Mitigation modeling of locked-mode disruptions

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Sherwood Meeting

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Motivation

- Disruption mitigation is ITER will be applied as a last resort when a disruption is imminent and cannot be avoided by passive or active control

- NTMs leading to locked-modes were found to be the most common root cause of disruptions in JET* (with other root causes also sometimes leading to mode-locking)

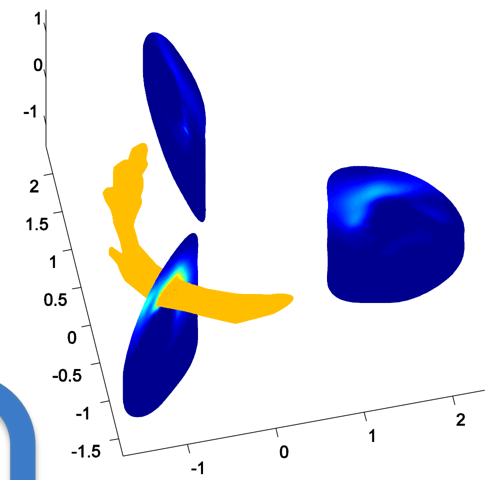
→ We can assume that disruption mitigation will very frequently be employed when large/locked islands are already present in the plasma

- Disruption mitigation studies with pre-existing islands/locked-modes, using both massive gas injection (MGI) and shattered pellet injection, are part of a 2016 experimental Joint Research Target

*P.C. de Vries, et al, Nucl. Fusion 51 (2011) 053018

NIMROD extended MHD code is combined with KPRAD atomic physics code to model massive gas injection (MGI)

Ionized Ne density

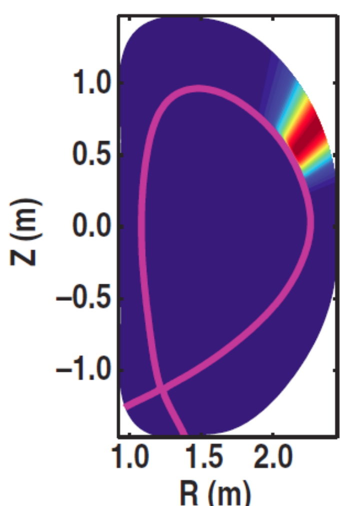


Beginning with DIII-D equilibrium, impurities are deposited as neutrals

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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Outline

Part 1: The physics of impurity plume expansion during massive gas injection (MGI)

Part 2: Results of MGI simulations with pre-existing islands

-Comparison of 2/1 islands with different phases and amplitudes

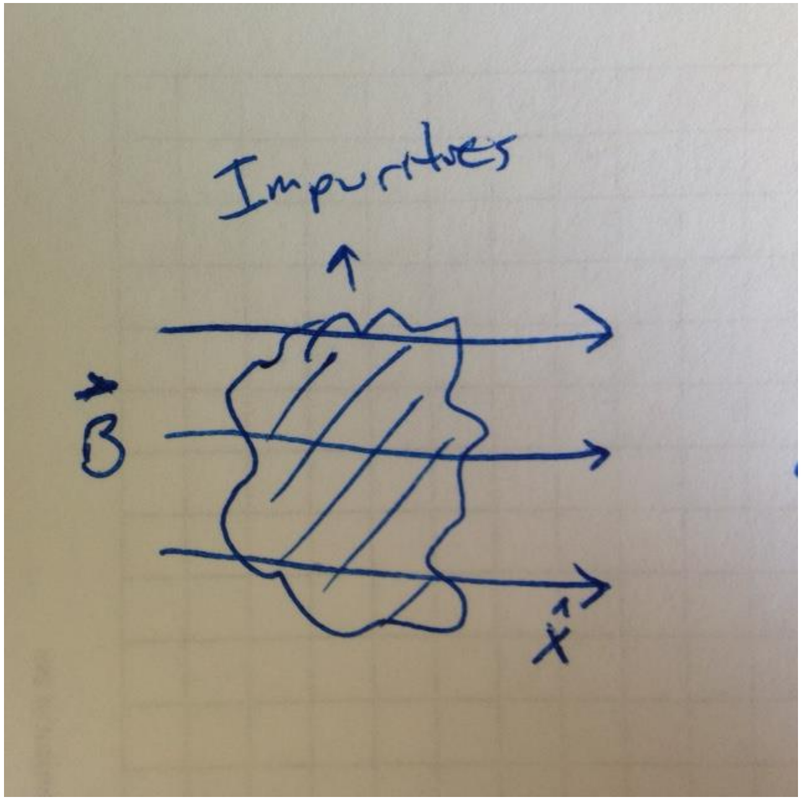
-The role of the n=2 mode

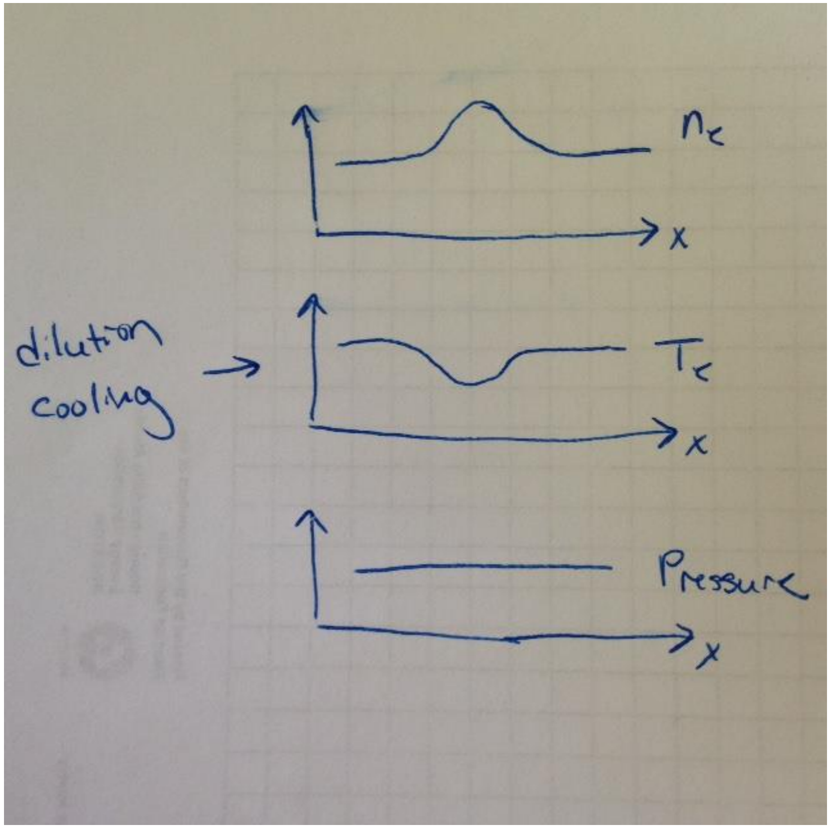
-Simulation with pre-imposed 4/2 island

Part 3: Consequences for radiated energy fraction and toroidal peaking factor

PART 1: The physics of impurity plume expansion during massive gas injection (MGI)

Massive gas injection deposits localized blob of impurities onto edge field lines





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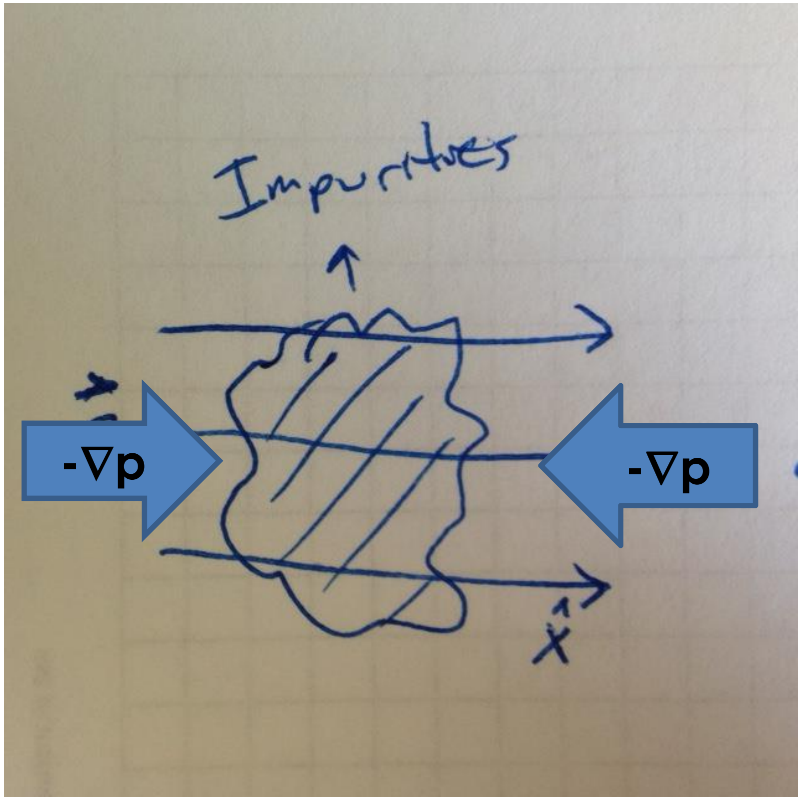
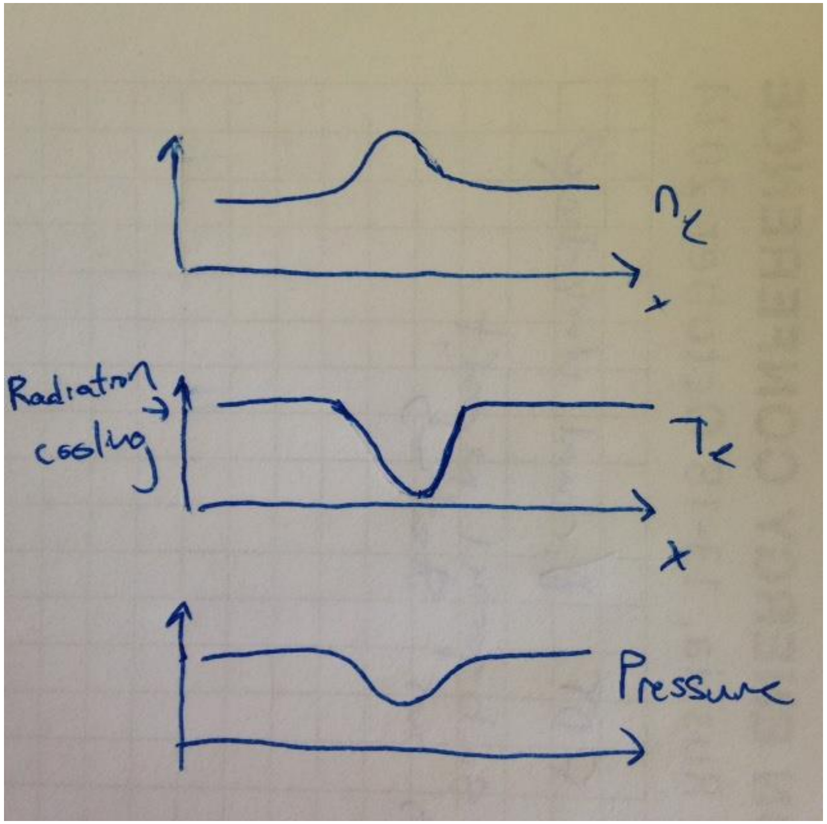
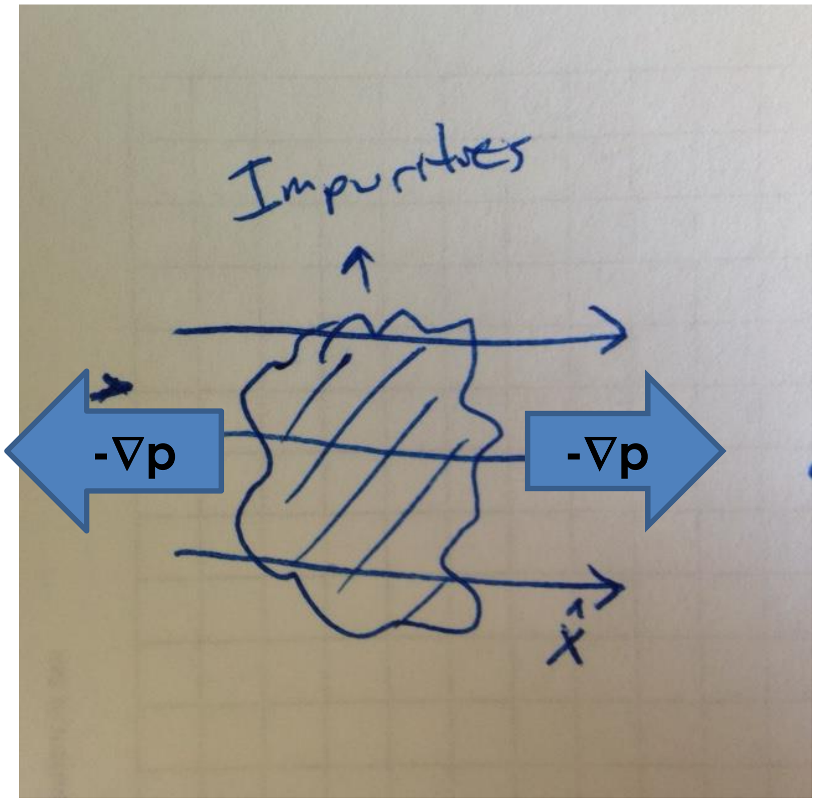
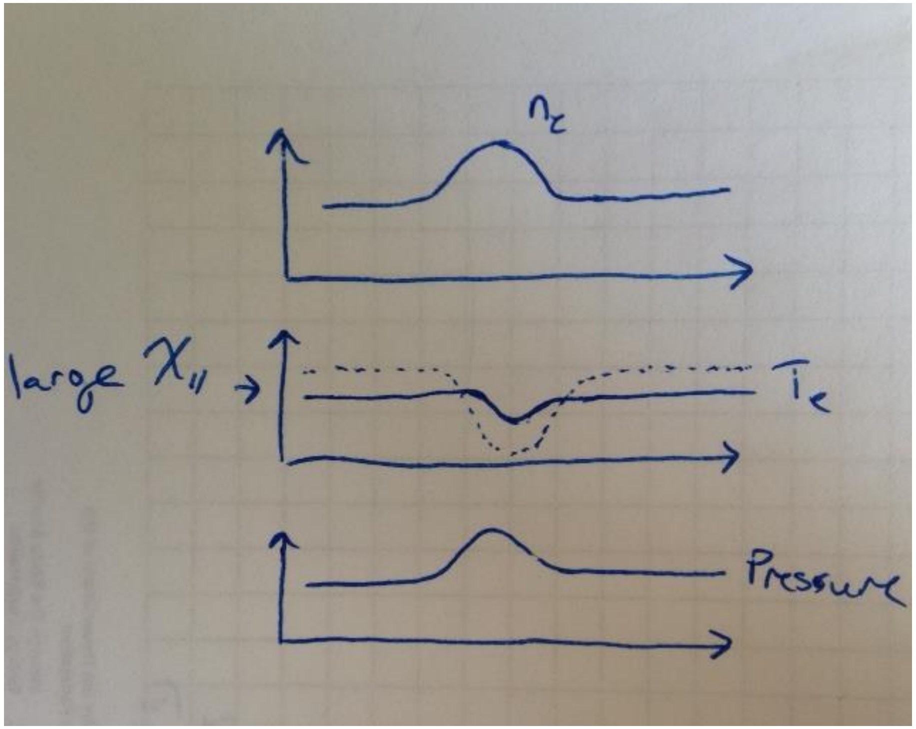
Radiation cooling results in reduced pressure at the blob location





