Radiation Asymmetries During Disruption Mitigation with One and Two Gas Jets on Alcator C-Mod

G. Olynyk, R. Granetz, D. Whyte

MIT Plasma Science and Fusion Center

Workshop on Theory and Simulation of Disruptions
PPPL
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Outline

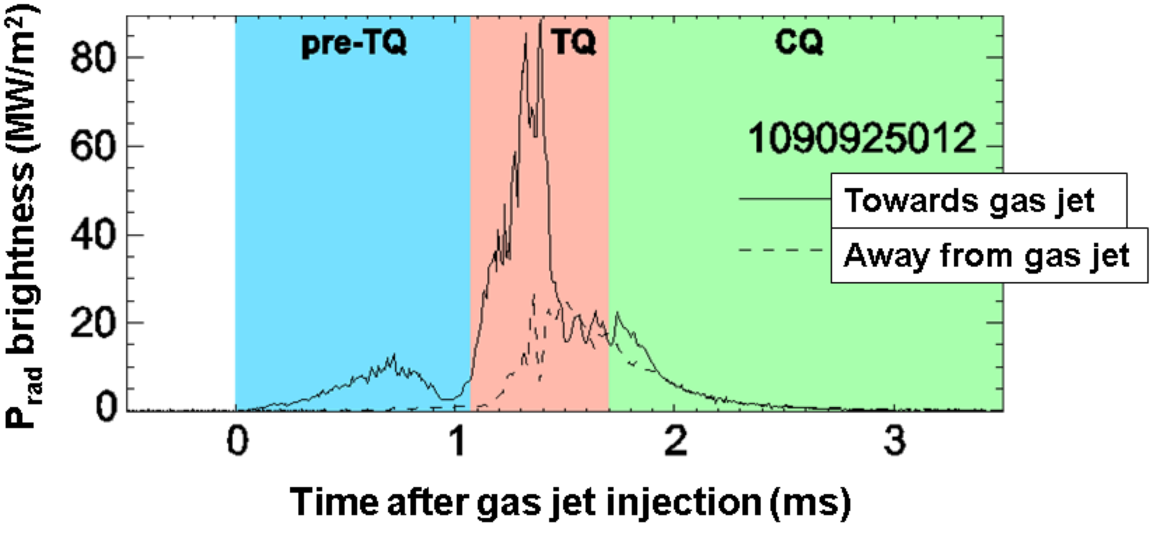
1) Review P_{rad} asymmetry results from last year's campaign with two gas jets

   – Unexpected finding during thermal quench (TQ) phase

2) New results on rotating P_{rad} structures and correlation with n=1 MHD modes and toroidal asymmetries

Motivation: Large P_{rad} asymmetry is often observed during gas jet disruption mitigation with a single gas jet

- Measurements on Alcator C-Mod and other tokamaks show radiated power during mitigated disruptions can vary toroidally by a factor of 10.[1]

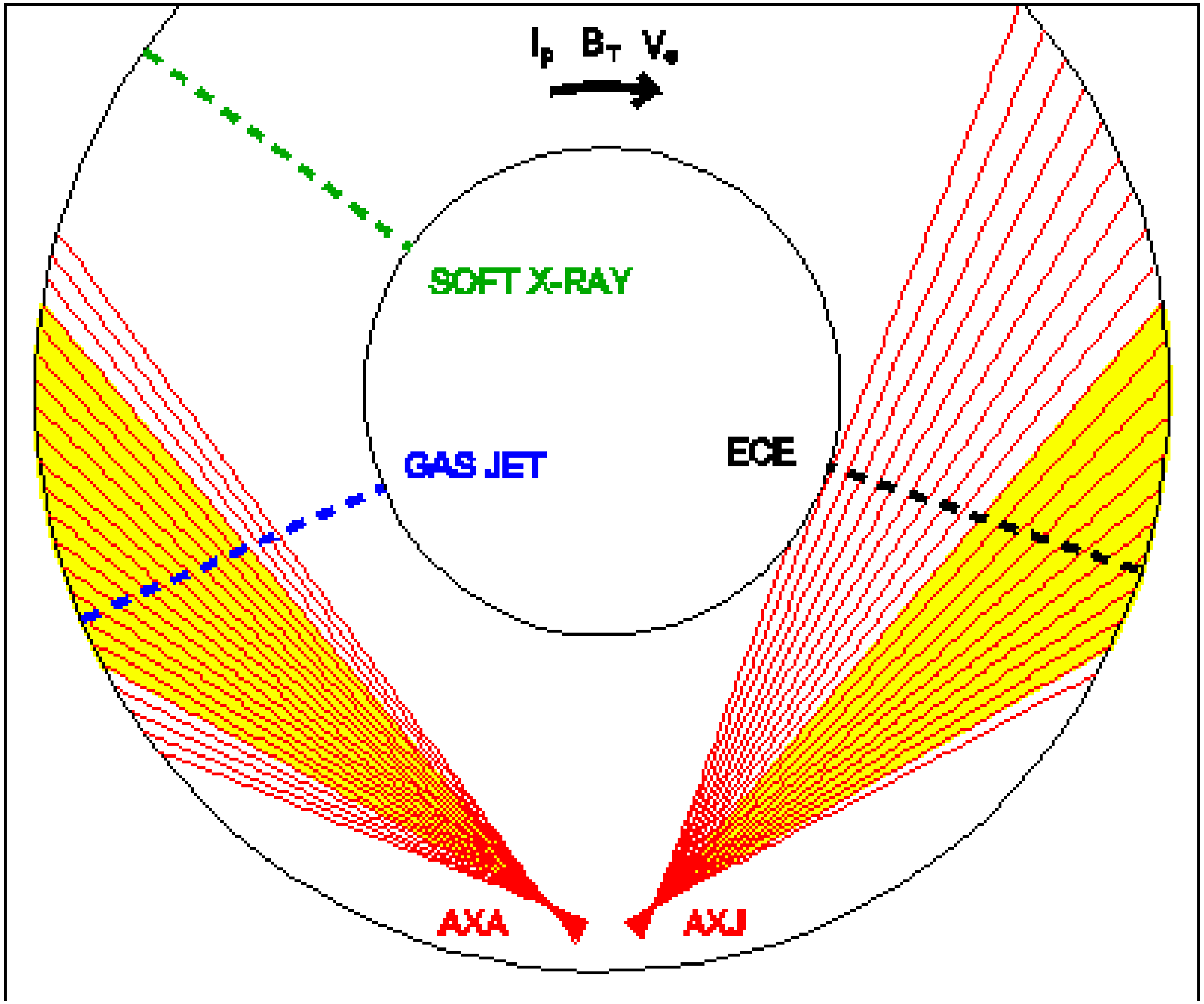


- The ITER allowable is a factor of 2-4 [2]
- Simultaneous gas injection at multiple toroidal locations has been proposed to reduce the toroidal variation, and has been incorporated into the ITER disruption mitigation system.

[1] M.L. Reinke *et al*, Nucl. Fusion **48** (2008) 12504

[2] M. Sugihara *et al*, Nucl. Fusion **47** (2007) 337

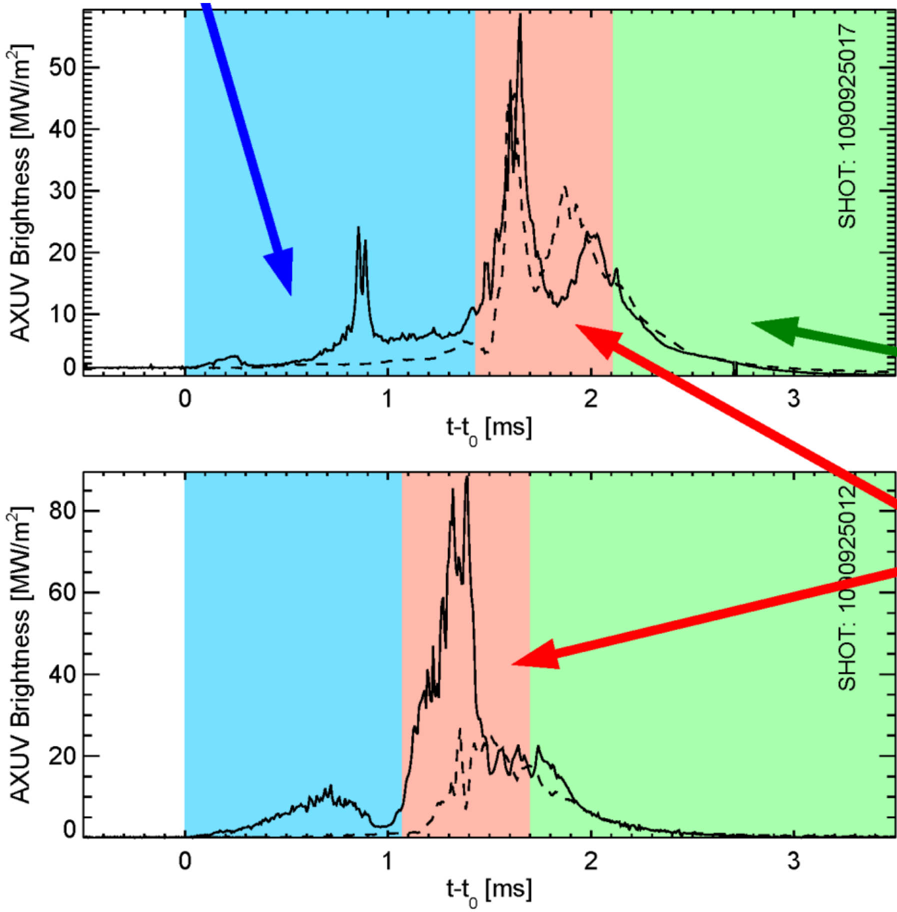
Geometry of initial single gas jet and midplane AXUV P_{rad} arrays



