Exploiting Instability-Driven and Externally-Applied Magnetic Fields to Avoid and Mitigate Runaway Electrons

by

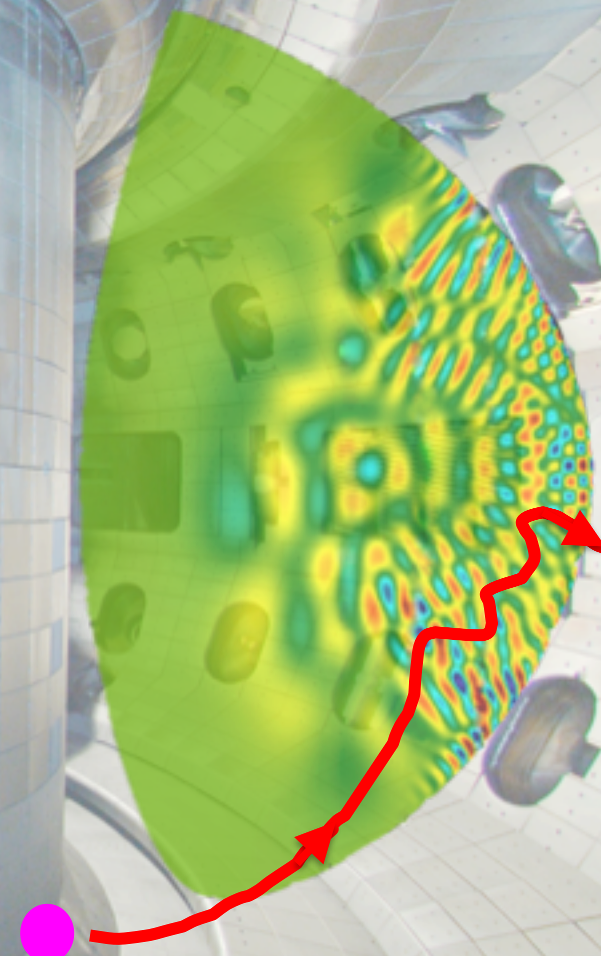
C. Paz-Soldan[1]

with contributions cited throughout

[1] General Atomics

Presented at:

TS Disruption Workshop, Aug 8th 2019



Seminar Outline

- **Introduction and Motivation**
- **Limit Maximum RE Energy with Whistler Modes**
- **Deconfine REs with Lab-Frame 3D Fields**
- **Deconfine REs with Alfvenic Modes**
- **Conclusion**

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ITER's Baseline Strategy for RE Mitigation Is Raising the Density (Collisional Dissipation)

Scientific validation of DMS requirements

Baseline concept:

- ***dissipating thermal and magnetic energy*** through line radiation
- ***preventing runaway electron formation*** by increasing the density

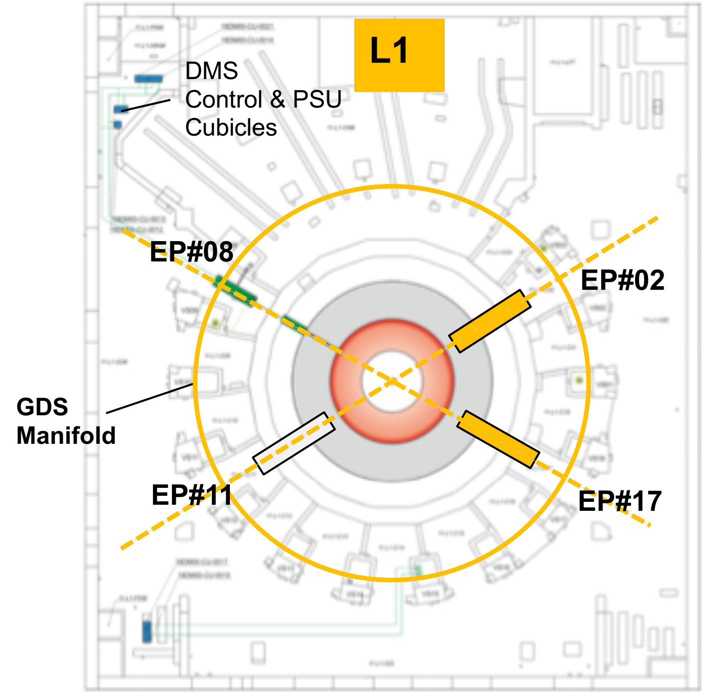
Baseline technique:

- *injection of* ***Ne***, ***Ar*** *and* ***D_2*** *through* ***Shattered Pellet Injection***

<u>Assumption:</u>

Assimilated density scales with number of injectors … all the way to the critical density for RE dissipation

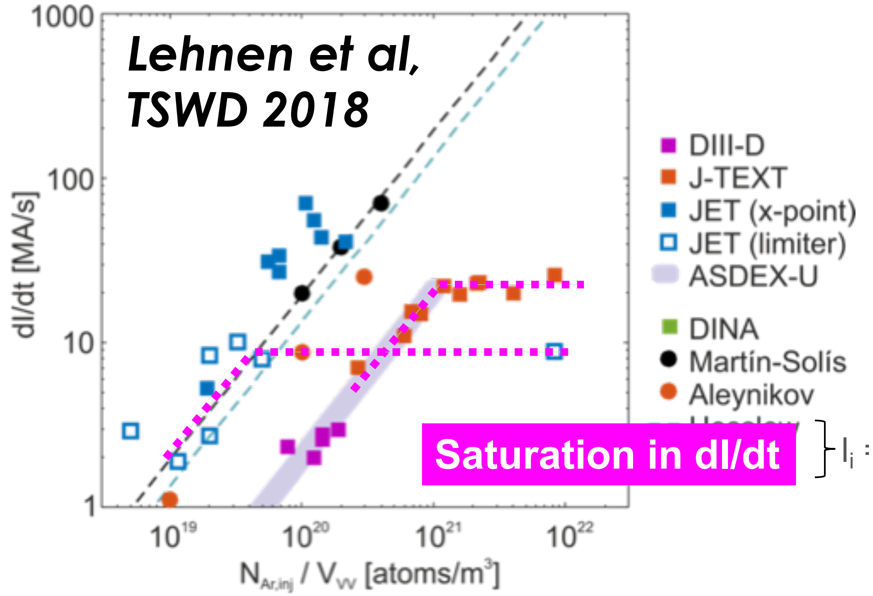
Will nature be this kind?



RE *Mitigation* via Collisional Dissipation Not Projected to Succeed in ITER (RE Avoidance TBD)

Fatal Flaw #1: Assimilation Saturation

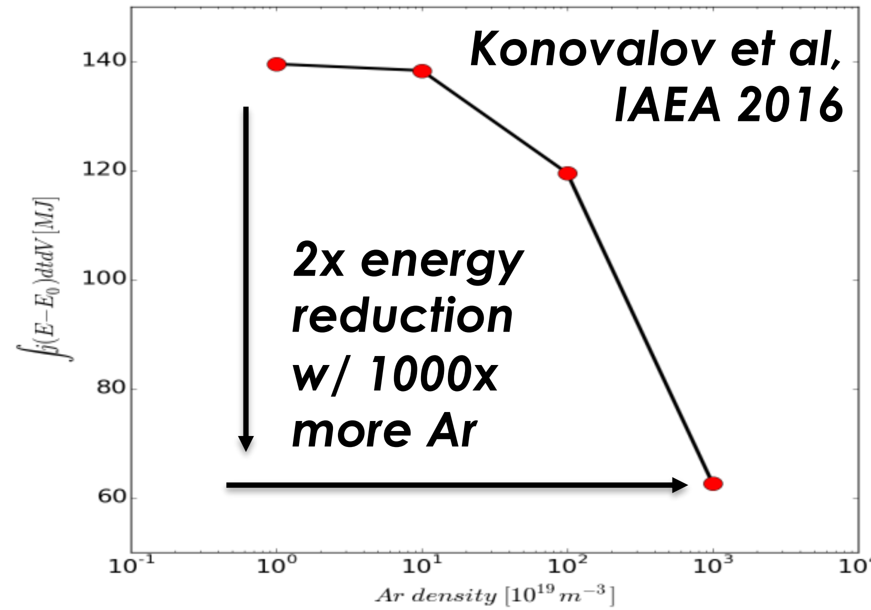
Dissipation vs Ar injected



More Argon ->
Colder Te ->
Slower Diffusion ->
Not enough Ar gets in before wall strike

Fatal Flaw #2: VDE Dynamics

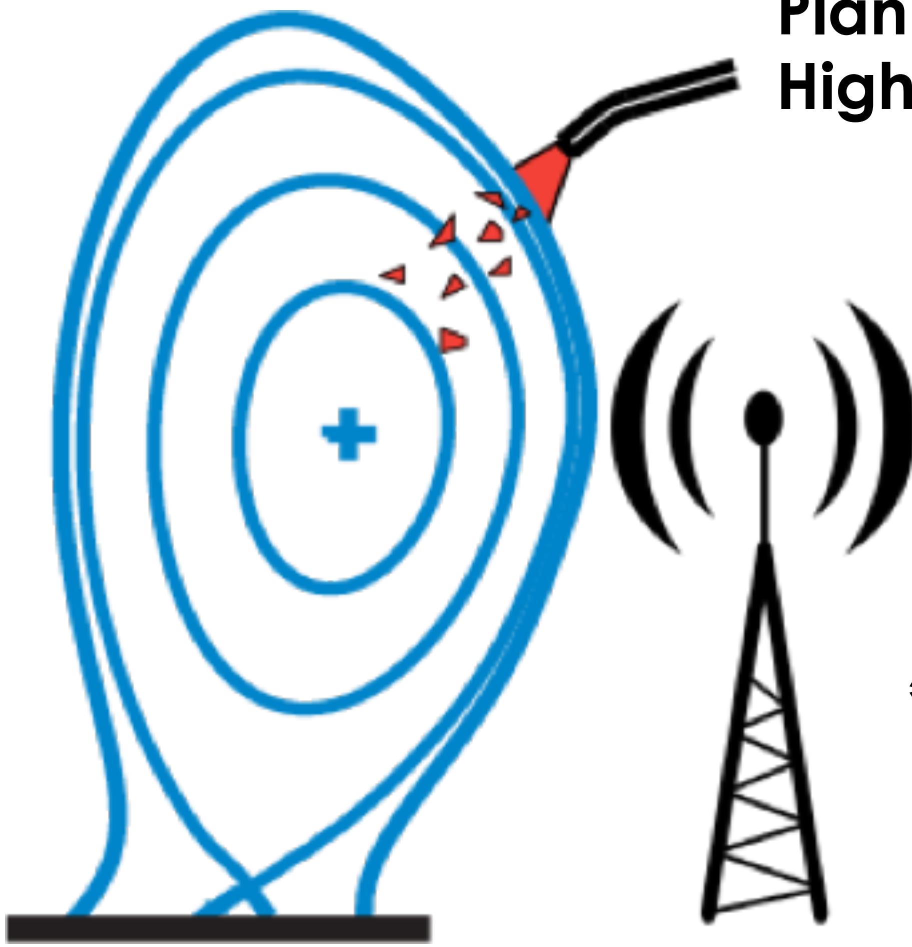
RE energy deposited to wall



More Argon ->
Faster RE dissipation ->
Faster IP drop ->
Faster VDE ->
~ Similar RE current @ strike

Can't be seen in present devices (wall time too short)

Is there a plan B?



