PFC Activities in Alcator C-Mod

G.M. Wright, The Alcator C-Mod Team, The PSI Science Center Team
Plasma Science & Fusion Center, MIT, Cambridge USA

Outline:

1. A closer look at operation with melted W tiles

- **Bruce Lipschultz, H. Barnard, J. Coenen, N. Howard, M. Reinke, G.M. Wright, D.G. Whyte**

2.Initial results from field-aligned ICRF antenna operations

- **Steve Wukitch, I. Czeigler, M. Garret, Y. Lin, J. Terry**

3.Initial results from dual gas jet disruption mitiagtion

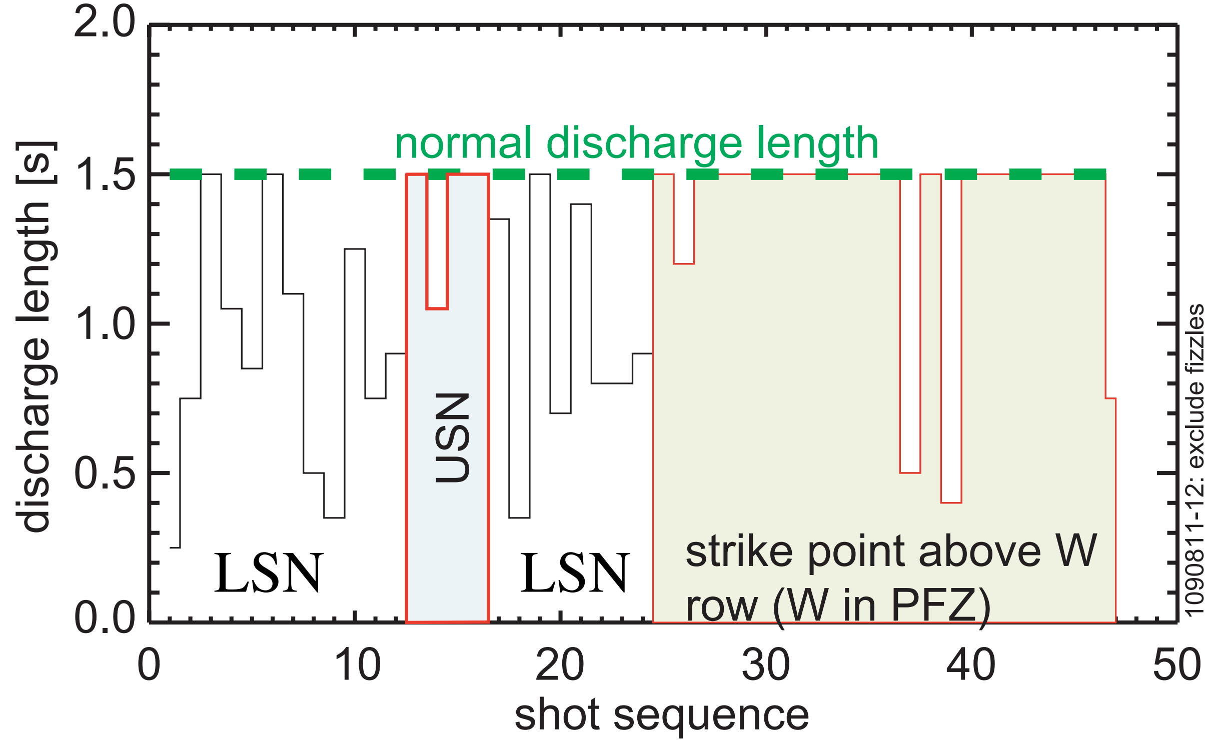
- **Geoff Olynyk, R. Granetz**

What happens when suddenly the tile surface is not smooth anymore?

- During the third run campaign in 2009 several tiles became loose with one falling out
  - ➢ What level of melting is acceptable?
  - ➢ Will the surface become smooth again – 'heal'?
  - ➢ Where does the melted tungsten go?

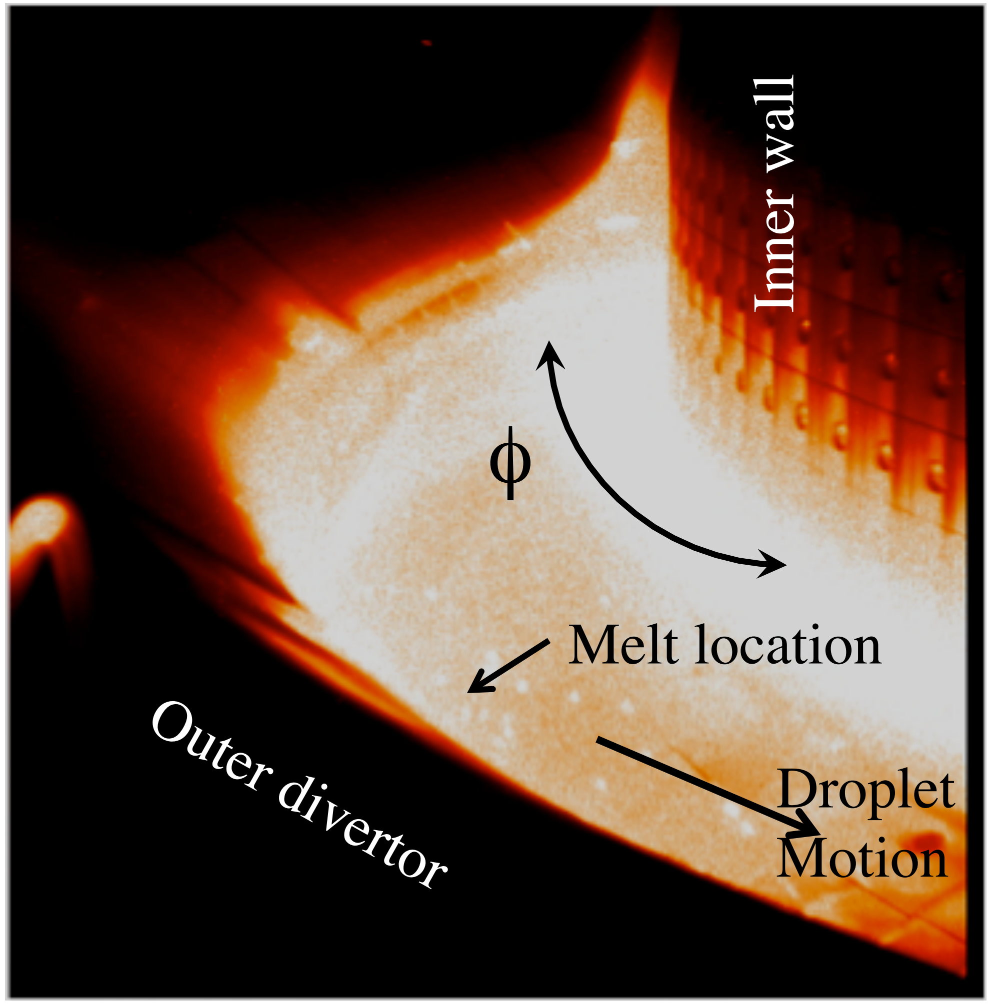
Sudden onset of tungsten-induced disruptions as power was raised

- About one month into the next run campaign (2009) the disruptivity, normally around 10%, increased suddenly to ~ 80%.
  - Core spectroscopy identified tungsten entering the core plasma
  - Movement of the strike point off of the tungsten row reduced the disruptivity
  - **Strike point had to be kept above the tungsten row of tiles for the remainder of the run campaign**



