Runaway Electron Confinement Modeling for DIII-D, Alcator C-Mod and ITER

V.A. Izzo, E.M. Hollmann, A.N. James, J. Yu

UCSD

D.A. Humphreys, L.L. Lao, P.B. Parks,
P.E. Sieck, J.G. Wesley

General Atomics

R.S. Granetz, G.M. Olynyk, D.G. Whyte

MIT-PSFC

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Alcator C-Mod

UCSD

Outline

I. Motivation: Why runaway electron (RE) confinement matters. Results from RE experiments.

II. The Model: Rapid shutdown simulations with MHD + impurity radiation + RE orbits = NIMROD. Computational approach to experimental gaps.

III. Results: The sequence of events. Effects of plasma shape, fueling profile, and machine size

IV. Summary and conclusions

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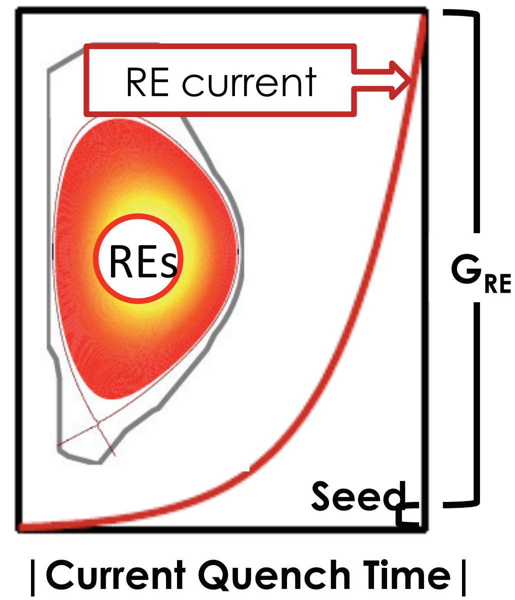
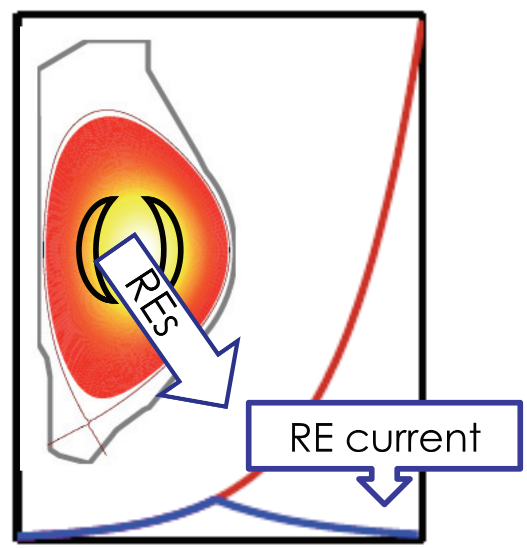
ITER Disruptions May Produce Large RE Current Due to Knock-on Avalanche Process

- **Seed RE population can grow exponentially**

$$G_{RE} \approx \exp[2.5 I_p (MA)]$$



- **Runaway gain in ITER is much larger than existing tokamaks**
- **Exponential growth can be prevented with a comparably sized (or larger) RE loss term**
- **One possible loss term is radial transport of REs out of the plasma due to MHD perturbations**
- **Will disruption-induced MHD provide a large enough loss term in ITER?**



Recent RE Experiments on DIII-D and C-Mod

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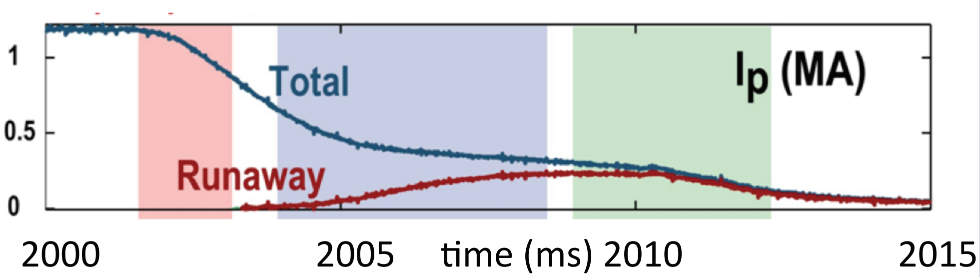
Rapid shutdown by Ar pellet injection

High Z material (Ar) in core ➔ RE seed

RE plateaus of up to 400 kA observed



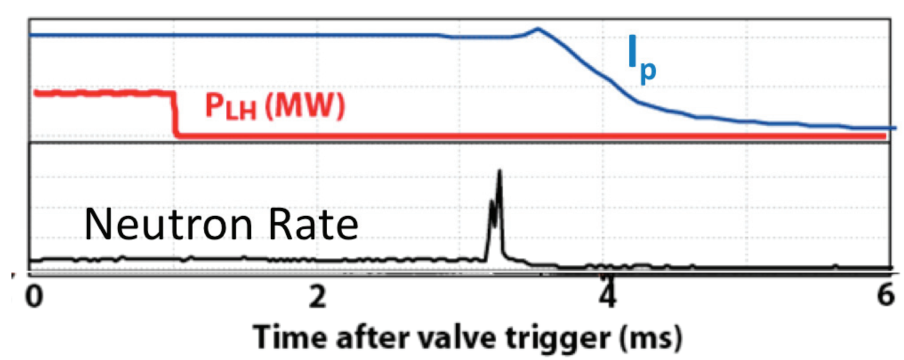
RE plateaus reliably produced for limited plasma shapes– lower reliability for diverted plasma shapes

Alcator C-Mod

Rapid shutdown by massive gas injection (MGI)

