# Extrapolation of the Runaway Electron Benign Termination Scenario to ITER

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N. Eidietis[2], E. Hollmann[5], C. Reux[6]

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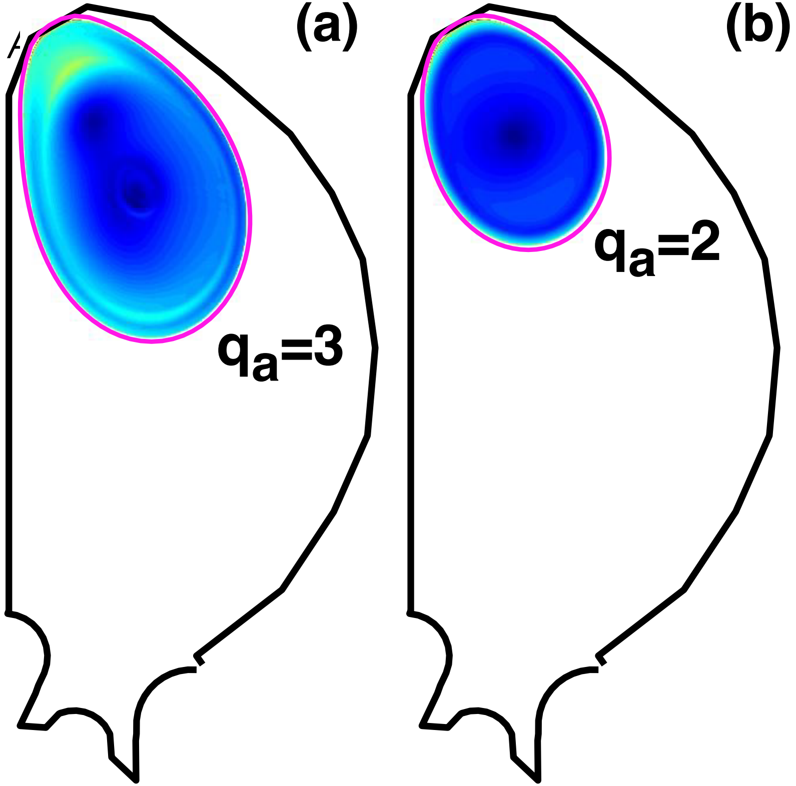
[4] ORNL, [5] UCSD, [6] CEA-France




**Presented at:**

## IAEA Technical Meeting on Disruptions
## ITER Headquarters
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COLUMBIA UNIVERSITY
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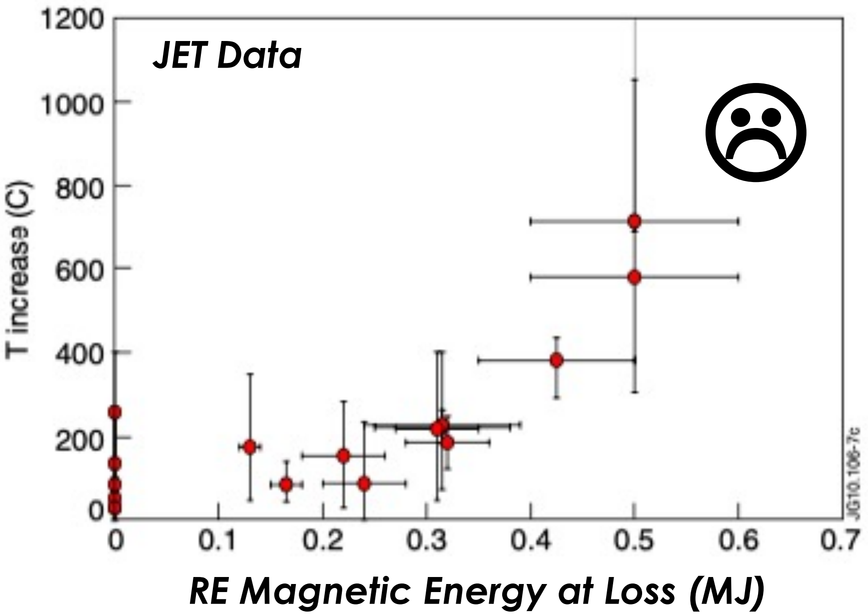
# Novel Path to Runaway Electron Mitigation Discovered




*V. Riccardo et al, PPCF 2010*

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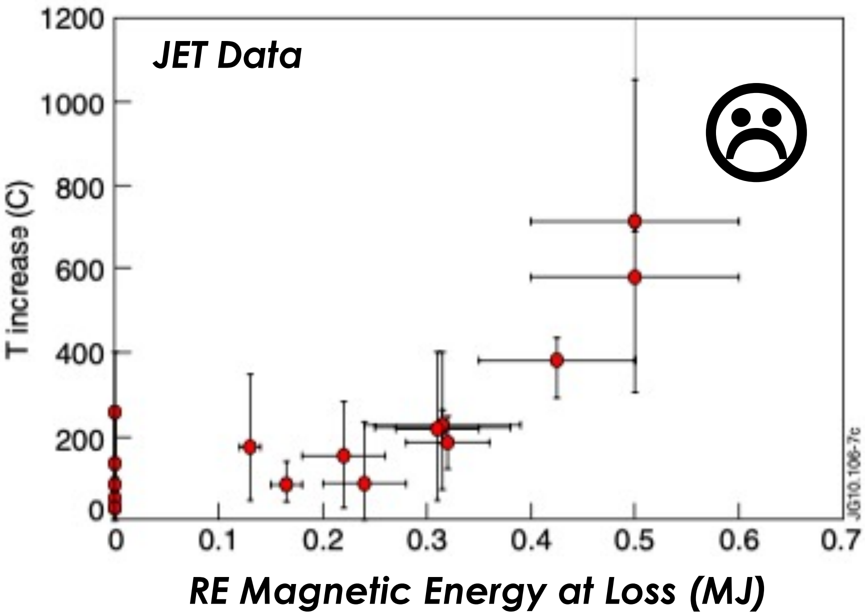


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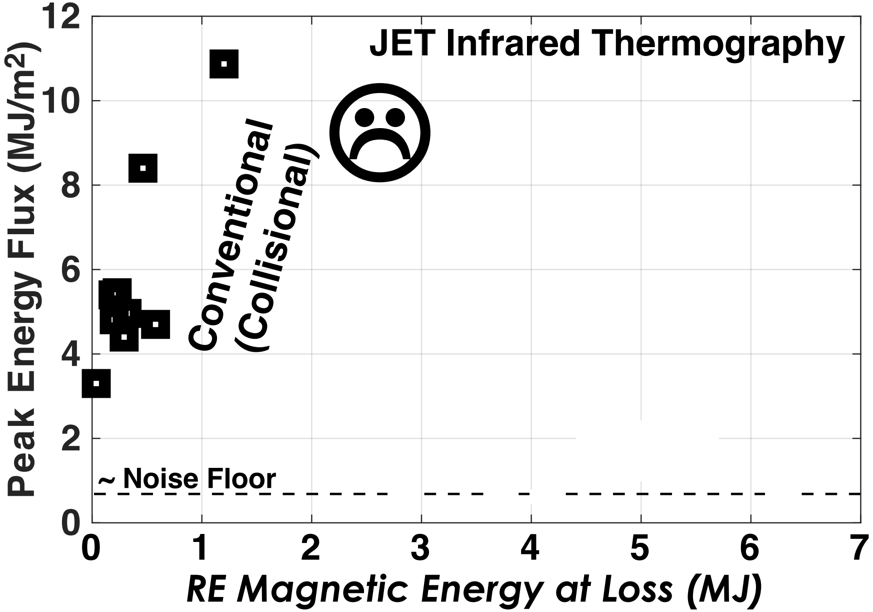


*C. Reux et al, PRL 2021*
*C. Paz-Soldan et al, NF 2021*

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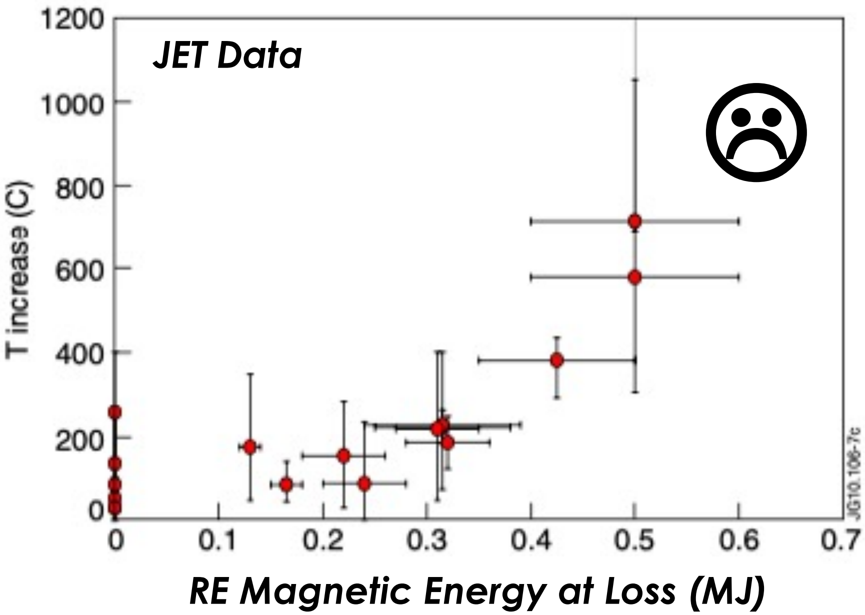


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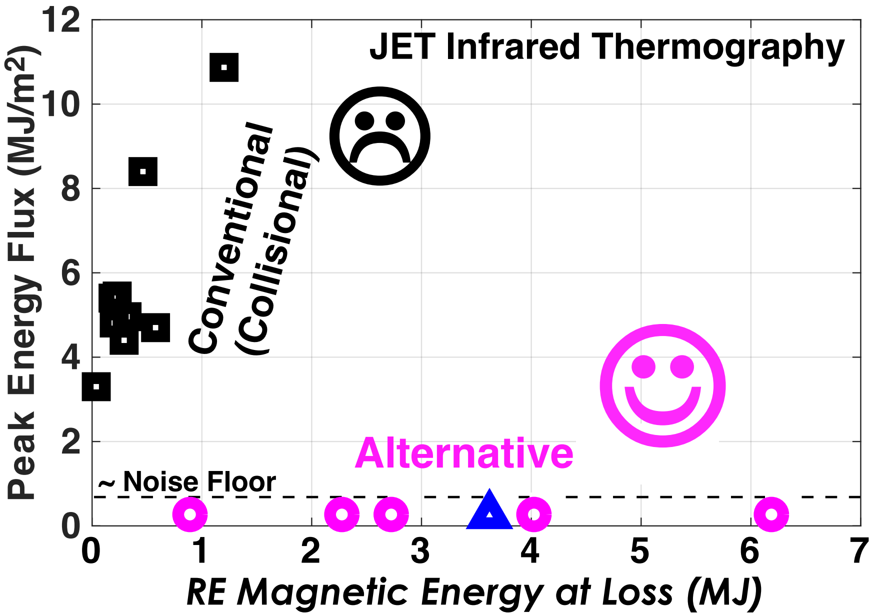



