Control and Dissipation of Runaway Electron Beams Created During Rapid Shutdown Experiments in DIII-D

by

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with

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Presented at

2012 IAEA Fusion Energy Conference
San Diego, California

October 8–13, 2012

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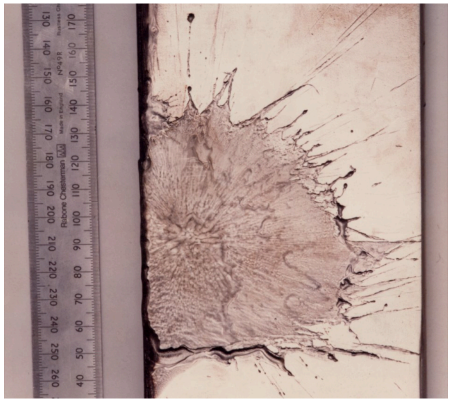
UCSD

Main Points

- **RE plateau will probably form after many ITER disruptions.**
- **Feedback control of RE plateau position and current achieved in DIII-D**
  - May not always be possible in ITER?
- **Rapid dissipation of RE plateau achieved with massive high-Z gas injection**
  - May be useful technique in ITER
- **Damage to ITER wall from RE beam may be less than expected**
  - No conversion of magnetic to kinetic energy if RE beam moves into wall quickly enough

Motivation: Disruption Runaway Electrons Pose Serious Threat to ITER Wall Tiles

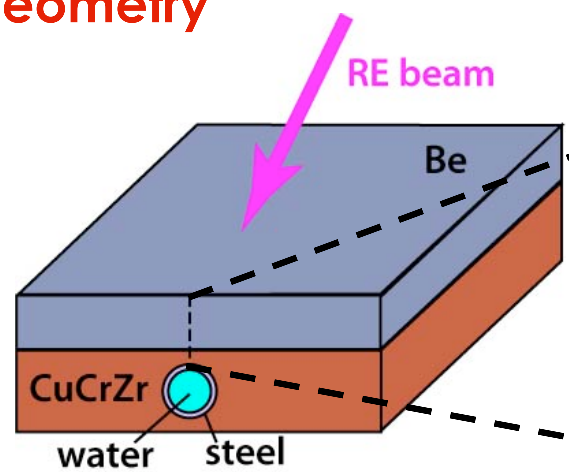
RE tile damage on JET



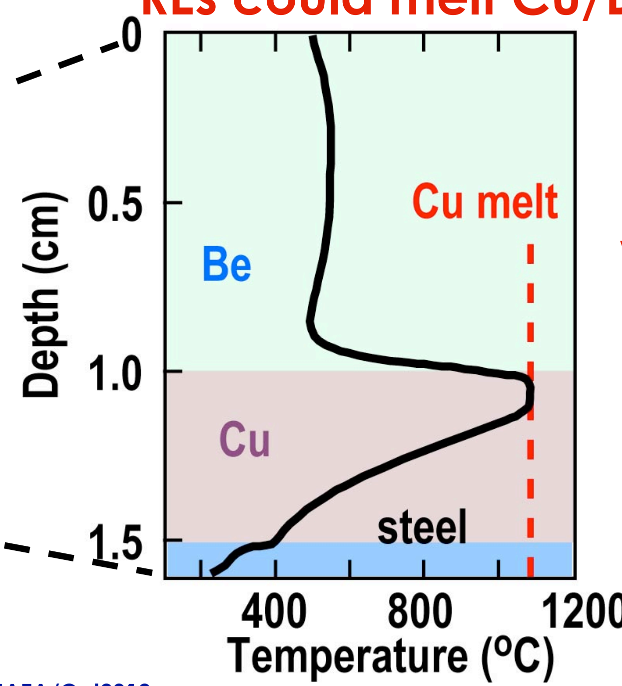
(courtesy of G. Martin)

- Disruption REs occasionally cause wall damage in present tokamaks
- In ITER, problem will be more serious:
  - Larger plasma current — large avalanche
  - Activated walls — continuous RE seed
  - Thin Be walls — possible damage to joints

ITER cooling channel geometry



REs could melt Cu/Be braze joint!

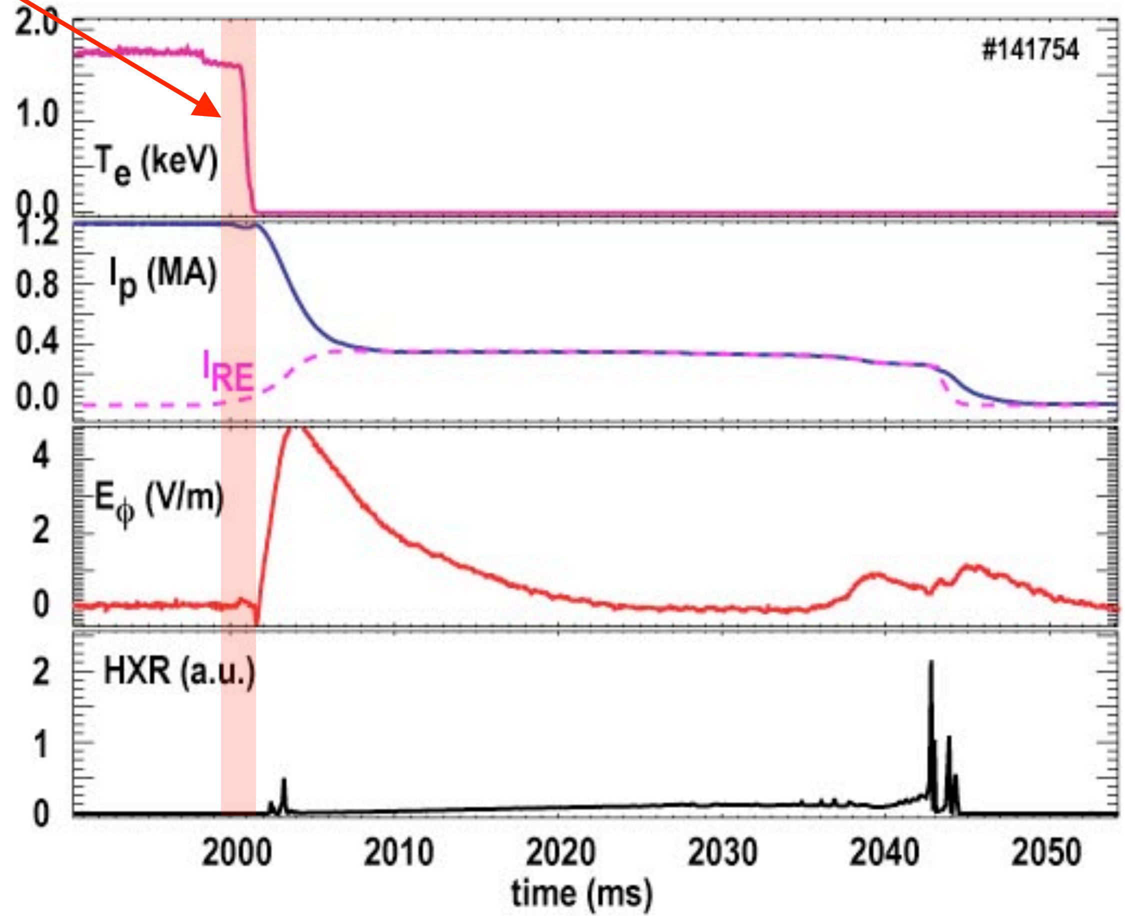


[Simulation from V. Sizyuk, Nucl. Fusion (2009)]

Time Evolution of Runaway Electrons During Rapid Shutdown

Thermal quench (TQ) - RE seed formation

DIII-D Ar pellet rapid shutdown time sequence



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Time Evolution of Runaway Electrons During Rapid Shutdown

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

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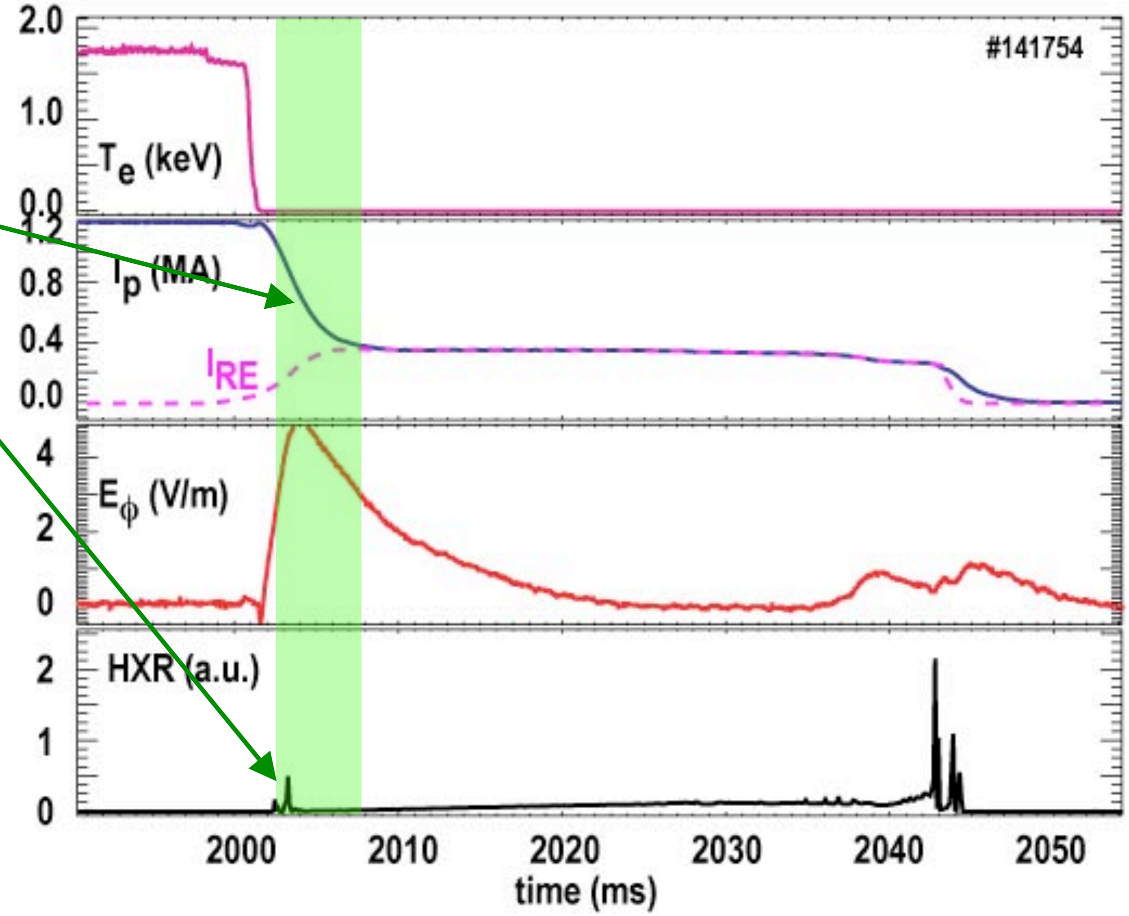

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Time Evolution of Runaway Electrons During Rapid Shutdown

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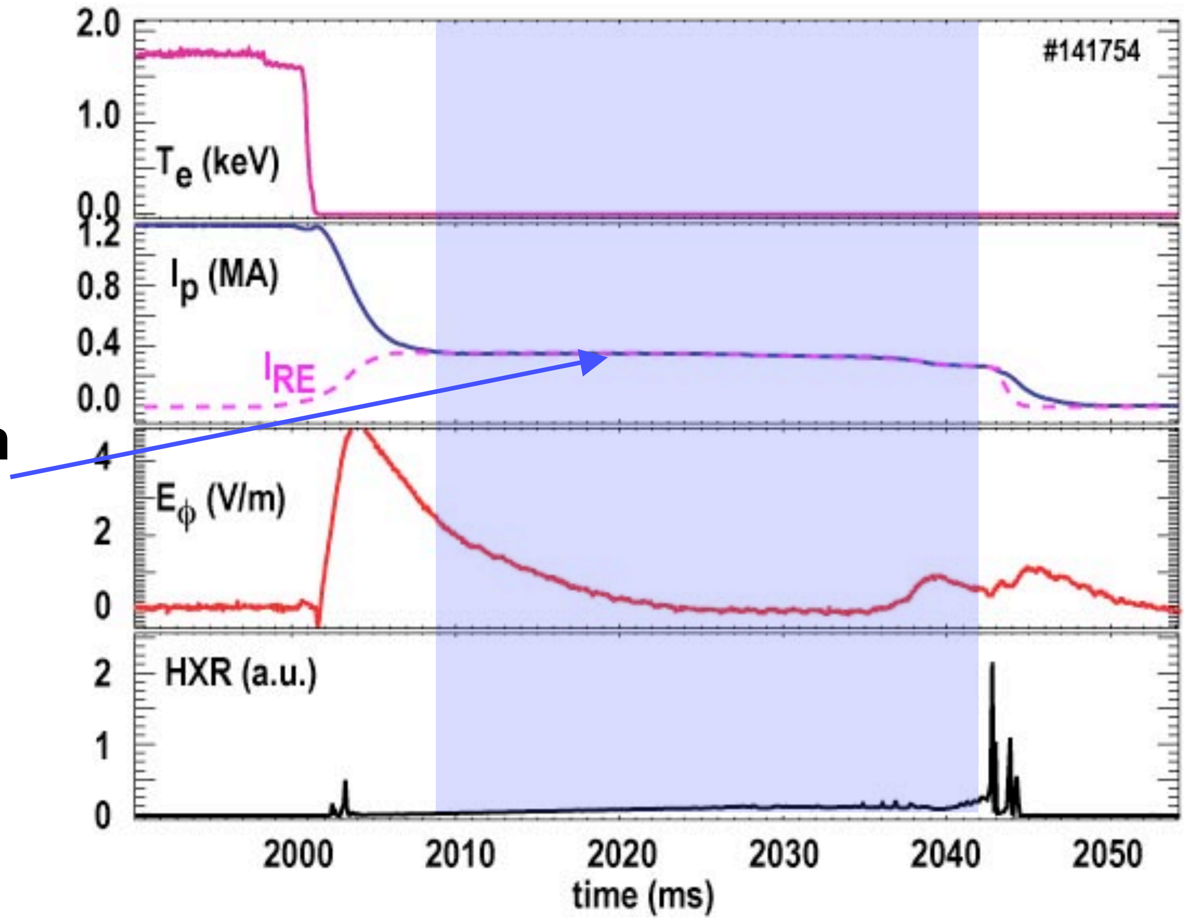

