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# Thick-wire ETI Growth under Dielectric Coatings

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# Motivation (MagLIF)

- In a z-pinch, electrical currents are axially driven through conductors (often axis-symmetric annuli called liners).
- Self-generated magnetic fields radially compress (via $\vec{j}\times\vec{B}$ forces) conductive material (and entrained matter) into a high energy-density state on axis.
- MagLIF[1] involves filling the liner with DT fuel and compressing it to conditions suitable for fusion.
- When the low-density magnetic field accelerates the high-density metal, they slip through each-other in what is called the Magneto-Rayleigh Taylor (MRT) instability.
- MRT sections the liner and disrupts compression. Sea monster of nuclear fusion. Represents a significant MagLIF threat.

[1]Slutz (2010)

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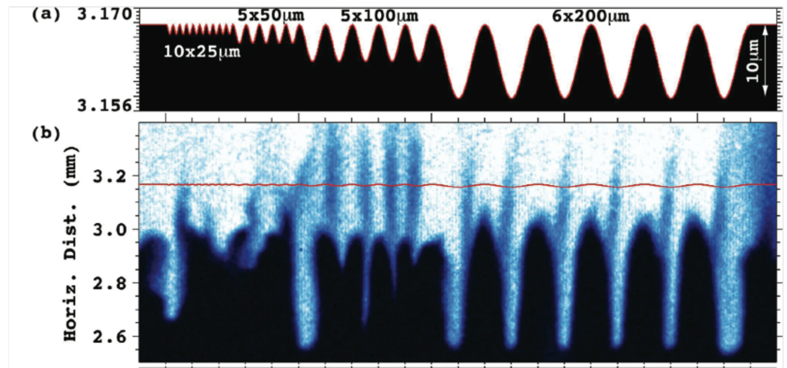
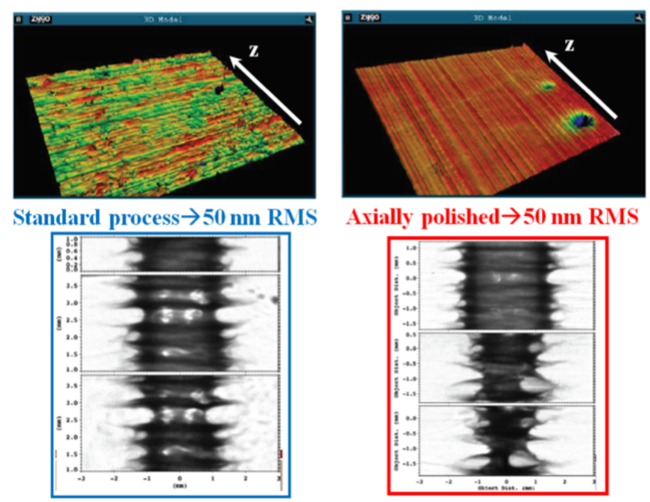
# The MRT Instability

- You would expect to see the same ratio between perturbations if growth were linear to initial perturbations.[1]
- Highly azimuthally correlated but surprisingly not with residual lathe structure.[2]
- So therefore everybody looked for another, earlier instability that generates azimuthal density perturbations capable of 'seeding' the liner for MRT.

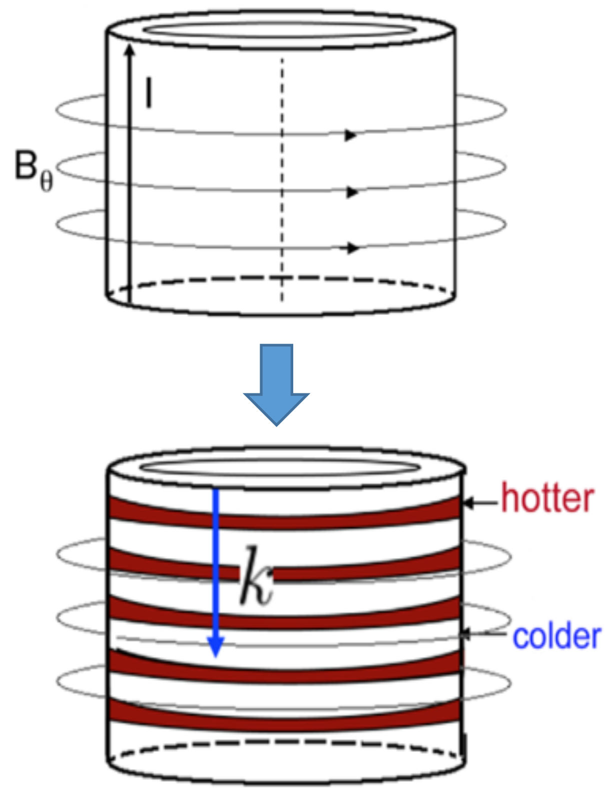



[1]Sinars (2010) [2]McBride (2012)

# Electro-Thermal Instability (ETI) Origins

- Suspicion came to rest on fast thermal instabilities that grow after melt.[1] Striation vs filamentation. Strata more readily couple to MRT than filaments.
- If: $c_v\rho\frac{\partial T}{\partial t} = \eta j^2 \; and\, \eta = \eta_0 + \frac{\partial \eta}{\partial T}T$
- Then: $\delta T = \delta T_0 e^{\gamma t}$ where $\gamma = \frac{j^2}{c_v\rho}\frac{\partial \eta}{\partial T}$
- The hypothesized evolution is $\delta T \rightarrow \delta p \rightarrow \delta\rho$, which carries the imprinted azimuthal symmetry into the compression phase.




