Three-dimensional metal deformation and plasma formation driven by resistive inclusions

SAND2019-12673C

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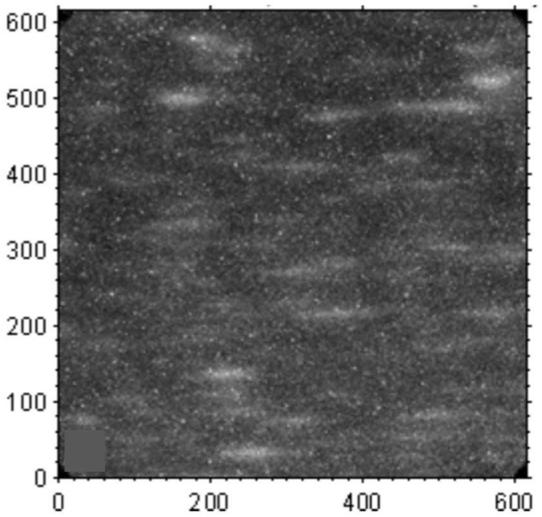
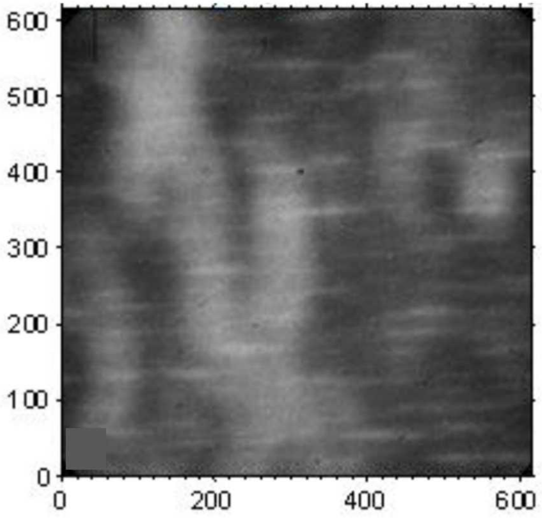
APS DPP 2019

Fort Lauderdale, FL





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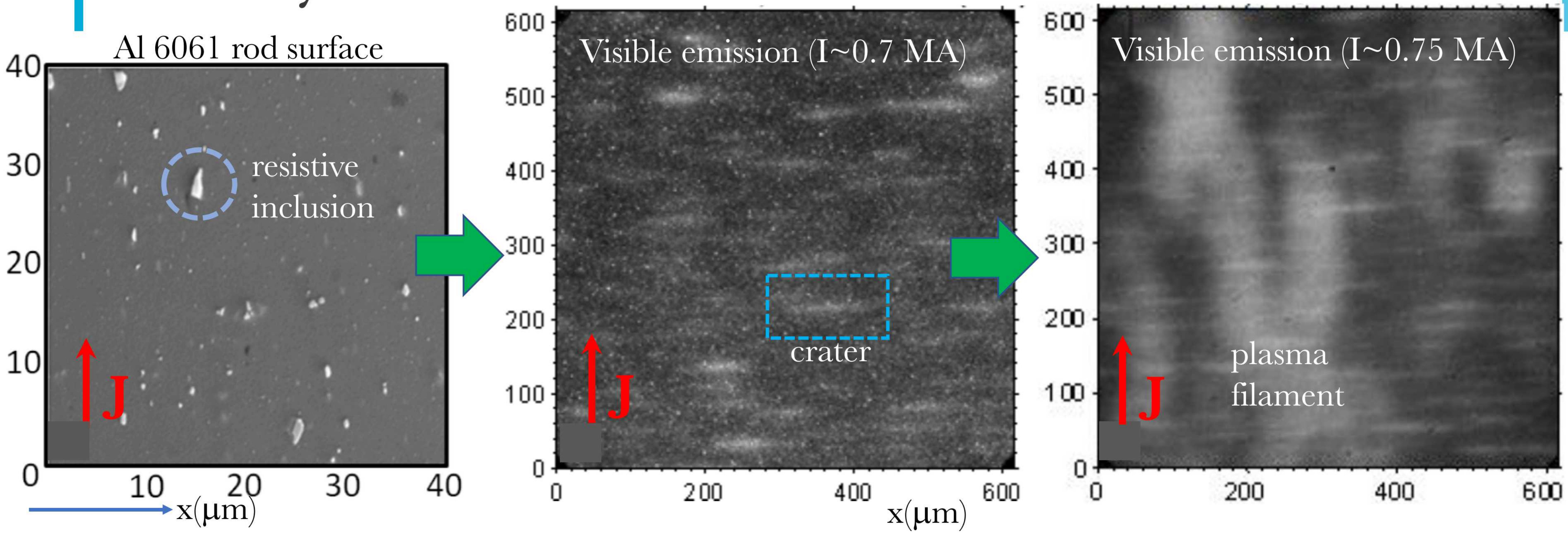
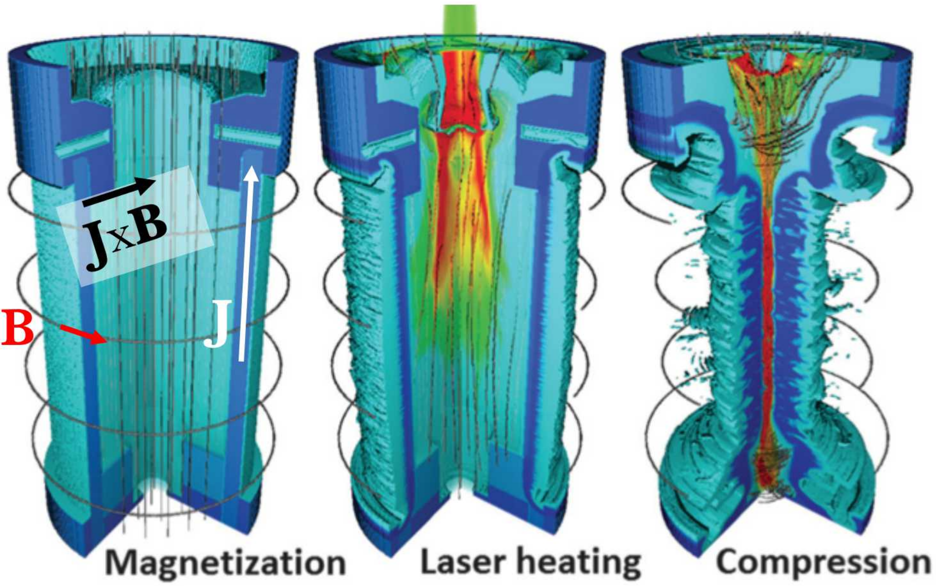
Summary



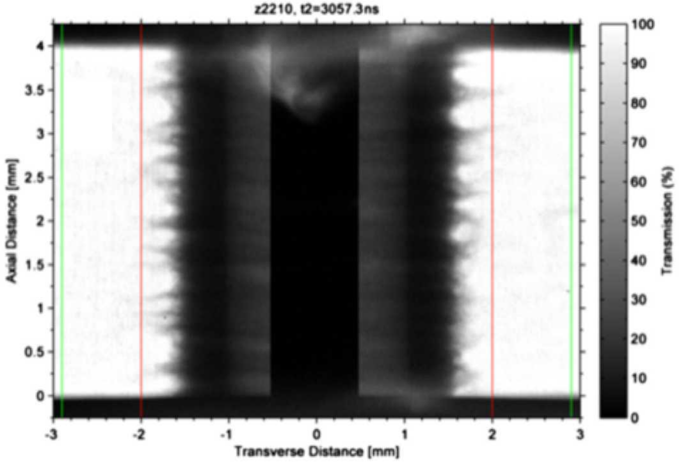
- Micron-scale resistive inclusions can transform into ~10X wider, deeper craters, important for later magneto Rayleigh-Taylor instability growth.
- Inclusions seed plasma formation, which is a 3D effect.

Accelerating liners are magneto Rayleigh-Taylor (MRT) unstable

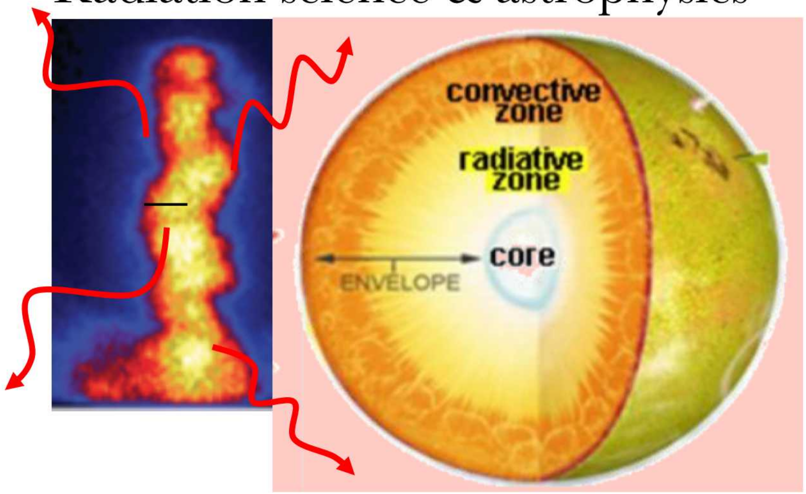
Magneto-inertial fusion (MagLIF)



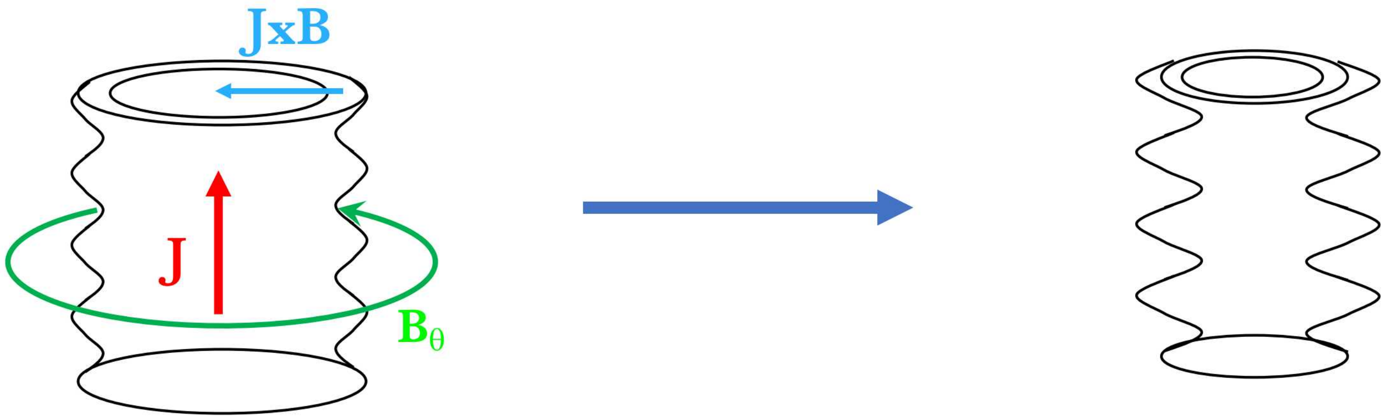
Dynamic material properties & planetary science



Radiation science & astrophysics

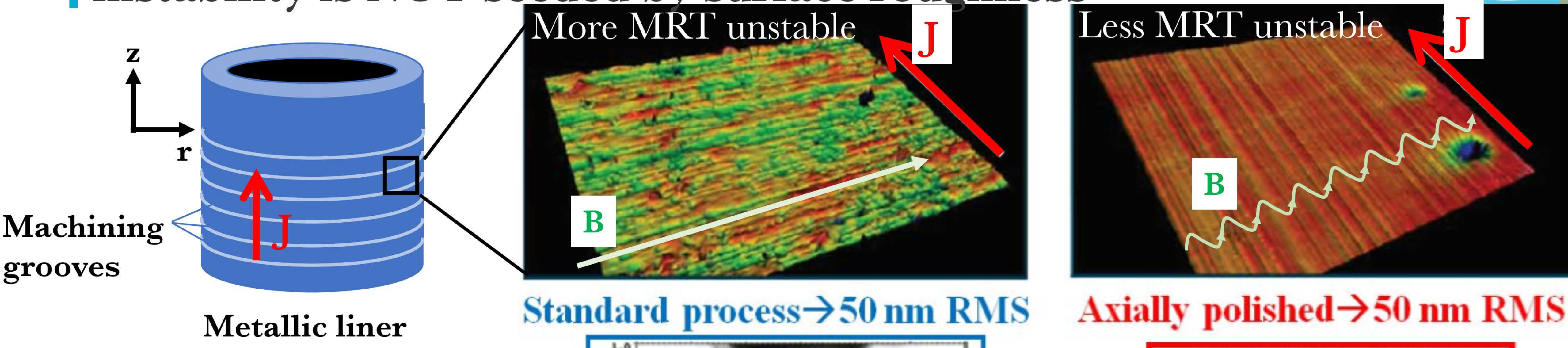


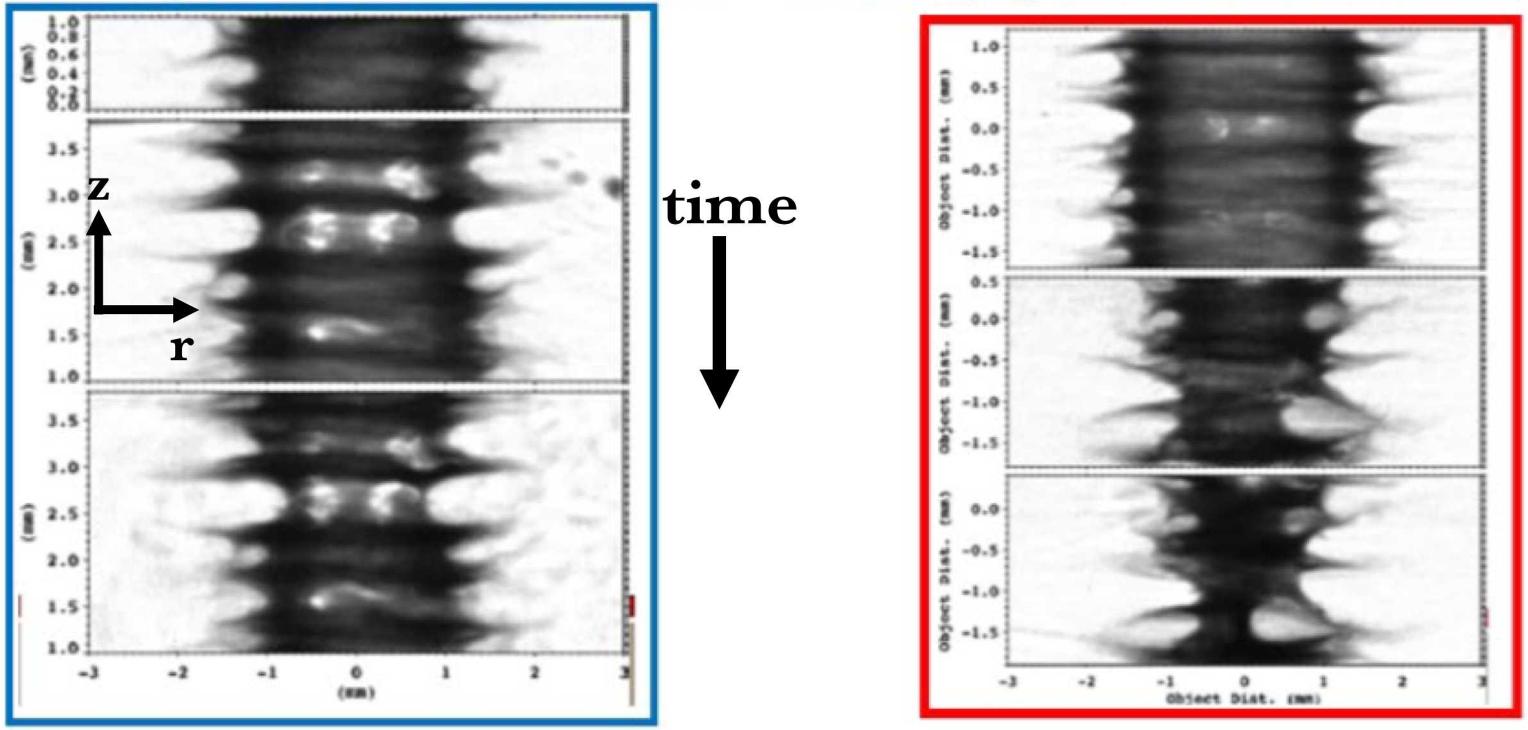
<u>D. Sinars</u>(FR1) – From Astrophysics to Z-pinches: HED Science with Pulsed Power
<u>M. Gomez</u>(GI3) – Performance Scaling with drive parameters in Magnetized Liner Inertial Fusion experiments



Q: what seeds MRT?

In sufficiently smooth liners, magneto Rayleigh-Taylor (MRT) instability is NOT seeded by surface roughness

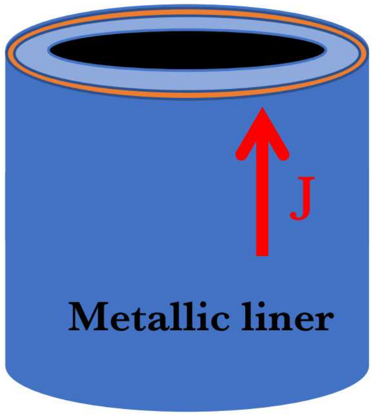




Experimental radiography (D. Sinars) is qualitatively the same!

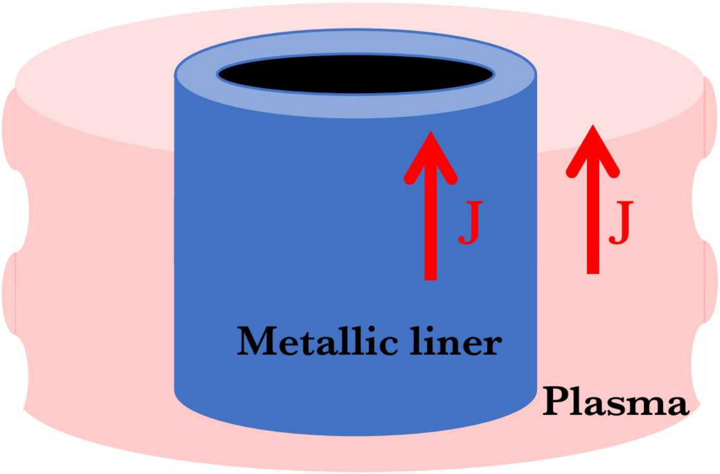
Q: what seeds MRT?

Another important design consideration is plasma formation



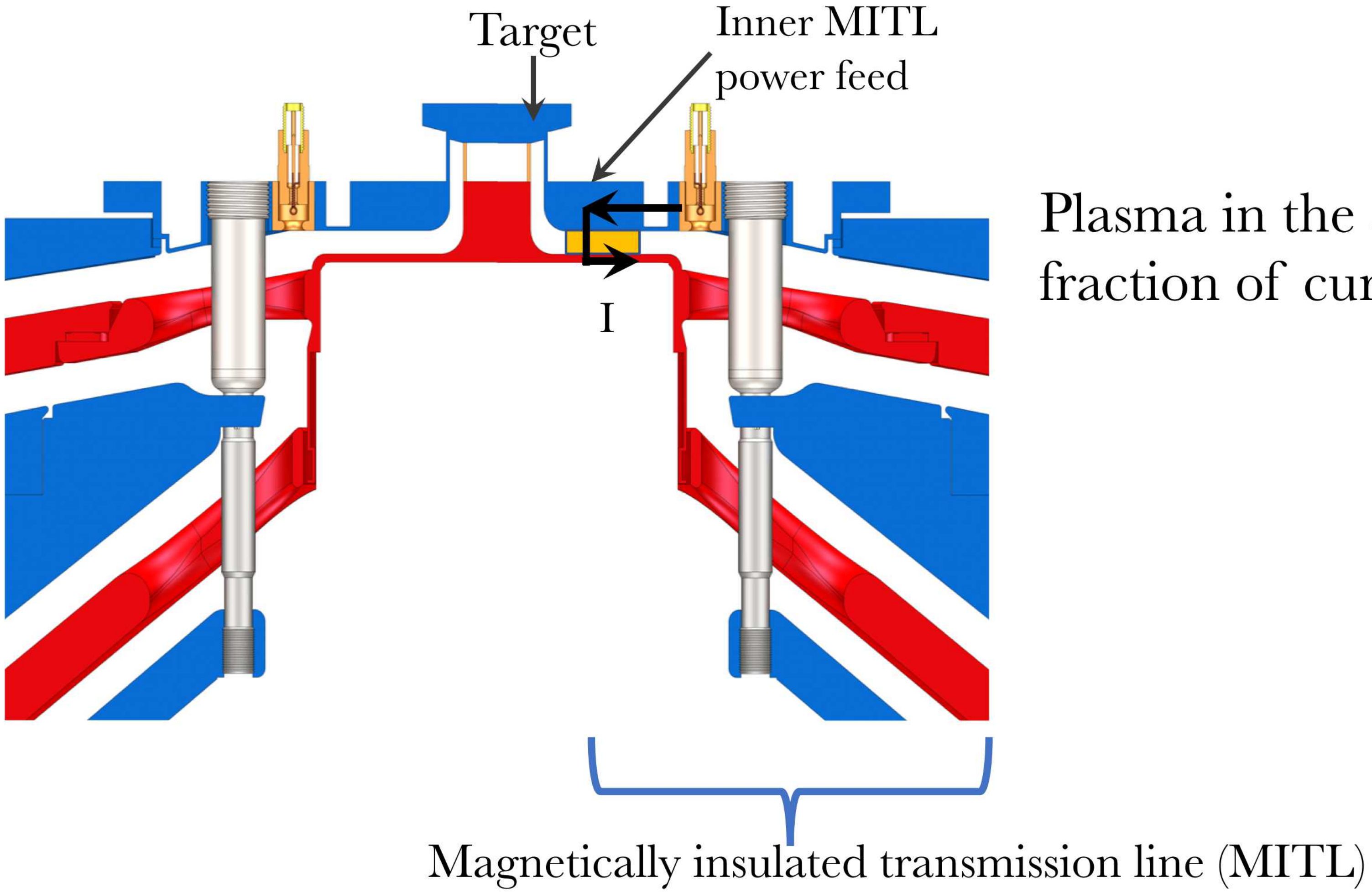
Outer surface of liner will Joule heat, and eventually explode

Plasma formation can compromise liner performance



Plasma will take some of the liner's current, as well as develop MHD instabilities

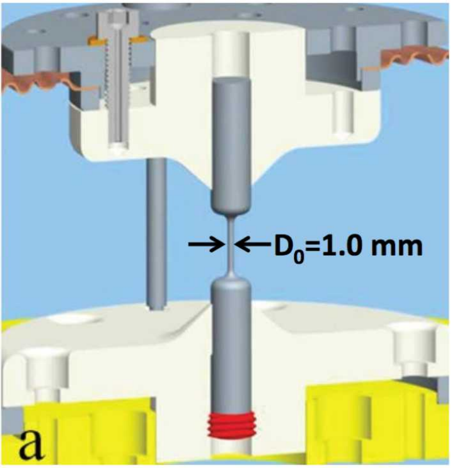
Plasma can result in current losses in pulsed power accelerators



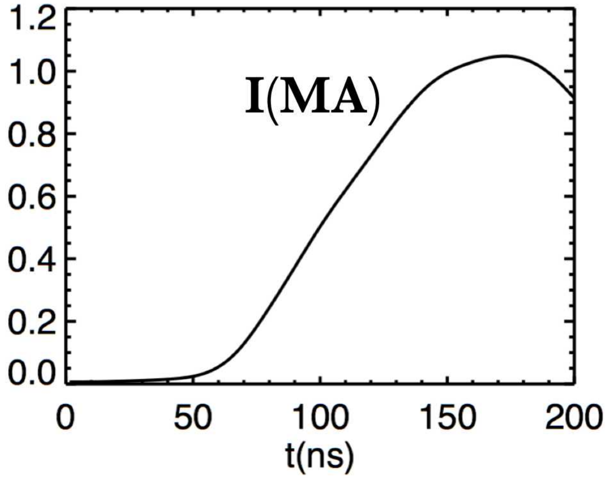
Plasma in the anode-cathode gap can short a fraction of current before it reaches the target.