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Time Evolution of Runaway Electrons During Rapid Shutdown

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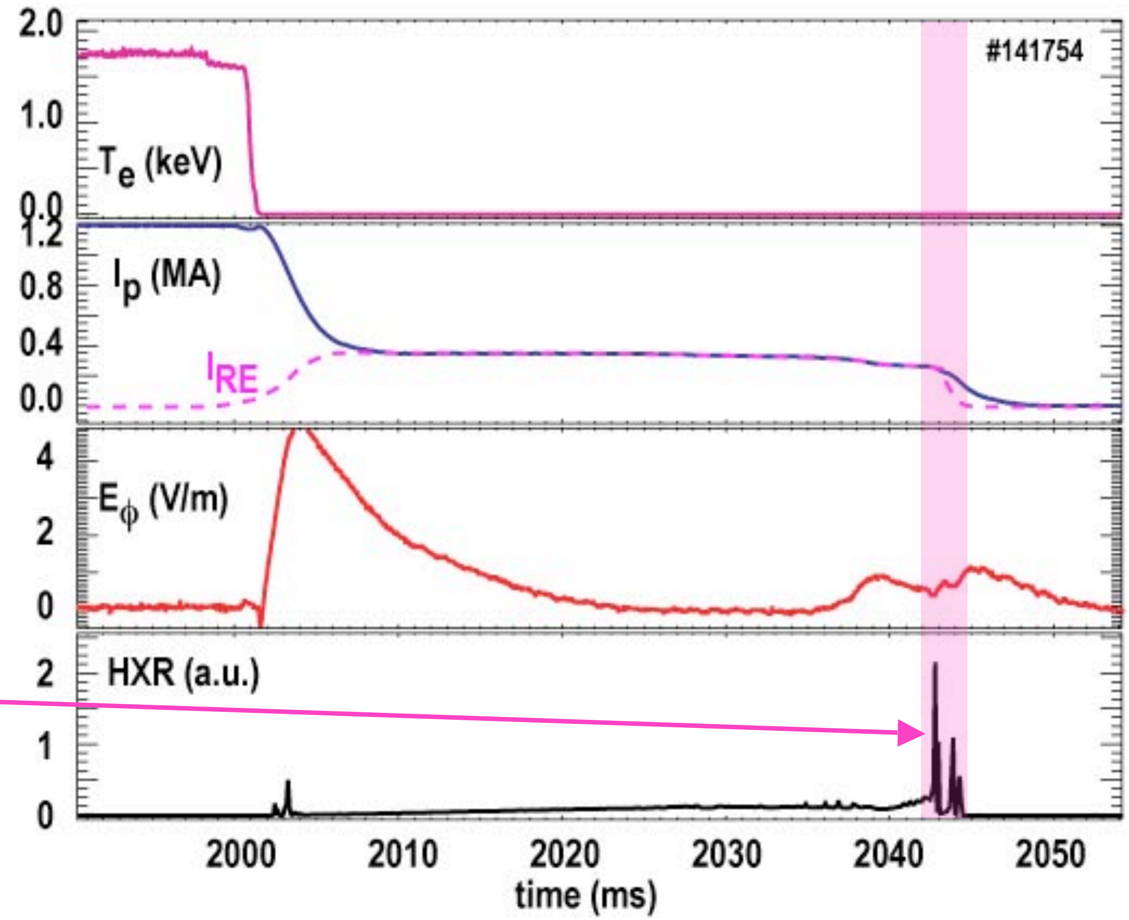

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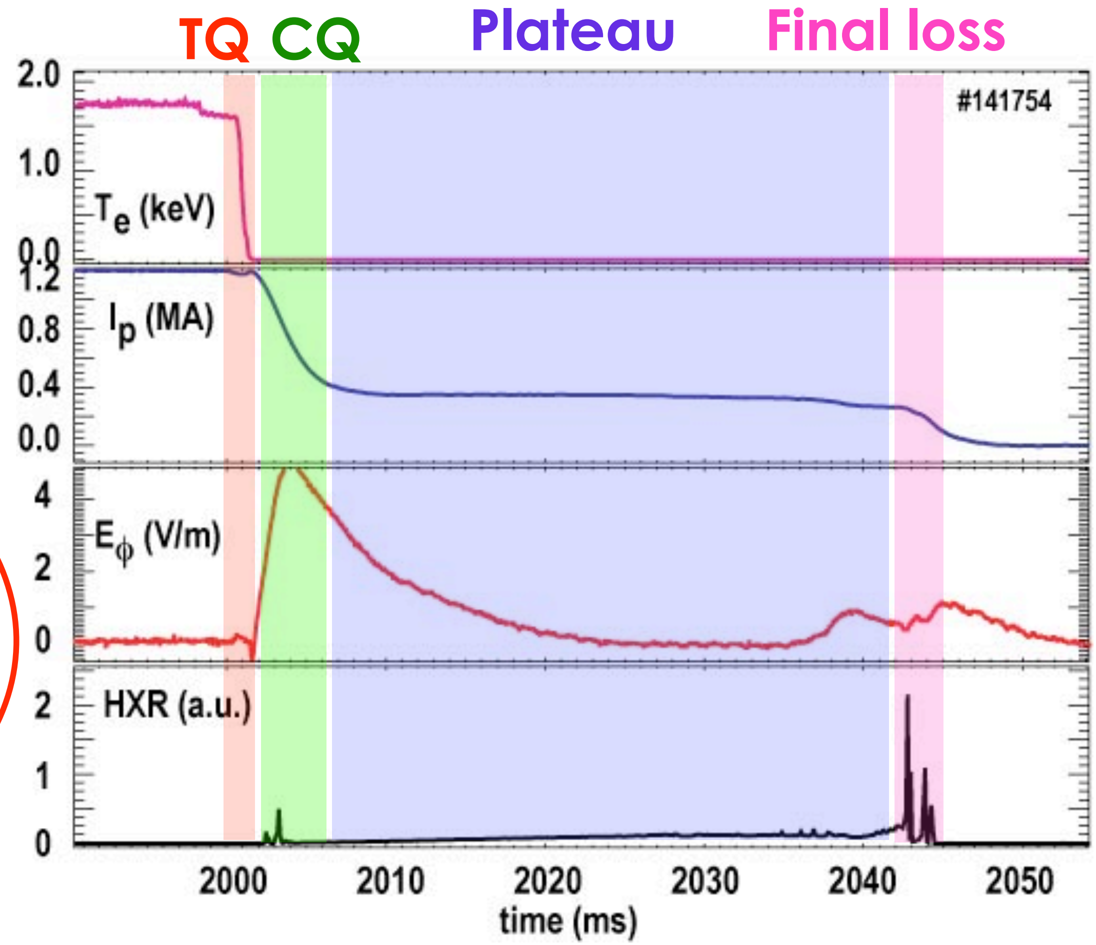
DIII-D Experiments Aim at Understanding and/or Minimizing Runaway Electrons in Different Phases

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)



Main focus of this talk

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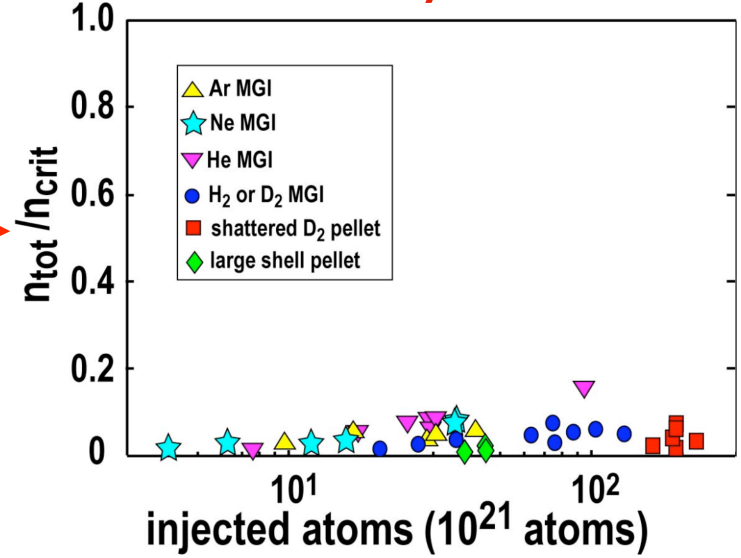
RE Plateau Will Probably Form in Many ITER Disruptions

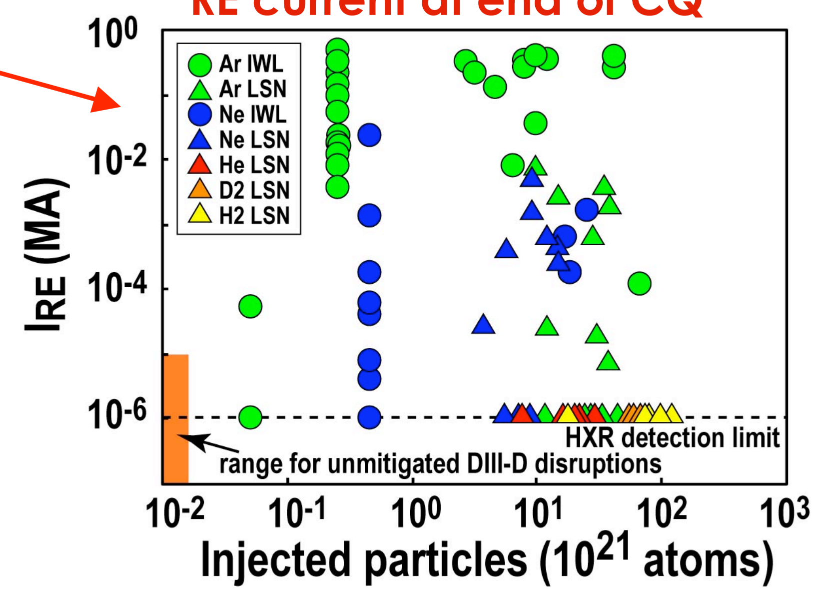
- **Avalanche theory predicts REs suppressed at density n_{crit}**
  - Only reached 20% n_{crit} in DIII-D rapid shutdown experiments
  - Outlook is similar for ITER
  - Reaching n_{crit} in ITER would give vessel force problems!

Total electron density/critical density



- **Large scatter in amount of REs formed**
  - Makes predicting RE seed in ITER challenging
  - Large RE avalanche in ITER means RE plateau likely

RE current at end of CQ



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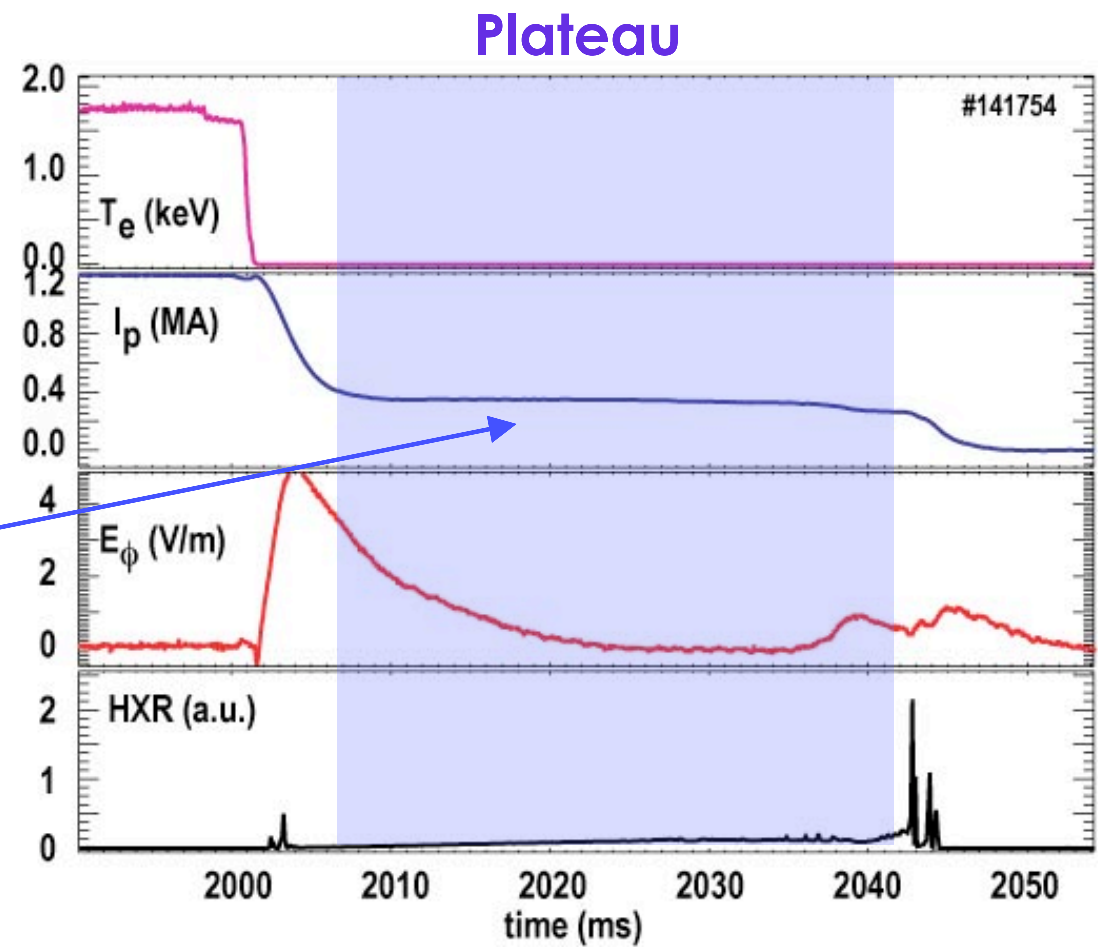
Experiments Toward Controlled Dissipation of RE Plateau

