3D Aspects of Massive Gas Injection

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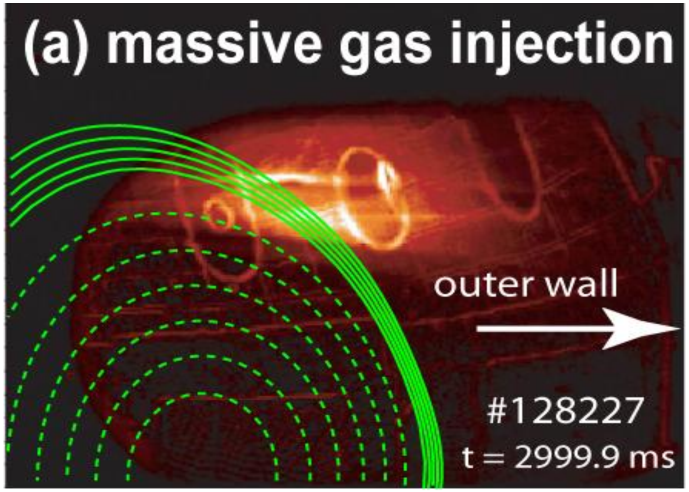
Motivation

Goal of massive gas injection (MGI) shutdown is to *isotropically* radiate plasma thermal energy

Radiated power during MGI can be spatially localized, potentially causing localized wall melting



→Localization of radiated power during the thermal quench is not just a consequence of having a limited number of MGI valves; other 3D physics processes are important

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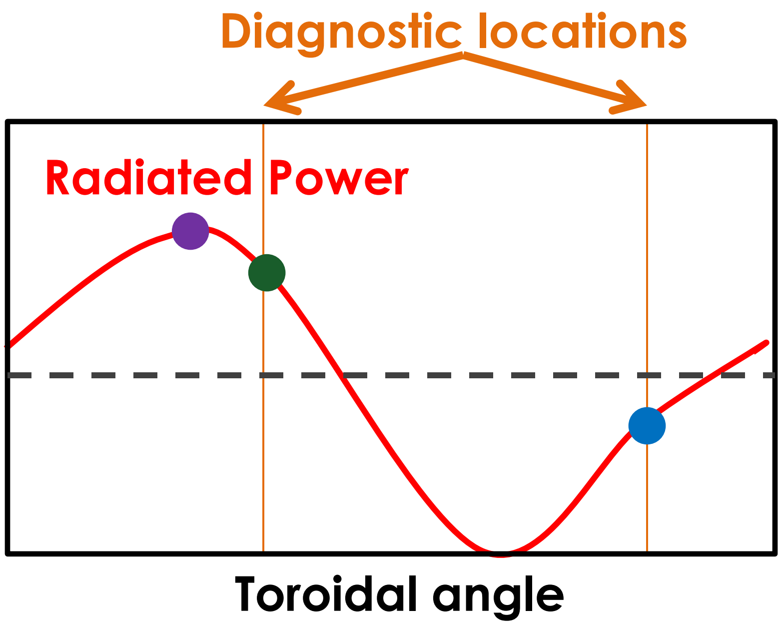
Definition of Toroidal Peaking Factor (TPF)

Given full toroidal information:

TPF = Max(Prad)/Mean(Prad)



Given limited diagnostics:

ΔP/ΣP = (Prad1-Prad2)/(Prad1+Prad2)

TPF = 1 + |ΔP/ΣP| = Max(Prad1,Prad2)/Mean(Prad1,Prad2)

Often integrate Prad over some phase of the disruption (say pre-TQ) and substitute Wrad for Prad in any of these equations

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Outline

I. Spatial localization of radiated power during MGI is determined by a variety of 3D physics processes:

A. Asymmetric spreading of impurity plume

B. Asymmetric heat flux/impurity mixing due to 1/1 mode
- Phase of the 1/1 mode matters
- What determines the phase?

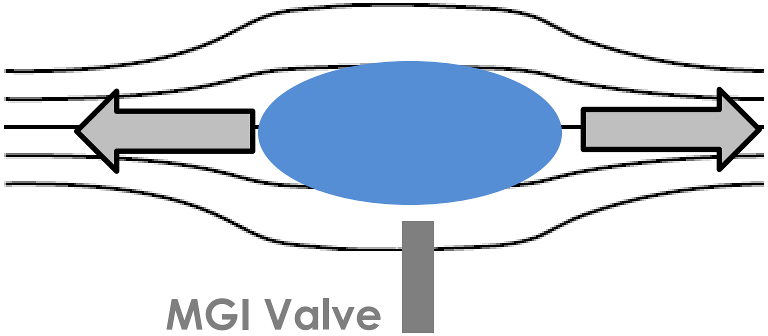
→ Relative location of multiple injectors w.r.t. field-line pitch is important

II. Comparison of DIII-D MGI experiments with NIMROD simulations

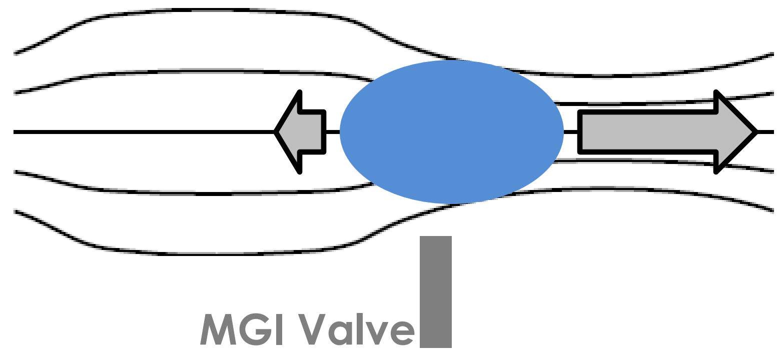
→ Measurement limitations may mask true variation in radiation toroidal peaking factor in experiment

Impurity plume expands helically along field lines; more rapidly toward HFS

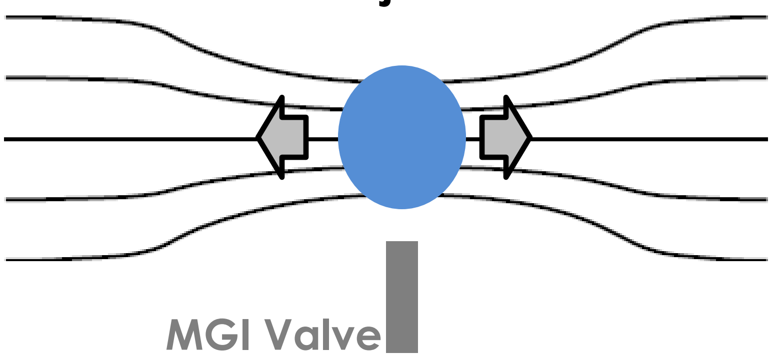
LFS Injection



Non-midplane Injection



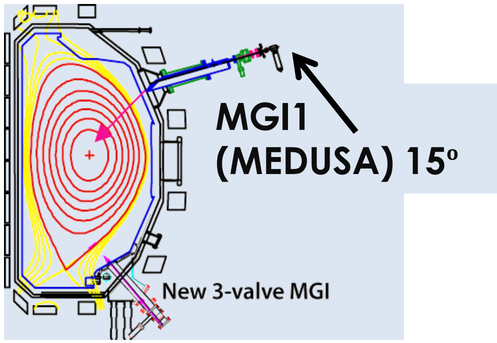
HFS Injection



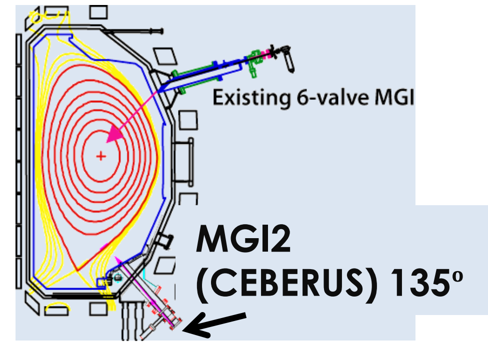
→ Magnetic nozzle effect accelerates impurities in direction of converging field lines; produces **asymmetric plume expansion** when injection is not at the midplane