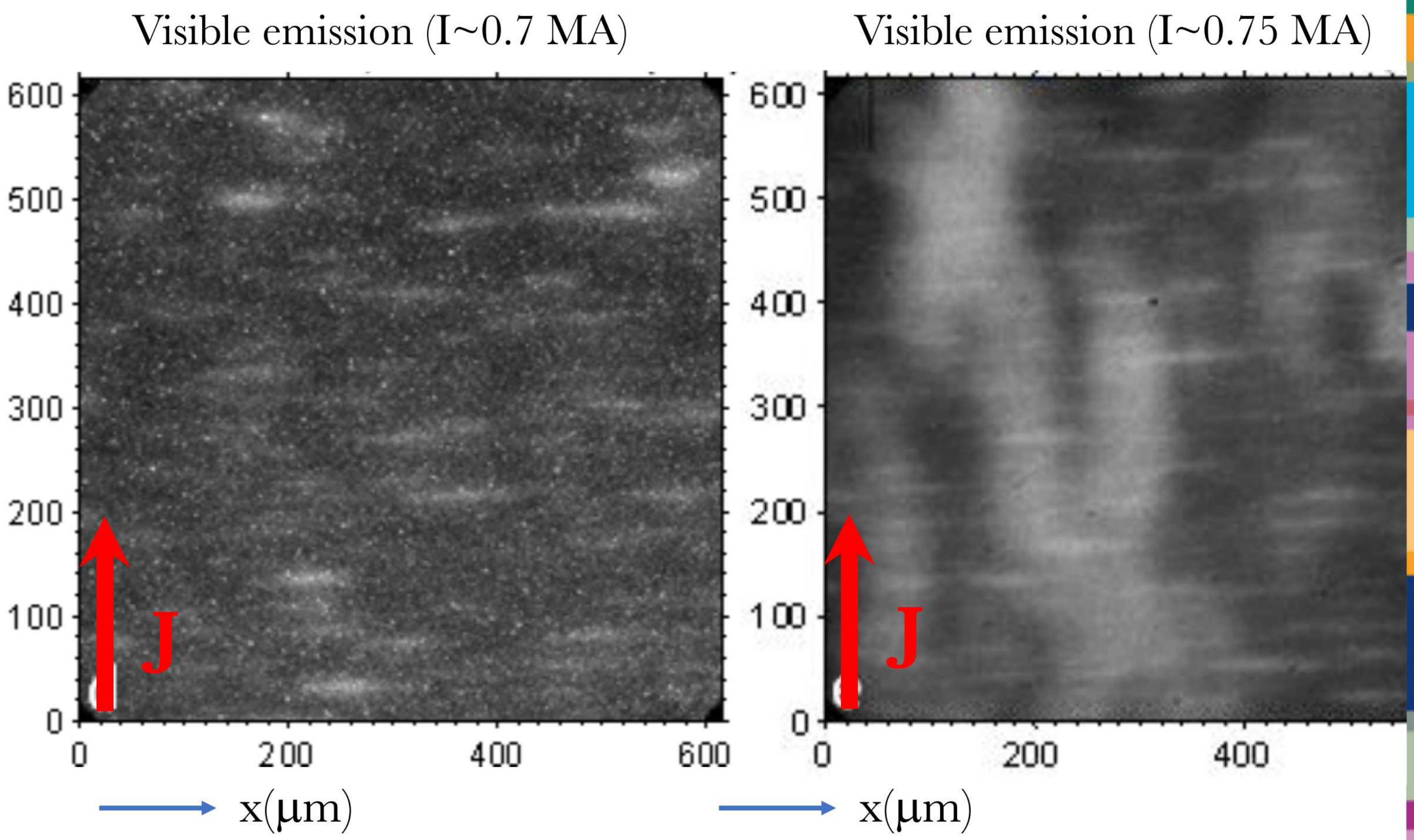
GI3:N. Bennett – Kinetic simulations of power flow in the Z accelerator

UNR experiments inform how metal heats and develops plasma, when subject to intense current



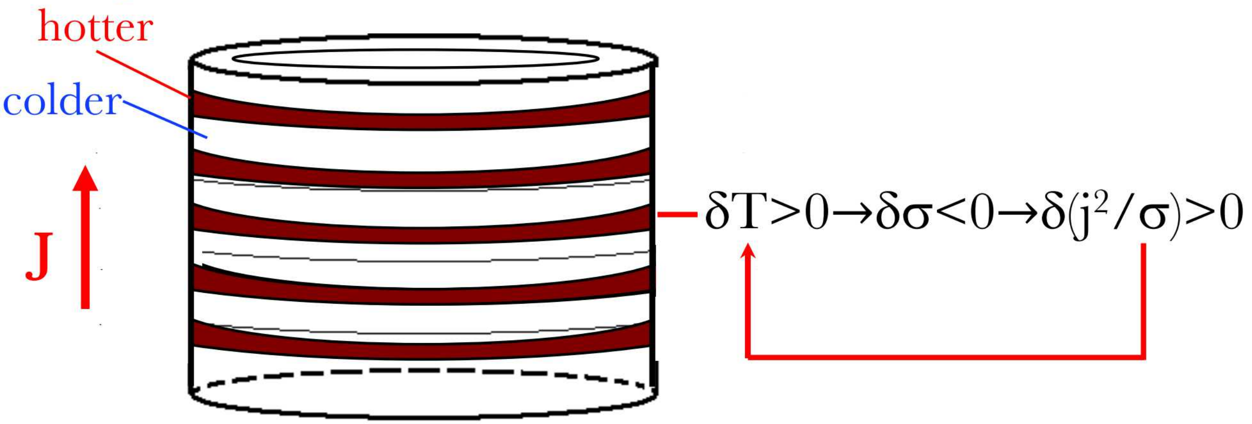
U. of Nevada, Reno (UNR) Zebra facility

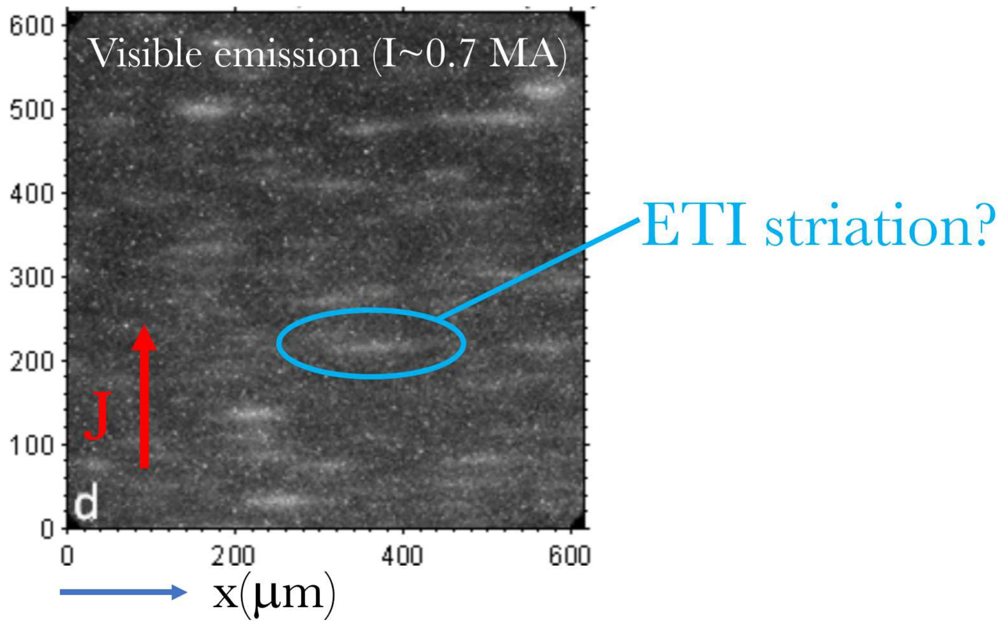




T.J. Awe et al., IEEE Trans. Plasma Sci. **45**, 4 (2017)

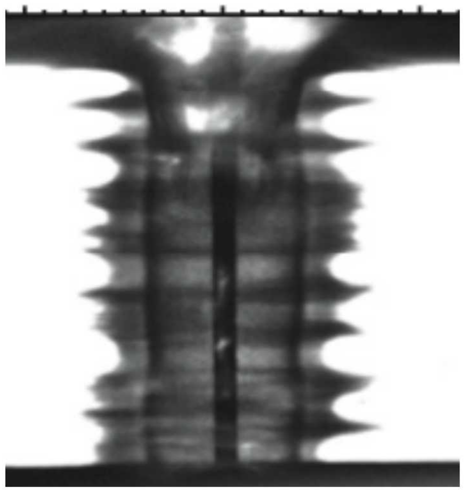
The electrothermal instability (ETI) is important to metal deformation





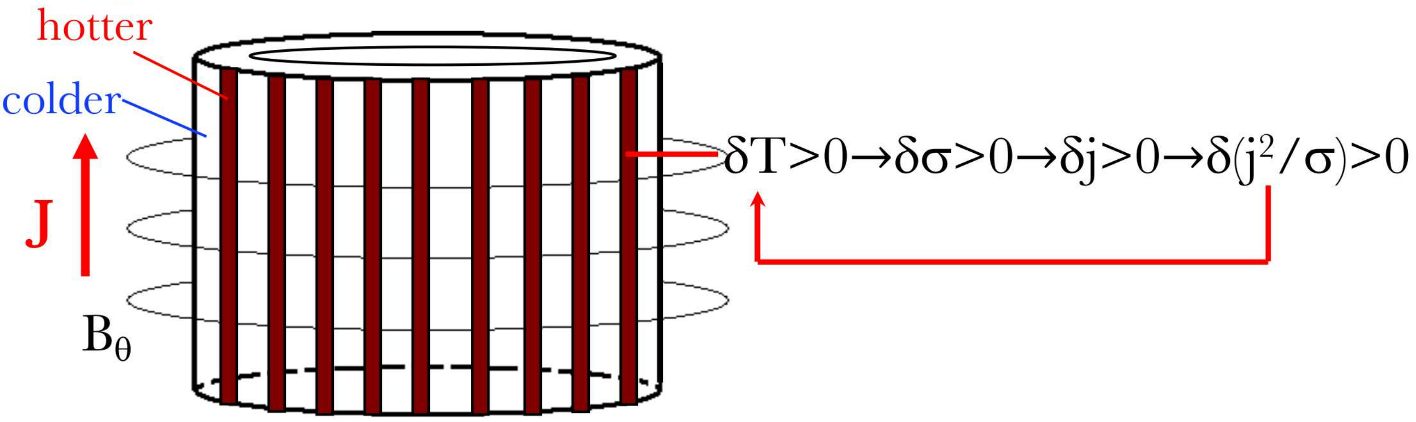
ETI is a Joule heating-driven instability.
In a metal ($d\sigma/dT<0$), the dominant mode manifests as hot/cold bands -- “striations”.

Q: what seeds the striation?

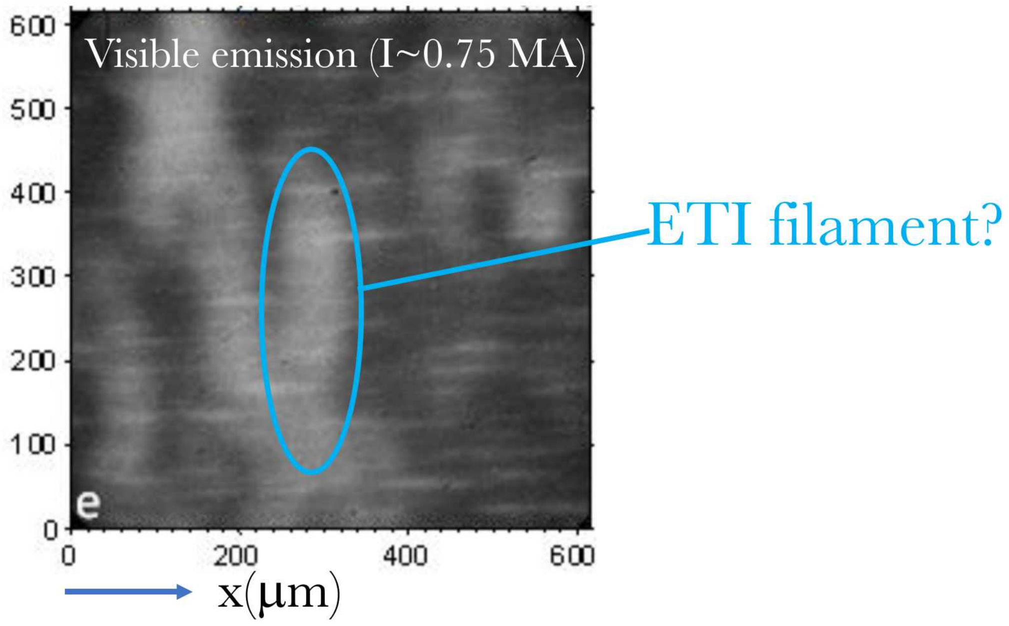


ETI striations can seed the MRT instability

The electrothermal instability (ETI) is important to plasma formation



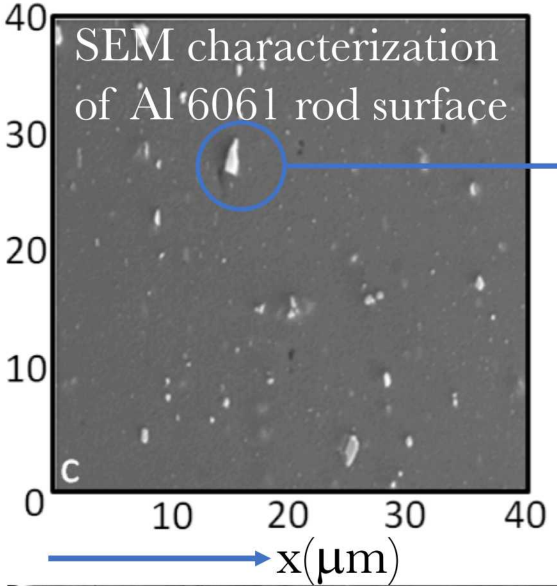
In a plasma ($d\sigma/dT>0$), the dominant mode manifests as hot/cold "filaments".

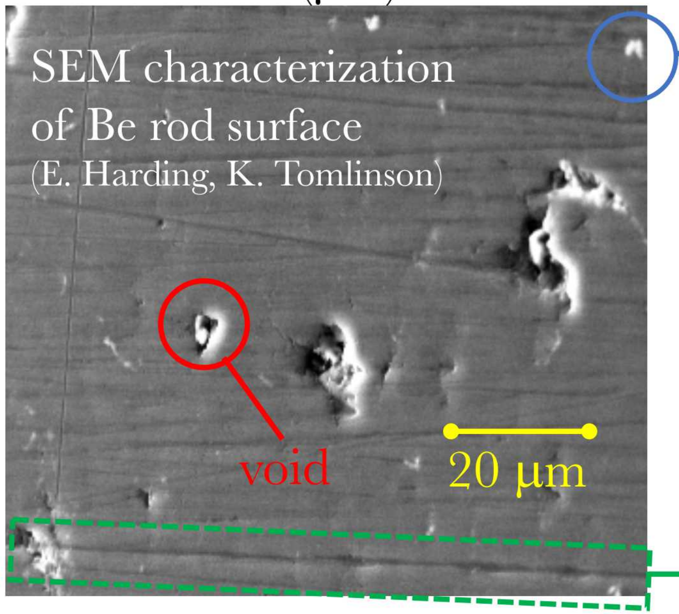


Q: How do striations⇒filaments?

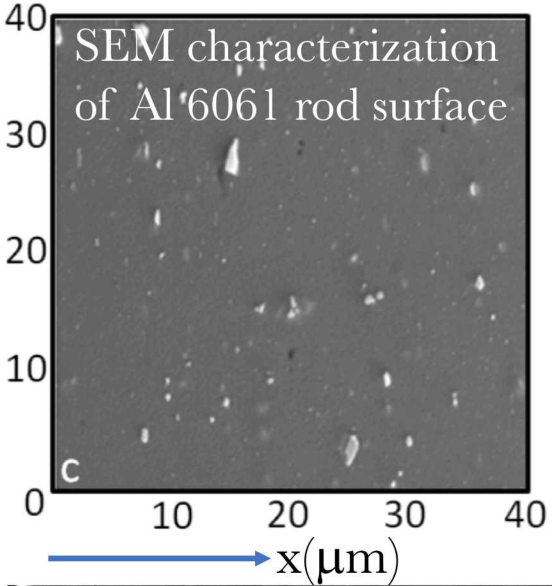
This is a 3D process, and likely requires a 3D perturbation

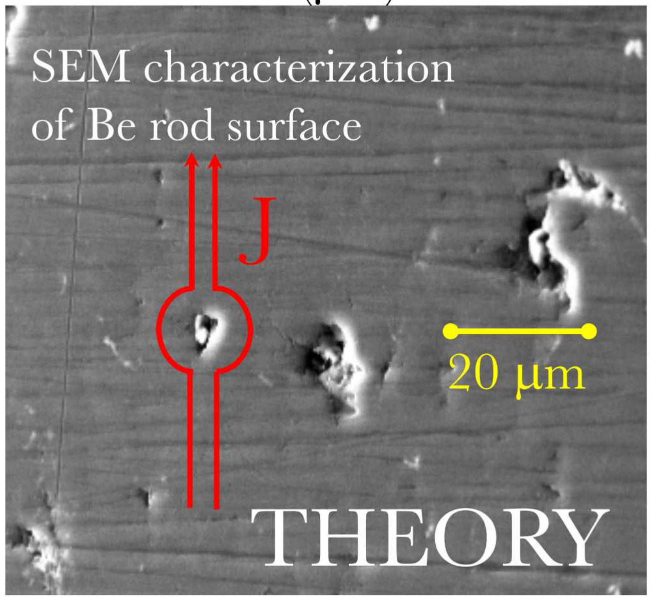
Metals generally possess resistive inclusions and voids





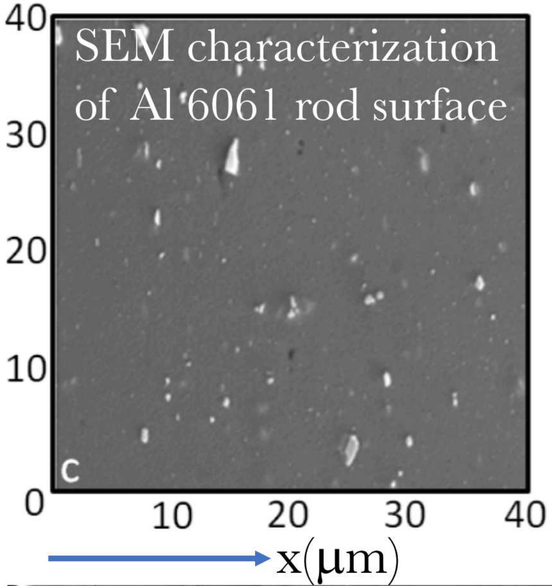
Can resistive inclusions or voids seed striations/filaments?

