Access and Extrapolation of Runaway Electron Mitigation via D2 Injection and Large MHD

C. Paz-Soldan[1,2], Y. Liu[2], K. Aleynikova[3], P. Aleynikov[3], N. Eidietis[2], E. Hollmann[4], C. Reux[5], the DIII-D team and JET contributors**

[1] Columbia University [2]GA [3]IPP-Greifswald [4]UCSD [5]CEA-France

**See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

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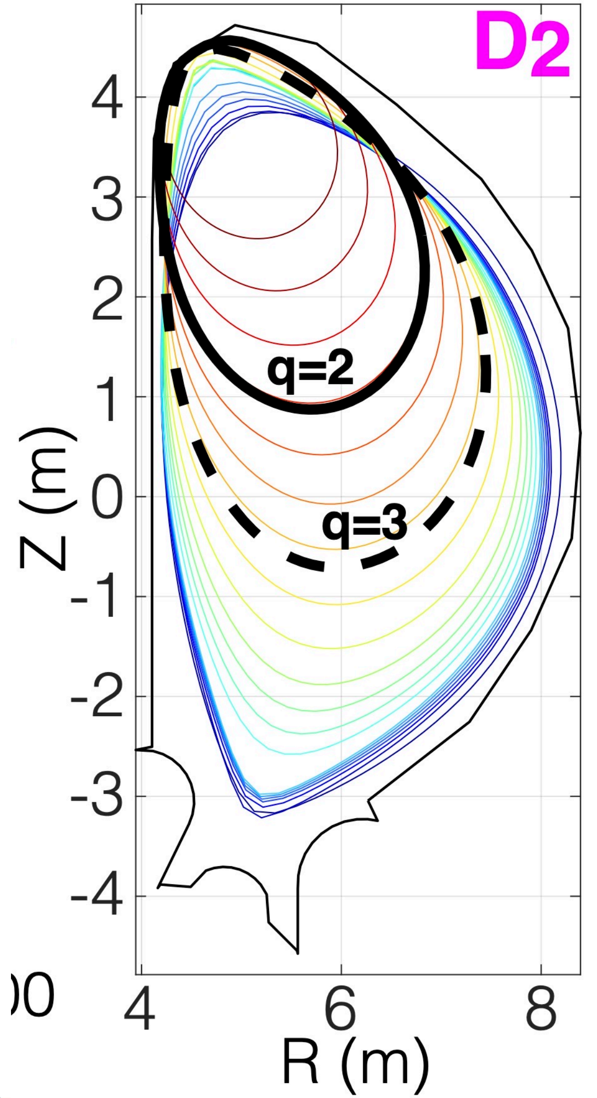
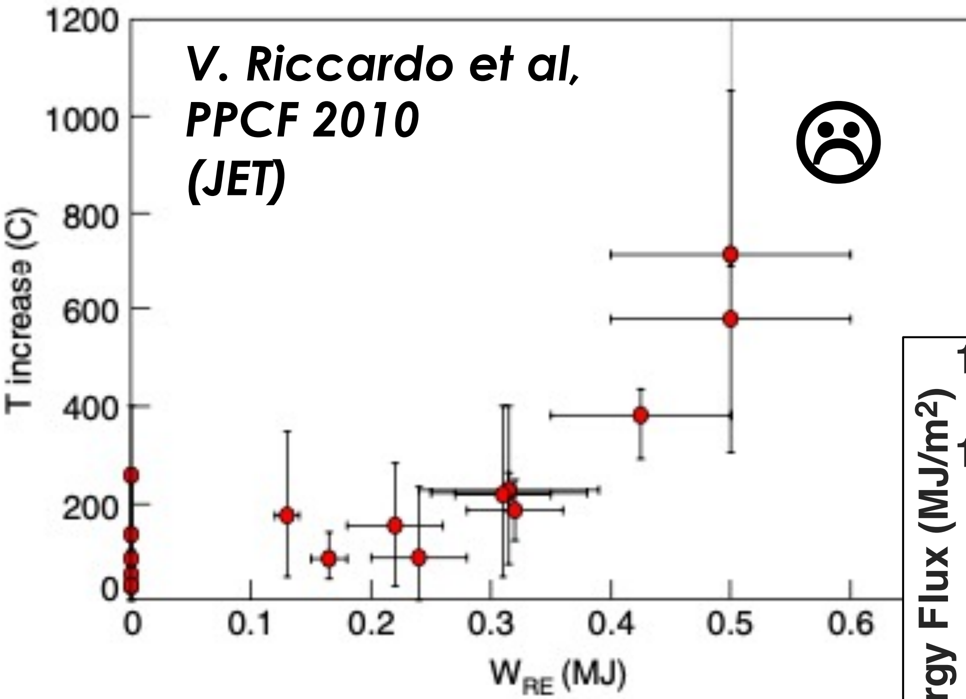
Presented at:

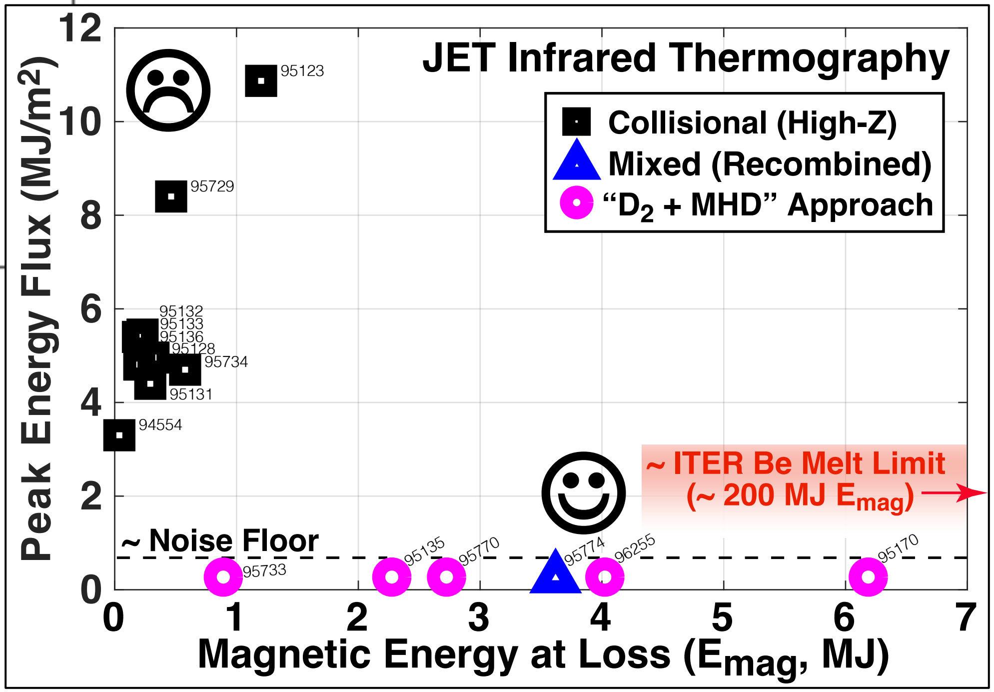
PPPL TSDW (Remote)

July 19th 2021



Motivation: High RE Energy, Yet Low Wall Flux / Heating





"D_2 + MHD"

External kinks?

Double tearing?

C. Reux et al, PRL 2021

C. Paz-Soldan et al, NF 2021 (in review)

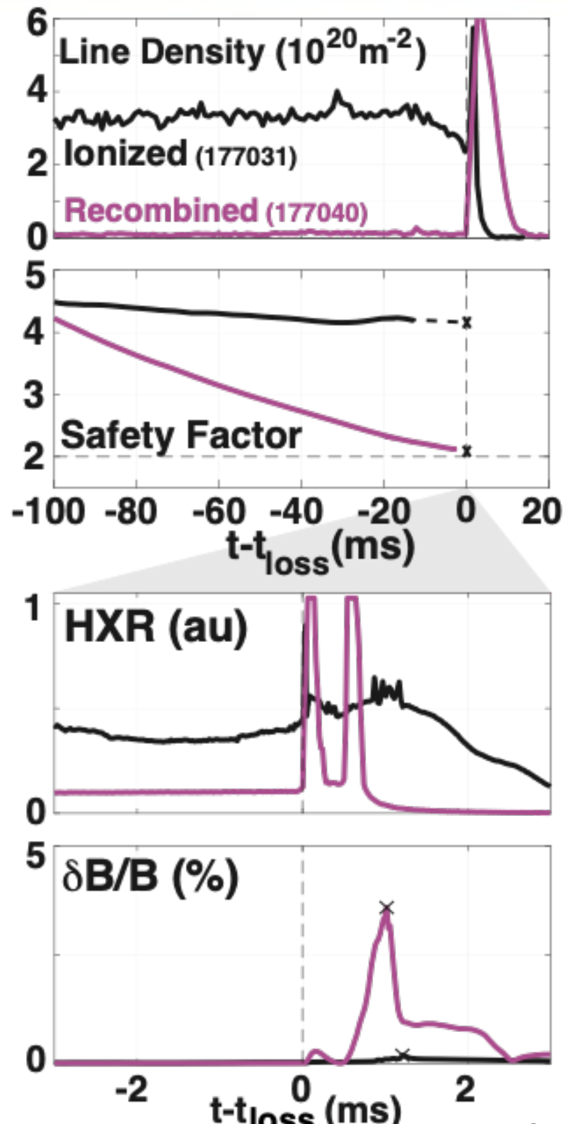
Contrasting Conventional and New Approaches Highlights Key Differences

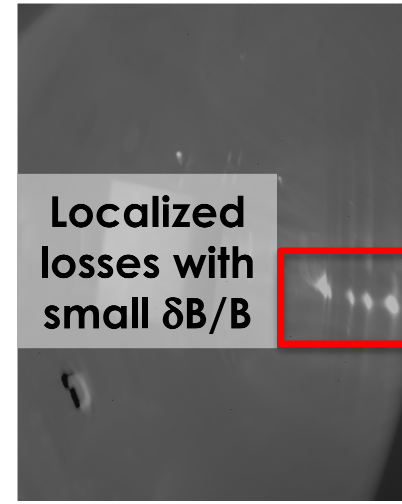
Conventional Approach:

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

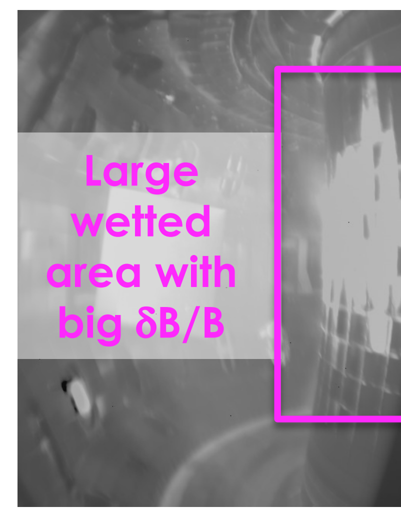
"D2 + MHD" Approach:

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





Conventional: q ~ 4



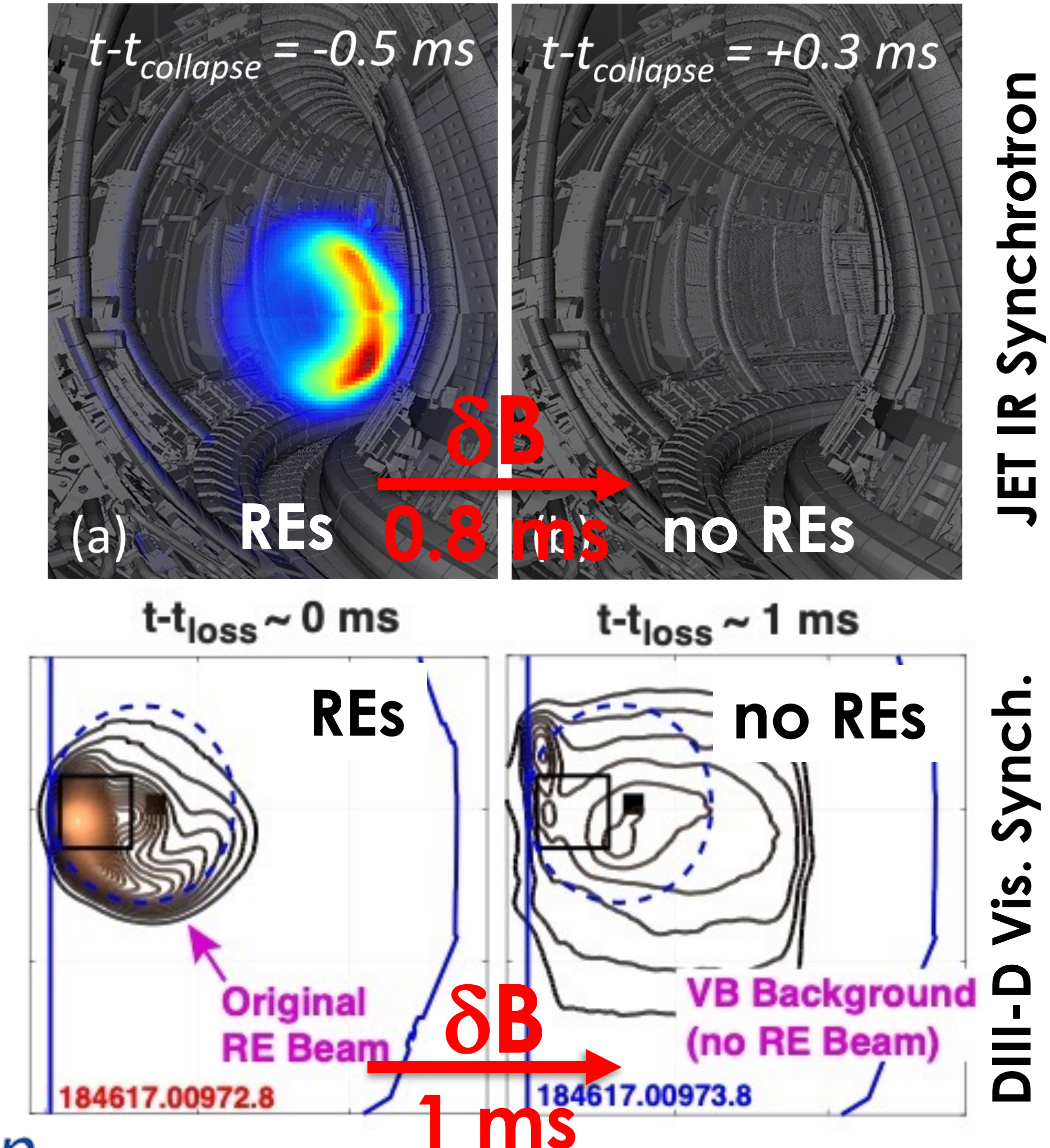
D2 + Kink: q ~ 2

[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

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**



Courtesy S. Silburn & Z. Papovic

Outline

- **Experimental Conditions to Access the Benign Termination**
  - Database of Multi-Machine Findings
  - New DIII-D Experimental Results (2021 Session)