Large toroidal asymmetry observed in some disruption thermal quenches, but not on others

Alcator C-Mod

pre-TQ emission from plasma/gas jet interface



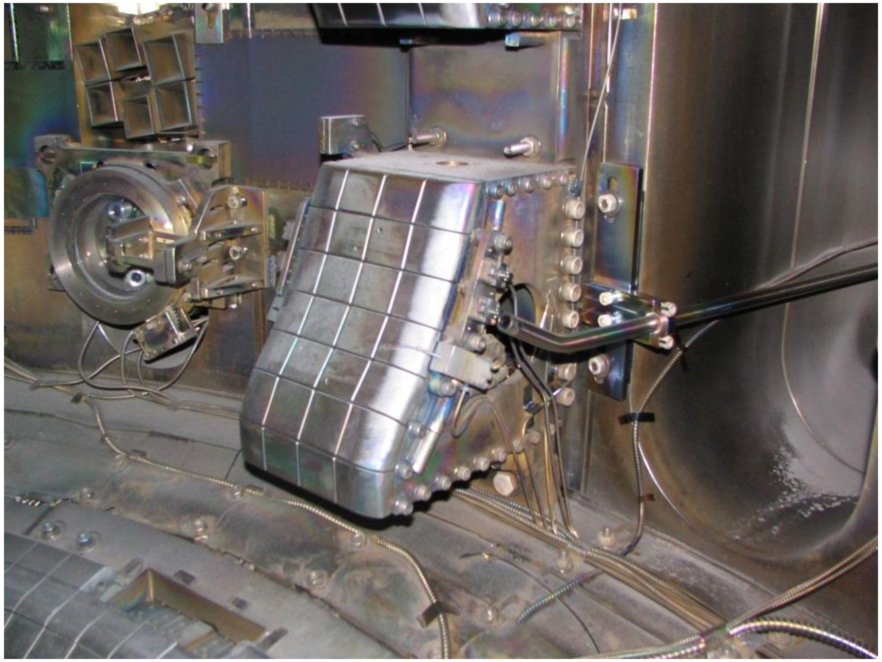
Viewing towards gas-jet ———

Viewing away from gas-jet – – –

Symmetric during current quench

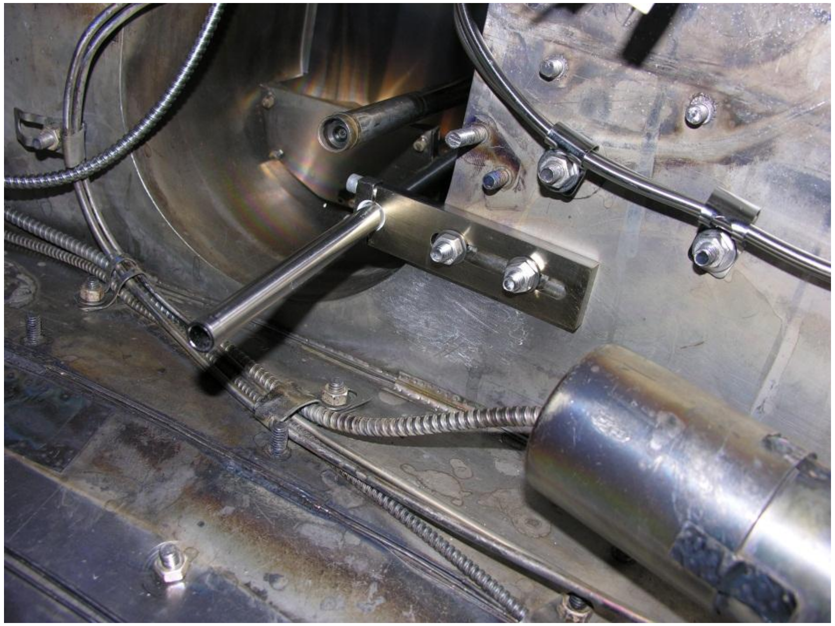
Observe shot-to-shot asymmetry variation in otherwise very repeatable mitigated disruptions

A 2nd gas jet and additional P_{rad} diagnostics were installed on Alcator C-Mod



original gas jet outlet

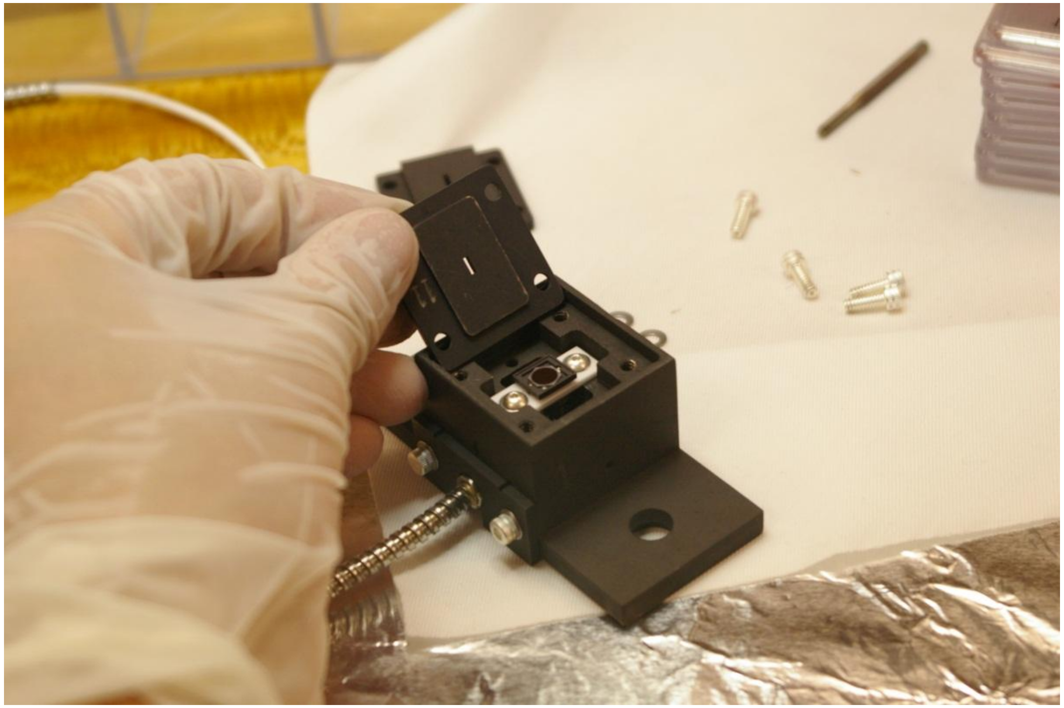
MGI valve hardware supplied by ORNL

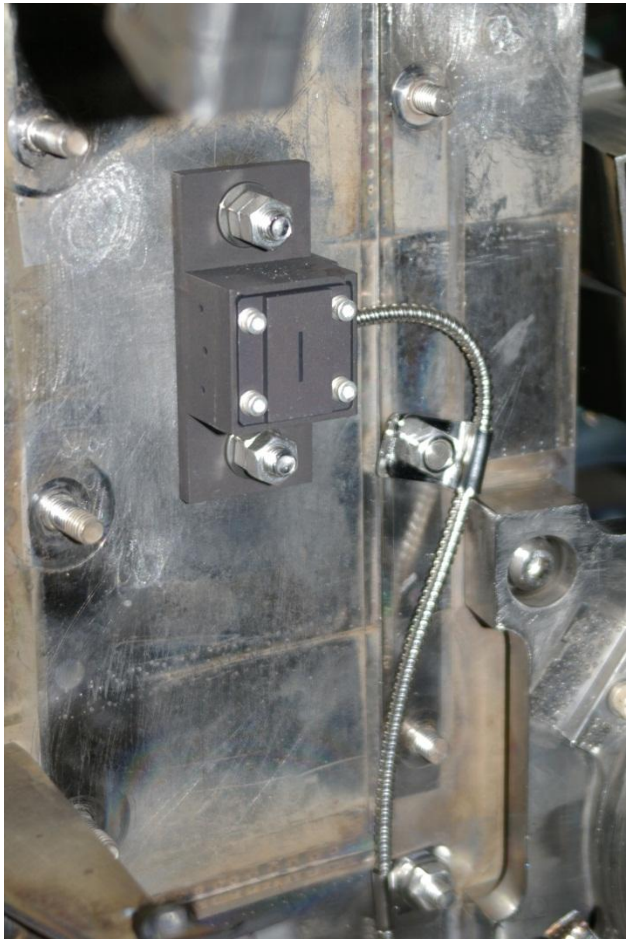


2nd gas jet

Outlet is at same major radius, but at lower height; no bend

New detectors measure P_{rad} from 'slices' of plasma at 6 toroidal locations





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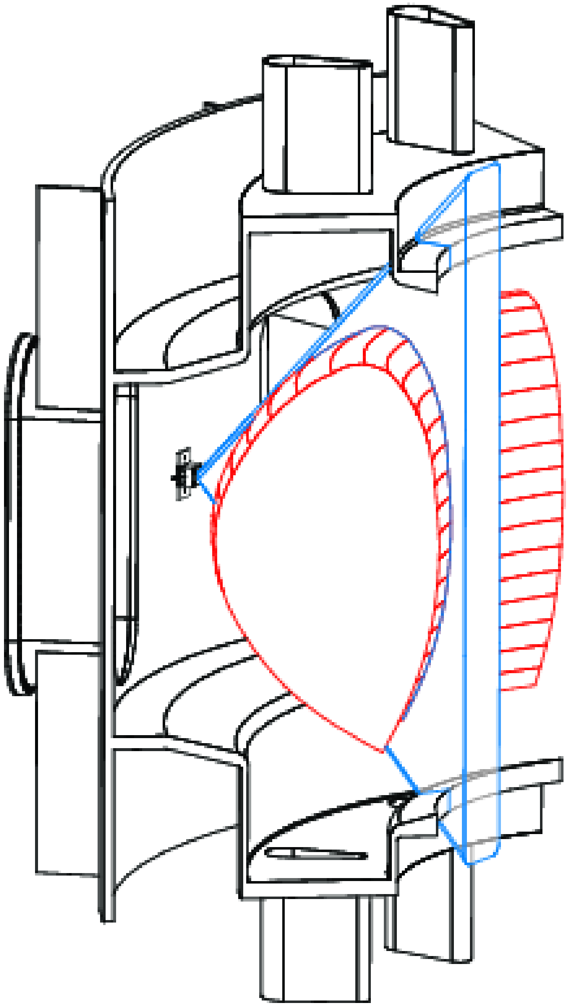

