Growth of tungsten nano-tendrils in the Alcator C-Mod Divertor

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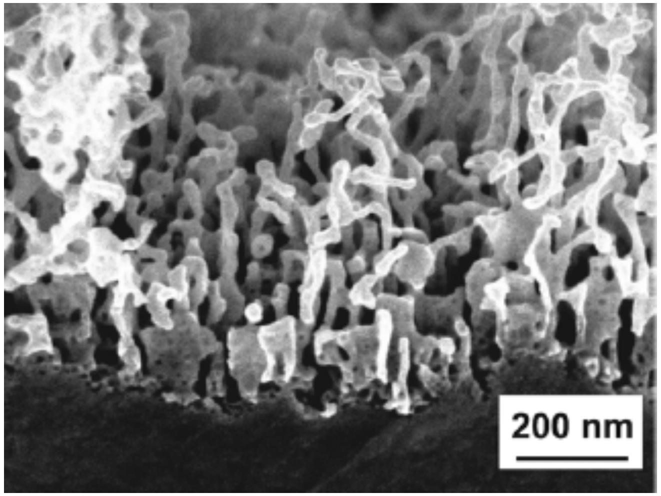
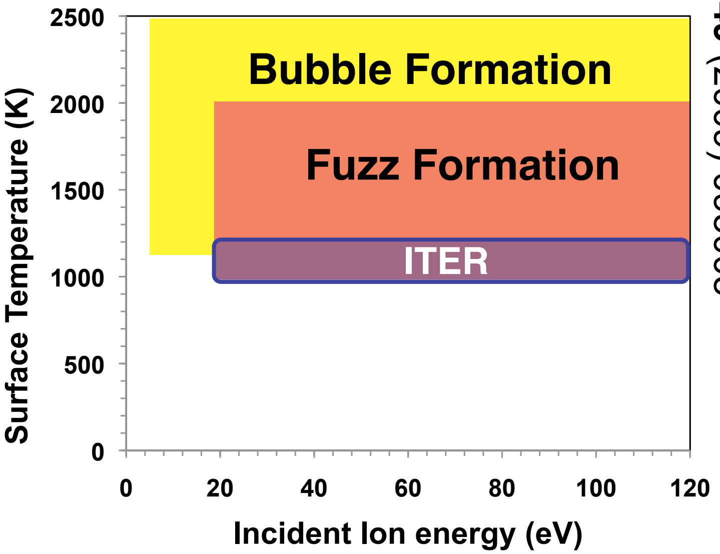
Alcator C-Mod

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

- Linear plasma devices, such as PISCES, have grown micron-thick nano-tendril or "fuzz" layers from metallic Mo/W surfaces
- He bubbles that precipitate in the bulk metal are playing an important role.
- The growth conditions are well-defined:
  - ➢ Clean, refractory metal surface
  - ➢ $1000\ K < T_{surface} < 2000\ K$
  - ➢ Flux of He-ions with $E_{He} \geq 20$ eV
  - ➢ $t^{1/2}$-dependence on layer thickness
- **All conditions are met for an all-W ITER divertor**





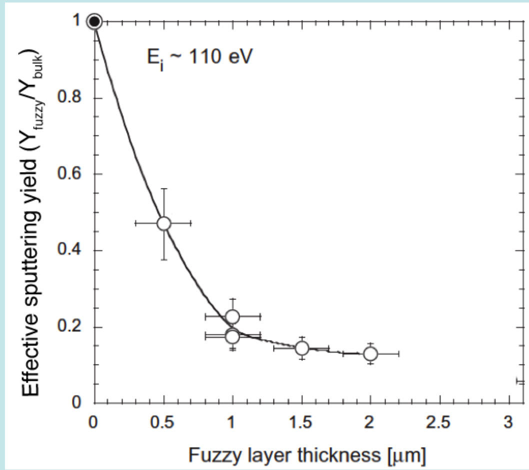
S. Kajita, Nucl. Fusion **49** (2009) 095005

What could a fuzzy divertor mean for ITER?

