A Novel Path to Runaway Electron Mitigation via Deuterium Injection and Current-Driven Kink Instability

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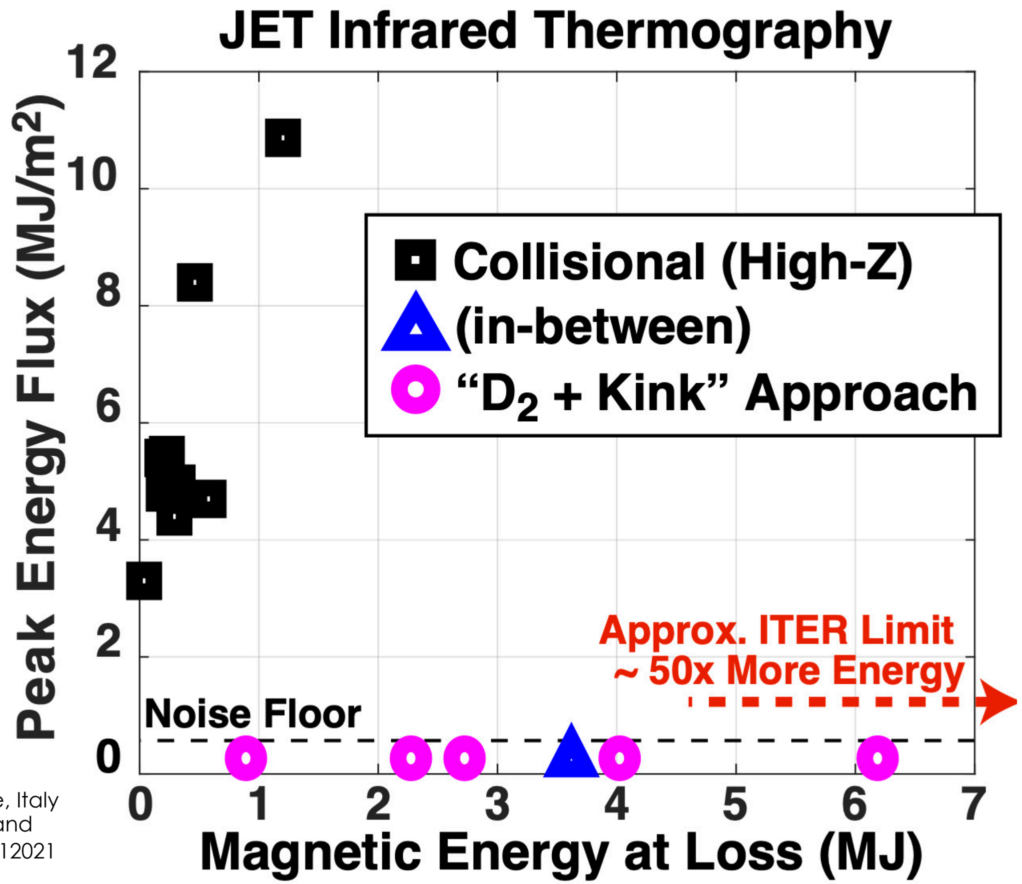

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COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

New Approach to RE Mitigation has Demonstrated Safe Termination of High Energy Mature RE Beams

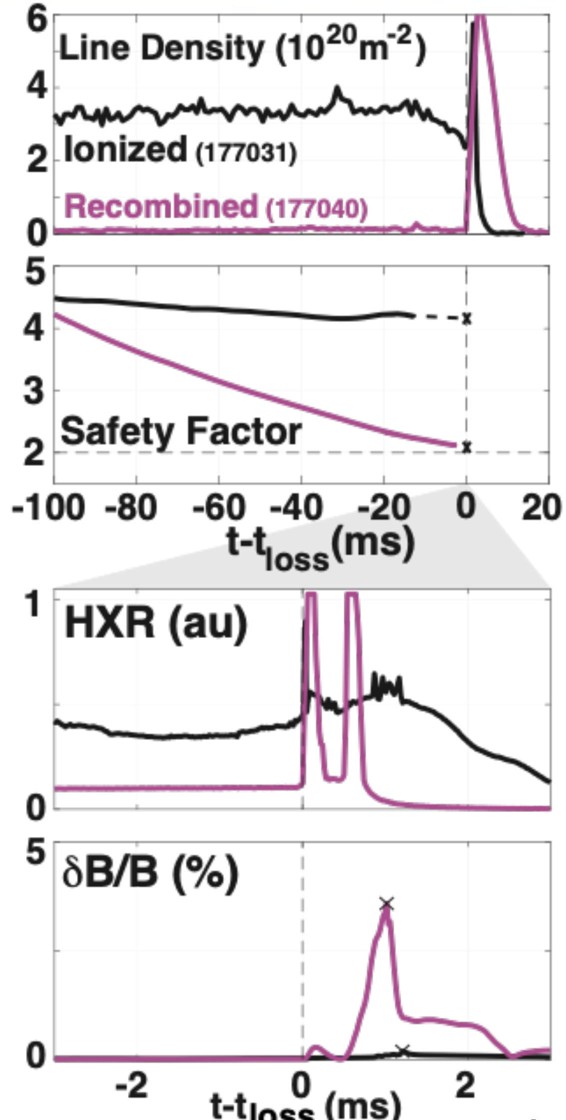
<u>Conventional Approach:</u>

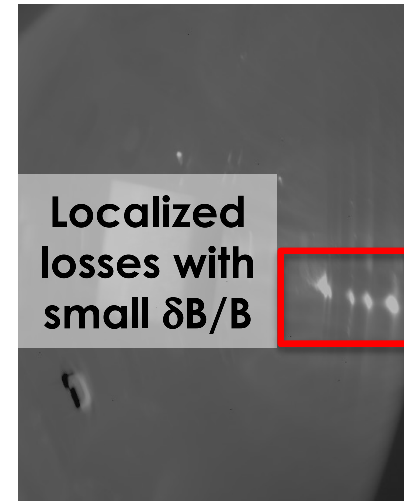
- **Inject High-Z (Ar/Ne)**
- **Collisionally dissipate REs**

<u>New Approach:</u>[1,2]

- **Inject D_2 → collisionless**
  - via high-Z expulsion and bulk recombination[3]
- **Access bigger & faster MHD kink instabilities**
- **~100% REs instantaneously dumped to the first wall**

Only New Approach Avoids First Wall Heating





Conventional: q ~ 4

D2 + Kink: q ~ 2

[1]C. Reux et al, Phys. Rev. Lett 2021
[2]C. Paz-Soldan et al, Plas. Phys. Contrl. Fus 2019
[3]E. Hollmann et al, Phys. Plasma 2020

A Novel Path to Runaway Electron Mitigation
-- Outline --

- **Phenomenology of the Benign Termination**
- **MHD Modeling of the Benign Termination**
- **Experimental Conditions to Access the Benign Termination**
- **Extrapolating the Scenario to ITER**