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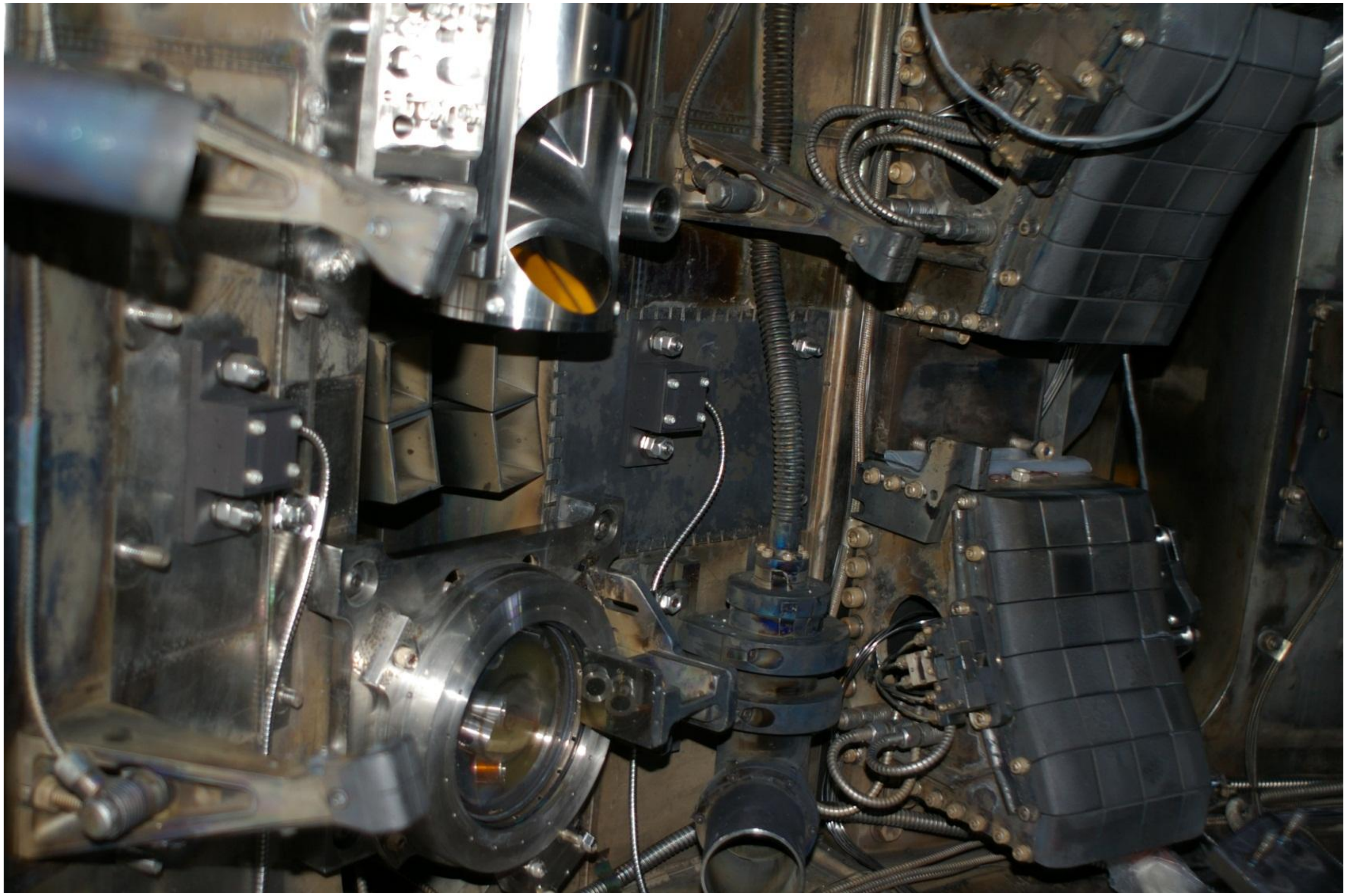
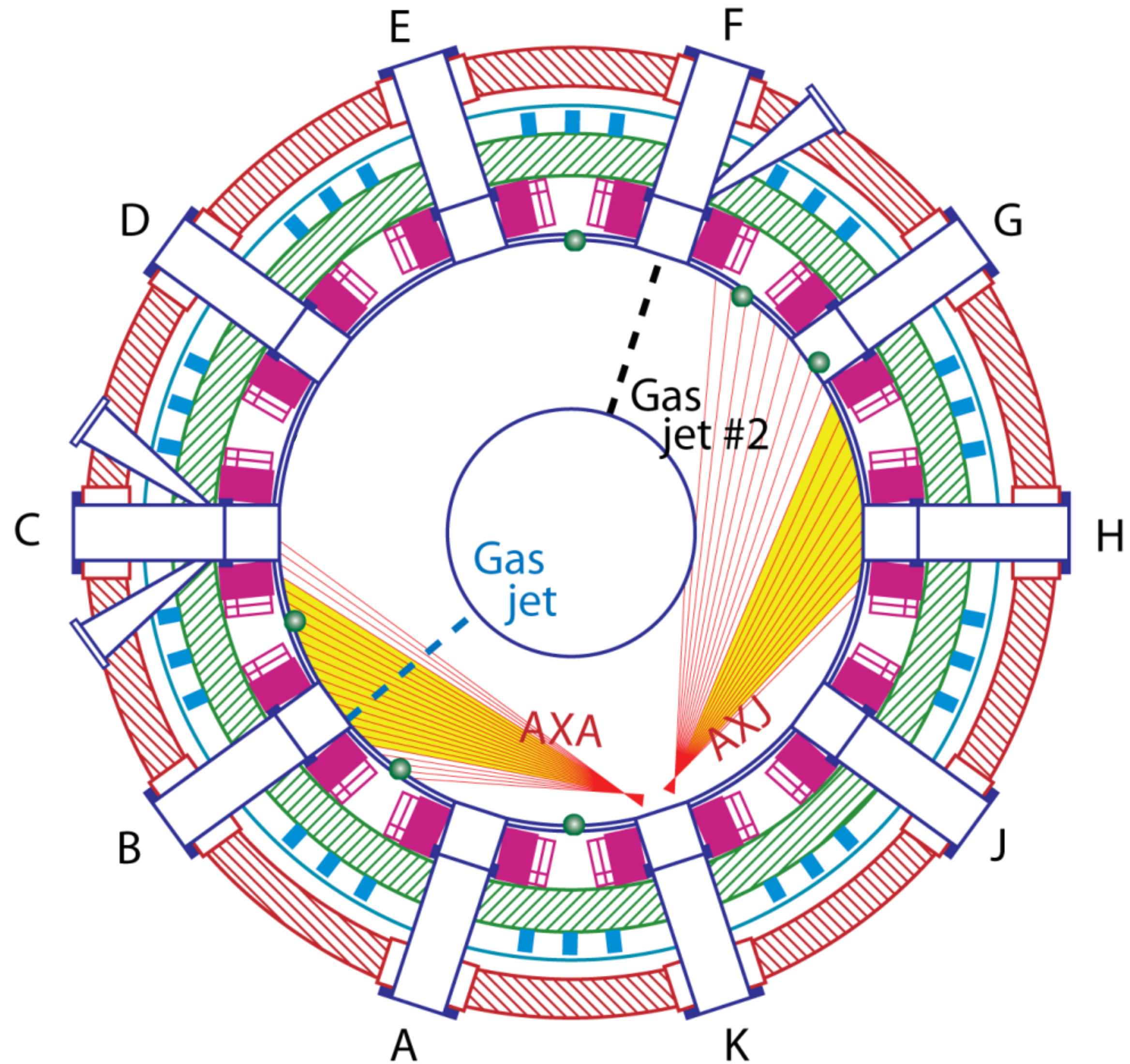


2^{nd} gas jet is nearly 180° around torus; Additional AXUV detectors installed

Alcator C-Mod



Two AXUV P_{rad} diagnostic sets

The two different AXUV P_{rad} diagnostic sets have proven to be useful for two distinctly different purposes:

- Midplane AXUV arrays are best suited for measuring toroidal “asymmetry factor”
- Toroidal set of 6 single AXUV diodes are best suited for detecting rotation of peaked P_{rad} structures and correlating with n =1 MHD modes