The Good:
- Lower sputtering of W
- Reduced hydrogenic permeation
- Reduced crack formation from thermal cycling

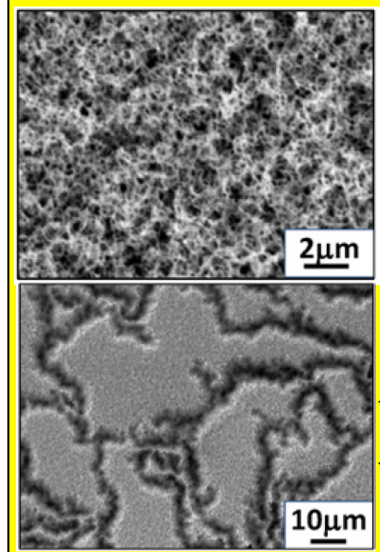
The Bad:
- Mechanically fragile nano-tendrils
- Increased unipolar arcing
- **Likely higher net erosion and W dust production**

The Unknown:
- Impact on operational control?
- *Is there a maximum attainable fuzz layer thickness in ITER?*



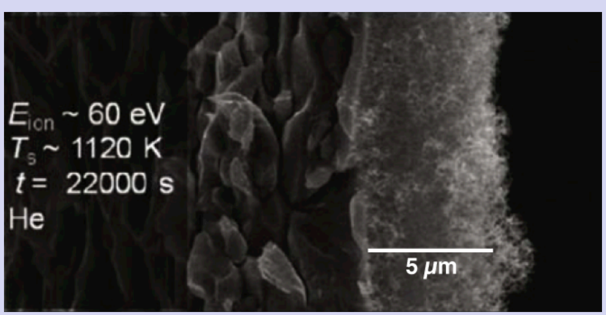
D. Nishijima et al. J. Nucl. Mater. 415 (2011) S96

Lower sputtering



M. Tokitani et al. Nucl. Fusion 51 (2011) 102001

Uni-polar arc tracks



M.J. Baldwin et al. J. Nucl. Mater. 390-391 (2009) 886

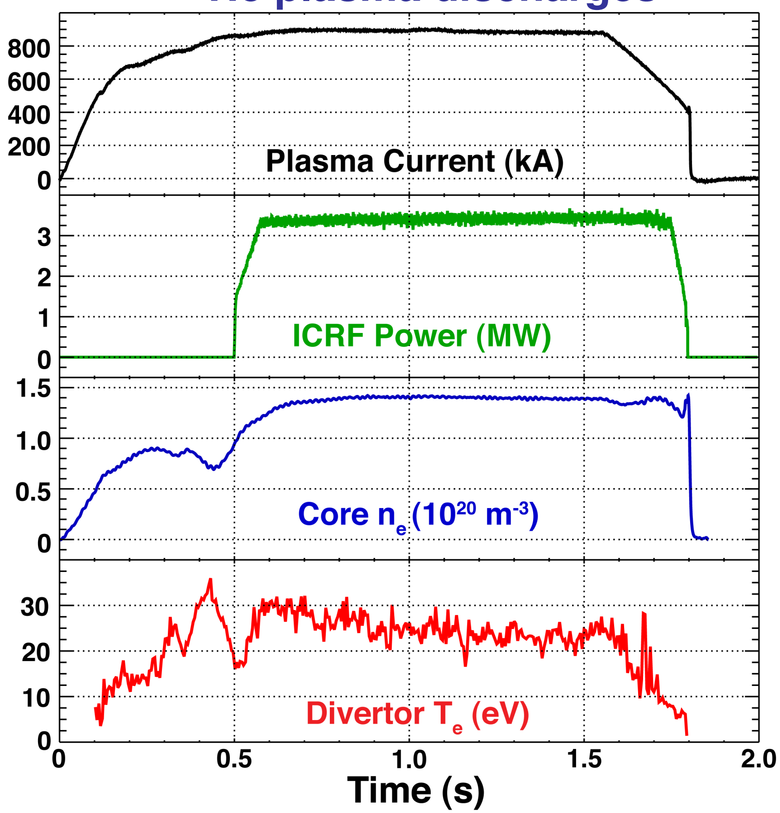
5 um thick W fuzz layer

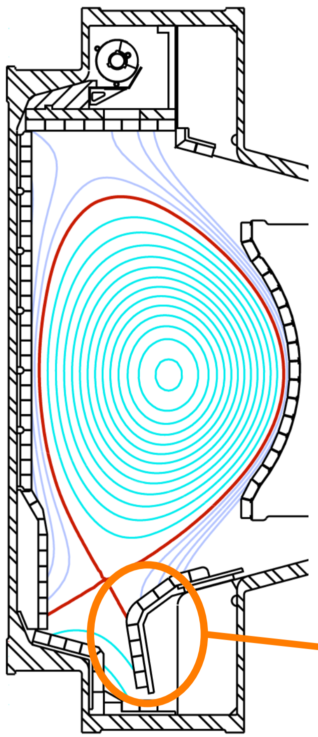
Will inherent differences between tokamak plasmas and linear device plasmas prevent fuzz growth in a tokamak?