- **Extrapolating the Scenario to ITER Conditions**
  - Equilibrium Evolution during VDE
  - MHD Modeling of Wetted Area
  - Avalanche Gain Considerations

- **Conclusions & Open Questions**

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Parameters of A-Priori Interest to Access the Benign Termination

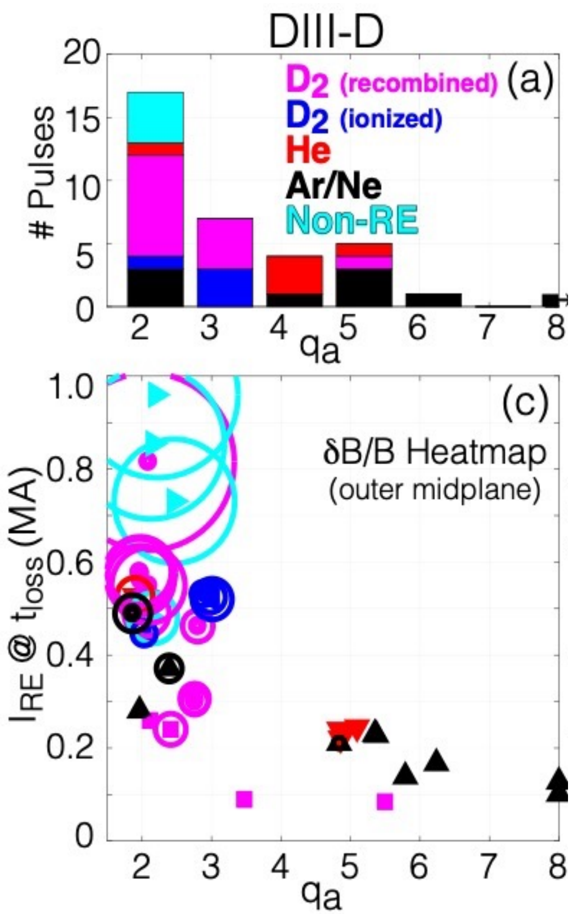
- **Safety factor (q), and parameters that set the safety factor:** $q_a \sim \frac{aB_T}{I_P}$
- **Background plasma species**
- **Vertical instability**

Let's explore with a database and dedicated scans

D_2 Injection: 1) Facilitates Low Safety Factor Access

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

- **DIII-D δB/B ingredients:**
  - High Ip and low qa
  - Recombined state



DIII-D NATIONAL FUSION FACILITY EUROfusion

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- **DIII-D δB/B ingredients:**
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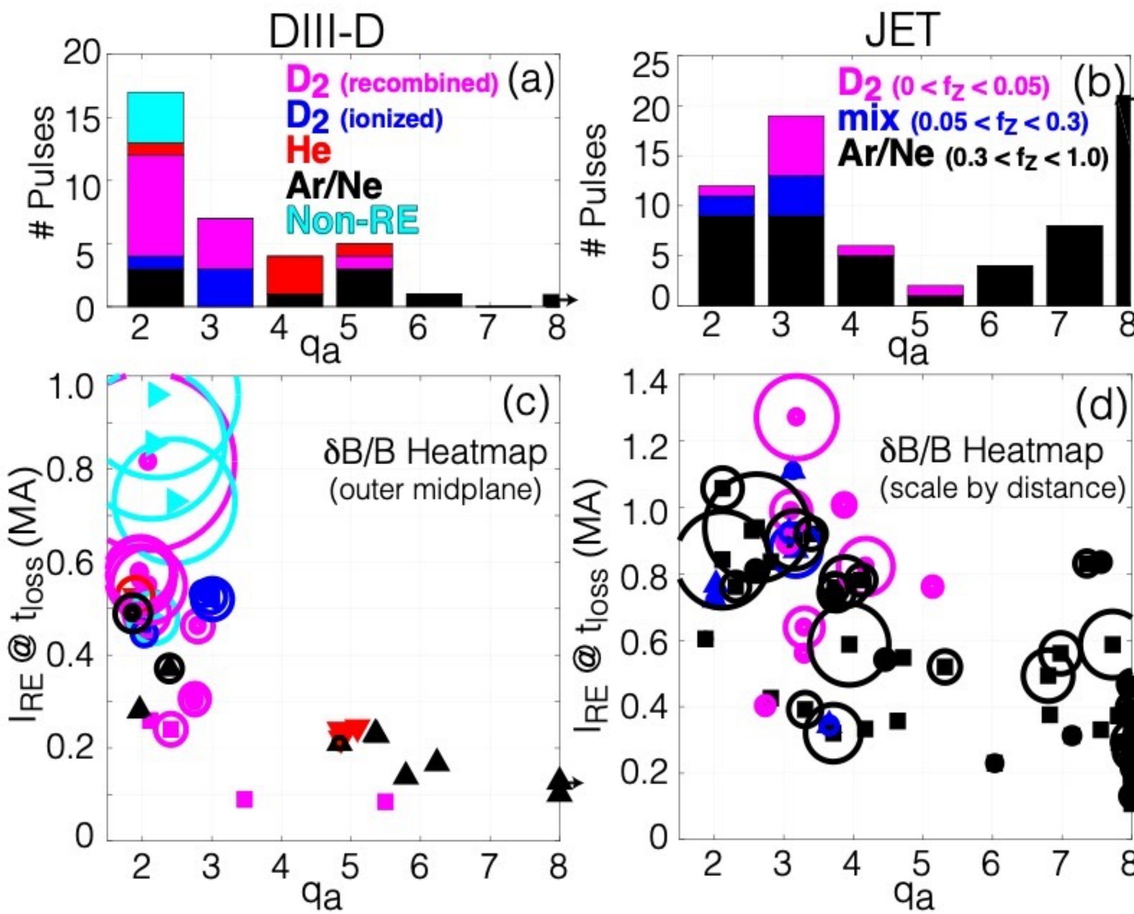
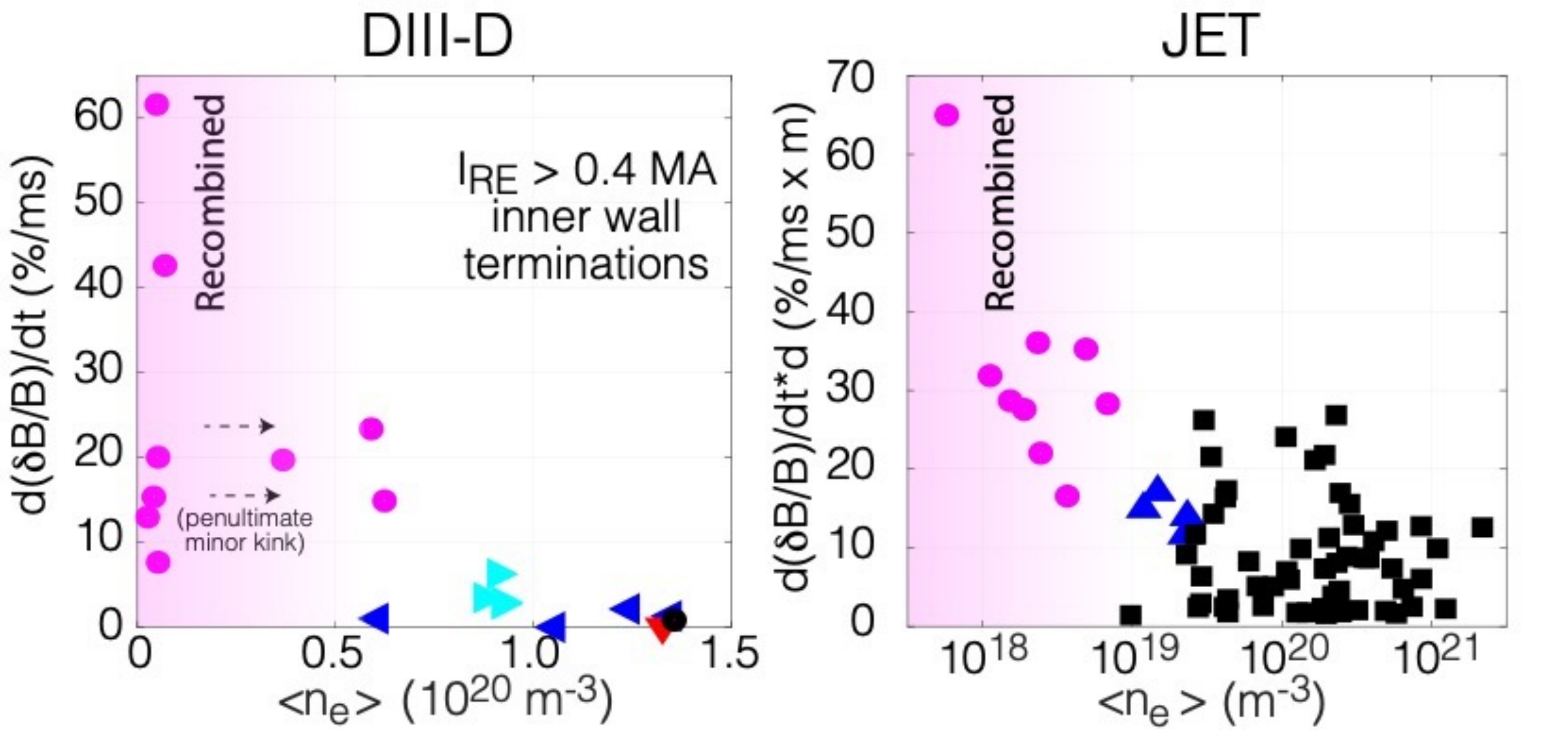
  - Recombined state
- **JET: more complex picture for δB/B**
  - Greater variability in the current profile?



Courtesy C. Reux

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

- **Key D_2 correlation: bulk recombination**
  - Decreases density, shortens Alfven time
  - ***Accelerates MHD growth rates***



Courtesy C. Reux

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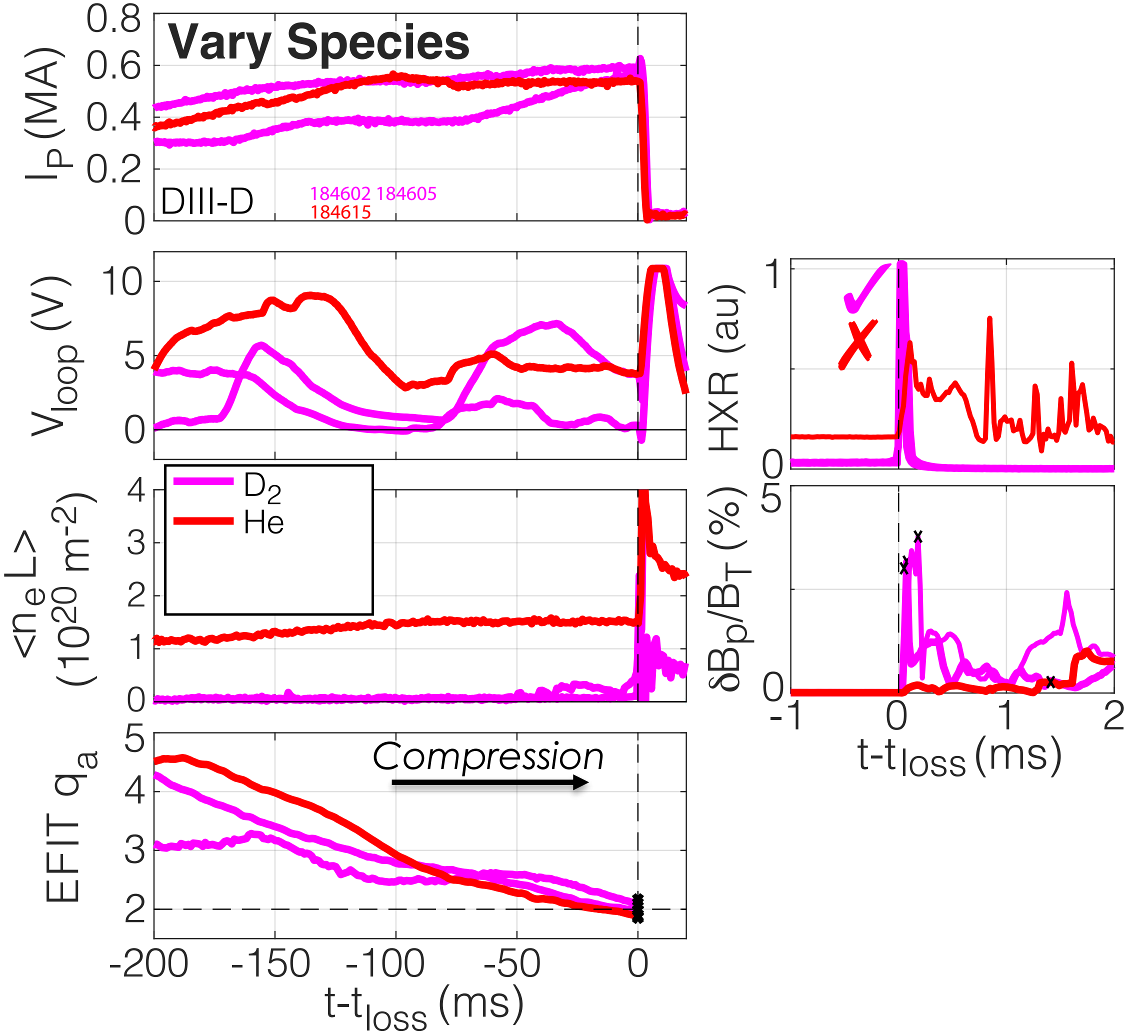
Controlled experiment of Z-effect at matched qa / IP … Recombined (via D_2) beam unique in terms of dB/dt