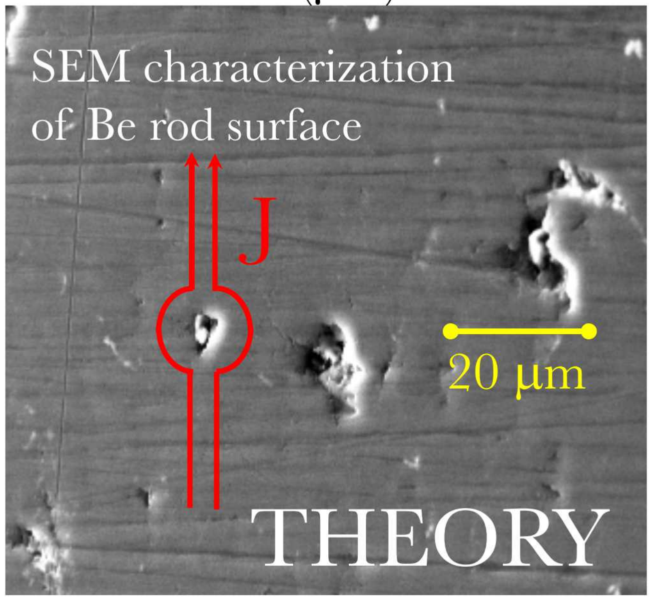


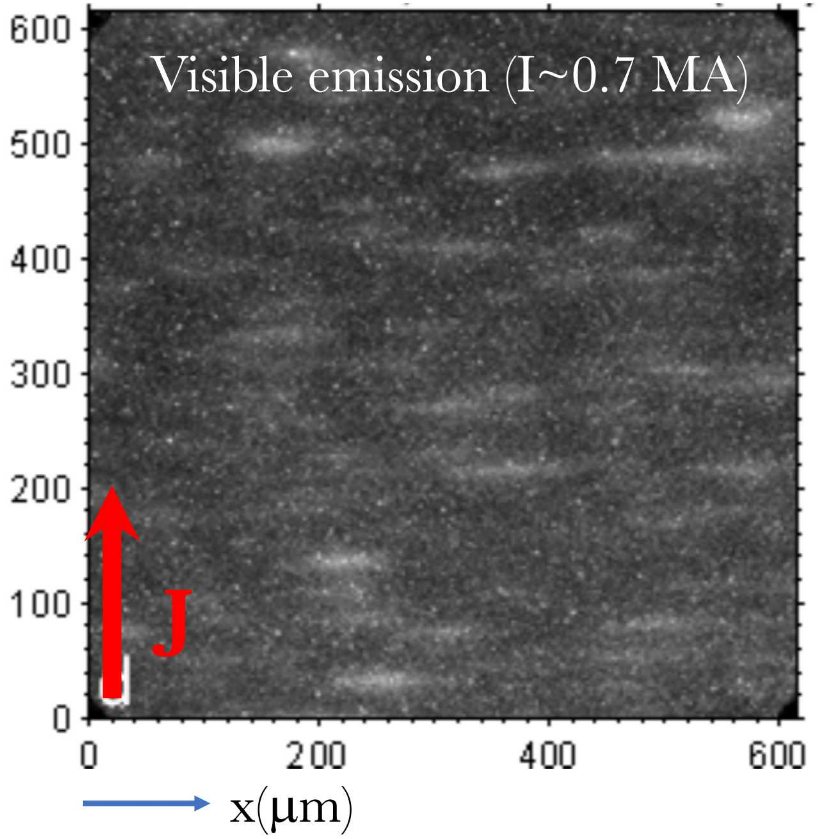


Q: How does current density **J** divert and amplify around inclusions, surface roughness?

Can resistive inclusions or voids seed striations/filaments?



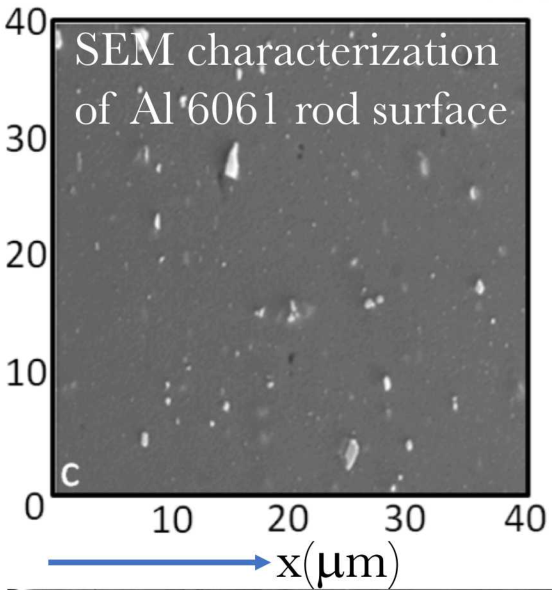


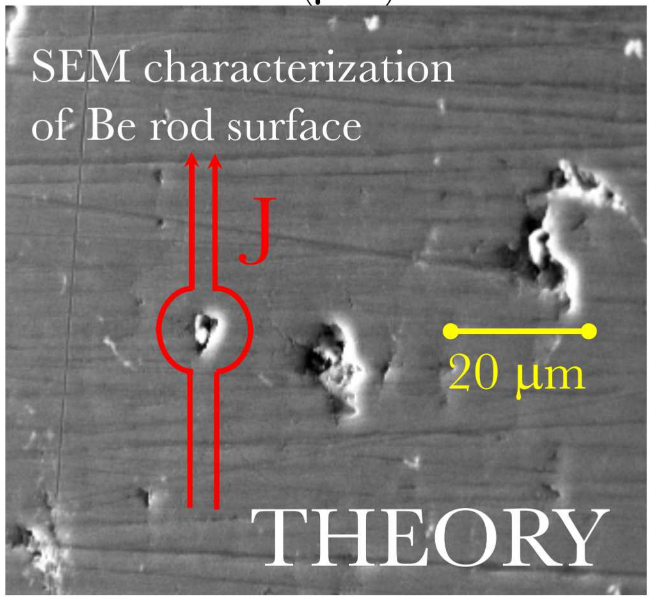


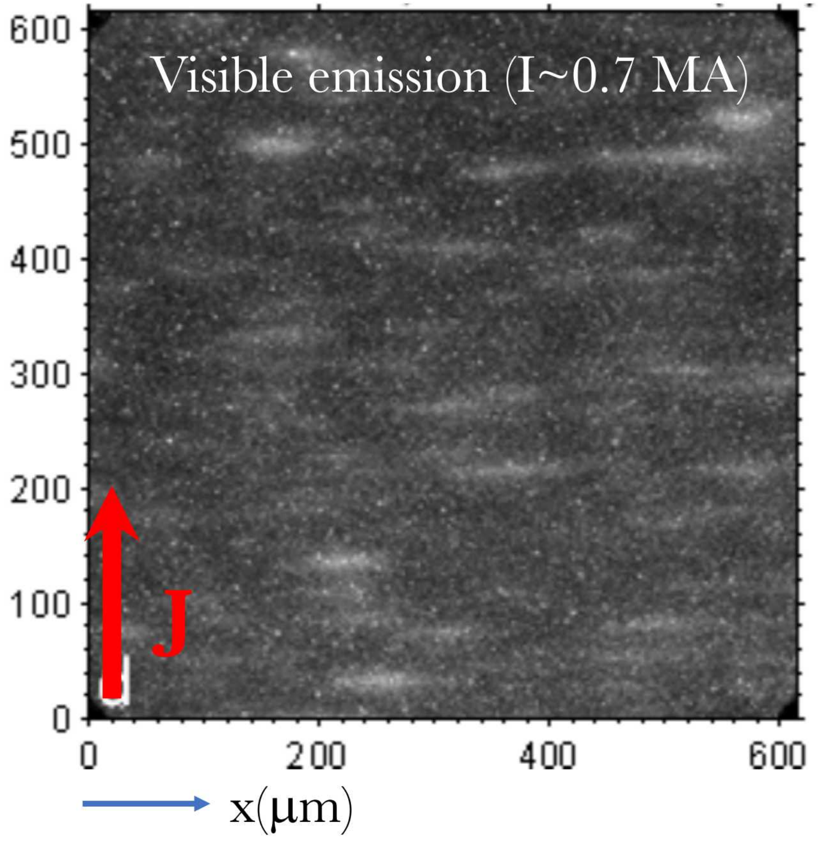
3D MHD simulation

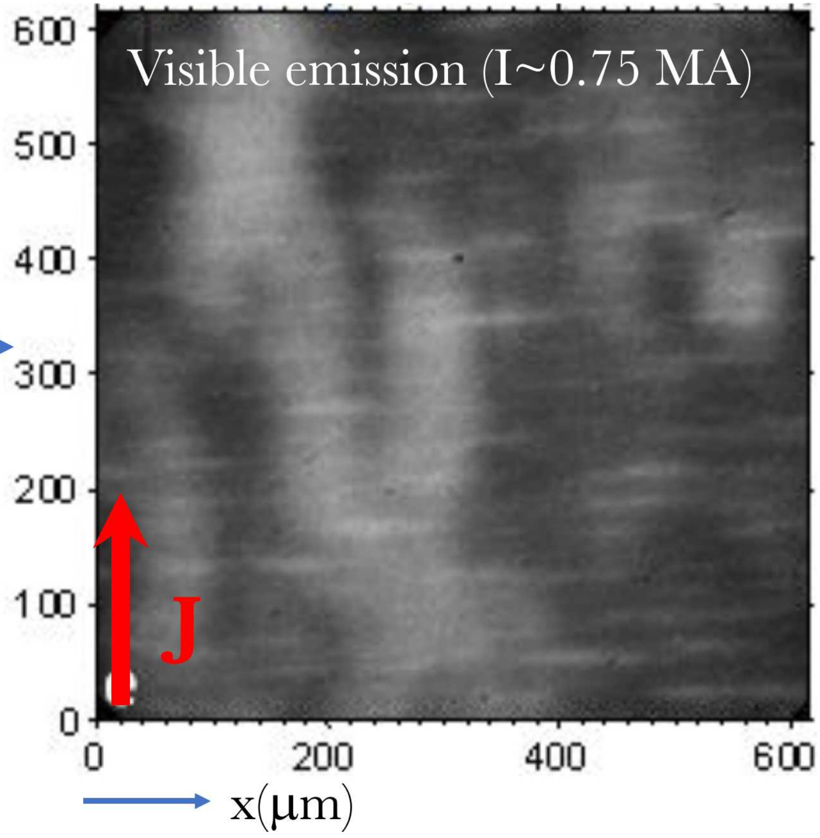
Q: Can **J** amplification allow μm-scale inclusions to transform into much larger striations?

Can resistive inclusions or voids seed striations/filaments?







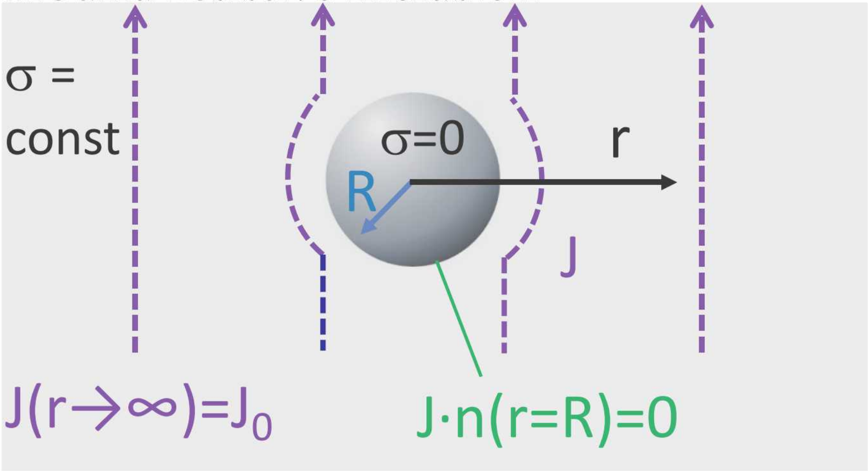


3D MHD simulation

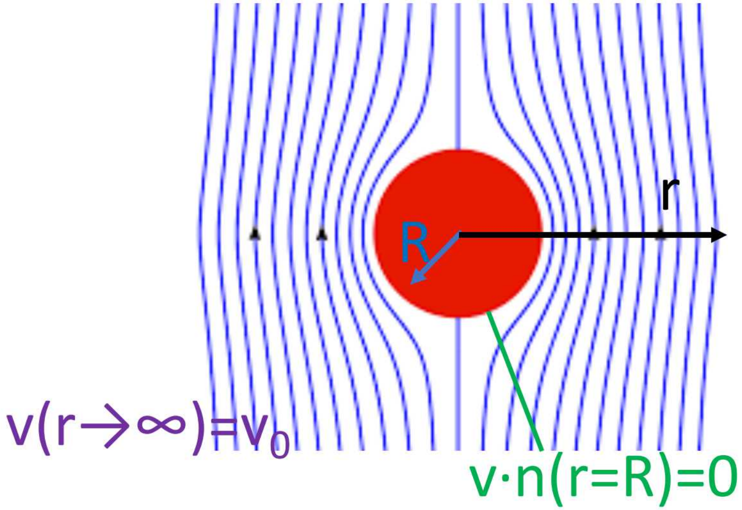
Q: How do striations convert to filaments?

Analogy between electrical current and fluid flow*

Steady-state, electrical current flow around resistive inclusion



Incompressible, potential fluid flow around sphere



J and **v** satisfy the same equations ⇒ we get **J** "for free" from hydrodynamic solution.

$$E = -\nabla\phi$$

$$J = \sigma E = -\sigma\nabla\phi$$

$$\nabla \cdot J = 0 \Rightarrow \nabla^2\phi = 0$$

$$J \cdot n(R) = 0 \Rightarrow \nabla\phi \cdot n = 0$$

$$v = \nabla\phi$$

$$\nabla \cdot v = 0 \Rightarrow \nabla^2\phi = 0$$

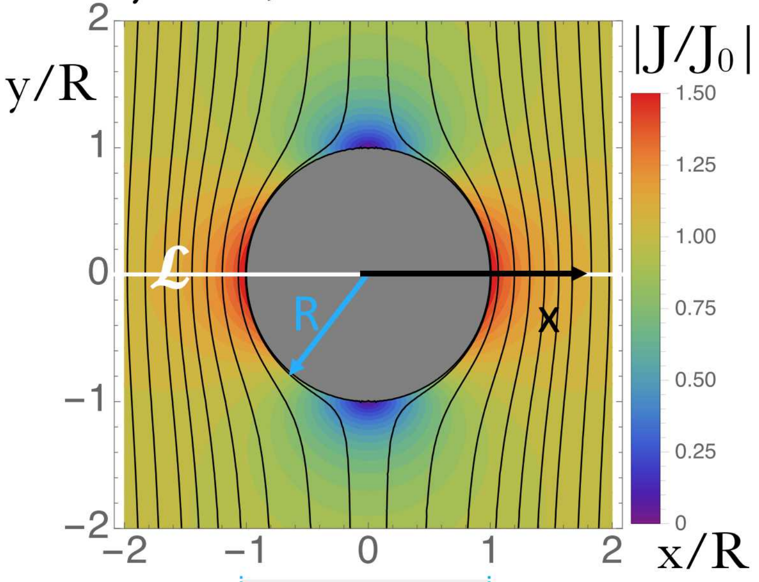
$$v \cdot n(R) = 0 \Rightarrow \nabla\phi \cdot n = 0$$

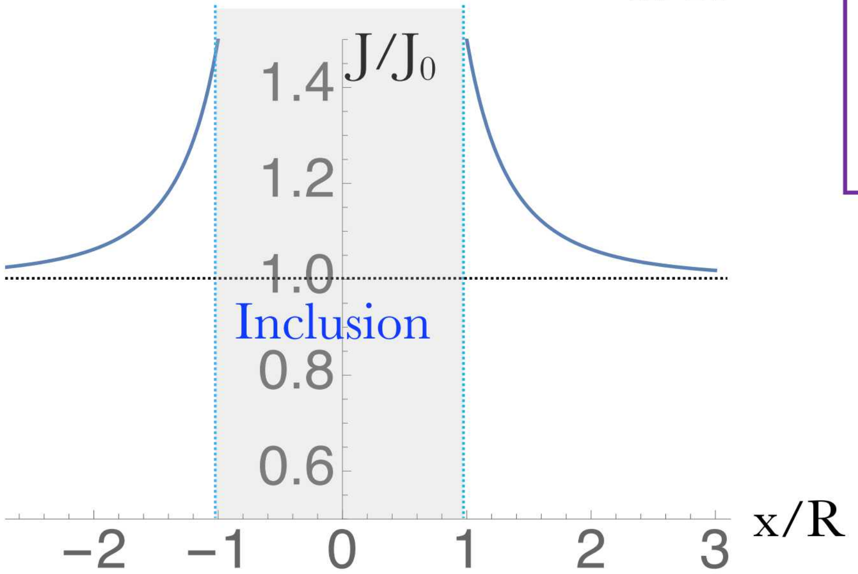
J ⟷ **v**

*H. Lamb, Hydrodynamics (1879)

Resistive sphere amplifies J around its equator

Steady-state, electrical current flow (assuming skin depth≡$\delta \gg$ R)



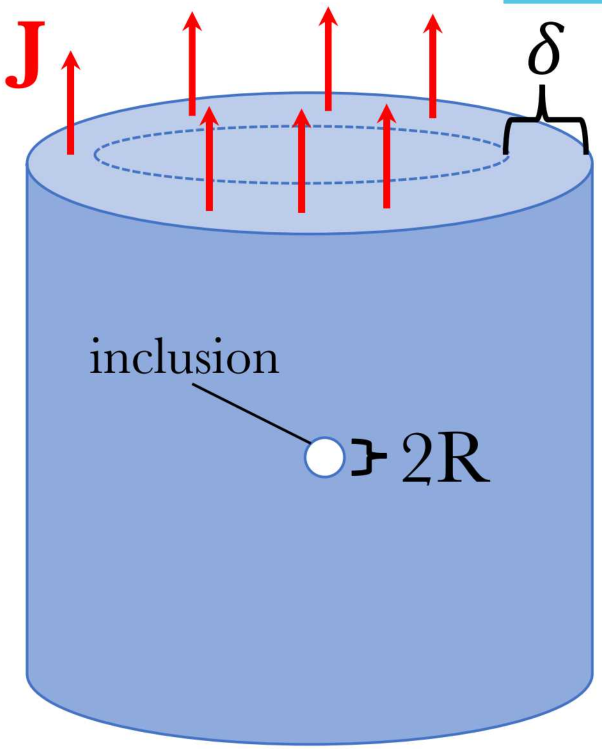


Stream lines deflect around the sides of sphere, leading to faster flow there.

Along the line $\mathcal{L}$,

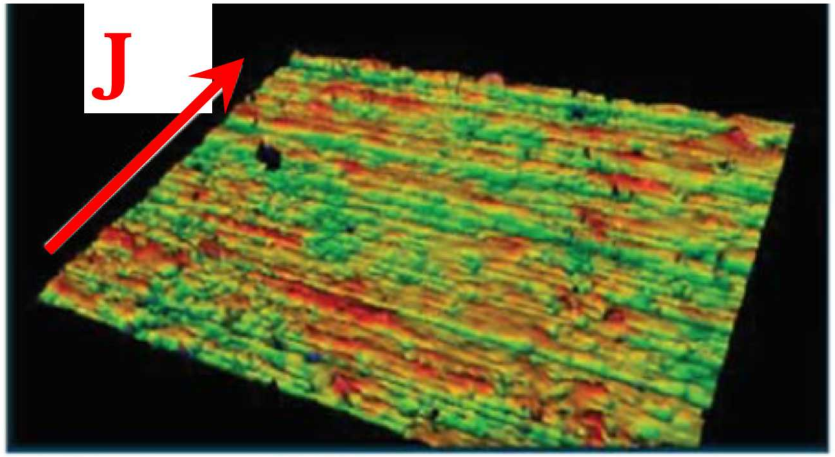
$$J = J_0(1 + \frac{R^3}{2|x|^3}) \text{ for } |x| \geq R$$

•Maximum value is $J=(3/2)J_0$, <u>independent</u> of R! Amplification is significant, even for tiny inclusions.