Experimental capabilities

Alcator C-Mod

- The two gas jets can be fired independently, i.e. either
  - simultaneously, staggered, or either gas jet by itself
- The two plena are supplied from a single gas bottle
  - usual gas mix: 15% argon, 85% helium
- Timing and gas quantity was characterized for each gas jet individually
  - Slight differences observed; Approximately compensated by appropriate adjustments to valve throughput, timing, and programming
- Measure toroidal asymmetry with different relative valve timings of the two gas jet valves, in L-mode and I-mode plasmas

Definition of “asymmetry factor”

1) Use the signals from the central chords of the AXA and AXJ arrays (P_{rad} brightness)

2) Integrate over pre-TQ period and TQ period to get:

   W_{rad} (B side) and W_{rad} (F side) in pre-TQ
   W_{rad} (B side) and W_{rad} (F side) in TQ

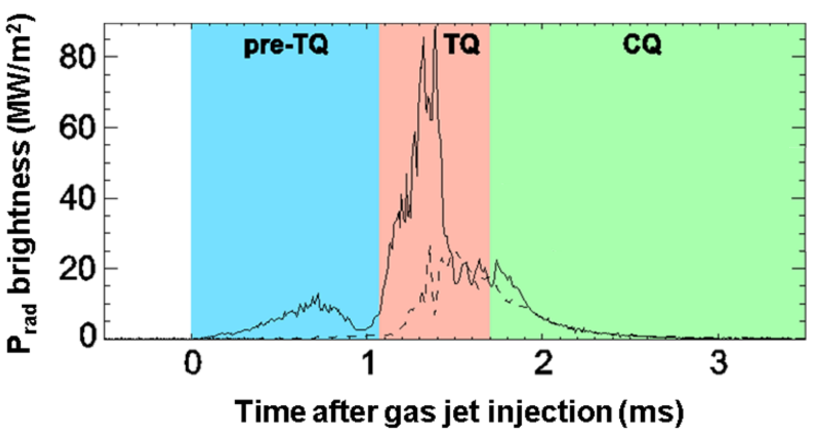
3) Define “asymmetry factor” to be: Difference / Sum

$$\frac{W_{rad}\,(\text{B side}) - W_{rad}\,(\text{F side})}{W_{rad}\,(\text{B side}) + W_{rad}\,(\text{F side})}$$

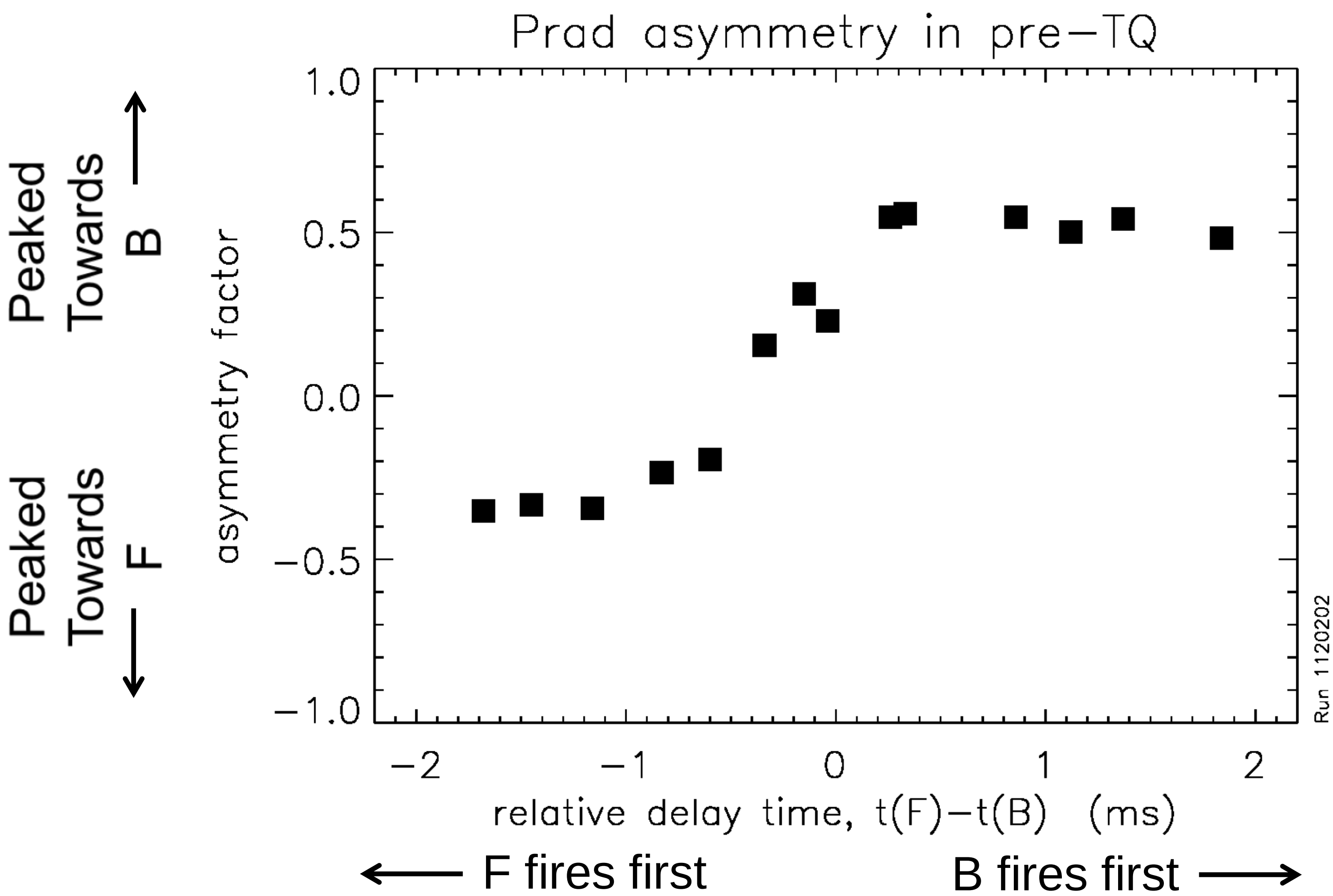
for both pre-TQ and TQ

4) Range of asymmetry factor:

   +1: W_{rad} all on B-side
   0: W_{rad} exactly balanced
   - 1: W_{rad} all on F-side