- **Recombined RE beam (D_2): large $\delta B/B$ and dB/dt @ stability boundary**
- **Helium RE beam: does not exhibit large $\delta B/B$ and has conventional final loss**

Z-effect @ same IP/qa:

(radius compression)



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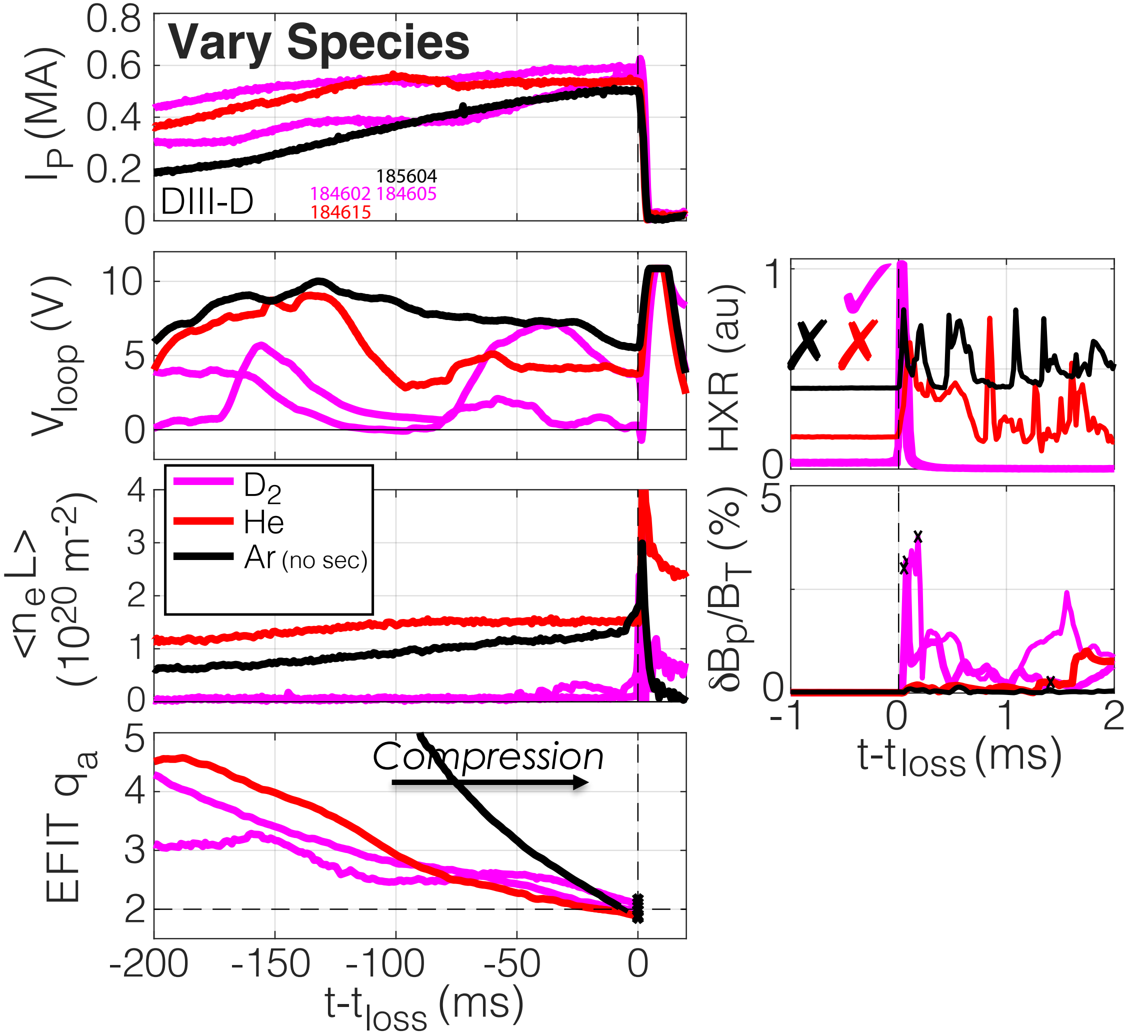

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- **Helium RE beam: does not exhibit large δB/B and has conventional final loss**
- **Regular (Ar only): does not exhibit large δB/B and has conventional final loss**
- **Non-RE plasma ref: still had large δB/B but a much slower dB/dt**

Z-effect @ same IP/qa:

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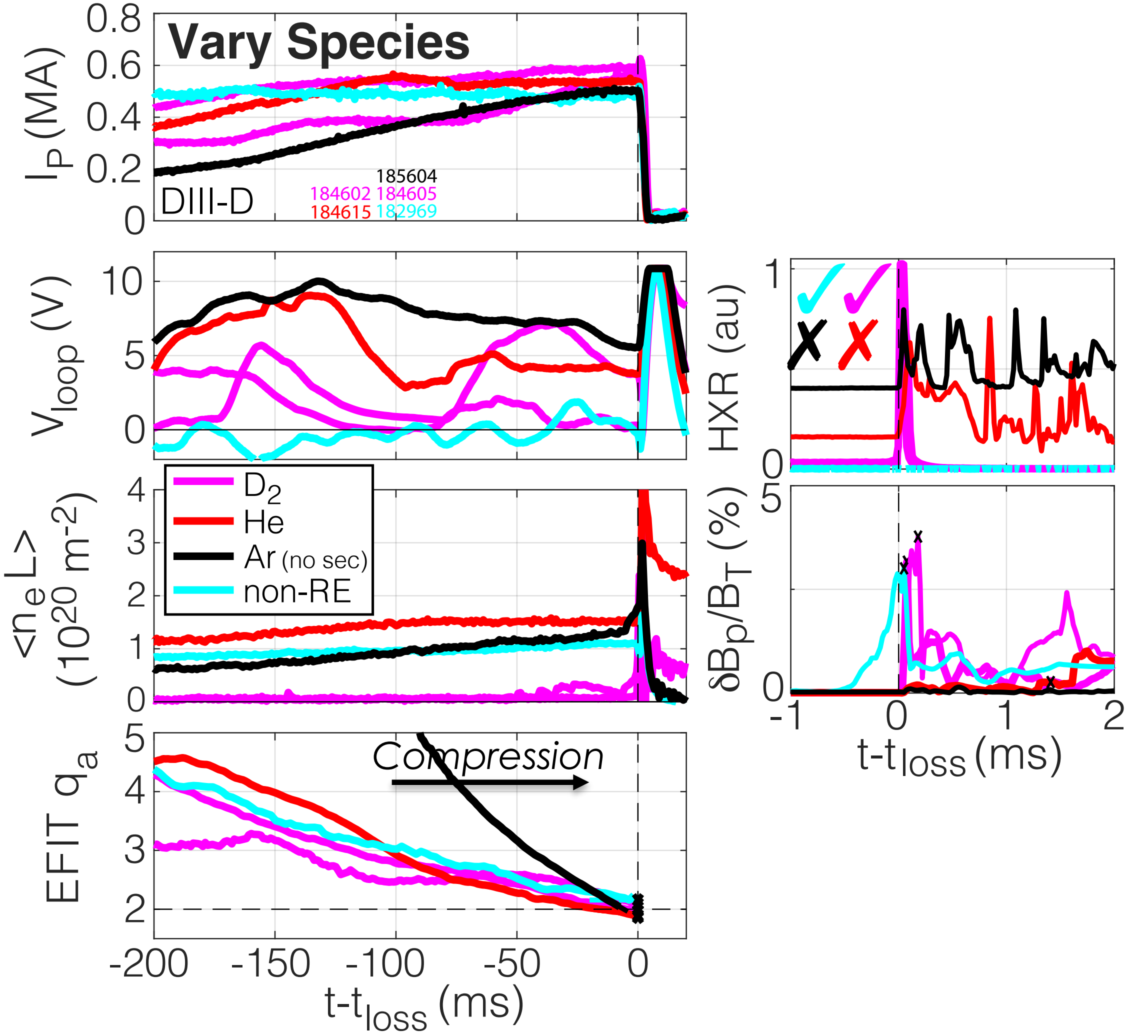

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D_2 Quantity Scan Reveals Limiting Phenomena Bracketing the Optimal Injection for Big δB/B

Limits of D2 Quantity:

- **Just Right: Robustly recombined but robust to the minor kink instabilities**
  - Strong δB/B spike

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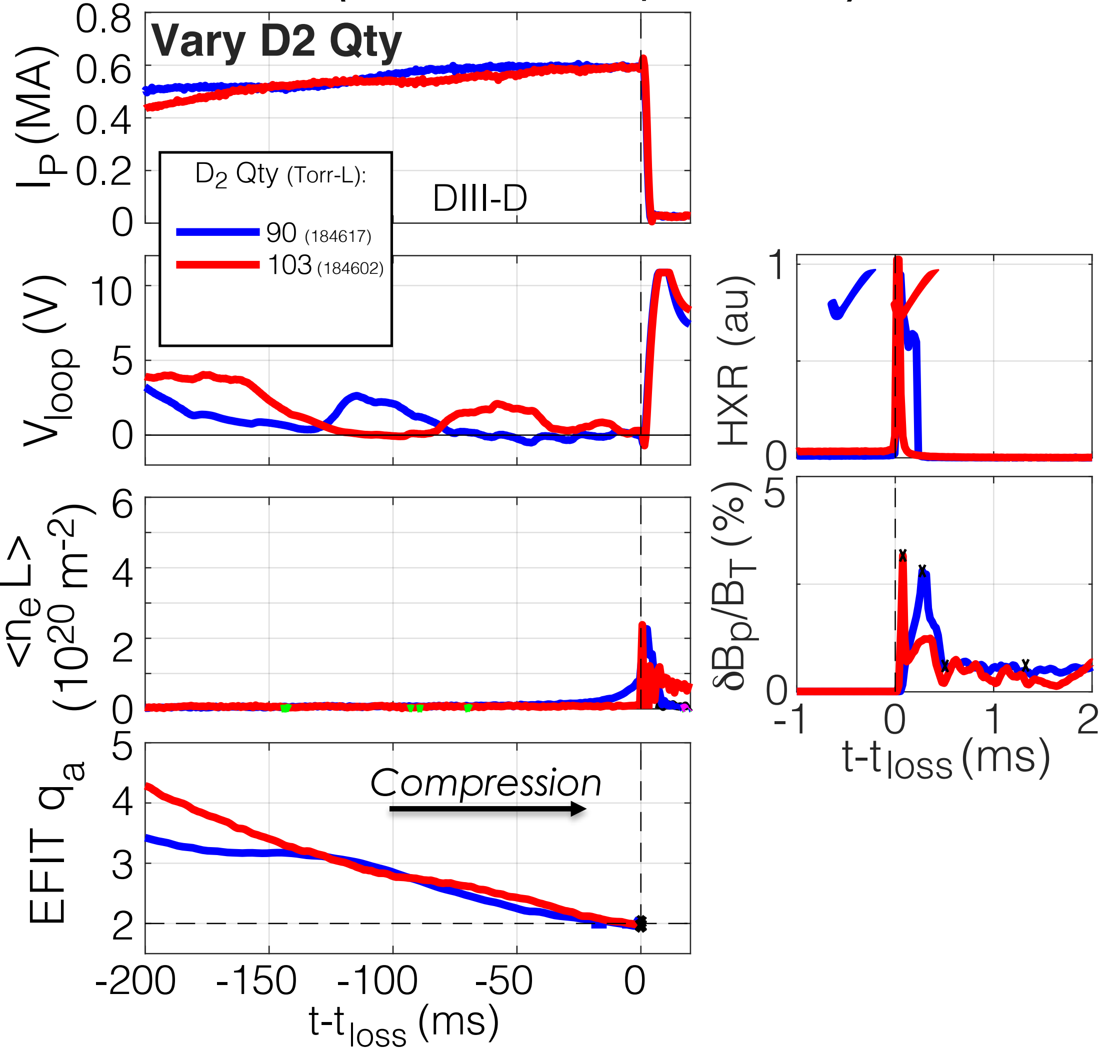