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)



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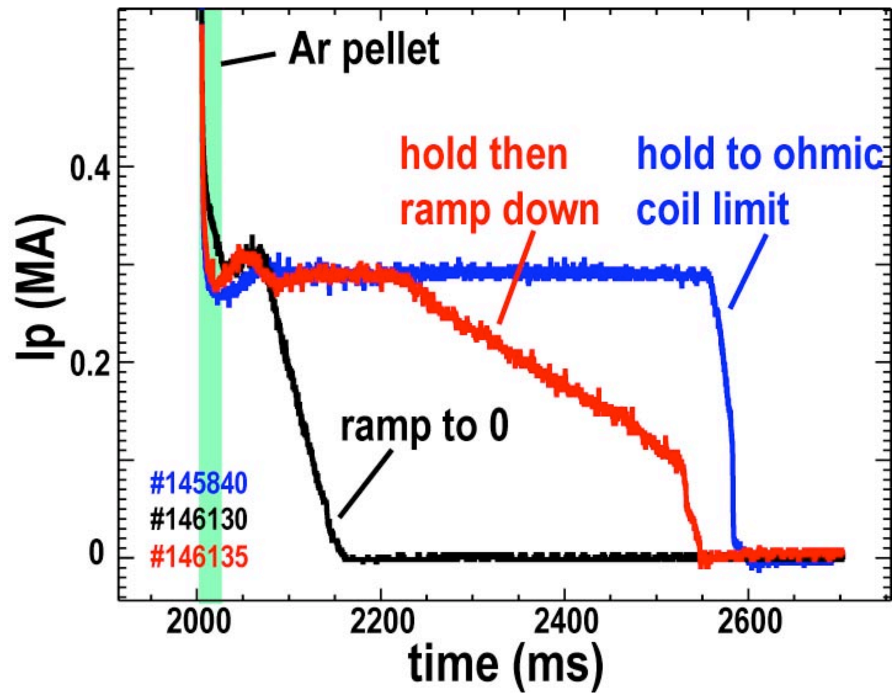
Feedback Control of RE Plateau Position and Current has been Achieved in DIII-D

- **Control system modifications have enabled position control of RE plateau**
- **RE current has been held steady to flux limit or ramped down to 0**
  - Probably not possible in ITER?
  - Power supply voltage limitations
- **REs in ITER probably subject to slow vertical instability**
  - Can REs in ITER be dissipated in time before striking wall?

RE current control with ohmic coil



(from N. Eidietis, APS 2011)

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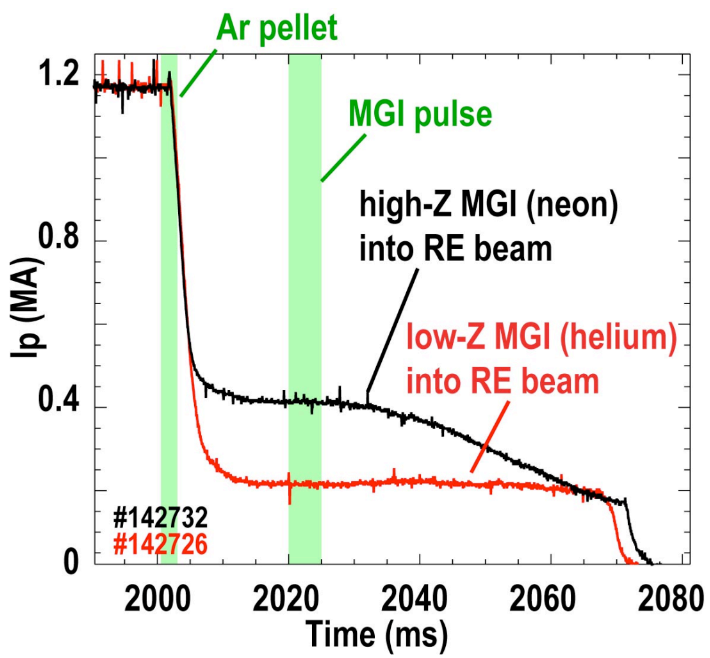
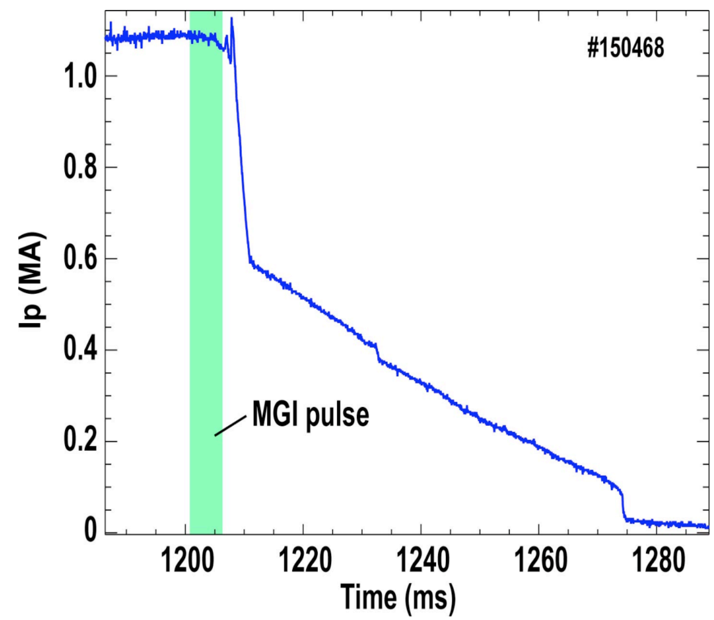
Dissipation of RE Plateau Current by Massive High-Z Gas Injection Has Been Achieved in DIII-D

- **High-Z MGI fired into RE plateau shows enhanced dissipation of RE current**
- **Ramp down of RE current nearly to 0 achieved with RE plateau created by Ar MGI**
- **Motivates study of RE plateau structure, injected particle assimilation, and current dissipation**



MGI into RE plateau



RE plateau created by Ar MGI

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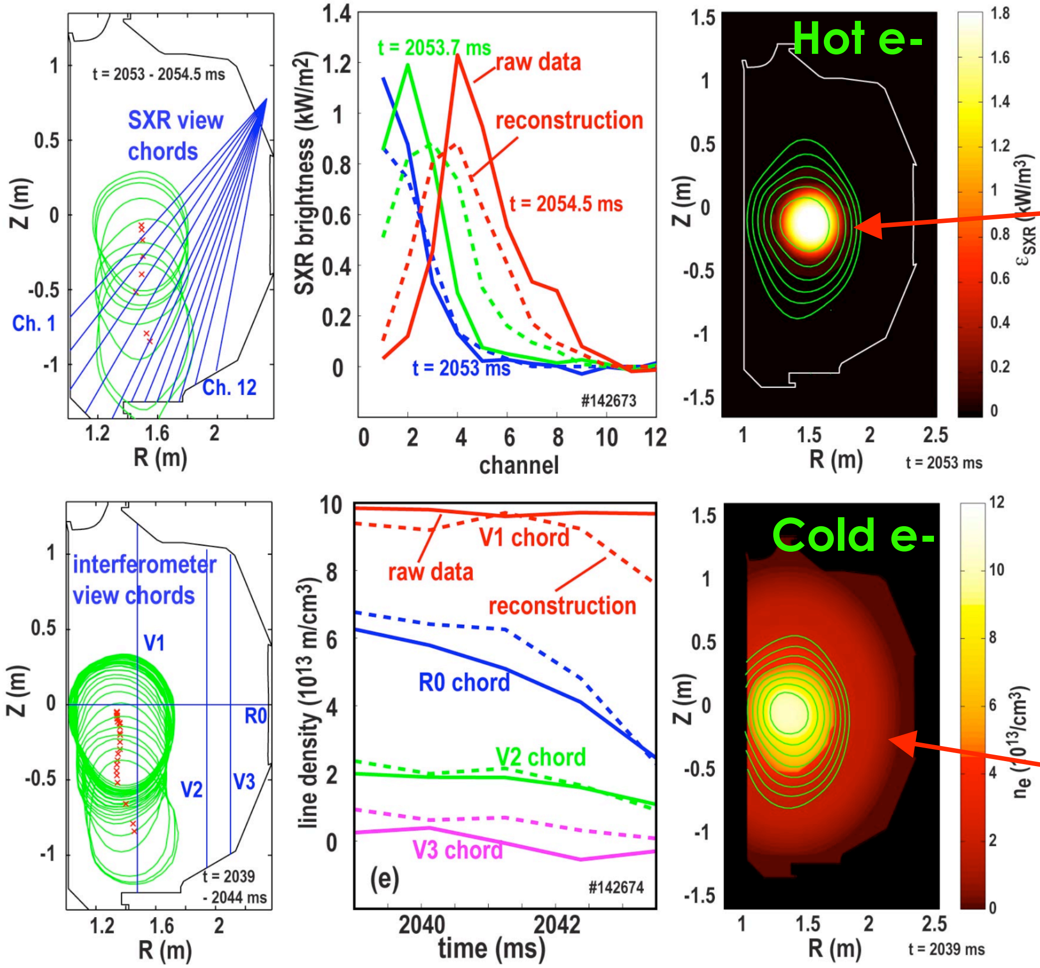
Hot Electrons Form Narrow Beam Inside Dense Cold Electrons

Tomographic inversions of RE plateau hot and cold electron densities

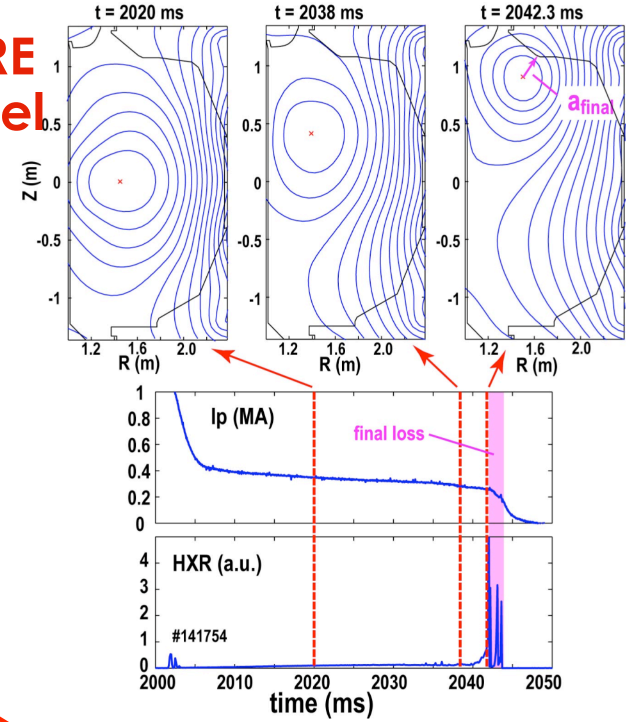


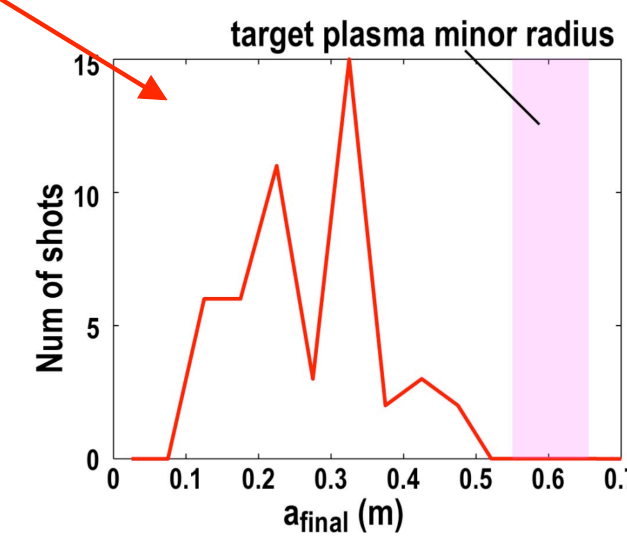
- **Make use of vertical instability to get profile data**
- **Soft x-ray emission structure shows REs dominantly in narrow (*a* < 0.2 m) beam**
- **Magnetic flux surface inversions give reasonable estimate of RE beam position**
- **Interferometers show that cold electrons fill much of vacuum chamber**

