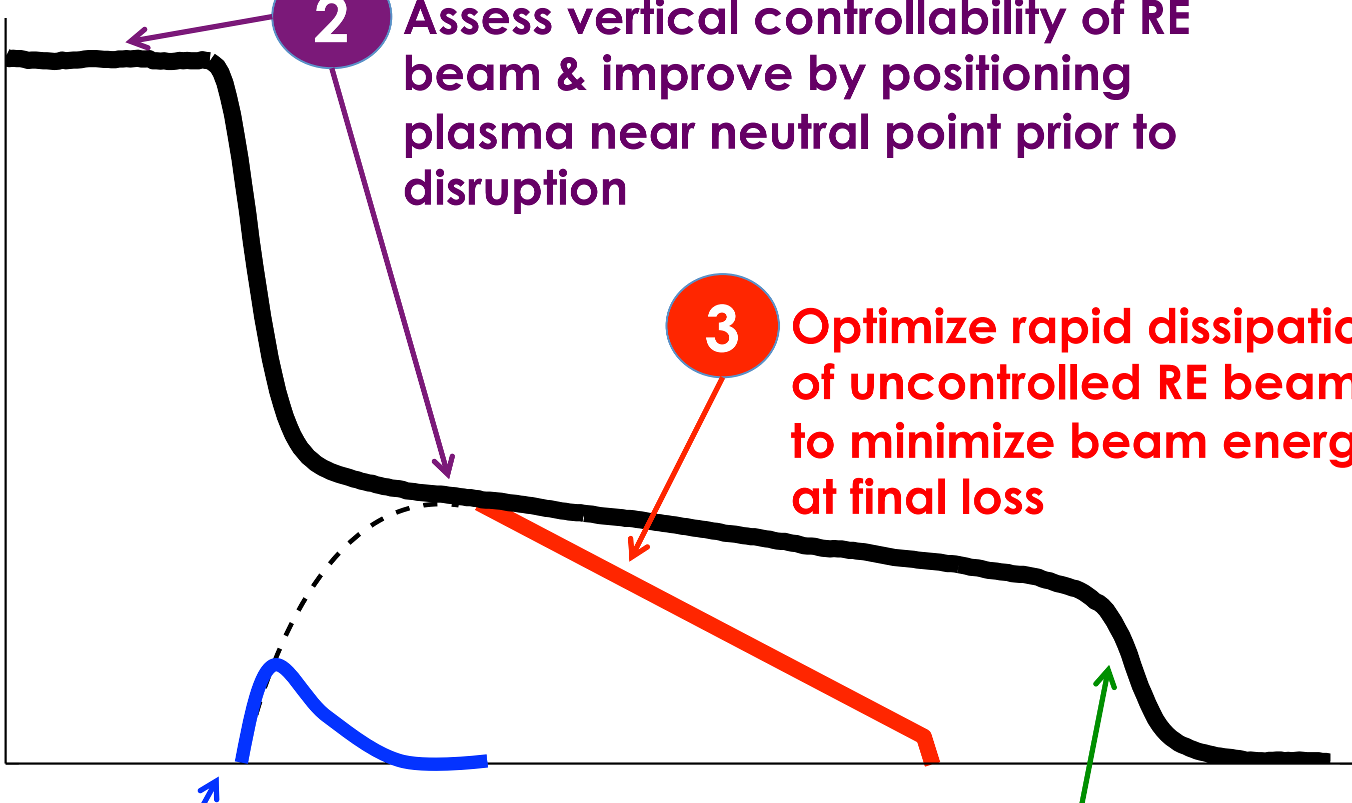
1. Radiated power asymmetry during MGI

2. Runaway electron dissipation

Rapid Loss of Relativistic (10's MeV) RE to Wall May Cause Intense Localized Damage to Vessel Components



