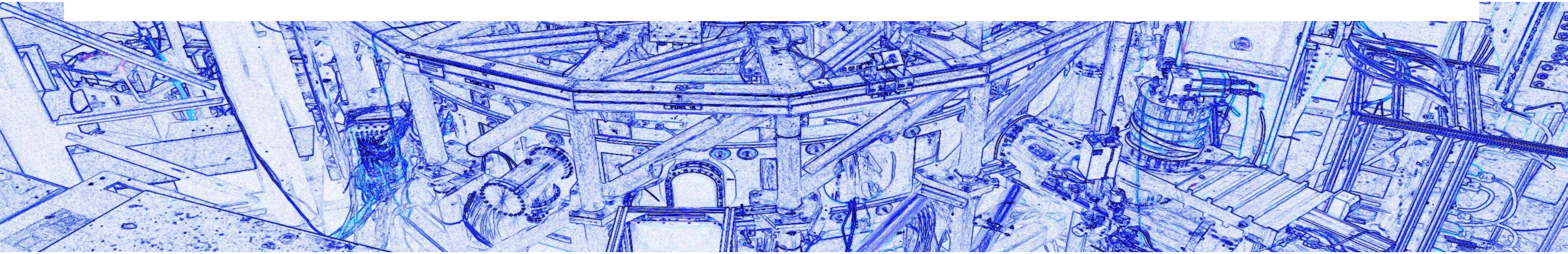
Full suppression of runaway electrons by magnetic perturbation during disruptions

Z. Y. Chen (HUST), L. Zeng (ASIPP), D. Weisberg(GA), X.D. Du (GA)



Outline

- Introduction
- RE suppression by magnetic purturbation
- RE suppression by RMP
- RE suppression by SMBI
- Runaway avoidance during CQ
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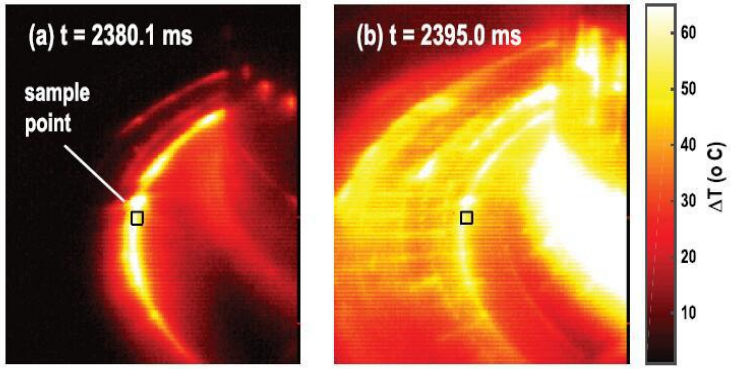
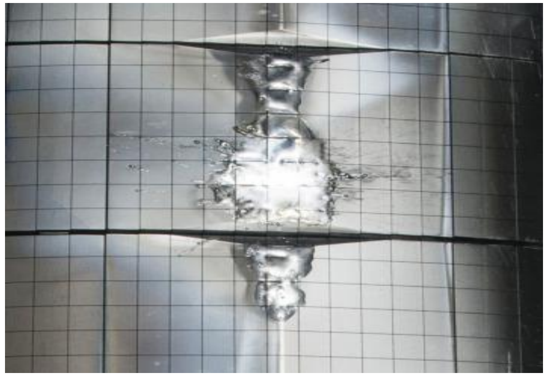
Major Disruption

Heat loads (TQ) | **Electromagnetic force** (CQ) | **Runaway electrons** (CQ)



Hollamnn E.M.D., et al., POP (2018)

Coutesy of A. Kellman



Mattews G. F., et al., Phys.Scr. (2016)

Major disruptions have 3 damaging effects on tokamak machine:

1）high heat loads on the divertor surfaces (during thermal quench);

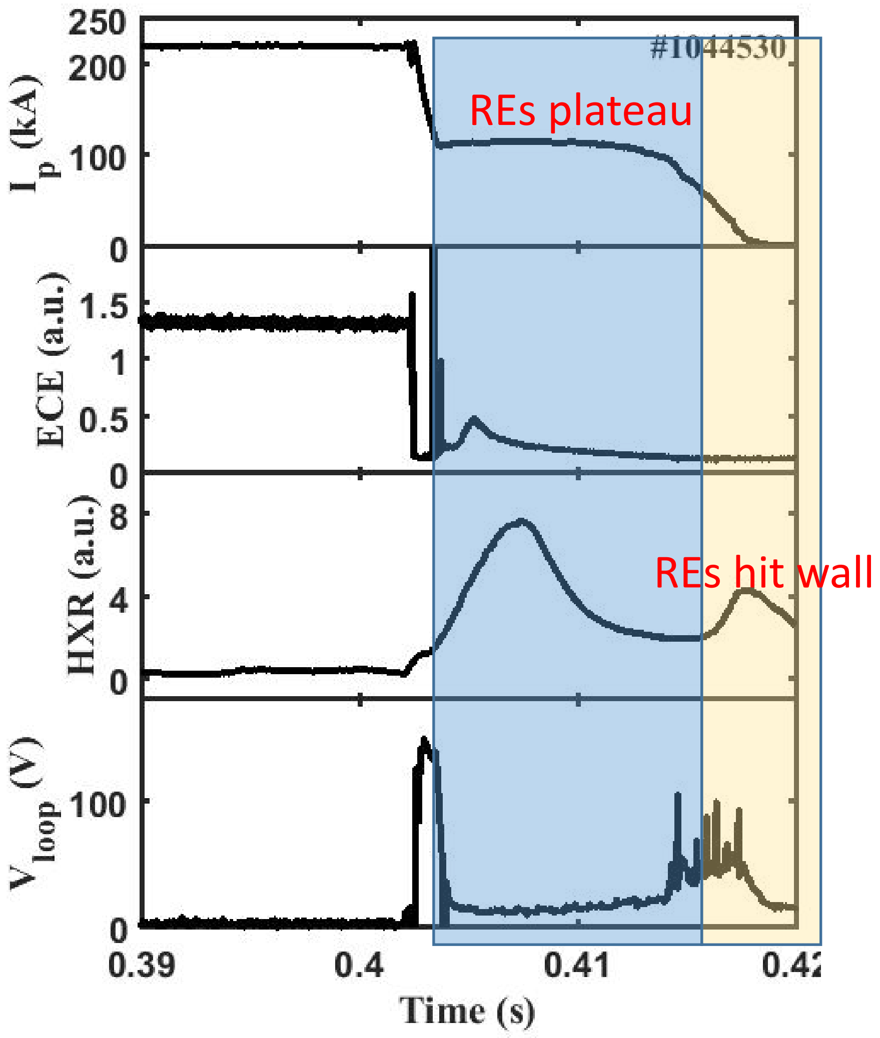
2）electromagnetic force（J×B）via poloidal Halo current (during current quench) ;

3）conversion of plasma current into runaway current, loss of runaway electrons (REs) to PFC (during current quench).

Runaway electrons

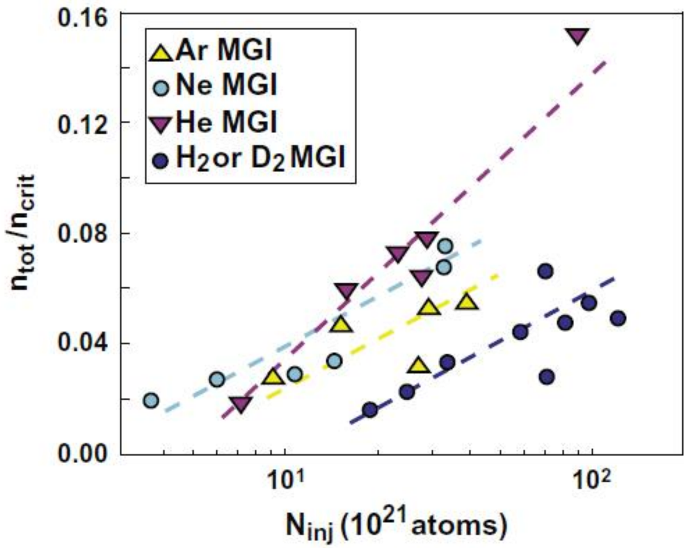
- Conversion of magnetic energy into runaway kinetic energy!
- Serious problem for high I_p operation;
- ~10MA runaway current with ~100MeV runaway beam for ITER;
- Localized impact of REs can damage tokamak wall . ~ten thousands electronic torches!

