Impurity spreading during MGI and plans for runaway electron modeling as part of SCREAM

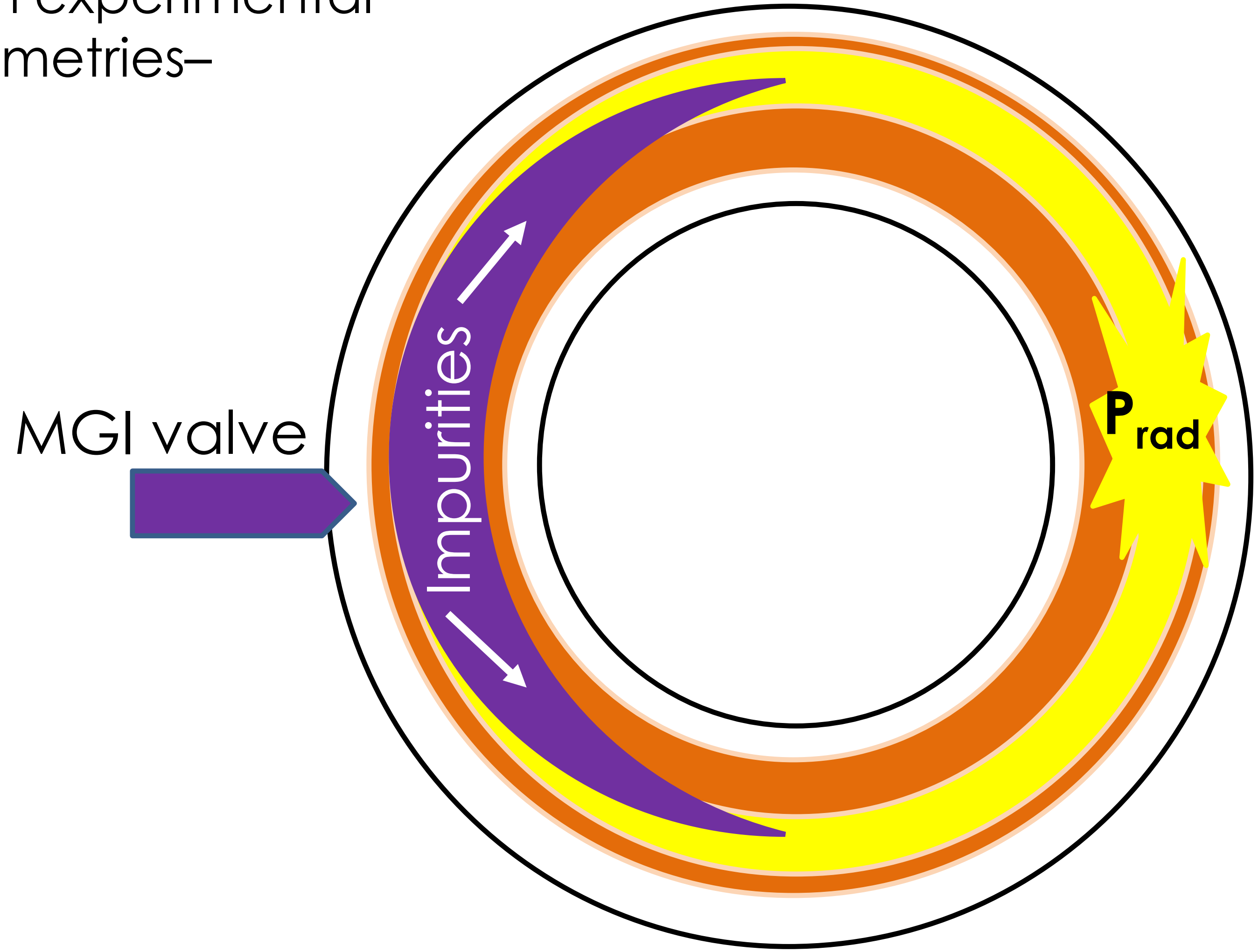
V.A. Izzo
CEMM Meeting
San Jose
30 Oct. 2016

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

UC San Diego

Motivation: what physics governs impurity spreading during massive gas injection?

Need to understand **spreading of injected impurities** to know how disruption mitigation experimental results– especially radiation asymmetries– extrapolate to ITER



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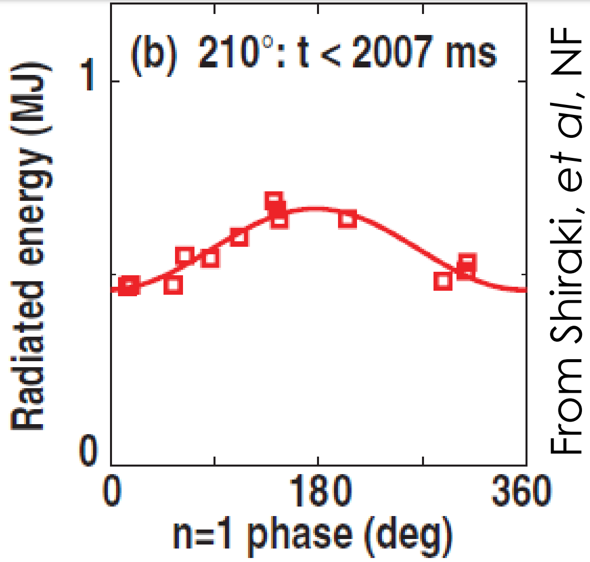
DIII-D MGI asymmetry results indicate that n=1 mode (during TQ) determines radiation asymmetry. No obvious effect of impurity distribution. Uniform by TQ?



From Shiraki, *et al*, NF **55** (2015) 073029

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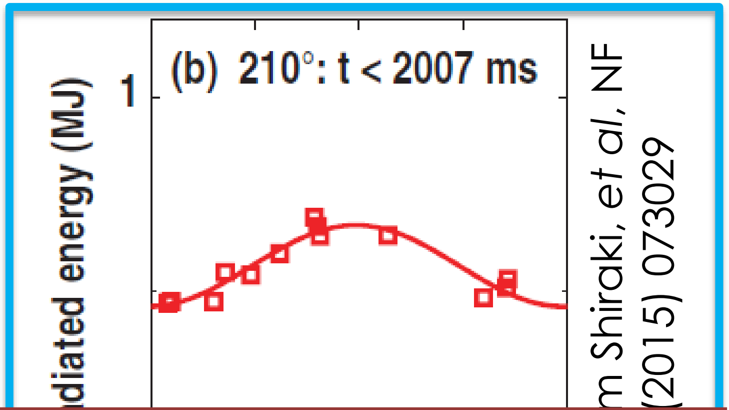
JET results indicate more significant effect of impurity distribution, especially with pre-existing locked modes

Species dependent asymmetry (possible sound speed effect) also point to role of impurity distribution



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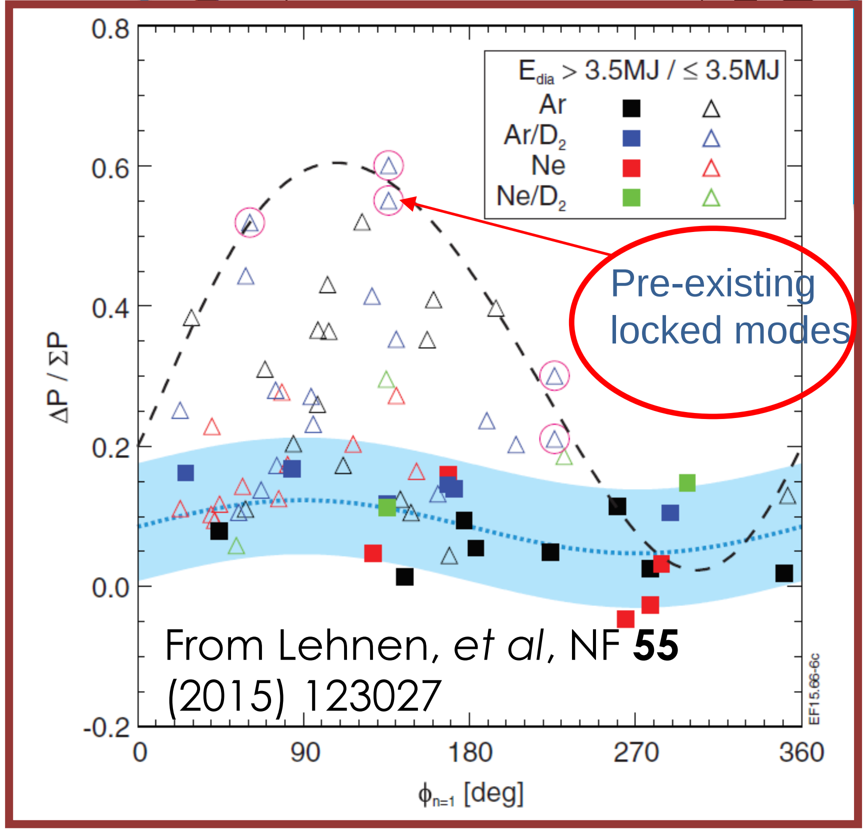


Pre-existing locked modes

From Lehnen, *et al*, NF **55** (2015) 123027

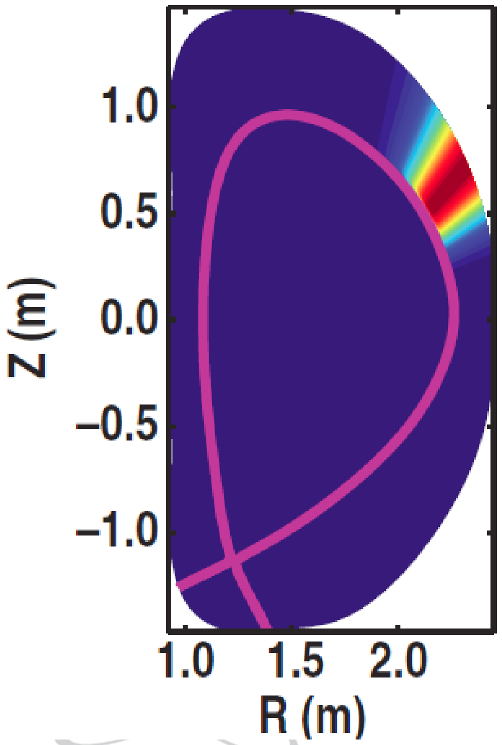
NIMROD can model impurity spreading, ionization, and radiation leading to thermal quench

Beginning with DIII-D equilibrium, impurities are deposited as neutrals

KPRAD calculates ionization, recombination and radiation cooling

NIMROD calculates MHD response to edge cooling, diffuses and advects impurities along with main ion species

Neutral Ne density



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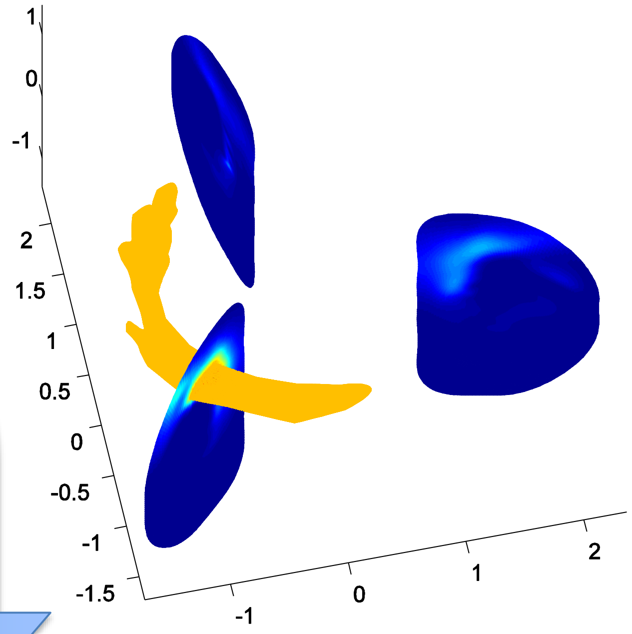

Summary

Impurities spread along field lines most rapidly at low order rational surfaces, and toward the HFS

Magnetic topology is important: Large pre-existing islands impede impurity spreading; higher-n harmonics that break up large islands enhance impurity spreading

Rotation can play a role: large rotation near the edge can enhance parallel impurity spreading, but changes in MHD have negative consequences for toroidal peaking

Summary

Impurities spread along field lines most rapidly at low order rational surfaces, and toward the HFS