C. Reux et al, PRL 2021
C. Paz-Soldan et al, NF 2021

# Novel Path to Runaway Electron Mitigation Discovered Deploys Combo of Hydrogenic ($D_2$) Injection and Large-Scale MHD

**Alternate Approach (D2 + MHD)[1,2]:**

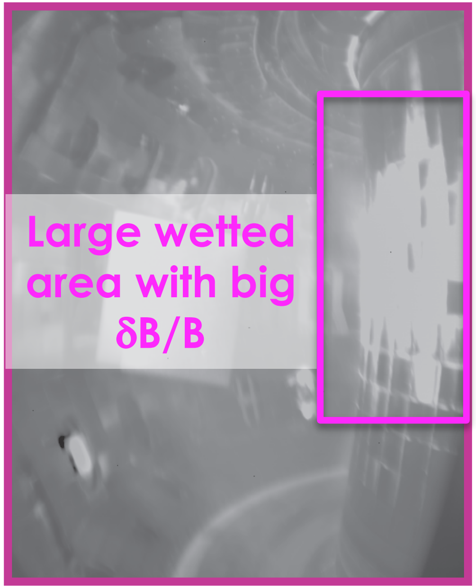
1. ***Recombined* low density plasma**
   - Very fast Alfven times ($\tau_A \sim n_e^{1/2}$)
2. **Access large & fast MHD modes**
   - Similar to the passive coil but intrinsic to the plasma
3. **MHD kicks out *all* the runaways**
   - Loss occurs on Alfvenic timescale

**RE kinetic energy:**

- **Lost over large wetted area**

**Magnetic energy:**

- **Lost as radiation after MHD event**


***This talk: ITER extrapolation, open questions***

[1]C. Paz-Soldan et al, Plas. Phys. Contrl. Fus 2019
[2]C. Reux et al, Phys. Rev. Lett 2021

# Presentation Outline

- **Access Condition #1: Recombination**
- **Access Condition #2: Macroscopic Stability Limit**
- **Consequences #1: Kinetic Energy Handling**
- **Consequences #2: Magnetic Energy Handling**

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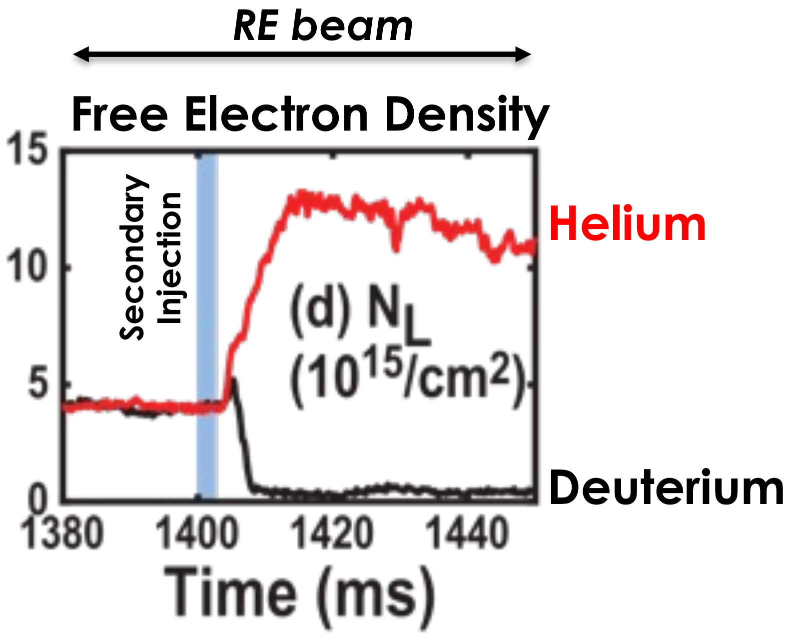
# Injecting Hydrogenic Atoms ($D_2$) Causes Background Plasma to *Recombine*




[1]*Hollmann et al, PoP 2020*

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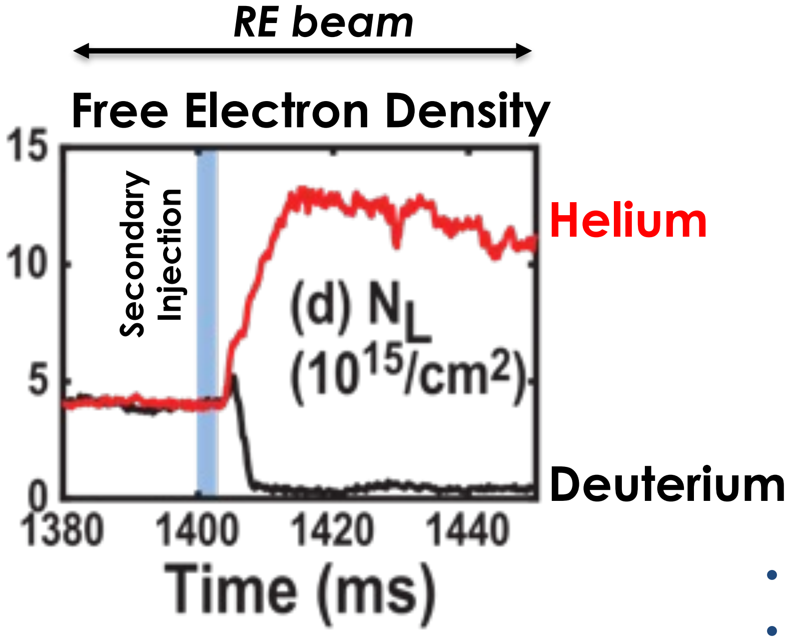
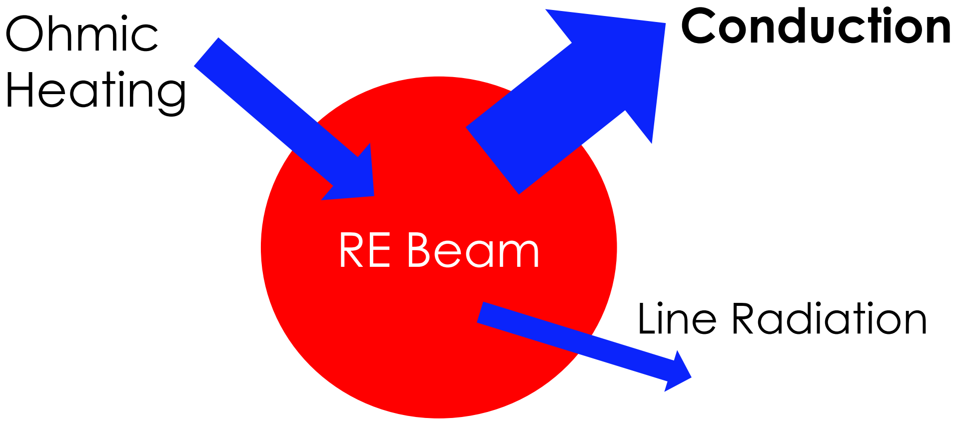



[1]*Hollmann et al, PoP 2020*

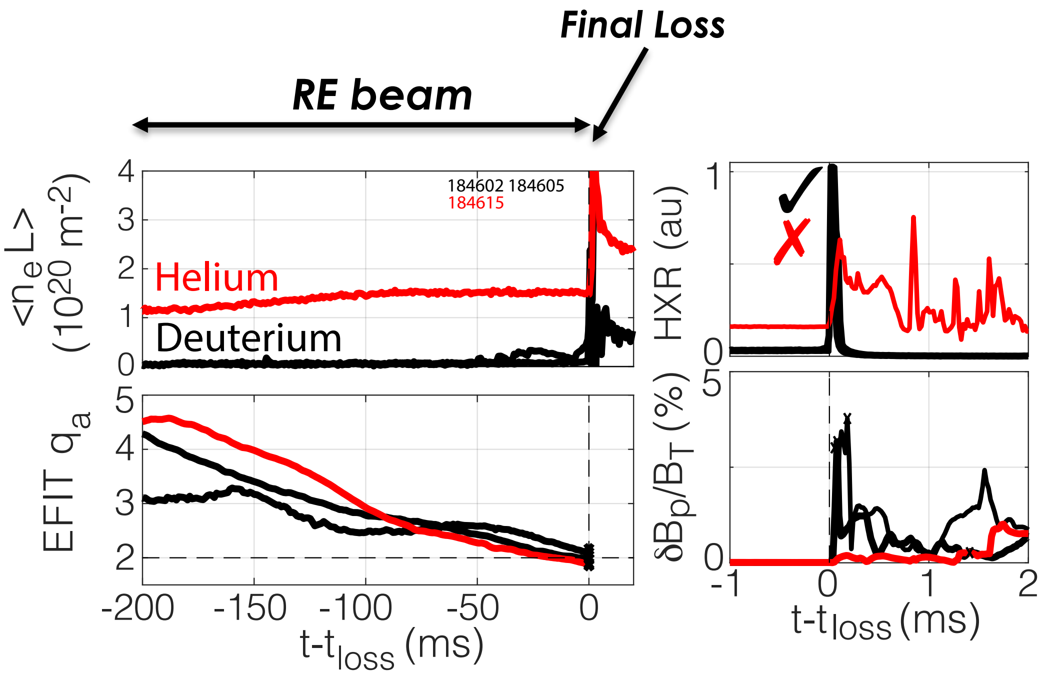



- **Heat conduction very large for $D_2/H_2$, not He**
- **Bulk temperature below ionization threshold**
- **Bulk plasma recombines**
- **Runaways unaffected**

***So far seen only with D/H injection***

# Helium and Deuterium Yield Totally Different Final Loss Dynamics

- **Discharges prepared with the same equilibrium dynamic**
- **Only <u>Deuterium</u> recombines the plasma**
- **Helium: small dB/B and persistent crashes (non-benign)**
- **<u>Deuterium</u>: singular crash, IP spike, no HXR in CQ (benign)**