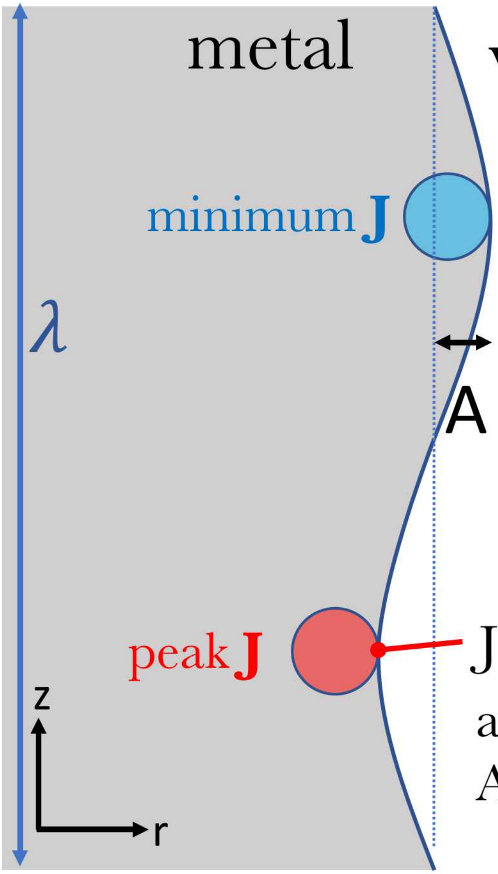


Inclusion is dominant perturbation in UNR experiment

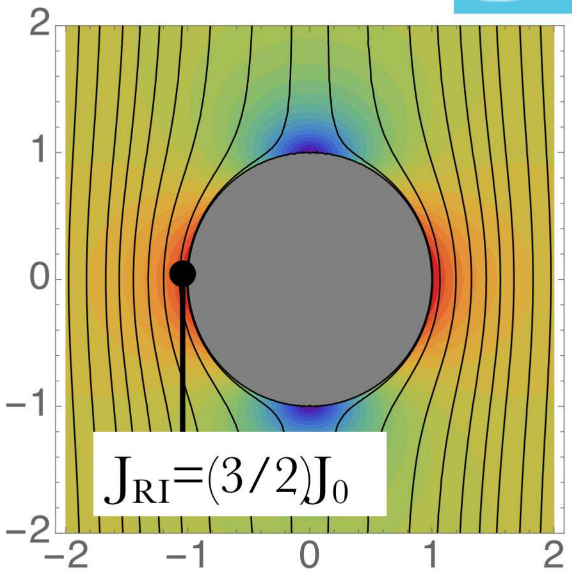
Machining grooves on rod surface



Steady-state, electrical current flow

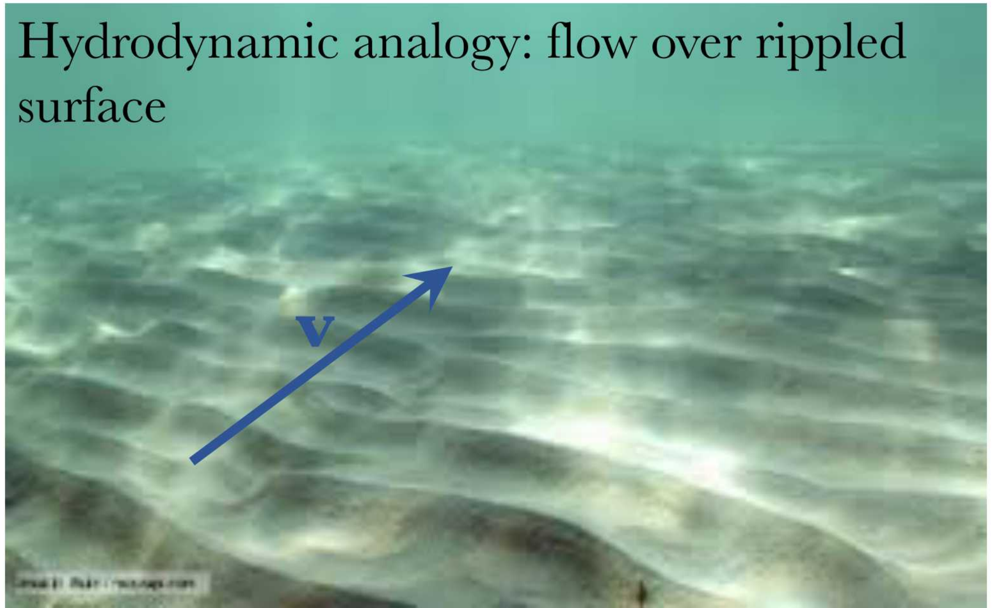


$J_{SR} \simeq J_0(1+2\pi A/\lambda)$ assuming $\delta \gg \lambda$, $A<\lambda$



In experiment of interest*
$A \sim 42$ nm, $\lambda \sim 5$ μm,
$J_{SR} \sim 1.05 J_0 \Rightarrow$ inclusion is dominant perturbation

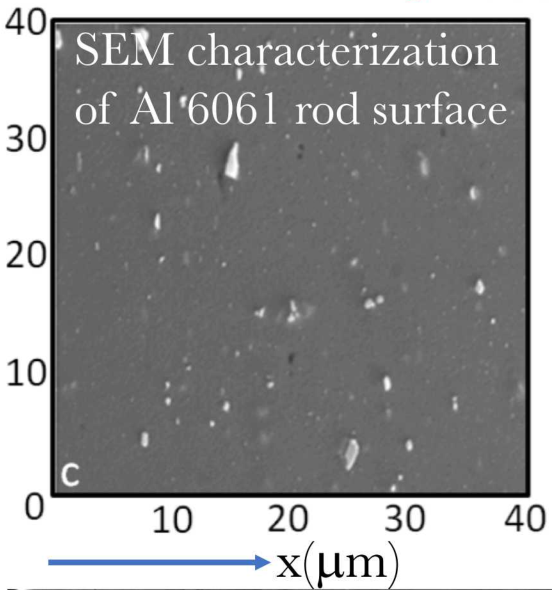
Hydrodynamic analogy: flow over rippled surface

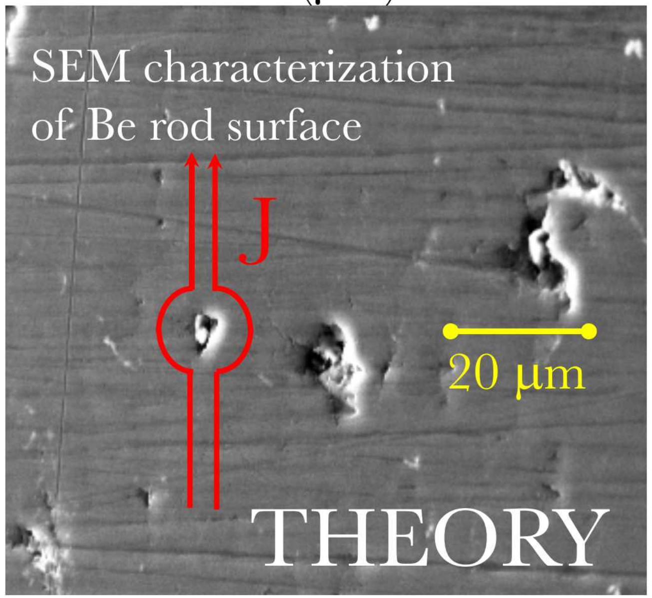


Amplification depends on A/λ, not just A

*T.J. Awe et al., IEEE Trans. Plasma Sci. **45**, 4 (2017)

Can resistive inclusions seed striations/filaments?





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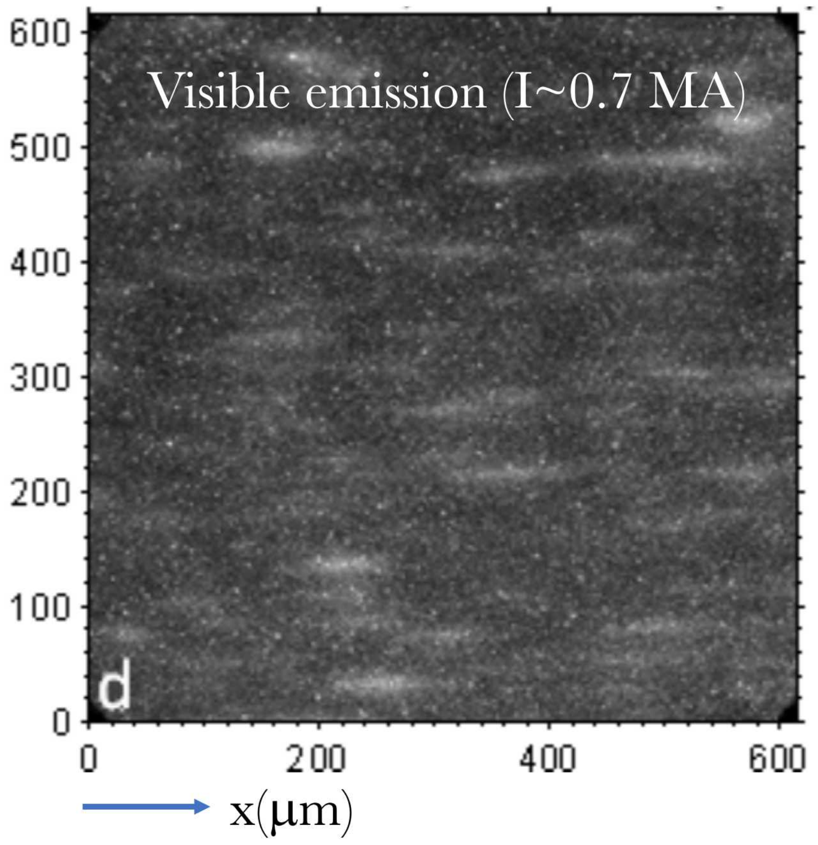
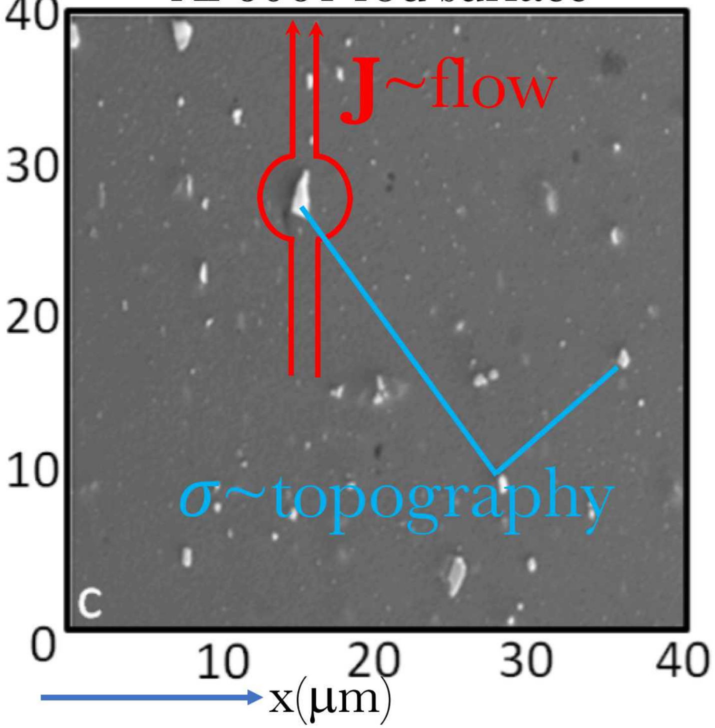
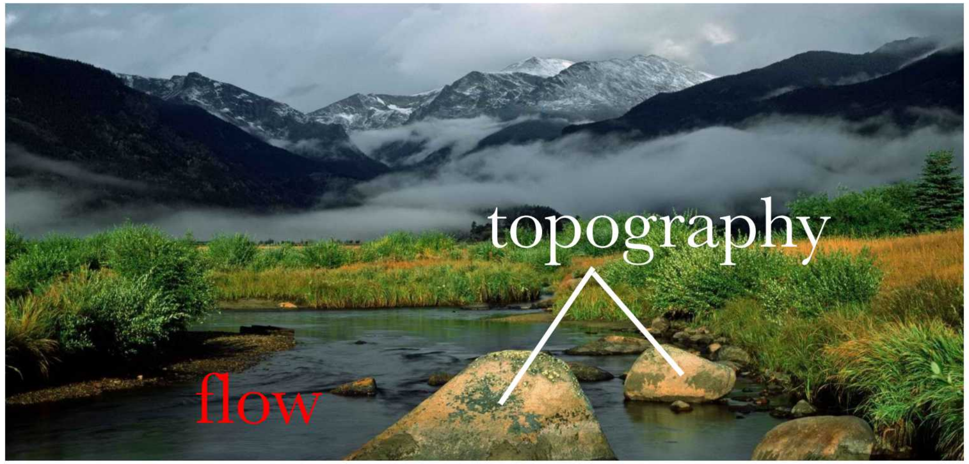


J and σ constantly evolve through <u>feedback</u>



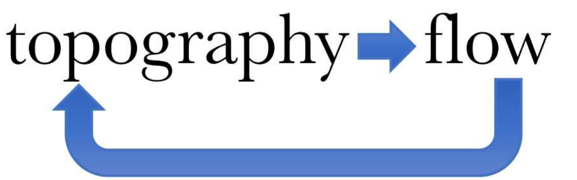


"Weak" flow:

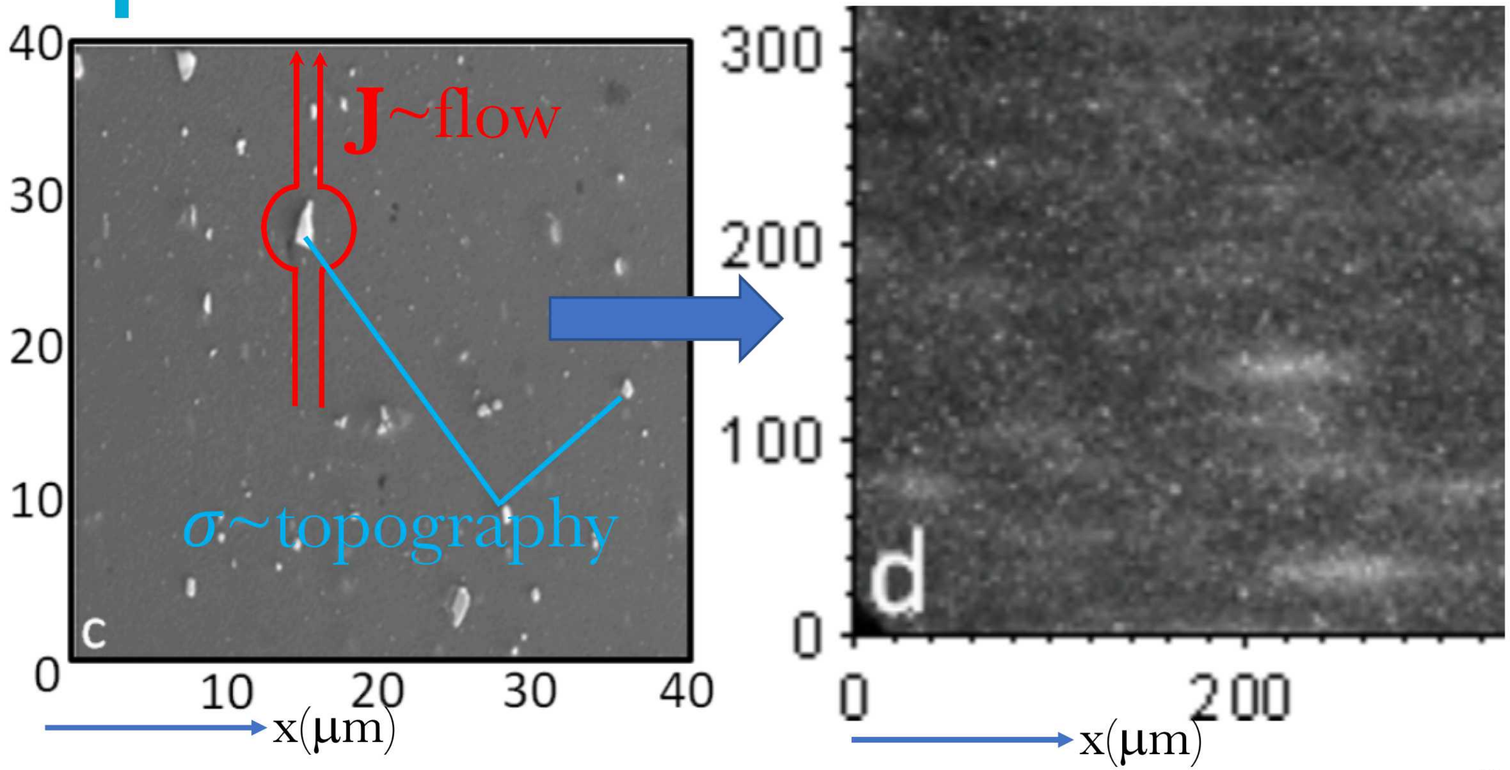
topography ➡ flow

topography determines flow

"Strong" flow:



Feedback transforms μm-scale inclusions into larger striations



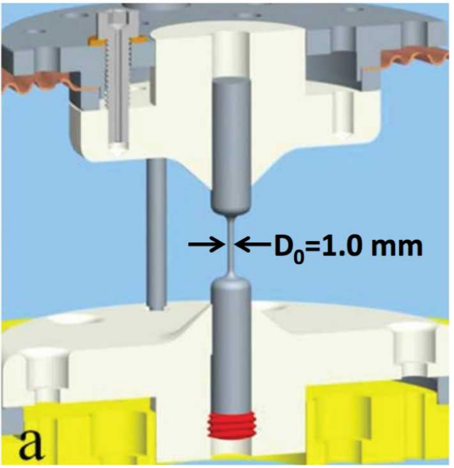
In a metal, the feedback between σ and J is mediated by Joule heating:

flow — topography

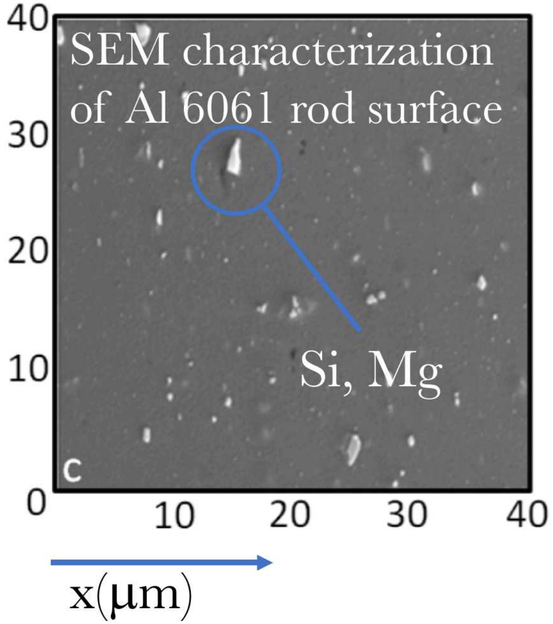
$$\delta J > 0 \Rightarrow \delta \eta J^2 > 0 \Rightarrow \delta T > 0 \Rightarrow \delta \sigma < 0$$

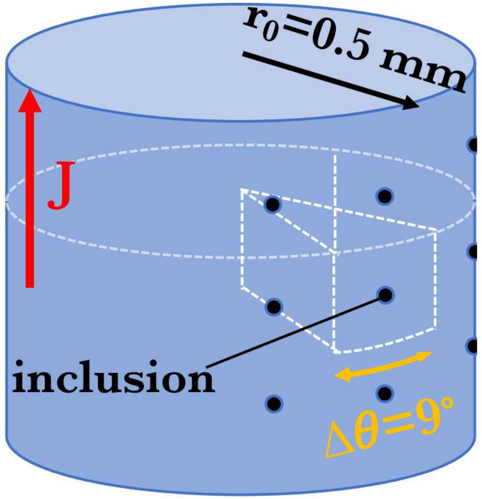
Need 3D MHD to study this process.

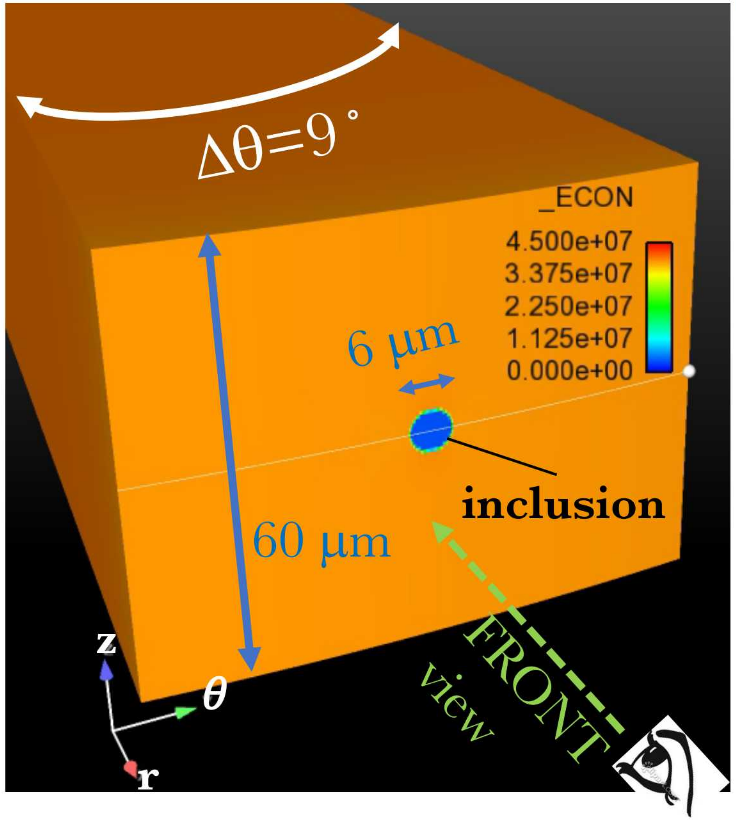
3D MHD simulation of Al rod + resistive inclusion

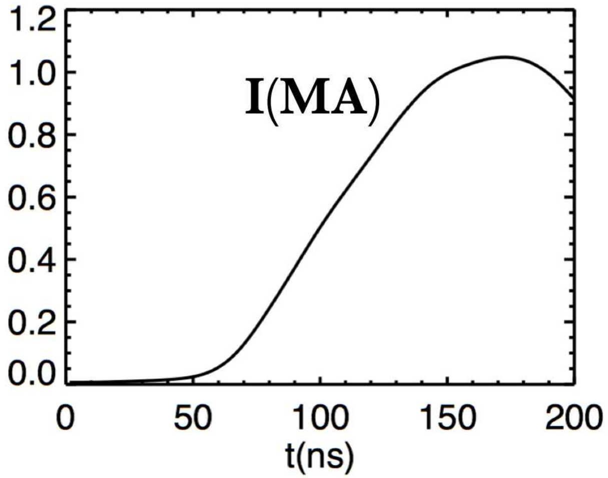


U. of Nevada, Reno Zebra facility







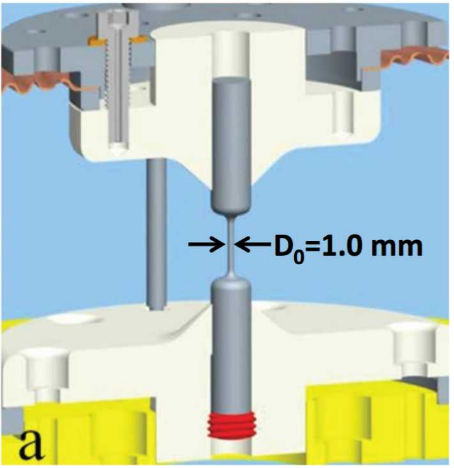


<u>3D MHD Code (ALEGRA)</u>

- Periodic BCs axially and azimuthally
- Hemispherical inclusion (R_{pit}= 3 μm): Al with σ/10, κ/10
- LMD thermal/electrical conductivity
- SESAME EOS Al 6061* (Thanks, K. Cochrane, T. Sjostrom, T. Hutchinson!)
- No radiation
- All units are SI

*T. Sjostrom, S. Crockett, S. Rudin, PRB **94**, 144101 (2016)

