Runaway Electron Production & Dissipation on DIII-D

by

N.W. Eidietis

for the

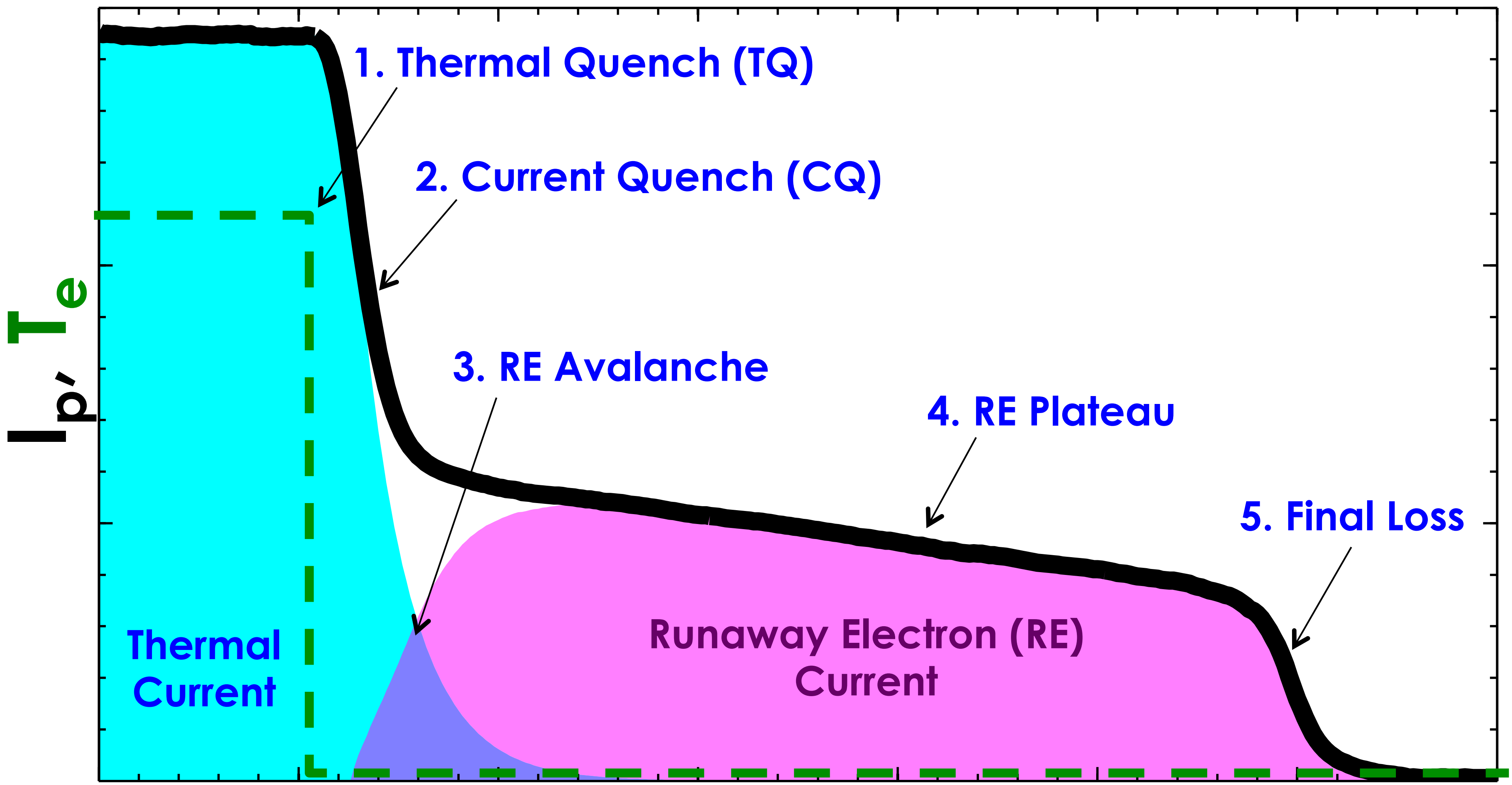
DIII-D Disruption Task Force

Presented at the

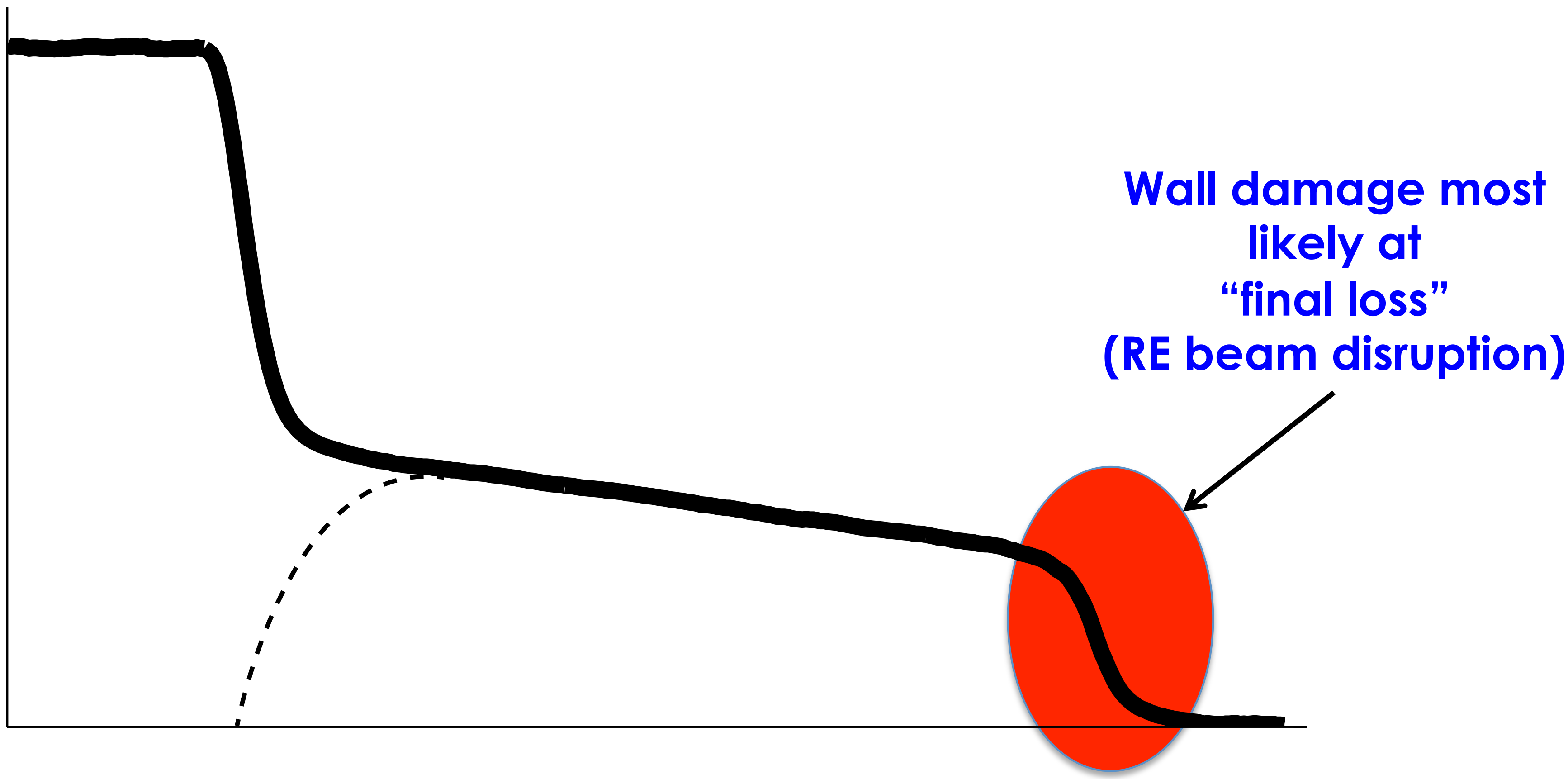
PPPL Theory & Simulation of Disruptions Workshop
Princeton, NJ (USA)

July 18, 2013

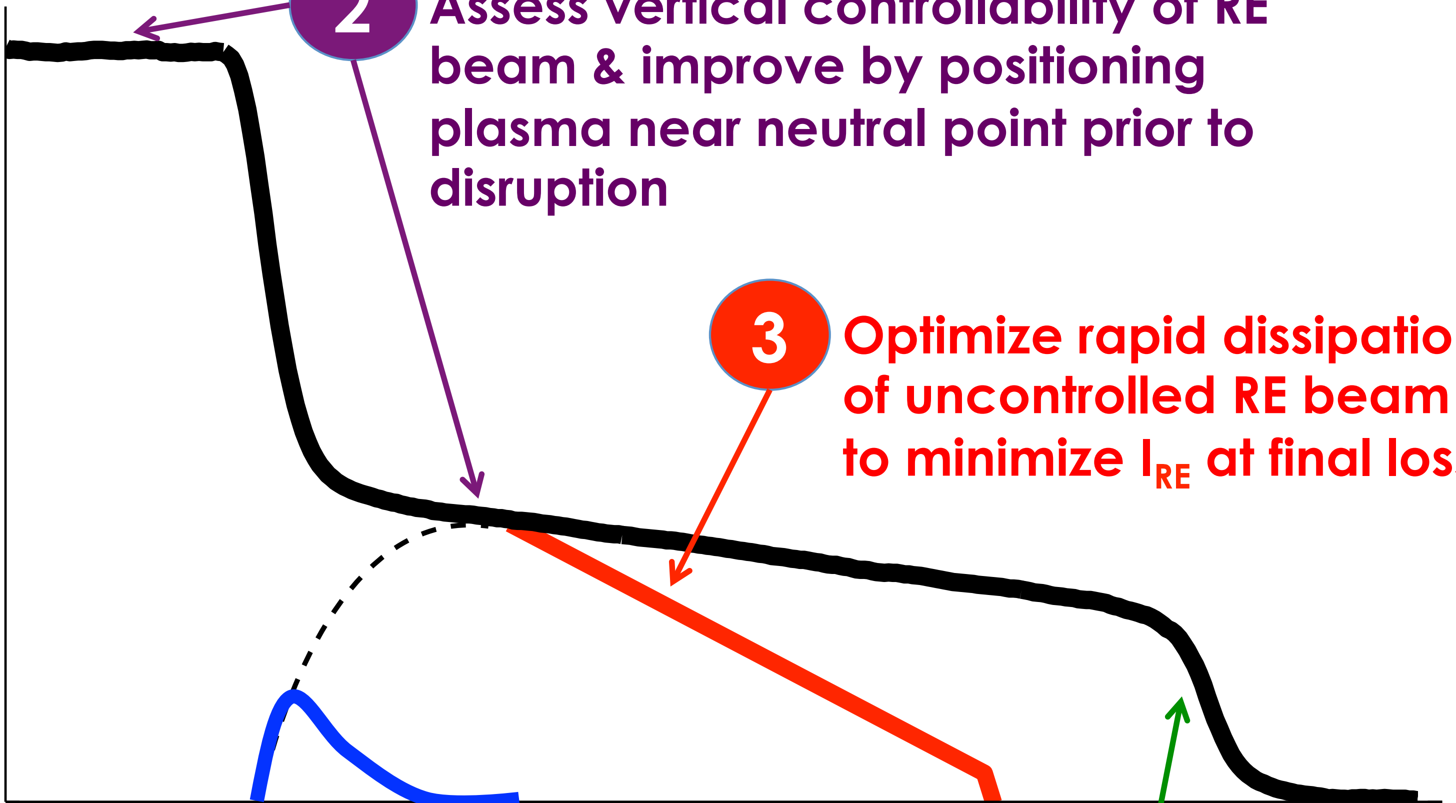
Life Cycle of a Runaway Electron (RE) Beam



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 I_{RE} 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

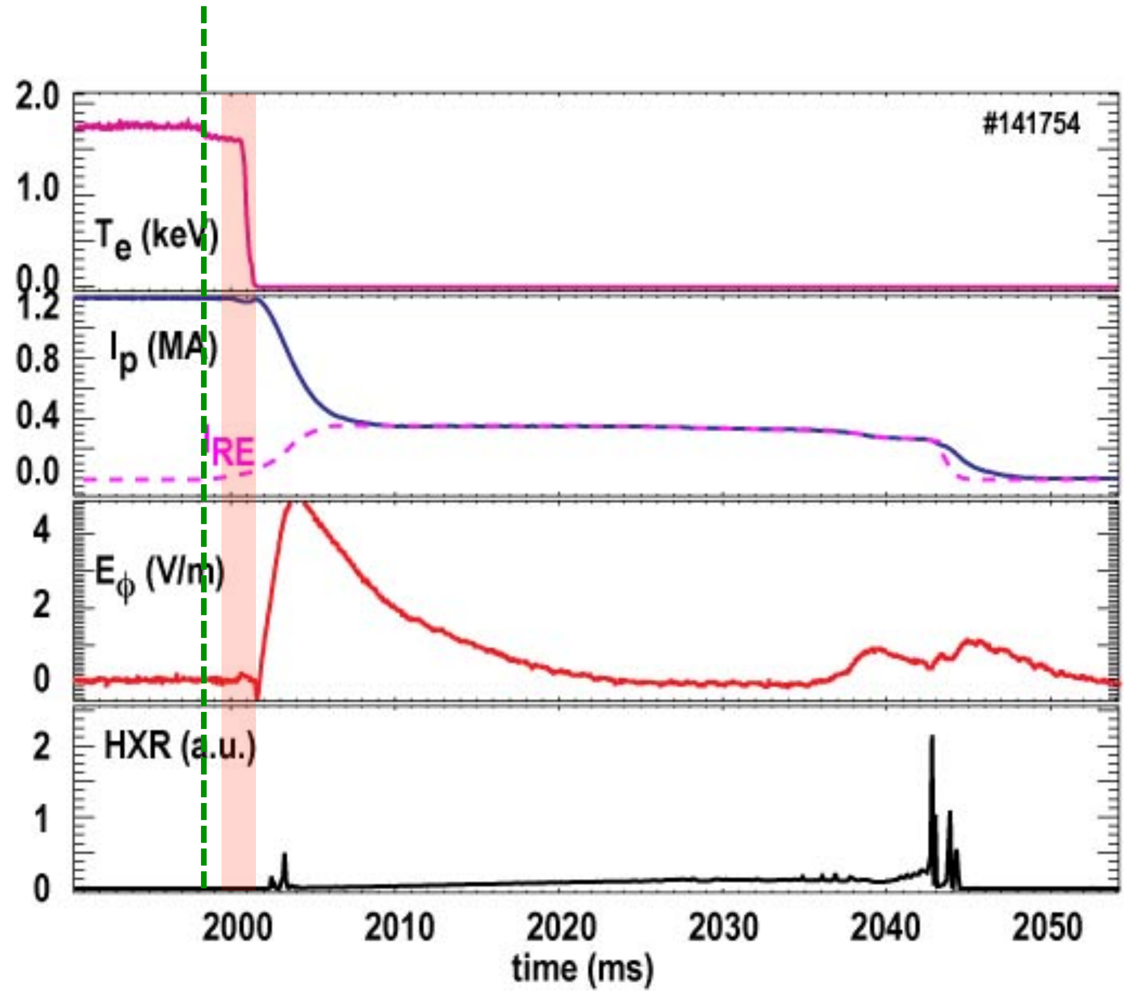
Outline

1. Formation
2. Anatomy
3. Dissipation
4. Final Loss

1. Formation
2. Anatomy
3. Dissipation
4. Final Loss

Formation of a DIII-D RE Beam: Formed by Argon Pellet Injection (not natural disruptions)