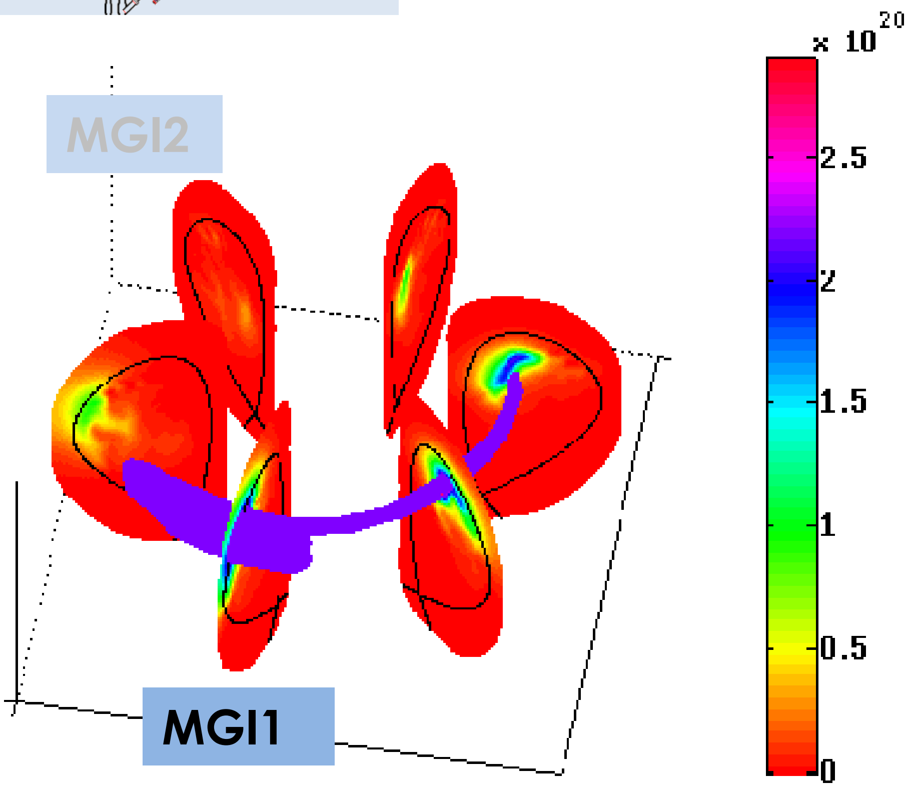
→ cf. Izzo V.A., PoP **20**, 056107 (2013) for HFS vs LFS injection

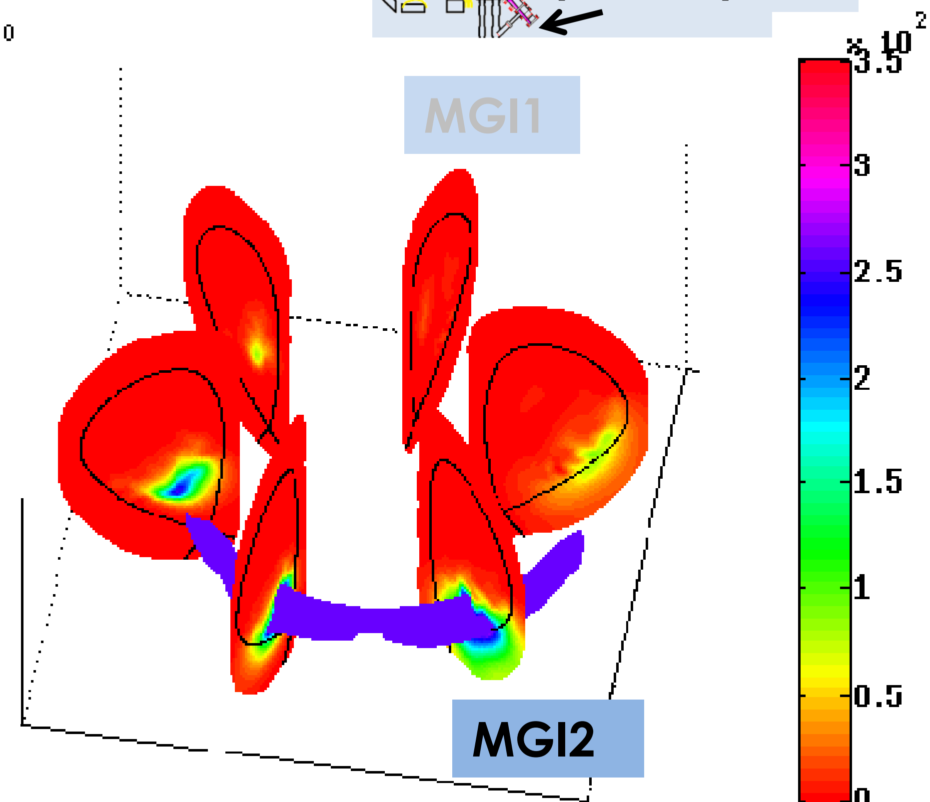
Two DIII-D jets spread in opposite directions toroidally