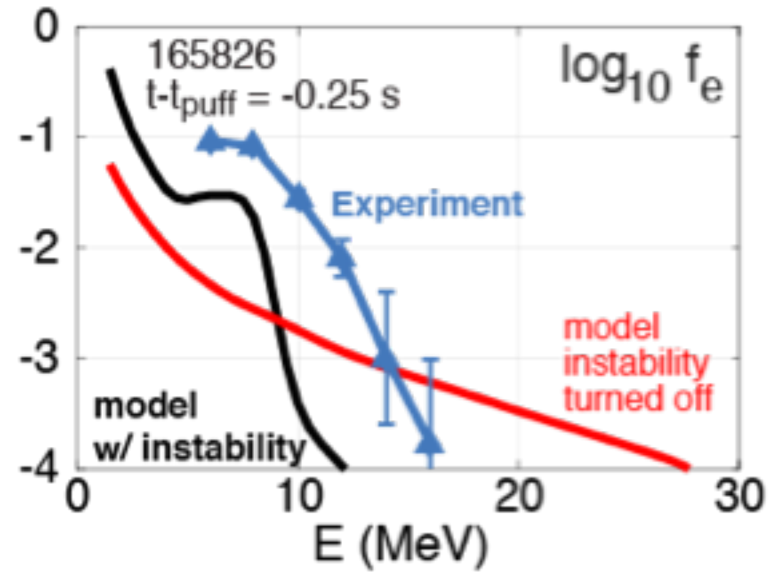
Plan A:
High-Z Injection

Plan B:
Applied Waves or DC Fields

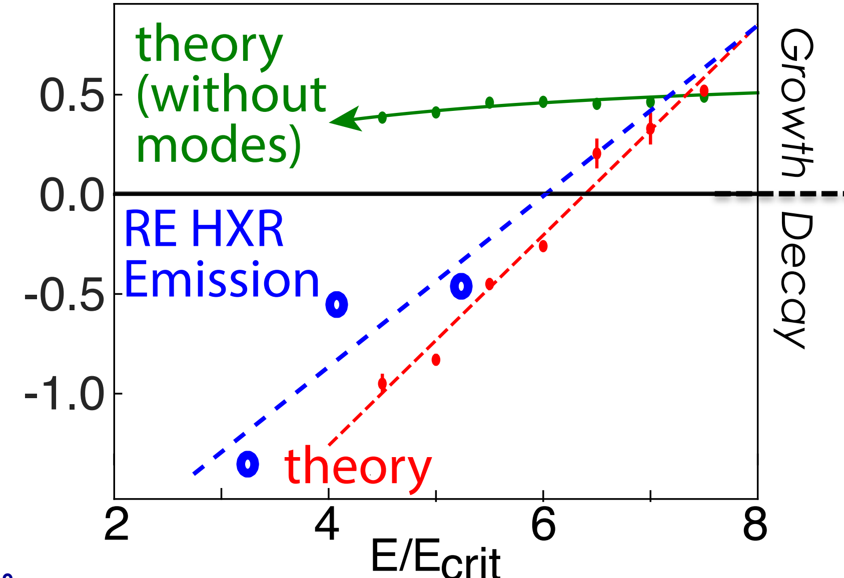
**** OR BOTH?**

Background: Inclusion of Kinetic Instability Improves Agreement of Bremsstrahlung with Modeling

- **Slope of distribution better matched when kinetic instability included**

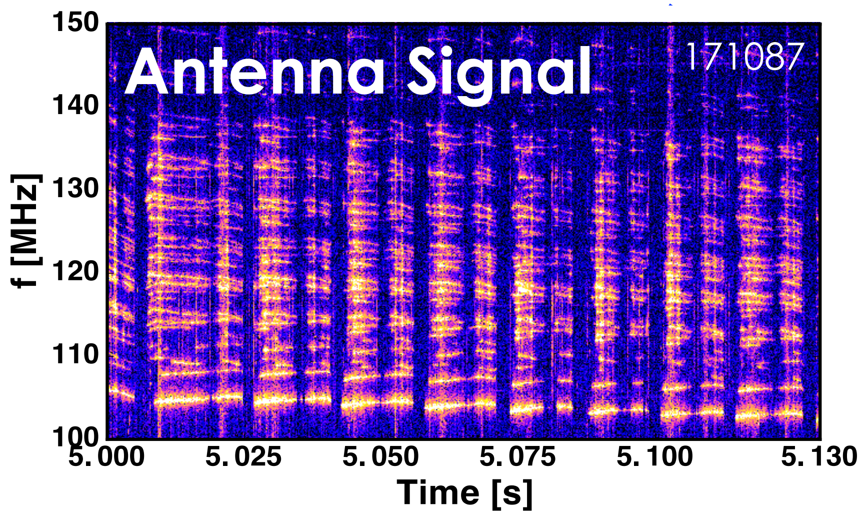


- **Calculation reproduces experimental E/E_{crit} threshold**

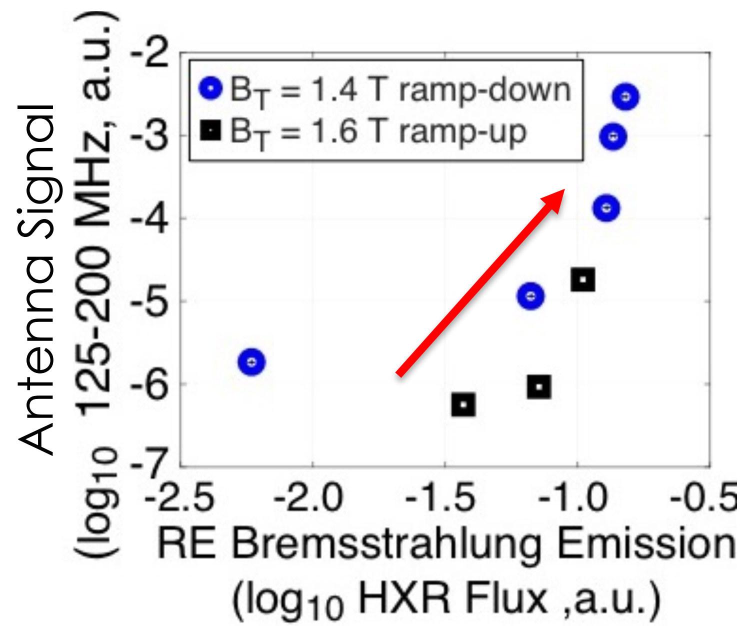


C. Liu et al, PRL 2018

Antenna Reveals Kinetic Instabilities at ~100 MHz
Intensity Proportional to # REs

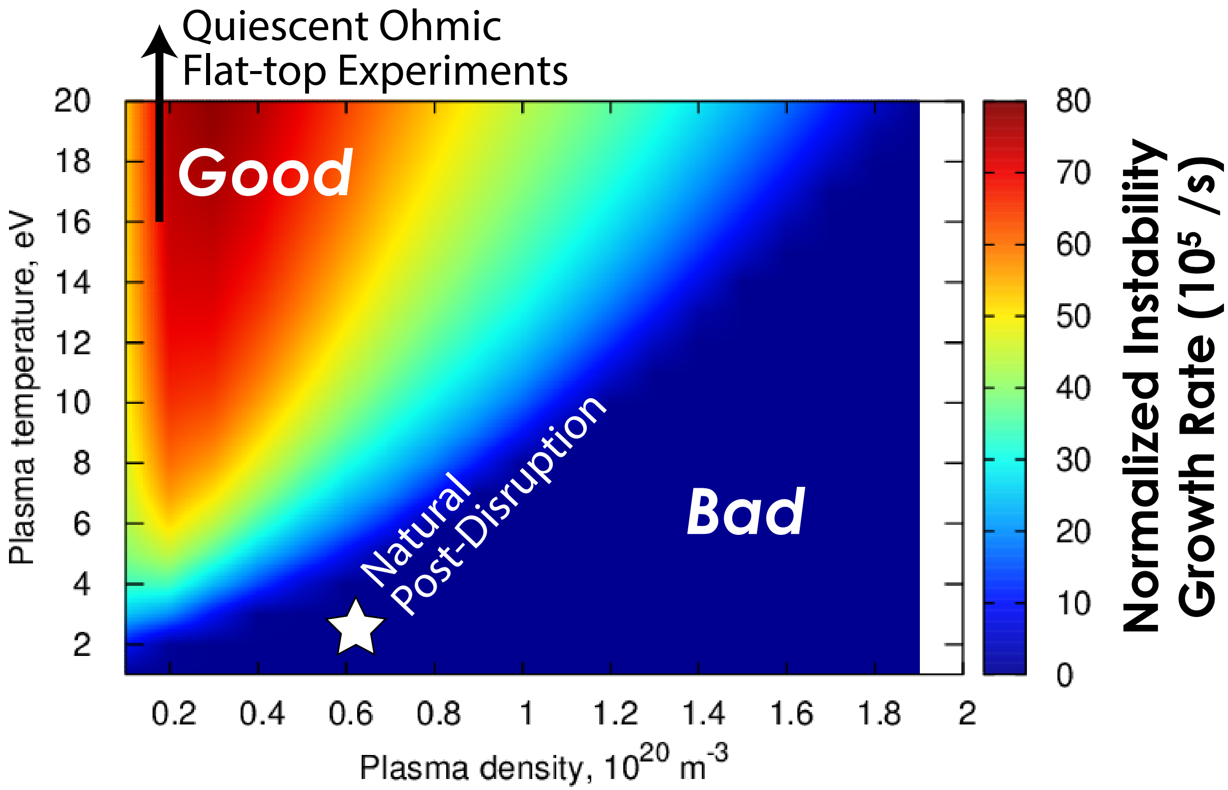


- **Instabilities were robustly present above critical RE intensity**
  - Got stronger with more REs



D. Spong et al, PRL 2018

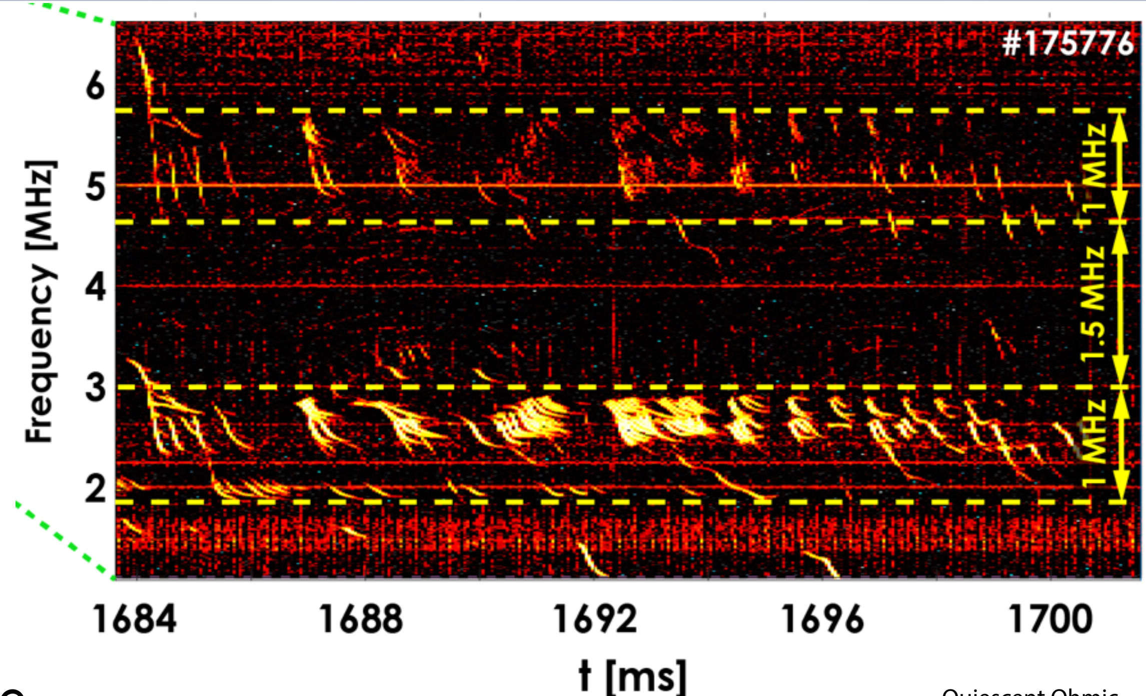
Previous Results were in Collisionless "QRE" Regime … Kinetic Instability Favors Collisionless Bulk Plasmas