Fast parallel temperature equilibration drives outward plume expansion





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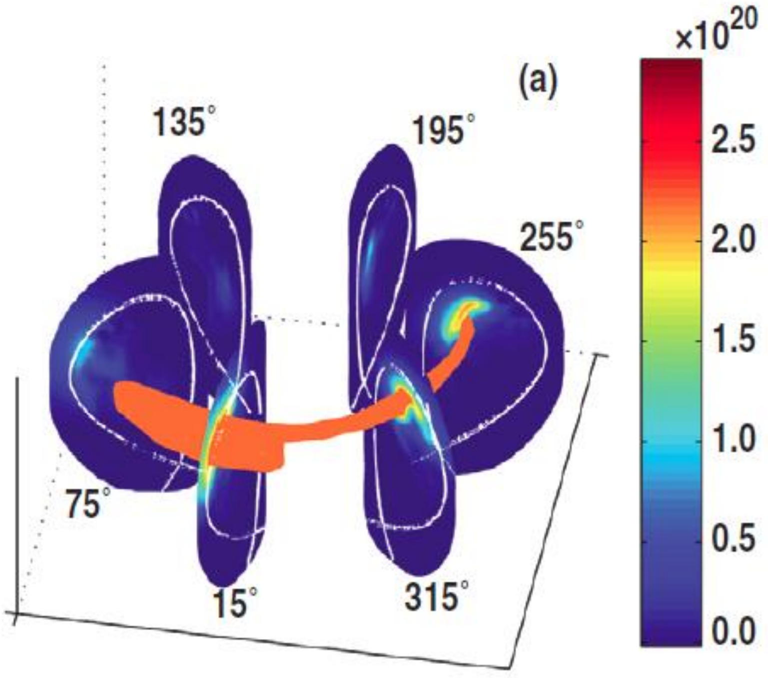
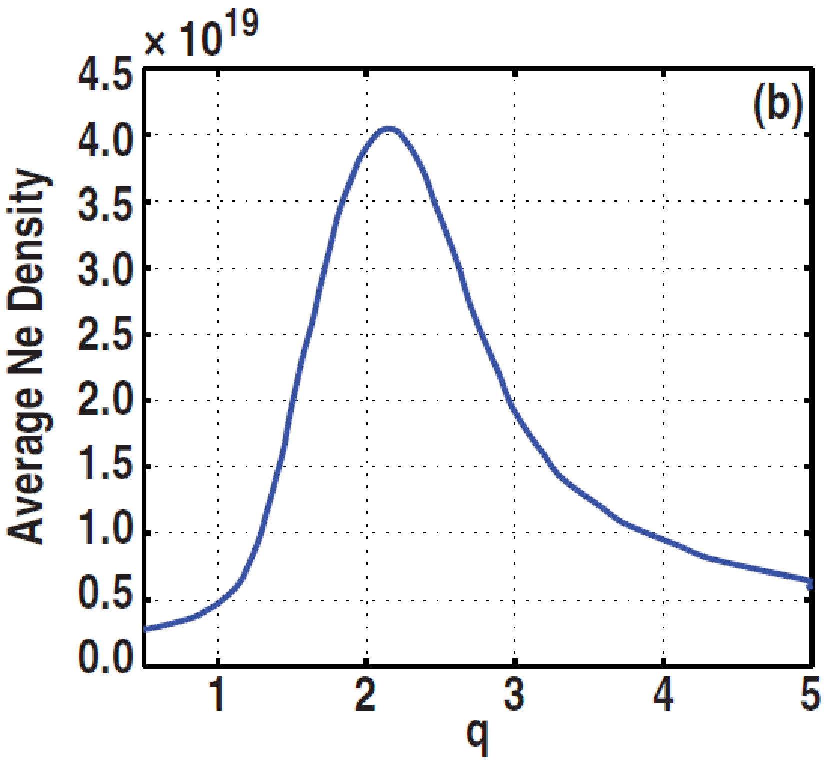
Parallel temperature equilibration is much faster on a low order rational surface

Rational surfaces have a much shorter parallel connection length→ only a single flux tube must equilibrate





NIMROD simulations find that parallel plume expansion happens once the impurities penetrate to the q=2 surface

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Expansion is also toroidally asymmetric due to magnetic field gradient

Nozzle equation explains preferential HFS spreading:

Continuity $$\rho AU = \text{constant}$$

$$BA = \text{constant} \Rightarrow \quad \frac{dr}{r} + \frac{dU}{U} - \frac{dB}{B} = 0$$

Momentum $$\rho UdU = -dp = -(dp / d\rho)d\rho = -C_s^2 d\rho$$

$$\Rightarrow \frac{dU}{U} = \frac{1}{(1-M^2)} \frac{dB}{B}$$

Flow starts at M<1, is thwarted where dB/B<0, accelerates where dB/B>0

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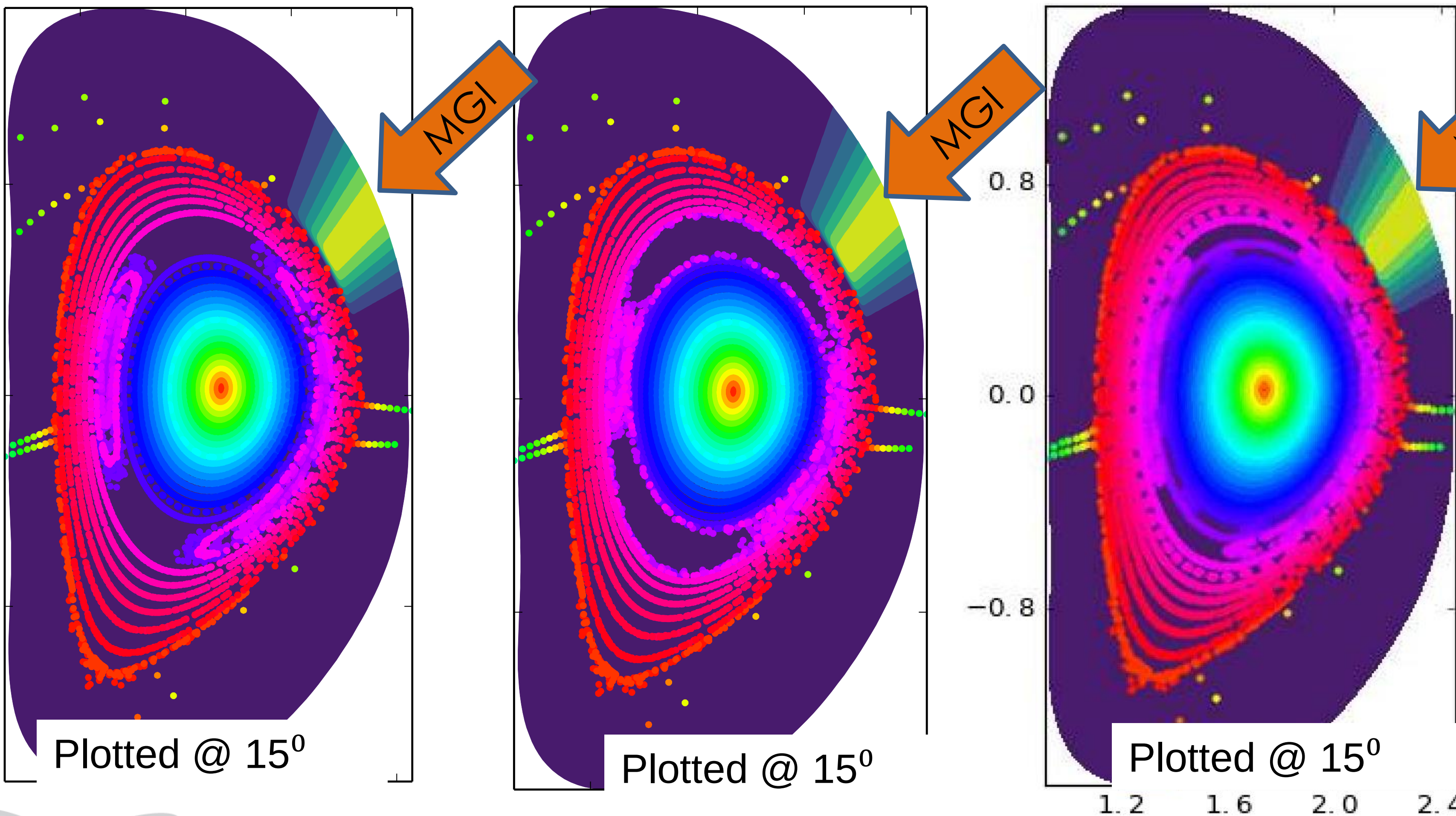
Summary of Part 1:

MGI gas plume expands helically along the field lines, at the q=2 surface, toward the high-field-side

PART 2: Results of MGI simulations with pre-existing islands

Three simulations are initialized with 2/1 magnetic islands

0-phase, large island | 180-phase, large island | 0-phase, small island



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

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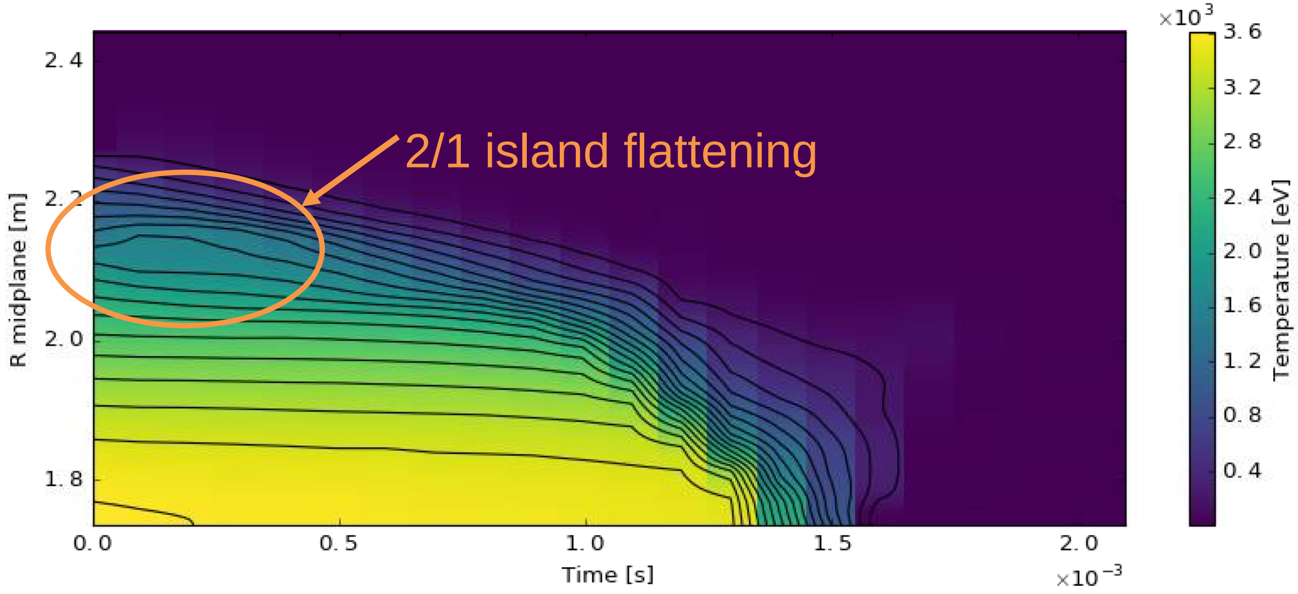
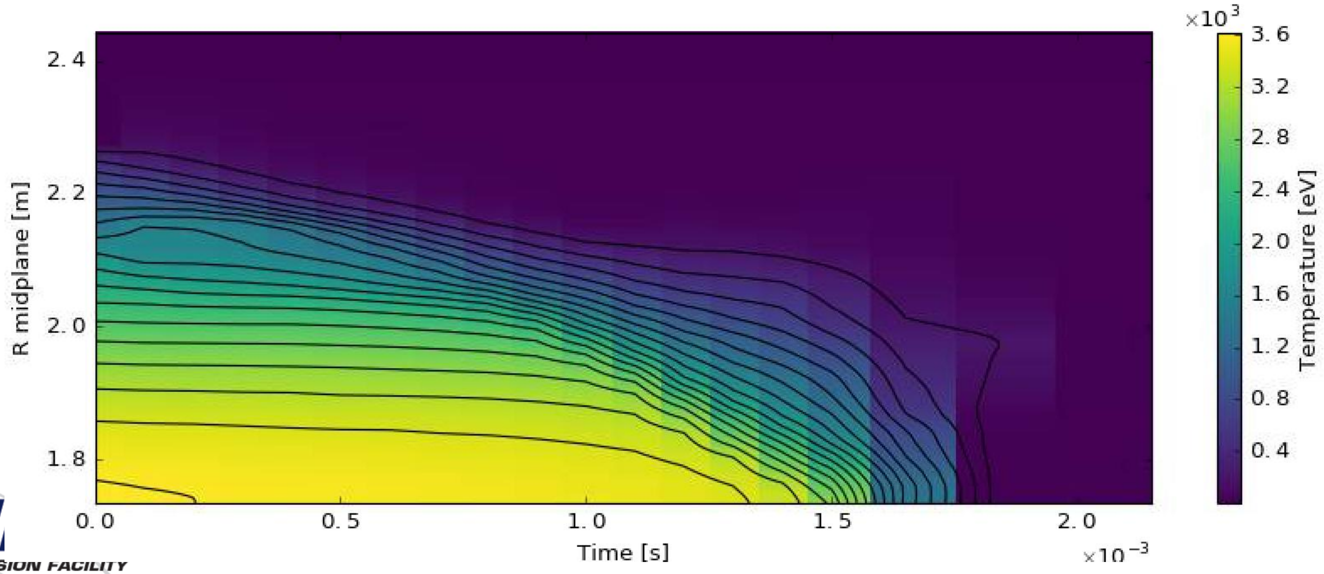
Thermal quench onset times for two phases are not significantly different



