Recent DIII-D Disruption Mitigation Experimental Results

by
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for the
DIII-D Disruption Mitigation Task Force

Presented at the
IEA Workshop: Theory & Simulation of Disruptions
PPPL

July 14, 2015

Outline

1. First tests of Shattered Pellet Injection (SPI) for TQ mitigation
2. Mitigation of unstable plasmas
3. Analysis of toroidal/poloidal radiation asymmetries during Neon MGI
4. RE suppression by secondary injection into early CQ
5. RE plateau dissipation

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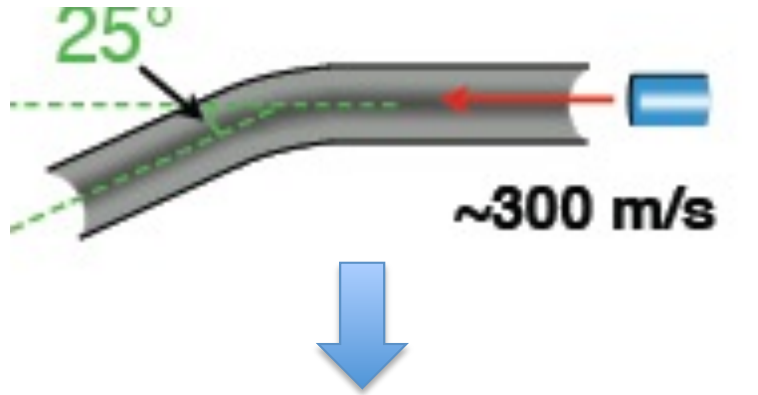
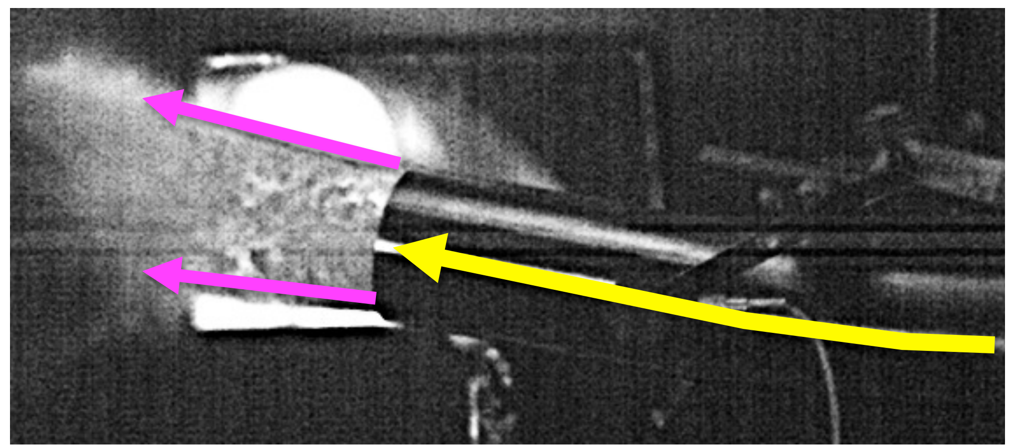
Shattered Pellet Injection (SPI) provides large cryogenic pellet mass while avoiding "bullet"

- **SPI developed by ORNL & deployed at DIII-D**

- **Favorable SPI attributes:**
  1. Collimated pellet stream (high local density)
  2. Deep plasma penetration
  3. Fast response time



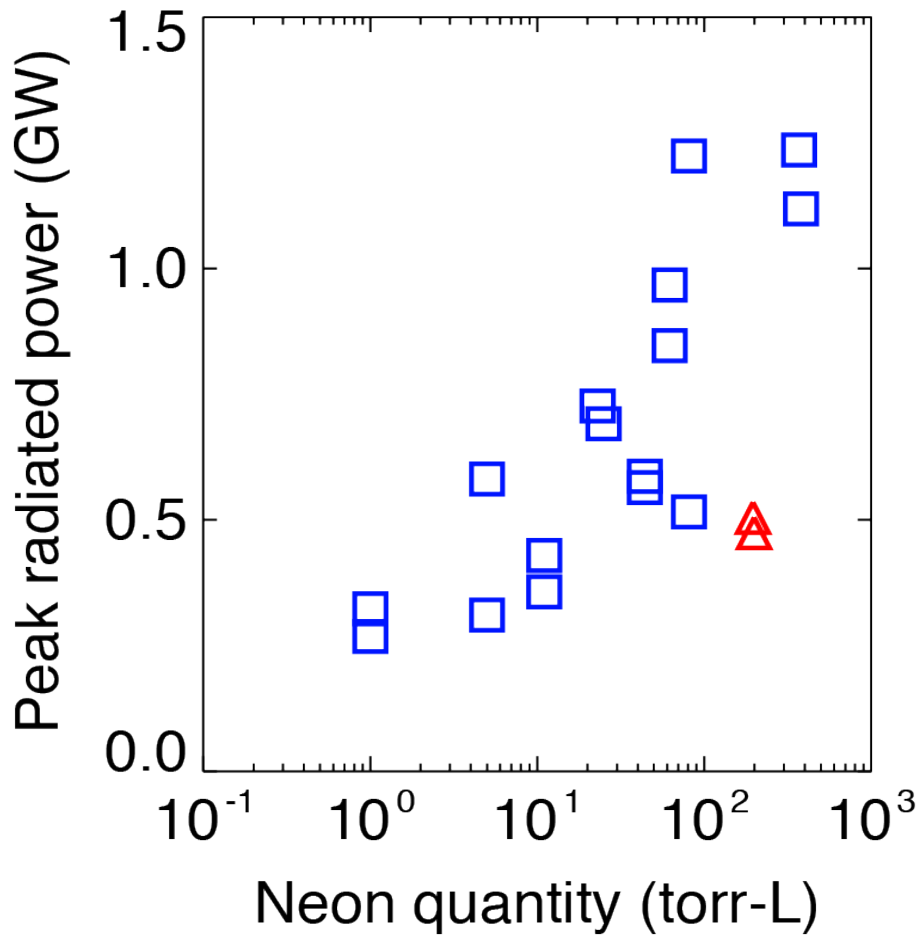


Mixed Ne/D2 pellets allow control of TQ radiated power

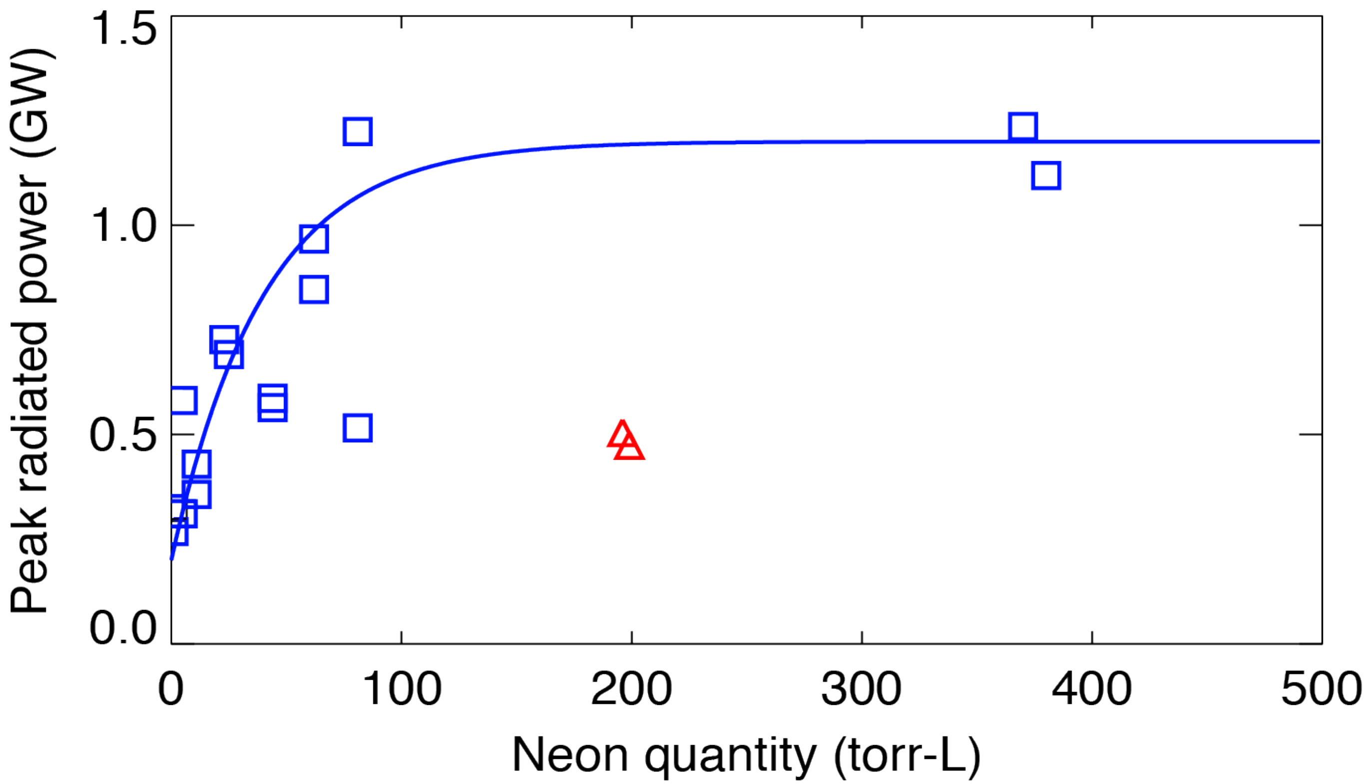
- **SPI pellets not easily changed in size, so composition (pure D_2 to pure Ne) scan is closest approximation to MGI quantity scans**

- **Factor ~4 increase in TQ radiated power over range of scan**

- **Two outliers from broken pellets**



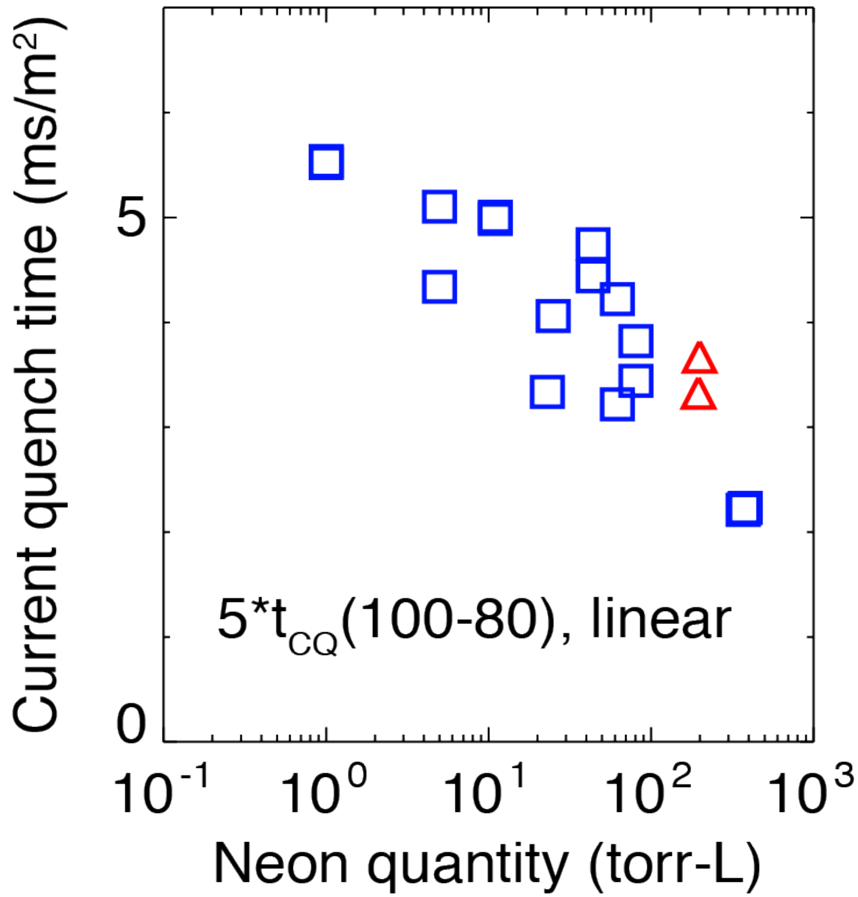
Impact of neon saturates for large quantities



- **Consistent with observations of high radiation fractions with MGI using similar quantities**

Mixed Ne/D2 pellets allow control of CQ timescale

- **Factor ~2 variation demonstrated over range of scan**
- **Saturation effect observed**
- **Broken pellets fit overall trend**



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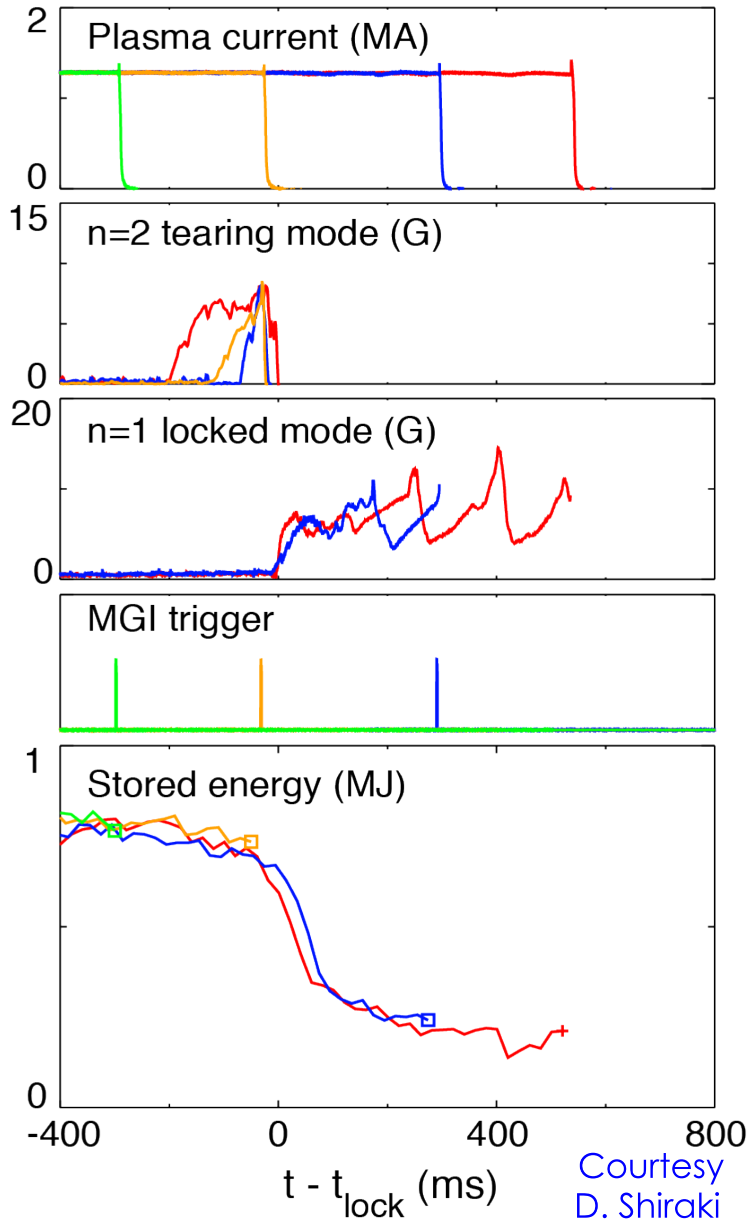
Neon MGI triggered asynchronously to cover entire evolution of healthy→tearing→locking plasma plasma

- **Target = Low torque ITER baseline scenario plasma**
  - Reliably produces n=2 tearing followed by locked mode
- **300 Torr-L Neon MGI**
- **Asynchronous triggering of MGI**
  - H-mode (stable)
  - *m/n* = 3/2 Tearing Mode
  - *m/n* = 2/1 Locked Mode
  - Unmitigated (No MGI)



