DIII-D Exploration of the D_2 + Kink Path To Runaway Electron Mitigation in Tokamaks

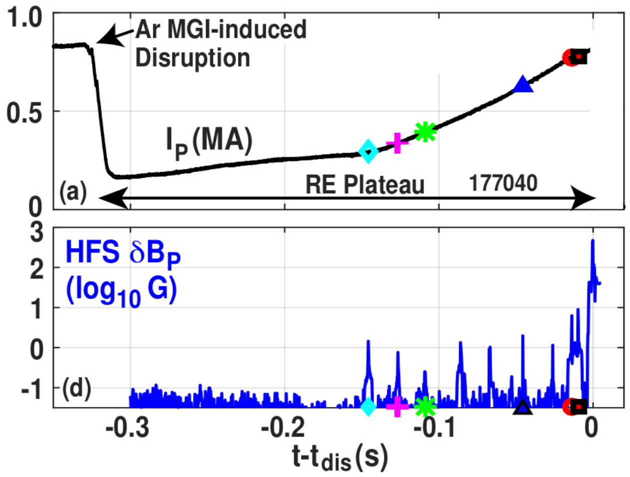
by:

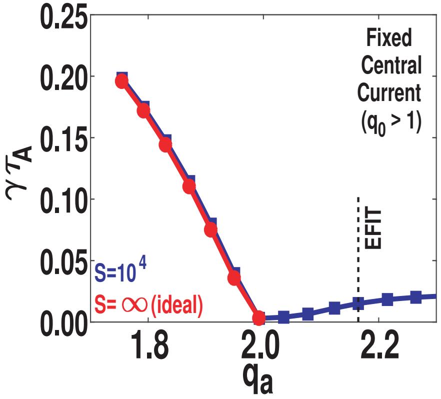
C. Paz-Soldan[1]

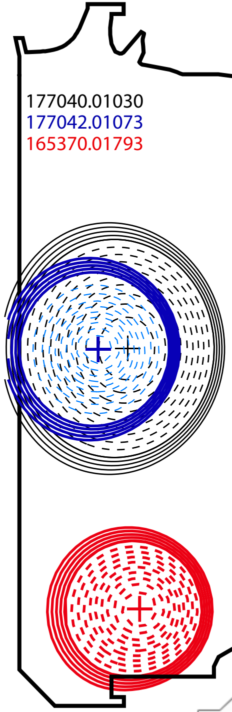
with contributions from:

Y.Q. Liu,[1] N. Eidietis,[1] E. Hollmann,[2]
P. Aleynikov,[3] A. Lvovskiy,[1] D. Shiraki,[4]

[1]GA, [2]UCSD, [2]IPP-Greifswald, [4]ORNL







Presented at the

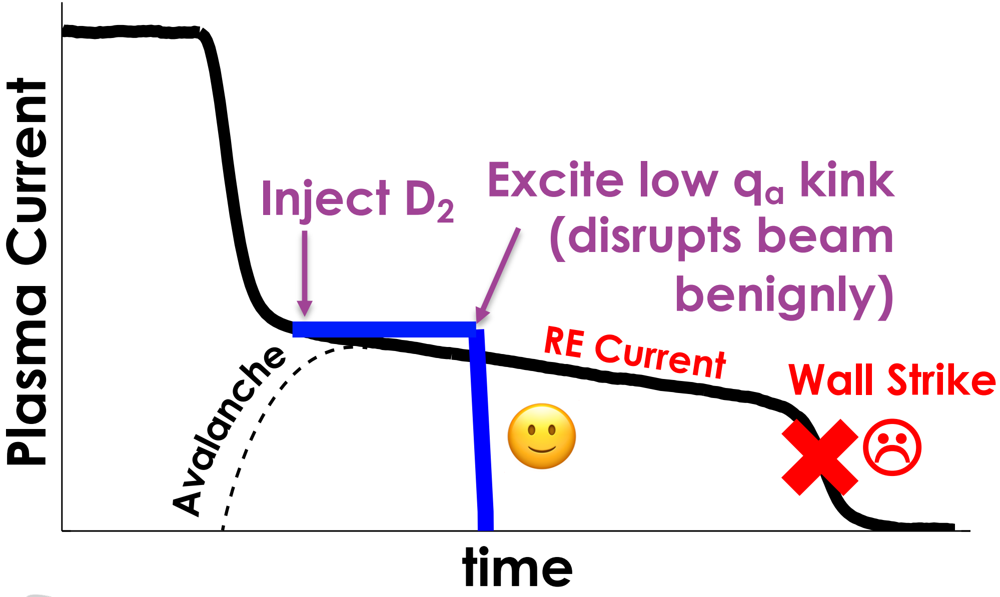
1st IAEA-TM on Disruptions
(Remote Talk)
July 20-23, 2020

DIII-D NATIONAL FUSION FACILITY

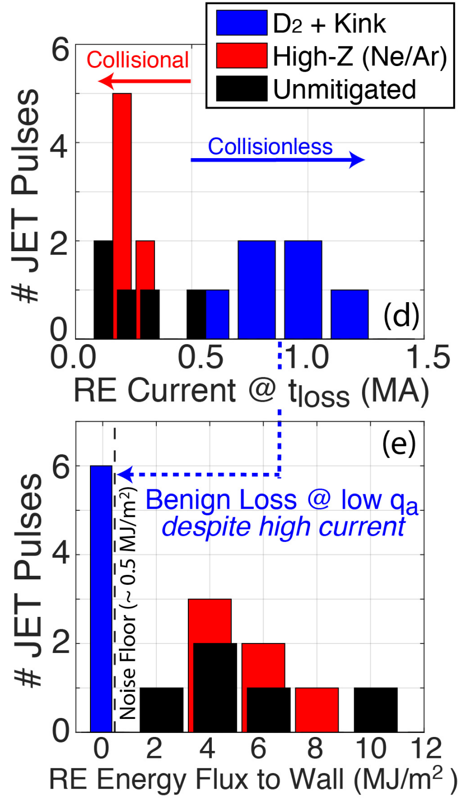
GENERAL ATOMICS

Excite a Disruptive Kink Instability of RE Beam: An Alternate Path to RE Mitigation?

Recipe requires "purged" (collisionless) RE beam, via D_2 secondary injection



Low Energy Flux to First Wall !! (JET)



C. Reux et al, this conference
C. Paz-Soldan et al, IAEA-FEC "2020"

DIII-D NATIONAL FUSION FACILITY

Outline

- Phenomenology of RE Loss at Low q_a
- Observed Pathways to D_2 + Kink RE Loss
- MHD Modeling of RE Loss via Kink Modes
- Database Study: Effect of Z, q_a, I_P

Outline

- Phenomenology of RE Loss at Low q_a
- Observed Pathways to D_2 + Kink RE Loss
- MHD Modeling of RE Loss via Kink Modes
- Database Study: Effect of Z, q_a, I_P

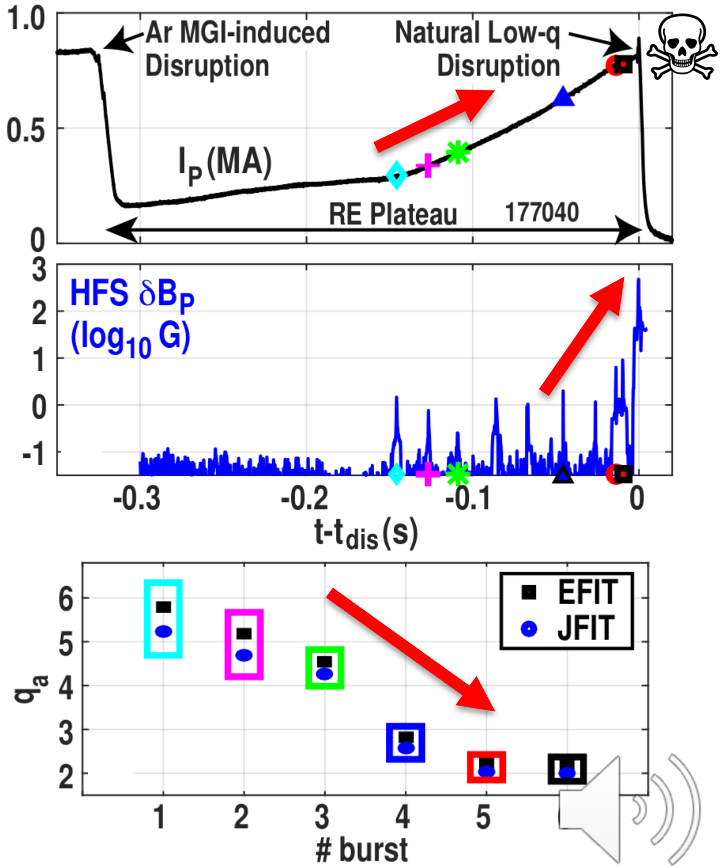
Low Safety Factor RE Dynamics Accessed by Deliberately Increasing the RE Beam Current

- Applied loop voltage (solenoid push) causes increased RE current

- Eventually reach $q_a = 2$

- Magnetic bursts get progressively larger as $q_a = 2$ is reached
  - 1 kG kink mode → **δB/B ~ 5%**

- RE beam is promptly terminated by huge δB/B (second disruption)