➢ **REs mitigation is key task force for future reactor-scale tokamaks!**

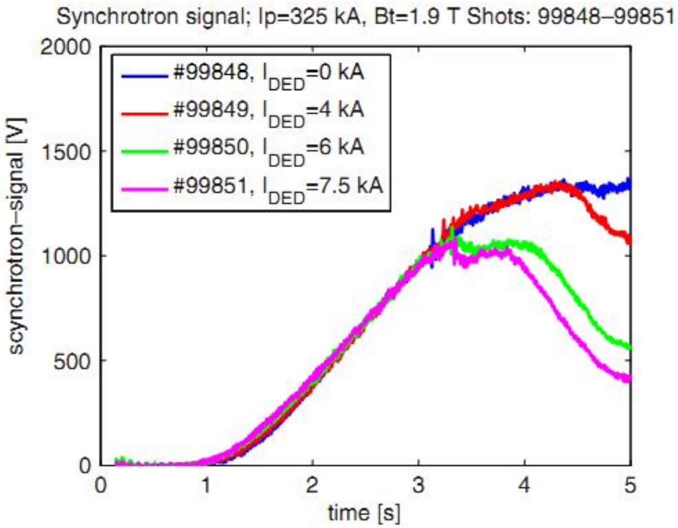


Runaway electrons mitigation

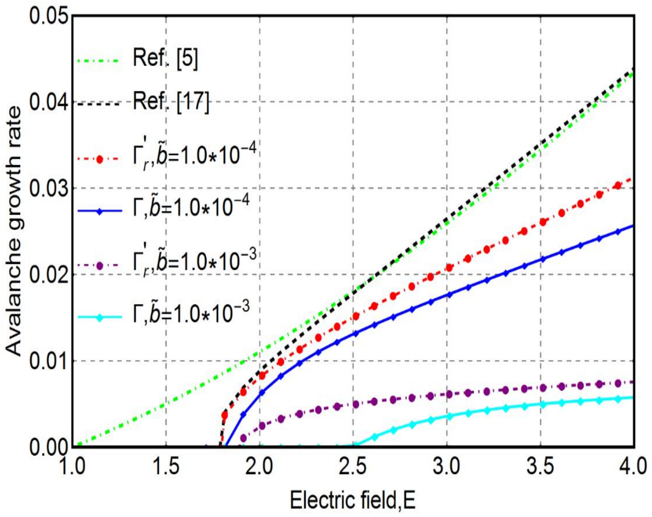
- **Methods for REs mitigation:**
  - Collision suppression: massive gas injection (MGI), shattered pellet injection (SPI);
  - Deconfinement of REs: resonant magnetic perturbation (RMP);



Hollmann E.M., et al., POP (2010)



TEXTOR, NF (2006, 2007)



S. C. Li, et al., PPCF (2017)

- **Collision suppressin by impurity injecton (MGI/SPI) is limited by the impurity mixing efficinecy.**
- **Suppression of REs with the RMP provide alternative solution.**
- **Advantages of magnetic perturbation: 1) Increase of threshold electric field *E* for runaway generation;**
  2) Reduction of avalanche growth rate.

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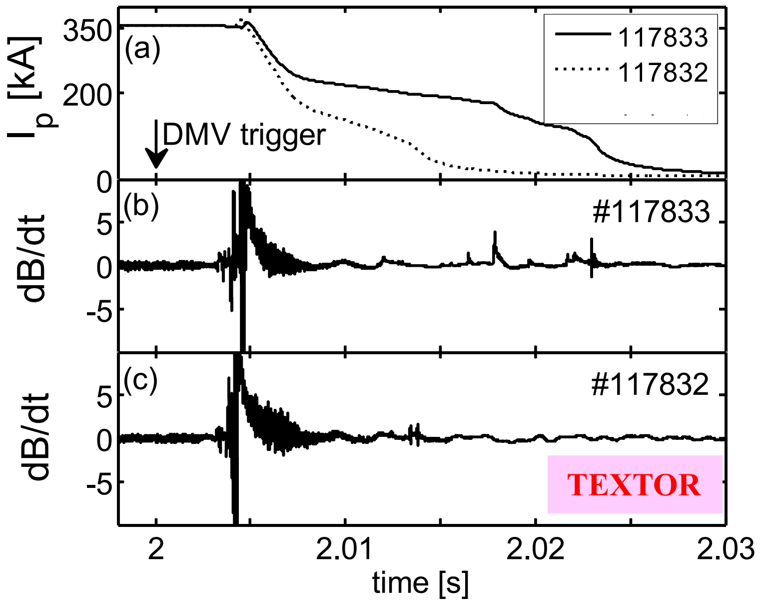
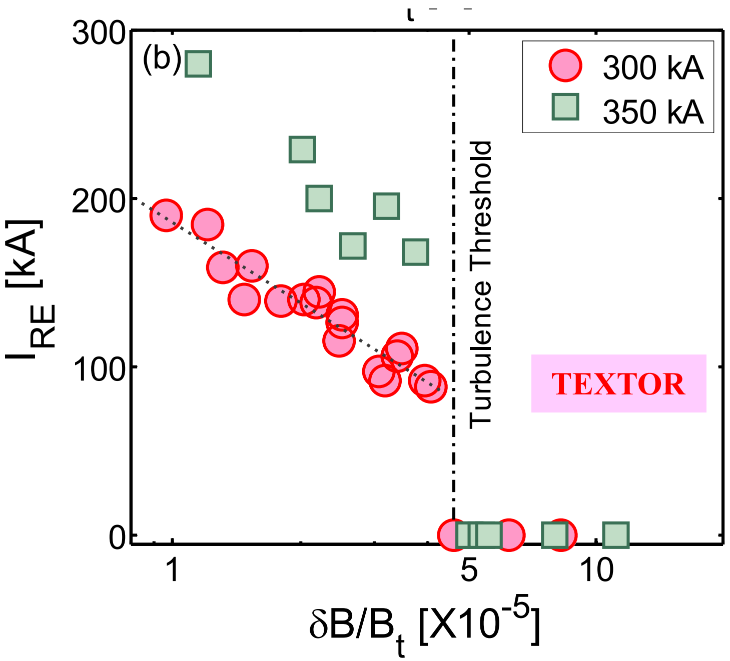
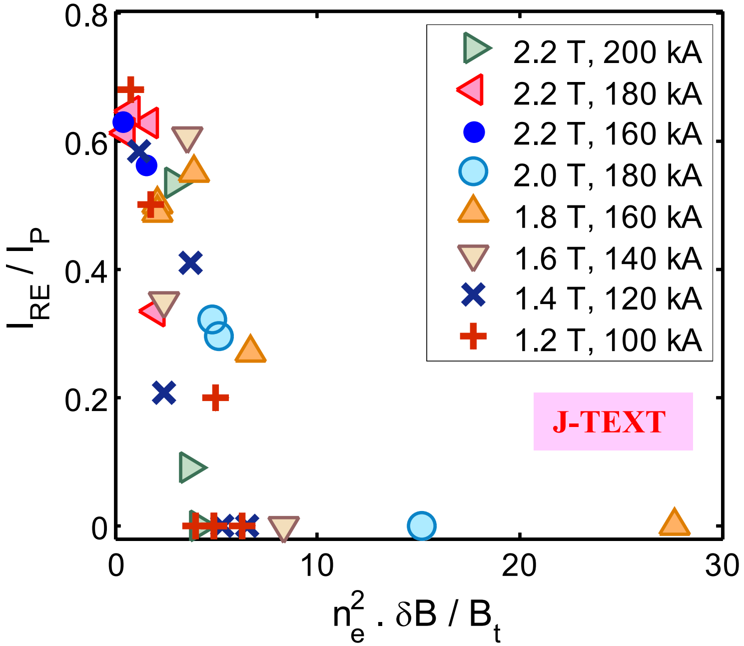
RE suppression by magnetic perturbation







- **In the same toroidal magnetic field, the RE plateau is not reproducible.**
- **The magnetic turbulence level could be the reason to cause the difference.**

- **Runaway suppression has been experimentally found only with magnetic turbulence larger than a threshold.**
- **The runaway current is a function of the maximum magnetic turbulence during the current quench both in TEXTOR and J-TEXT.**

L. Zeng, PRL, 110 (2013) 235003; L. Zeng, NF 57 (2017) 046001.

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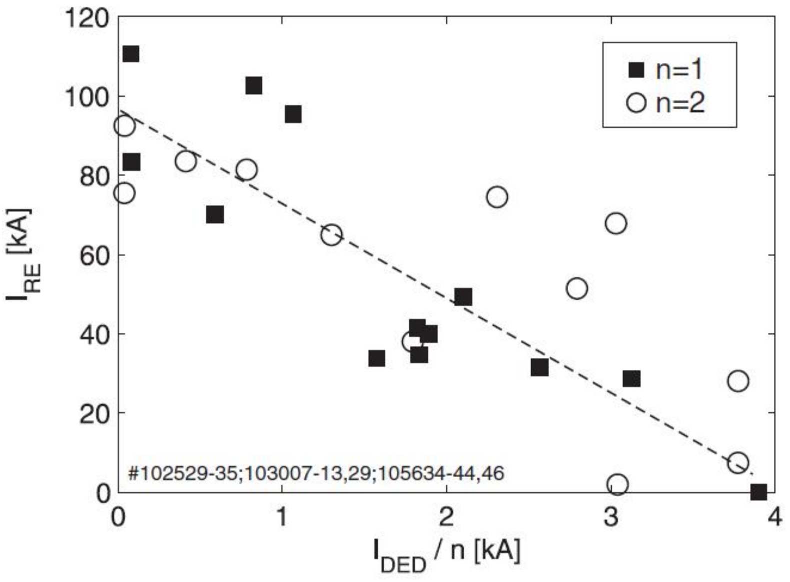
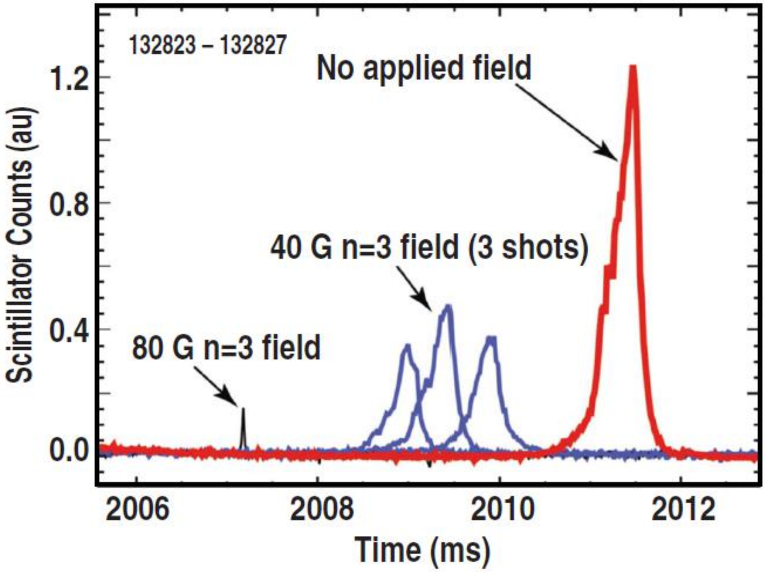
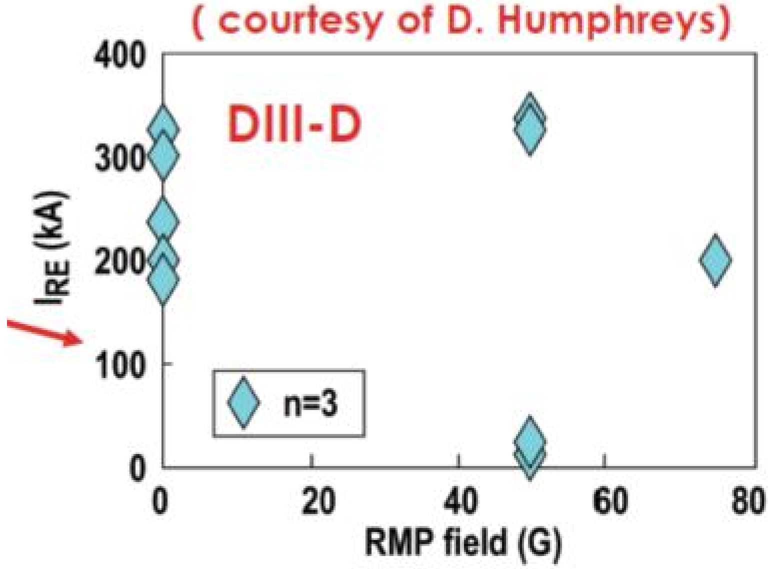
Reduction of REs by RMP



