PFC Activities and Tungsten Nano-tendril growth in Alcator C-Mod

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Outline:

1.I-mode and what it means for PFC

- **Dennis Whyte, Amanda Hubbard, Jerry Hughes, Bruce Lipschultz**

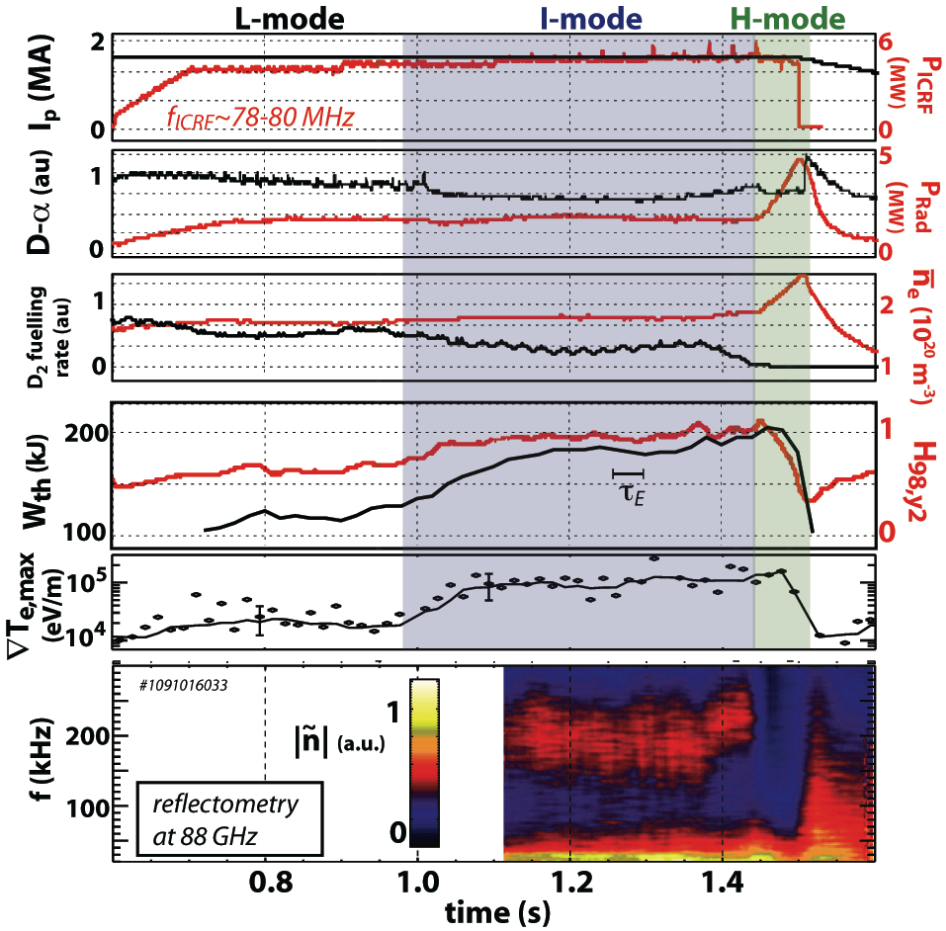
2.Measurement of thermal footprint and heat exhaust channel width