C. Paz-Soldan et al, PPCF 61 054001 (2019)

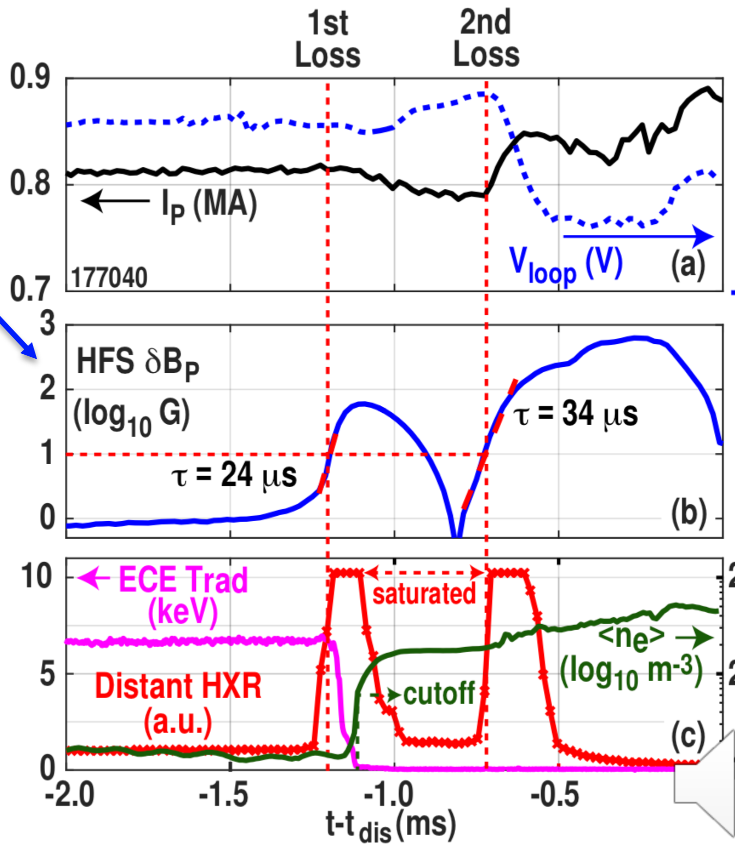
DIII-D NATIONAL FUSION FACILITY

Detailed View Reveals Prompt Loss of all REs Followed by Prompt Conversion of RE to Bulk Current

Detailed order of events (sub-ms)

1. Stab. boundary crossed (q_a=2)
2. Fast (Alfvenic) MHD excited
3. HXR flash + ECE drop → RE loss
4. $n_{e,free}$ jump → RE to bulk current
5. I_P spike → disruption of beam
6. Regular current quench follows
   – No indications of surviving REs

(this one was a double-burst)



C. Paz-Soldan et al, PPCF 61 054001 (2019)

DIII-D NATIONAL FUSION FACILITY

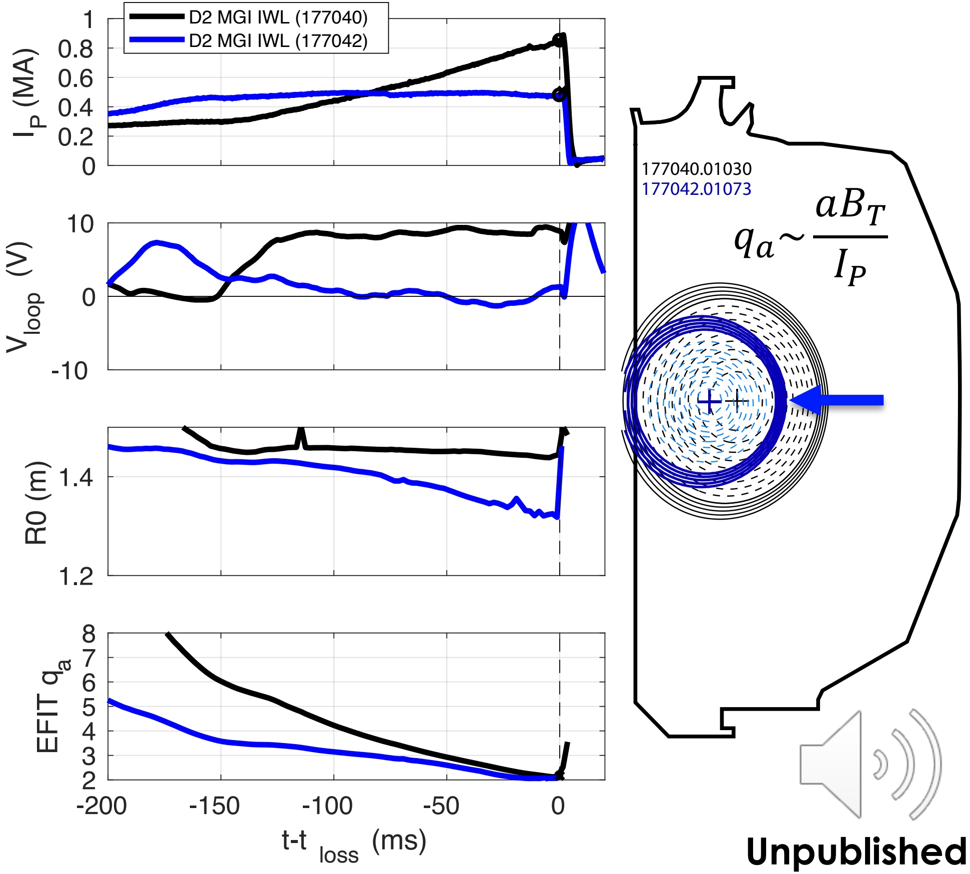
Outline

- Phenomenology of RE Loss at Low q_a
- Observed Pathways to D_2 + Kink RE Loss
- MHD Modeling of RE Loss via Kink Modes
- Database Study: Effect of Z, q_a, I_P

Same Phenomenon seen with constant I_P & VDE Access Low q_a Instability via Cross Section Contraction

<u>Low Safety factor (q_a~2) achieved at constant I_P by</u>

- Imposed cross-section shrinkage (outer PF push)



Unpublished

DIII-D NATIONAL FUSION FACILITY

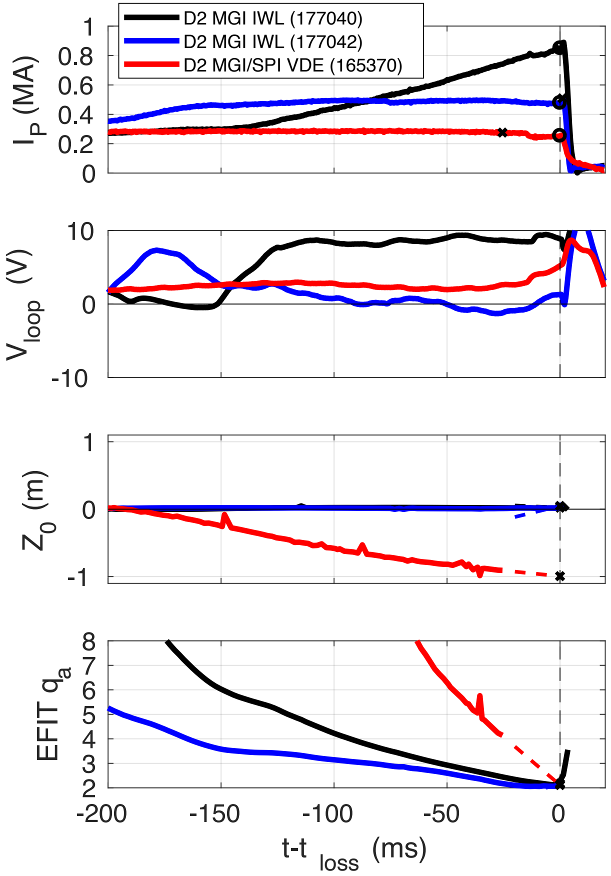
C. Paz-Soldc

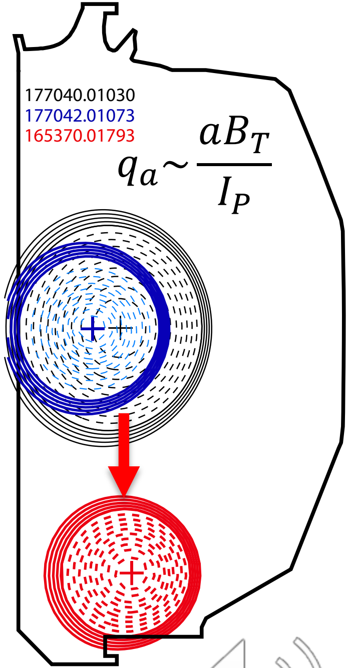
Same Phenomenon seen with constant I_P & VDE Access Low q_a Instability via Cross Section Contraction

Low Safety factor (q_a~2) achieved at constant I_P by

- Imposed cross-section shrinkage (outer PF push)
- Natural cross section shrinking during VDE

Requires High D_2 Purity to See Effect





$$q_a \sim \frac{aB_T}{I_P}$$

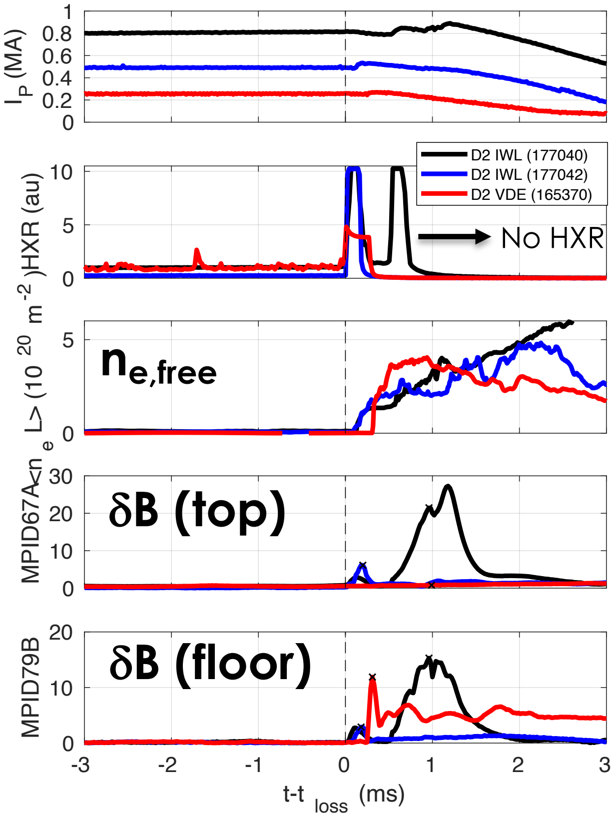
Unpublished

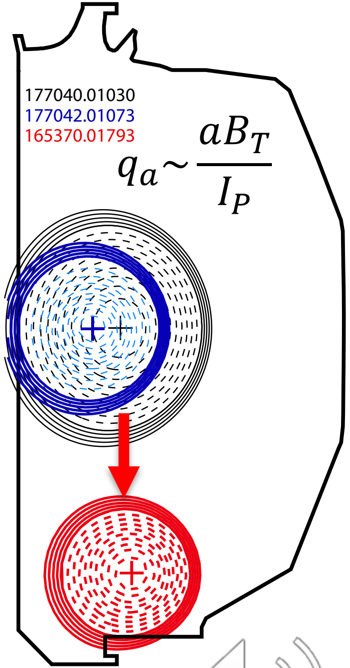
Final Loss Phase again Reveals 1-2 Massive δ B Bursts … Followed by Prompt Conversion of RE to Bulk Current