	Tokamak	Linear Device
B-field	~1 T, Grazing incidence	~0.1 T, Typically normal incidence
Parallel Heat flux	~100 MW/m^2	~1 MW/m^2
Exposure stability	Transient	Steady-state
Ionization MFP, Re-deposition	Short, prompt re-deposition	Typically > plasma column radius, little or no redeposition

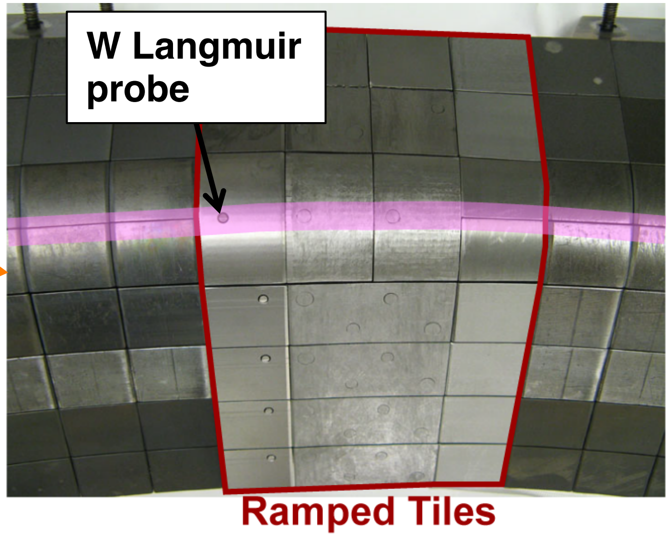
- Exploit ITER/reactor similar C-Mod divertor to find the answer
  - **High parallel heat flux**
  - **Mo and W first wall**
  - **ITER-like densities**

Alcator C-Mod helium plasmas produced necessary plasma conditions for fuzz growth at the outer strike point





Strike point run above vertical divertor face to reduce flux expansion allowing for higher local surface temperatures.