Use LHCD prior to MGI to produce large RE seed

No RE plateaus observed



Use modeling to make connections between all of these results…

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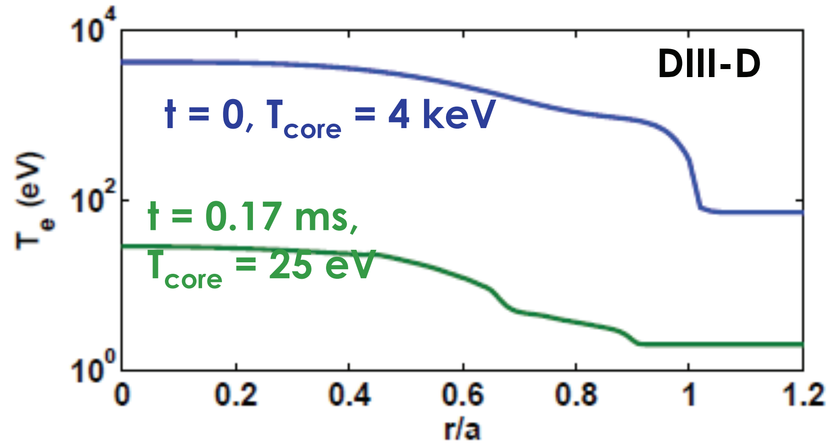
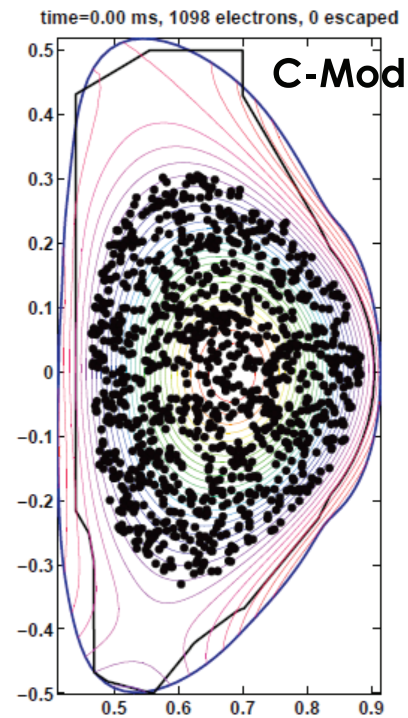
NIMROD Can Simulate Mitigated Disruptions (Rapid Shutdowns)

- Simulation of current quench (CQ) phase (cool, resistive plasma)
- Extended MHD plus impurity (Ar) radiation
- Simplified (instantaneous) Ar delivery → compressed thermal quench (TQ) time
- Guiding-center drift motion of test (trace) population of REs is calculated as MHD fields evolve
- RE orbit calculation provide info on radial RE transport and strike-points of REs on the first wall



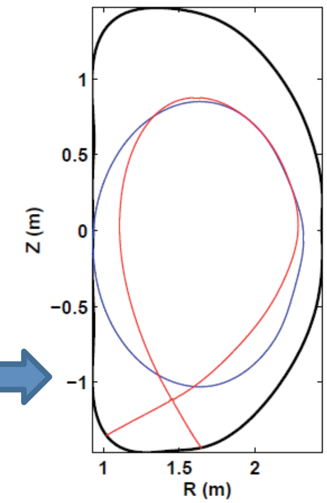


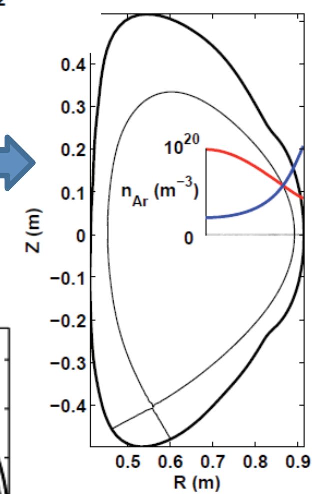
Electrons are initiated inside closed flux region with suprathermal, but non-relativistic energy (150 keV)

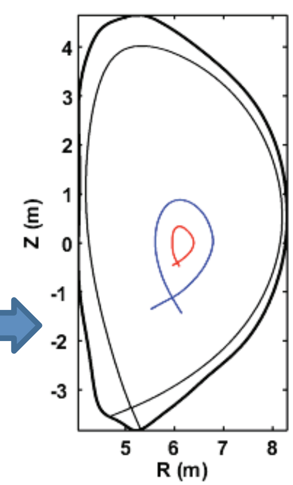
NIMROD Simulation Address Effects of Three Experimental Factors on RE Confinement

Simulations model experiments that have been done, and "fill in the gaps" for experiments that haven't been done…

Physics Issue	Computational approach
Plasma shape: Limited vs. diverted	Two DIII-D simulations using "Ar-pellet model" for rapid shutdown, but different plasma shape
Impurity injection method: pellet vs. gas-jet	Two C-Mod simulations with same (diverted) equilibrium. One with "Ar-pellet model", one with edge-peaked "Ar gas-jet model"
Machine size	Three simulations: C-Mod, DIII-D, and ITER w/ diverted equilibria and "Ar-pellet model"







