MHD modeling in support of thermal quench and runaway electron mitigation for ITER

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Theory and Simulation of Disruptions Workshop

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with contributions from:
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Alcator C-Mod

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This talk concerns mitigated disruptions (aka "Rapid Shutdowns")

Part 1. ***Radiative*** heat loads during a mitigated TQ: Toroidal (and poloidal) radiation peaking

→ Spatial symmetry of radiated power is not just a function of the impurity distribution

Part 2: Runaway electron confinement during a mitigated TQ

→ Evidence suggest that deconfinement by MHD fluctuations will not be an effective strategy for ITER

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Outline:

Part 1. ***Radiative*** heat loads during a mitigated TQ: Toroidal (and poloidal) radiation peaking

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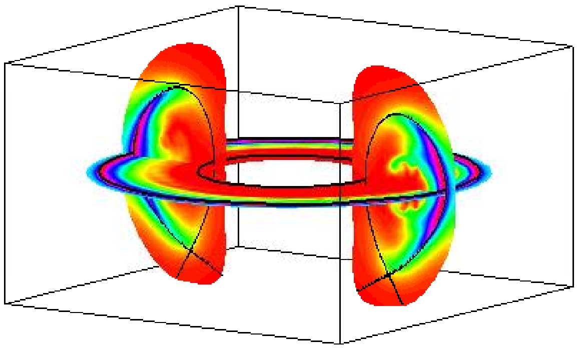
NIMROD extended MHD code is combined with KPRAD atomic physics code to model massive gas injection (MGI)

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

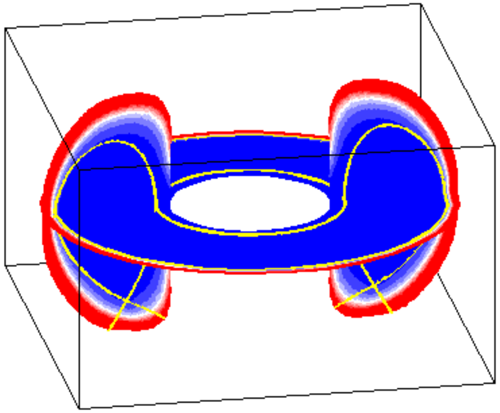
KPRAD calculates ionization, recombination and radiation cooling

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

Ionized Ne density

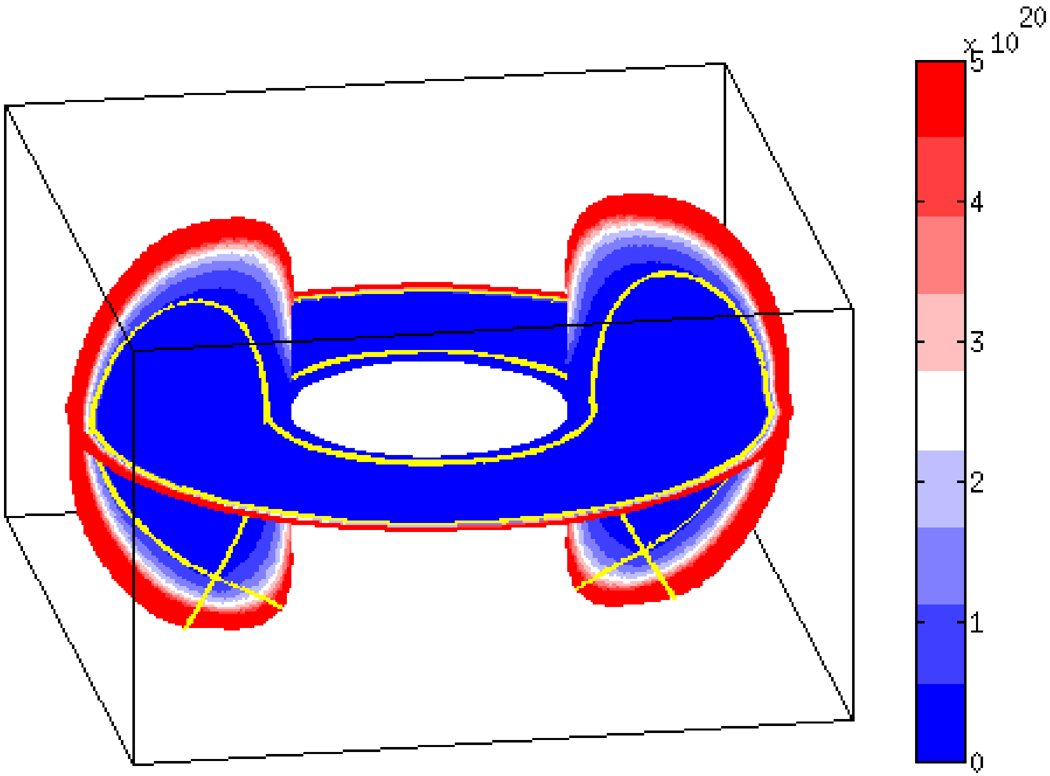


Neutral Ne density



Case 1: Toroidally symmetric Ne injection on the low field side (LFS)

<u>Contours of injected neutral Ne density</u>

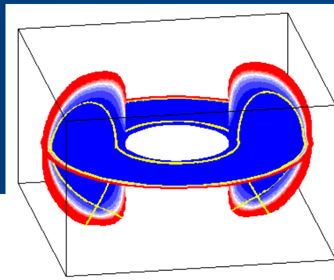


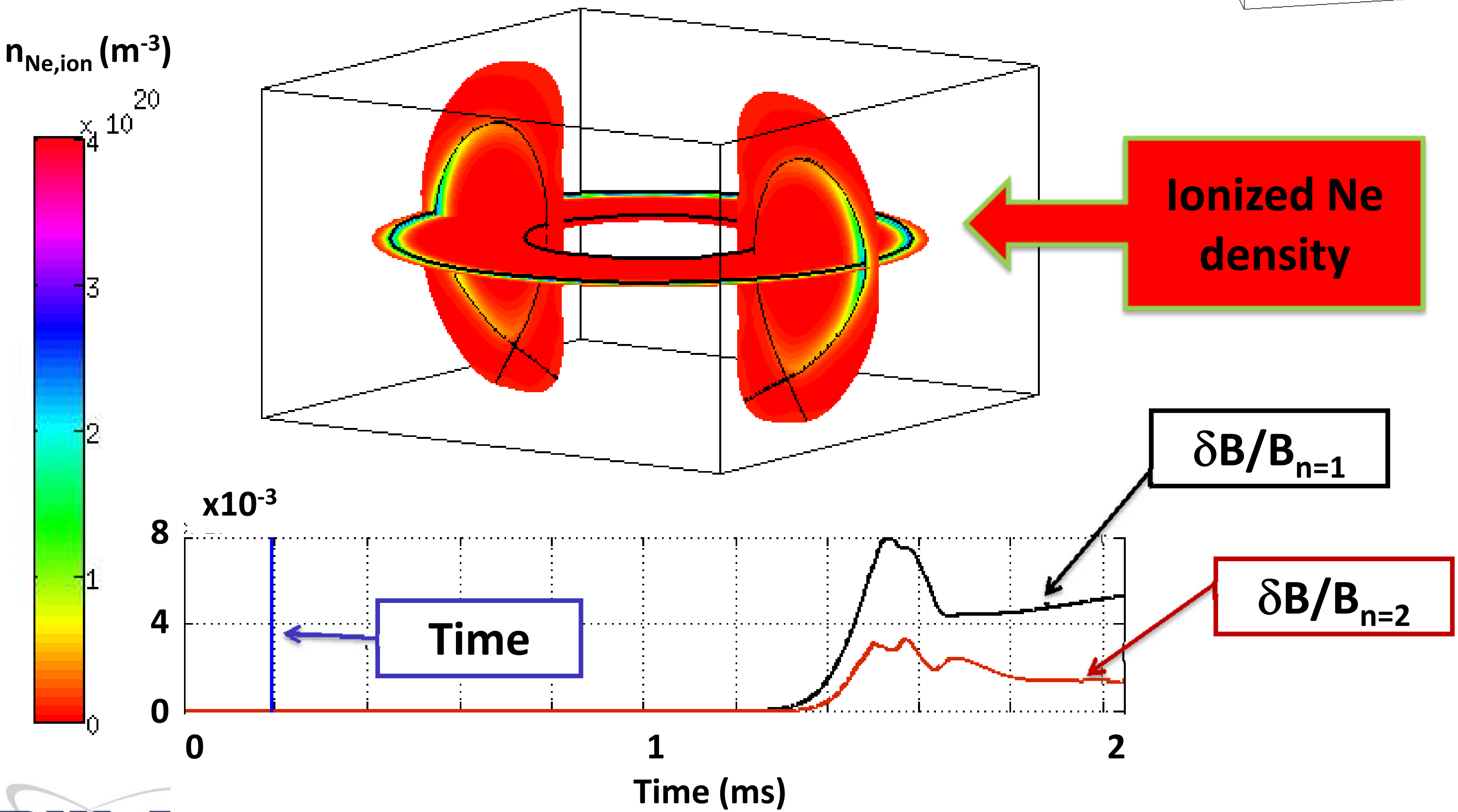
Key results:

- *MHD activity during the thermal quench (TQ) produces rapid mixing of impurities into the core*

- ***Radiated power asymmetry occurs even with symmetric gas injection*** *due to the 1/1 mode*

Ne first diffuses slowly, then mixes rapidly when MHD modes appear





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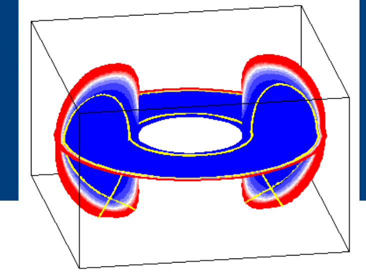
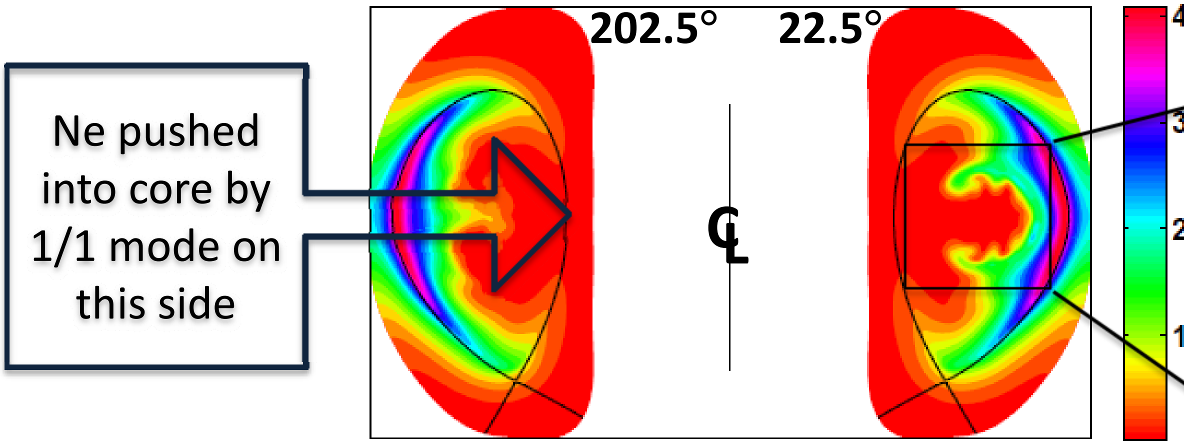
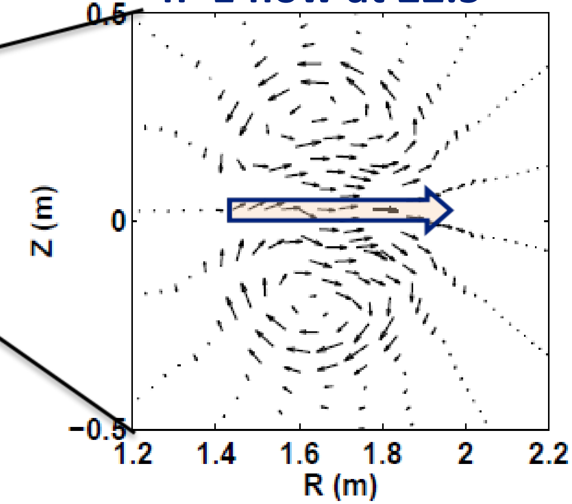
1/1 mode is primarily responsible for rapid mixing



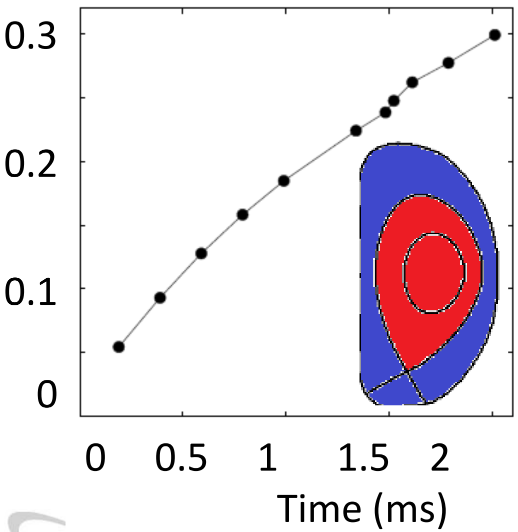
Ionized Ne density (1.52 ms)



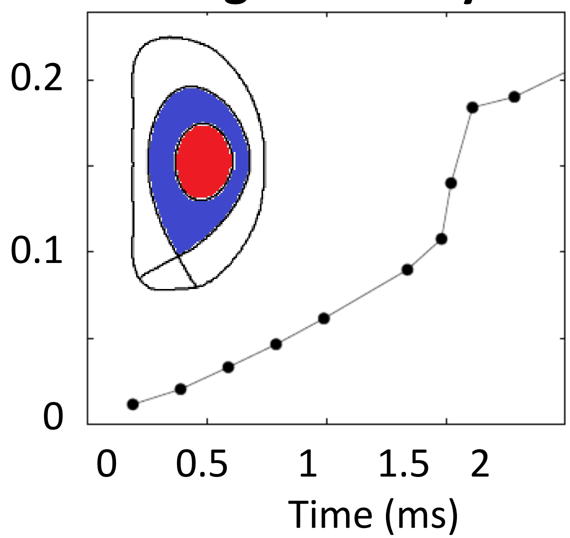
n=1 flow at 22.5°



Assimilation Efficiency



Mixing Efficiency



- **Assimilation efficiency:** Fraction of total Ne inside the separatrix
  - ***Dominated by diffusion across the separatrix***
- **Mixing efficiency:** Fraction of Ne in plasma that is inside 50% flux surface
  - ***Rises rapidly during TQ due to 1/1 mode flows***