Contours of Ne density for two gas injection locations

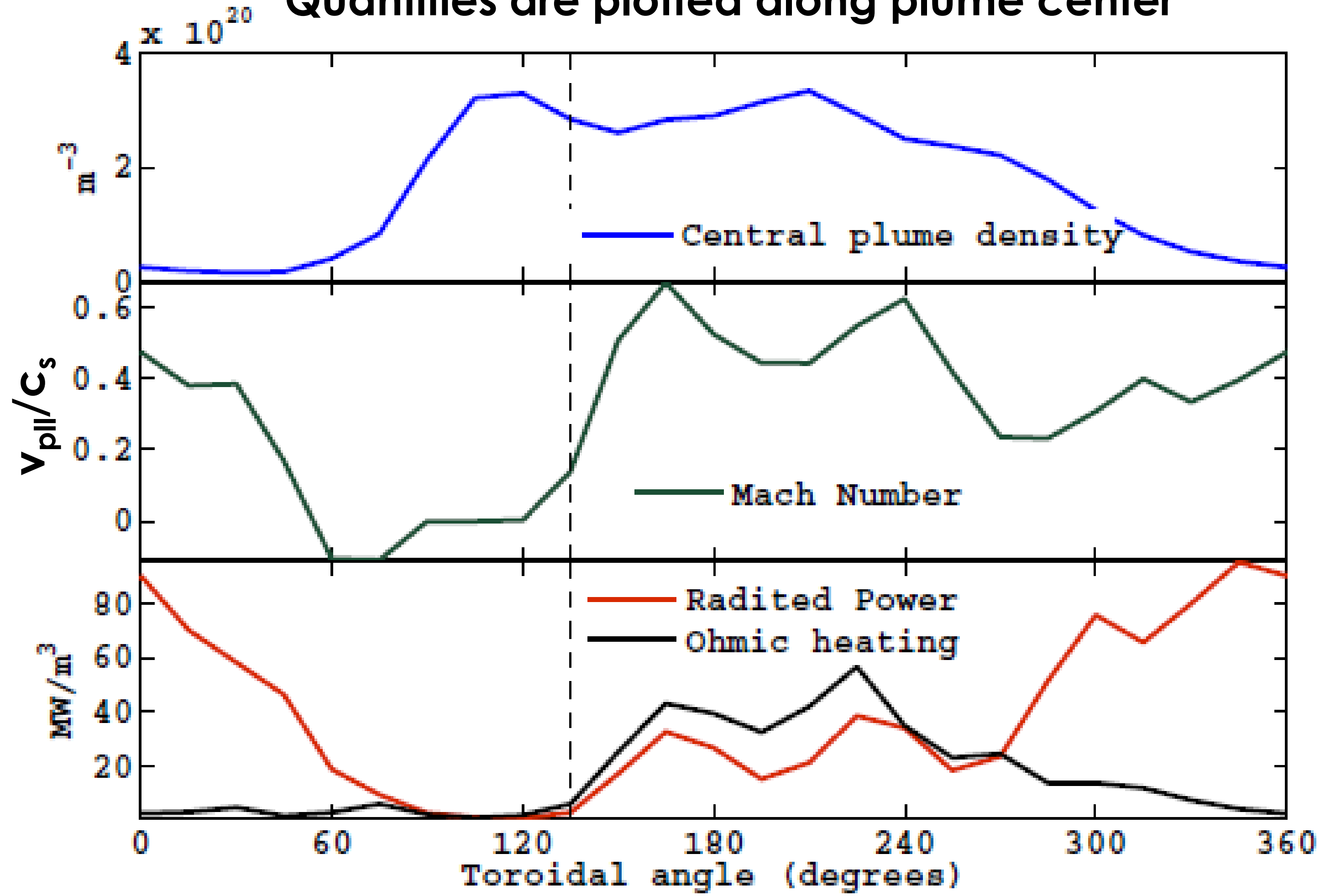






Flow profile along plume shows stagnation on non-expanding side (CERBERUS case)

Quantities are plotted along plume center



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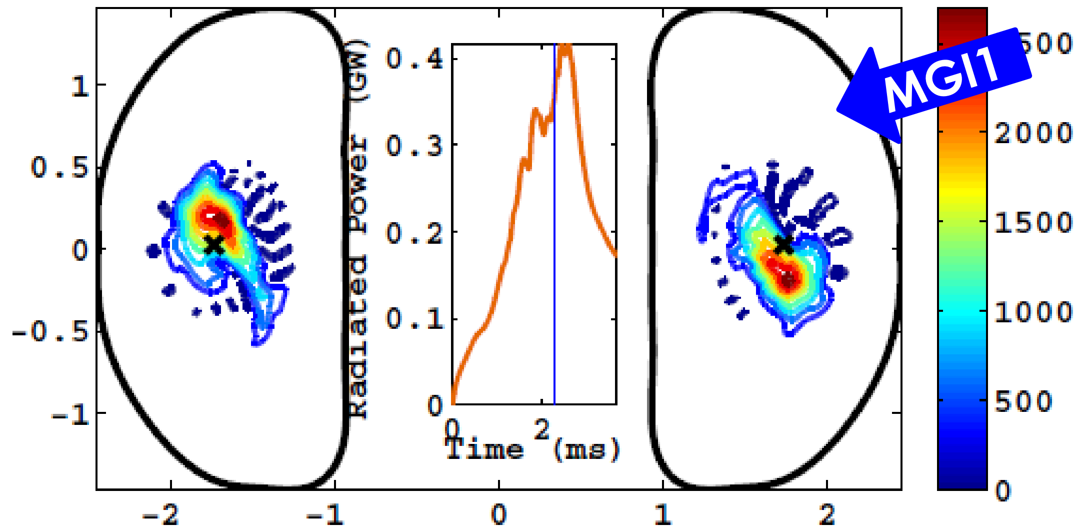
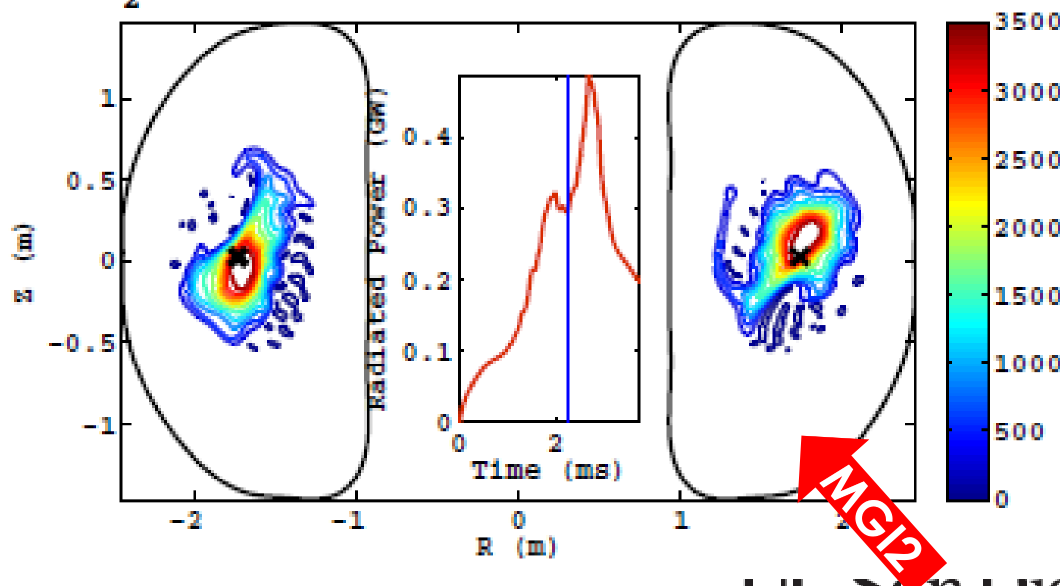
In late TQ, n=1 convected heat flux leads to final TQ flash, Te drop



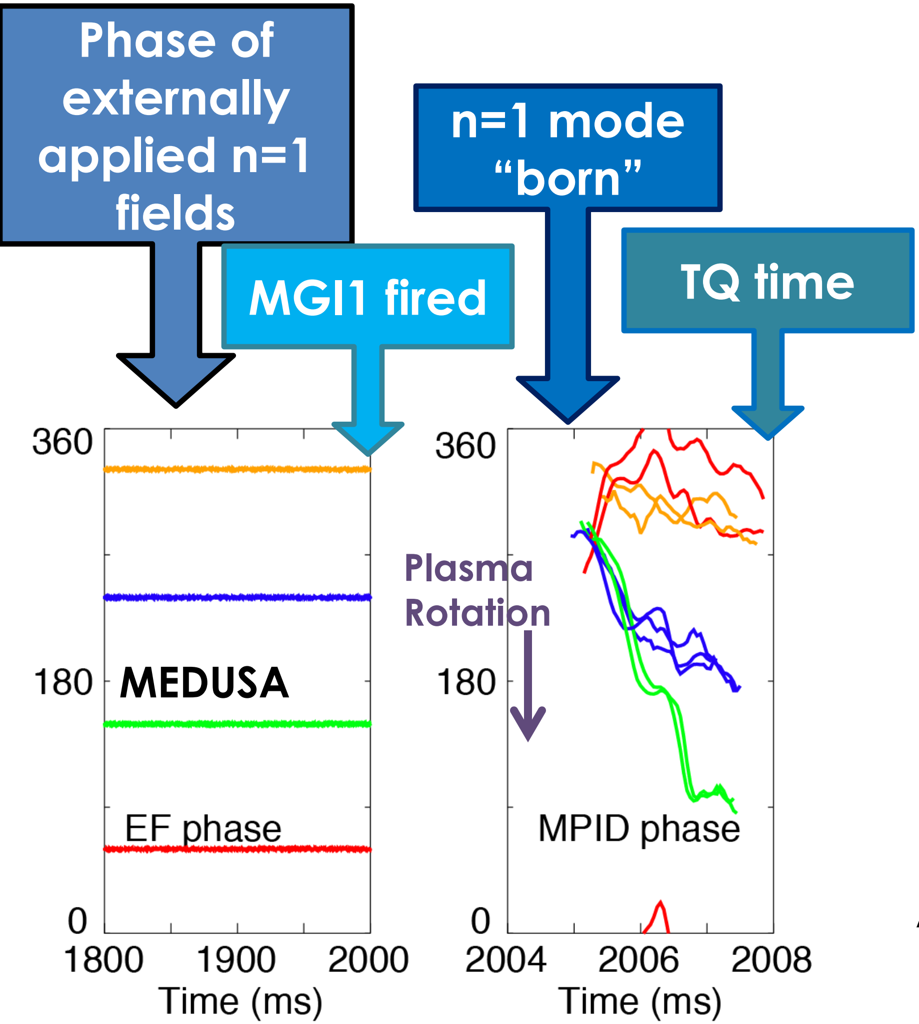
→Temperature contours just prior to TQ radiation flash show n=1 motion of hot core