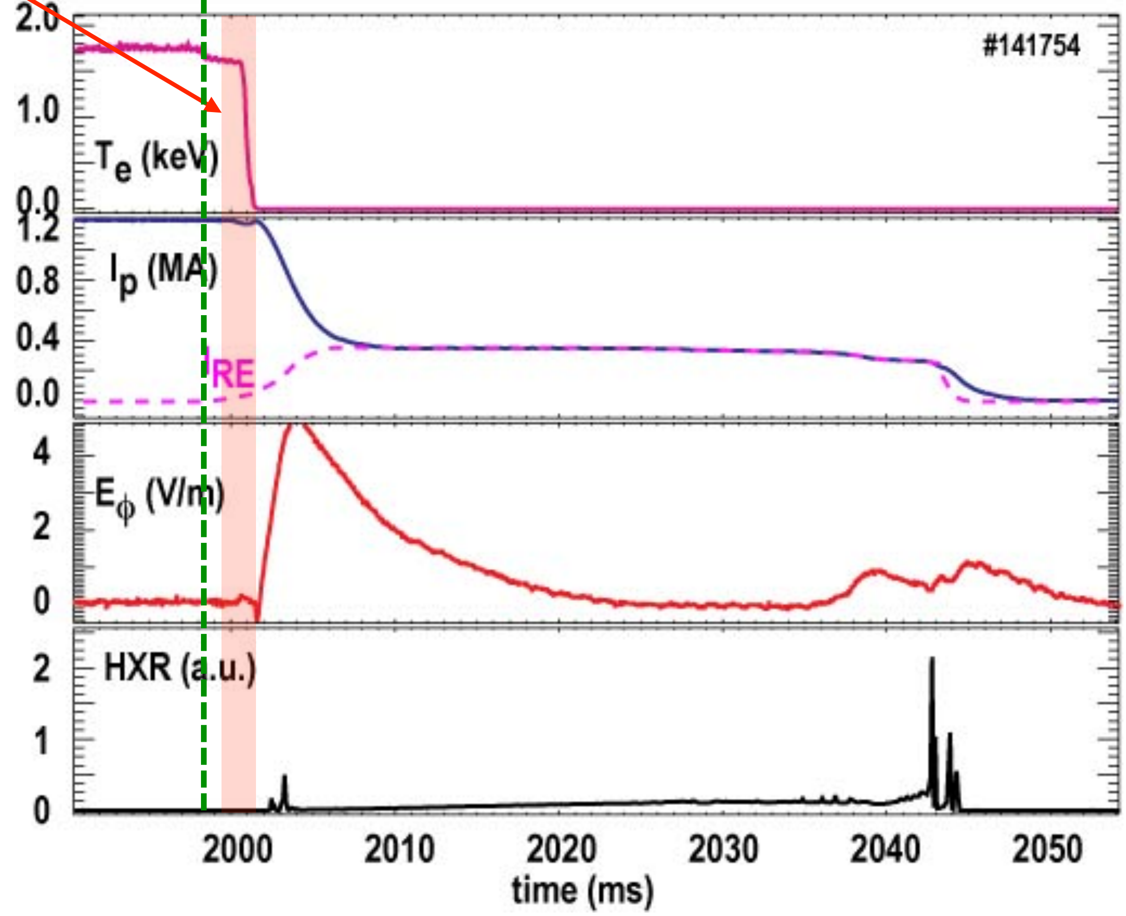
~ 10 torr-L Argon pellet hits plasma edge



Formation of a DIII-D RE Beam: Formed by Argon Pellet Injection (not natural disruptions)

Thermal quench (TQ) - RE seed formation

~ 10 torr-L Argon pellet hits plasma edge

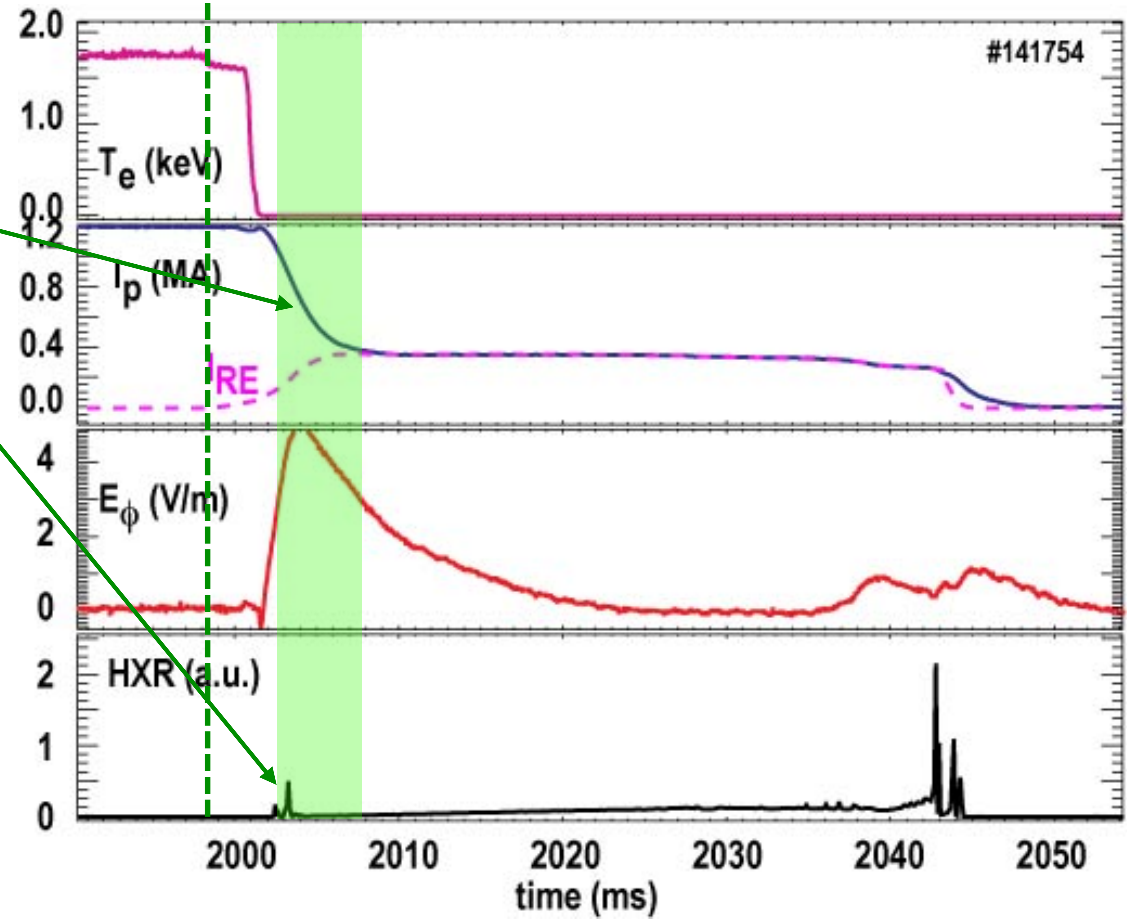


Formation of a DIII-D RE Beam: Formed by Argon Pellet Injection (not natural disruptions)

Thermal quench (TQ) - RE seed formation

Current quench (CQ) (prompt RE loss and RE avalanche)

~ 10 torr-L Argon pellet hits plasma edge



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

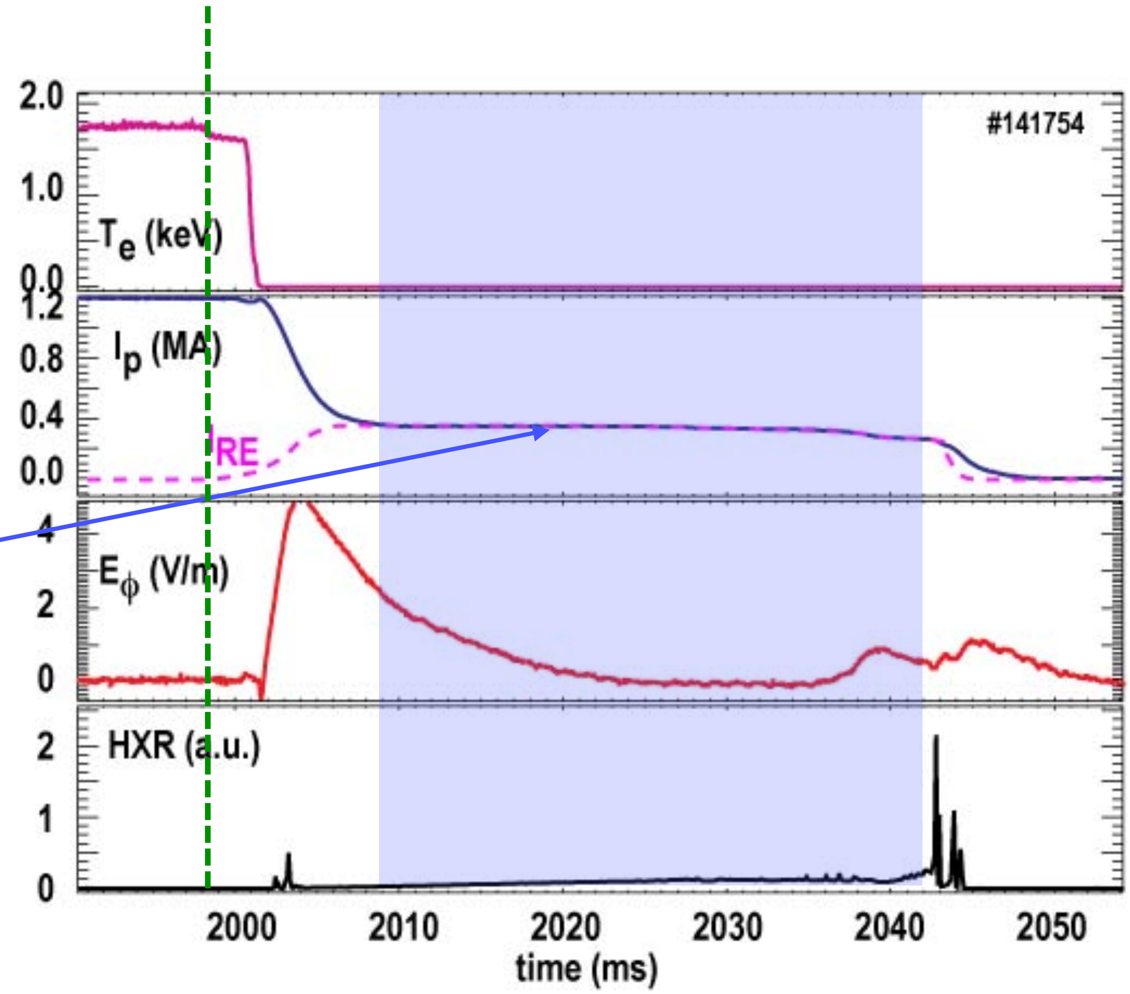
Formation of a DIII-D RE Beam: Formed by Argon Pellet Injection (not natural disruptions)

Thermal quench (TQ) - RE seed formation

Current quench (CQ) (prompt RE loss and RE avalanche)

RE plateau (equilibrium with RE-dominated current)

~ 10 torr-L Argon pellet hits plasma edge



Formation of a DIII-D RE Beam: Formed by Argon Pellet Injection (not natural disruptions)

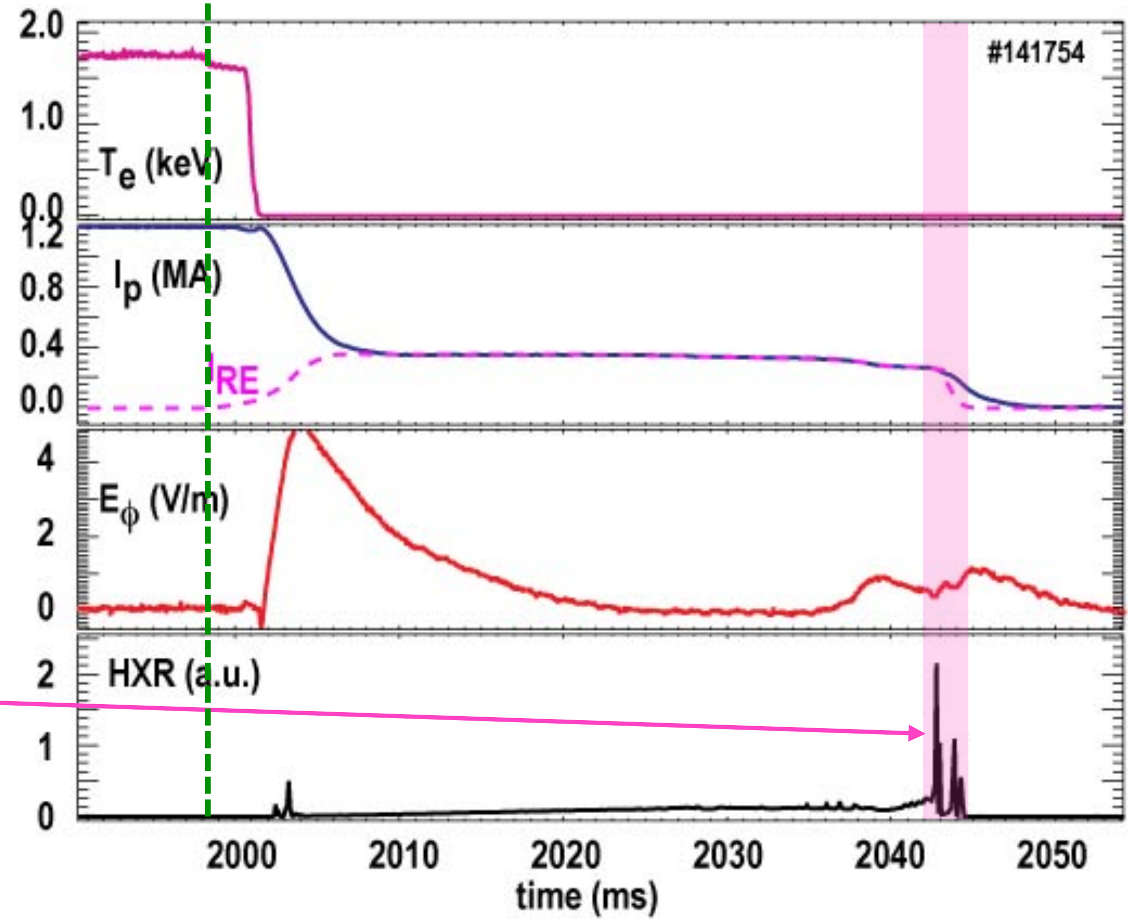
Thermal quench (TQ) - RE seed formation

Current quench (CQ) (prompt RE loss and RE avalanche)

RE plateau (equilibrium with RE-dominated current)

RE final loss (phase most dangerous for wall)

~ 10 torr-L Argon pellet hits plasma edge



Formation: Historically, inner wall limited (IWL) targets much better RE plateau producers than lower single null (LSN)

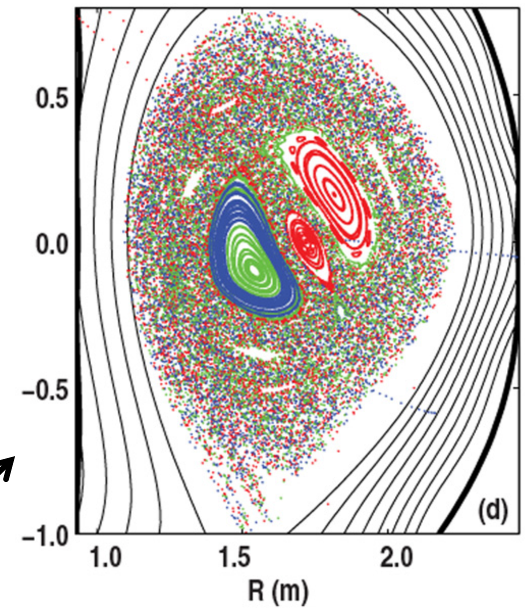
- **With Argon pellet injection, RE plateau yields:**
  - **LSN: < 15% shots**
  - **IWL: > 60% on some run days**

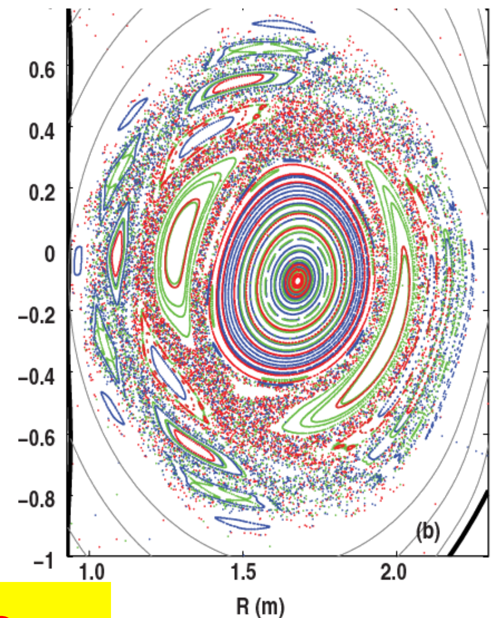
- **Similar trends reported on JET**
  – Gill, *NF* **42**(2002) 1039-1044

- **NIMROD modeling indicates much larger stochastic regions in LSN vs IWL → faster loss of RE seeds**
  – Unfortunately for ITER, increasing size reduces this effect