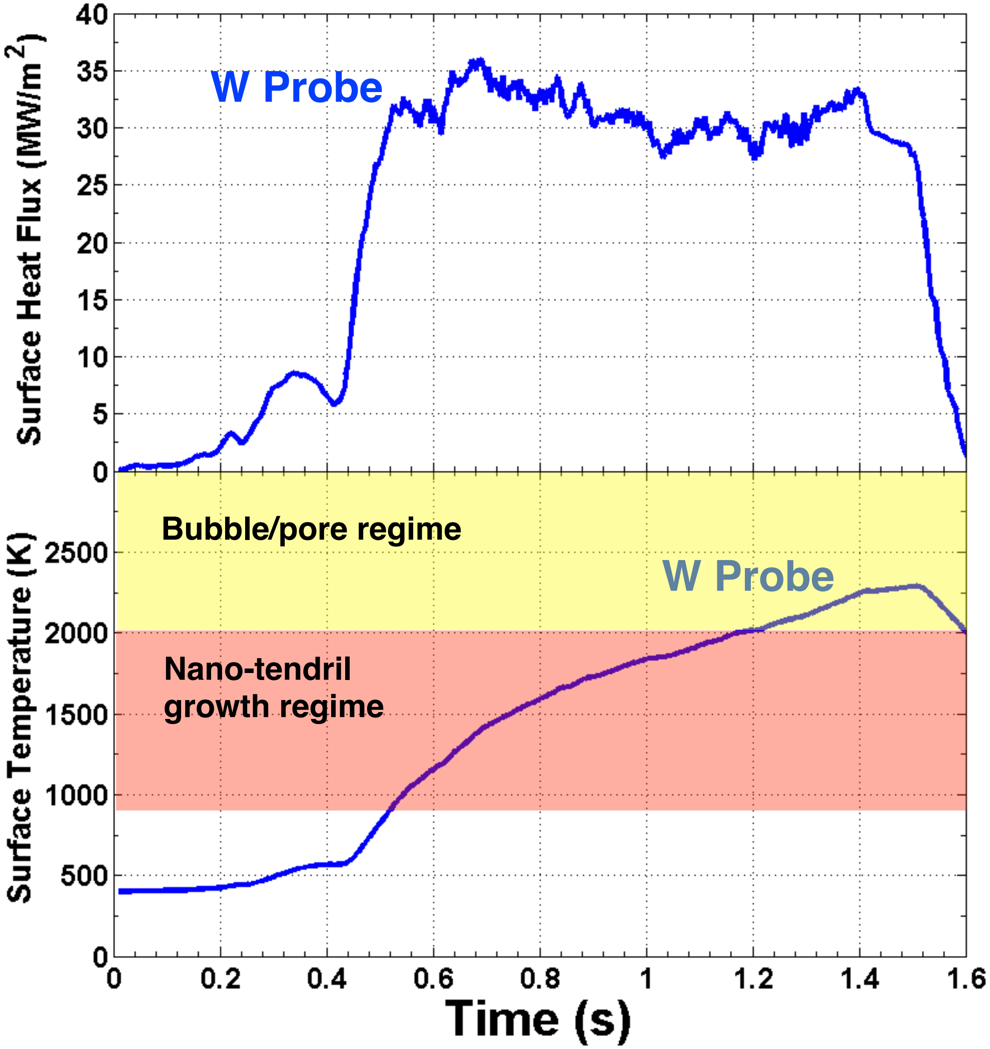


Tiles ramped ~2° into toroidal field

- 14 repeated L-mode discharges
- $T_{e,divertor}$ 20-25 eV, $q_{||}$ > 0.2 GW/m²

➔~13 s of total exposure at appropriate growth conditions

Tungsten Langmuir probe reached and exceeded surface temperatures required for fuzz growth



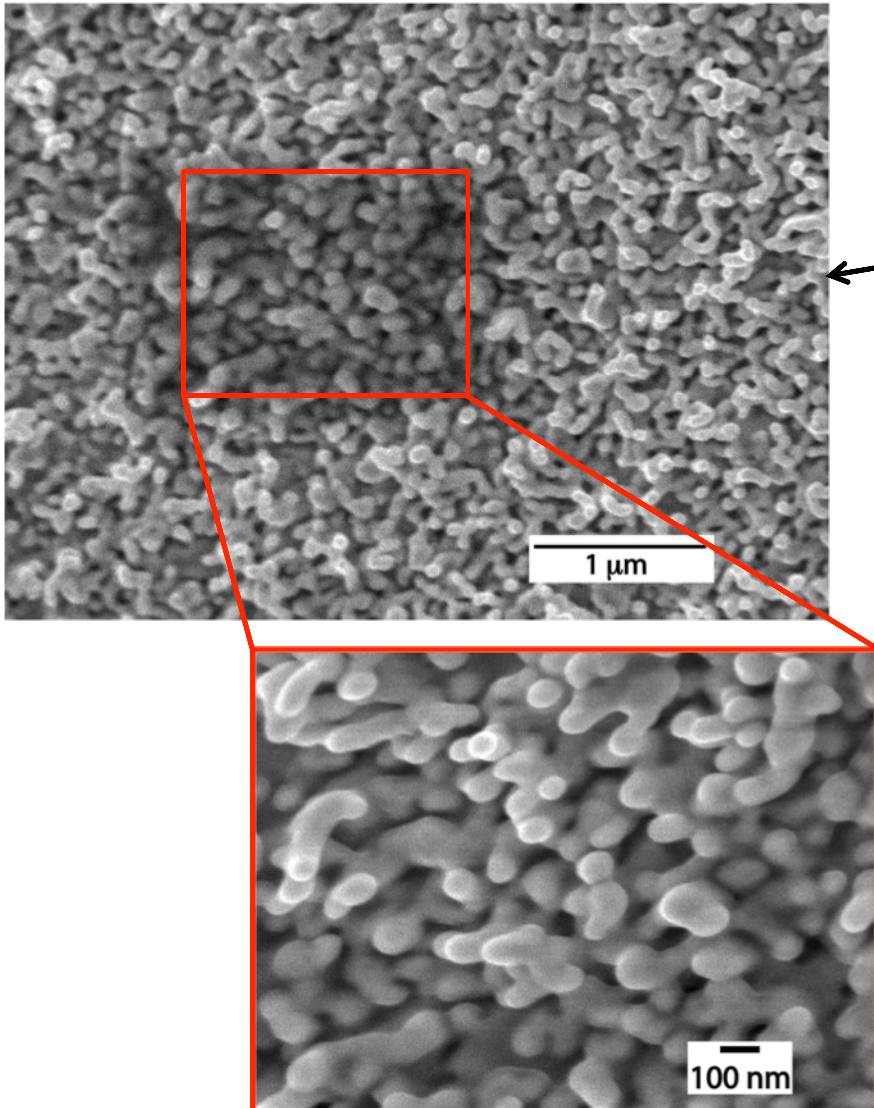
W Langmuir probe ramped ~11° into parallel heat flux and is actively biased during plasma discharges, -150 V - +50 V in 100 Hz triangle wave.