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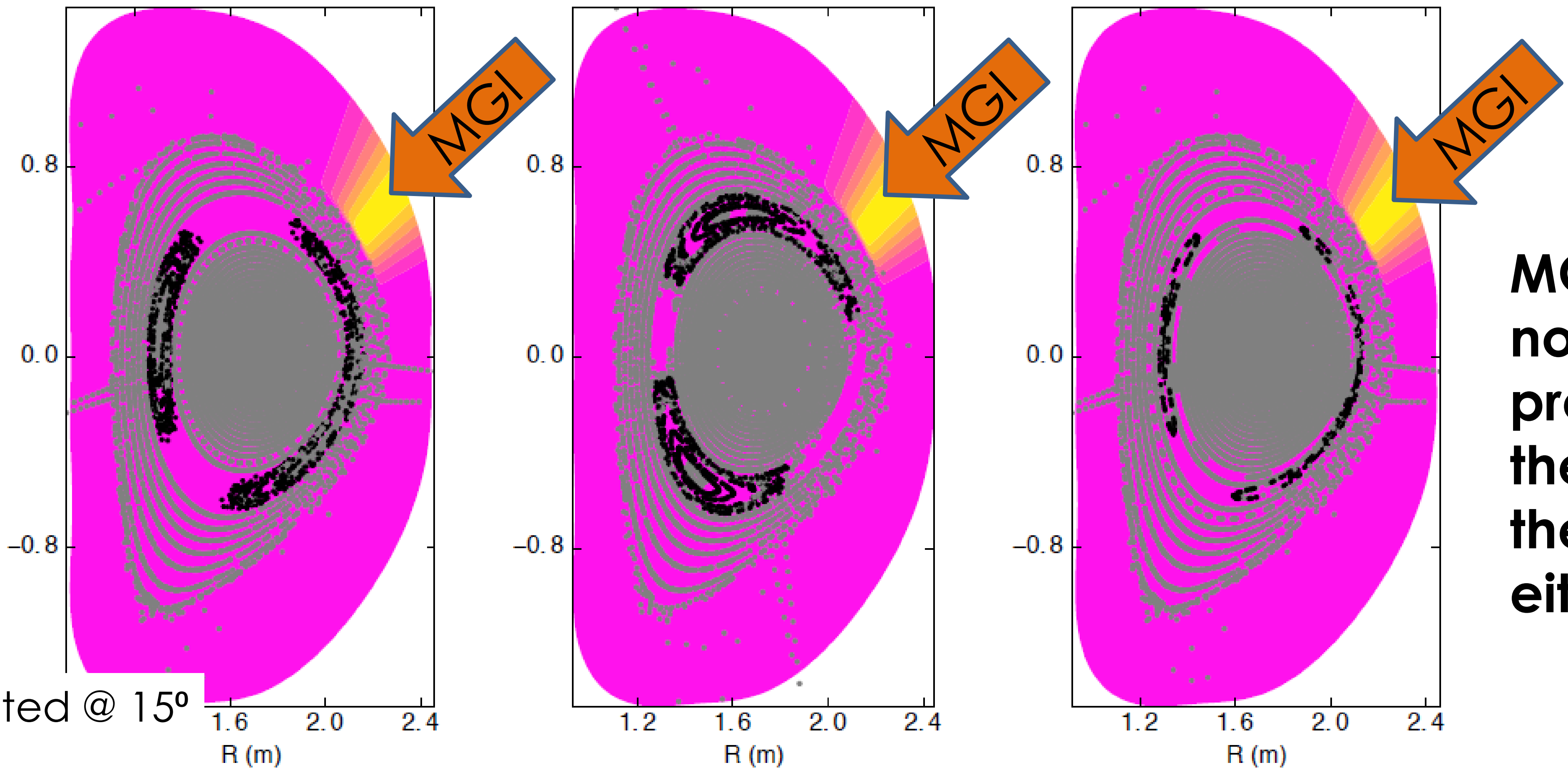
Three simulations are initialized with 2/1 magnetic islands

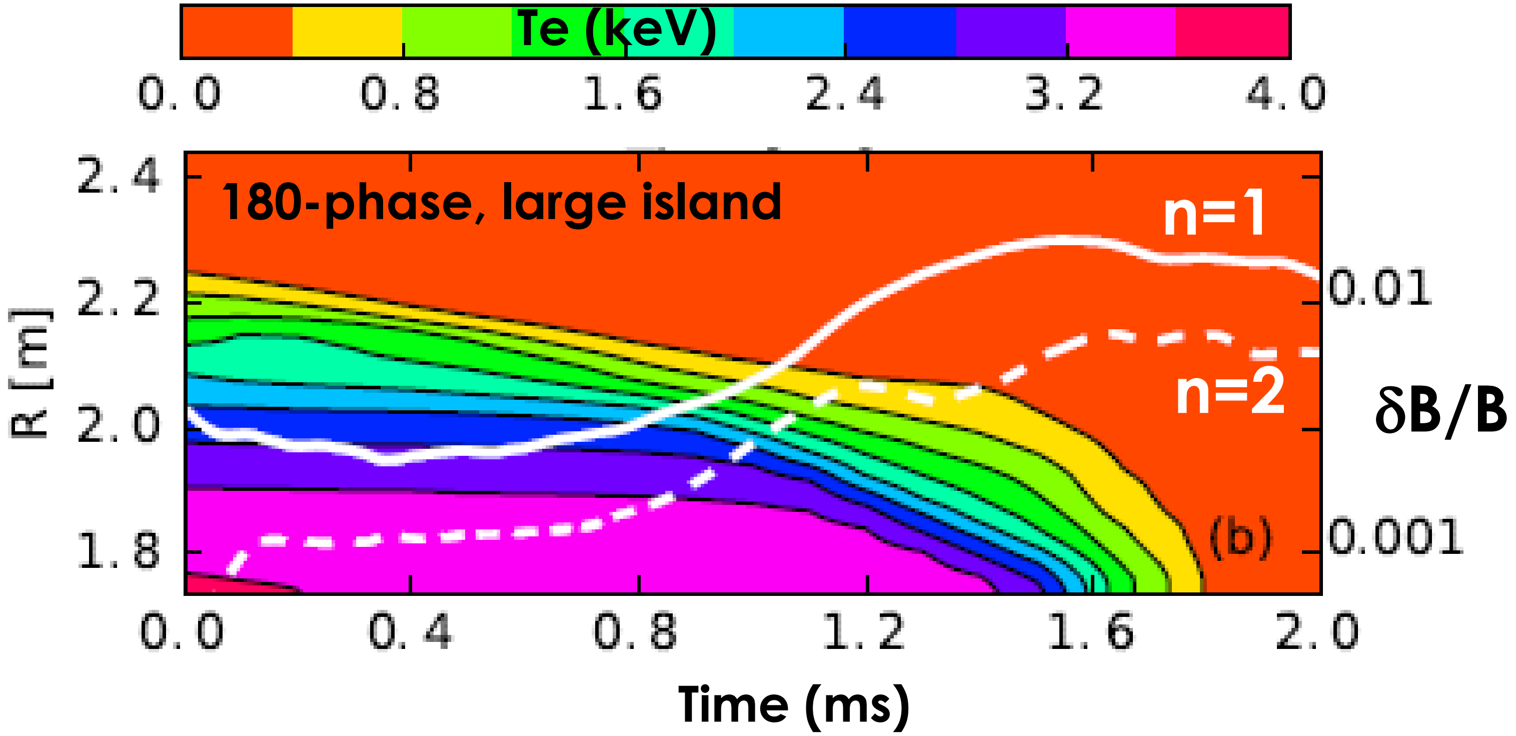


Plotted @ 15º

MGI location is not aligned precisely with the x-point or the o-point for either phase

Edge cools slowly, then central T_e drops rapidly

Temperature evolution at outer midplane



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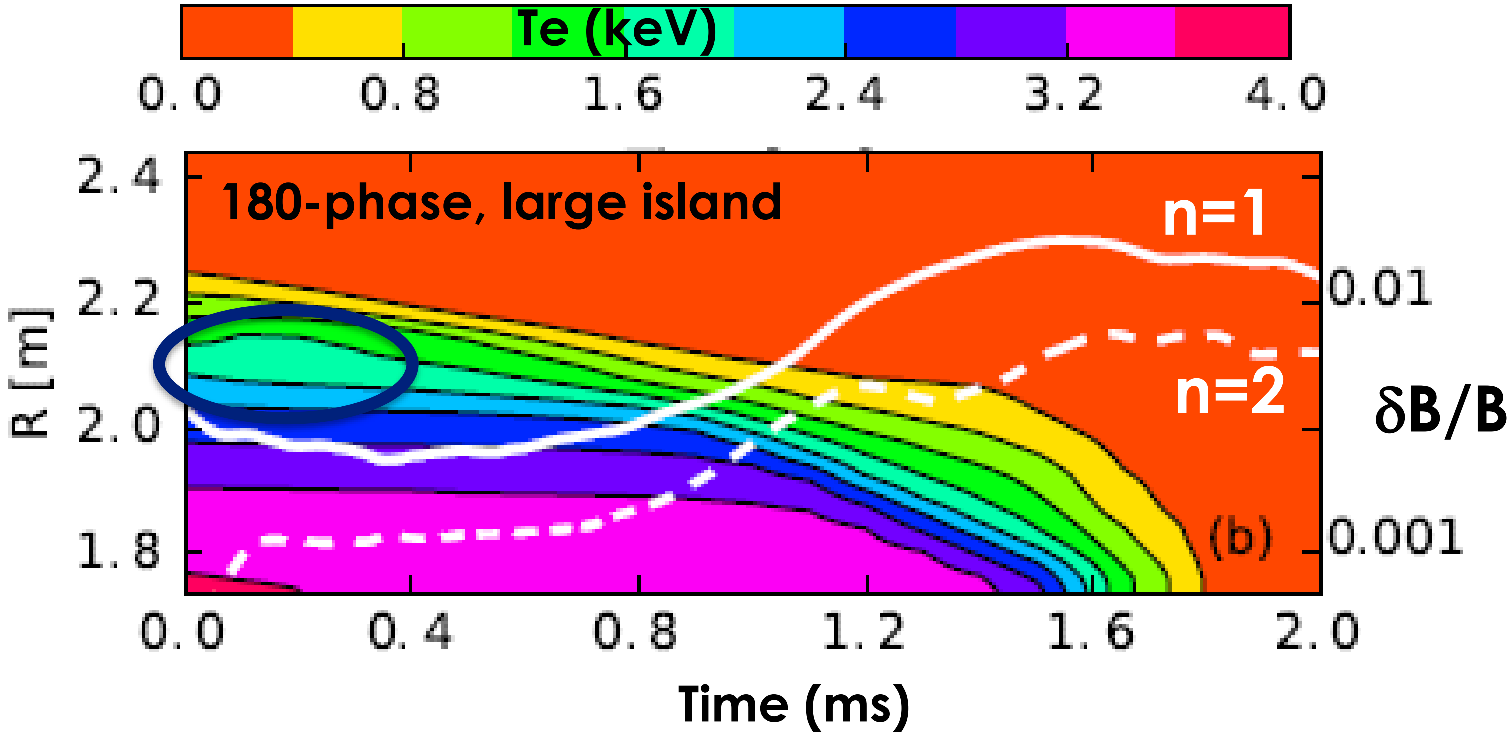