Multiple Points of Interest Along the the RE Beam Life Cycle



2 Assess vertical controllability of RE beam & improve by positioning plasma near neutral point prior to disruption

3 Optimize rapid dissipation of uncontrolled RE beam to minimize beam energy at final loss

1 Assess feasibility of completely suppressing or "stunting" RE avalanche

4 Develop physics basis for onset, power transfer, & footprint of final loss

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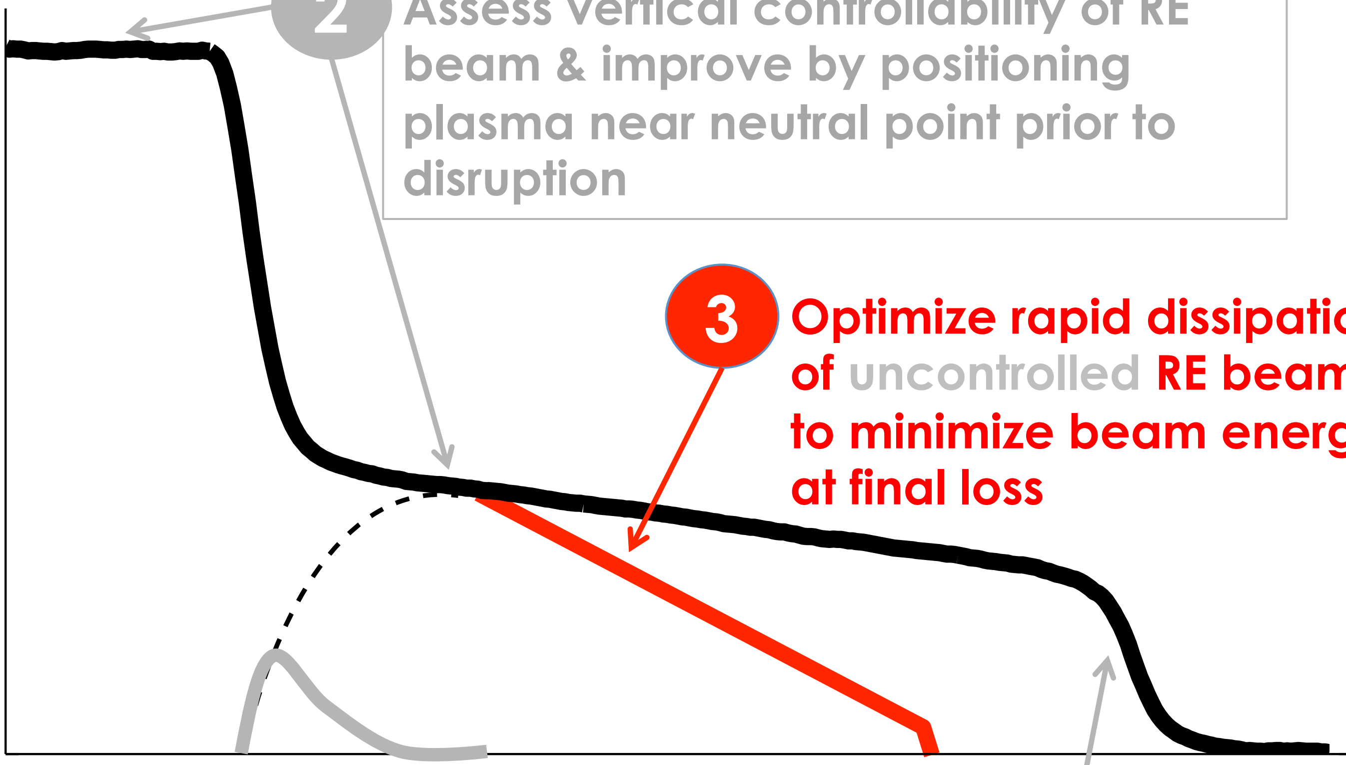