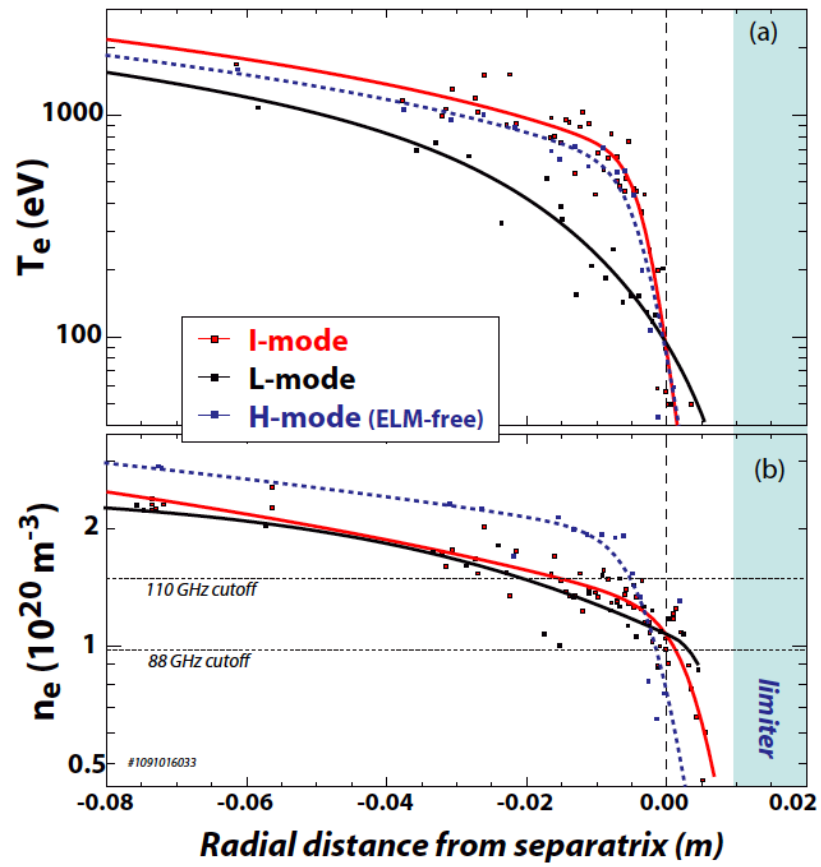
- **Brian LaBombard, Jim Terry, Dan Brunner, Jerry Hughes**

3.Tungsten Nano-tendril growth in the Alcator C-Mod lower divertor

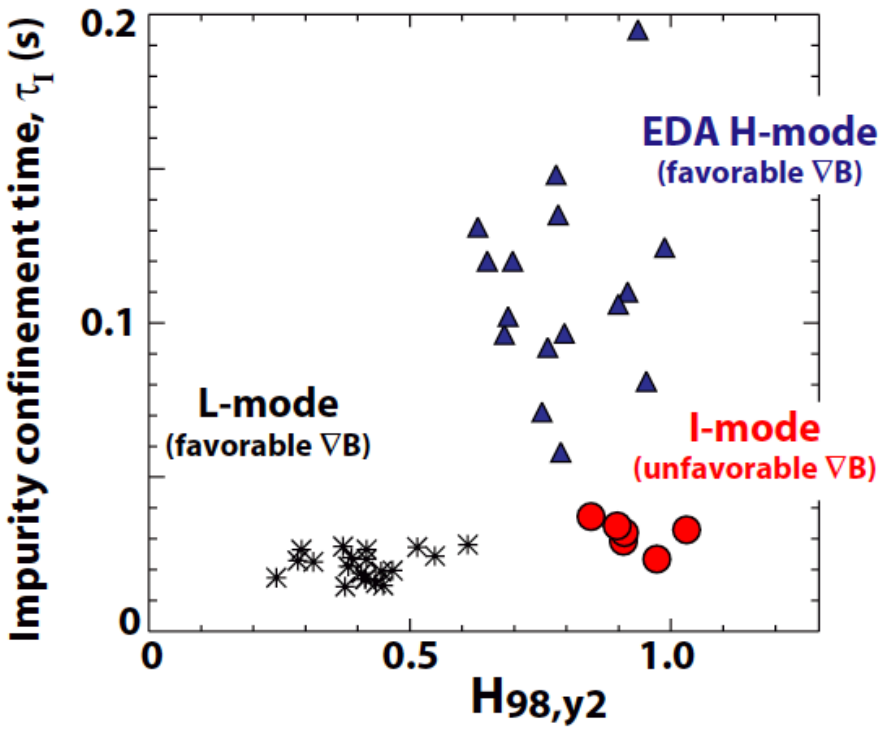
- **Graham Wright, Dennis Whyte, Dan Brunner**