- **1-2 large δB & HXR bursts in all cases**

- **I_P spike & CQ without HXRs**
  - No magnetic→kinetic energy transfer implied
  - See C. Reux's talk for calculated values in JET

Requires High D_2 Purity to See Effect





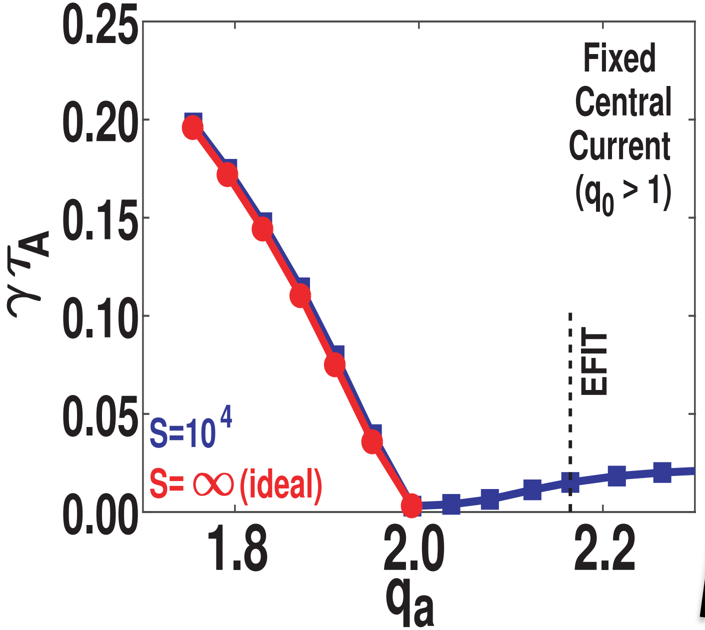
Unpublished

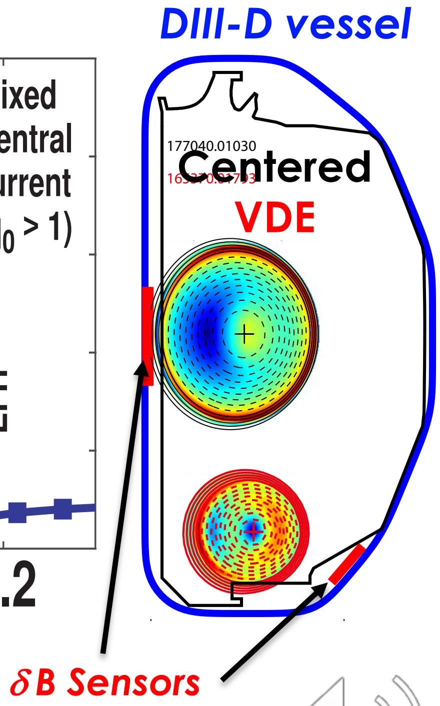
Outline

- Phenomenology of RE Loss at Low q_a
- Observed Pathways to D_2 + Kink RE Loss
- **MHD Modeling of RE Loss via Kink Modes**
- Database Study: Effect of Z, q_a, I_P

q_a~2 Kink Instability of RE Beam Modeled[1] with MARS-F in Centered and Vertically Unstable Equilibria

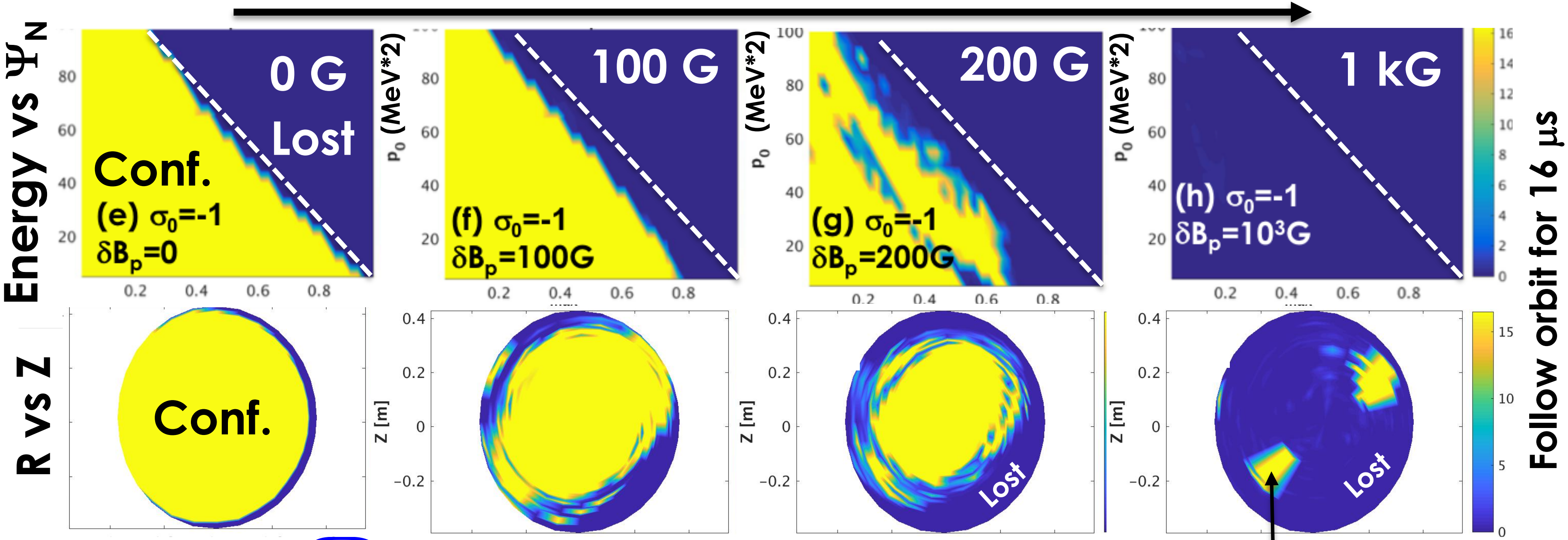
- **Use resistive MHD framework**
  - No special provision for REs
- **Recovers fast (~10 μs) Alfvenic MHD growth**
  - As seen in experiment
- **Extract q_a~2 kink mode eigenfunction trace RE orbits with δB scaled to experiment**
- **δB's quoted are *at the*** ***magnetic sensor location***

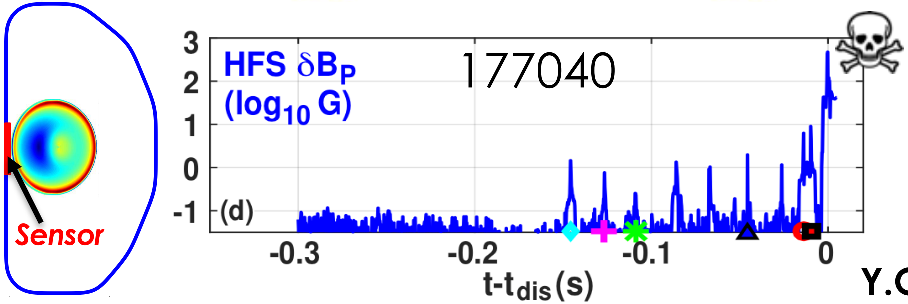




Y.Q. Liu et al, Nucl Fusion 2019
Y.Q. Liu et al, PoP 2020 (in review)

Orbit Following w/ MARS-F Predicted Mode Structure Used to Determine the Critical δB for Complete RE Loss

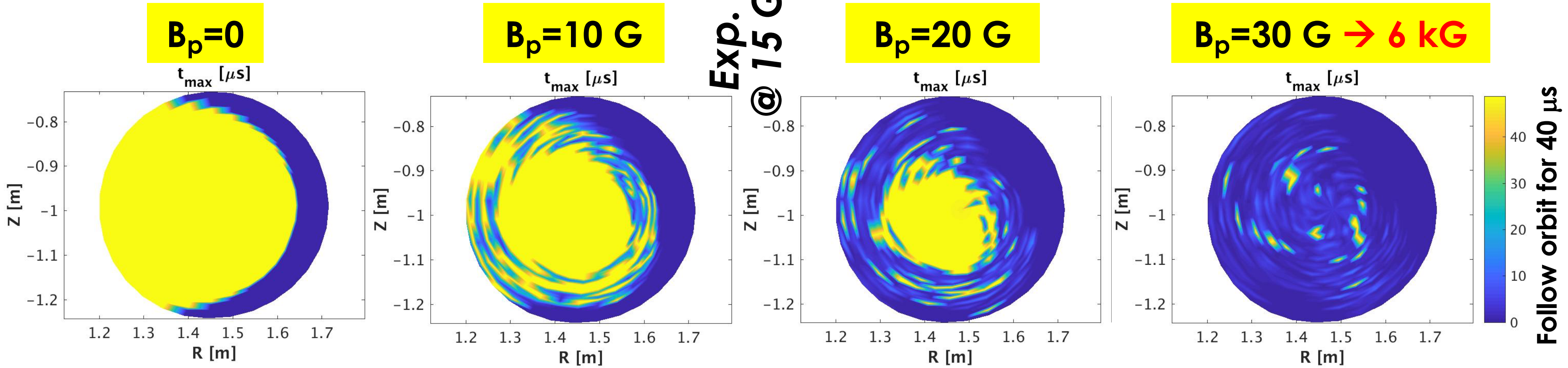




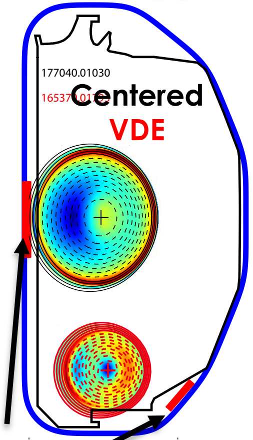
Likely will be lost after 16 μs ... kink active for ~ 500 μs