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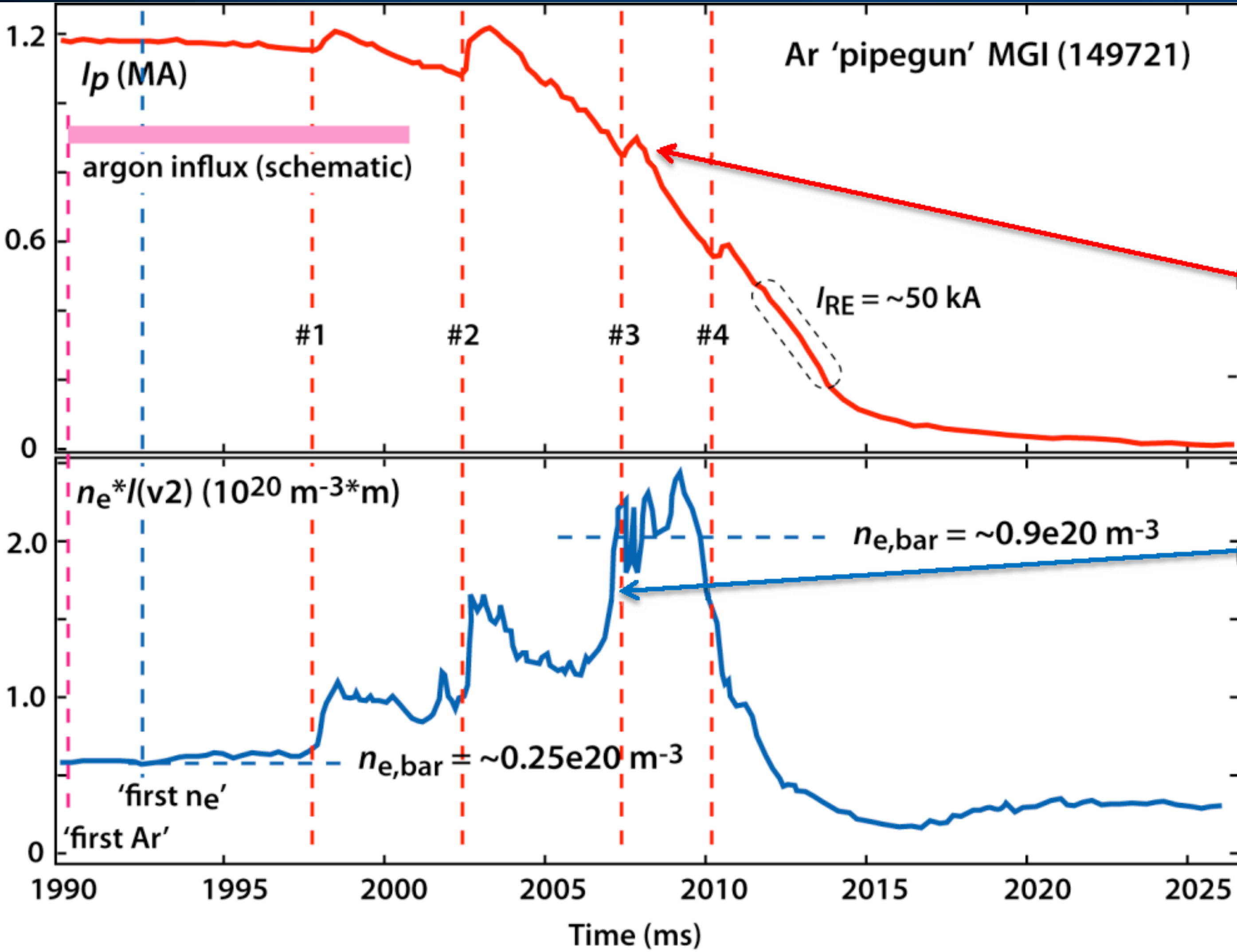
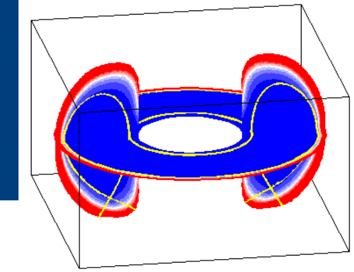
DIII-D data illustrates rapid density rise caused by MGI-induced reconnection event

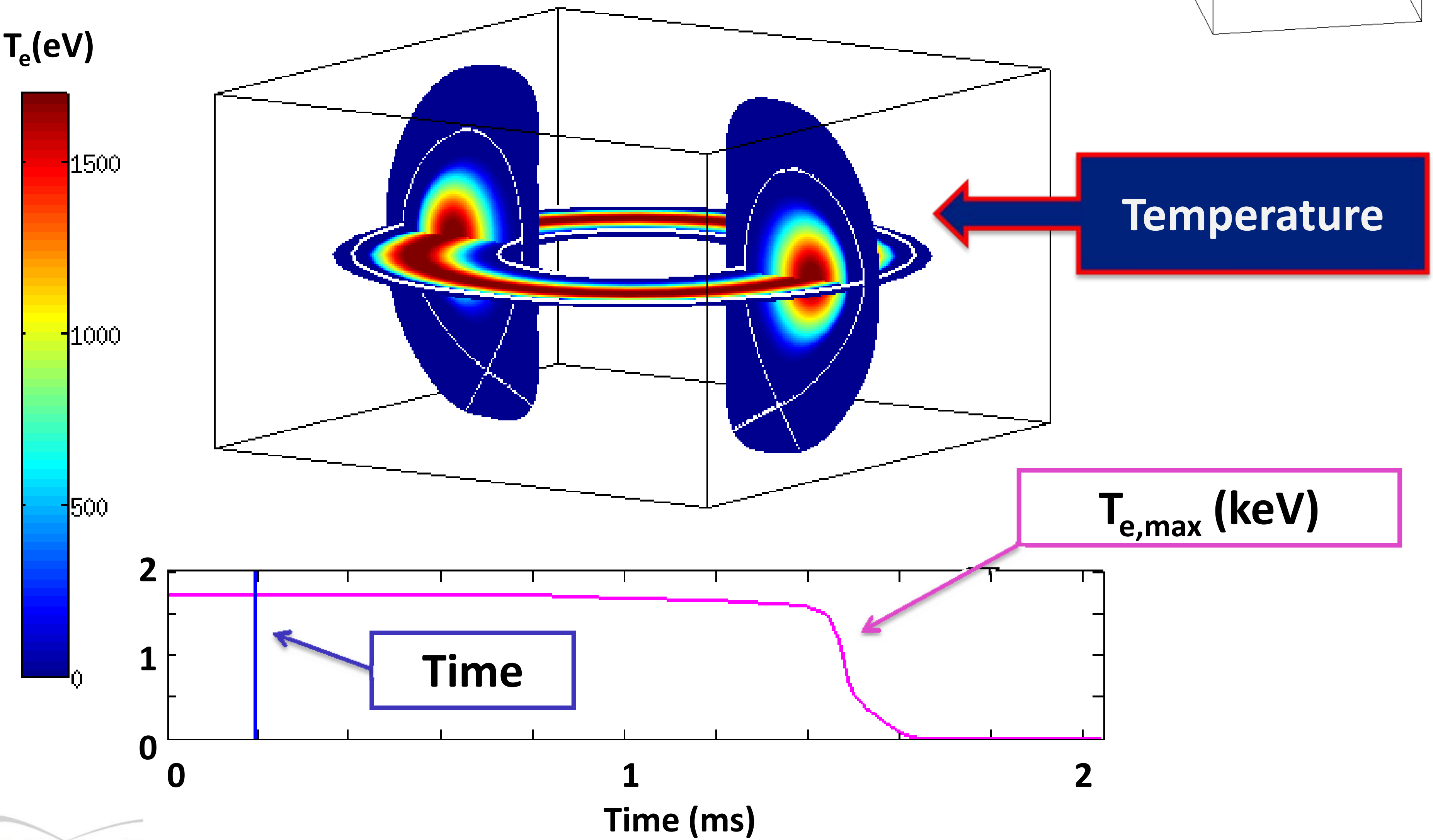


- Weak gas injection shot :
- **Multiple reconnection events …**
- **Simultaneous density jumps**

➔ **MHD mixing**

Hot core is expelled by the 1/1 mode at the time of the TQ





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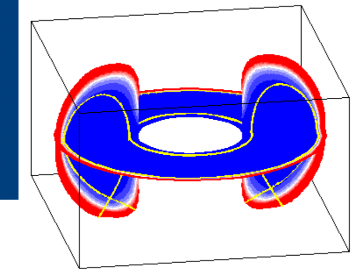
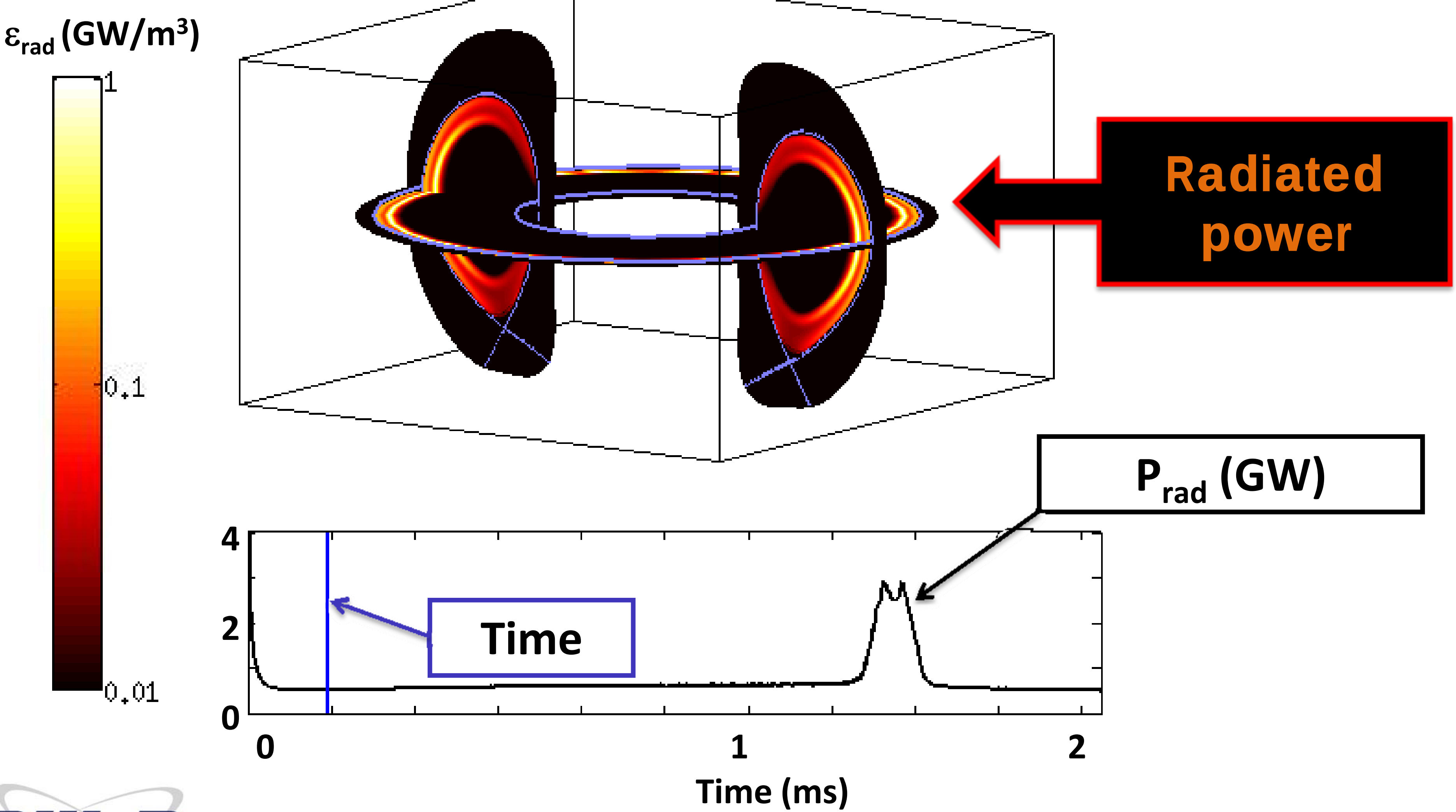
Radiated power spikes during TQ





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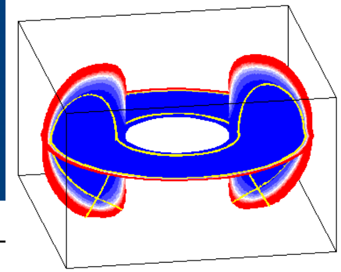
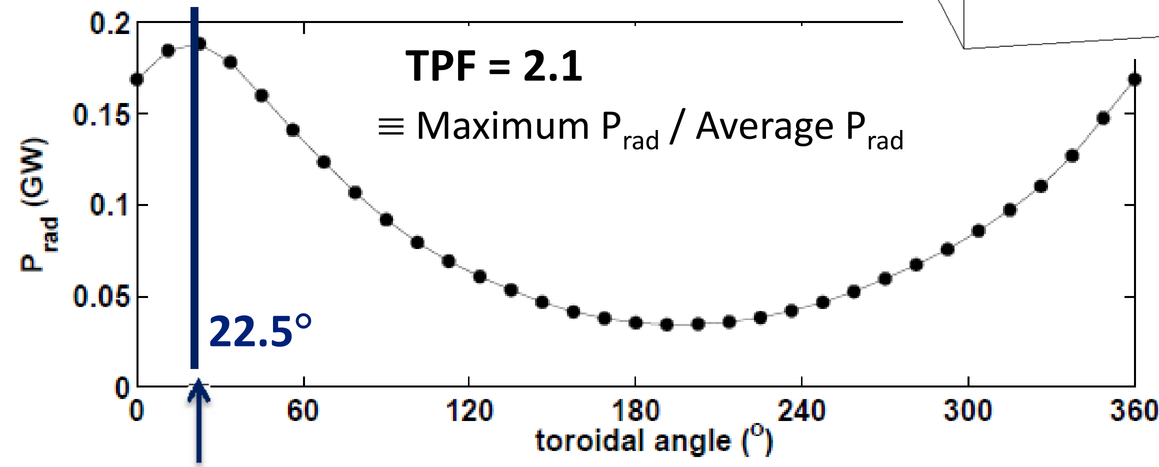
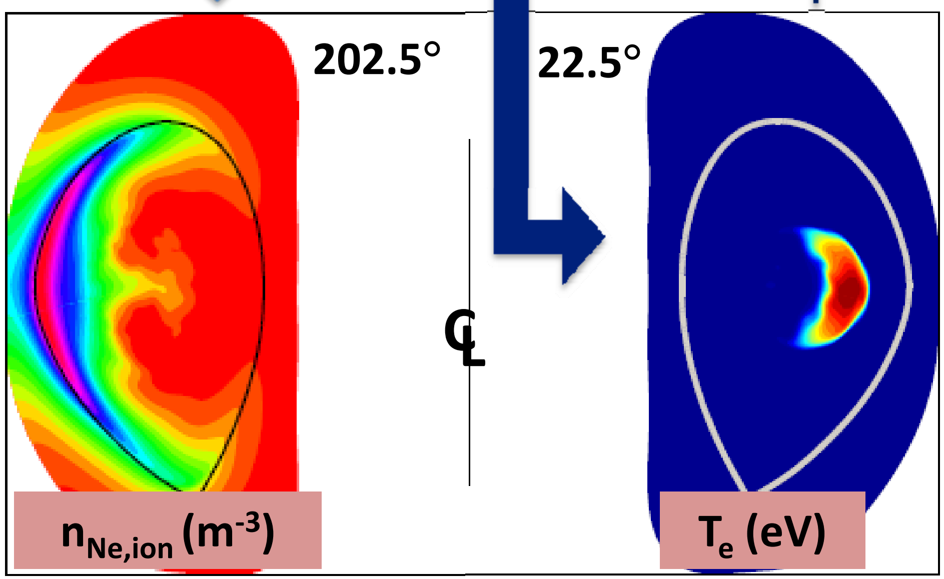
Radiation asymmetry occurs even with a symmetric Ne source