→At toroidal location of gas injection, n=1 motion is consistently away from gas jet

→ cf. Izzo V.A., PoP **20**, 056107 (2013) (n=1 phase 180 from gas jet)



The n=1 phase is determined by a combination of jet location, residual rotation, external fields



- Mode first appears at phase determined by gas jet
- Generally, phases tend to rotate in direction of initial plasma rotation (pre-MGI), but order of magnitude slower (~1kHz)
- Final phase can be explained by combination of initial phase, plasma rotation, and torque from applied n=1 fields

Analysis by D. Shiraki

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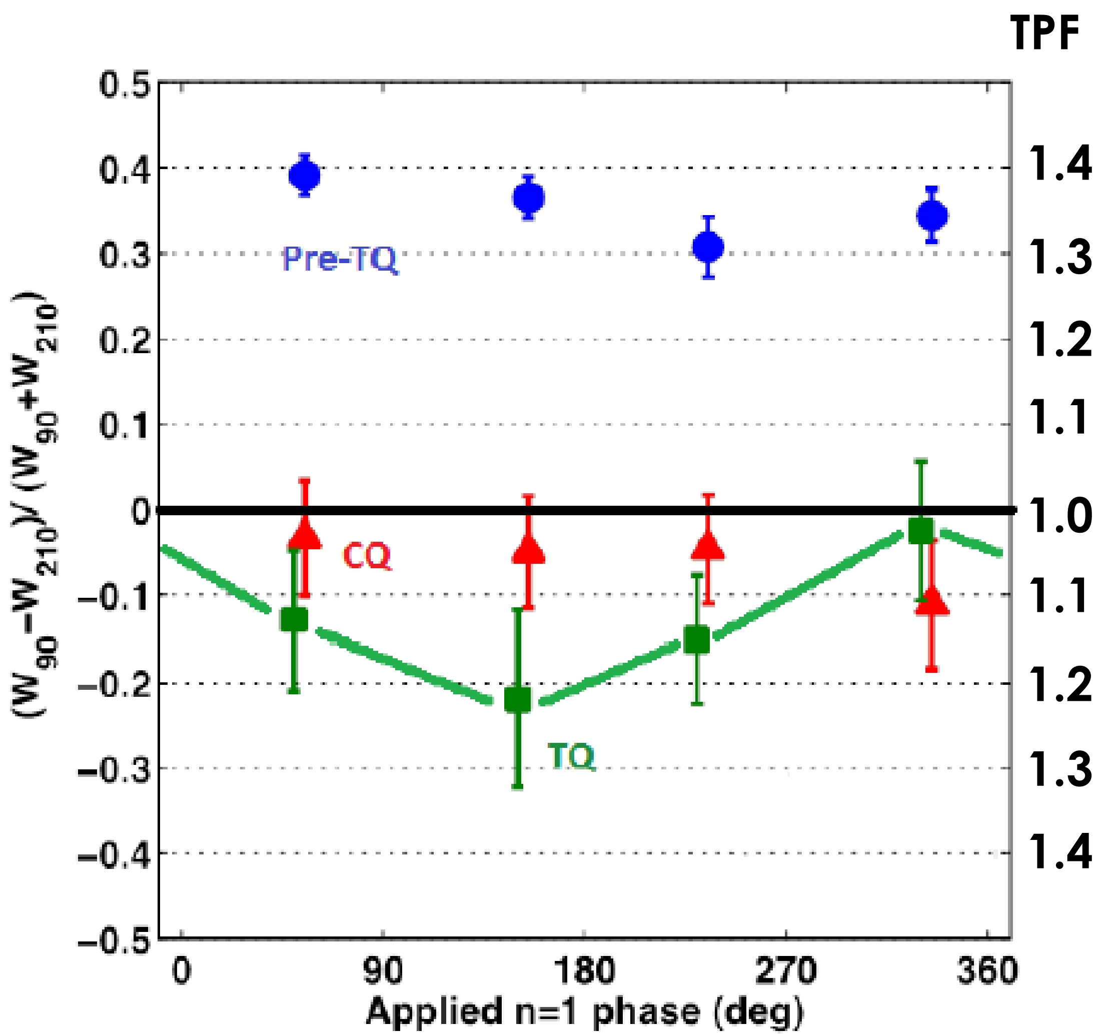
Phase of applied n=1 fields affects radiation peaking in DIII-D (also seen on JET)

Pre-TQ phase: Peaked toward gas jet, no effect of n=1 phase

CQ phase: Very symmetric, no effect of n=1 phase

TQ phase: Peaked (in some cases) away from gas jet, sinusoidal dependence on n=1 phase



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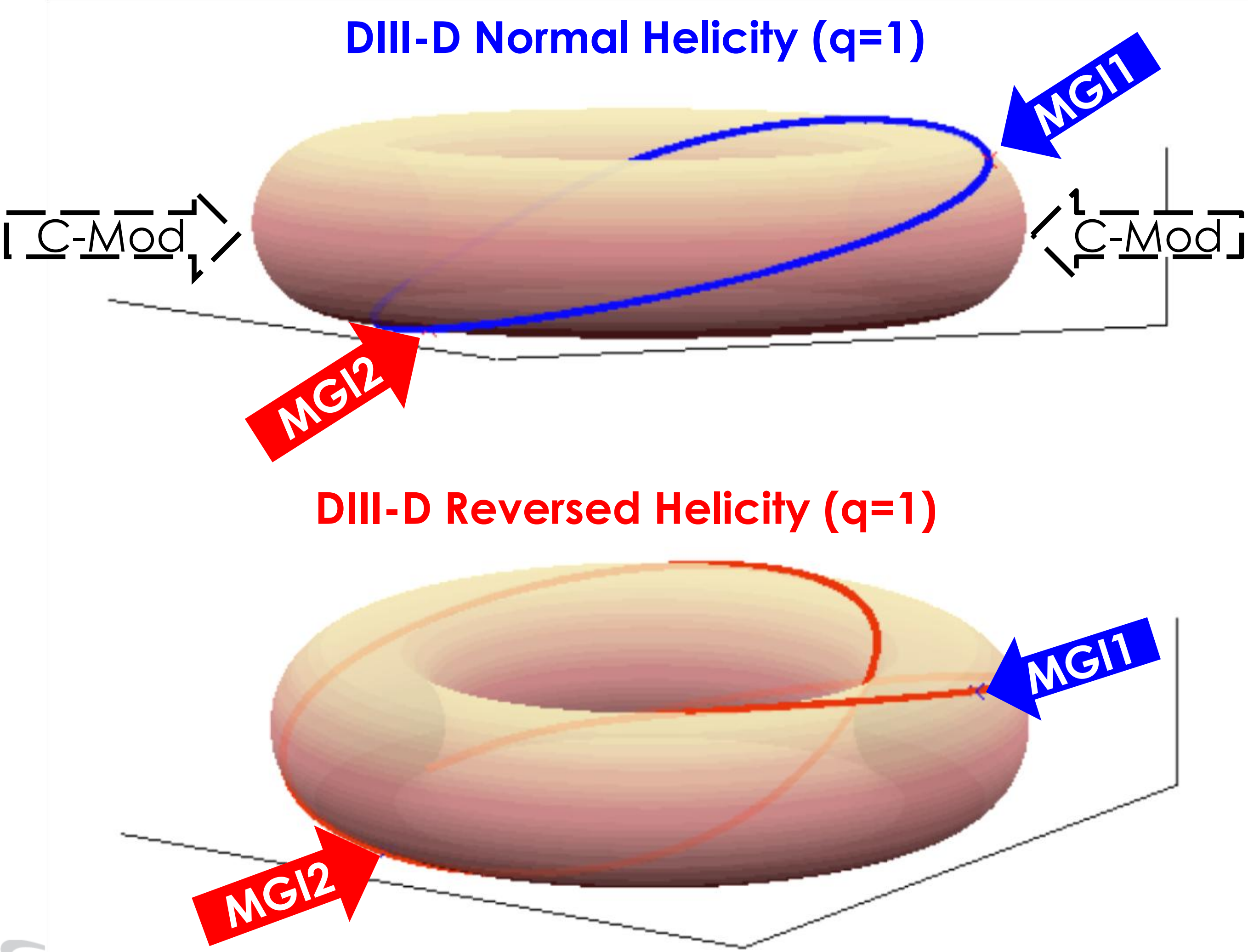
The relative location of two gas jets matters (with respect to the field line pitch, n=1 mode phase)