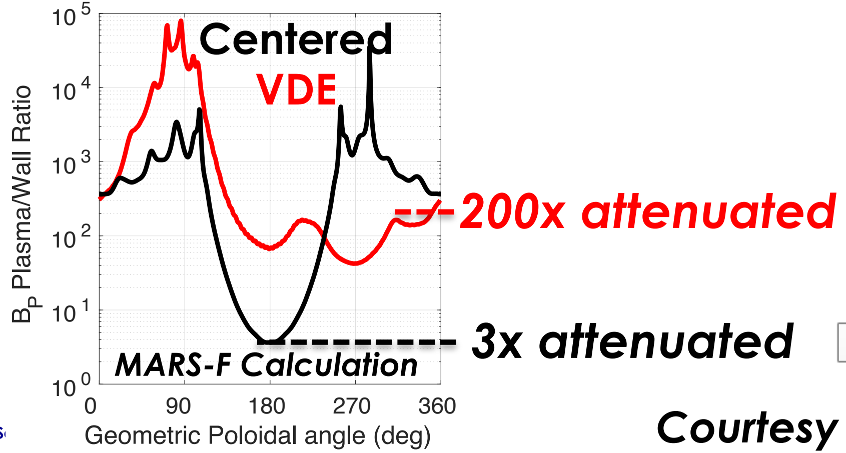
Y.Q. Liu et al, Nucl Fusion 2019
Y.Q. Liu et al, PoP 2020 (in review)

VDE Case Reveals Similar δB Required for Loss … after Distance Correction (200x) Included



Following only λ_0=0.1, 25 MeV



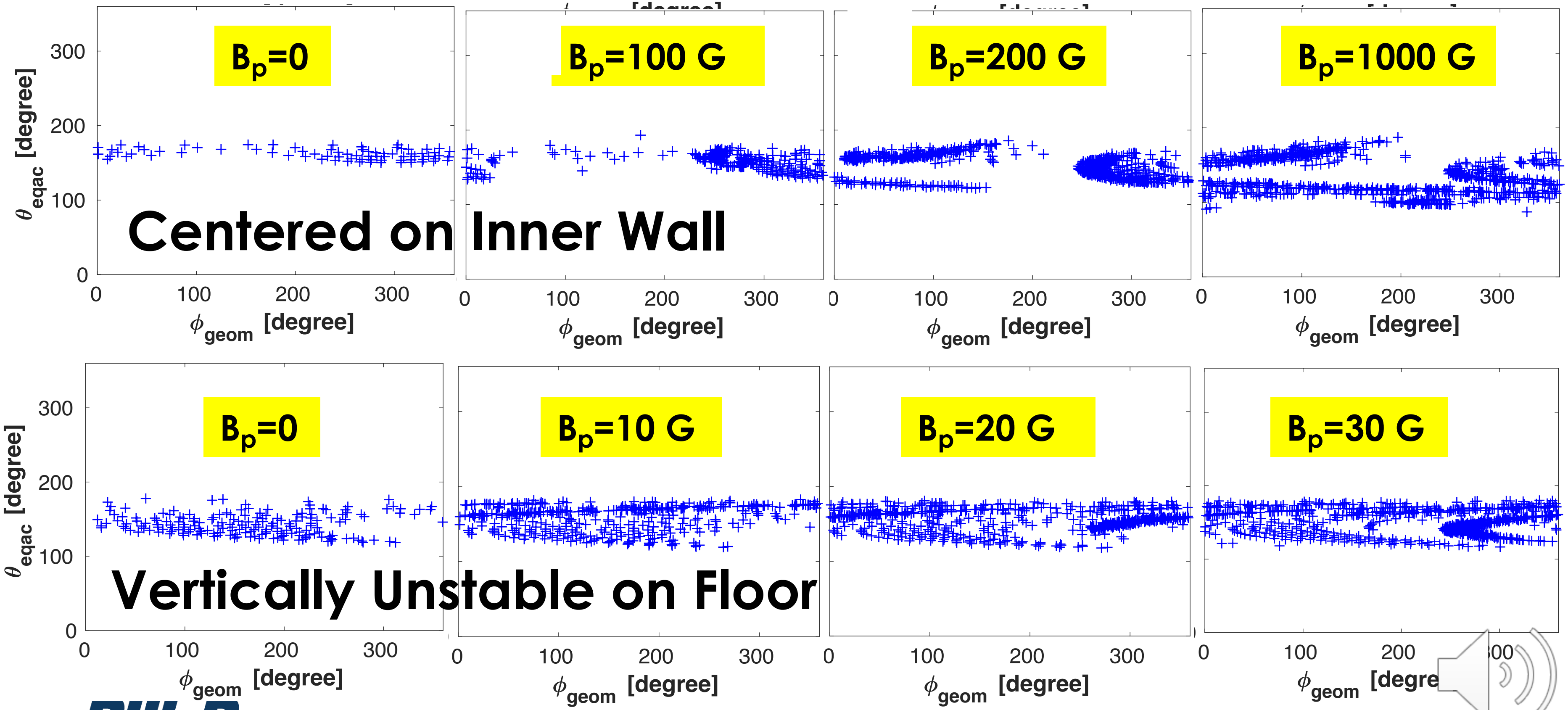


C. Paz-S

Courtesy Y.Q. Liu

DIII-D NATIONAL FUSION FACILITY

Loss Pattern Becomes more Distributed as δB Increases in Both Scenarios = Hypothesis For Lack of Wall Heating



Courtesy Y.Q. Liu

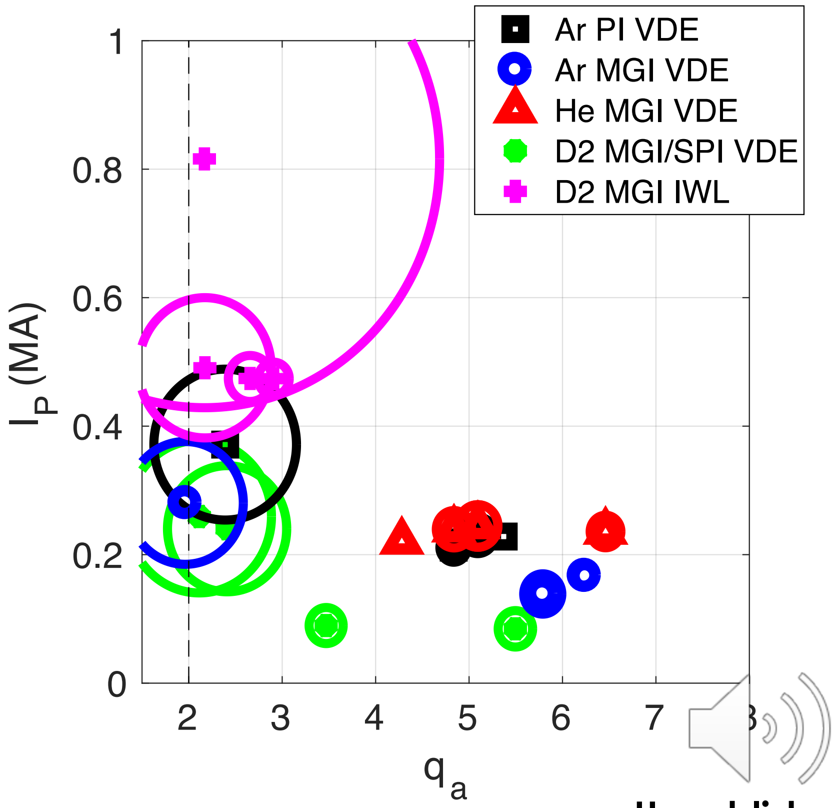
Outline

- Phenomenology of RE Loss at Low q_a
- Observed Pathways to D_2 + Kink RE Loss
- MHD Modeling of RE Loss via Kink Modes
- Database Study: Effect of Z, q_a, I_P

Database Reveals Largest δB at low q_a and high I_P
No Clear δB Difference with Species if I_P/q_a matched

- **Highest δB @ high I_P & low q_a**
  - Only accessed with D_2 so far
- **Roughly similar MHD (δB) so long as I_P & q_a matched**
  - Systematic data lacking
- **Let's look deeper**

Radius = size of MHD (δB)

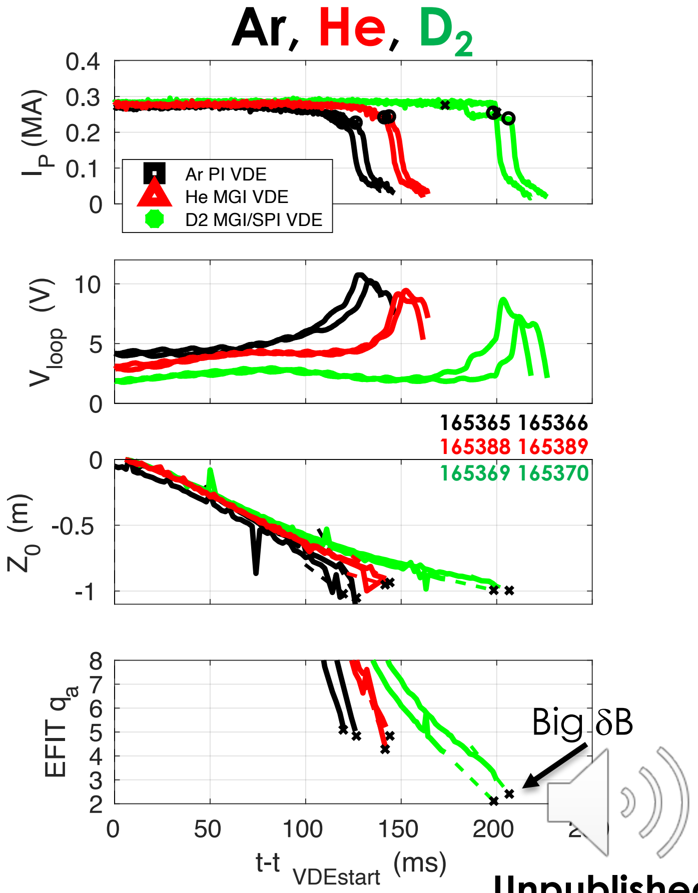


Unpublished

DIII-D NATIONAL FUSION FACILITY

2016 VDE Experiment Supports Difficulty of Low q_a & High I_P Equilibrium Access with high-Z Injection

- **Same VDE imposed by external PF coils, background species varied**
- **D_2 cases shrink to low q_a @ const. I_P**
  - Large kink @ q_a=2 then dumps all REs
- **Ar/He cases suffer many smaller kinks at higher q_a and lose I_P**
  - Don't reach low q_a @ high I_P (if ever)
  - Helium appears "high-Z" in this regard