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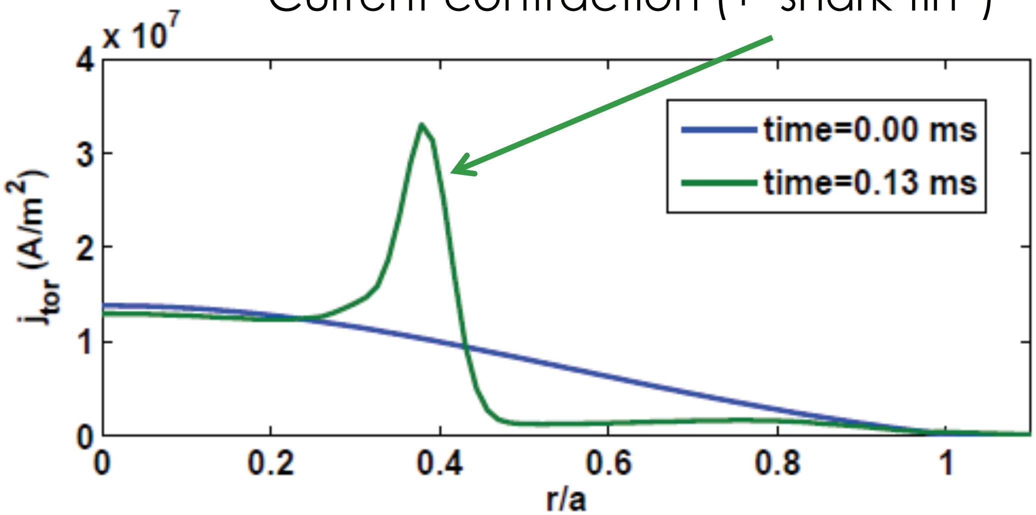
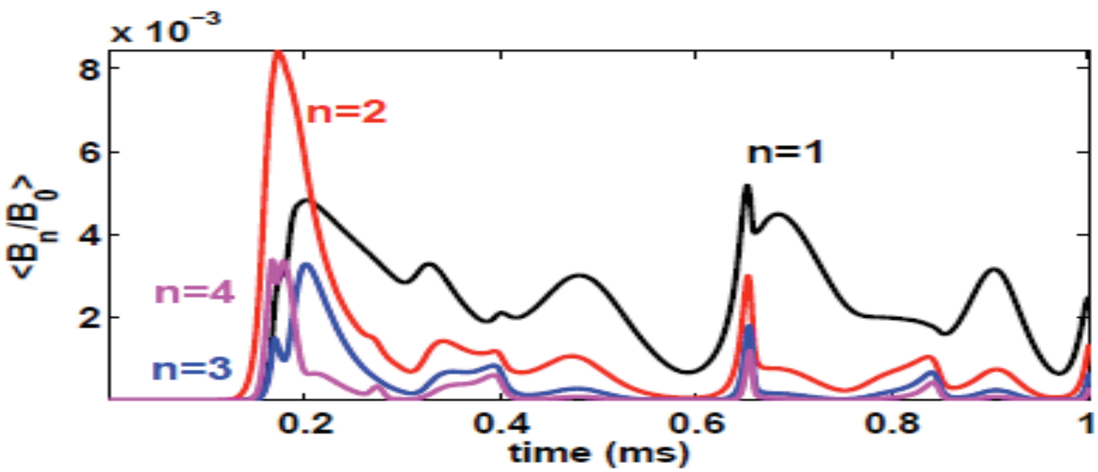
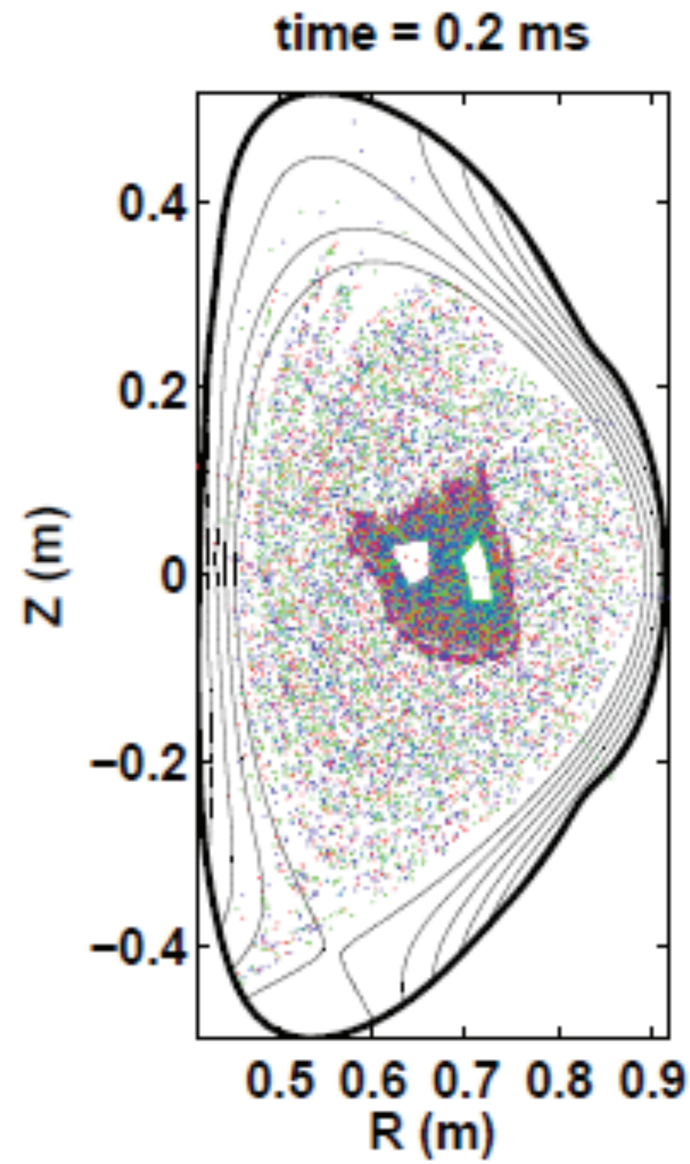
Rapid Cooling Leads to Contraction of Current Profile, Onset of MHD Instability

C-Mod (diverted + edge-peaked)

Current contraction (+"shark-fin")