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Today

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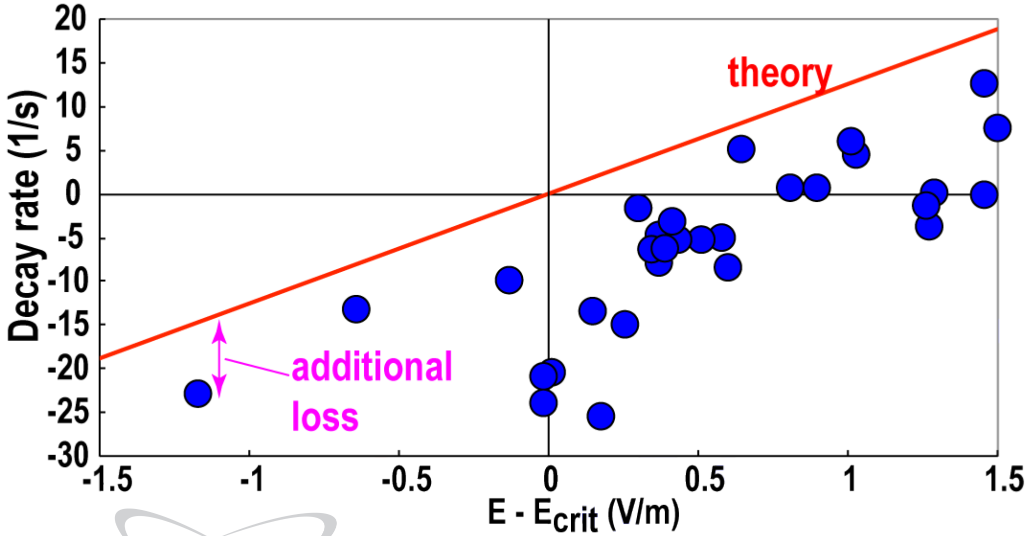
Motivation: Understand dissipation of RE magnetic and kinetic energy after injection of high-Z gas

- High-Z ions cause rapid dissipation of RE energy
- May be useful way to reduce RE beam energy before wall strike in ITER.
- Current dissipation rate faster than expected from avalanche theory (Putvinski, NF, 1994).

Measured and predicted RE plateau decay rate in middle of plateau with ~10% Ar content



Hollmann NF **53**, 083004 (2013)

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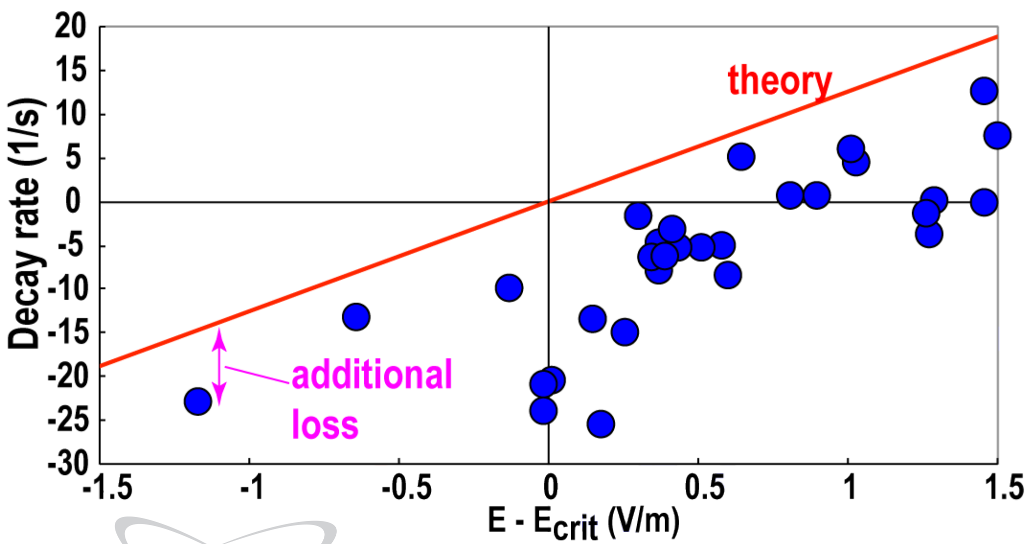
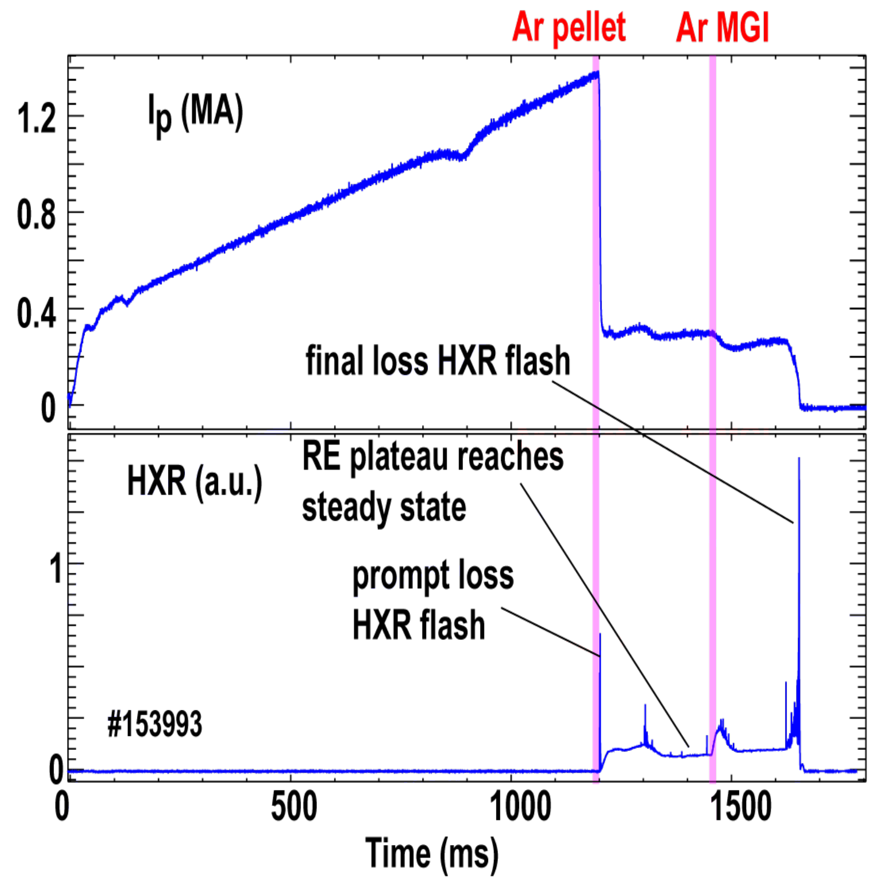