[1]Peterson (2012)

# Thin-Wire ETI is analytically treatable:

- Where $T^*$ depends quadratically on $\gamma$ and contains EOS parameters specific to material.
- The hydro version predicts that $\delta T \sim i\ \delta\rho$, so troughs are hotter than peaks.[1]
- This term is also called the electrochoric instability (ECI).[2]
- ETI is predicted to grow fastest when conductor is a liquid-vapor bi-phase. If you can keep material out of this regime it is less dangerous.

Without Hydrodynamics

$$\gamma = \frac{j^2 \frac{\partial \eta}{\partial T} - k_z^2 \kappa}{c_v \rho}$$

$$\lambda_{min} = \frac{2\pi}{j} \sqrt{\kappa \left(\frac{\partial \eta}{\partial T}\right)^{-1}}$$

With Hydrodynamics

$$\gamma = \frac{j^2 \frac{\partial \eta}{\partial T} + \frac{\rho}{T^*}\left(c_v \frac{\partial T}{\partial t} - j^2 \frac{\partial \eta}{\partial \rho}\right) - k_z^2 \kappa}{c_v \rho + \frac{p}{T^*}}$$

[1]Oreshkin (2008)
[2]Pecover (2015)

# Application of EOS tables w/out hydro to thin-wire case implies ETI wavelengths grow in time.

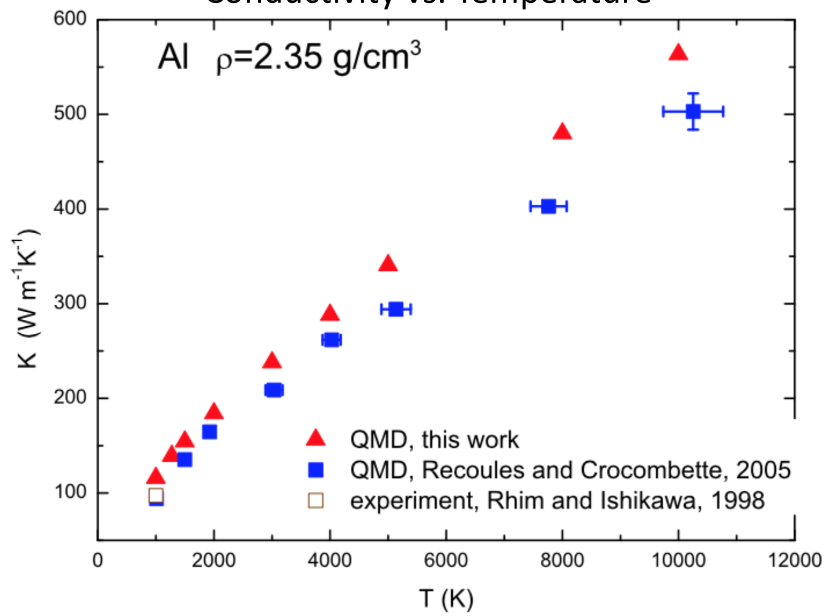
- The Wiedemann-Franz relation, $\frac{\eta\kappa}{T} = \frac{\pi^2 k_b^2}{3e^2}$ is suitable for $\frac{\partial\eta}{\partial T}$ in the thin wire case.[1]

$$\longrightarrow \quad \lambda_{min} = \frac{e\kappa}{jk_b}\sqrt{12}$$

- On the surface: $\frac{\partial T}{\partial t} > 0$ means that $\frac{\partial\kappa}{\partial t} > 0$, and since $\frac{\partial j}{\partial t} < 0$:

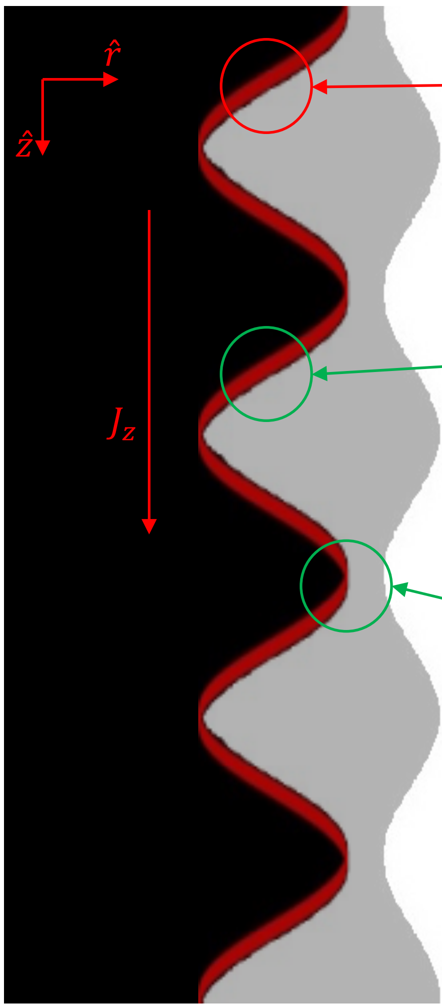
$$\longrightarrow \quad \frac{\partial\lambda_{min}}{\partial t} > 0$$

Liquid Aluminum Thermal Conductivity vs. Temperature[2]




[1]Recoules (2005) [2]Knyazev (2013)