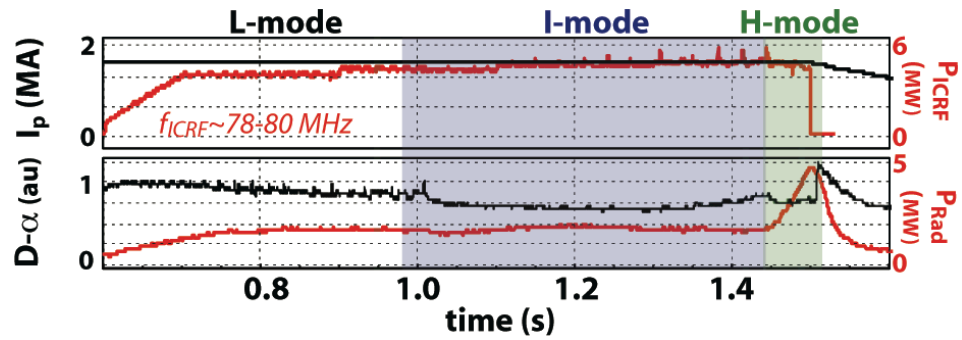
I-mode provides H-mode energy confinement with L-mode particle confinement. What does this mean for PSI?





Impurity confinement time decreases but hot core plasma remains, which is highly beneficial when running with high-Z walls



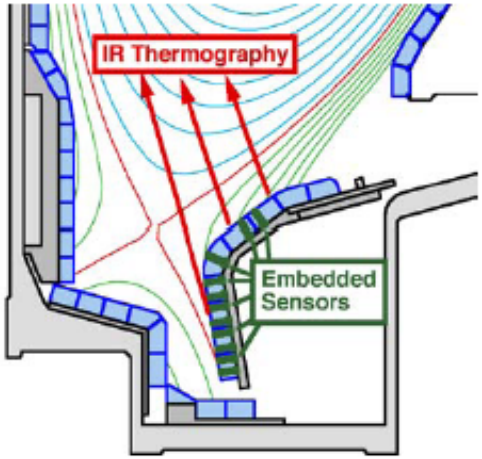


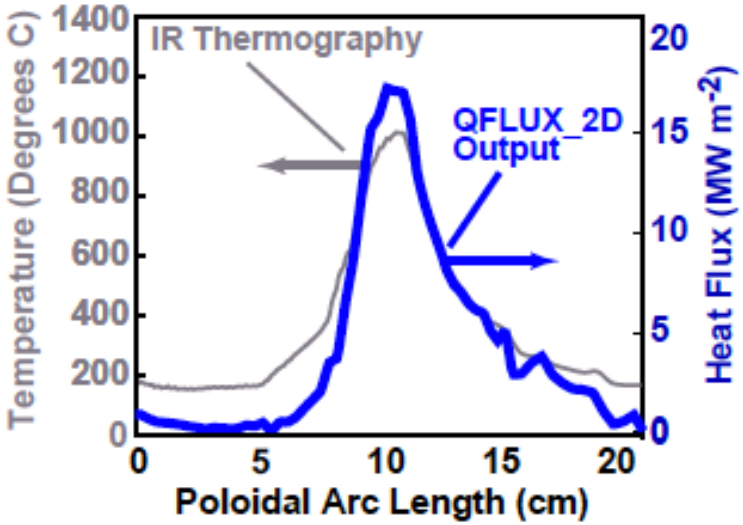
- P_{rad} remains at L-mode levels even with 4.5 MW P_{ICRF}