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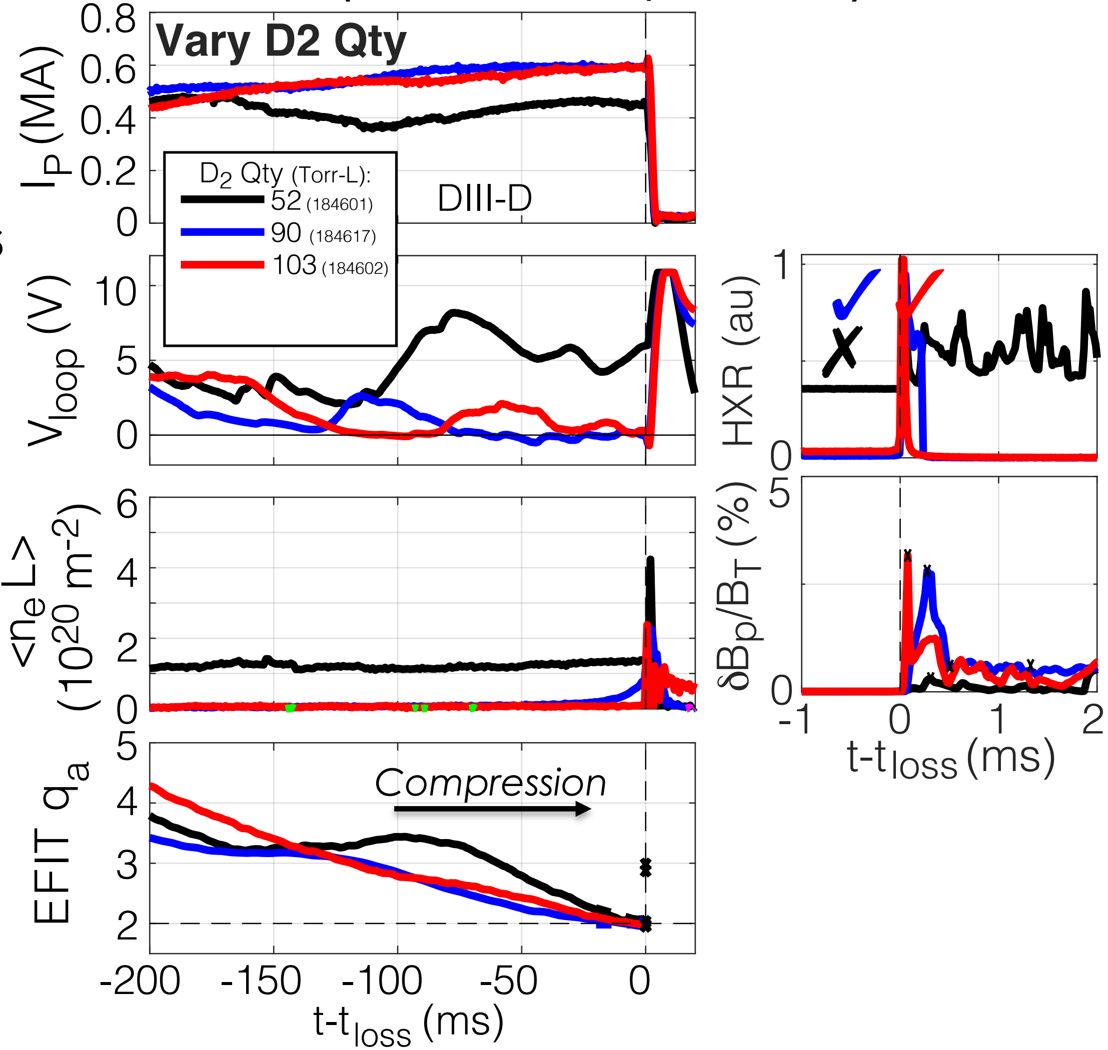

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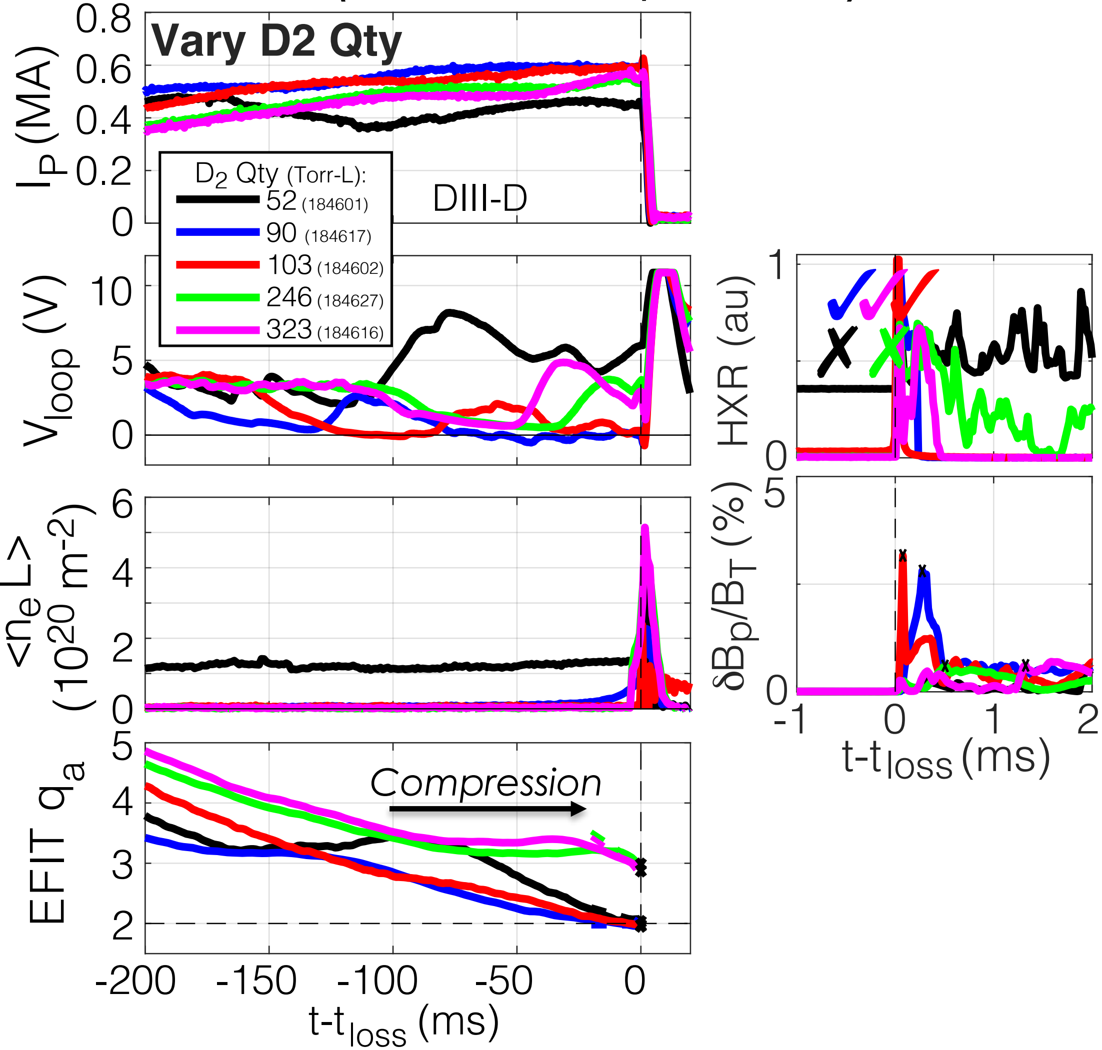
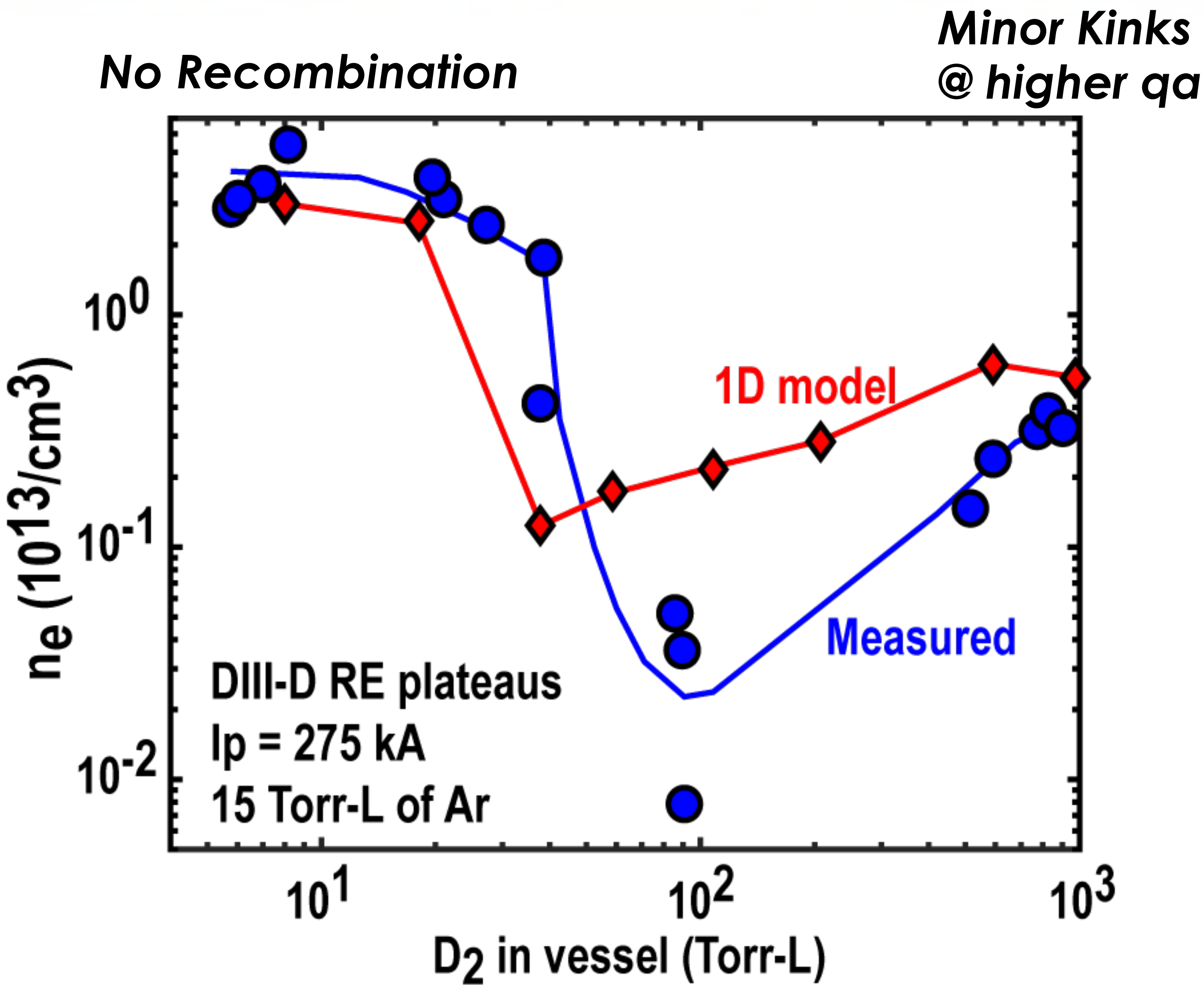
  - Weak δB/B spike
- **Too Much: Plasma re-ionizes after minor MHD events at higher q_a**
  - Weak δB/B spike

(radius compression)



1-D Diffusion Model[1] Predicts Optimum D_2 Quantity for Recombination in DIII-D



Depends on RE Current (Ohmic Heating), High-Z Quantity (Radiation)

[1] Hollmann et al, PoP 2020

Courtesy E. Hollmann

Vertical Displacement Event: Deuterium Injection Facilitates access to Low Safety Factor (Final Loss Delayed – Why?)