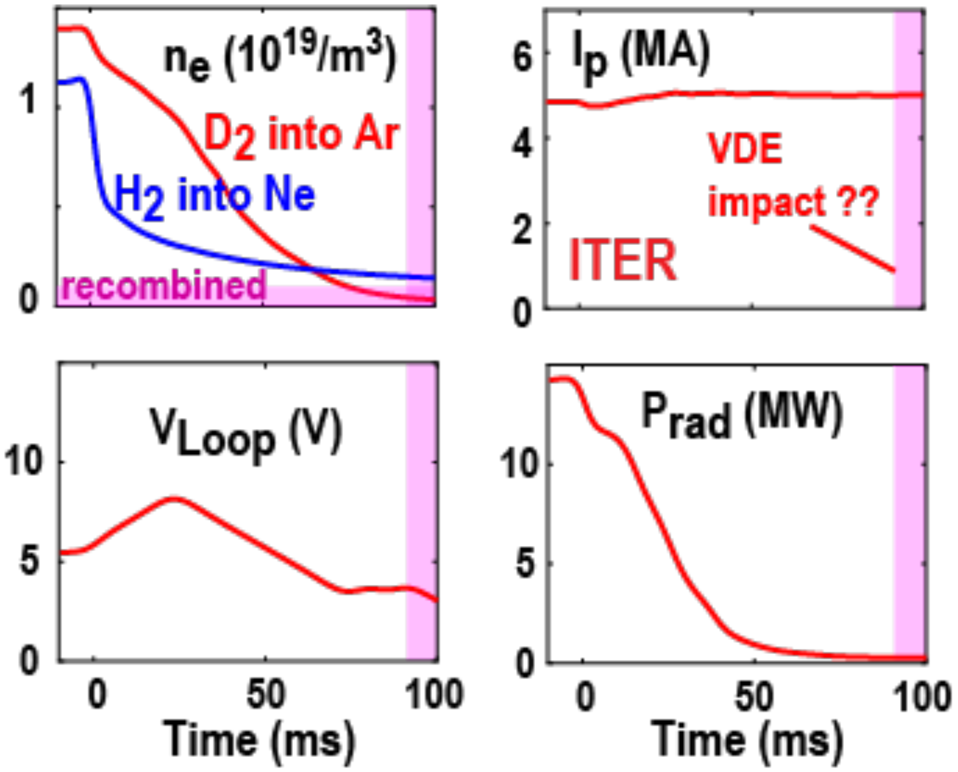


# Recombination Time Scale Predicted To Be Sufficiently Fast for ITER

- Recombination time scale should be faster than (VDE) time in ITER
  - Expect 100 ms ITER RE VDE time [Kiramov,PoP,2017]
  - Probably even slower after $D_2$ 2nd injection due to lower resistivity

- Simulated recombination time scales for ITER < 100 ms

- $H_2$ predicted to be faster than $D_2$ (faster conduction)



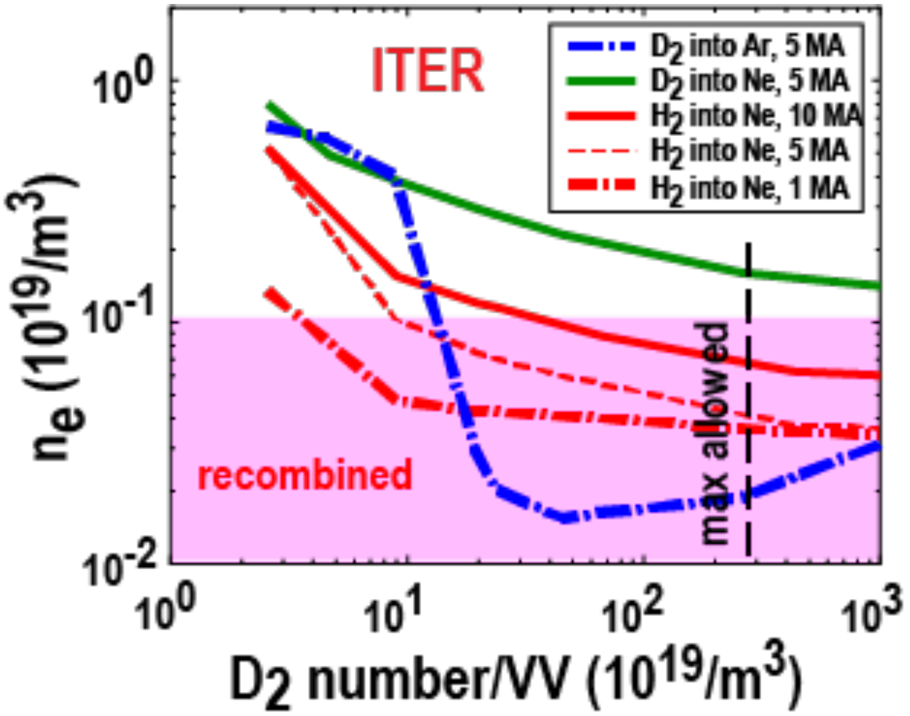

[1]E. Hollmann et al, NF 2022 (in review)

# ITER Simulations indicate RE plateau Recombination Not Achieved in Some Conditions

- Results vary by species mix:
  - $H_2$ into Ar → best (not shown)
  - $D_2$ into Ne → worst
  - $H_2$ into Ne → medium (ITER)

- Larger RE currents make achieving recombination more difficult (more input power to conduct)
  - Marginal for $H_2$/Ne @ 10 MA
  - Easier at lower RE currents

*No Recombination* ← → *Too collisional*

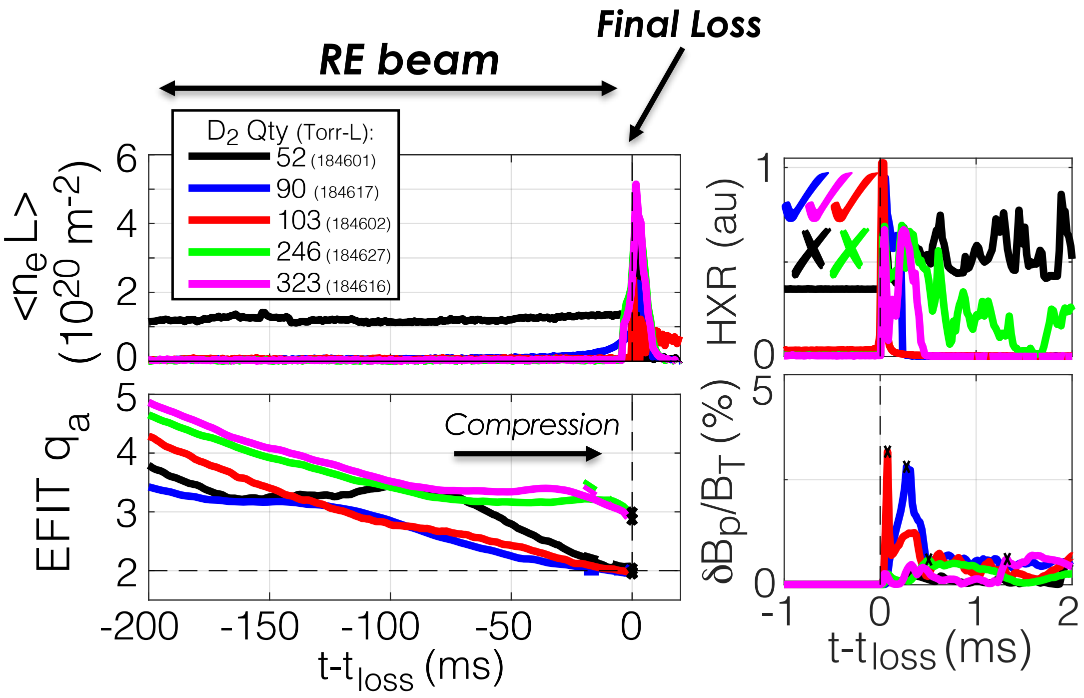



[1]*E. Hollmann et al, NF 2022 (in review)*

# $D_2$ Quantity Scan in DIII-D Reveals Possibility of Upper Bound: "Too Much" $D_2$ ?

**Limits of D2 Quantity:**

- **Too Little: plasma does not recombine, remains collisional**
  - Weak δB/B spike
- **Just Right: Robustly recombined but robust to the minor kink instabilities**
  - Strong δB/B spike
- **Too Much: Plasma re-ionizes after minor MHD events at higher $q_a$**
  - Weak δB/B spike






C Paz-Soldan/IAEA-TM/2022-07

# Open Questions on Recombination and Impact on MHD

- **Is recombination really essential?**
  - So far, data indicates yes, but, could it be indirect ?
- **What is the underlying mechanism making recombination important?**
  - Hypothesis: fast Alfven times == fast MHD → How to test the hypothesis?
  - Alternate hypothesis: indirect current profile effect? (any others?)
- **How different are results with Ne + $H_2$ vs Ar + $D_2$?**
  - Present experiments can benchmark model(s)
- **Is there an upper limit in $D_2$ injection?**
  - Only DIII-D finds one so far

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# Instability After Macroscopic Stability Limit Is Crossed

**DIII-D:**

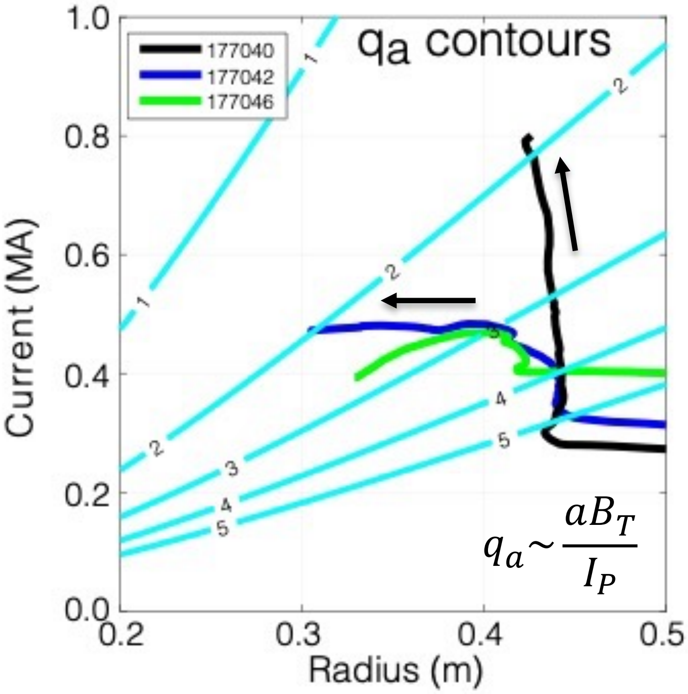
- **Instability fully explained by low order rational $q_a$ crossing**
  - Via raising current
  - Via radial compression
  - Via VDE (== radial compression)

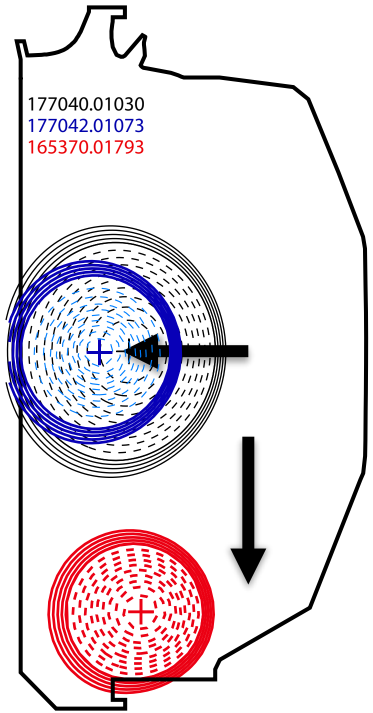
**AUG:**

- **Low $q_a$ picture also works well**
  - See U. Sheikh talk, this conference

**JET:**

- ***More complex picture[1]***
- **Higher $q_a$, some non-rational $q_a$**
- **Current profile? Island overlap?**