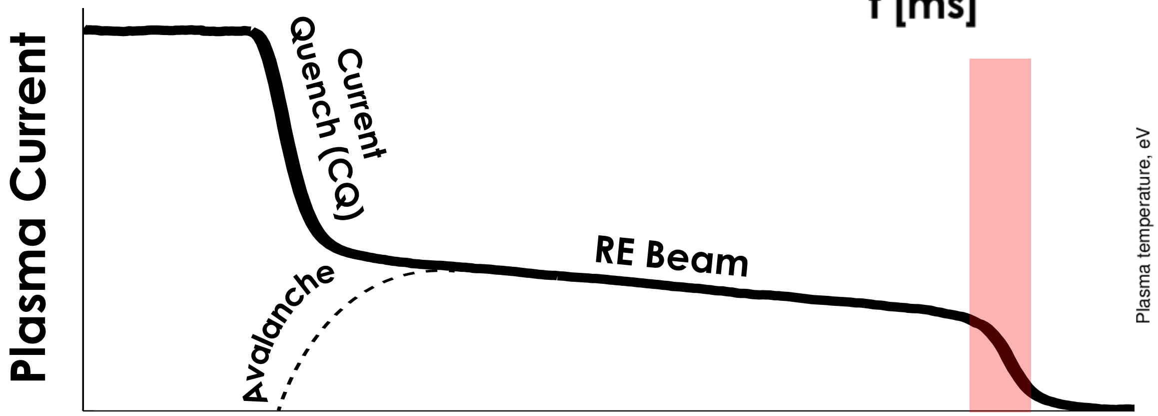


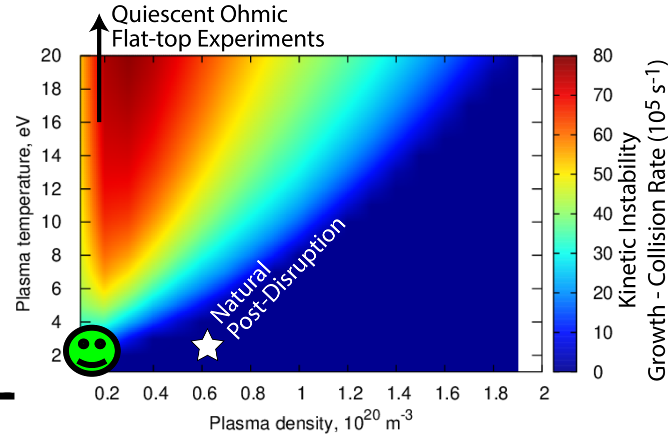
This scaling is why kinetic instabilities were not taken seriously

P. Aleynikov & B. Breizman, NF 2015

Naturally Excited Kinetic Instabilities Now Observed in Many Phases of Post-Disruption Evolution

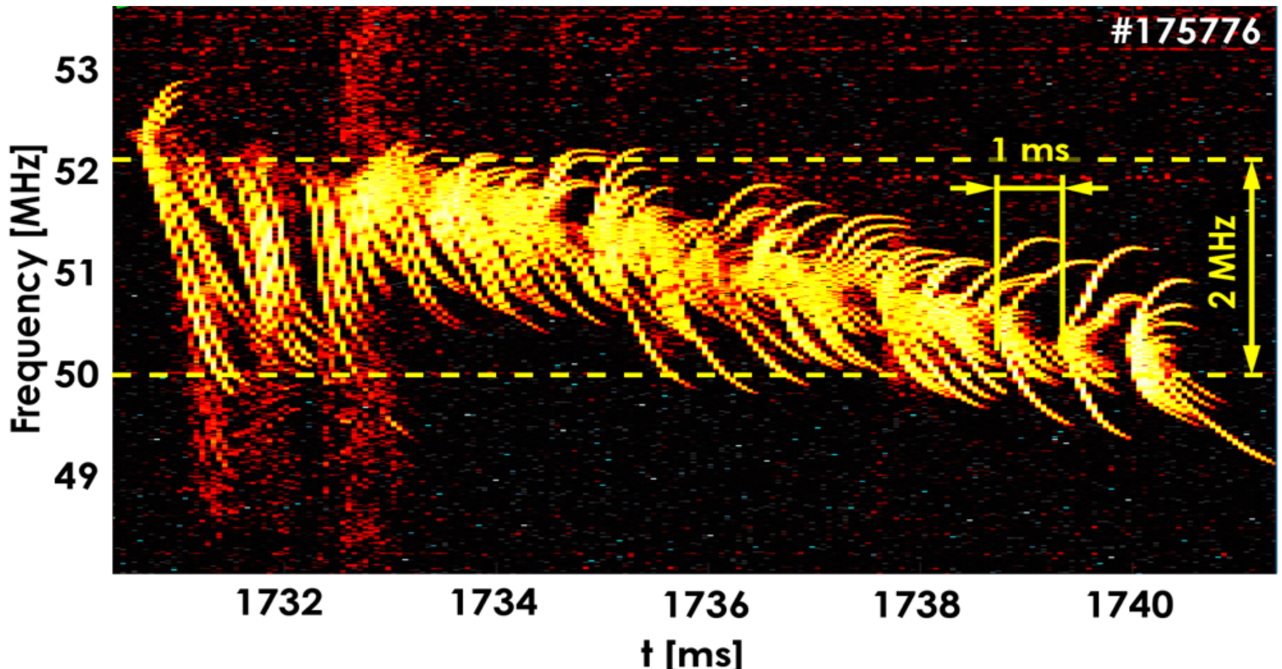


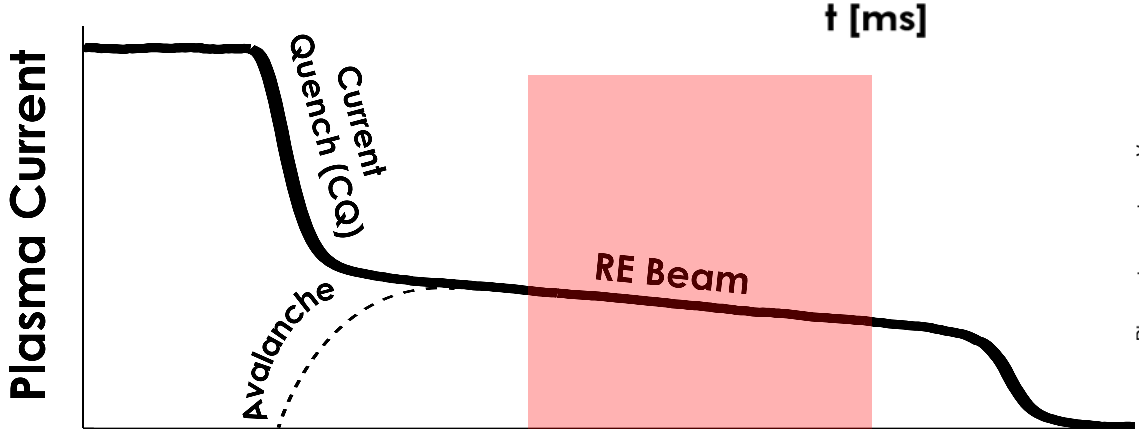


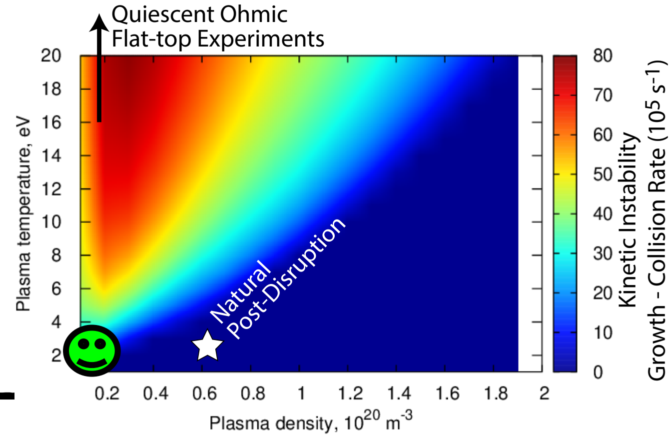


A. Lvovskiy et al, NF 2019 (in review)

Naturally Excited Kinetic Instabilities Now Observed in Many Phases of Post-Disruption Evolution