3D MHD simulation of Al rod + resistive inclusion



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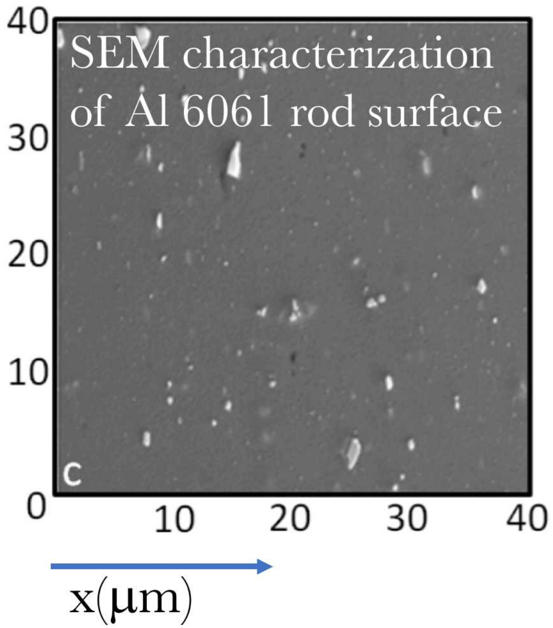

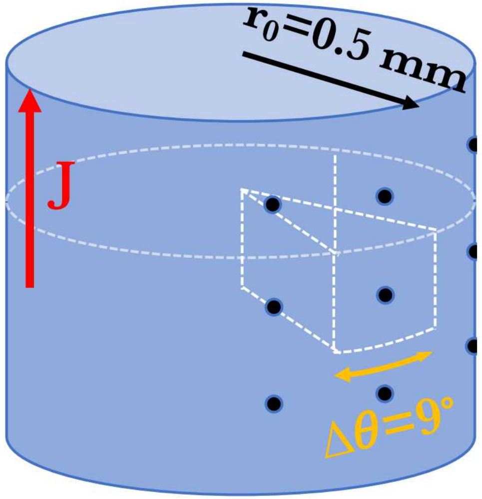

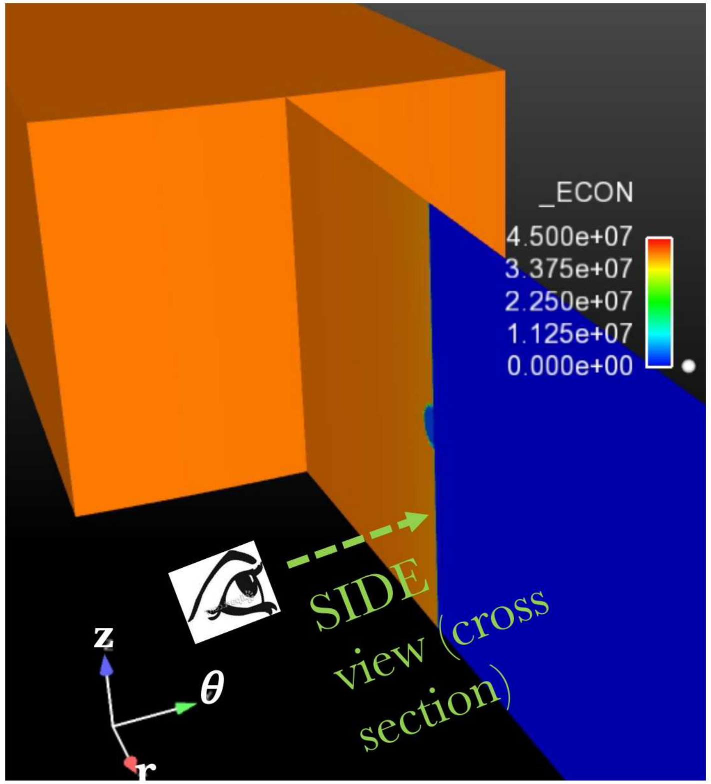

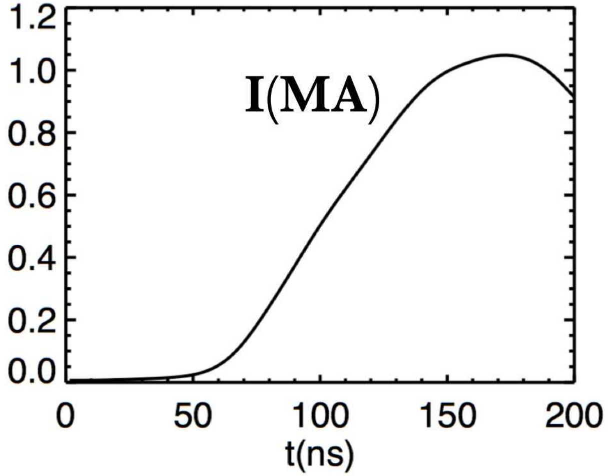

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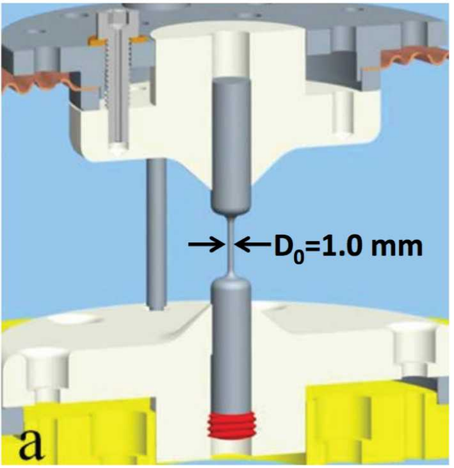

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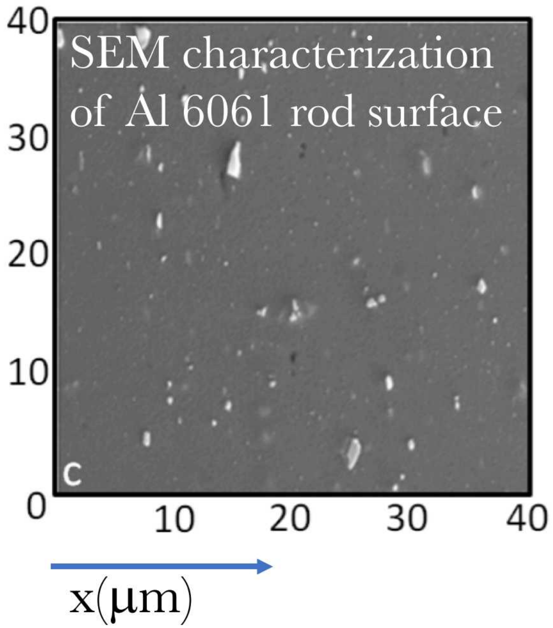
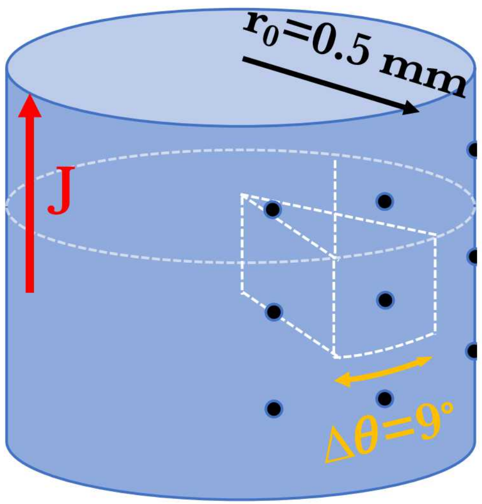
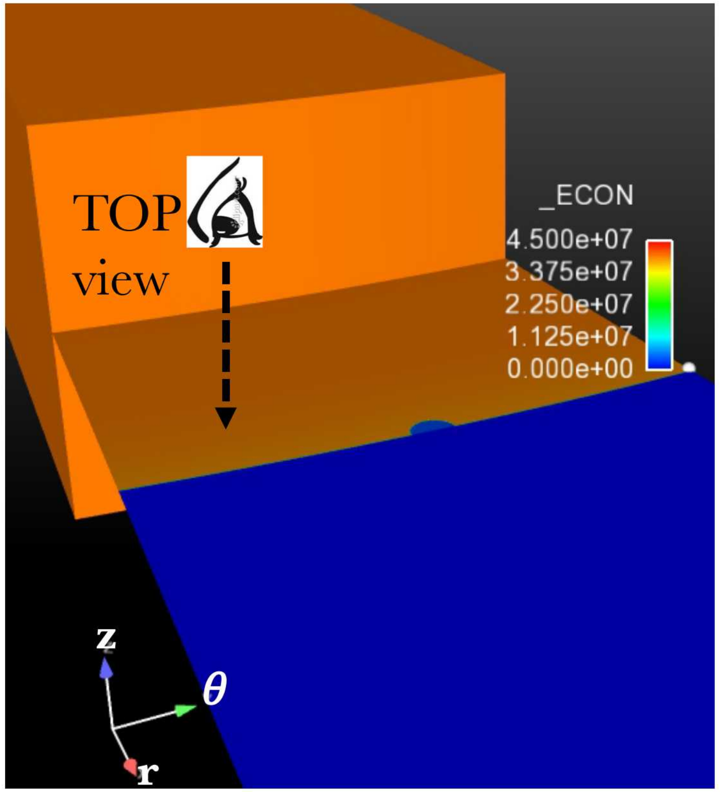
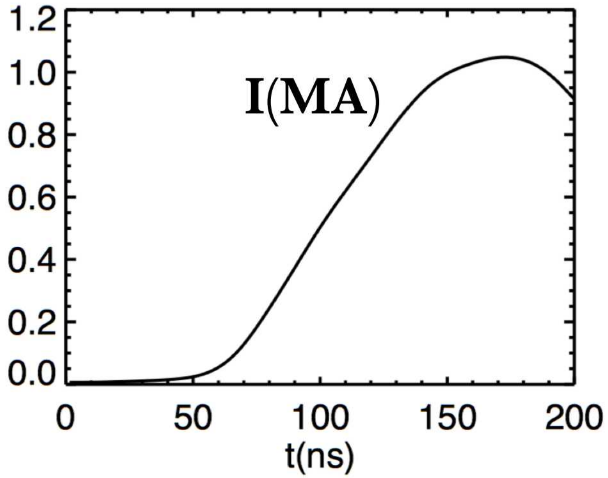
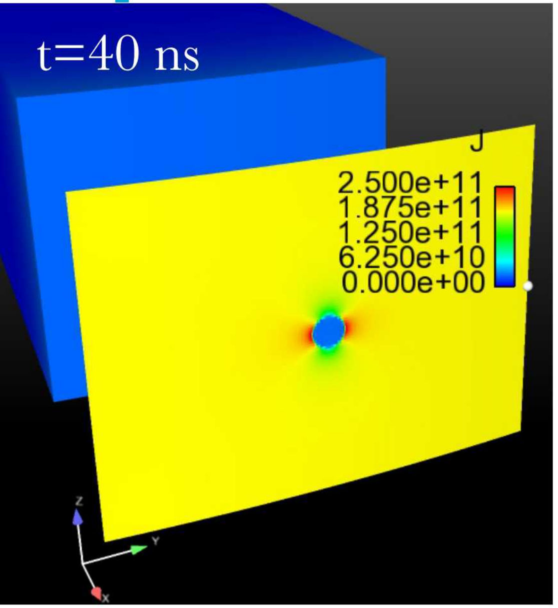


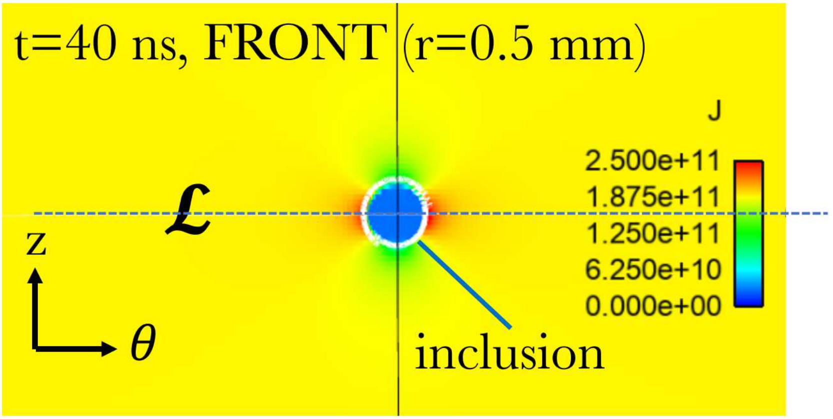


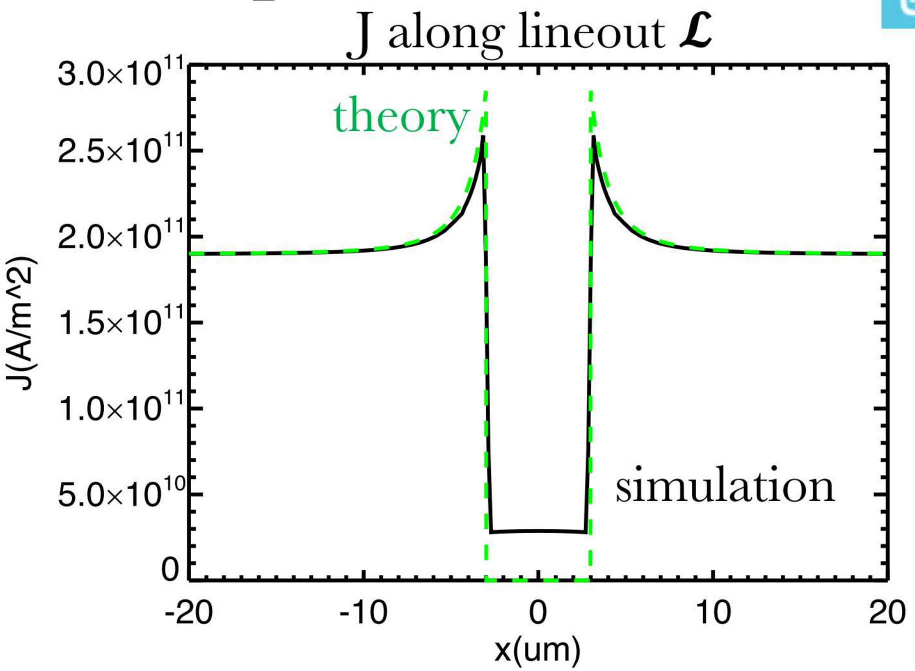


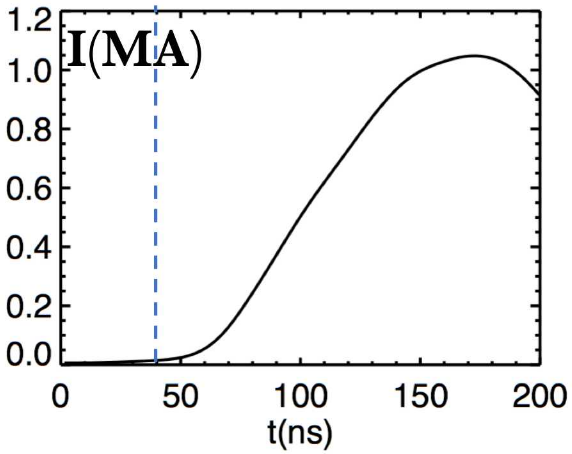


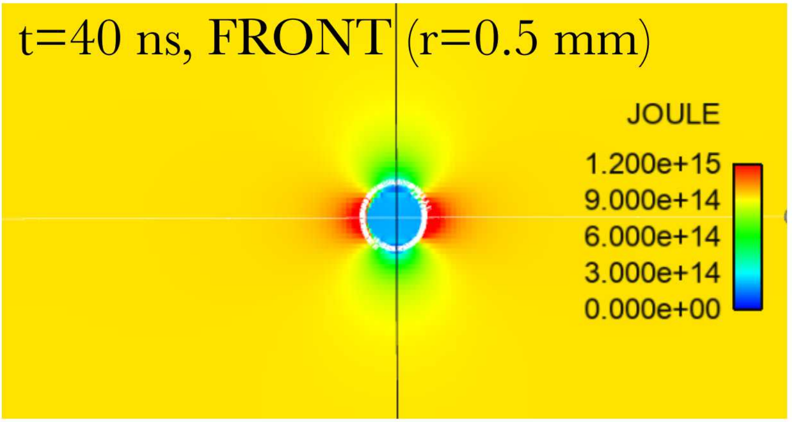
Initially, simulation reproduces flow around a sphere





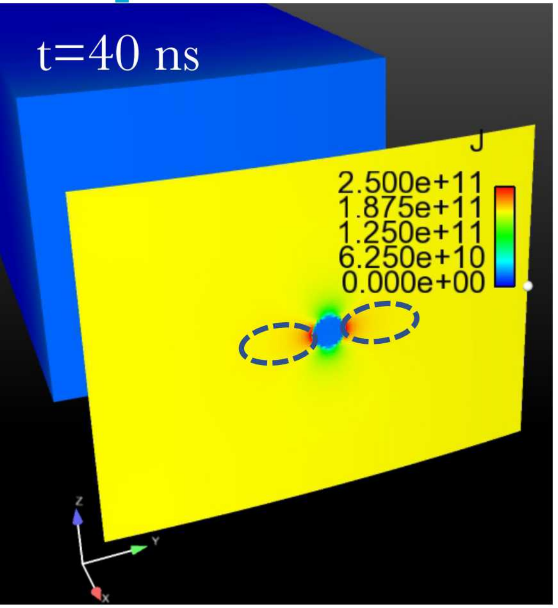


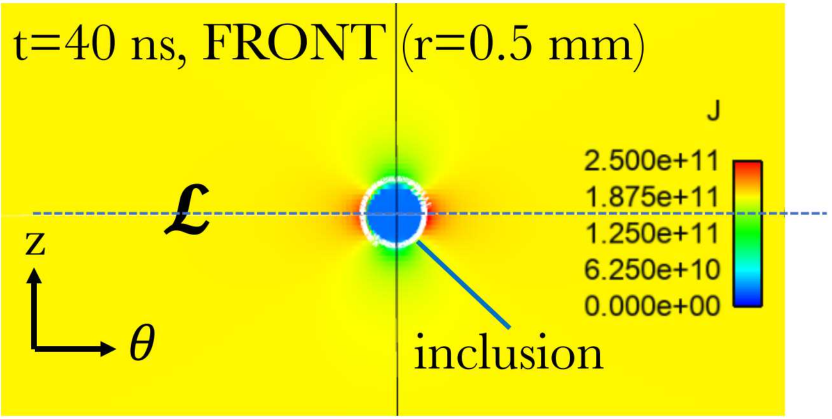


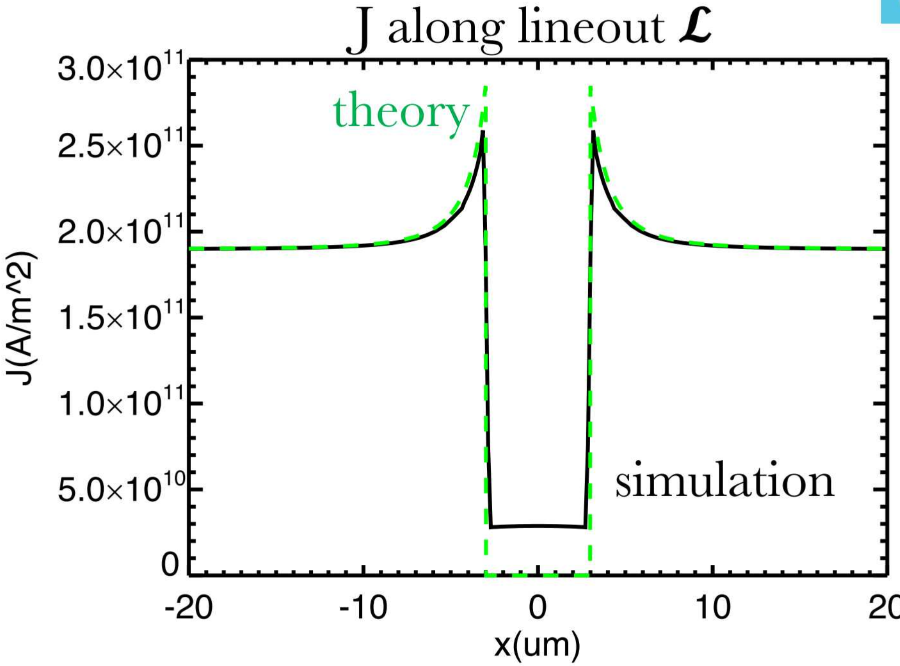


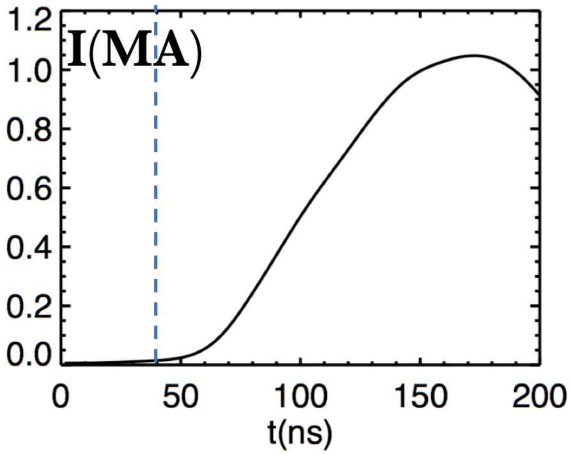
This is at an early time, before feedback loop has initiated.