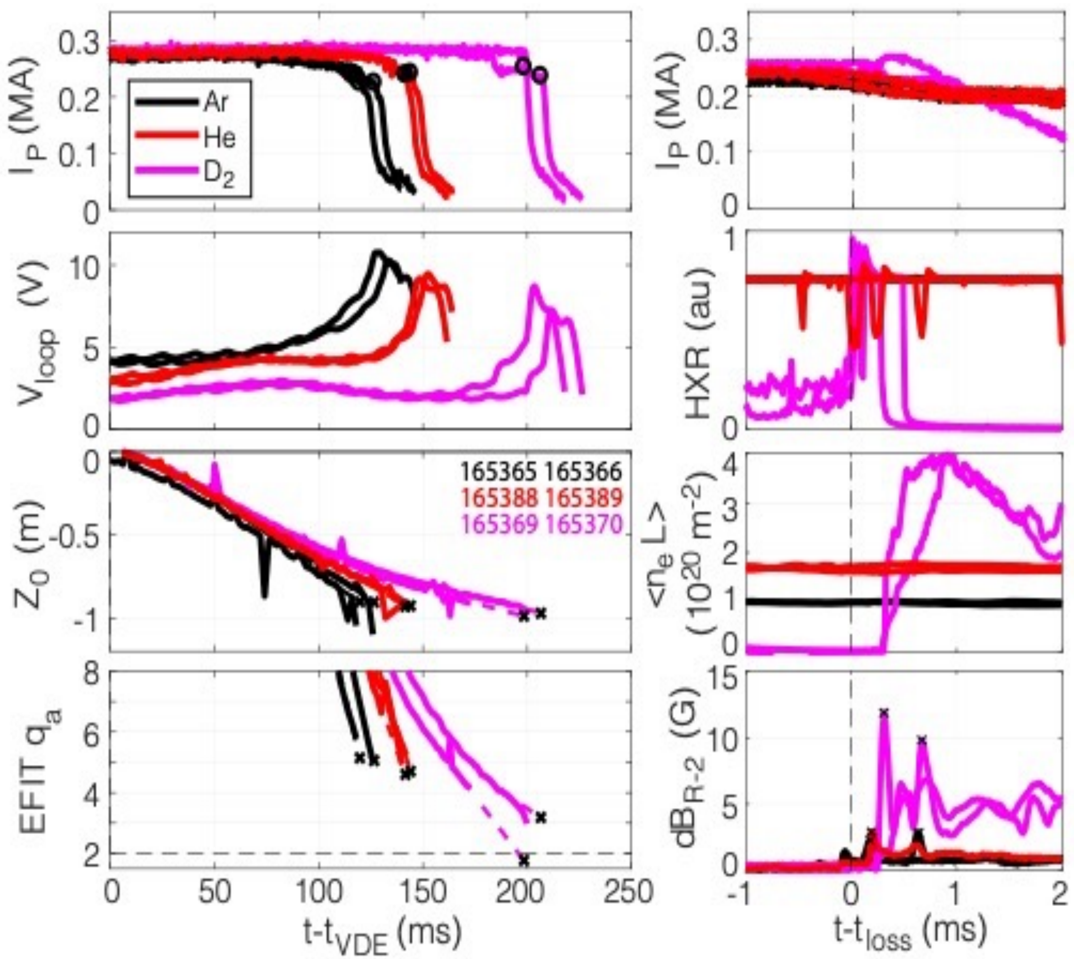
DIII-D

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

- **Final loss instabilities begin at higher safety factor**
- **Small δB/B**

<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



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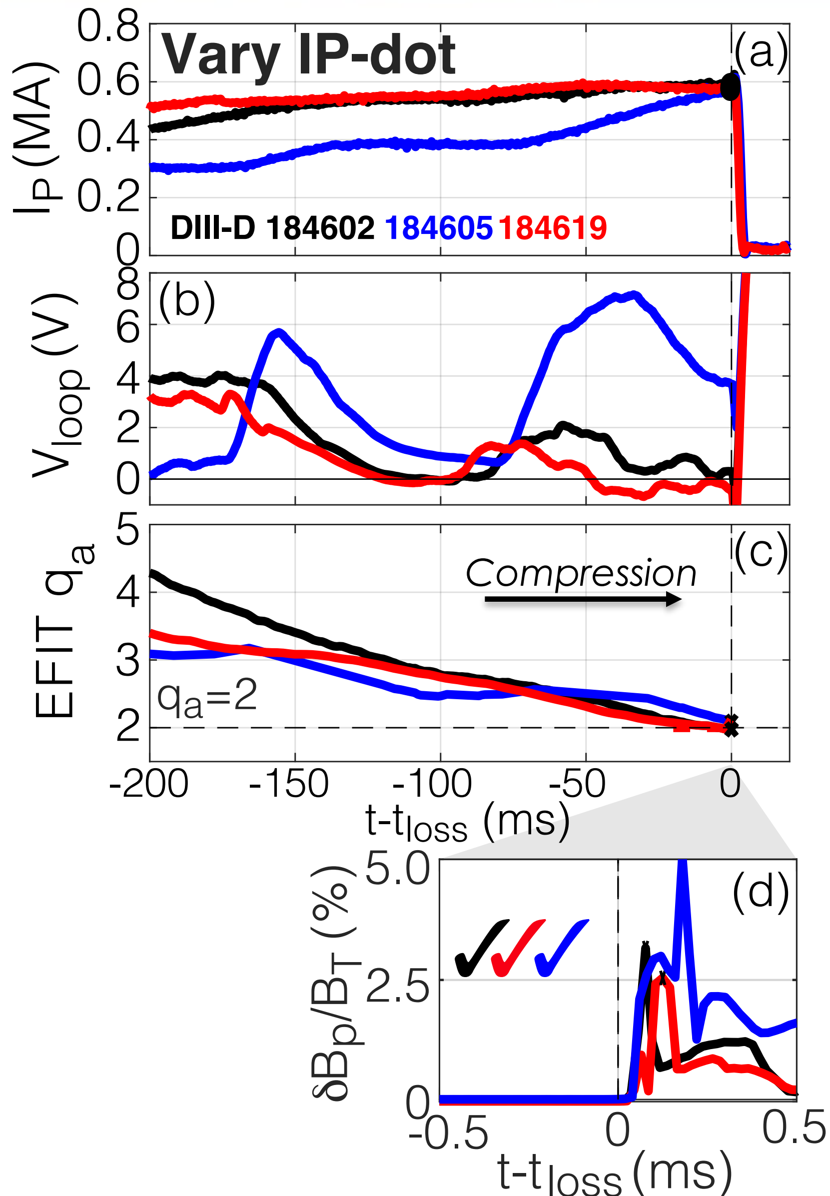
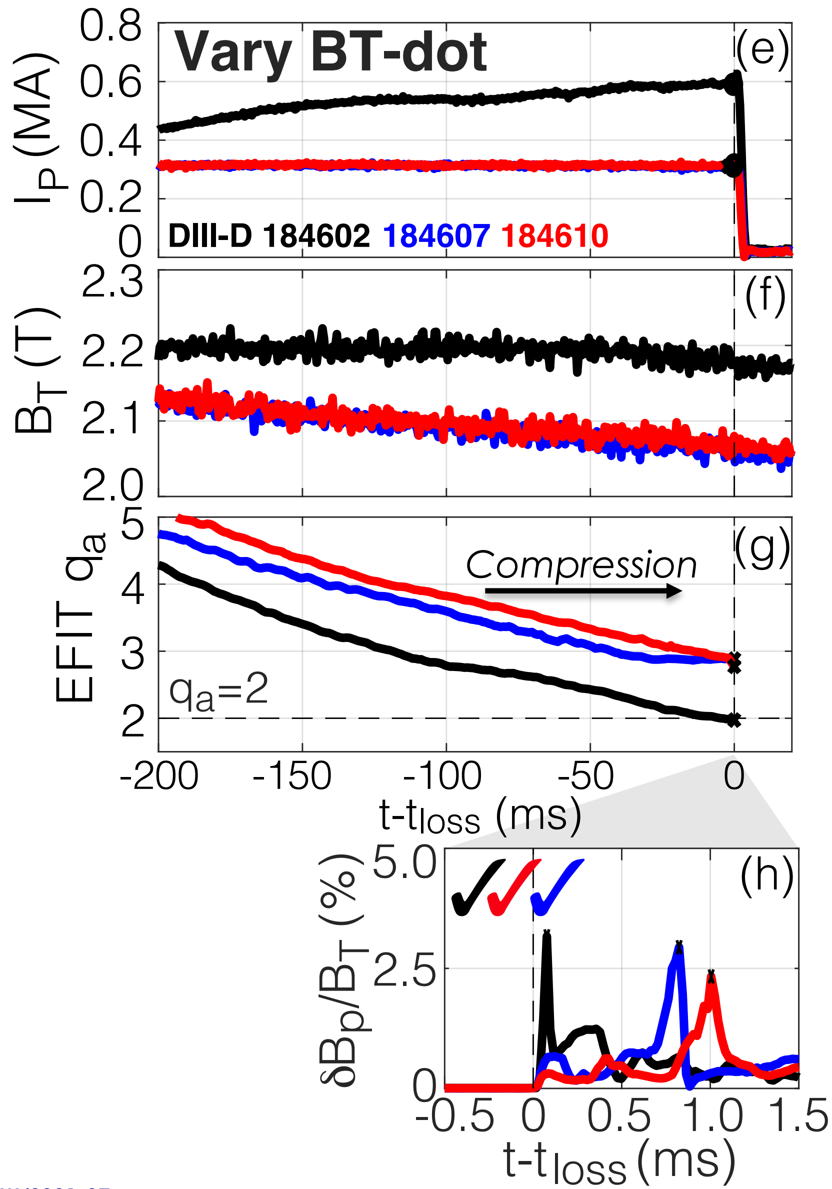
No Big Effect of Crossing q=2 Stability Boundary with Different IP Ramp Rates

- **Past data features rising IP to lower qa**
  - ITER will have flat or falling IP, but contracting radius
  - Motivates IP-dot Scan $q_a \sim \frac{aB_T}{I_P}$
- **Large δB/B at q=2 for variety of IP-dots**
- **IP-dot appears to have sub-dominant effect on MHD magnitude**
- **Experimentally could not access large negative IP-dot**
  - (Plasma is not very resistive)



Falling BT Drives Off-axis Current and Allows Exploration of Current Profile Broadness Effect

- **Current profile broadness invoked for why JET can find modes at higher qa**
- **Dropping BT in DIII-D showed benign kink termination at qa=3 (not 2!)**
  - Similar to many JET examples
- **Consistent with broader current profile facilitating instability**
  - JET current profiles proposed to be broad or even hollow[1]



[1]O. Ficker, EPS 2021

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Conclusions: Benign Termination w/ D2 Not Automatic. Following Access Conditions Appear Important:

- **Species: Hydrogenic is unique! Not simply "low-Z"**
  - Helium didn't work!
- **Optimal D2 quantity to minimize free electron density**
  - Too little: no recombination
  - Too much: too many electrons
  - Optimize injection quantity? Hollmann Model & MDC-23 effort
- **VDE: D2 benefit seen in VDE trajectory**
  - Why was lower qa access promoted? Not known.
- **IP-dot: Appears unimportant**
- **BT-dot: Promotes broader J-profile and instability at higher qa**
  - Supports J-profile as why JET phenomenology is more "diverse"

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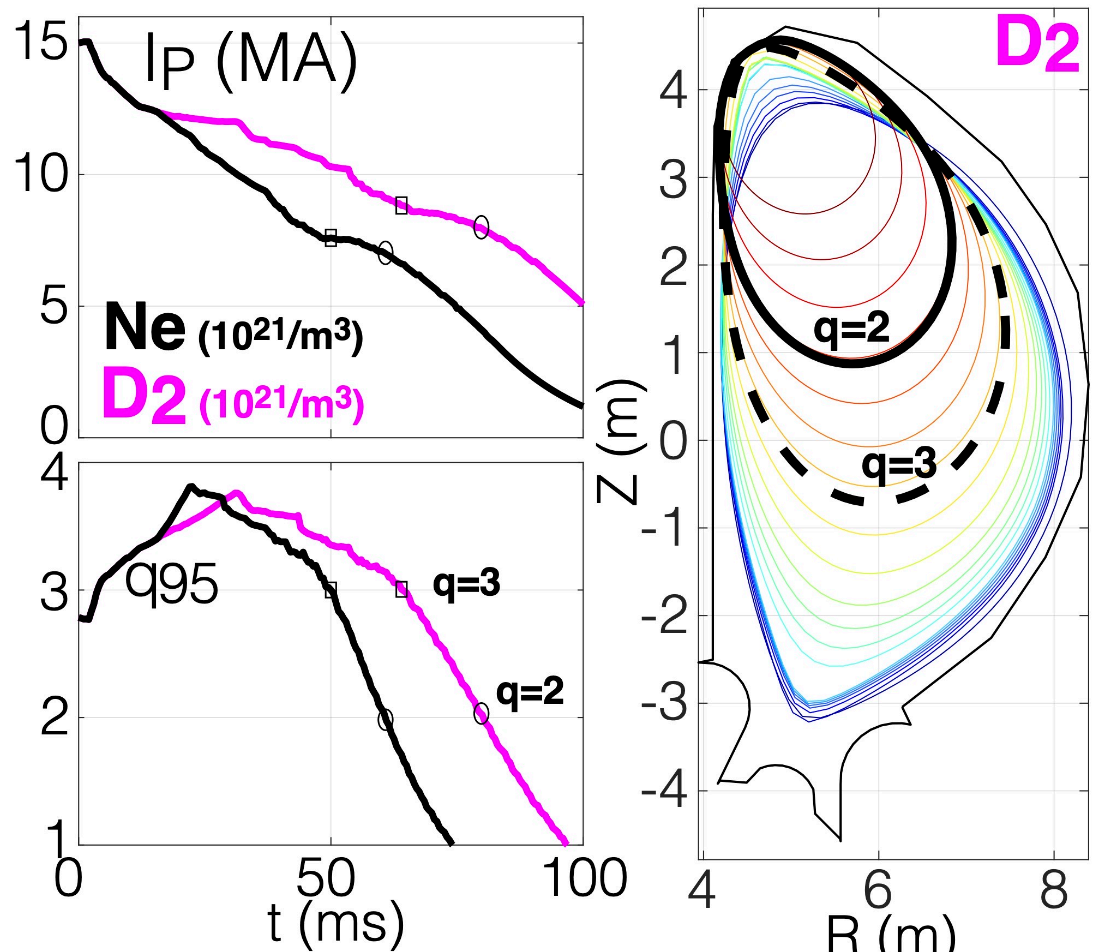
Computed Post-Disruption Evolution for ITER Finds Low Safety Factor is Robustly Accessed

- **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**
  - Recombination not captured by model
- **Lower RE current cases will have to compress further before access to q=3 or q=2**

Low q should be expected (in principle!)