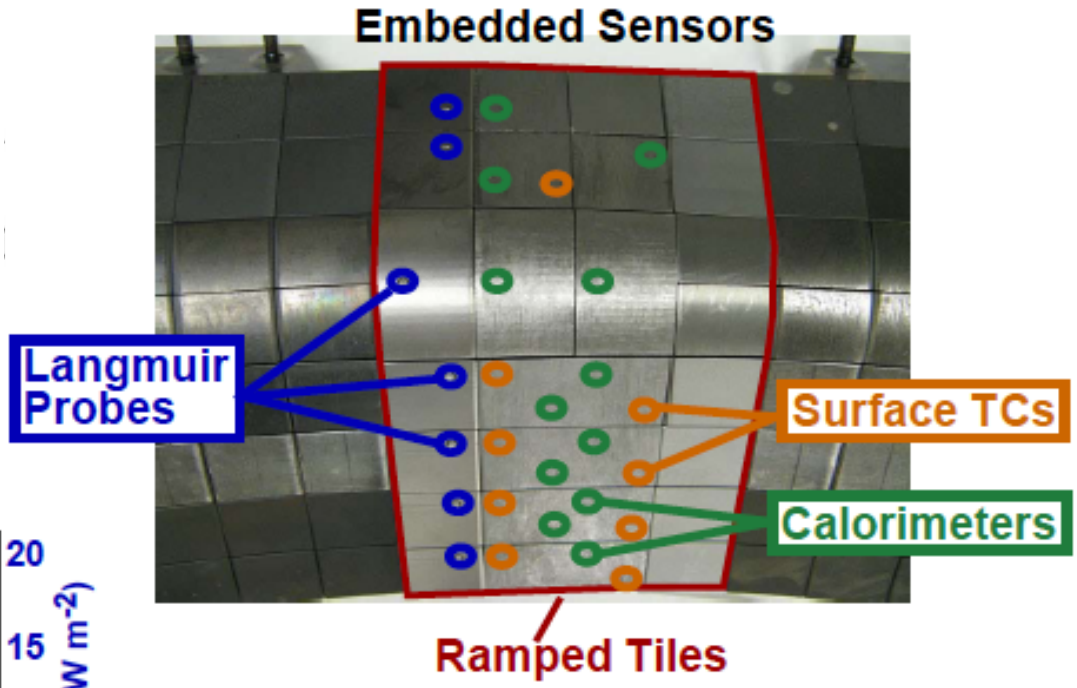
- I-mode is ELM-free in all cases. Unfavorable ∇B leads to symmetric heat loads (to the ISP).

- Z_{eff} ~1.4-1.6 with q_{95} ~ 4.8 in I-mode. Z_{eff} ~2-2.3 with q_{95} ~ 3

New thermal/heat load diagnostics have allowed great progress to be made in terms of wall heat load research on C-Mod

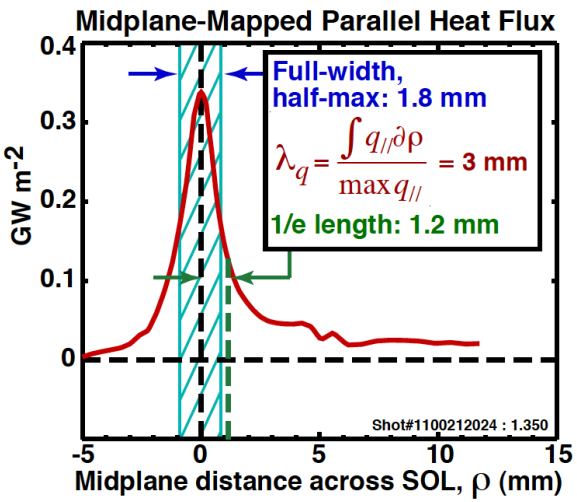






- Able to obtain surface temperature profiles.
- And heat flux/thermal footprint profile through modeling (QFLUX_2D)

There is very limited understanding of the heat channel width, λ_q, in the SOL despite this being critical in predicting wall heat fluxes



[Kirnev, *et al.*, PPCF 49 (2007) 689]

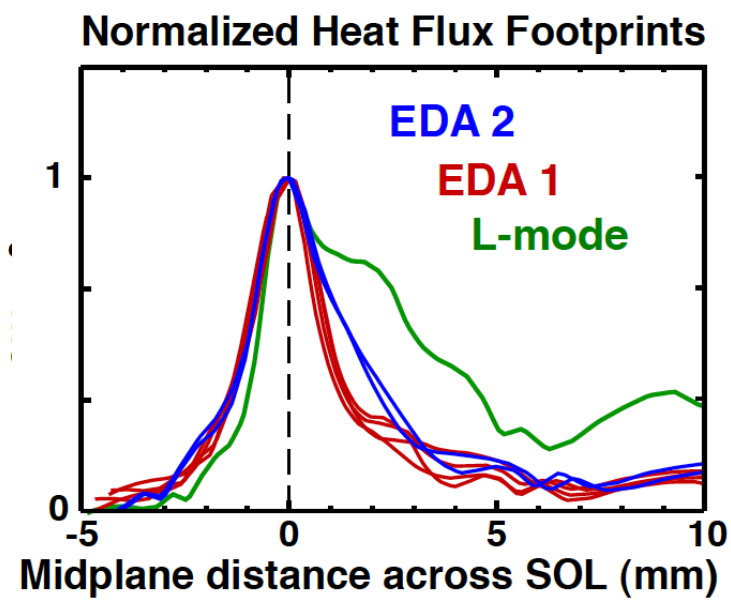
$$\lambda_q \propto P_{SOL}^{-0.5} B_\phi^{-1} q_{95} n_{e,u}^{0.25} R^2$$