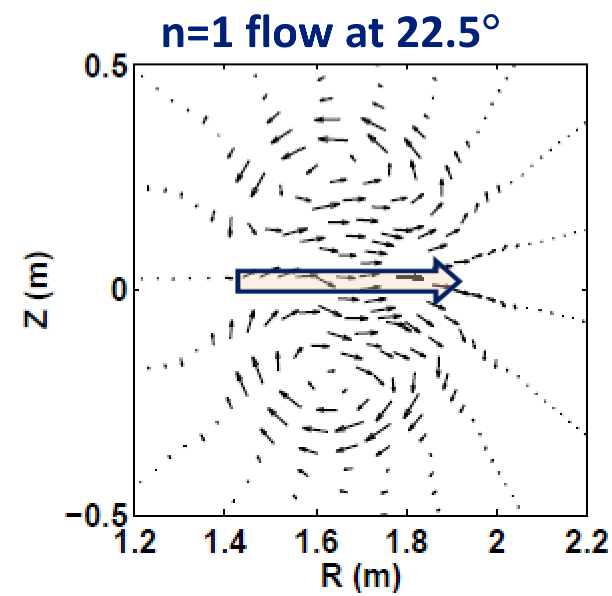


Radiation is peaked here…

…not here







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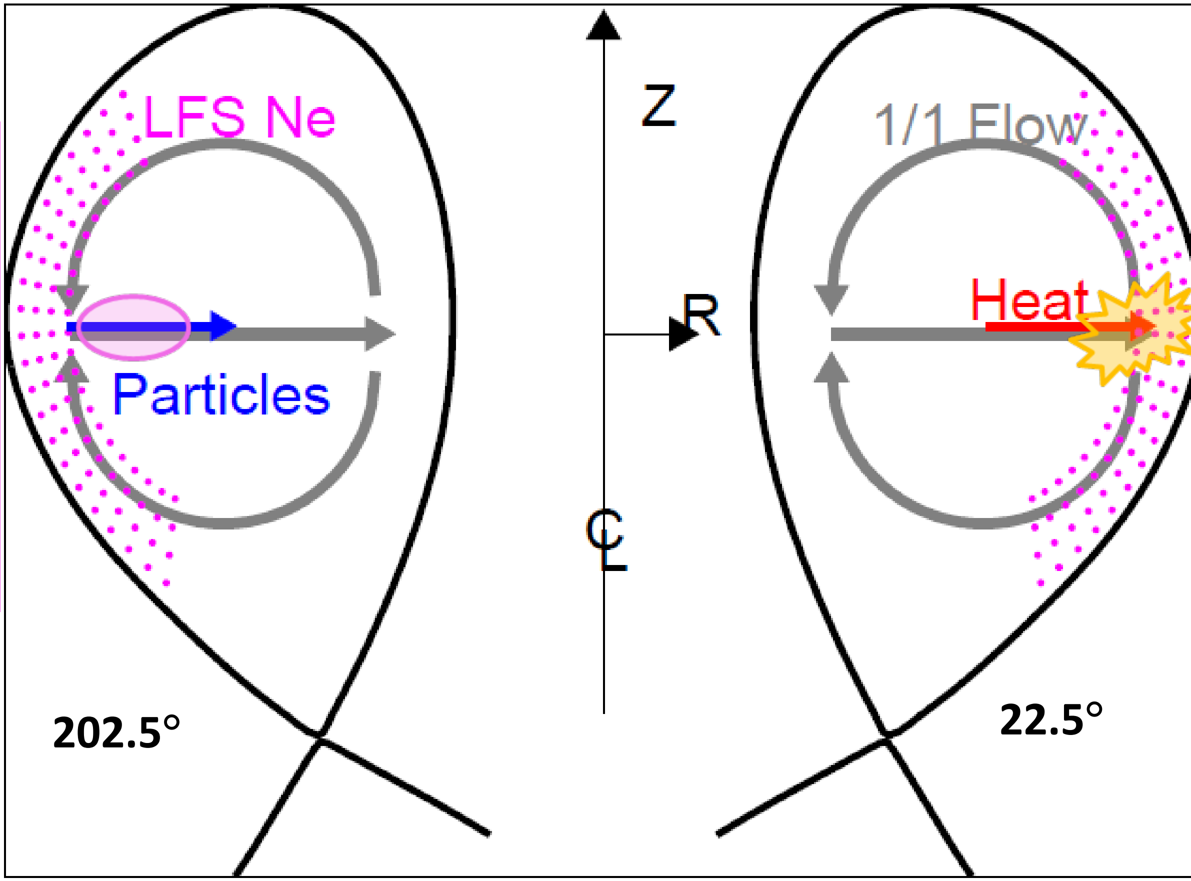
1/1 mode responsible for both P_{rad} flash during TQ and rapid mixing of impurities

Mode convects particles from edge to core <u>and</u> heat from core to edge

Flow is aligned to pull impurities into the core mainly on one side of the torus

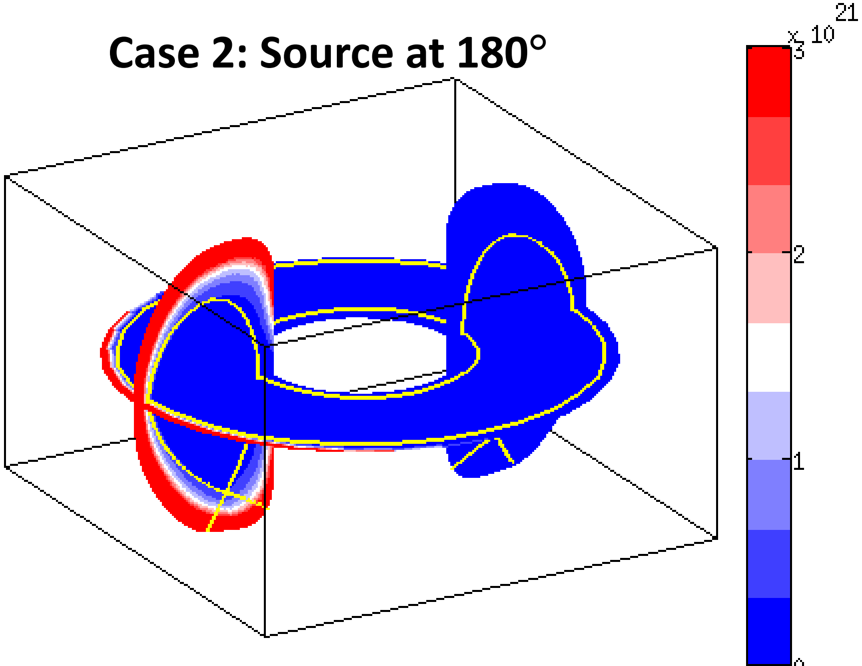


Radiated power flash is concentrated where expelled hot core hits impurities at the edge

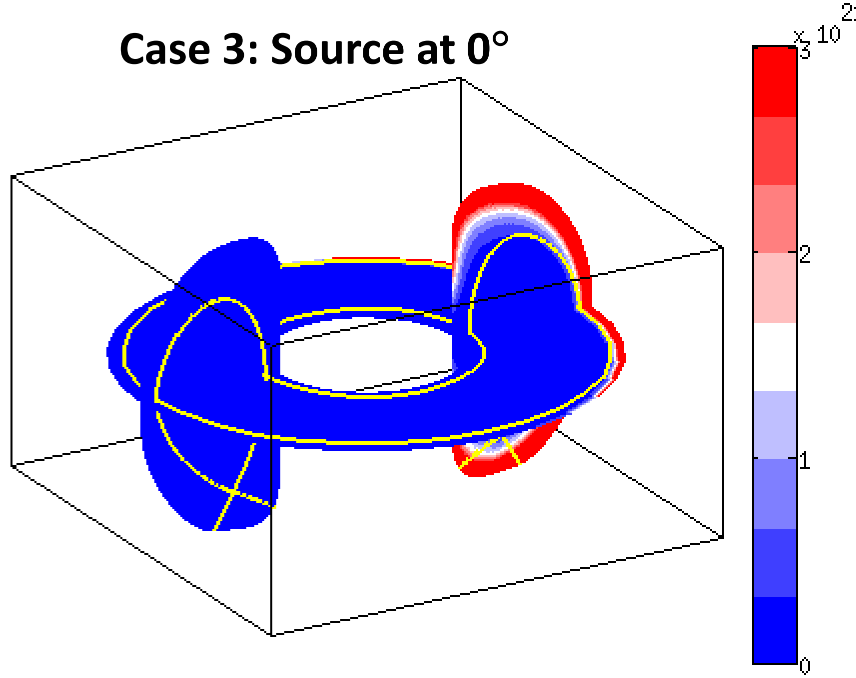
Cases 2 and 3: Toroidally peaked Ne injection on the low field side (LFS)

<u>**Contours of injected neutral Ne density**</u>

Case 2: Source at 180°



Case 3: Source at 0°



Key results:

- ***Location of radiation toroidal peak is determined by the phase of the 1/1 mode****, may not be at the MGI valve location*
- *In the <u>simulations</u>, mode phase is determined by the source location (may not hold true in experiments)*

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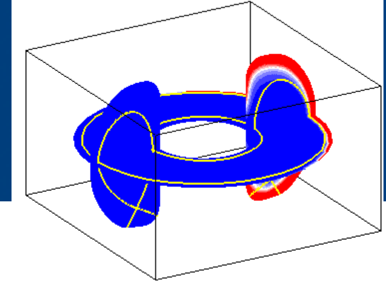
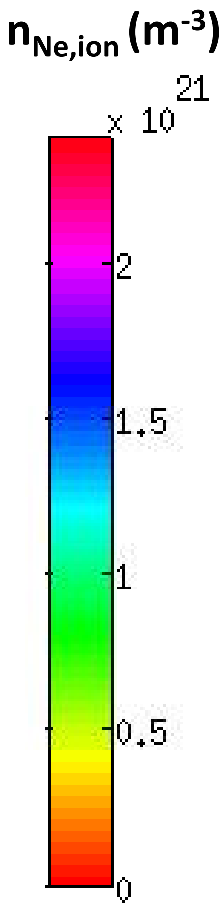
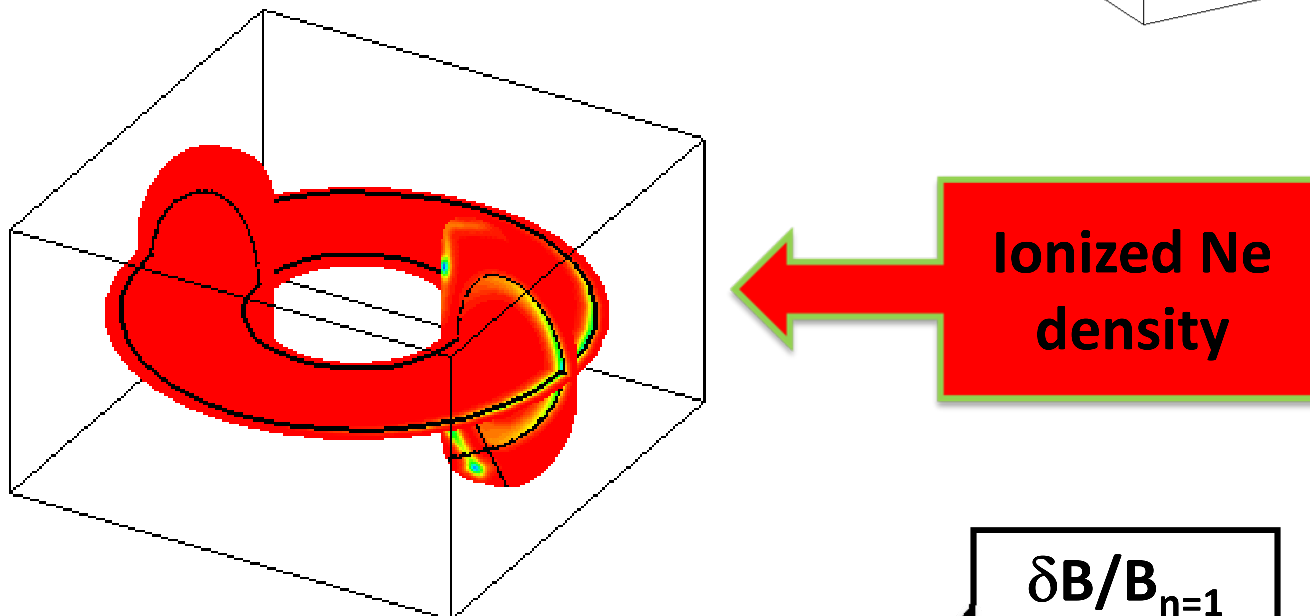
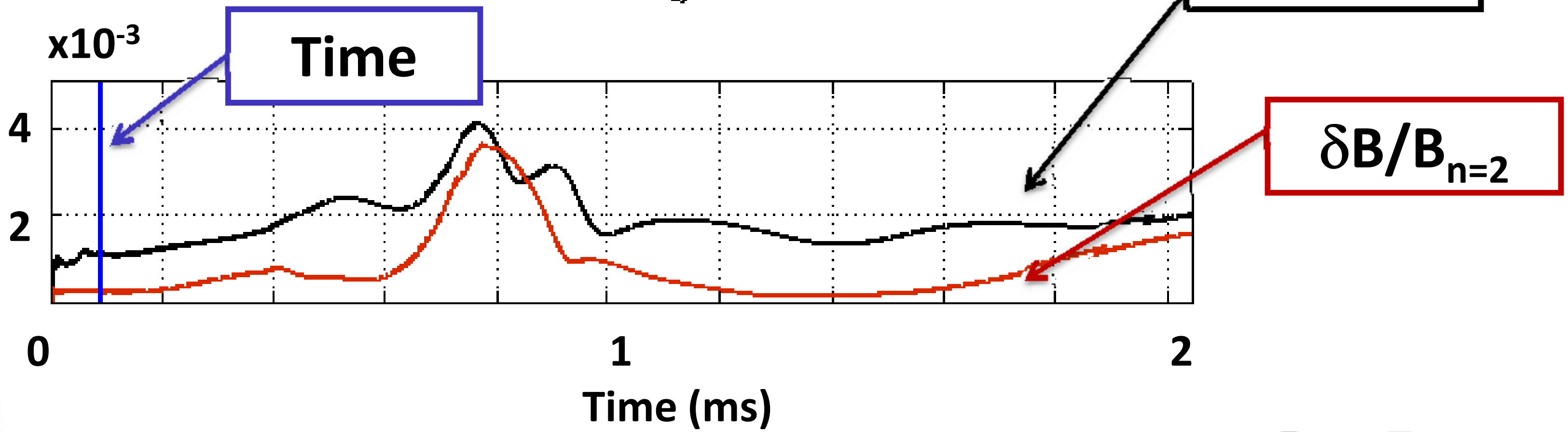
∇_ϕP drives rapid toroidal spreading, then stagnation on far side of torus