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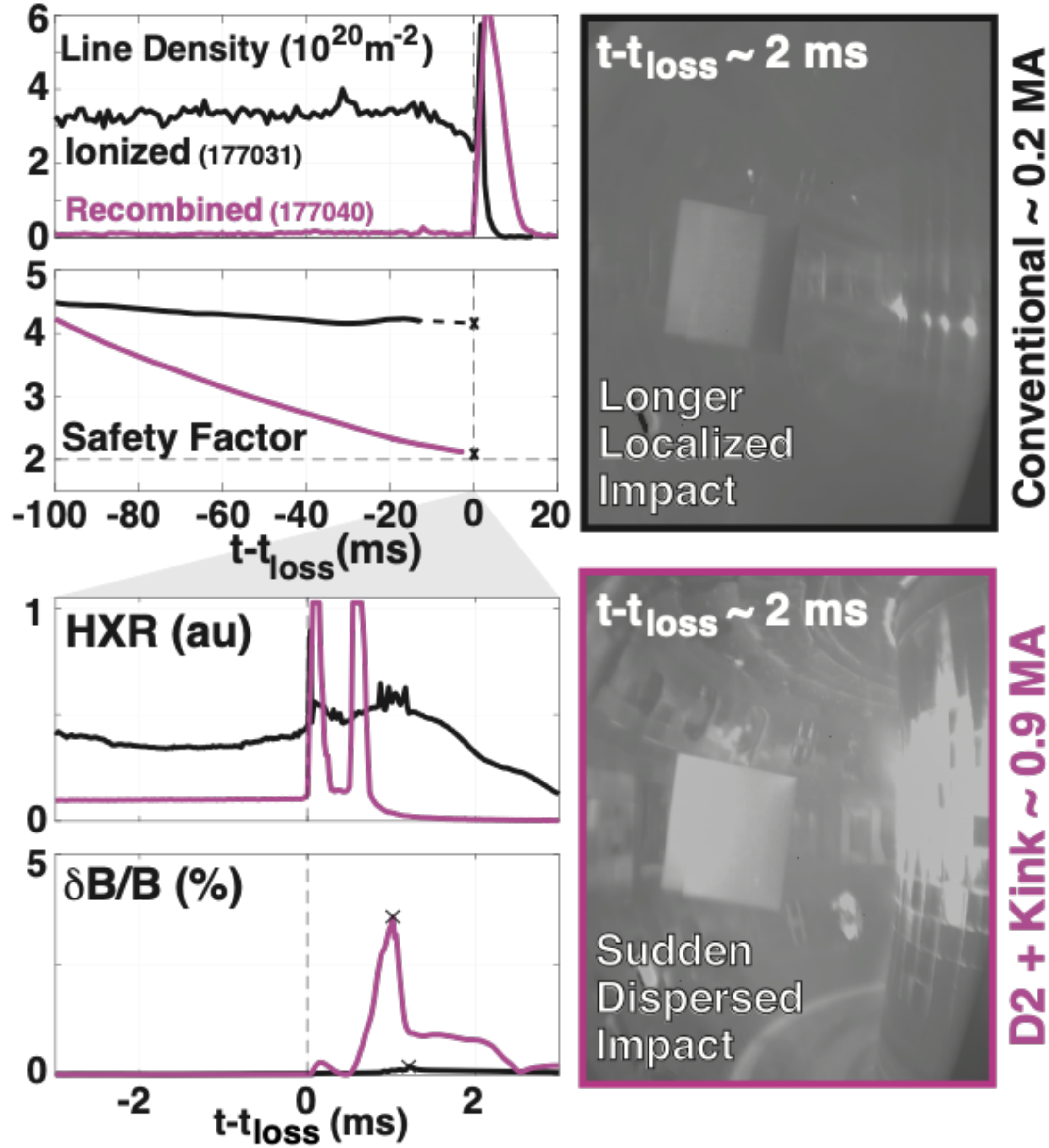
Contrasting Conventional and New Approaches Highlights Key Differences

Conventional Approach:

- Collisional dissipation reduces RE current
- Loss occurs in more MHD stable situation (less δB)
- Localized & repetitive impacts (*persistent HXR*)

"D2 + Kink" Approach:

- Recombined plasma facilitates low q_a access
- Access bigger & faster MHD kink instabilities
- Singular dispersed loss event for all REs



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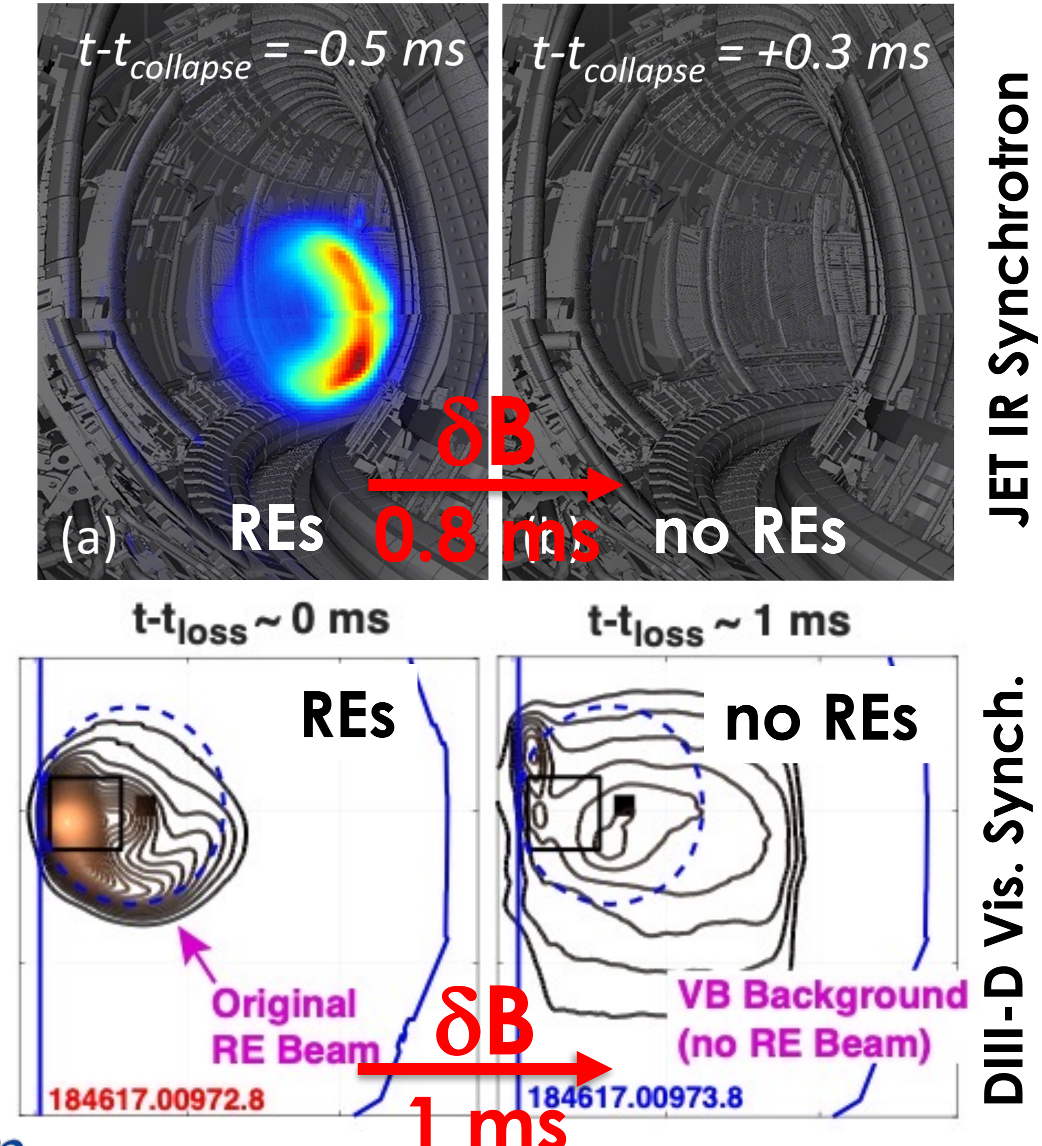
Synchrotron Emission Confirms Full RE Termination on Sub-Millisecond Timescales

- **After D_2 injection: REs can persist very long time**
  - Up to 5 seconds in DIII-D
- **After crossing MHD instability boundary REs vanish in < 1 ms**