    Izzo, *NF* **51**(2011) 063032

    Izzo, PPCF **54** (2012) 095002



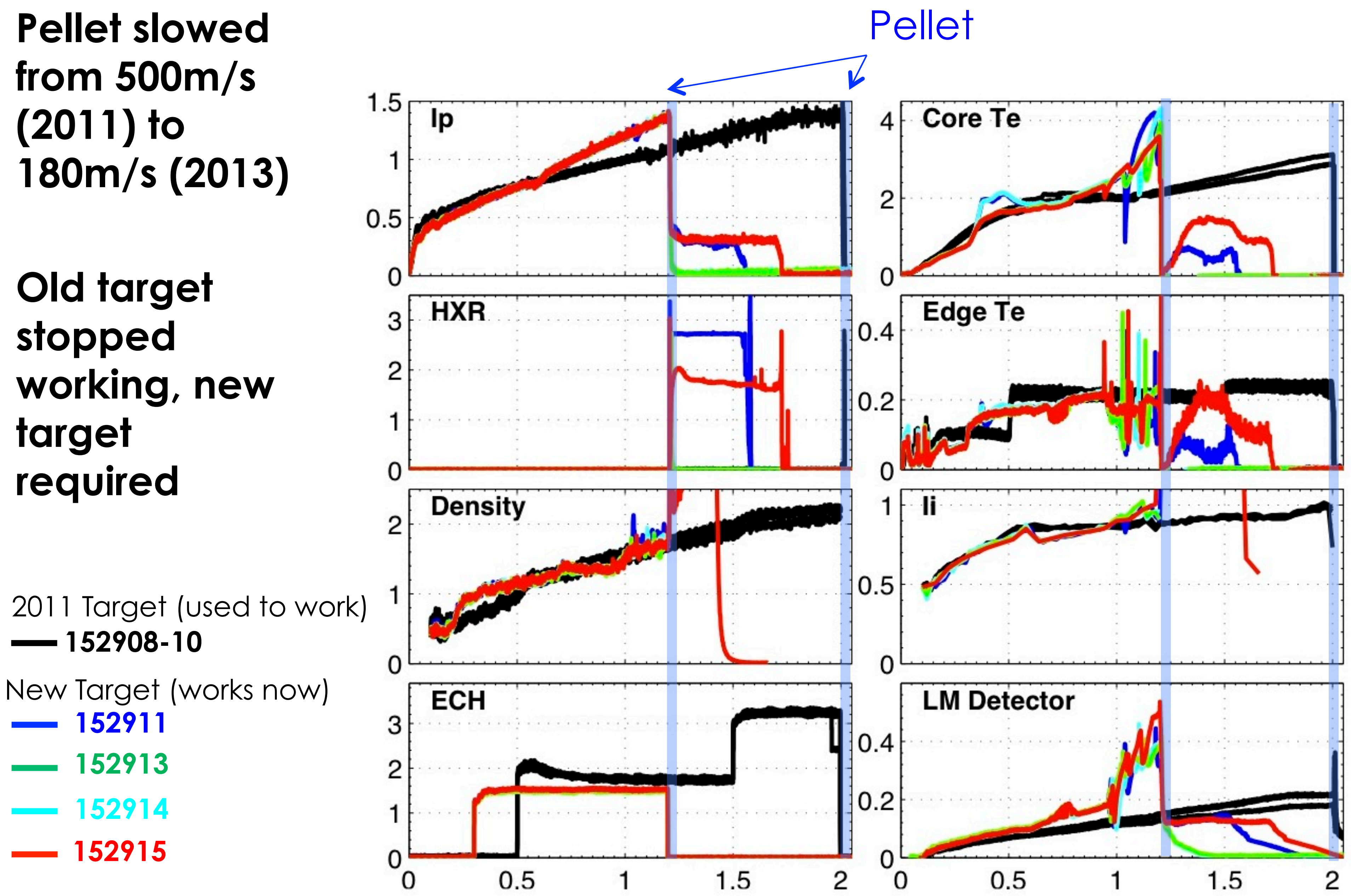


But this is clearly not the complete picture…

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

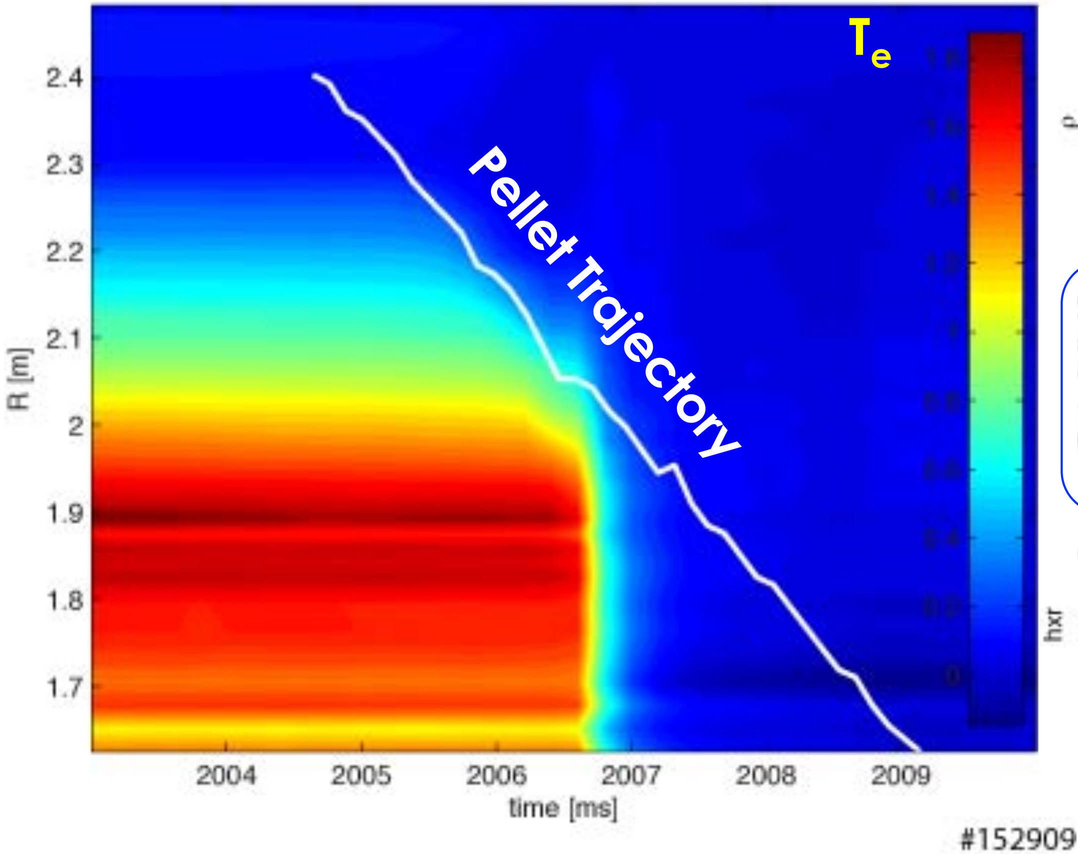
Formation: Subtle changes (like pellet speed) seem to have large effect upon RE production (IWL)

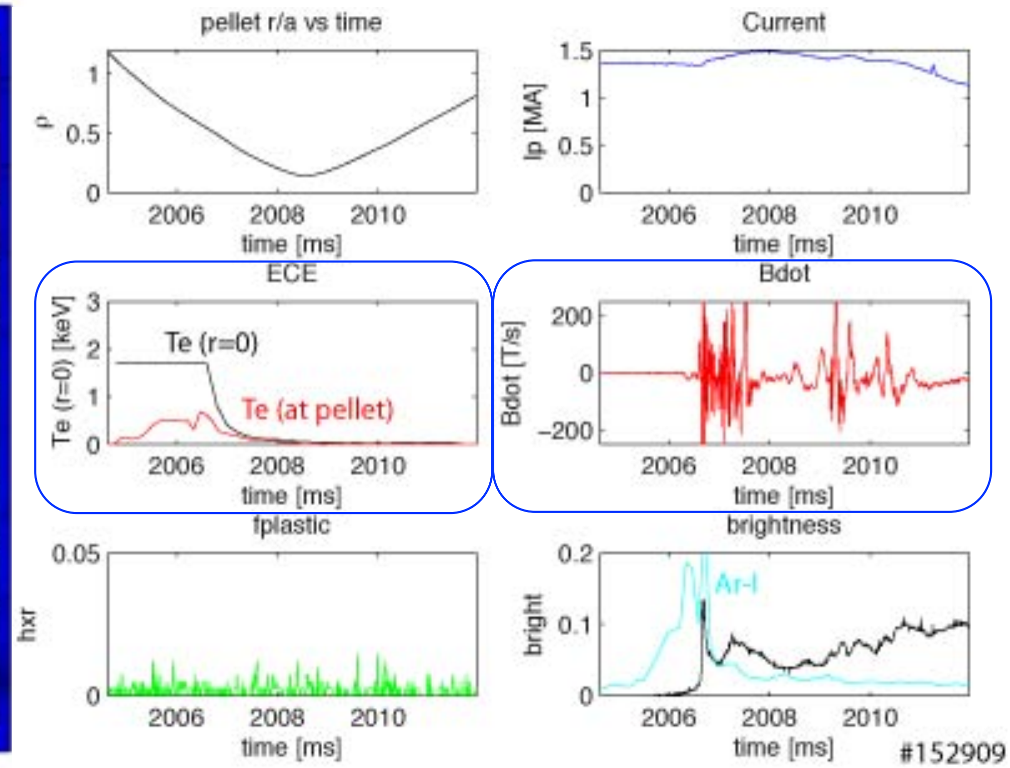
- **Pellet slowed from 500m/s (2011) to 180m/s (2013)**
- **Old target stopped working, new target required**



Formation: Subtle changes (like pellet speed) seem to have large effect upon RE production (IWL)

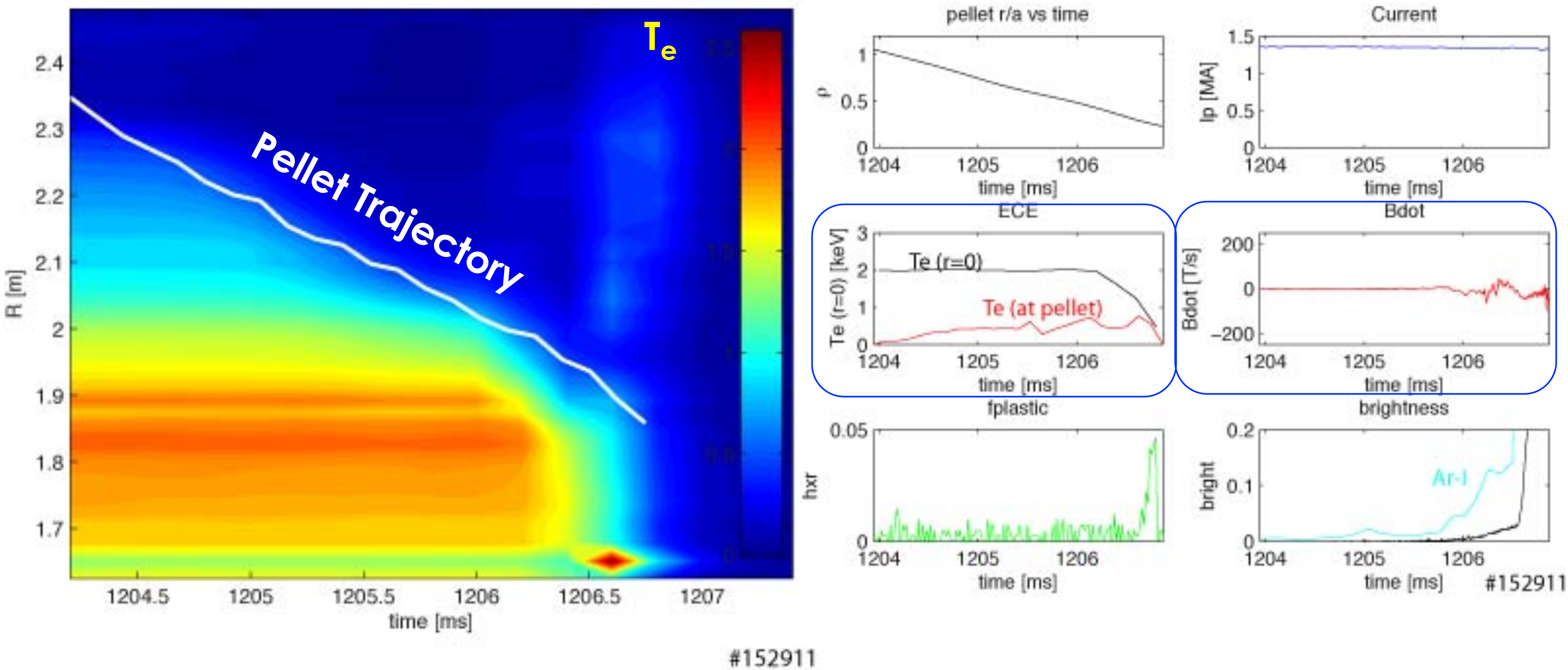
Old target, 180 m/s pellet, no significant RE



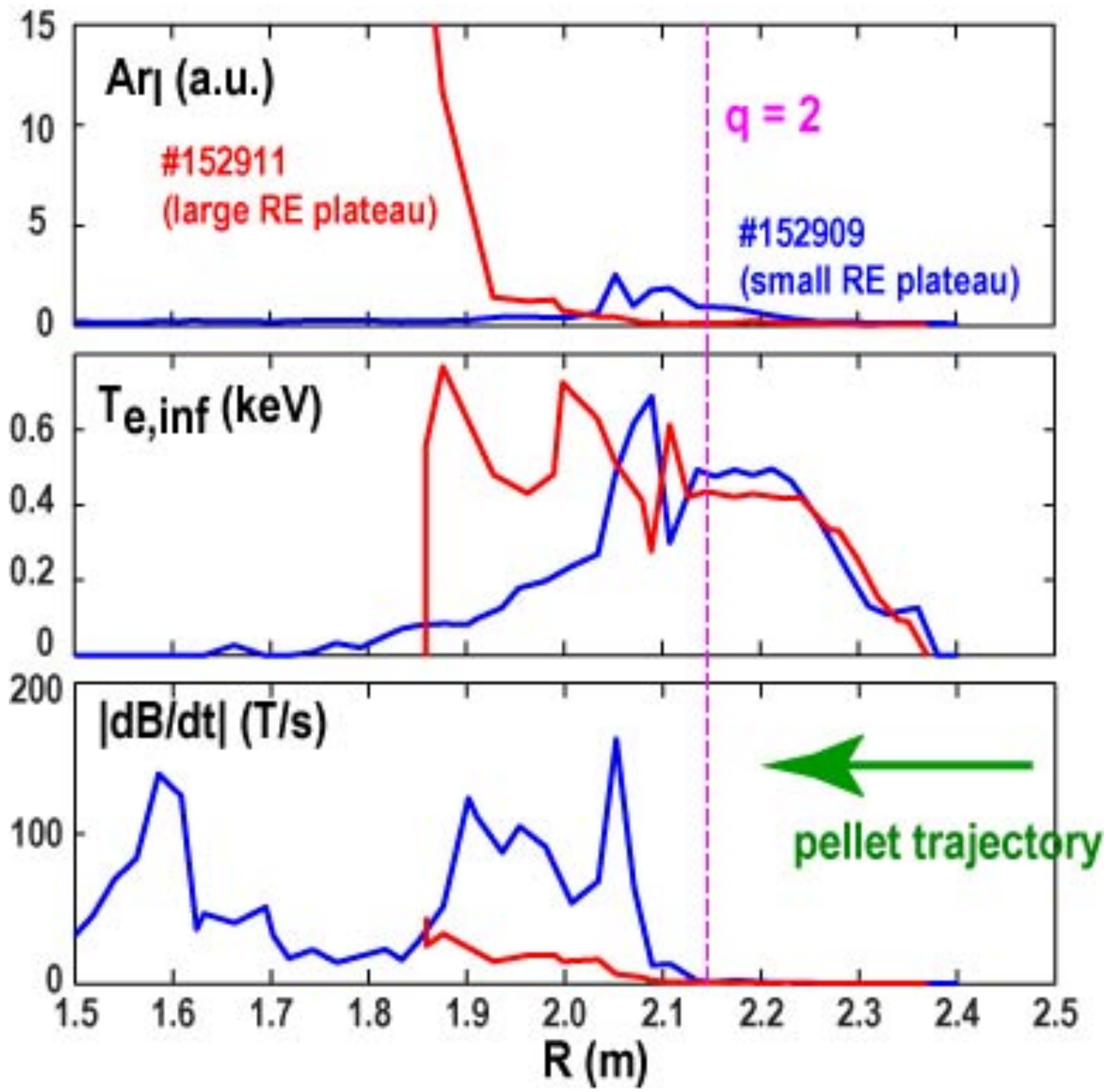


Formation: Subtle changes (like pellet speed) seem to have large effect upon RE production (IWL)

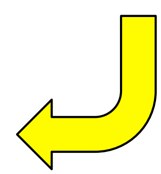
New target, 180 m/s pellet, long RE plateau