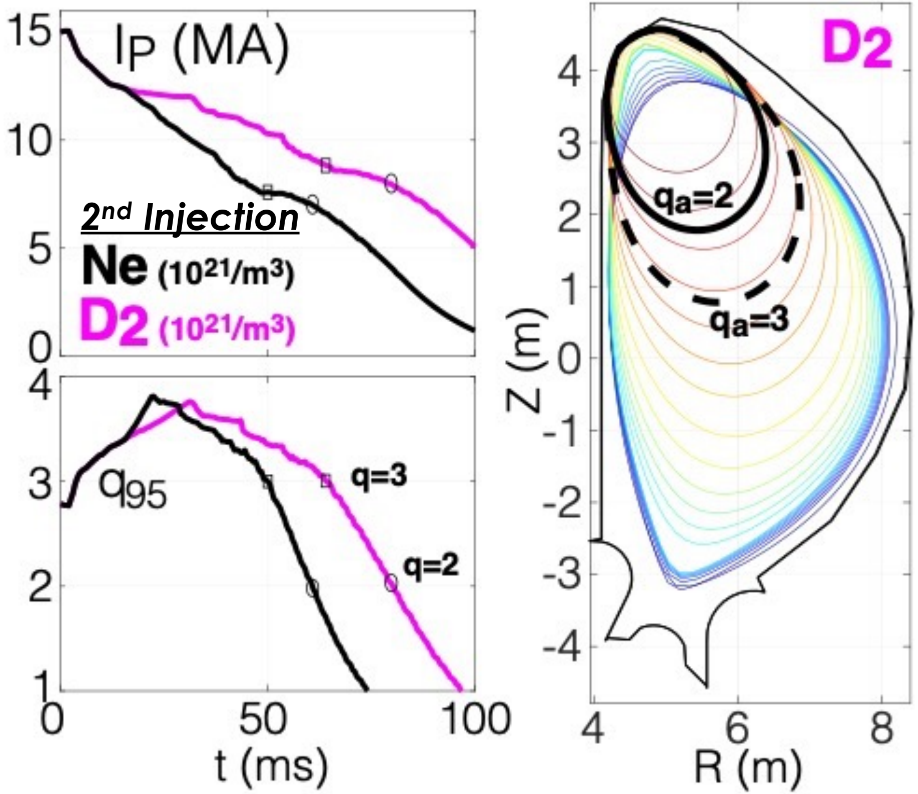




[1]C. Reux et al, PPCF 2022

# Computed Post-Disruption Evolution for ITER Finds Low Safety Factor is Robustly Accessed

- **Expect $q_a$=3 to be crossed near 8 MA**
- **Comparable VDE with *or* without $D_2$**
  - Caveat: Recombination not included in DINA
- **Lower RE current cases will have to compress further to access instability**

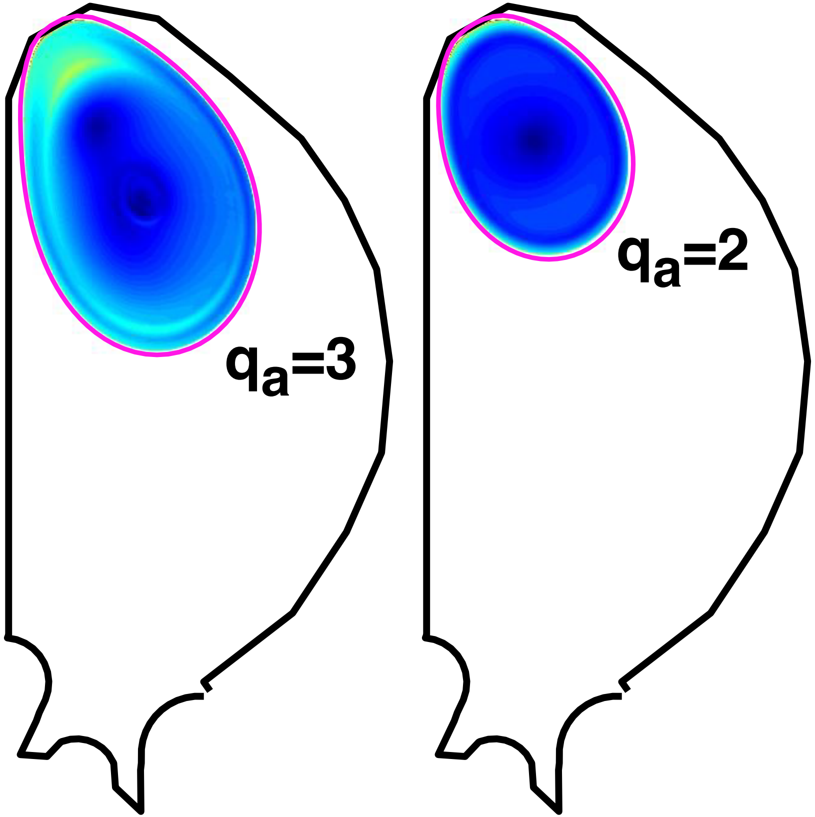
**DINA ITER Simulations**




K. Aleynikova et al, Plas. Phys. Rep. 2016

# MARS-F Linear Stability Modeling[1] Identifies Eigenmodes of Low q "Resistive External Kink"

- Equilibria near $q_a$=2, 3 extracted from modeled VDE trajectory
- Linear instability analysis reveals unstable modes at the rational q-crossings




[1]Y.Q. Liu et al, NF 2019 & PoP 2020

# Open Questions on Access to MHD Instability

- **Does variability in current/J-profile matter? Can it preclude benign termination?**
  - How does variability impact the observed MHD modes size and speed?
  - Is there a risk of edge-localization to the MHD for some current profiles? (=incomplete loss)
- **Is island overlap (double-tearing) an alternate path to the final loss event in ITER?**
  - If yes, much harder to predict the onset criteria
- **Million Euro Question: How large will $\delta B/B$ be in ITER?**
  - Non-linear MHD modeling is the path forward
  - Work is ongoing with M3D-C1, JOREK

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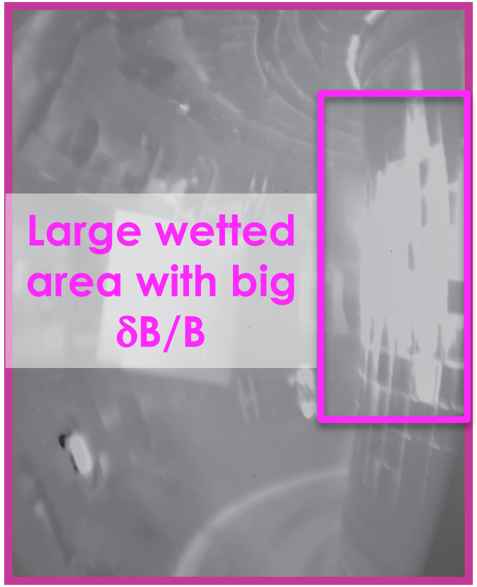
# Kinetic Energy Handling → Large Wetted Area is the Key Phenomena


Collisional Dissipation




Alternate (D2 + MHD)

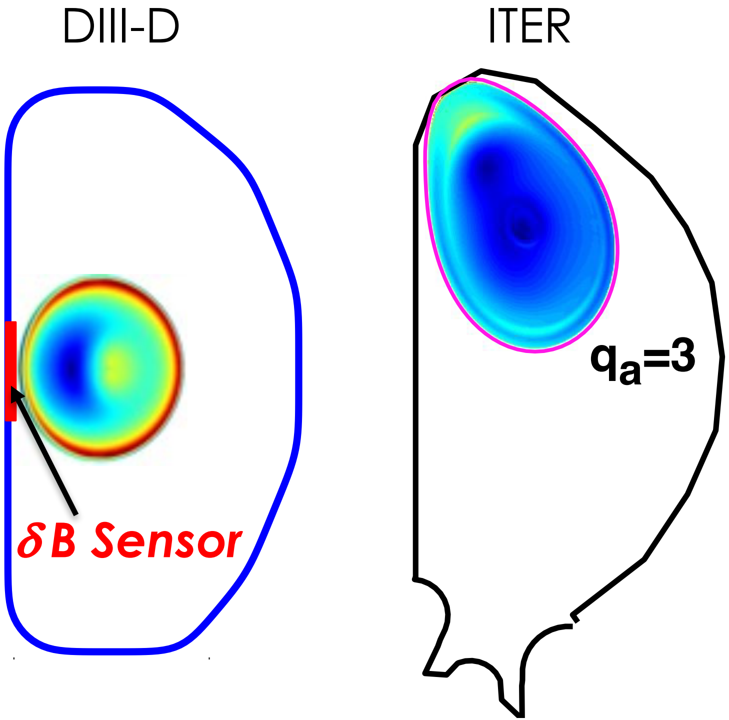
Big δB/B →



DIII-D NATIONAL FUSION FACILITY

# Simulation Approach: Scale Linear Instability Up/Down, Follow RE Orbits

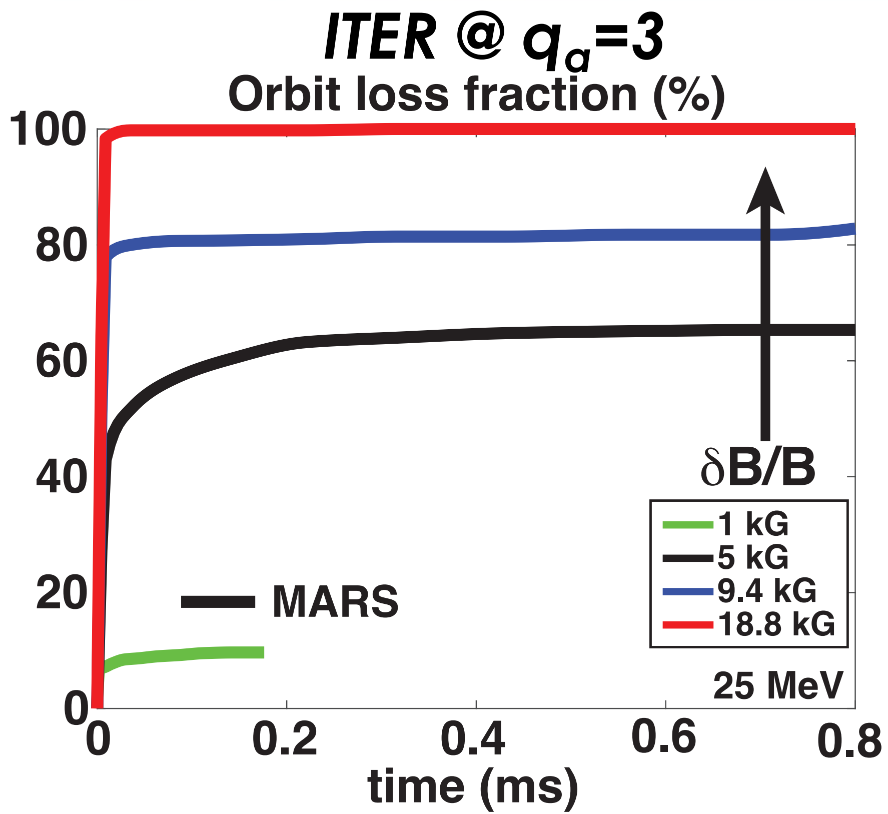
- **DIII-D magnetic sensor provides guess on magnitude of MHD possible in ITER**
  - Assume similar δB/B @ wall
  - ((Caveat: mode structure matters))
- **Linear MHD MARS-F modeling extracts mode structure based on equilibrium**
  - Scale mode structure up and down
- **Follow RE orbits: what % hit the wall?**
  - MARS-F: Guiding center model
  - KORC: Full orbit simulation
  - (small difference in initial conditions)