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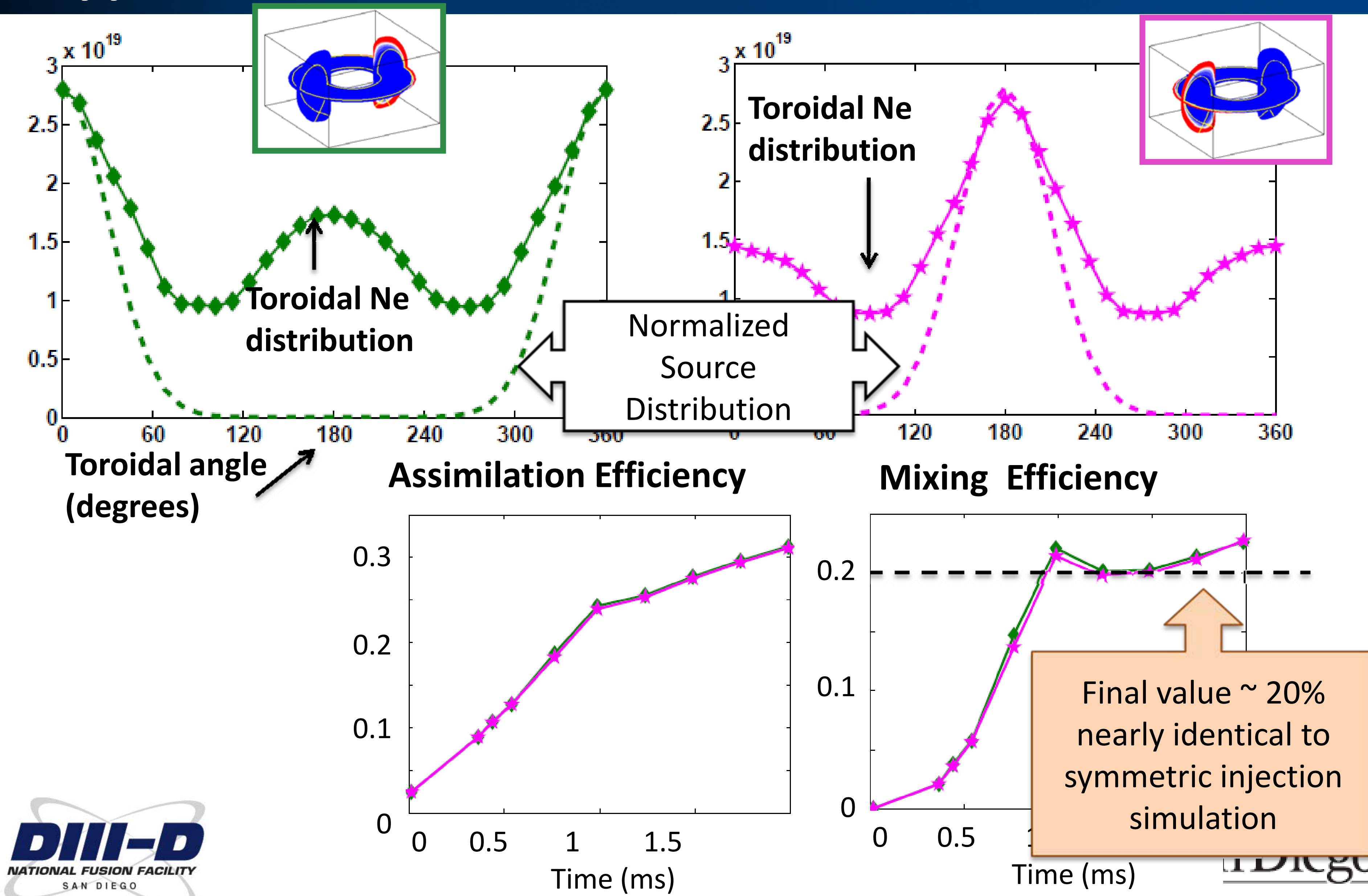
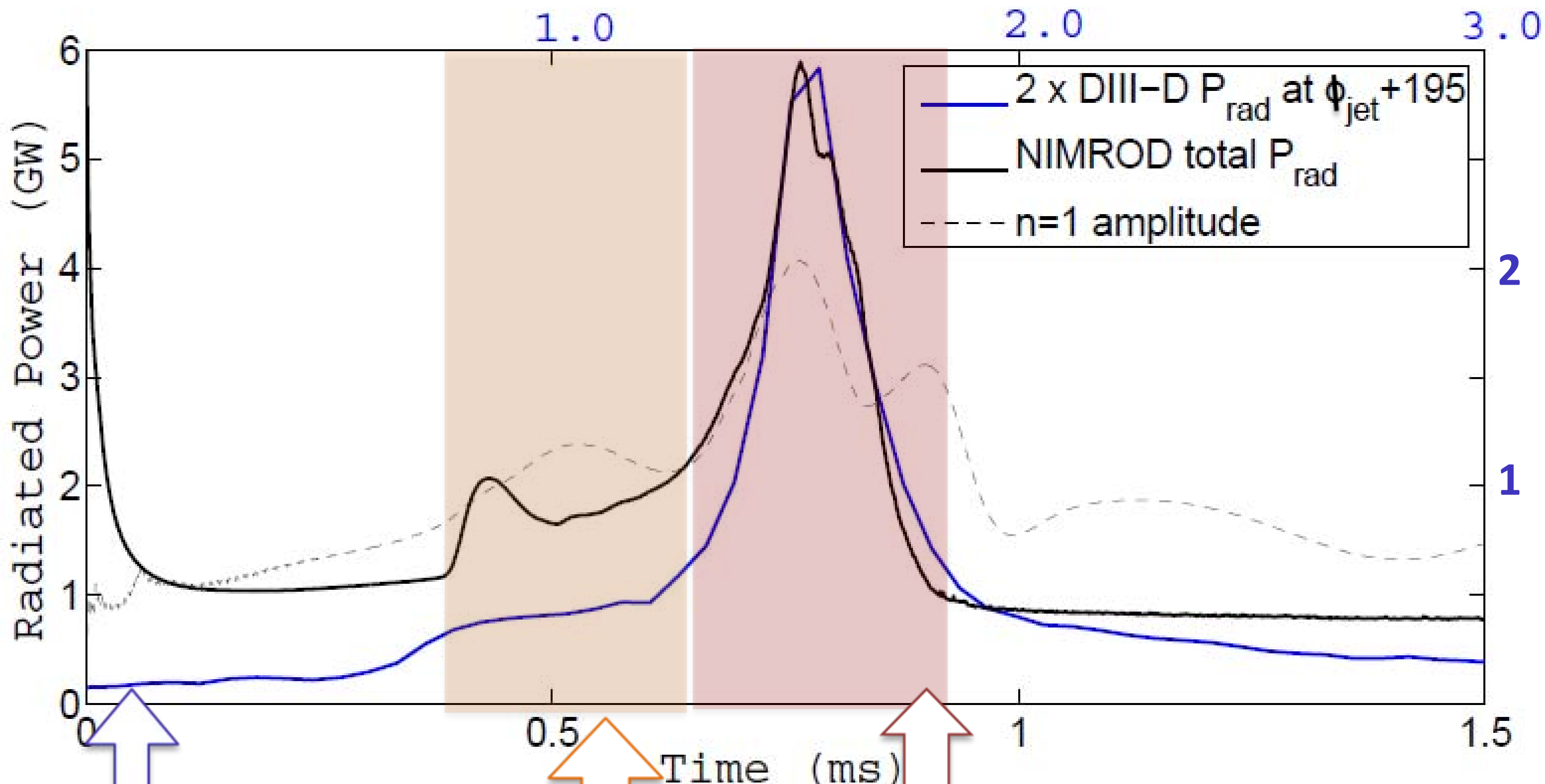
Toroidal distribution of impurities at TQ has small peak on opposite side from source



Total P_{rad} compares well with DIII-D measurements within factor of two

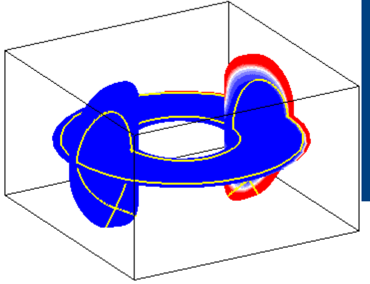


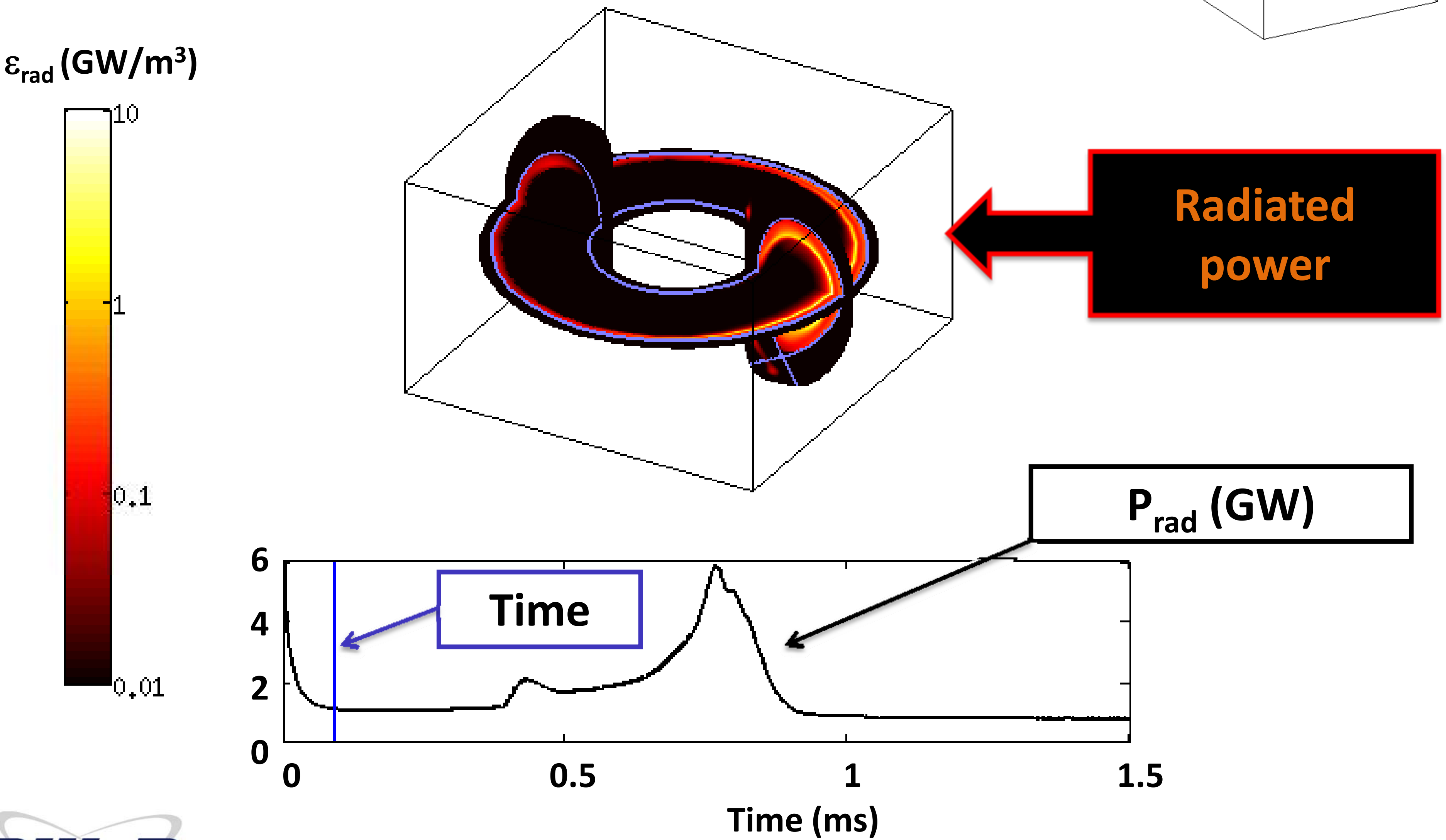
In pre-TQ, less radiation at $\Delta\phi$=195 is expected

TQ part 1: 2/1 + n>1 modes increase radial heat flux

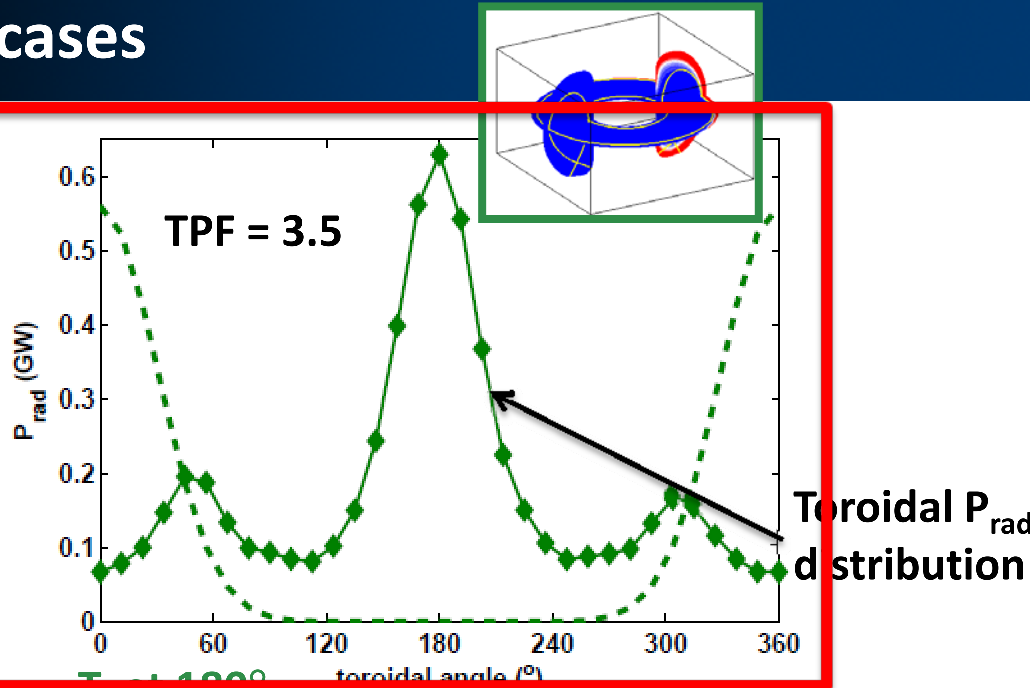
TQ part 2: 1/1 mode convection produces large P_{rad} spike

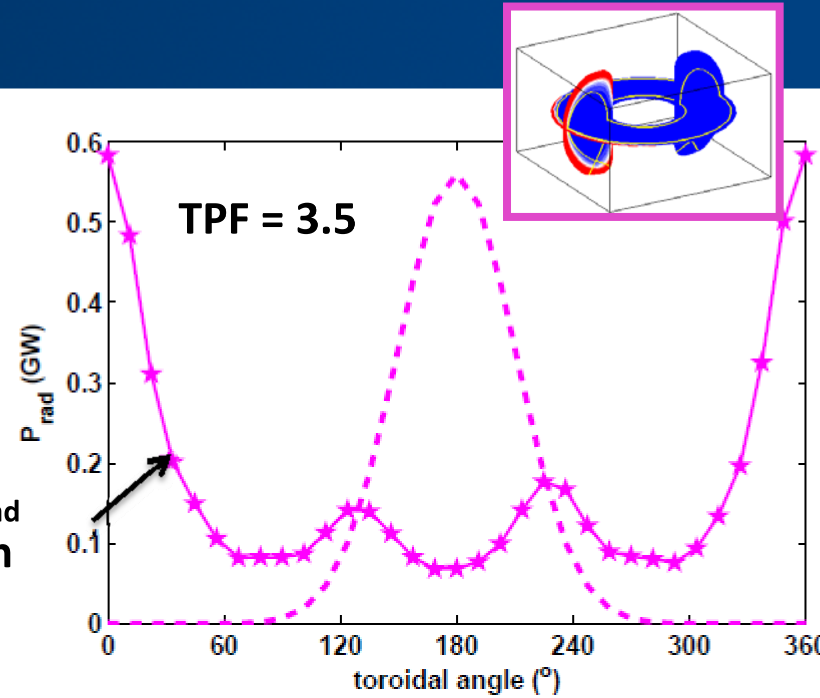
Location of radiated power peak transitions from jet side to opposite side



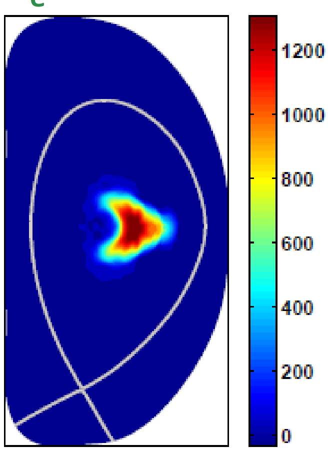


Location of toroidal peak is opposite Ne injection site in both cases

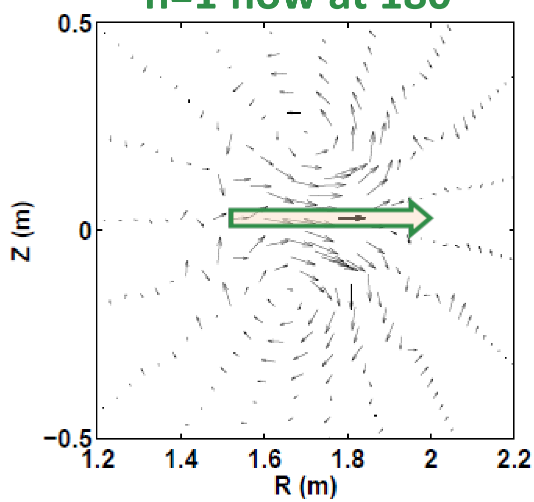




T_e at 180°



n=1 flow at 180°



- Radiation peak occurs where hot core is expelled toward LFS
- Mode phase flips when source location flips
- More toroidally peaked than symmetric injection