Formation: Pellet Ablation Deeper into Core Corresponds to Larger RE Production



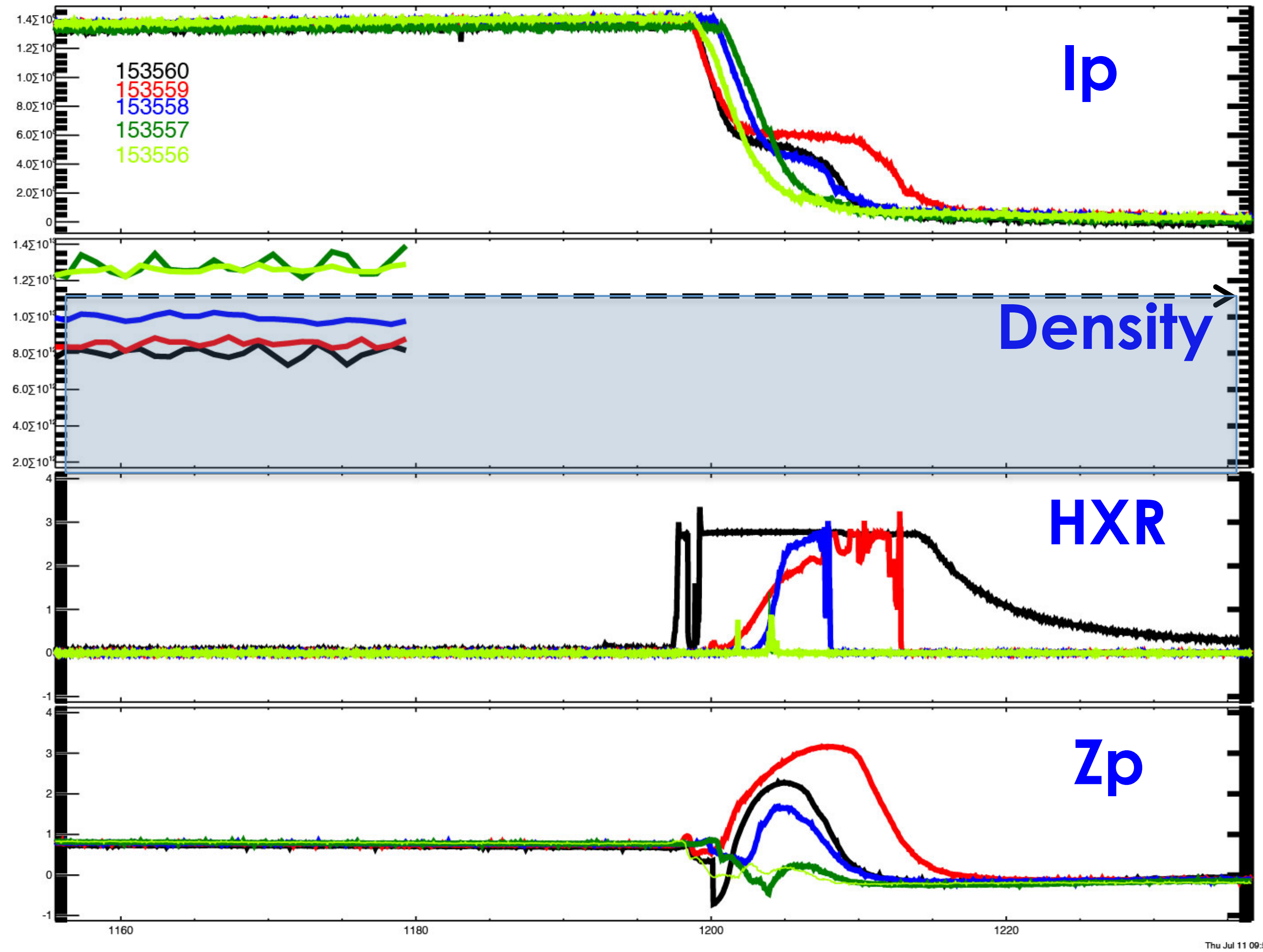
Does smaller MHD allow longer pellet interaction distance?



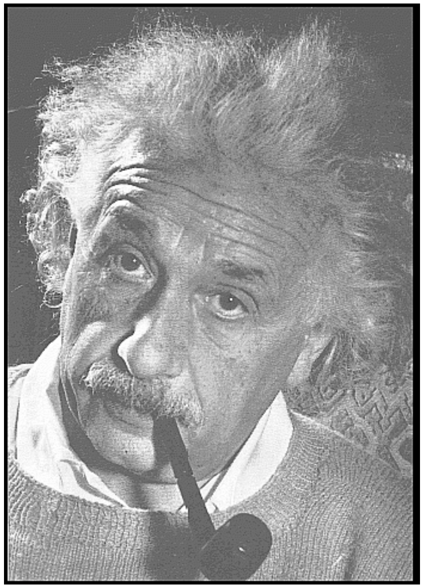
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Formation: Change in target evolution, density, seem to significantly alter LSN RE production as well

- Switched to "new" target evolution in LSN shape
- Once n_e decreased below 1E19m^{-3}, LSN RE production shot up (3/3)



Modeling Moment: RE formation



1. Why would pellet deposition radius strongly effect RE production?

2. Why is pellet ablation so different for old/new targets when T_e seen by pellet does not vary significantly?
   – MHD? Trace slide-aways?

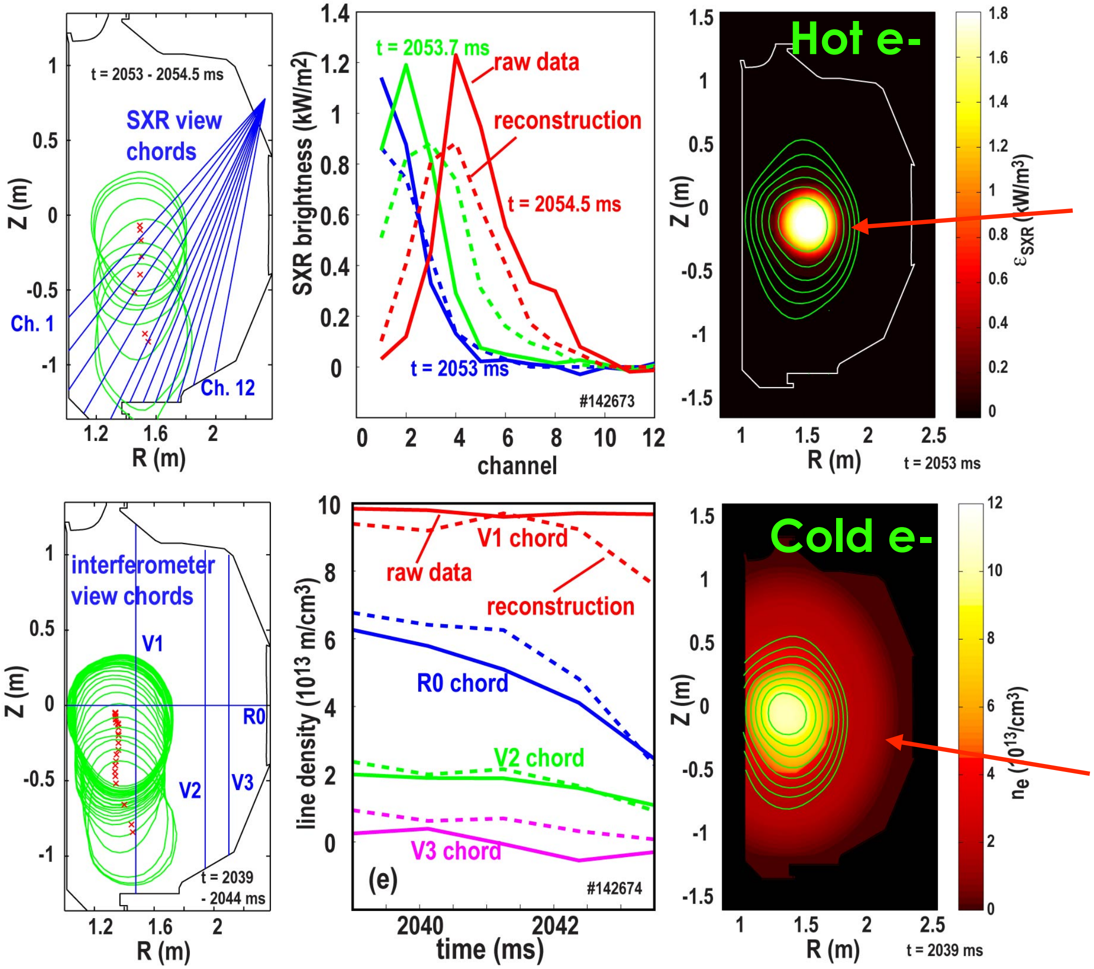
3. Why does "new" target seem to increase LSN RE plateau production significantly, & why does it care about flattop density?

4. Do any of these subtleties matter for ITER?

1. Formation
2. **Anatomy**
3. Dissipation
4. Final Loss

Anatomy of RE Plateau: Hot Electrons Form Narrow Beam Inside Dense Cold Electrons

Tomographic inversions of RE plateau hot and cold electron densities



- Make use of vertical instability to get profile data
- Soft x-ray emission structure shows REs dominantly in narrow (*a* < 0.2 m) beam
- Magnetic flux surface inversions give reasonable estimate of RE beam position
- Interferometers show that cold electrons fill much of vacuum chamber

Hollmann, NF 53 (2013) 083004

Anatomy of RE Plateau: RE Energy Distribution Function in Presence of Argon Skewed to Lower Energies

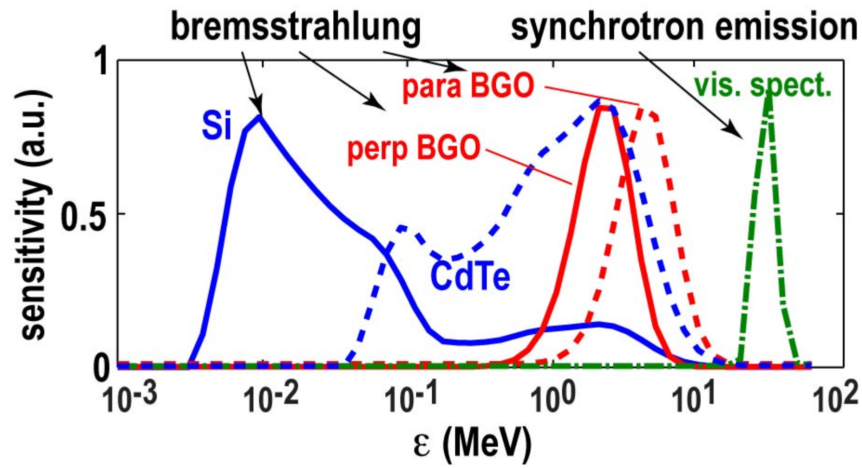
- **Perp and para bremsstrahlung and synchrotron emission measurements combined to give RE energy spectrum**
- **Fits depend on RE pitch angle θ for higher energies ε > 1 MeV**

– Typically find θ ~ 0.2

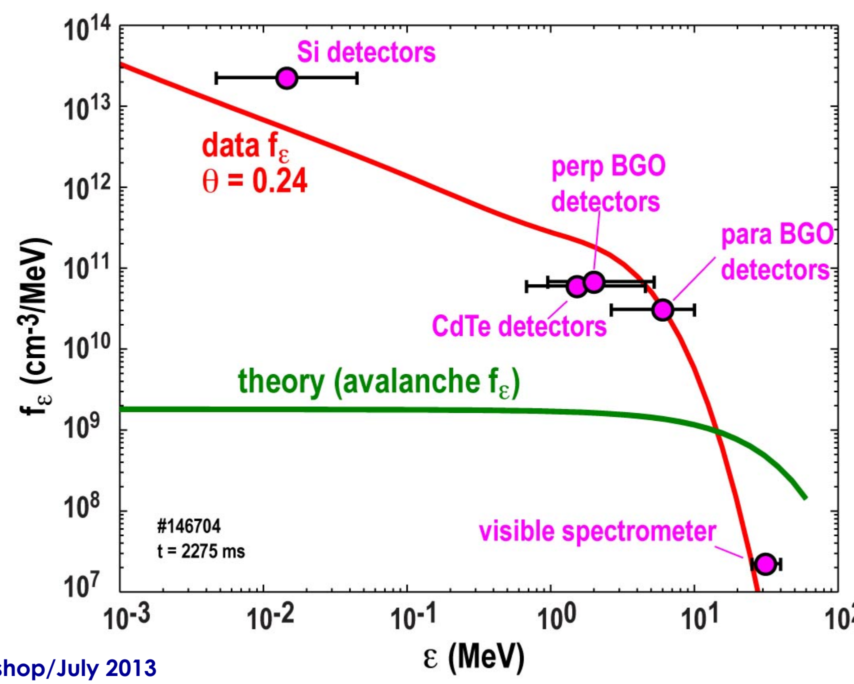
- **Find distribution function more skewed to low energies than expected from avalanche theory (Putvinski, Nucl. Fusion 1994)**

– Suggests extra drag on REs not included in avalanche theory

– Pitch angle scattering off high-Z ions?



RE energy spectrum

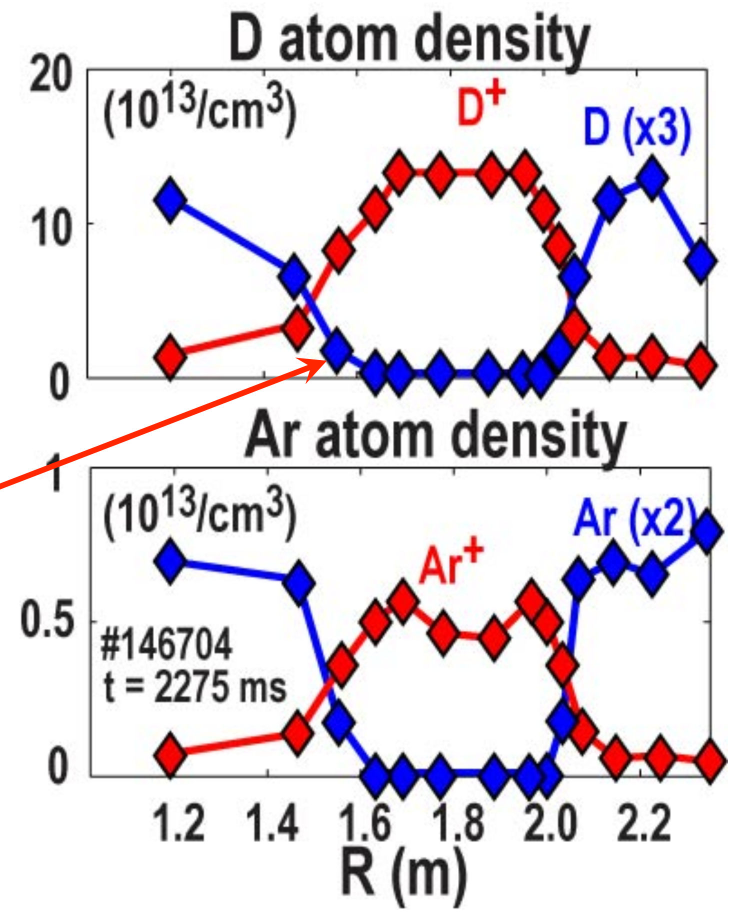


Hollmann, NF 53 (2013) 083004

Anatomy of RE Plateau: Neutrals Largely Excluded From RE Beam

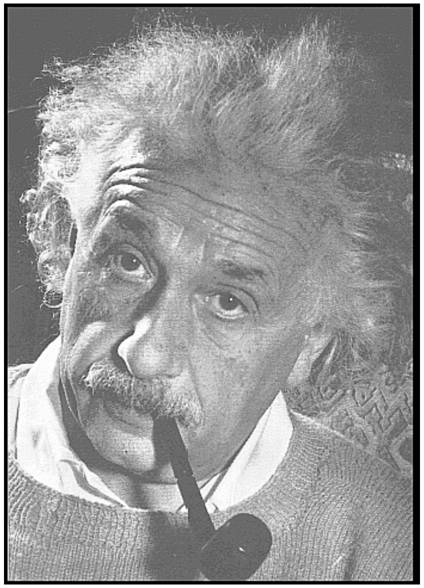
- Neutral distribution important for comparing observed RE current dissipation with theory
- Can estimate neutral distribution from line brightness profiles
- Center of RE beam found to contain mostly ions, not neutrals
- Dominant ions in RE beam are D^+, Ar^+ (5%–20%), and C^+ (1%)