DINA ITER Simulations

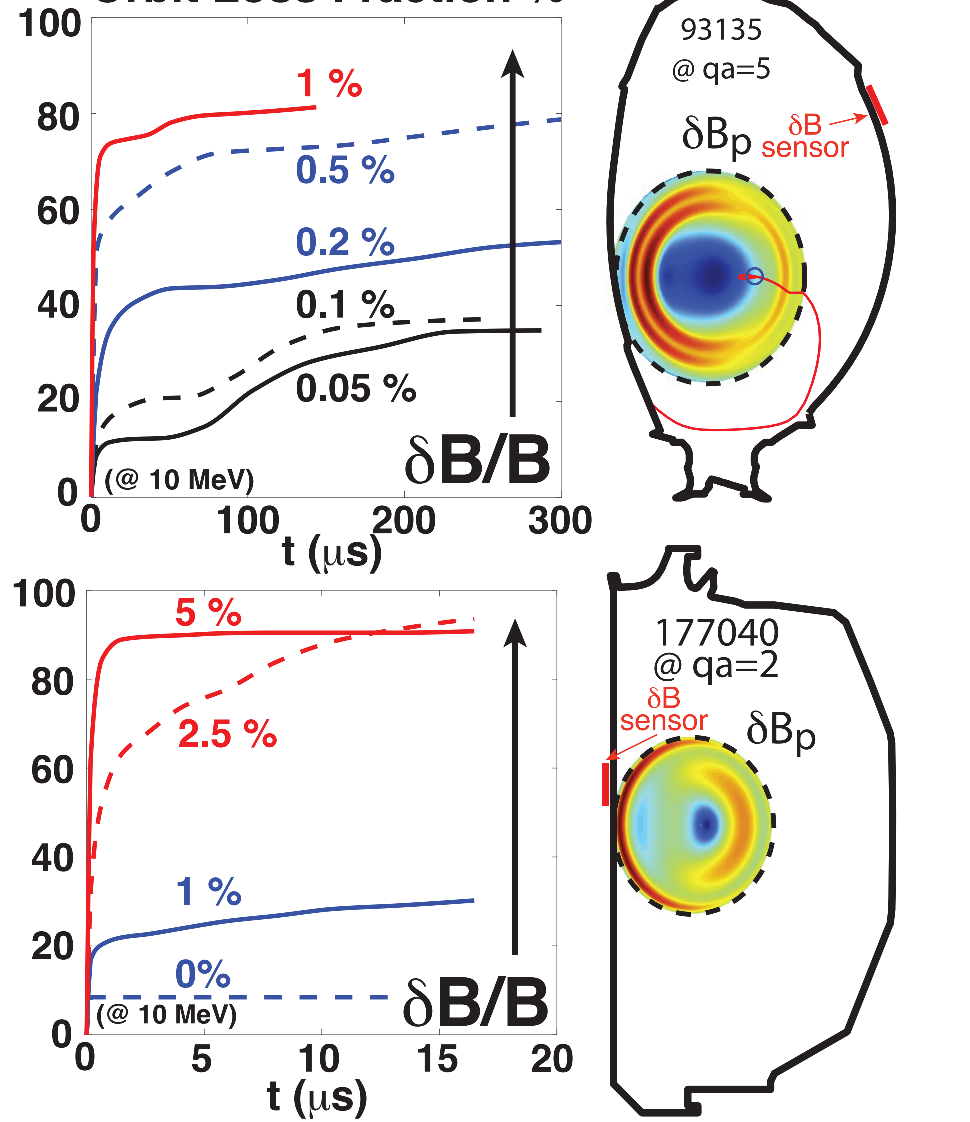


K. Aleynikova et al, Plas. Phys. Rep. 2016

Courtesy K. Aleynikova

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

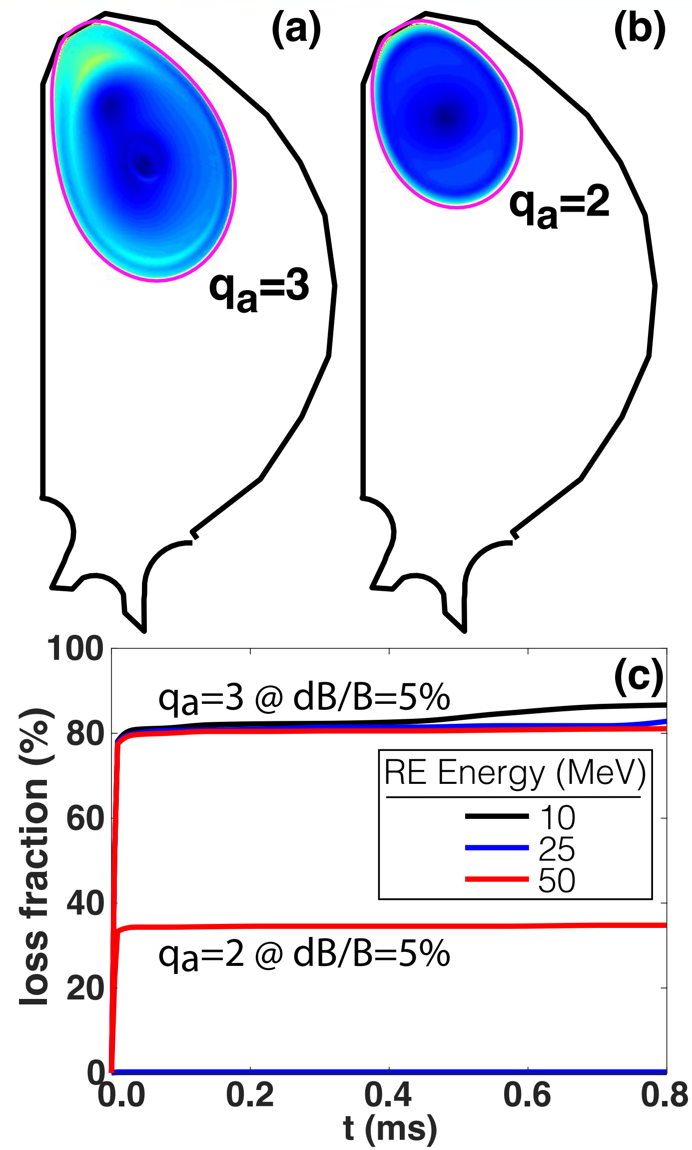
- **RE orbits followed in linear MHD eigenmode structure scaled to experimental δB/B**
- **δB/B at experimentally relevant values (~ 5%) causes most orbits to be lost to the first wall**



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

ITER Simulations Underway for DINA Equilibria Shows Smaller than Expected RE Loss – Ongoing Work

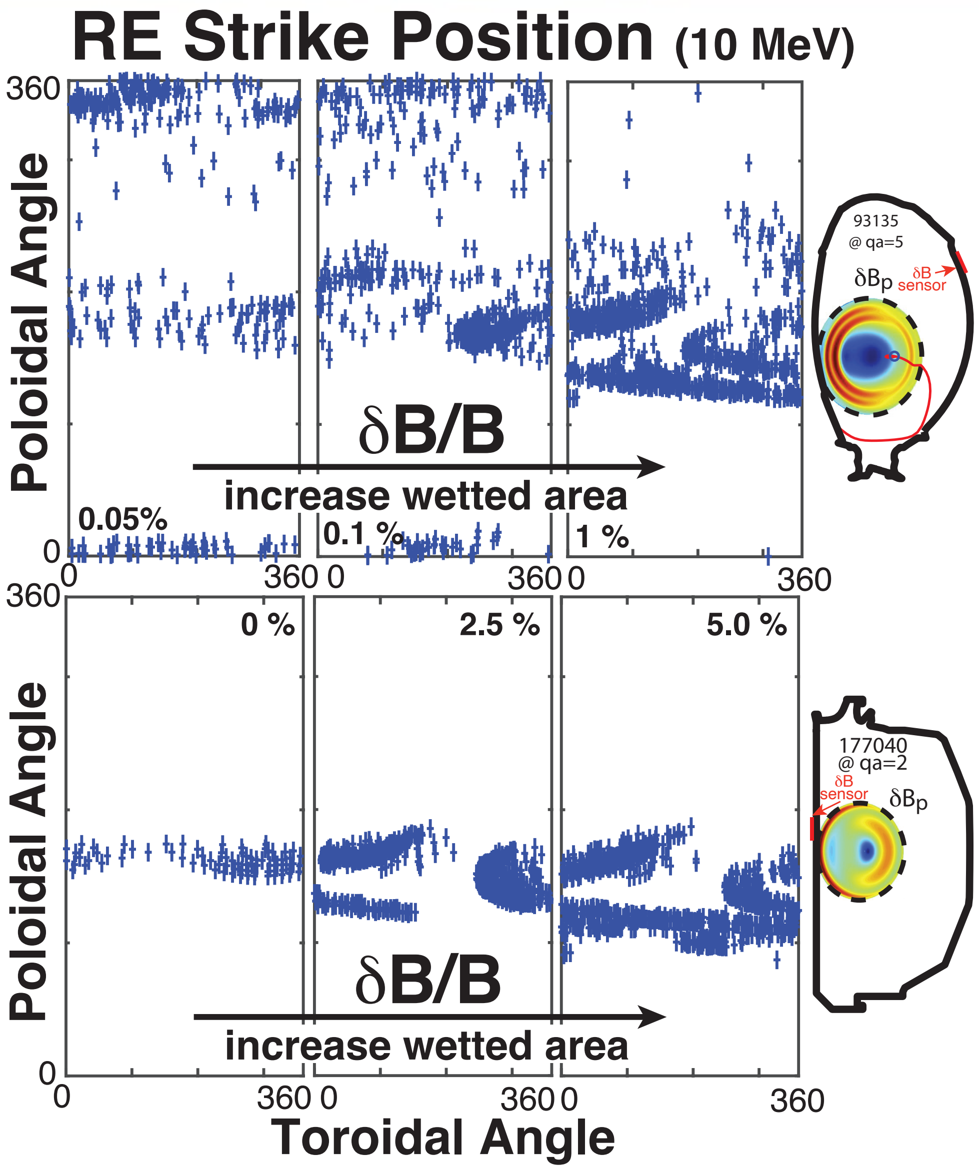
- **Equilibria near qa=2, 3 extracted from the VDE sequence**
- **Linear instability analysis reveals edge kink instability structure**
  - qa=3 is more global
  - qa=2 edge localized (artifact?)
- **Comparable δB/B as in DIII-D/JET providing smaller RE loss fractions**
  - Under investigation
- **Extended MHD modeling needed to predict the δB/B expected**
  - Non-linear saturation!



Courtesy Y.Q. Liu

Large dB/B Maps to Large Wetted Area in Modeling

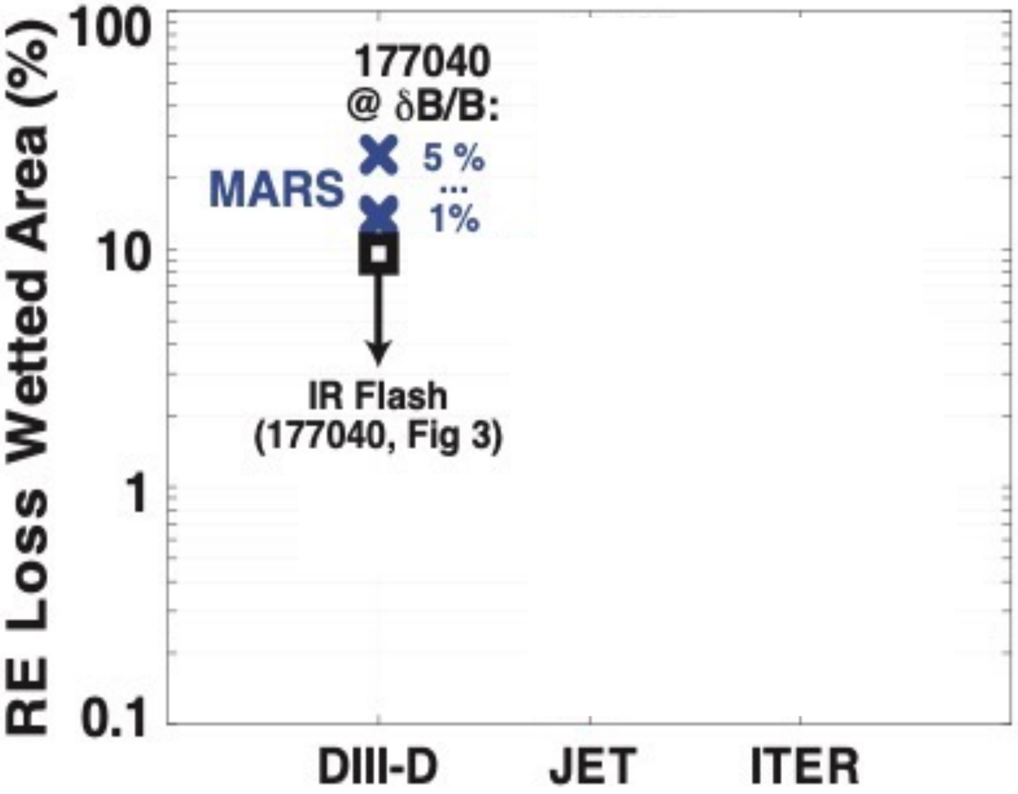
- **Orbits connect to a wider fraction of the first-wall area**
- **RE kinetic energy disperses into a large surface area**
  - Reduced peak heat flux
- **Similar calculations repeated for ITER equilibria**