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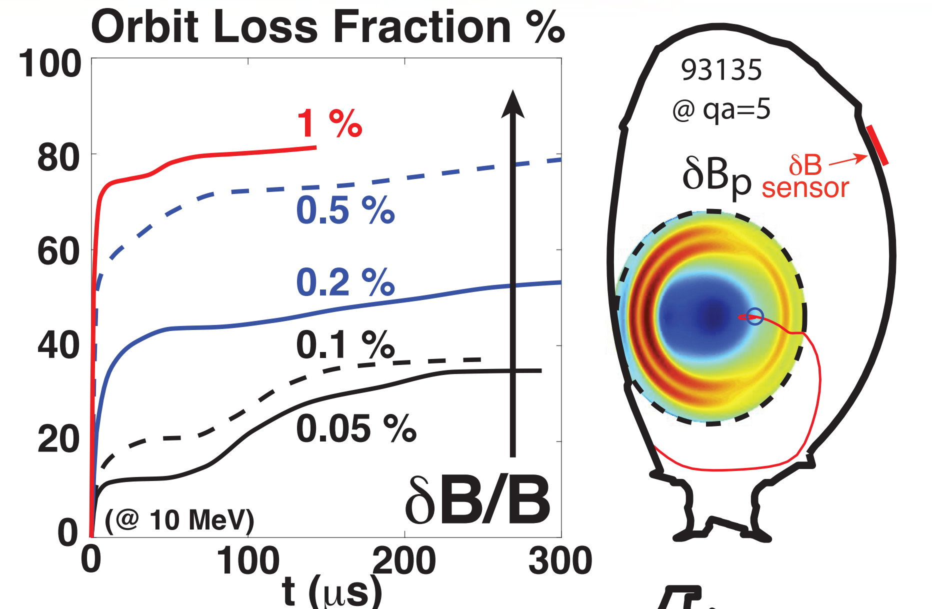
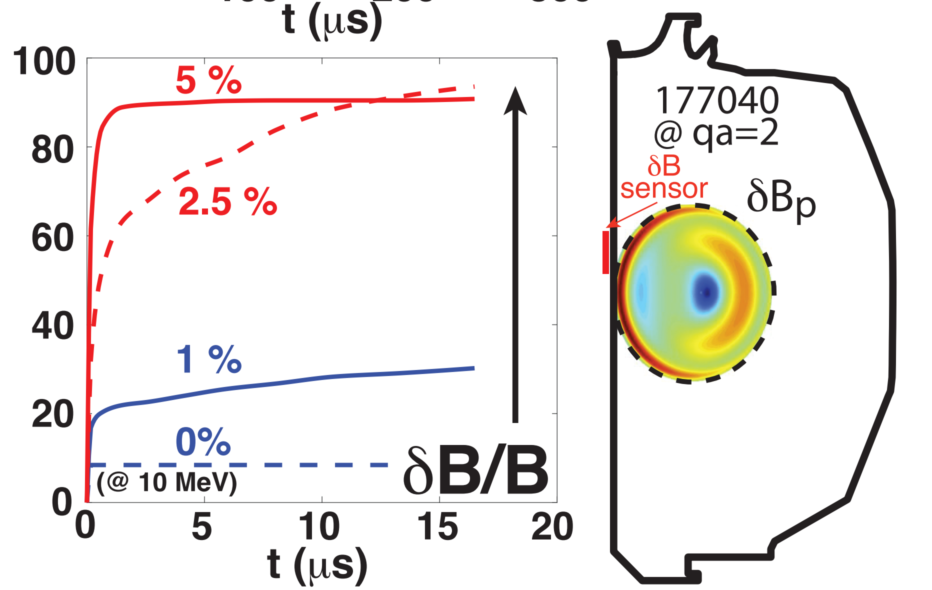
MHD Model + Orbit Following[1] w/ Observed δB/B Levels Confirms Nearly all RE Orbits are Lost to the First Wall

- **RE orbits followed in linear MHD eigenmode structure scaled to experimental δB/B**

- **δB/B at experimentally relevant values (~ 5%) causes most orbits to be lost to the first wall**





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

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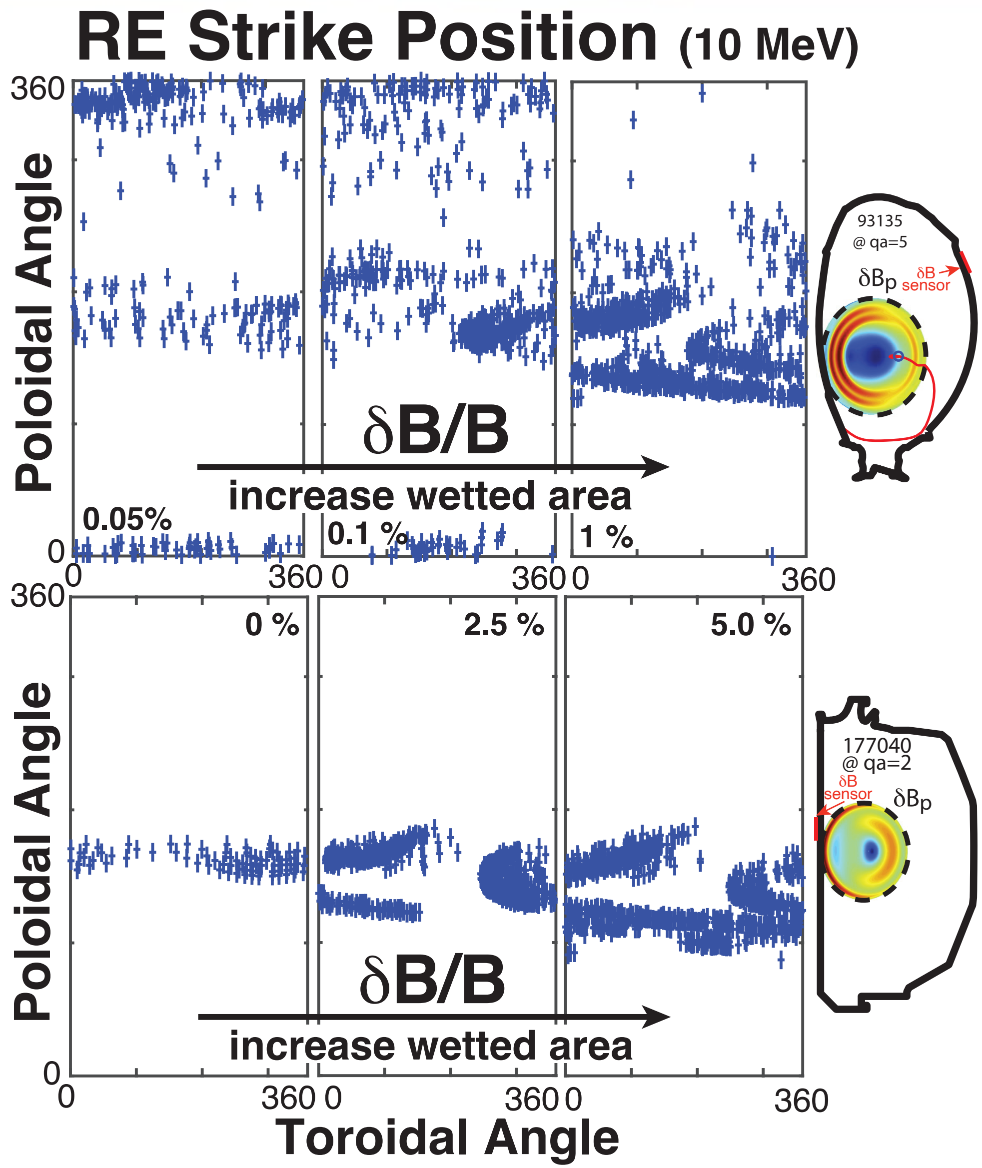
- **RE orbits followed in linear MHD eigenmode structure scaled to experimental δB/B**
- **δB/B at experimentally relevant values (~ 5%) causes most orbits to be lost to the first wall**
- **RE kinetic energy disperses into a large surface area**
  - Reduced peak heat flux