# Given an initial axisymmetric perturbation in $\rho$ or $\eta$ (i.e. consider 2-D thick ETI with hydro)

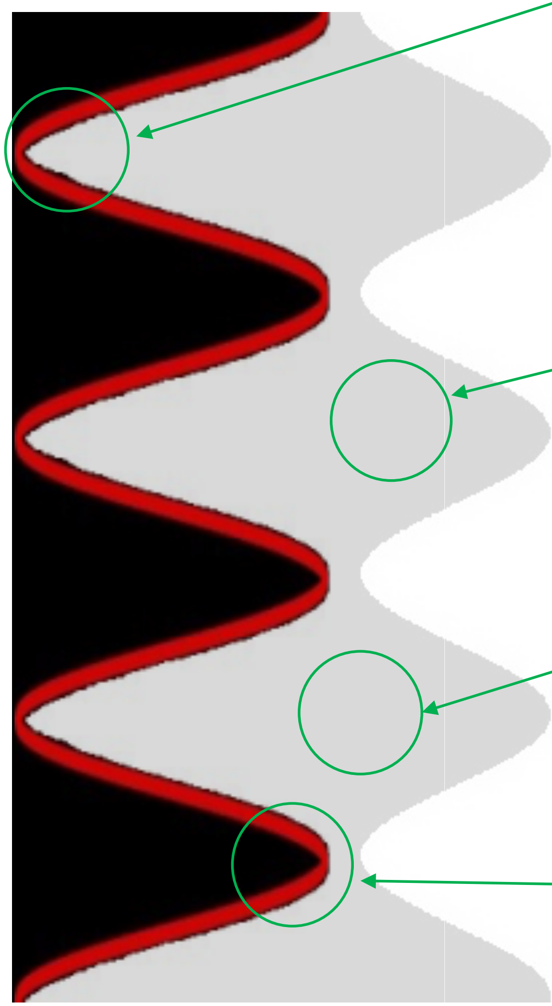



$\vec{j}$ travels as close to the surface as magnetic diffusion permits.

Per axial unit length, $I$ must be the same for each section, so $\vec{j}$ must be smaller when it has a radial component and larger at smaller radii.

Finally, $\vec{j}$ is also smaller at larger radii due to Ampere's Law.

# ETI/ECI drives deepening axisymmetric groves



Since $\vec{j}$ is larger here, $\eta\vec{j}^2$ is larger. Consequently, the temperature grows faster and results in (for $\partial\eta/\partial T > 0$) more resistive and if after melt (since $\partial\eta/\partial\rho < 0$) less dense material.

Less dense material means flux penetration depth is greater, and $\vec{j}$ is larger (i.e. $\vec{j}$ 'dips' inwards to take a lower resistance path (even if inductance goes up marginally))

Since $v_A^2 \sim \rho^{-1}$, low density material can correlate most quickly, so w/out axisymmetry, '$\vec{B}$-hernias' azimuthally correlate fastest here.

Result is large-amplitude high-density perturbations suitable for MRT initialization.

# Dielectric Coatings suppress $\dot{\delta\rho}$

- Dielectric coatings are theorized to constraining mass redistribution and therefore MRT seeds.

$$\gamma = \frac{j^2 \frac{\partial \eta}{\partial T} + \frac{\rho}{T^*}\left(c_v \frac{\partial T}{\partial t} - j^2 \frac{\partial \eta}{\partial \rho}\right) - k_z^2 \kappa}{c_v \rho + \frac{p}{T^*}}$$

- Coatings affect MRT in two intertwined but distinct ways:

1. Dielectric inhibits $\dot{\delta\rho}$, suppressing the ETI growth rate dependence on $\frac{\partial \eta}{\partial \rho}$, the so-called Electrochoric Instability (ECI).[2]
2. Dielectric limits MRT initialization amplitudes by constraining $\delta p \rightarrow \delta \rho$ evolution independent of ETI/ECI growth rates.

[1]Oreshkin (2008) & Peterson (2012, 2013, 2014) [2]Pecover (2015)