- Temperature flattening at q=2 due to large initial island as edge cools

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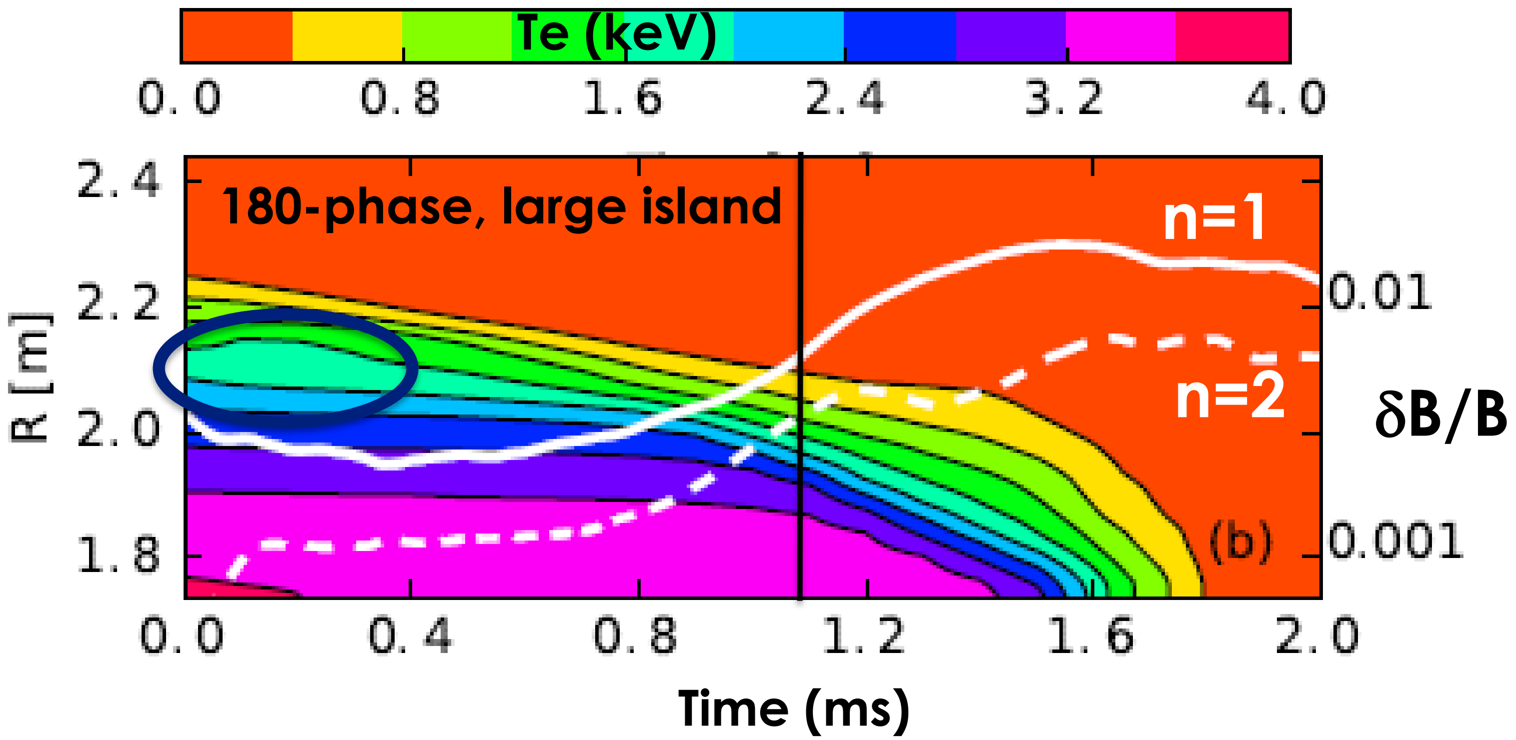
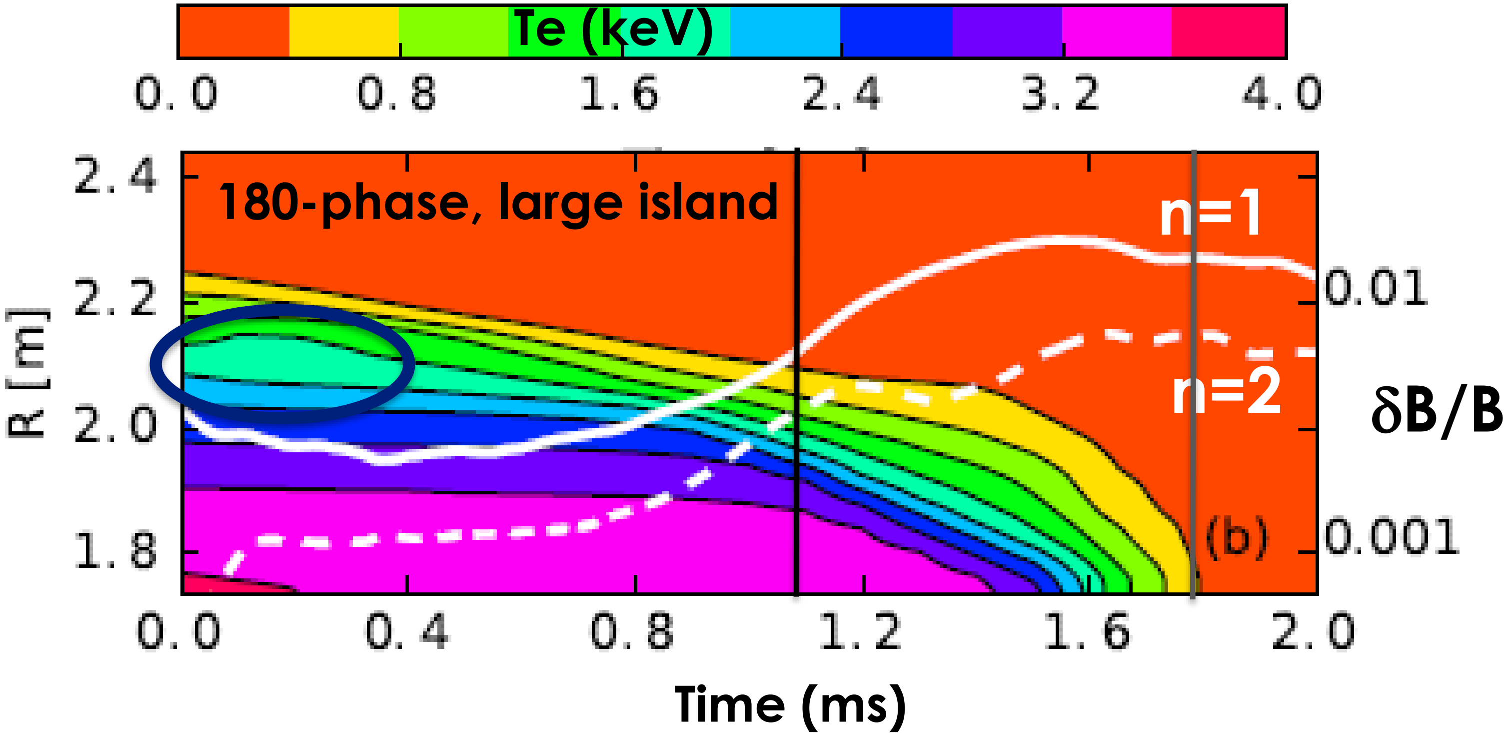


- **Temperature flattening at q=2 due to large initial island as edge cools**
- **Central Te begins to drop as n=1 grows rapidly (TQ begins)**

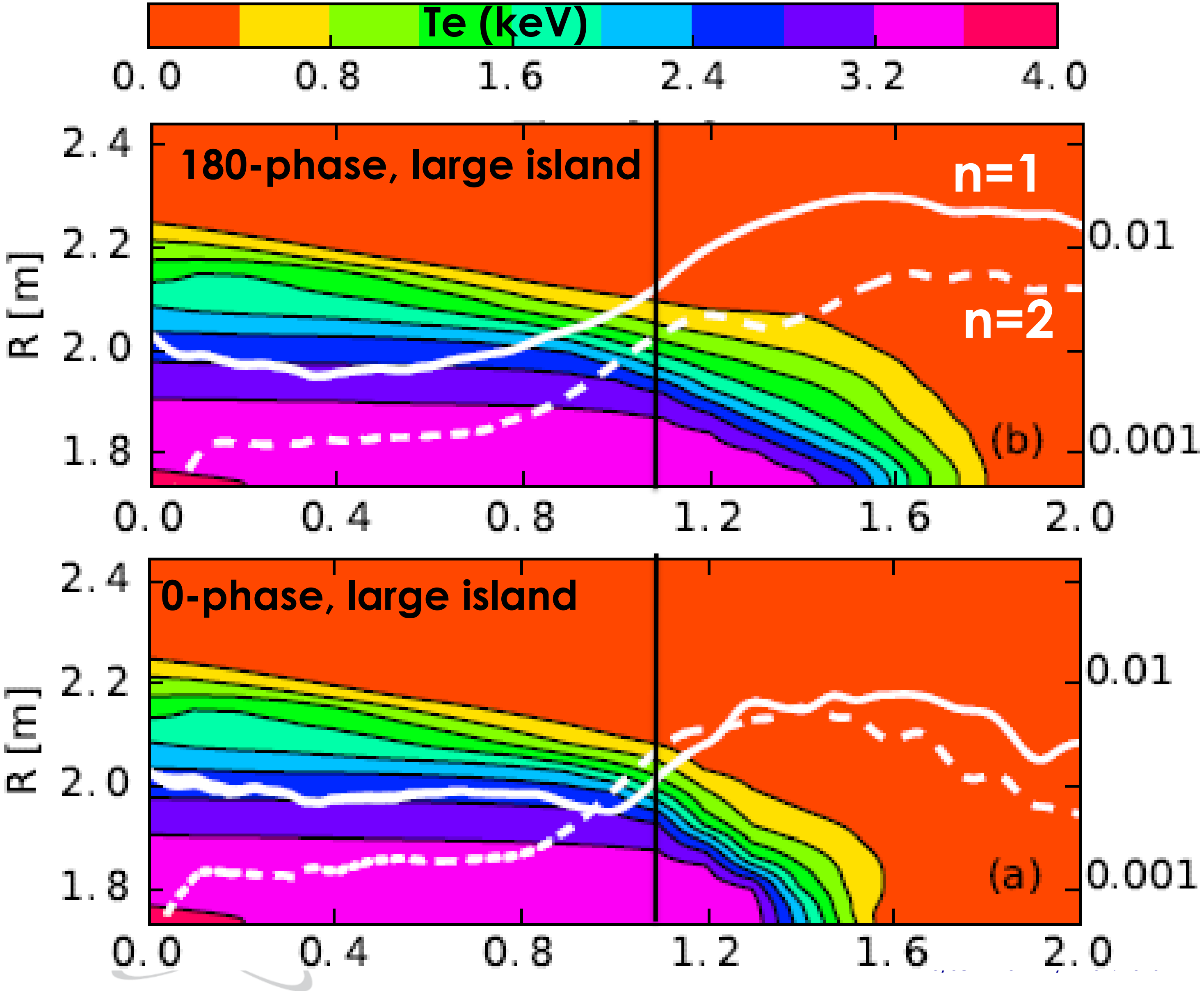
Edge cools slowly, then central T_e drops rapidly

Temperature evolution at outer midplane



- **Temperature flattening at q=2 due to large initial island as edge cools**
- **Central Te begins to drop as n=1 grows rapidly (TQ begins)**
- **TQ ends within 1 ms of onset**

Thermal quench duration is shorter for 0-phase, where n=2 mode briefly dominates



- For large island cases, TQ onset time is nearly identical

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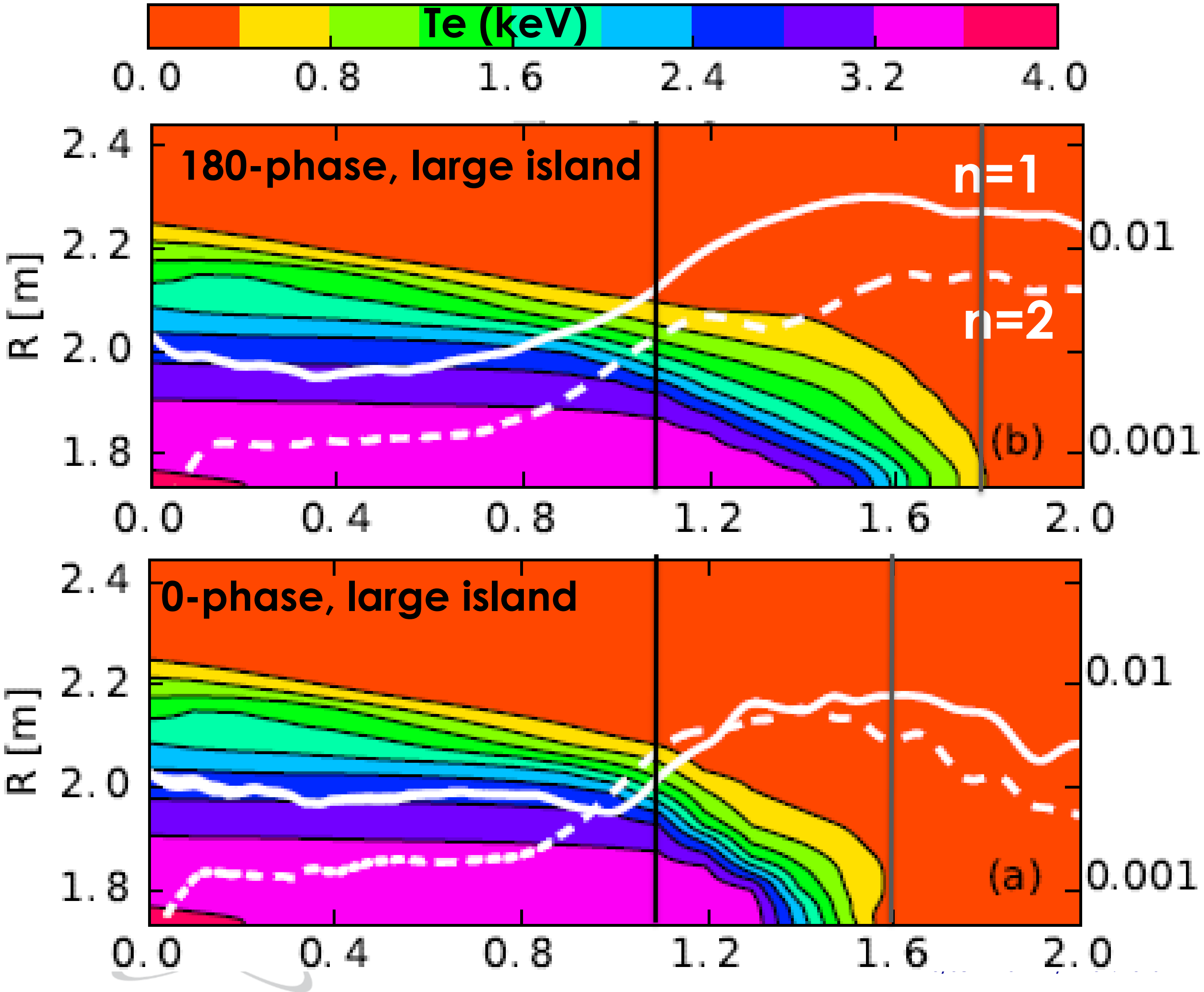