Inversions of neutral atom profiles



Hollmann, NF 53 (2013) 083004

Modeling Moment: RE Anatomy



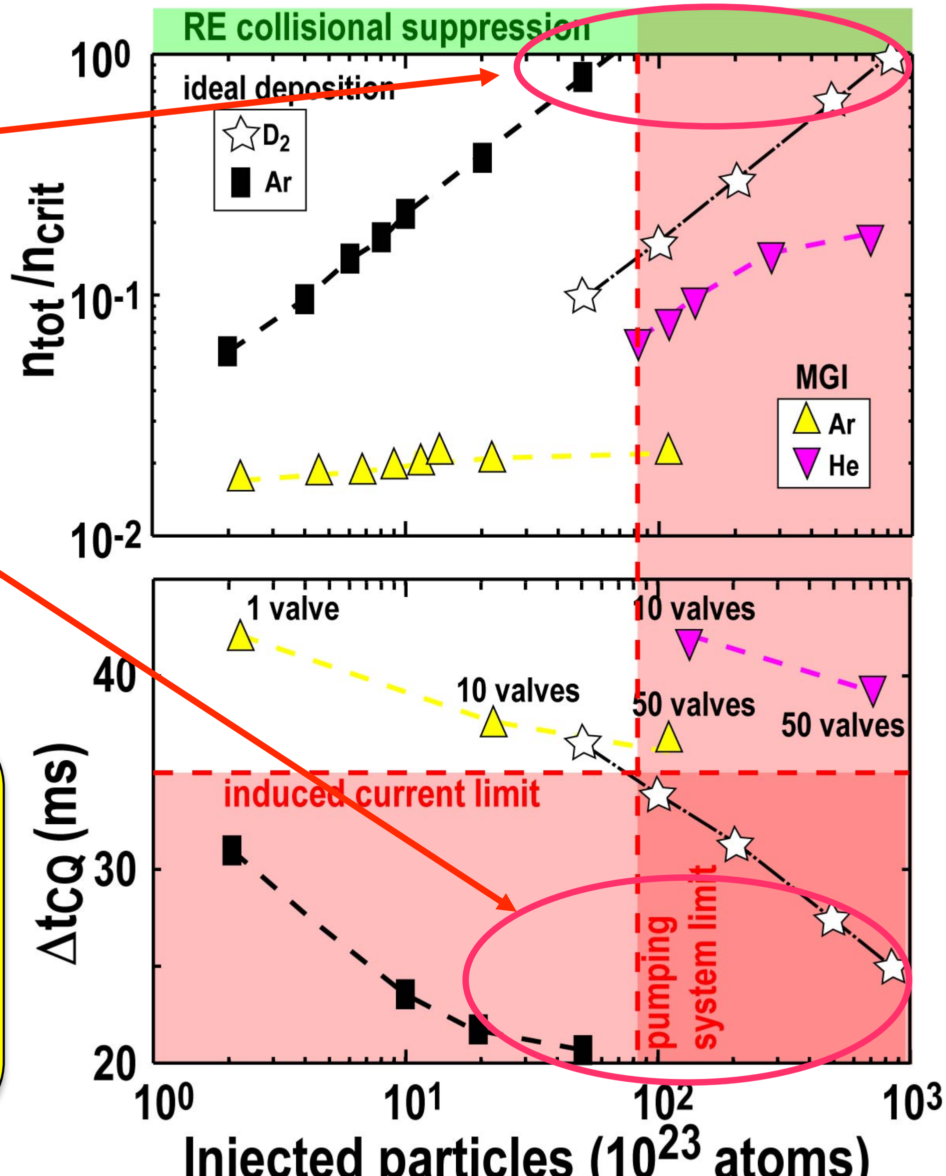
1. **What determines size of RE core?**
   - Importance will be seen later

2. **Why is RE energy distribution skewed to low energy?**

1. Formation
2. Anatomy
3. **Dissipation**
4. Final Loss

Dissipation: Meeting "Rosenbluth" Critical Density for Avalanche Suppression in Self-consistent Manner Unlikely

- Can reach n_{crit} with instantaneous "ideal" deposition of mass.
- But these cases cause unacceptably fast CQ!
- Conclusion: rapid shutdown important to study for ITER TQ heat load mitigation, but cannot be counted on for RE mitigation!



0-D simulations of rapid shutdown of ITER

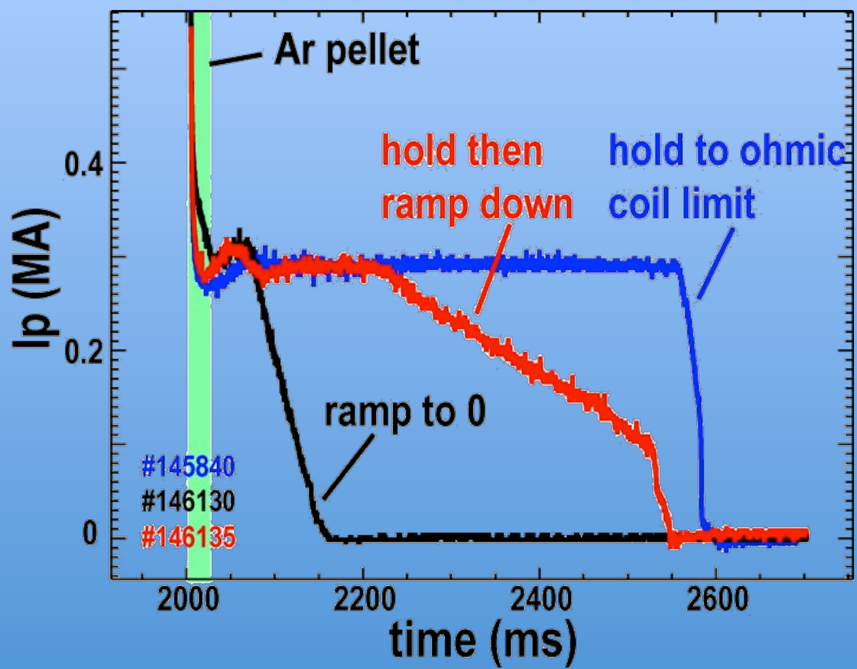
Questions:

1. Is n_{crit} necessary, or upper bound?
2. Can we design scenarios for secondary dissipation of existing beam?

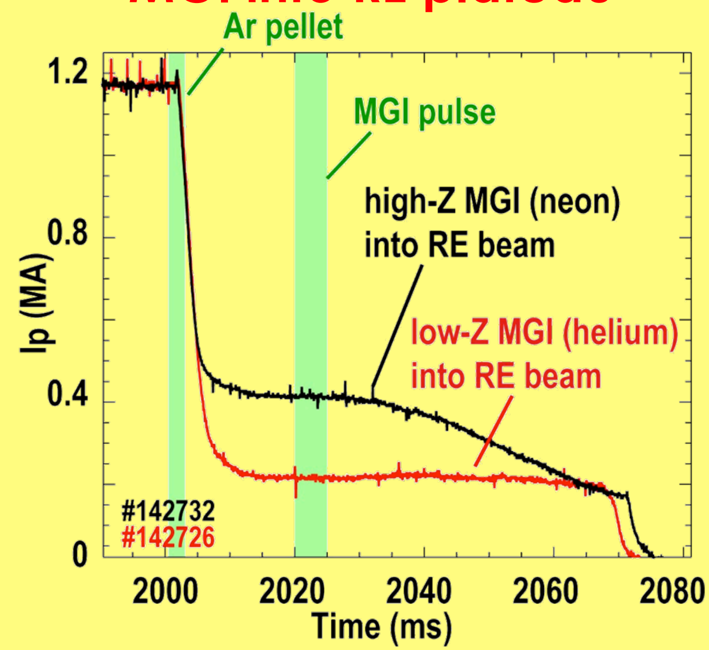
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Dissipation: Control Allows Numerous Paths for Measuring RE Plateau Dissipation

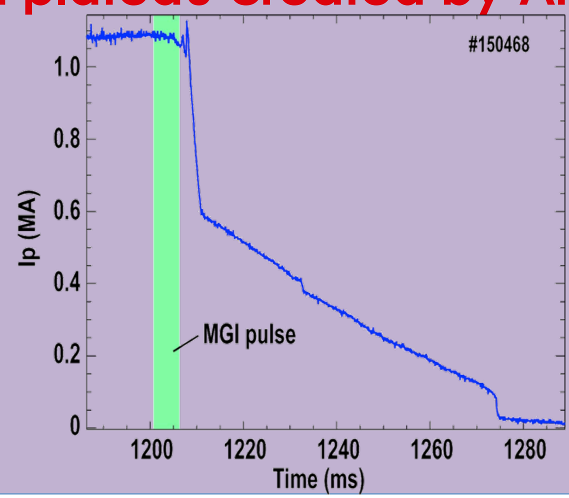
RE current control with ohmic coil



MGI into RE plateau



RE plateau created by Ar MGI

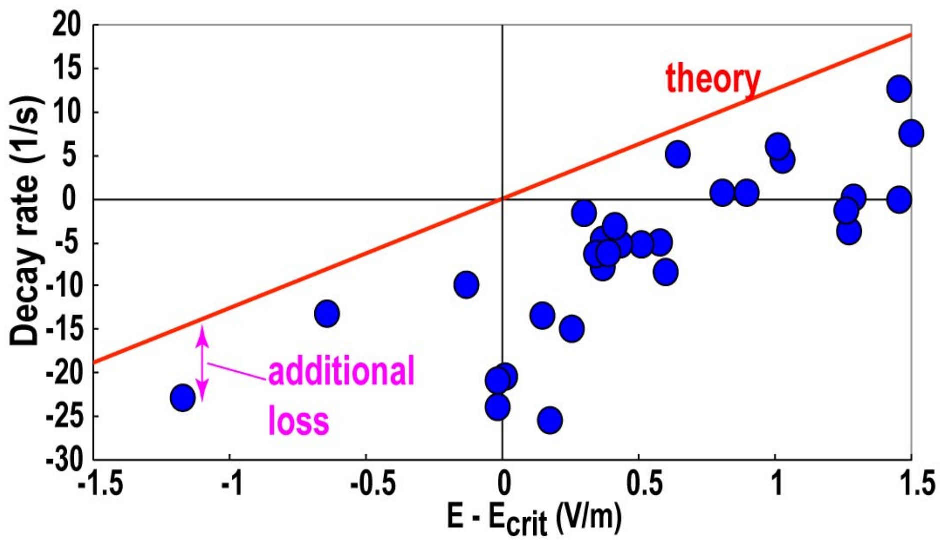


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

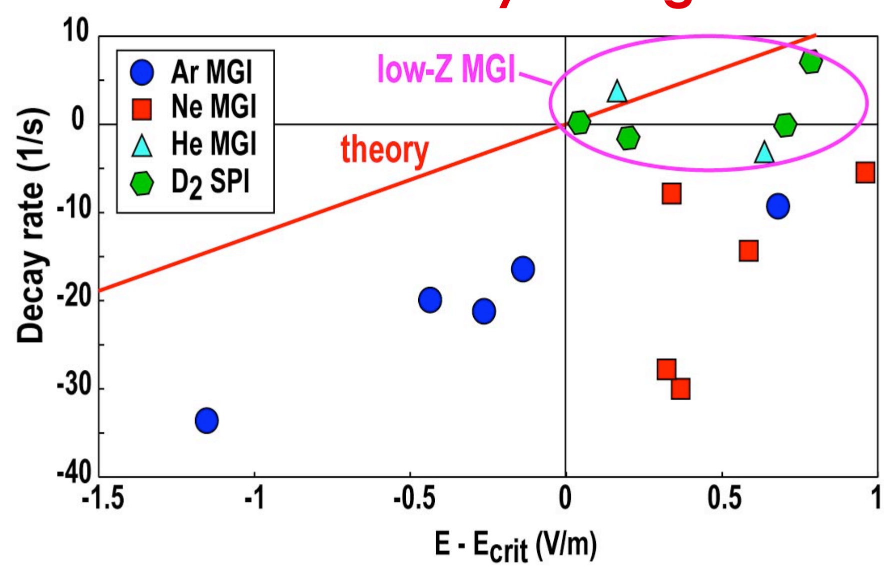
Dissipation: Current Decay of RE Plateau Faster Than Expected From Electron-electron Collision Drag

- **Avalanche theory (electron-electron collisions) predicts current decay rate $I^{-1}dI/dt = \nu_R \sim (E - E_{crit})$**
- **E estimated from magnetic reconstructions, E_{crit} from ion composition**
- **Vary E with ohmic coil ramps, vary E_{crit} with impurity injection**
- **Anomalous additional decay of about 10–20/s seen in data**
- **Lower anomalous additional decay following massive low-Z injection**
  - Suggests anomalous decay is due to high-Z ions in beam

RE current decay during ohmic ramp



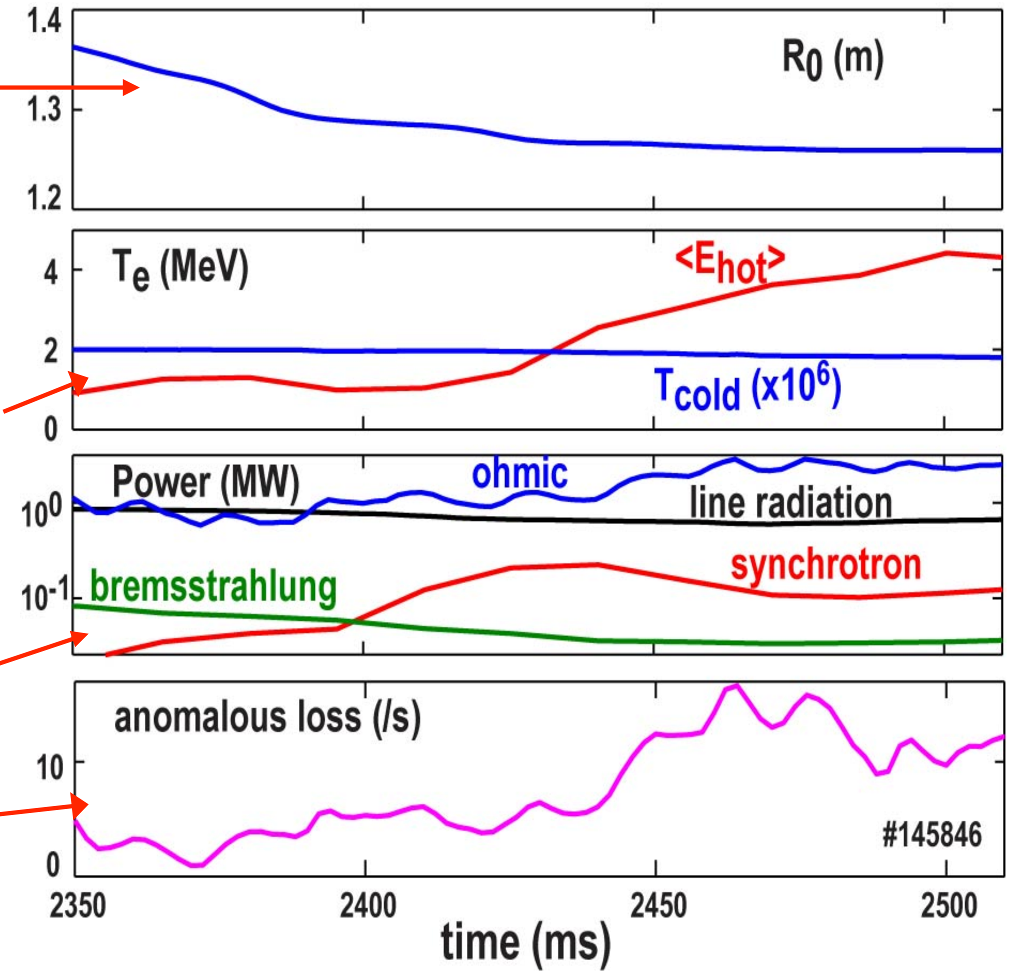
RE current decay during MGI



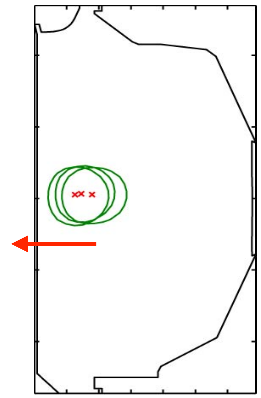
1. Hollmann, NF 53 (2013) 083004 2. Hollmann, NF 51 (2011) 103026

Dissipation: Increasing Anomalous Loss as RE Beam Moves Closer to Wall Suggests Transport Loss of REs

- **If ohmic feedback is turned off, RE channel current decays and drifts into center post**
- **Shrinking beam increases internal *E*-field**
- **Decreased coupling between hot and cold populations as RE beam heats!**
- **Increasing power balance deficit consistent with RE loss to wall**
- **Increasing anomalous loss rate consistent with increased RE loss to wall**