0-phase, large island case



180-phase, large island case

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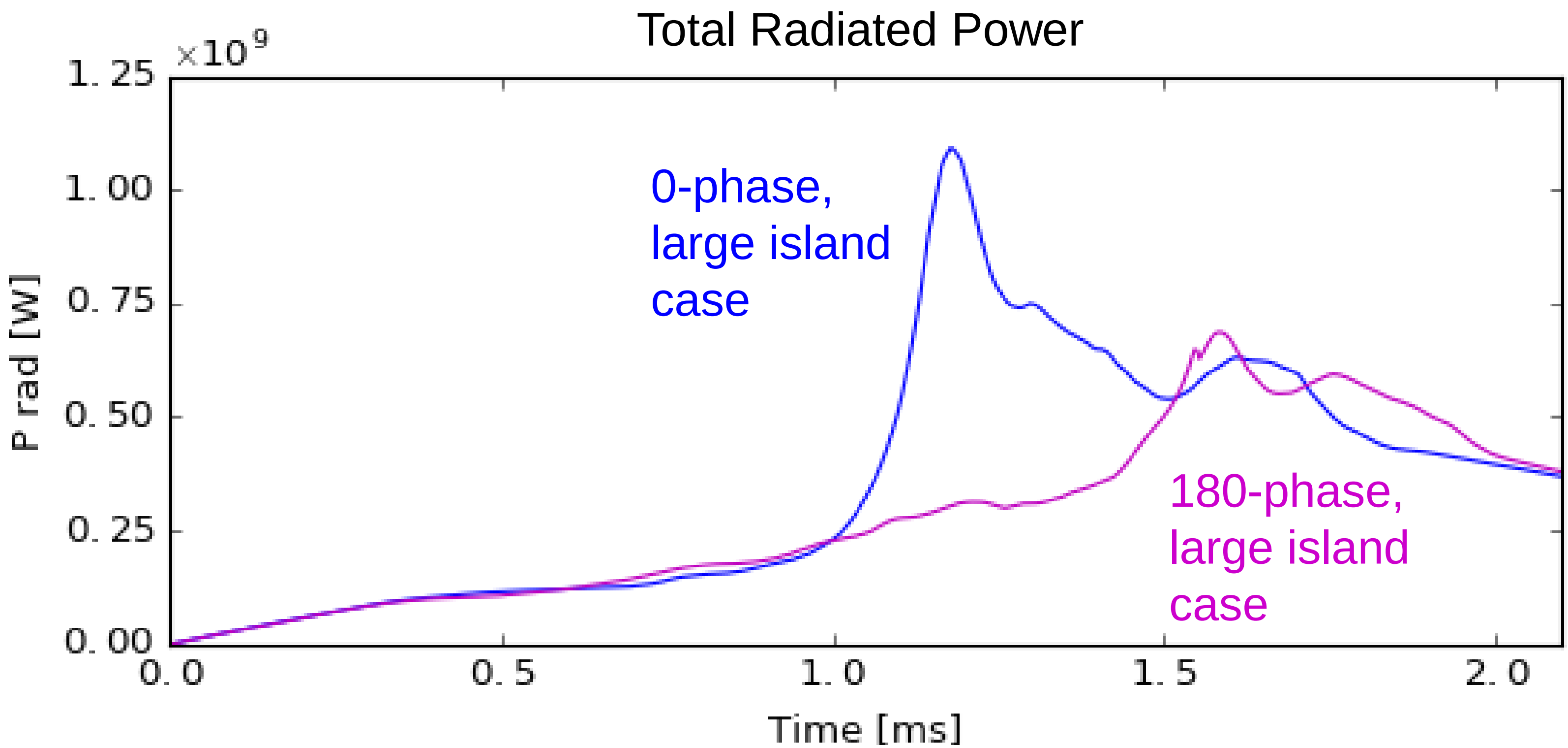
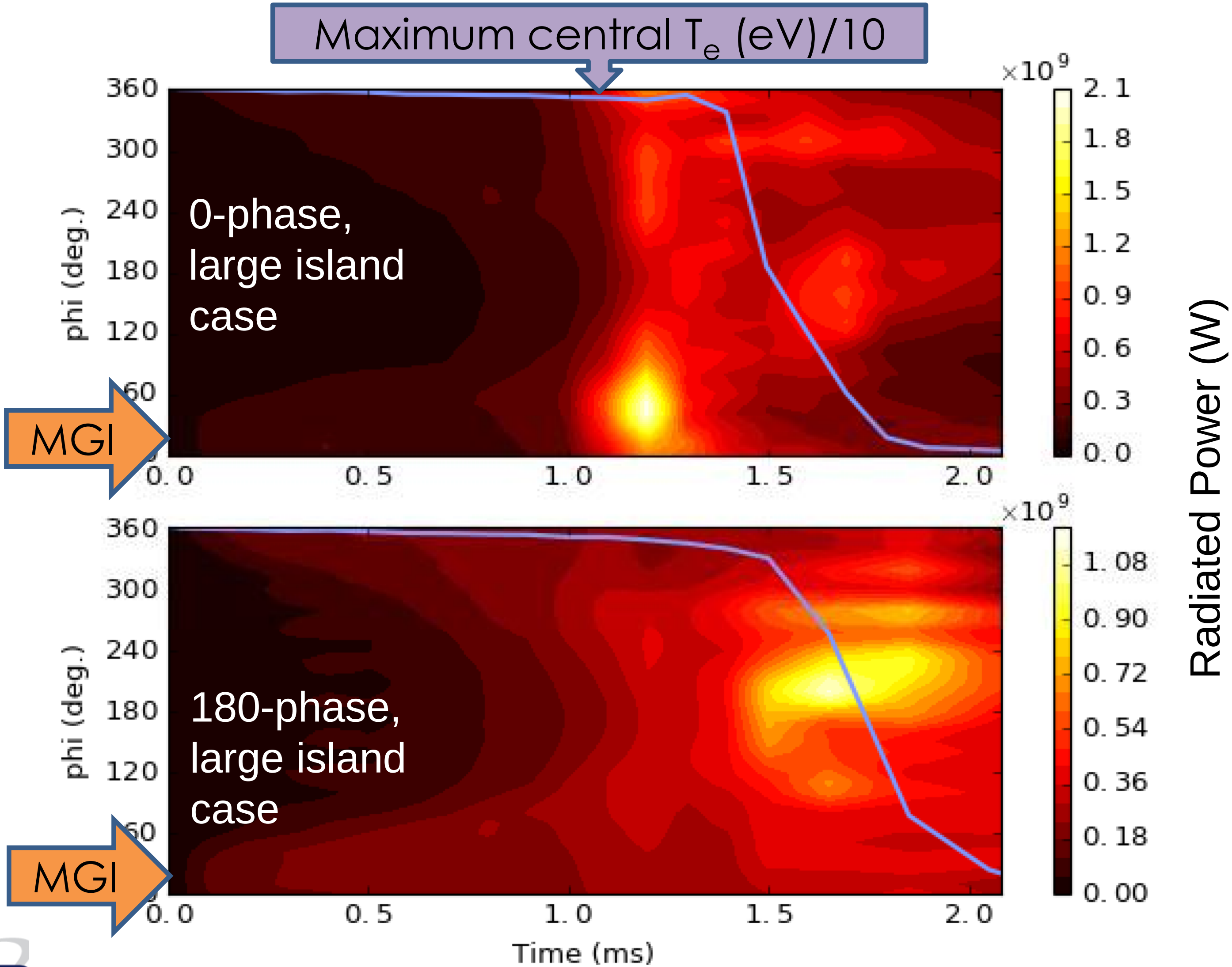
Peak in radiated power is later for 180-phase with same size island



At 0-phase, large initial flash in radiated power appears that is almost completely absent for 180-phase island

Timing of radiation flash relative to central Te collapse differs significantly



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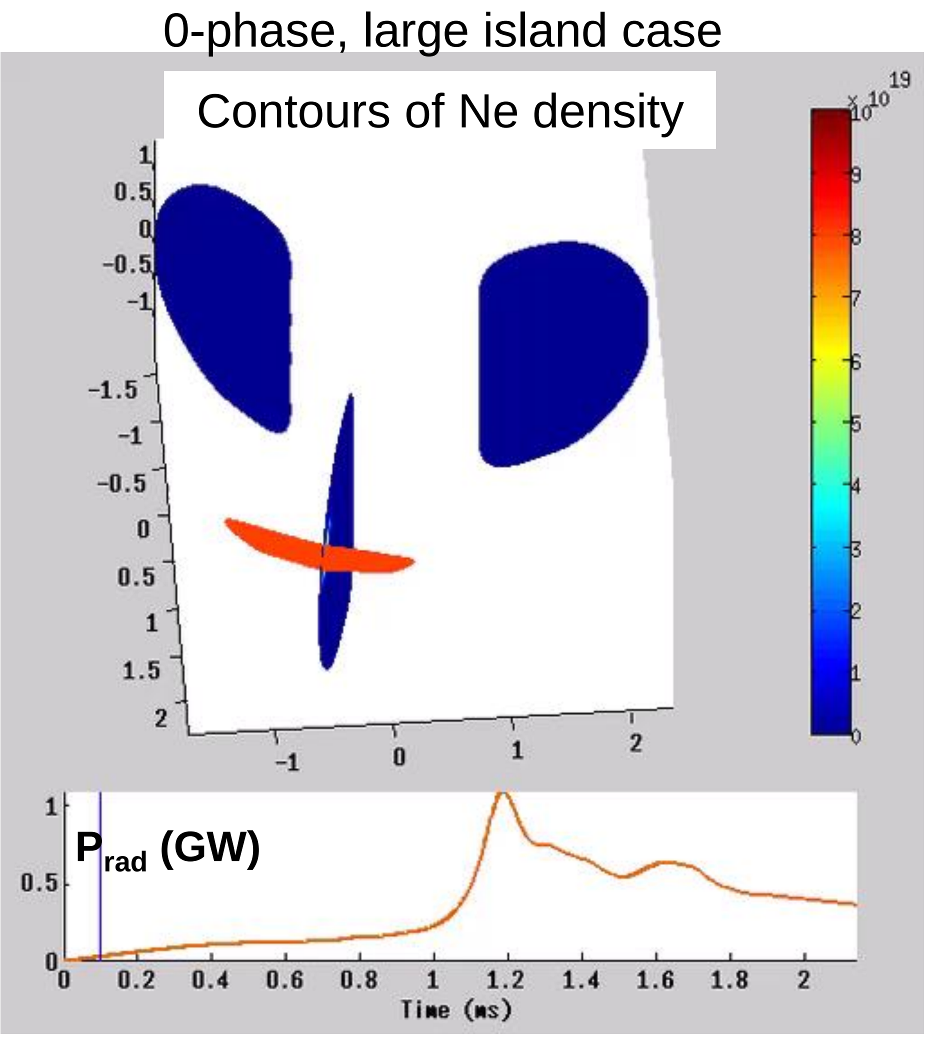
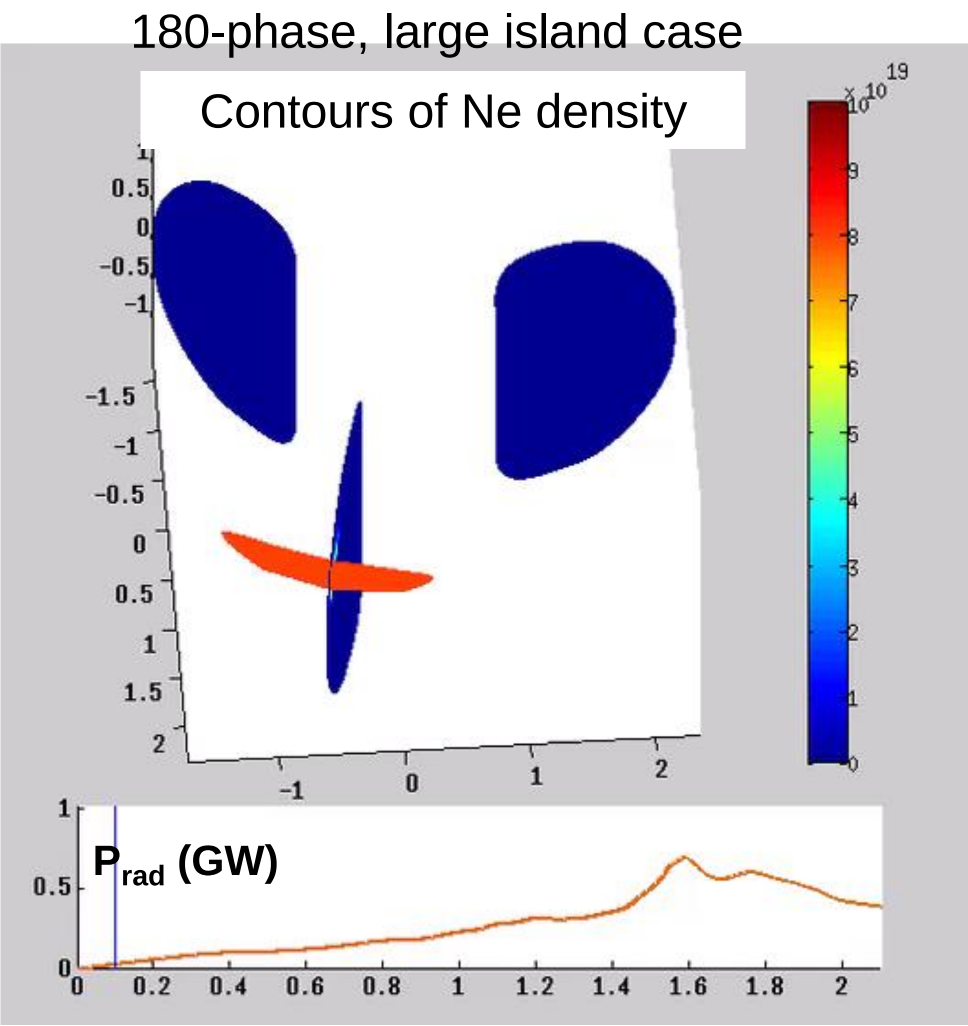
After 1ms, impurity parallel spreading differs between the two phases