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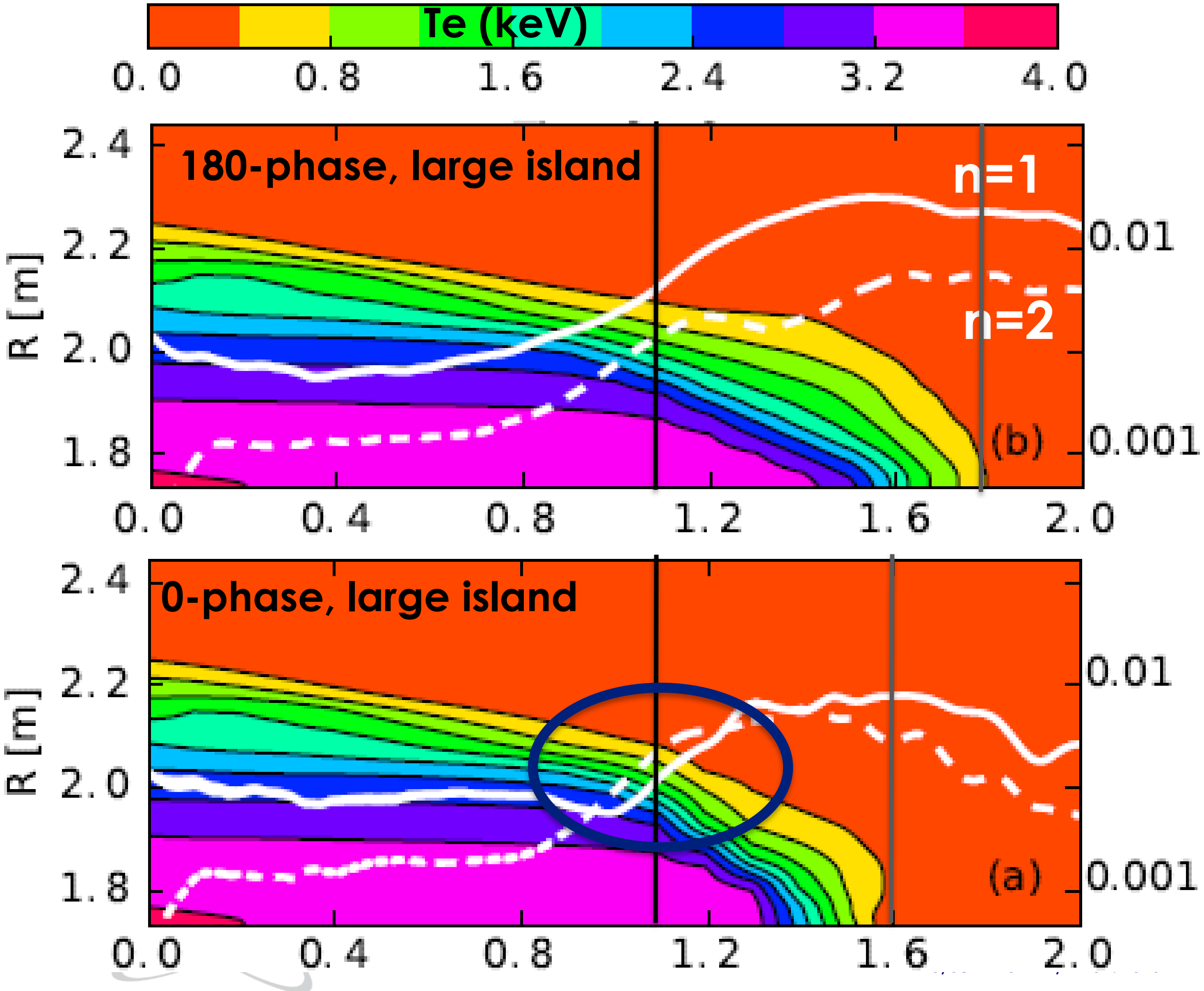
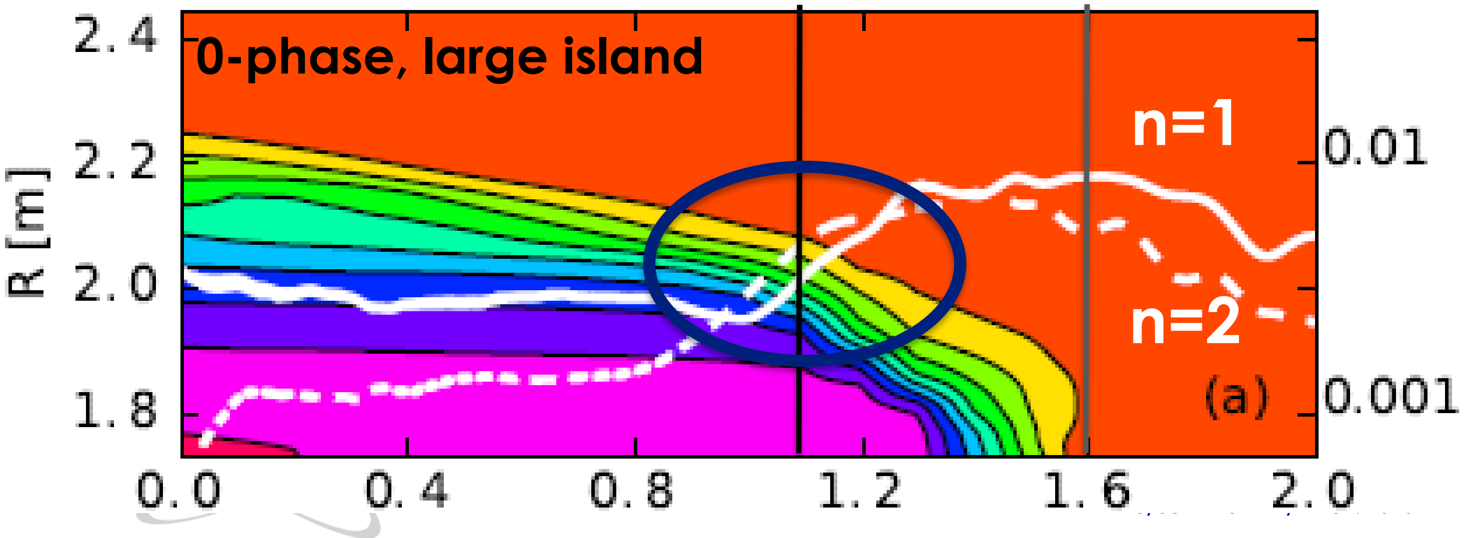


- **For large island cases, TQ onset time is nearly identical**

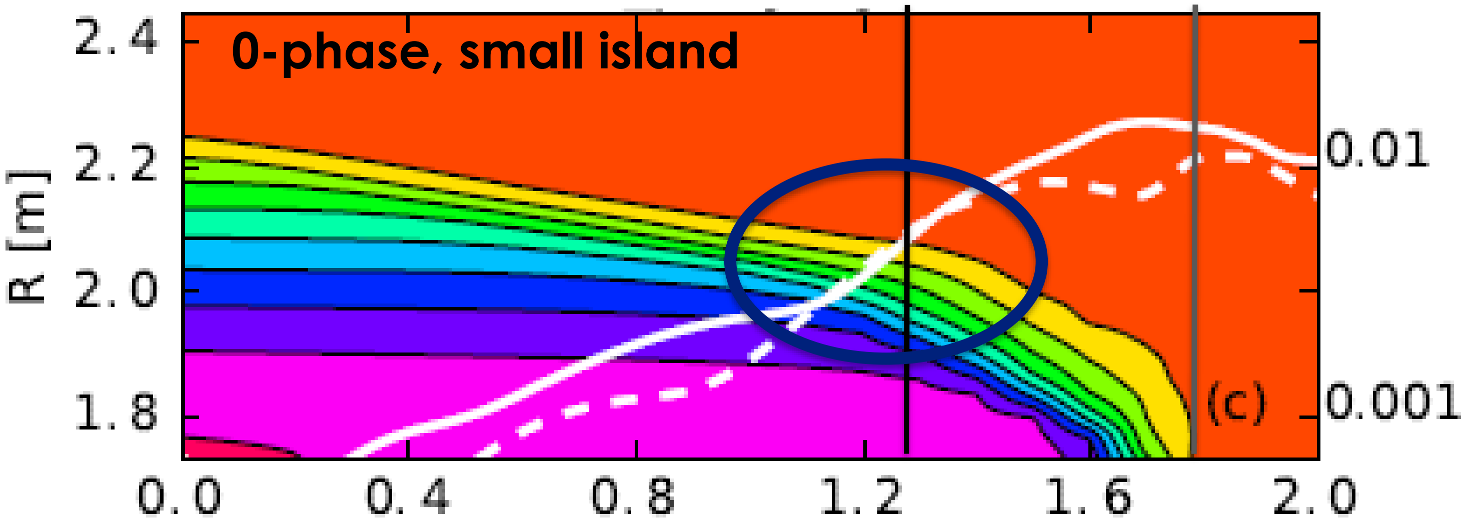
- **TQ duration is much shorter for 0-phase**

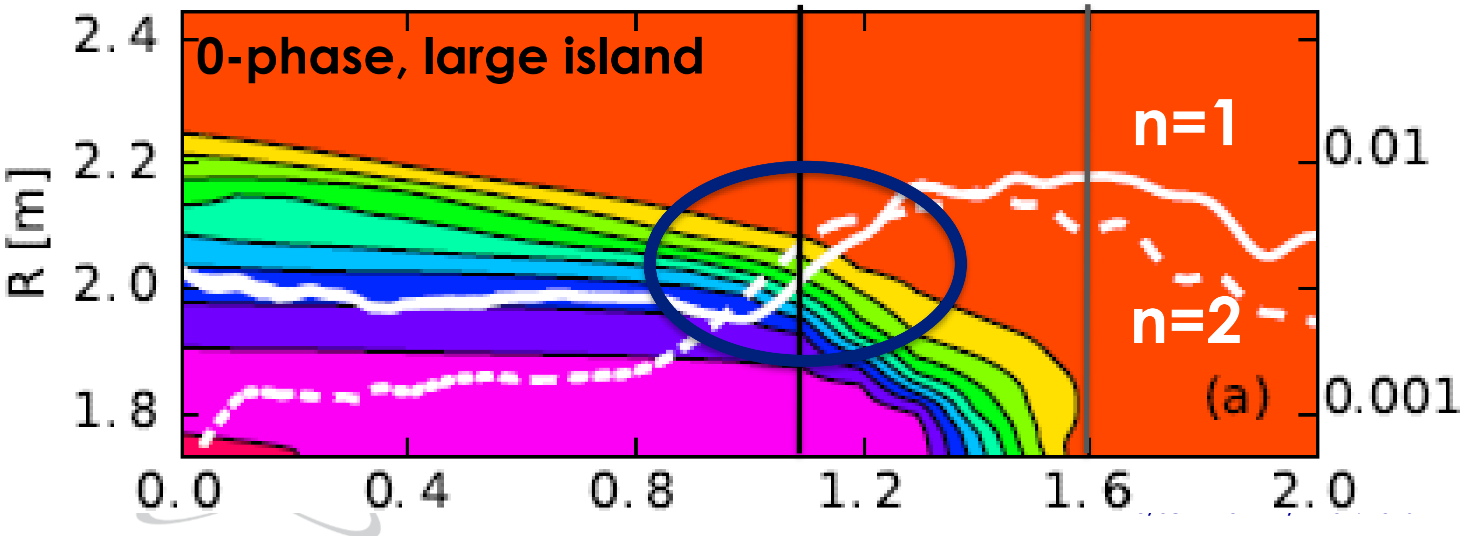
- **For 0-phase, n=2 mode becomes dominant for a short time**

Dominant n=2 is consistent feature of 0-phase, mode amplitude affects onset time



Same phase cases have qualitatively same behavior; time delay for smaller initial island