Camera images determined the approximate location of the tungsten source

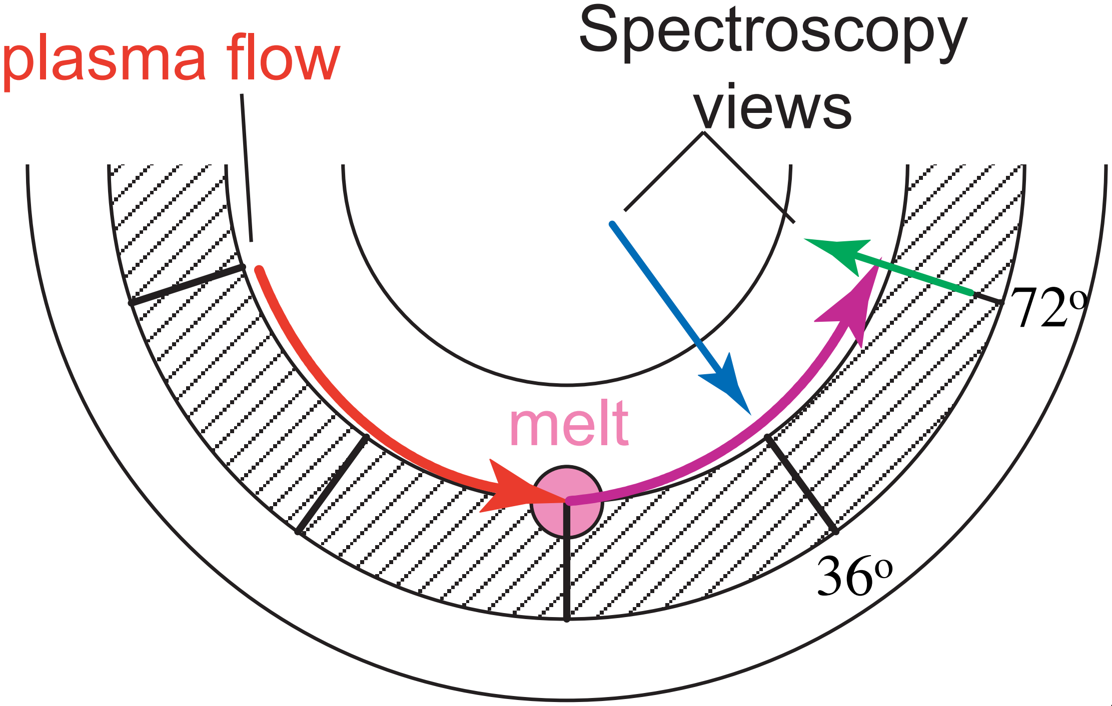
- Camera views localized the source to one point toroidally – but no direct view of the damaged tile



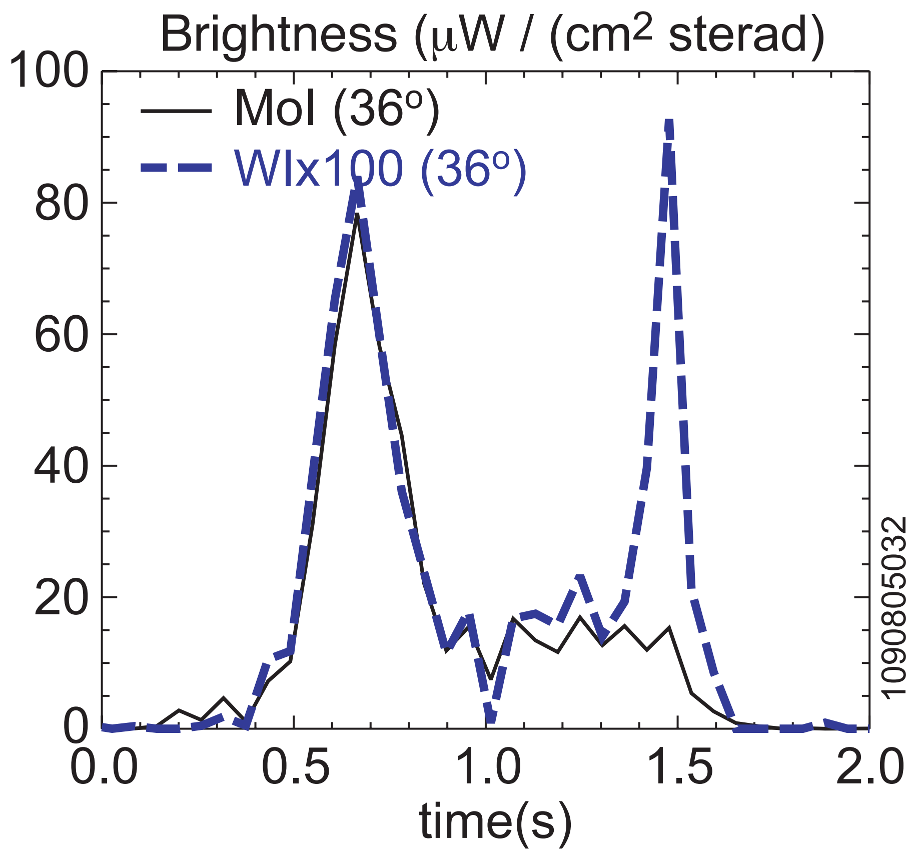
Camera images determined the approximate location of the tungsten source

- Camera views localized the source to one point toroidally – but no direct view of the damaged tile
- Droplet motion and plasma flow in the same toroidal direction
- Divertor spectroscopy views 36° and 72° away toroidally