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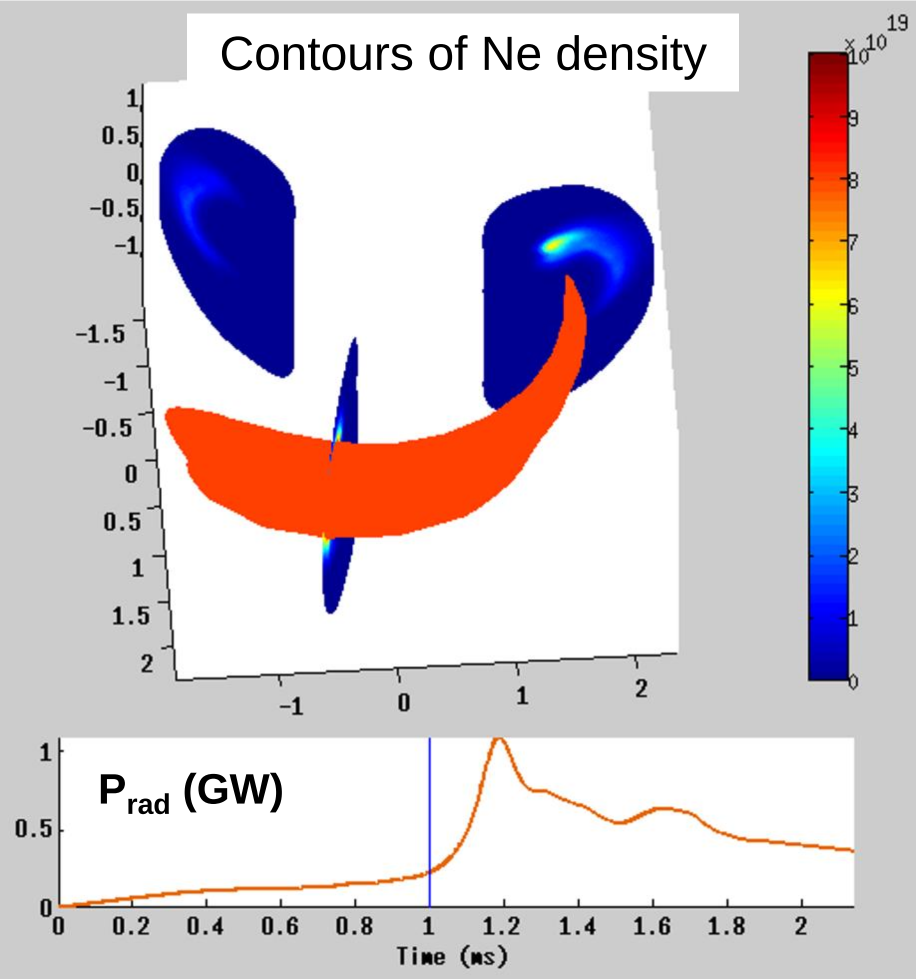
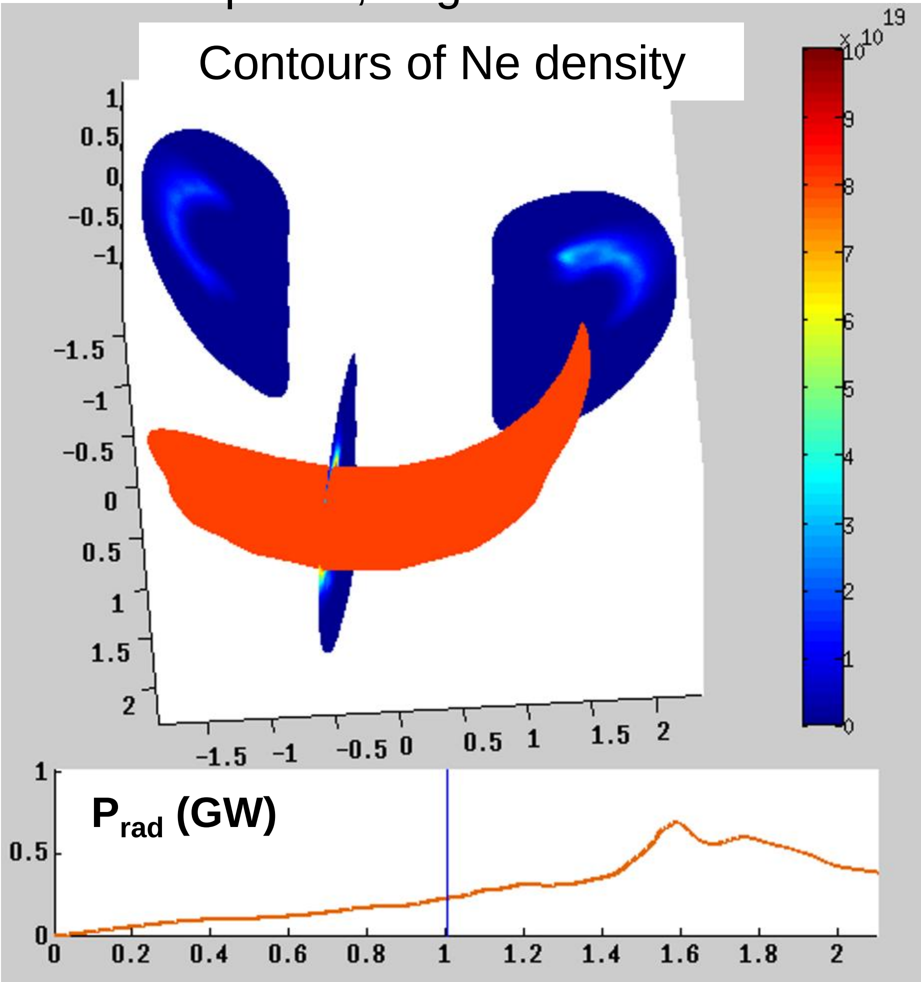
For the two phase, impurity spreading is very similar up to 1ms