Y.Q. Liu et al, Nucl. Fusion 2022

# Orbit Loss Calculations Estimate Critical δB/B Required for Total RE Loss in ITER

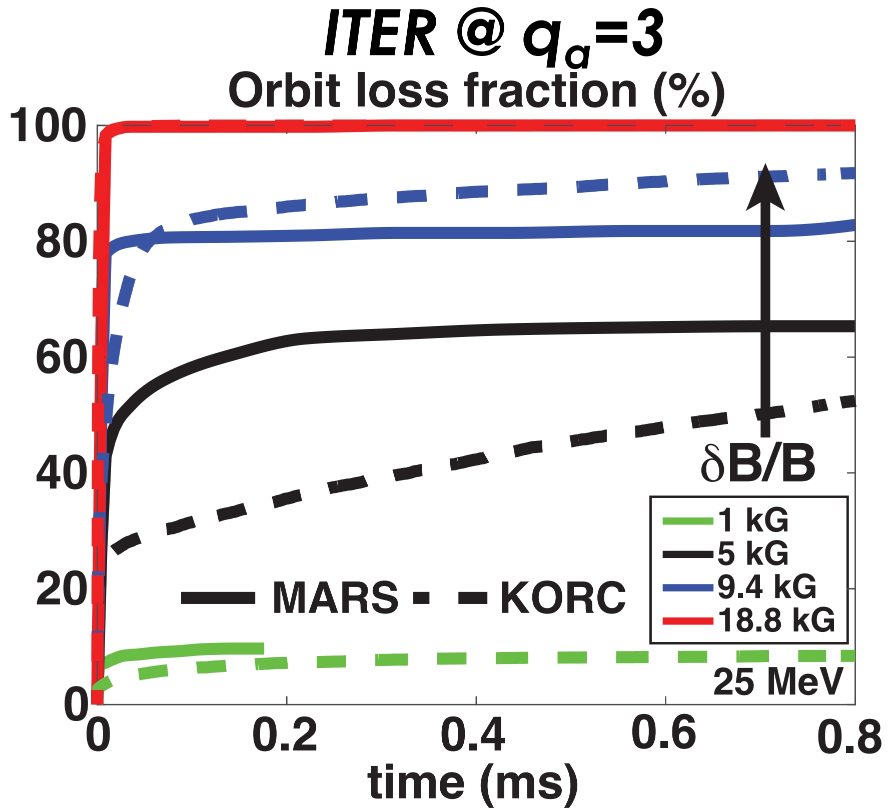
- **MARS: REs lost as δB/B increases**




Y.Q. Liu et al, Nucl. Fusion 2022

# Orbit Loss Calculations Estimate Critical δB/B Required for Total RE Loss in ITER

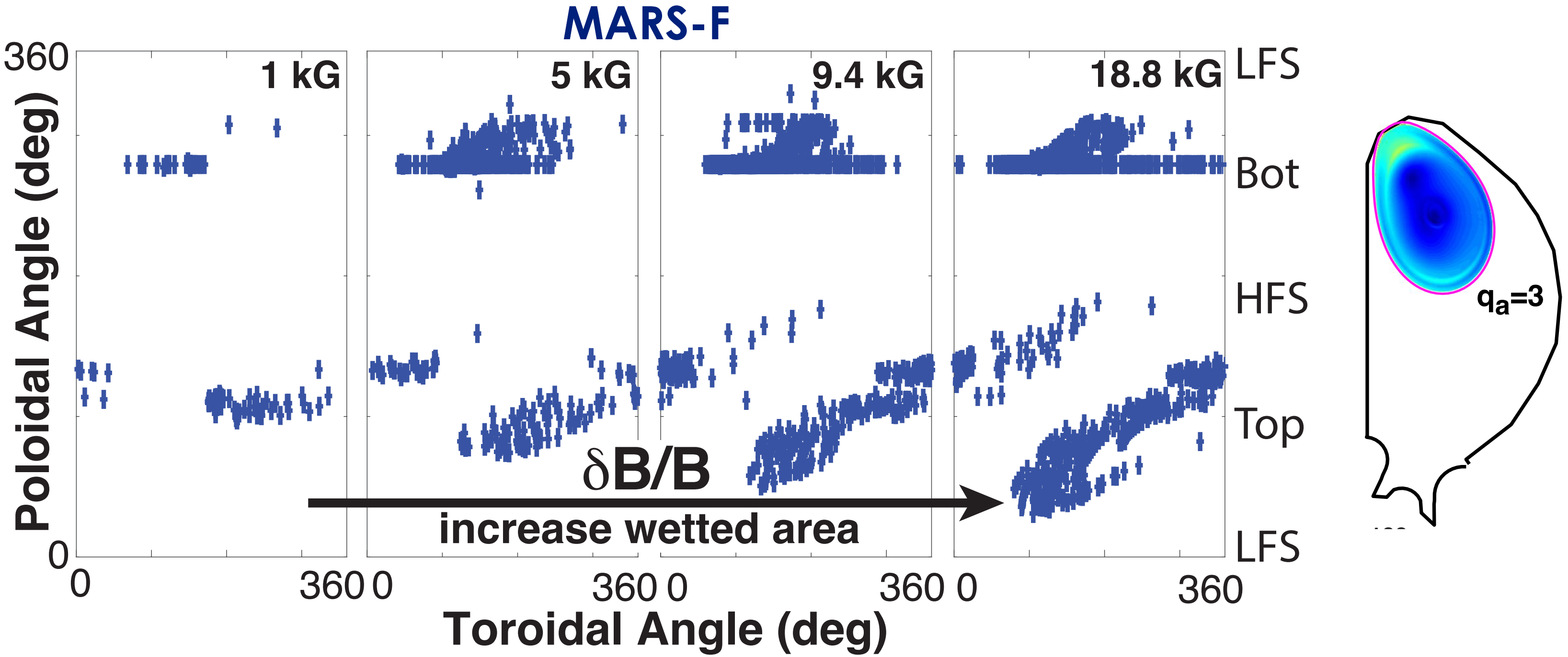
- **MARS: REs lost as δB/B increases**
- **KORC: REs lost as δB/B increases**
- **Eventually all orbits are lost**
  - @ 2x larger δB/B than DIII-D case




Y.Q. Liu et al, Nucl. Fusion 2022
+ Courtesy M. Beidler

# Large δB/B Maps to Large Wetted Area and Dispersed Energy Loading

- **With large δB/B, orbits connect to a wider fraction of ITER's first-wall area**
- **RE kinetic energy disperses to larger area → reduced peak heat flux**




*Courtesy Y.Q. Liu & M. Beidler*

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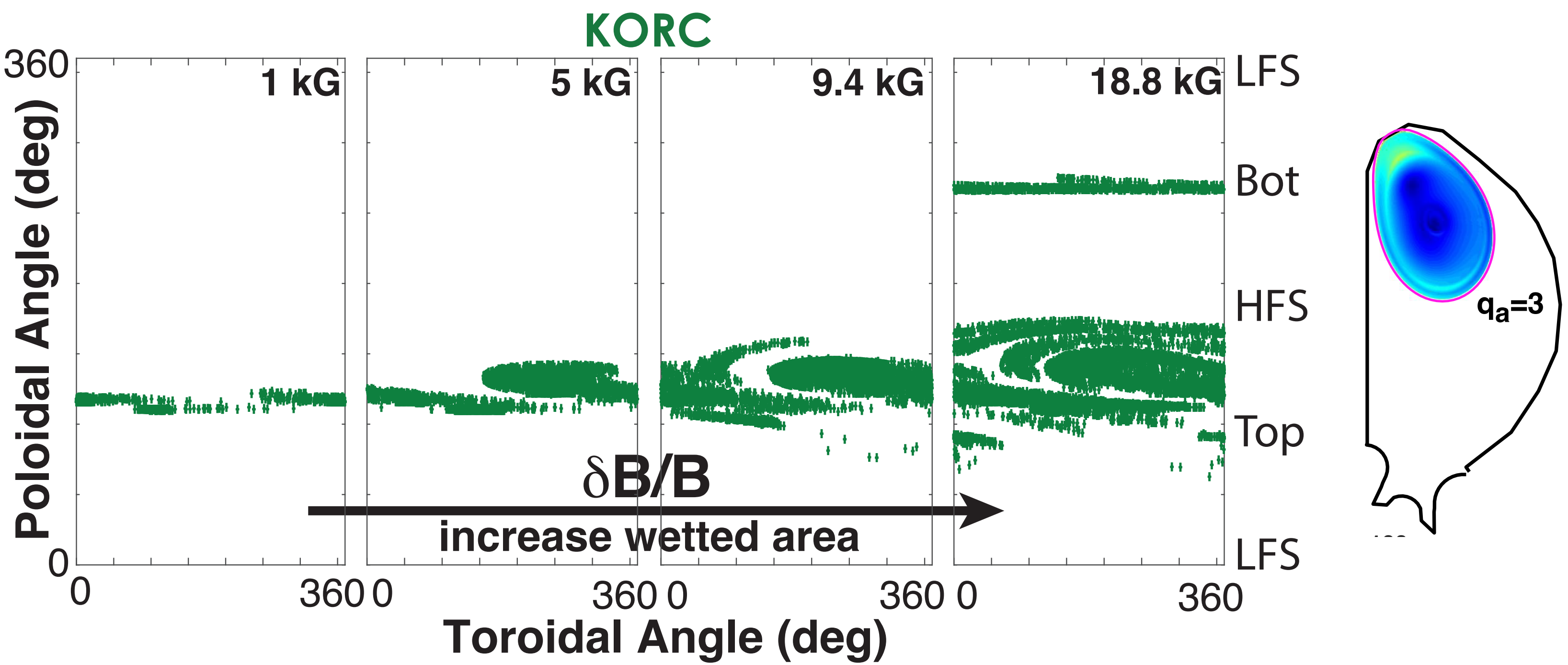