Power balance of RE beam moving into wall



RE beam position

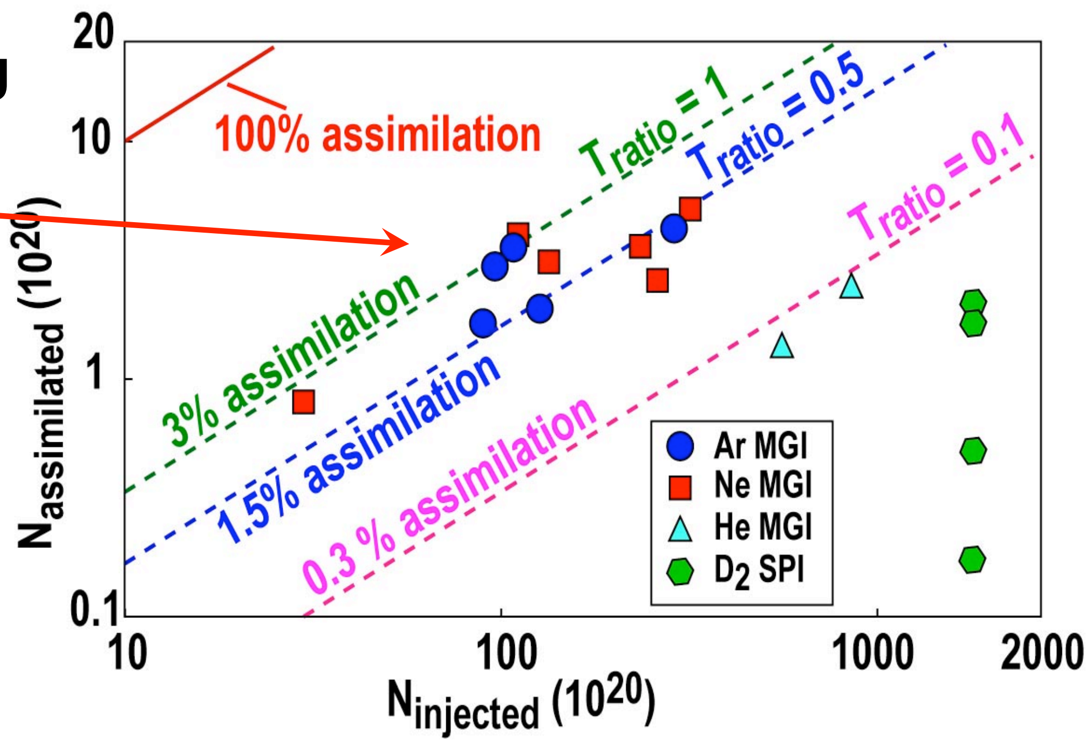
Hollmann, NF 53 (2013) 083004

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Dissipation: Assimilation of Impurities Injected Into RE Plateau Low But Predictable

- **Measure initial ion/neutral temperature ratio T_{ratio} ~ 0.5 with line Doppler broadening**
- **Assimilation of additional gas injected into RE plateau consistent with nT = constant**
- **Low assimilation of low-Z injected gas suggests lower T_{ratio}**
  - Low radiation efficiency of low-Z gas allows core ions to heat up?

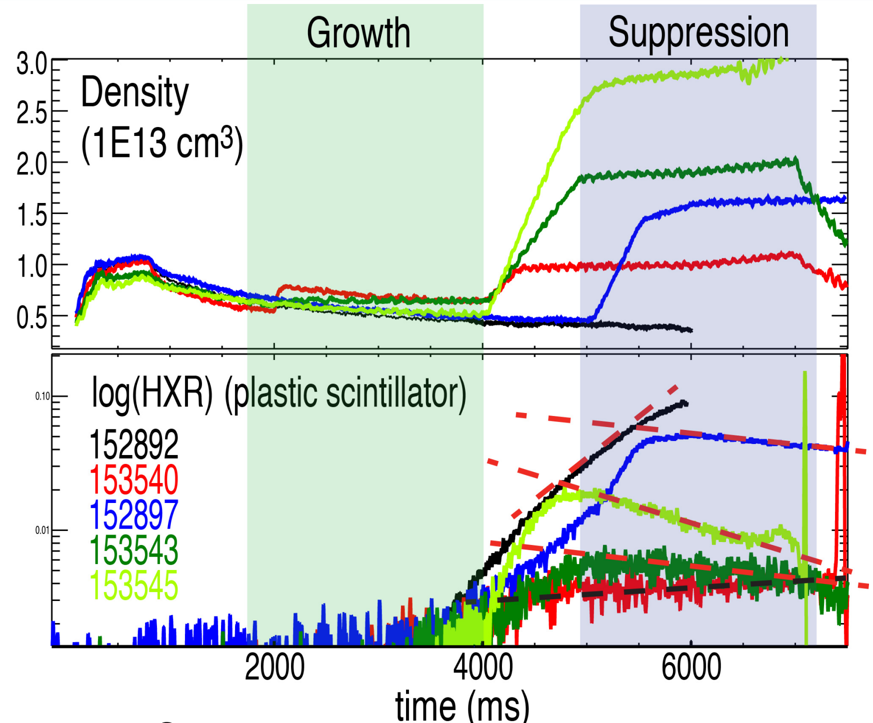
Assimilation of impurities injected into RE plateau

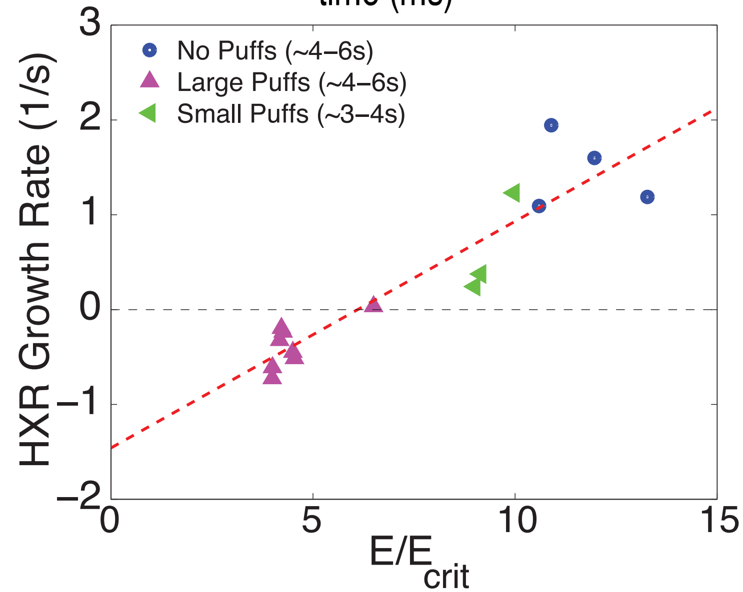


Hollmann, NF 53 (2013) 083004

Dissipation: Impurity-free collisional suppression of quiescent runaway electron (QRE) beams may indicate anomalous losses without high-z impurity

- **Very low density Ohmic flat-top operation excites QRE beam free of instabilities**
- **Gas puffing re-introduced into tail end of discharge to suppress QRE beam**
  - Critical electric field for RE suppression is linear in density
- **Relationship found between critical electric field and QRE suppression, as measured by HXR scintillators**
  - Zero crossing appears anomalous ($E>E_{crit}$)
- **Characterization of QRE beam in progress to understand result**

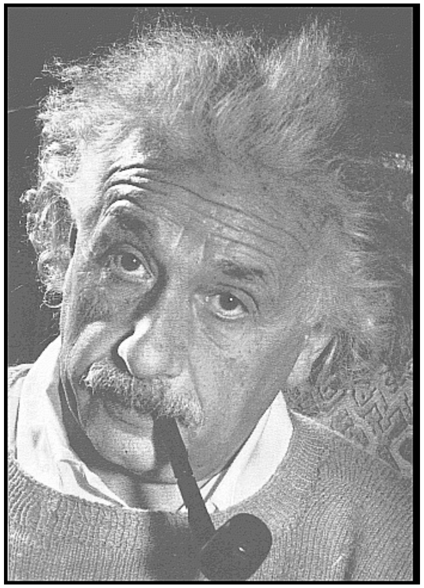




Very early results…

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Modeling Moment: RE Dissipation



1. **What are physics mechanisms behind measured anomalous losses?**
2. **What are their relative strengths?**
3. **Quantitative predictions of dissipation?**
   - Self-consistent secondary dissipation scenarios
4. **Can anomalous loss reduce "Rosenbluth density" enough that suppression is technically feasible?**
   - Must meet ITER pumping, CQ limitations

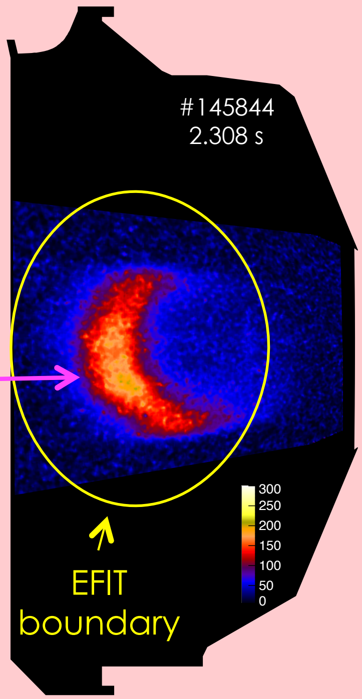
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

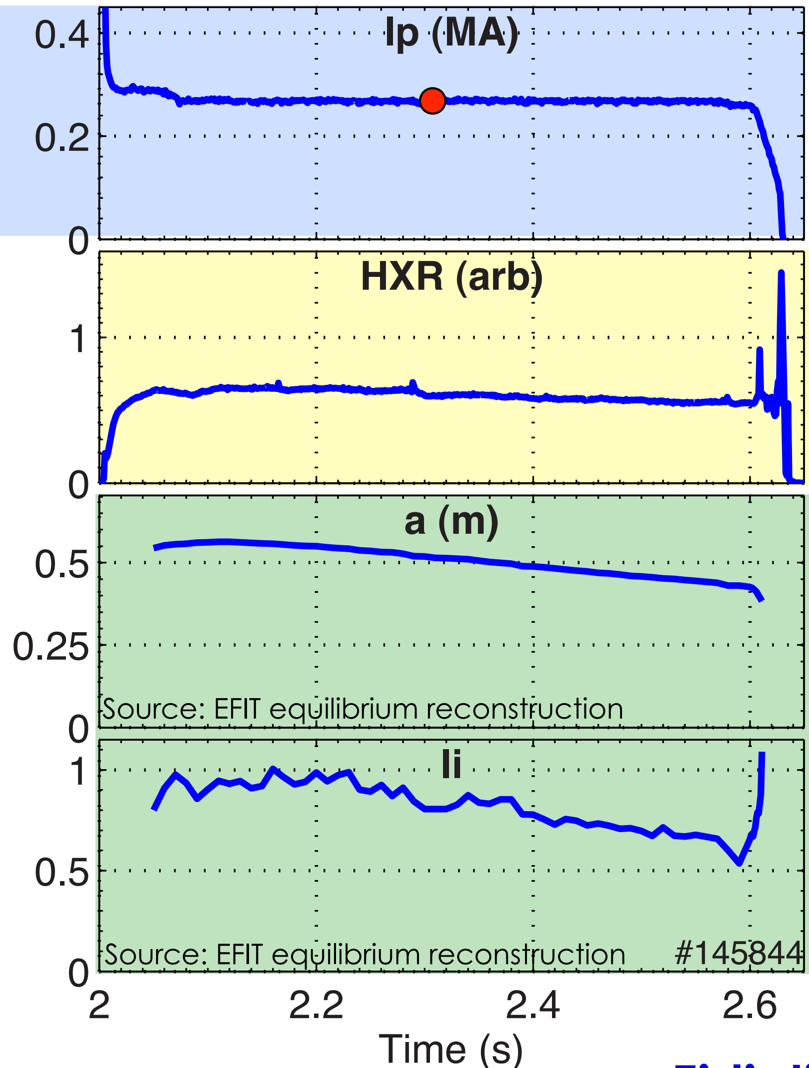
1. Formation
2. Anatomy
3. Dissipation
4. **Final Loss**

Final Loss: Ip/Rp Control Enables Long-lived, Slowly Evolving RE Beams

- **Ip control:**
  300kA for > 600ms
  (to OH flux limit)

- **Maintain low-κ inner wall limited (IWL) shape**





- **HXR steady, indicating constant RE population & loss rates**

- **Cannot hold constant radius**
  - li decreasing
  - PF coils cannot approach 0A to maintain steady equilibrium

Eidietis, PoP 19 (2012) 056109

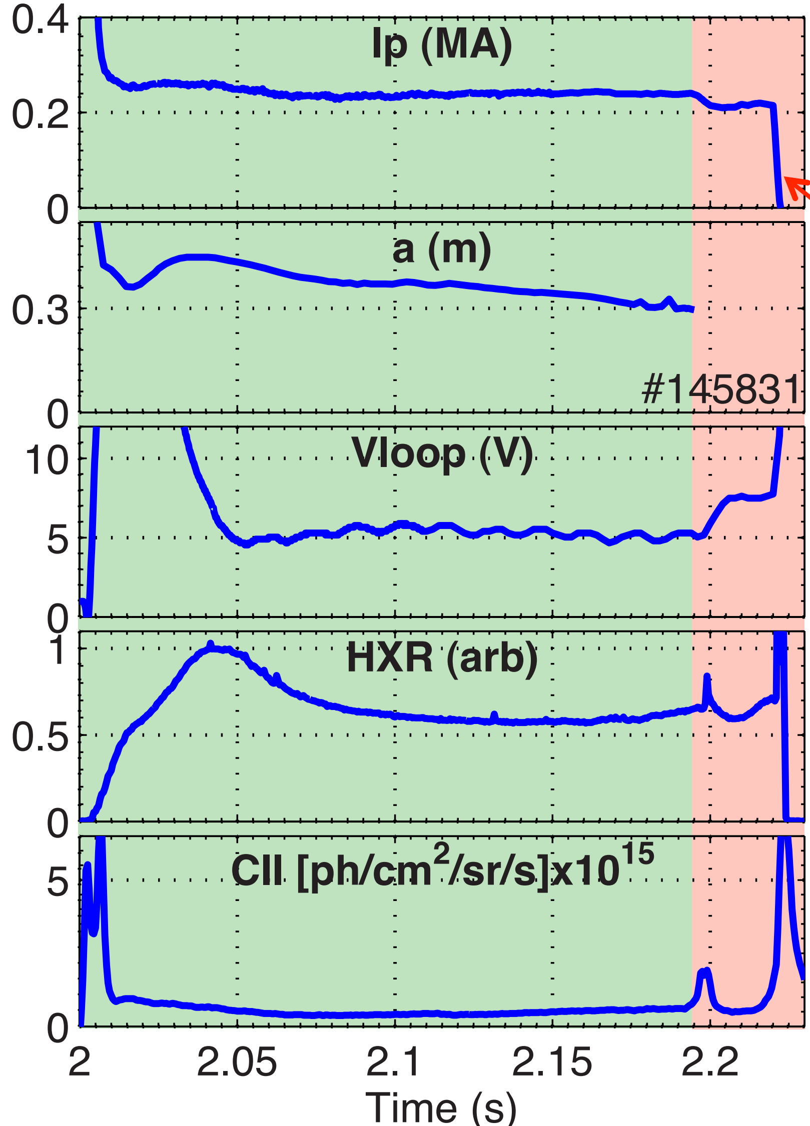
Final Loss: Intensity of RE Interaction with Inner Wall Exhibits Threshold in Minor Radius

a > 30cm

Measurements of interaction RE with inner wall

- V_{loop}
- HXR
- Carbon emission

fairly independent of beam dimensions



a < 30cm

← Ip loss

Terminal instability (stationary n=1, occasionally w/ n=2)