RE Beam Current Forms Narrow Beam

Estimating radius of RE beam current channel

- **Beam current channel position can be estimated from external magnetic signals**
- **Final loss onset begins at some small minor radius a_{final} ~ 0.2–0.4 m**
- **Consistent SXR beam radius a ~ 0.2 m: indicates current carried by REs, not ohmic plasma**





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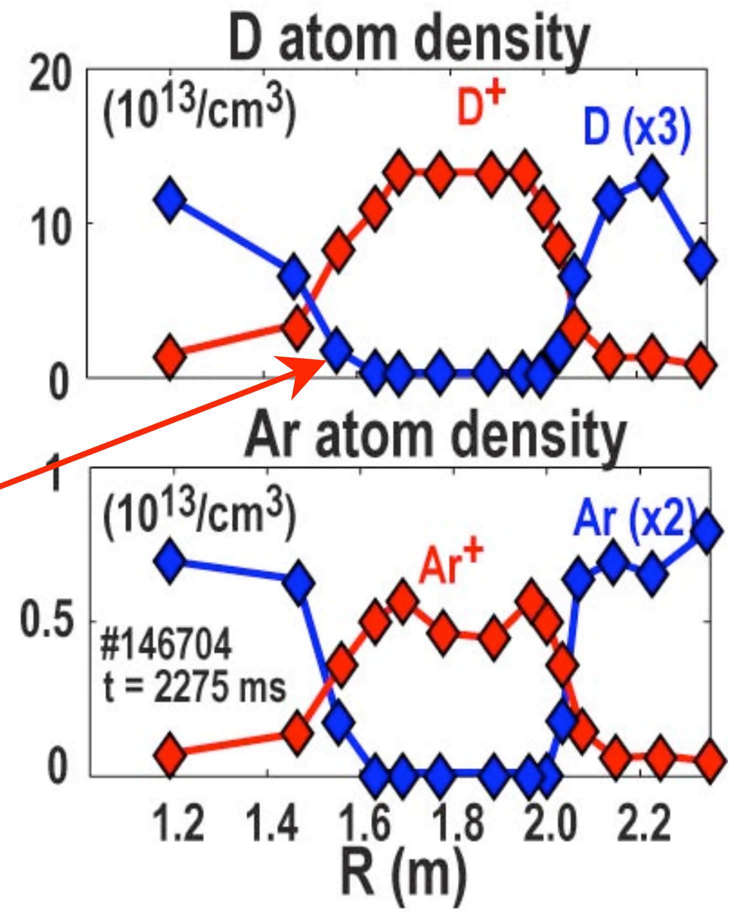
Neutrals Largely Excluded From RE Beam

- **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

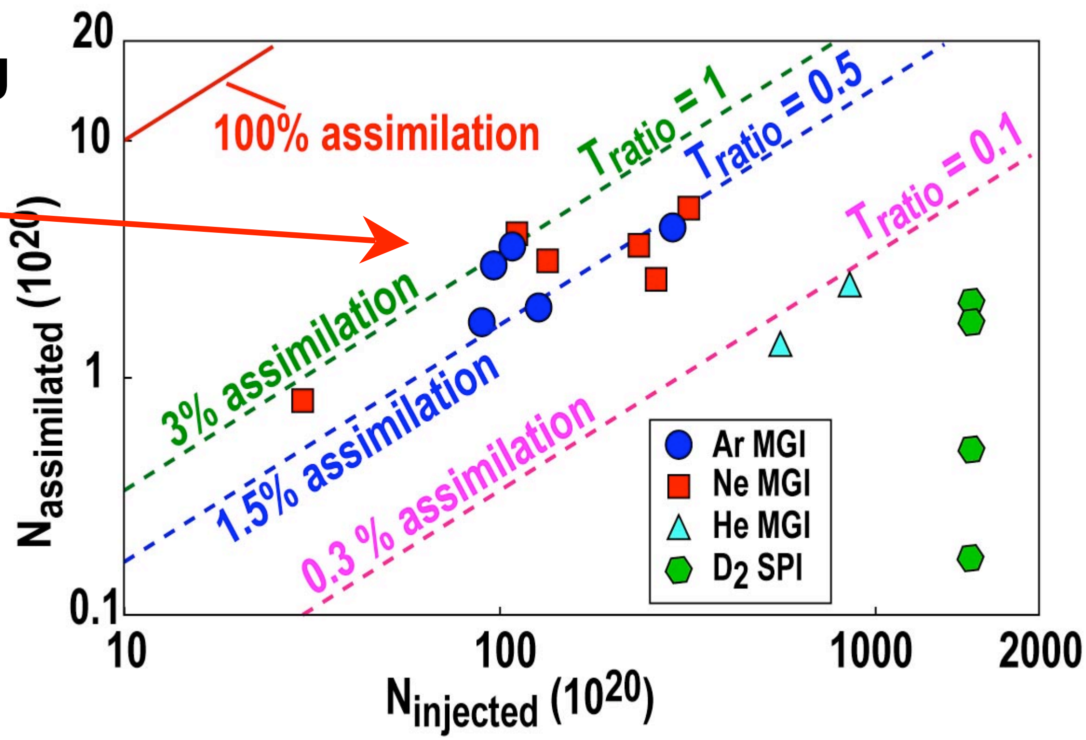


Assimilation of Impurities Injected Into RE Plateau Low But Predictable

- **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



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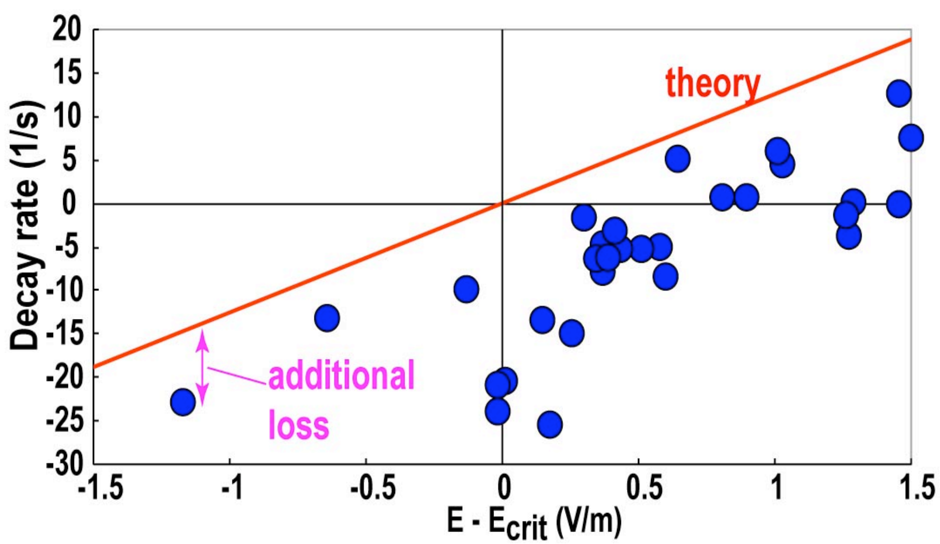
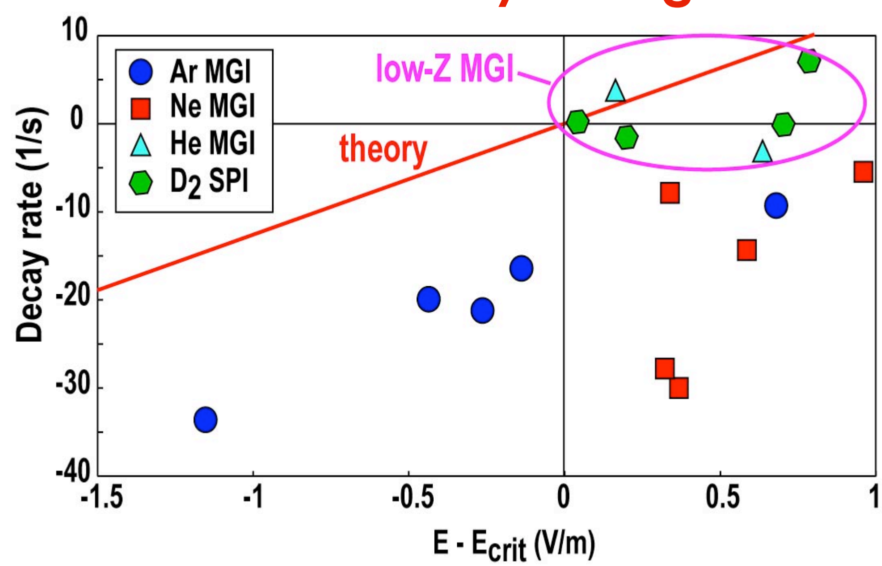
Current Decay of RE Plateau Faster Than Expected From Electron-electron Collision Drag

- **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



RE Energy Distribution Function in Presence of Ar Supports Enhanced Scattering of REs

- **Perp and para bremsstrahlung and synchrotron emission measurements combined to give RE energy spectrum**

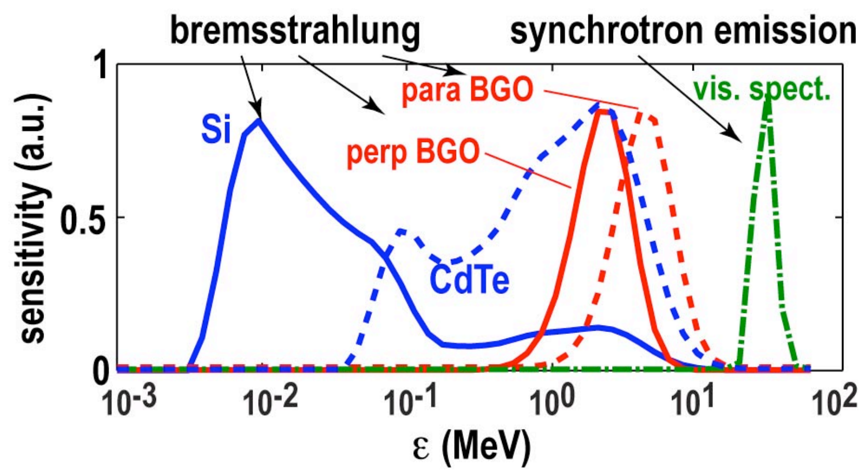
- **Fits depend on RE pitch angle θ for higher energies ε > 1 MeV**

– Typically find θ ~ 0.2

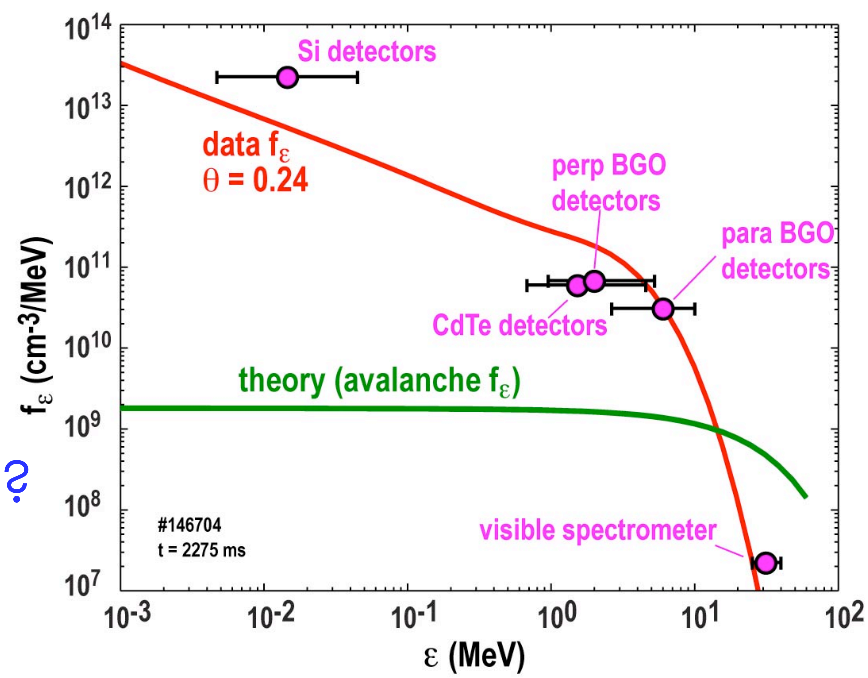
- **Find distribution function more skewed to low energies than expected from avalanche theory (Putvinski, Nucl. Fusion 1994)**

– Suggests extra drag on REs not included in avalanche theory

– Pitch angle scattering off high-Z ions?