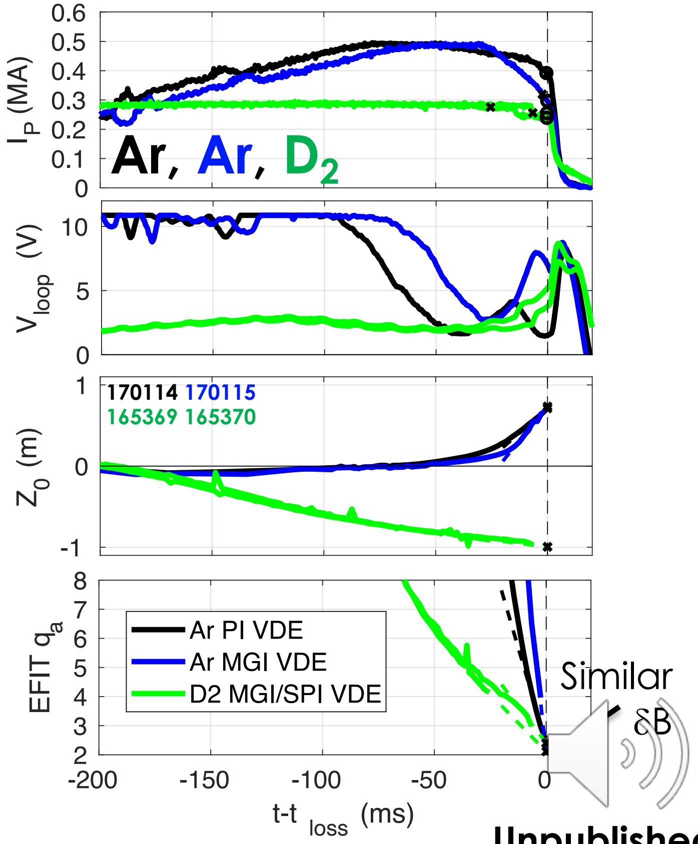


Unpublished

DIII-D NATIONAL FUSION FACILITY

Matching I_P and q_a from Low to High-Z Only Seen when Starting From Higher I_P Pre-VDE

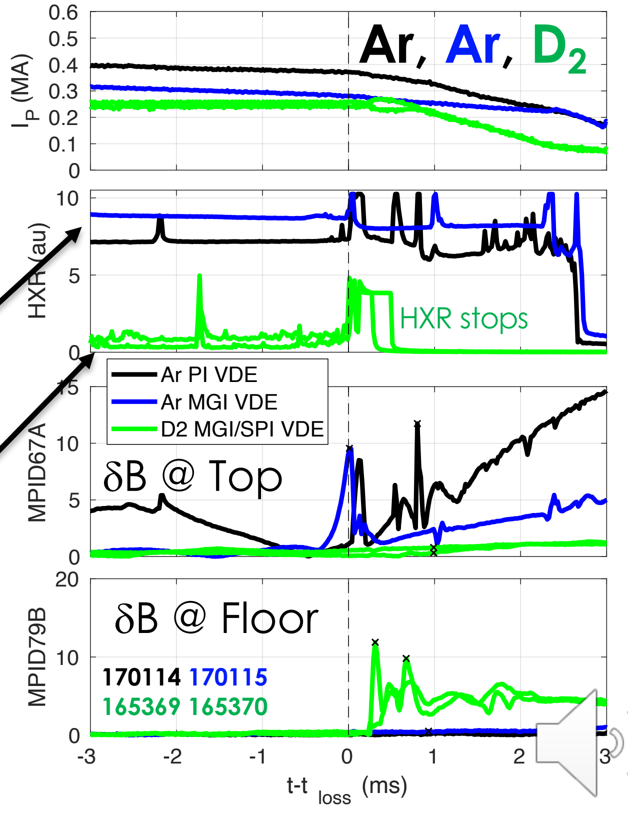
- **Similar MHD Magnitude found at final loss (matched I_P/q_a)**
- **Solenoid stops pushing in high-Z cases**
  - Need dedicated experiment



Unpublished

Matching I_P and q_a from Low to High-Z Only Seen when Starting From Higher I_P Pre-VDE

- **Similar MHD Magnitude found at final loss (matched I_P/q_a)**
- **Solenoid stops pushing in high-Z cases**
  - Need dedicated experiment
- **Multiple kinks seen with High-Z**
  - REs persist / are regenerated
- **Single kink + I_P spike seen with D_2**
  - REs dumped in one event

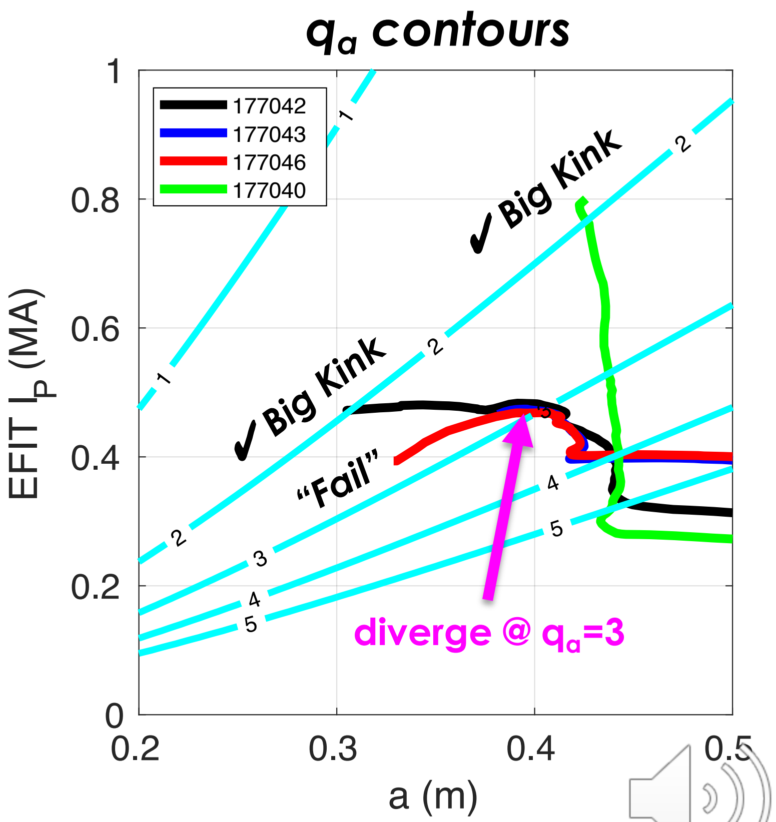


Unpublished

DIII-D NATIONAL FUSION FACILITY

Discharges with Same Program Can Fail to Reach q_a=2

- **Same I_P & Shape Program**
  - Qty of Ar used to form RE differs
  - "Clean" vs "Dirty" Beams
- **Divergence of trajectories occurs when crossing q_a=3**

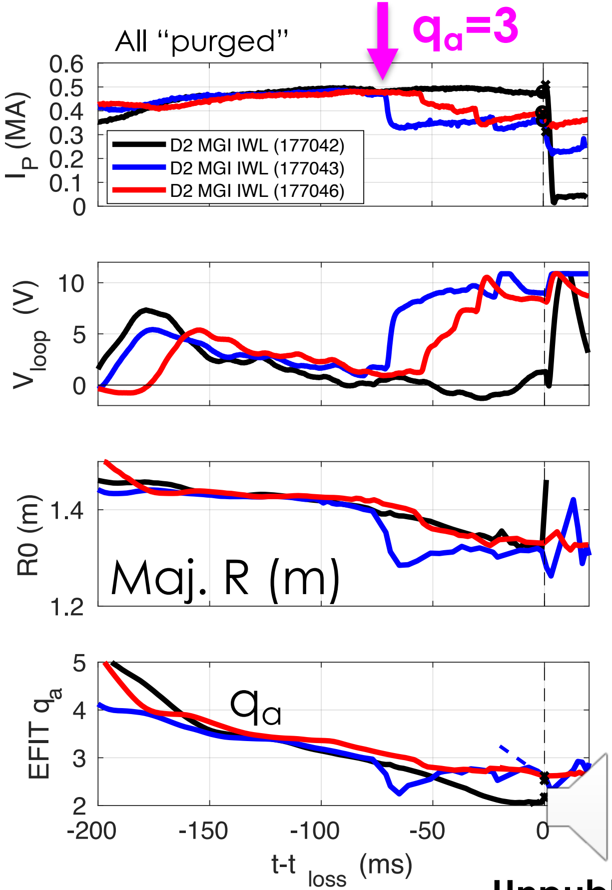


Unpublished

DIII-D NATIONAL FUSION FACILITY

Discharges with Same Program Can Fail to Reach q_a=2

- **Same I_P & Shape Program**
  - Qty of Ar used to form RE differs
  - "Clean" vs "Dirty" Beams
- **Divergence of trajectories occurs when crossing q_a=3 w/ minor kinks**
  - MHD loses some of I_P in 2/3 shots
  - Compression not enough for q_a=2