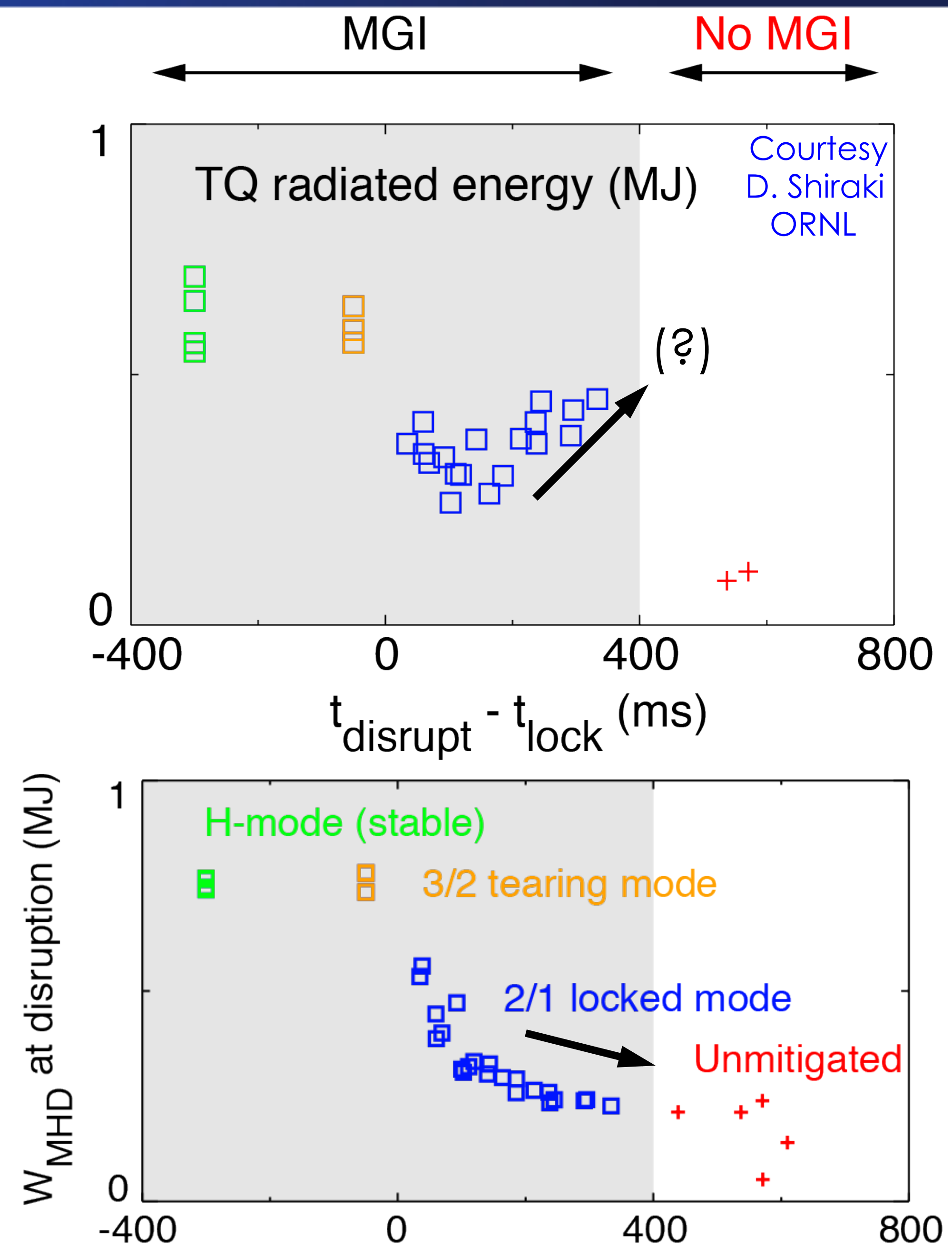
Courtesy D. Shiraki ORNL

See Shiraki NF 2015

Mitigation late in locked mode remains much more effective than no mitigation at all

- **Late MGI: Impurity mixing, radiation fraction hold steady, possibly increase, as locked mode progresses**

- **May imply importance of existing MHD for initial assimilation of MGI**



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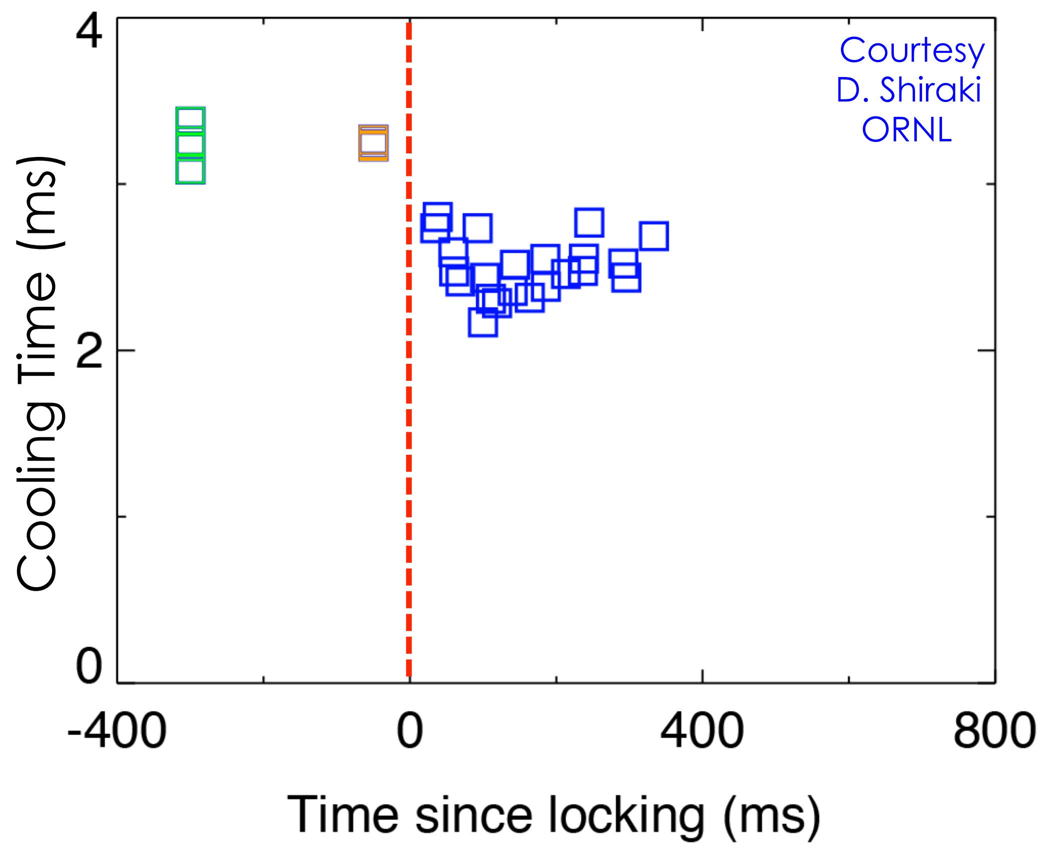
Cooling time reduced once plasma locks

- **Cooling time = Δt from MGI arrival at edge to CQ spike**

- **Consistent with IDDB scaling (decreasing thermal energy → decreased cooling time)**



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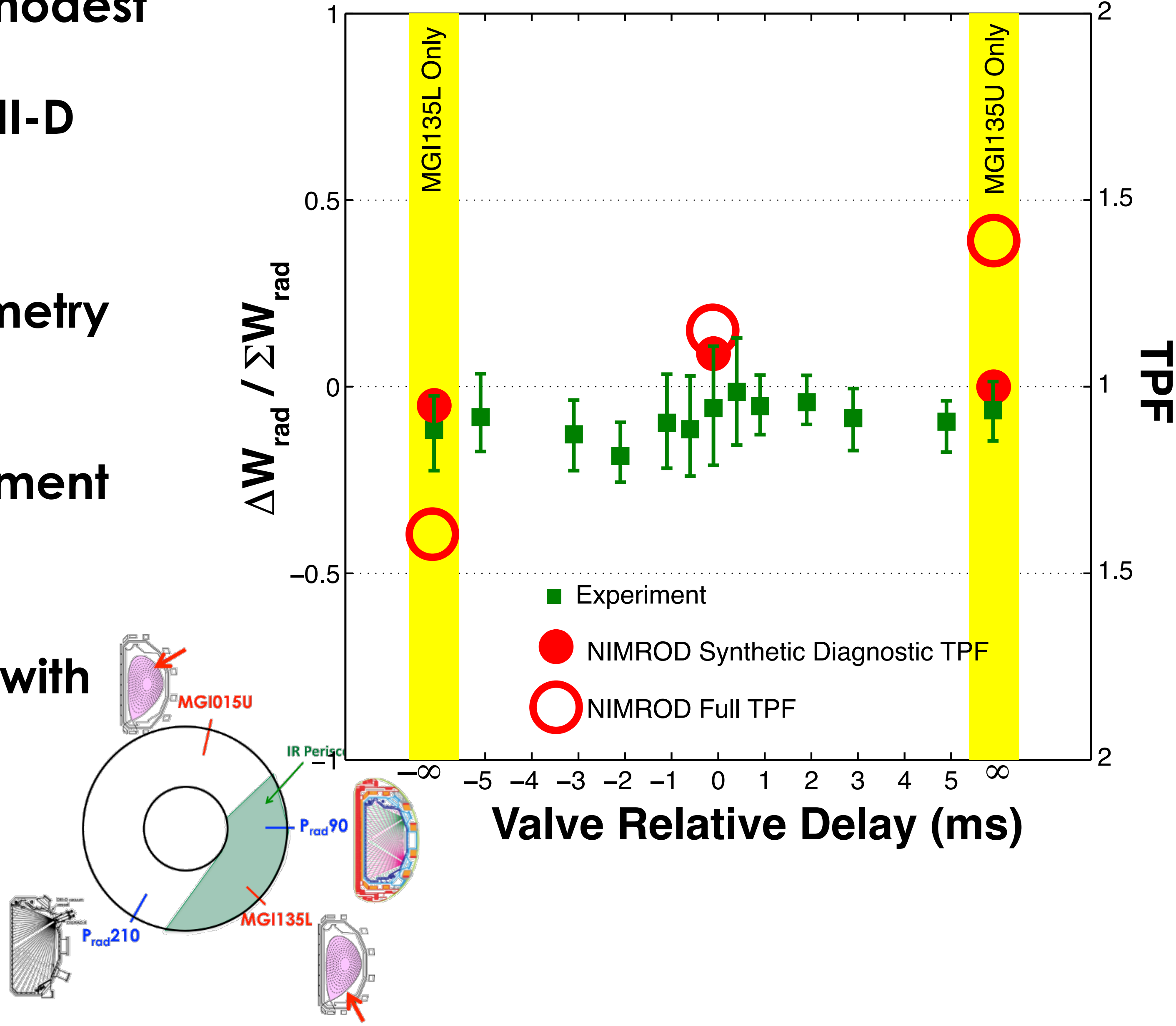
At previous workshop, large discrepancy between observed/ predicted asymmetries blamed on poor toroidal P_{rad} resolution

- **NIMROD predicts modest (TPF ~1.4) toroidal asymmetries for DIII-D using single valve**
- **Observable asymmetry much lower using synthetic 2-point radiation measurement**
- **NIMROD synthetic diagnostic agrees with DIII-D data**

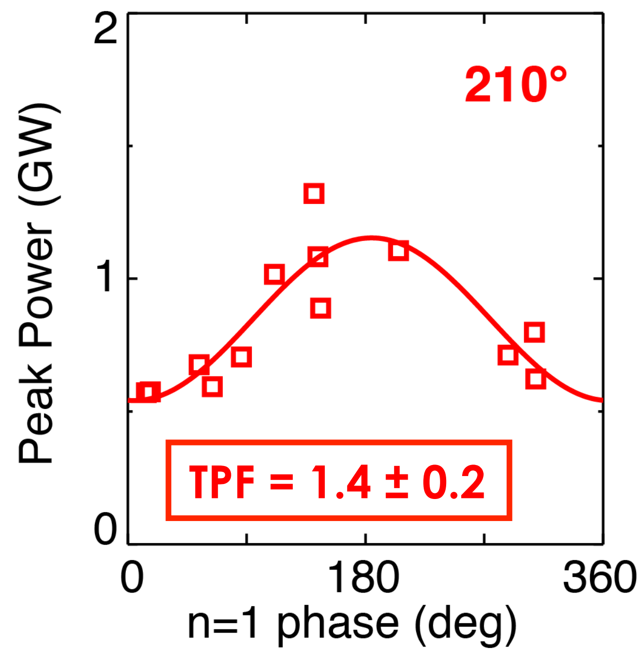


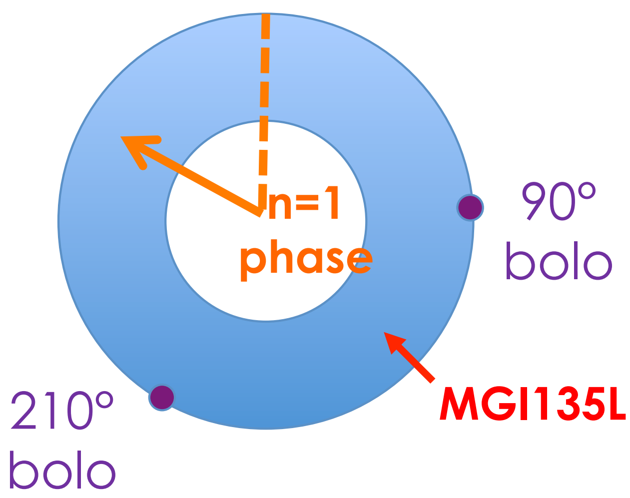
Modified experiment confirms NIMROD TPF predictions using n=1 steering to improve improve toroidal resolution

- **Instead of differencing 2 bolometers, shift MHD mode (& P_{rad}) phase with applied error field shot-to-shot to measure P_{rad} variation at single bolometer**

- **Minimize pre-MGI rotation to give EF maximum control, fine phase control**

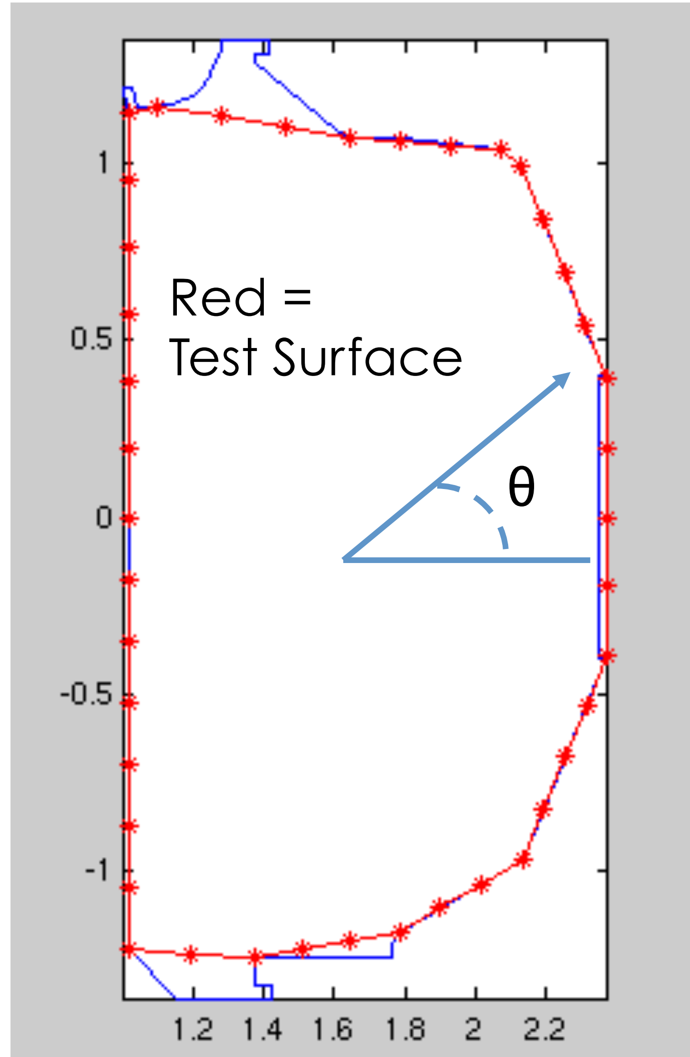
- **NIMROD/experiment agree upon peak TPF = 1.4 (first quantitative validation)**