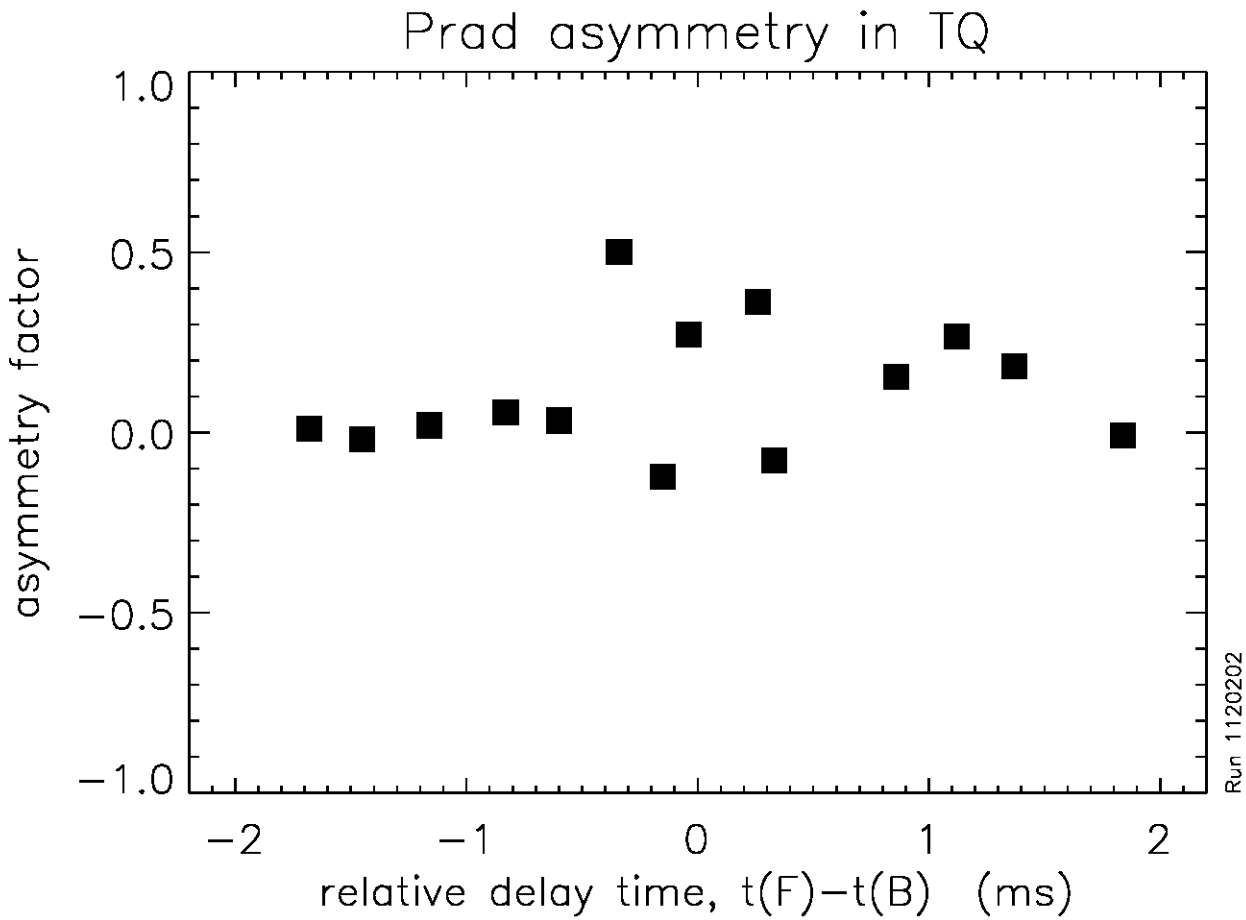


L-mode: asymmetry averaged over pre-TQ



- During pre-TQ, P_{rad} asymmetry is controllable with two gas jets

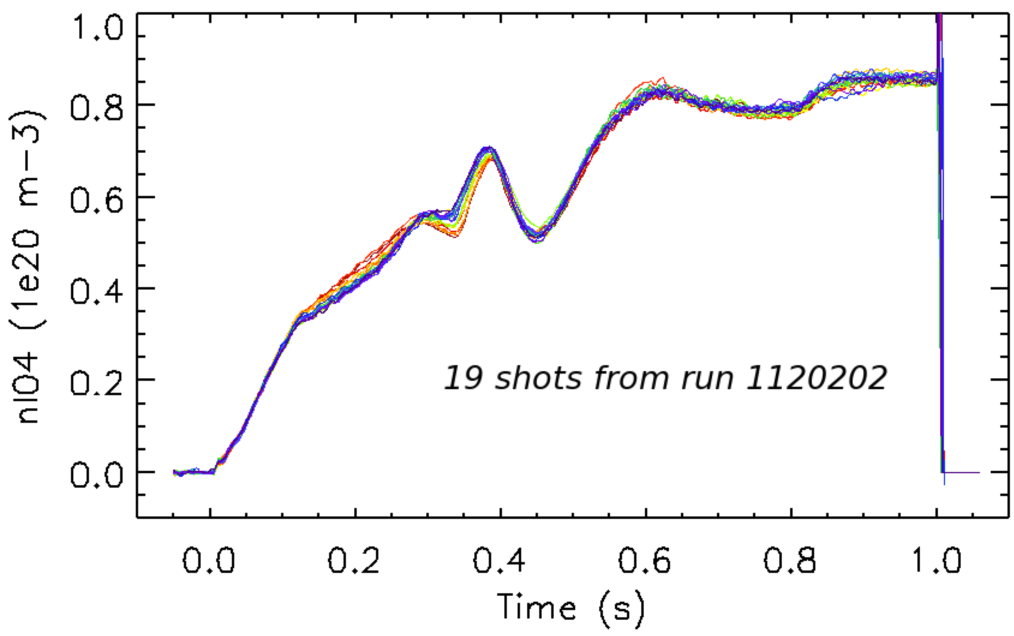
L-mode: asymmetry averaged over TQ

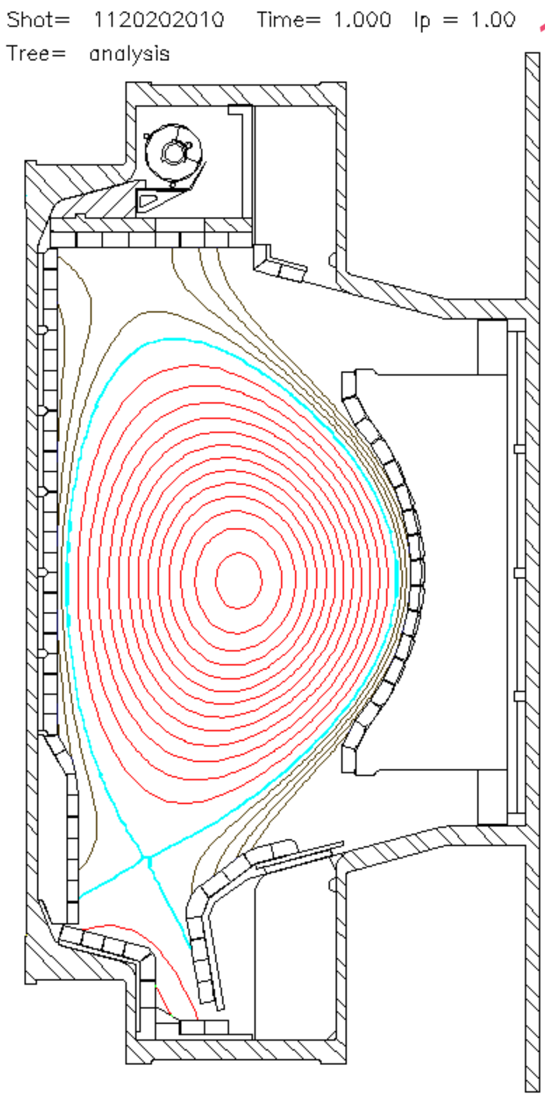


- During TQ, P_{rad} asymmetry is not controllable or reproducible with two gas jets
- Seems to be more symmetric with “single” jet

L-mode run day on Alcator C-Mod

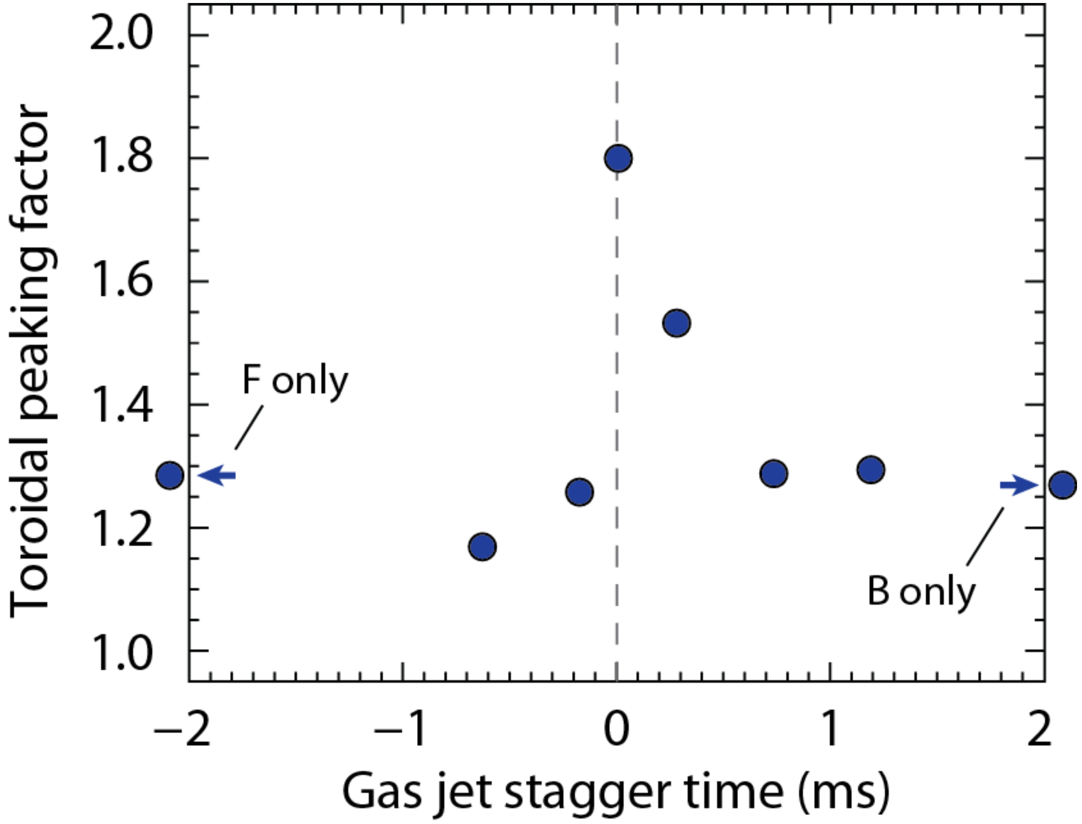
- Series of very reproducible standard discharges
  - 1 MA, 5.6 tesla, 1.5×10^{20} m^{-3},
  - 1 MW ICRF
  - L-mode, lower single null





I-mode: asymmetry averaged over TQ

Alcator C-Mod



- During TQ, P_{rad} asymmetry seems to be enhanced with two gas jets firing simultaneously
- Seems to be more symmetric with "single" jet

Unexpected results

Two gas jets can control the P_{rad} asymmetry during the pre-thermal quench, *BUT NOT DURING THE THERMAL QUENCH (TQ)*

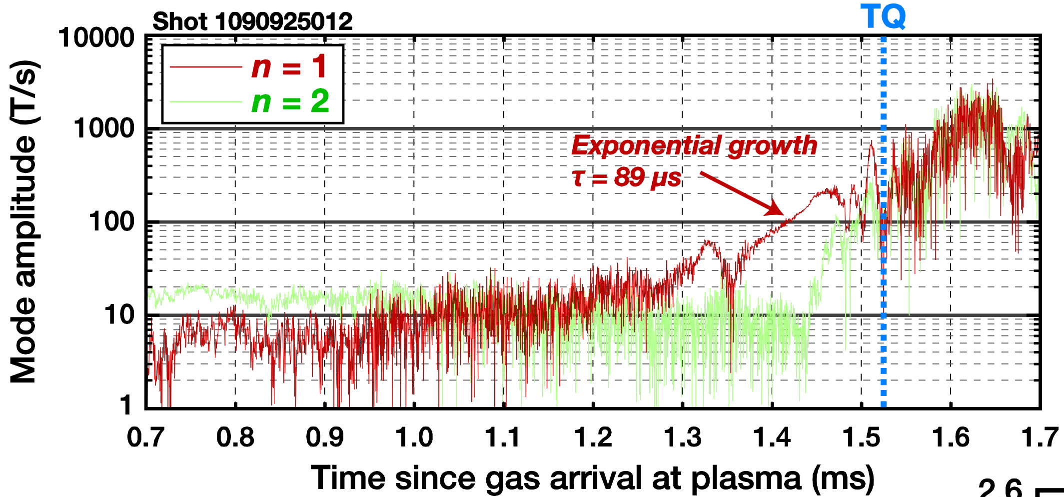
There is no correlation of the P_{rad} asymmetry with macroscopic plasma parameters (i.e. B_T, I_p, n_e, shape, confinement regime, etcetera)