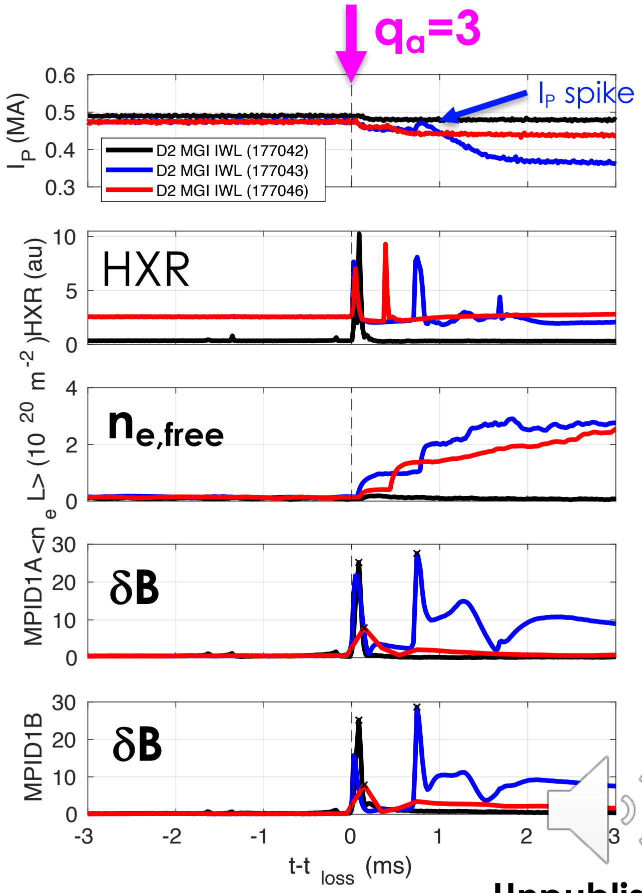


Unpublished

DIII-D NATIONAL FUSION FACILITY

Discharges with Same Program Can Fail to Reach q_a=2

- **Same I_P & Shape Program**
  - Qty of Ar used to form RE differs
  - "Clean" vs "Dirty" Beams
- **Divergence of trajectories occurs when crossing q_a=3 w/ minor kinks**
  - MHD loses some of I_P in 2/3 shots
  - Compression not enough for q_a=2
- **δB at q_a=3 similar in all 3 shots !!**
  - Beams with more Ar loses "purge", becomes resistive, suffers minor kinks
  - Cleaner D_2 beam survives q_a=3 without losing collisionless state



Unpublished

DIII-D NATIONAL FUSION FACILITY

Conclusions

- **Phenomenology of RE Loss at Low q_a**
  - 1-2 big kinks dump ***all*** REs benignly – ***a new path to RE mitigation?***
  - Kinetic energy spread throughout first wall via large wetted area
  - Magnetic energy dissipated Ohmically during long CQ without REs
- **Observed Pathways to D_2 + Kink RE Loss**
  - Phenomenon seen with 1) rising I_P, 2) constant I_P, 3) with imposed VDE
  - All examples in DIII-D have D_2 secondary injection and reach q_a=2
- **MHD Modeling of RE Loss via Kink Modes**
  - Supports large $\delta B/B$ (~ 5 %) dumping all REs with large wetted area
- **Database Study: Effect of Z, q_a, I_P**
  - Find D_2 "purity" enables eq. access to low q_a @ high I_P → big δB
  - Low purity: high q_a minor kinks increase Z & drop I_P. → No big δB
  - High purity: survives minor kinks to reach big kinks @ low q_a / high I_P
  - Similar δB at all purities if q_a and I_P are matched – but impact differen

Disclaimer and Acknowledgements

Work supported by US DOE under DE-FC02-04ER54698 and DE-SC0020299

Bonus Slides

Open Questions for Further Exploration (Exp. + Model)

- **Does the recipe require the solenoid to be pushing?**
  - Can we promote low q_a in ITER via PF pushing? (Area contraction)
- **D_2 Purity: Why does same δB lead to different outcomes on I_P?**
  - Direct kinetic effect of δB interaction with f(E) in high vs low Z?
  - Role of partial screening in avalanche? (see bonus slide)
- **Can we minimize internal inductance in ITER? (RE seed @ edge)**
  - Allows access to large kink instability (large δB) at higher q_a
- **What is the maximum D_2 purity achievable in ITER?**
  - … while maintaining high-Z for primary injection / TQ loads
- **How do we predict the δB assuming low q_a is accessed?**
  - Will the RE loss be complete enough that the subsequent CQ doesn't re-accelerate REs via avalanching (purity matters also)?

My Views on Differences Observed from JET:

- **Almost all central features are the same. Idiosyncrasies exist:**
- **JET sees phenomenon at q_a=2,3,4,5 while DIII-D only at q_a=2**
  - Internal Inductance role? If JET is lower l_i, expect big kinks @ q_a>2
  - Magnitude of I_P may matter: higher I_P may compensate higher q_a
- **JET reports largest δB found with high argon fraction & low I_P**
  - ???
  - Possible role of dB/dt? See C. Reux's talk at this conference…

Abstract

DIII-D Exploration of the D2+Kink Path to Runaway Electron Mitigation in Tokamaks

C. Paz-Soldan[1], Y.Q. Liu[1], N. Eidietis[1], E. Hollmann[2], P. Aleynikov[3], A. Lvovskiy[1], D. Shiraki[4],

[1]General Atomics, PO Box 85608 San Diego, CA 92186-5608, United States of America
[2]University of California-San Diego, La Jolla, CA 92093, United States of America
[3]Max-Planck Institute for Plasma Physics, Greifswald, Germany
[4]Oak Ridge National Laboratory, Oak Ridge, TN 37831, United States of America

A novel path to runaway electron mitigation in tokamaks found by combining an impurity-free (deuterium) background plasma with current-driven kink excitation at low safety factor (qa) is being explored for its application to ITER and beyond. This contribution will 1) summarize published DIII-D results [1], 2) present more recent database studies and 3) discuss a planned DIII-D experiment targeting open questions in this topic.

Discussion of published [1] results will focus on the details of the final loss and magnetic reconstruction of the candidate instability. The detailed dynamics of the kink MHD-driven final loss using fast interferometry support a prompt (sub-ms) conversion of RE to bulk Ohmic current without regeneration. Sub-ms loss of REs is predicted to be due to a near-complete MHD-driven prompt loss of the RE population. MHD instability magnetic reconstruction reveals that early instabilities at high qa ($\gtrapprox 4$) are likely internal or resistive kinks (at higher poloidal mode number), while at qa $\approx$ 2 the most destructive instabilities are either internal or external kinks with low-order poloidal mode number (m=2). The HXR loss magnitude is found to be proportional to the perturbed magnetic field and exhibits a helical spatial pattern.

A recent database analysis reveals that similar dynamics to that discussed in [1] has also been observed in impurity-free vertically unstable RE beams, with large-scale MHD found as the plasma cross section contracts, lowering qa. This database also reveals that both a large RE current as well as a low qa promote the large kink amplitude needed to promptly deconfine the REs. The role of the background impurity content is found to modify the vertical instability dynamics but does not appear to clearly modify the kink amplitude if plasma current and qa are matched.

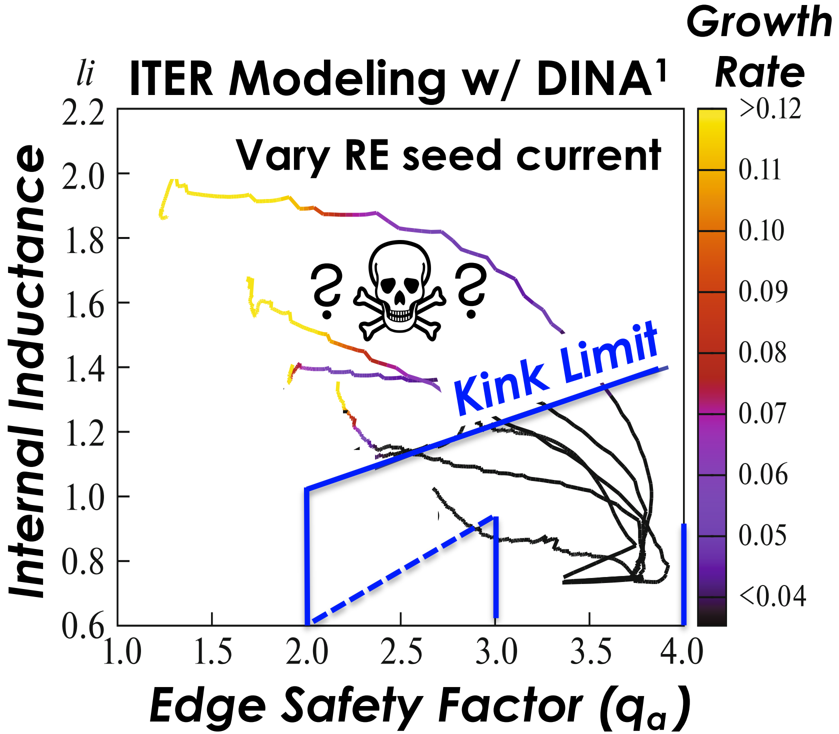
New DIII-D experiments are planned to assess several open questions related to this novel path to runaway electron mitigation. The experimental plan will be summarized, and if results are available by the time of the conference they will be presented in a preliminary fashion.

Work supported by US DOE under DE-FC02-04ER54698 and DE-SC0020299.

[1] C. Paz-Soldan et al, Plasma Phys. Control. Fusion **61** 054001 (2019)

RE Beams in Fusion-Grade Plasmas Should be More Susceptible to Low q_a Kink Instability due to High I_P