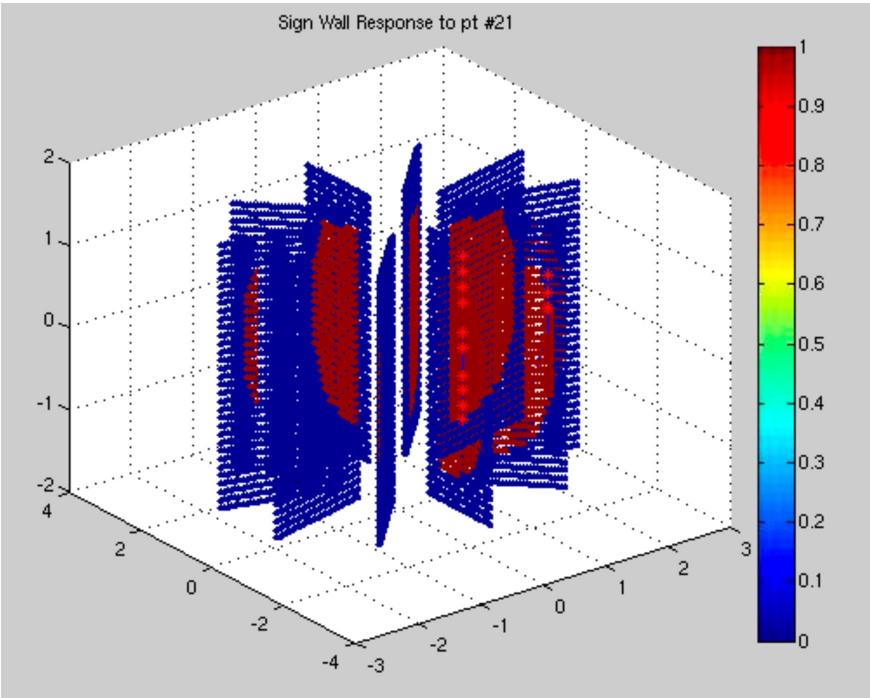
Poloidal asymmetry analysis methodology

1. **Extract emissivity (E) RZ grid from fast bolometry inversion (typically 10x20 grid)**
2. **Create 3D grid array at multiple toroidal locations (assumes axisymmetry)**
3. **Calculate response functions (G) for heat flux at test surface point (simplified first wall) (e.g. Hollmann NF 2012)**
4. **Remove "blind spots"**
5. **E * G = heat flux to wall**

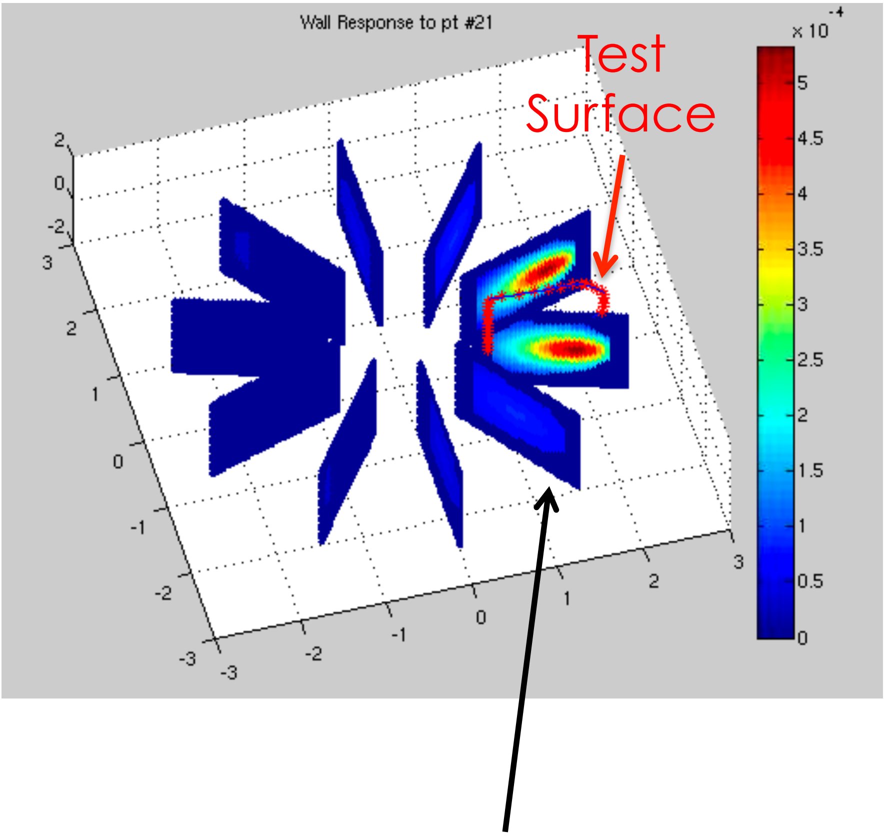


Methodology: 3D grid maps

Visibility map

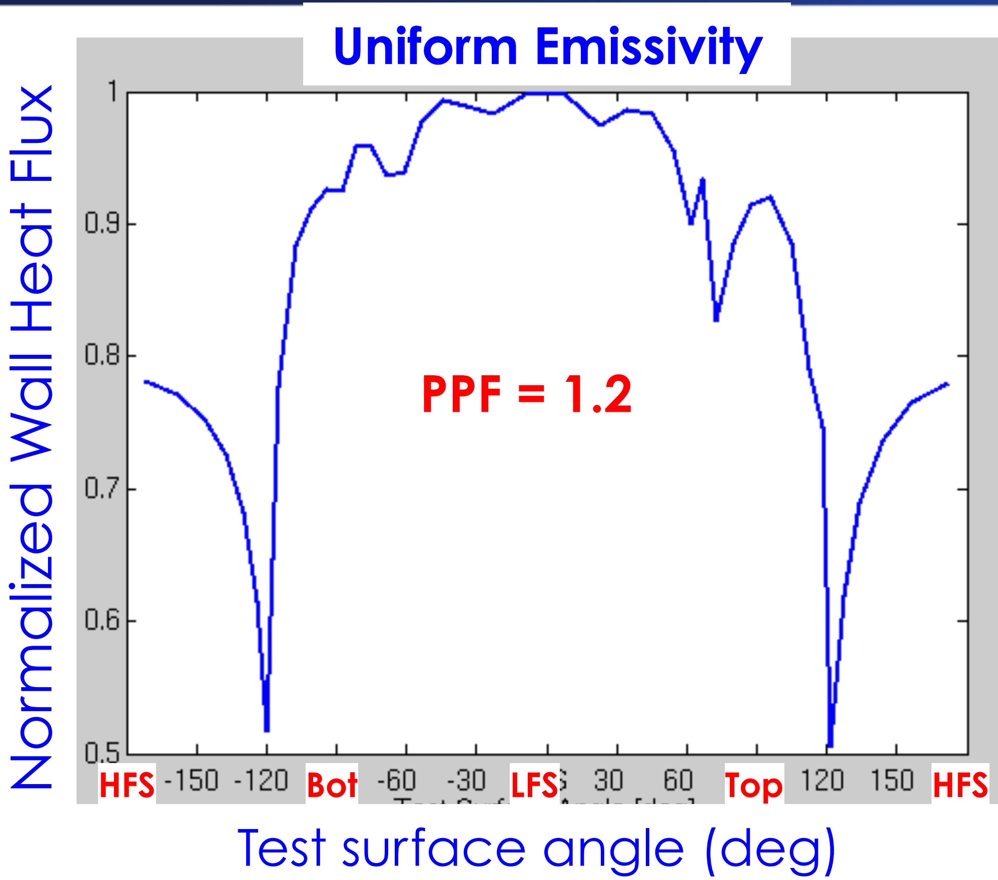


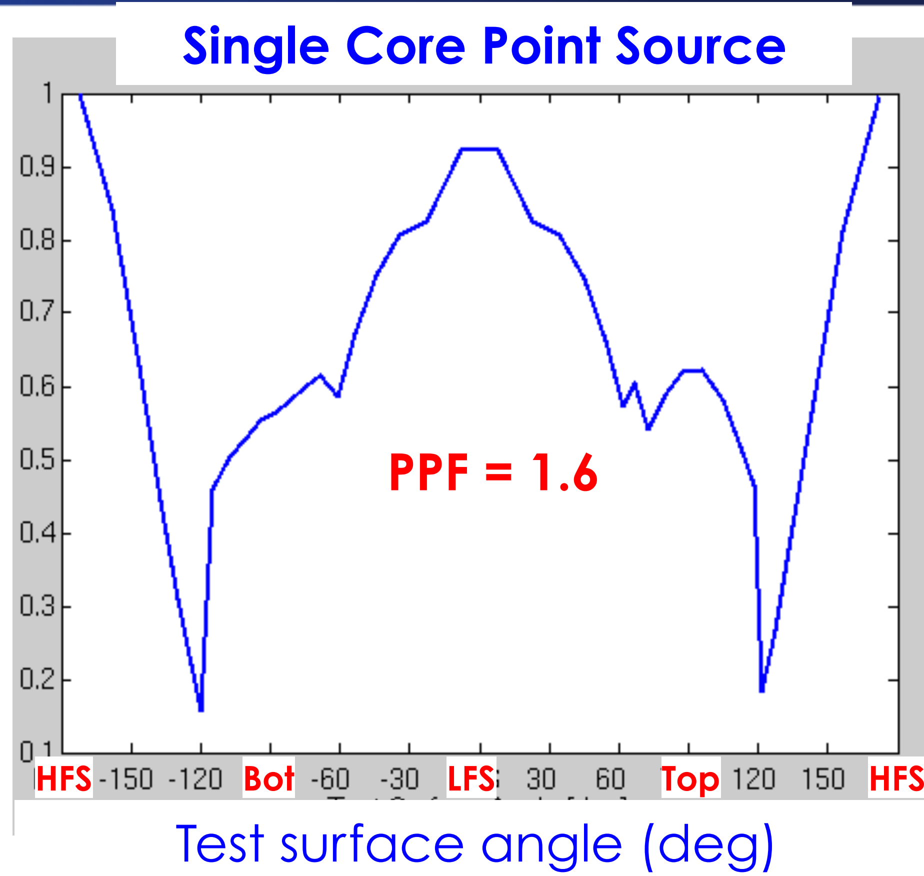
Wall response map (W/m^2 per W/m^3)



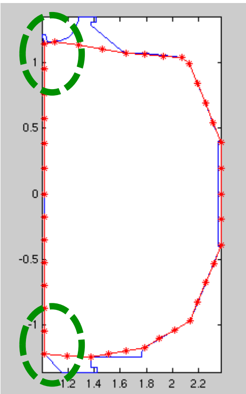
Note that wall response falls off rapidly with toroidal distance so axisymmetric assumption is not unwarranted

Test cases illustrate inherent asymmetry in wall heat flux





Poloidal Peaking Factor (PPF) = simple Max/Mean



Choice of test surface shape effects PPF calculation.

What is most logical standard?

Strict to wall, smoothed wall, LCFS?