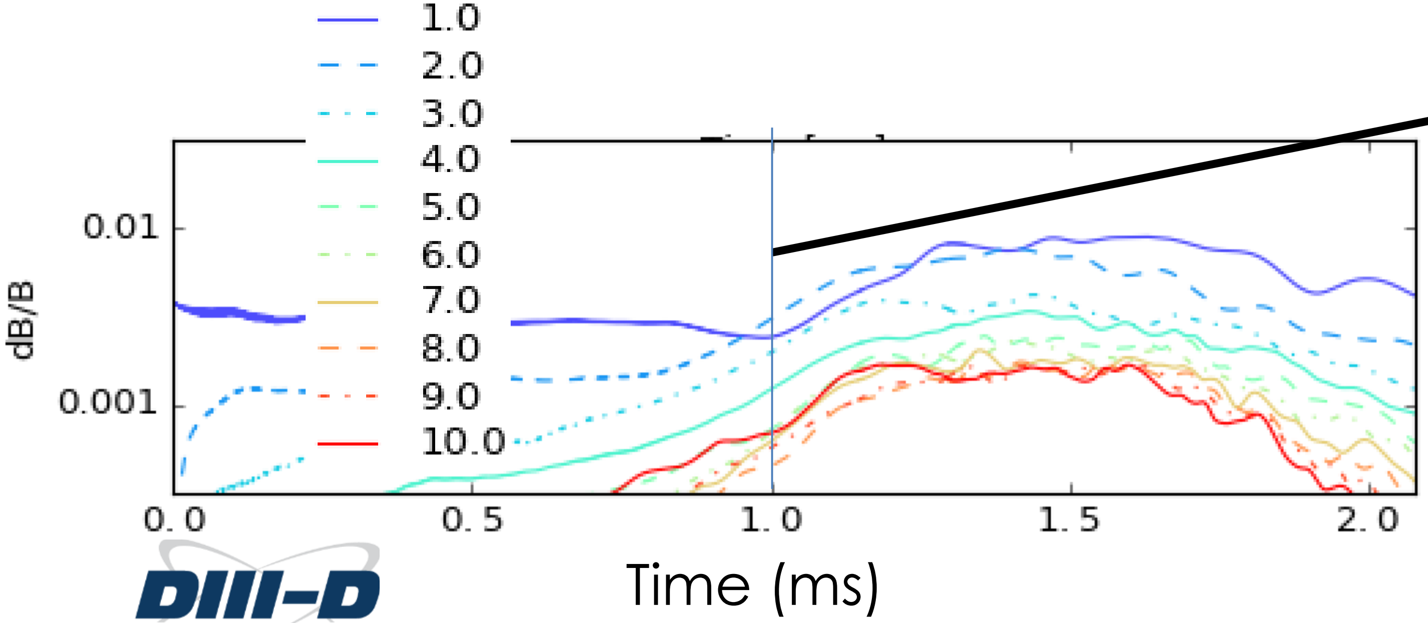


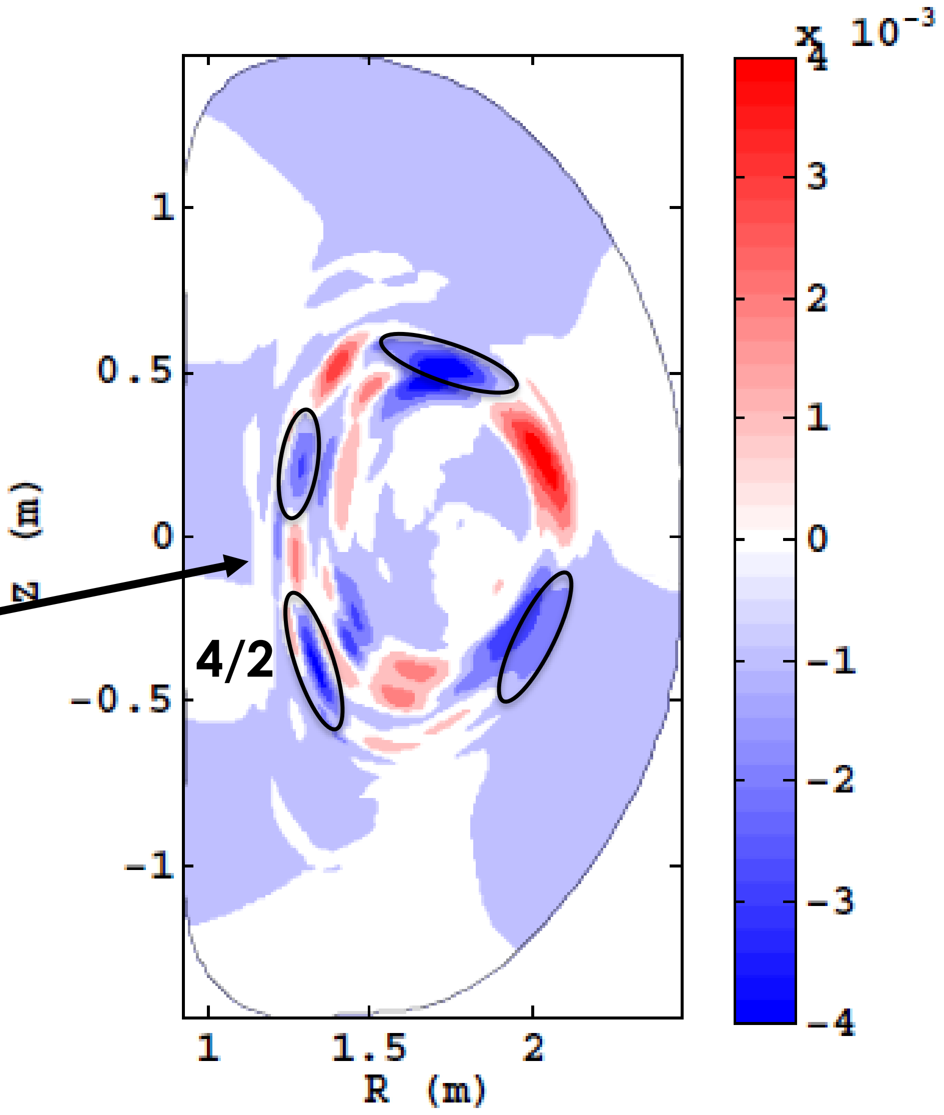


- **Smaller island, longer to reach saturation, later TQ-onset**
- **TQ duration is roughly the same for 0-phase cases**
- **In both 0-phase cases, dominant n=2 appears**

In 0-phase cases, dominant n=2 mode is mostly 4/2 harmonic of 2/1

- Relative phase of n=1 mode and (predominantly) n=1 source excites the 4/2 harmonic in 0-phase cases
- Results in break-up of large 2/1 island into smaller island chains, change in impurity spreading …

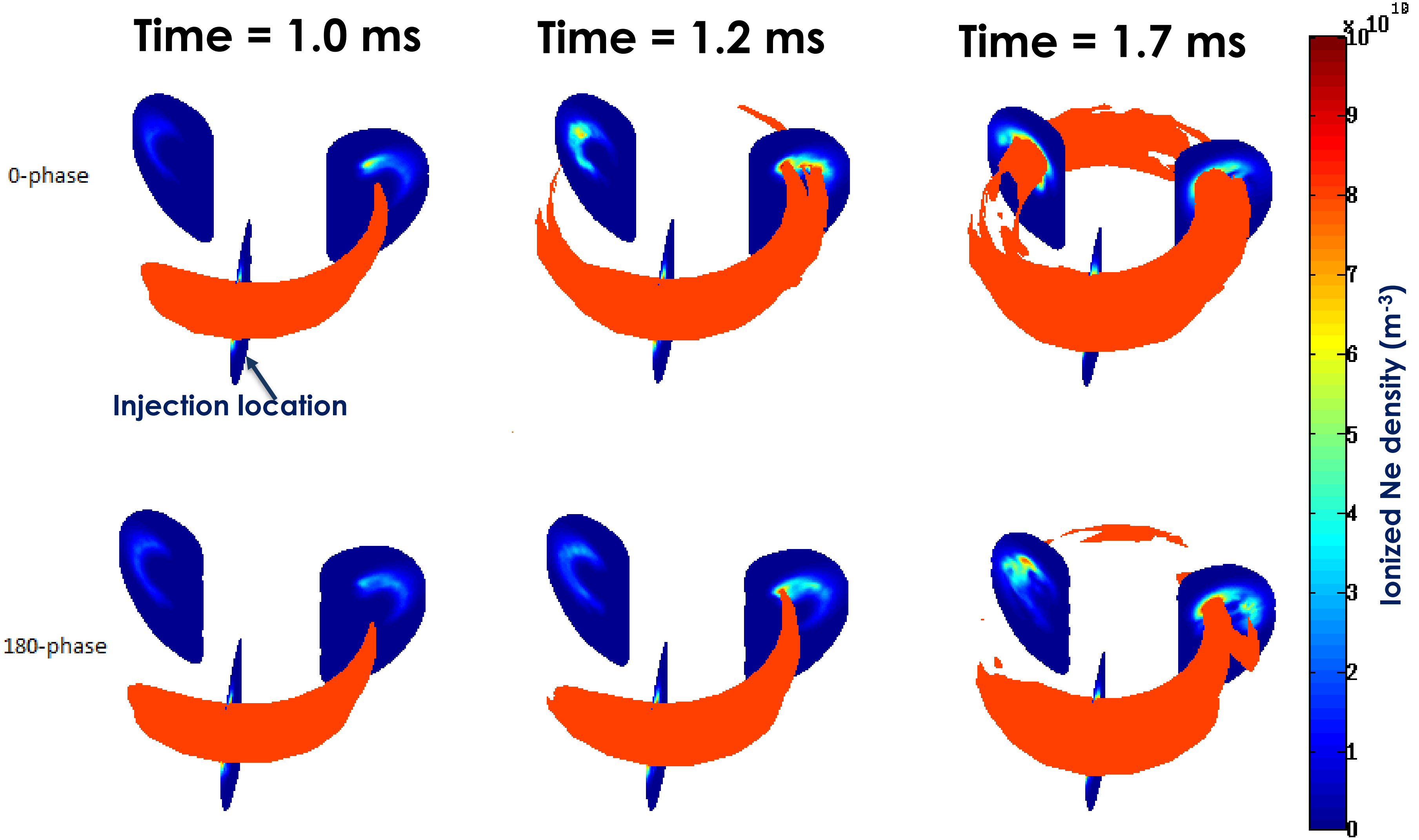




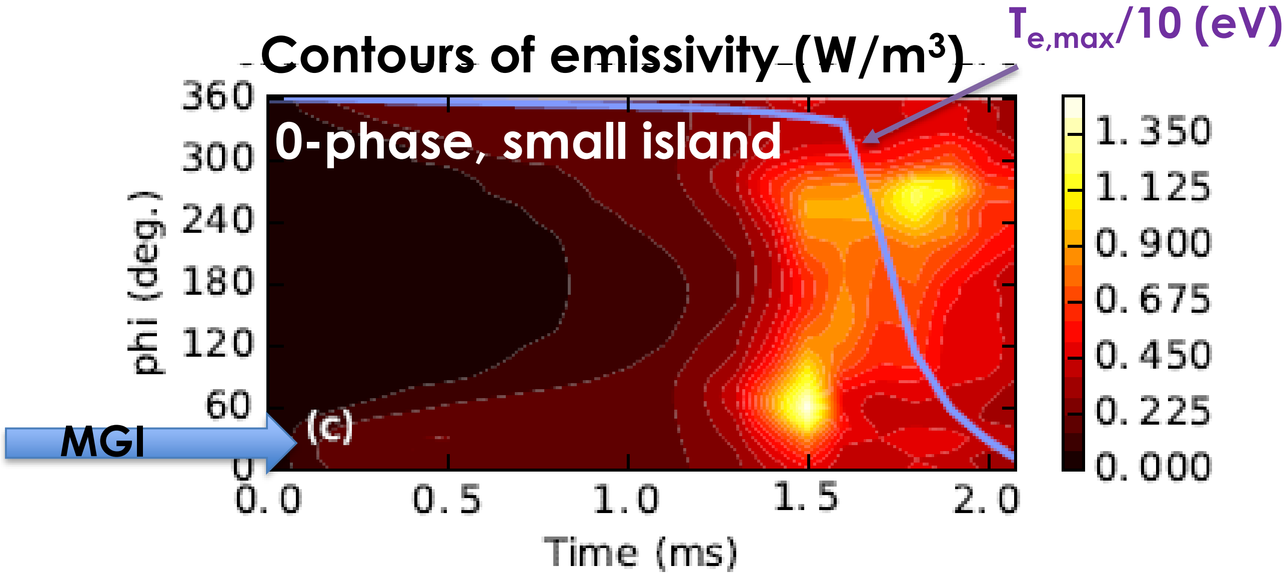
When 4/2 harmonic appears, impurities begin to spread more rapidly than case with dominant n=1

0-phase case in which 4/2 mode becomes dominant @ 1.0 ms

180-phase case, in which 2/1 mode remains dominant



Two radiation flashes in each case; difference in relative amplitude



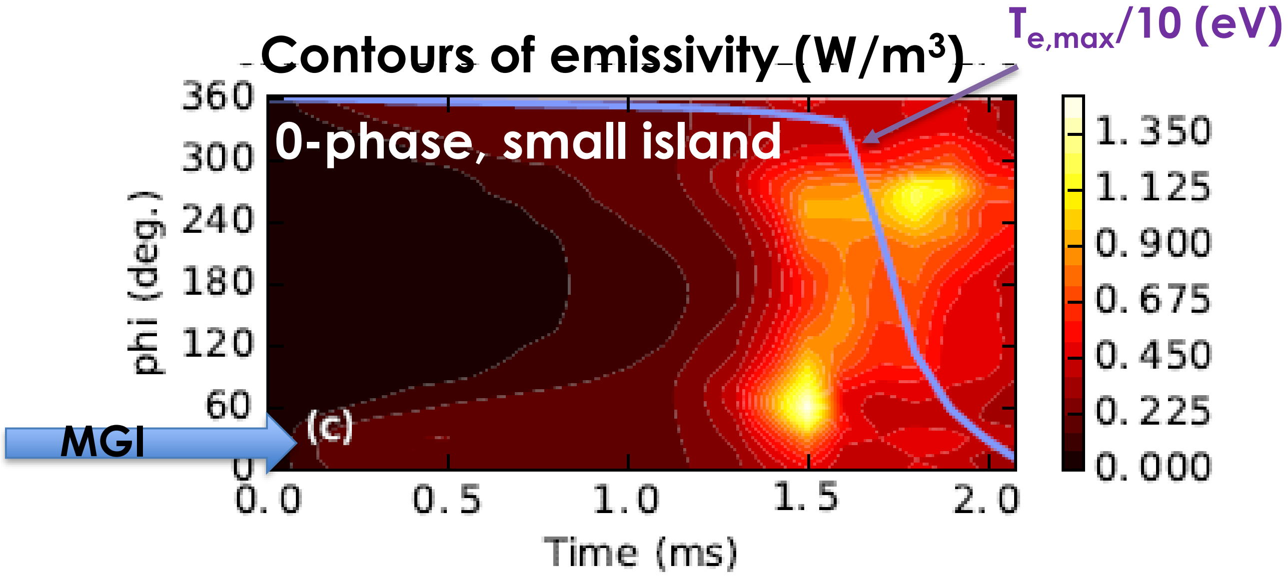
- Short-duration radiated power flash occurs near injection location (15° toroidally) just before drop in central T_e