Prediction: Integral λ_q ~ 0.7 mm

[Loarte, *et al.*, JNM 266-269 (1999) 587]

$$\lambda_q \propto P_{div}^{0.44} B_\phi^{-0.45} q_{95}^{0.57}$$

Prediction: Integral λ_q ~ 5 mm



- λ_q is invariant within the various modes despite several parameters evolving.

EDA 1 - rising density & impurities

➢ λ_q independent of n_e, P_{SOL}, P_{div}

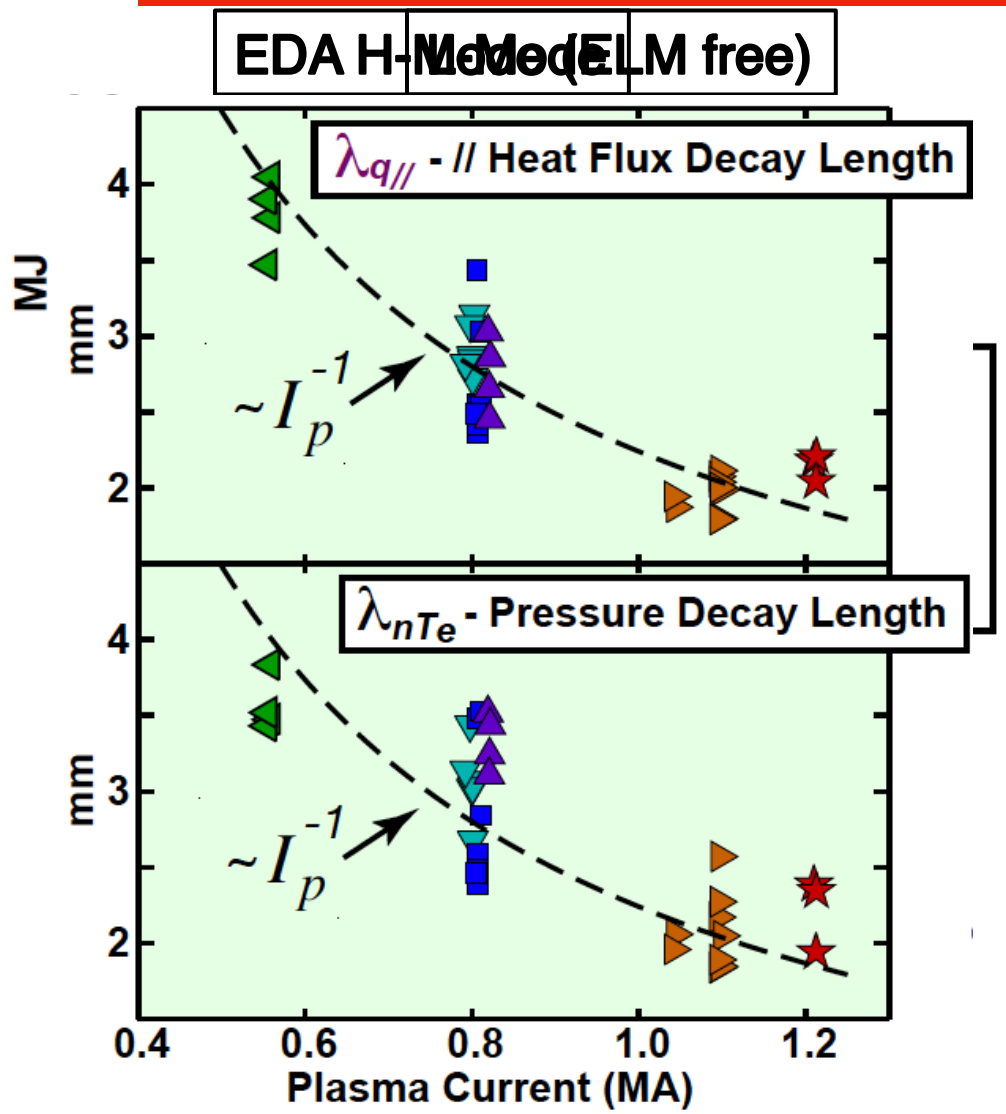
EDA 2 - falling density & impurities

- λ_q is strongly dependent on confinement mode.

Heat flux channel at the midplane at time slices of a single shot.

➢ key physics is being missed with empirical scalings.

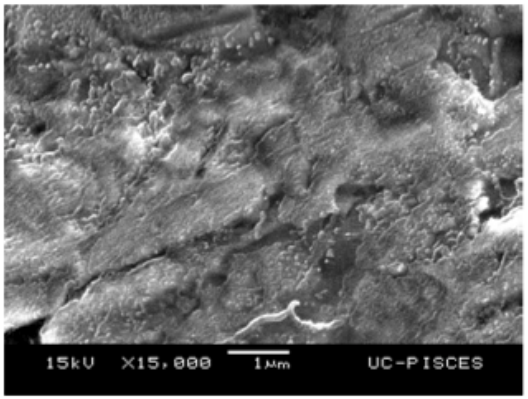
The strongest dependence of λ_q appears to be on plasma current; a scary thought for ITER.



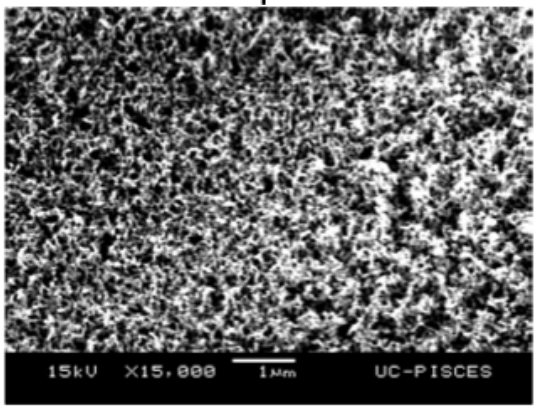
- $\lambda_q \sim I_p^{-1}$, so as plasma current increases, W_{Th} increases but the exhaust channel shrinks.
  - λ_q has a weak dependence on W_{Th} independent of I_P ($\lambda_q \sim W_{Th}^{-0.27}$)
- λ_q is independent of B_T, thus ruling out dependence on q_{95} or connection length.