TEXTOR
Lehnen, M. et al., PRL (2008)





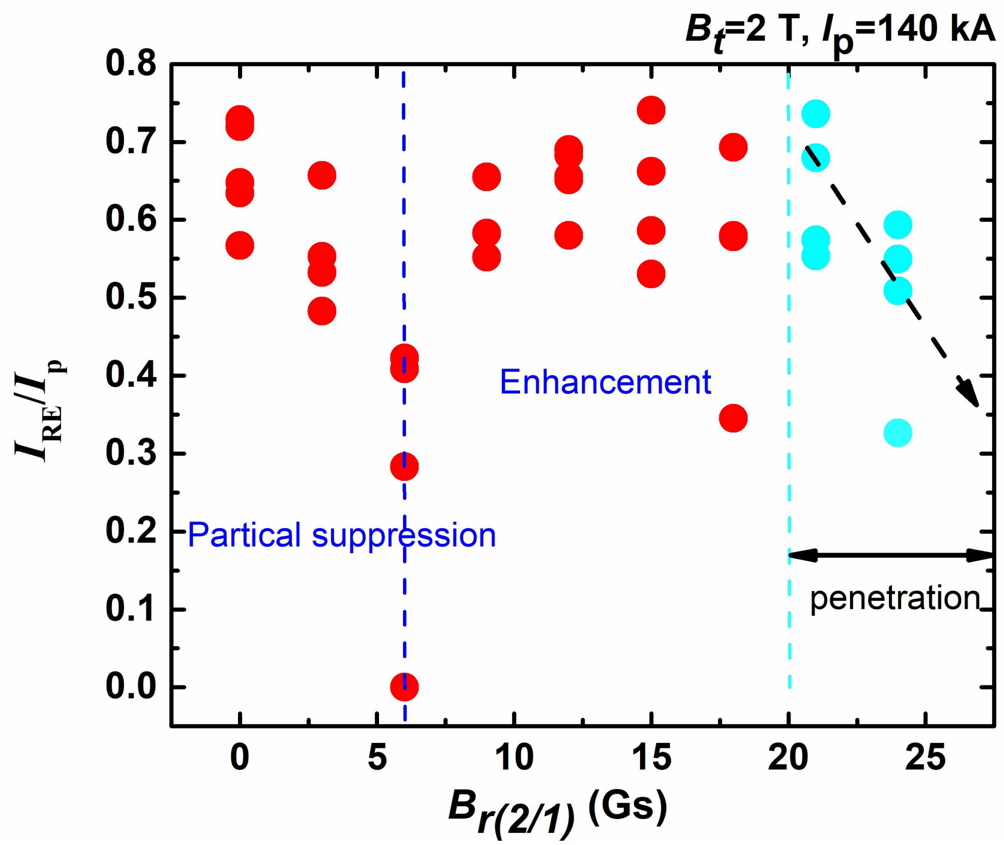
- ➤ **Clear reduction of REs by n=1 magnetic prturbation in TEXTOR.**
- ➤ **Not so clear for n=2 RMP.**

- ➤ **Reduction of REs by n=3 magnetic perturbation in D3D.**

- ➤ **Without robust reduction of REs by n=3 magnetic perturbation in D3D.**

Three interaction regimes of REs with RMP

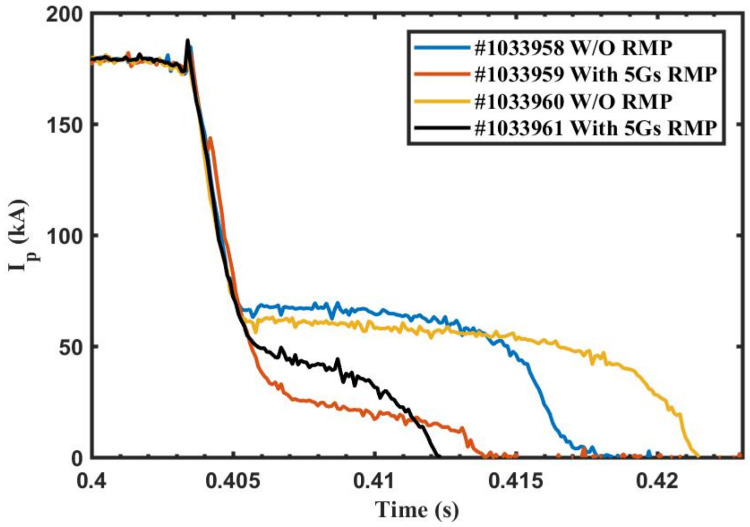
- ✓ **1. Partial RE suppression;**
- ✓ **2. Enhancement of RE generation;**
- ✓ **3. Full RE suppression.**

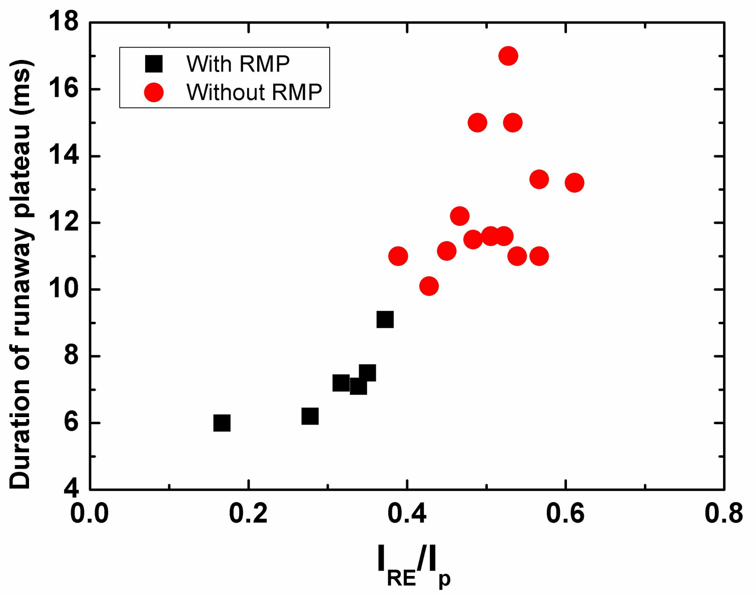


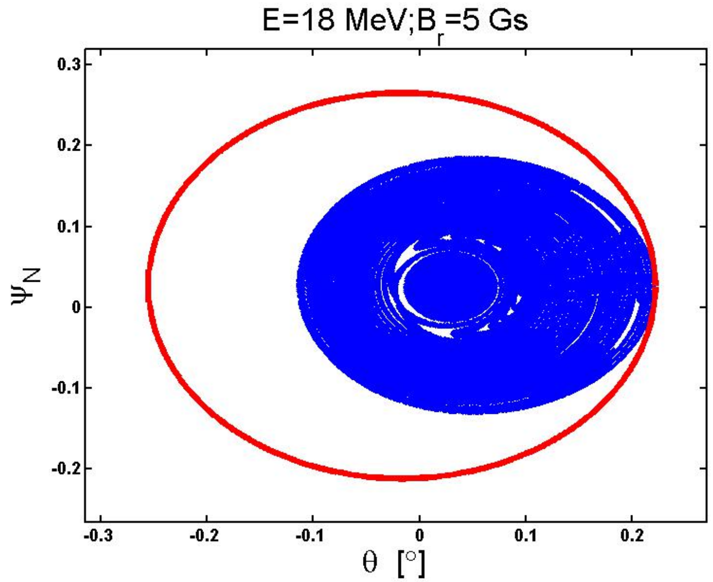
q_a~4.4, n_e~1.0×10^{19} m^{-3}

1. Partial RE suppression by RMP

- **MGI fast shutdown with 5Gs RMP (m/n=2/1):**
  - Reduction of runaway current;
  - Reduction of the duration of runaway plateau.