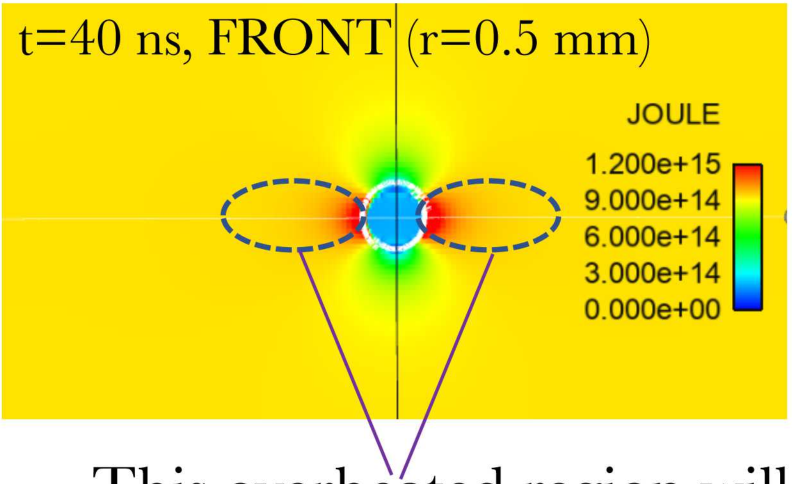
Initially, simulation reproduces flow around a sphere





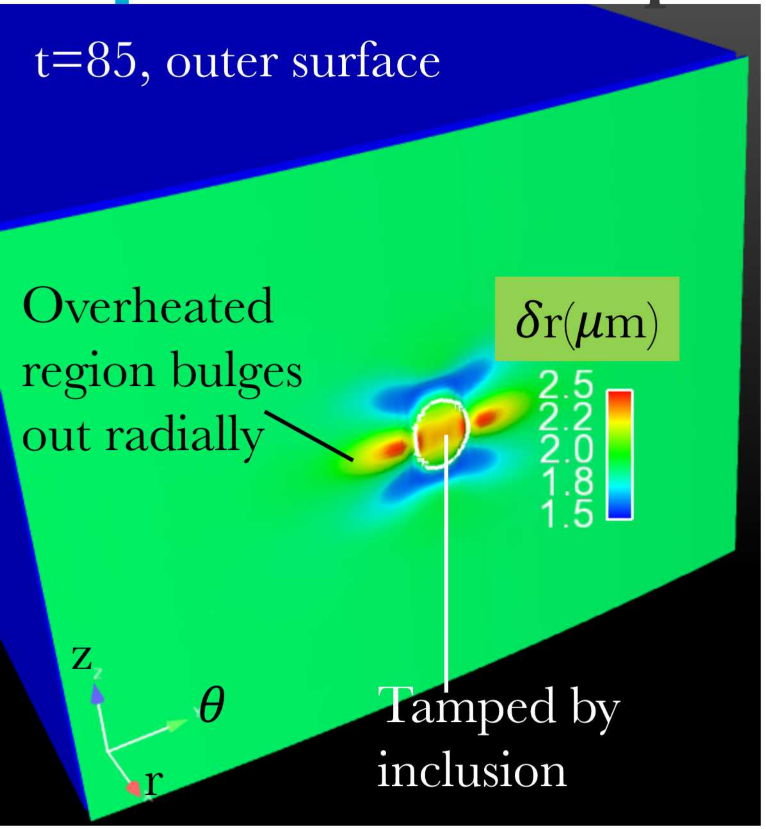


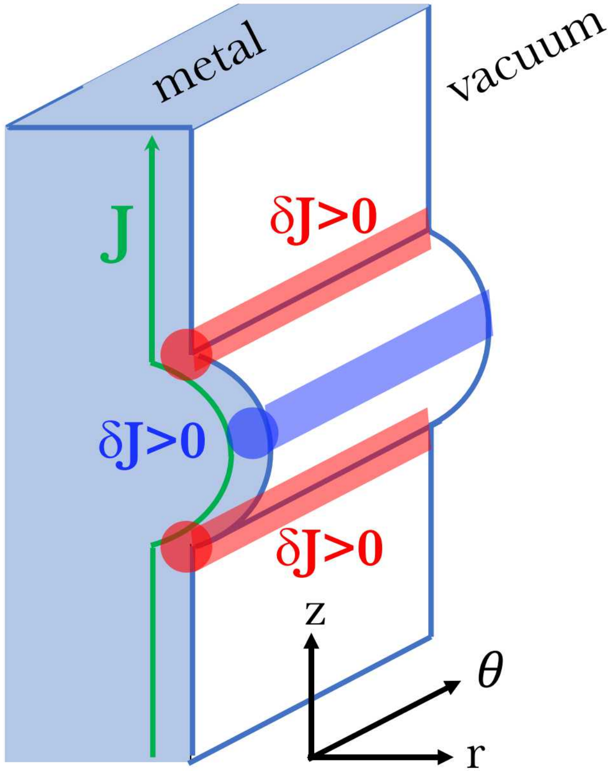




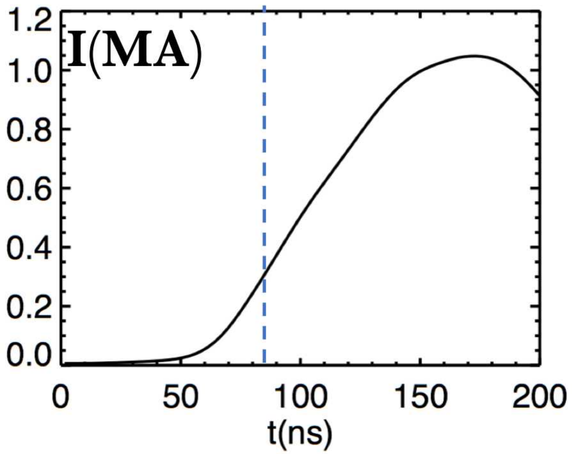
This overheated region will melt early, and expand outward.

Flow around sphere converts to flow over bulge

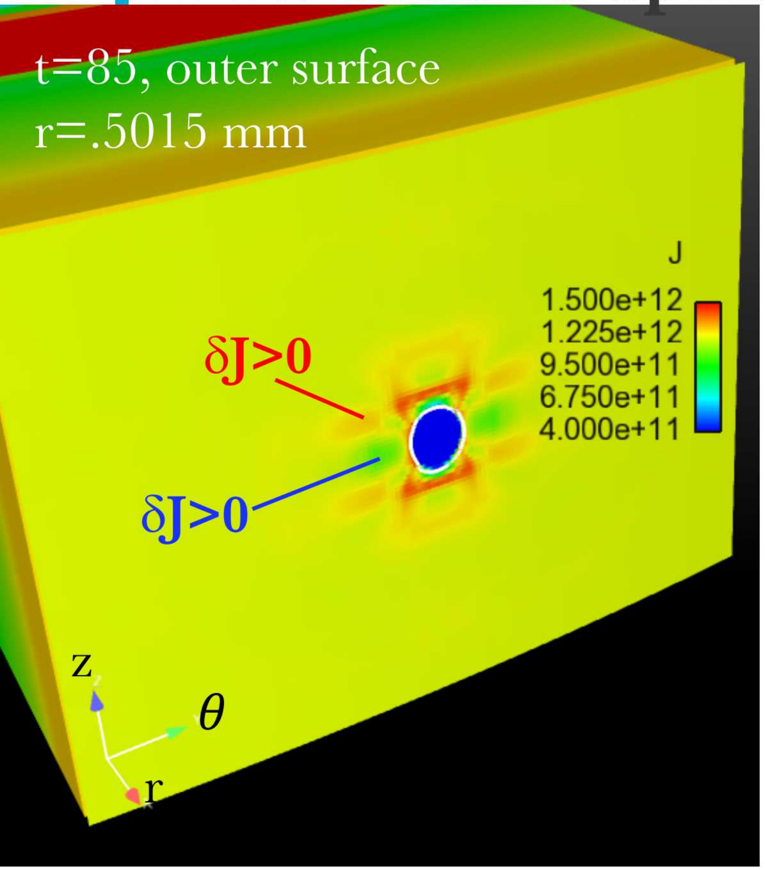


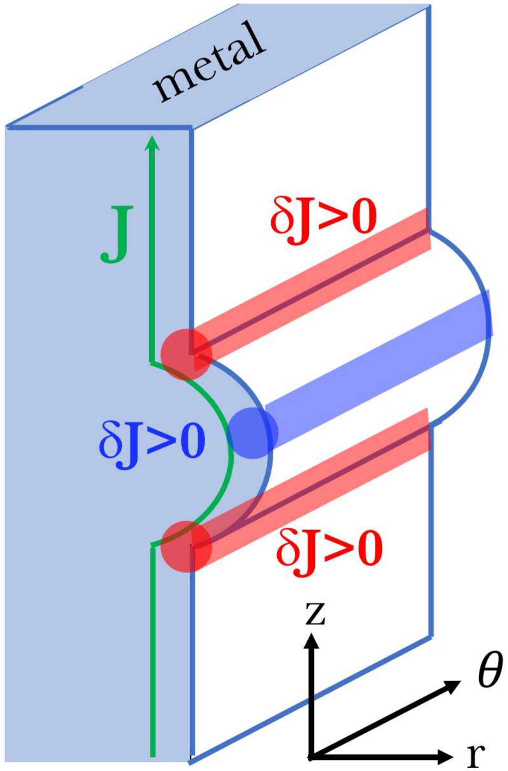


Milne-Thomson, Theoretical Hydrodynamics

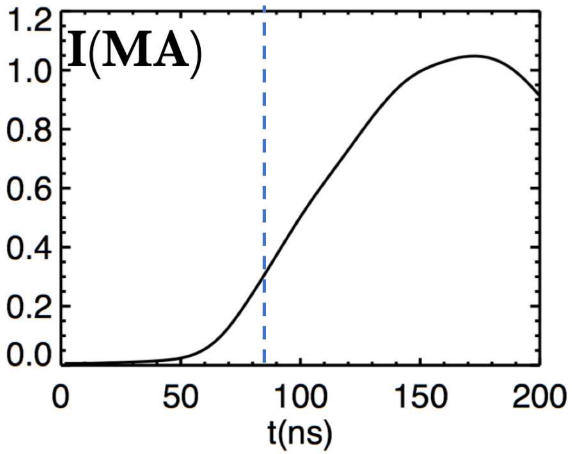


Flow around sphere converts to flow over bulge



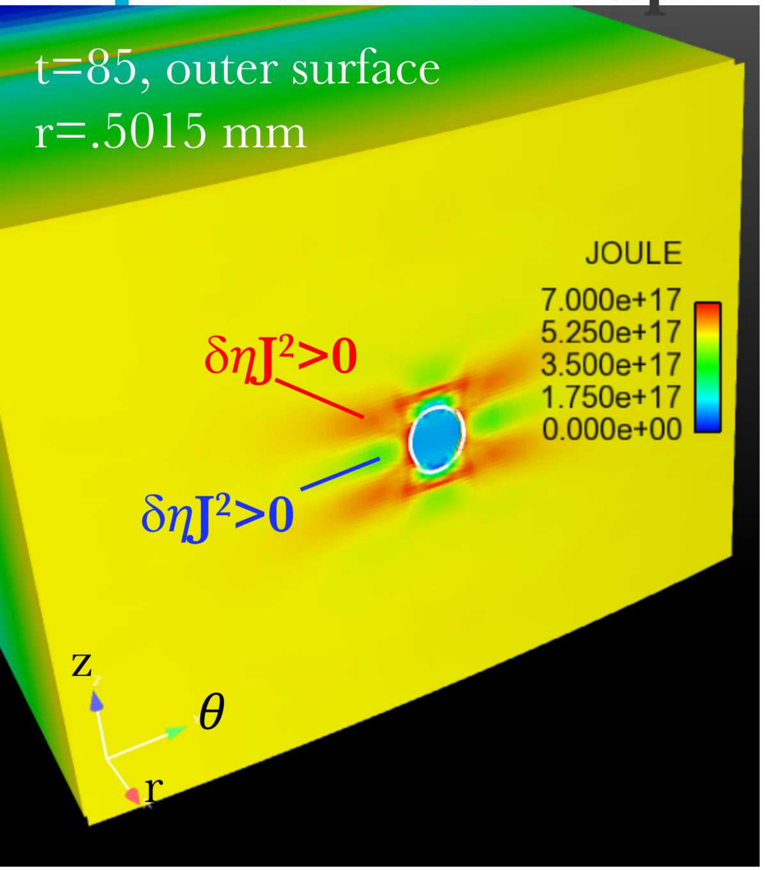


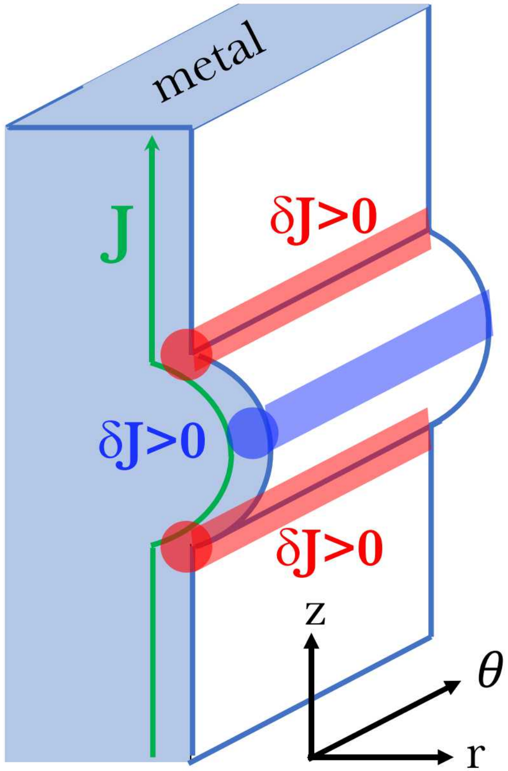
Milne-Thomson, Theoretical Hydrodynamics

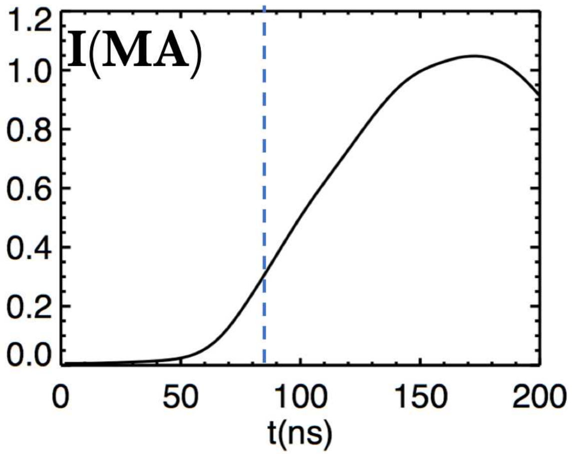


Simulation qualitatively matches hydrodynamic solution.

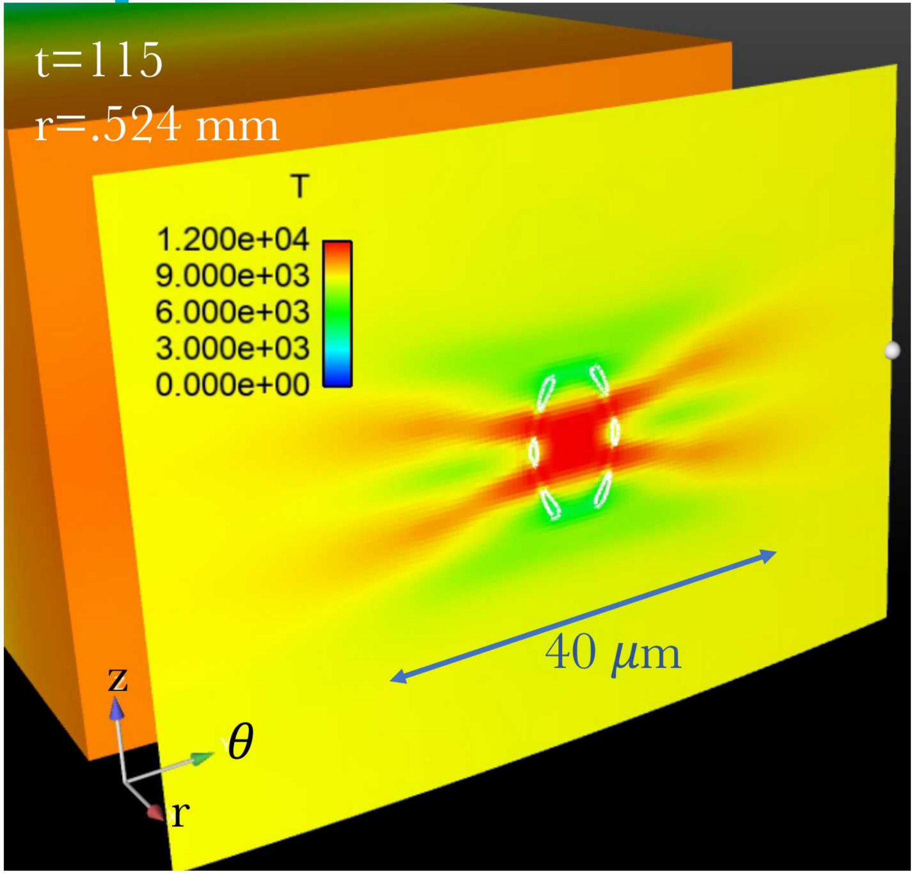
Flow around sphere converts to flow over bulge

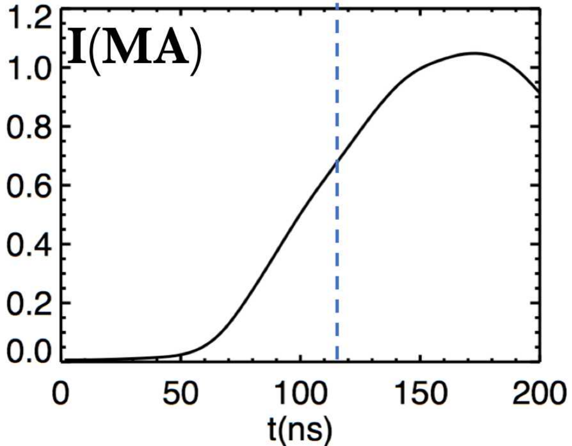






An ETI striation has developed

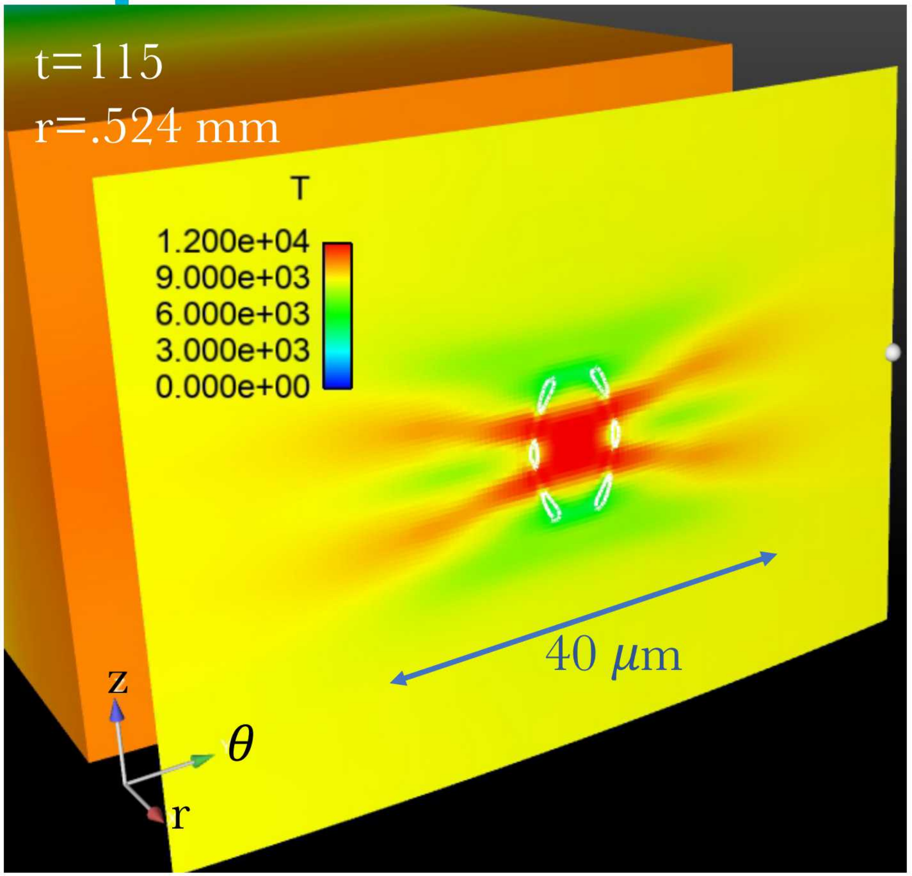


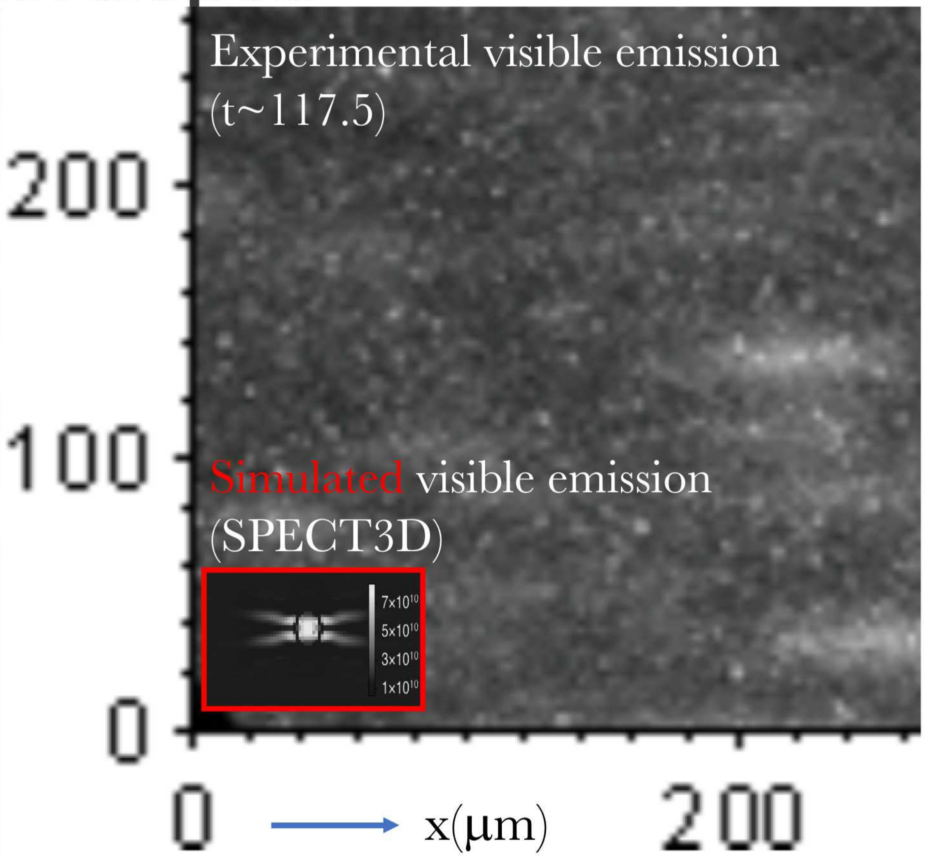


The Joule heating pattern from "flow over bulge" has imprinted on T

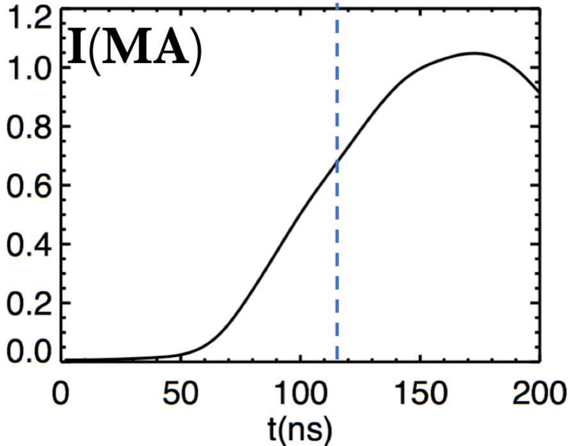
Through feedback, a 1eV, ~40 μm hot strip has developed – the ETI striation