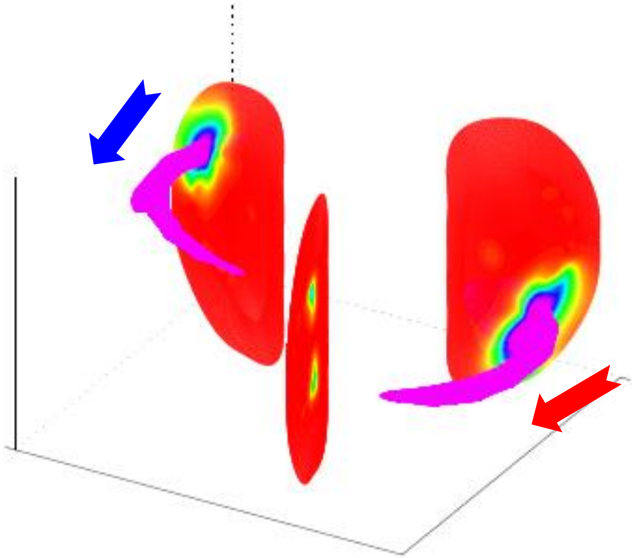


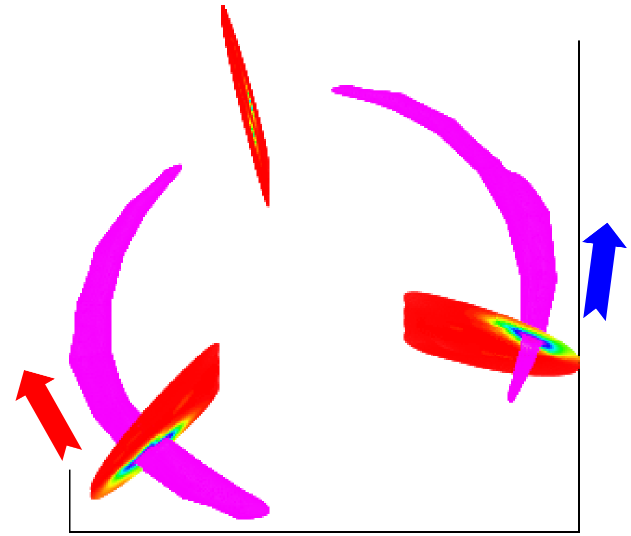
DIII-D jets have same 1/1 mode phase, jets propagate away from each other toroidally

(C-Mod case: opposite 1/1 mode phase)

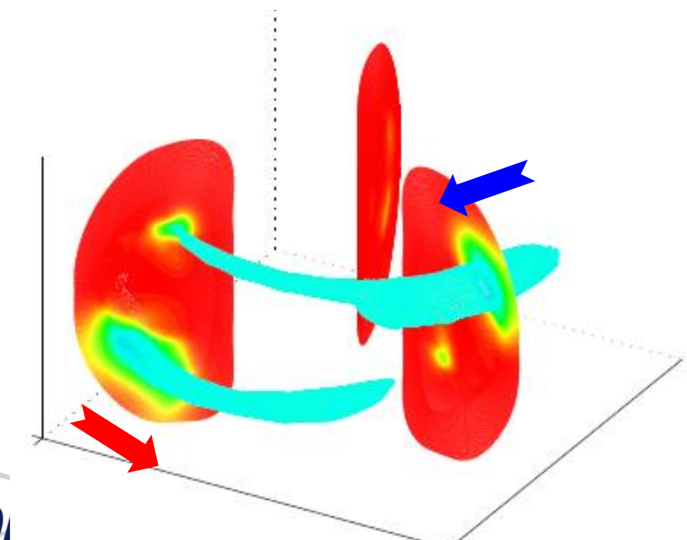
In reversed helicity, jets have different 1/1 phase, propagate toward each other toroidally

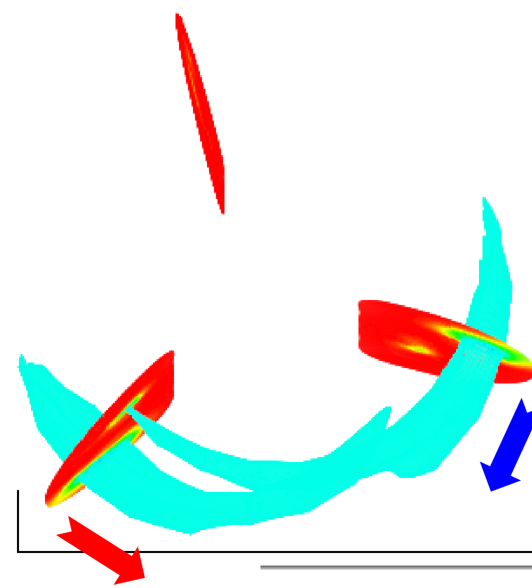
Two DIII-D simulations with opposite current direction show difference in plume spreading