➔W Langmuir probe intercepts significant parallel heat flux and *rapidly* reaches ***high surface temperatures***.

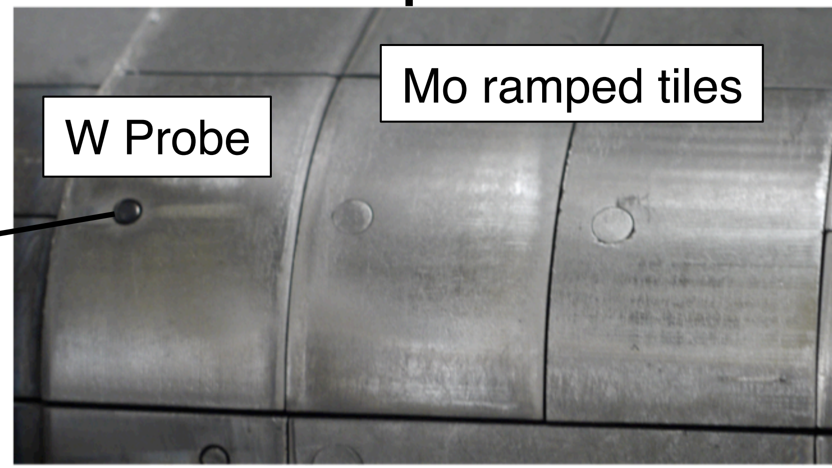
W Langmuir probe surface heat flux is obtained directly from probe measurements, T_{surf} is determined from 1-D heat flux modeling.

Note: Surface continues to be modified at T_{surf} > 2000 K but the morphology changes

Nano-tendrils are fully formed on surface of the tungsten probe exposed to heat fluxes of 30-40 MW/m^2

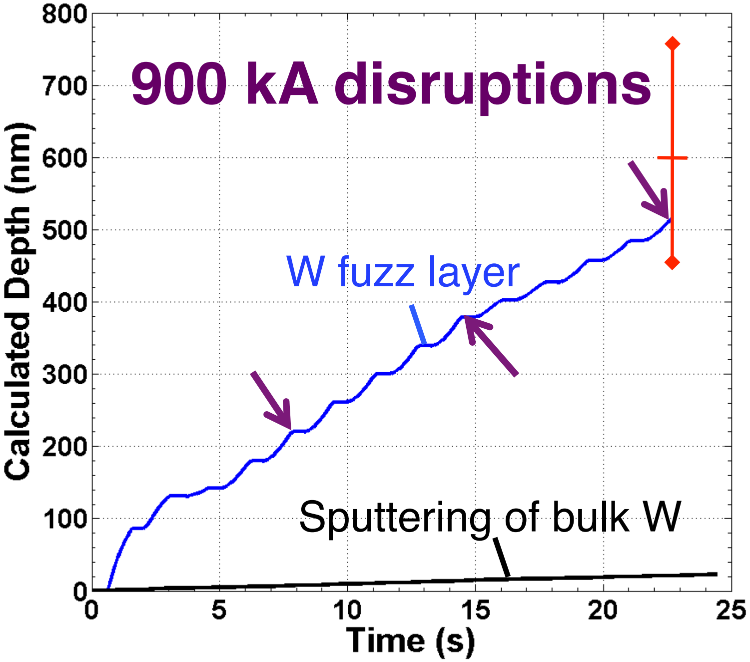


After exposure



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

Is the growth rate determined with linear plasma devices applicable to fuzz grown in a tokamak?