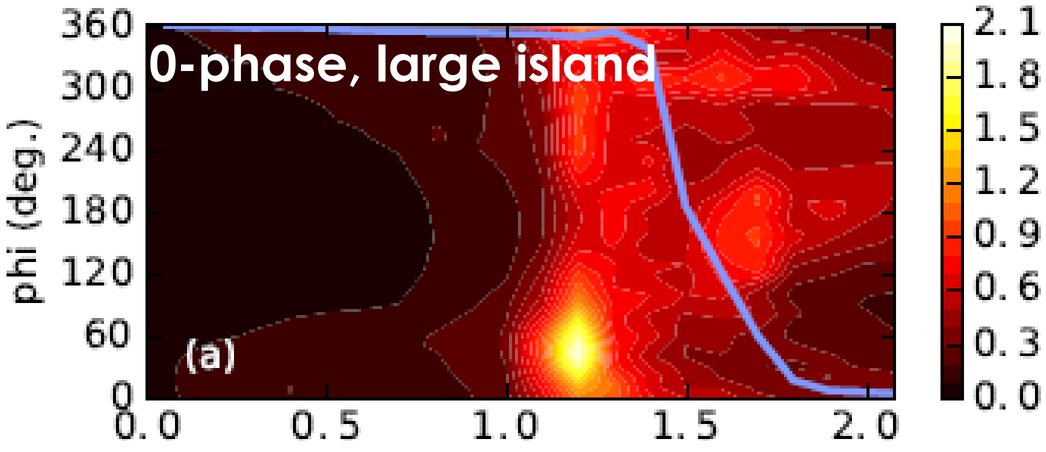
→ **Conduction** due to outer flux surface break-up

- Longer time duration flash far from the injection location (opposite side toroidally) during central T_e collapse

→ **Convection** due to 1/1 mode

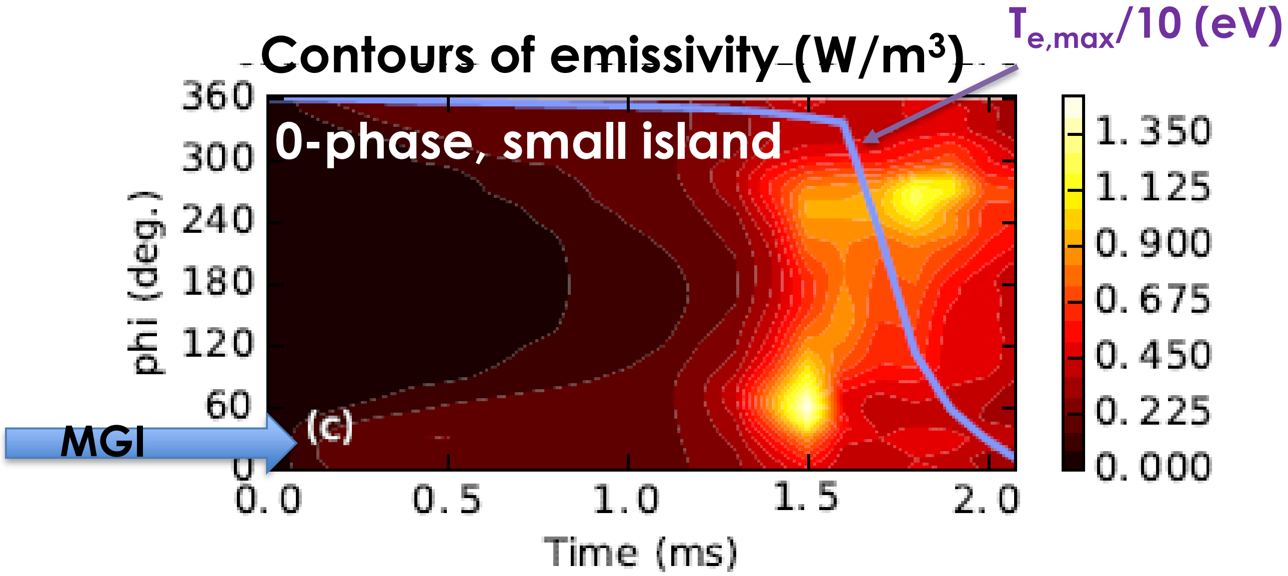
Two radiation flashes in each case; difference in relative amplitude





- **Pre-TQ flash is very large in 0-phase, large island case (~ time when n=2 becomes large)**

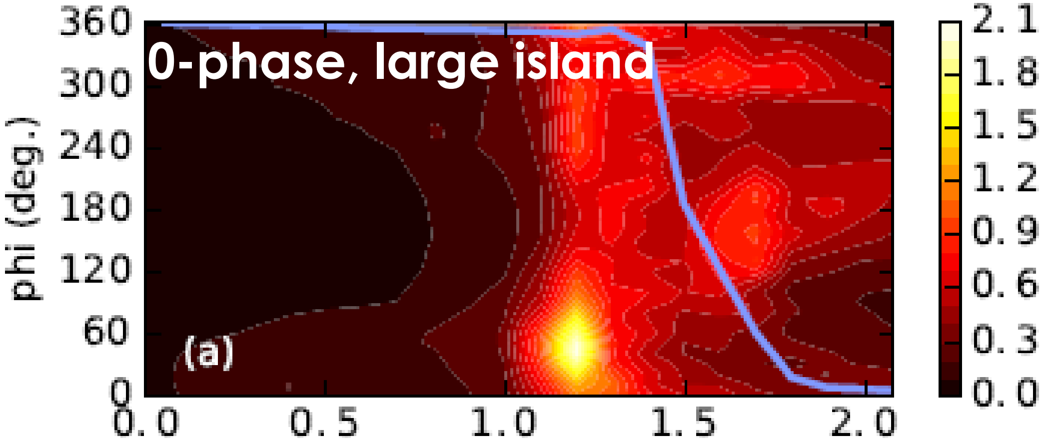
Two radiation flashes in each case; difference in relative amplitude

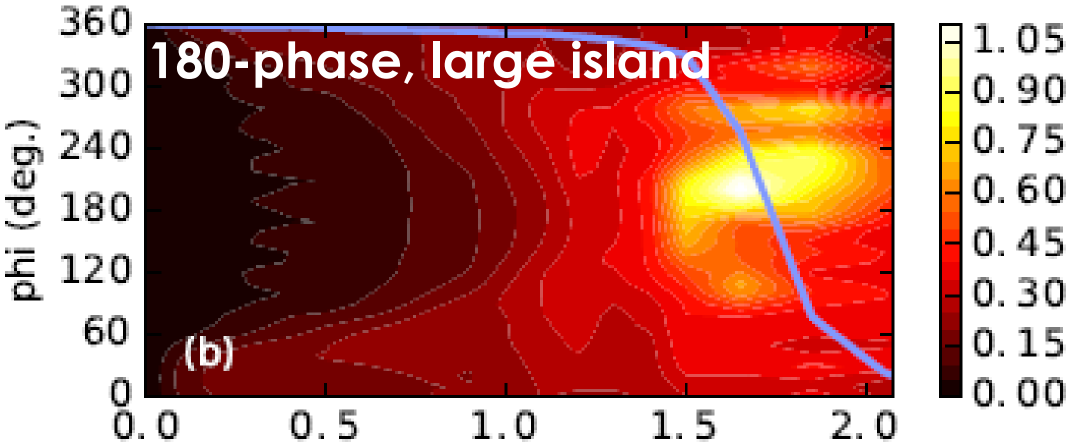


Contours of emissivity (W/m³)

$T_{e,max}/10$ (eV)

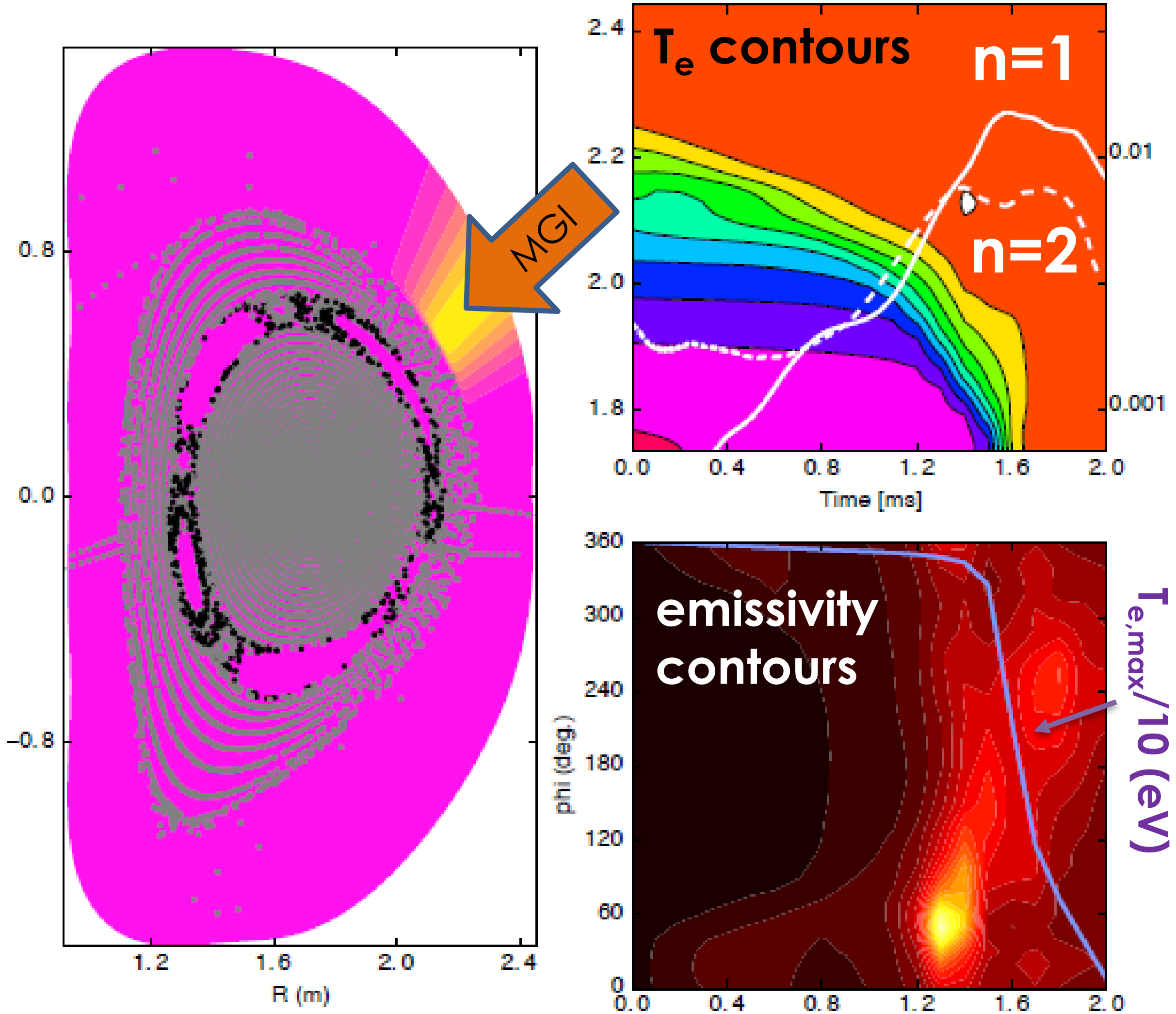
MGI





- Pre-TQ flash is very small in 180-phase, large island case, nearly all radiation during the TQ

Direct imposition of 4/2 island can force 180-phase to behave like 0-phase case



- Simulation with initial 4/2 mode *instead of* 2/1 mode (no 2/1 component). Same phase and amplitude as 180-phase large island
- After n=1 grows to comparable amplitude to n=2, evolution is quite similar to 0-phase case
- Fast pre-TQ radiation flash resembles 0-phase case with spontaneous 4/2 mode.

Summary

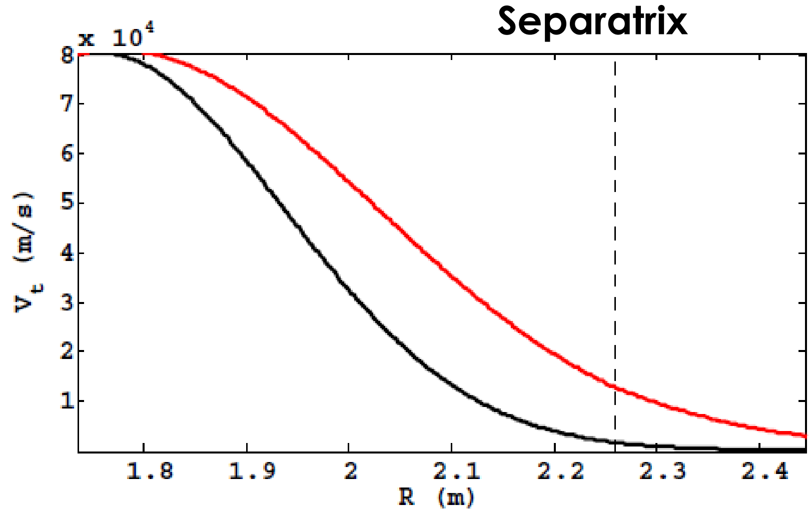
Impurities spread along field lines most rapidly at low order rational surfaces, and toward the HFS

Magnetic topology is important: Large pre-existing islands impede impurity spreading; higher-n harmonics that break up large islands enhance impurity spreading