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

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
- **KORC simulations yielding similar (but smaller) values[1]**
- **ITER requires greater than 3% to avoid surface melt**
  - >1% to avoid deep melting



[1]M. Beidler & D. D.C.N (in progress)

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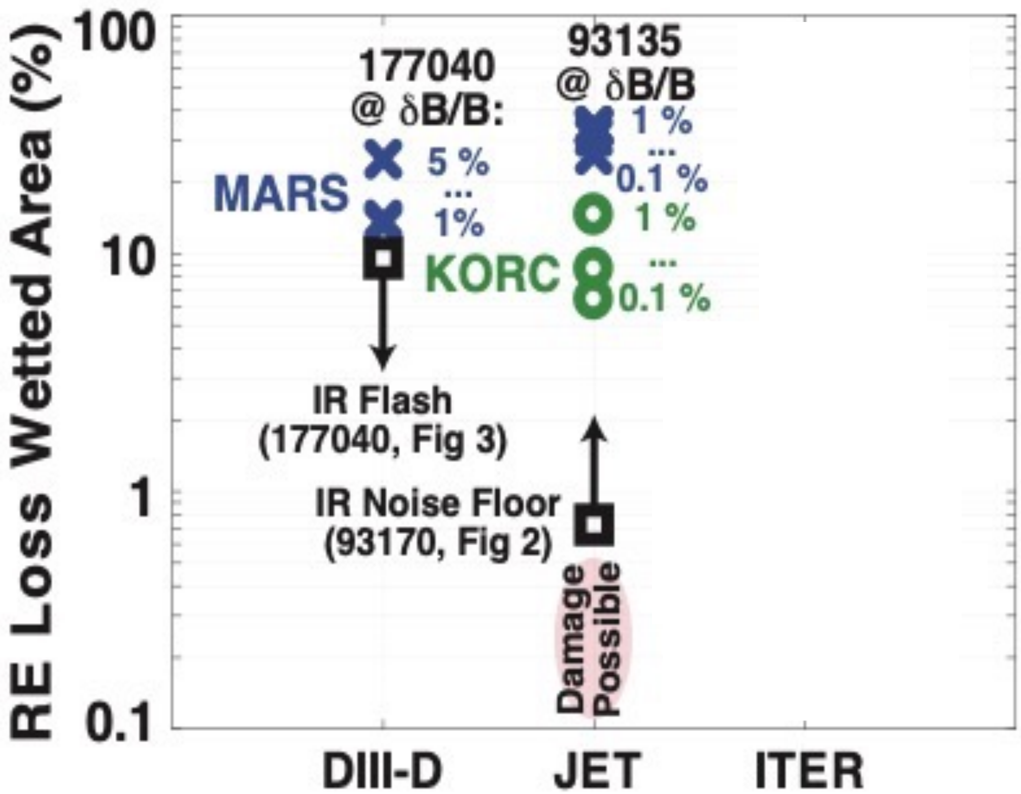

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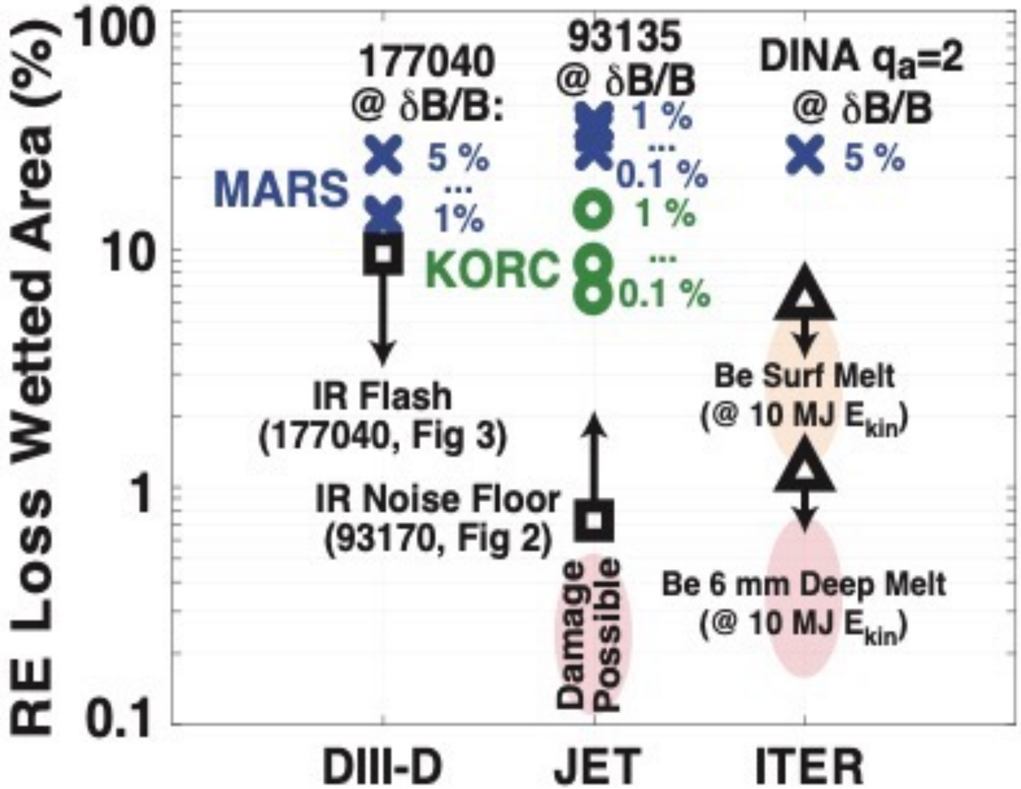

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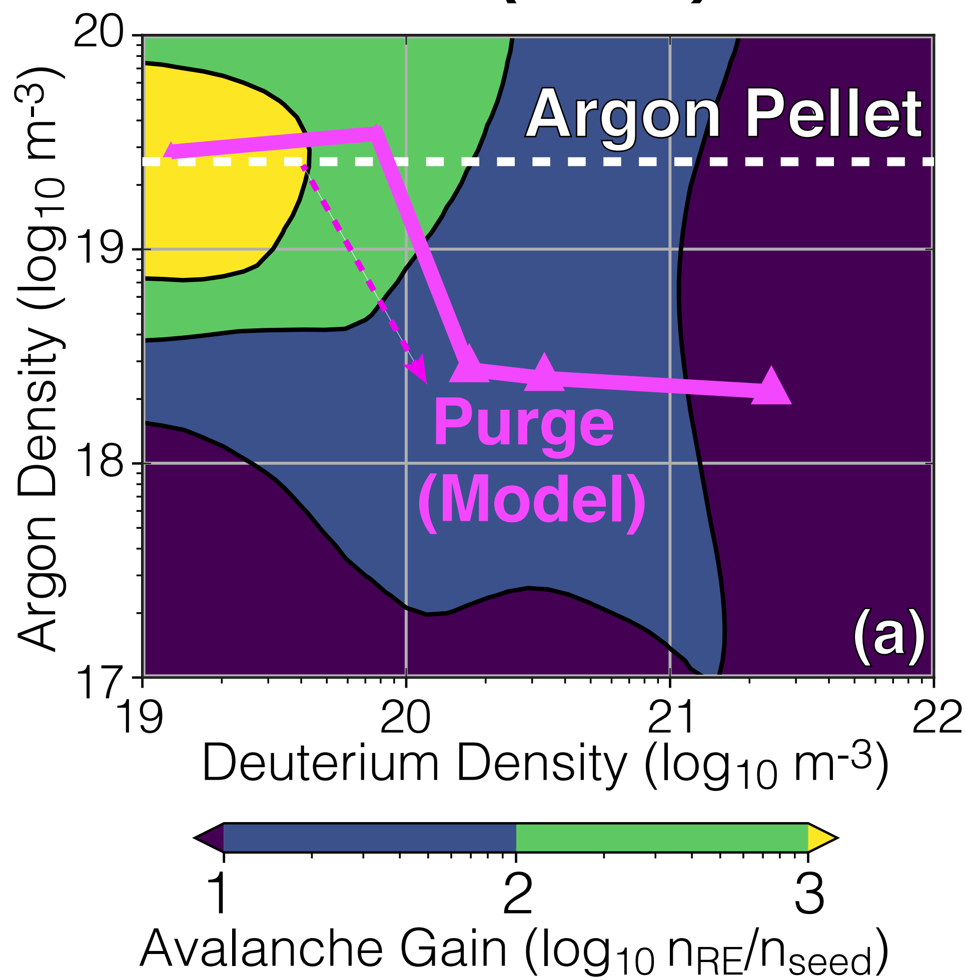
Avalanche: High-Z Purge Improves Gain in DIII-D & JET

- **D2 reduces Ar quantity through "purging" phenomenon**
  - Less avalanche gain since fewer bound electron secondary targets
- **DIII-D: about a factor of 10 improvement in the (small) gain factor**
- **Purge computed with Hollmann's model[1]**

DIII-D (0.5 MA)



[1]Hollmann et al, PoP 2020

Courtesy P. Aleynikov

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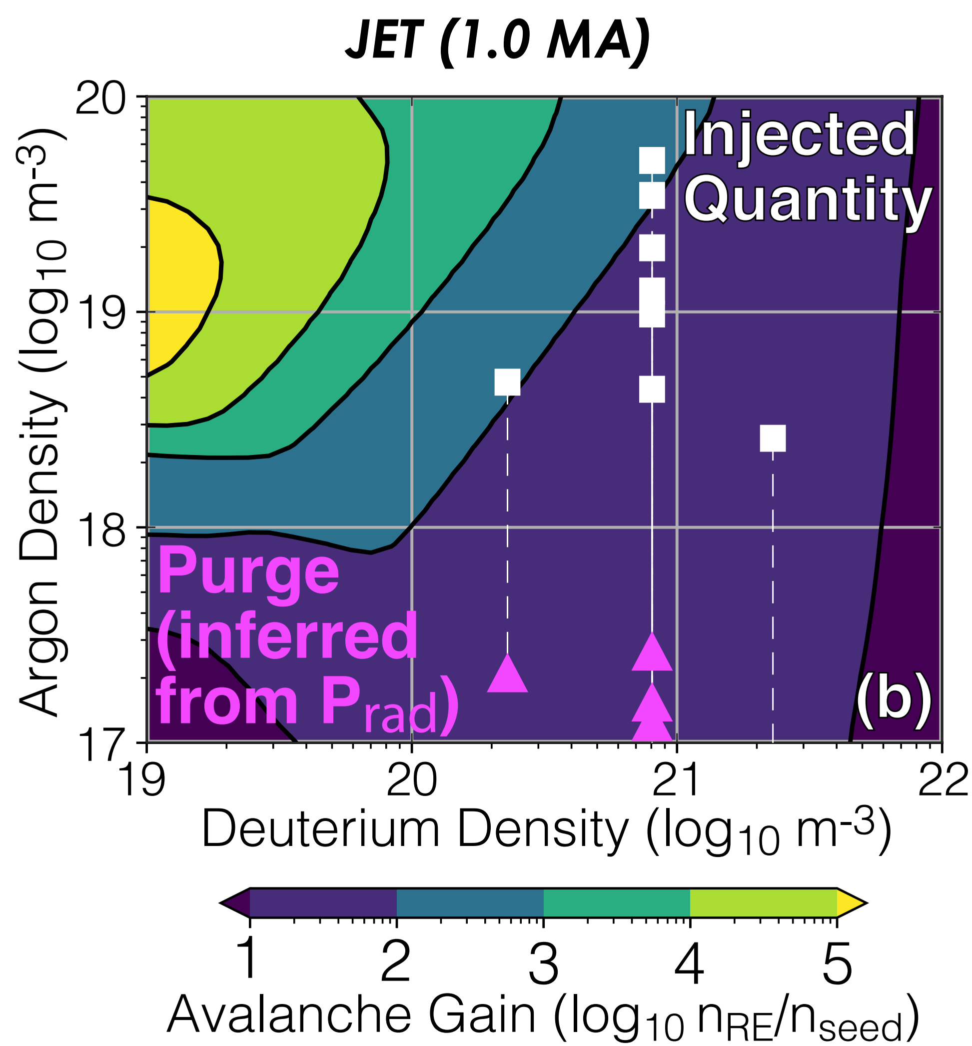
Avalanche: High-Z Purge Improves Gain in DIII-D & JET

- **JET's D2 quantity fixed by the pellet geometry (3 sizes)**
- **Finer scan carried out in Ar quantity**
- **@ High Ar / high avalanche gain: "remnant" RE beam is re-born after near-total loss!**
  - Suggests RE remnant not less than $1/10^5$ of initial at these conditions