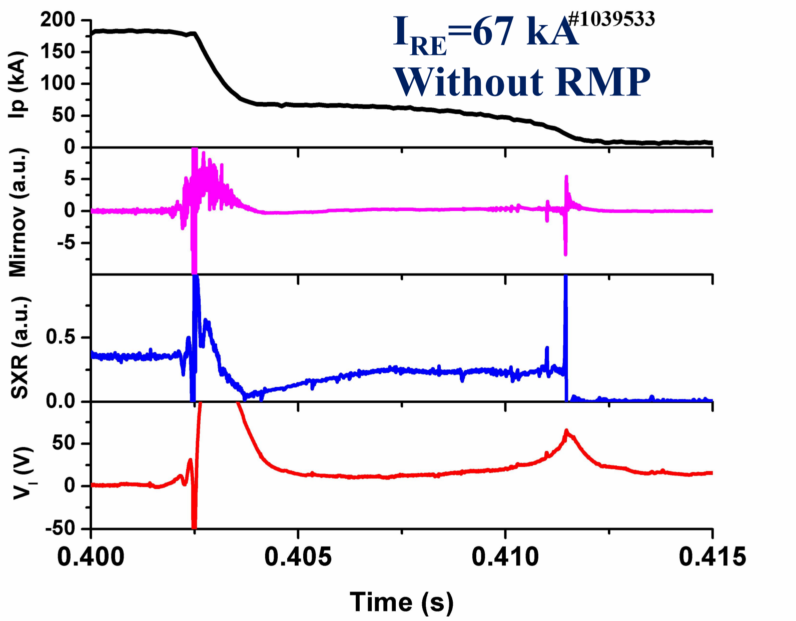


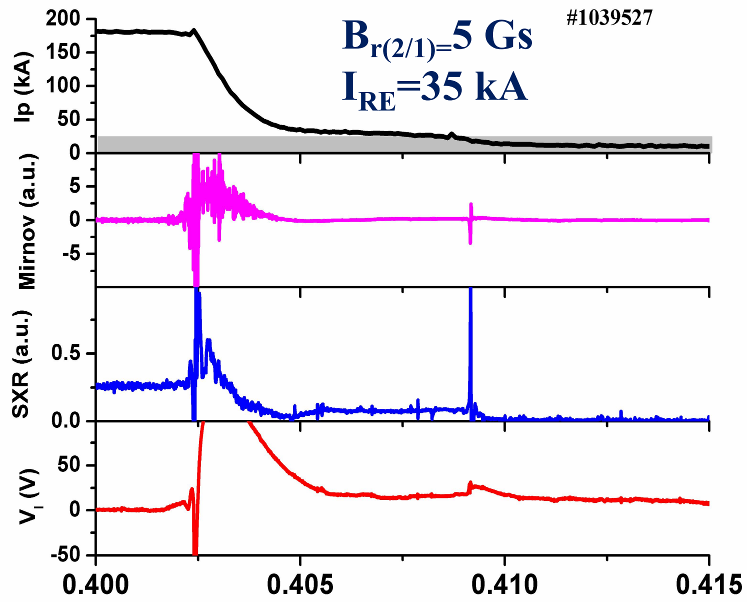


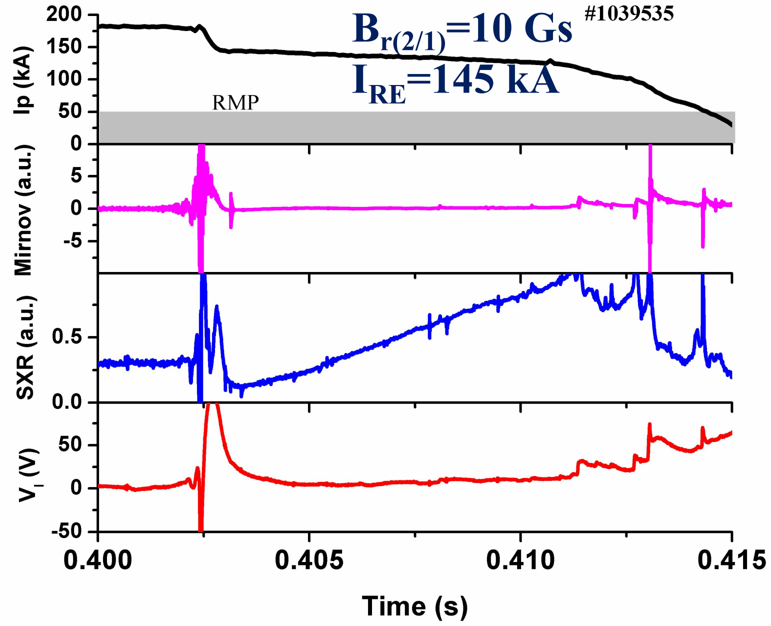
- **Simulation indicates the REs loss:**
  - Related to the radial position of REs ;
  - Shrinkage of confinement region.

Chen Z. Y., et al., NF (2016). Jiang Z. H., et. al., NF (2016).

2. Enhancement of RE generation by RMP

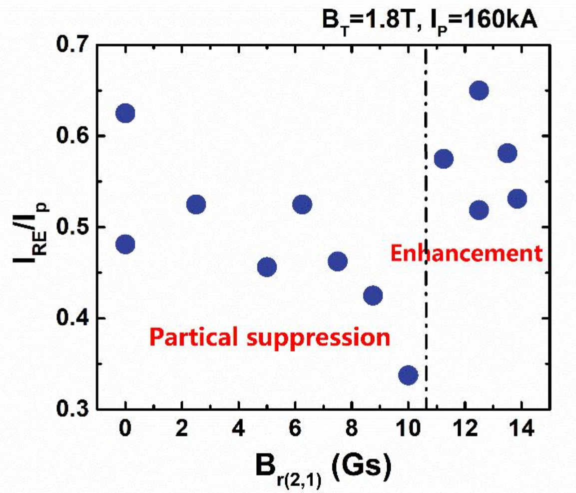






B_T=2.2 T, I_p=180 kA, q_a~4, n_e~1.0×$10^{19}m^{-3}$.

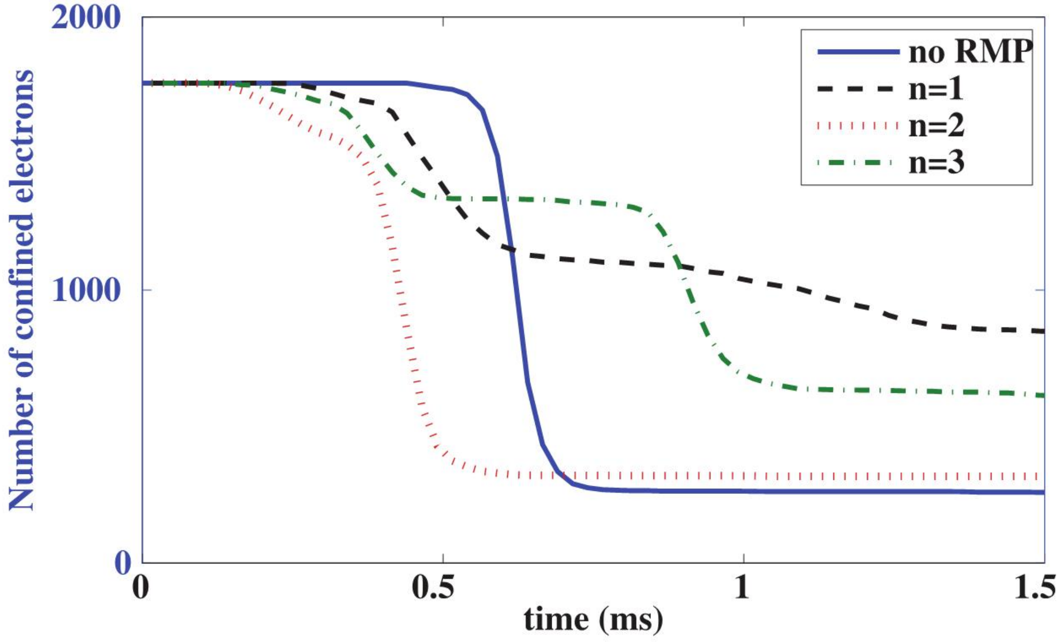
Ar MGI at 0.4 s to induce stable runaway current plateau.



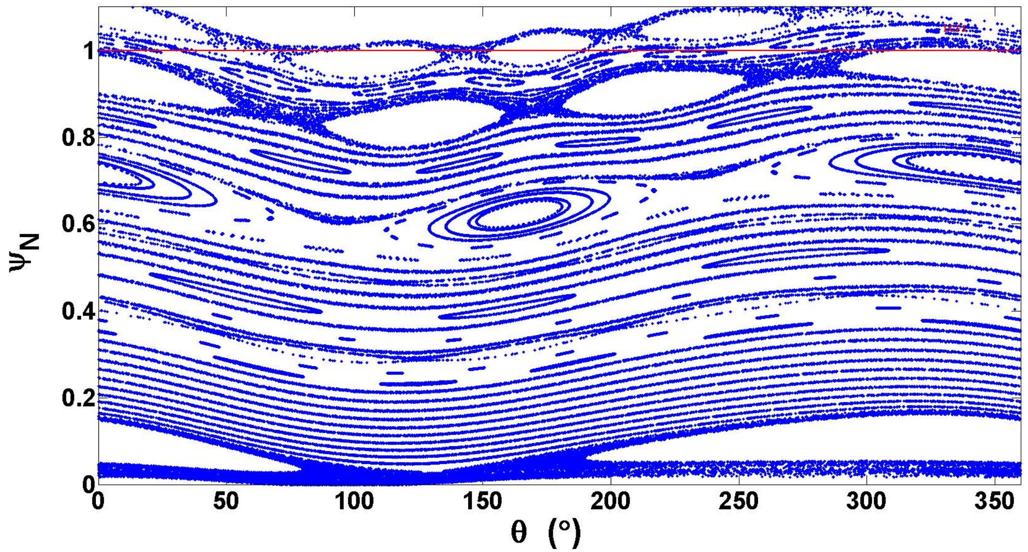
- **The runaway current is enhanced instead of suppression when the amplitude of RMP was increased to a higher level.**

Chen Z. Y., et al., NF (2016)

➢ NIMROD Simulation (by V.A. Izzo):