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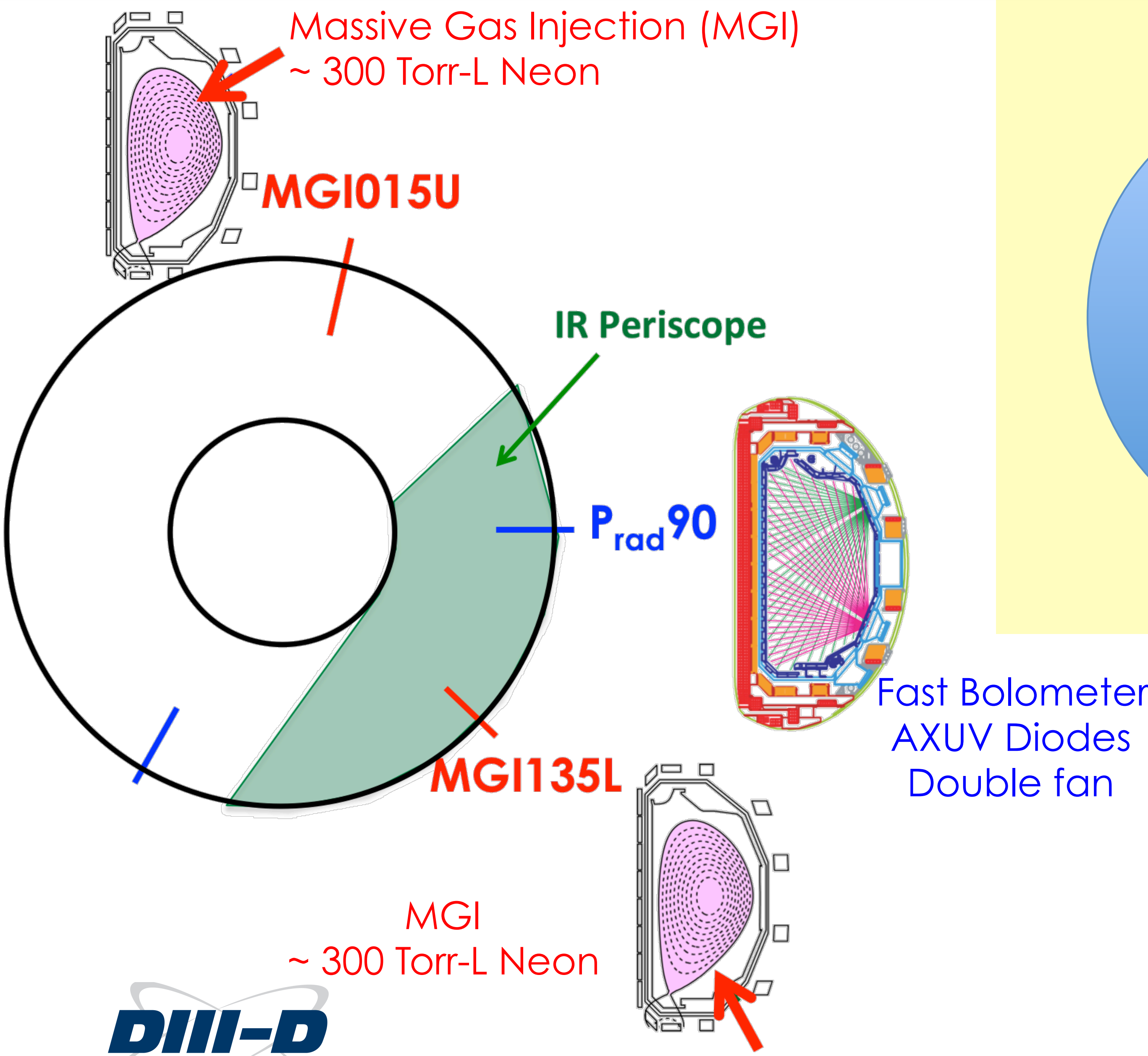
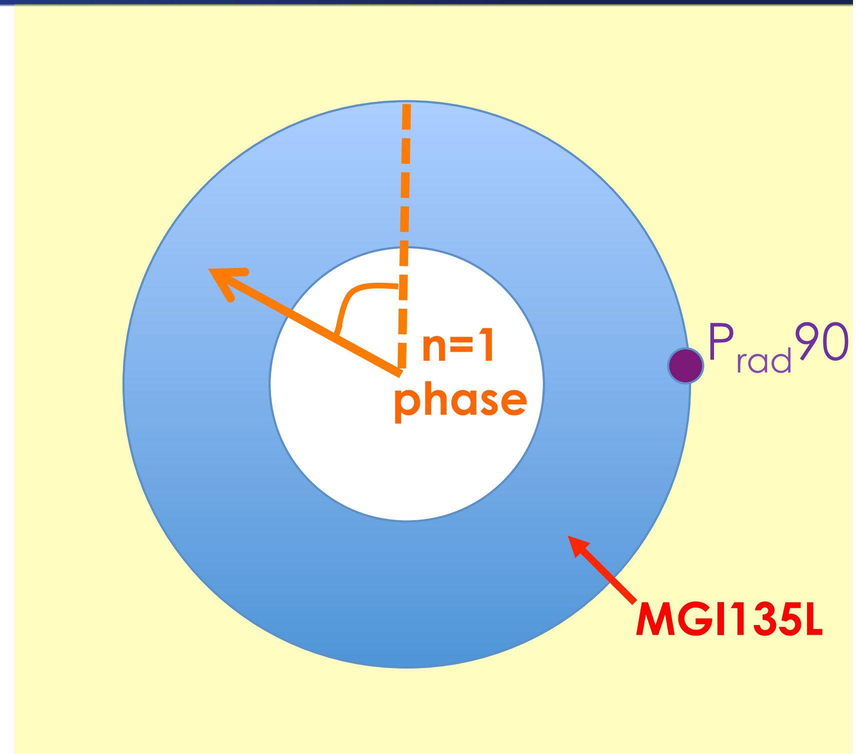
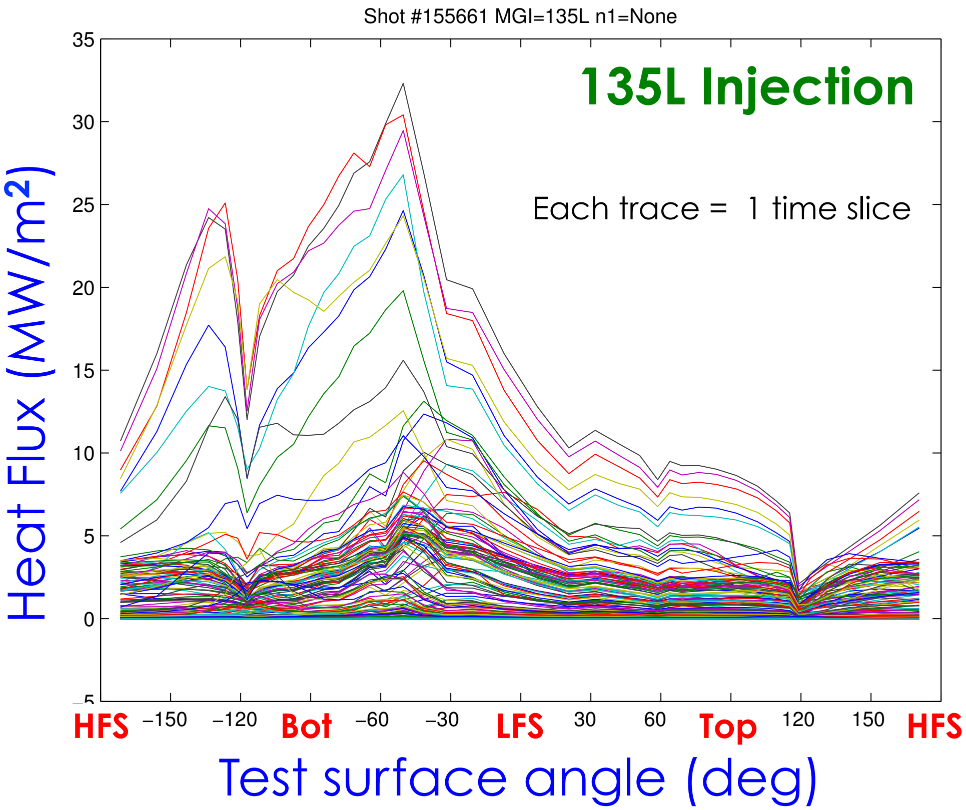
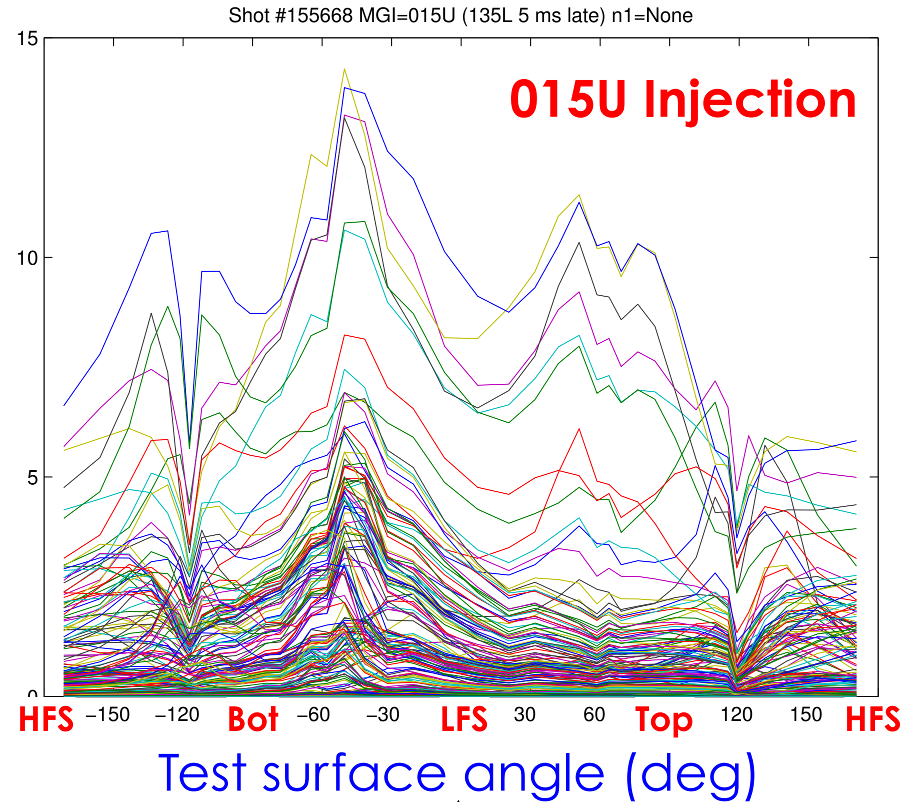
Experimental setup for preliminary poloidal asymmety measurements





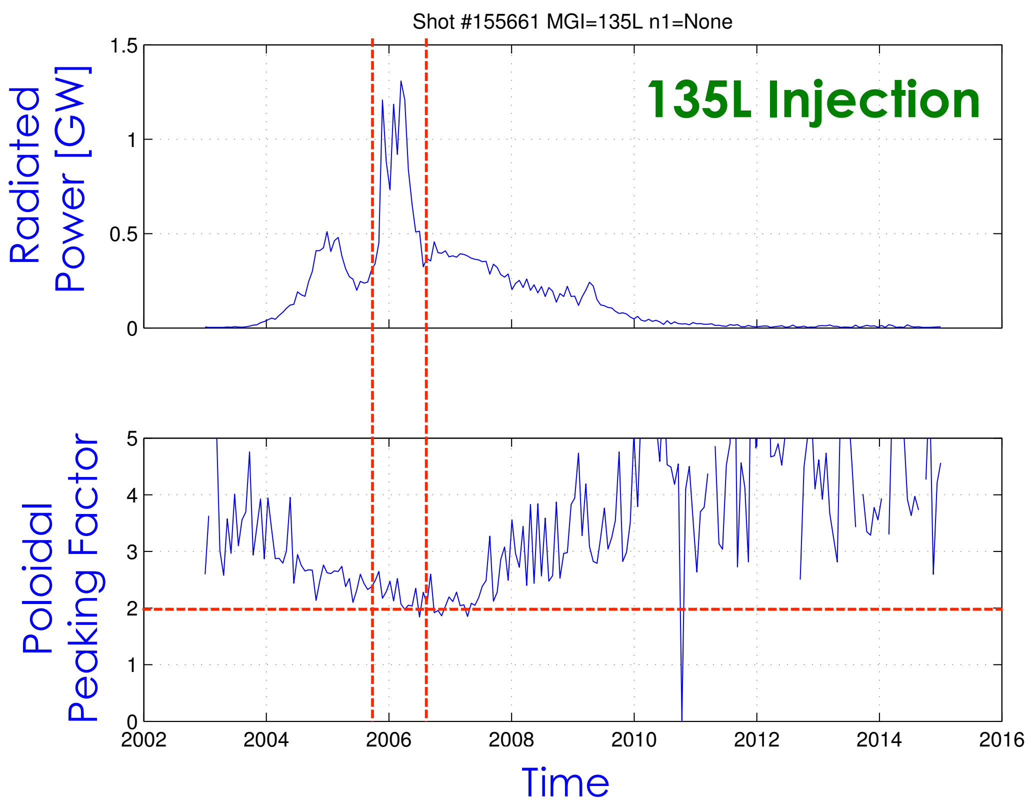
Lower & upper injection show qualitatively different poloidal radiation patterns…

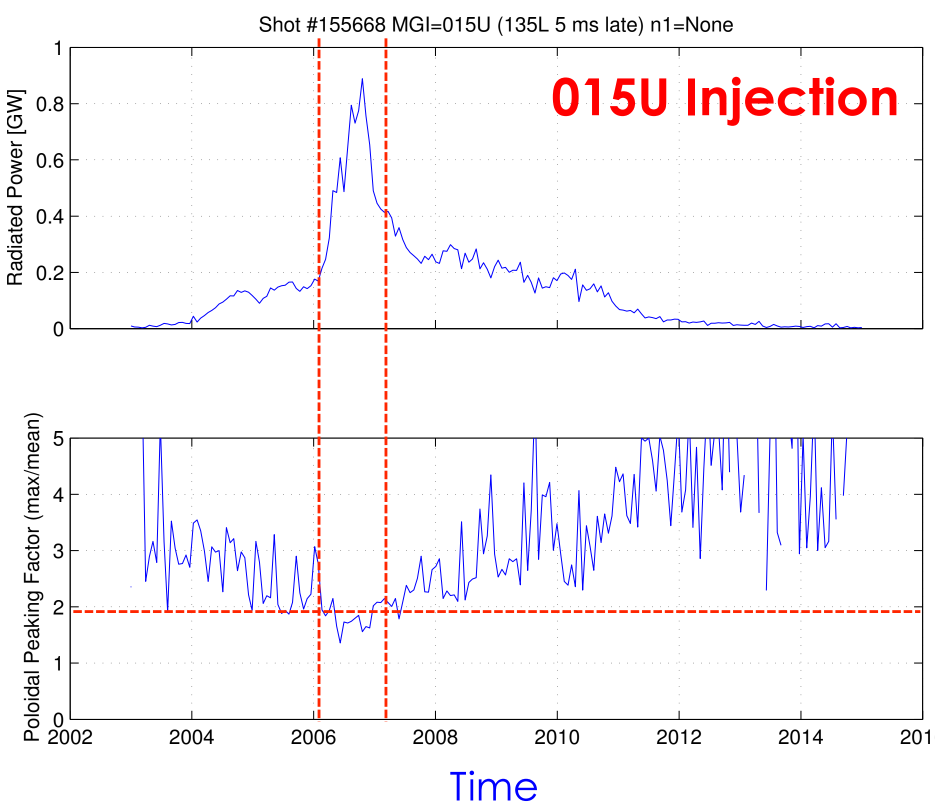




Note: 015U has much wider guide tube, resulting in slower, more spread out emission

… which is manifested as slightly different PPF during TQ

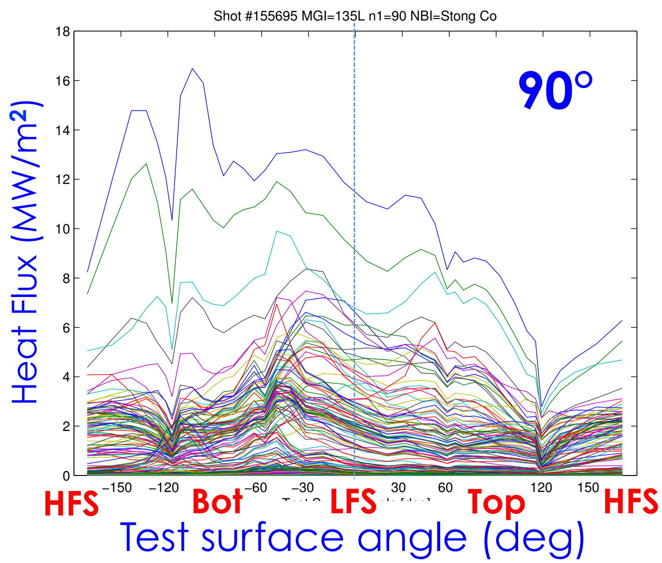


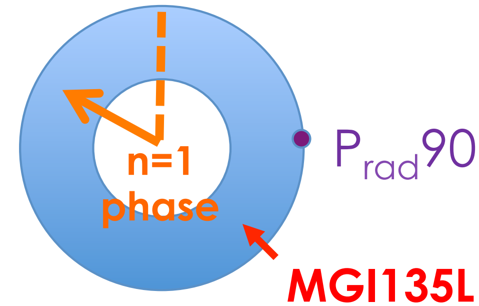


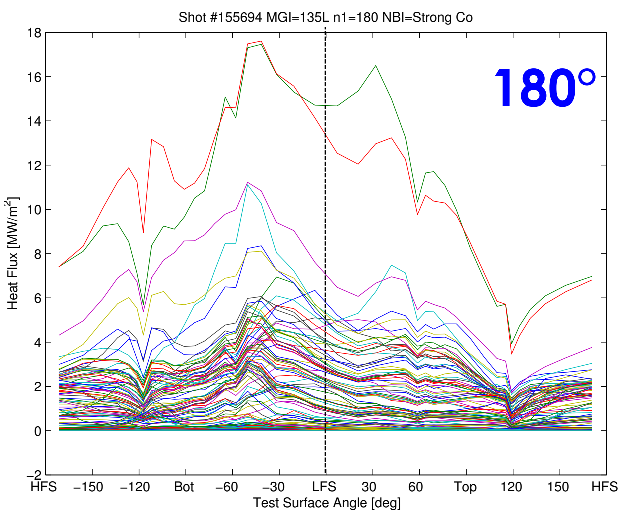
PPF ~ 2-2.5

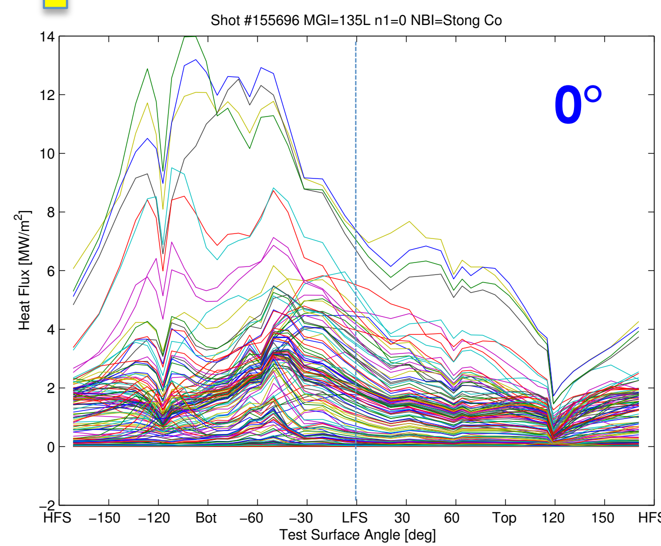
PPF ~ 1.5-2

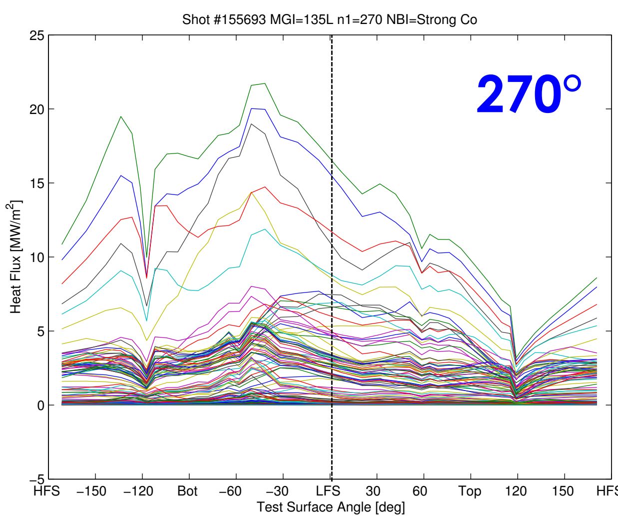
Effect of applied error field on poloidal asymmetry: Qualitative shift in angular distribution evident