BUT

A strong correlation is seen with n =1 MHD modes triggered by the gas jet injection, *specifically the mode growth rate*

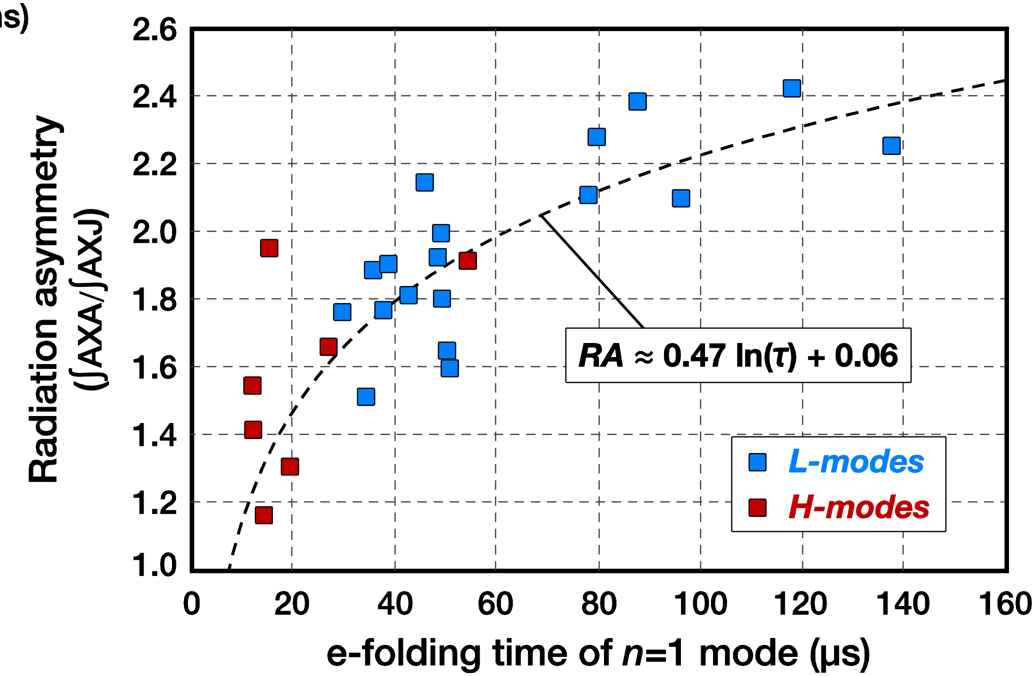
Correlation of *n* =1 mode growth rate with P_{rad} asymmetry in pre-TQ in previous single jet experiments

Alcator C-Mod



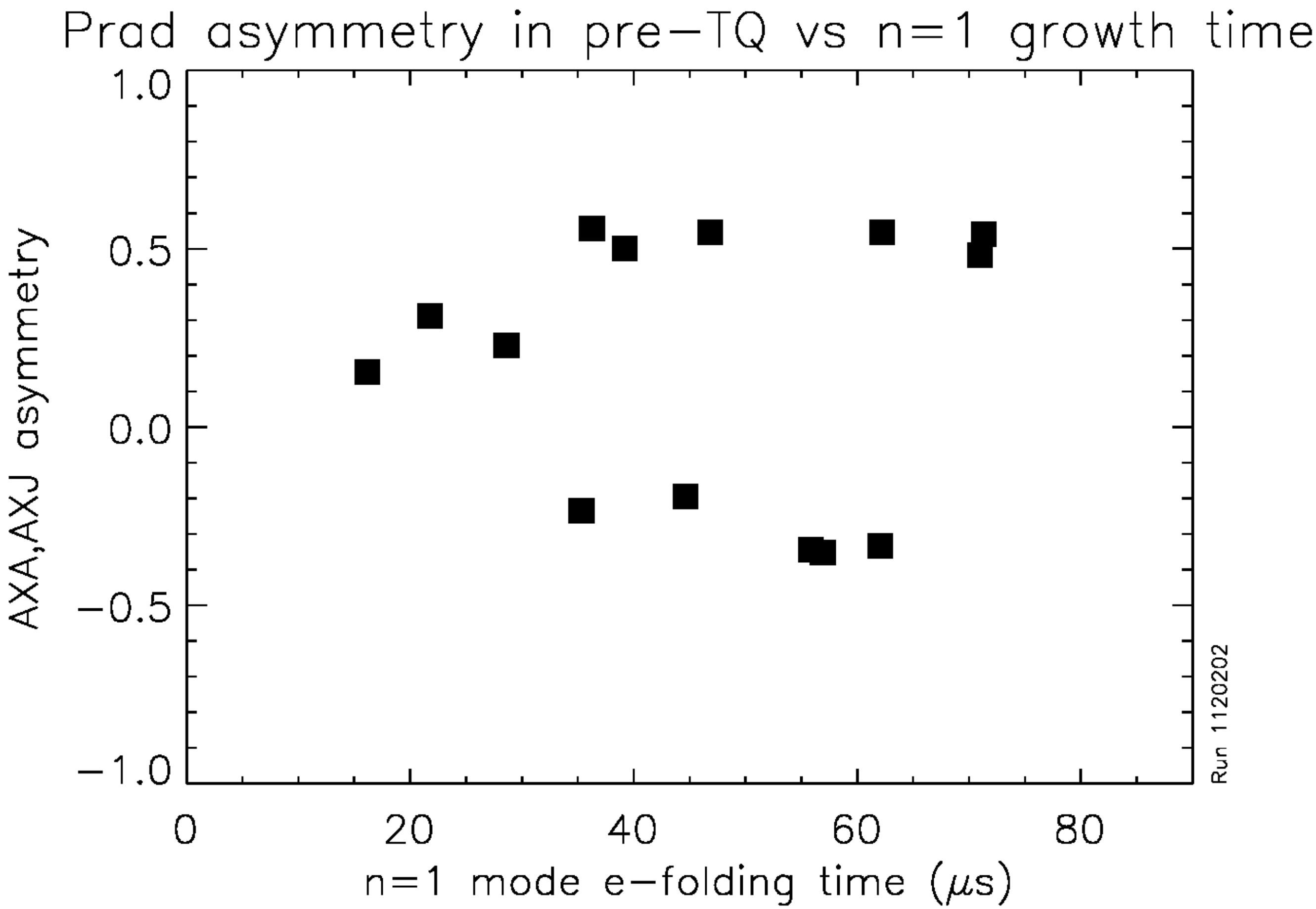
- When this fitting is done at every time step, a coherent *n*=1 mode is always present. The *n*=2 modes are usually incoherent.

- There is a strong correlation between the growth time of the *n*=1 mode and the radiation asymmetry in pre-thermal quench



The same correlation between *n* =1 growth rate and P_{rad} asymmetry in pre-TQ was again evident in the two gas jet experiments

Alcator C-Mod



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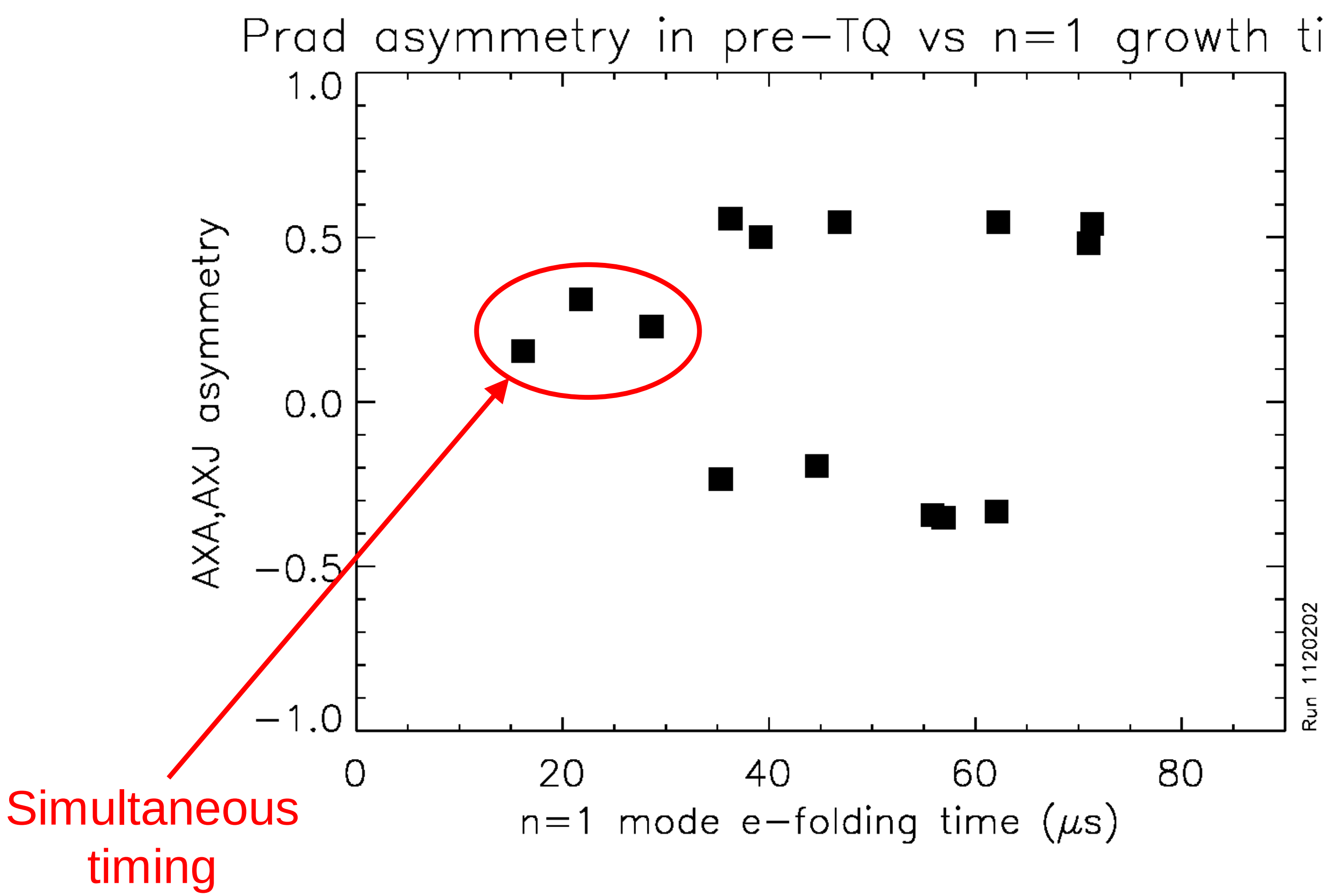