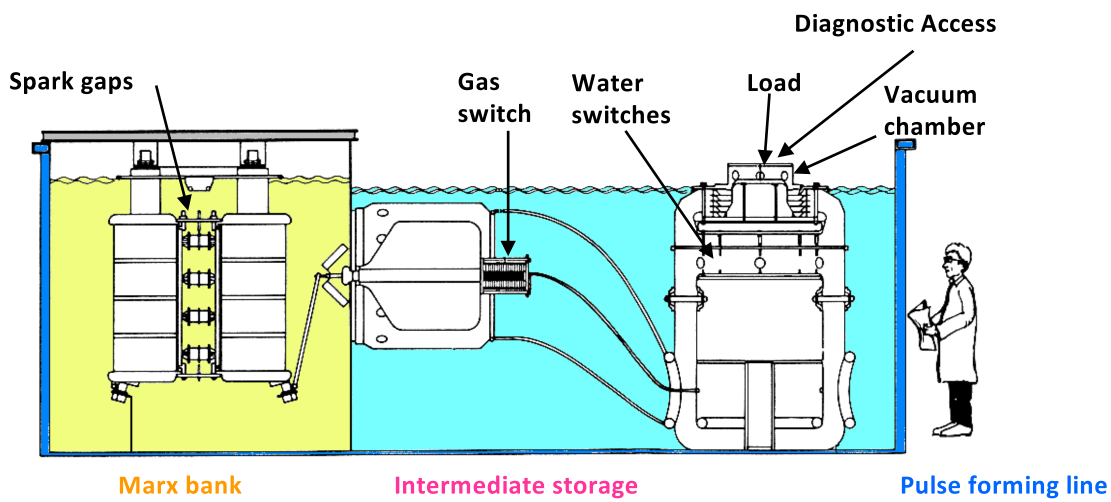
# Important unknowns remain

- Thin wire experiments demonstrate that dielectric overcoats suppress plasma formation, inhibiting the current from shunting and permitting greater energy deposition in the wire.[1] Analytic thin-wire theory implies that greater energy deposition rates mean *faster* instability growth, so must the theory be inapplicable for the thick-wire case since an applied dielectric reduces instabilities?[2]
- Oreshkin and Pecover argue in opposition whether conductor strength is relevant for ETI growth.
- Experiments have verified that on Z, the dielectric carries sufficient current to implode with the liner,[2] but simulations do not predict an imploding dielectric.[3] This disparity motivated the experiments we have performed.

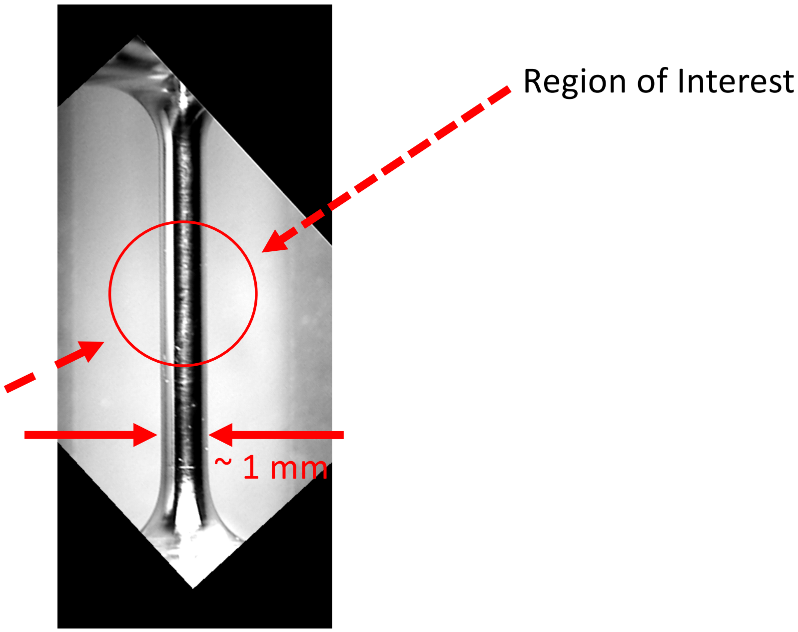
[1] Sinars (2010b) & Sarkisov (2004) [2]Awe (2016) & Peterson (2014) [3]Peterson (2014).

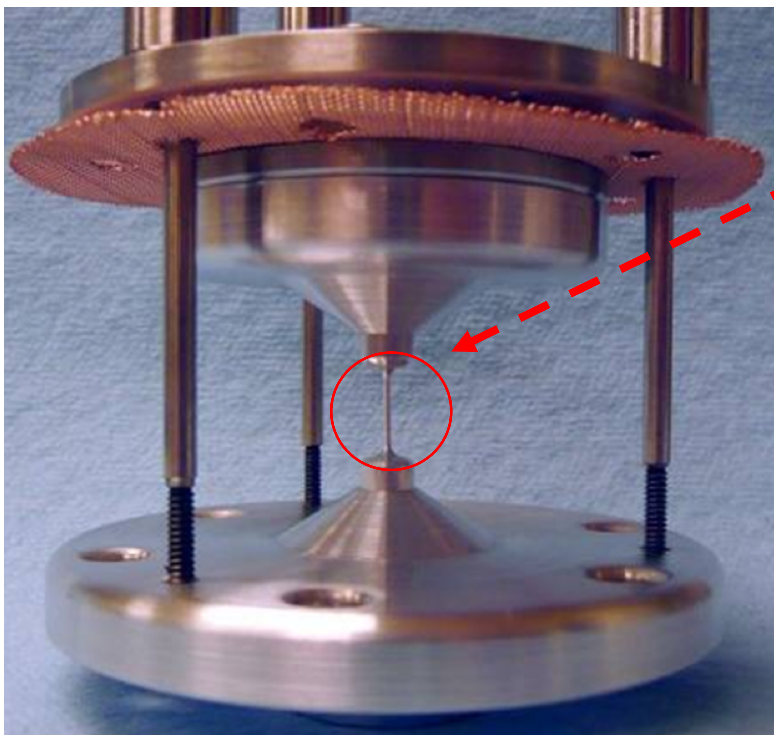
# Zebra Pulsed Power Accelerator

- Zebra is a Marx-configured 1 MA driver at UNR. Chamber is return can, so optical ports are >13’’ from TCC.
- Bank stores 150 kJ, and delivers in 100 ns via a transmission impedance of $1.9\ \Omega$ to our $\sim m\Omega$ loads. Given the impedance mismatch, small variations in load resistance do not affect accelerator performance.
- We define 500 kA to be at 100 ns: Zebra --> 11 kA/ns (~ 3-8 T/ns) linear current until $0.9\ MA$.