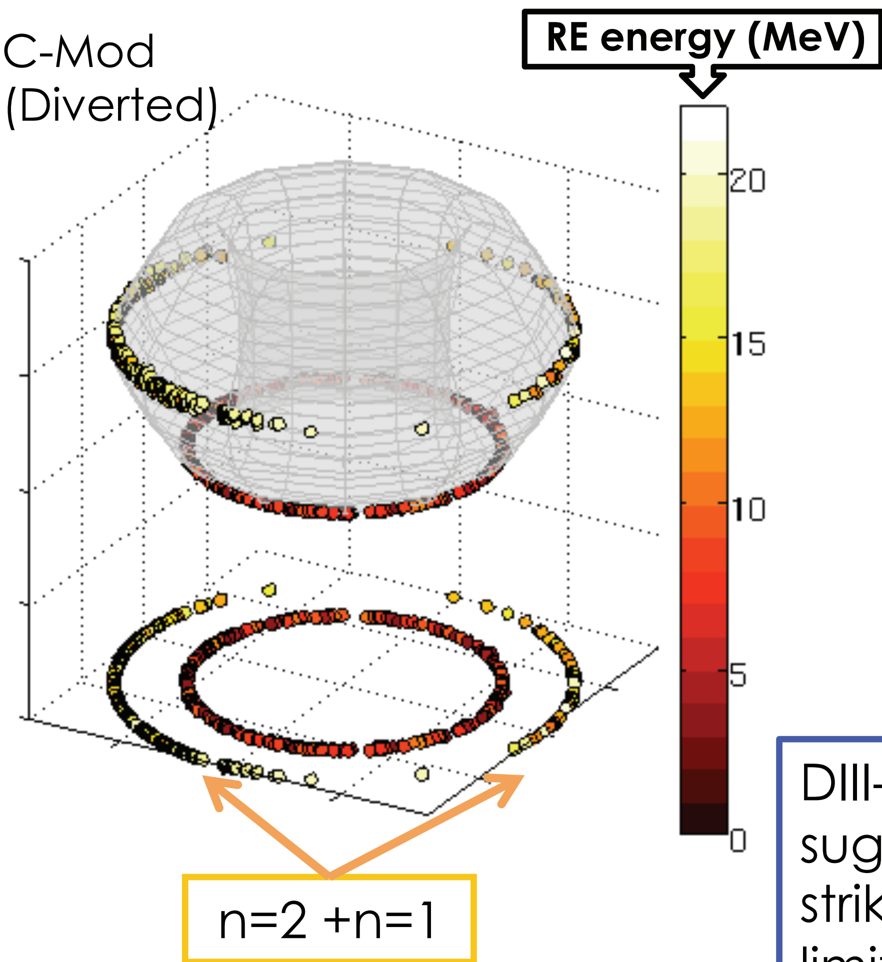


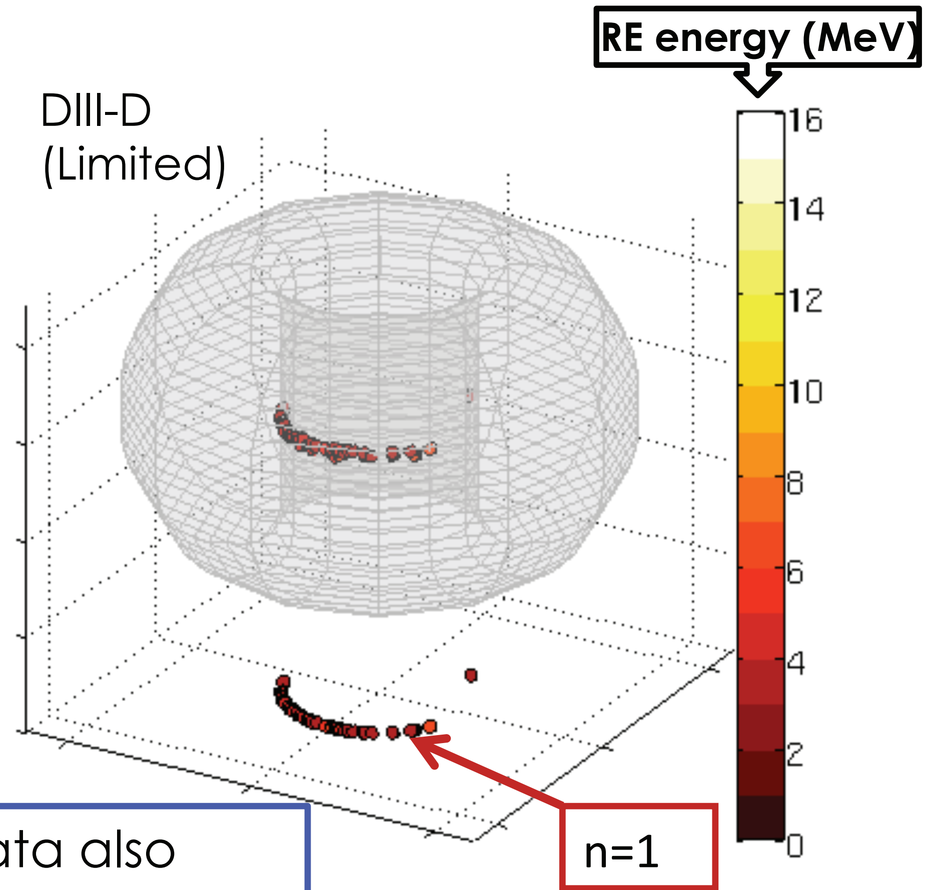




At MHD Onset, REs Escape, Strike the Wall in Poloidally Localized Regions

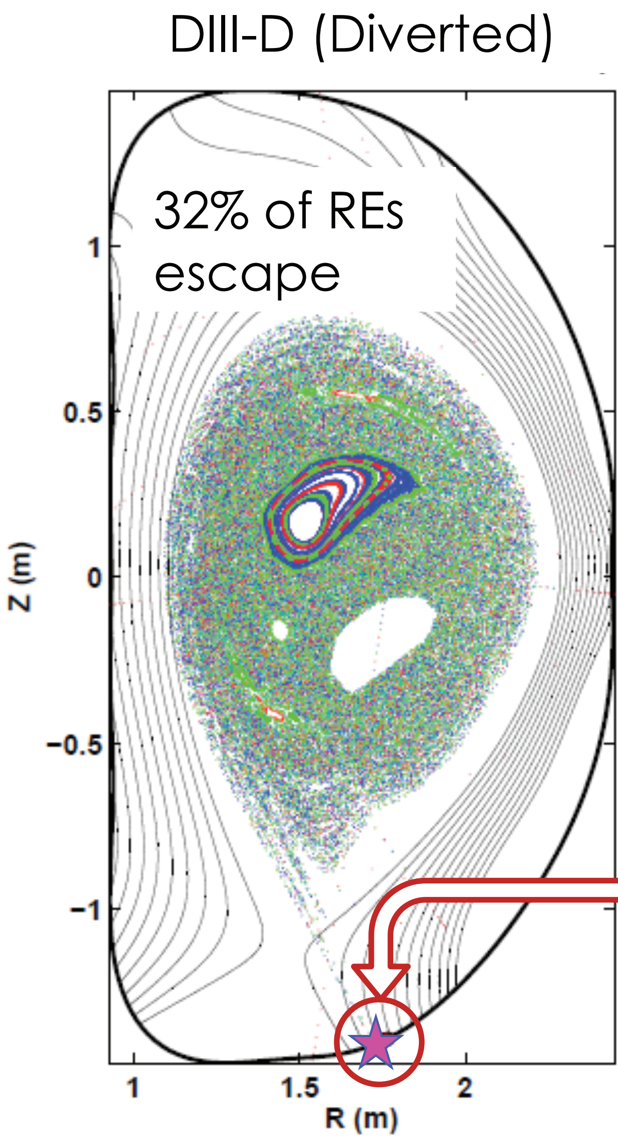
REs strike outer divertor in toroidally symmetric pattern. Outer or inner midplane strike pattern exhibits dominant MHD toroidal mode number.