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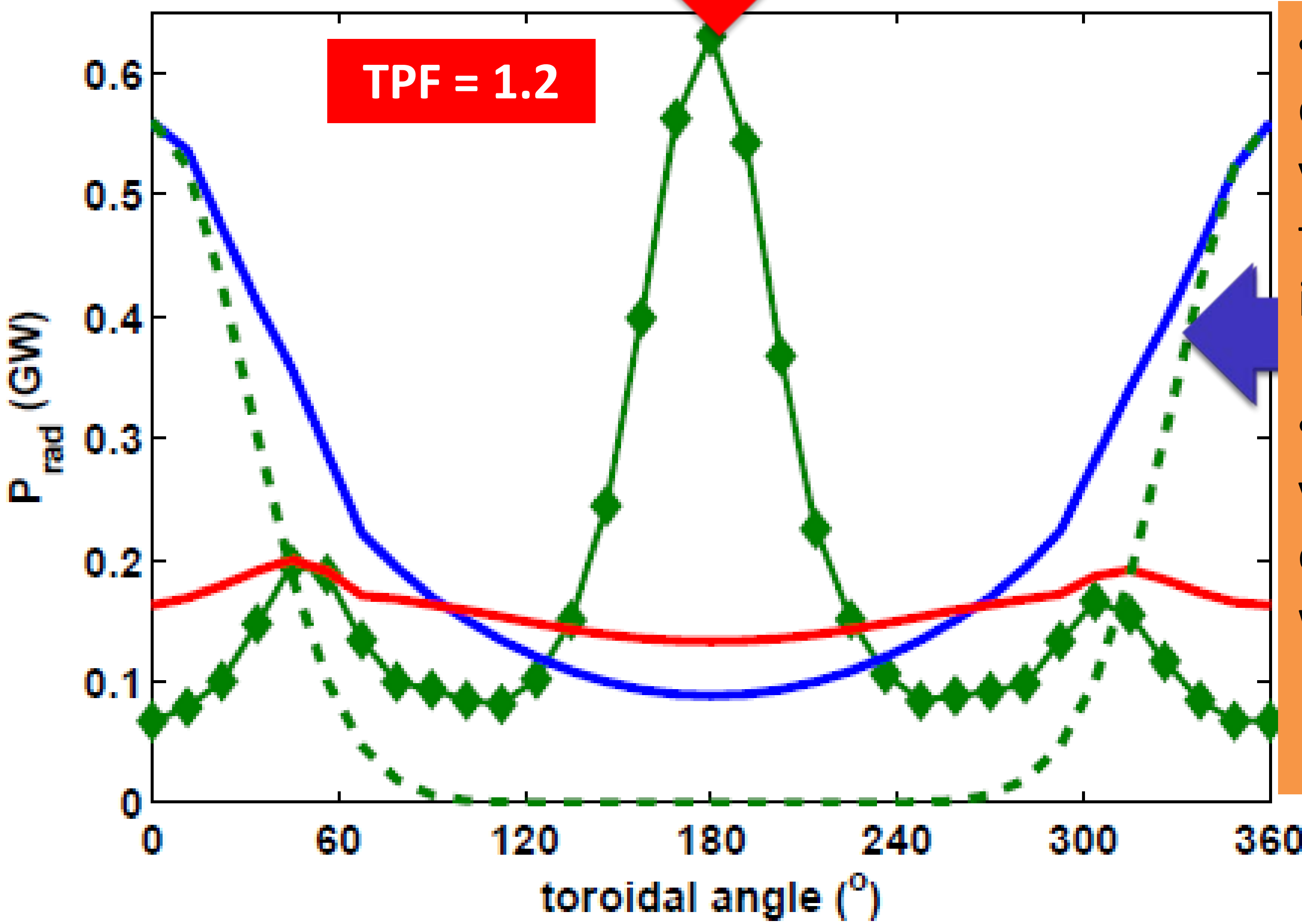
Toroidal radiation distribution roughly given by square of impurity distribution times n=1 T_e variation

$(n_{Ne})^2[1+\cos(\phi-180)]$



- Under the right conditions, 1 gas valve could be better than symmetric injection
- Adding a second valve could very easily make things worse.

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As first observed on C-Mod: Adding a second valve really can make things

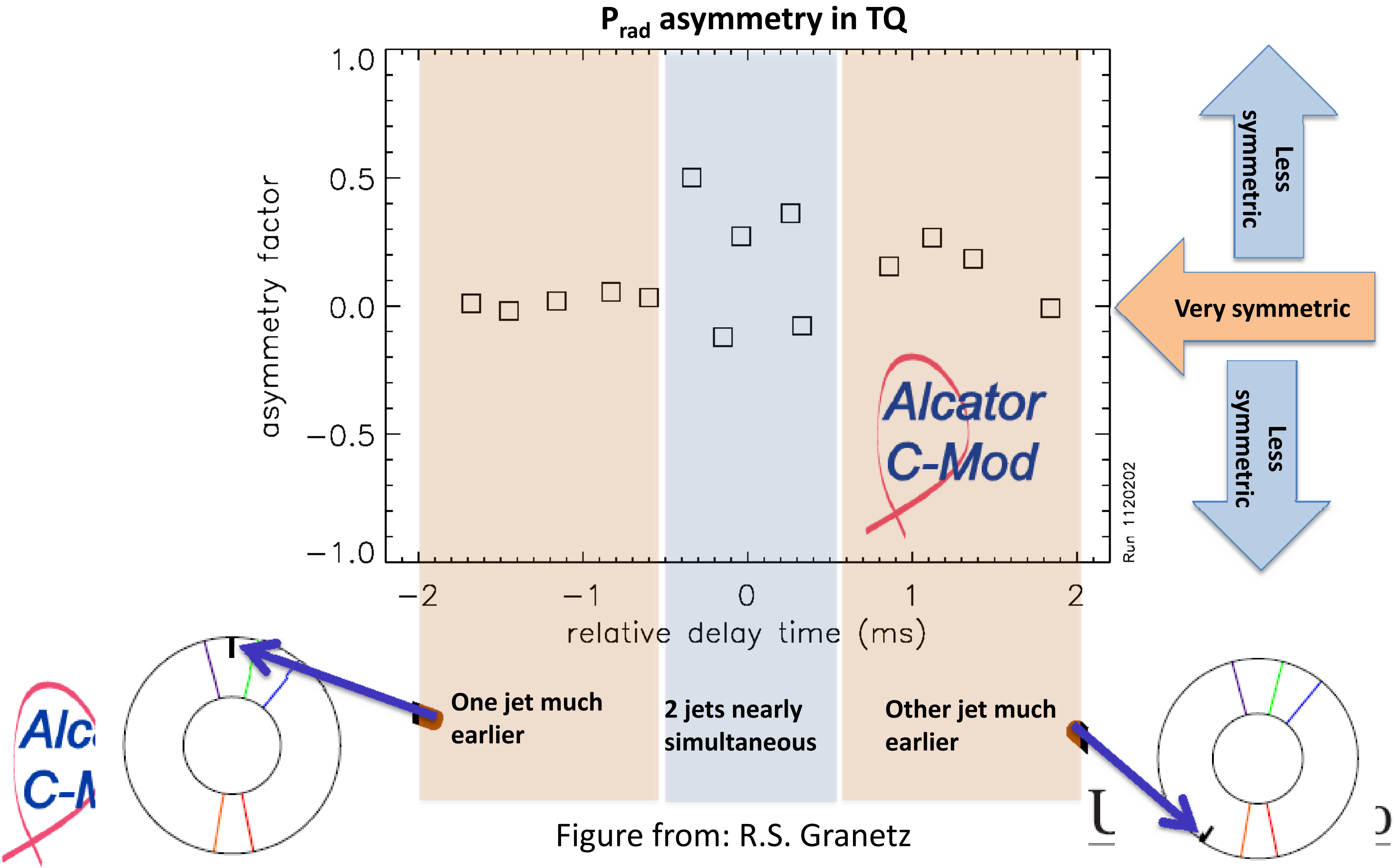
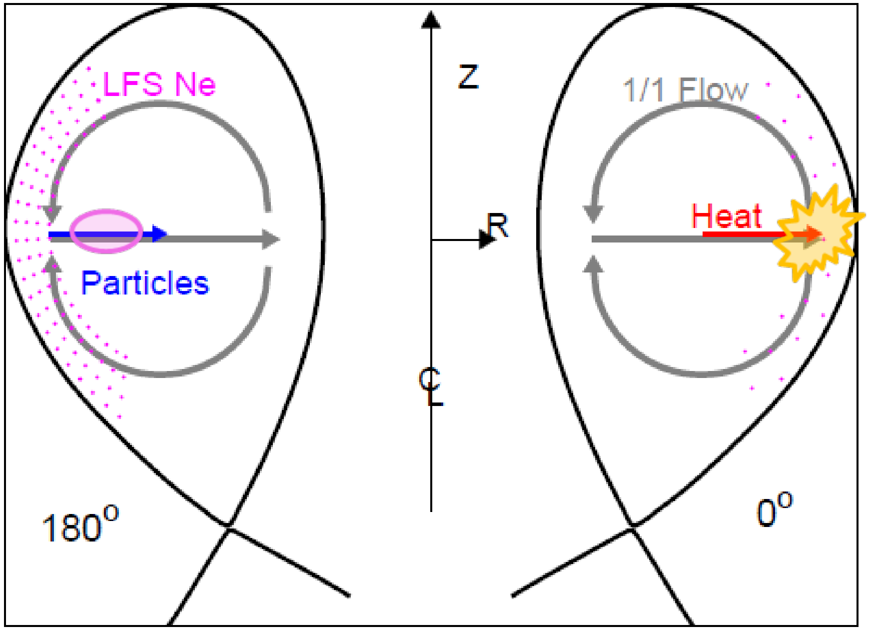


Figure from: R.S. Granetz

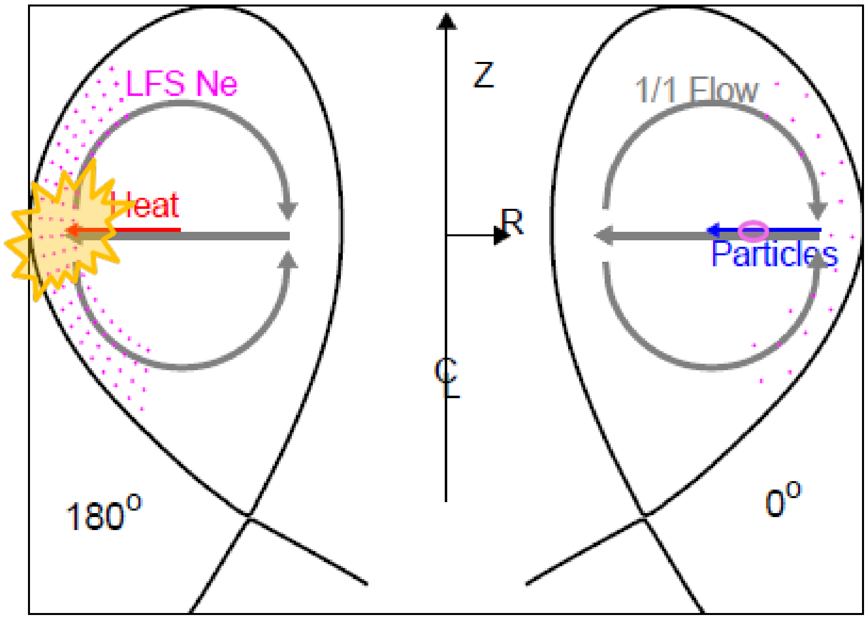
What if the mode phase changed relative to the injection location?

This is what happens in both simulations:



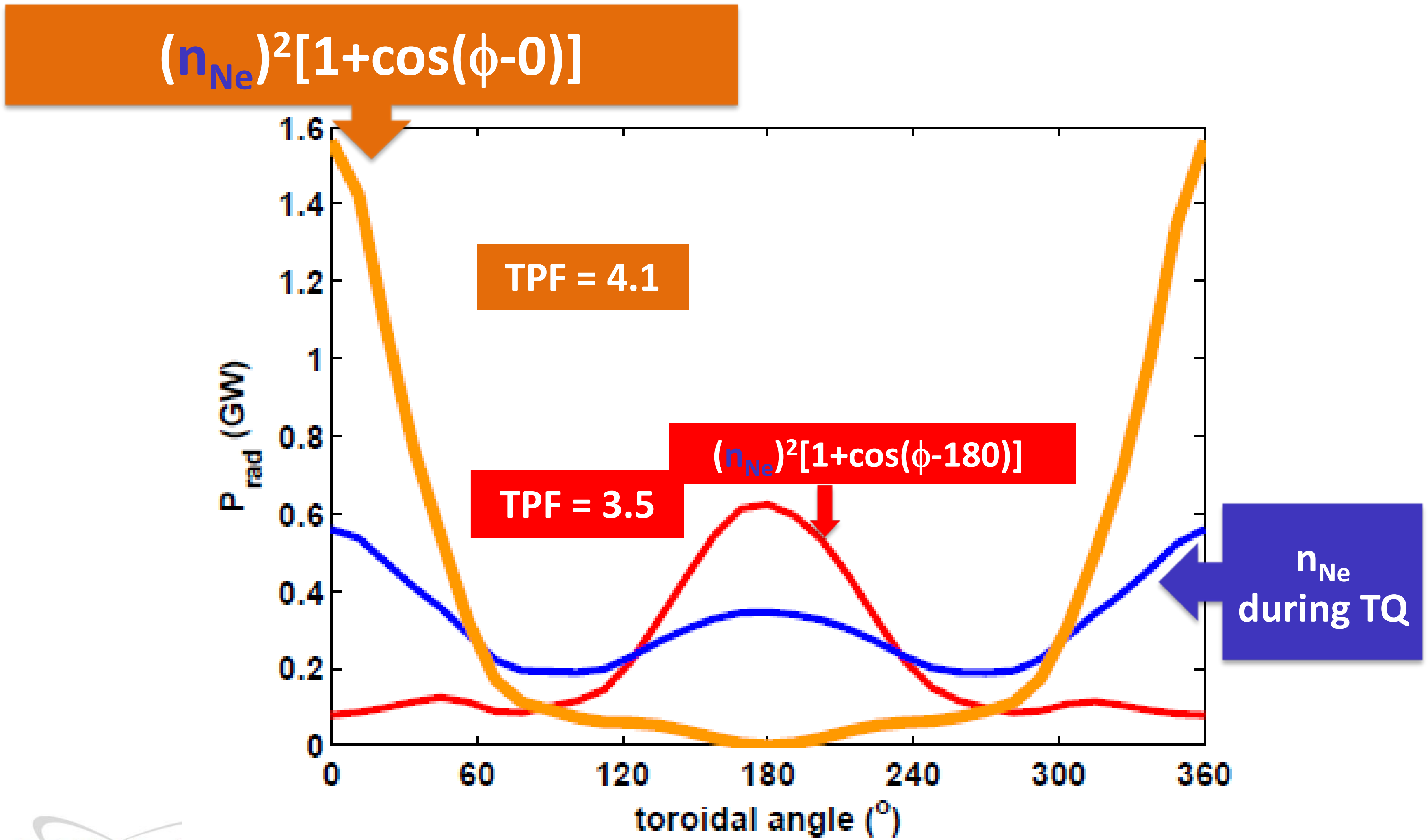
- Flow points from bigger Ne peak toward core
- Hot core hits smaller Ne density peak, TPF range from very symmetric to peaked on opposite side

But what if it were this?