NORMAL HELICITY





REVERSED HELICITY

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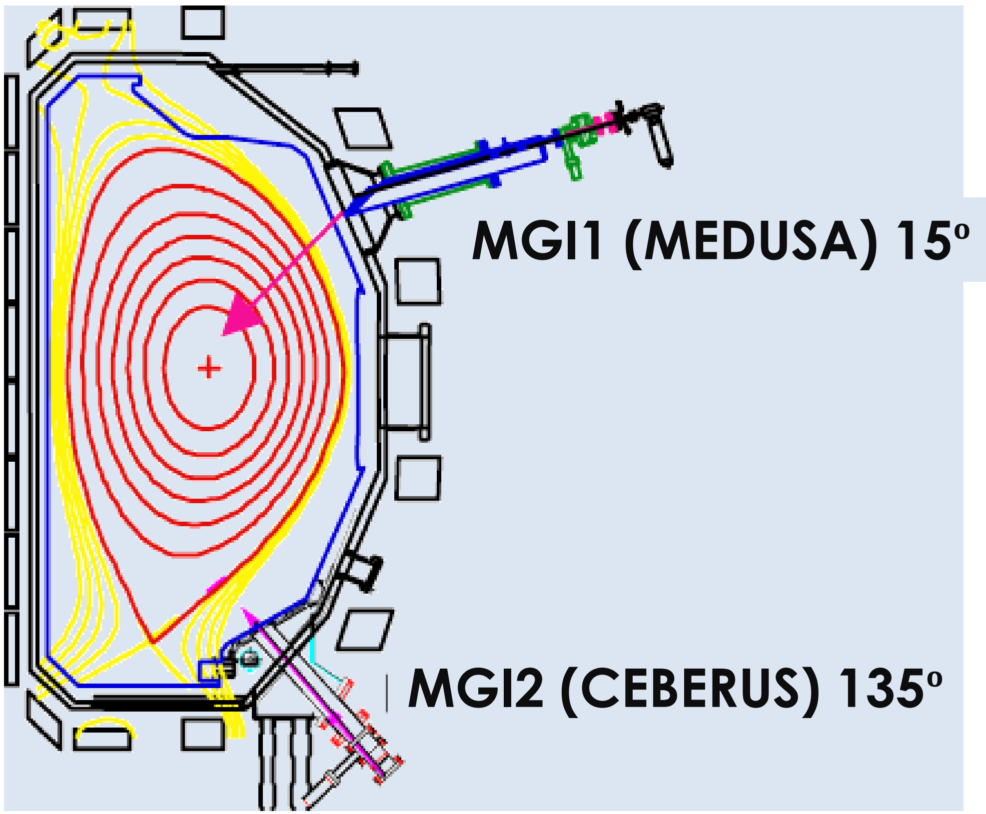
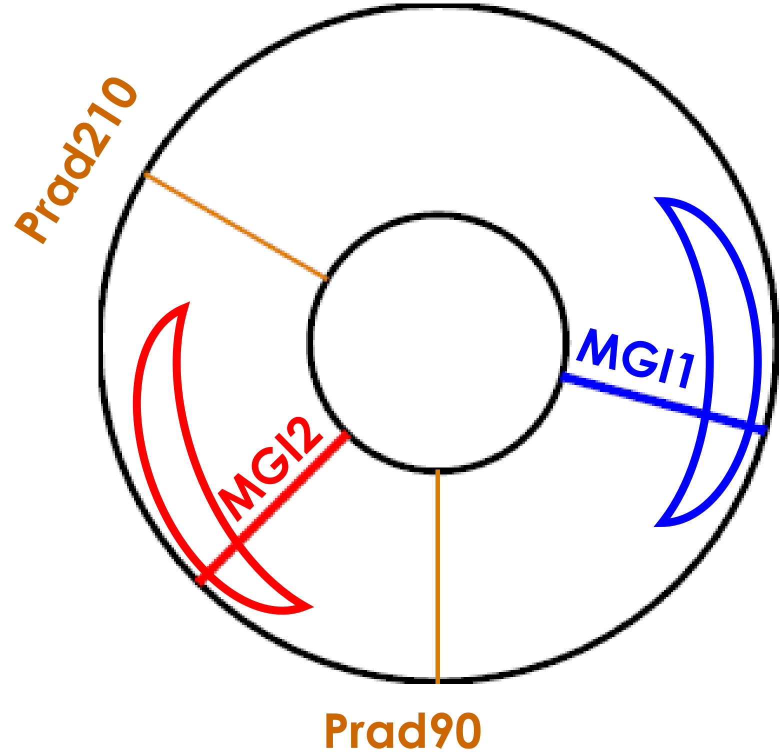
Radiated power diagnostics for DIII-D

→ **DIII-D has two gas jets and two radiated power measurements**





→ **Both jets are closer to Prad90, both plumes propagate faster toward Prad210** (in normal helicity)

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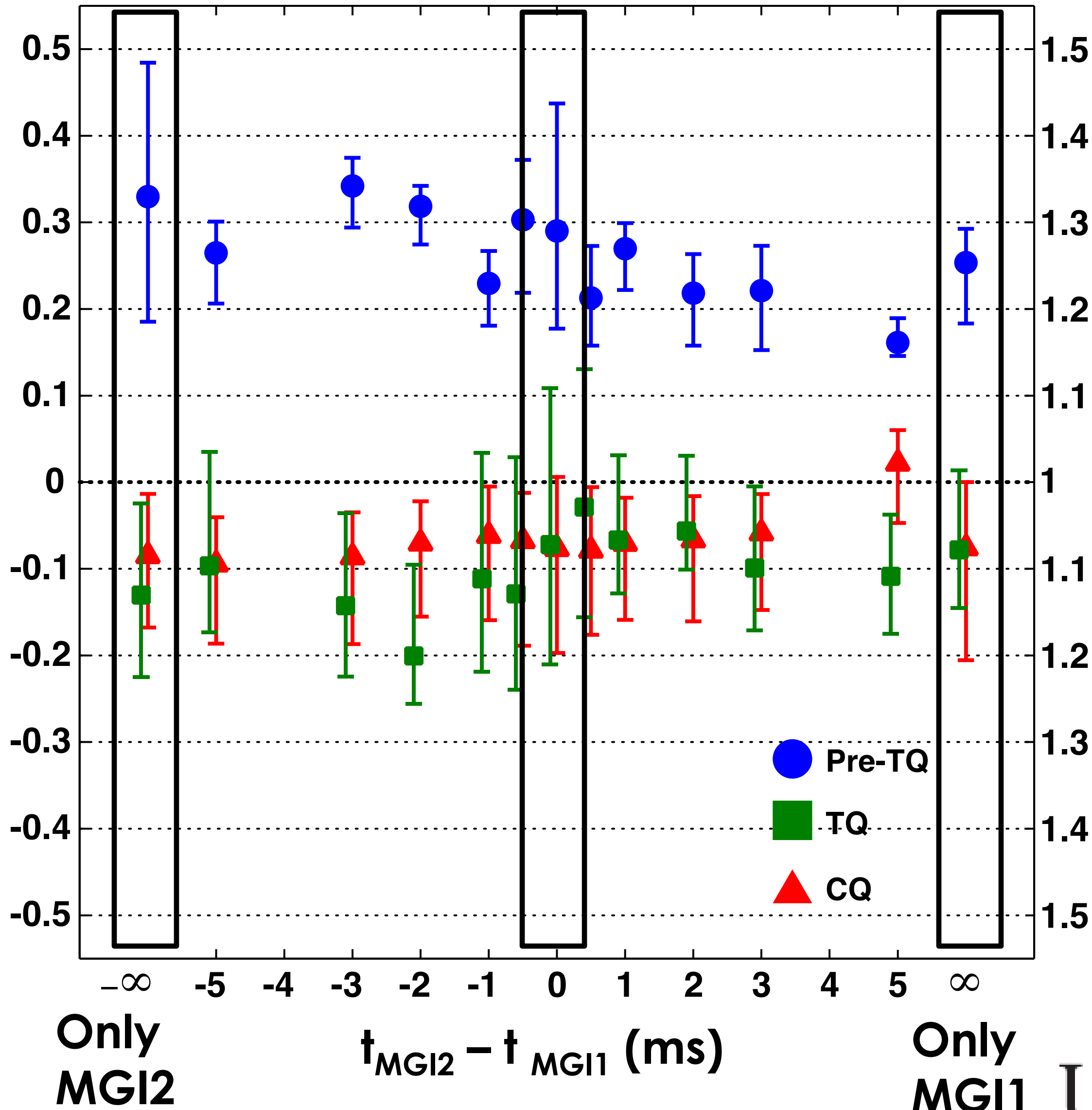
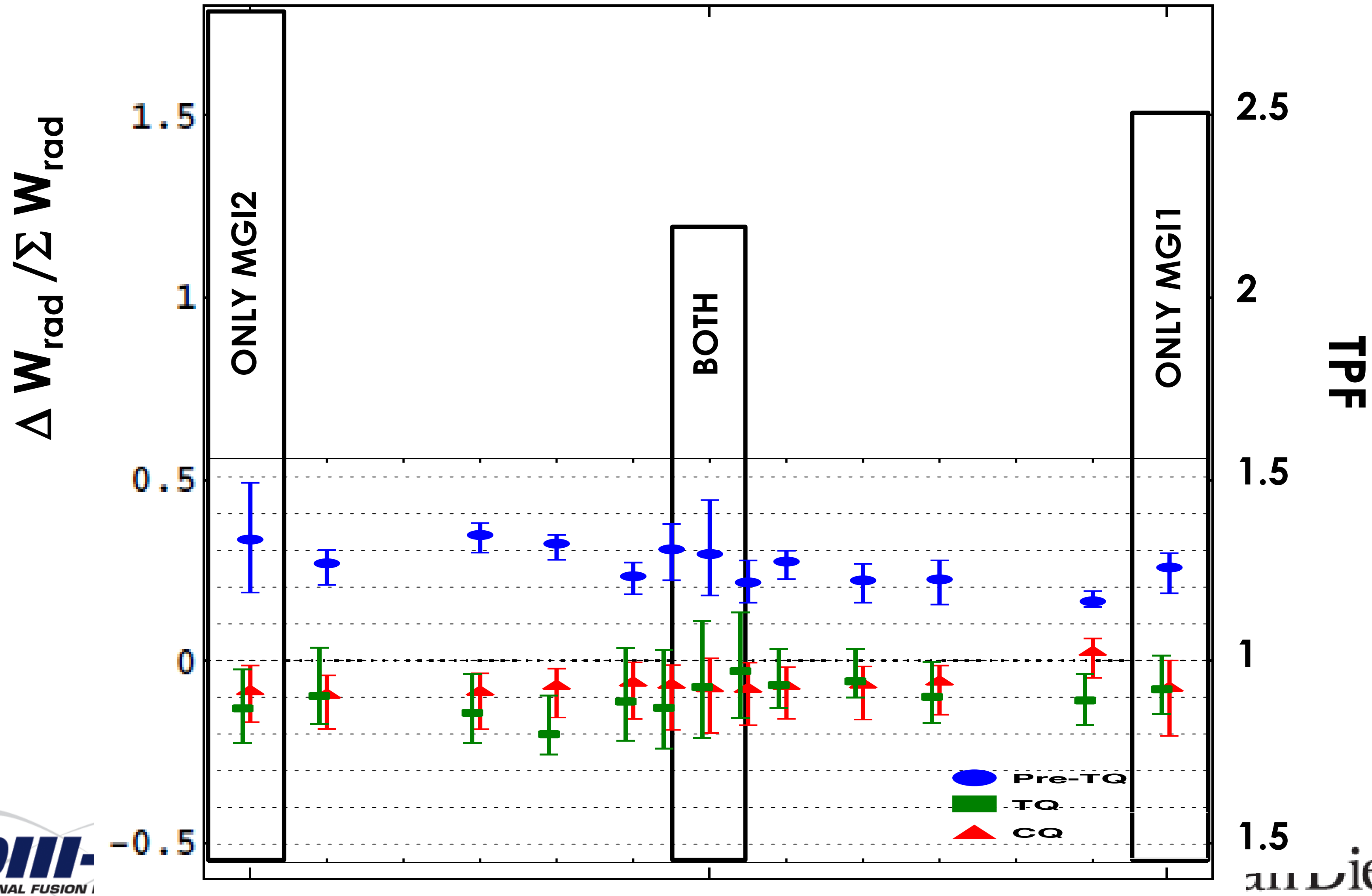
DIII-D finds little or no variation in the TPF as a function of relative jet timing