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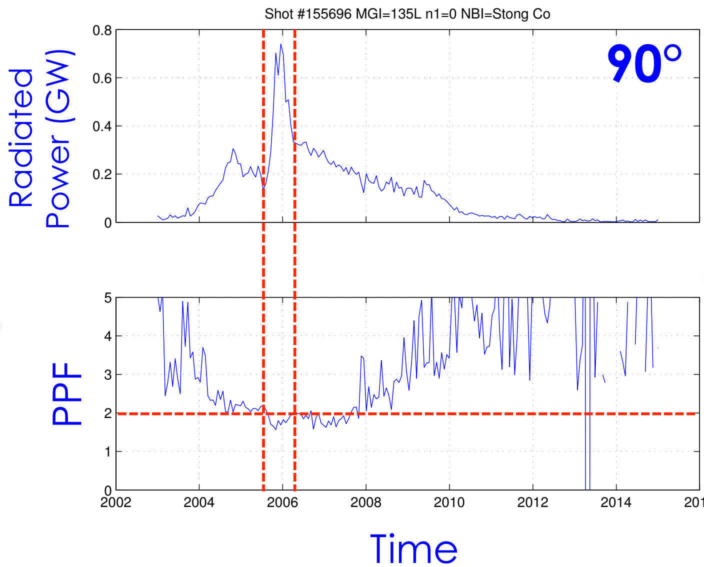
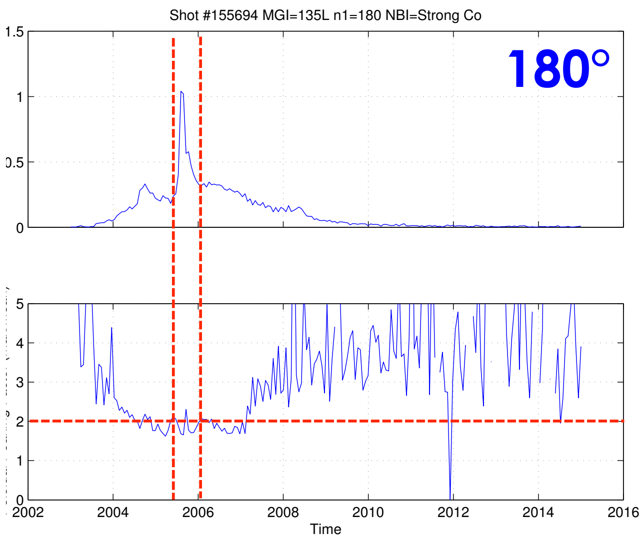
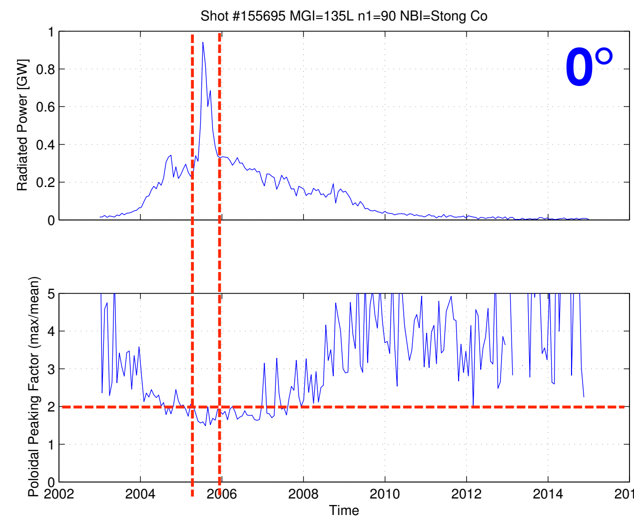
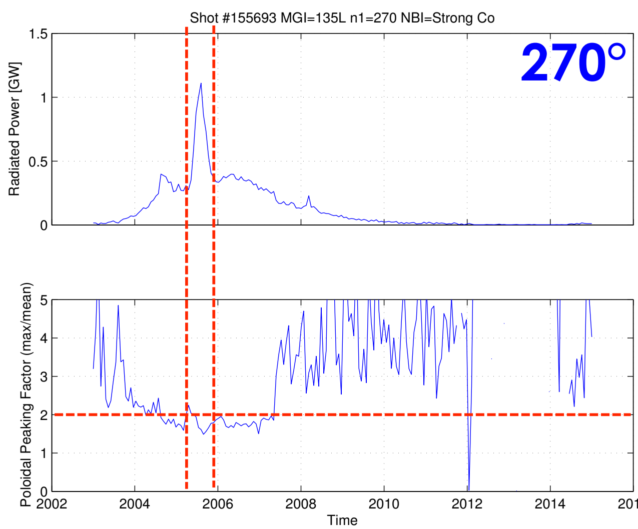
Effect of applied error field on poloidal asymmetry: No noticeable change in PPF

PPF slightly < 2









Lack of change in PPF consistent with picture of n=1 asymmetry being shifted toroidally

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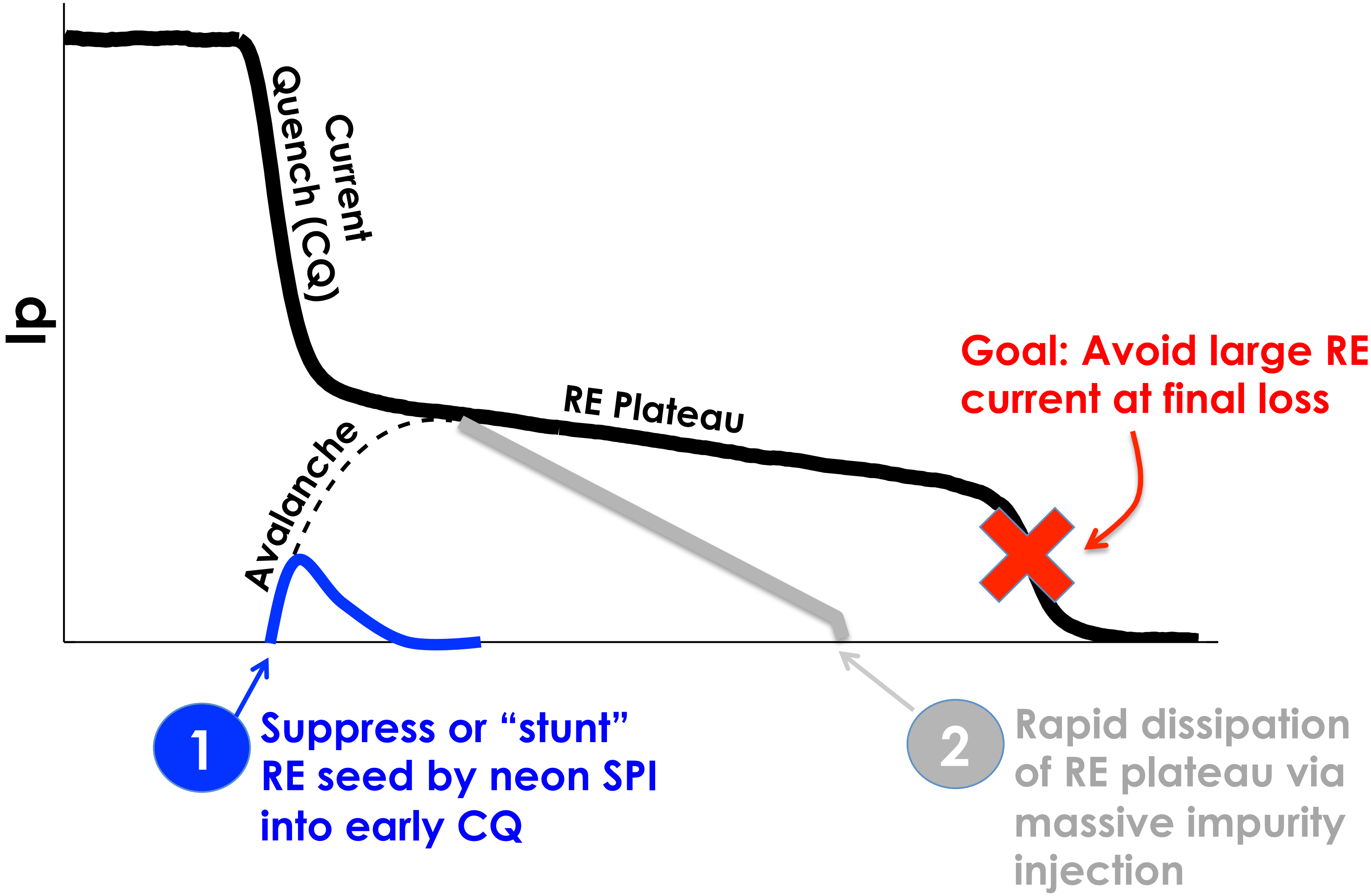
DIII-D Pursuing RE Mitigation Techniques Using Anticipated ITER Disruption Mitigation Hardware

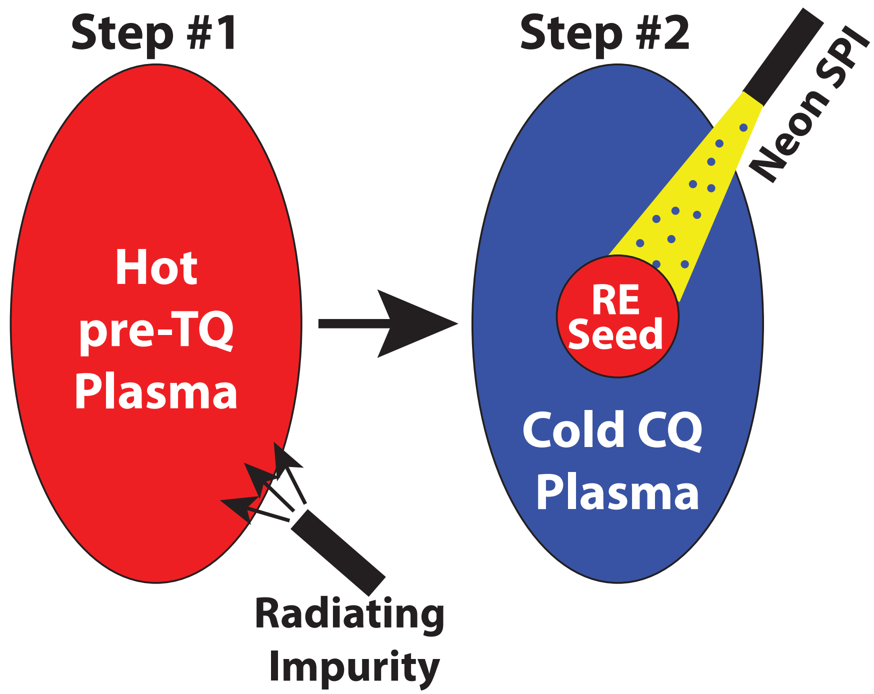


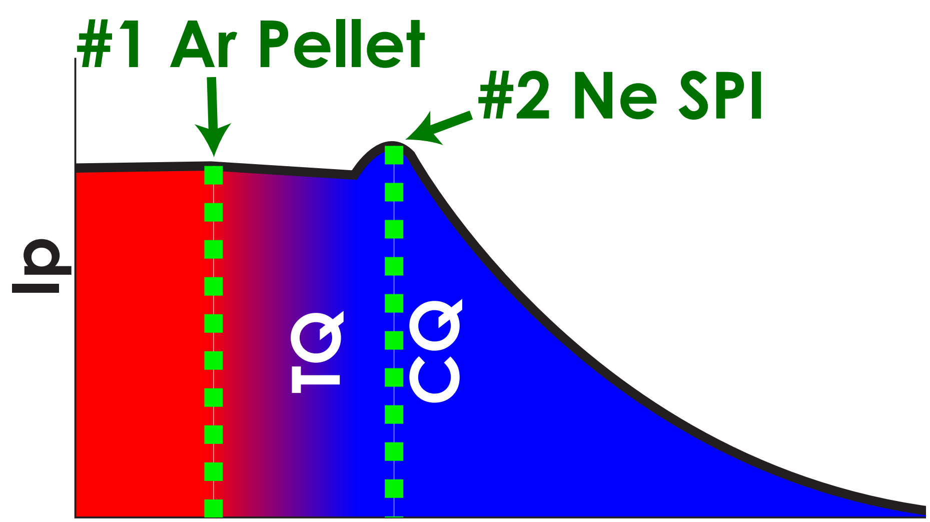
DIII-D Testing 2-step Disruption Mitigation Process to Deliver High Localized Density for RE Seed Suppression with Modest Particle Input

1. **Initial impurity injection cools plasma, induces thermal quench**

2. **Ne shattered pellet injection (SPI) into early CQ for RE suppression**
   – SPI ablation only occurs at location of RE seeds in core

- **High critical density (~4x10^{22} m^{-3}) at RE location required for suppression**





Modest particle deposition in small volume can yield high local densities for RE seed suppression

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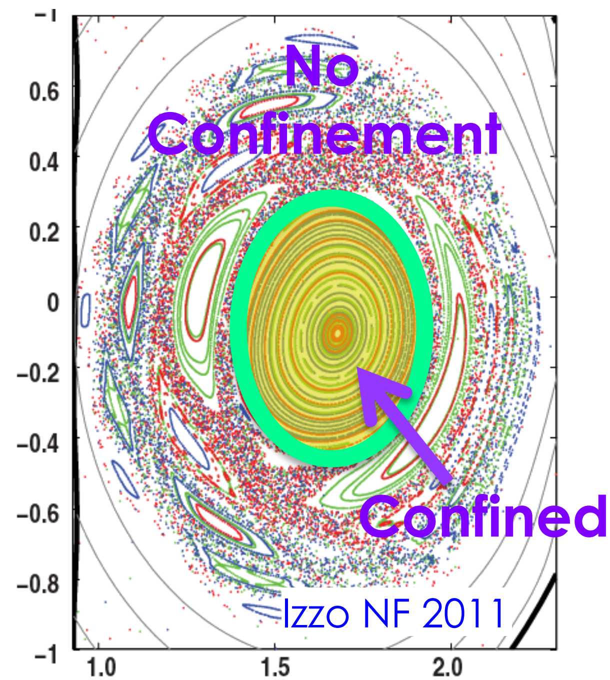
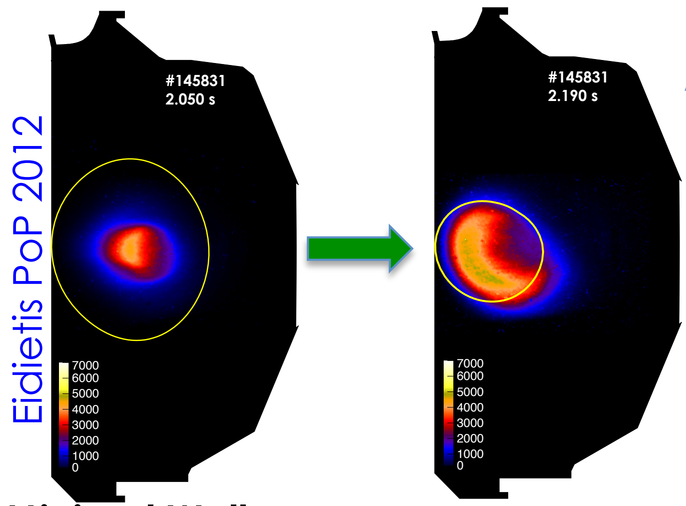
Indirect Evidence for Small RE Volume Motivates Highly Directed Impurity Injection

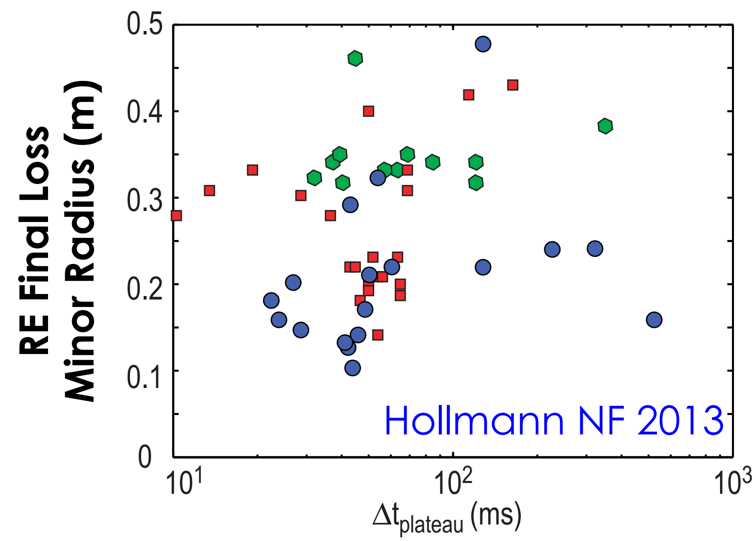
1. **NIMROD:** Only small portion of plasma volume confines seed RE early in CQ