What is happening to f(E) during this dissipation?

Hollmann NF **53**, 083004 (2013)

Overview of experiment timing for injecting MGI into RE plateau

- Start with circular, ECH heated low density target.
- Shut down at 1200 ms with 15 torr-l Ar pellet injection, creating RE plateau.
- Request plasma control system to hold RE plateau centered with 300 kA current.
- Equilibrium reached (steady HXR) at about 1350 ms.
- Fire MGI into RE plateau at 1450 ms.
- Run out of V-s and lose plasma to wall around 1600 ms.

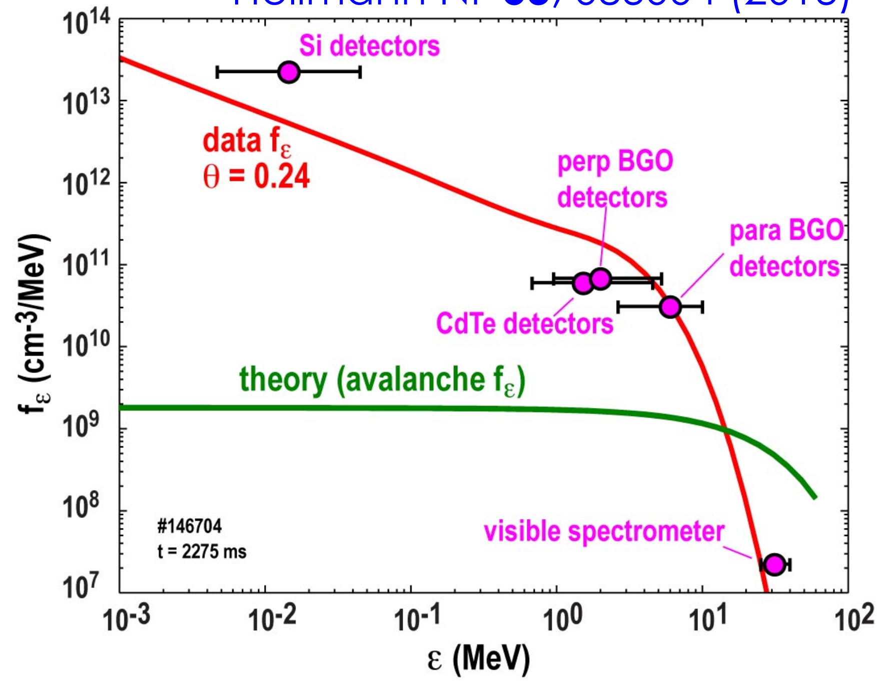


Previous reconstruction of RE f(E)

- Previously, attempted to reconstruct RE f_E during stationary RE plateau.
- Assumed constant pitch angle θ.