Improved Scenario for Kinetic Energy Handling



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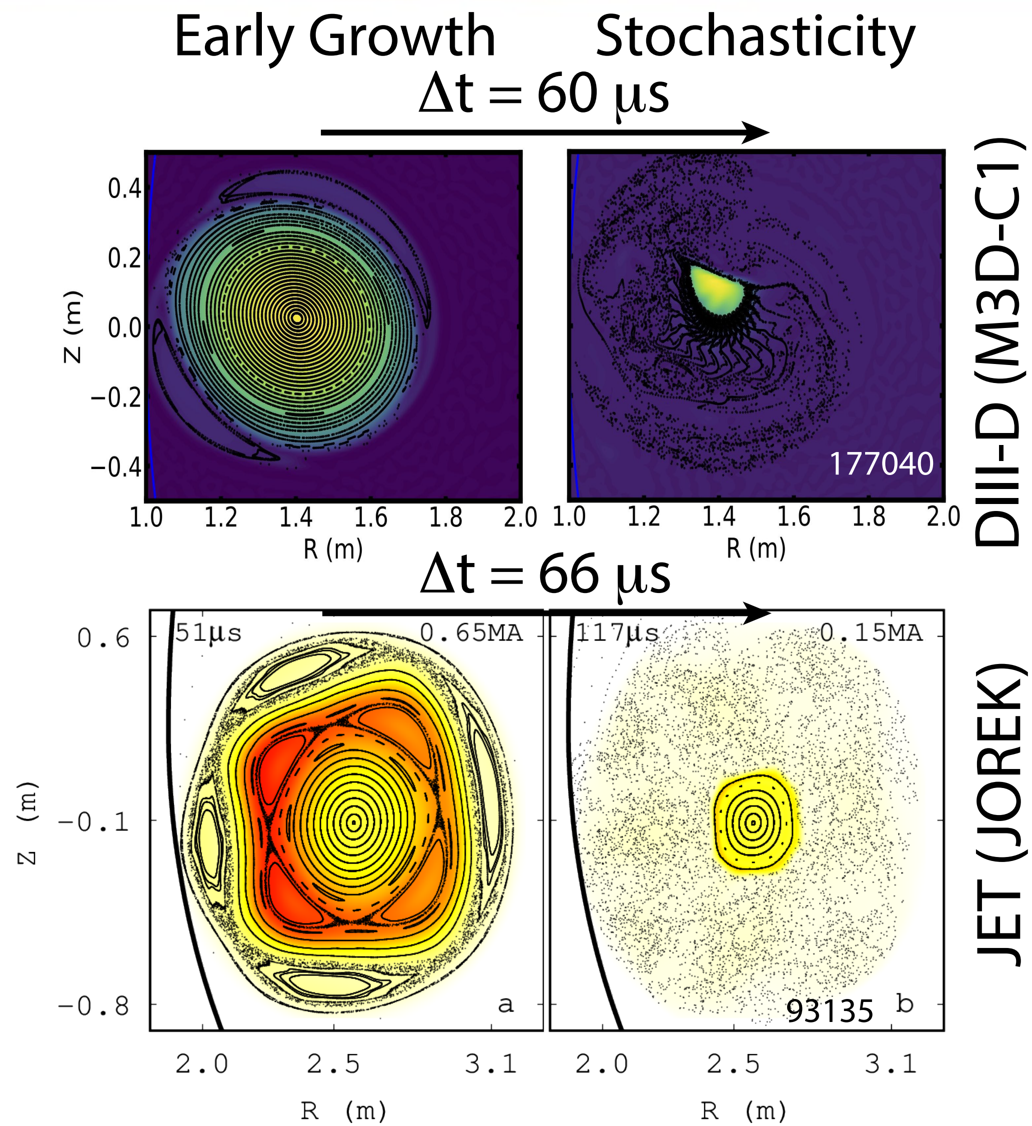
Extended MHD Modeling Reproduces RE → Ohmic Current Transfer in DIII-D and JET

- **M3D-C1 and JOREK with RE fluid model deployed**
- **Near-total stochasticity found in both simulations**



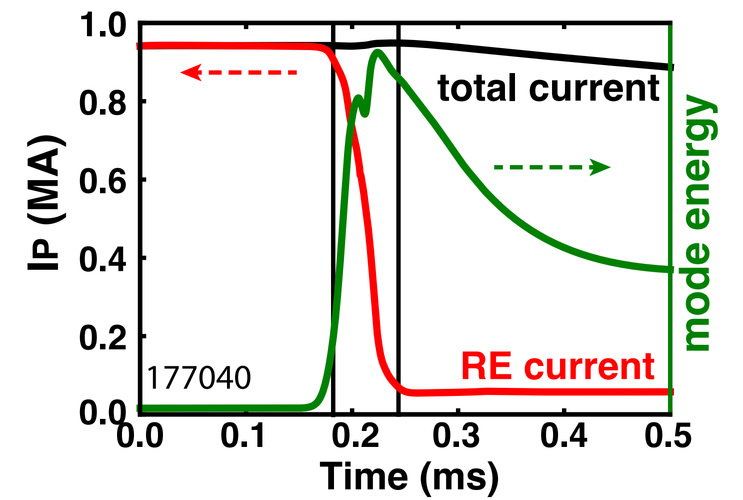
C. Liu et al, Phys. Plasmas (in preparation, 2021)
V. Bandaru et al, Plas. Phys. Contrl. Fus. 2021

Extended MHD Modeling Reproduces RE → Ohmic Current Transfer in DIII-D and JET

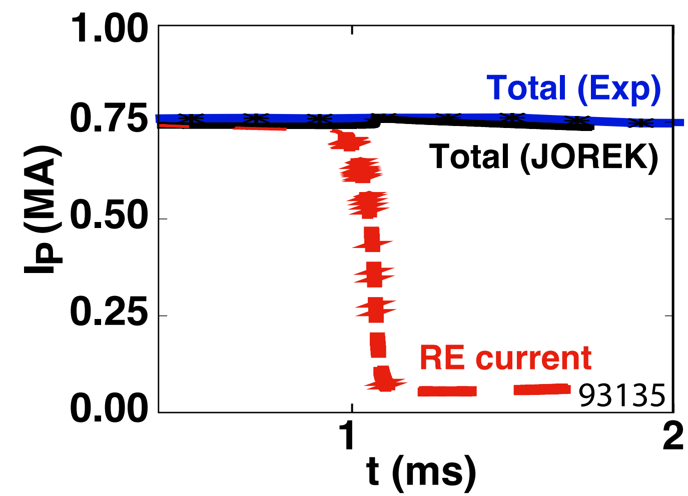
- **M3D-C1 and JOREK with RE fluid model deployed**
- **Near-total stochasticity found in both simulations**
- **Prompt loss of REs drives current transfer to the bulk**
- **Dissipation of magnetic energy into line radiation**
  - … Not back into RE energy

Ideal Scenario for Magnetic Energy Handling

Early Growth Stochasticity



DIII-D (M3D-C1)



JET (JOREK)