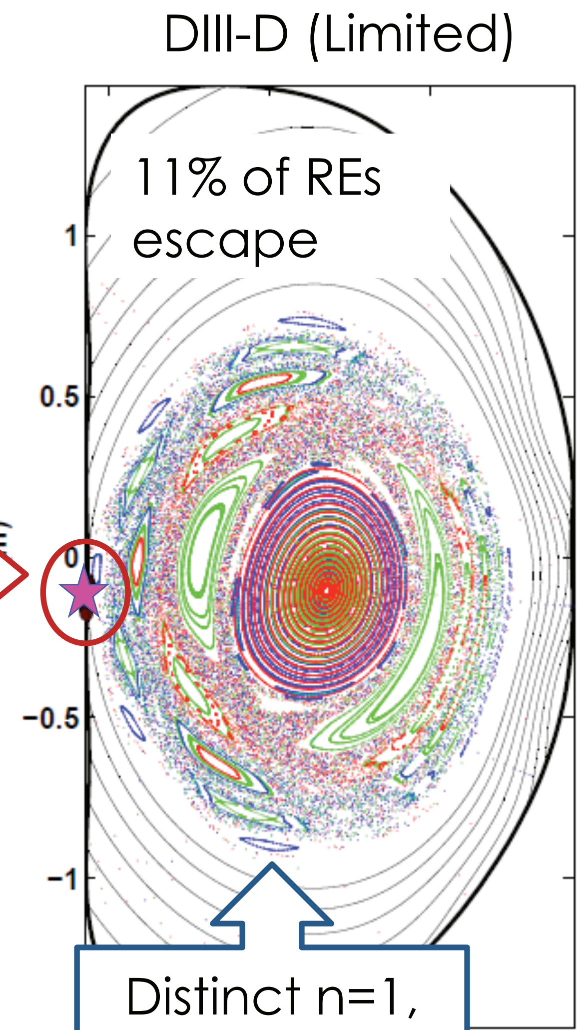




DIII-D data also suggests n=1 striking pattern in limited discharges

RE Loss Mechanism Differs for Limited vs Diverted Shape in DIII-D





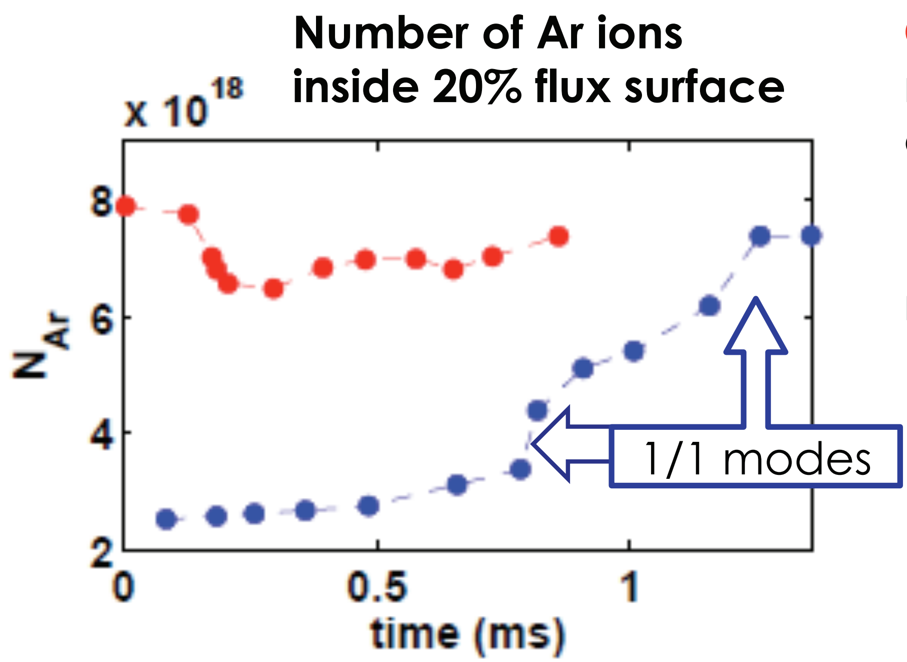
Limited plasma: REs lost due to n=1 shift of equilibrium into center column