  - Independence on connection length is confirmed with dedicated experiments.
- Same dependence found in L-mode.
- λ_q is set by pressure profile?

Will surface morphology of tungsten divertor material modify into "fuzz" under Helium bombardment in ITER and reactors?

- Linear plasma device like PISCES have grown micron-thick nano-tendril or "fuzz" layers from metallic Mo/W surfaces
- Recipe: Low-energy Helium ions + $T_{surface}$ ~900-1400 K
- These conditions are expected in ITER and reactor divertors.
- **However, fuzz never documented in tokamak divertor which has large differences to linear plasmas**
  - Grazing magnetic field vs. perpendicular
  - Transient vs. steady-state
  - Short ionization MFP & fluid-like transport vs. weak ionization & recycling.
- Exploit ITER/reactor similar C-Mod divertor
  - High heat flux, ITER density, Mo metal surfaces



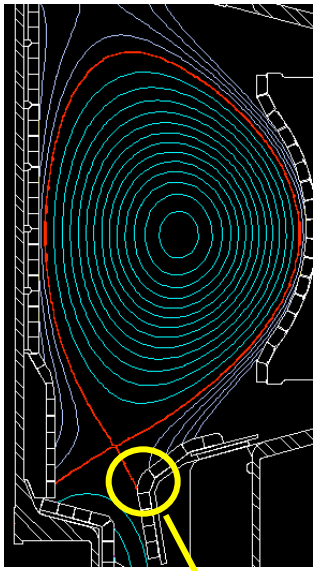
Unexposed



Exposed

Tungsten "fuzz" made in PISCES T_{surf} ~ 1100 K

C-Mod Helium plasmas produced necessary conditions for fuzz growth at the outer strikepoint