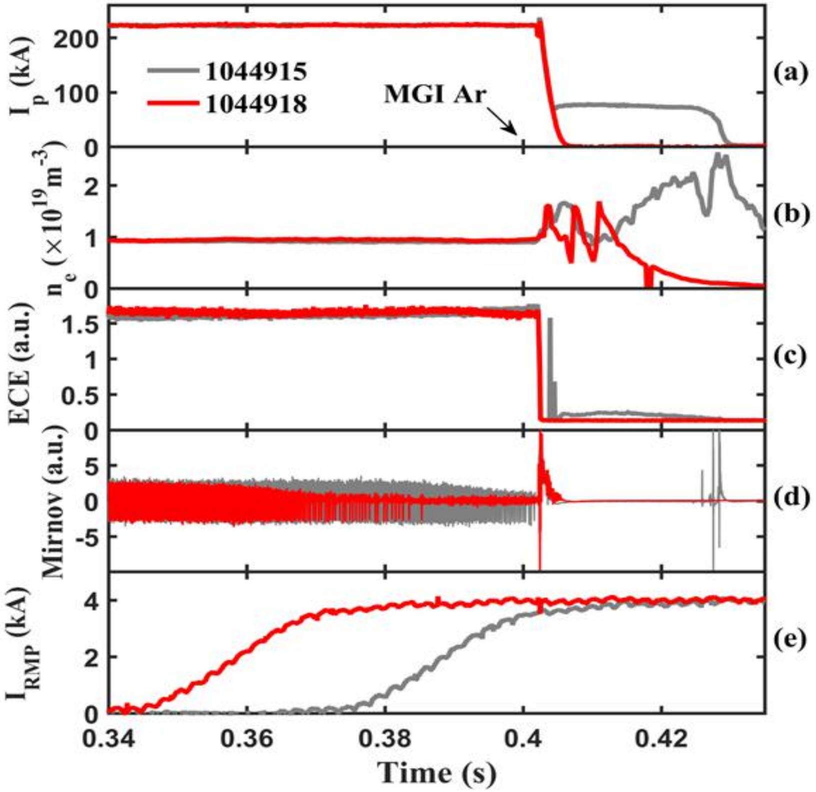
- Number of confined RE test particles vs. time for three NIMROD simulations of disruption with RMP.
- It is found that n=1 and n=3 RMP has the potential for runaway enhancement.

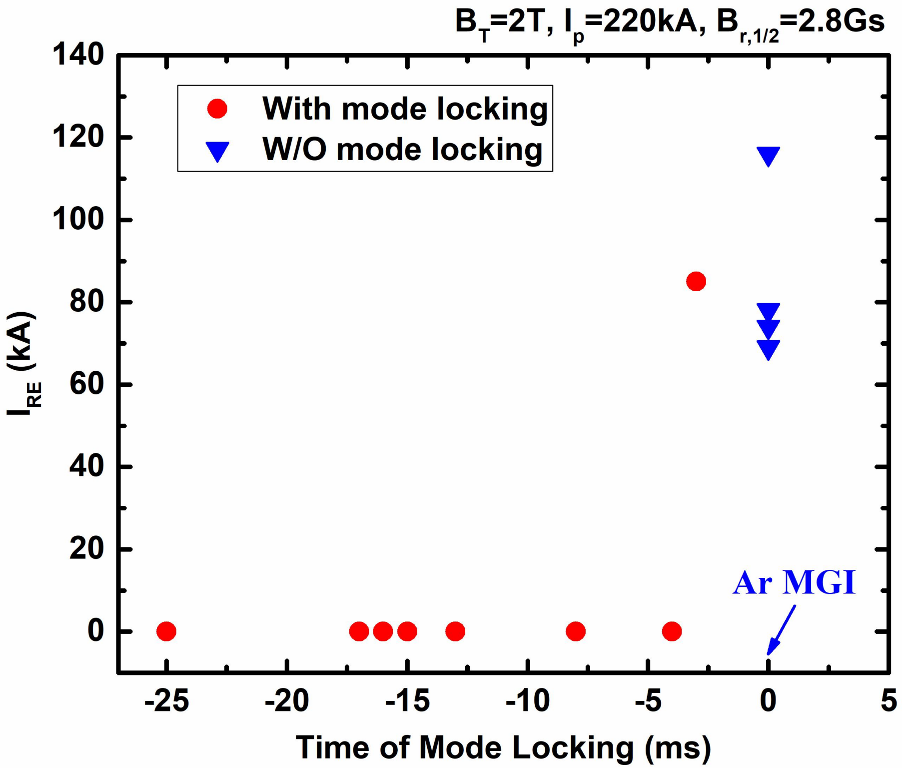


- Poincare plotting of the magnetic surface with 4 kA m/n=2/1 mode RMP.
- Big size magnetic islands near q=2 surface was formed by the application of 4 kA m/n=2/1 mode dominated RMP.
- The runaway seed can survive in the magnetic islands!

3. Full suppression of RE by RMP-mode locking

Target plasma with 2/1 tearing mode. B_T=2 T, I_p=220 kA, q_a~2.8, n_e~1.0×$10^{19}m^{-3}$.





- Locked mode before disruption by RMP suppressed runaway current generation!
- RMP coils may far away from the plasma core. The strength of RMP is limited in the core regime.
- Mode locking by RMP need only small amplitude.
- This scenario is possible for large scale device.

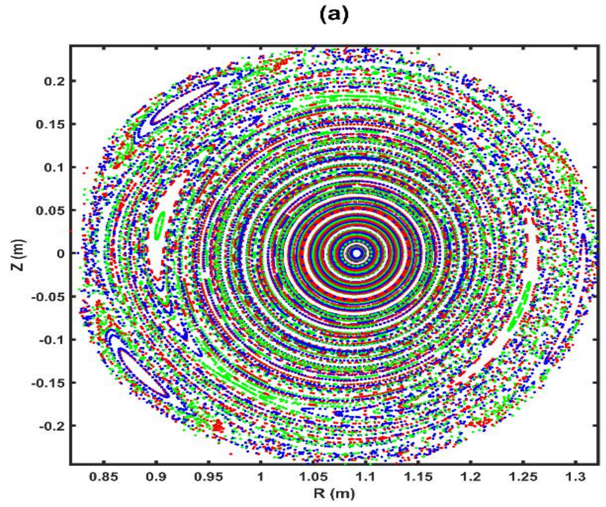
The mode locking implemented large magnetic islands inside the plasma which acted as an “explosive bomb” during disruptions and led to stronger stochasticity in the whole plasma cross section which deconfine the runaway seed!

Chen Z. Y., et al., NF (2018)

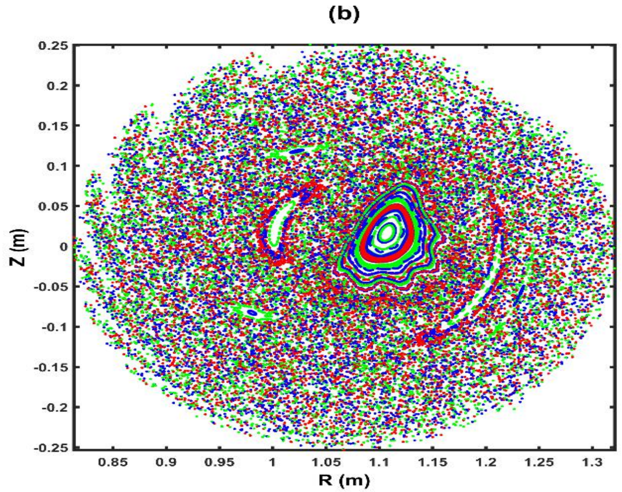
NIMROD Simulation:

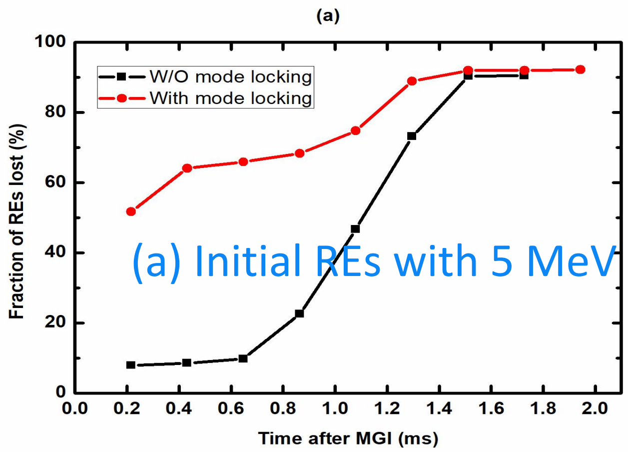
- The NIMROD simulation indicates that this strong stochasticity expel out the runaway seeds and results in runaway free disruptions on J-TEXT.
- This might provide an alternative runaway suppression technique during disruptions for large-scale tokamaks.