$$\frac{W_{rad,90} - W_{rad,210}}{W_{rad,90} + W_{rad,210}}$$

$$TPF = \frac{\max(W_{rad})}{\mathrm{mean}(W_{rad})}$$

NIMROD results: Two-point measurements of TPF may mask significant variation with jet number



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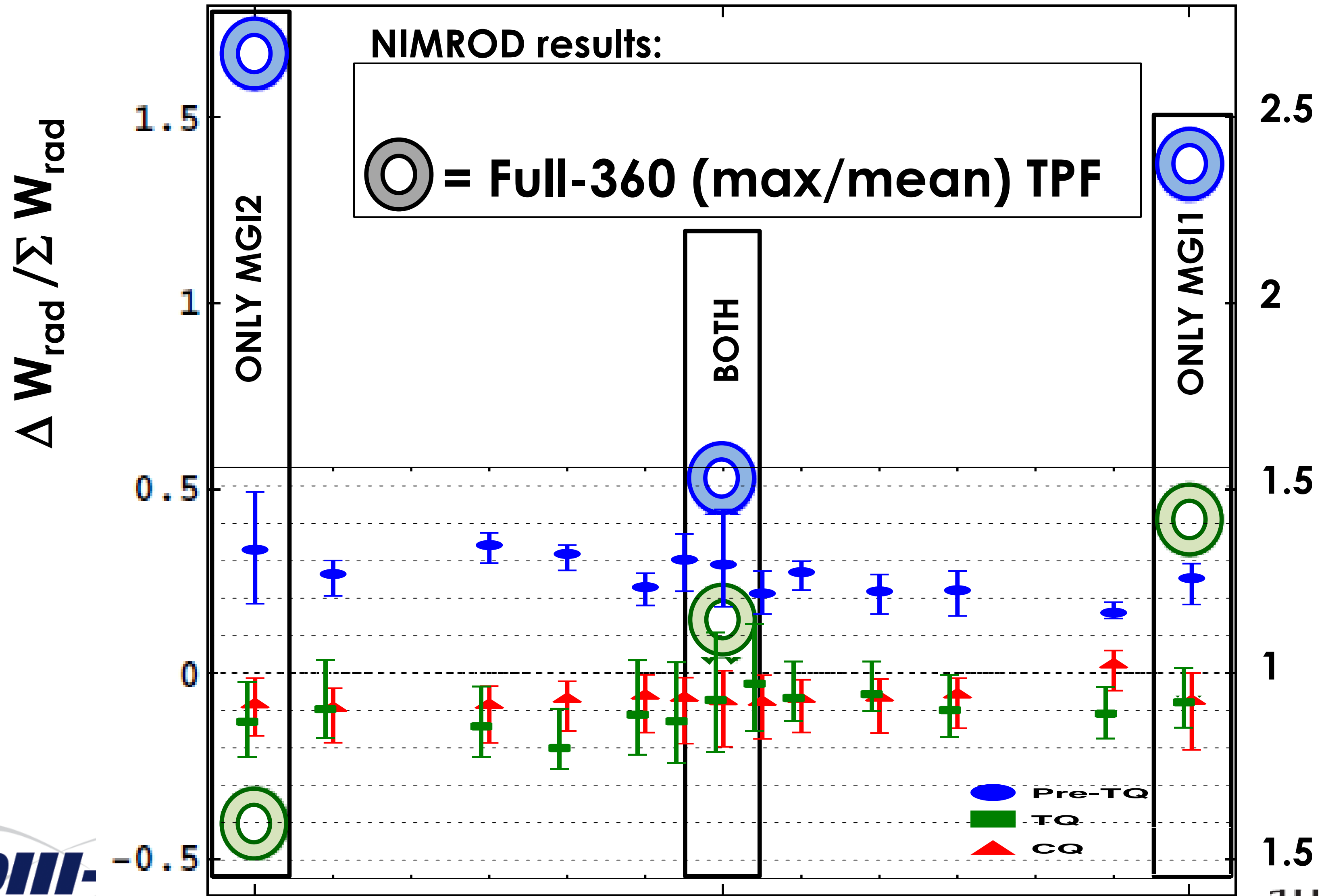