2. **D3D Experiment:** Significant wall interaction with RE plateau does not occur until small (a~0.3m) RE synchrotron core touches wall

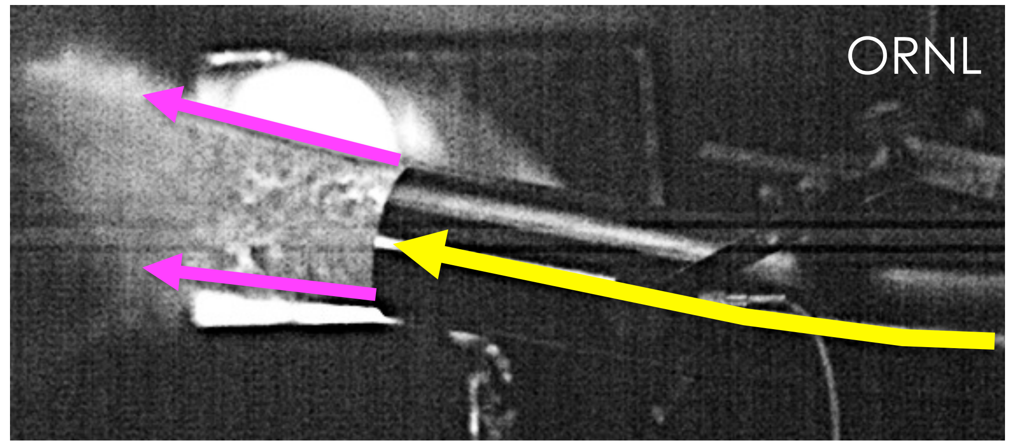


Minimal Wall Interaction | **Strong Wall Interaction**

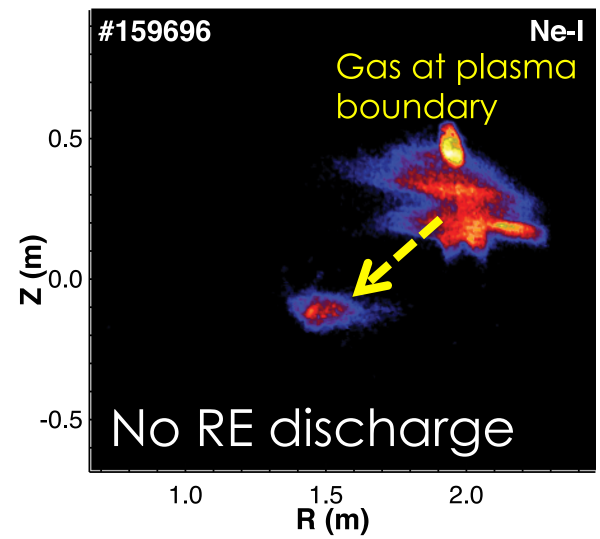


Shattered Pellet Injection (SPI) is Good Technology Choice for Localized Deposition of Impurities

Collimated →



Deep penetration →

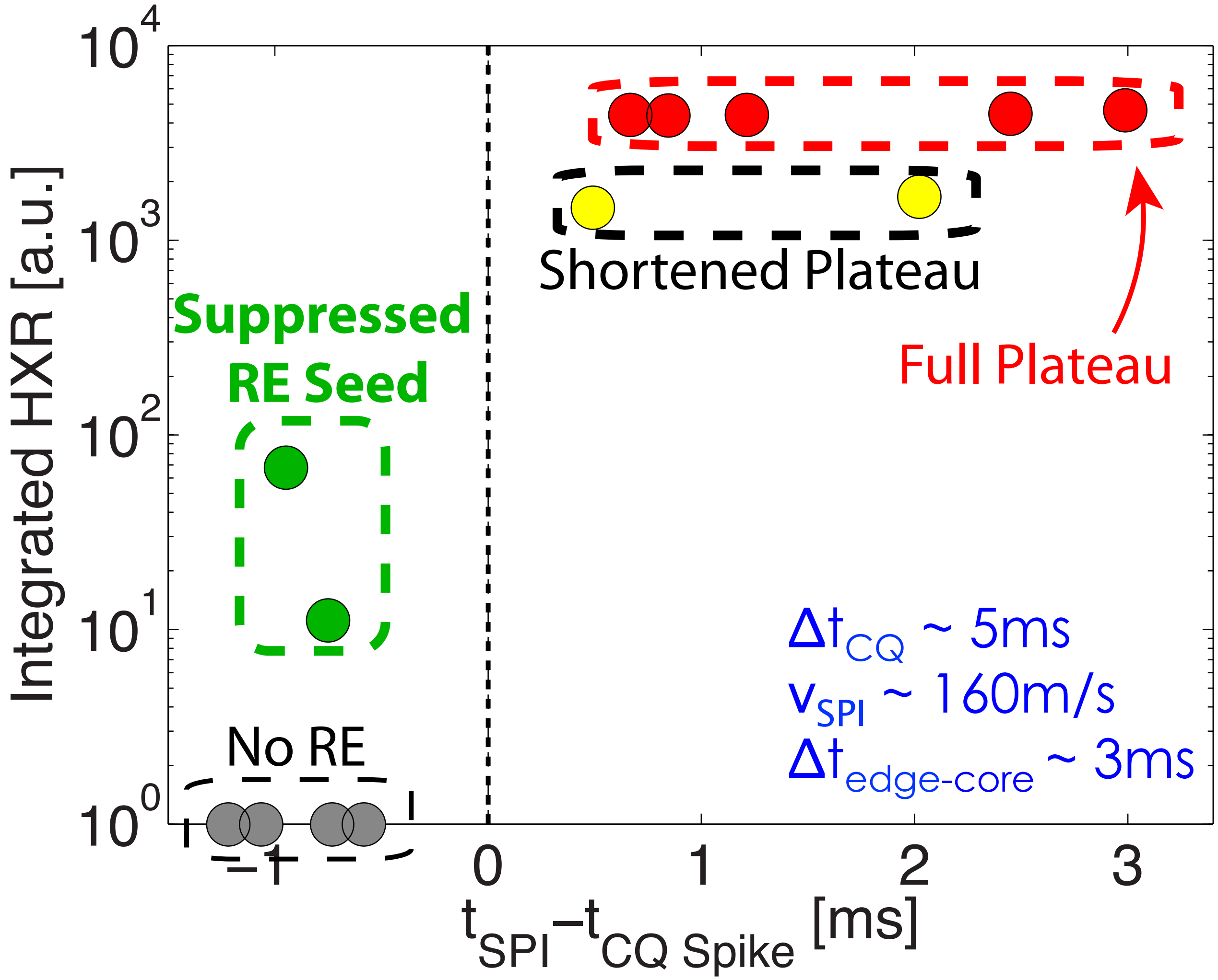


Courtesy R. Moyer (UCSD)

Initial Tests Reveal RE Seed Suppression Process Very Sensitive to Relative Timing of SPI Arrival at Edge & Start of CQ

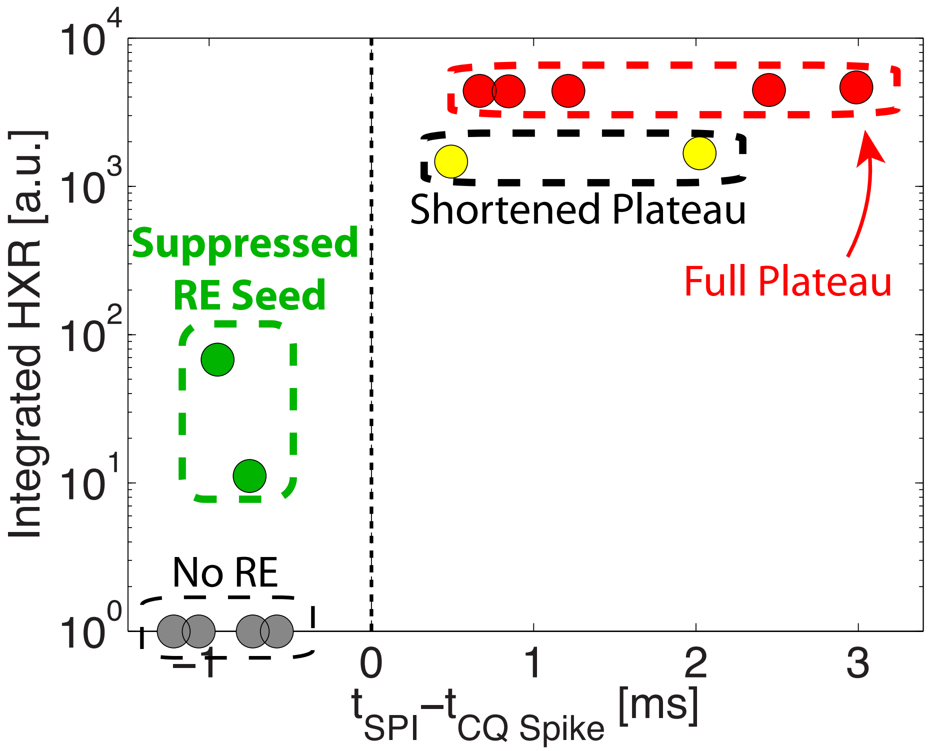
- **Early SPI:** Arrival before CQ exhibits evidence of RE seed suppression

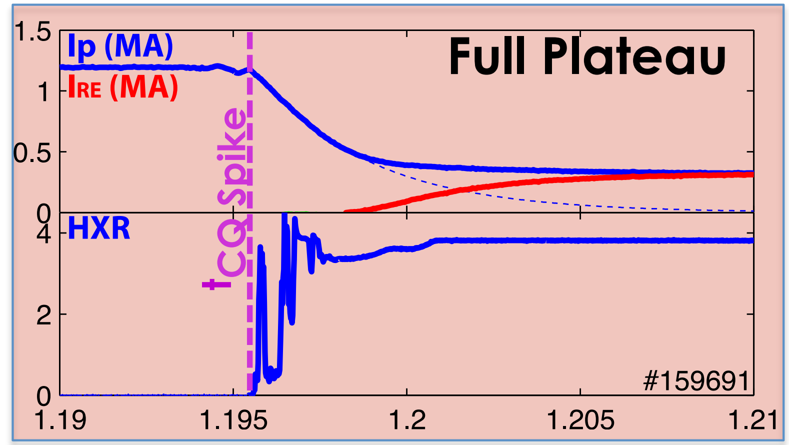
- **Late SPI:** Arrival shortly after start of CQ has little or no effect upon RE amplification

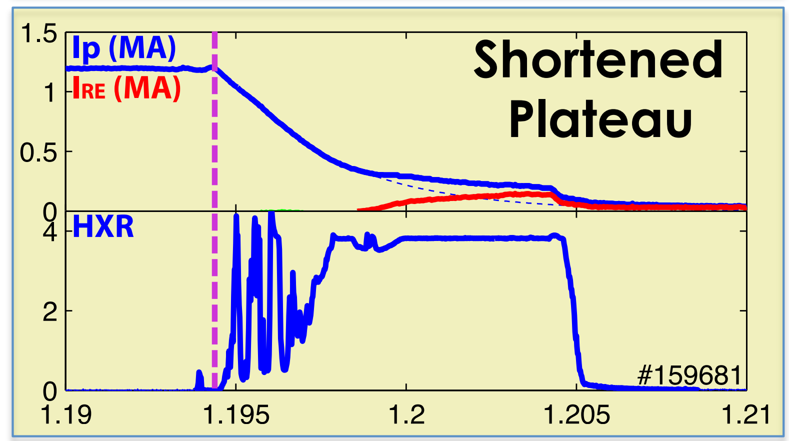


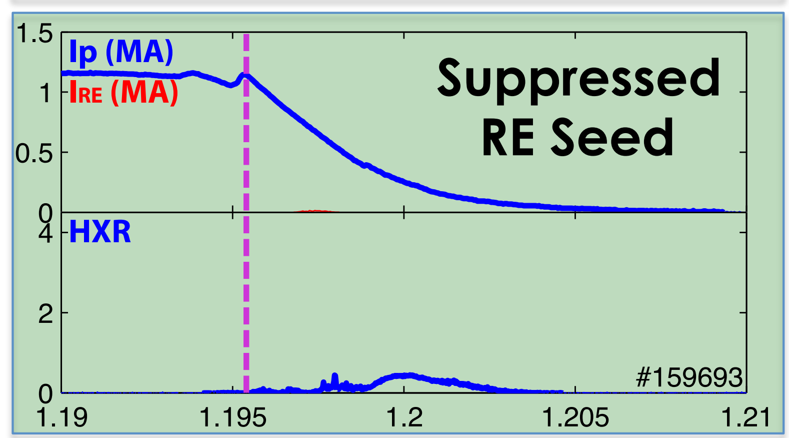
t_{SPI} = SPI arrival at plasma edge

Initial Tests Reveal RE Seed Suppression Process Very Sensitive to Relative Timing of SPI Arrival at Edge & Start of CQ





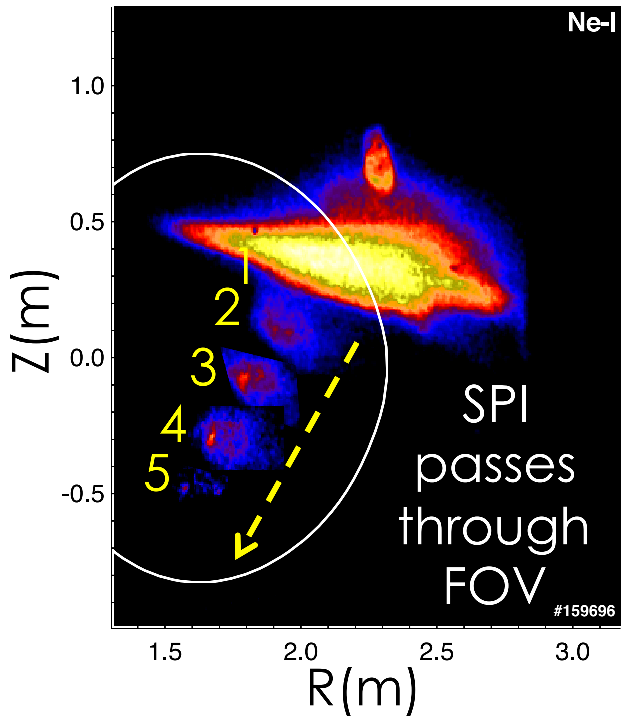


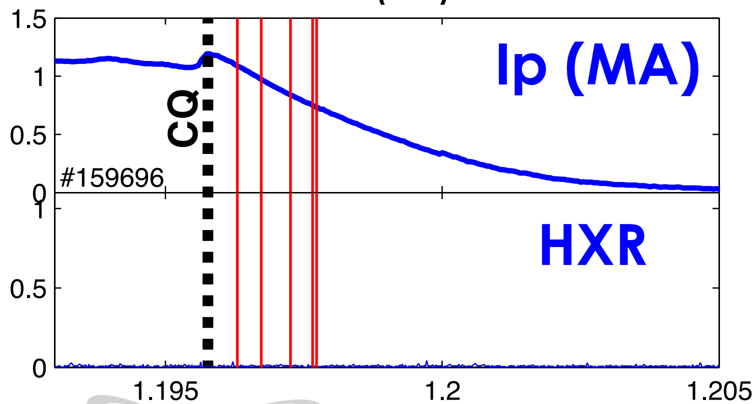


NB: Initial RE seed population may be affected by changes in TQ evolution. No direct measurement exists of initial RE seed.