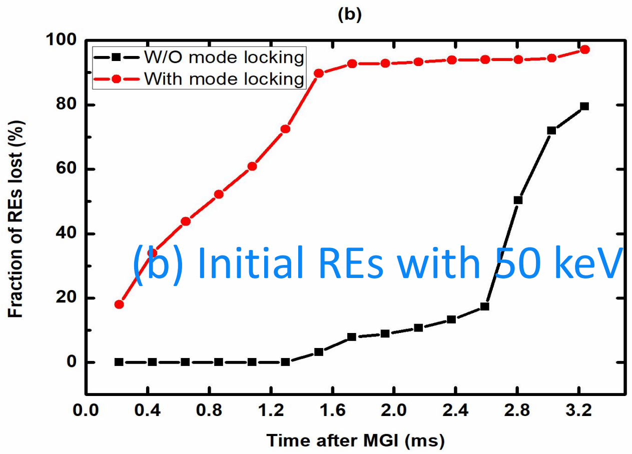
mode locking in 0.2ms



mode locking in 3ms, just before TQ phase

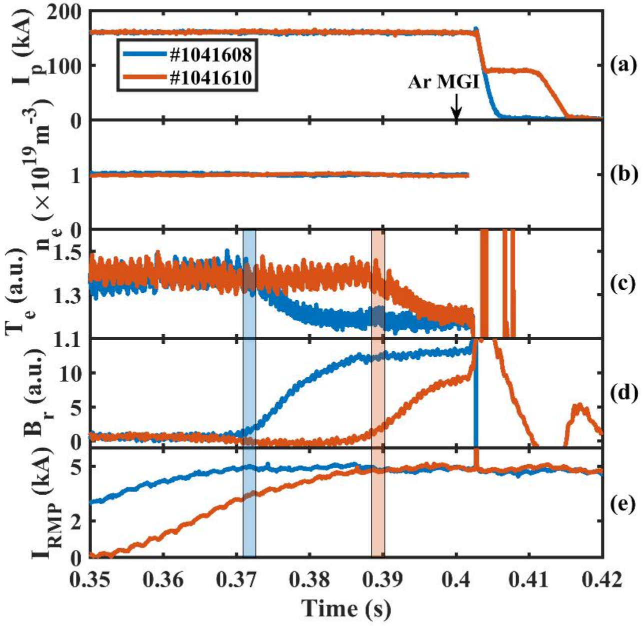


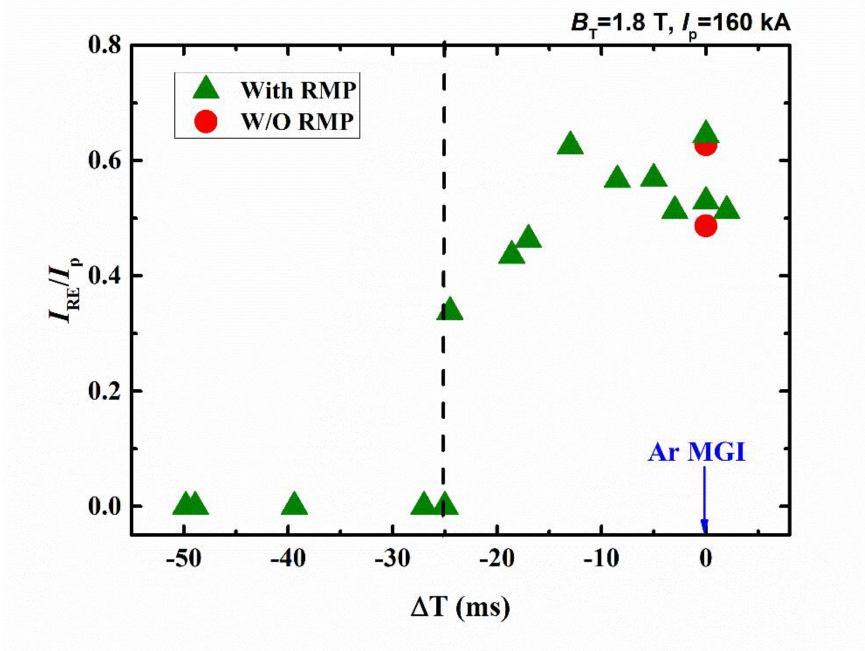


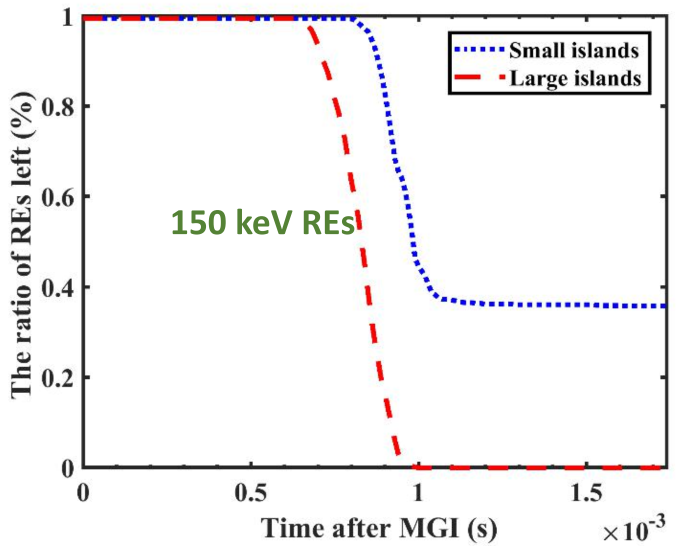


3. Full suppression of RE by RMP-mode penetration

Tearing mode free plasma. RMP: m/n=2/1, q_a~3.48, $B_{r,2/1}$ ~12.5Gs (@ r=a)







- **Robust runaway suppression has been achieved by RMP mode penetration early than Ar MGI (~ 25ms). Similar mechanism with mode locking.**
- **NIMROD simulation indicate: Threshold of magnetic islands width: ~0.16a (4cm for J-TEXT)**
- **Due to the large distance of RMP coil with the plasma center, this scenario is a chanllenge for large scale device.**

Lin Z. F. et al., PPCF (2019)

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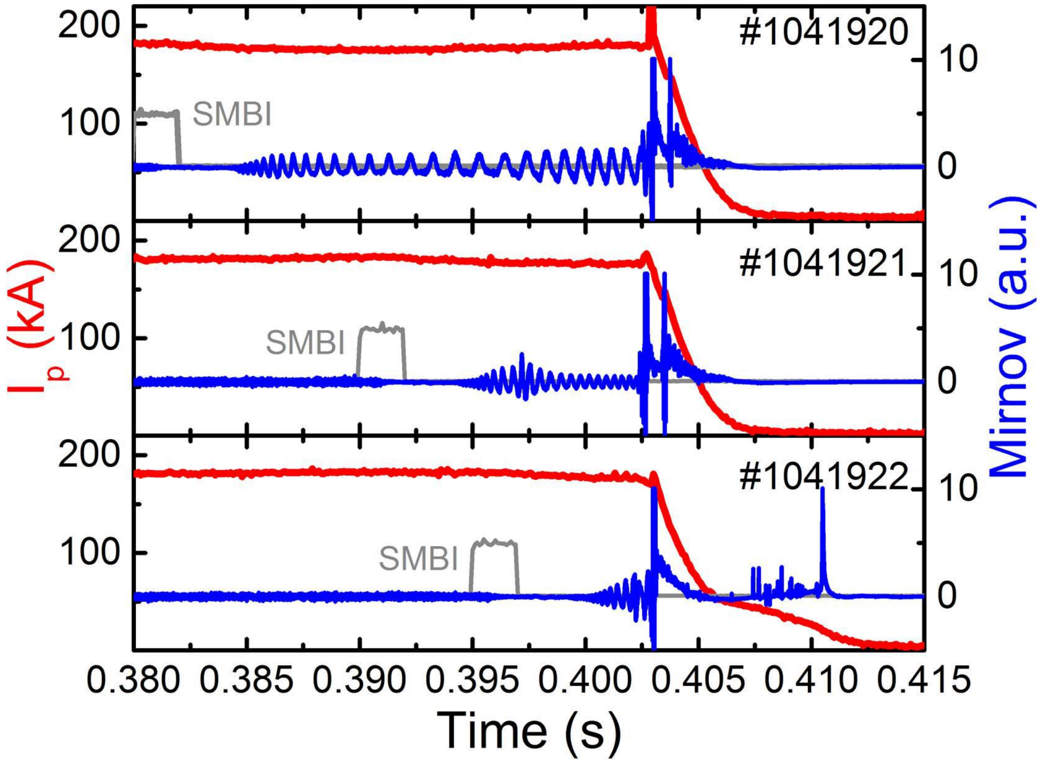
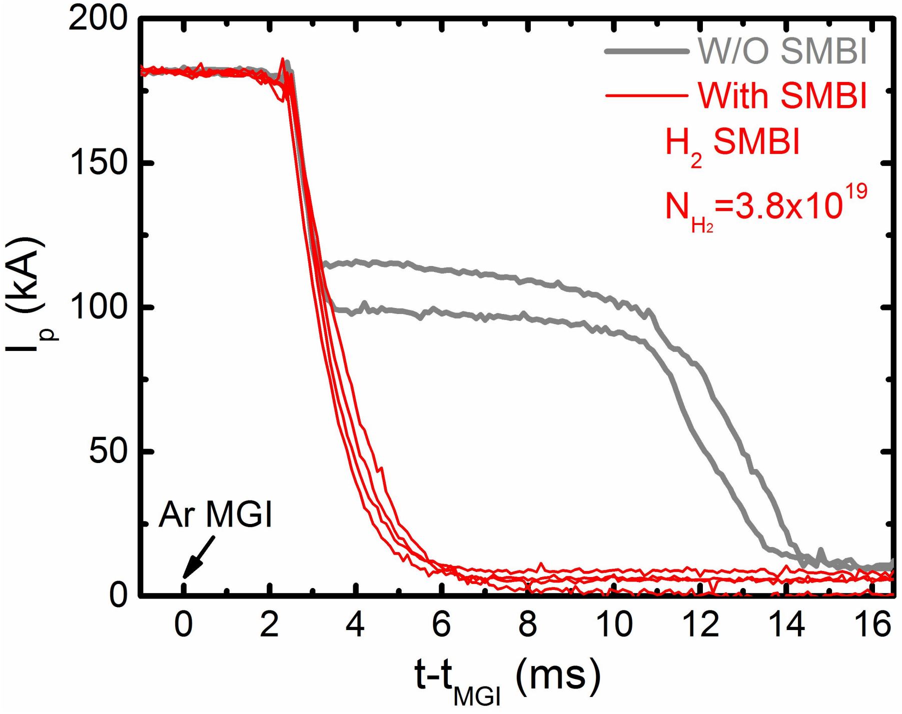
RE suppression by SMBI (H_2) induced magnetic pertubation