RE energy spectrum



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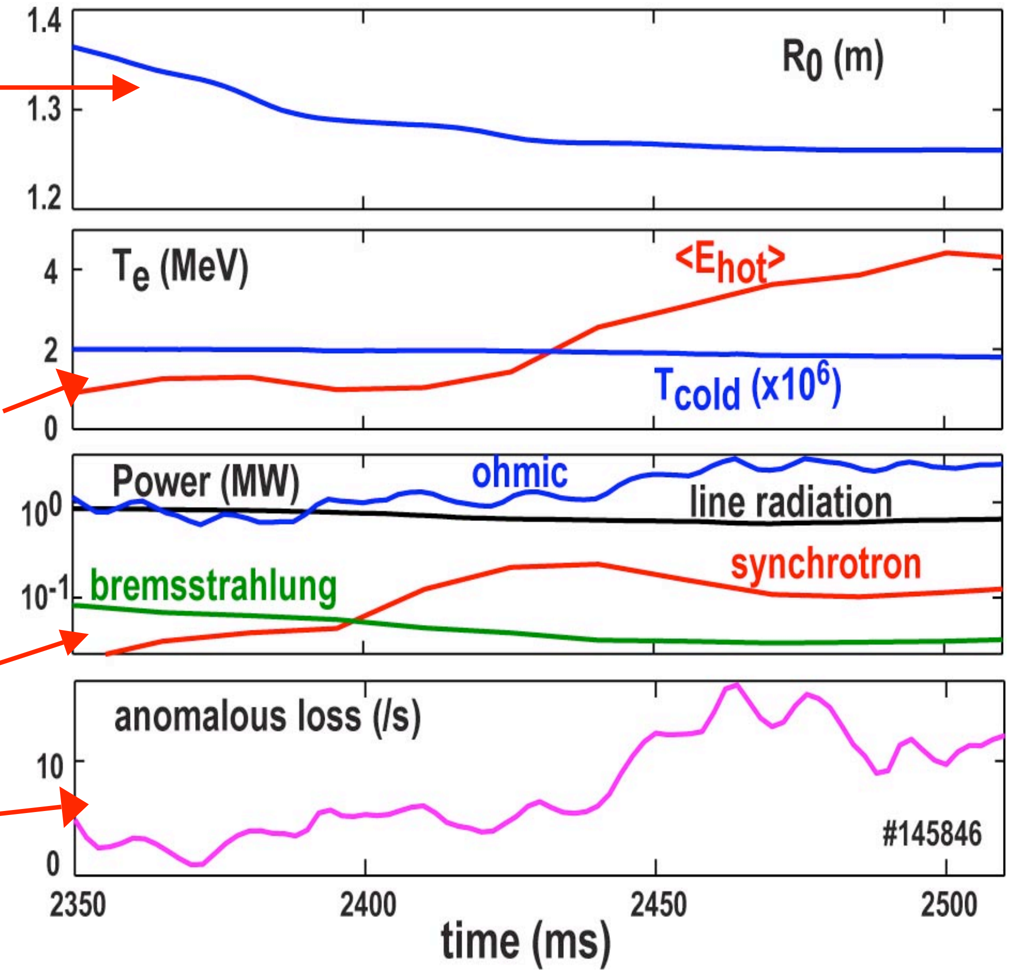
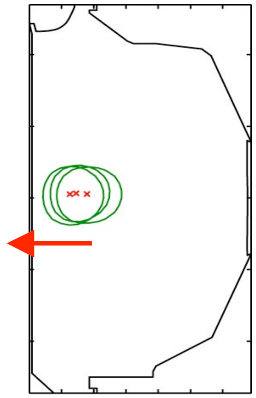
Increasing Anomalous Loss as RE Beam Moves Closer to Wall Suggests Transport Loss of REs

- 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

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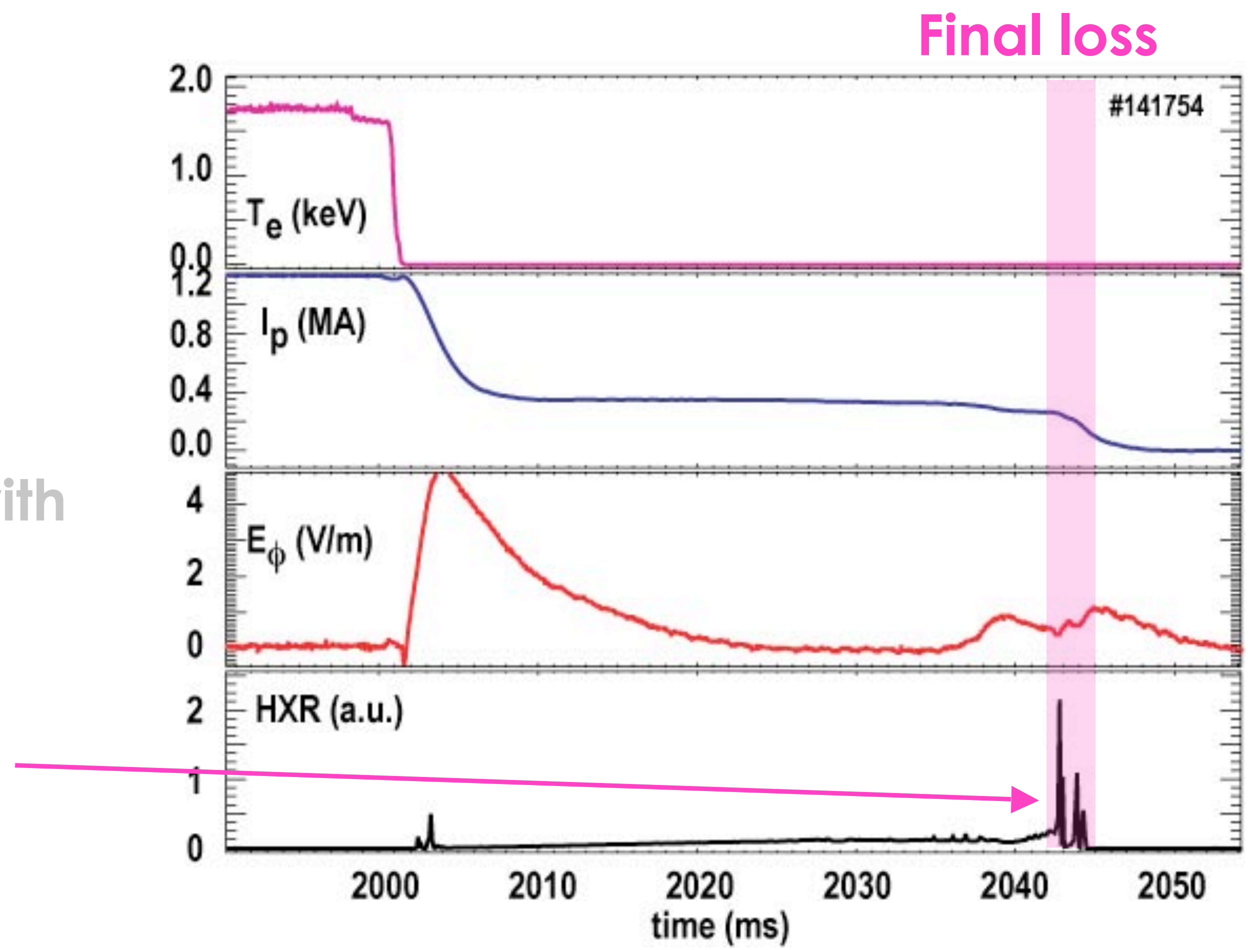
Understanding RE Final Loss

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)



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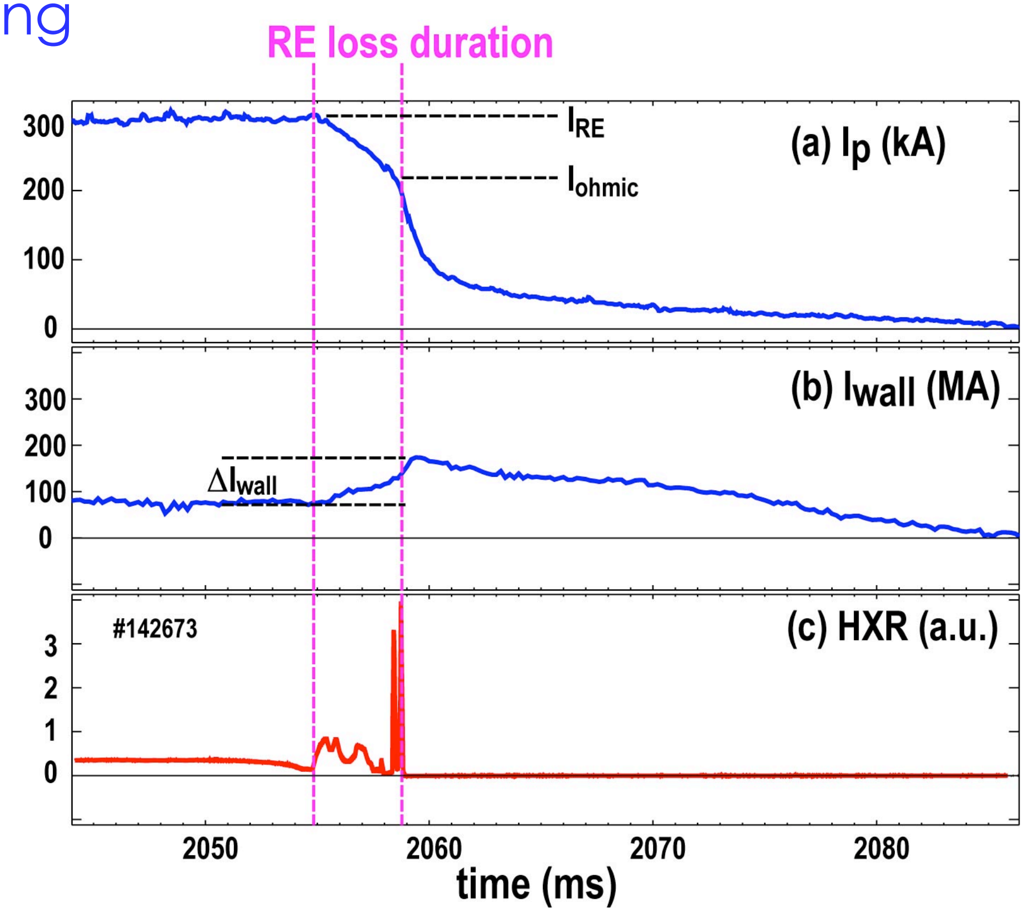
RE Current Partially Transferred to Ohmic Current and Wall Current During Final Loss

- **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**

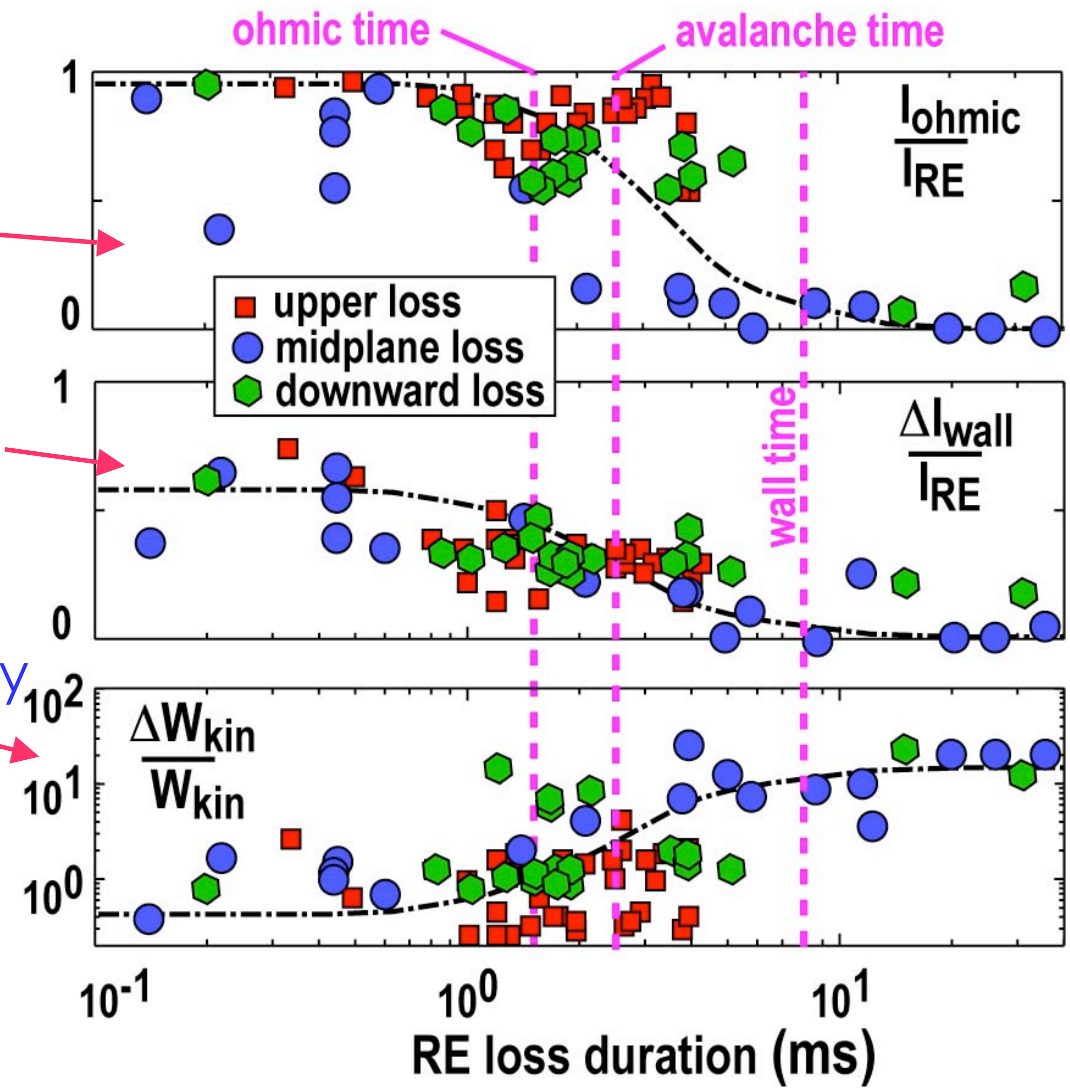
Transfer of RE current into ohmic current during final strike



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?