0-phase, large island case

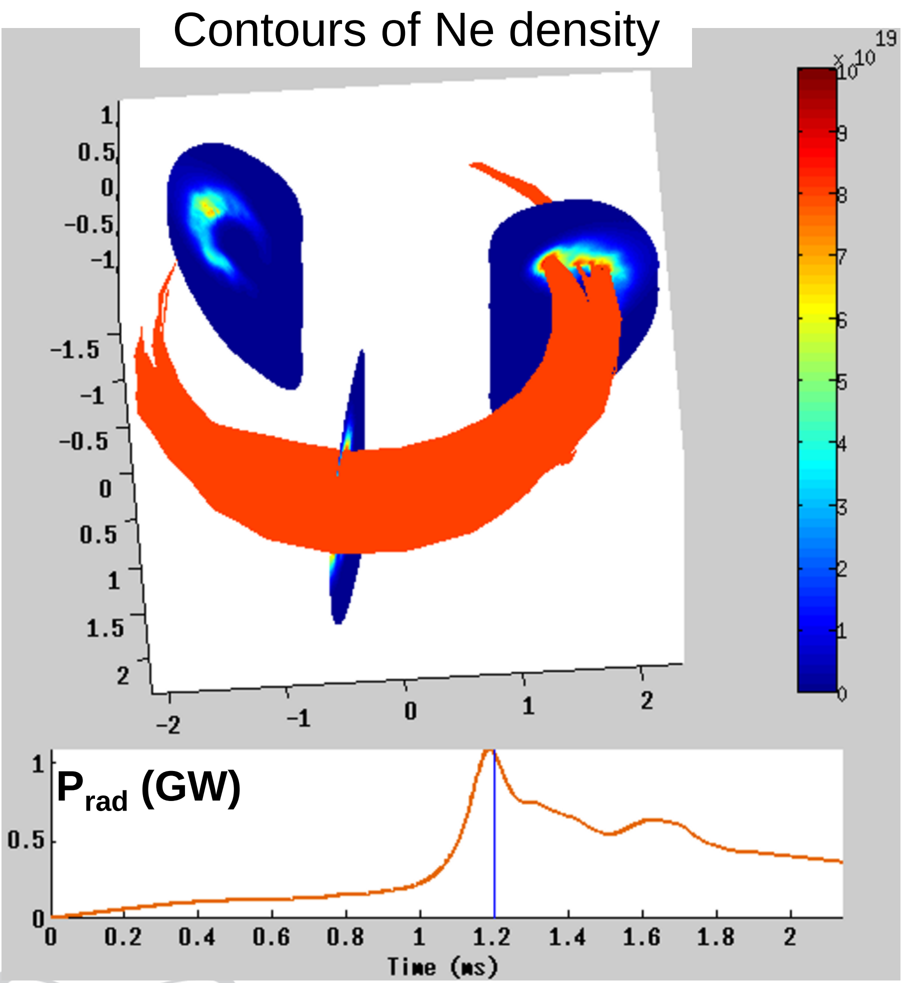


180-phase, large island case

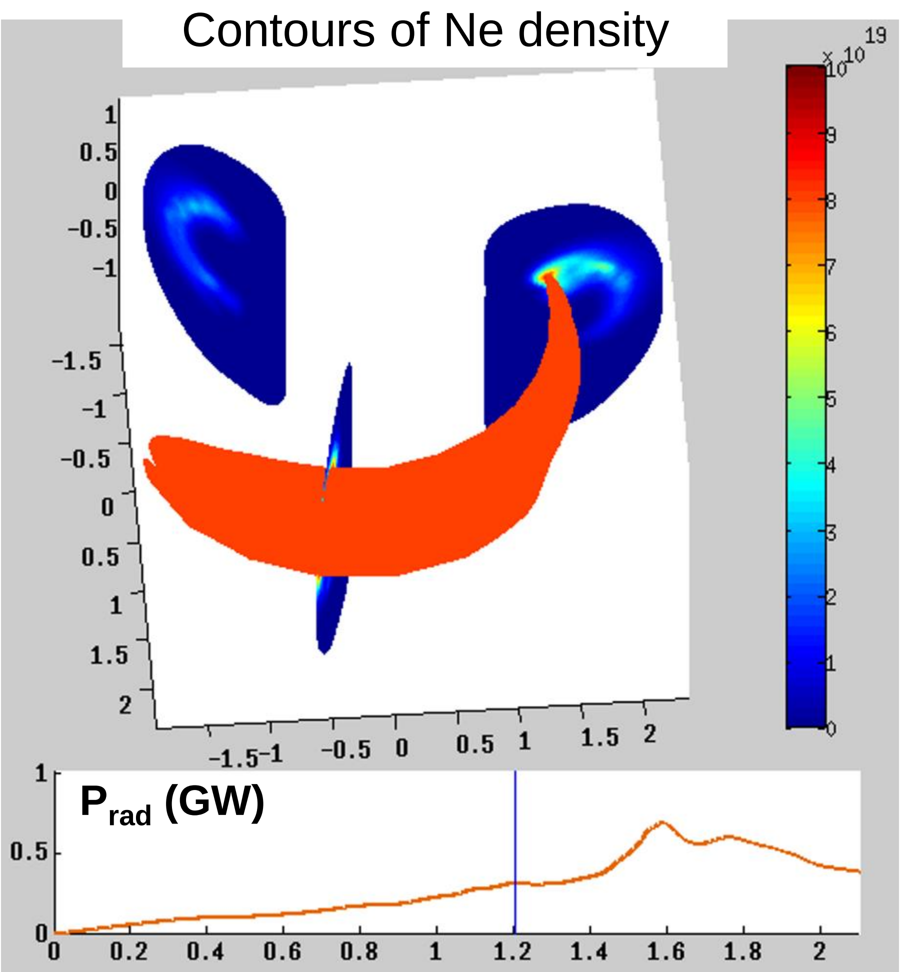


After 1 ms, 0-phase case begins to spread much more rapidly

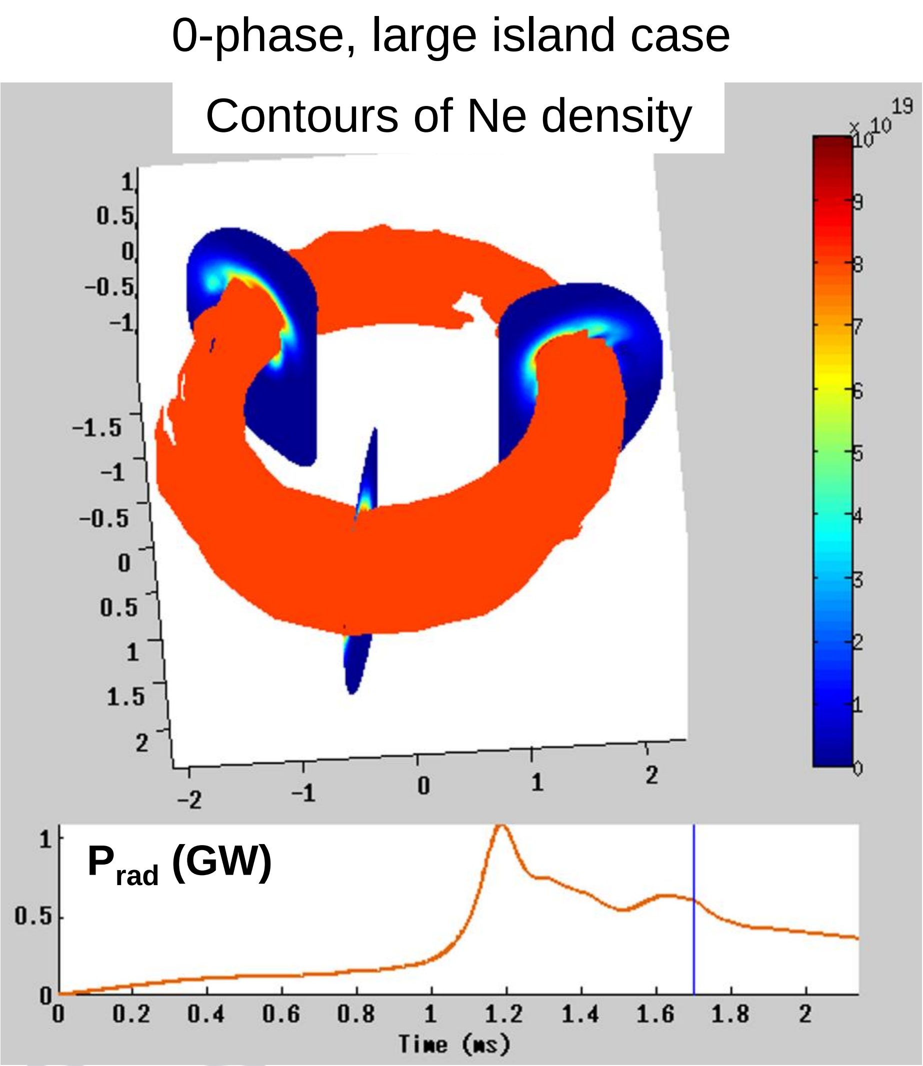
0-phase, large island case

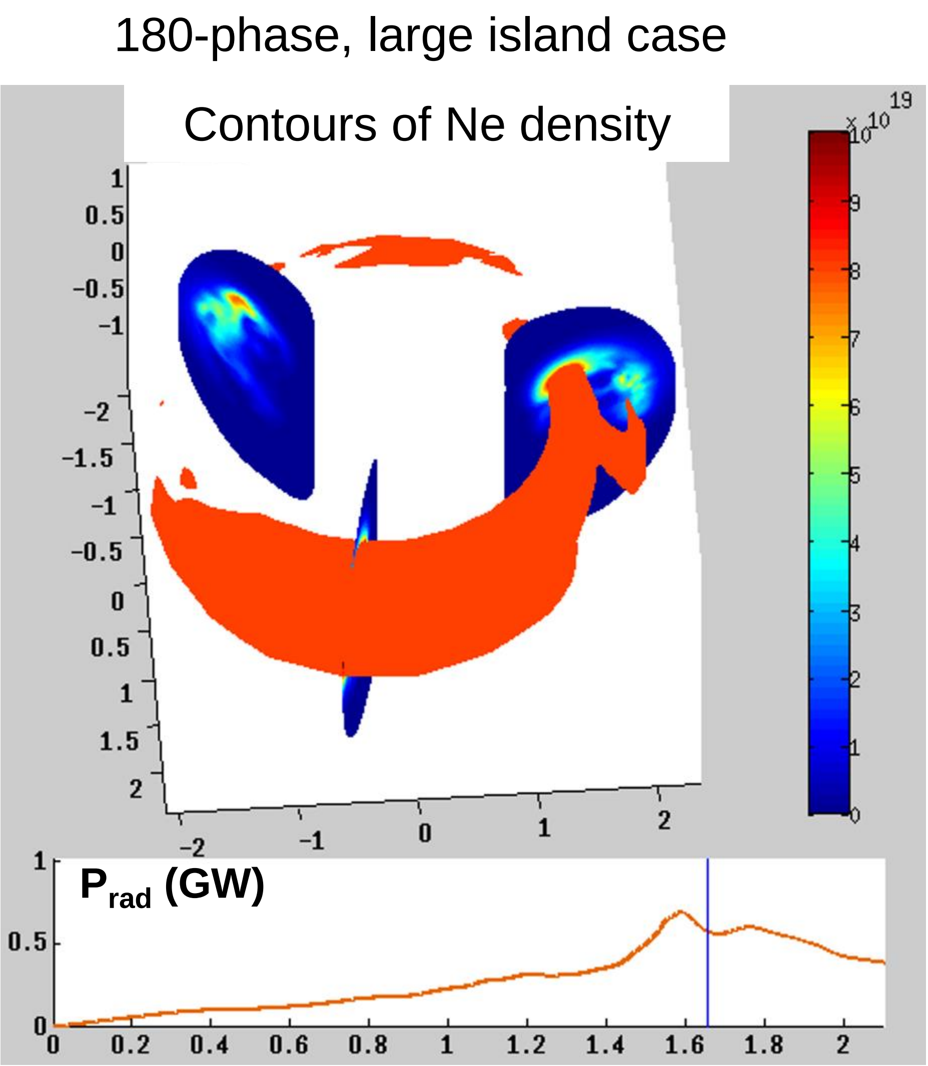


180-phase, large island case

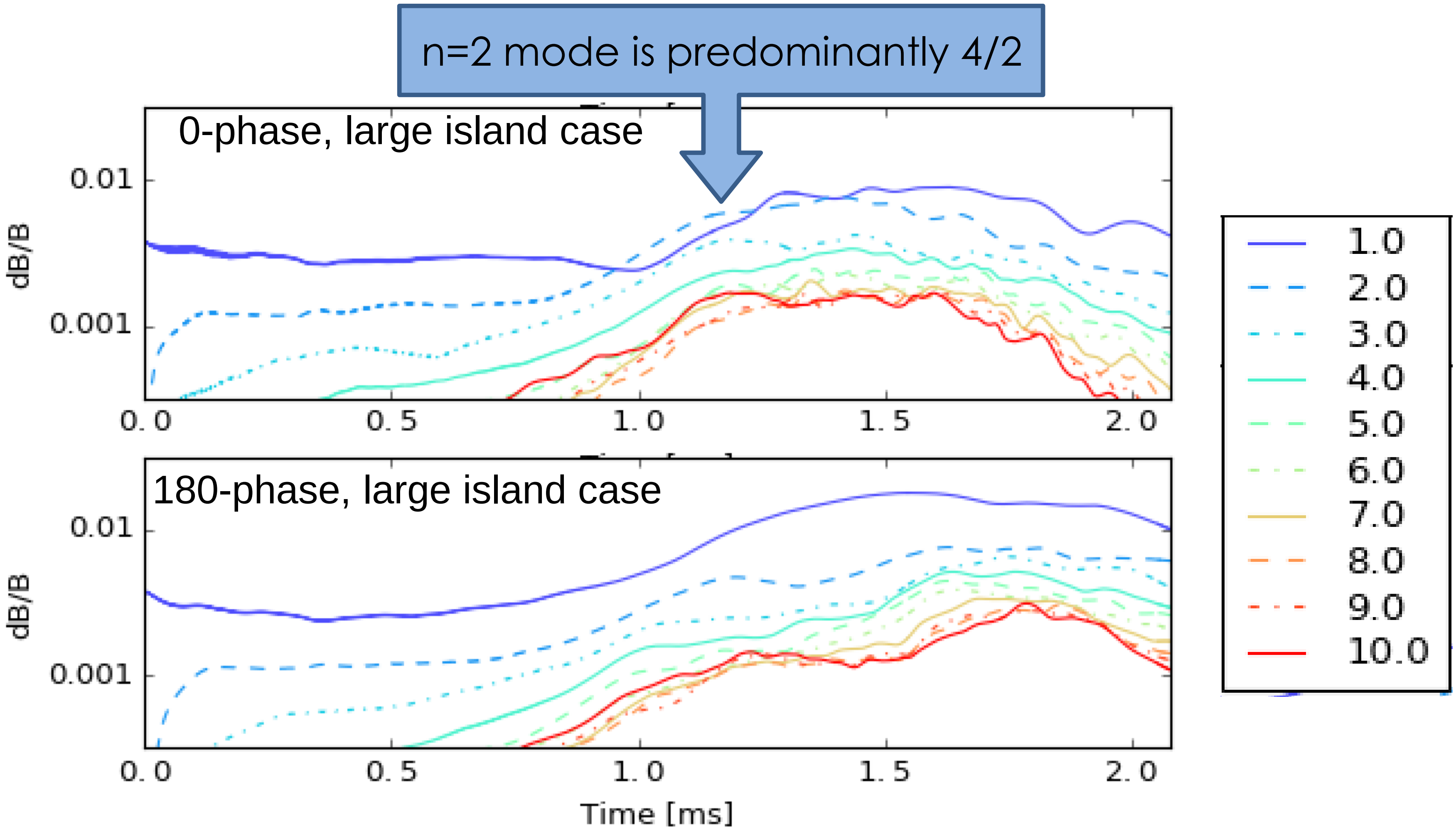


Late in TQ, 0-phase case has much more uniform impurities





Change in impurity spreading rate coincides with appearance of large n=2 mode



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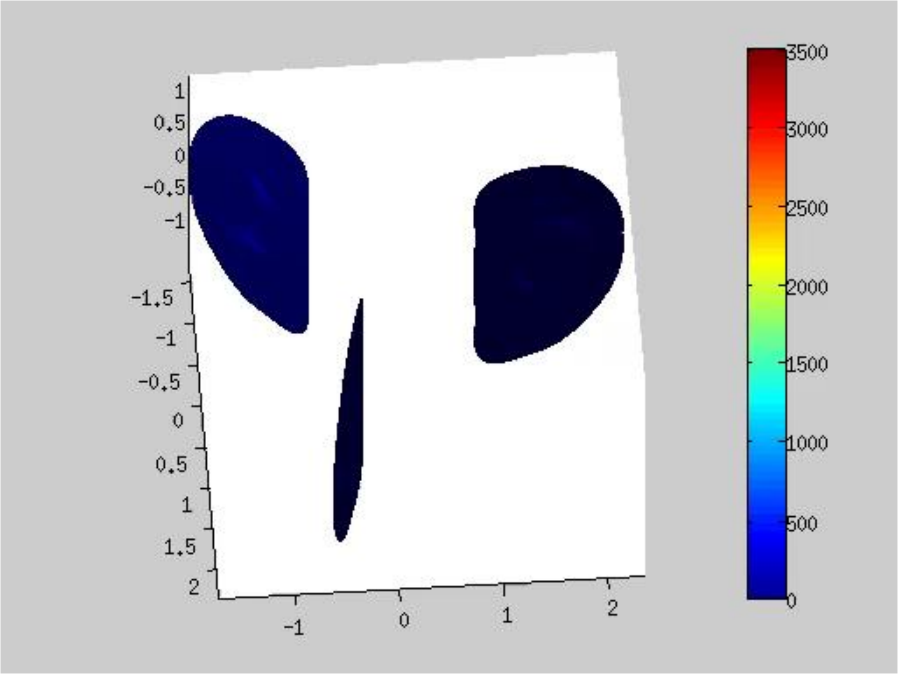
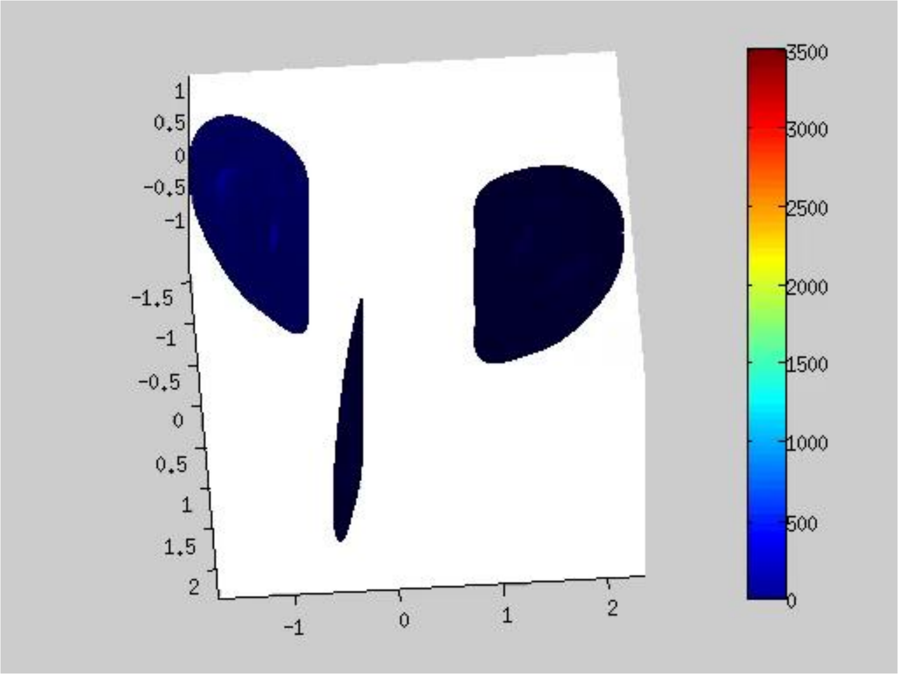
Changes in cooling near the 2/1 island are also evident when n=2 mode appears