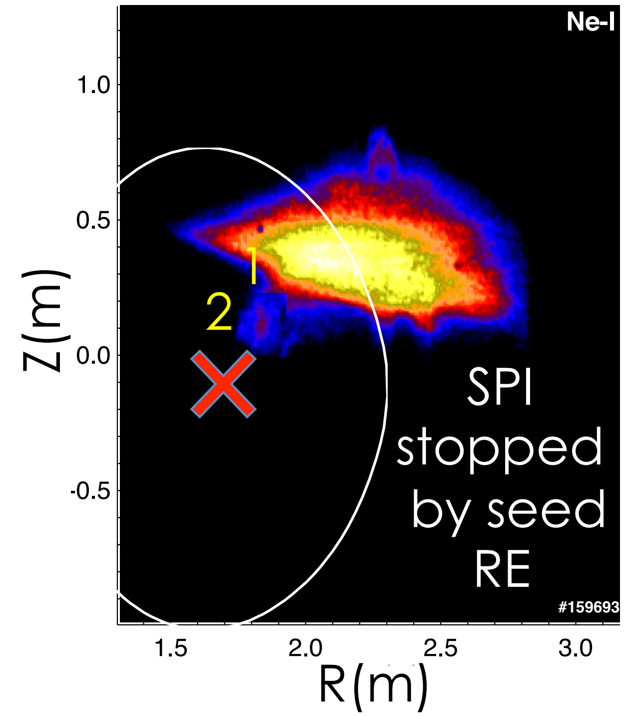
Fast Visible Imaging Indicates SPI Ablation by RE Seed in RE Suppression Cases

No RE production

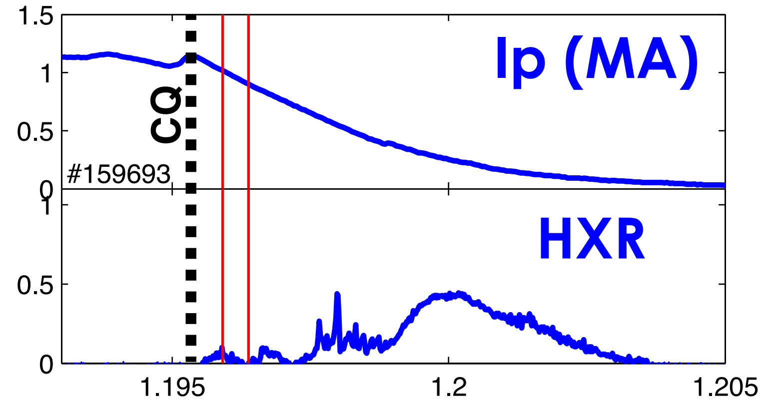




RE Seed Production



Images & analysis courtesy R. Moyer (UCSD)



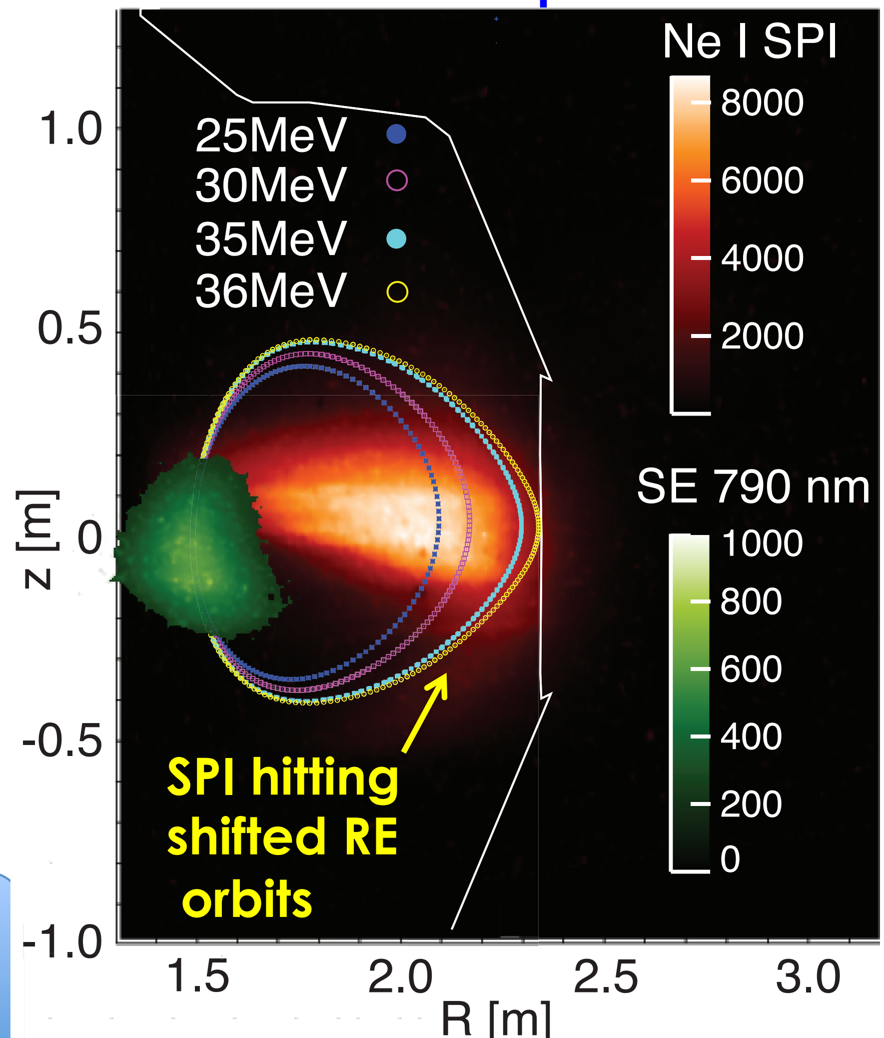
Basic concept of SPI penetrating to RE & ablating appears sound

SPI Ability to Penetrate RE Decreases Rapidly as RE Current & Energy Increase

- **Mature RE plateaus largely exclude injected impurities from beam…**
  Hollmann NF 2013
- **As beam matures, dissipation slows to 10's ms process**
- **Outward shifted RE orbits act as "vanguard"**
- **Likely reason for sensitivity of suppression process to SPI delay**

Critical for SPI to arrive very early in CQ

SPI impact upon mature RE plateau



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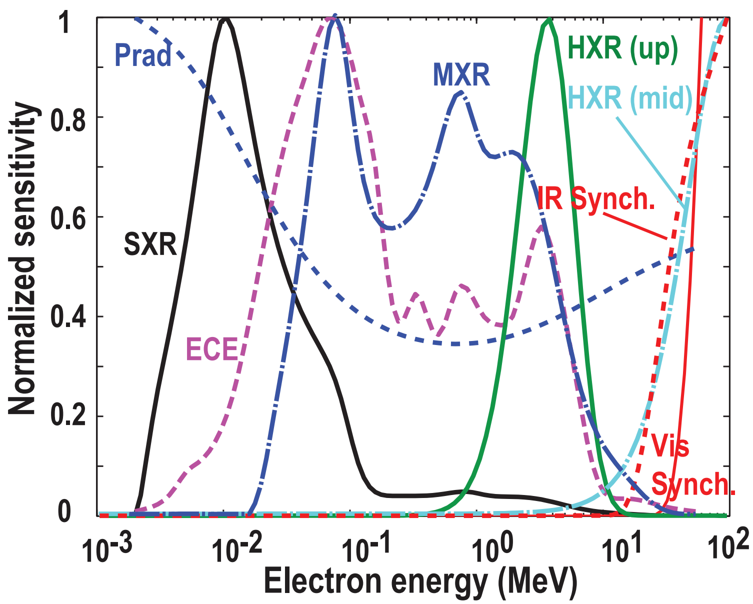
Improved Analysis Allows Resolution of Plateau RE Energy Distribution Function (f_ε) & Pitch Angle (θ)



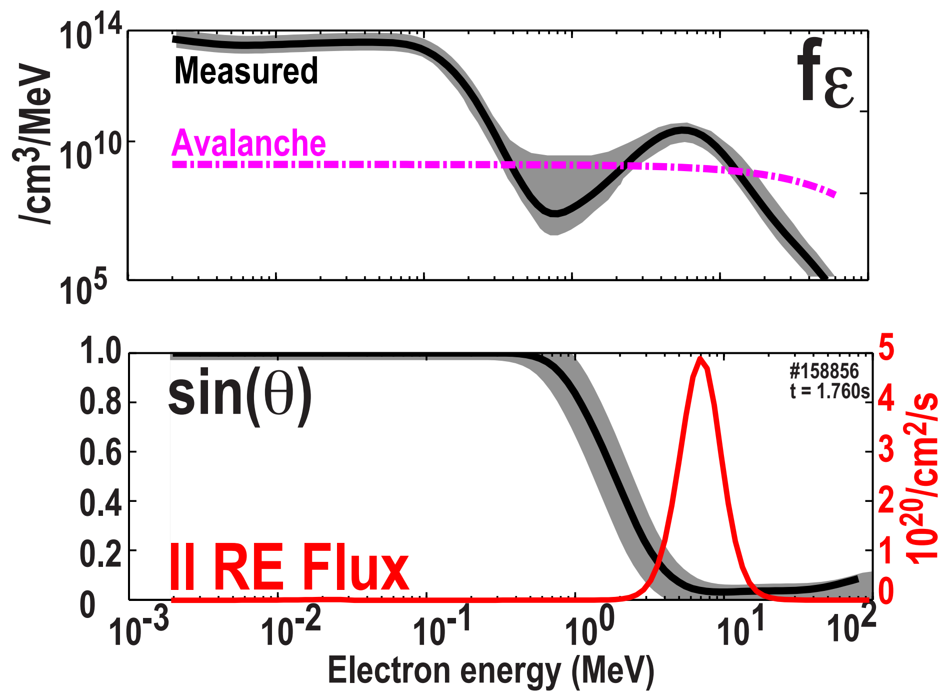
- **Multiple diagnostics constrain f_ε over wide energy spectrum (keV→10's MeV)**

Hollmann NF 2013

- **New Features: Ip, P_{rad} & IR constraints + energy-dependent θ**

- **f_ε skewed to much lower energies than avalanche prediction**

- **Current driven by 2-10 MeV RE**
  - Pitch scattering most effective way to reduce I_{RE}



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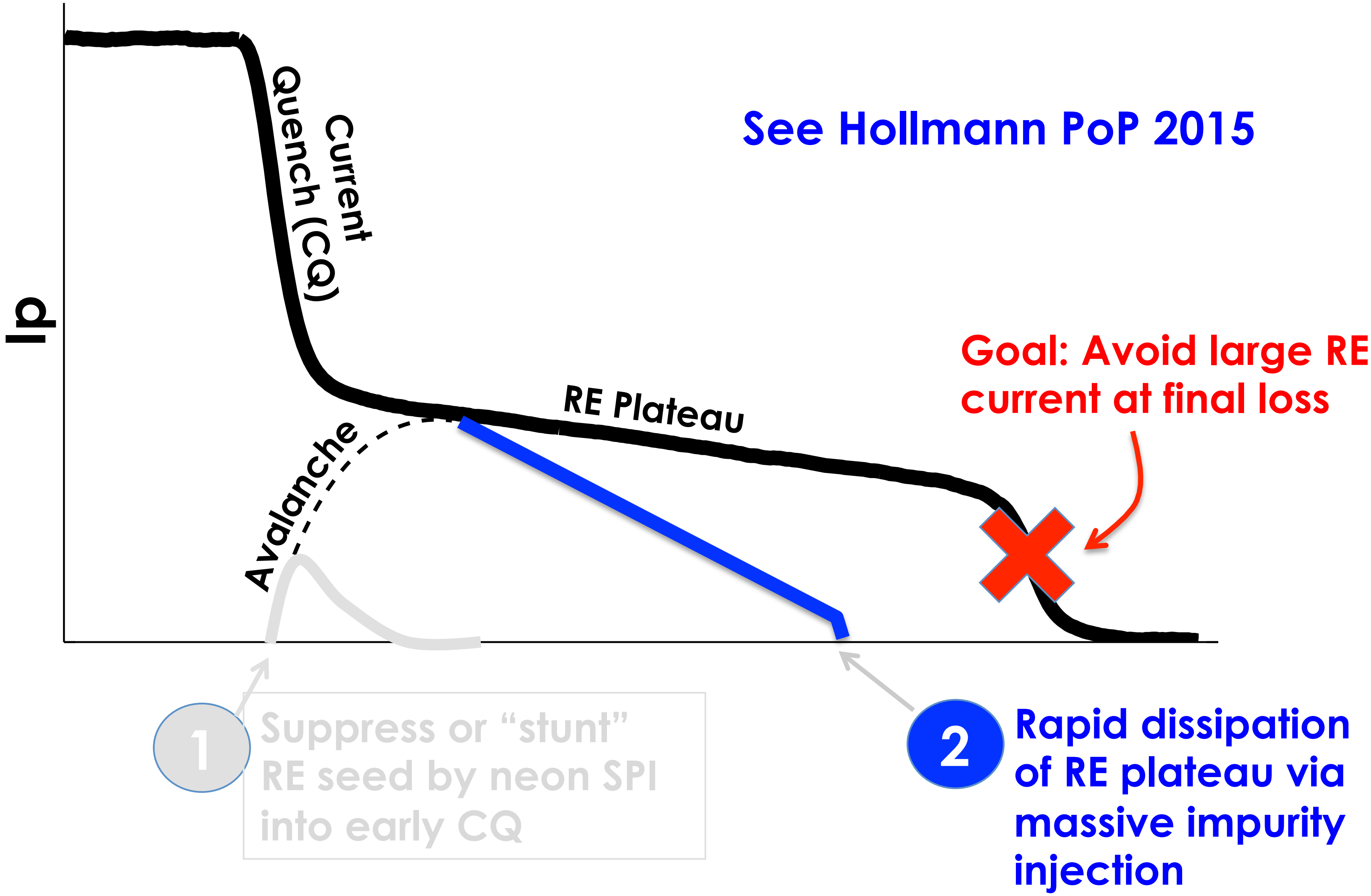
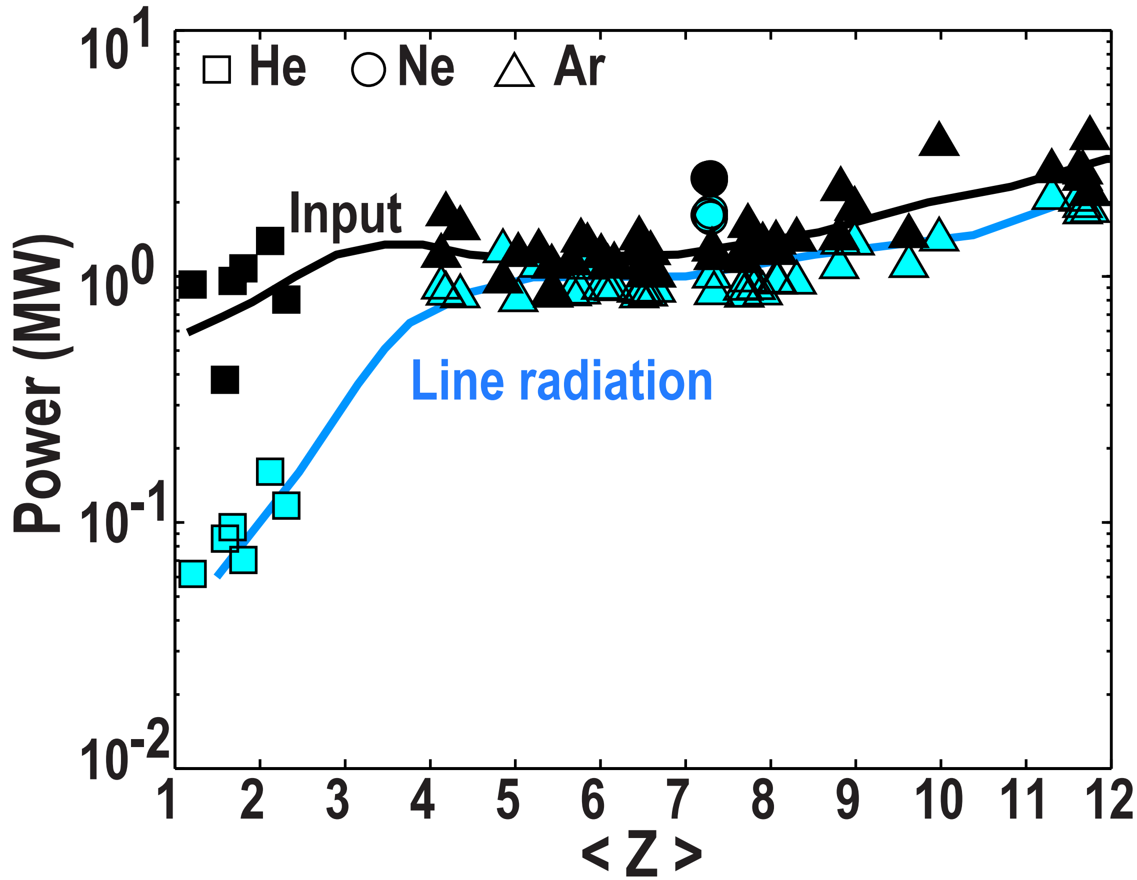