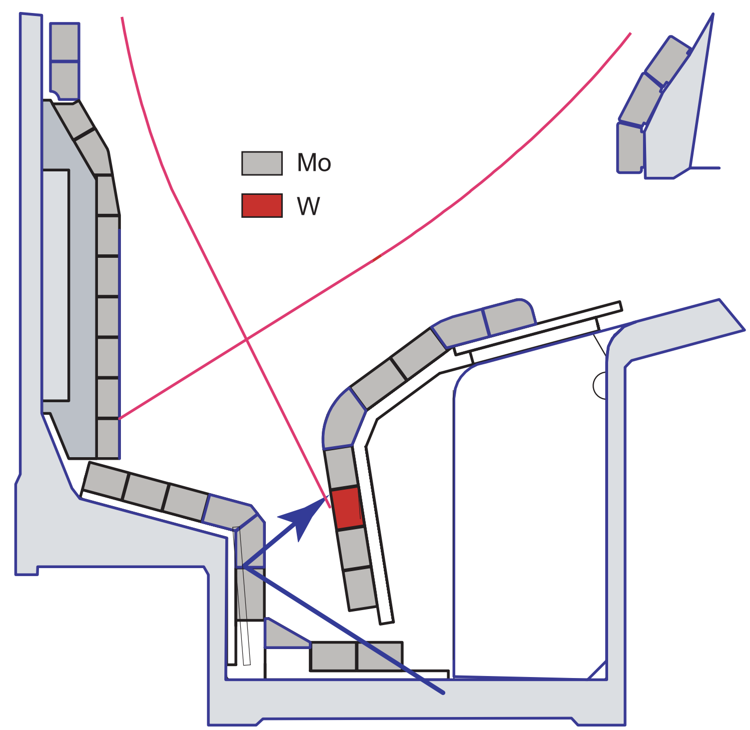
Top view of tokamak



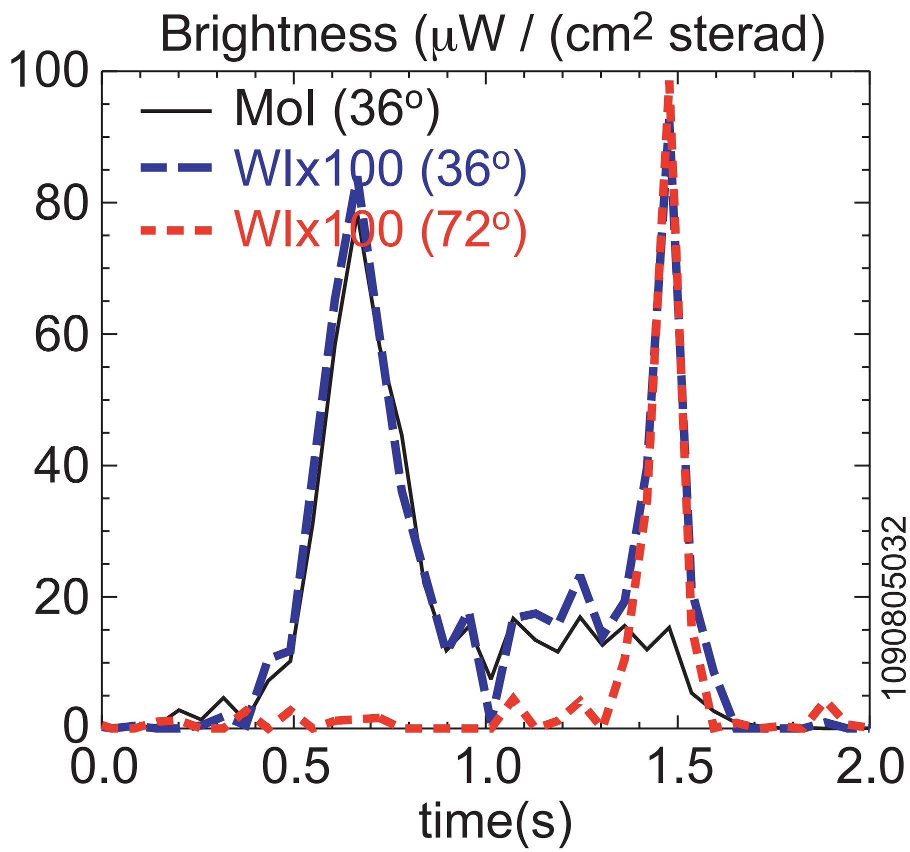
Sudden increase in WI relative to MoI ➔ change from sputtering to melting



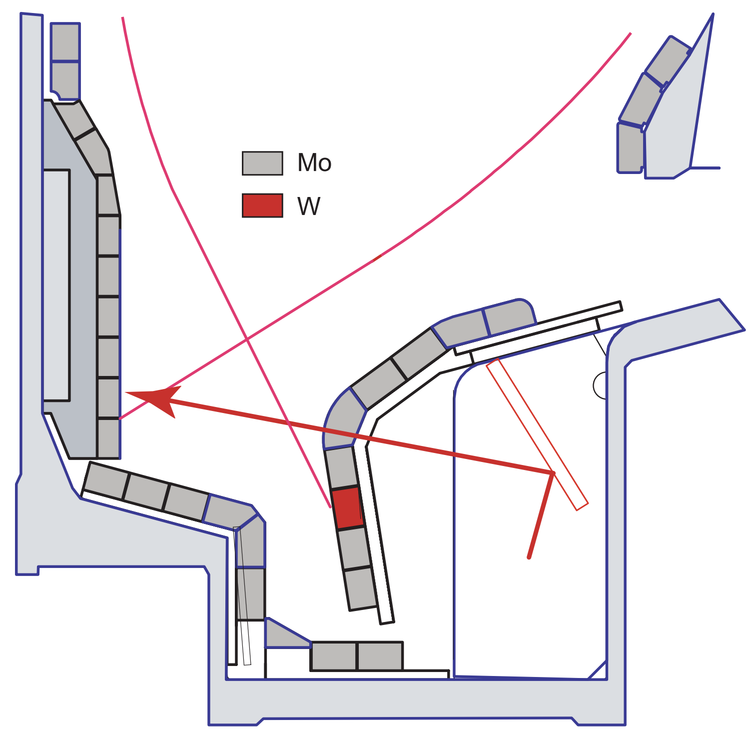
- Sudden increase in WI indicates melting



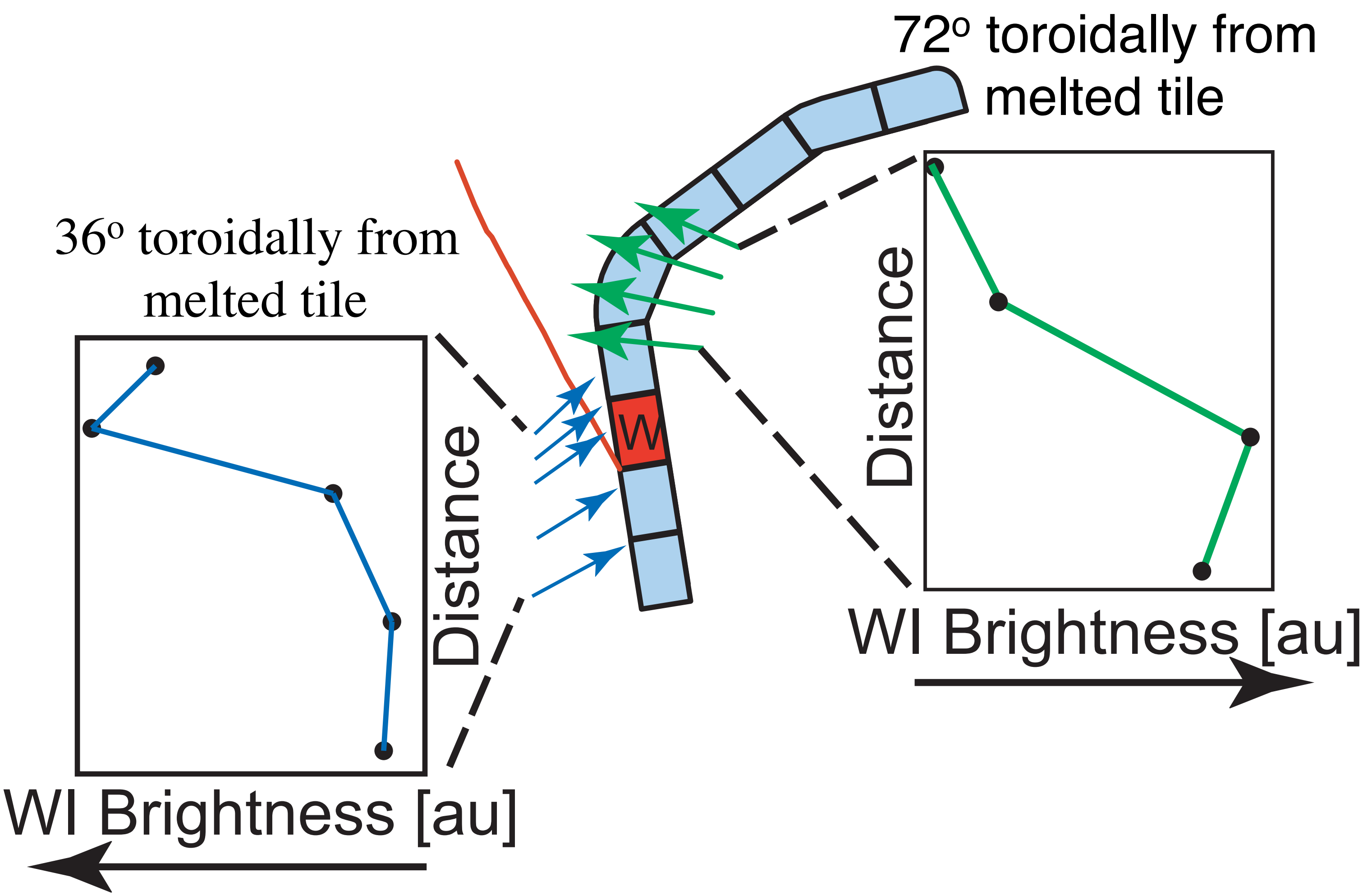
Sudden increase in WI relative to MoI ➔ change from sputtering to melting



- Sudden increase in WI indicates melting
- Increase in WI also observed for views looking through outer to inner divertor
- BUT – melted tile is 72° away toroidally
  - **=> Tungsten moving toroidally as multi-atom 'cluster' or droplets**