Magnetic energy transfer in different RE-wall final strikes

Summary: DIII-D Experiments are Helping ITER Develop Plan to Avoid Disruption RE Damage

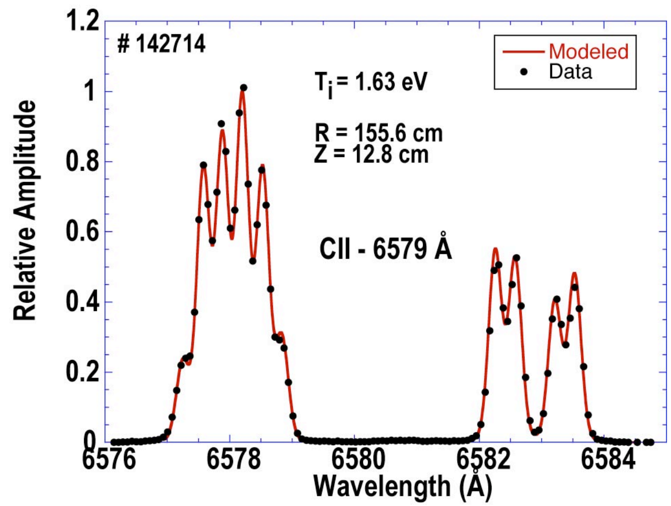
- **RE plateau will probably form frequently following ITER disruptions**
  - Expect slow vertical loss of RE beam
- **Rapid dissipation of uncontrolled RE beam with massive high-Z gas injection promising**
  - Assimilation is low but sufficient to cause rapid dissipation of RE current
  - Good progress in understanding assimilation and dissipation; can be extrapolated to ITER?
- **Damage to ITER wall from RE beam may be less than expected**
  - Present 2 MA upper bound assumes 40% W_{mag} conversion
  - May be lower in ITER, depending on RE final loss timescale?

(Backup slides)

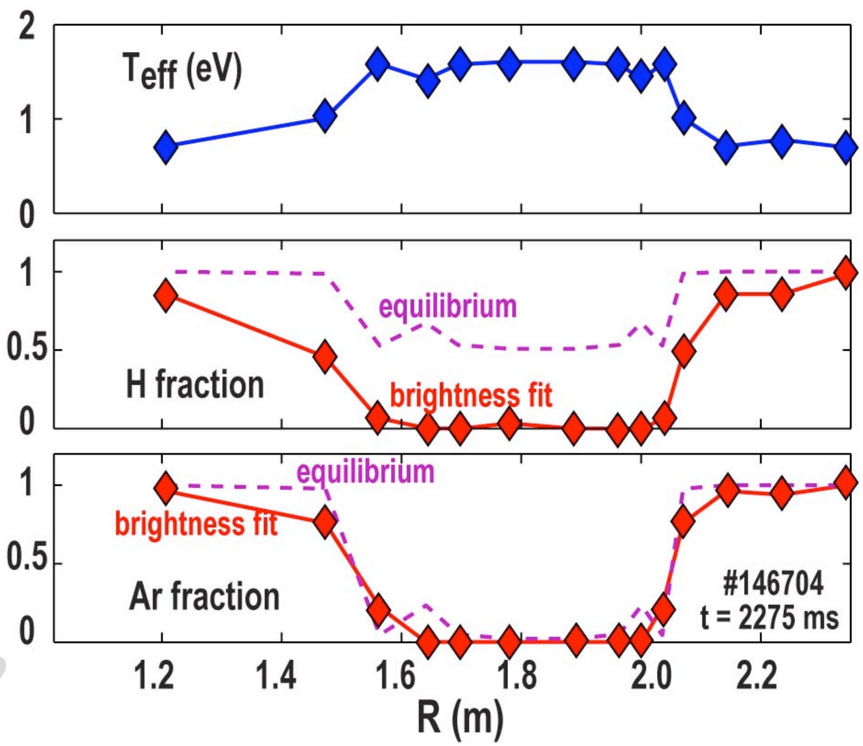
Line emission mostly from cold electrons

- Line brightness match gives effective temperature ~1.5 eV in core and ~ 0.8 eV in edge.
- Rough agreement with Doppler temperatures of core ions (1.6 eV) and edge neutrals (1.2 eV).
- Indicates line emission mostly from cold electrons (not from hot REs).

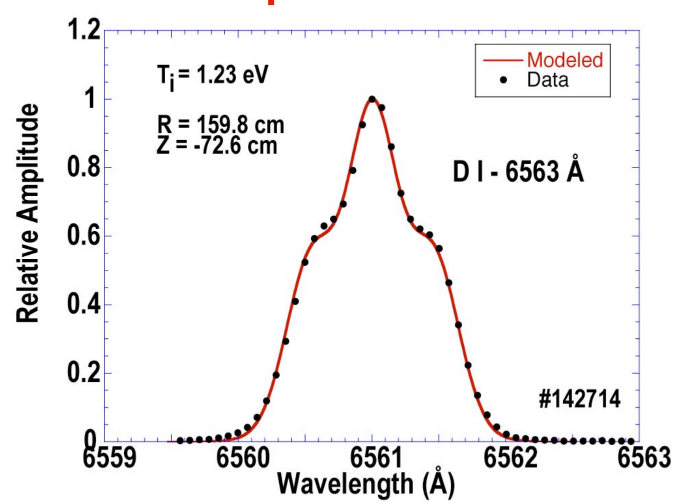
C^+ temperature fit



Effective temperature profile from line brightnesses



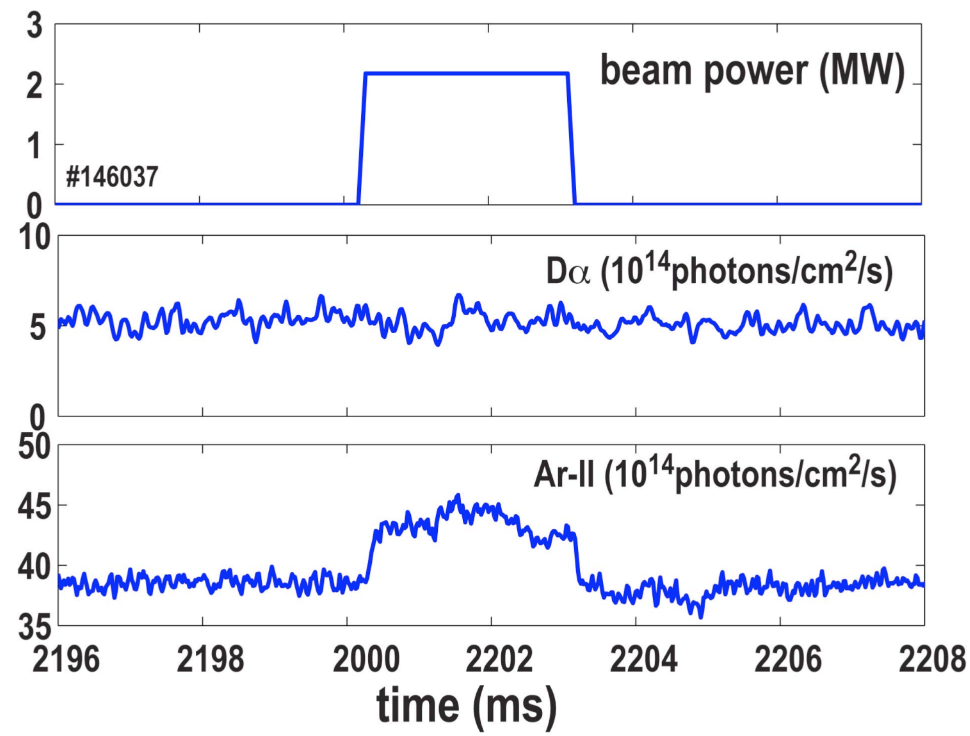
D temperature fit



Neutral beam pulses demonstrate that line emission comes from cold electrons

- Neutral beams heat ions which are expected to be well-coupled to cold electrons (but not hot REs).
- See increase in ion line brightnesses during neutral beam pulses.
- Consistent with cold electrons in core heating and causing increased line emission.

Magnetic energy transfer in different RE-wall final strikes

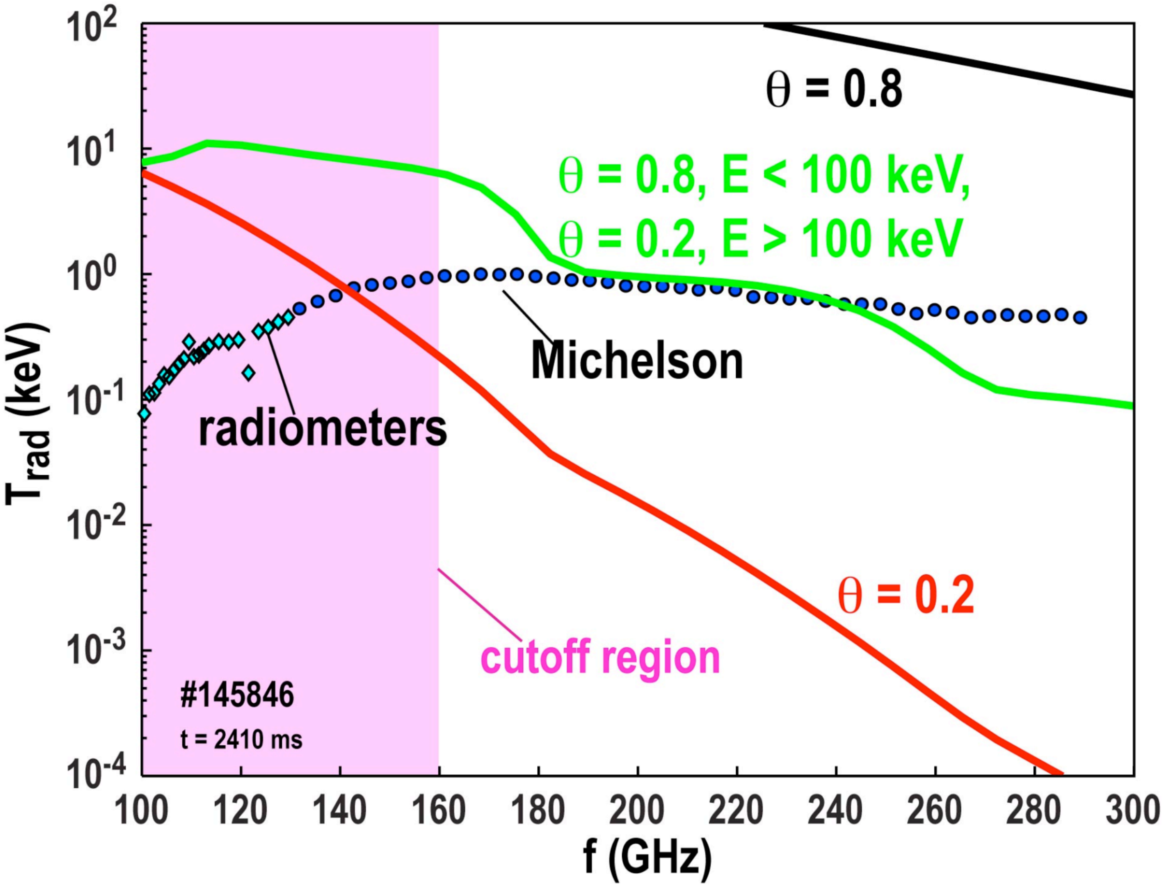


Fast electron pitch angle increases at lower energies

- Perp nonthermal electron cyclotron emission extremely sensitive to pitch angle.

- Fits to ECE microwave spectrum indicate θ increases toward isotropic for ε < 100 keV

RE ECE spectrum



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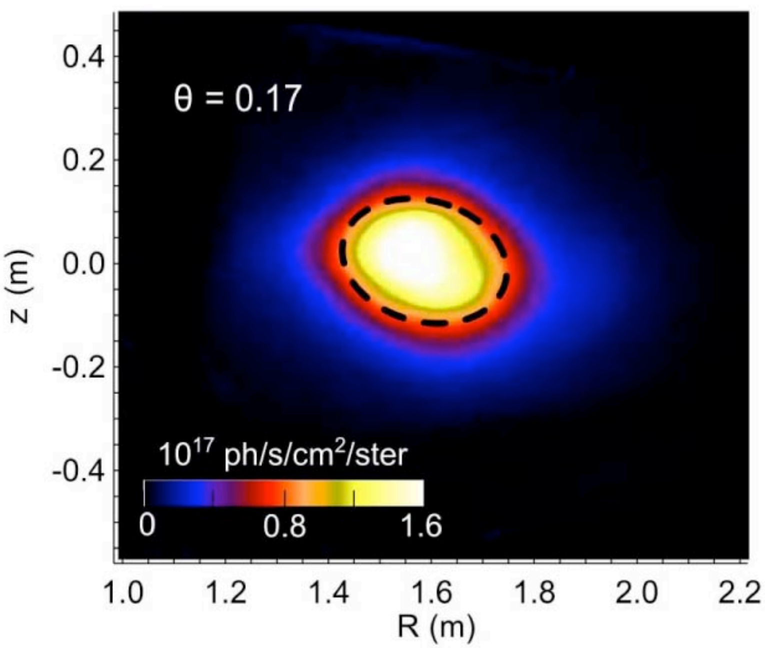
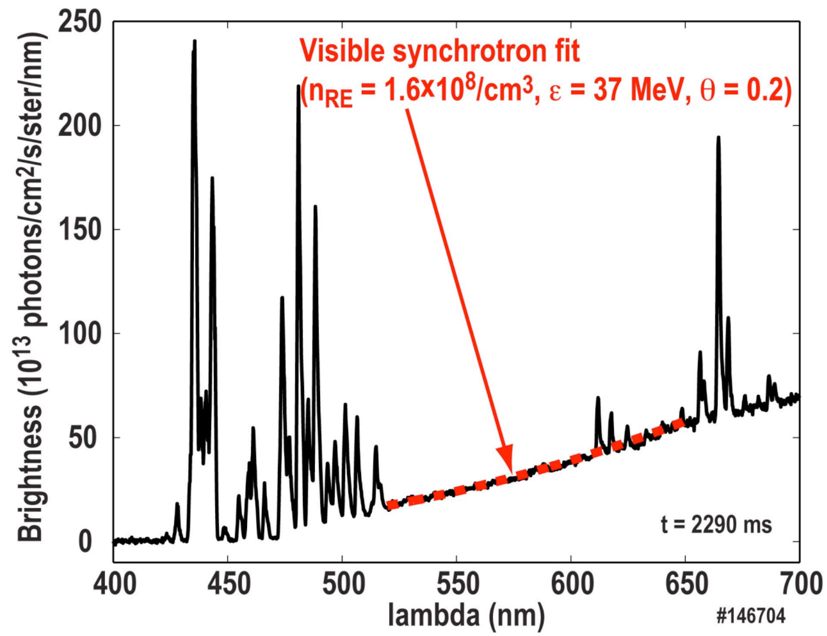
Fits to synchrotron continuum give energies of ~40 MeV for highest-energy REs

- Synchrotron continuum brightness depends on RE energy and pitch.
- Peaks in IR, only comes into visible for energies > 35 MeV.
- Comparison of forward vs backward spectra confirms that continuum only exists in forward-beamed direction.
- Pitch angle θ ~ 0.1 – 0.2 estimated from shape of RE synchrotron spot.