Diverted plasma: REs lost due to transport on stochastic fields

Distinct n=1, m=2-6 islands

★ **RE strikepoint**

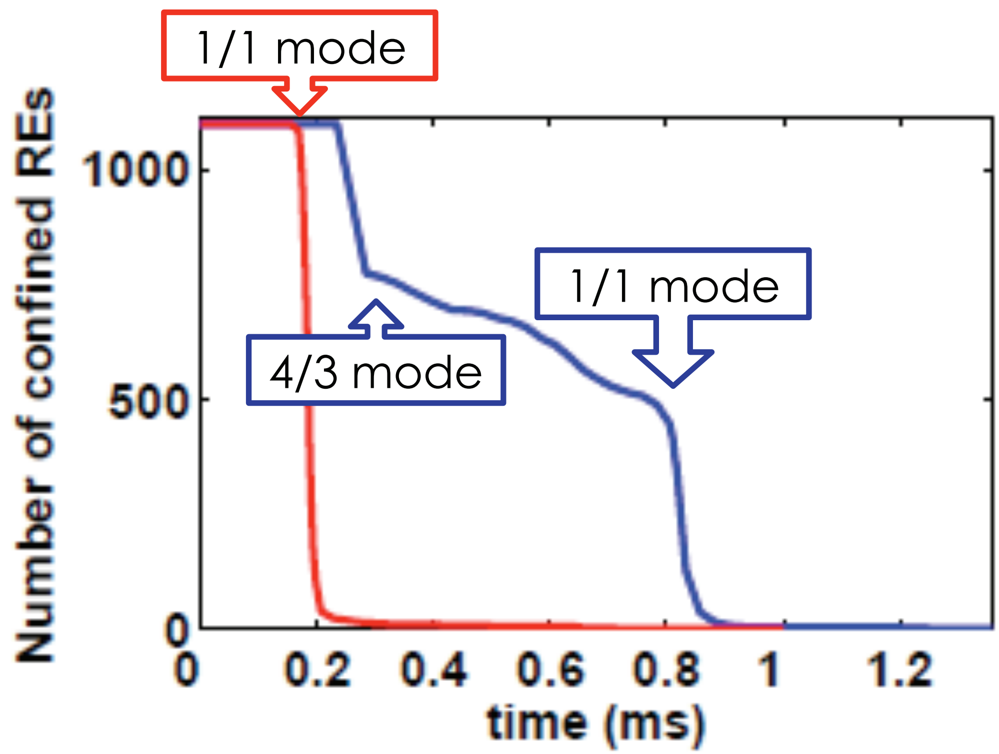
C-Mod Exhibits Total Loss of REs Regardless of Core-peaked or Edge-peaked Ar Profile



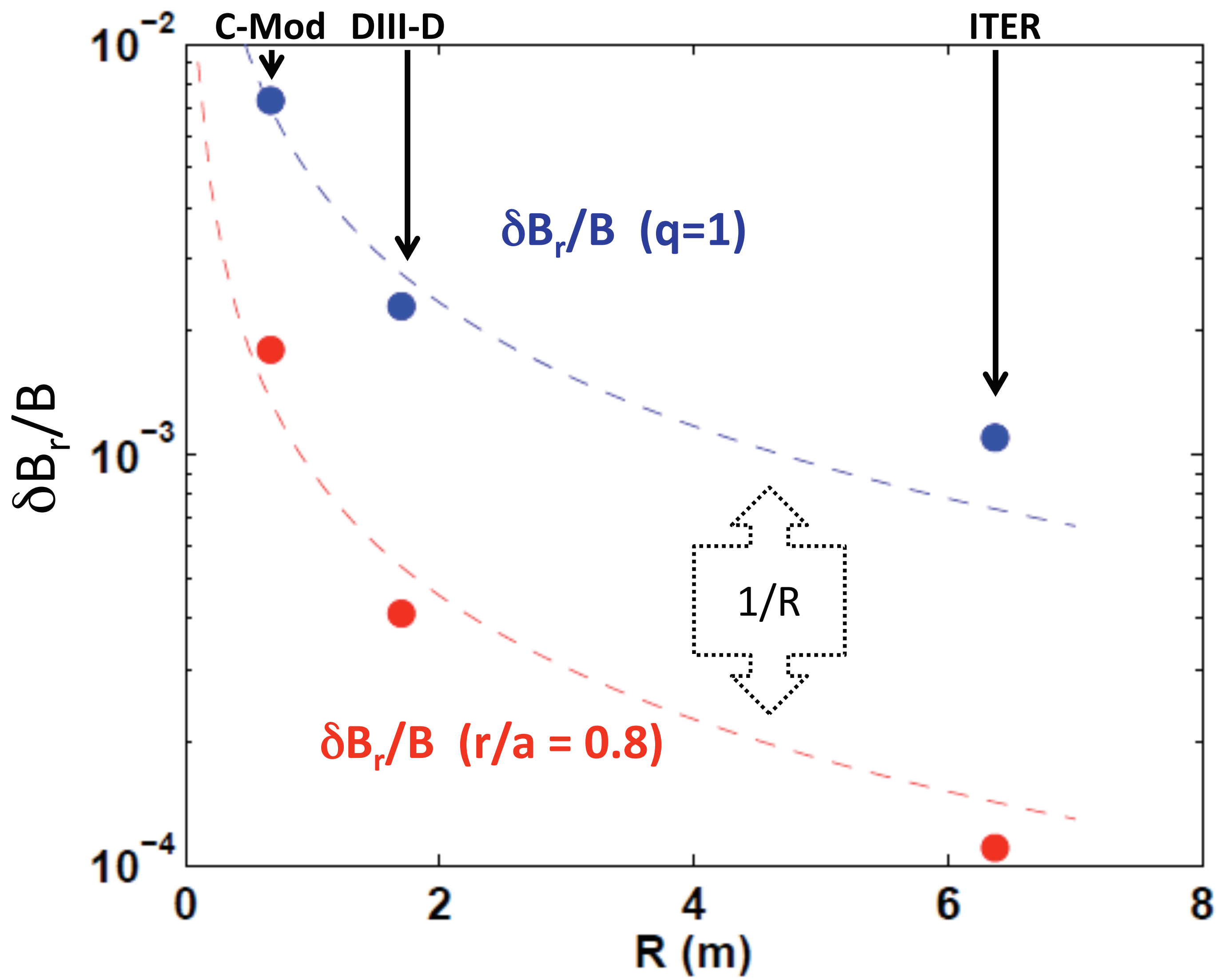
Core-peaked Ar case has immediate 1/1 mode onset, loss of nearly all REs in one event

Edge-peaked Ar case has delayed 1/1 mode onset, delayed loss of core REs

Same 1/1 mode mixes Ar into the core in Edge-peaked Ar case and causes loss of core REs