B_T=2.2 T, I_p=180 kA, q_a~3.8, n_e~1.0×$10^{19}m^{-3}$

SMBI and MGI are triggered **simultaneously**



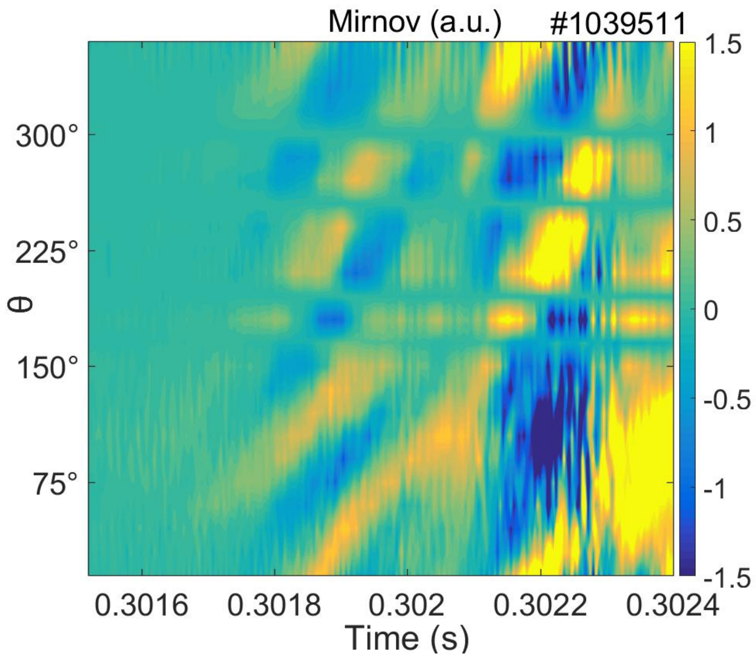


- The magnetic perturbation can be induced by the SMBI H_2;
- The runaway current has been suppressed by the magnetic perturbation of SMBI.

Huang D.W et al., PPCF (2017)

RE suppression by SMBI (H_2) induced magnetic pertubation

- The supersonic H_2 beam reaches plasma edge earlier than Ar.
- The combination of supersonic H_2 beam and the following massive Ar gas jet enhances the stochasticity of magnetic field during disruption.

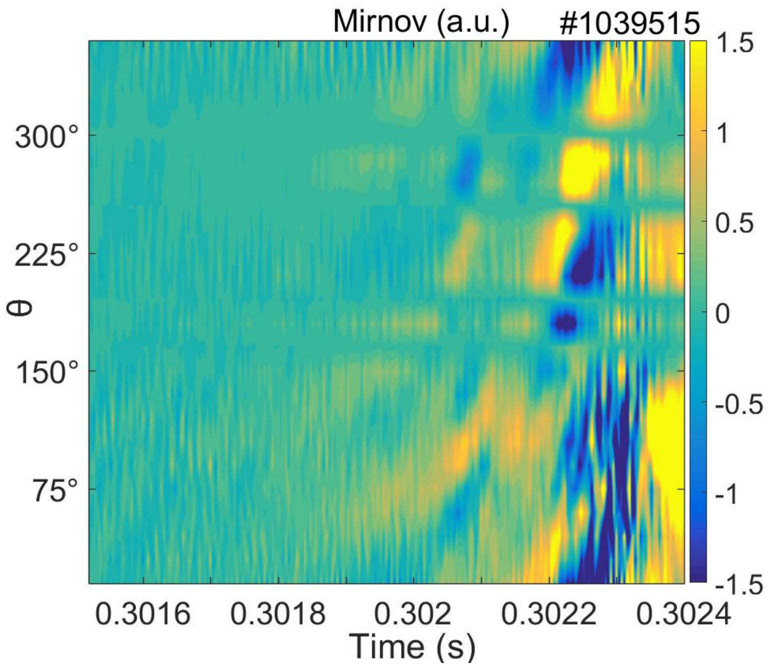


SMBI+MGI:

RE free

0.3017s: m/n=3/1

0.3022s: m/n=2/1



Only MGI

With runaway current

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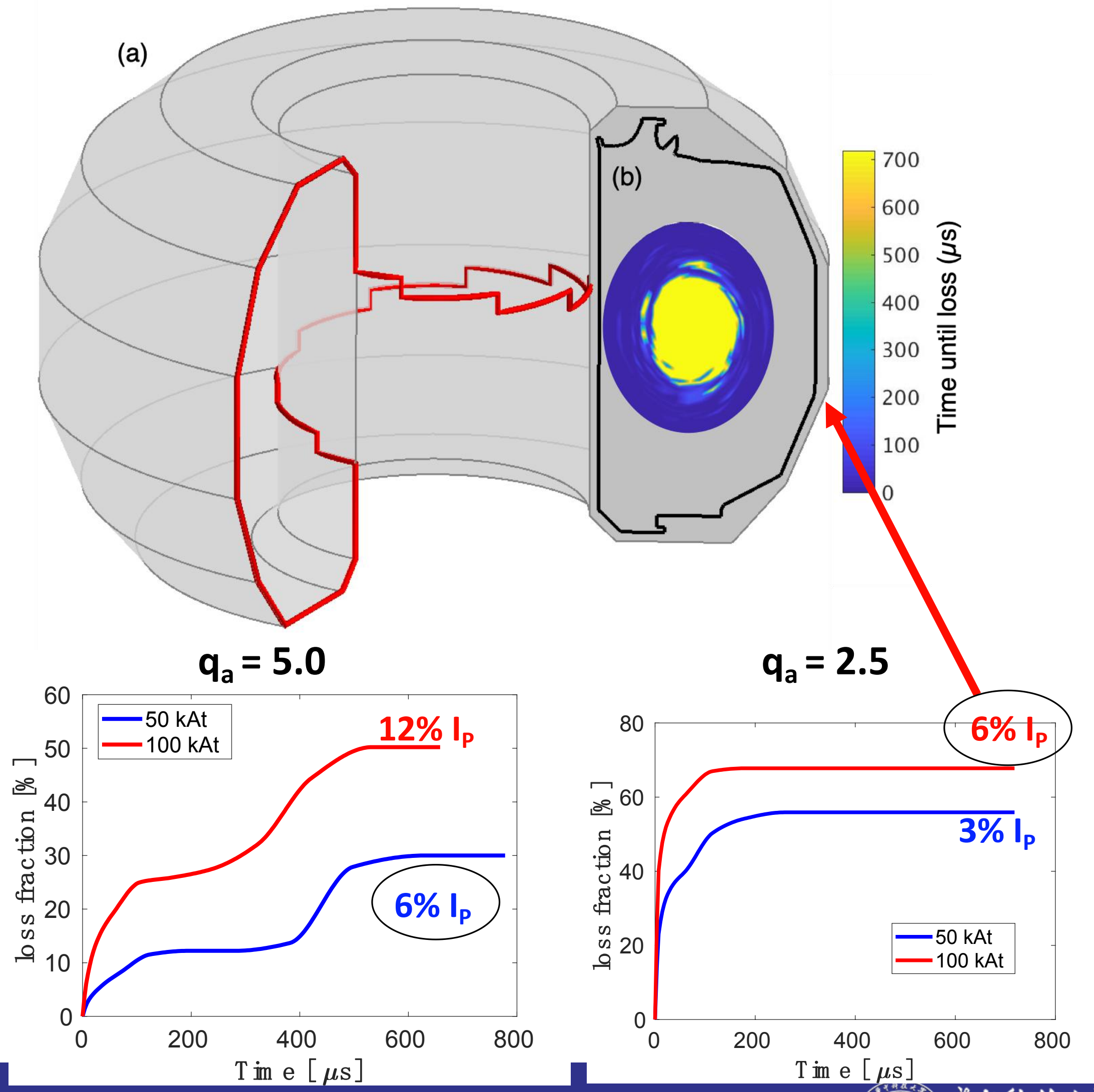
Runaway avoidance: by Passive Helical Coil

MHD modeling shows that a passive helical coil is effective at deconfining runaway electrons in DIII-D

- **A 3D helical coil is being studied for passive deconfinement of REs during the current quench**
  - CQ inductively drives current in 3D coil
- **MARS-F[1] is used to model the full plasma response and trace RE drift orbits during a DIII-D disruption**
  - Induced coil current is expected to be **6%** of pre-disruption I_P
  - 3D coil is predicted to deconfine **30%** of RE population in low-current equilibrium ($q_a = 5$)
  - RE loss fraction increases to **70%** in high-current equilibrium ($q_a = 2.5$)

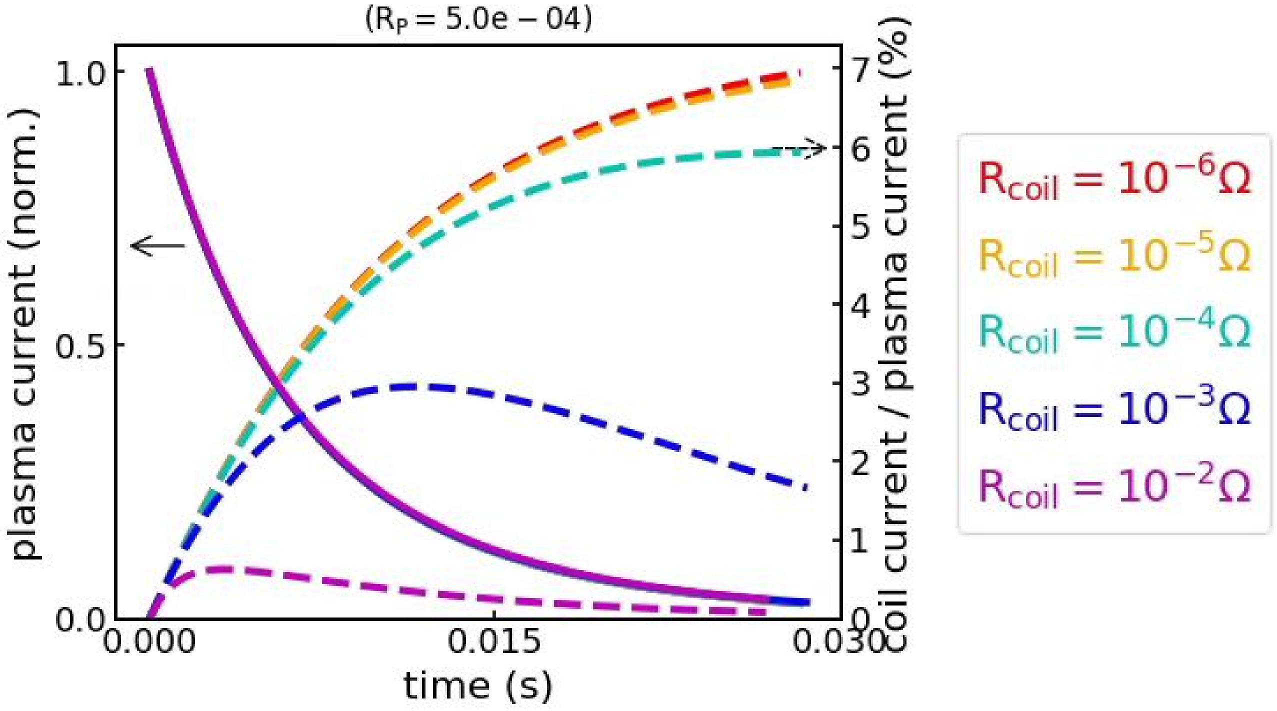


Liu et al, Nuclear Fusion 59 (2019) 126021

Runaway avoidance: by Passive Helical Coil (cont.)