Fit to RE beam shape giving θ = 0.17



Fit to synchrotron emission giving ε = 37 MeV

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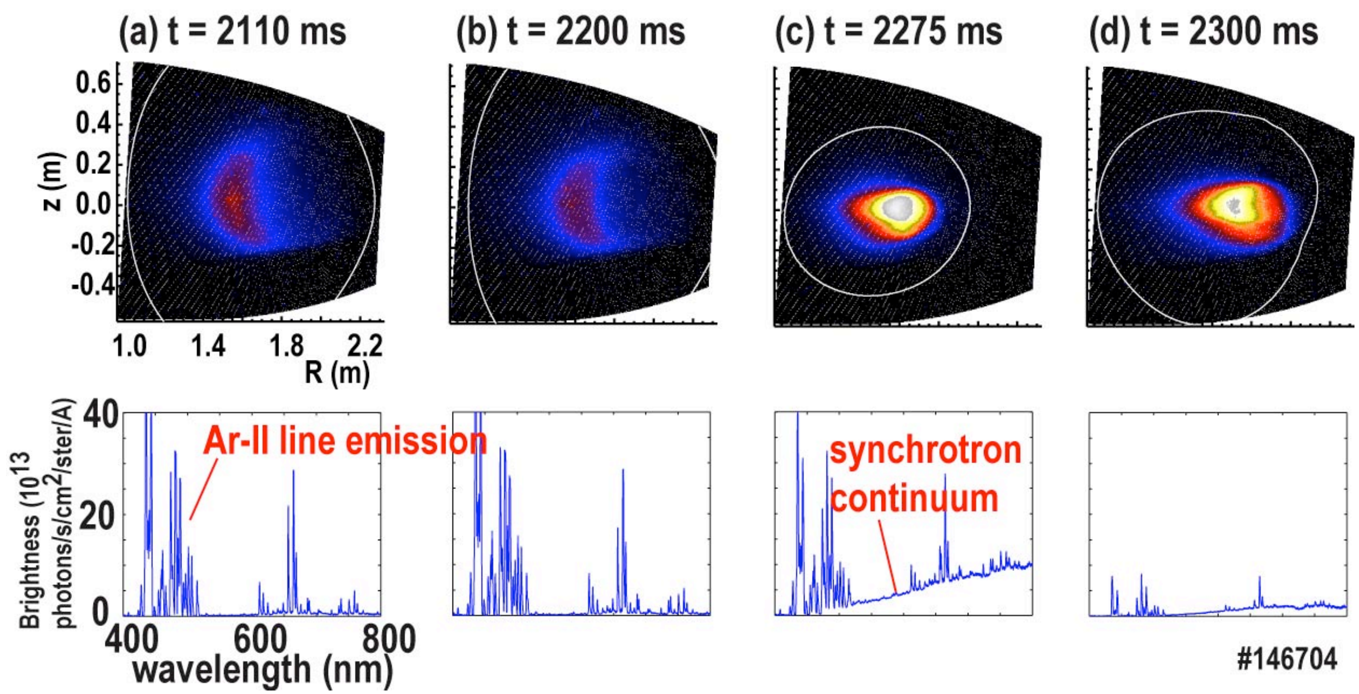
RE beam shrinks and heats during motion into center post

• **Shrinking beam (major and minor radii) increases internal loop voltage.**

• **Increased RE energy seen in increased synchrotron emission.**

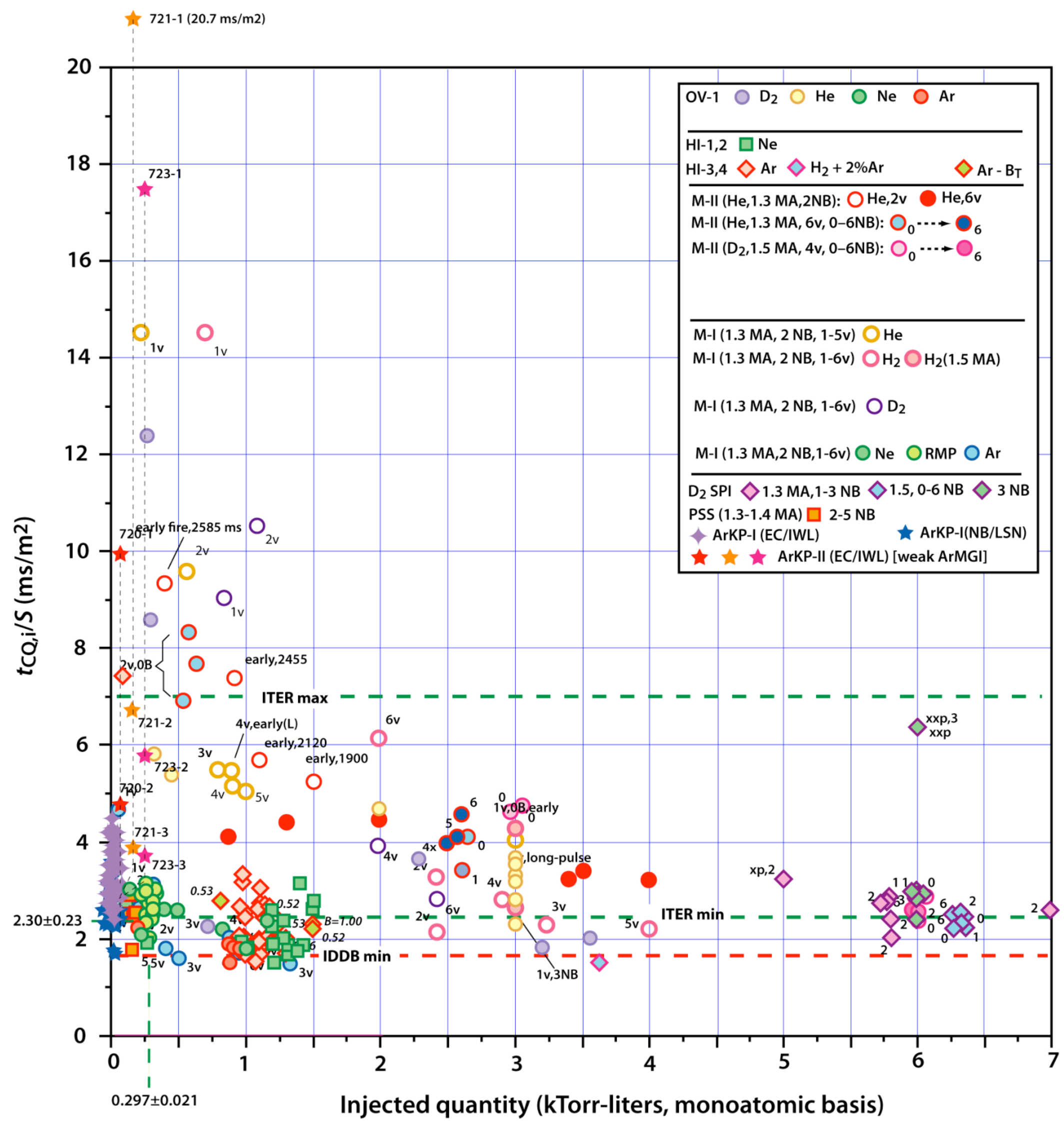
Appearance of visible synchrotron continuum as RE beam moves to center post.



DIII-D rapid shutdowns already reaching min allowable ITER-equivalent CQ duration

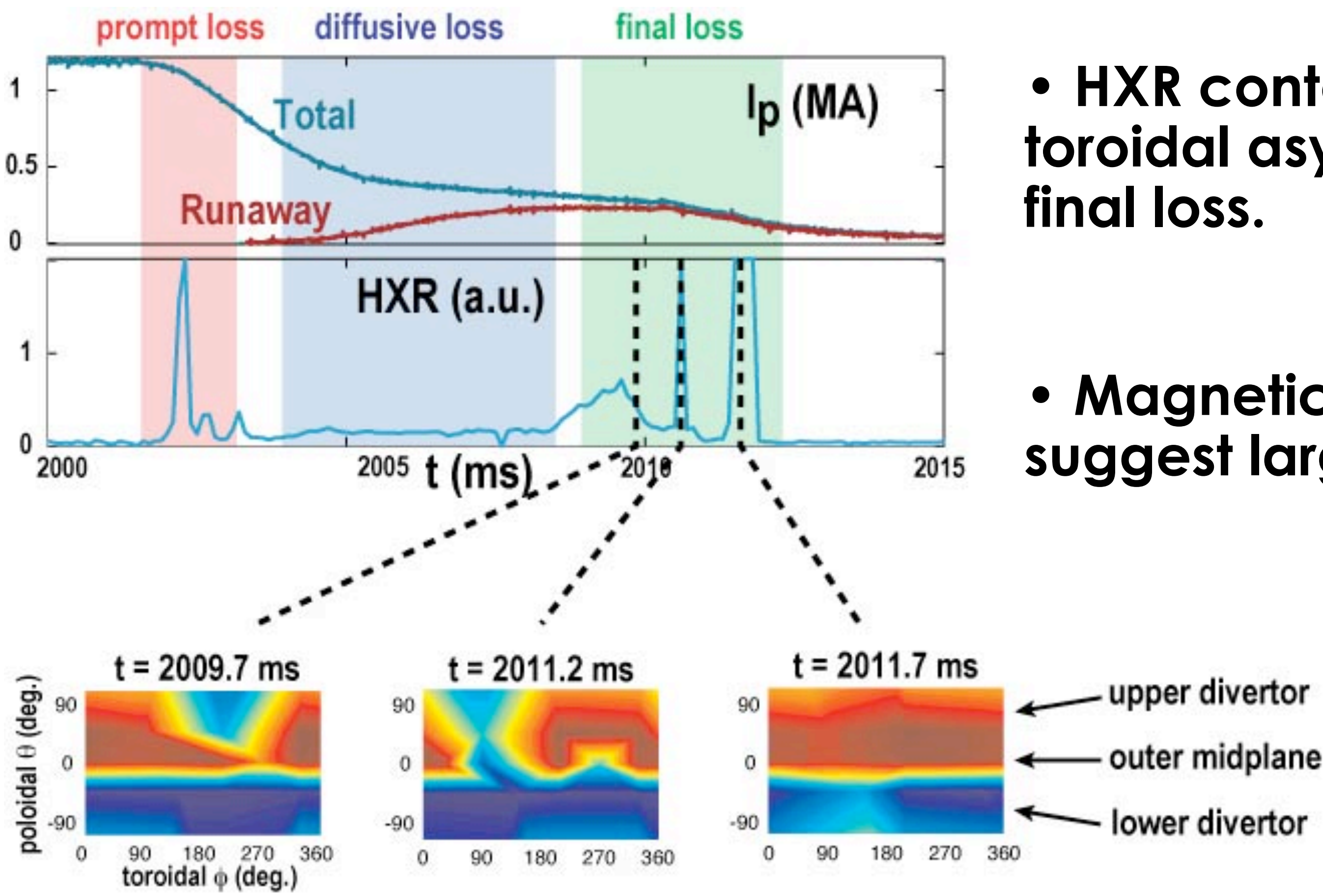
- CQ duration/plasma area gives rough machine-independent CQ duration.
- DIII-D rapid shutdowns only at 20% of n_{crit} in mid-CQ but already at/below min allowable ITER-equivalent CQ duration.
- Increasing injection rate/quantity will push below min allowable ITER-equivalent CQ duration!

Scaled CQ duration in DIII-D rapid shutdowns



(J. Wesley, ITPA 2012)

RE final loss shows toroidal asymmetry



- HXR contours show large toroidal asymmetry during RE final loss.
- Magnetics and SXR data suggest large n=1 structure.