Size Scaling: Fluctuating Field Amplitudes at q=1 and r/a=0.8 show ~1/R Trend

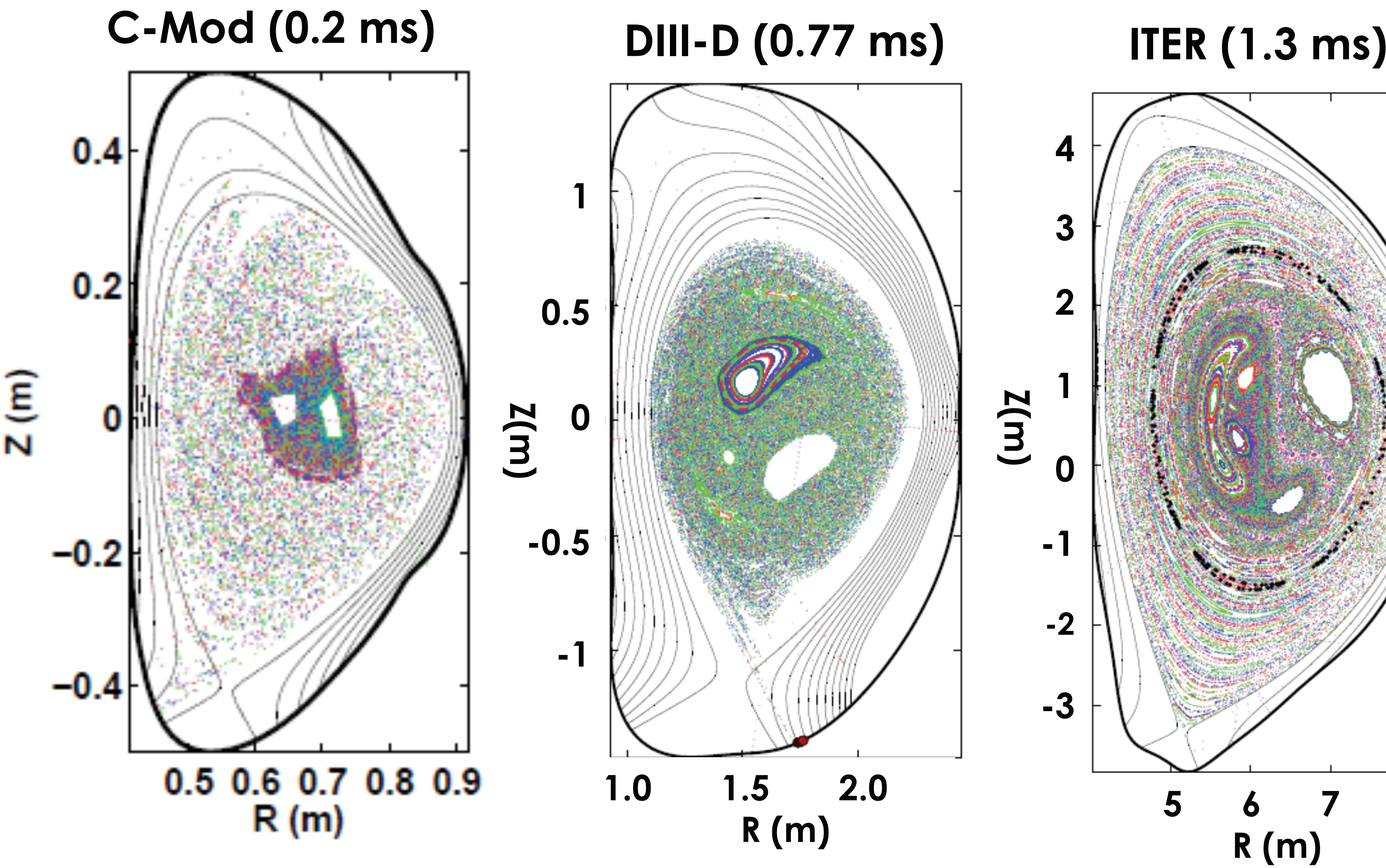


No systematic trend in maximum $\delta B_r/B$ versus major radius

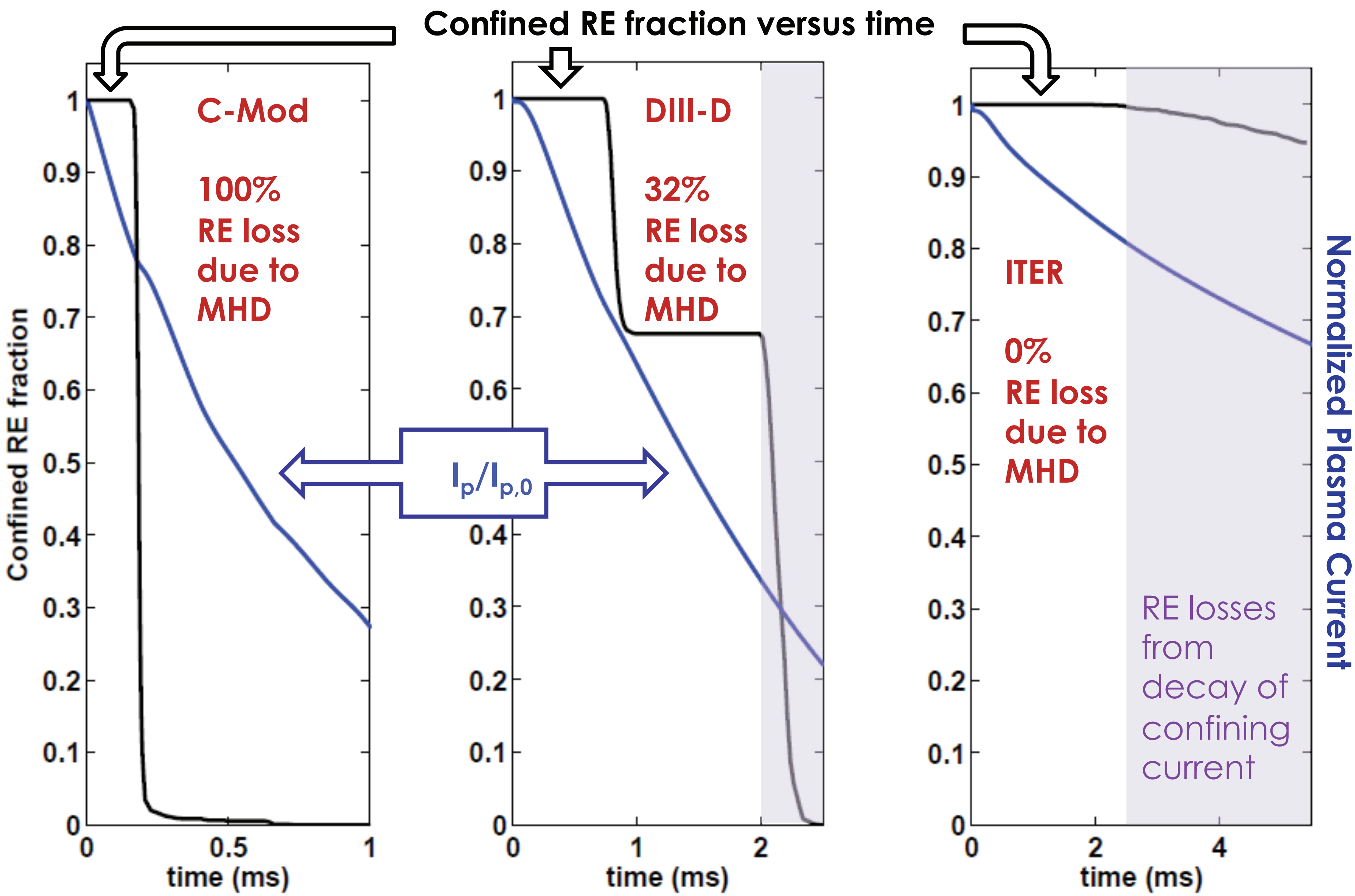
$\delta B_r/B$ falls off slightly slower than 1/R at q=1