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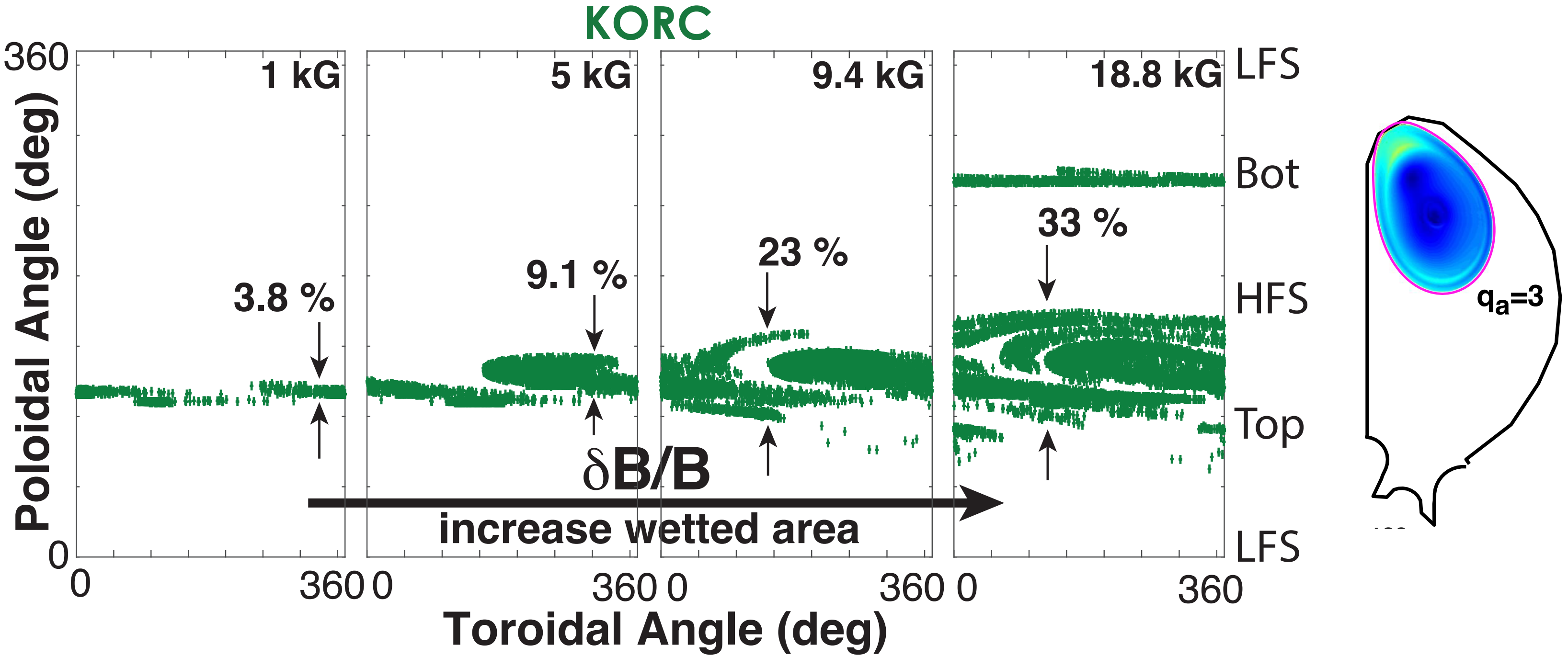
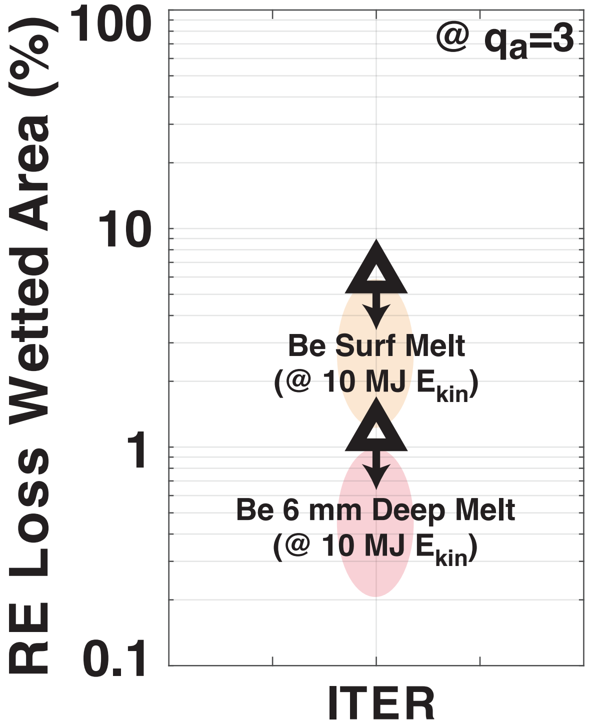



*Courtesy Y.Q. Liu & M. Beidler*

# Kinetic Energy Handling:
# Wetted Area Must be Large to Avoid FW Melting in ITER

- **Wetted area > 6% needed to avoid surface melt, >1% to avoid deep melt**
  - Based on old ITER blanket module limits[1]




[1]M. Lehnen et al, IAEA-TM Disruptions 2019

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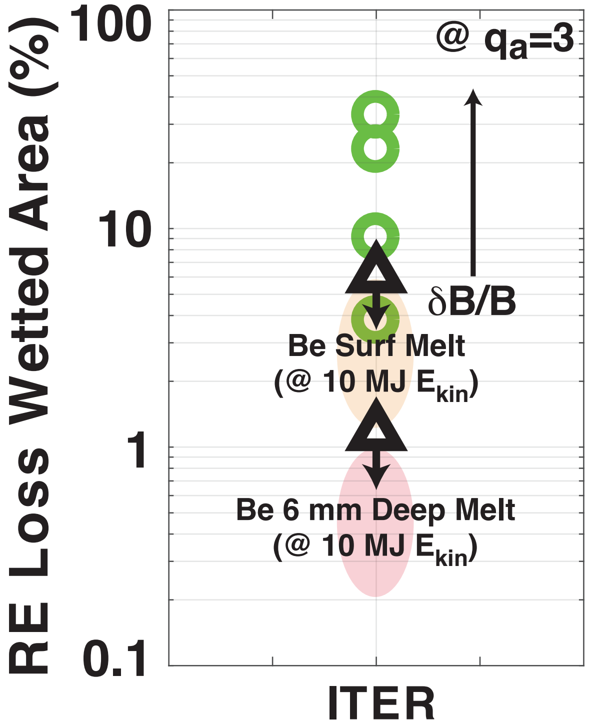
- **KORC simulations predict sufficiently large wetted areas if δB/B above 2%**

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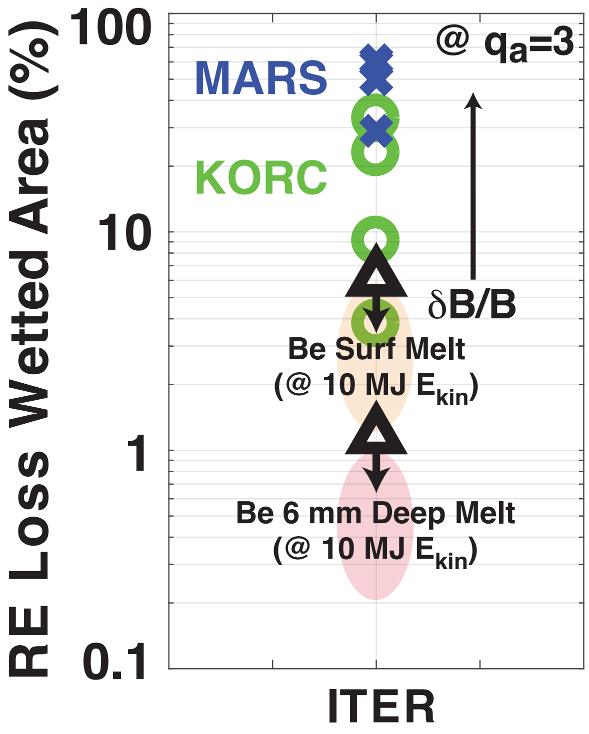
- **KORC simulations predict sufficiently large wetted areas if δB/B above 2%**

- **MARS-F simulations more favorable**

***Method relies on accessing large δB/B !***




[1]M. Lehnen et al, IAEA-TM Disruptions 2019

# Open Questions on Kinetic Energy Handling

- **Can a more quantitative prediction of ITER surface heating be generated?**
  - YES! (Assuming a given $\delta B/B$ + mode structure)
  - Work underway in ITPA MDC-DSOL-1 joint activity
  - Presentation this week by M. Beidler presents ongoing work (without $\delta B/B$ effects)

- **Can existing device IR heat maps be used to validate models?**
  - YES! AUG/DIII-D/JET all have good IR data. Models need to catch up (almost there).

- **Does the structure of the MHD mode affect the wetted area / surface heating?**
  - Hypothesis: $\delta B/B$ is the dominant effect – but sensitivity studies are needed
  - Experimental results appears robust (benign despite varying trajectories to instability)

- **What is the tolerable RE current @ final loss, assuming zero re-avalanche?**

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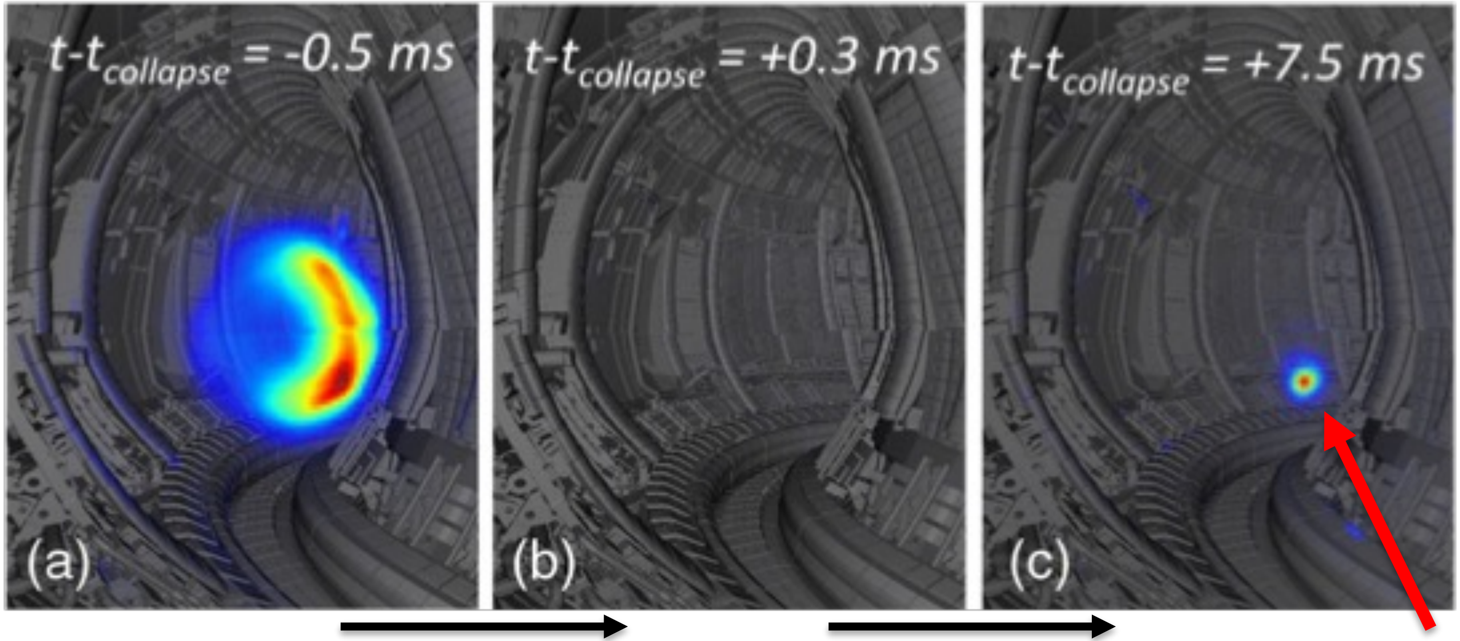
# Does Benign Termination Preclude Avalanche?
# NO: Images from JET[1] Show Consequence of Secondary Gain