An ETI striation has developed

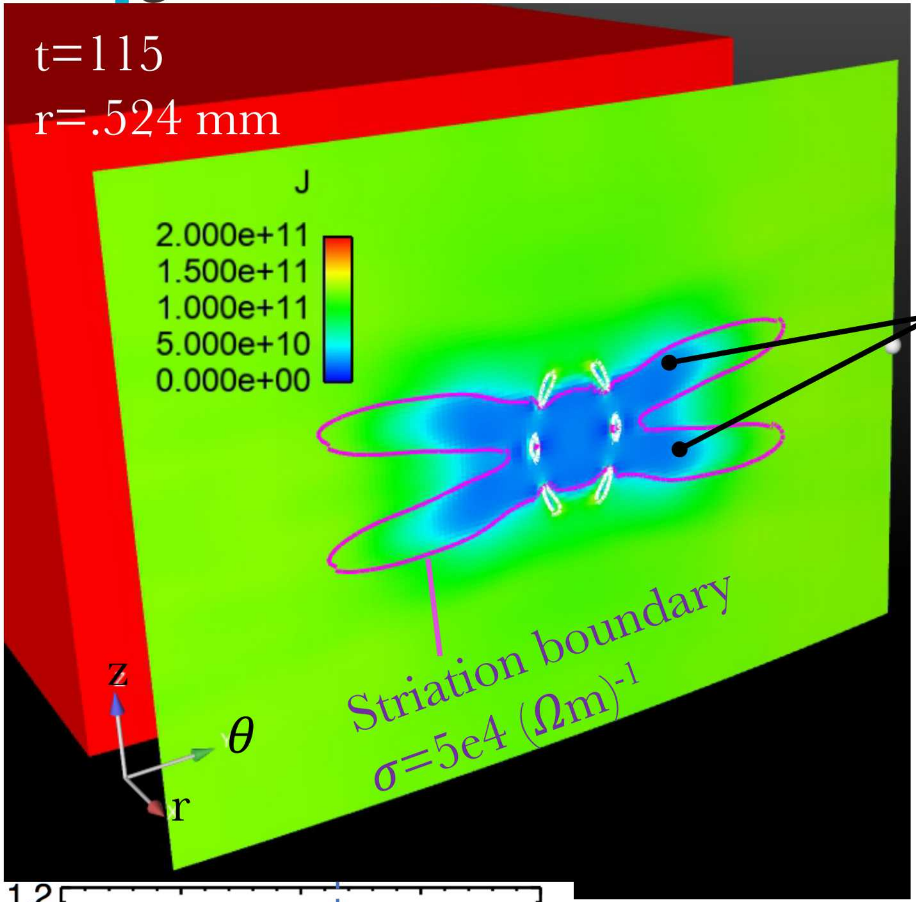


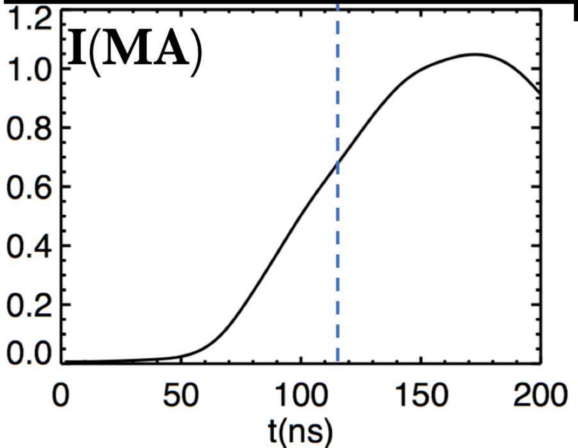


Simulated and experimental images on same spatial scale



J transforms from flow over bulge to flow over mound



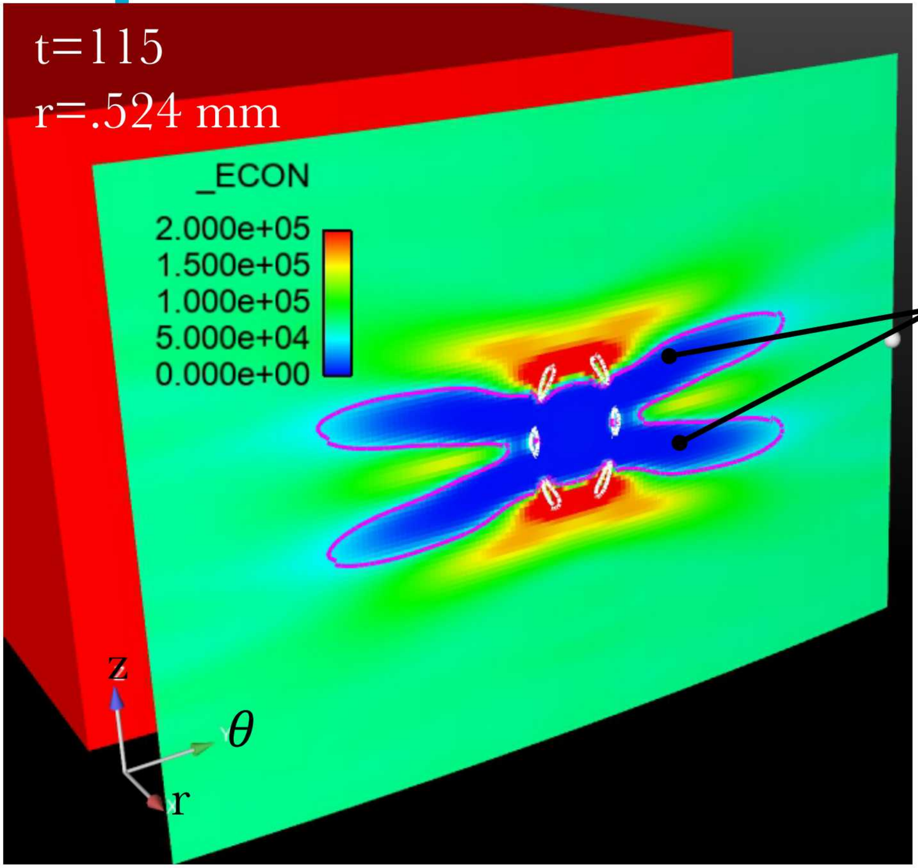


In "flow over a bulge", d**J**>0 here

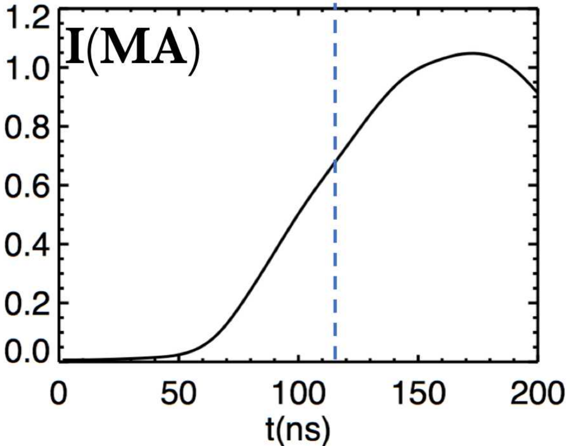
...but now d**J**<0.

Where did **J** go?

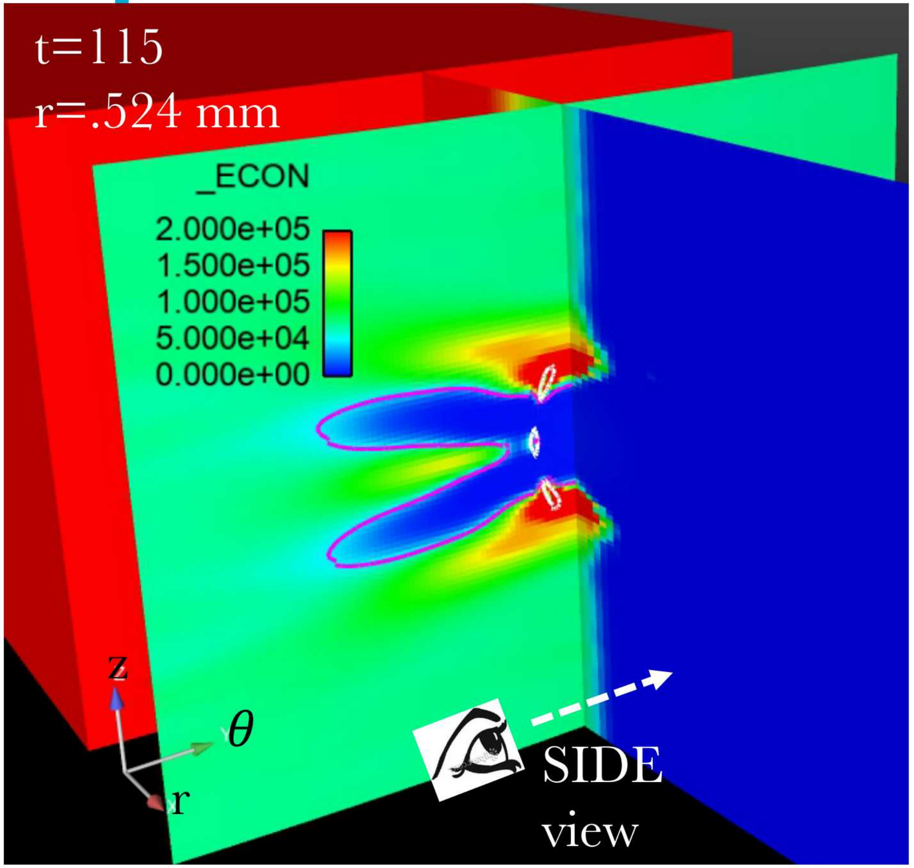
J transforms from flow over bulge to flow over mound

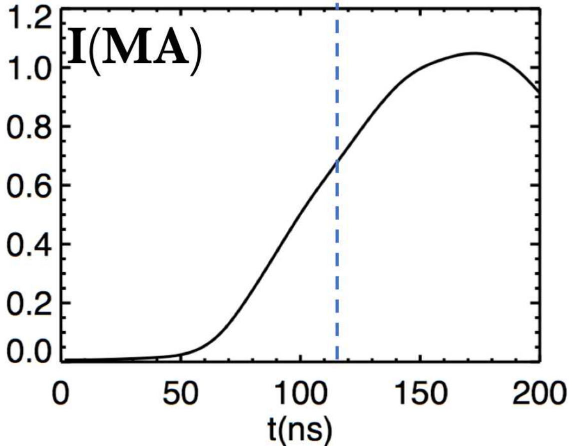


The striation has heated and expanded enough that $d\sigma<0$ there

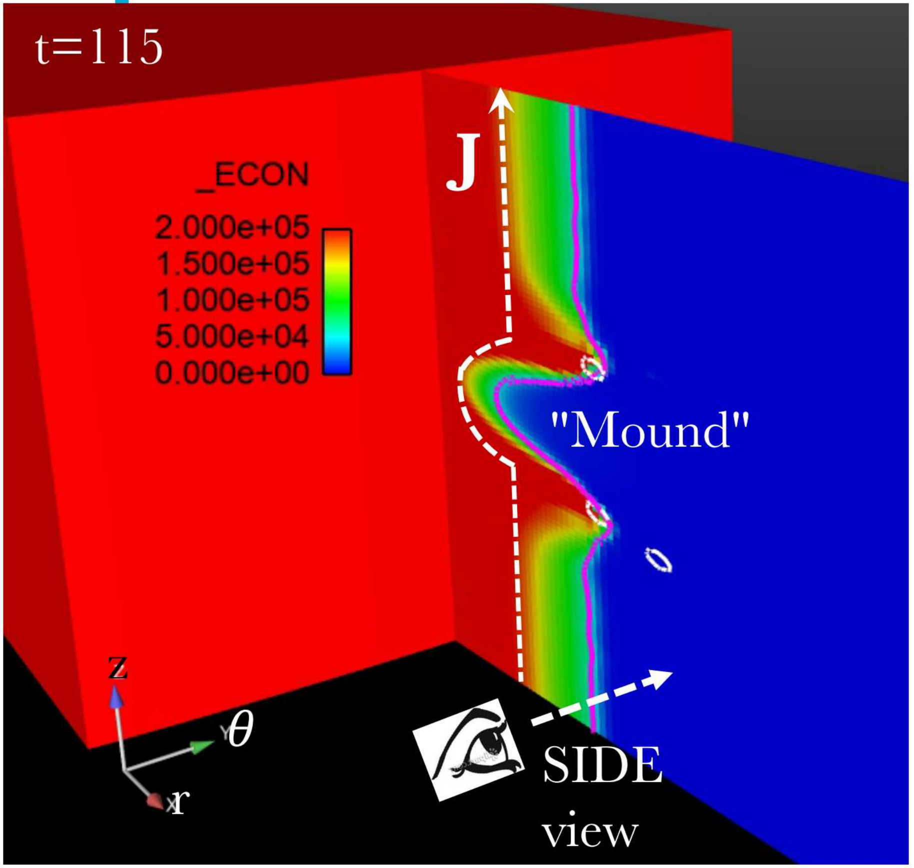


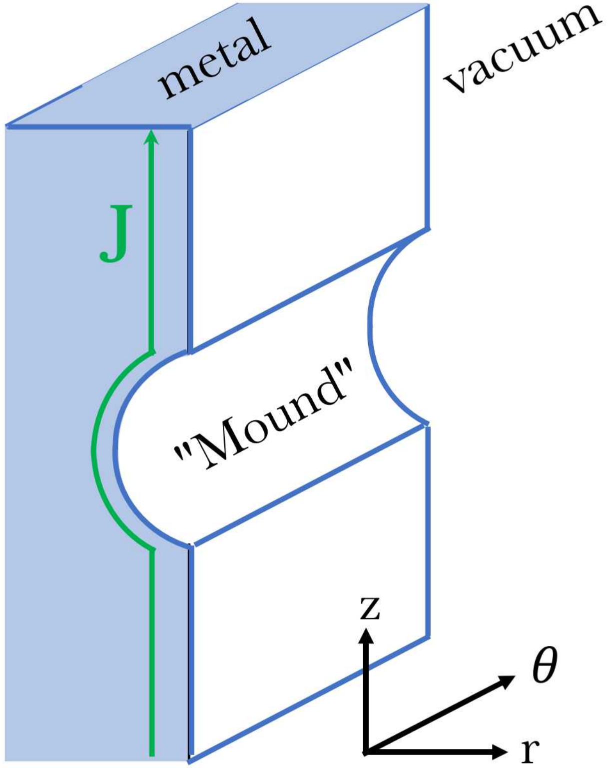
J transforms from flow over bulge to flow over mound

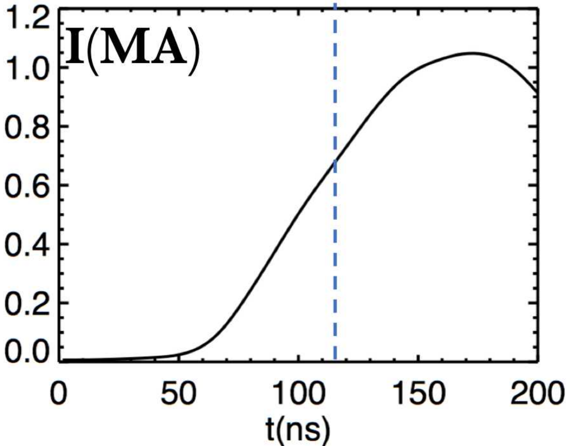




J transforms from flow over bulge to flow over mound

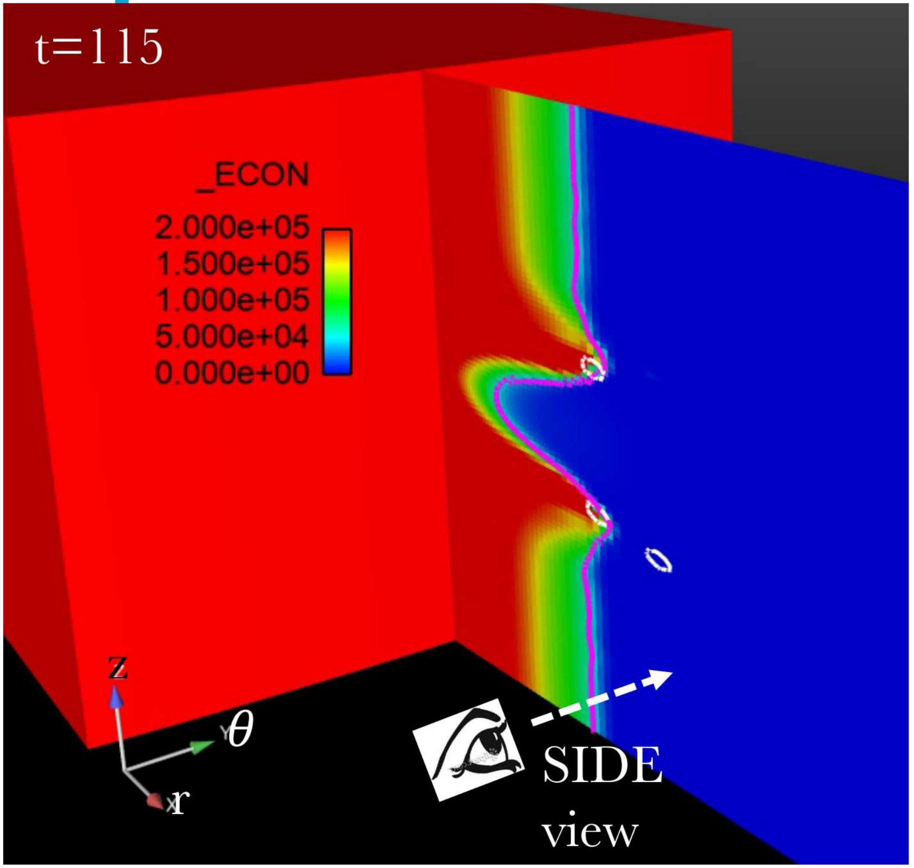


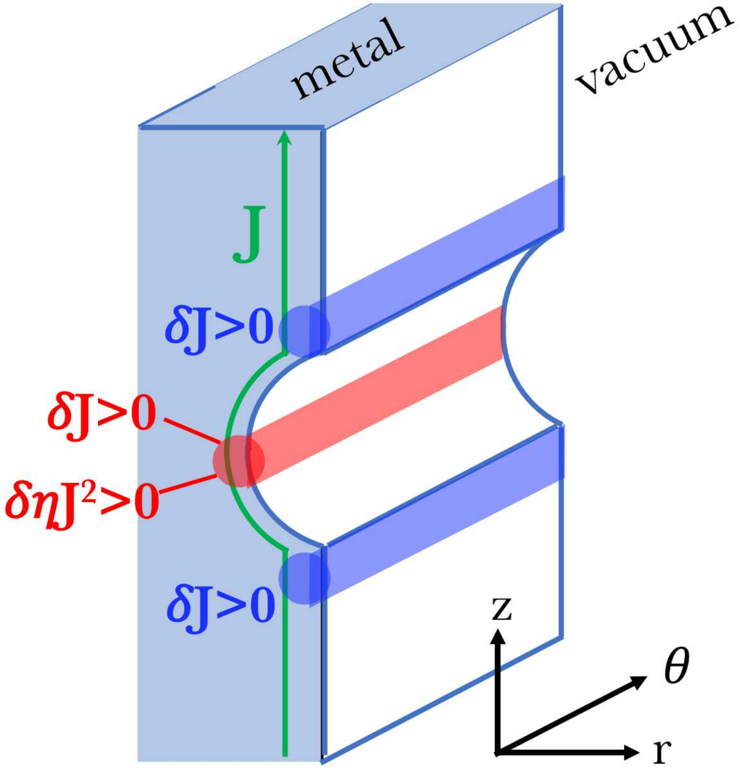


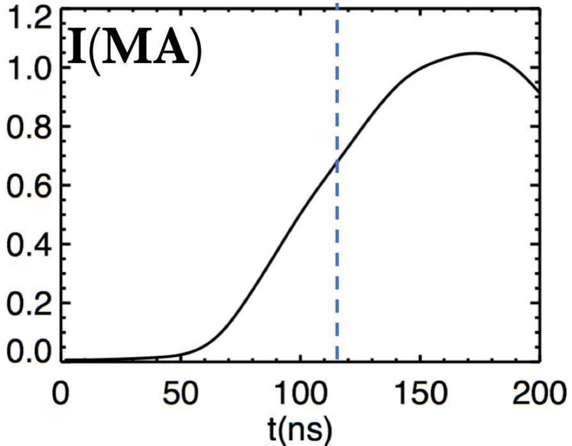


J must flow around the low-σ striation. This is equivalent to "flow over a mound"