Contours of -ΔT



0-phase

Contours of -ΔT



180-phase

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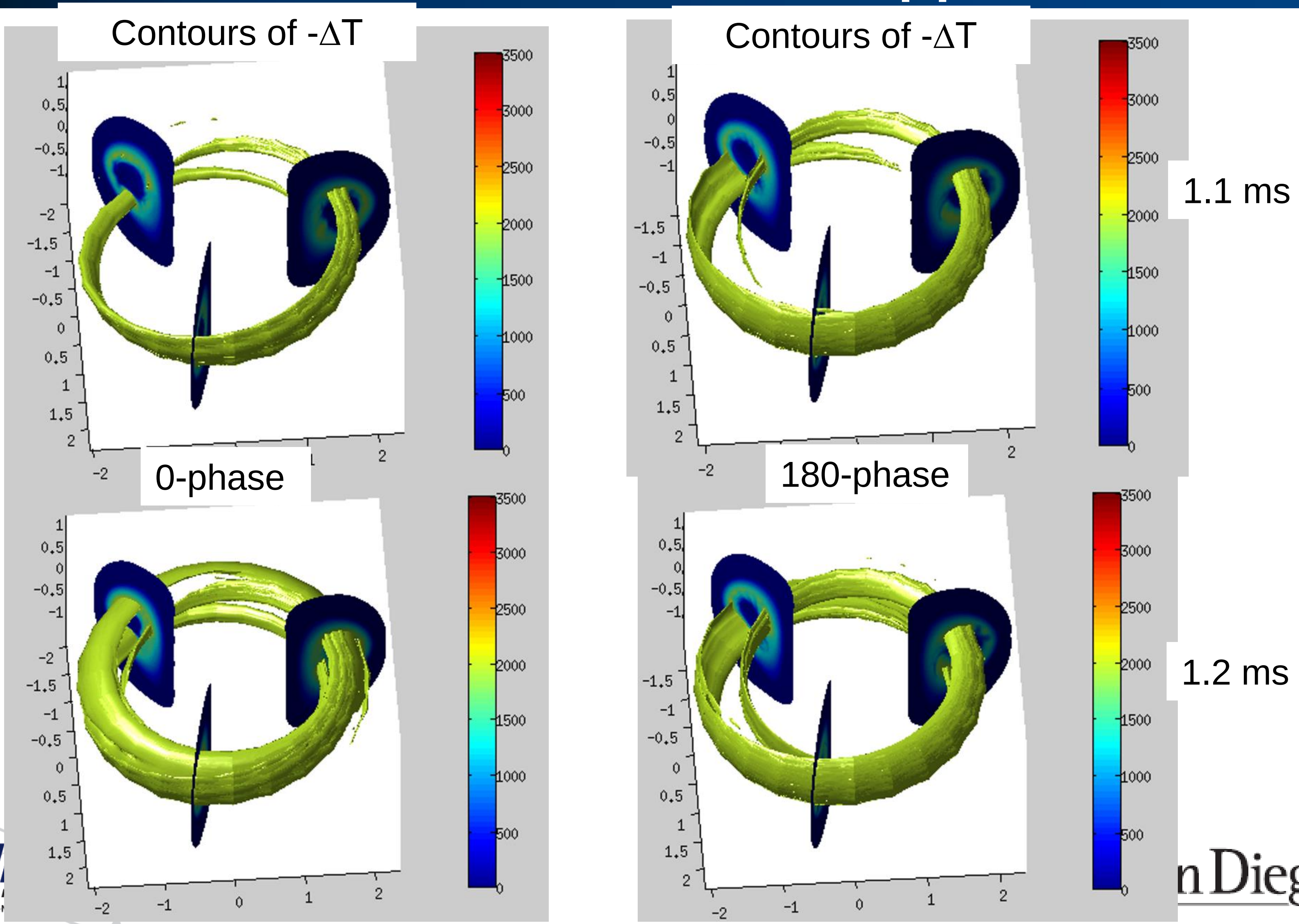
Changes in cooling near the 2/1 island are also evident when n=2 mode appears

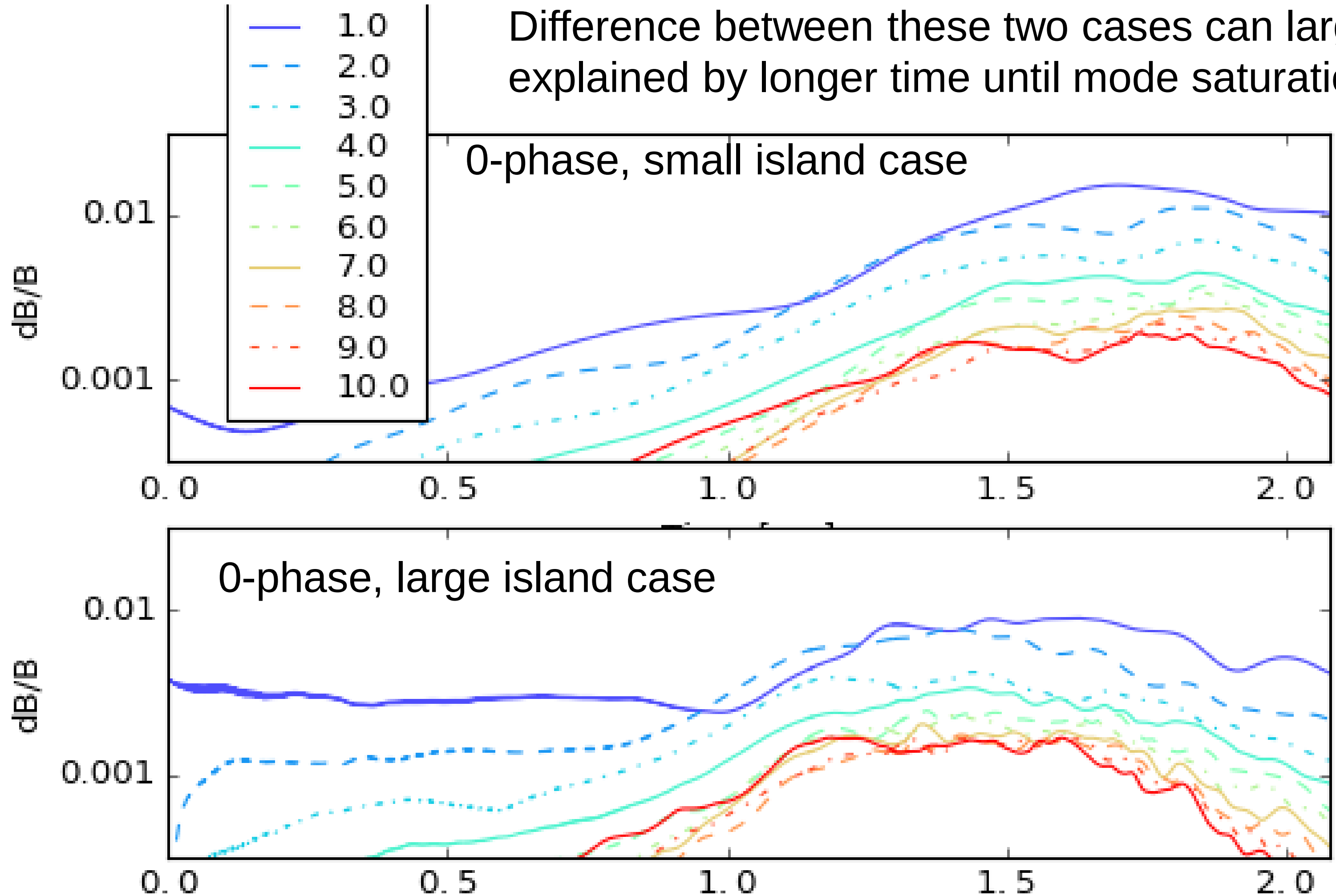


Q1: Why does the n=2 mode appear?

Hypothesis: Certain relative phases of the gas jet and the imposed island excite the n=2 harmonic

Appearance of n=2 mode is associated with 0-phase island at either amplitude

Difference between these two cases can largely be explained by longer time until mode saturation



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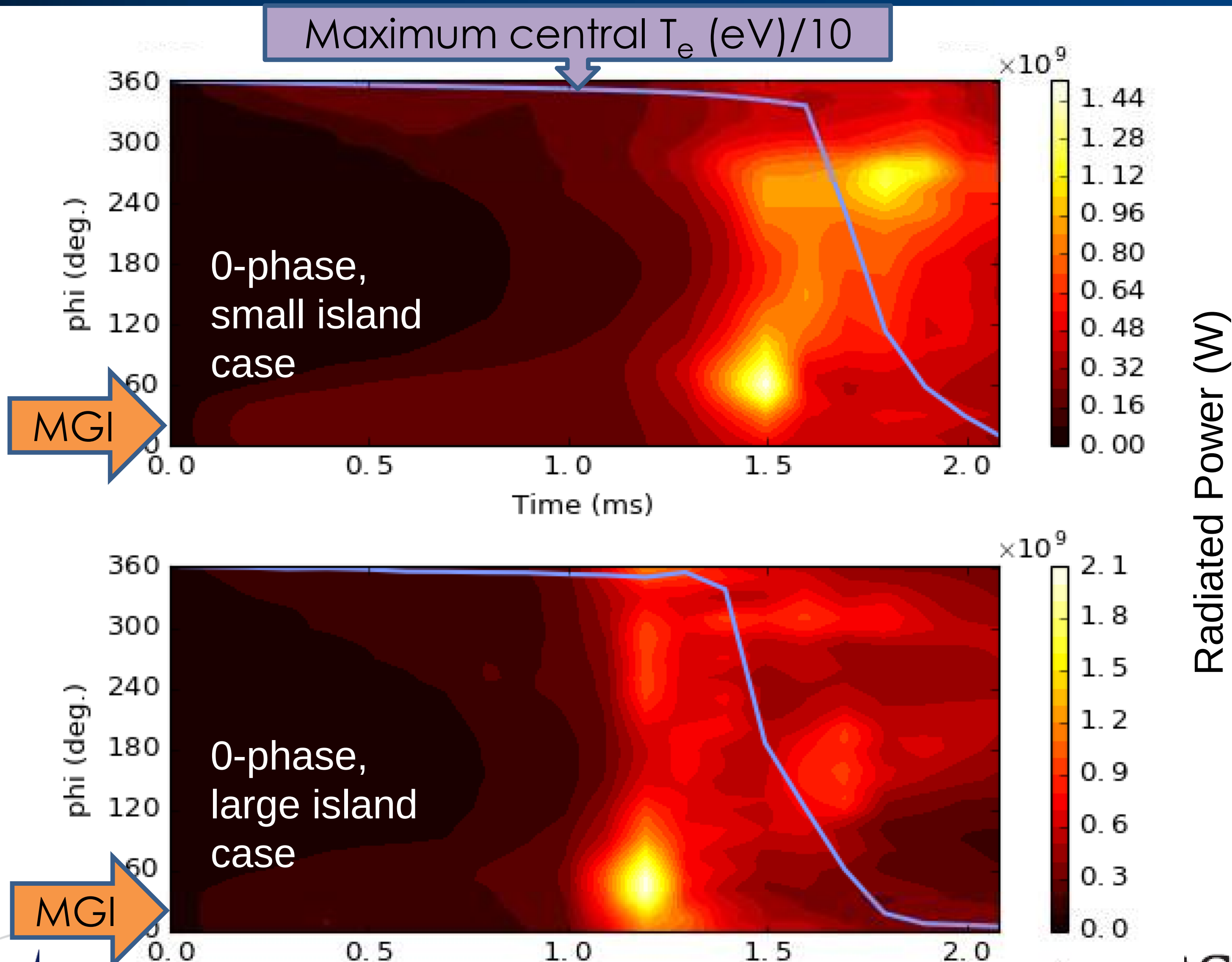
Small island case has later TQ, smaller pre-TQ radiated power flash