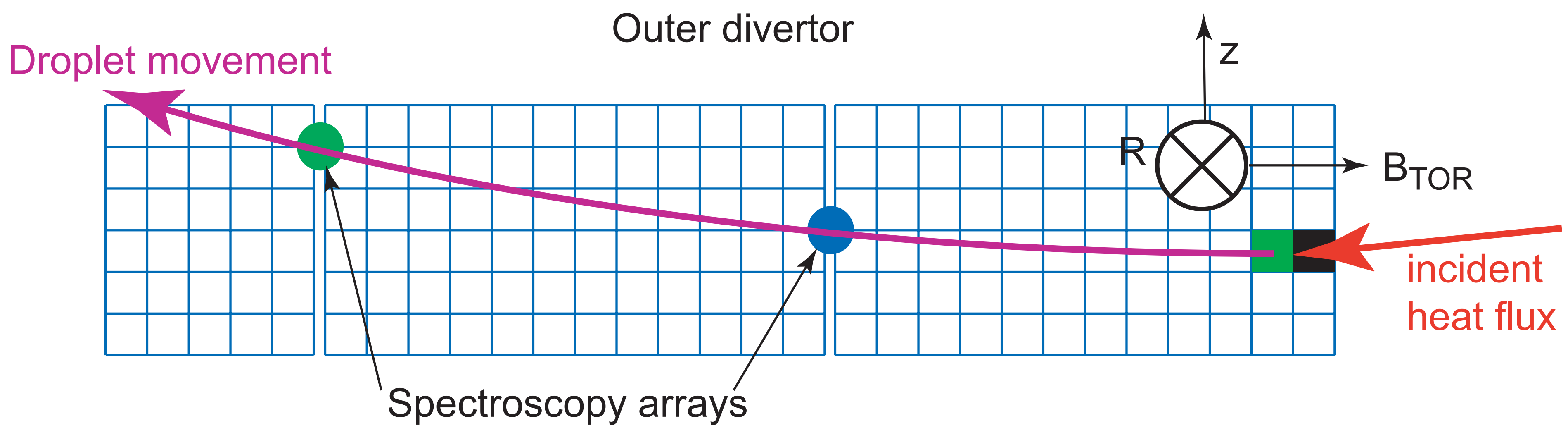


Spectroscopy data also indicates droplet movement up and out of the divertor



Spectroscopy data also indicates droplet movement up and out of the divertor

- Droplet movement toroidal with plasma flow, but up out of the divertor

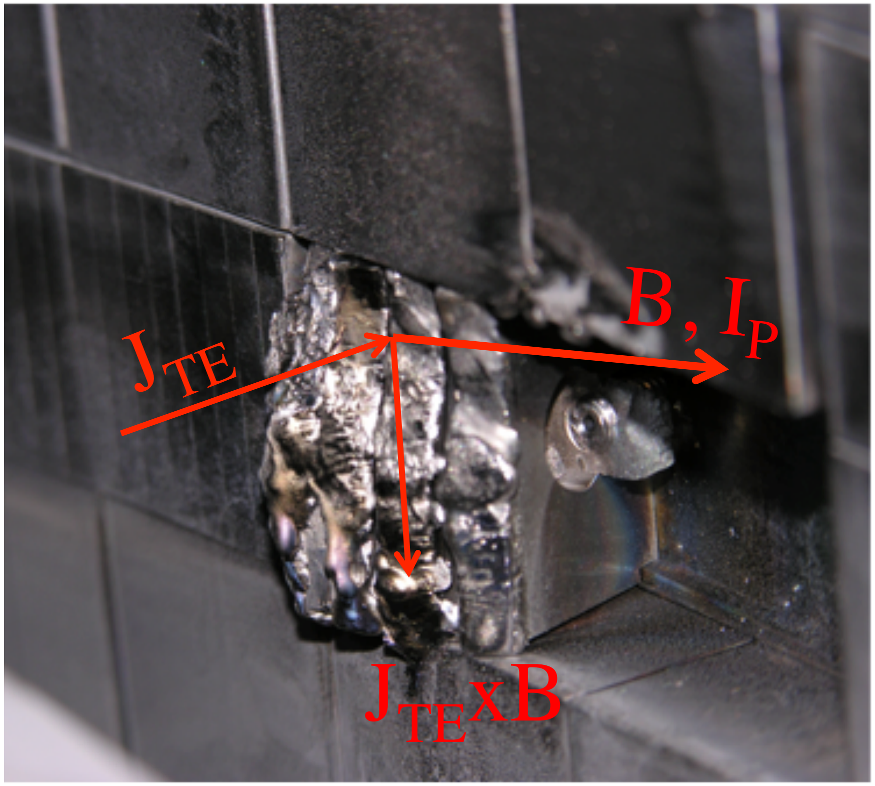


- Model* predicts movement toroidally in the direction of the flow but downwards

*Krasheninnikov S. I., et al., *Physics of Plasmas* **11** (2004) 3141

During the following vacuum break we found two melted tiles

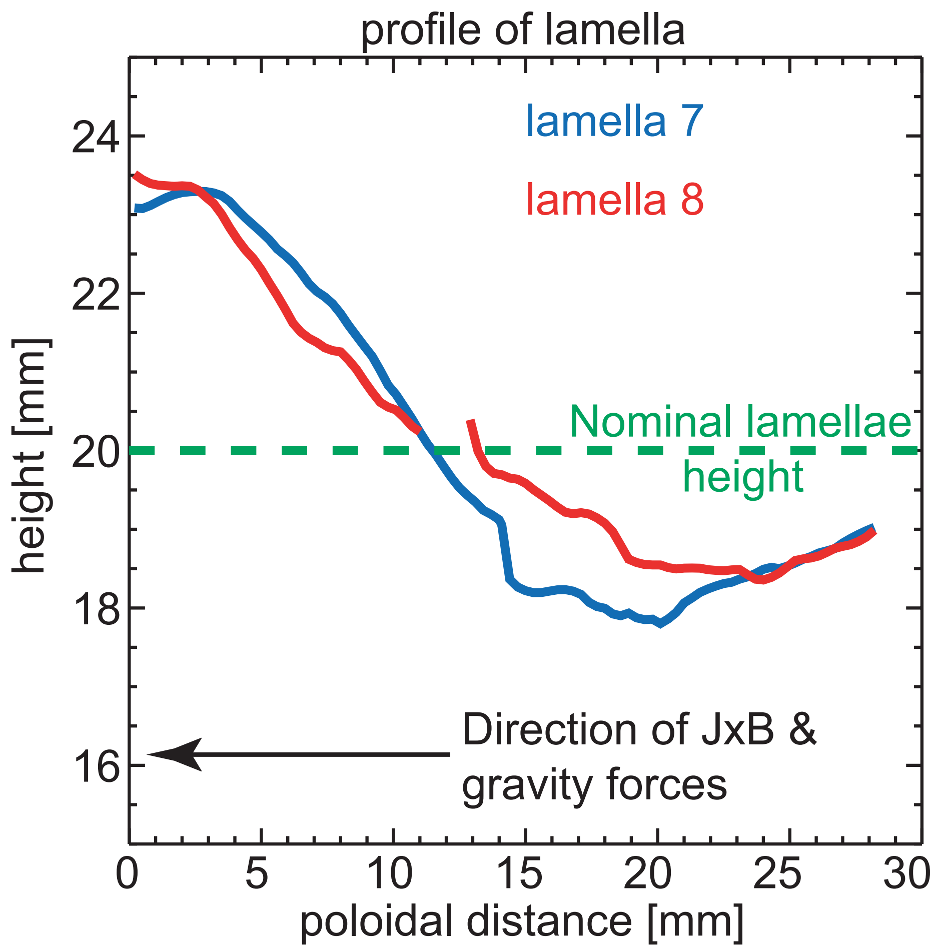
- The tiles were not only leading edges – but they were sticking out into the divertor plasma by > 4mm => taking the power load from ~ 14 other tiles!
- The movement of tungsten is consistent with thermoelectric - emission JxB forces as in TEXTOR studies*



*Coenen J. W., Philipps V., Brezinsek S. *et al.*, *Nuclear Fusion* **51** (2011) 083008