# Load hardware reproducibly mitigates non-thermal breakdown



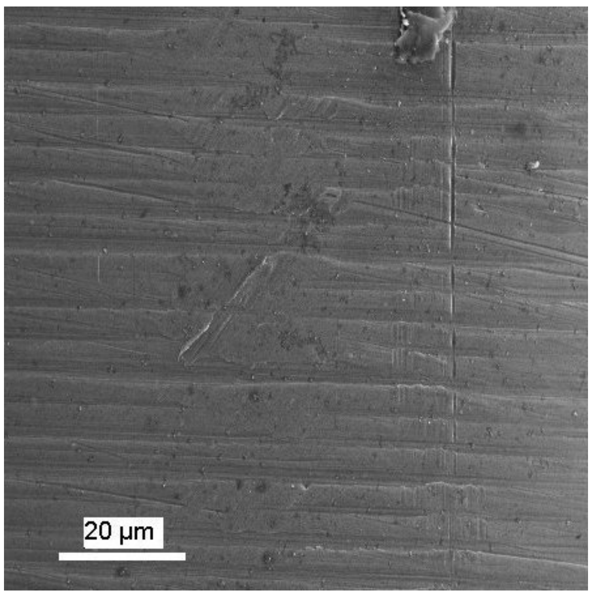
Cathode

Buried knife-edge contacts mitigate arcing/break oxide layer, and smooth electrode transitions inhibit avalanche breakdown.

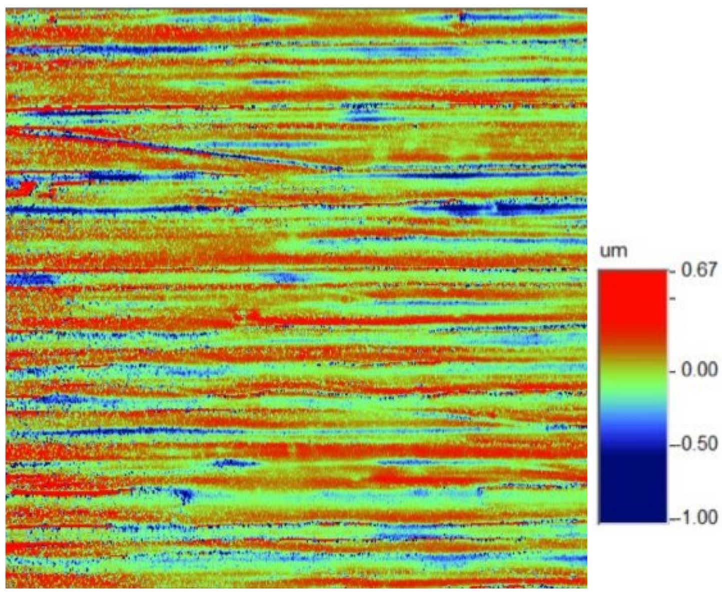
# Tested Load Types and Surface Features well characterized

(CM) Eleven Conventionally Machined Pulse-Oxide Electropolished $\varnothing\ 974 \pm 9\ \mu m$ :: Machining is consistently $5.1 \pm 0.2\ \ \mu m$
(CH) Five CM then had $70\ \pm 5\ \mu m$ Parylene-N Chemical Vapor Deposited

CM Scanning Electron Micrograph SE



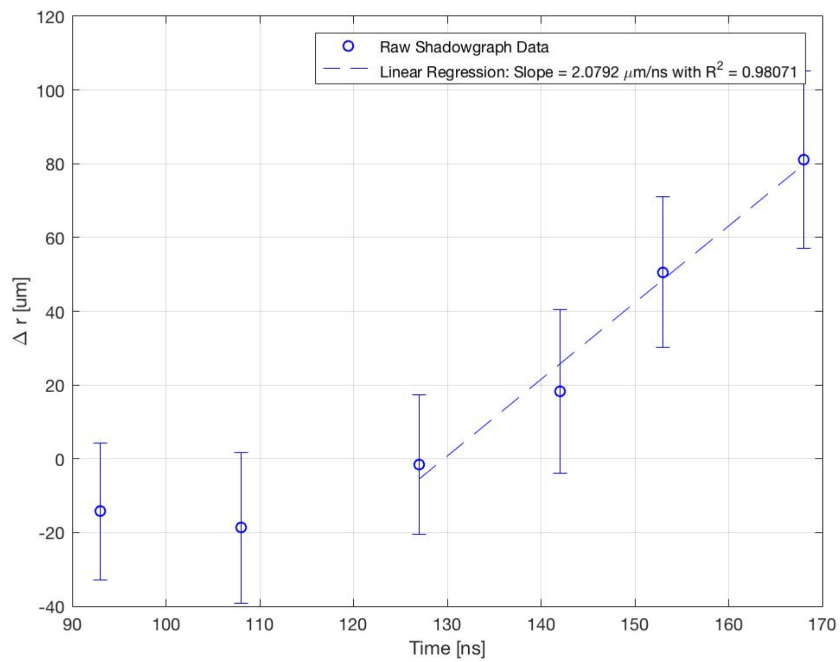

CM White Light Interferogram




Preshot Backlit Optical Micrograph

# Shadowgraph Diameters -> Expansion

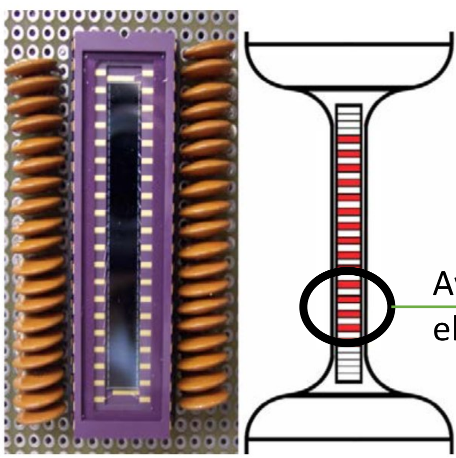
- Experimental CH expansion speed is $2.1 \pm 0.27\ \mu m/ns$. $\pm$ is due to linear regression fitness.
- Expansion speeds have previously been measured for uncoated aluminum are $3\ \mu m/ns$ using the same method.[1]
- This reduction in expansion speed is consistent with hydrodynamic tamping of expanding low-density vapor.