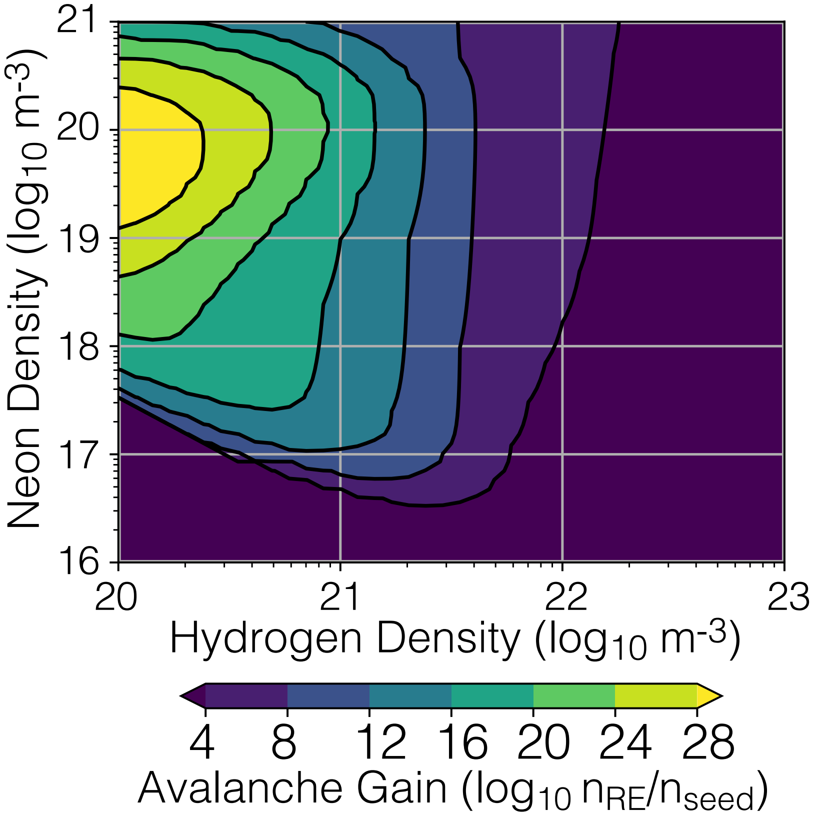

MHD-driven "Total" Loss
(analogous to TQ)

Re-avalanche of "tiny" remnant
(analogous to CQ)

Avalanched "Remnant"
(==seed*gain)

[1]C. Reux et al, PRL 2021

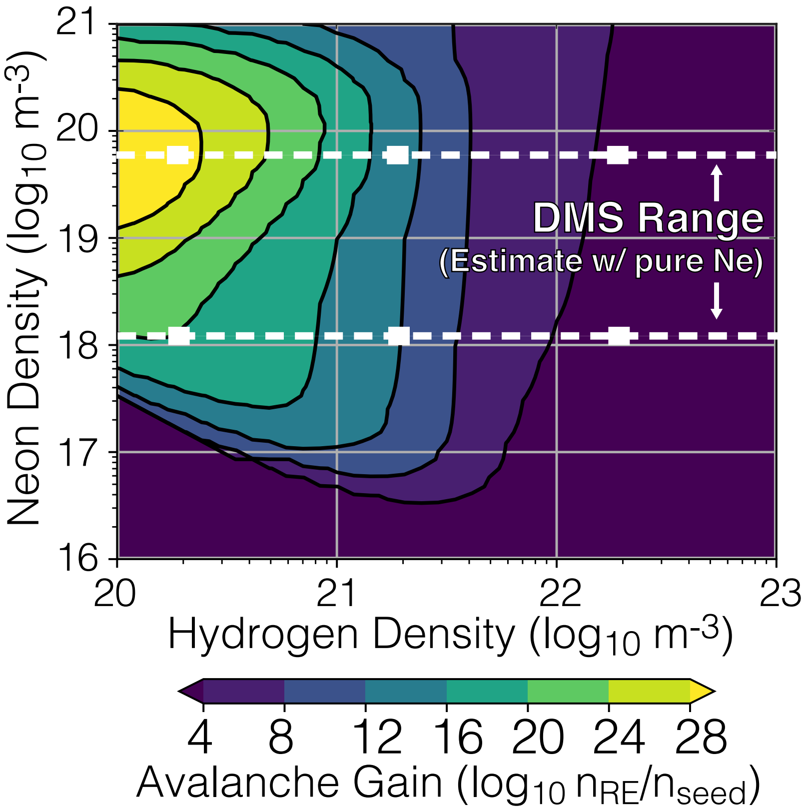
# Large Avalanche Gain Still Possible If RE Loss Incomplete Depends on RE Beam Composition during MHD Loss Event




***Courtesy P. Aleynikov***

# Large Avalanche Gain Still Possible If RE Loss Incomplete Depends on RE Beam Composition during MHD Loss Event

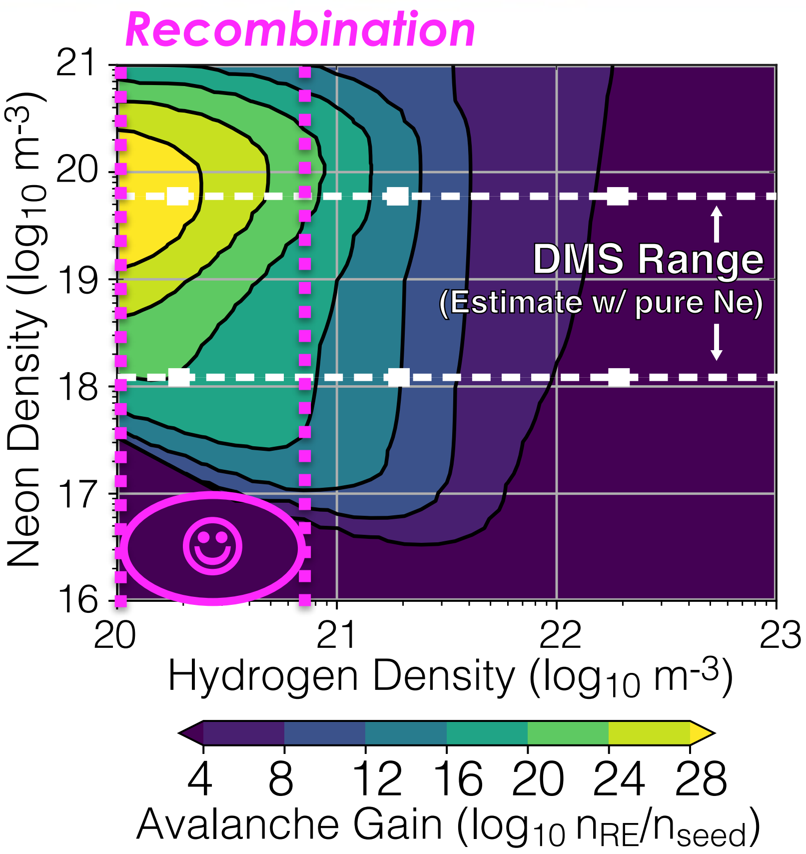
- **Thermal / EM load mitigation sets limits on pure Ne injection**
  - Ne + H mixtures require assessment




***Courtesy P. Aleynikov***

# Large Avalanche Gain Still Possible If RE Loss Incomplete Depends on RE Beam Composition during MHD Loss Event

- **Thermal / EM load mitigation sets limits on pure Ne injection**
  - Ne + H mixtures require assessment
- **Recombination thresholds indicate hydrogen density should be low**
  - *Any upper limit in H injection for recombination??*
- **Simultaneously low neon quantity minimizes avalanche gain**
  - Neon needed to radiate thermal loads

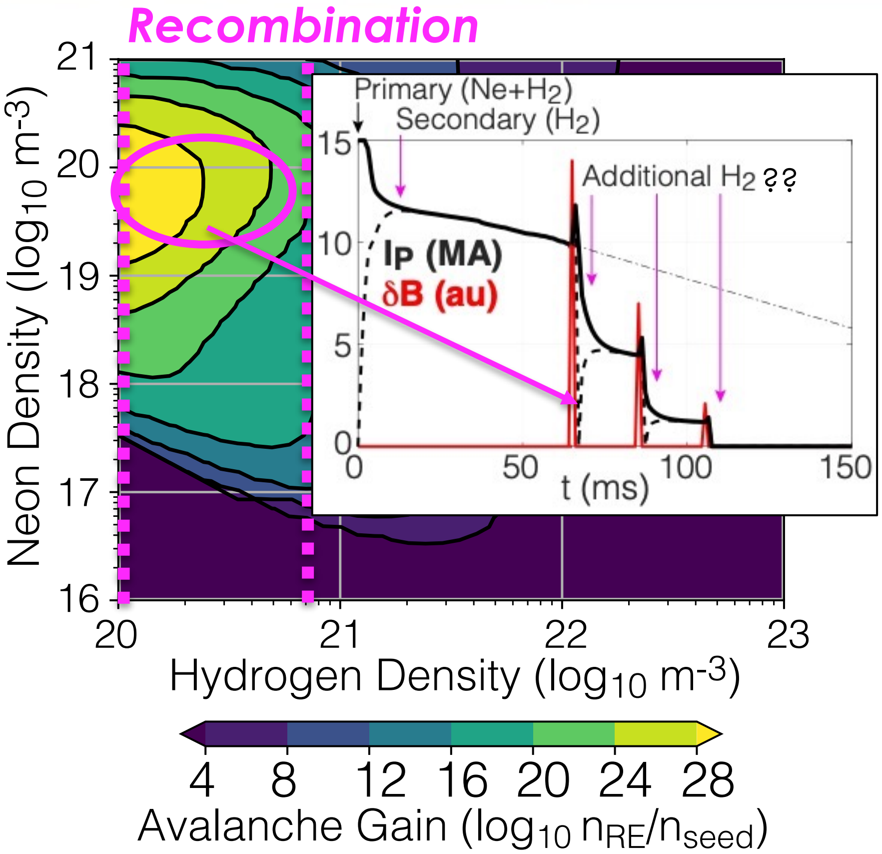



**Courtesy P. Aleynikov**

# Large Avalanche Gain Still Possible If RE Loss Incomplete Depends on RE Beam Composition during MHD Loss Event

**If High Gain Unavoidable:**

- **Aim for multiple benign loss events**
  - Would additional $H_2$ injections help restart recombination process (?)
- **Magnitude of residual beam set by:**
  - Pre-loss RE current
  - Size of remnant (== totality of loss)
  - Background Ne content in bulk
- **Difficult to explore this dynamic in existing devices (need high RE current)**