$\delta B_r/B$ falls off slightly faster than 1/R at r/a=0.8

Stochasticity Extends to Separatrix in Smaller Devices, Not ITER

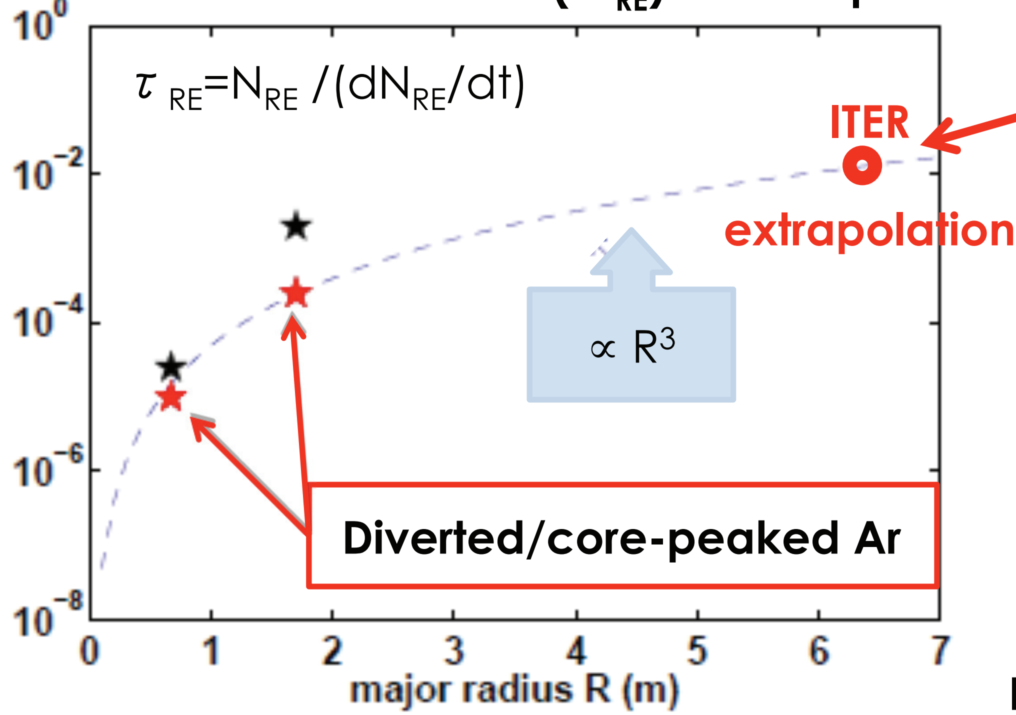


RE Losses Due to MHD Decrease as Device Size Increases



RE Confinement Time in DIII-D Much Larger than C-Mod

RE confinement time (τ_{RE}) at MHD peak



Scaling extended to ITER = 10 ms

Rechester-Rosenbluth:
$D \sim R(\delta B_r/B)^2 \sim R(1/R)^2 \sim 1/R$
$\tau_{RE} \sim R^2/D \sim R^3$

Characteristic RE confinement time differs between C-Mod and DIII-D by factor of $25 \approx R^3$

Duration of MHD fluctuations increases only linearly with R: Longer than τ_{RE} in C-Mod, comparable in DIII-D, much shorter in ITER

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Summary of Results

Physics Issue	Simulation Result
Plasma Shape: Limited vs. Diverted (DIII-D)	Different RE loss mechanism: Diverted-Transport on stochastic fields; Limited-External shift of plasma into center column
Impurity Injection Method: pellet vs. gas-jet (C-Mod)	Change only in timing of 1/1 onset: 100% loss of C-Mod REs in both cases
Machine Size (C-Mod, DIII-D & ITER)	MHD induced RE losses decrease as R increases: Edge $\delta B_r/B \sim 1/R$, RE confinement time increases as R^3

Conclusion

- **Disruption-induced MHD is not likely to deconfine REs in ITER**
  - RE confinement time increases faster with R than MHD fluctuation decay time

- **Only one ITER simulation has been performed so far; need to explore**
  - Role of wall and proximity to plasma
  - Use of scaled down ITER to isolate R as variable
  - Use of external perturbations to increase edge $\delta B_r/B$
  - True MGI-like cooling, triggering 2/1 or other edge mode

- **Alternate strategies for RE mitigation/control may be needed**