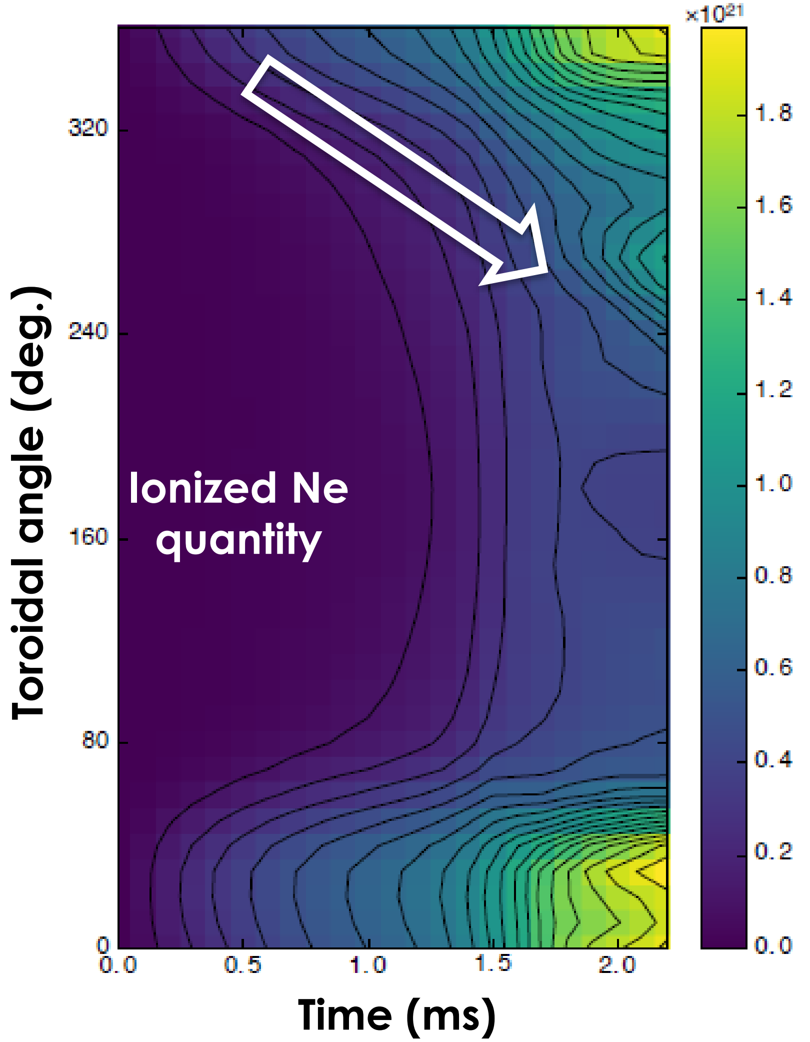
Rotation can play a role: large rotation near the edge can enhance parallel impurity spreading, but changes in MHD have negative consequences for toroidal peaking

Plasma rotation can reverse the dominant direction of impurity spreading, and enhance overall spreading

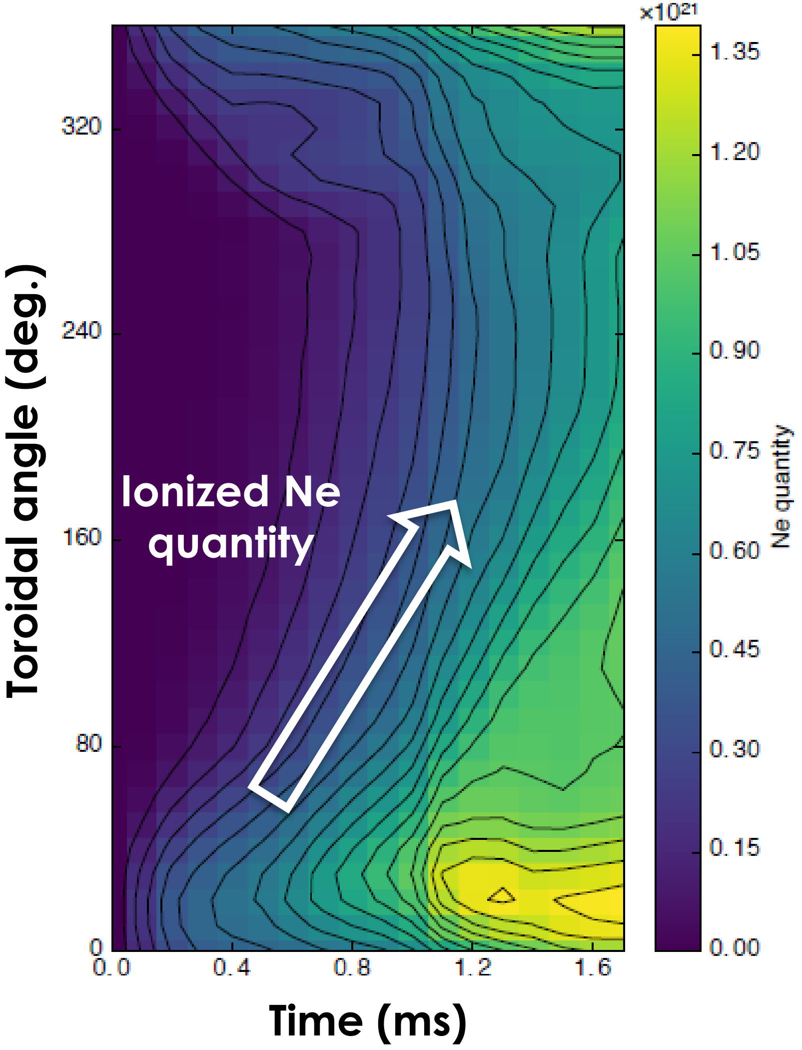
Two simulations with 8kHz core rotation and varying edge rotation are compared to stationary case



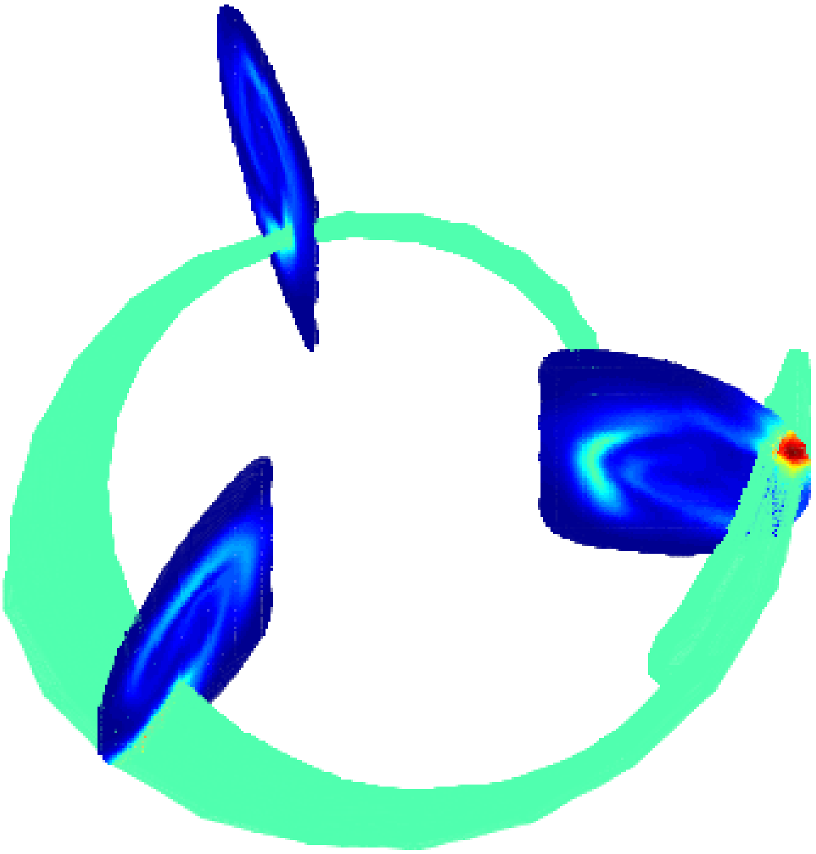
Non-rotating Simulation



Highest-edge rotation



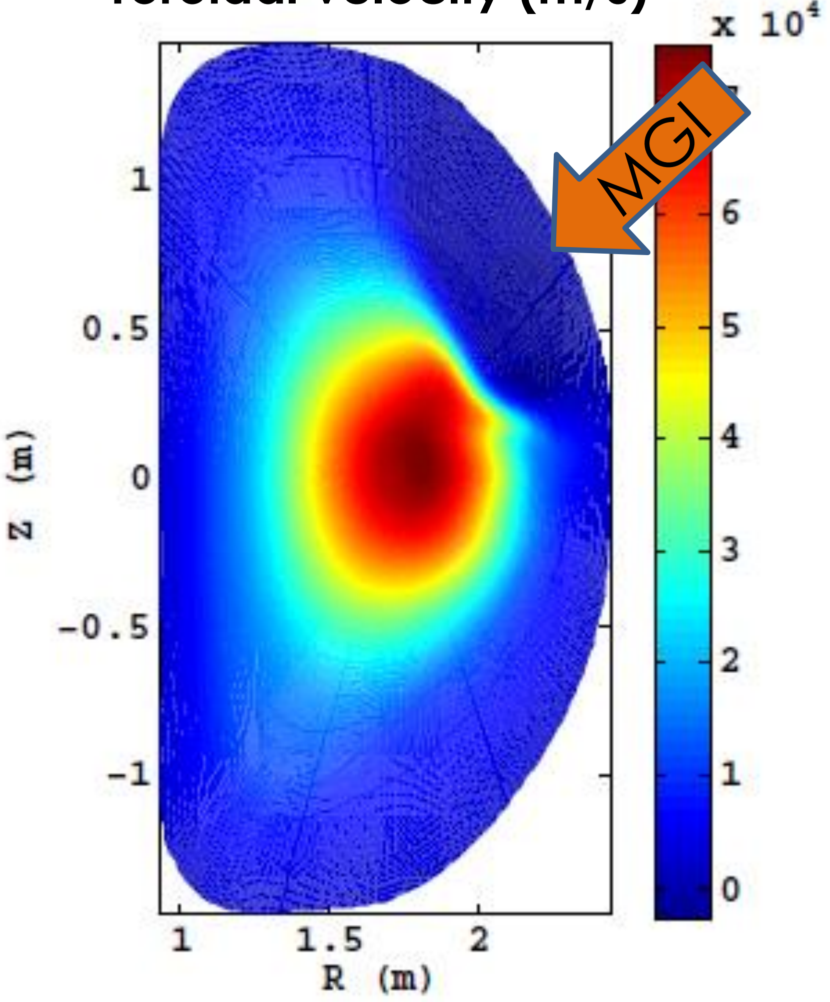
Impurities propagate in rotation direction, eventually damp rotation locally



Ionized Ne density

- Despite **massive** gas injection, gas is introduced gradually. Initial “slow trickle” can spread quickly before edge rotation becomes strongly damped

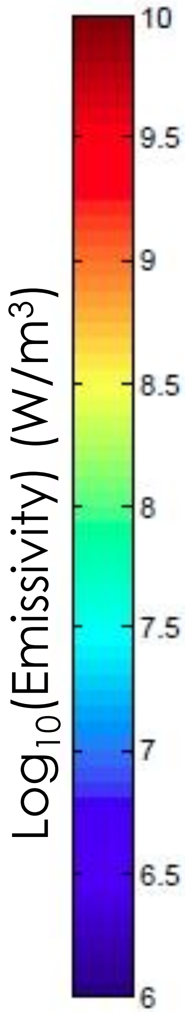
- Rapidly spreading ribbon toward LFS (direction of rotation) is seen most prominently with high-edge rotation



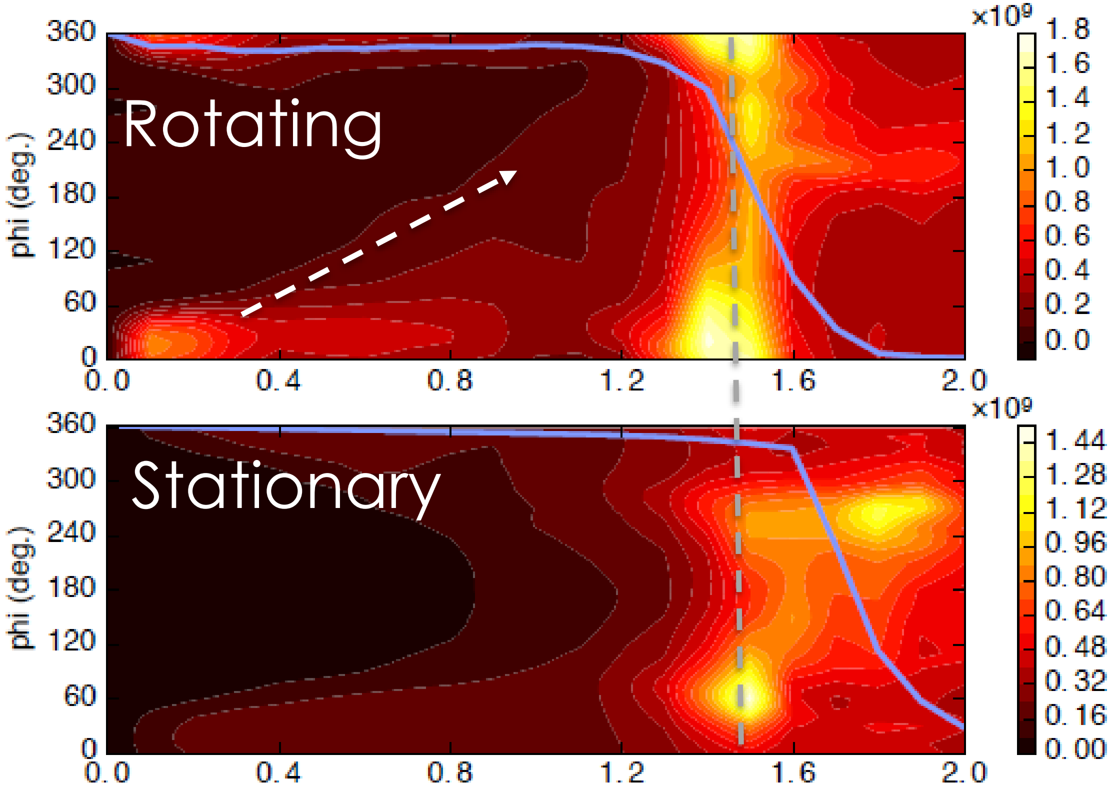
Toroidal velocity (m/s)