  - Used θ ~ 0.2 based on visible synchrotron spot aspect ratio.
- Found f(E) more skewed to low energies than expected from avalanche theory.

Hollmann NF **53**, 083004 (2013)



RE energy spectrum in stationary plateau

Recent improvements to reconstruction of RE f(E)

- Attempt to reconstruct f_E which best fits multiple diagnostics:

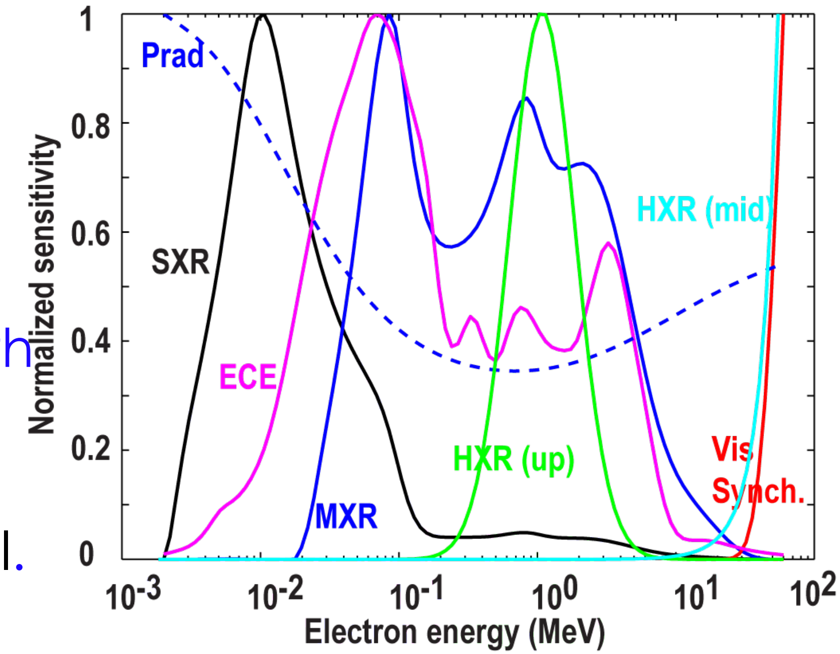
  - SXR, MXR, HXR, visible synchrotron

  - New: add constraint to match I_p and P_{rad} (line radiation).

  - New: allow pitch angle to vary with energy (assume a single θ at each energy, no $f(\theta)$).

  - Don't use ECE; very hard to fit well.

Normalized sensitivity vs energy for different diagnostics (assuming Ar bremsstrahlung)



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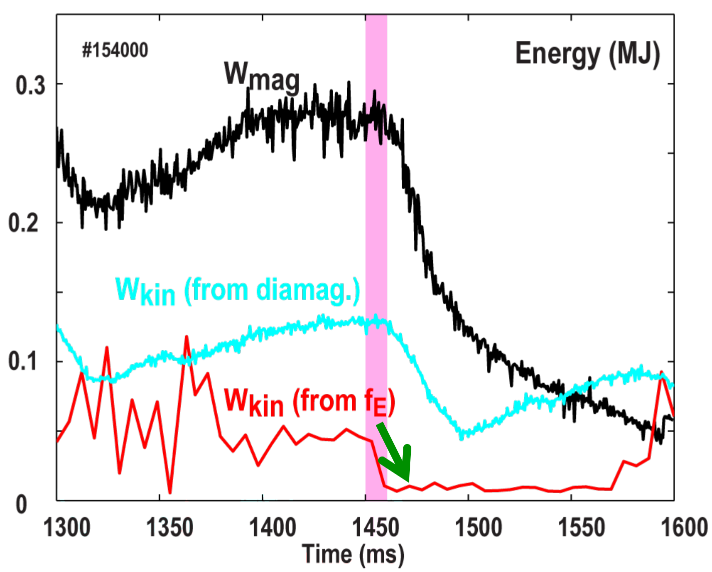
Ar appears to dissipate RE kinetic energy much more effectively than Ne