- Flow points from smaller Ne peak toward core: **worse mixing efficiency?**
- Hot core hits maximum Ne density: **higher TPF, peaked at injection location?**

Flipping the mode phase could result in very strong toroidal peaking



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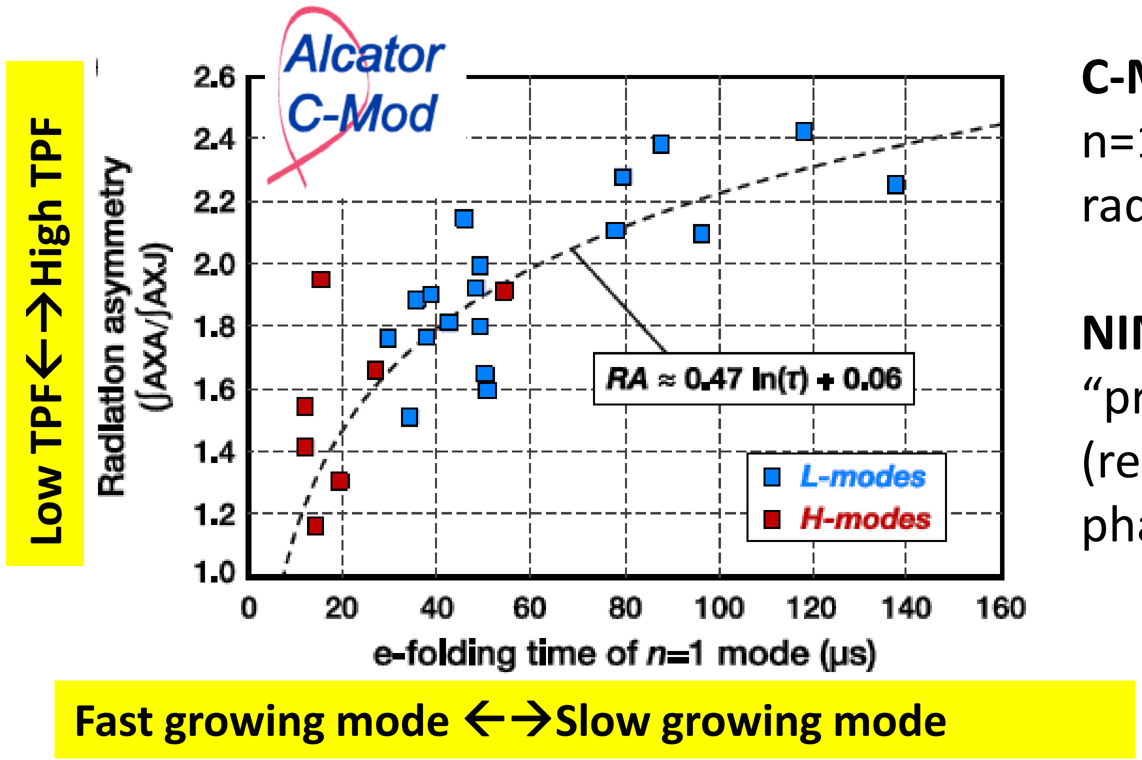
C-Mod finds connection between n=1 mode and radiation asymmetry



C-Mod finding: Faster growing n=1 mode leads to lower radiation TPF

NIMROD finding: n=1 mode "prefers" a particular phase (relative to gas jet), and that phase tends to minimize TPF

Speculation: Phase of n=1 mode varies in experiment, but when n=1 mode has the phase it "prefers" it grows faster, with the opposite phase it grows slower.

Summary of Part 1: Radiation asymmetry

- During an MGI shutdown, the 1/1 mode drives radial mixing of impurities and produces toroidally asymmetric heat flux

- Even with toroidally symmetric impurity injection, the radiated power is asymmetric

- The relationship between the 1/1 mode phase and the jet location(s) will be an important factor in determining the radiated power peaking

- **We need more data on the 1/1 mode phase in MGI experiments; is it random or affected by the gas jet? does it rotate? (how much?)**

- **Much MGI data has been collected on many devices, but very little with more than one jet. We know ITER will have more than one jet, but $1+1\neq2$ in the TQ phase. More multi-jet data is needed.**

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→ Spatial symmetry of radiated power is not just a function of the impurity distribution

Part 2: Runaway electron confinement during a mitigated TQ

→ Evidence suggest that deconfinement by MHD fluctuations will not be an effective strategy for ITER

NIMROD calculates drift orbits for RE test-particles during rapid-shutdown simulations

$$dR = \underbrace{\frac{v_\parallel B_R}{B} dt}_{\text{basic motion}} + \underbrace{\frac{1}{B^2}\left[V_R\left(B_\phi^2 + B_Z^2\right) - B_R\left(V_\phi B_\phi + V_Z B_Z\right) + \eta\left(J_\phi B_Z - J_Z B_\phi\right)\right] dt}_{\vec{E}\times\vec{B}\text{ drift}}$$

As REs become highly relativistic, curvature drift begins to affect confinement

$$dZ = \underbrace{\frac{v_\parallel B_Z}{B} dt}_{\text{basic motion}} - \underbrace{\frac{20\,kT_e}{eB}\frac{1}{R} dt}_{\text{grad-B drift}} - \underbrace{\frac{\gamma m v_\parallel^2}{eB}\frac{1}{R} dt}_{\text{curvature drift}} + \underbrace{\frac{1}{B^2}\left[V_Z\left(B_R^2 + B_\phi^2\right) - B_Z\left(V_R B_R + V_\phi B_\phi\right) + \eta\left(J_R B_\phi - J_\phi B_R\right)\right] dt}_{\vec{E}\times\vec{B}\text{ drift}}$$

$$d\phi = \underbrace{\frac{v_\parallel B_\phi}{RB} dt}_{\text{basic motion}} + \underbrace{\frac{1}{RB^2}\left[V_\phi\left(B_R^2 + B_Z^2\right) - B_\phi\left(V_R B_R + V_Z B_Z\right) + \eta\left(J_Z B_R - J_R B_Z\right)\right] dt}_{\vec{E}\times\vec{B}\text{ drift}}$$

$$dv_\parallel = \underbrace{\frac{e\eta J_\parallel}{m_e\gamma^3} dt}_{\text{electric field}} - \underbrace{\frac{e^4 \ln\Lambda}{4\pi\epsilon_0^2 m_e^2} n_e\left(Z_{\text{eff}} + 1 + \gamma\right)\frac{1}{v_\parallel^2}\frac{1}{\gamma^4} dt}_{\text{collisional slowing}} - \underbrace{\frac{e^2}{6\pi\epsilon_0 m_e c^3} v_\parallel^3 \gamma\left(\frac{1}{R_0^2} + \frac{19.4\,e^2 B^2 v_{te}^2}{m_e^2 v_\parallel^4}\right) dt}_{\text{synchrotron}} - \underbrace{n_e \frac{e^4\left(Z_{\text{eff}} + 1\right)}{548\,\pi^2\epsilon_0^2 m_e^2 c^2}\frac{1}{\gamma^2}\left(\ln\left(2\gamma\right) - \frac{1}{3}\right) dt}_{\text{bremsstrahlung}}$$

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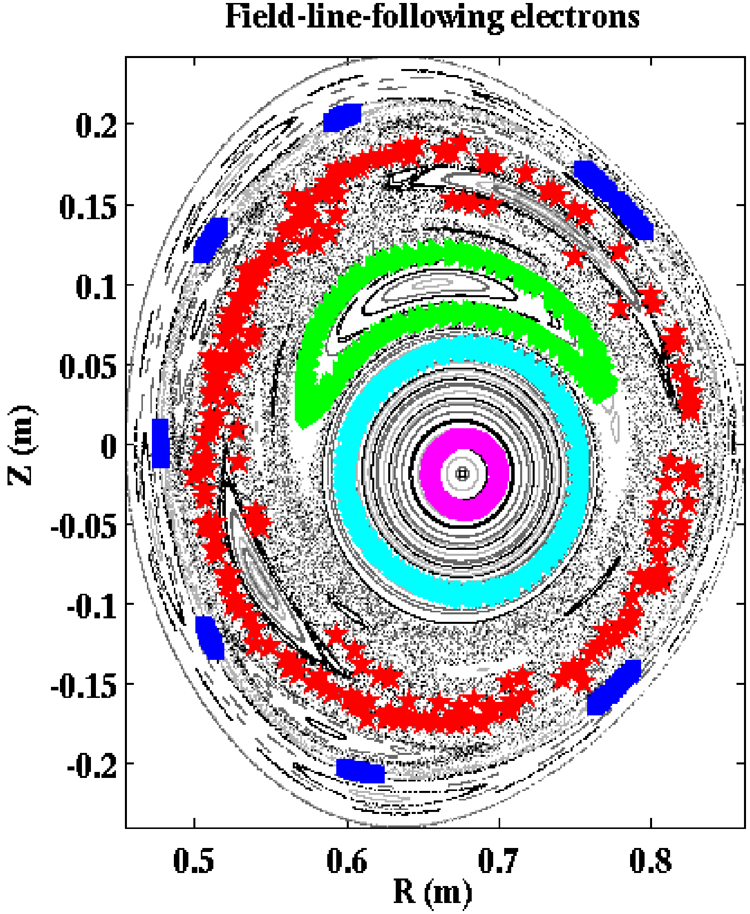
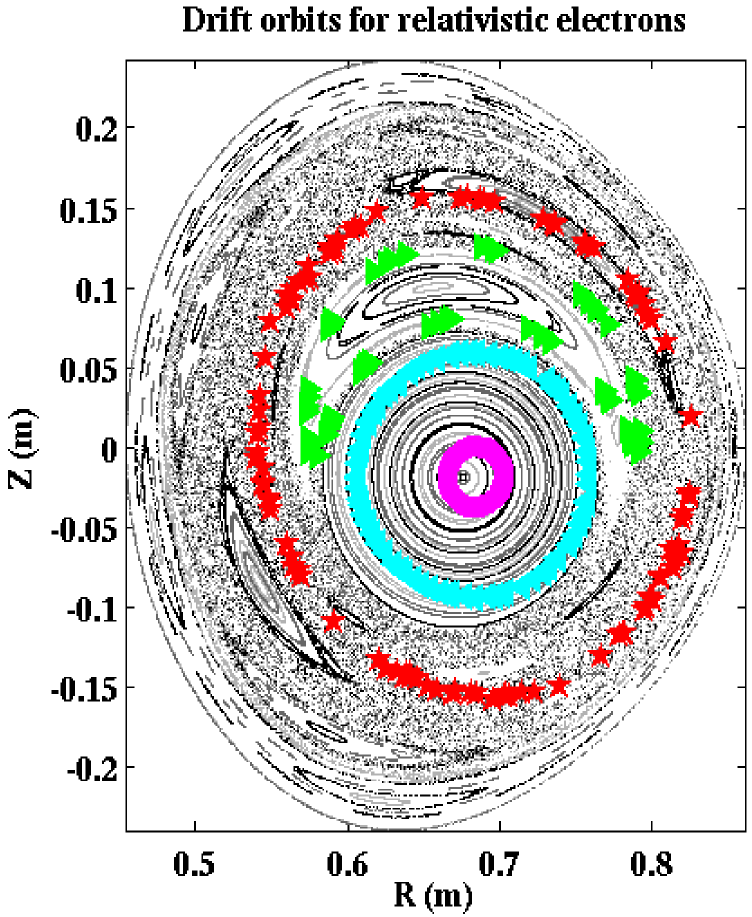
Example of 10 MeV orbits in C-Mod





At γ=20 (about 10 MeV), electron drift displacement is ~ few cm. Displacements > perturbation width can average, appearing well confined, as "red" electron

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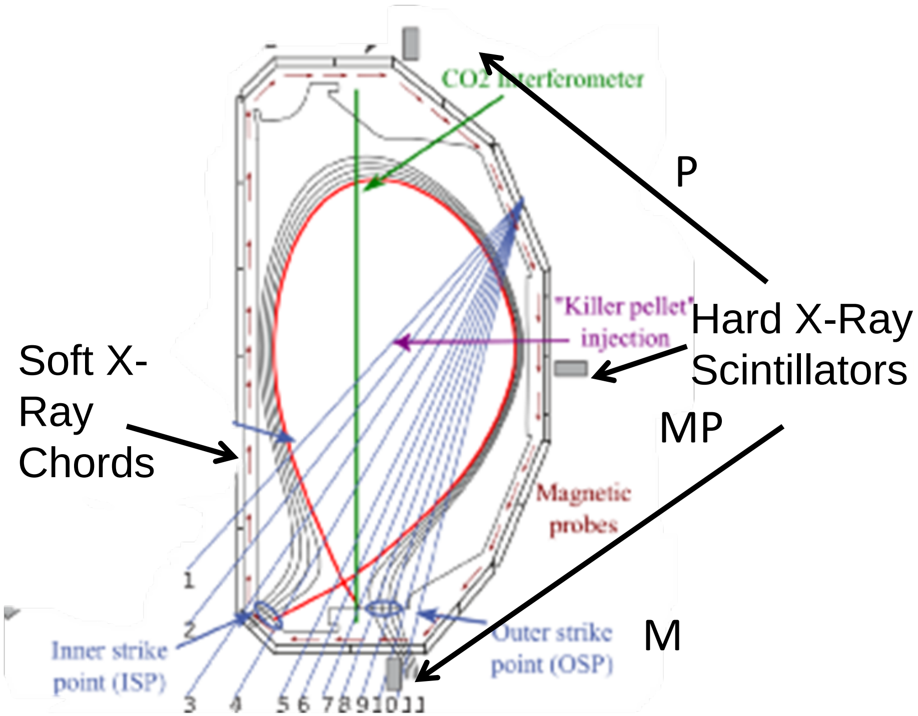
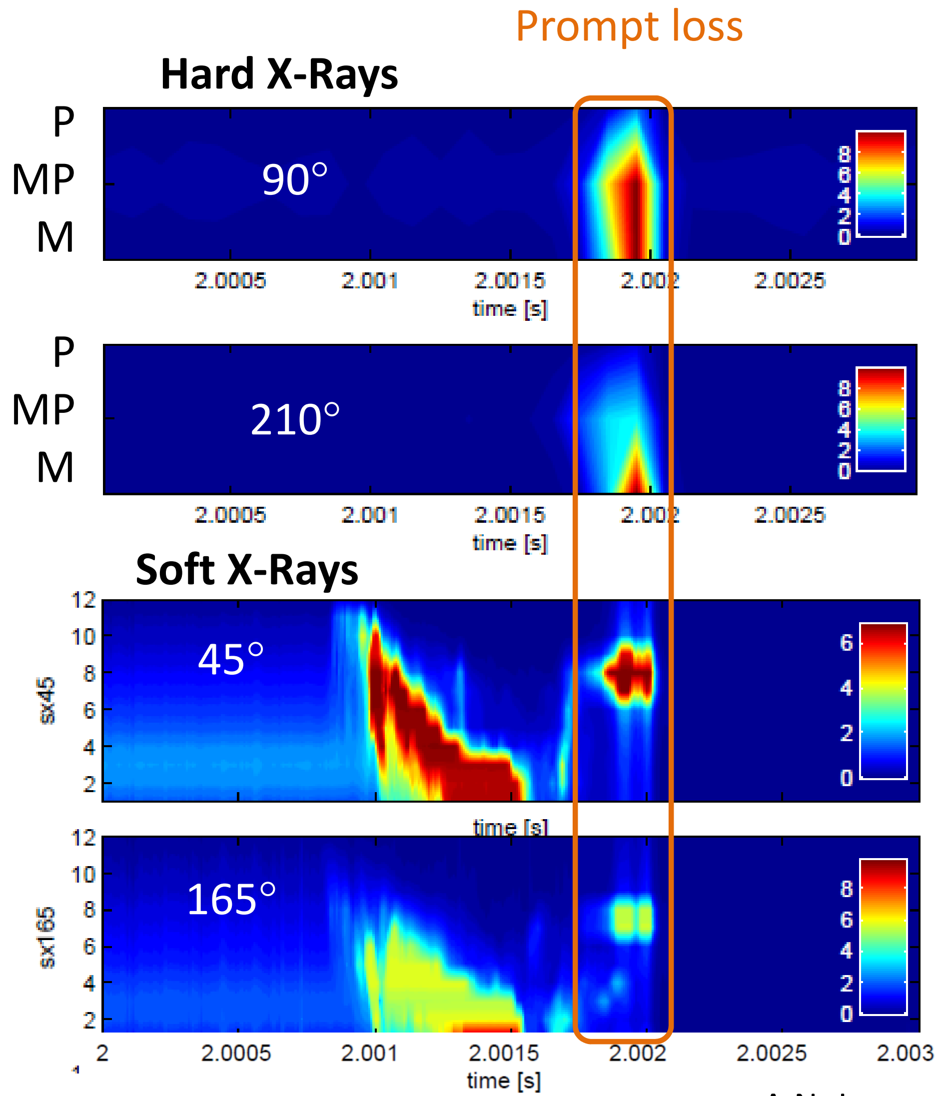
"Prompt-loss" of REs during TQ is major suspect for shot-to-shot non-reliability of RE plateau production