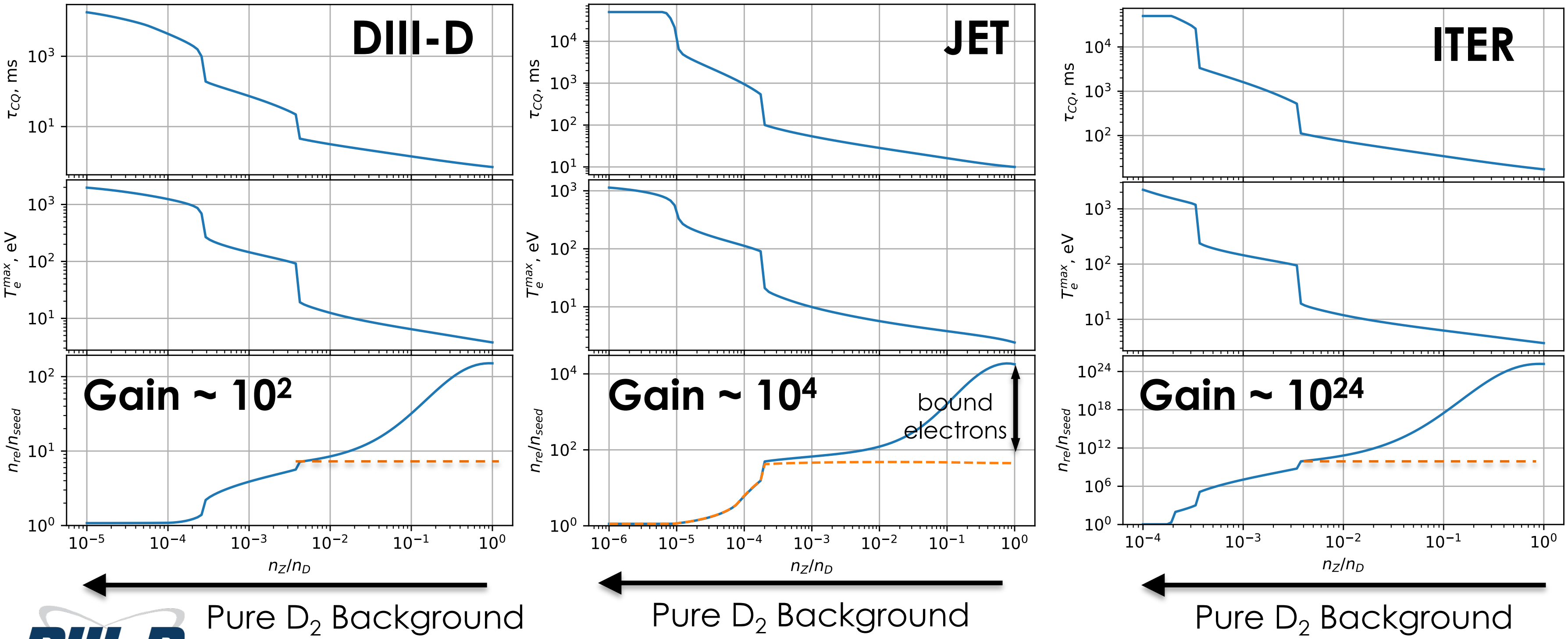
- **Predicted[1] RE beam equilibrium evolutions in ITER often cross macroscopic MHD limits**
  - Predict low safety factor (q_a)
- **More difficult to access low q_a in present experiments (low I_P)**
  - Significant radius contraction generally needed (& I_P still low)
  - It's a current driven instability !!



[1]Aleynikova et al, Plas. Phys. Rep. 2016

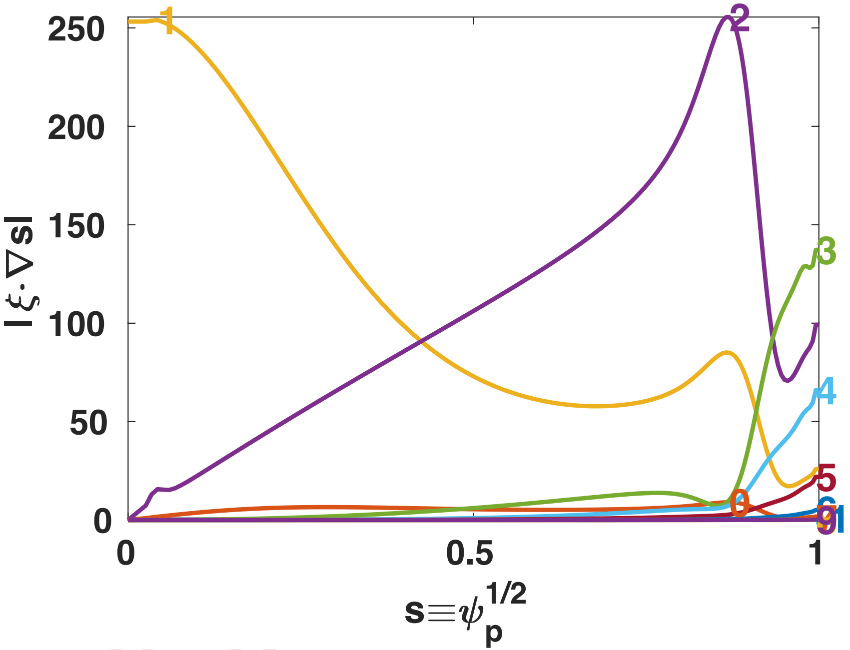
Post-Kink Current Quench Can Re-Avalanche REs … in ITER, Require Very High Fraction of RE Loss via Kink

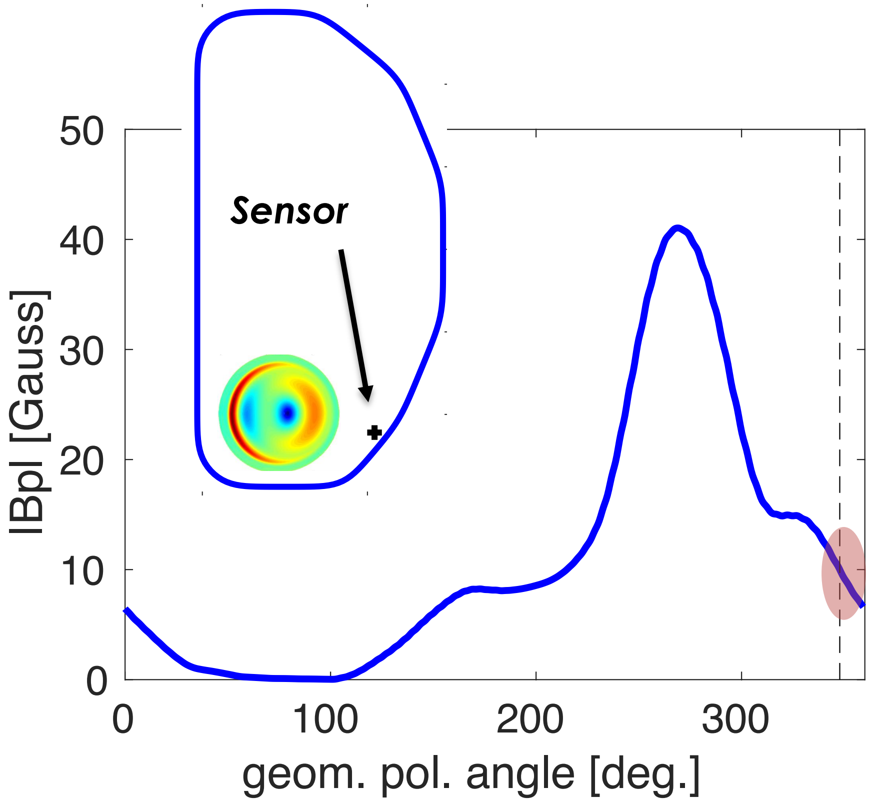
- **Increasing Purity Reduces Avalanche Gain at All Scales**



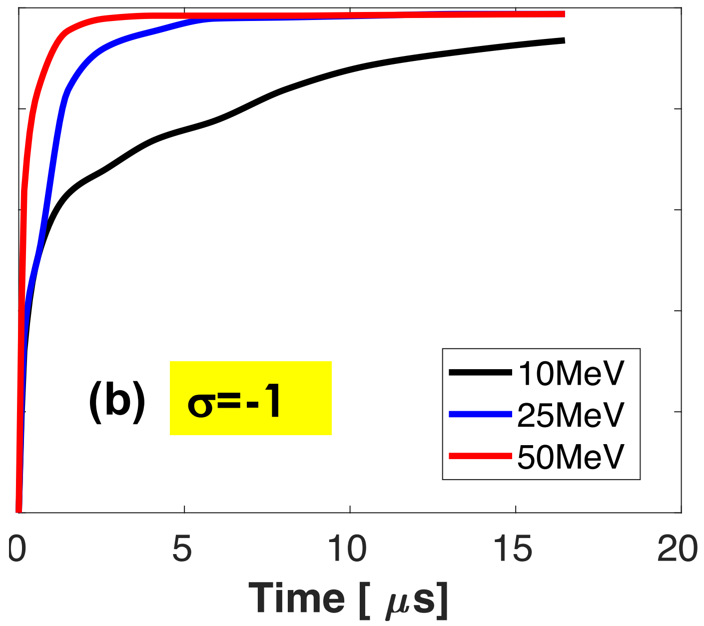
Courtesy P. Aleynikov

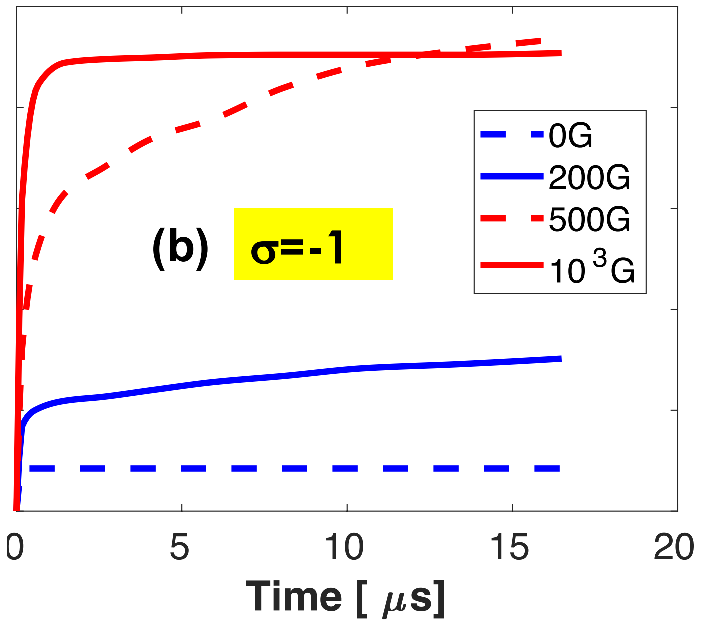
Instability Found in Vertically Unstable Case Sensor Samples Eigenfunction Weakly vs. Floor