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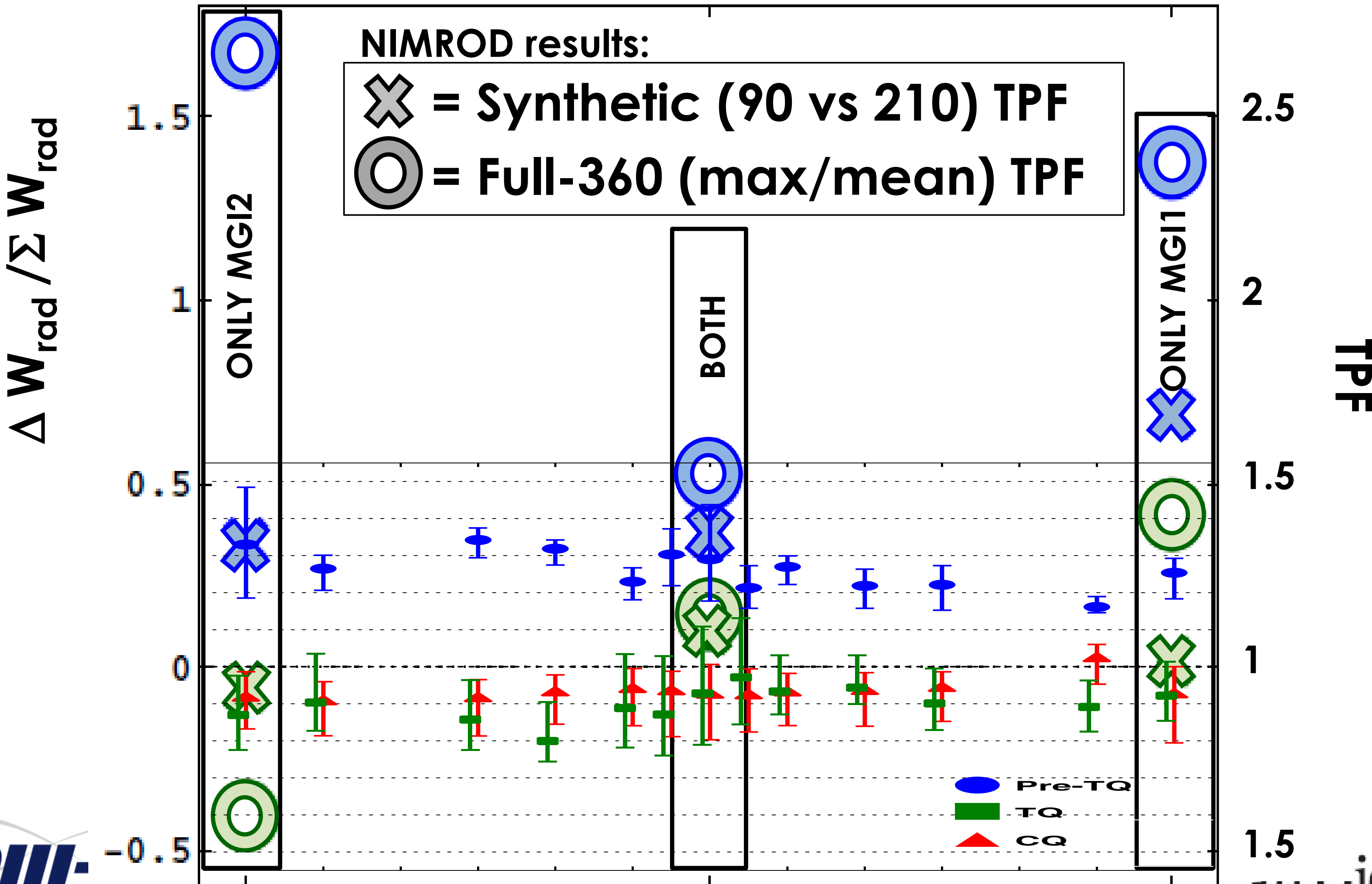
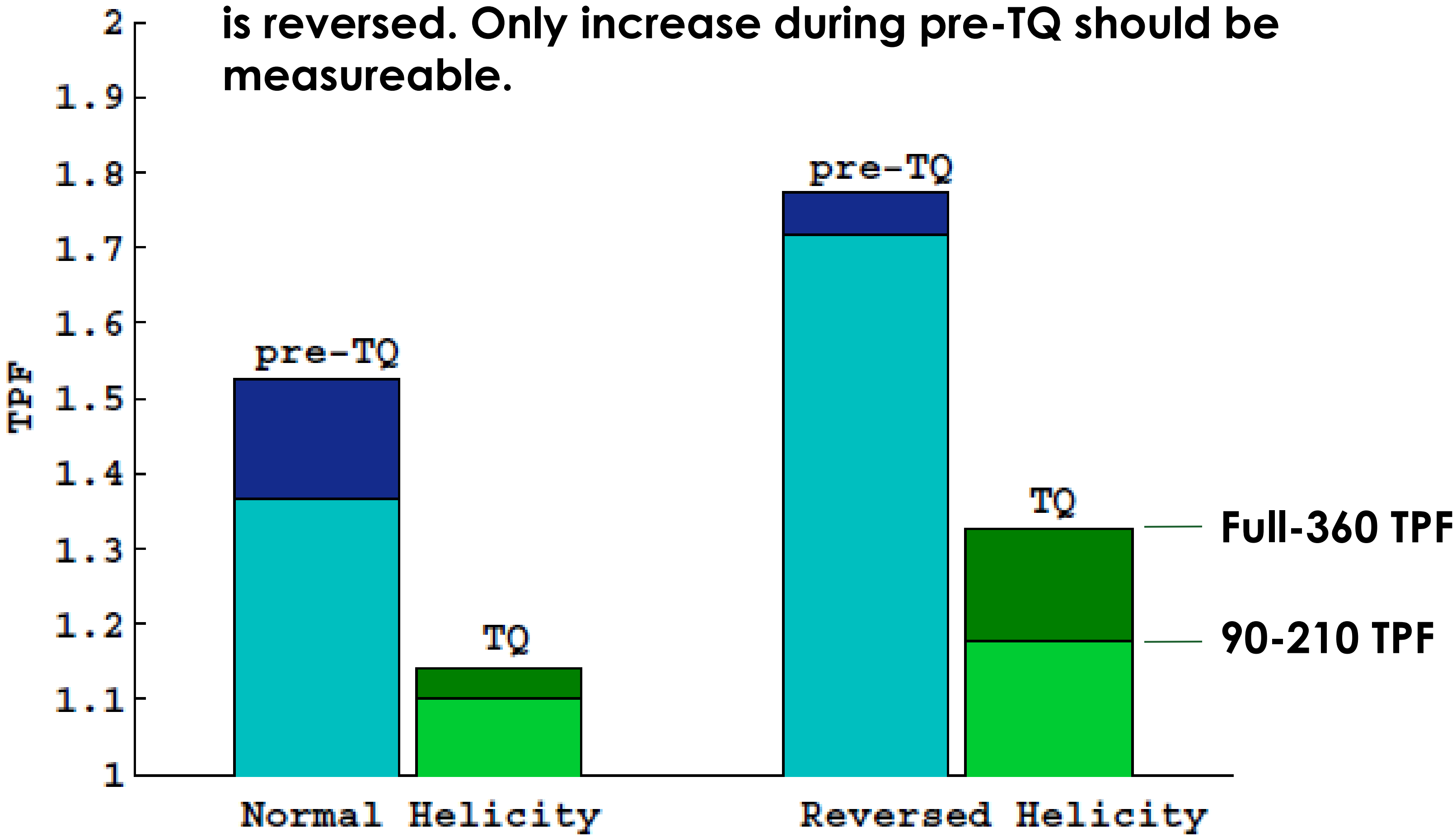


NIMROD prediction: TPF worse for two simultaneous jets in reversed helicity

TPF increases for pre-TQ and TQ when current direction is reversed. Only increase during pre-TQ should be measureable.



Two Simultaneous Jets

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Summary

• **Multiple 3D processes impact the spatial distribution of radiated power during MGI, not just number/spacing of jets**

-Non-midplane injection produces non-symmetric plume spreading (NSTX will be a good test of this)

-Localized heat flux from n=1 mode interacts with impurity distribution to determine TPF. Phase of n=1 matters. (Experimentally demonstrated on DIII-D and JET). Relative location of multiple jets matters.

• **NIMROD 1- and 2-jet MGI simulations predict measured DIII-D TPFs reasonably well**

-Also strongly suggest that DIII-D measured TPFs do not reflect reality with only 2 measurement locations

- In forward helicity, two jets better than one, but not in reversed helicity. Should be able to measure change in pre-TQ TPF when current is reversed.

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