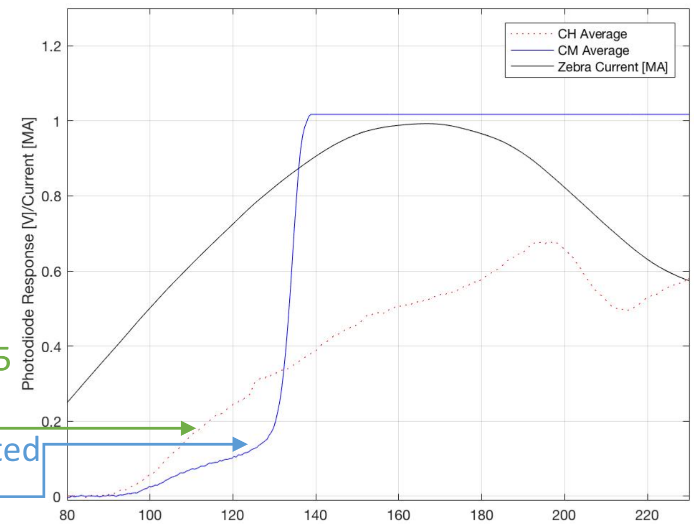



[1] Awe, T. Dissertation pg. 209.

# VIS Radiometry for CH Loads -> initially hotter, then cooler emitter

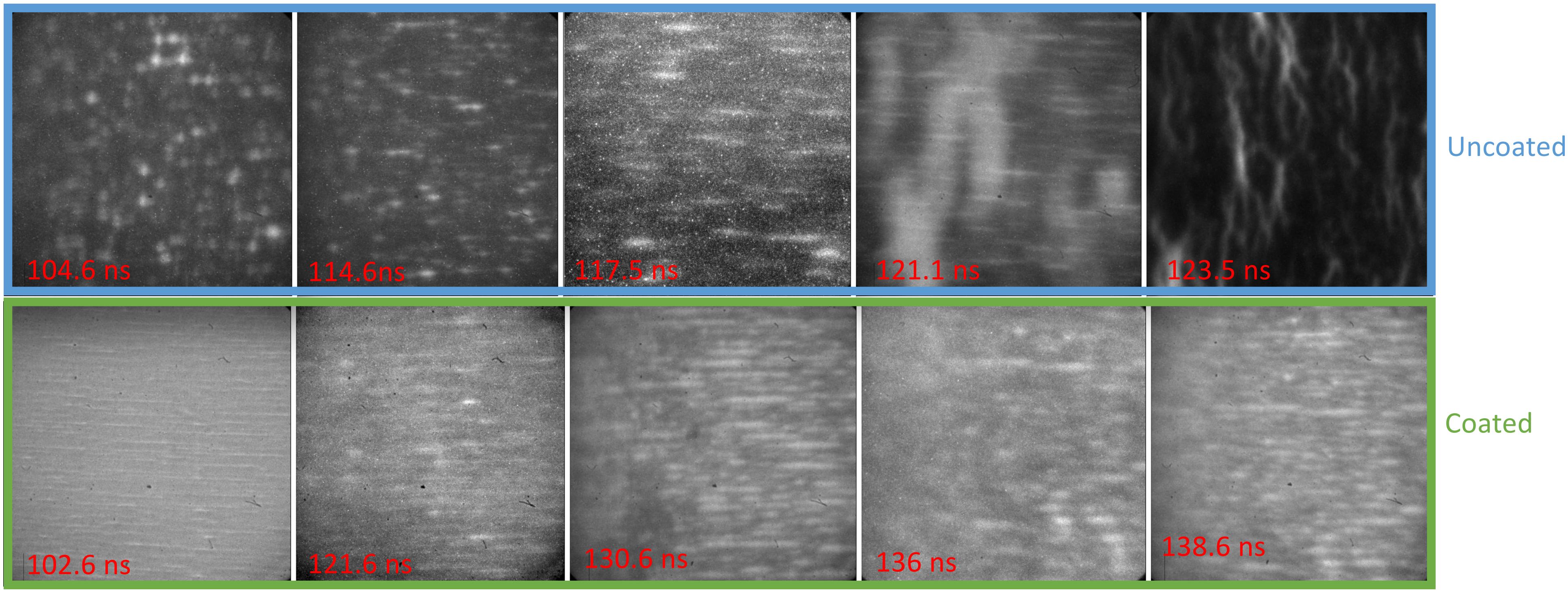
- Literature[1,2] suggests breakdown is correlated with a rapid increase in VIS emissions, which we see for uncoated (~140 ns) but not coated loads. Available implication is plasma doesn't form.
- During the 'ramp' section of 95-125 ns, the ratio of coated to uncoated emissions is a nearly constant $2.7 \pm 0.1$ (taking into account $T_r = 85\%$)
- That the ratio is > 1 is consistent with thin-wire experiments in that the dielectric overcoat increases energy deposition (therefore radiance).