Time Dependence of RE Loss for Centered Case

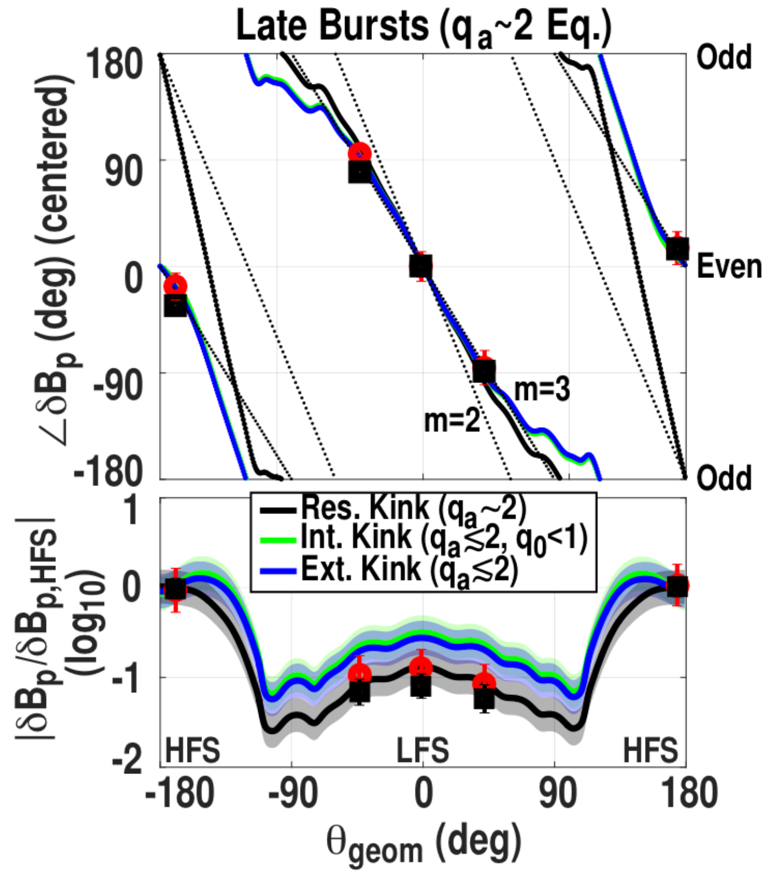




DIII-D
NATIONAL FUSION FACILITY

Magnetic Structure of Penultimate and Final Instability Consistent with External (or Internal + External) Kink

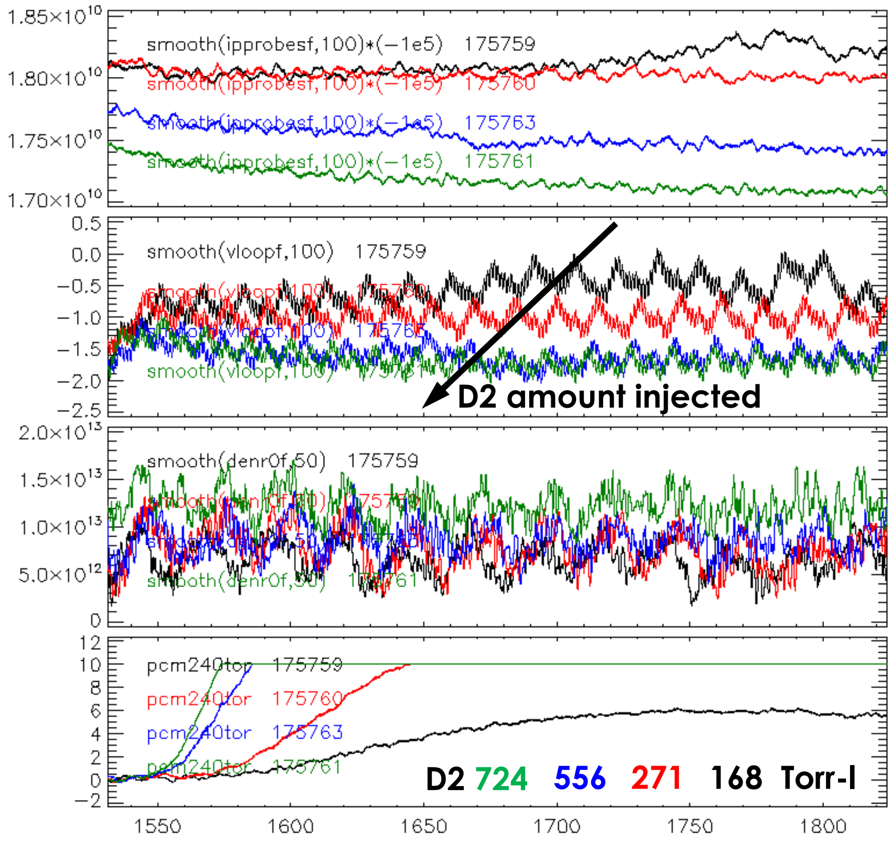
- **Data compared to MARS-F modeling**
  - MARS-F details: YQ Liu et al
- **Mode phase follows predictions for 2/1kink mode**
  - Resistive kink excluded based on mode phase
- **Amplitude strongly HFS localized due to spatial proximity of RE beam to HFS**



C. Paz-Soldan et al, PPCF 61 054001 (2019)

V_{loop} increases with D_2 injection - supports dissipation on neutrals

- Greater V_{loop} is required to run the RE current when more D_2 is injected
- This is a good support for hypothesis that RE dissipation on D_2 neutrals is important

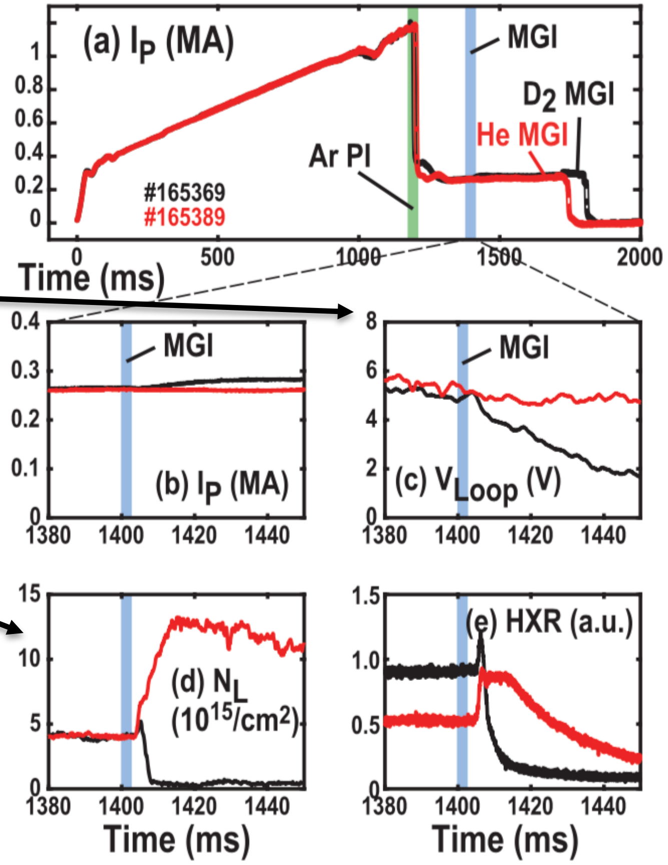


DIII-D NATIONAL FUSION FACILITY

Big Kink Phenomenon is Observed *Only* When RE beam is "Purged"[1,2] of Ar by D_2 Injection

<u>Features of D_2 Purged RE State:</u>

- **Ar expelled (no Ar line radiation)**
- **Collisionless (low V_{loop})**
  - Dissipation on D_2 neutrals[2,3]
- **Fully recombined (no $n_{e,free}$)**
- **Generically observed worldwide**



[1]Shiraki et al, NF 2018 [2]Hollmann et al, PoP 2020
[3]Lvovskiy et al, NF 2020

High-Level Goals of Upcoming Experiment

- **Explore role of VDE to big kink (compare centered to VDE)**
  - and related role of solenoid (regulating I_P vs not)
  - Cross kink boundary via I_P-dot, a-dot, B_T-dot
  - **Key data gap: D_2 VDEs at high IP w/ High-Z Match**

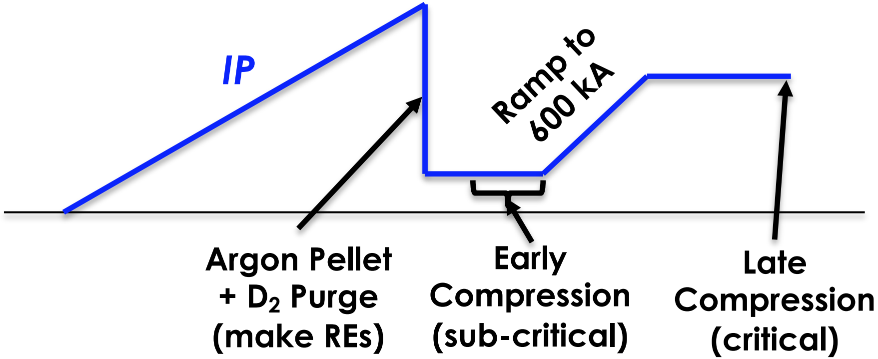
$$q_a \sim \frac{aB_T}{I_P}$$

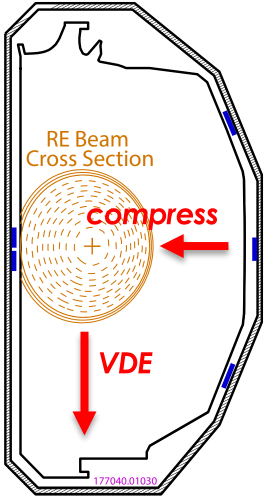
- **Explore role of D2 / Z / purity to kink + loss phenomenology**
  - Proposal: use centered beams to simplify this part

- **Explore stability space to big kink in DIII-D (more stats)**
  - Natural knobs are IP, BT, and beam size

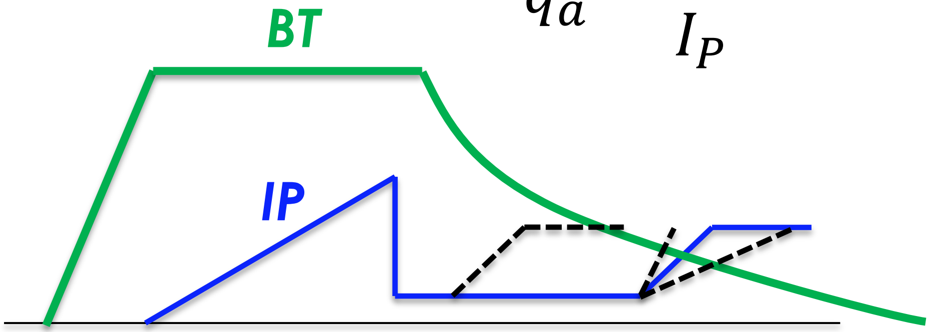
Important note: Plan around DIII-D's RE current limit of 0.6 MA

Simplest Path to Study Phenomenon of Interest: D_2 Purge, take I_P to limit, and slowly compress into CP





$$q_a \sim \frac{aB_T}{I_P}$$



I_P timing = B_T scan
I_P ramp rate = l_i scan