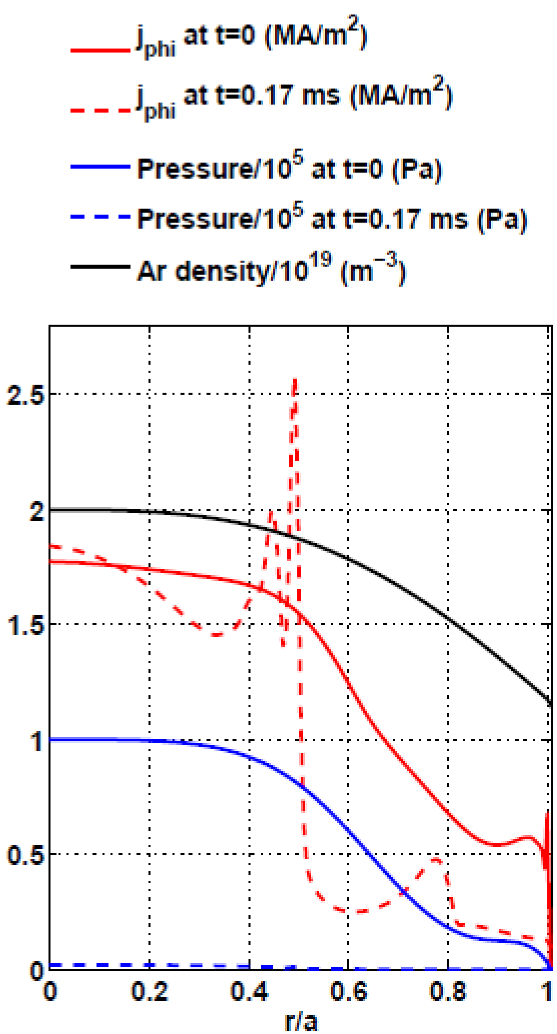


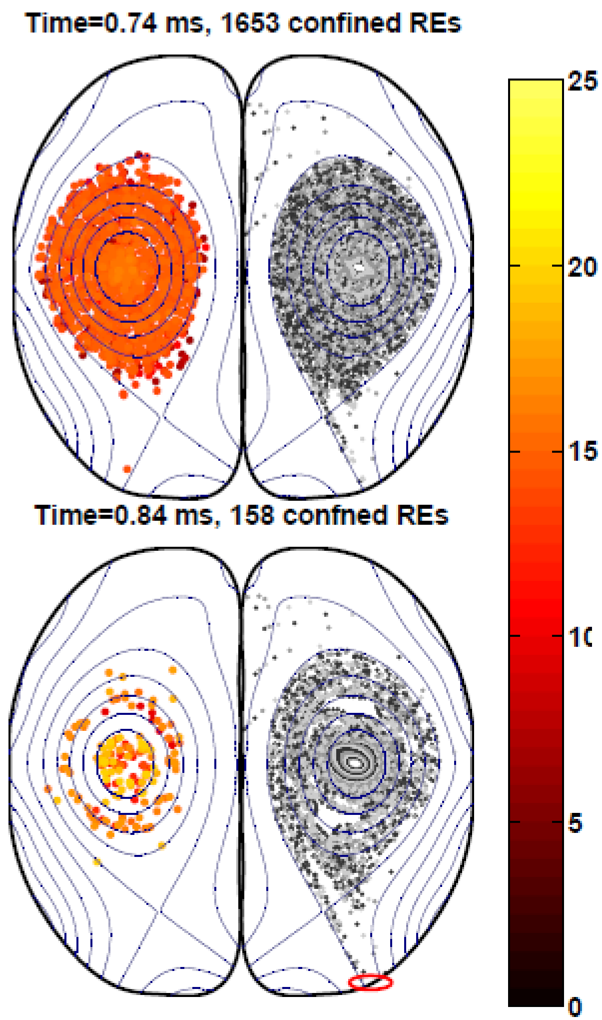


- Hard X-Ray scintillators indicate prompt loss of REs just before 2002 ms.
- Soft X-Ray measurements with better poloidal resolution indicate prompt loss location is outer divertor strike point.

A.N. James

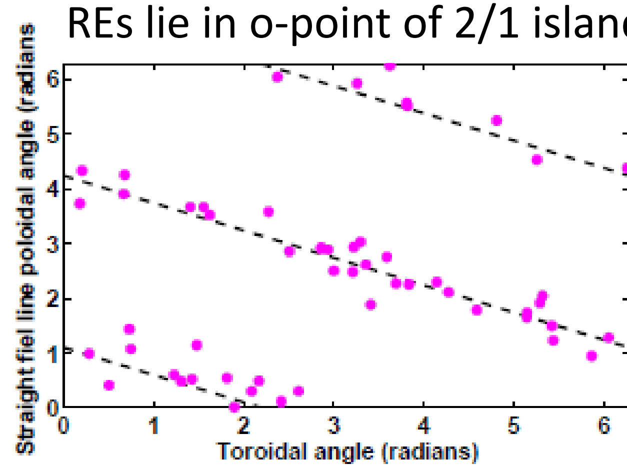
NIMROD modeling of Ar pellet shots shows prompt loss of REs during TQ





Most of the initial RE test-population is lost during a brief interval, excluding those in regions where good flux surfaces or large islands remain

REs lie in o-point of 2/1 island



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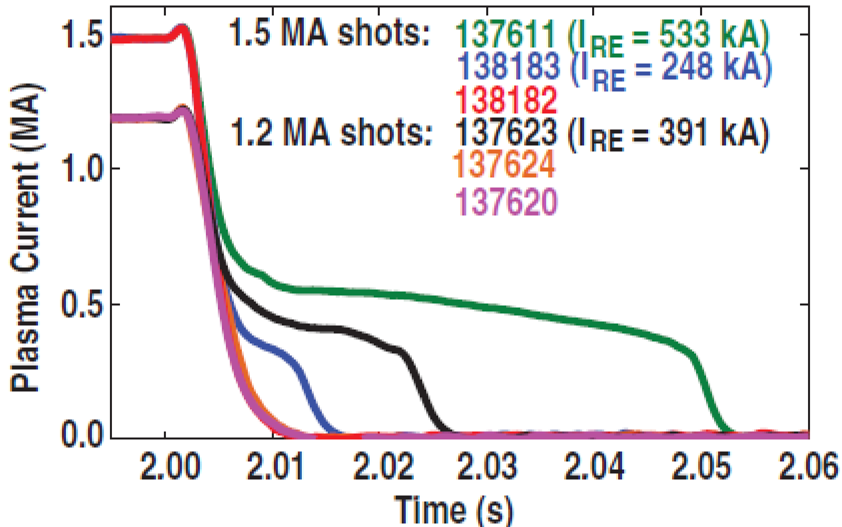
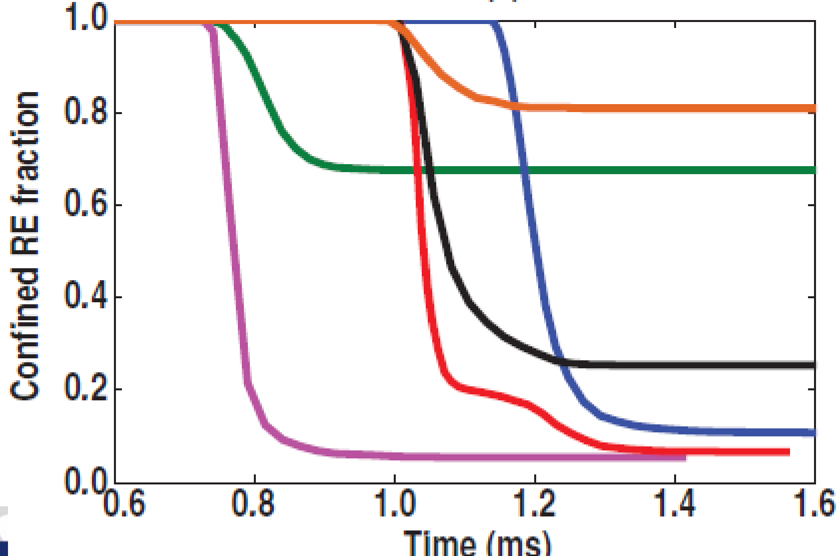
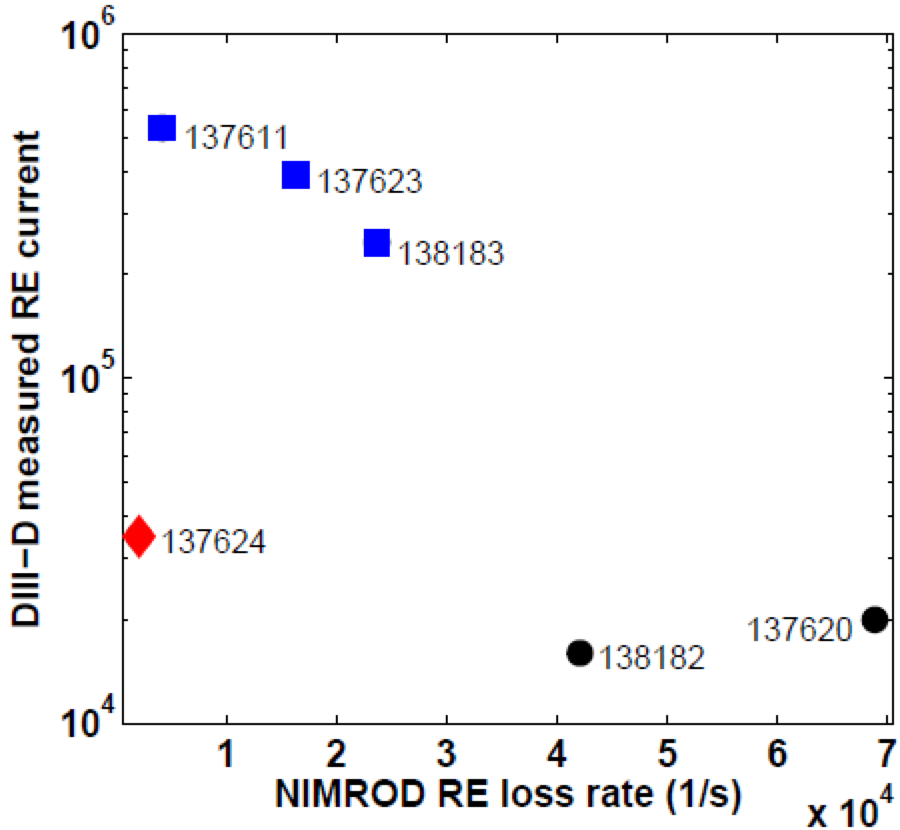
NIMROD predictions of prompt-loss variation correlate with DIII-D observation of RE plateau currents







With the exception of 137624, NIMROD find larger prompt-loss for shots with lower RE current

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DIII-D may occupy a special regime of marginal RE confinement → cause of non-reproducibility

- In DIII-D, time between destruction and re-healing of flux surfaces (τ_{MHD}) is ~ few tenths of a ms
- Typical confinement time for REs when fields become stochastic (τ_{RE}) is also ~ few tenths of a ms
- These times do not necessarily scale together (simulations suggest $\tau_{RE} \propto R^3$, whereas $\tau_{MHD} \propto R$).

Can we count on significant fluctuation induced losses in ITER?

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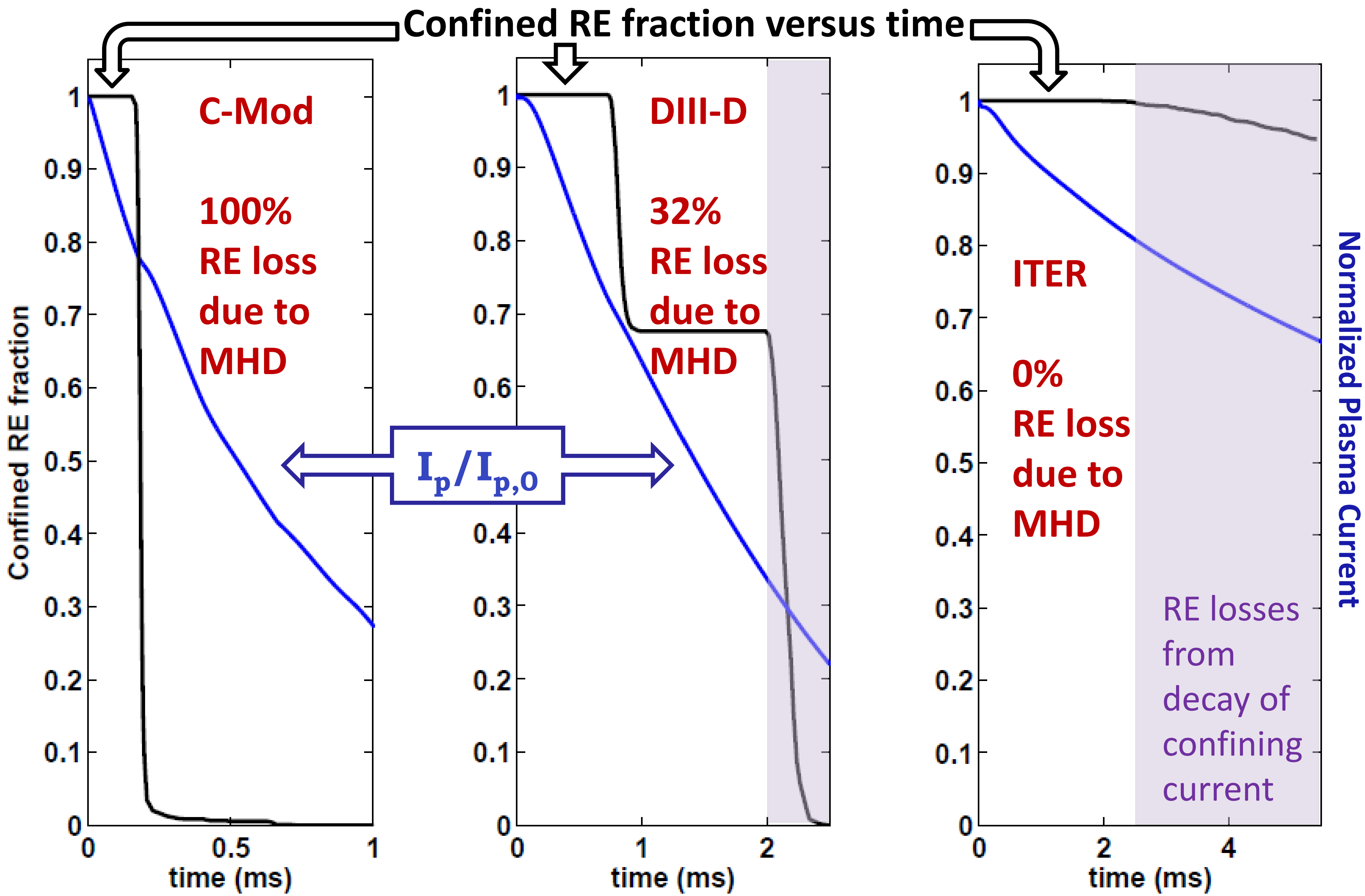
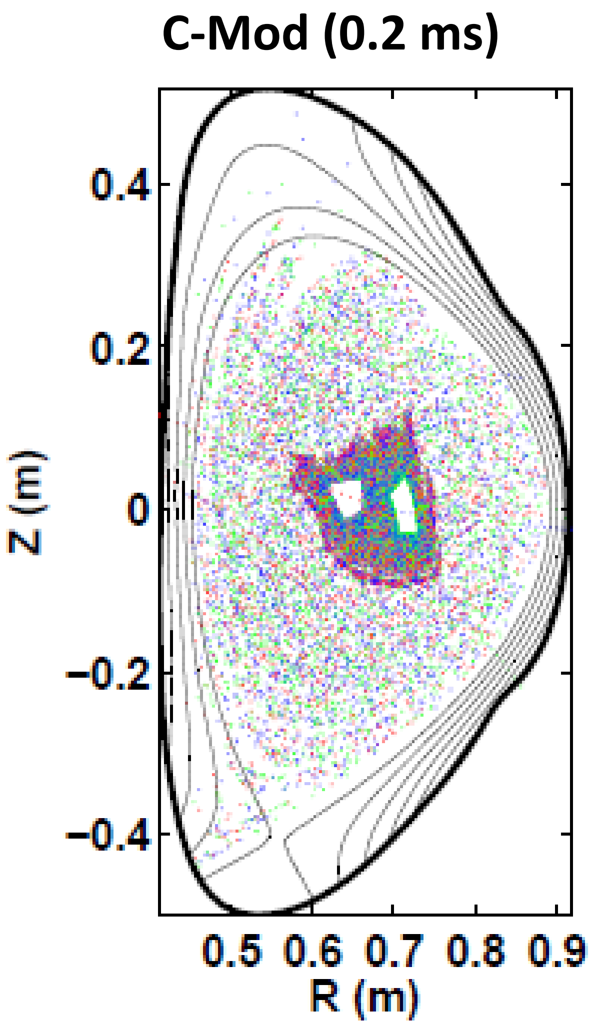
It's probably not a good bet



At time of maximum MHD fluctuations, stochasticity does not extend to the edge in ITER



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ego

Summary of Part 2. Runaway electron confinement

- Runaway electron orbit calculations during for pellet and gas injection simulations reproduce prompt-loss seen during TQ

- NIMROD predicts shot-to-shot variation in prompt-loss that is (in most cases) consistent with shot-to-shot RE current variation in DIII-D

- Simulations show better RE confinement in larger devices (for diverted plasmas)

- **There is no good reason to believe that MHD deconfinement will be an effective strategy for RE mitigation in ITER**

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Conclusions

Part 1. Radiative heat loads during a mitigated TQ: Toroidal (and poloidal) radiation peaking

→ **Spatial symmetry of radiated power is not just a function of the impurity distribution.** MHD (especially n=1) plays an important role. More data with multiple jets (and better asymmetry measurements) are needed.