There was significant movement of the melted tungsten with large loss rates

- Hills (3 mm in height) of tungsten accumulated over ~ 100 discharges
  - Lamella weights show lost tungsten from a single tile of order 10 grams*
  - Second tile tungsten loss ~ 5-10 grams
    - **W sputtering loss (previous 2 run campaigns) from full toroidal row ~ 0.1g[1] (4000s of operations)**



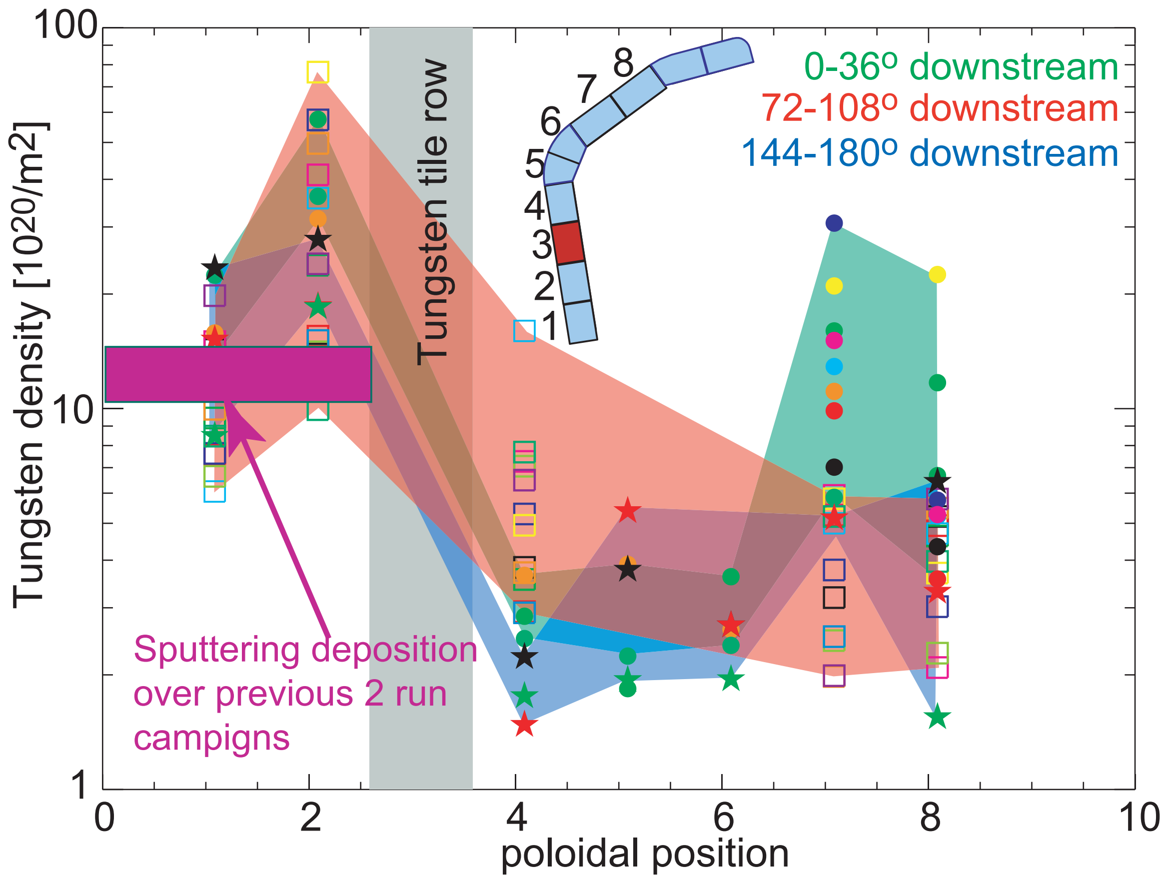
- Note the positive feedback loop

  If a melt 'hill' builds up then it will intercept more power – leading to more protrusion from the surface

[1]H. Barnard et al, J. Nucl. Mater. 2011

A small fraction of the melted/missing W can be found on the outer divertor

- W areal density on Mo tiles measured on 3 of 10 divertor sections after the 2009 run campaign
  - Difference to pre-campaign W measurements gives amount due to W migration from melting
  - The deposited W only accounts for of order 0.1g,~ 1% of the melt loss
  - => most melted W ended up as dust



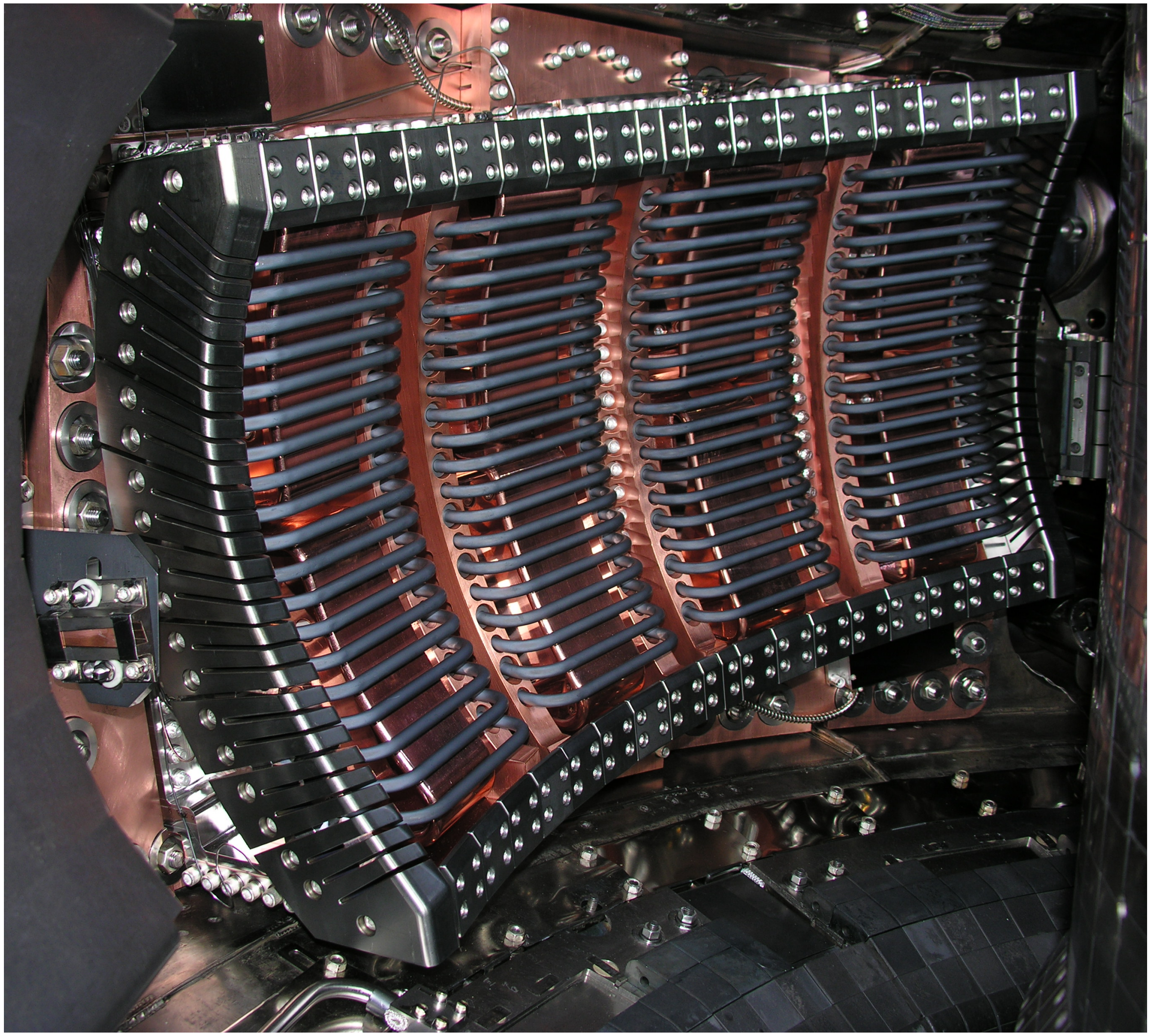
The effect of droplets on ITER will be less than in C-Mod

- Mo and W dust sizes observed at C-Mod, TEXTOR, ASDEX-Upgrade, QSPA range from 20 microns to 100 microns
- Droplet size required to radiate all the input power (based on Cooling rates*)
  - 160 microns for C-Mod (➔ multiple droplets affecting the C-Mod plasma)
  - 900 microns for ITER
    - 100 micron droplet ➔ <1 MW in ITER
    - Require 750 droplets, 100 microns in dia., to radiate all ITER power
- Distance from the divertor to the separatrix
  - L_{ITER}/L_{CMOD} ~ 9, longer distance over which the droplet will be eroded => likely much less of the droplet crosses the separatrix in ITER

- Larger threat to ITER operation may be due to leading edge intercepting more power than cooling tubes can carry away -> cooling tube failure and water leak.