C. Liu et al, Phys. Plasmas (in preparation, 2021)
V. Bandaru et al, Plas. Phys. Contrl. Fus. 2021

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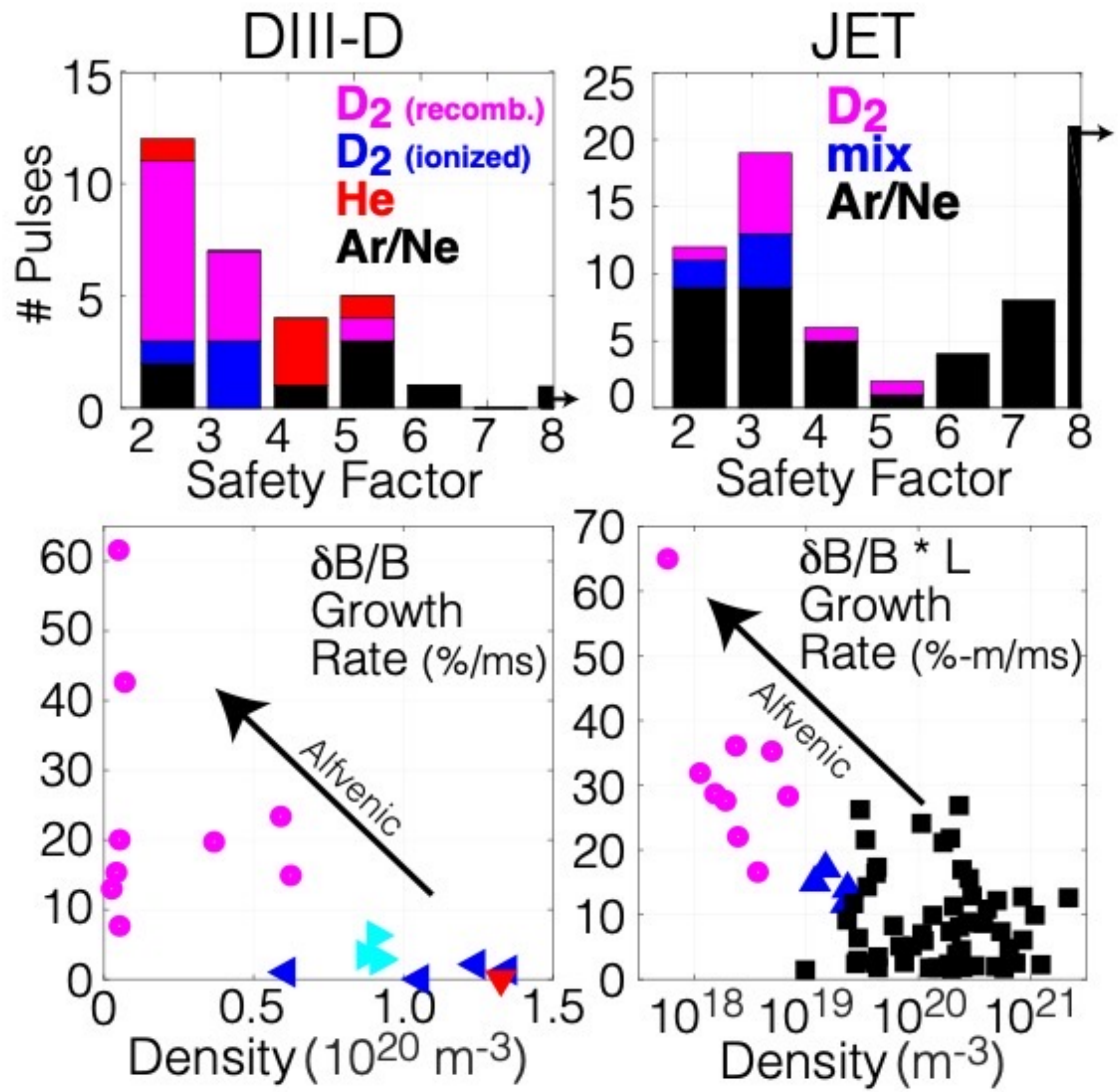
D_2 Injection: 1) Facilitates Low Safety Factor Access 2) Accelerates Ideal MHD Growth Rate

- **D_2 cases tend to evolve to lower safety factor (more unstable)**
  - … not guaranteed
  - … nor essential

- **Key D_2 affect: bulk recombination**
  - Decreases density
  - Shortens Alfven time
  - ***Accelerates MHD growth rates***



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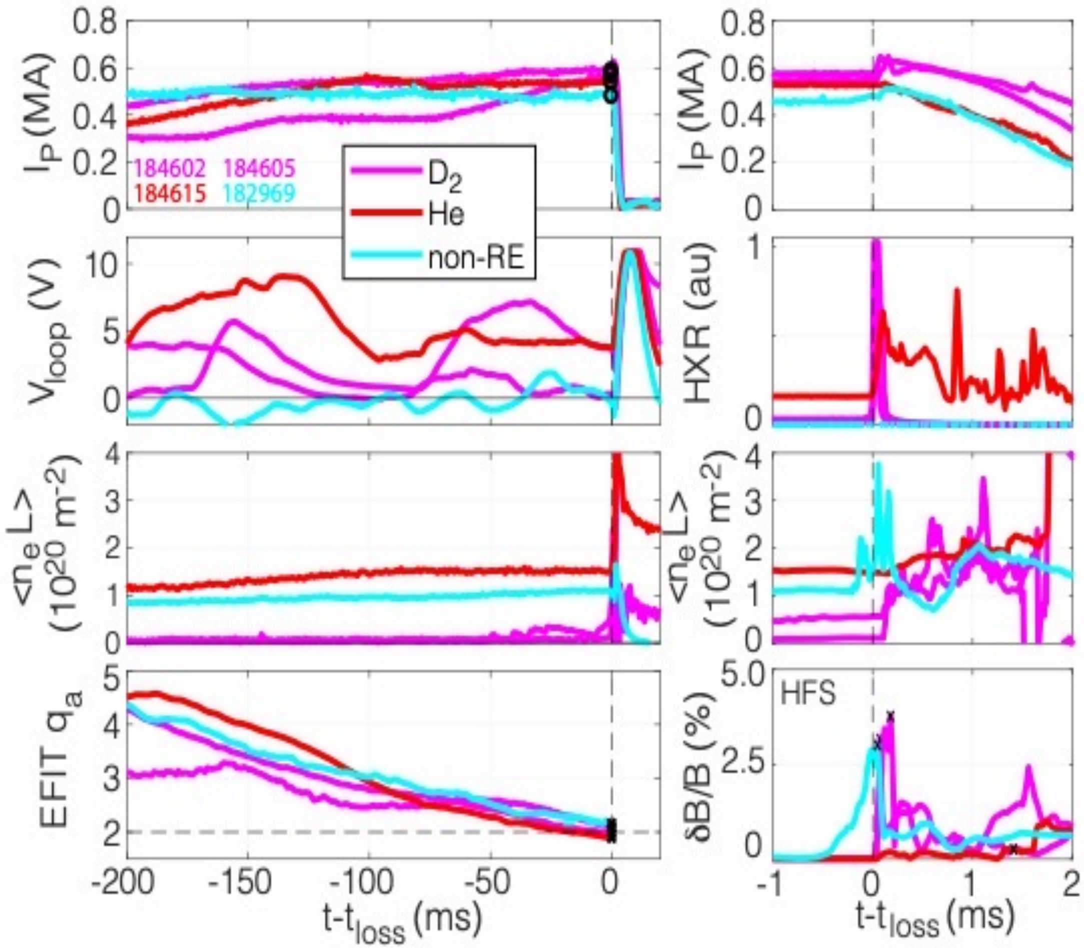
Controlled experiment of Z-effect at matched qa / IP … Recombined (via D_2) beam unique in terms of dB/dt

Z-effect @ same IP/qa:

- **Recombined RE beam (D_2)**: large δB/B and dB/dt @ stability boundary
- **Helium RE beam**: does not exhibit large δB/B and has conventional final loss
- **Non-RE plasma ref**: still had large δB/B but a much slower dB/dt