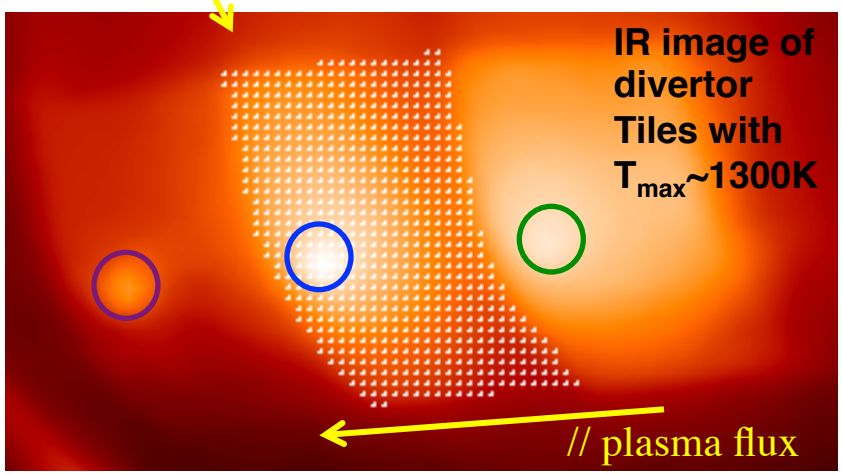
12 shots, ~ 3 MW ICRF, L-Mode

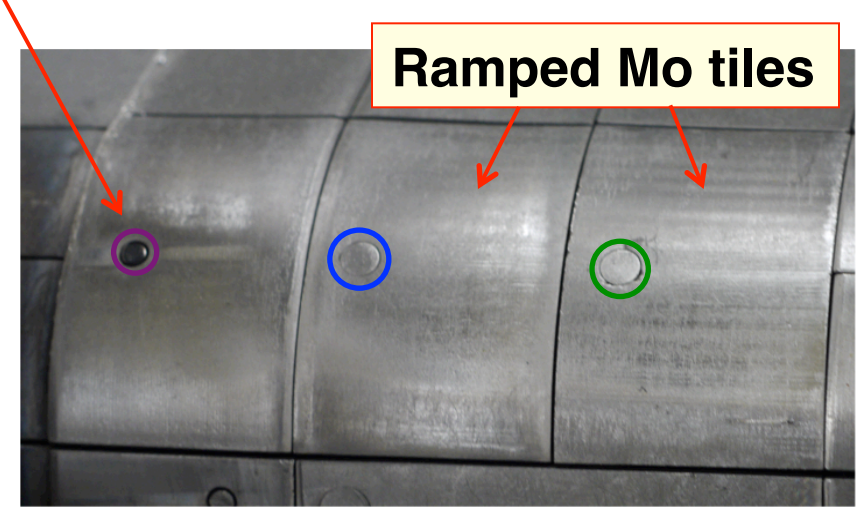
$T_{e,divertor}$ ~ 20 eV, $q_{//}$ > 0.2 GW/m^2