*Post D.E., Jensen R.V., et al., *Atomic Data and Nuclear Data Tables* **20** (1977) 397

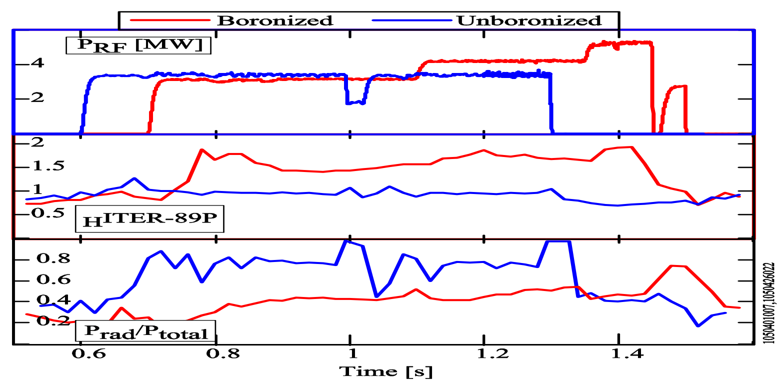
Field Aligned (FA) ICRF Antenna



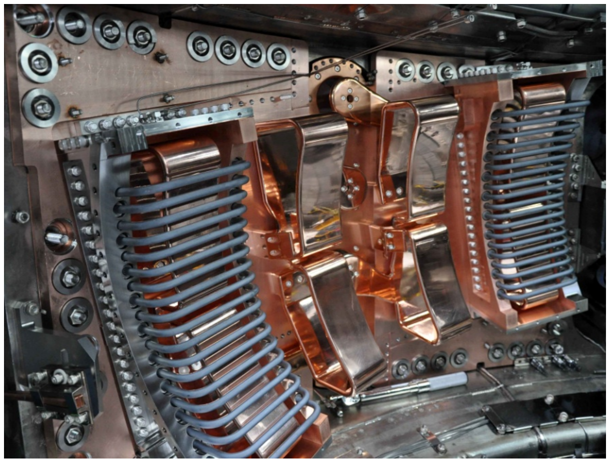
Motivation: Impurities with ICRF Antenna Operation are Universally Observed

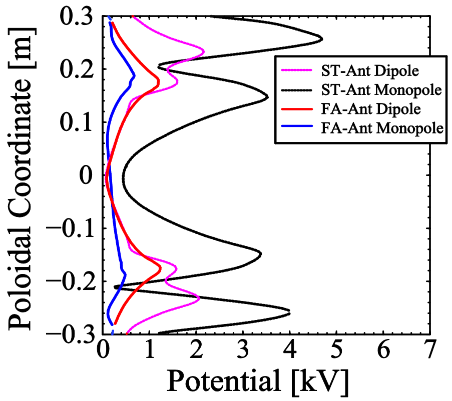
- Impurity influx during ICRF operation can limit plasma performance, particularly high performance discharges.
  - ➢ H-mode performance with ICRF and metallic PFCs is insufficient.

- While increased impurities with ICRF is generally observed, the underlying physics is yet unclear and detailed phenomenology often differs.
  - ➢ **C-Mod ➔** data indicates the primary RF impurity source is away from the antenna.
  - ➢ **ASDEX-Upgrade ➔** data indicates RF source is the RF limiters.
  - ➢ **JET ➔** data indicates the Faraday screen was primary source.



Can a field aligned antenna reduce ICRF-induced impurities? Symmetry is the key





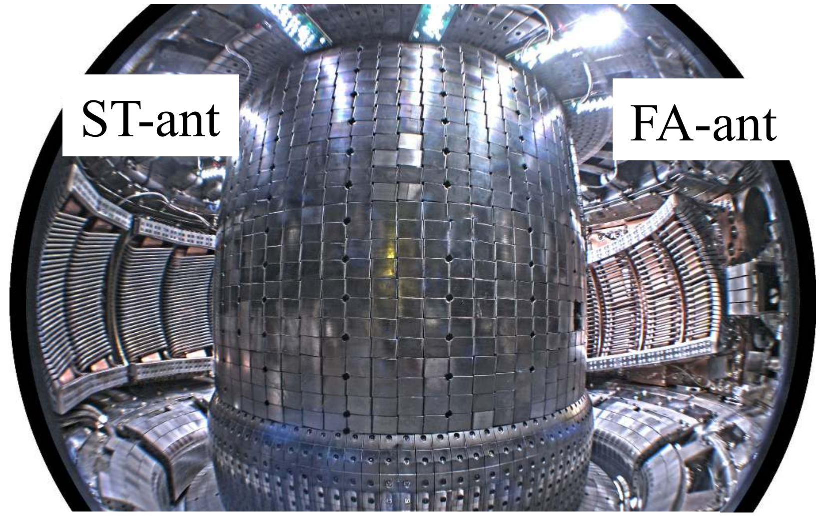
- Underlying cause of impurity contamination is thought to be the presence of unwanted $E_{||}$.
- Rotate antenna straps and structure 10° to be perpendicular to total B field.
  - Along a field line, integrated $E_{||}$ will be minimized due to **symmetry**.
  - Enforced each strap to have same flux area.
- To reduce impurities, present standard antennas are operated in dipole phasing rather than monopole to minimize impurities.
  - ➢ Significant reduction in integrated Ell is shown in simulations.
- For a Field Aligned antenna, the integrated $E_{||}$ fields are reduced for all antenna phases.
  - For [0, π], estimated sheath field is reduced ~2-3.
  - For [0,0], sheath field is negligible – a surprising prediction.

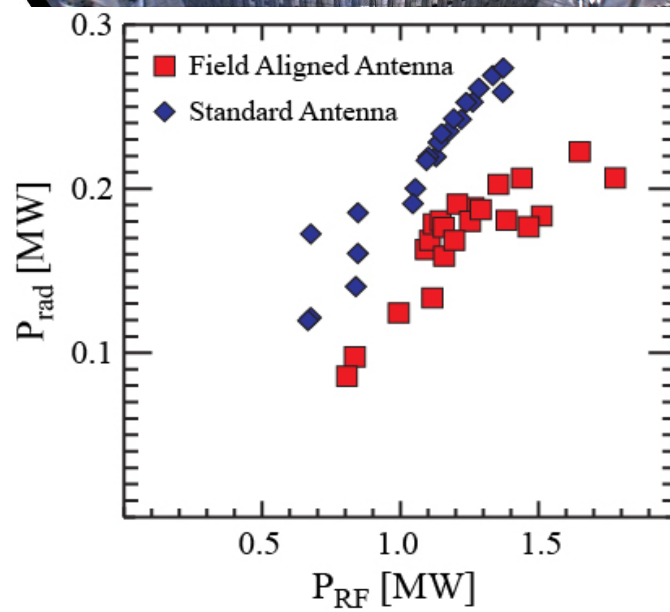
Initial Results are Promising

- Electrically the FA-antenna has performed well.
  - Antennas plasma conditioned very quickly (~15 discharges) to 2 MW (~7-8 MW/m^2).
  - Boronization recovery was faster than standard antennas (ST-ant).
  - Achieved 45 kV into plasma.
  - Neutral pressure limit exceeds that for ST antenna by factor 2 at a minimum.