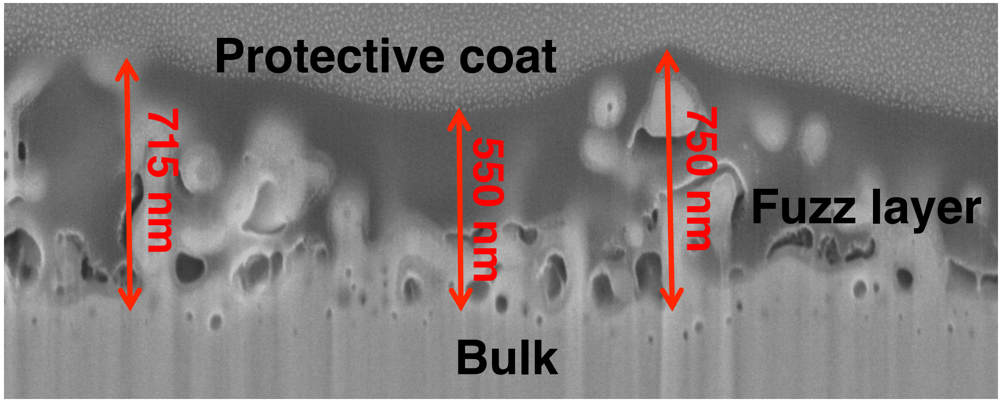
- Growth is estimated through $t^{1/2}$-dependence:

$$\textbf{layer depth} = \delta \times G(T_{surf}) \times t^{1/2}$$

where $G \propto \exp(-E_{act}/kT_{surf})$, $E_{act} = 0.71$ eV

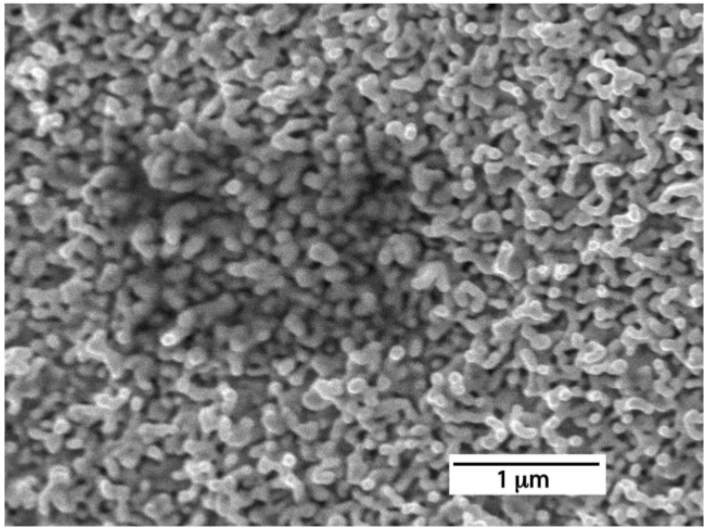
M.J. Baldwin, R.P. Doerner, Nucl. Fusion 48 (2008) 035001

- Calculated cumulative layer depth of ~515 nm for W probe
- Sputtering only a small contribution in W case (~28 nm bulk W)



- The measured fuzz layer thickness was **600 ± 150 nm** from FIB cross-sectioning.

Conclusion: W fuzz can be grown in a tokamak environment



- **C-Mod Growth rate is in-line with empirical formula from PISCES work**
  - Work is on going to obtain more growth rate data from linear devices (Pilot-PSI) at these high surface temperatures (1500-2000+ K)
- **No signs of melting or arcing on W fuzz despite heat fluxes of 30-40 MW/m^2 and three 900 kA plasma disruptions.**
- **Projections for growth in ITER?**
  - Complicated by potential Be deposition, ELMS, and impurity seeding

THANK YOU FOR YOUR ATTENTION!

Special thanks to:

Matt Baldwin (*UCSD*), Russ Doerner (*UCSD*), and the Alcator C-Mod team