~ 12-15 seconds exposure

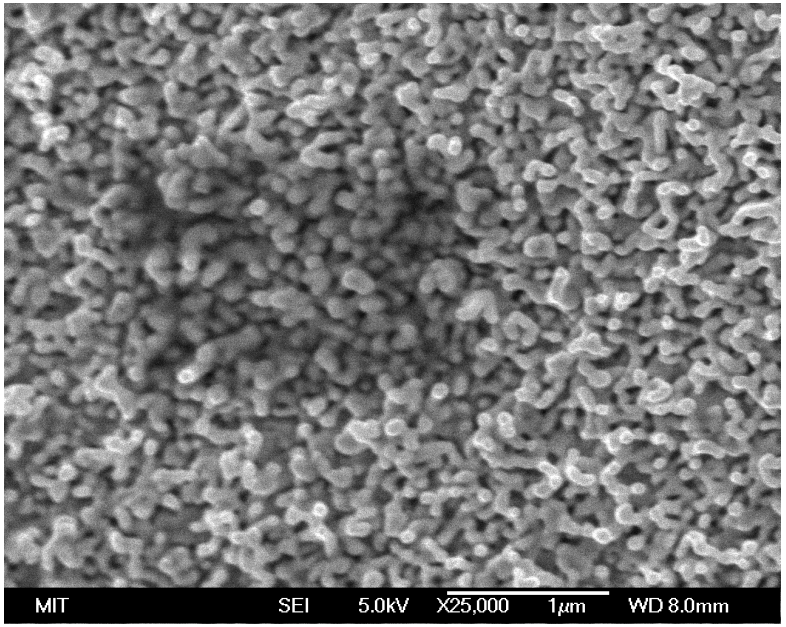
W langmuir probe and Mo calorimeters were hottest

Clearly reduced reflectivity of W probe indicative of fuzz



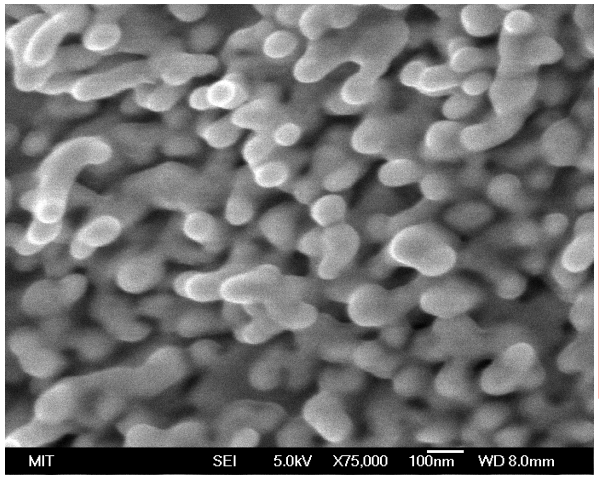


High resolution SEM imaging shows nano-tendrils are fully formed on surface of the tungsten probe

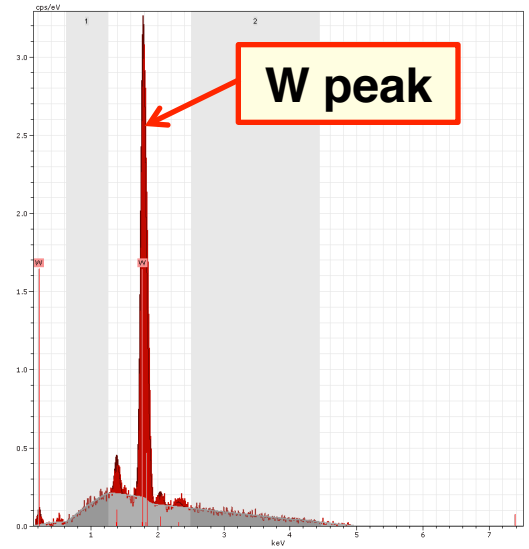


Fully formed nano-tendrils have almost total surface coverage of the probe tip.

EDX measurements confirm that the fuzz is ~100 % tungsten.



Thickness of individual tendril is 50-100 nm, which is thicker than tendrils grown in linear devices (20-30 nm)



Summary

- I-mode provides L-mode-like particle transport with H-mode-like energy confinement.
  - Impurity confinement time is low allowing for high P_{ICRF} without high P_{rad} or Z_{eff}.
- Measurement of heat channel width, λ_q, on C-Mod conflicts with previous empirical formulae, and instead shows a strong dependence on plasma current and confinement regime.
  - $\lambda_q \sim 1/I_P$, Independent of P_{SOL}, P_{div}, B_T, n_e
  - $\lambda_{q,\ L\text{-}Mode} >> \lambda_{q,\ H\text{-}Mode}$
- Tungsten nano-tendrils ("fuzz") has been grown in the C-Mod lower divertor.
  - PSI effects/implications of this fuzz layer is still largely unknown
  - Follow up experiments in DIONISOS to determine why no fuzz was grown on the Mo tiles.