[1]Lindemuth (2010) [2]Raizer (1991)

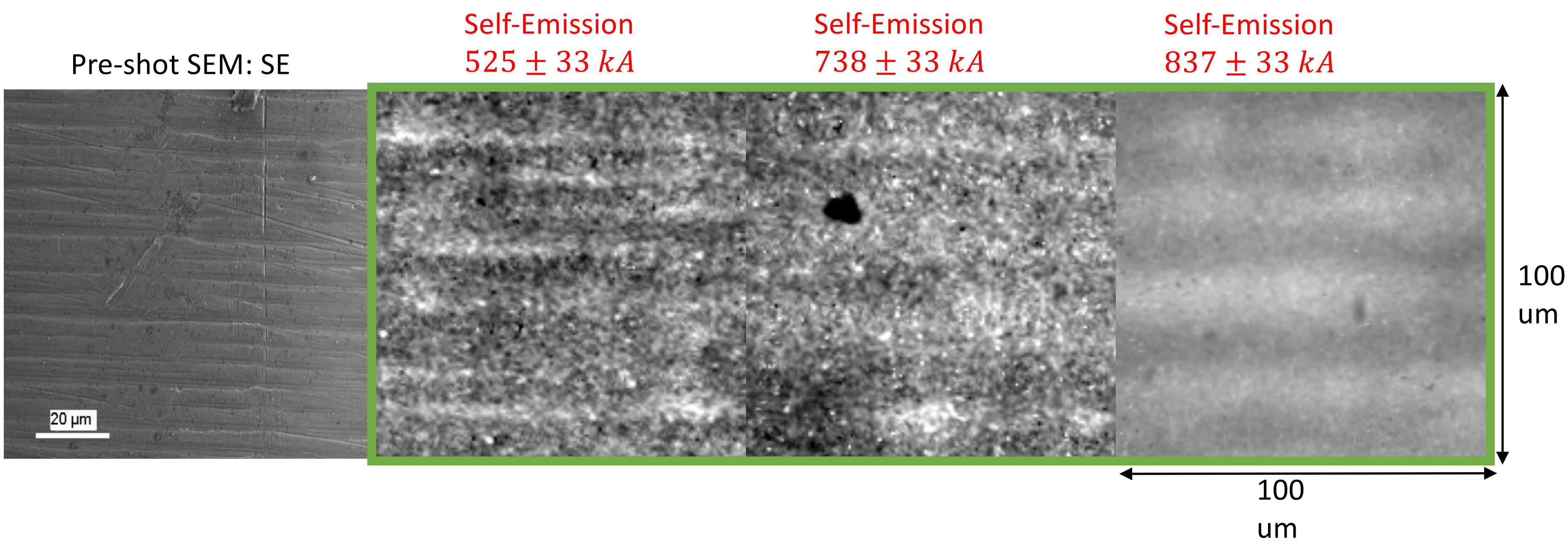
# Dielectric Strongly Modifies Evolution of VIS




Uncoated display: dots --> strata --> filaments. Filamentary plasma emissions rapidly overwhelm strata that ALEGRA suggests grows underneath.

Coated display: strata throughout. CH load-averaged emissions are greater than uncoated load-averaged emissions until these uncoated loads form filaments.

# The coated relationship between machining and self-emission evolution is clear qualitatively



$$R(\lambda,T) = \overbrace{SR(\lambda,T)}\ \underbrace{P(\lambda)}\ \overbrace{N_f(\lambda)}\ \underbrace{Q_E(\lambda)}\ \overbrace{S_A}\ \underbrace{E_A}\ \overbrace{A}\ \underbrace{r}\ \overbrace{g_a}\ \overbrace{g_t}\ \underbrace{p_t}\ \underbrace{O_{ldm}(\lambda)}\ N_B(\lambda)/\underbrace{P_n}$$

Plank's Law [W/m³/str]

Pellicle [% Transmitted]

Notch Filter [% Transmitted]

Photocathode Quantum Efficiency [% = photo-e⁻ / # photons ~ A/W]

Solid Angle [str]

Emitter Area [m²]

Conversion Factor [e⁻/s/A]

ICCD Window, Debris Shield, Chamber Window [% Transmitted]

Gain Setting [counts/ e⁻]

MCP Gate [s]

Parylene Transmission [% Transmitted]

Two Aluminum mirrors, AR coating and BK7 glass [% Transmitted].

Nikon & Barlow [% Transmitted]

Number of Pixels

$r = 0.96^6$

$g_a = 339\frac{counts}{e^-}\ \text{SNL and } 498\frac{counts}{e^-}\ \text{UNR (typical)}$

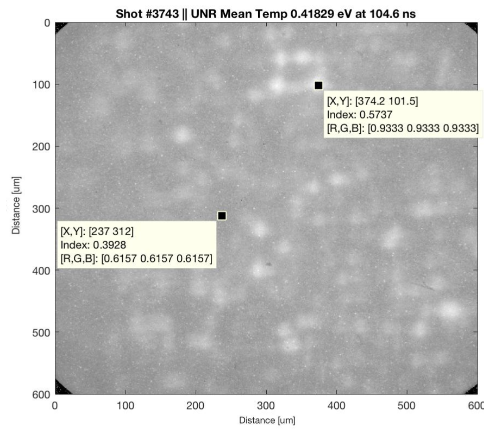
$g_t = 2\ ns$ for SNL and $3.5\ ns$ for UNR (typical)