- In L-mode with weak single pass absorption, FA antenna has lower core radiated power than ST antenna.
  - H fraction evolved from 10% to 20% during a discharge.
  - More typical H fraction is 5%.

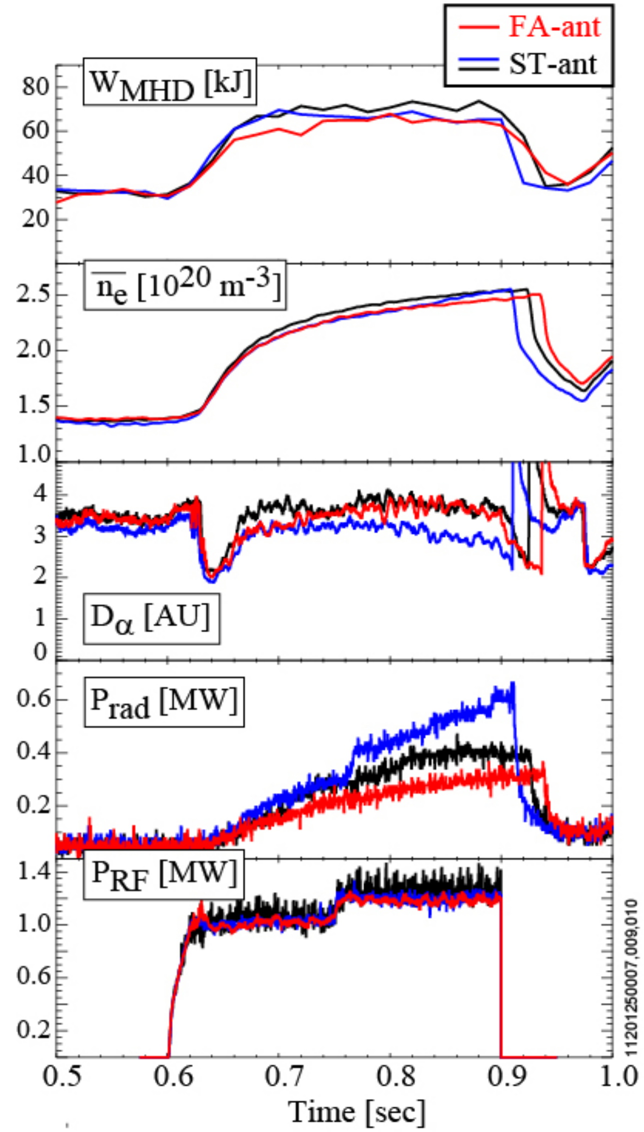
- Mechanical failure limited the FA antenna to two strap operation for this data.





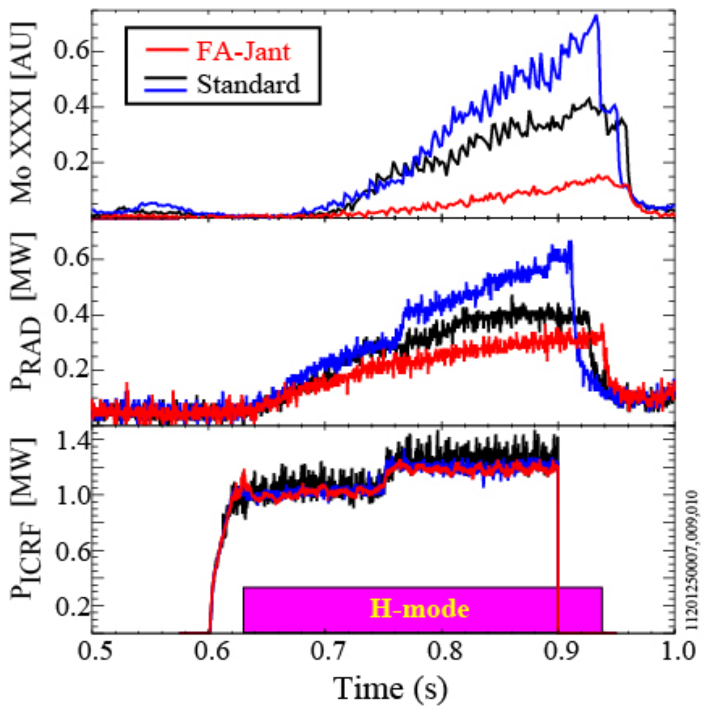
In H-mode, 2-Strap FA-Antenna has Lower Impurity Contamination

- H-mode performance is similar for all antennas.
  - Density, D_α, and stored energy time histories are similar.
- FA-antenna has lower radiated power.
  - Radiated power is ~20-30% lower than for the standard antennas.



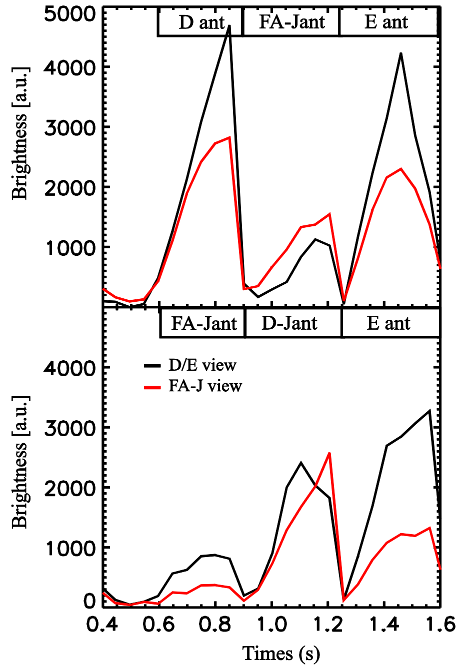
In H-mode, 2-Strap FA-Antenna has Lower Impurity Contamination

- H-mode performance is similar for all antennas.
  - Density, D_α, and stored energy time histories are similar.
- FA-antenna has lower radiated power.
  - Radiated power is ~20-30% lower than for the standard antennas.
- Core Mo is significantly lower for FA antenna compared to standard antennas.
  - Antenna protection tiles and PFC are Mo.