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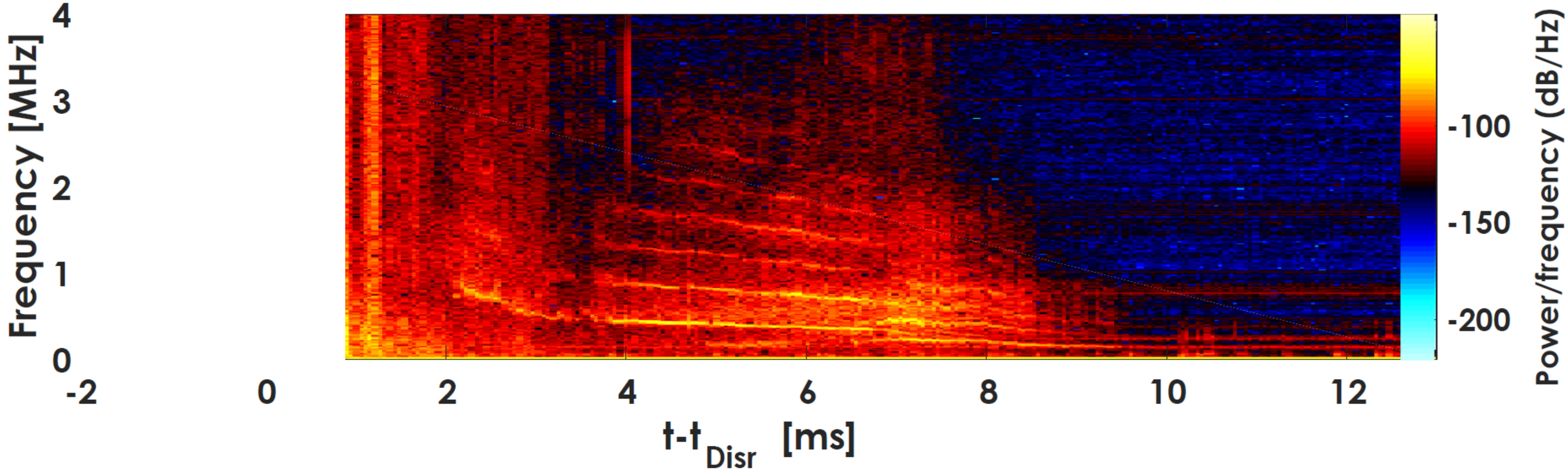
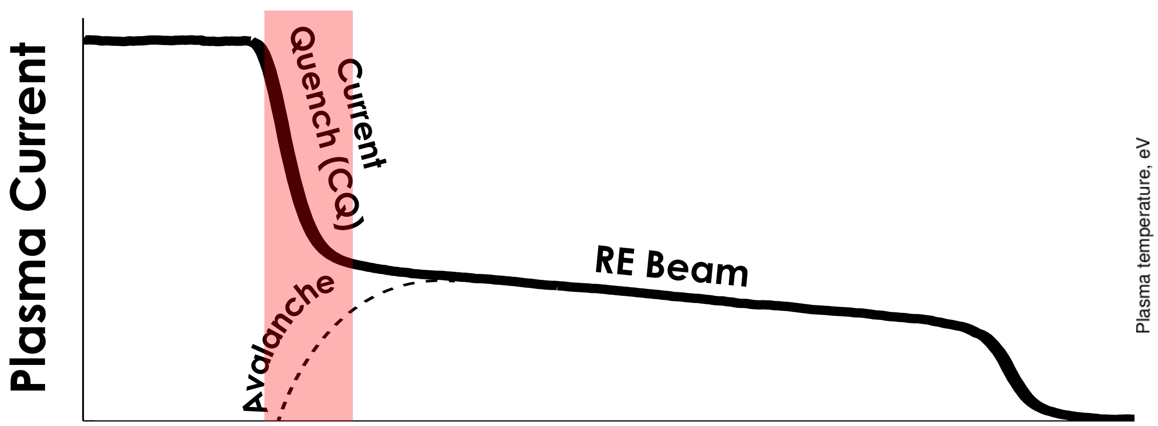
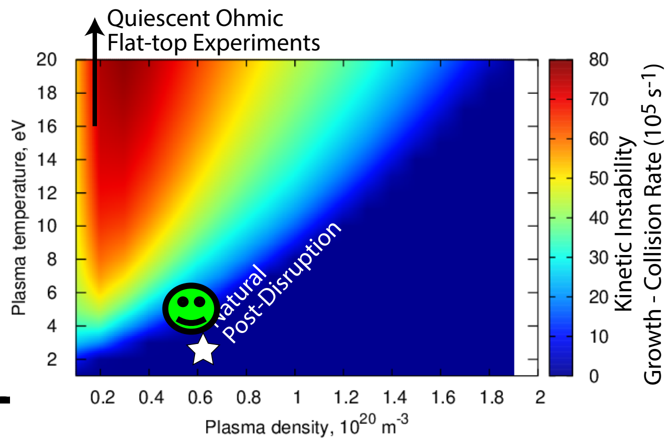
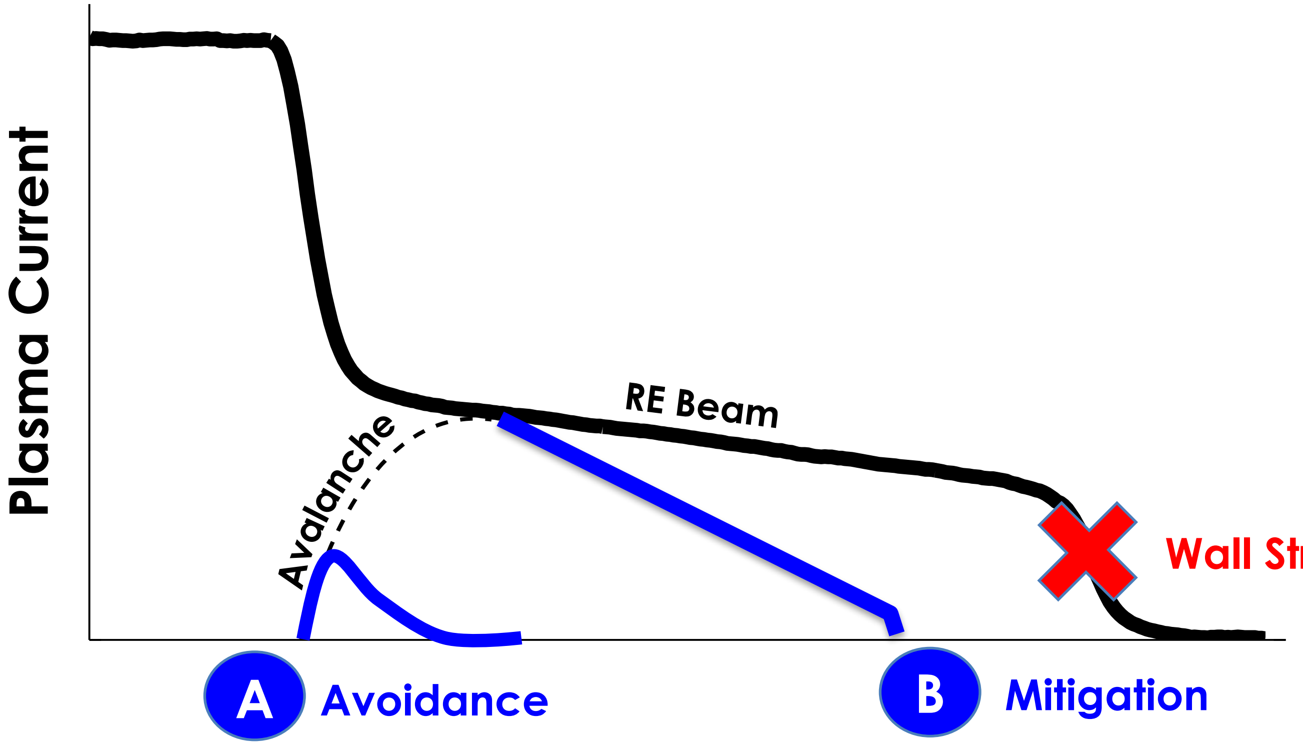






A. Lvovskiy et al, NF 2019 (in review)

Today I'll describe a few nascent activities @ DIII-D on RE mitigation and avoidance with waves / 3D fields



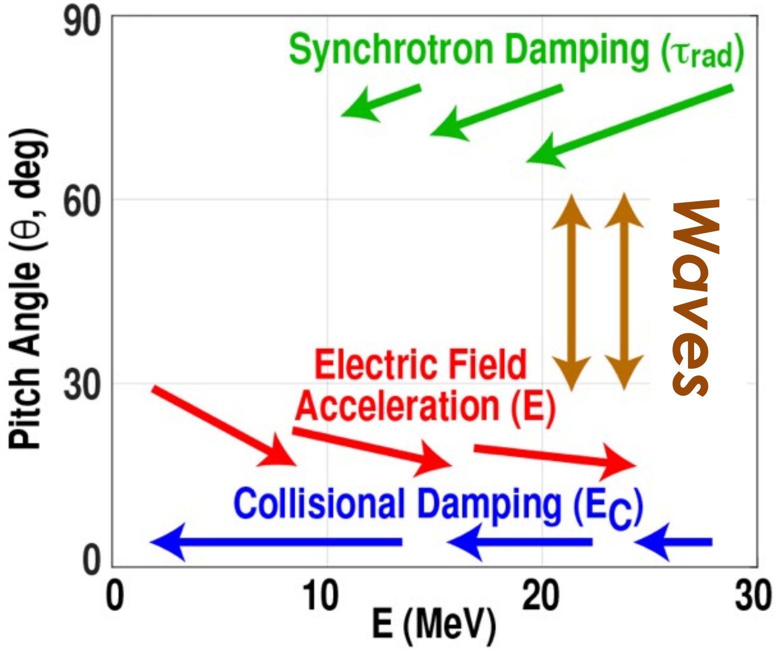
Alfvenic Modes
Passive Coils

Whistler Modes

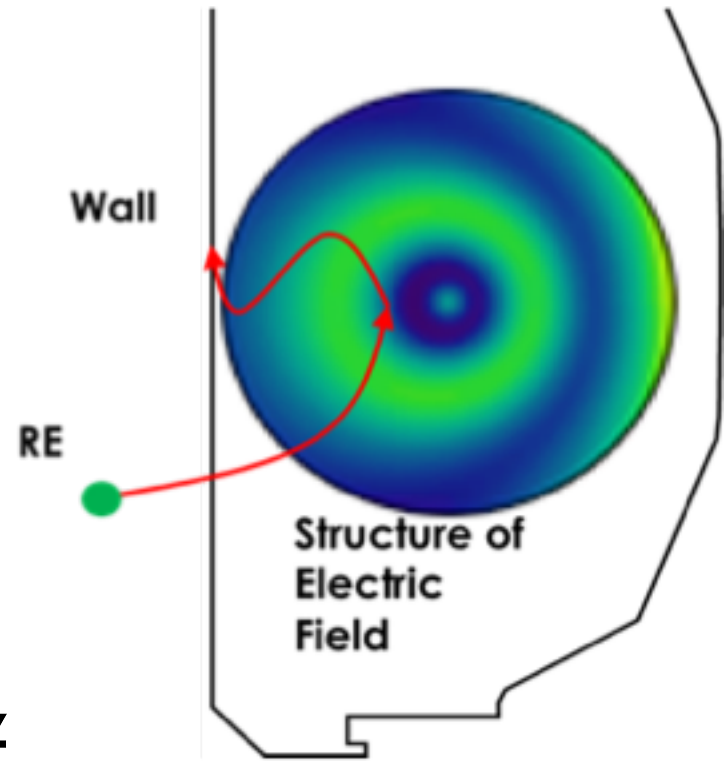
C. Paz-Soldan et al, NF 2019

Mechanism of Instability/Wave/3D Effect on REs Depends on their Frequency w.r.t. Transit Frequency

$f_{wave} >> f_{transit}$:
Pitch-angle scattering



$f_{wave} << f_{transit}$:
RMP-like
Radial Transport



$f_{transit} \sim c/(2\pi R_0 q) \sim$ **30-40 MHz**

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  - Injection-based RE control methods have possible fatal flaws
  - Magnetic-field based approaches unjustifiably neglected
- **Limit Maximum RE Energy with Whistler Modes**
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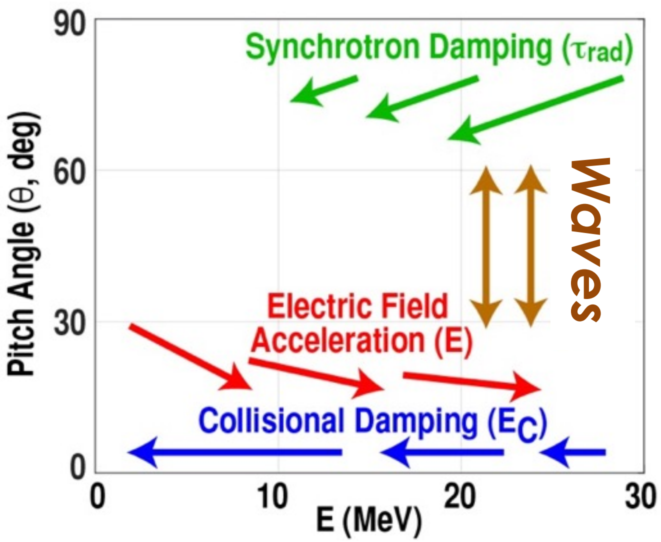
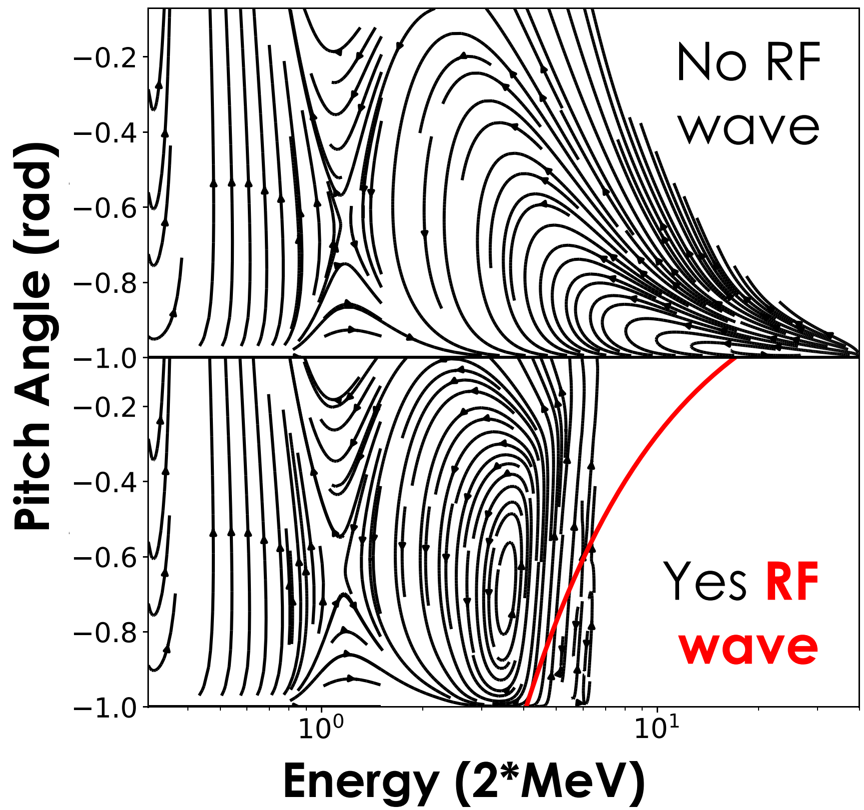
RE Mitigation Scheme: Externally Applied Whistler Waves Predicted to Limit Maximum RE Energy