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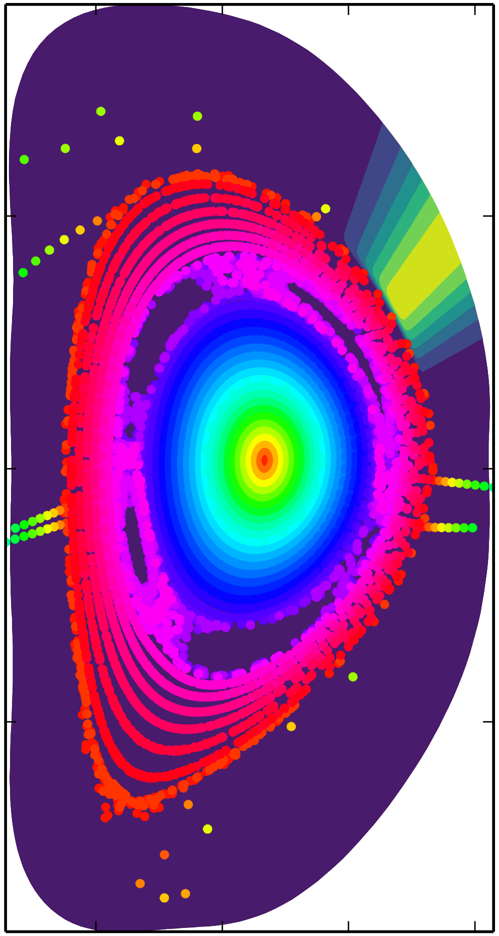
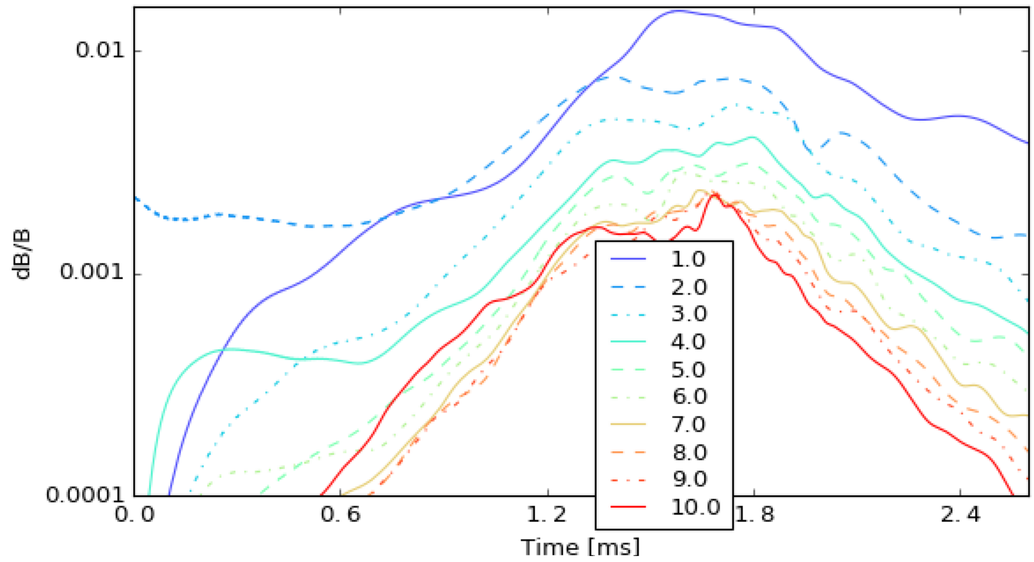
Q2: What does the n=2 mode do?

Hypothesis: It breaks up the 2/1 island into smaller (4/2) island chains, thereby reducing the parallel connection length, and thus enhances parallel impurity spreading

Simulation with pre-seeded 4/2 island (180-phase)





Initial island is pure 4/2 (no 2/1 component), same amplitude/phase as 180-phase, large island case

After n=1 grows to comparable amplitude to n=2, MHD behavior is similar to 0-phase, large island case

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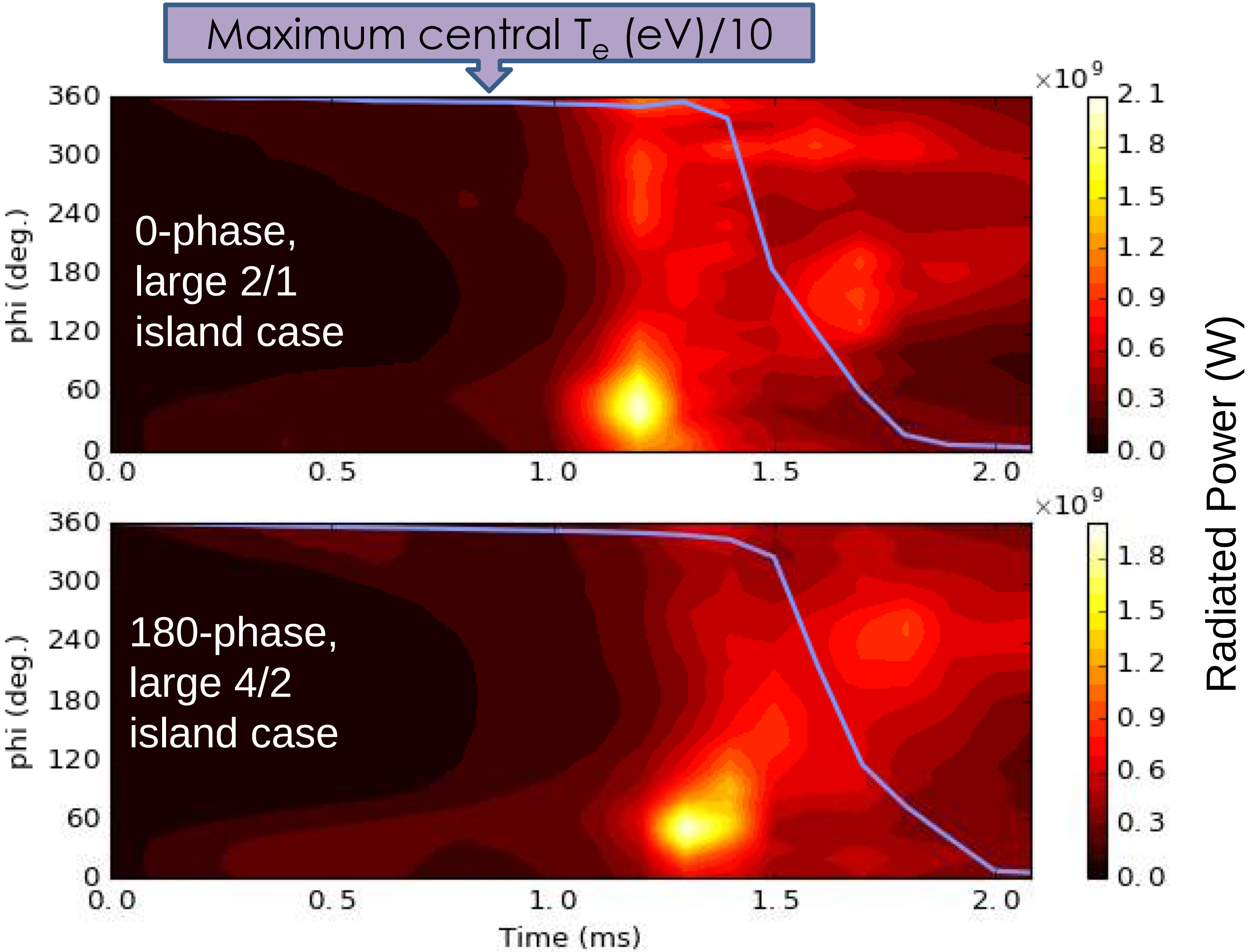
Radiation pattern is very similar to 0-phase case with spontaneously growing 4/2 mode



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PART 3: Consequences for radiated energy fraction and toroidal peaking factor

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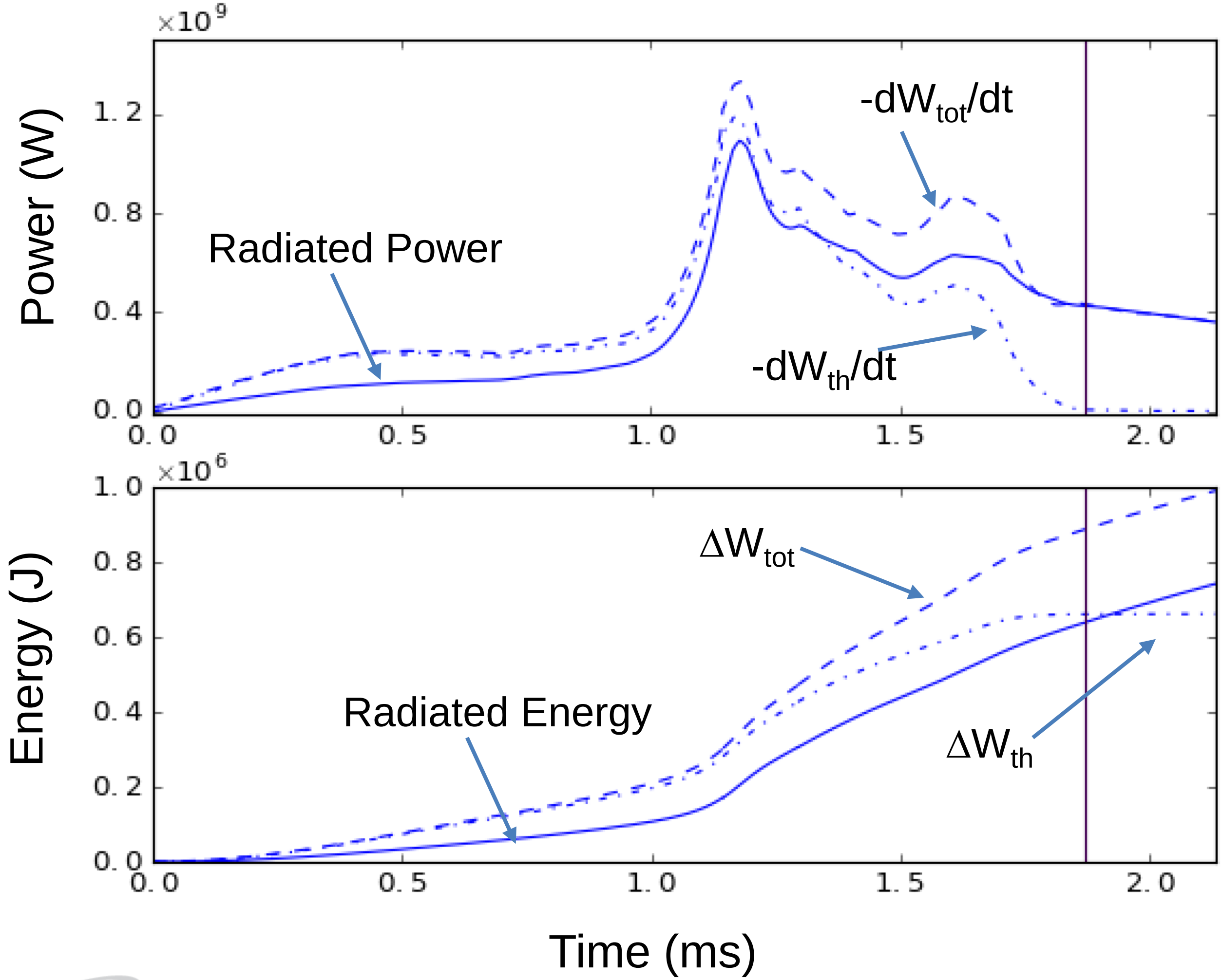
Radiated energy fraction needs to be robustly defined to compare across simulation



W_{rad}/W_{th} depends sensitively on how end of TQ is chosen

Important quantity is energy conducted to the divertor

Define conducted energy fraction:

$f_c = (\Delta W_{tot} - W_{rad})/W_{th}$

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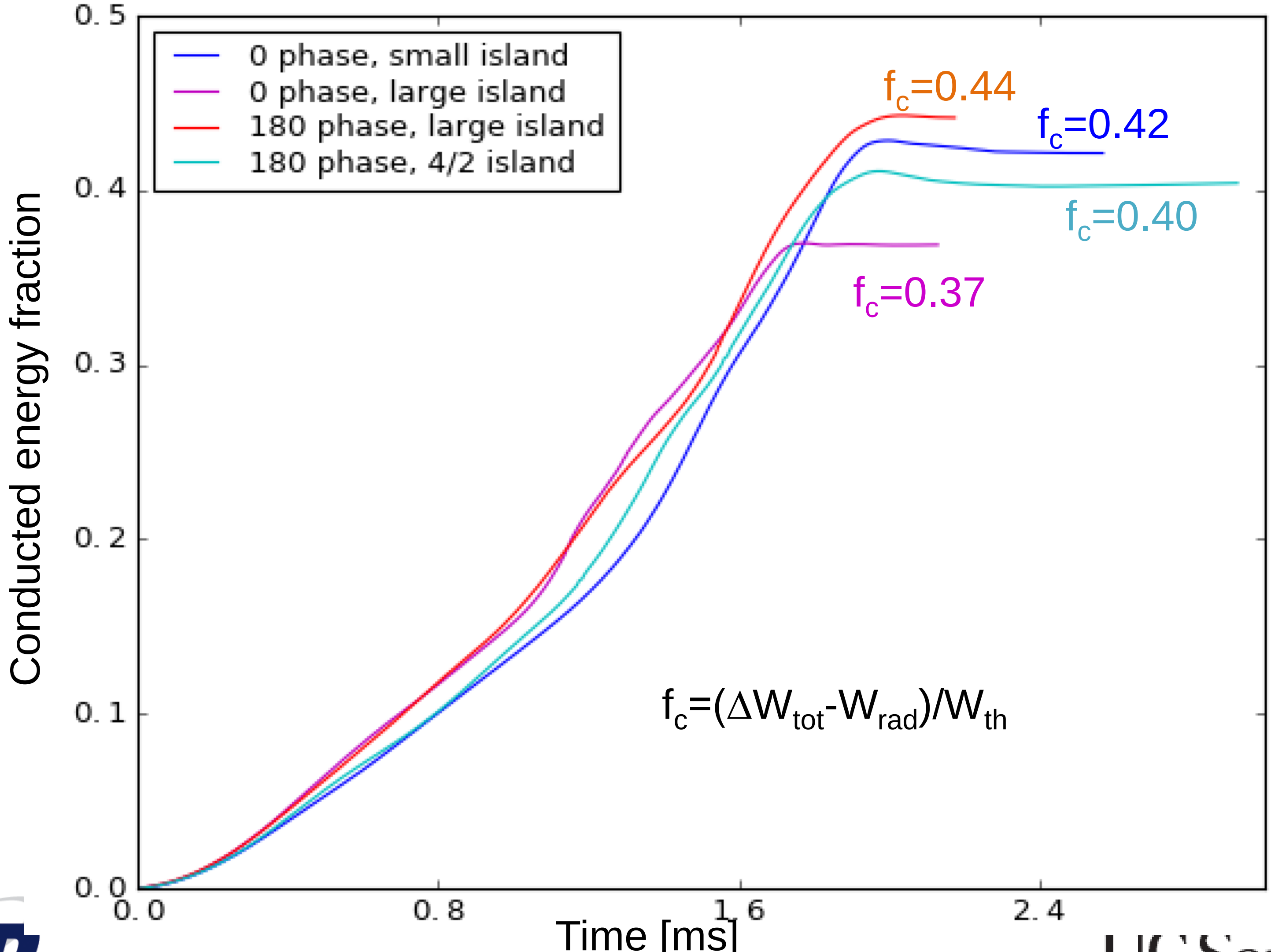
Conducted energy fraction is lowest for 0-phase large island case