DIII-D

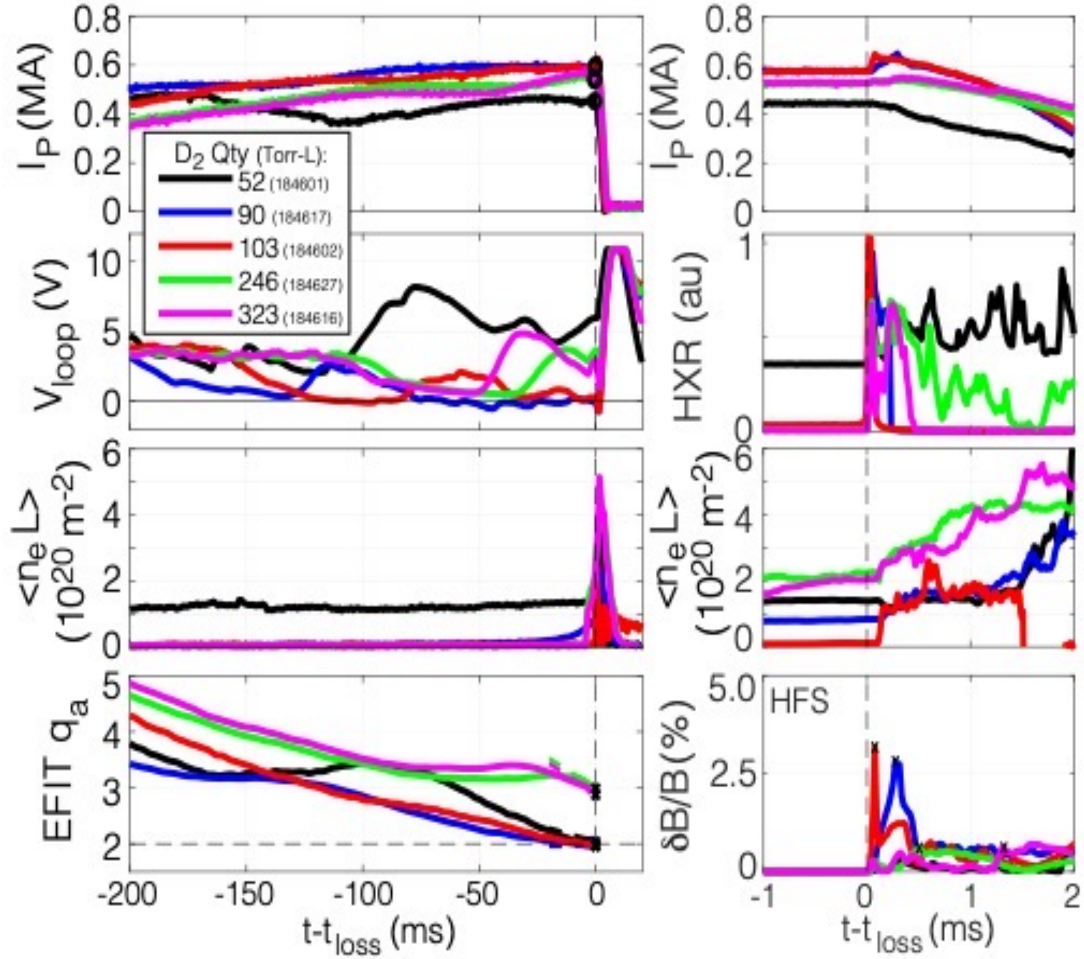


D2 Quantity Scan Reveals Optimum Quantity for Big δB/B

<u>Limits of D2 Quantity:</u>

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

DIII-D

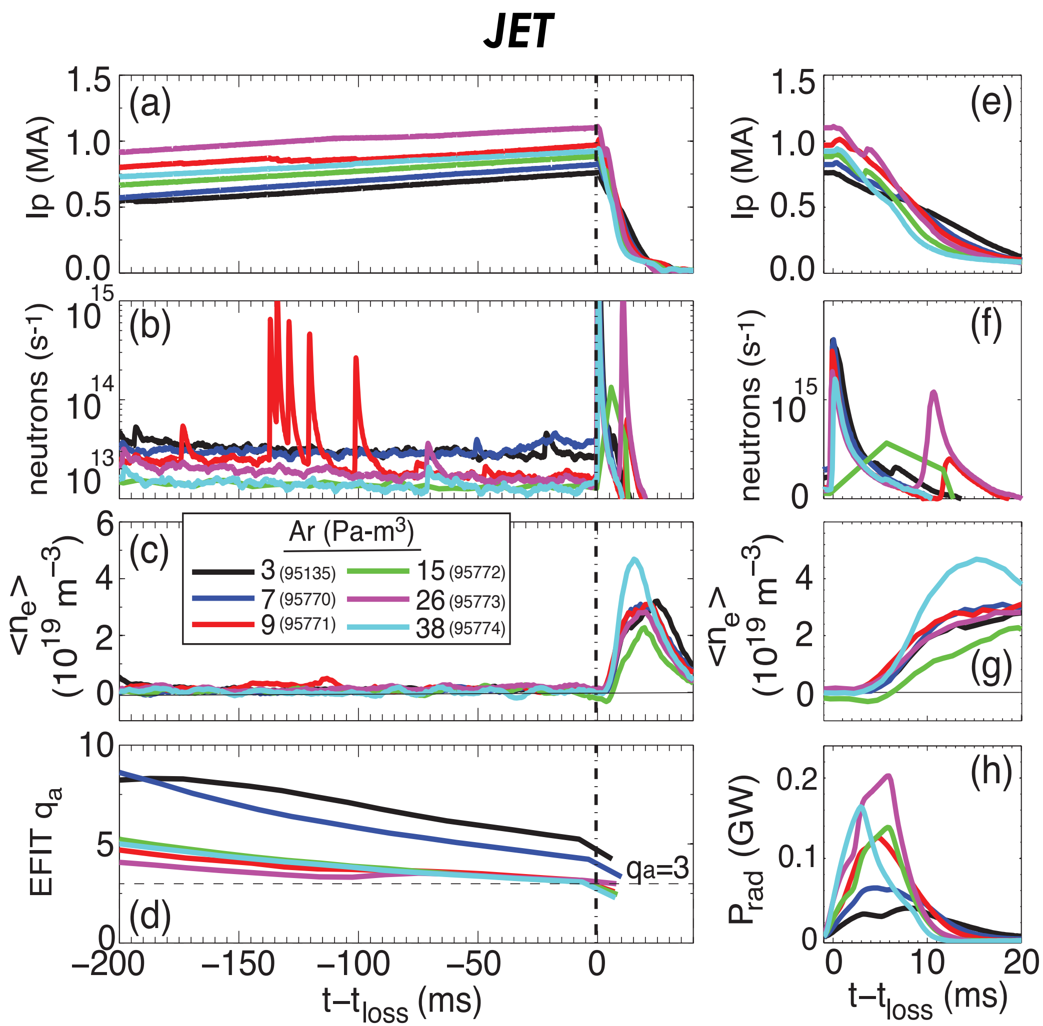


Higher Ar Quantity Facilitates RE Beam Re-Avalanching

Increasing Ar Quantity:

(via primary injection)

- **Is compatible with the recombined state and still allows large scale δB/B**
- **Increases radiation during the current quench (CQ) and thus accelerates it**
- **Fast CQ increases loop voltage that increases avalanche gain**
  - Via collisions w/ bound e⁻
- **Remnant RE beams can re-emerge at max Ar quantity**



Deuterium Injection Facilitates access to Low Safety Factor during Vertical Displacement Event