- **Modeling predicts applied waves of the right ω,k enhances RE pitch-angle scattering**
  - Synchrotron then drains RE energy

- **Same mechanism as self-excited whistlers in DIII-D experiments**



RE Distribution w/ and w/o RF wave

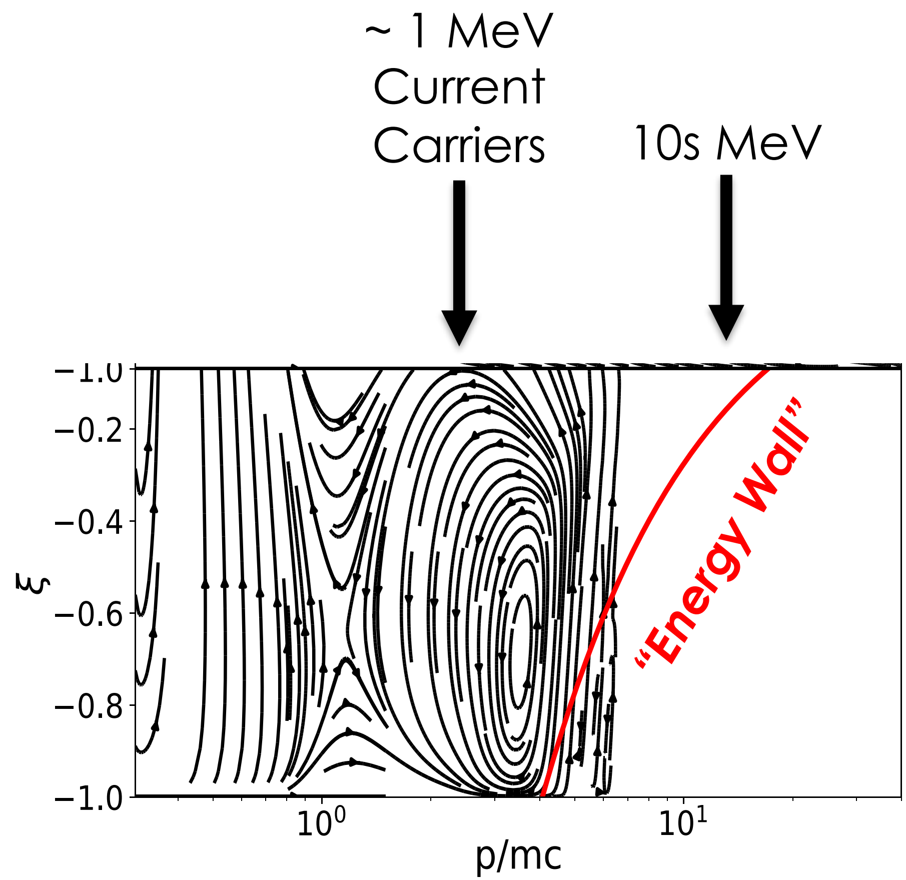


Z. Guo et al, Phys. Plasmas 2018

Wave-driven RE “Energy Wall” provides path for RE mitigation at constant IP

Advantages to less RE energy @ constant IP:

- **VDE rate slowed down as IP-dot is minimal**
  - More time for wave to act
  - Less energy at wall strike (?)
- **Penetrating fraction of RE population is eliminated**
  - Only surface melting?
- **High RE current means kink likely -> conversion inhibited?**



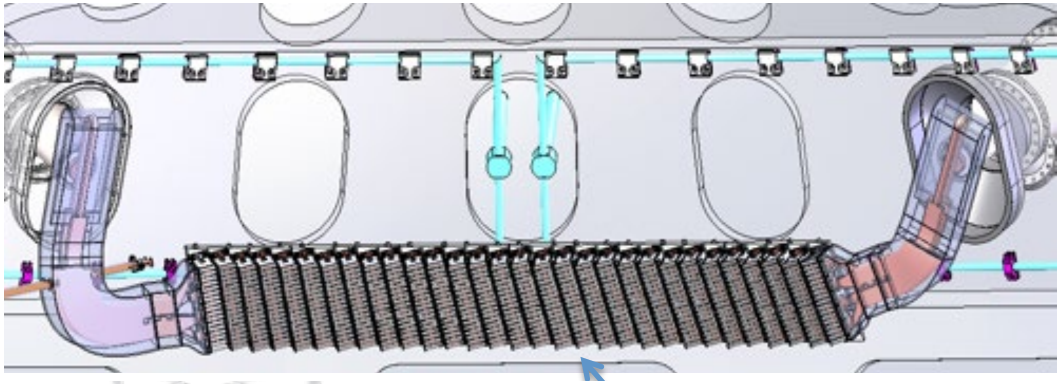
Modeling needed to assess if most optimistic outcome is a win -> (assume ad-hoc perfect energy wall)

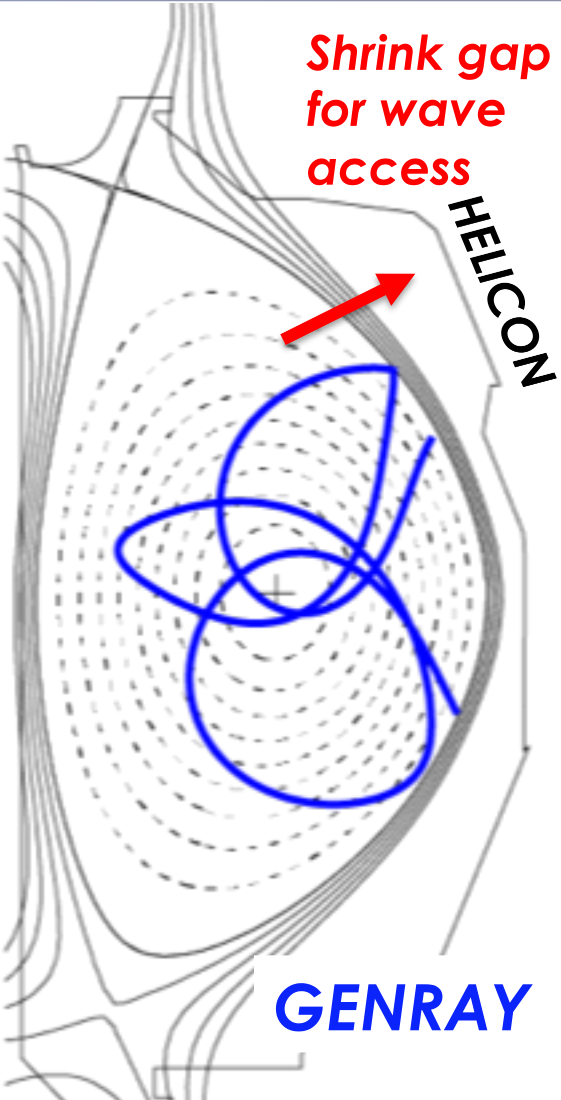
Z. Guo et al, Phys. Plasmas 2018

DIII-D Helicon antenna will be used for a proof-of-principle test in FY2020 run (Torkil Jensen Award)

- QRE scenarios are well suited to targeted study of helicon effect on distribution function
- Calculations in progress to see if 480 MHz is decent ω,k
- Phase 1: can we predict effect of existing wave actuator
- Phase 2: Optimization for best ω,k

Helicon antenna will be ready for 2020



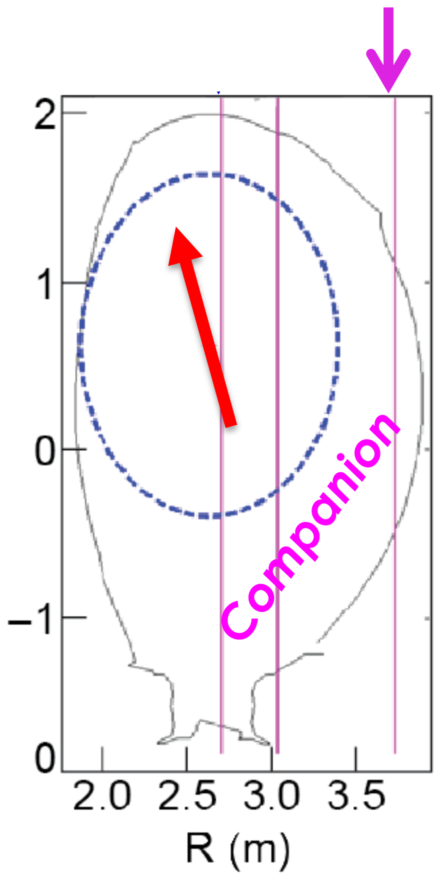


R. Pinsker, P. Parks
X.Z. Tang, C. McDevitt, Z. Guo

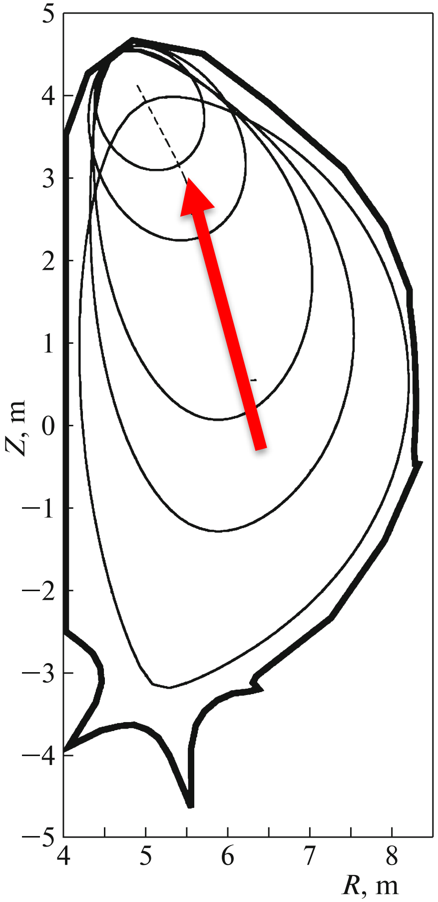
Accessibility issues need to be considered … together with effect of "companion plasma"

- **Wave must couple across large gap & uncertain SOL conditions**
  - Possible fatal flaw for technique
- **JET finds dense "companion plasma" exists (C. Reux et al)**
  - Gas quantity sets companion n_e
  - Should allow waves to couple