HXR contours of RE-wall strikes in DIII-D

(A. James, NF 2011)

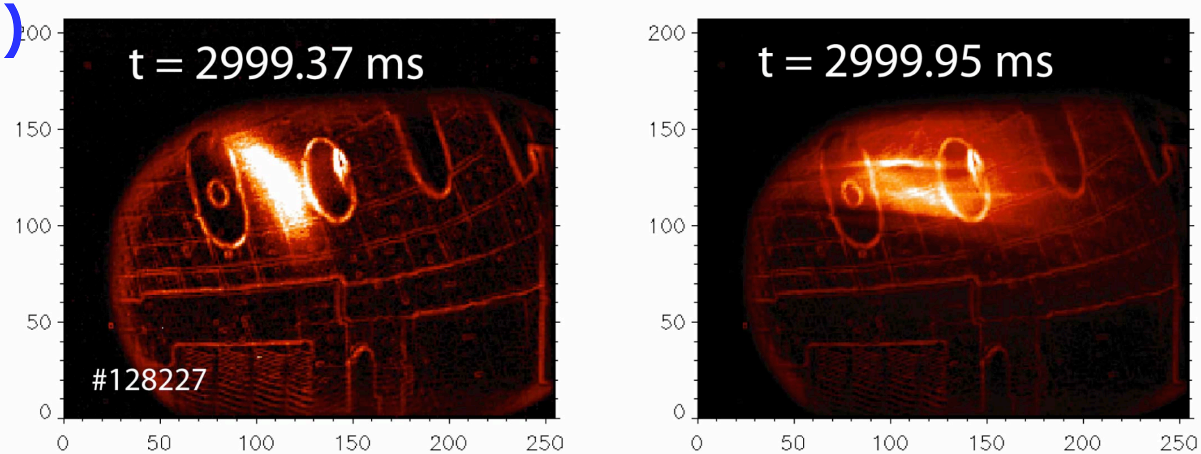
Many rapid shutdown methods studied in DIII-D

- massive gas injection (MGI)
- shattered pellets (SPI)
- large shell pellets

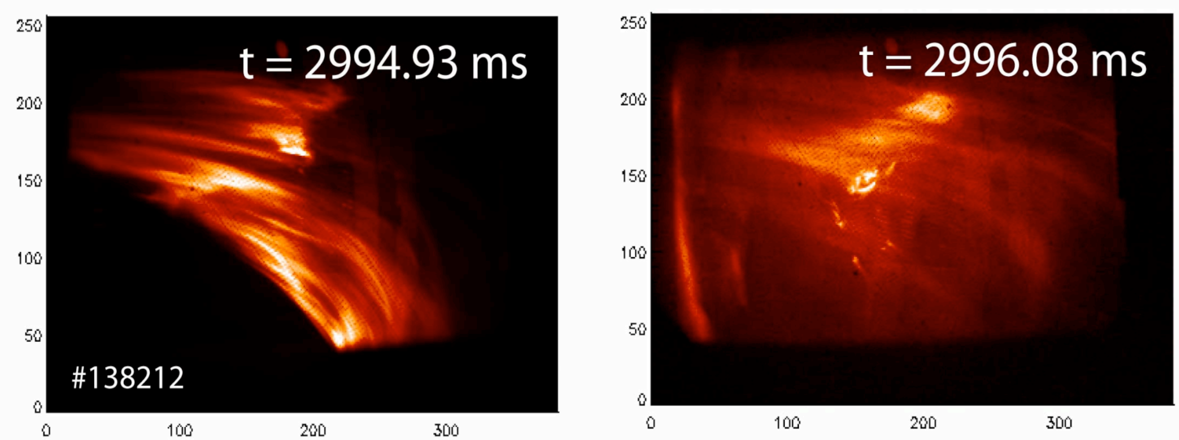
• Work well for TQ and halo current mitigation.

• Only reach 20% of theoretical mid-CQ critical density n_{crit} needed for collisional RE suppression.

Images of He MGI shutdown



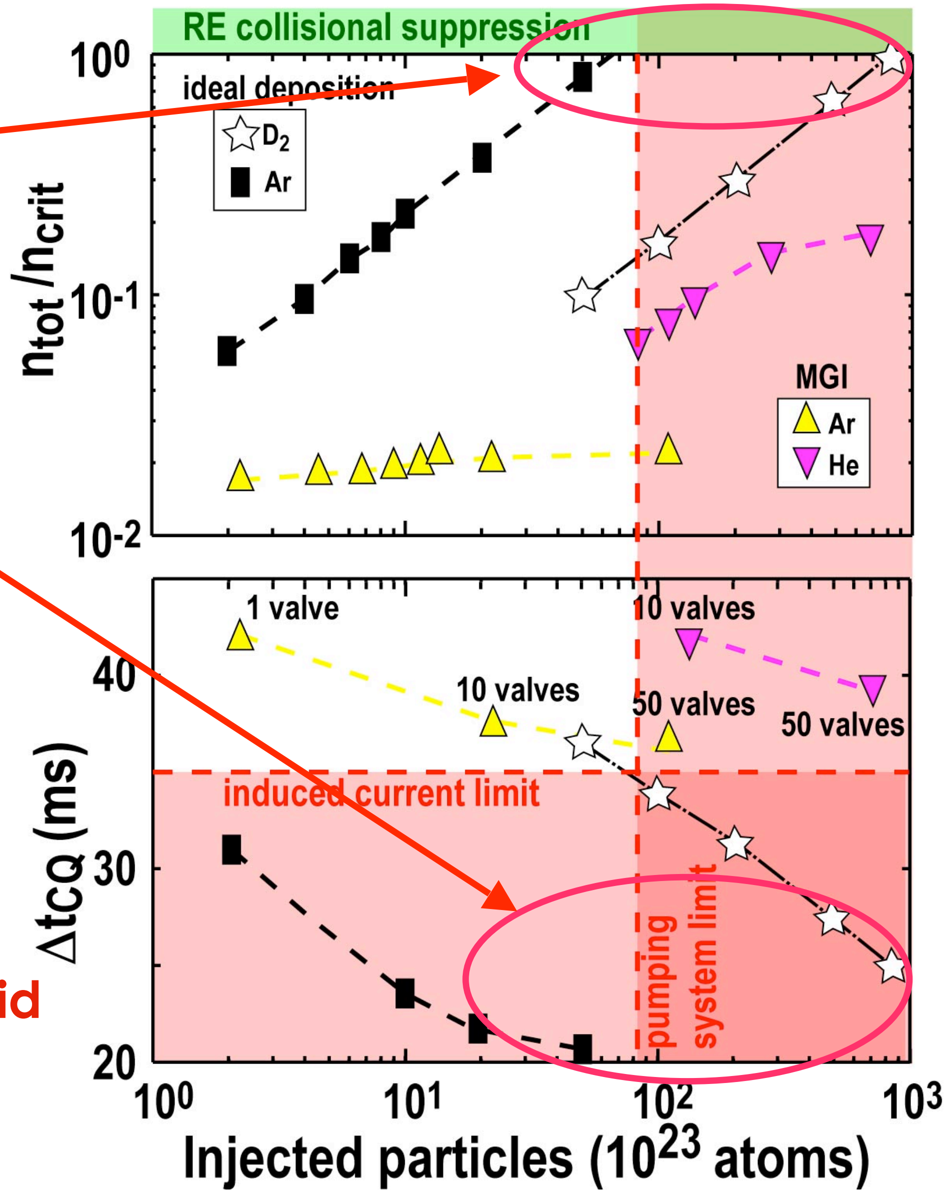
Images of shattered D_2 pellet shutdown



(from N. Commaux, NF 2010)

Outlook for ITER : collisional suppression of REs during CQ will be very challenging

- 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

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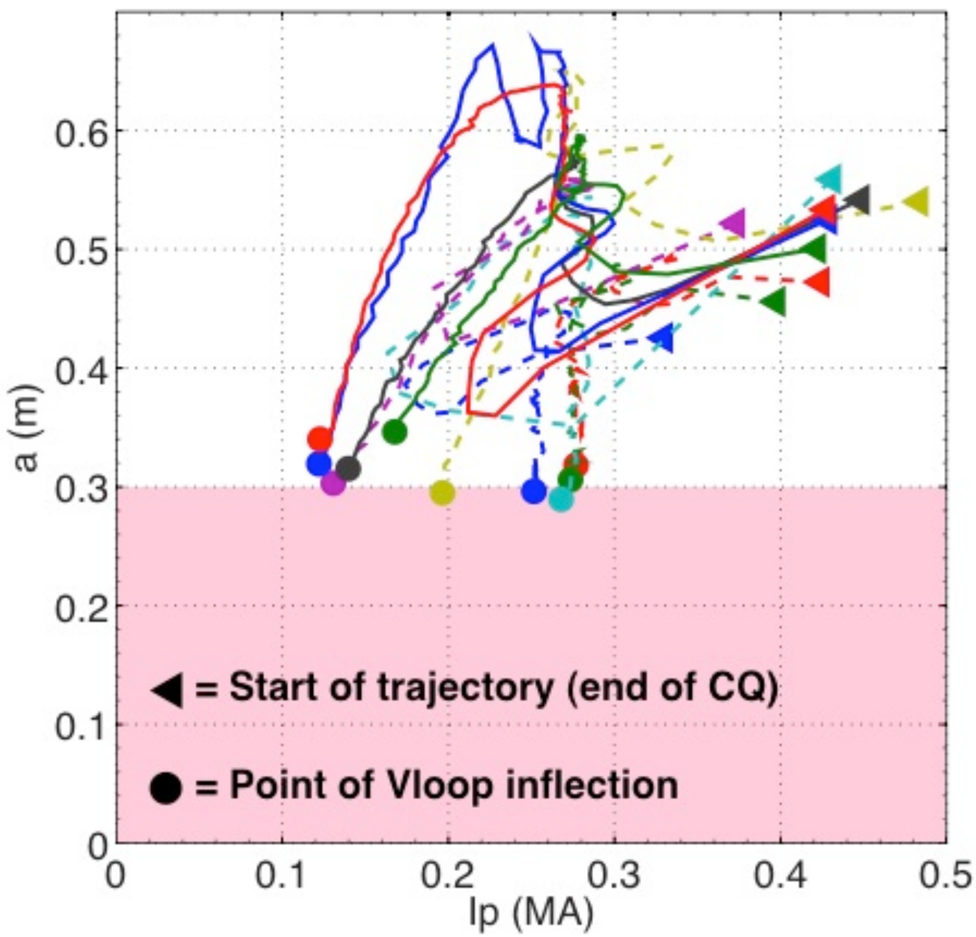
RE beam current dominantly found inside *a* < 0.3 m

- Beam current channel position can be estimated from external magnetic signals.
- Loss of RE current greatly accelerated when beam moves within 0.3 m of wall.
  - Accelerated loss over wide range of a/I_p - not MHD instability!
  - Indicates transport loss of *a* ~ 0.3 m of RE beam current channel.
- Consistent with current dominantly carried by REs.

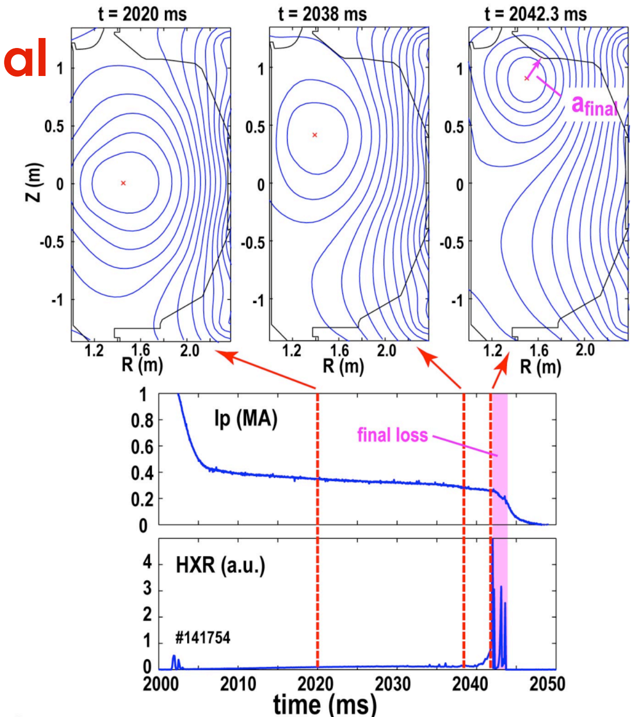
Radius at which final RE loss begins



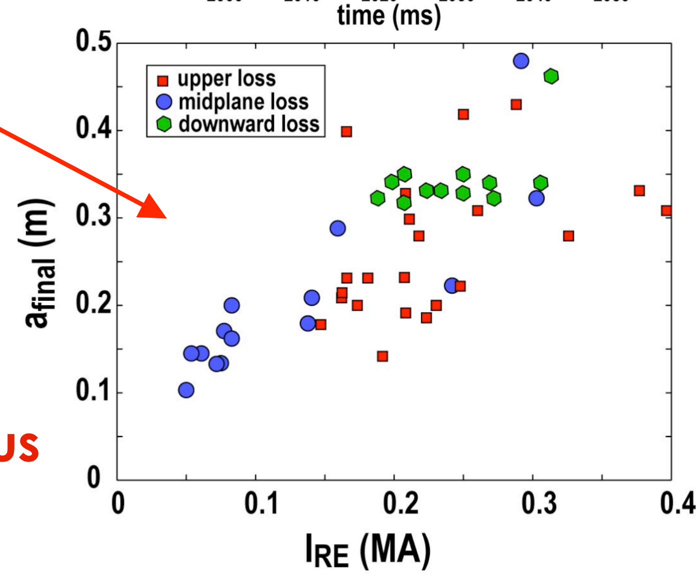
(from N. Eidietis, APS 2011)

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

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