*Courtesy P. Aleynikov*

# Open Questions on Magnetic Energy Handling

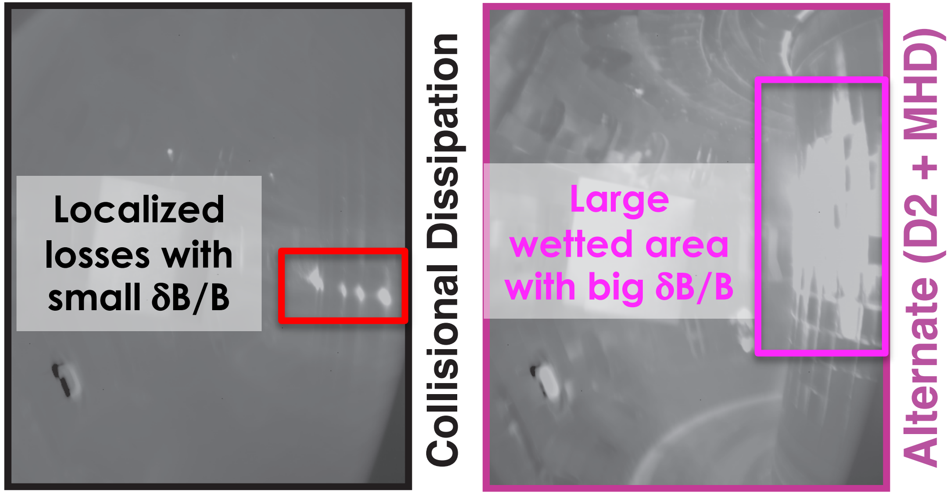
- **How much Ne is required for TQ/EM load mitigation? (assuming mixed w/ $H_2$)**
  - Input boundary condition to whatever the secondary injection must achieve
  - Area of active research (other talks this conference)

- **How can we use existing devices to better simulate re-avalanching physics?**
  - Use $D_2$+high-Z mixtures to match gain expected in some ITER situations? Focus for JET?
  - (Avalanche gain will be *far* better than the original disruption)

# Concluding Remarks: Big Picture

- **A new approach to RE mitigation is showing significant progress**
  - Accessed on DIII-D, JET, AUG, TCV with broad agreement on "the basics"

- **Work remains to improve confidence, but the tools exist and results are coming steadily from both experiment and theory**



# Concluding Remarks

- **Access Condition #1: Recombination**
  - ITER appears able to access recombination
  - Additional validation of modeling needed, especially w.r.t. different species
- **Access Condition #2: Macroscopic Stability Limit**
  - For low $q_a$ modes, access is predictable and robust (=hot VDE, dropping q)
  - Prediction of $\delta B/B$ plays an essential role, but is a challenge
- **Consequences #1: Kinetic Energy Handling**
  - Larger wetted areas reproduced by linear modeling
  - Detailed comparison to existing devices a low hanging fruit for this topic
- **Consequences #2: Magnetic Energy Handling**
  - Most serious concern, but depends on primary injection parameters

**Qualify Approach in ITER Pre-FPO @ ½ Field**

# Bonus Slides

# Disclaimer

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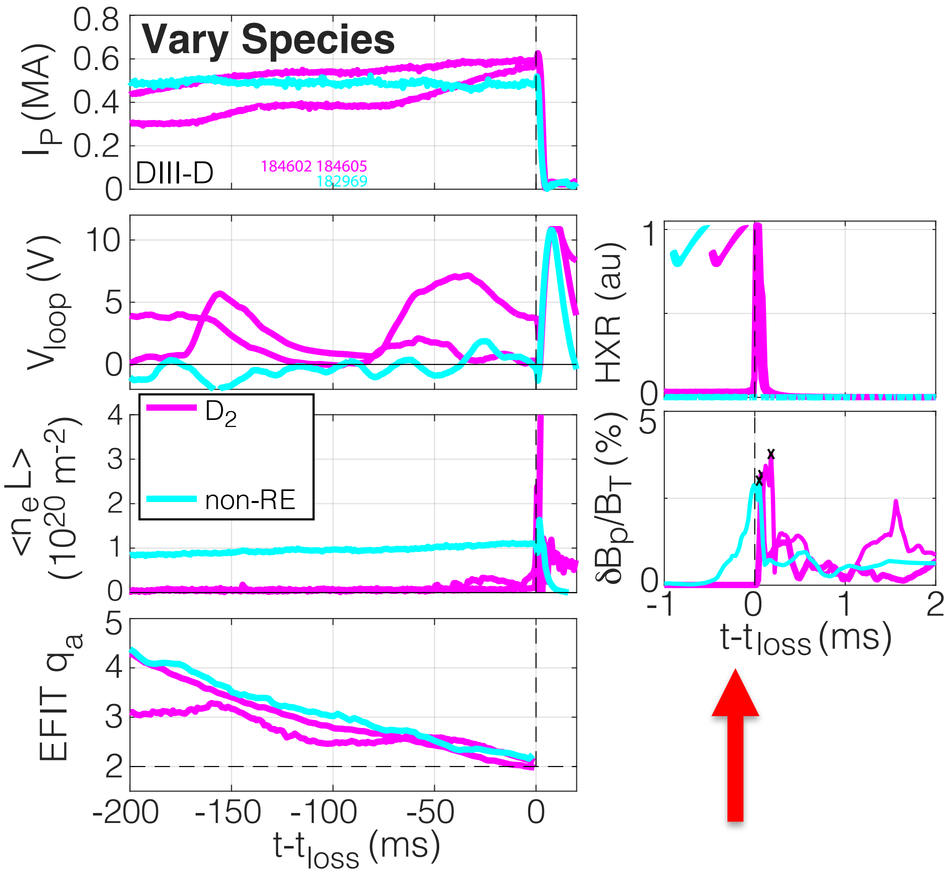
# Non-RE References Shed Light on Uniqueness of Benign Termination

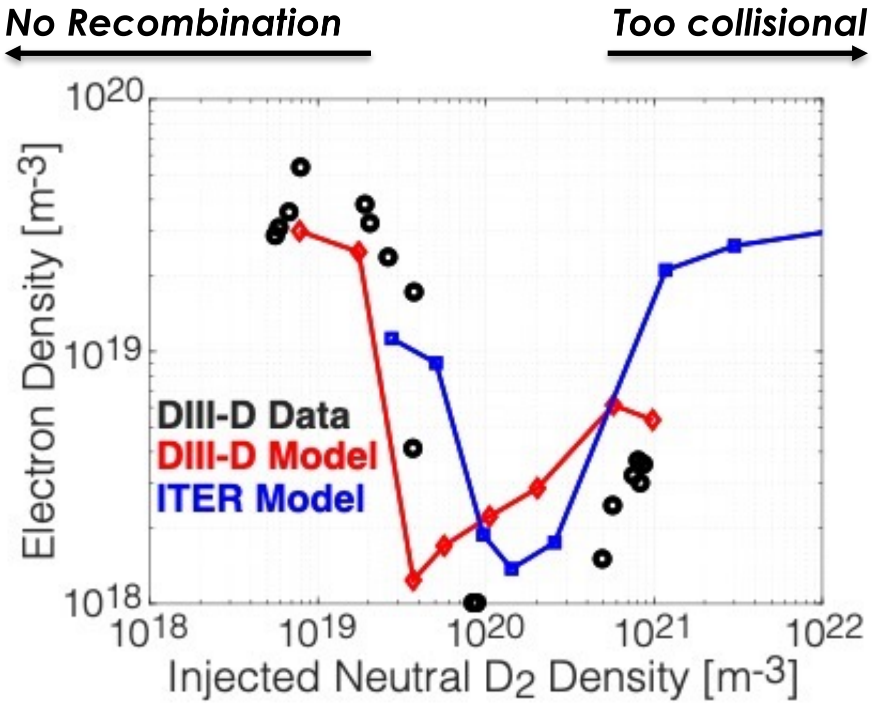
- **Non-RE reference (regular plasma) prepared with same equilibrium trajectory**
- **Comparable δB/B at IP spike**
- **Much slower MHD growth rate**
  - Due to much slower Alfven time?






C Paz-Soldan/IAEA-TM/2022-07

# 1-D Diffusion and Power Balance Model[1] Predicts Optimum $D_2$ Quantity for Recombination in DIII-D & ITER




[1]*Hollmann et al, PoP 2020*

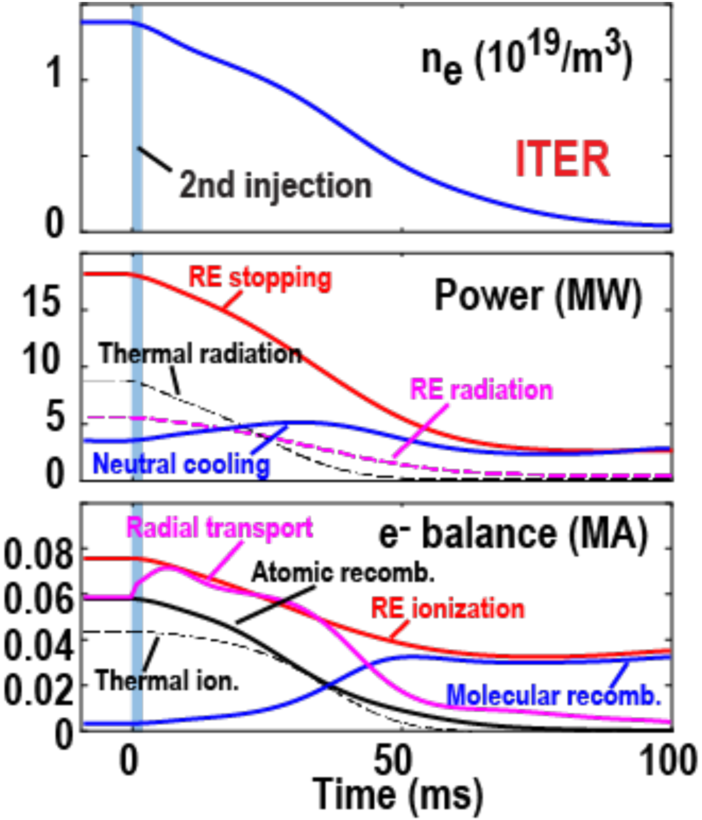
# 1D model highlights important processes for RE plateau recombination in ITER

- **Power input into bulk plasma: always comes from RE stopping power**

- **Power out of bulk plasma: shifts toward neutral conduction after 2nd injection (thermal line radiation before)**

- **Ionization: always dominated by RE impact**

- **Recombination: mixture of radial transport and atomic initially, shifts toward molecular recombination after 2nd injection**




[1] *E. Hollmann et al, NF 2022 (in review)*