← Rapid V_{loop} jump

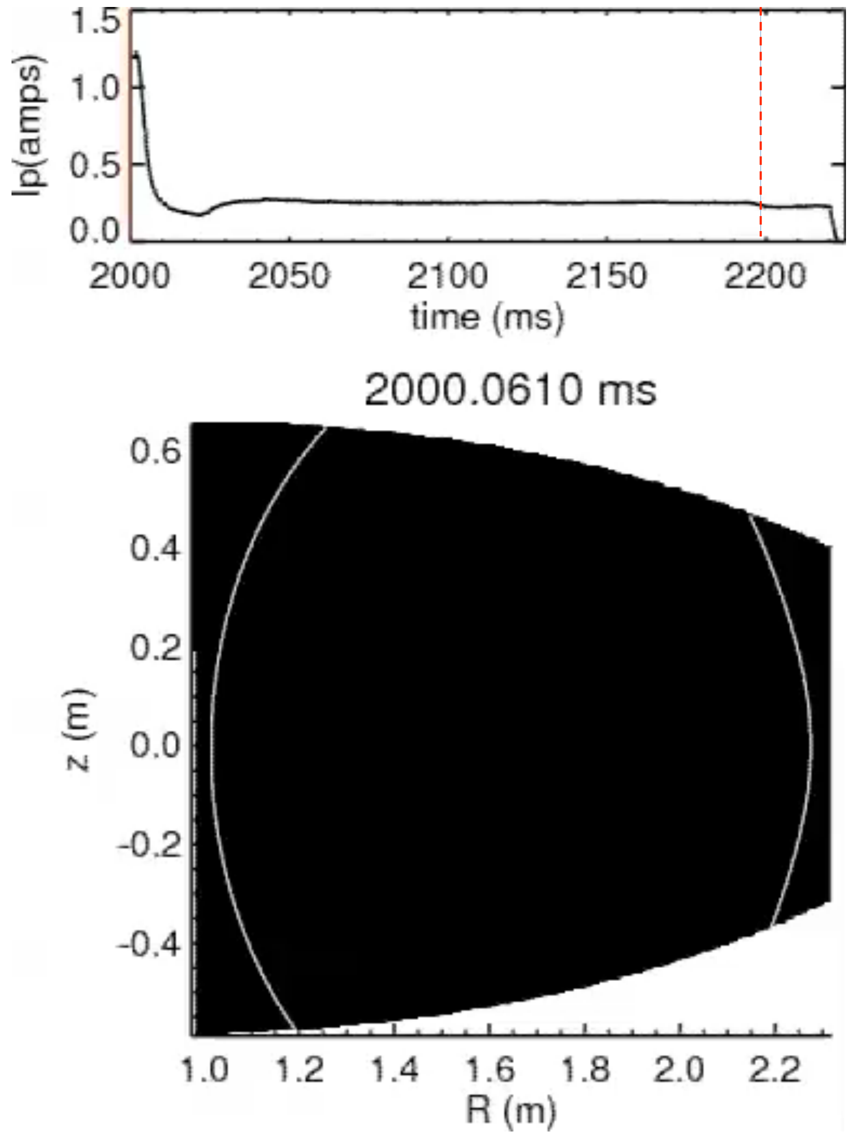
← Onset of fast deconfinement events (HXR)

← Carbon impurity bloom from wall tiles

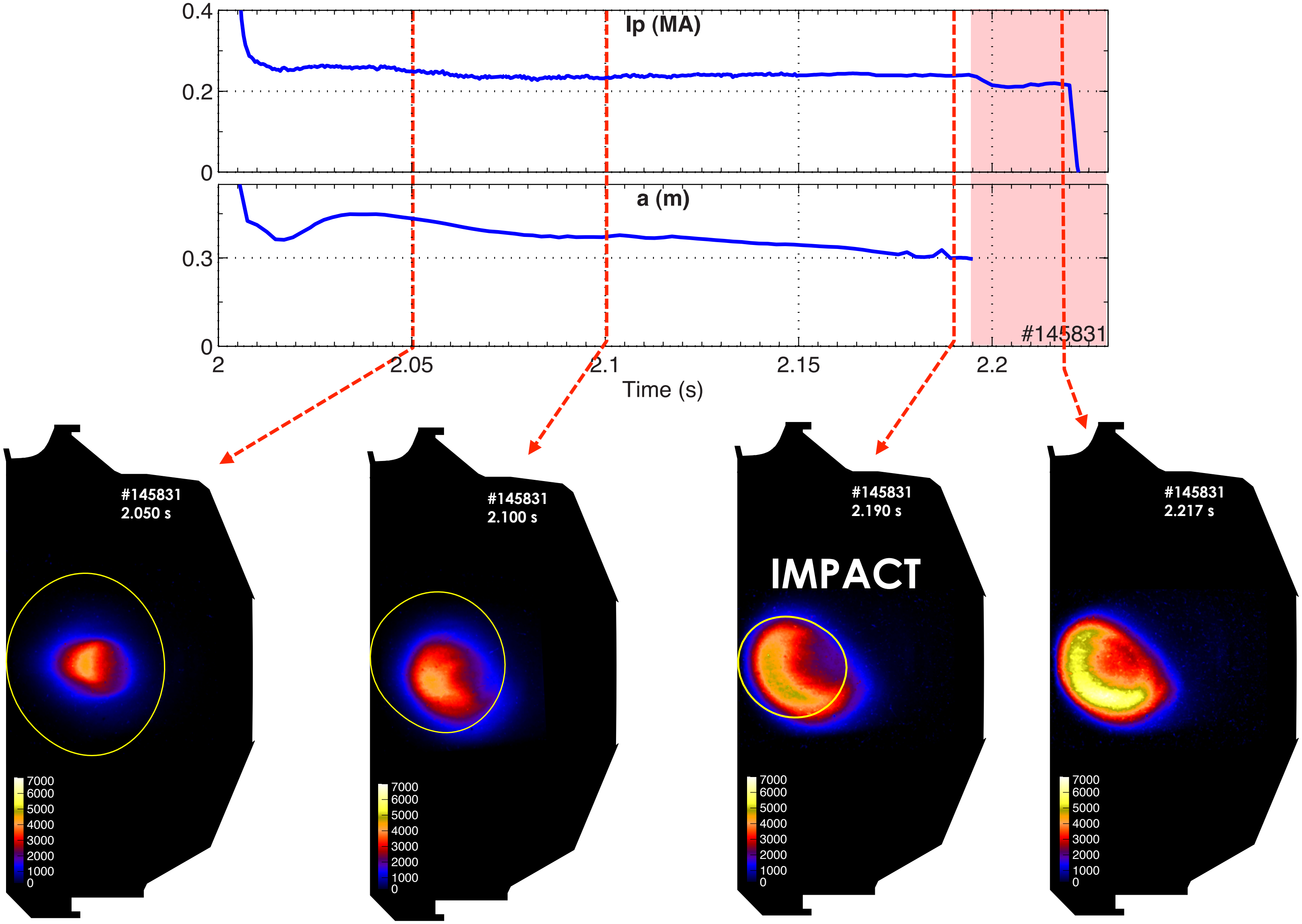
Eidietis, PoP 19 (2012) 056109

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Final Loss: Threshold for Increased Interaction Corresponds to Core of RE Synchrotron Emission Impacting Inner Wall



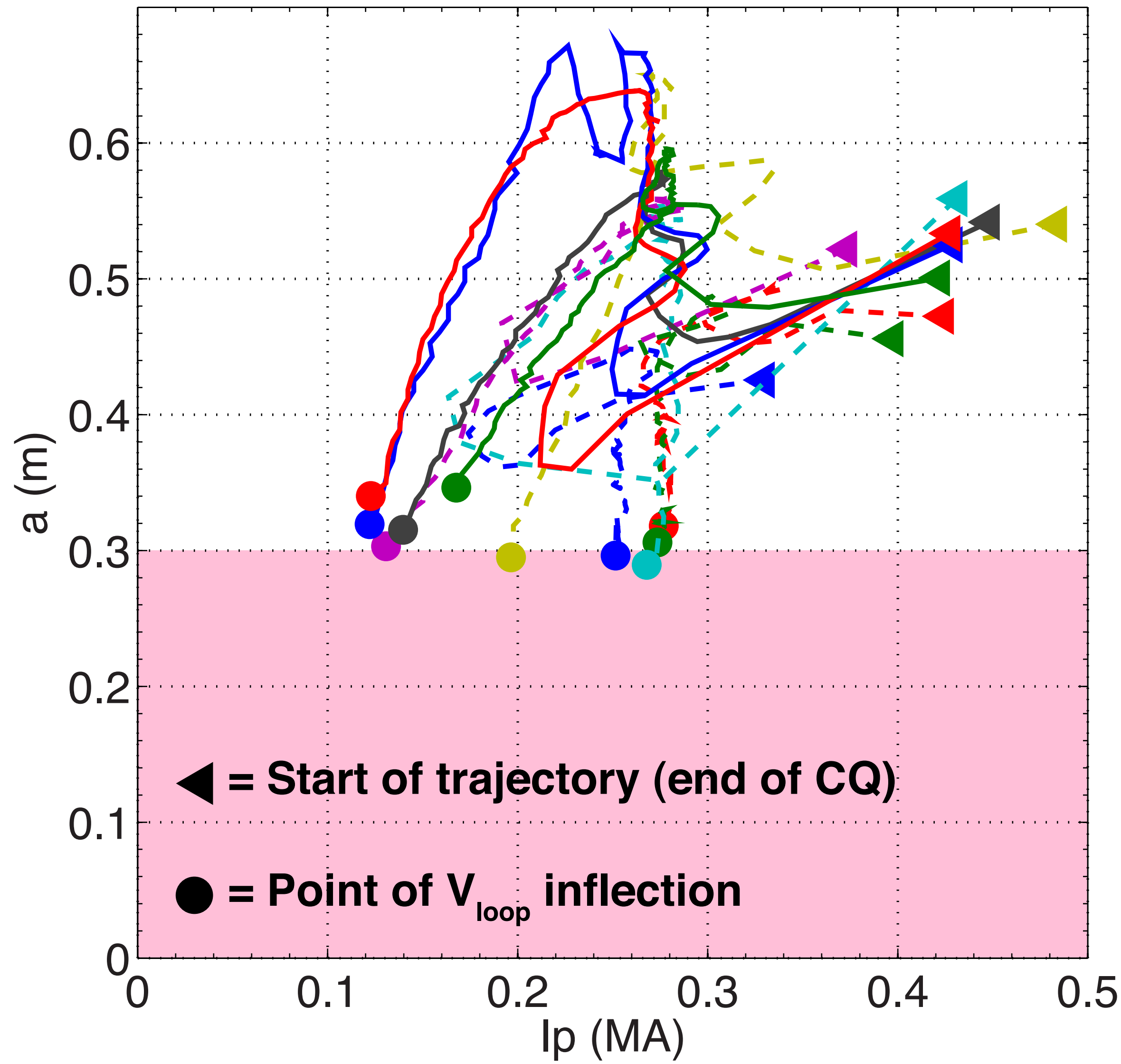
Final Loss: Threshold for Increased Interaction Corresponds to Core of RE Synchrotron Emission Impacting Inner Wall



Eidietis, PoP 19 (2012) 056109

Final Loss: Minor Radius of Threshold Consistent Across Varying $I_{RE,}$ Indicating Increased Wall Interaction is Not MHD-driven

- V_{loop} jump first & most robust indicator of increased wall interaction
- Regardless of path (constant current, slow ramp-down, fast ramp-down), interaction threshold occurs within narrow range of minor radius (30-35cm).
- q_{edge} at threshold always > 4, often higher



Eidietis, PoP 19 (2012) 056109

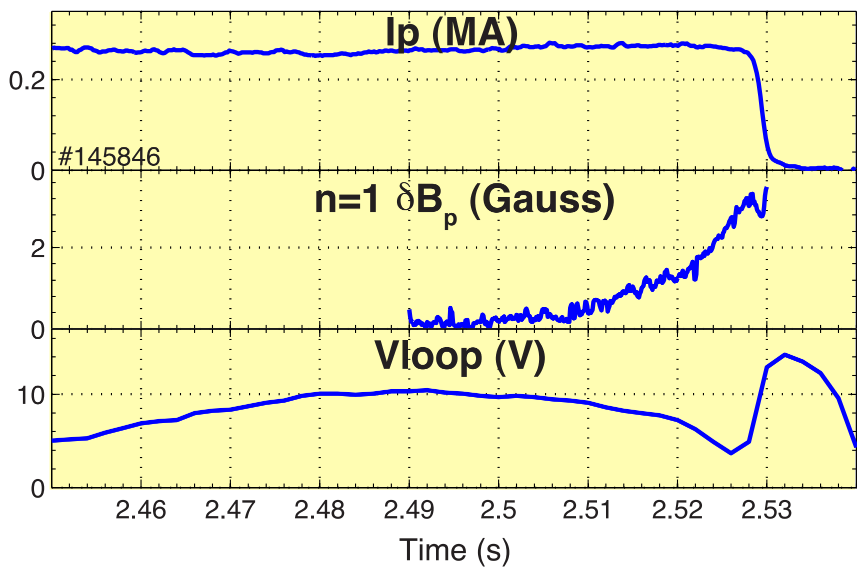
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

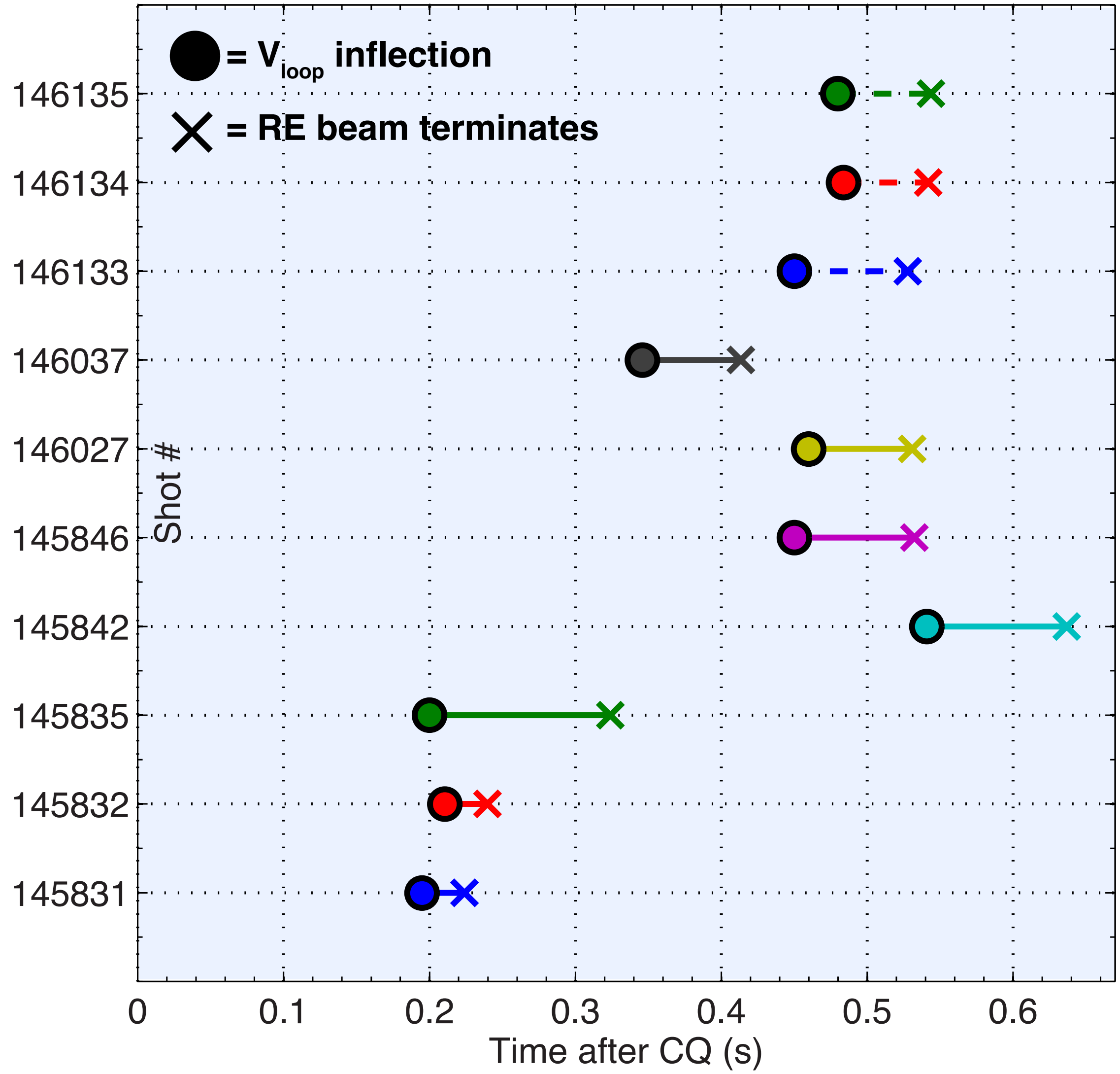
Final Loss: Intensified Wall Interaction is Common Precursor but not Direct Cause of Final RE Termination

- Δt from V_{loop} jump to final termination varies widely in controlled RE beams

- Typical terminal instability is non-rotating n=1 mode

  See: James, A.N. TP9.00027

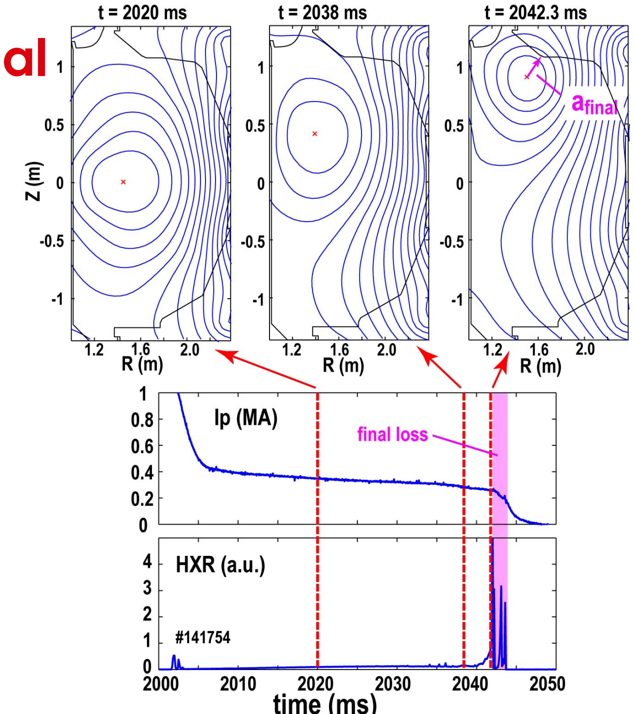




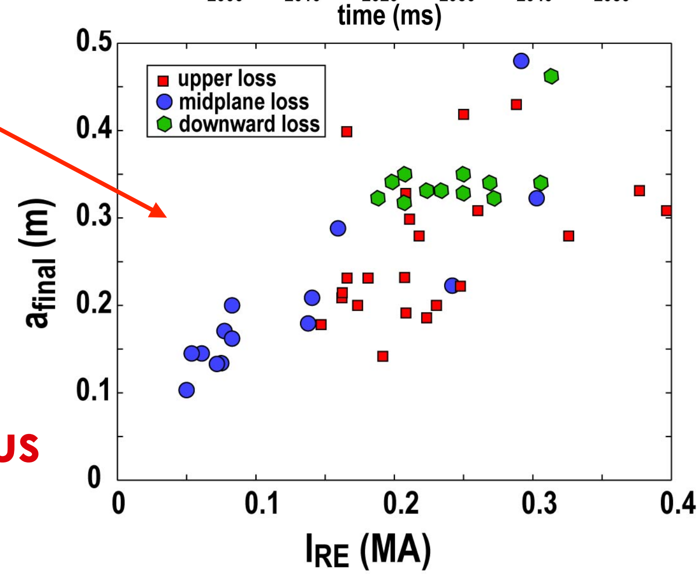
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Final Loss: RE beam current dominantly found inside $a < 0.3$ m

Estimating final loss radius



- Beam current channel position can be estimated from external magnetic signals.
- Final loss onset begins at some small minor radius a_{final} ~ 0.3 m.
- Consistent SXR beam radius, indicates current carried by REs.
- Small increase RE beam radius with RE current?
  - Not known what sets RE beam radius.