JET



ITER



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  - Could be a way out of mitigation quagmire (less energy per MA)
  - Potential of Helicon antenna in DIII-D will be tested in FY20 run
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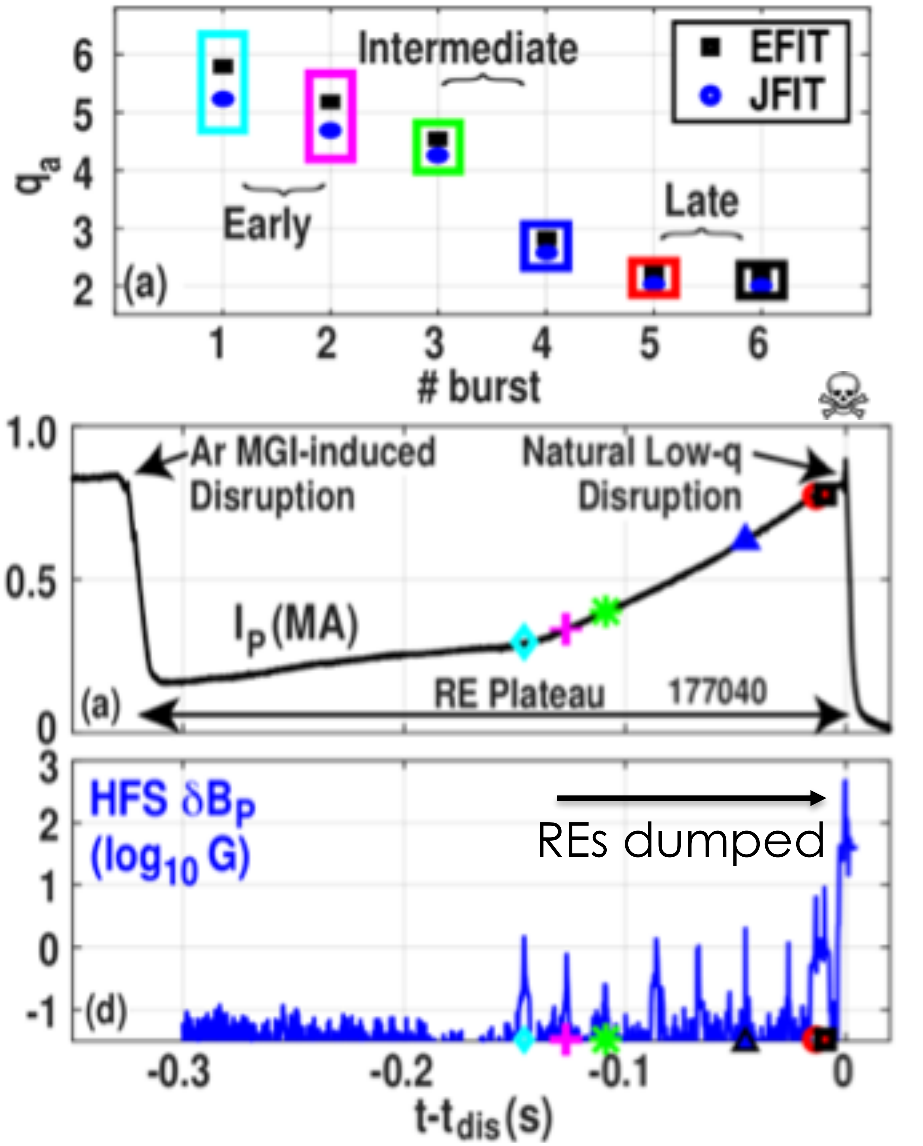
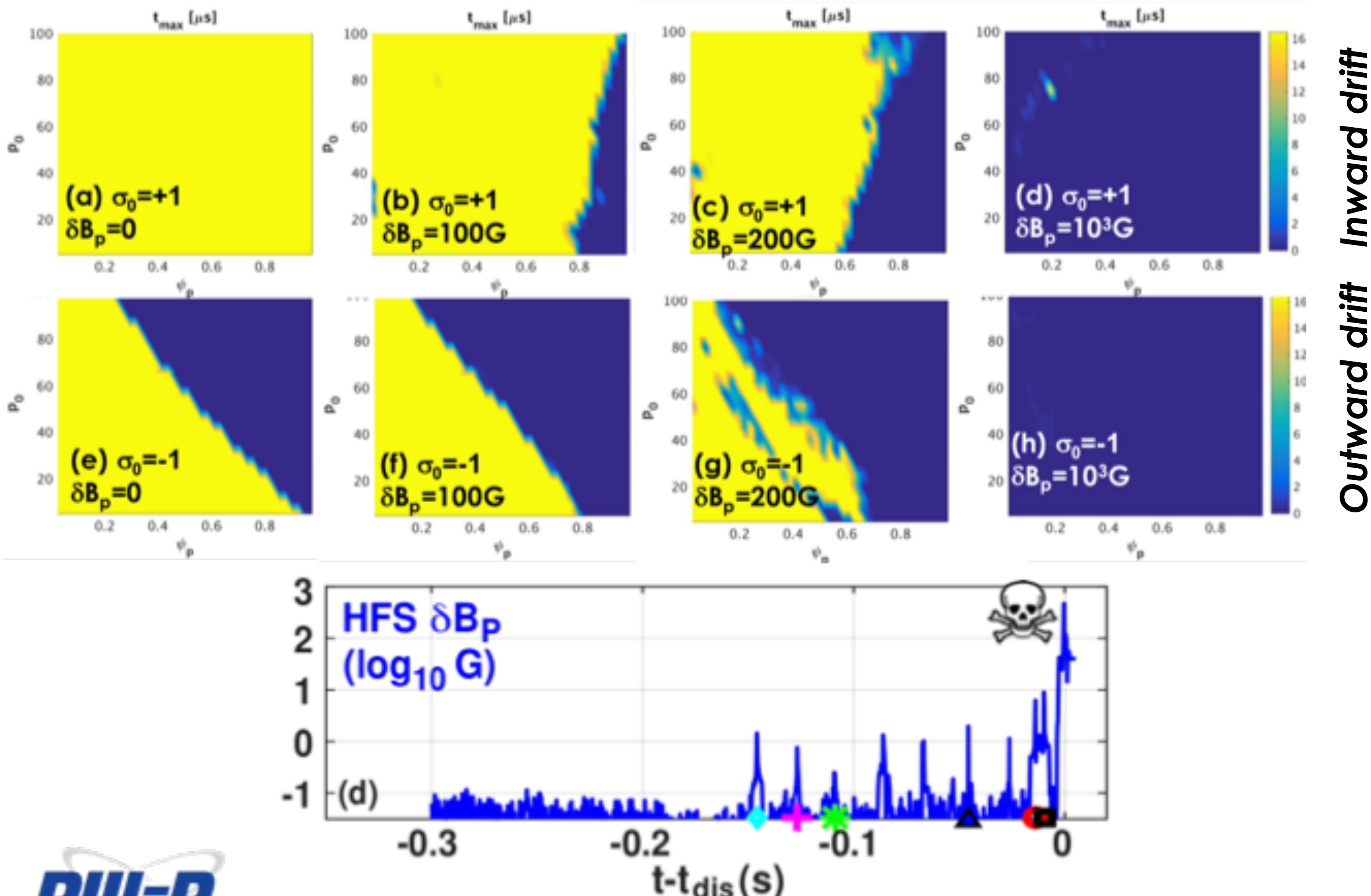
Large 3D Fields (from MHD instability) observed to promptly kill RE beam without regeneration

- **Accessed low q conditions via ~ 1 MA RE beam in DIII-D**
  - Read my paper for details
- **Big current-driven kink terminated RE beam *without regeneration***
- **Required δB around 1 kG**
  - (Measured on the wall)
  - δB/B ~~ 5%
- **Can the critical δB be predicted?**



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

Orbit Following in MARS-F Predicted Mode Structure Used to Determine the Critical δB for RE termination



Y.Q. Liu et al, Nucl Fusion (in review & APS-DPP 2019 invited)

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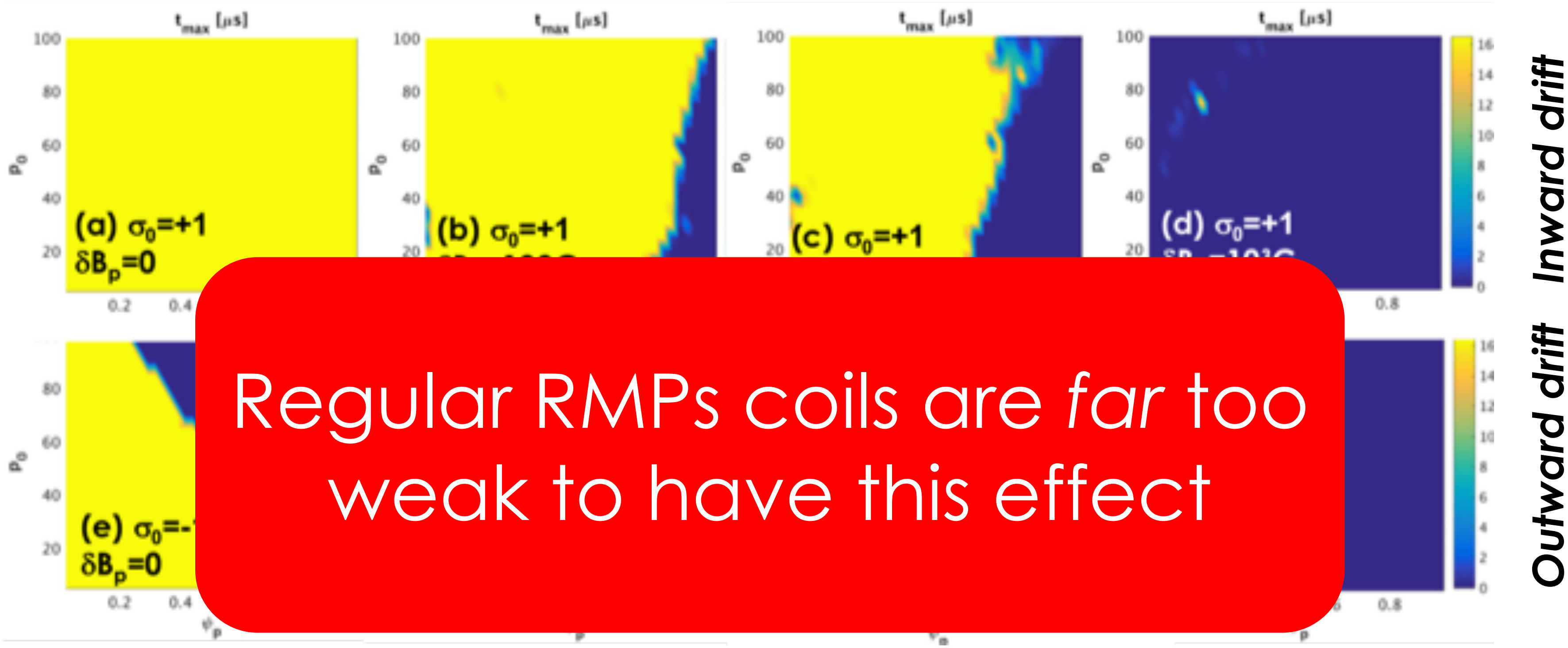
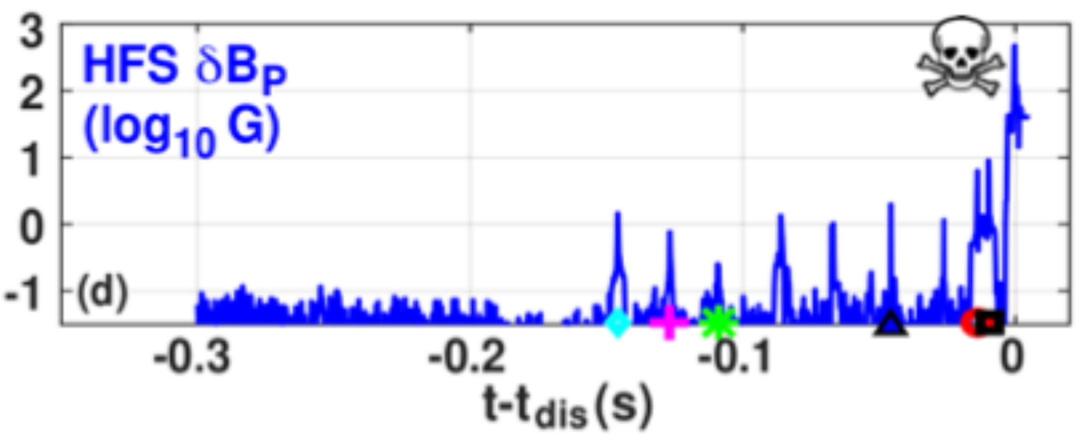