Modeling of equilibrium evolution predicts large coil currents on appropriate time scale

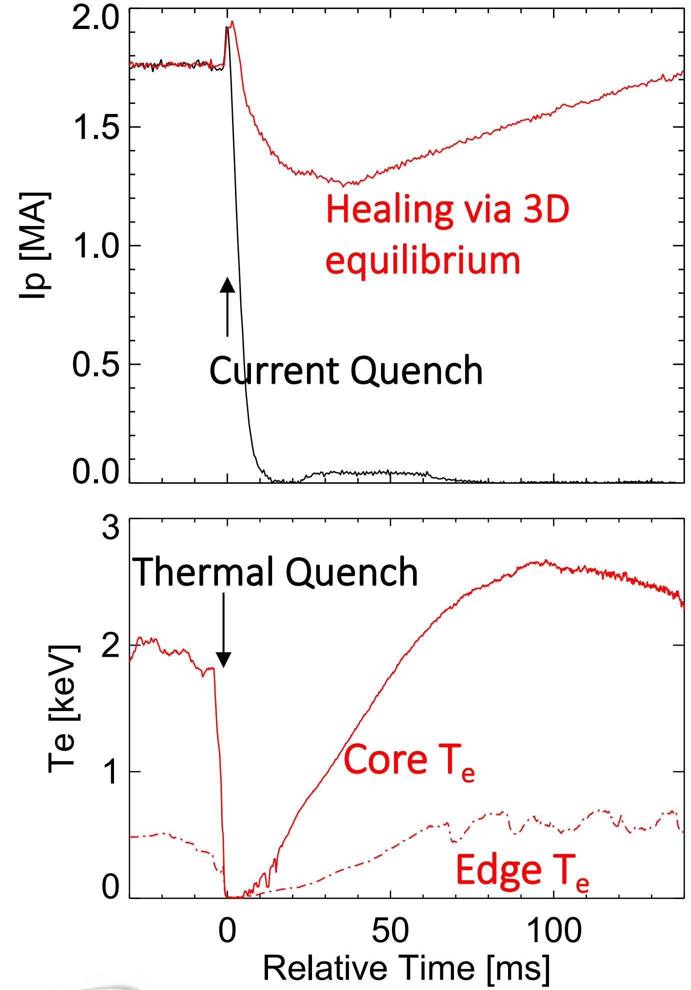
- **TokSys GS-Evolve² is used to model inductive coupling between 3D coil and disrupting plasma**
  - Choosing to build a coil with lower resistance increases induced current up to 6-7% of pre-disruption I_P
- **Extrapolation to larger devices suggests favorable scaling**
  - For constant safety factor and aspect ratio, inductive coupling is independent of size!
- **Engineering limits also scale favorably**
  - no active cooling required
  - J x B forces are well below stainless steel yield strength



Humphreys et al, Nuclear Fusion 47 (2007) 943

Runaway avoidance: by Plasma Recovery from CQ

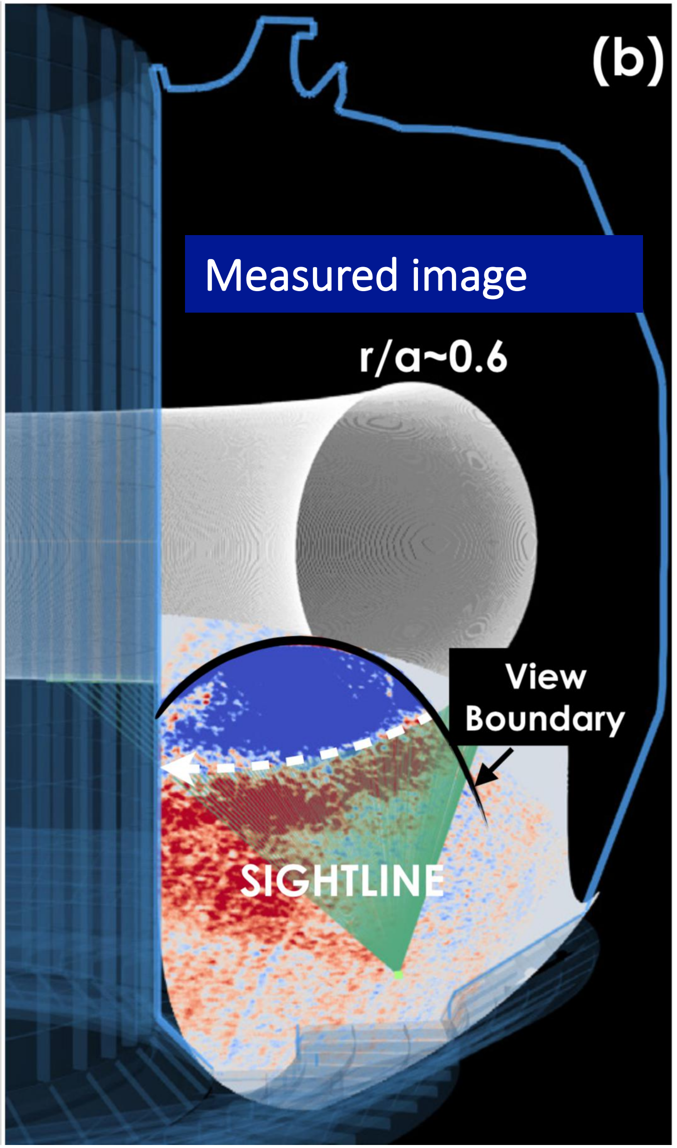
Plasma Recovery from CQ can be acheived by Generating large Core Magnetic Islands.

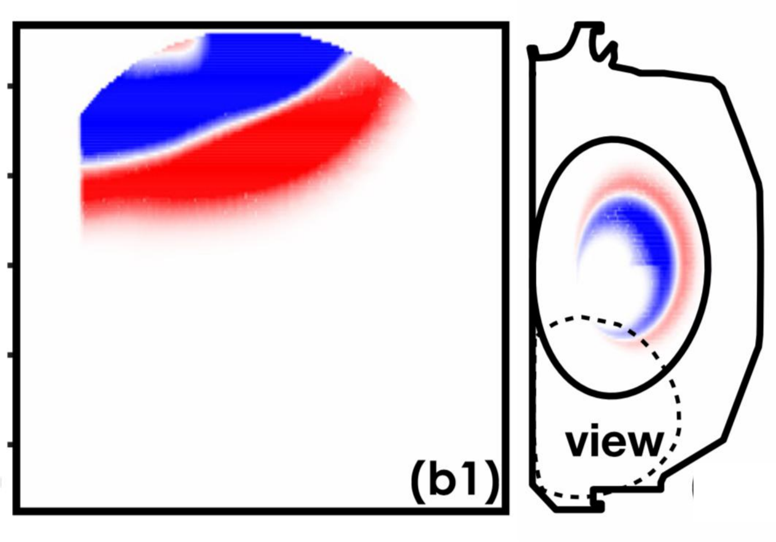


- **Recovery from major disruptions in aid of 3D fields is demonstrated in high plasma current operation regime**
  --In both IWL and Divertor configurations
- **This is realized by promptly generating magnetic islands in plasma core after thermal quench**
- **Very recent experiment shows that this scenario features a significantly extended current quench duration (from ~10 ms to 100 ms), when thermal quench is mitigated by neon puffing**
  --Absence of runaway formation and vertical unstable disruption

X.D. Du et al Nucl. Fusion 59, 094002 (2019)

Runaway avoidance: by Plasma Recovery from CQ (cont.)





SIMULATION
with 1/1 Island

- **The observed structure is consistent with large locked island with m/n=1/1**
  - With phase from 0-60 degree
  - Exact phase cannot be determined due to the large wavelength of perturbation relative to the small viewing area

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RE mitigation is essential for the next generation fusion machine. The magnetic perturbations have the ability to full suppress the REs during disruptions.

- High magnetic turbulence is favor for the runaway suppression.
- Two methods have been used to generate magnetic perturbation: **RMP (current)** and **SMBI (cold pulse)**.
- By the application of RMP, full runaway suppression has been achieved by mode locking/ mode penetration. Runaway suppression by mode locking is possible for large scale device.
- The **SMBI H_2** shows RE suppression effect due to the induced magnetic perturbation.
- MHD modeling shows that a passive helical coil is effective at deconfining REs in DIII-D
- RE avoidance has been observed on DIII-D during Plasma Recovery from CQ by Generating large Core Magnetic Islands.

Thank you for your attention!