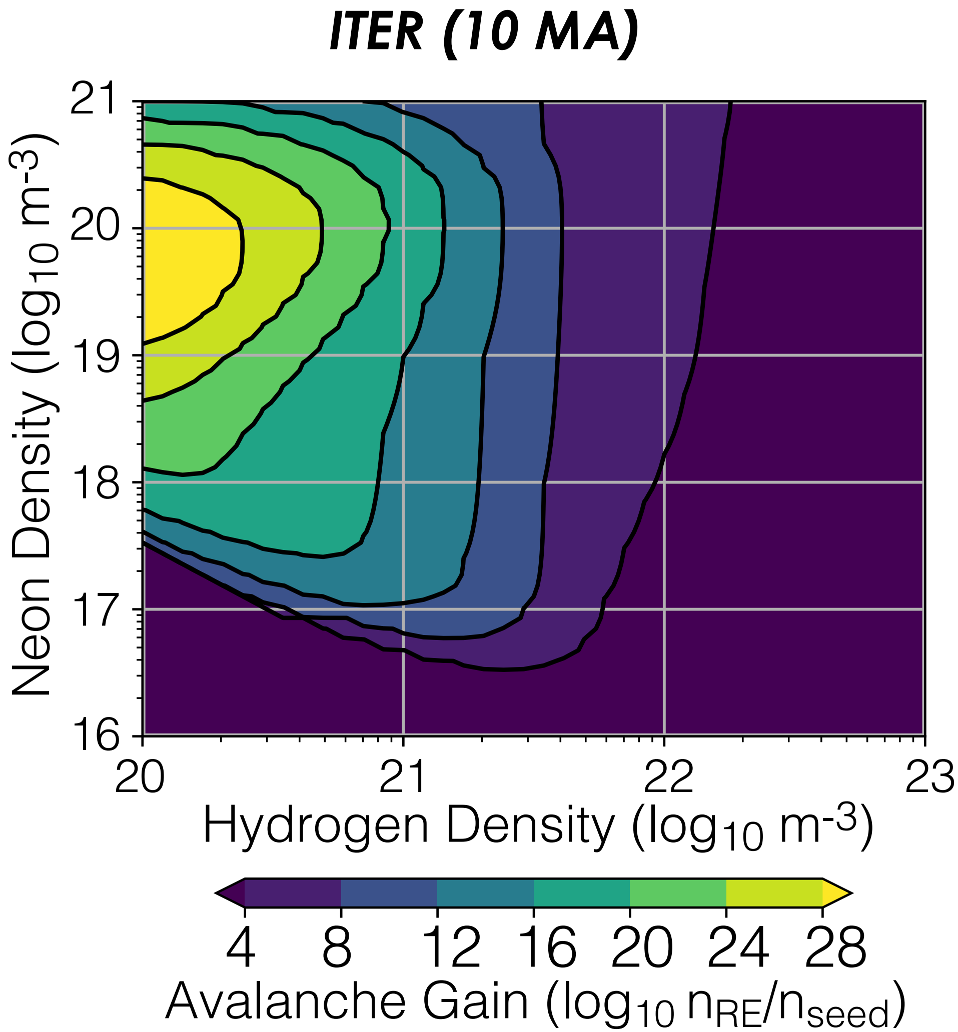


Courtesy P. Aleynikov

EUROfusion

ITER: Optimization space in H & Ne Requires Navigation to Promote Benign Termination (+ TQ/CQ Mitigation)

- **ITER avalanche gain space qualitatively similar, but numbers way higher**
  - If you exclude ex-vessel flux more like 10^{14} maximum



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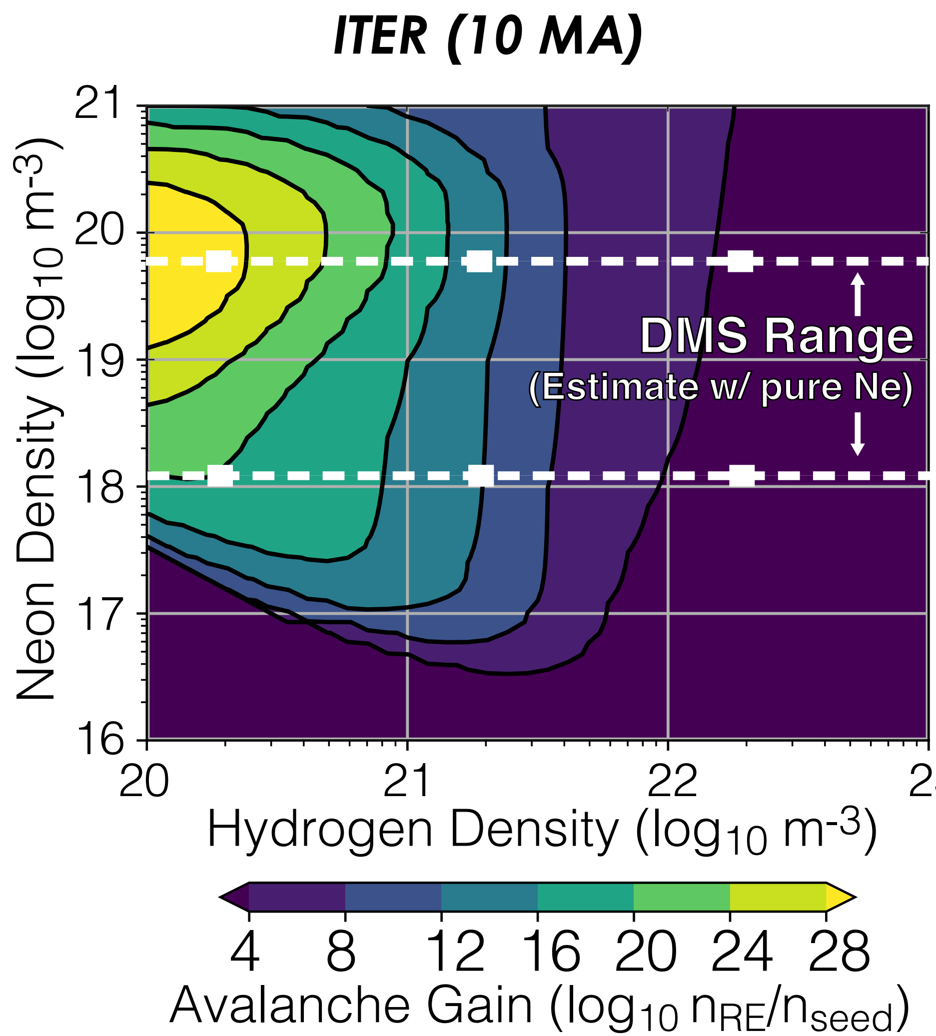
- **TQ/CQ Mitigation Sets Limits on Primary injection**
  - Pure Ne shown
  - Ne + H_2 Mixture ??



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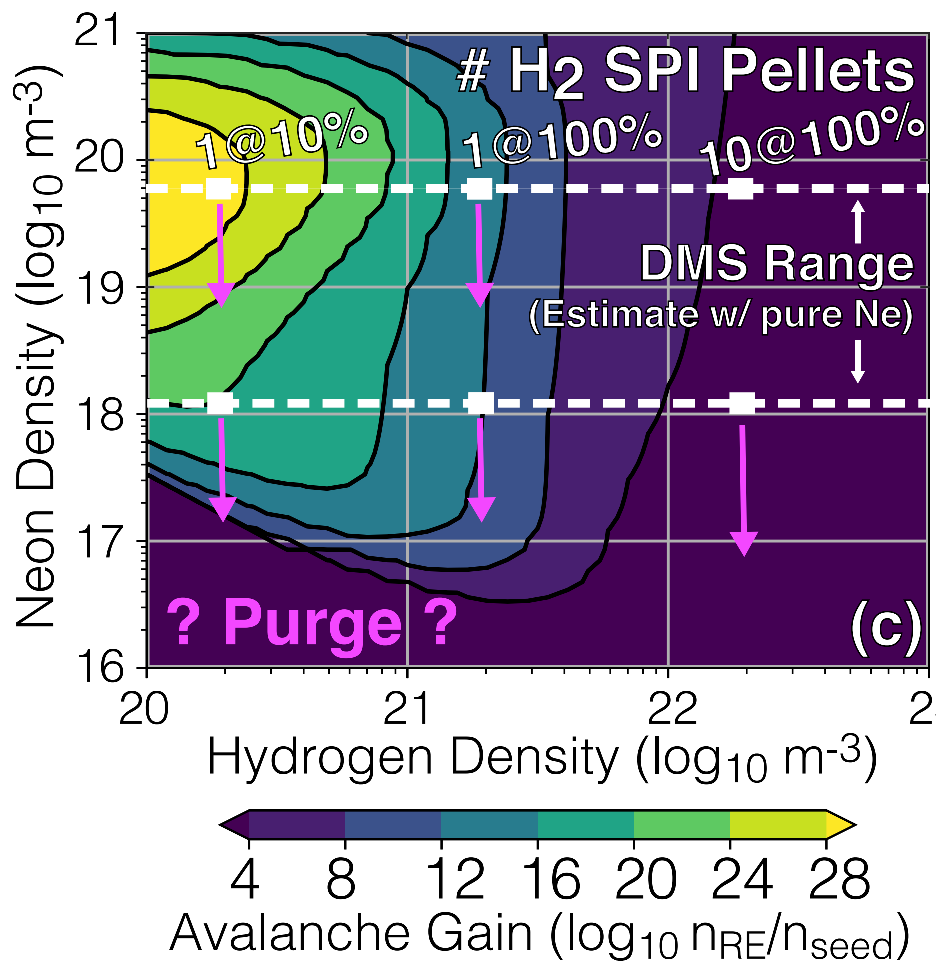
- **TQ/CQ Mitigation Sets Limits on Primary injection**
  - Pure Ne shown
  - Ne + H_2 Mixture ??
- **SPI pellet size also fixed**
  - Purge should bring it down
- **Low Ne quantity could make gain more manageable**

ITER (10 MA)



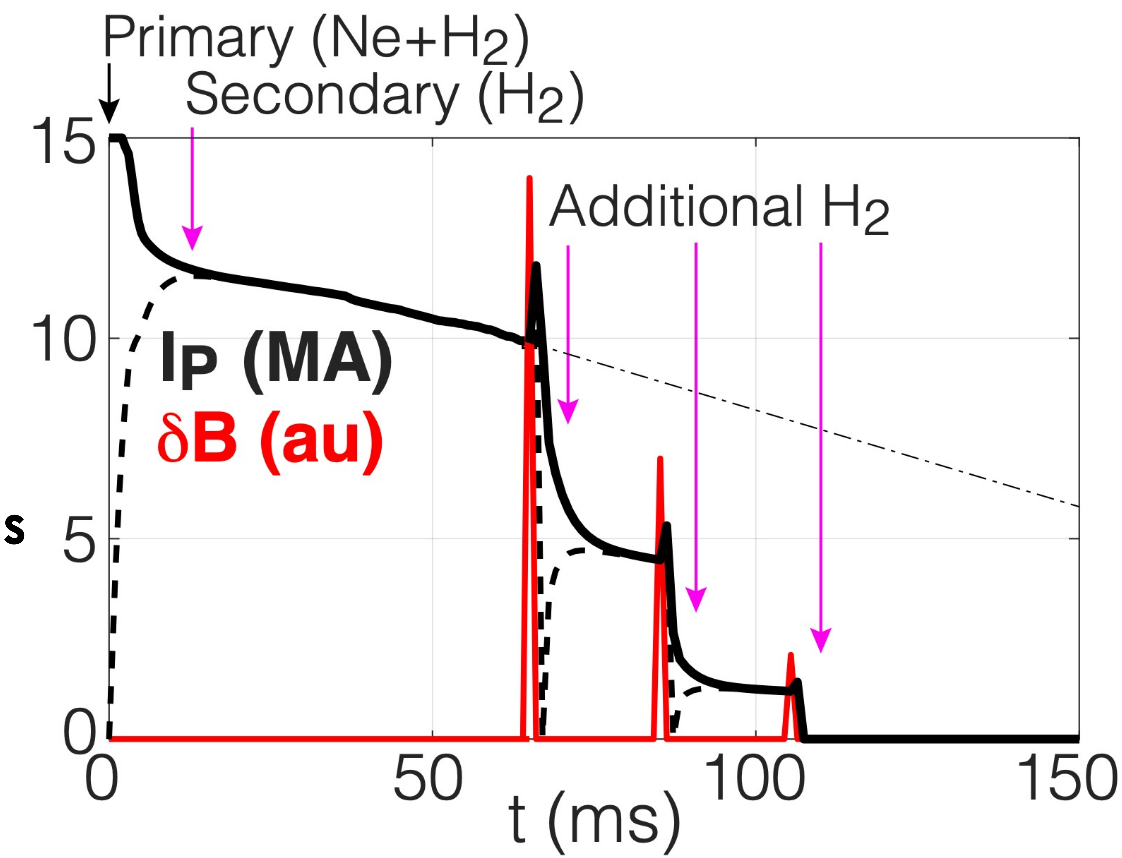
Courtesy P. Aleynikov

As Large Gain Likely Unavoidable, Deployment in ITER DMS Likely Will 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



Conclusion: Extrapolation of Benign Termination to ITER

- **Equilibrium Evolution: Likely access to low q during VDE**
  - Unless "high-Z-like" termination scenario appears first
- **Kinetic Energy handling: If large $\delta B/B$ accessed, expect large-scale dispersion / large wetted area**
  - Will be accessed ? See first half of presentation for insights.
  - Can ITER RE beam be recombined?
- **Magnetic Energy handling: Large avalanche gain hard to avoid**
  - Plausible scenario is repetitive events with H_2 injection in between

Open Questions: Still Many

- **Purge Physics / Dynamics with (Ne + H_2) vs (Ar + D_2)**
  - Making REs with Ne should be a priority experimentally
  - 1-D Diffusion Model should validate purge physics with this mixture

- **Prediction of $\delta B/B$**
  - Extended MHD is the way forward

- **JET dataset and the role of integer safety factor / external kink**
  - Not always clear – sometimes double tearing mode? Why?

- **VDE dynamics: VDE growth rate, Z-effect, more to understand**

- **Dynamics of Repetitive Benign Terminations?**
  - Need ITER to do this without high-Z

Bonus Slides