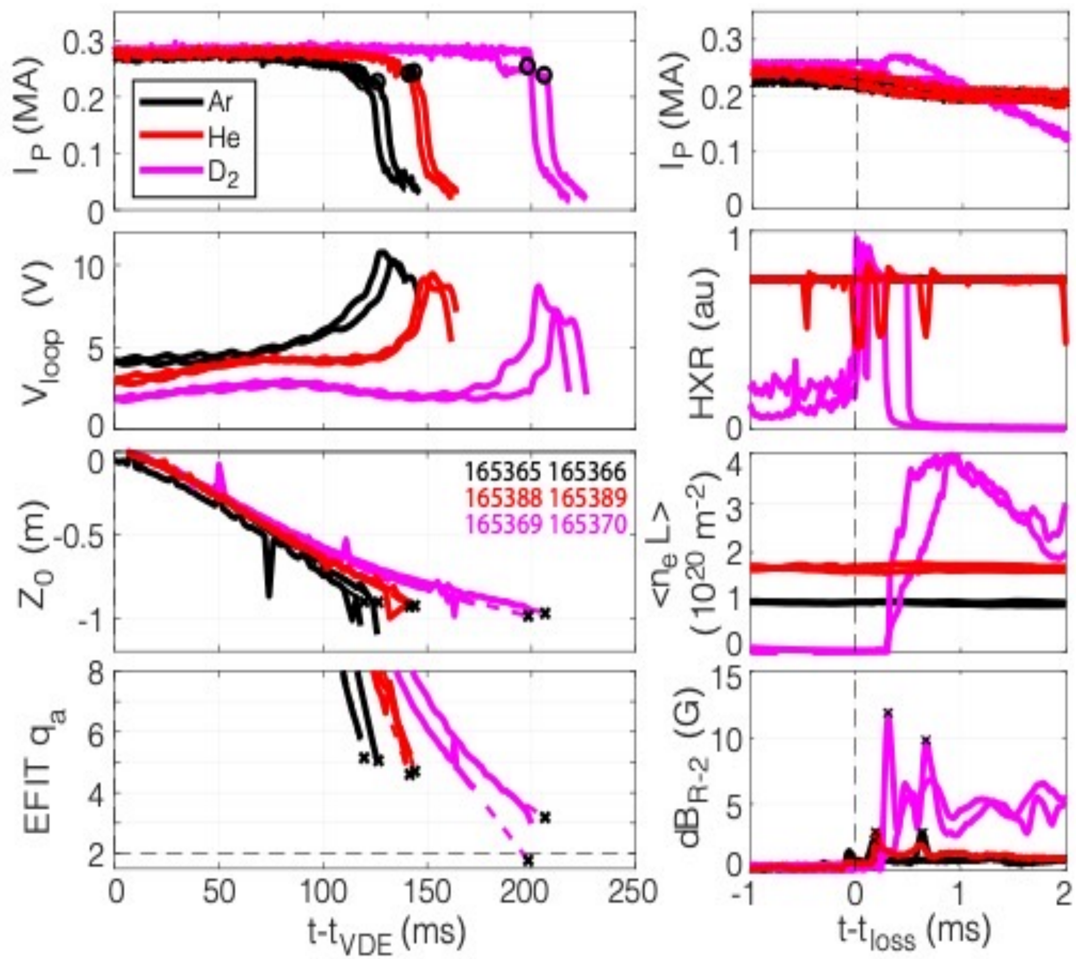
DIII-D

<u>High-Z (Ar / He)</u>

- **Final loss instabilities begin at higher safety factor**

<u>D2 Injection:</u>

- **Current channel contracts without driving final loss**
- **Accesses low safety factor big δB/B phenomenology**
  - After the stability boundary is crossed



Crossing Kink Stability Boundary via Different Paths: IP-Dot appears un-important, BT-dot facilitates instability

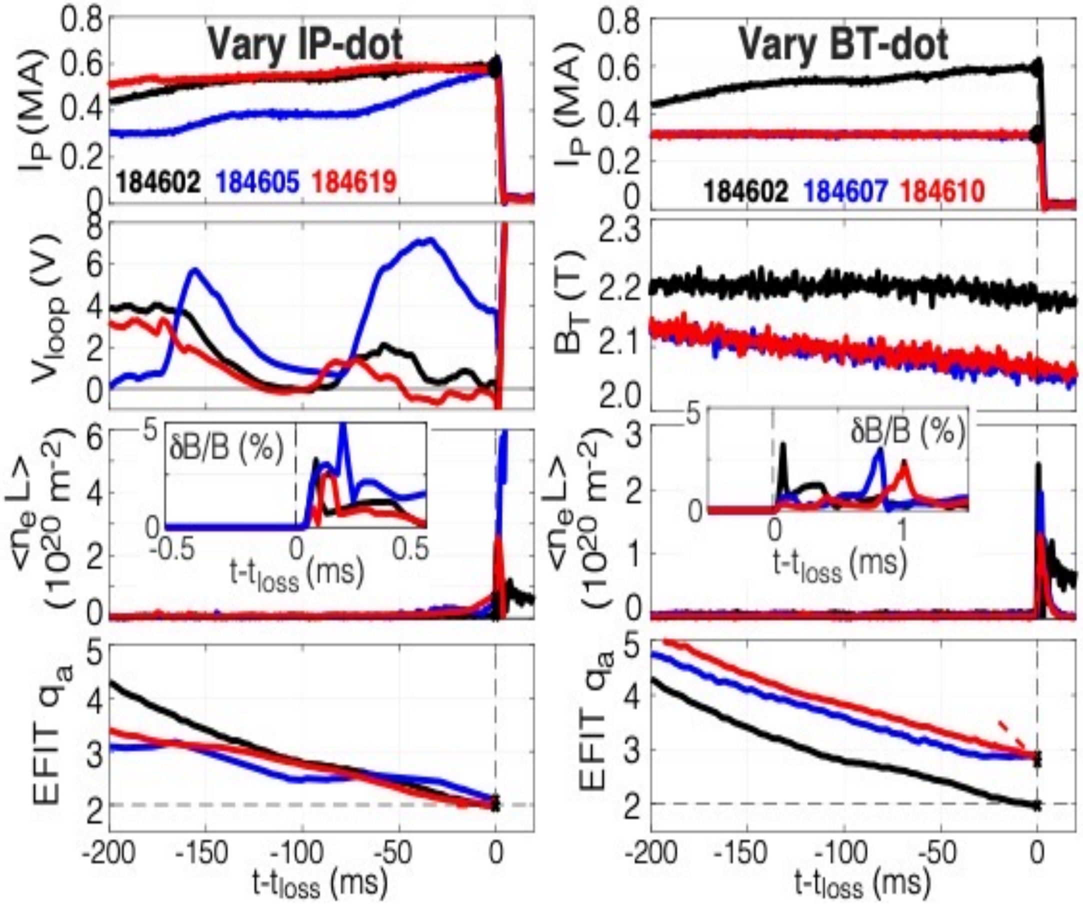
<u>IP-dot</u>

- **Large dB at q=2 for variety of IP-dot values**
- **Sub-dominant effect on MHD magnitude**

<u>BT-dot</u>

- **Surprisingly drives effect at qa=3, similar to JET cases**
- **Consistent with broader current profile facilitating instability**
  - JET current profiles thought to be broader[1]

DIII-D



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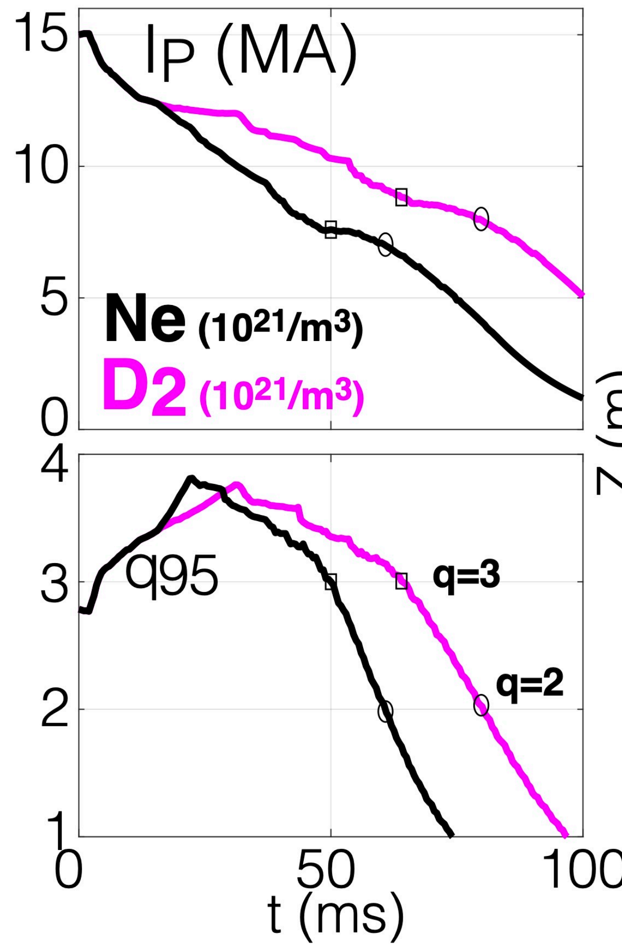
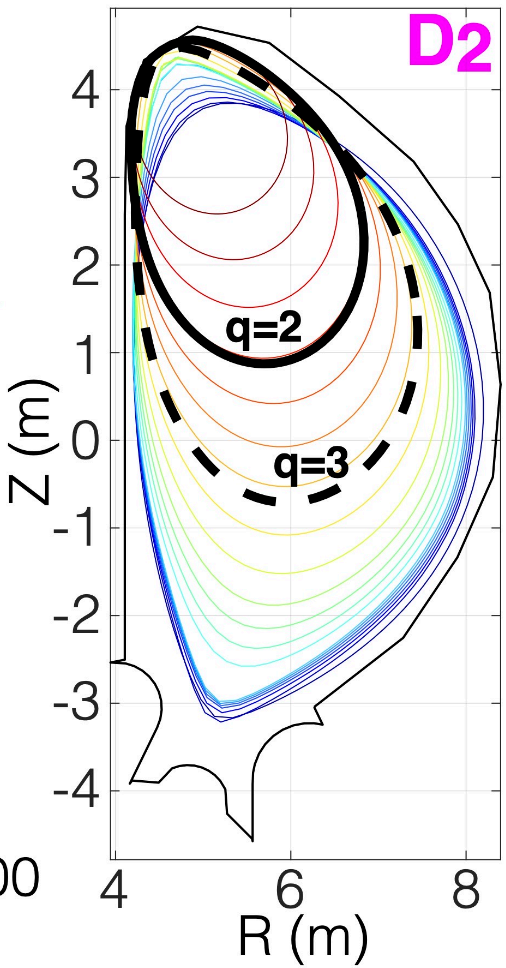
Computed Post-Disruption Evolution for ITER Finds Low Safety Factor is Robustly Accessed