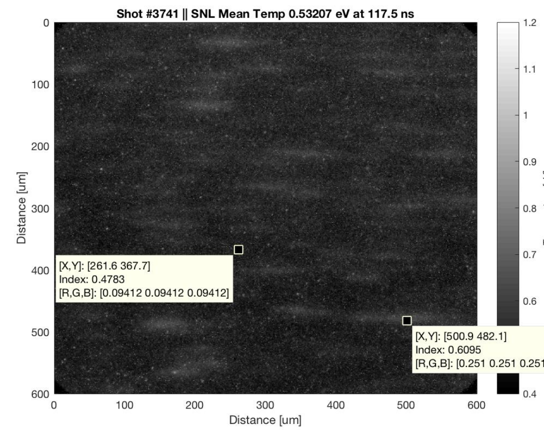
$E_A = 600^2 \mu m^2$

$P_n = 1024^2$

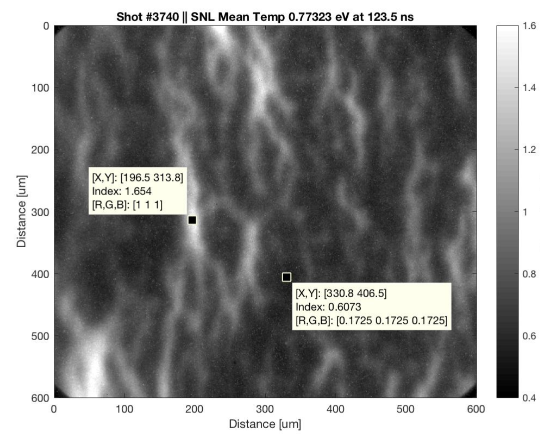
Note: the pellicle and quantum efficiencies will be different for SNL vs. UNR Cameras

# ICCD-Temp Maps :: Uncoated Loads



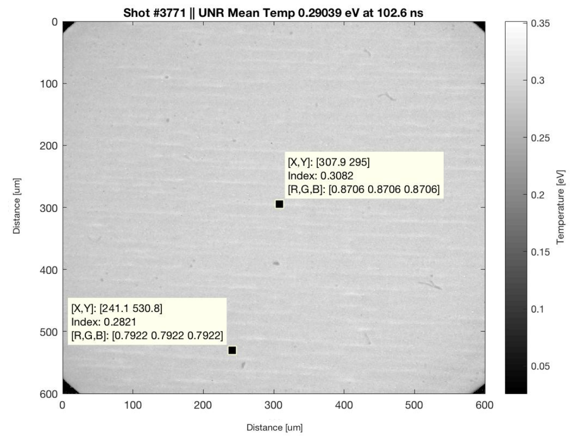



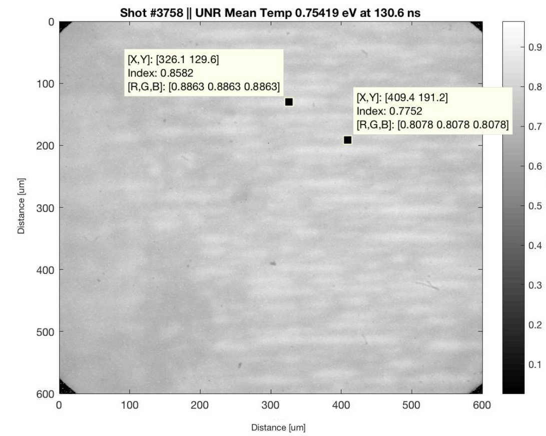

Time/Current



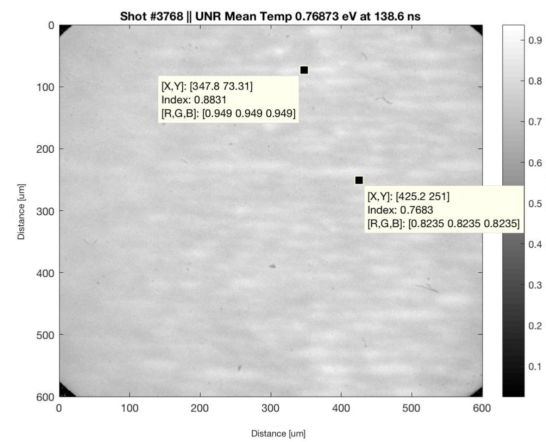

- Cameras disagree at > eV temperatures, which we believe is due to reliance on mfgr. Specs. Both cameras agree that:
  - dots and strata are 0.1-0.2 eV hotter than background.
  - Dots/strata do not appear above 0.8 eV.
  - Filaments are only observed 0.6 eV and hotter.

# ICCD-Temp Maps :: Coated Loads




Time/Current




- Strata appear with $T_{BB} \sim 0.27\ eV$, which is ~0.3 eV cooler than hot spots on uncoated loads at the same, early time. The dielectric appears to suppress hot spot formation completely
- Filaments are not observed as late as our ICCD images have been taken, suggesting $\partial\eta/\partial T$ does not change sign and therefore that plasma does not form.

# Summary

- We think CH-coated loads do not form plasma because:
  - Shadowgrams displays no appreciable MRT
  - Shadowgraph expansion speeds do not change near peak current
  - PDA never displays a sharp increase in VIS emissions.
  - Filaments are not observed.

Consistent with hydrodynamic tamp.

- ETI persists for ~50 ns, and remain highly (but perhaps decreasingly) azimuthally correlated. Suppression of hot spots is consistent with hydrodynamic tamping of ECI.
- Evidence suggests dielectric does not carry current.

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