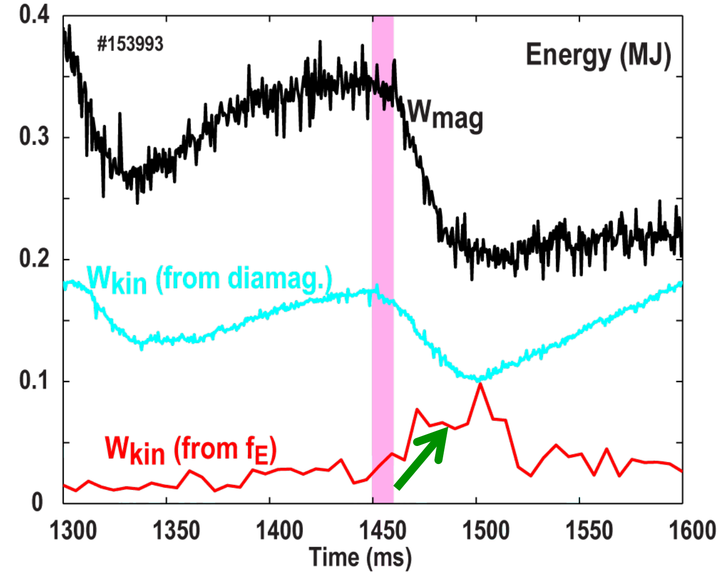
- Very rough estimate of W_{kin} can be made from diamagnetic loops.
- W_{kin} can also be estimated by integrating f_E.

Data indicates drop W_{kin} after Ar MGI, but rise after Ne MGI, despite larger V_{loop} in Ar MGI case

Ar MGI



Ne MGI



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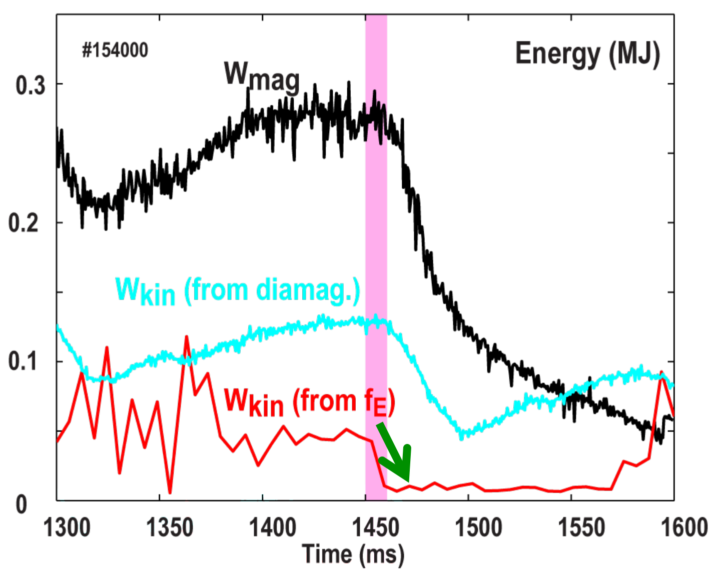
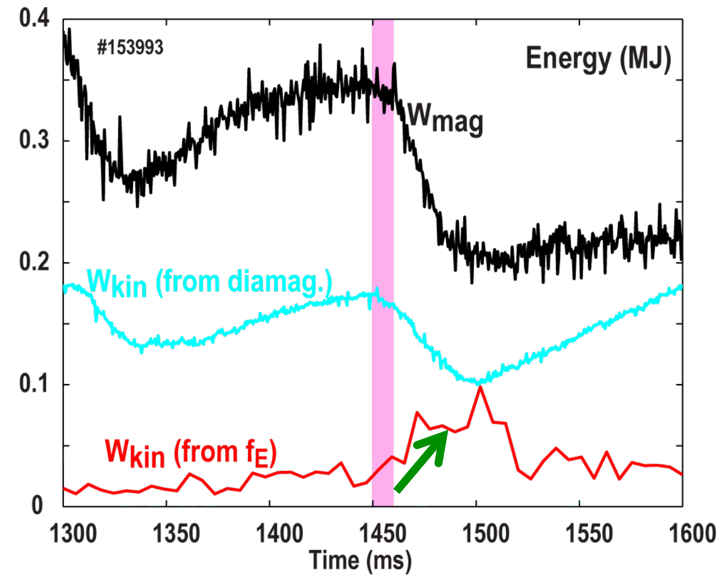