Final loss radius vs RE current

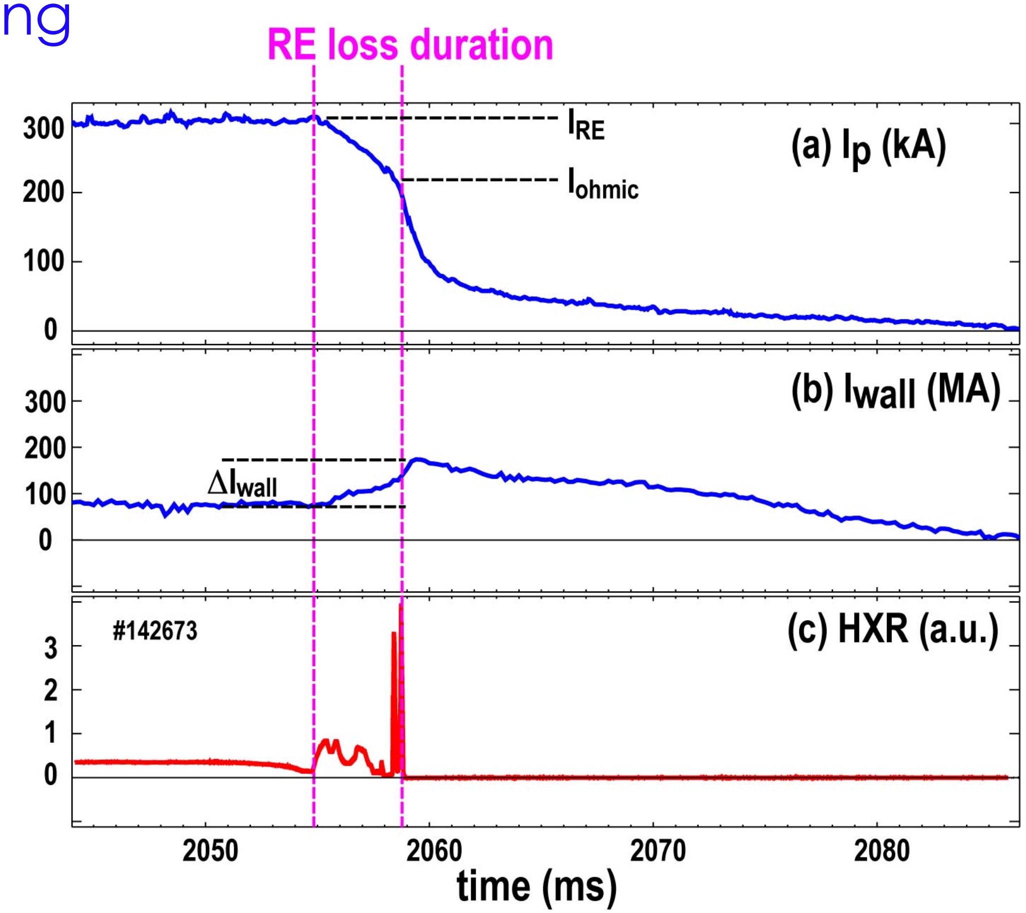
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Hollmann, NF 53 (2013) 083004

Final Loss: RE Current Partially Transferred to Ohmic Current and Wall Current During Final Loss

- **RE beam energy mostly magnetic**
  - But kinetic energy causes melting damage!
- **Conversion of RE magnetic energy to kinetic energy concern for ITER**
  - 40% of W_{mag} assumed to convert to W_{kin} [Loarte, Nucl. Fusion (2011)]
- **In DIII-D, significant RE current appears to go into ohmic current**
- **… and into wall current**

Transfer of RE current into ohmic current during final strike

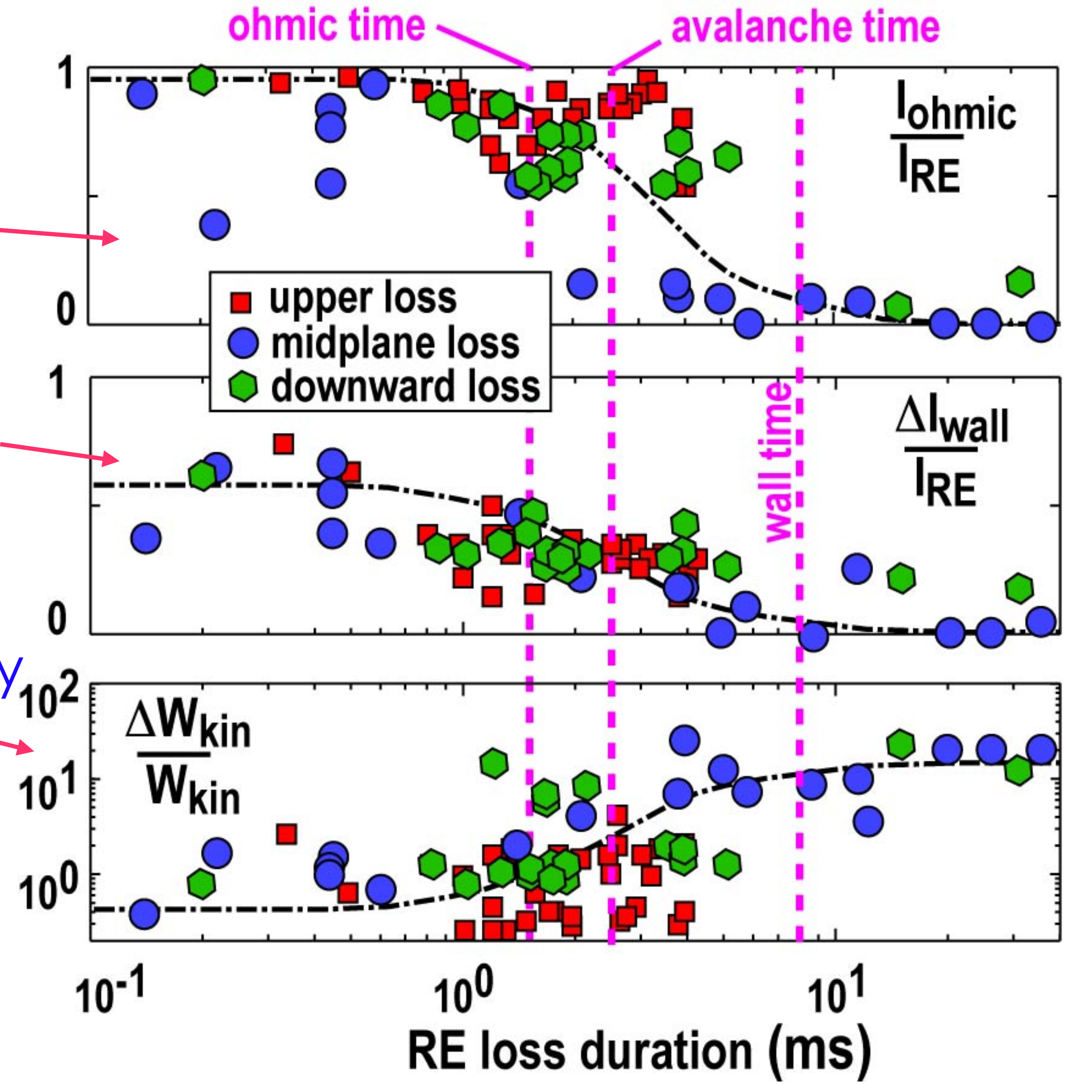


Hollmann, NF 53 (2013) 083004

Final Loss: Shots With Rapid Final Loss Release Less Kinetic Energy into Wall, Consistent With Lower W_{mag} Conversion

- **Shorter RE final loss gives:**
  - Large conversion of RE current into ohmic plasma current
  - Larger conversion of RE current into wall current
  - Lower increase in kinetic energy during final loss
  - Possibly good news for ITER, depending on RE loss time?

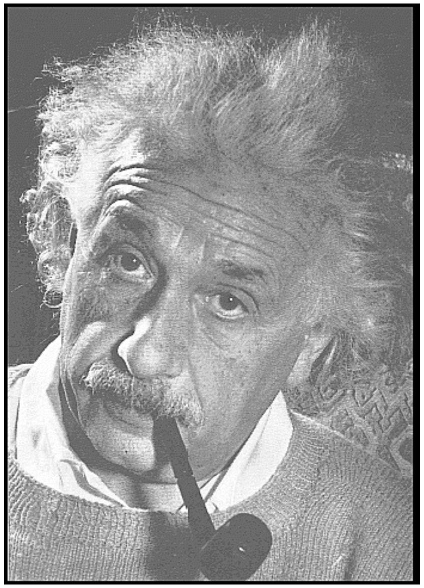
Hollmann, NF 53 (2013) 083004



Magnetic energy transfer in different RE-wall final strikes

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Modeling Moment: RE Final Loss



1. **How wide will the RE "core" be in ITER?**
   – Largely determines how much beam compression can occur before it damages wall (i.e. smaller core → more time for mitigation)

2. **Can we make predictive physics model for $W_{mag} \rightarrow W_{kin}$ conversion during final loss?**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Conclusions

- There are many interesting & important questions to be answered by theory & simulation regarding RE
  - Formation
  - Anatomy
  - Dissipation
  - Final Loss

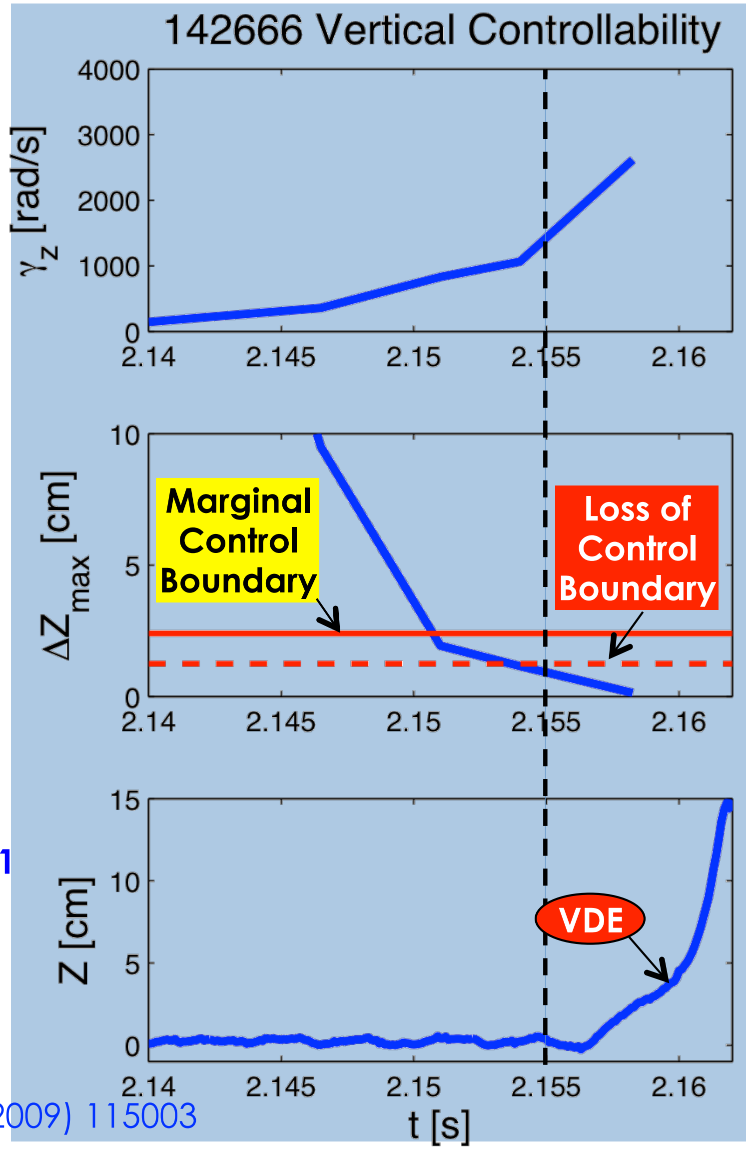
- Much data exists, waiting for the right questions to be asked

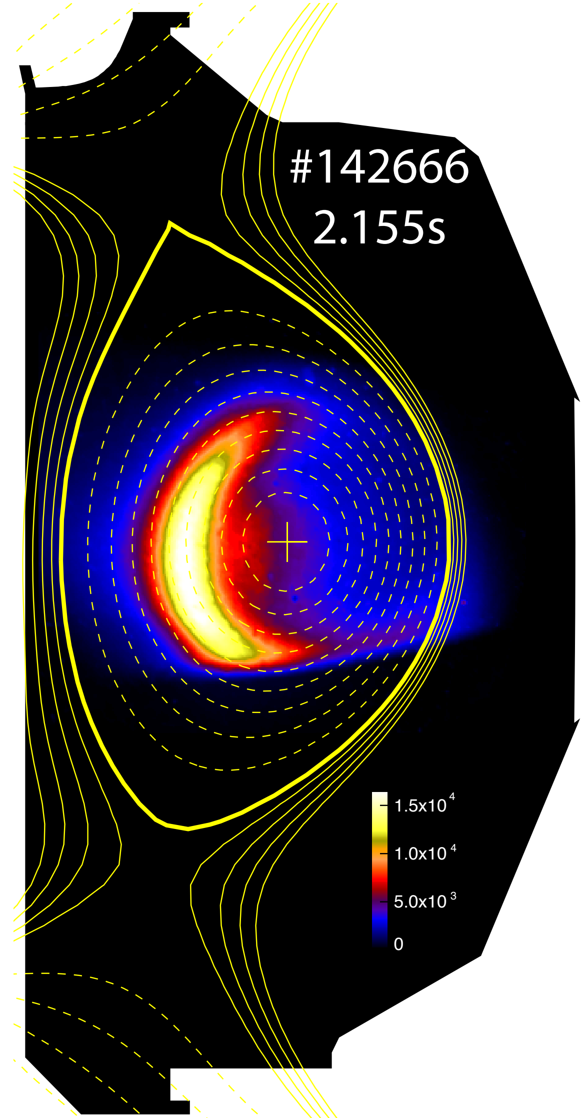
Theory/modeling collaboration with the DIII-D disruptions group is welcomed and encouraged.

EXTRA

RE beam vertical stability consistent with standard predictions

- **Early control iterations produced elongated, diverted RE beams**
- **RE beam stabilized by standard DIII-D vertical control system**
- **Vertical displacement event (VDE) onset consistent with predicted controllability boundaries for DIII-D Z control system[1]**





1. D.A. Humphreys *et al.*, *Nucl. Fusion* **49** (2009) 115003

DIII-D NATIONAL FUSION FACILITY SAN DIEGO