- **Expect q=3 to be crossed near 10 MA**
  - ~ 200 MJ Mag. Energy
  - ~ 5 MJ Kin. Energy
- **Comparable evolutions found with *or* without D_2**
- **Lower RE current cases will have to compress further before access to q=3 or q=2**

DINA ITER Simulations

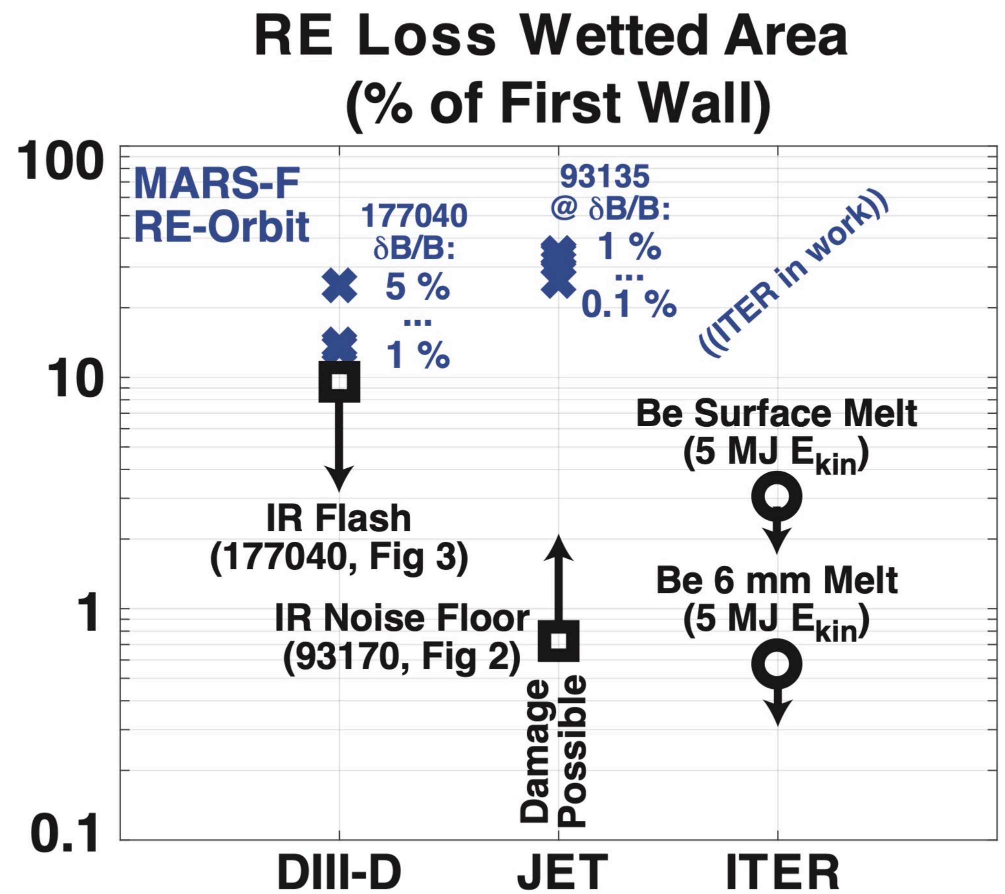




K. Aleynikova et al, Plas. Phys. Rep. 2016

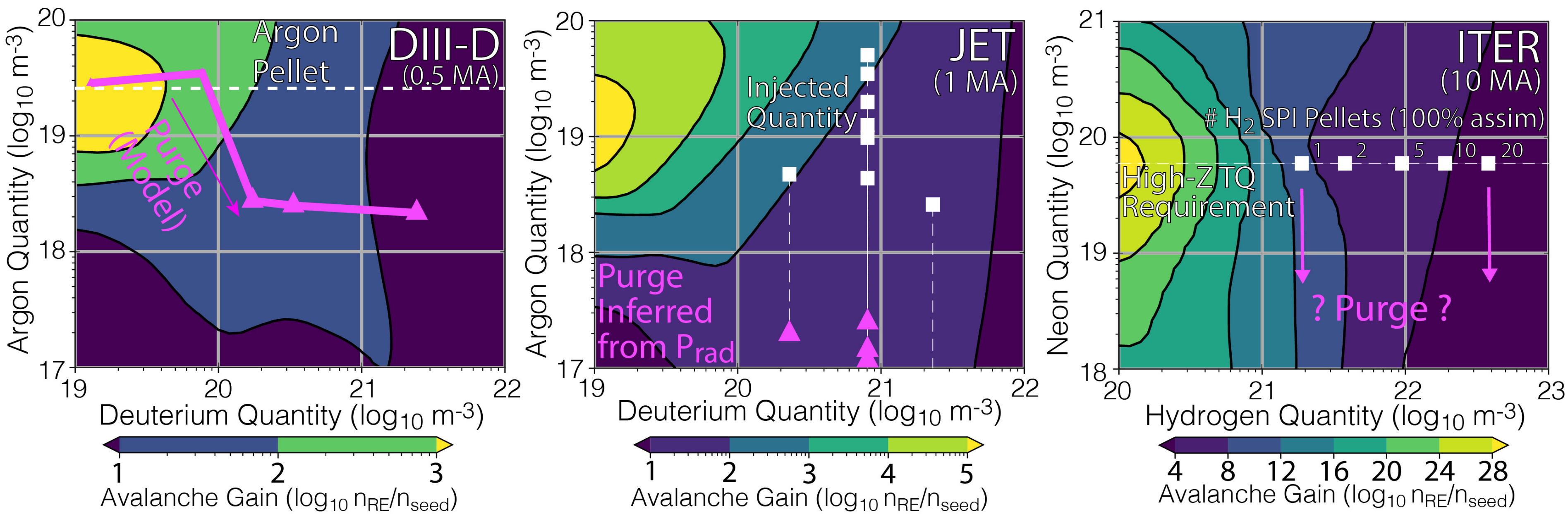
RE Impact Wetted Area Must be High to Avoid Melting

- **IR flash (DIII-D) and lack of IR heating (JET) provide boundaries on wetted area**
  - > 1% and < 10% of first wall
- **MARS-F simulations predict very large wetted areas**
  - > 10 % of first wall
- **ITER requires greater than 3% to avoid surface melt**
  - >1% to avoid deep melting



DIII-D and JET Avoid Large Avalanche Gain with D_2 ITER Will be Unable to Avoid Significant Gain

- **D2 reduces Ar quantity through "purging" phenomenon**
  - Less avalanche gain since fewer bound electron secondary targets
- **JET @ high Ar / high avalanche gain: remnant RE beam is re-born**
  - Suggests RE remnant at high Ar quantity is not less than $1/10^5$ of initial
- **ITER: Even only $1/10^{20}$ surviving, expect significant remnant re-birth**



New Approach Deployment in ITER DMS Will Likely Involve Multiple Loss Events (& Pellets?)

- **Candidate scheme foresees multiple, *but benign*, loss events**
- **Goal: keep recombination & promote large MHD**
- **Will multiple H_2 injections be required?**

Validation Needed
@ High RE Current / Gain
… in ITER Pre-FPO Phase

Candidate ITER DMS Scheme