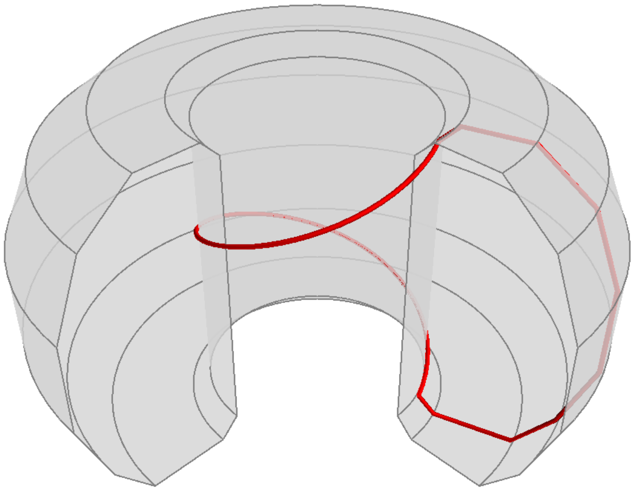
Regular RMPs coils are *far* too weak to have this effect



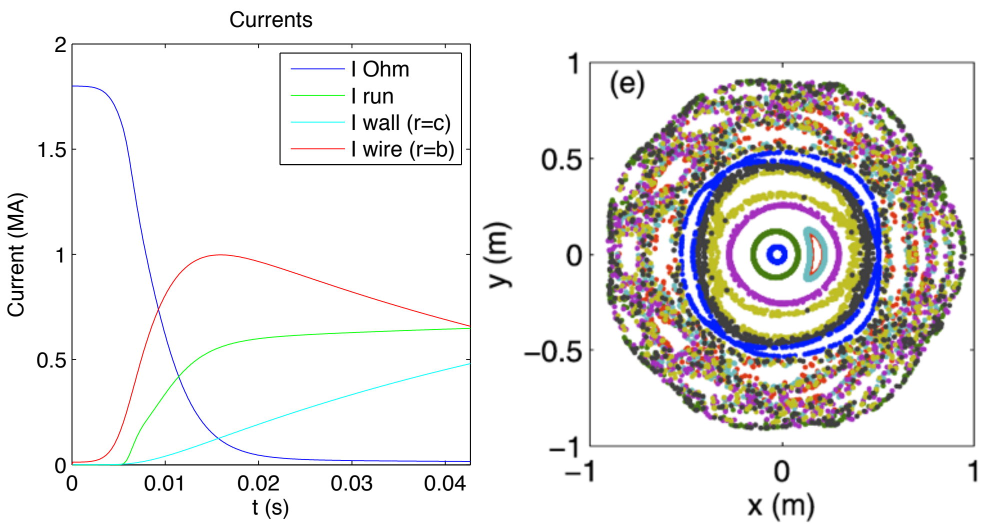
Y.Q. Liu et al, Nucl Fusion (in review & APS-DPP 2019 invited)

RE de-confinement via passive in-vessel winding "RE killer coil" under study using these same tools

- **Principle: disruption-induced voltage drives current through an in-vessel winding**
  - "Spark-gap" prevents current during normal operation
  - Currents are far in excess of a regular RMP coil



- **Goal: optimize configuration and assess feasibility of demonstration at DIII-D**



- **Too late for ITER**
  - (unless it has no choice?)

Smith, Boozer, Helander, PoP 2013

D. Weisberg

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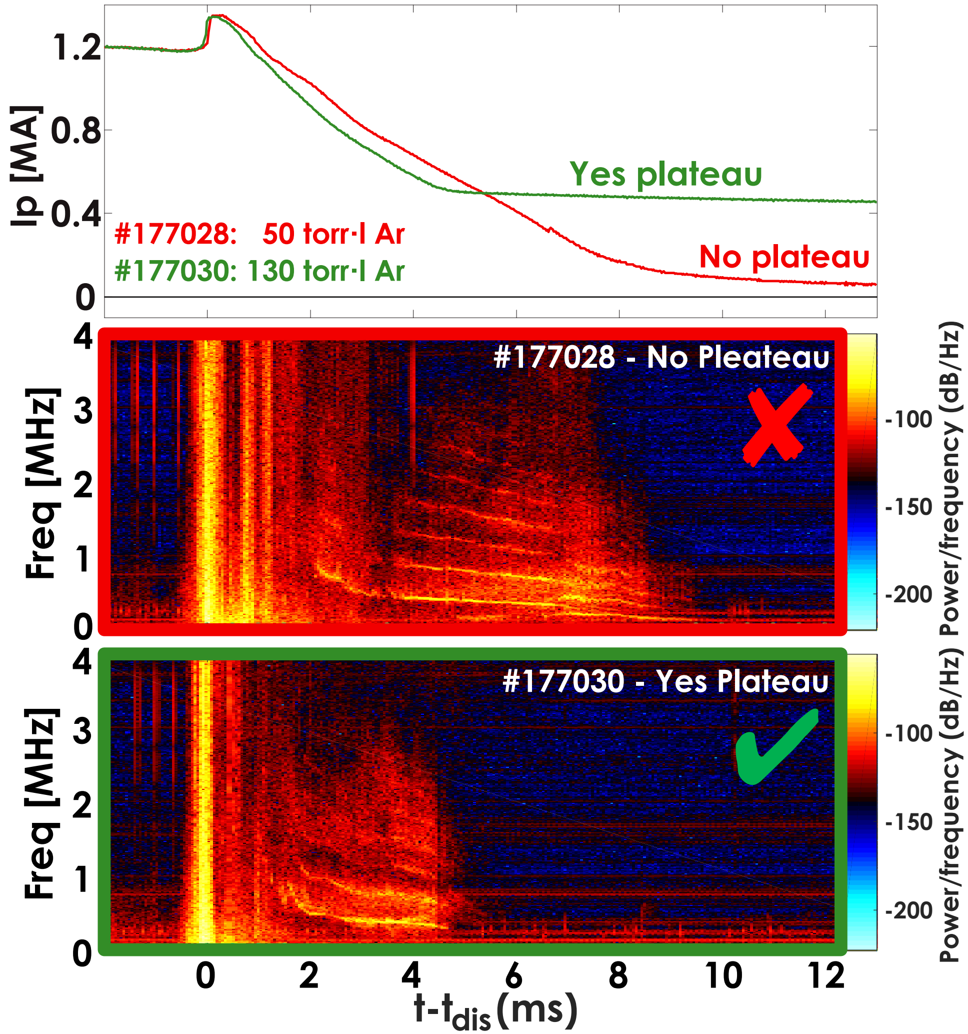
Already Observed RE Seed Suppression with Naturally Excited Compressional Alfven Eigenmodes?

- **Avoided RE plateaus correlate with intense & coherent MHz-frequency modes**
  - Candidate: compressional Alfven wave driven by REs



A. Lvovskiy et al, PPCF 2018

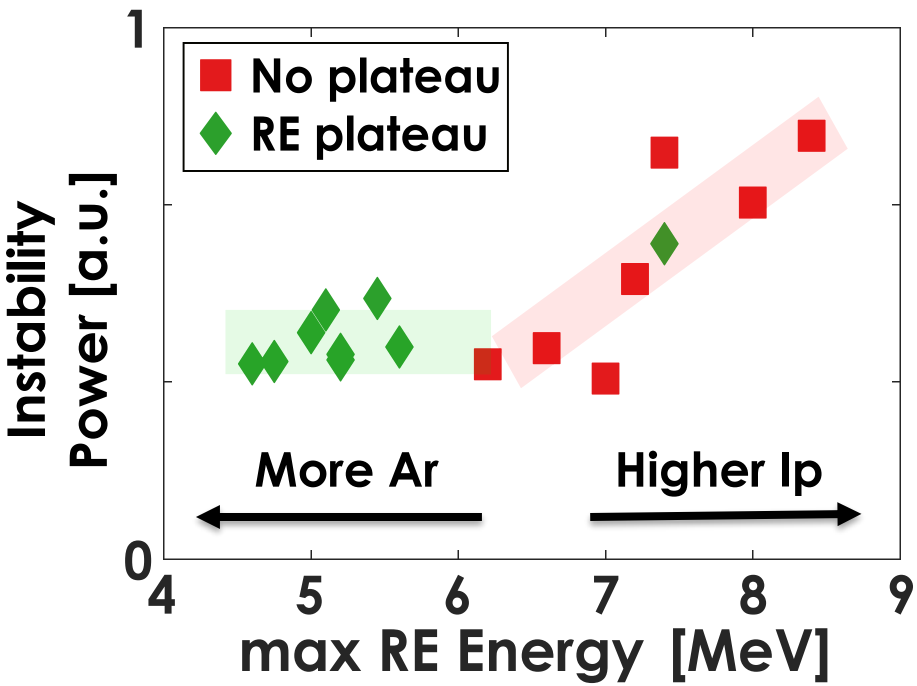
Paz-Soldan/PPPL/08-2019

Already Observed RE Seed Suppression with Naturally Excited Compressional Alfven Eigenmodes?

- **Avoided RE plateaus correlate with intense & coherent MHz-frequency modes**
  - Candidate: compressional Alfven wave driven by REs

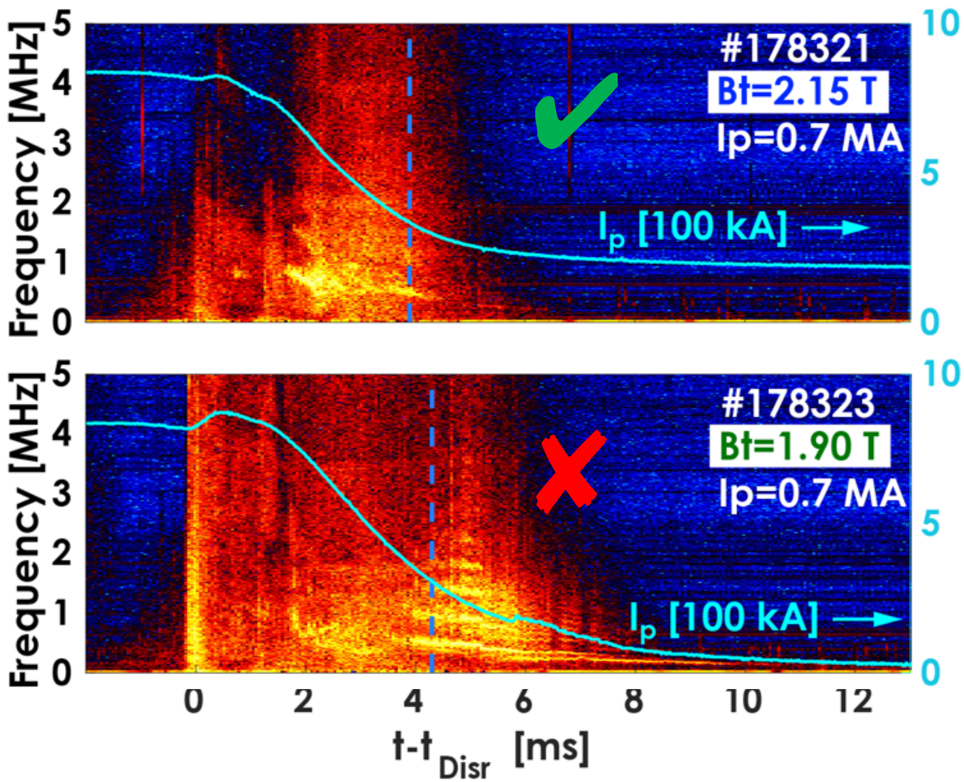
- **Offers candidate explanation for counter-intuitive RE formation thresholds**

? Correlation or Causation ?