Energy Dissipation: Power Balance Indicates Line Radiation is Dominant Loss Mechanism in Centered, High <Z> RE Plateaus

- **Line radiation roughly balances ohmic input for <Z> > 4**



<Z> = Effective nuclear charge seen by RE

Parks PoP 1999

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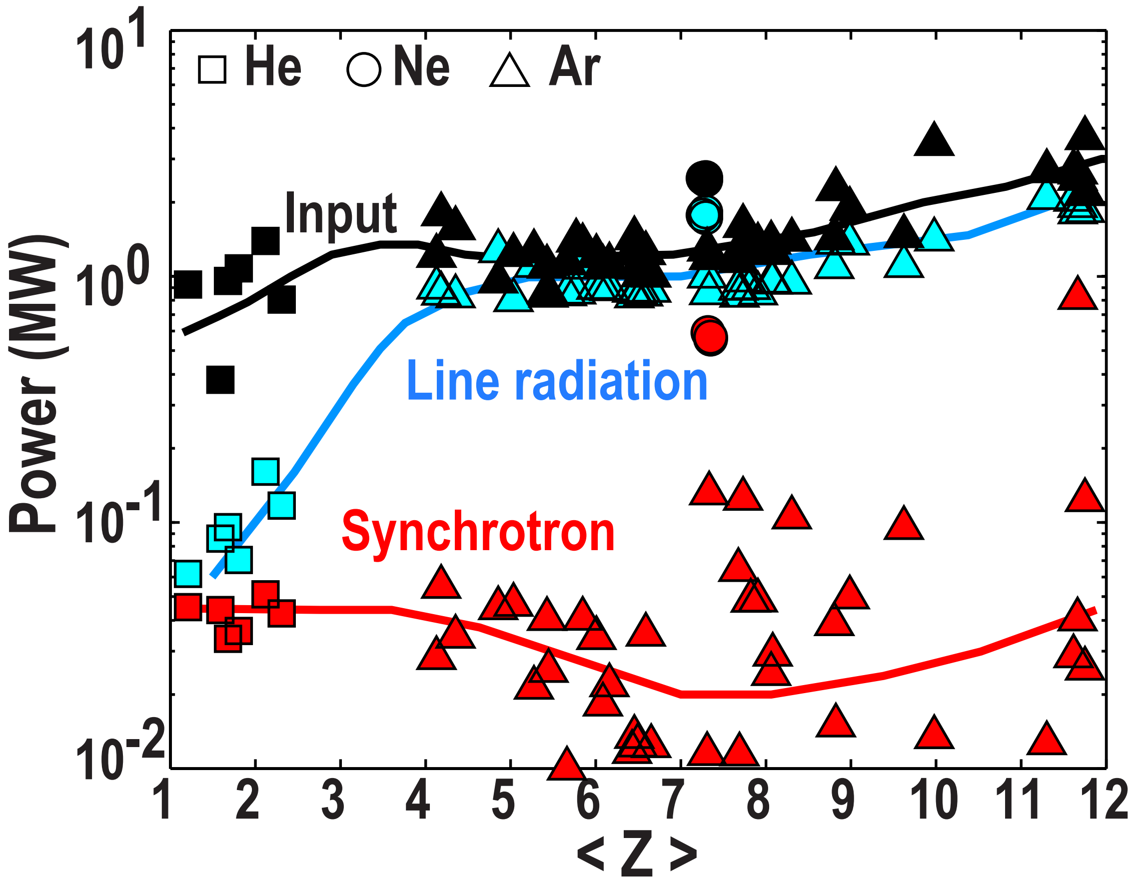
Energy Dissipation: Power Balance Indicates Line Radiation is Dominant Loss Mechanism in Centered, High <Z> RE Plateaus

- **Line radiation roughly balances ohmic input for <Z> > 4**
- **Synchrotron emission not significant at mid-high <Z>**
- **Discrepancy in power balance at low <Z>**

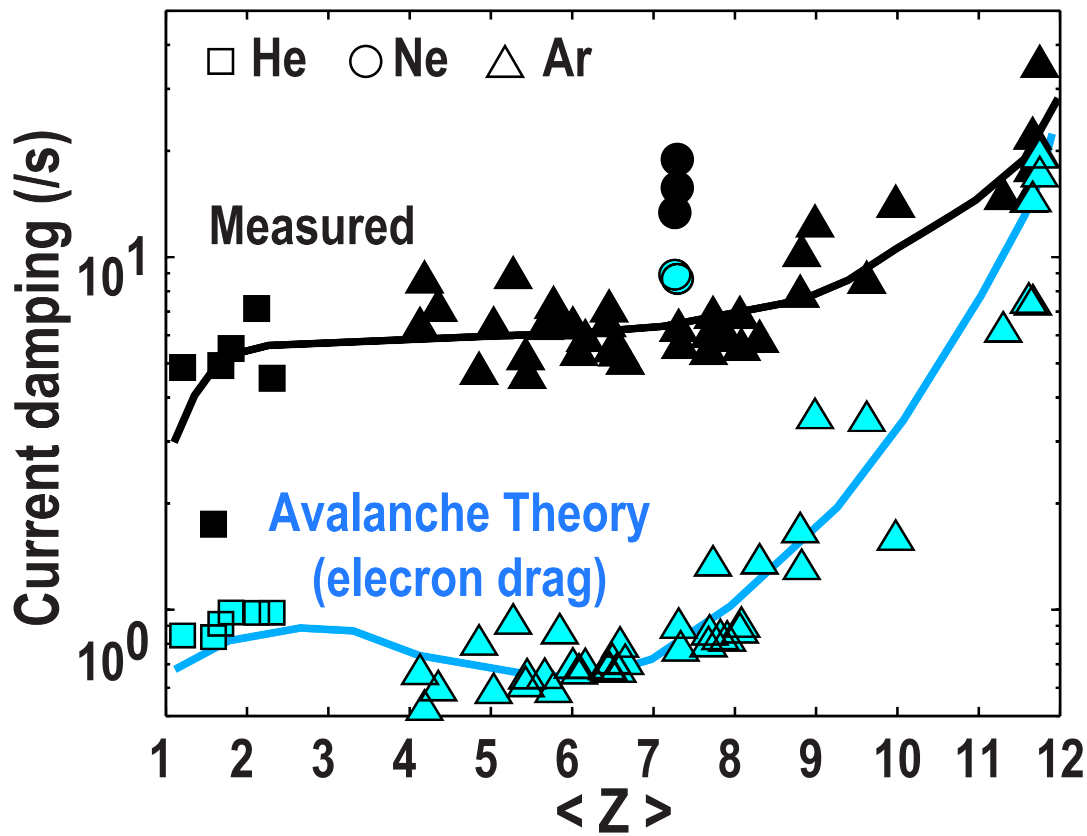


<Z> = Effective nuclear charge seen by RE

Parks PoP 1999

Current Dissipation: Observed RE Plateau Current Damping Rate Significantly Greater than Avalanche Predictions

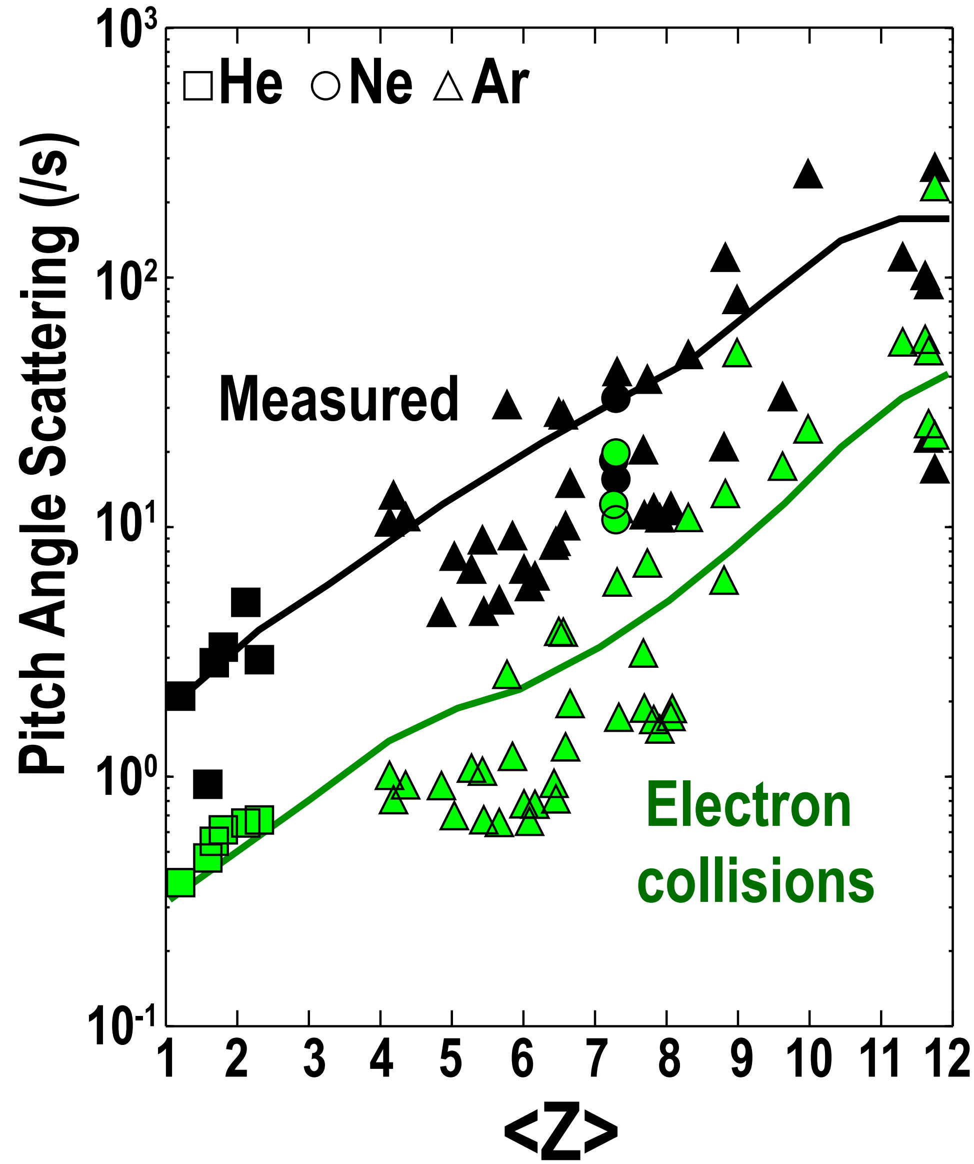
- **Discrepancy up to 10x except at highest <Z>**
- **Consistent with previous measurements of anomalous RE current damping**



See:
Hollmann & Parks NF 2011
Hollmann NF 2013
Paz-Soldan PoP 2014
Granetz IAEA 2014

Current Dissipation: Pitch Angle Scattering from RE->ion Collisions May Account for Discrepancy in RE Current Damping Rates

- **Avalanche theory only accounts for electron drag**



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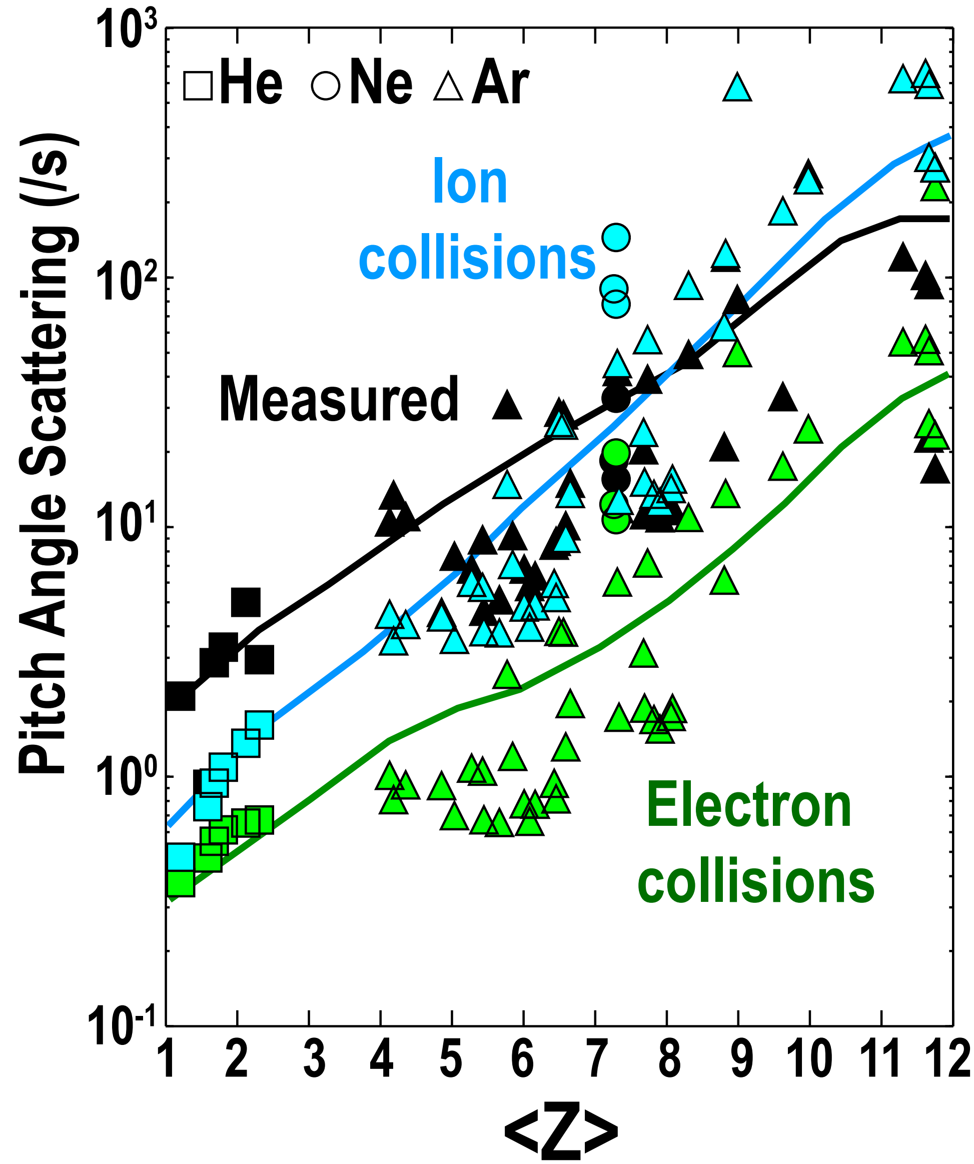
Current Dissipation: Pitch Angle Scattering from RE->ion Collisions May Account for Discrepancy in RE Current Damping Rates

- **Avalanche theory only accounts for electron drag**
- **RE-ion scattering 5-10X greater then RE-electron over wide range of <Z>**
- **Including RE-ion scattering in current damping calculations may largely resolve "anomalous" RE current dissipation**
  - Analytical Fokker-Planck treatment agrees



See Hollmann, PoP 2015

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Conclusions

- **First tests of SPI underway. Look positive, but limited in scope.**
  - Developing SPI source/ablation models is important task
- **Mitigation of locking/ed modes can still be effective & desirable**
- **Toroidal radiation asymmetry appears well-described by NIMROD**
  - Analysis of poloidal radiation peaking underway
- **SPI into early current quench shows promise for viable RE suppression method, but sifnigicant ambiguity**
- **“Anomalous” current dissipation in RE plateau appears to be acounted**