Ne MGI



Consequence: Ar dissipation may result in much more benign RE beam by time of final loss compared to neon

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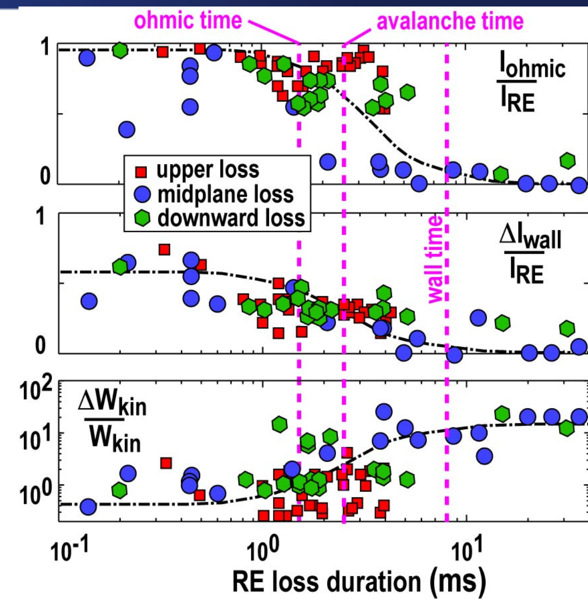
RE Plateau Dissipation: To Do List

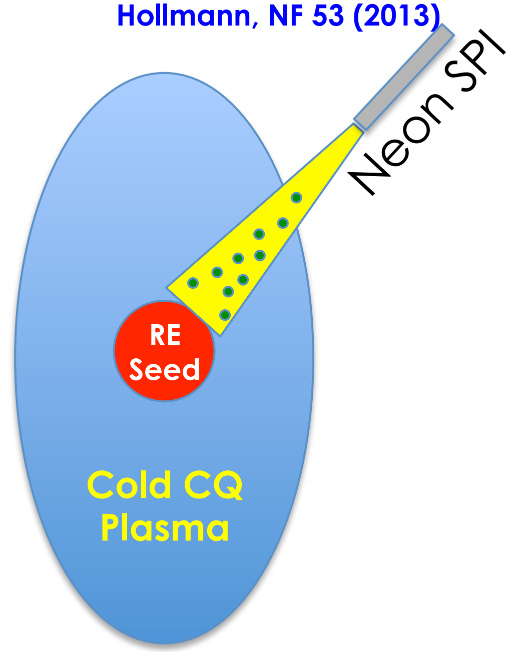
1. **Verify RE kinetic energy measurements using various gases for dissipation** (planned this summer)
   – IR imaging to constrain "knee" in f(E)

2. **Can correct high-Z impurities minimize magnetic-kinetic energy transfer during final loss** (planned this summer)

3. **Can RE be suppressed/stunted by SPI into early CQ (localized, very high density deposition at seed lcoation)**



Hollmann, NF 53 (2013)



Conclusions

- **Radiation asymmetry**
  - Highly localized radiation at injector not significant
  - Little variation seen in toroidal radiation asymmetry 1-2 injectors (will be best explained by NIMROD, next)
  - MHD modes seem to play significant role an radiation asymmetry (as predicted by NIMROD)

3D modeling doing excellent job of describing this process

- **RE dissipation**
  - f(E) measurements indicate that Argon much more effective than neon at reducing RE kinetic energy

Understanding and quantitatively reproducing this result good opportunity for theory/modeling progress