Part 2. Runaway electron confinement during a mitigated TQ

→ **Evidence suggests that deconfinement by MHD fluctuations will not be an effective strategy for ITER.** (Of course applied perturbations at *some* level of external current could work). Other possibilities include collisional suppression (if compatible with CQ requirements), or control and dissipation of existing RE beam.

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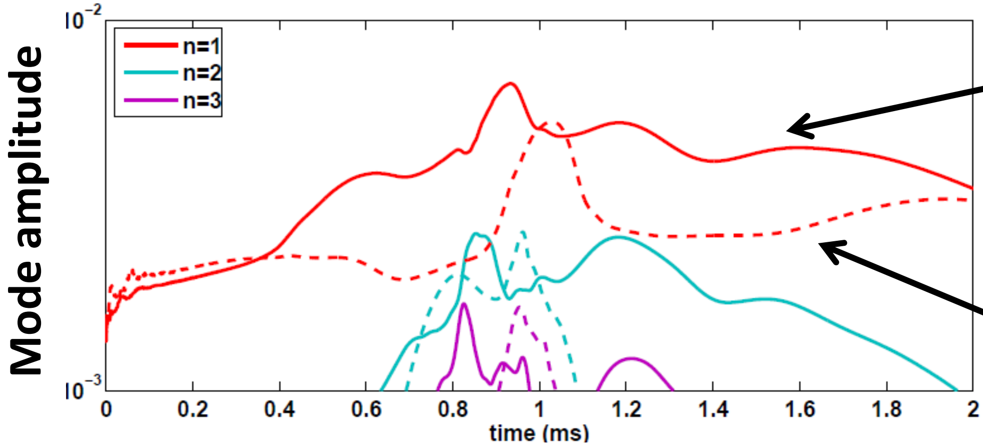
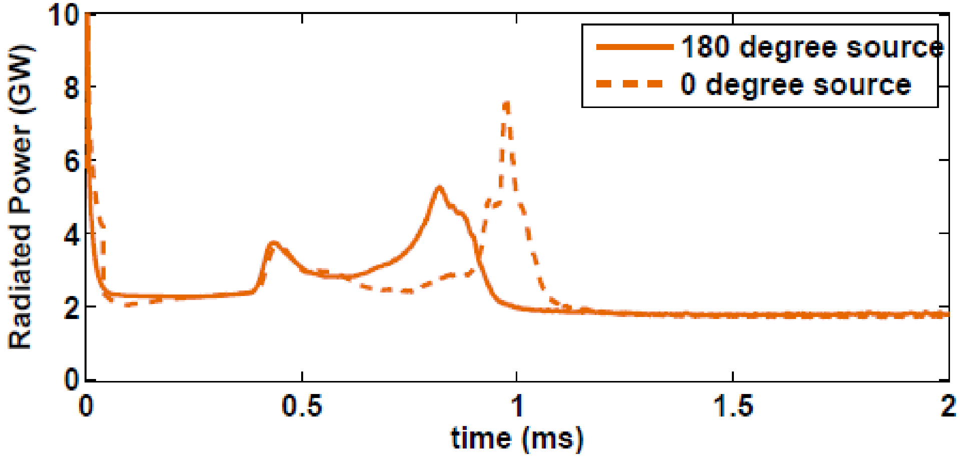
EXTRA SLIDES

Mode phase appears fairly stubborn in the simulations, but applied fields do affect growth rate

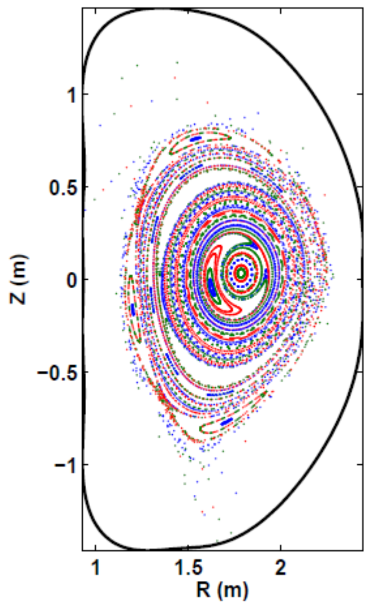


Applied fields aligned with preferred phase

Applied field anti-aligned with preferred phase



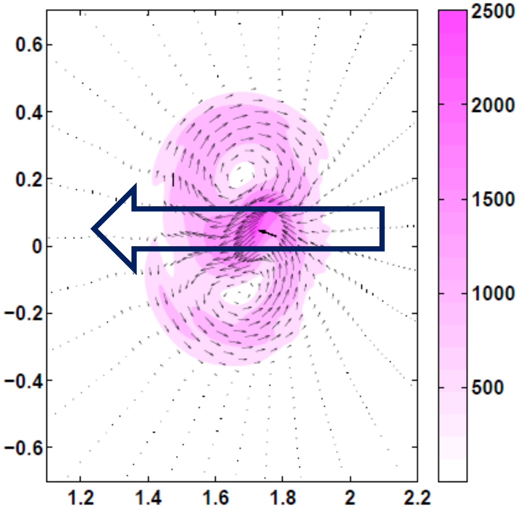
Applied n=1 vacuum fields



External n=1 perturbations have the same phase in two simulations while the location of the source is moved 180°. Mode amplitude and time of saturation is affected, but …

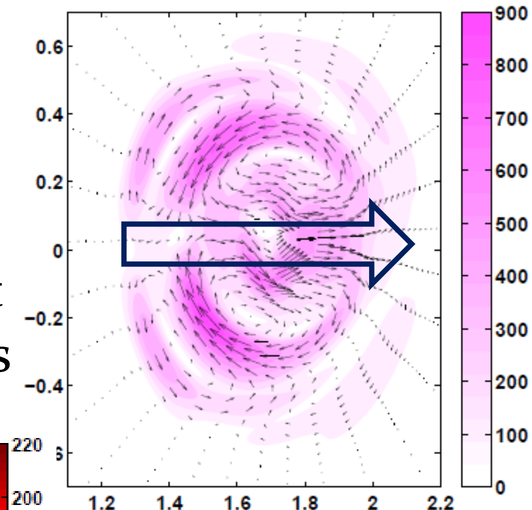
Phase of unstable 1/1 mode is not ultimately affected by applied fields

n=1 poloidal flow at ϕ=0° at 1.0 ms

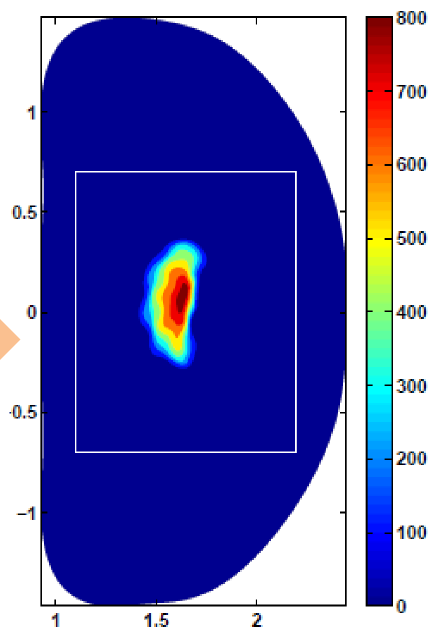


Applied fields have same phase in each case. Saturate mode phase is opposite due to opposite MGI source location. As always heat flux is away from the source.

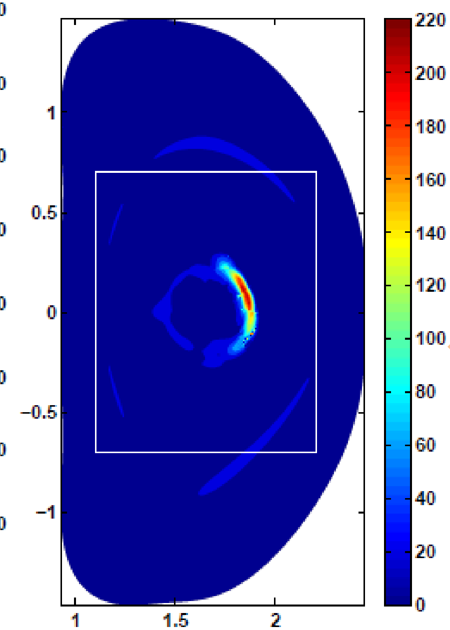
n=1 poloidal flow at ϕ=0° at 0.95 ms



Temperature at ϕ=0° at 1.0 ms



Temperature at ϕ=0° at 0.95 ms



Source at 0°

Source at 180°

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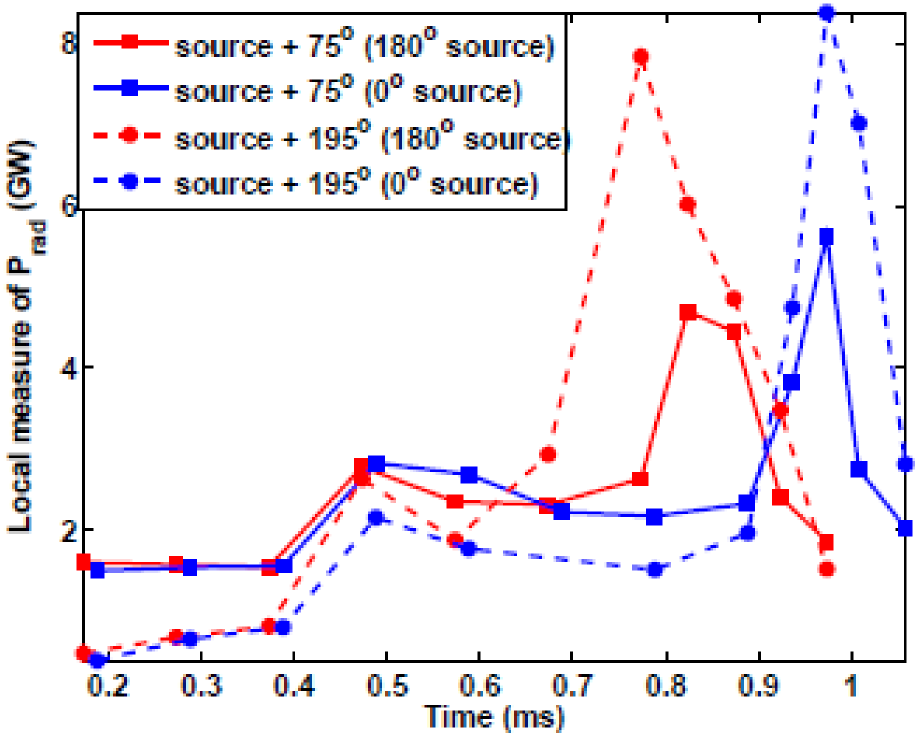
Upcoming DIII-D experiment (Next week). Hope to lock mode to n=1 I-coil fields

- Experiment will apply n=1 fields with I-coils prior to MGI. Phase of applied fields will be varied from shot-to-shot

- If we really can force the mode to take a particular phase (despite simulations results), significant variations in locally measure radiated power may be observed.

- Even if mode phase does not change, simulations suggest some effect should be observed.

Very crude synthetic diagnostic



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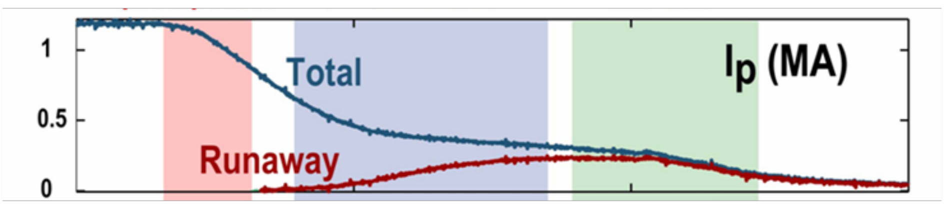
DIII-D produces post-CQ RE current plateaus with moderate reliability

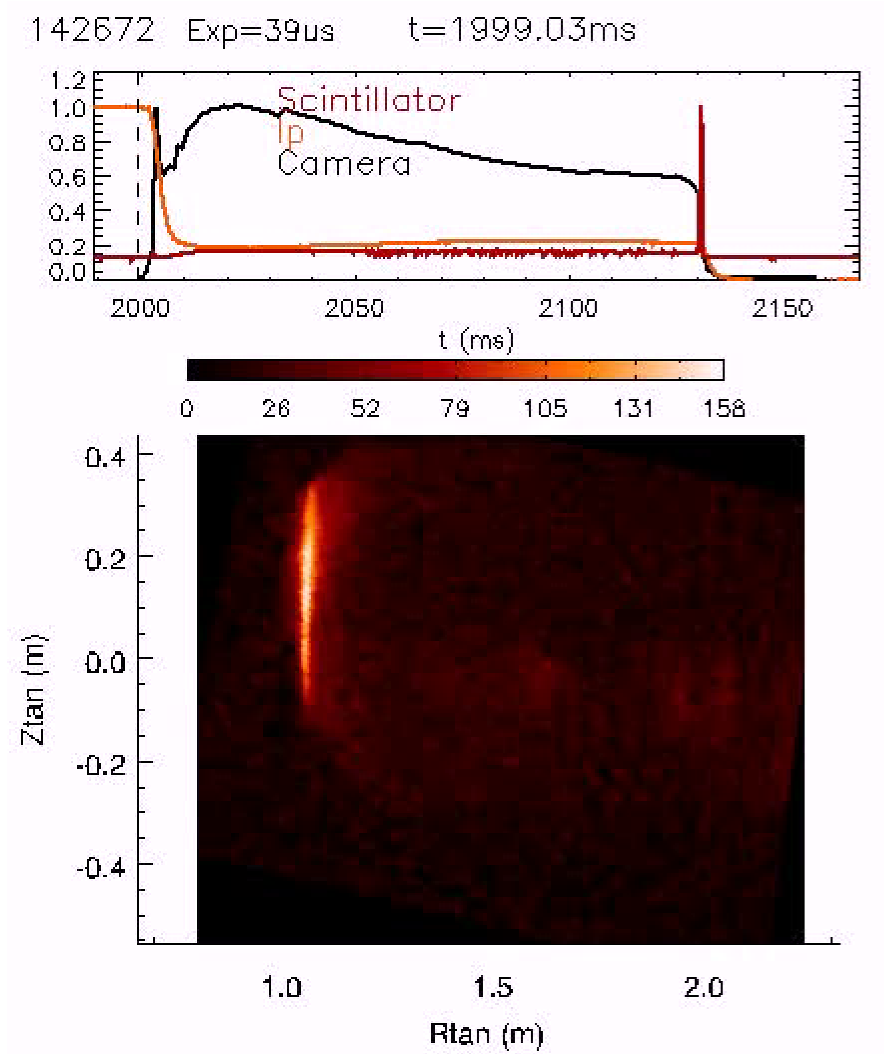
Rapid shutdown by Ar pellet effective at producing REs in DIII-D

High Z material (Ar) in core → RE seed

RE plateaus of up to 500 kA observed



RE plateaus reliably produced for limited plasma shapes– lower reliability for diverted plasma shapes



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