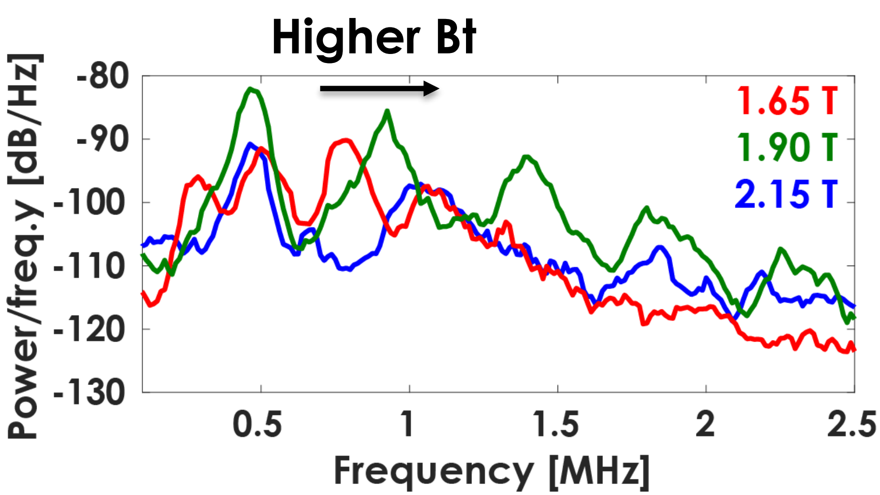


A. Lvovskiy et al, PPCF 2018

CQ mode dynamics change across critical BT for RE formation – persistent modes appear at low BT



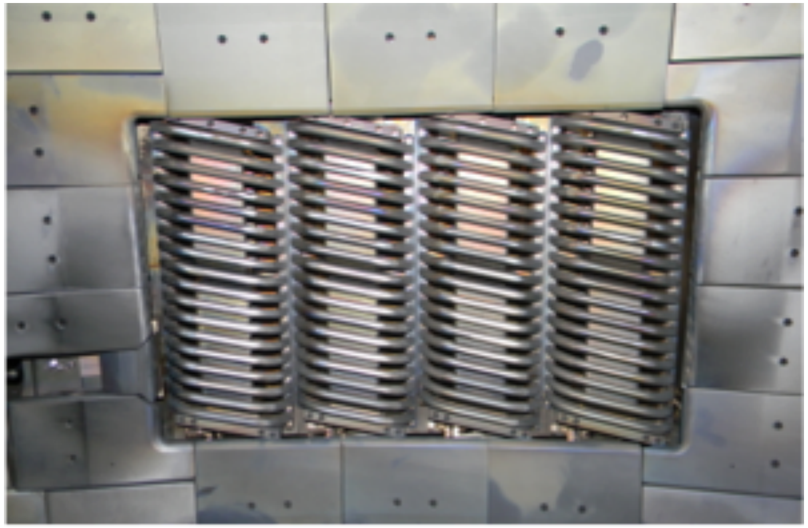
- At high BT modes are short and incoherent
- At low BT modes persist and correlate with additional RE loss
- Frequencies and spacing decreases as B_T decreases

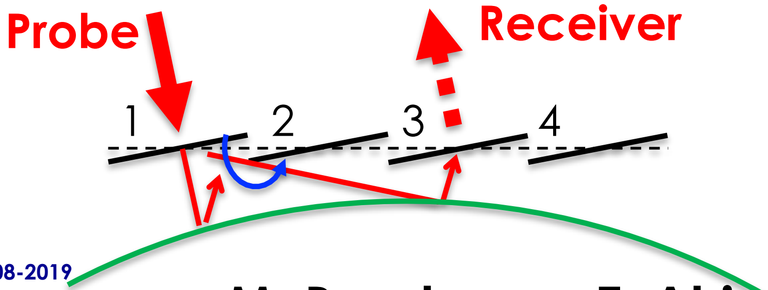


A. Lvovskiy

Initiative Started at DIII-D to Assess Feasibility of ~ 1 MHz-wave Launch with Mothballed ICRF Antennas

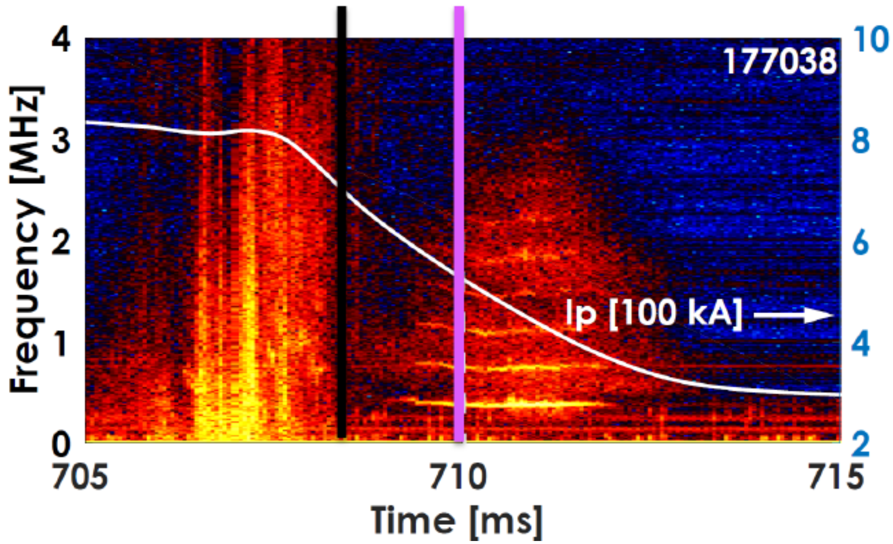
- **Transfer function of existing waveguides OK @ ~ 1 MHz**
  - ✓ Any needed work can be done far from tokamak pit
- **Low power antenna loading experiments planned in June**
  - Low power MHz source in-hand
- **AORSA modeling activity also planned w/ PPPL collaborators**
  - Investigate accessibility issues
- **Frequency is AM radio band**
  - Sources should be cheap (??)

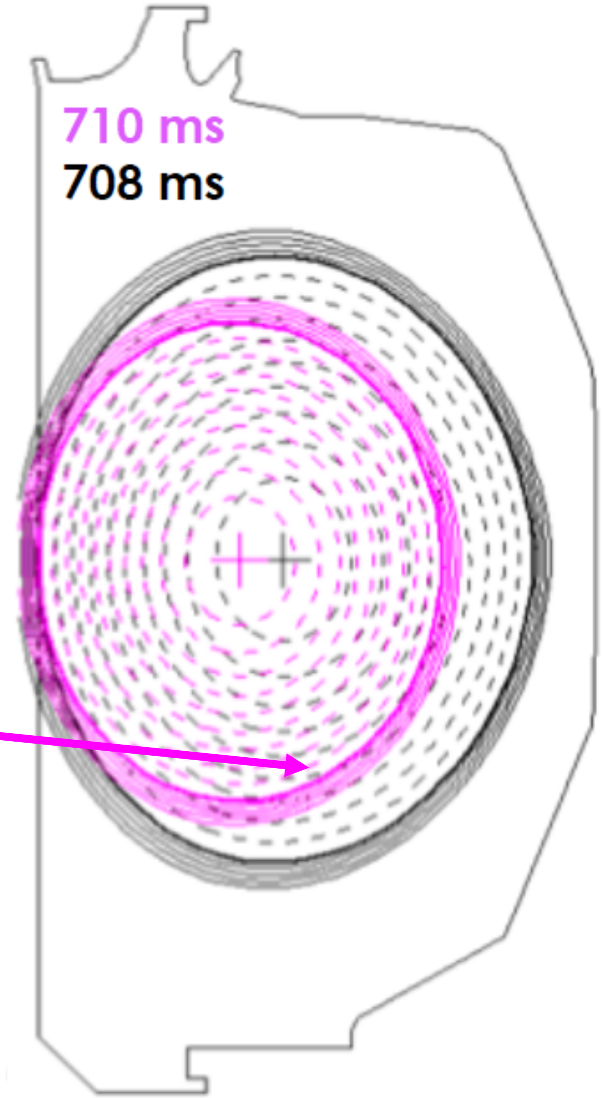




M. Brookman, T. Akiyama

AORSA fast wave simulations for RE-driven CAEs Initiated





- **Frequency scan for a DIII-D scenario @ 710 ms**
  - 0.25 – 1 MHz
  - $n_\phi = 1$
- **n_e = CONST. = 4.8 x 10^{19} m^{-3}**
- **T_e = CONST. = 2 eV (cold plasma)**
- **Plasma species: electron and D**

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N. Bertelli, C. Liu, D. Brennan

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- **Deconfine REs with Lab-Frame 3D Fields**
- **Deconfine REs with Alfvenic Modes**
  - Correlation of RE plateau failure with CAEs –> Causation?
  - Potential of ICRF antennas in DIII-D under study
- **Conclusion**

Conclusion: Several Approaches Exist for Evaluation

- **Introduction and Motivation**
  - Injection-based RE control methods have possible fatal flaws
  - Magnetic-field based approaches unjustifiably neglected
- **Limit Maximum RE Energy with Whistler Modes**
  - Whistlers predicted to affect RE dynamics in QRE regime
  - Potential of Helicon antenna in DIII-D will be tested in FY20 run
- **Deconfine REs with Lab-Frame 3D Fields**
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All help appreciated !
Particularly modeling these control scenarios !

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DISCLAIMER

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Awards DE-FC02-04ER54698. DIII-D data shown in this paper can be obtained in digital format by following the links at **https://fusion.gat.com/global/D3D_DMP**.

Bonus Slides

Non-Material Injection DMS Strategies (B-fields/Waves) Called out as Priority 1 Research Need for ITER

Ref.	System/ Issue	Required R&D	Category*
A.1	SPI-single injector. Pellet injection optimization for RE avoidance (incl. TQ and CQ mitigation)	Optimization of shard size, velocity, amount, gas vs. shard fraction, composition (D + impurity) to achieve RE avoidance with optimum TQ, CQ (incl. wall loads)	1
A.2	SPI-single injector demonstration for runaway mitigation	Determination of feasibility to dissipate the energy of formed runaway beams (amount, assimilation) and to improve scheme	1
A.3	SPI-multiple injections	Determination of effectiveness of multiple injections to achieve RE avoidance with optimum TQ, CQ (incl. wall loads) compared to single injections (incl. timing requirements)	1
A.4	SPI-multiple injectors	Determination of effectiveness of multiple injection from different spatial locations to achieve RE avoidance with optimum TQ, CQ (incl. wall loads)	1
A.5	DMS – alternative injections techniques	Demonstration of the feasibility of the technique to inject material in a tokamak and comparison of mitigation efficiency with SPI	1
A.6	**DMS – alternative disruption mitigation strategies**	**Exploration of disruption mitigation by schemes other than massive injection of D2 and high Z impurities**	**1**

Abstract

Recent DIII-D experimental results motivate a serious assessment of the applicability of non-axisymmetric magnetic fields to mitigate runaway electrons (REs) in ITER and beyond. Such magnetic fields can originate from intrinsic instabilities or external actuators such as antennas or coils. This presentation will summarize several recent DIII-D examples of magnetic-field driven RE avoidance and mitigation as well as summarize ongoing research activities to explore external drive of similar perturbation fields.

Starting at the high frequency extreme, recent observations and modeling in the quiescent regime support the view that RE-driven kinetic instabilities in the 0.1 - 10s GHz range drive significant RE dissipation via wave-enhanced pitch-angle scattering. Planned proof-of-principle experiments in the quiescent regime to utilize the new DIII-D 1 MW 0.48 GHz system to externally drive similar enhanced scattering will be described.

Moving to lower frequency, recent empirical observations support the view that RE-driven kinetic instabilities in the MHz range (likely compressional Alfven Eigenmodes, CAEs) drive significant RE loss during the current quench. Instability power is correlated with the failure of RE plateau formation, with CAE modes being strongest at high current and low injected Ar quantity. Modeling and experimental activities exploring the potential for active launch in the MHz range using DIII- D's ICRF antennas will be described.

Instabilities at zero-frequency, namely current driven kinks, have been observed to completely terminate the RE beam at a critical amplitude. This amplitude, about delta-B/B of 1%, is consistent with MHD modeling and RE orbit following using the MARS-F code. Using this same technique the existing DIII-D 3D field coil sets are found to be far too weak to de-confine a significant number of REs. These studies provide a firm physical basis for specifying passive RE mitigation coil requirements and ongoing efforts in this direction will be described.