P_{rad} asymmetry and *n* =1 MHD mode

So there is a connection between gas jet injection, growth rates of *n* =1 MHD modes, and the P_{rad} asymmetry in the pre-TQ

Val Izzo is using NIMROD to investigate a possible connection between the location of a single gas jet relative to a fixed *n* =1 mode:

VA Izzo, PoP 20 (May 2013) p 056107

"Under certain circumstances, a single, localized gas jet could produce better radiation symmetry during the disruption thermal quench than evenly distributed impurities."

BUT

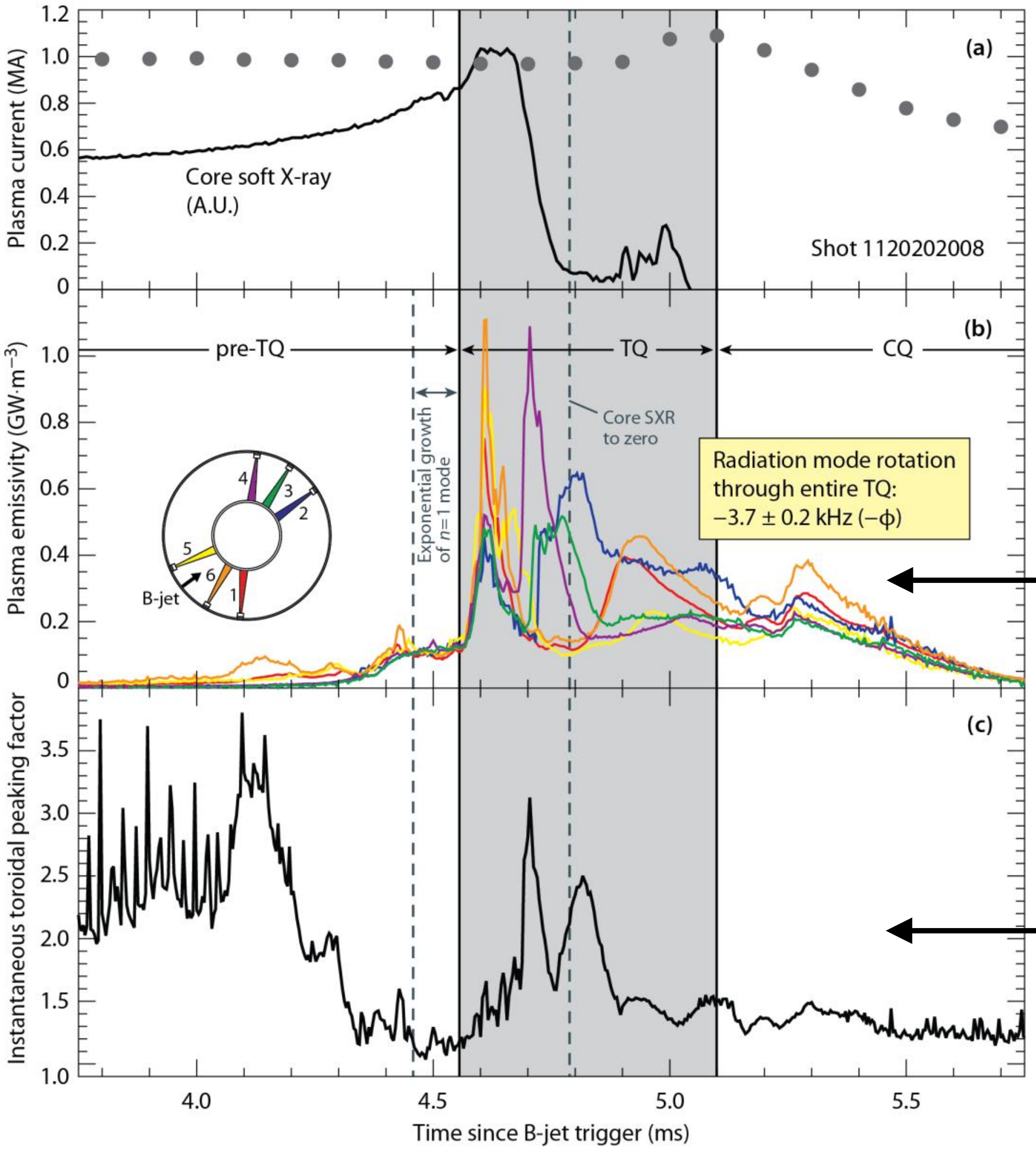
The connection with the *growth rate* is not explicitly discussed.

New Results on P_{rad} asymmetry in the TQ

Previous slides pertained to pre-thermal quench phase. What about the thermal quench phase?

Analysis of data from the set of single-channel AXUV detectors shows a toroidally peaked P_{rad} during the TQ, which often is rotating.

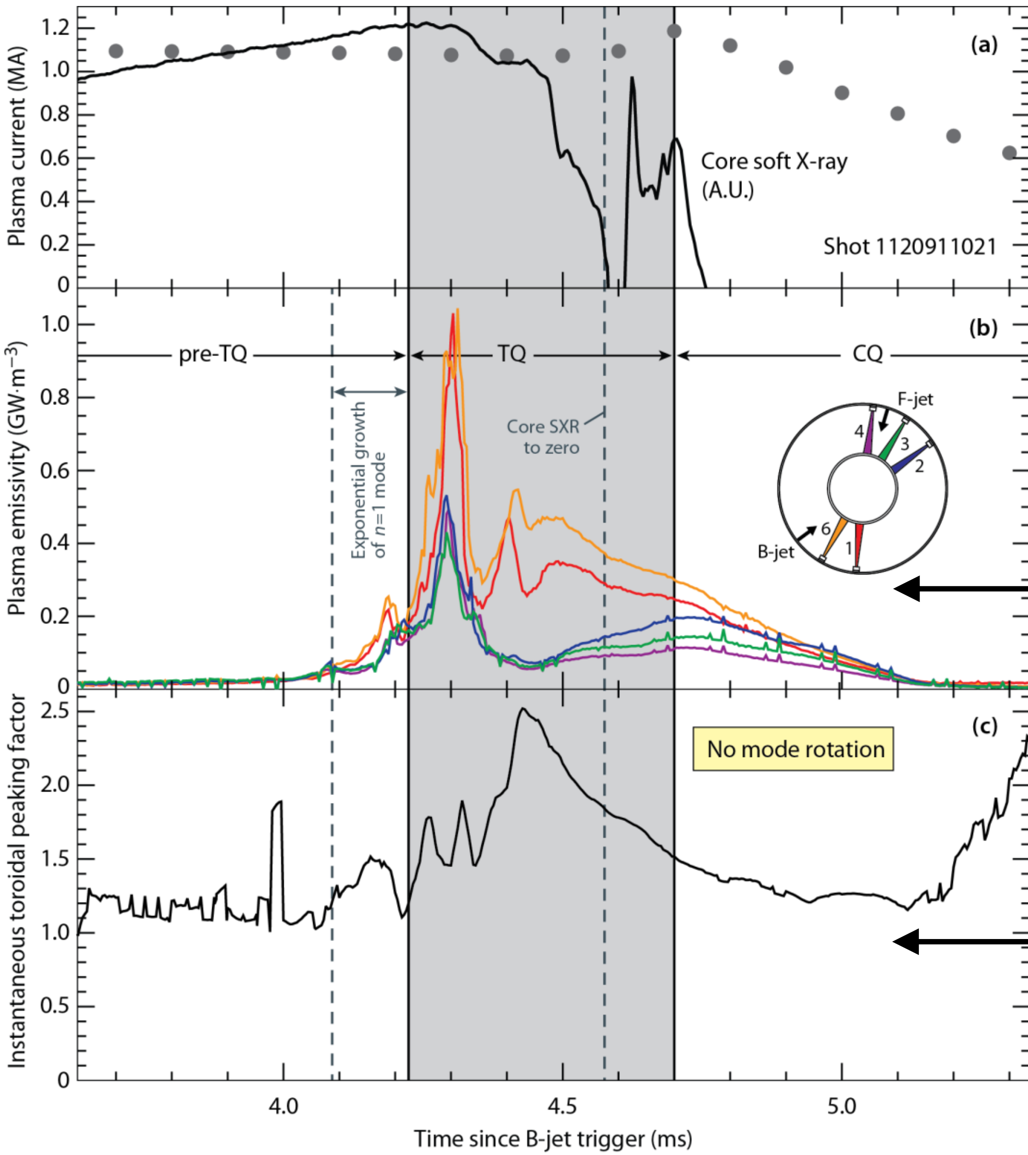
MGI disruption with rotating P_{rad} feature in TQ