Complete break up of flux surfaces produces strong radiation aligned with expanding plume at TQ

Rotating case
Time = 1.5 ms (maximum Prad)

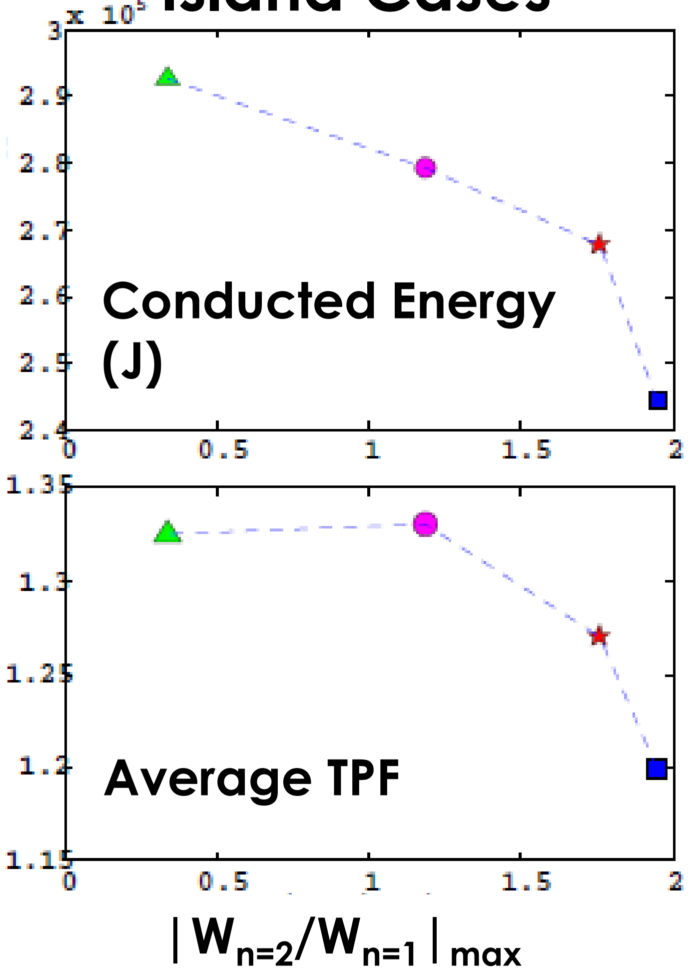


→ **Injection flash simultaneous in two cases, produces TQ in rotating case due to more thorough flux surface destruction**



Faster impurity spreading lowers conducted energy ☺ Complete flux surface destruction increases TPF ☹

Island Cases



Conducted Energy to Divertor:

Total energy lost – radiated energy

Lower = Better

Faster spreading always lowers CED

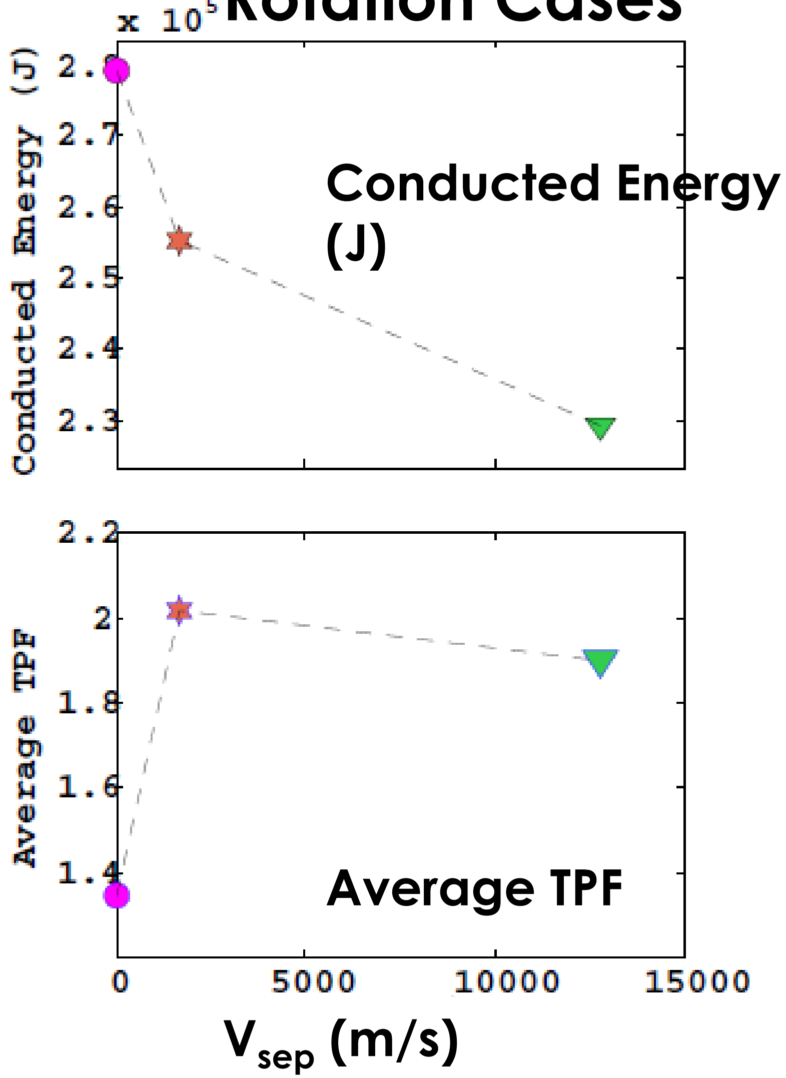
Average toroidal peaking factor (TPF):

$$\frac{\text{Maximum radiated energy } (\phi)}{\text{Mean radiated energy } (\phi)}$$

Lower = Better

Rotating cases, very high TPF!

Rotation Cases



Conclusions

- **Pre-existing large islands impede impurity transport and result in worse mitigation metrics (TPF, CED)**
  - Important since locked-modes are a very common cause of disruptions
  - Consistent with JET results showing highest TPFs when locked-modes are present
  - Effect can be mitigated by higher-n harmonics
- **Rotation can alter impurity spreading significantly and change the radiated power distribution**
  - Primary toroidal direction of spreading can reverse to match flow direction
  - In simulations, CED improves with rotation but TPF much worse
  - <u>Connection to rotating and non-rotating DIII-D experimental results is unclear, needs further study</u>

SCREAM is a FES/ASCR Collaboration between 12 Principal Investigators at 9 Institutions

Team Includes 9 Institutions with 12 PI’s
8 Associated with FES
4 Associated with ASCR
$4.9M / 2yrs

Mission: combine theoretical models with advanced simulation and analysis facilitated by direct participation of ASCR SciDAC institutes to focus on the runaway risk for ITER and tokamaks in general.

Collaborations underway between several groups

Principal Investigators:

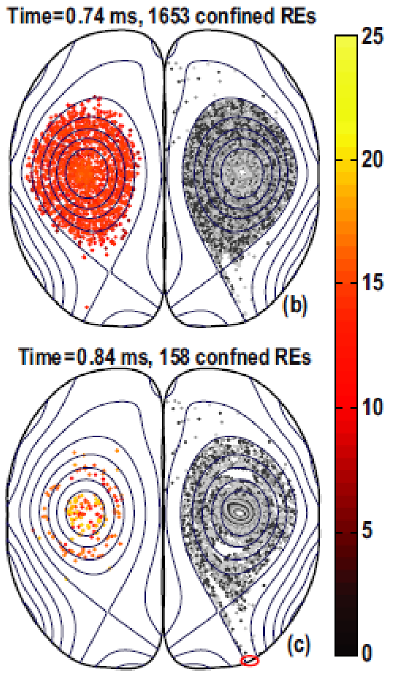
- FES:
  - Dylan Brennan (Princeton)
    - Lead PI - Universities
  - Xianzhu Tang (LANL)
    - Lead PI - Labs
  - Amitava Bhattacharjee (PPPL)
  - Allen Boozer (Columbia)
  - Boris Breizman (UT, Austin)
  - Diego Del-Castillo-Negrete (ORNL)
  - Valerie Izzo (UCSD)
  - Lang Lao (GA)
- ASCR
  - Mark Adams (LBNL)
  - Luis Chacon (LANL)
  - Irene Gamba (UT, Austin)
  - Guannan Zhang (ORNL)

Upgraded RE orbit model (from GA) and RE source model (from PPPL) will be incorporated into NIMROD

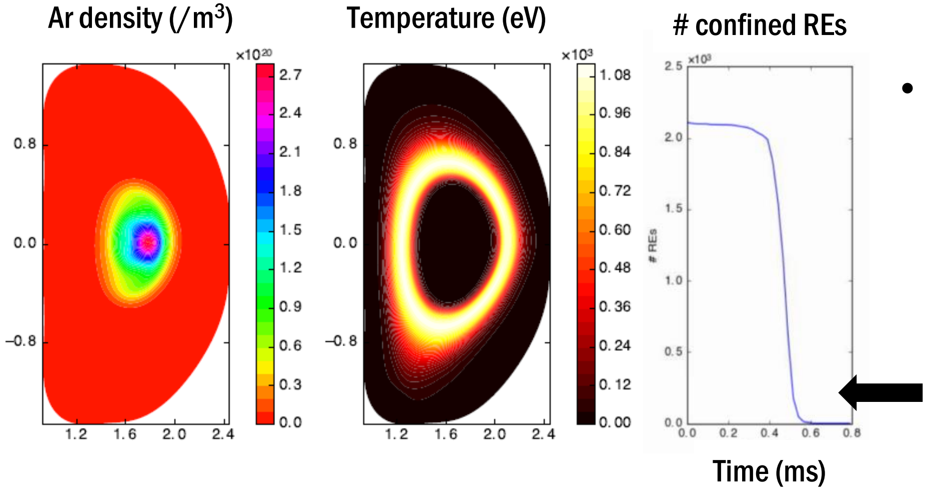
- NIMROD test particle model had been used to study RE confinement during the TQ phase of disruption in DIII-D, C-Mod and ITER

- Present guiding center model neglects pitch angle scattering, does not include a physics based RE generation model, and is not self-consistent (no RE feedback on MHD fields)

- Initial upgrades include new orbit equations (in collaboration with GA) and reduced model for RE generation (primary and secondary, with PPPL). Self-consistent modeling is longer term goal.



V.A. Izzo, et al, PPCF 54, 095002 (2012)



DIII-D "Shell pellet" simulation

- Planned physics studies include evaluation of RE generation and loss for various cooling profiles (disruption mitigation strategies) and the effects of external 3D fields

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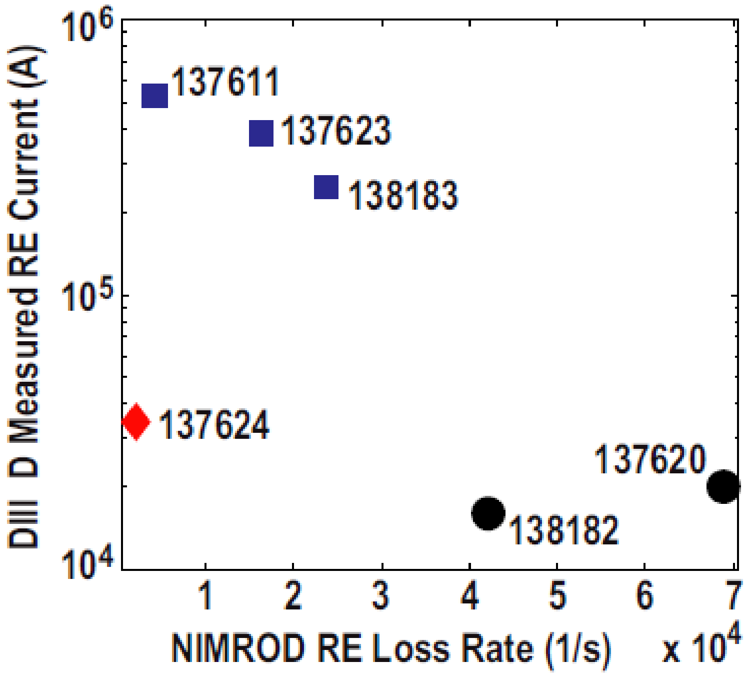
Model has been used to predict RE "prompt loss" in DIII-D experiments



Variation in RE current for DIII-D discharges correlated with predicted losses of seed REs during the thermal quench.

- Near term goal: repeat DIII-D simulations with RE generation model included
- Self-consistent incorporation of the RE current into the MHD equations is a longer term goal not included in objectives by end of the 2-year SCREAM funding

V.A. Izzo, et al, PPCF 54, 095002 (2012)

Initial efforts to increase number of RE orbits calculated during NIMROD runs

- Typically have run with ~1000 tracer particles (mainly so as not to slow down the computation)
- Much higher numbers needed for self-consistent RE current modeling. Somewhat higher numbers needed for inclusion RE generation model.
- Recently have tested cases with ~10000 RE orbits (~10% effect on run time compared to no RE orbits)
- Modified RE data I/O from ascii files to hdf5 format, implemented workflow in OMFIT to generate initial RE input files in hdf5 format and process outputs

SCREAM work has just started in Sept.