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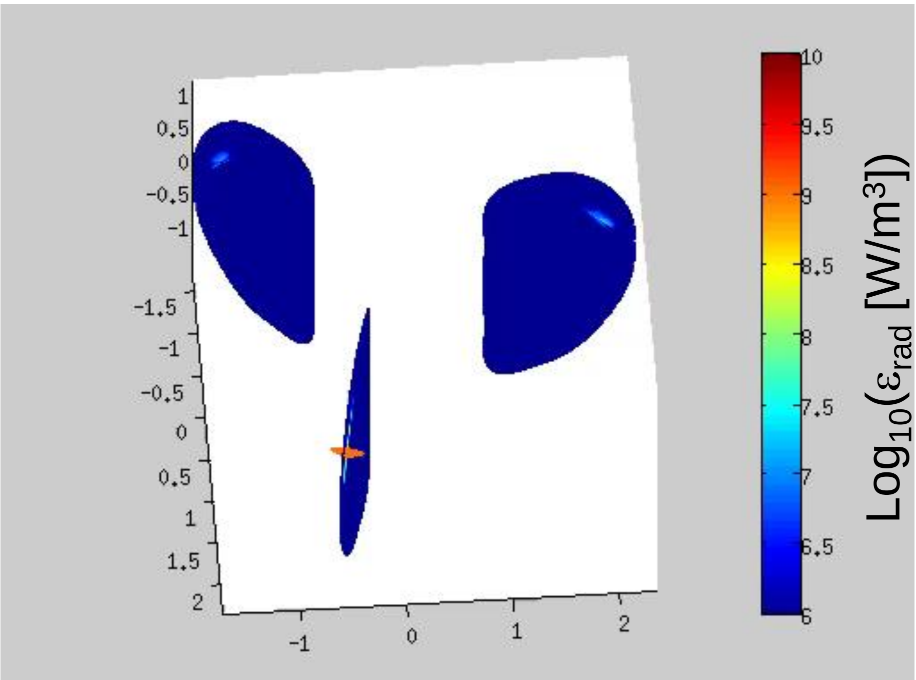
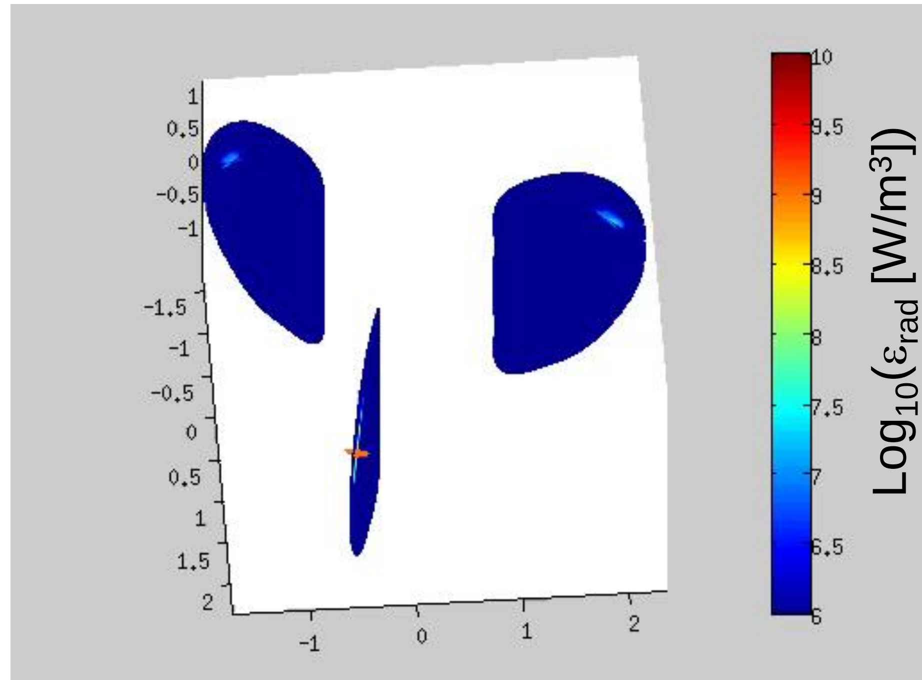
0-phase case has more uniform radiated power during most of the TQ

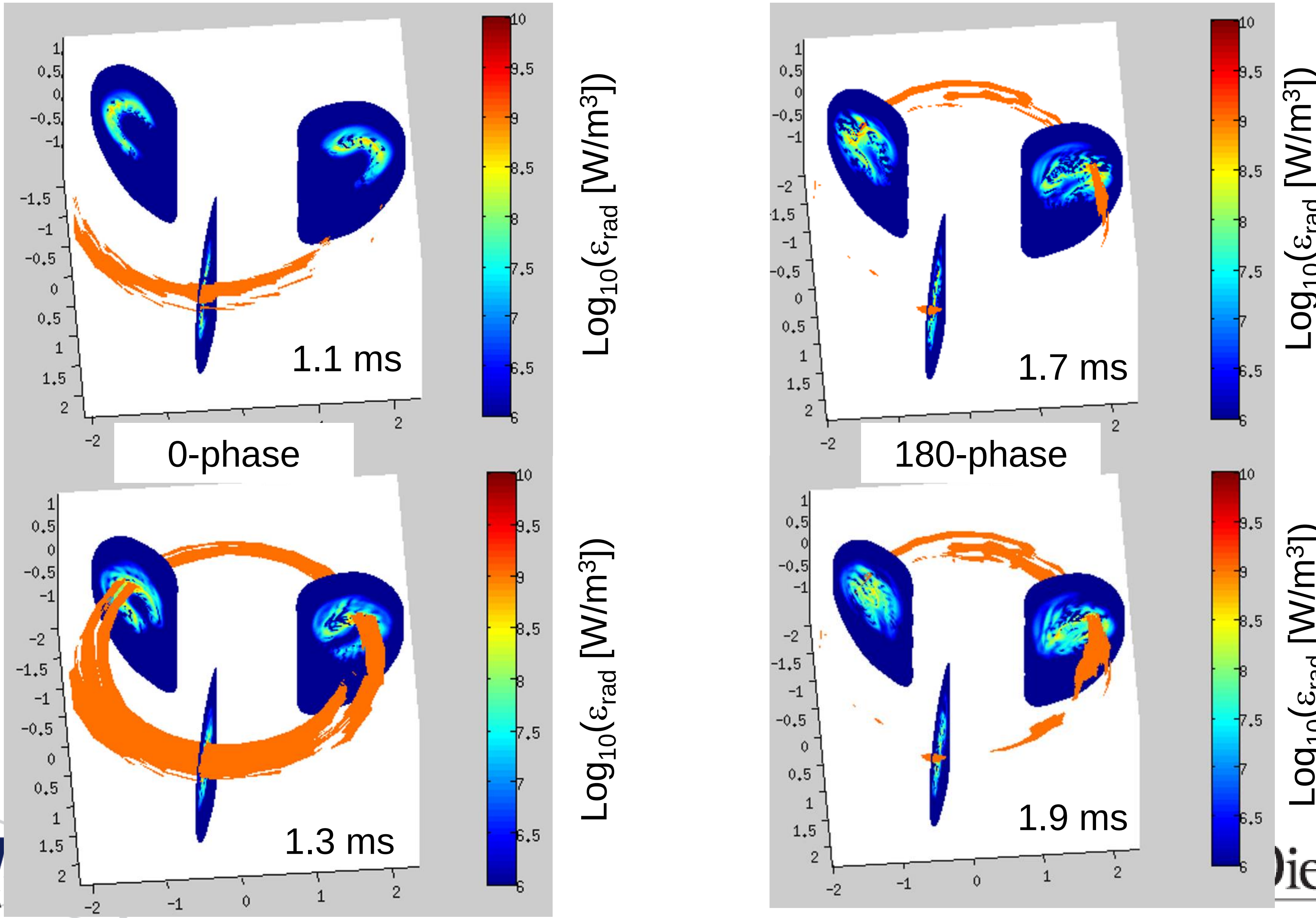


0-phase



180-phase

0-phase case has more uniform radiated power during most of the TQ



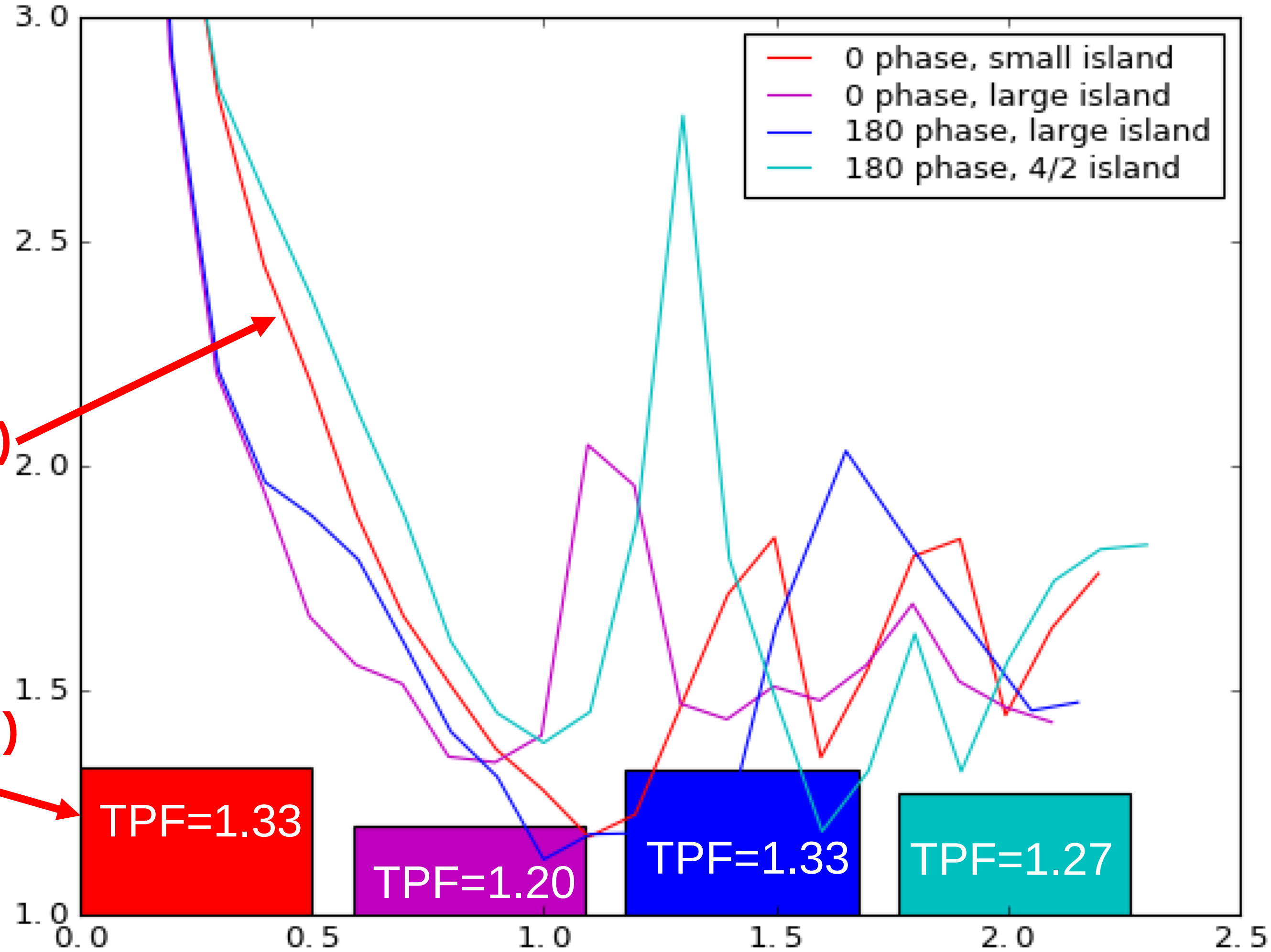
Time average TPF is lowest for 0-phase, large island case

Instantaneous toroidal peaking factor (TPF):

$\max(P_{rad})/\mathrm{mean}(P_{rad})$

Average TPF:

$\max(W_{rad})/\mathrm{mean}(W_{rad})$



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Conclusions

- The presence of large islands affects the heat conduction and spreading of impurities at the rational surface
- The break-up of the islands into smaller island chains enhances impurity spreading, and reduces average toroidal peaking and the conducted energy fraction
- For a single gas jet, the appearance of the n=2 harmonic occurs only for some island phases.
- A deliberately imposed 4/2 island produces a similar radiation pattern to the case with a spontaneously growing 4/2 mode

FUTURE WORK

- What role do multiple gas jets play in driving higher-n harmonics?
- How do results compare with DIII-D MGI-into-locked-mode experiments?