Six AXUV signals show a P_{rad} peak that rotates toroidally at a few kHz

Low toroidal peaking factor averaged over TQ

MGI disruption with stationary P_{rad} feature in TQ



Six AXUV signals show a P_{rad} peak, but no rotation

Higher toroidal peaking factor averaged over TQ

Analogy to rotating lighthouse beam

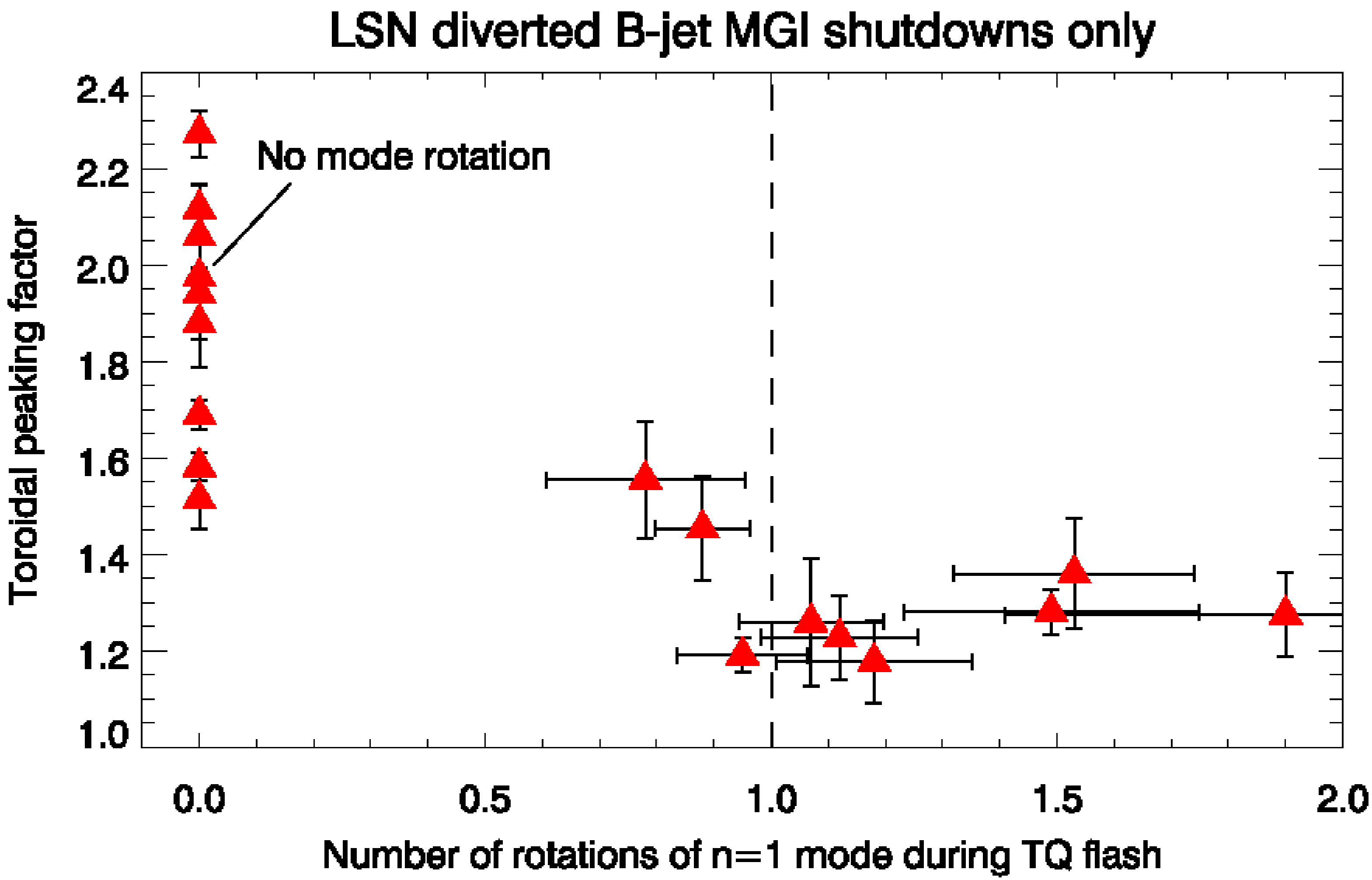
Alcator C-Mod

n =1

Multiple toroidal revolutions in TQ $\longrightarrow$ low average TPF

None or fractional toroidal rotation in TQ $\longrightarrow$ high average TPF

Correlation of TPF with P_{rad} rotation rate



Questions

Does the *n* =1 MHD mode in the pre-TQ have anything to do with the P_{rad} peak in the TQ?

Does the rotating P_{rad} peak in the TQ have anything to do with rotating halo currents occurring later in the CQ?

What determines the growth rate of the *n* =1 MHD mode in the pre-TQ?

- Simultaneous firing of the two gas jets gives fast growth rate, and low P_{rad} asymmetry

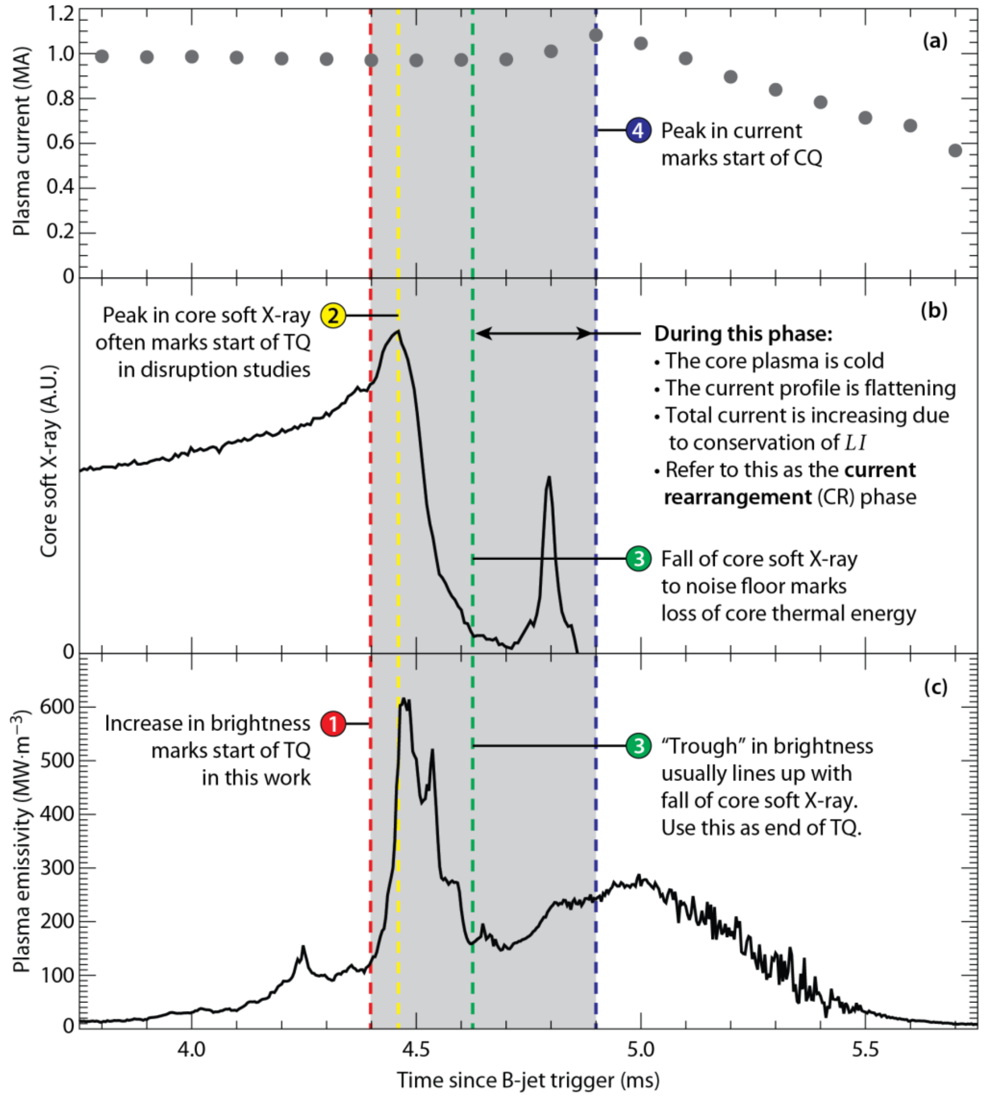
What determines the rotation of the P_{rad} peak in the TQ?

- Simultaneous firing of the two gas jets results in no rotation, and high P_{rad} peaking

Summary of C-Mod results with two gas jets and implications for ITER

- During pre-thermal quench, the P_{rad} asymmetry can be reproducibly reduced using two gas jets with proper timing
  - There is a correlation between P_{rad} asymmetry, n =1 MHD growth rate, and relative timing of multiple gas jets
- During the thermal quench, the P_{rad} asymmetry is not well controlled with two gas jets.
  - P_{rad} asymmetry is correlated with rotation of peaked P_{rad} and relative timing of multiple gas jets
  - In ITER disruptions, it is not known what fraction of energy will come out in pre-TQ vs TQ
- NEED TO DO THESE EXPERIMENTS ON ADDITIONAL TOKAMAKS (DIII-D, ASDEX-U, …)

Geoff Olynyk's definitions of TQ phase subdivisions



'Traditional' TQ phase can be split into 'TQ flash' and 'current rearrangement (CR)'