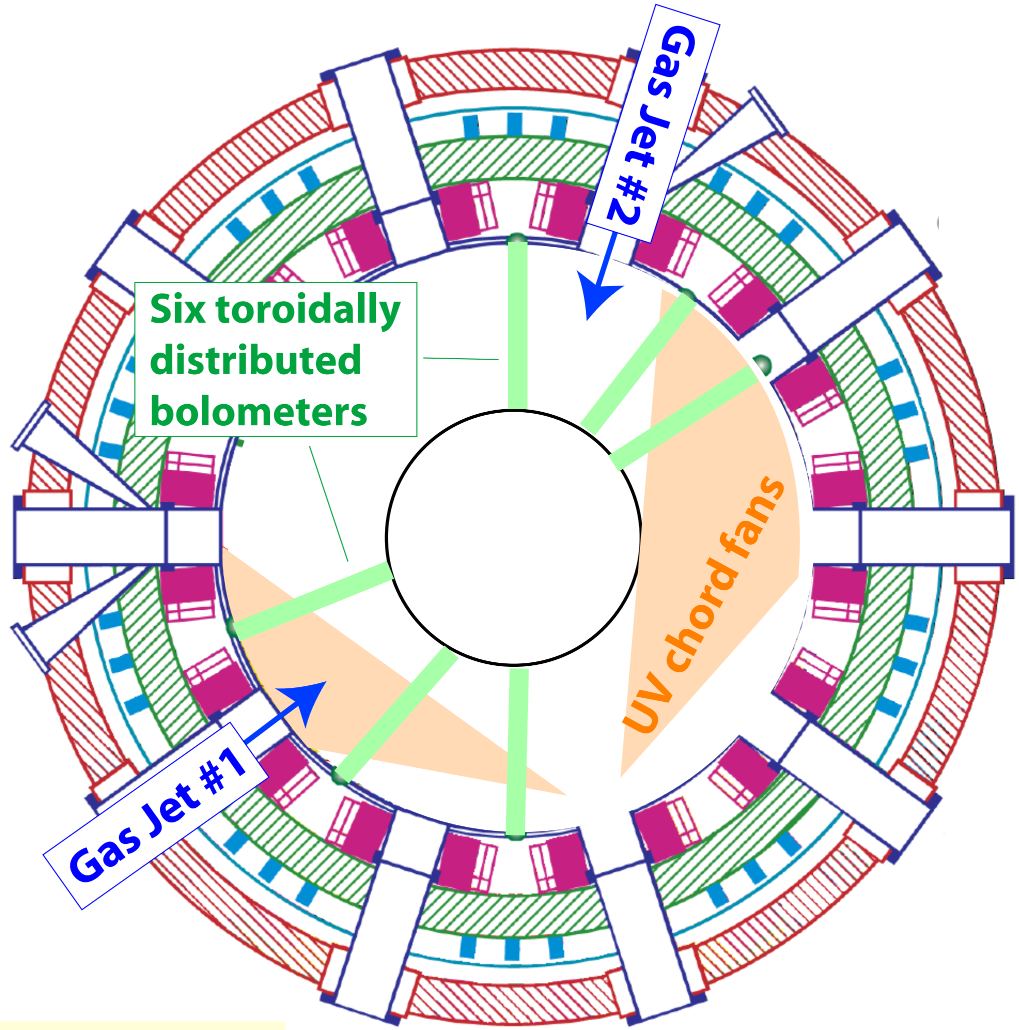
In H-mode, 2-Strap FA-Antenna has Lower Impurity Contamination

- H-mode performance is similar for all antennas.
  - Density, D_α, and stored energy time histories are similar.
- FA-antenna has lower radiated power.
  - Radiated power is ~20-30% lower than for the standard antennas.
- Core Mo is significantly lower for FA antenna compared to standard antennas.
  - Antenna protection tiles and PFC are Mo.
- Mo I source at FA-J antenna is lower than Mo source when D/E antennas are active.



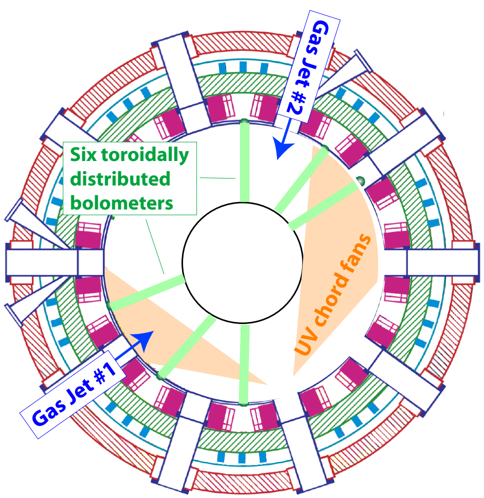
C-Mod has started to address the issue of radiation asymmetry during massive gas injection disruption mitigation

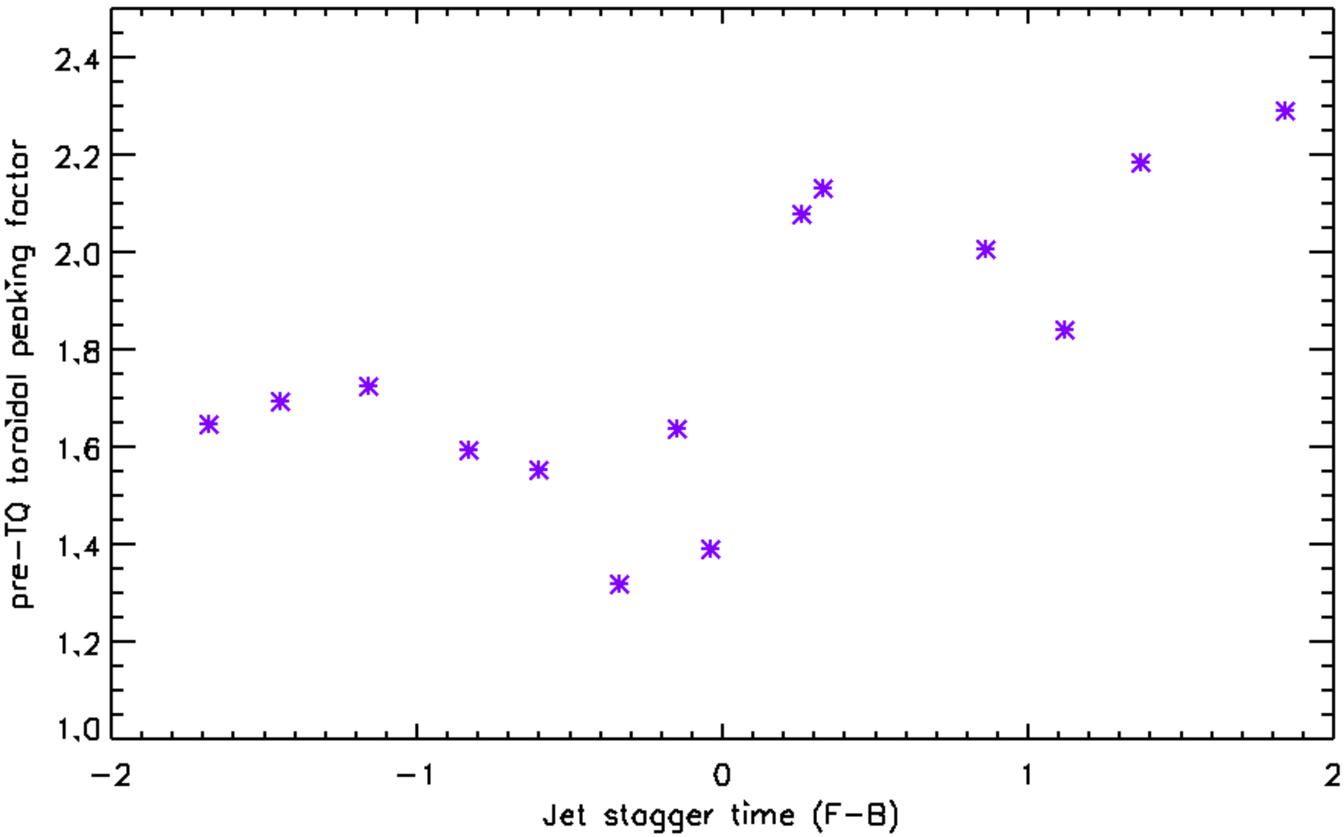
- **Two MGI jets distributed toroidally.**
- **Extensive bolometry upgrade to diagnose radiation patterns.**
- **Critical to US lead on disruption mitigation design for ITER**



G. Olynyk Ph.D. thesis

Initial results indicate that two gas jets affect (and improve) on radiation asymmetry early in mitigation





G. Olynyk Ph.D. thesis

Summary

- The melted W tile had an enormous effect on C-Mod operation
  - ➢ Normal strike point operation could not be utilized for the remainder of the campaign ➔ no "healing"
  - ➢ The melted tungsten appears to mainly convert to dust (e.g. ~10 g of mass loss from tiles but only ~0.1 g accounted for from deposition)
  - ➢ Radiation in the ITER core plasma from melt events is likely less than for C-Mod (longer ITER connection length to the seperatrix)
  - ➢ Main concern for ITER is overloaded cooling channels leading to a **water leak**.

- Field aligned ICRF antenna does reduce impurity contamination.
  - ➢ In L-mode, the radiated power fraction is lower 30% despite low single pass absorption.
  - ➢ In H-mode, the radiated power fraction is reduced by 20-30%.
  - ➢ Core Mo concentration is significantly reduced.
  - ➢ Mo source at the FA antenna is significantly reduced compared to when the standard antennas are operated.