Bulge flow converts to mound flow



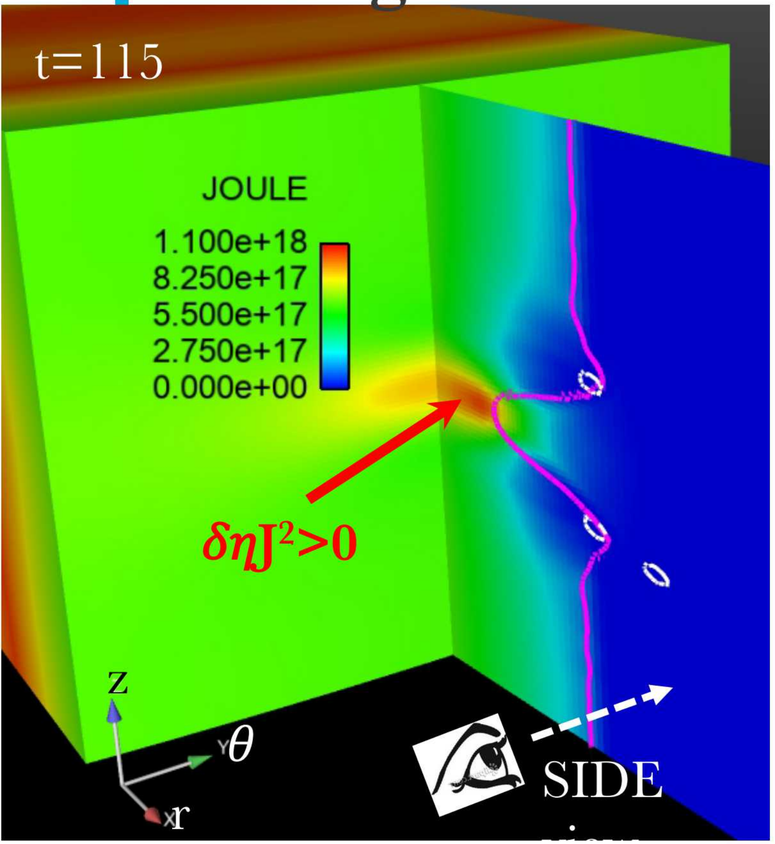


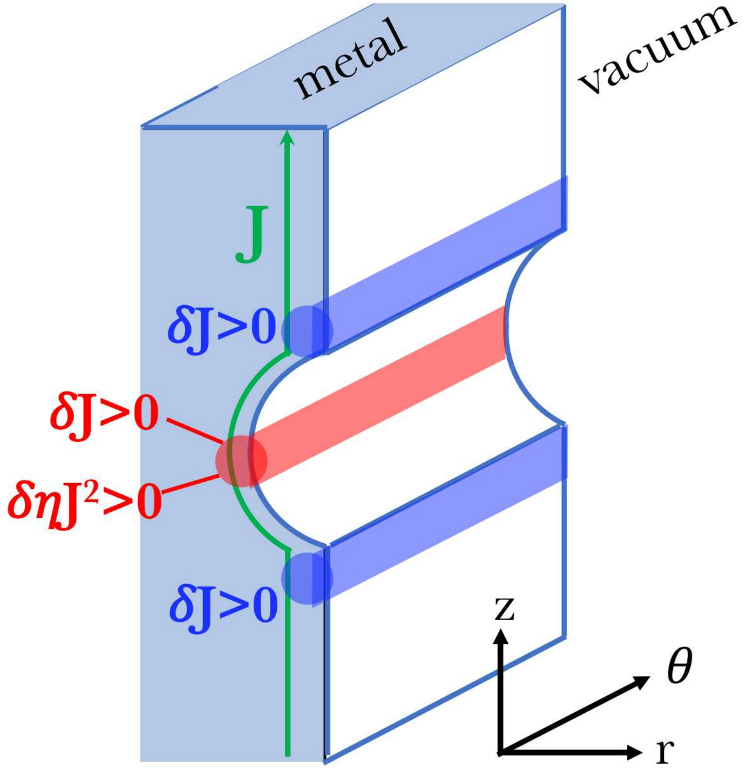


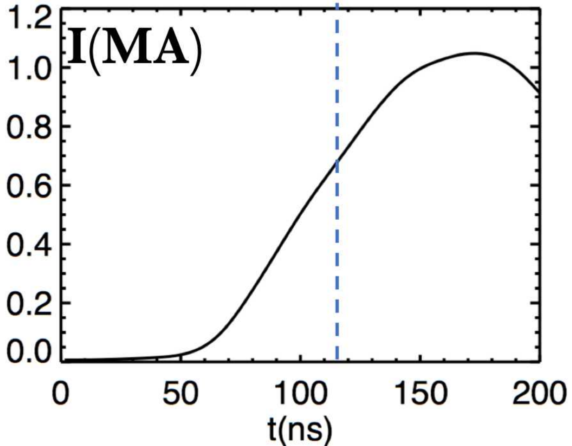
J must flow around the low-σ striation. This is equivalent to "flow over a mound"

Milne-Thomson, Theoretical Hydrodynamics

Through mound flow, striation continuously burrows deeper

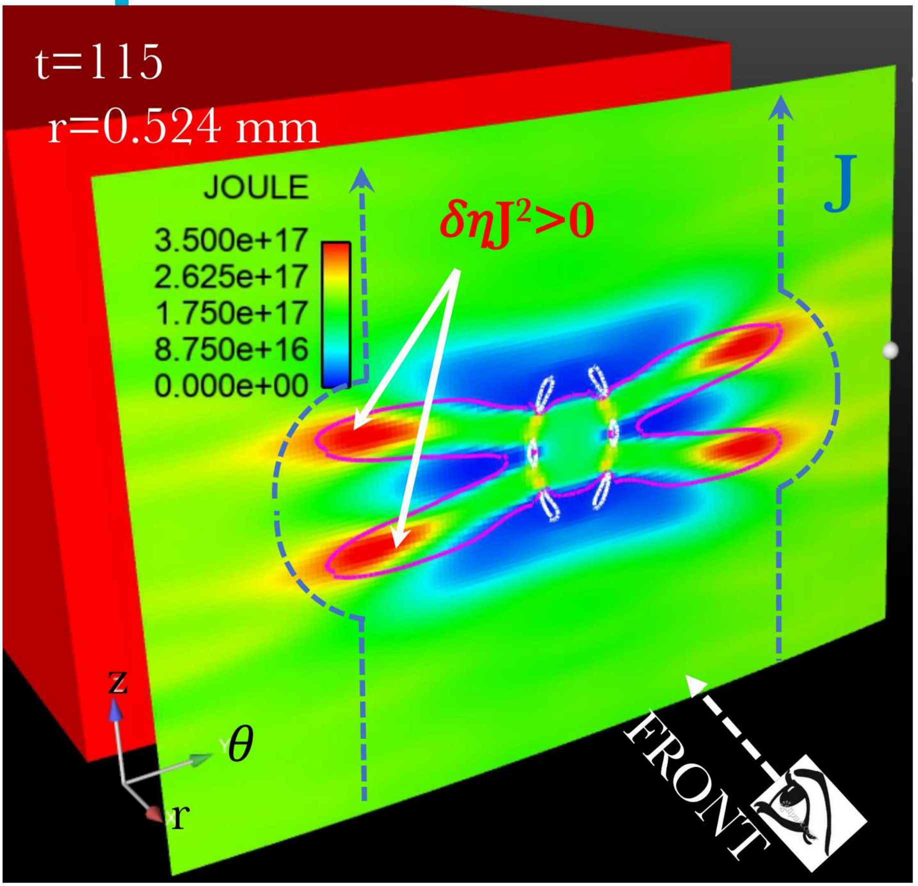


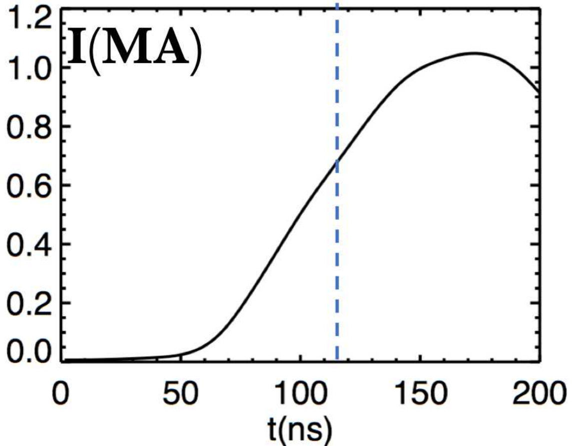




The enhancement in Joule heating at the tip of the mound is how the striation continuously propagates deeper into the metal.

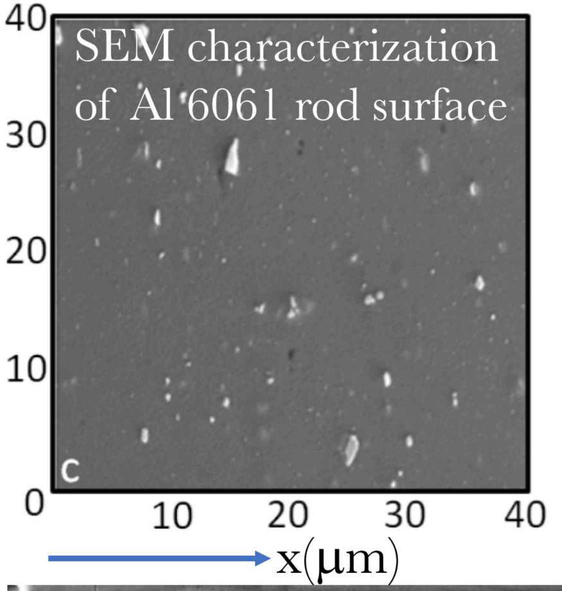
The ETI striation continuously widens

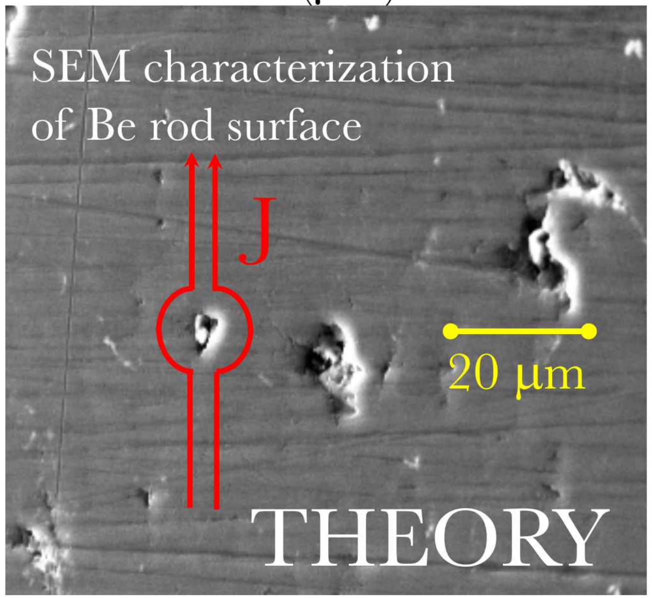


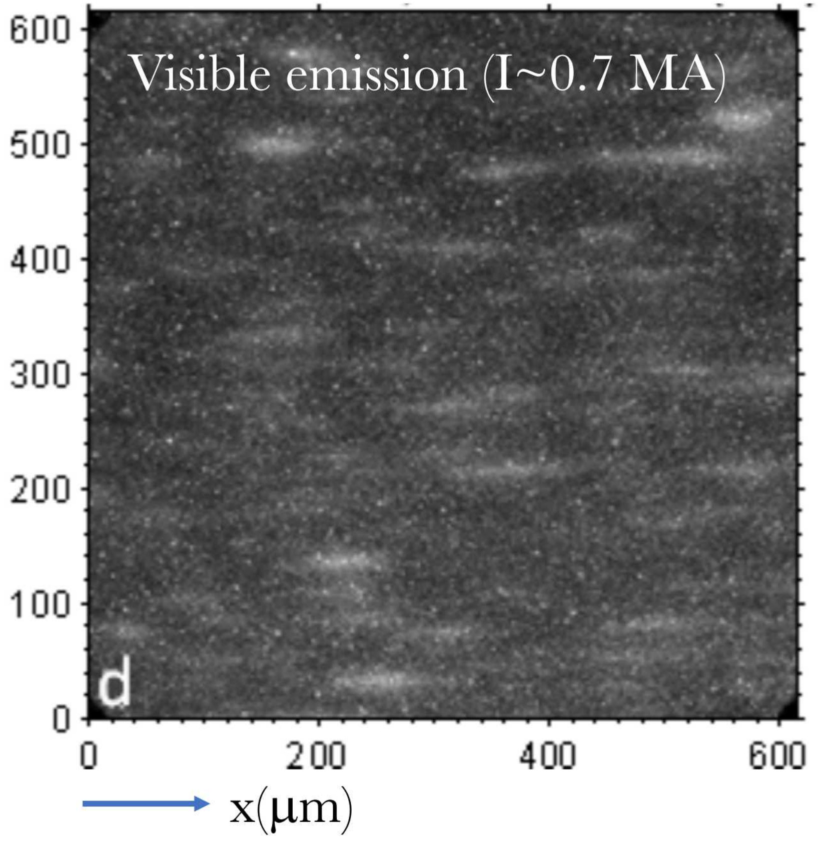


J deflects azimuthally around sides of the low-σ striation ⇒Joule heating is enhanced there, allowing the striation to continuously widen.

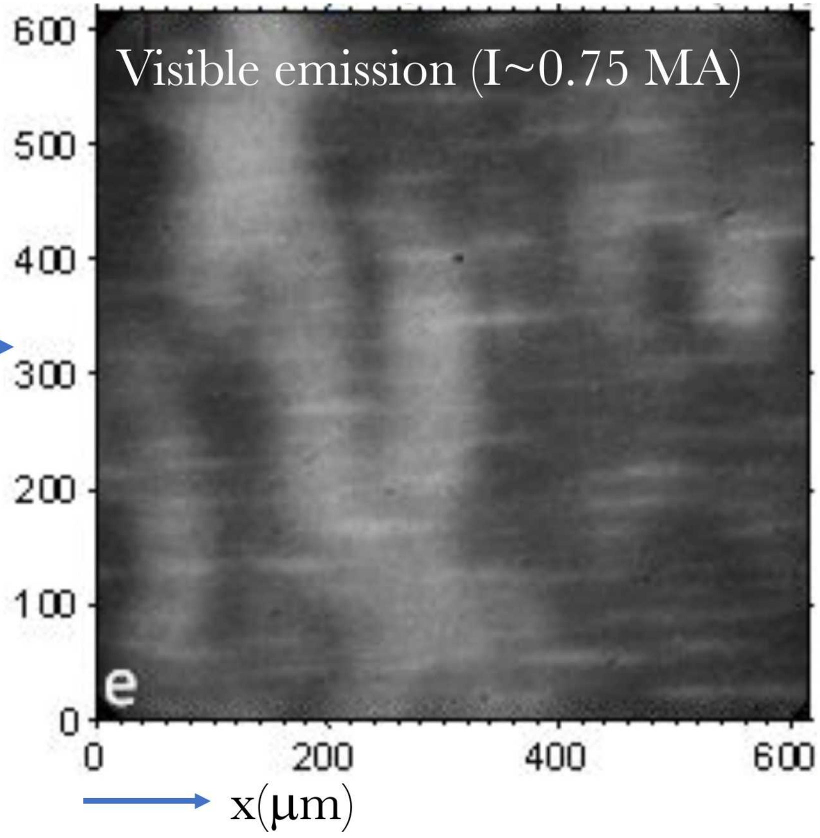
Can resistive inclusions or voids seed striations/filaments?





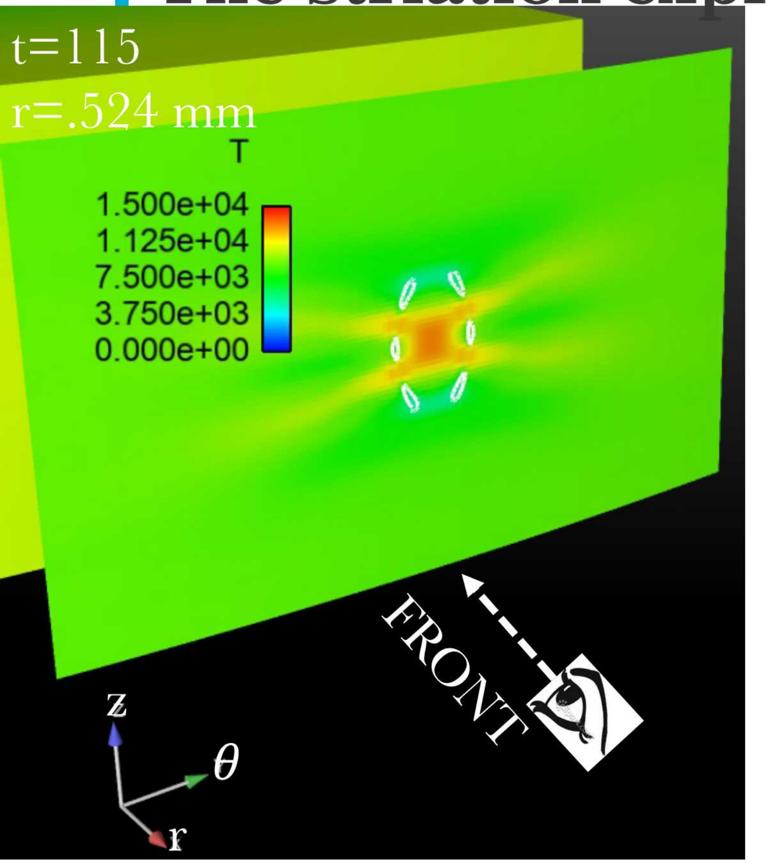


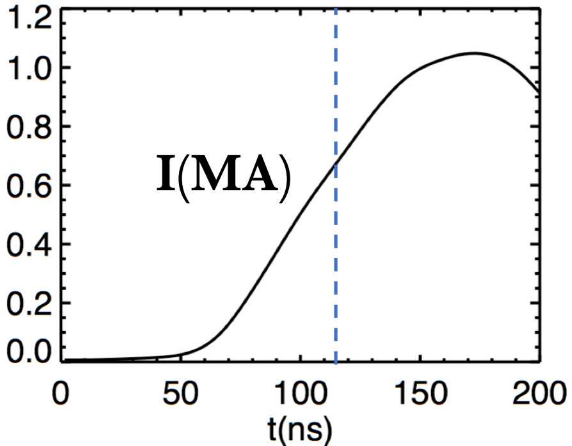
3D MHD simulation



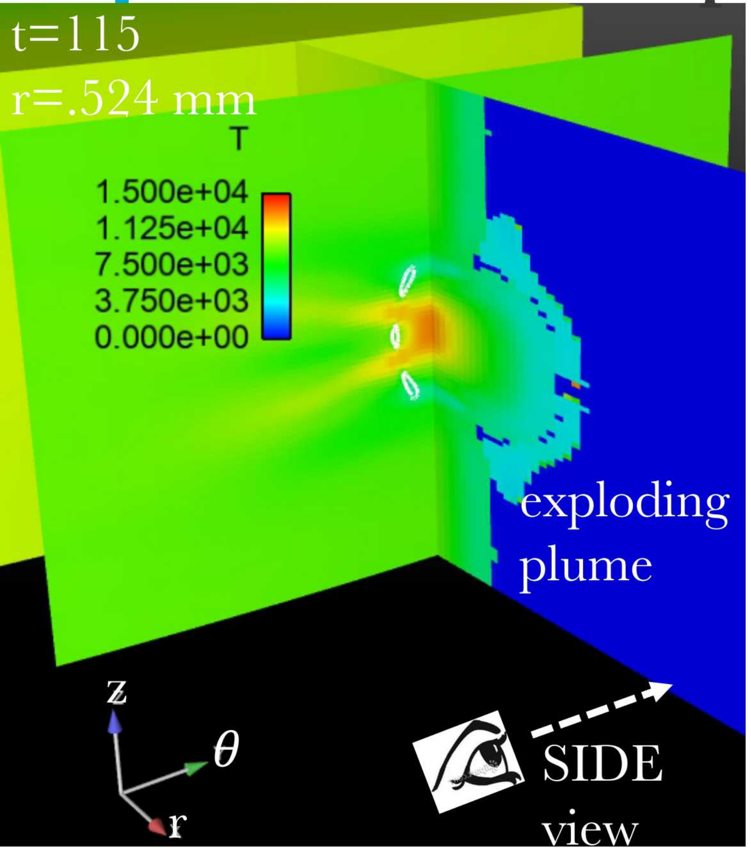
Q: How do striations convert to filaments?

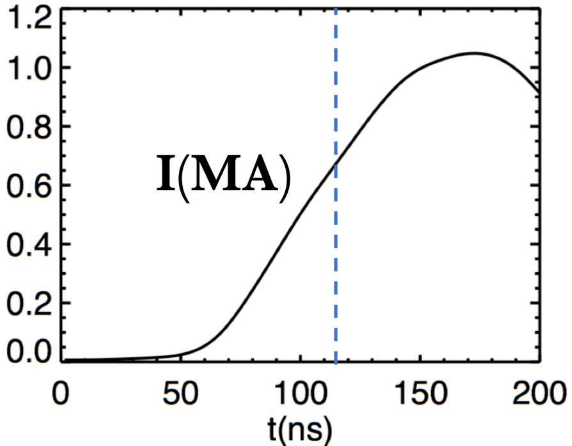
The striation explodes

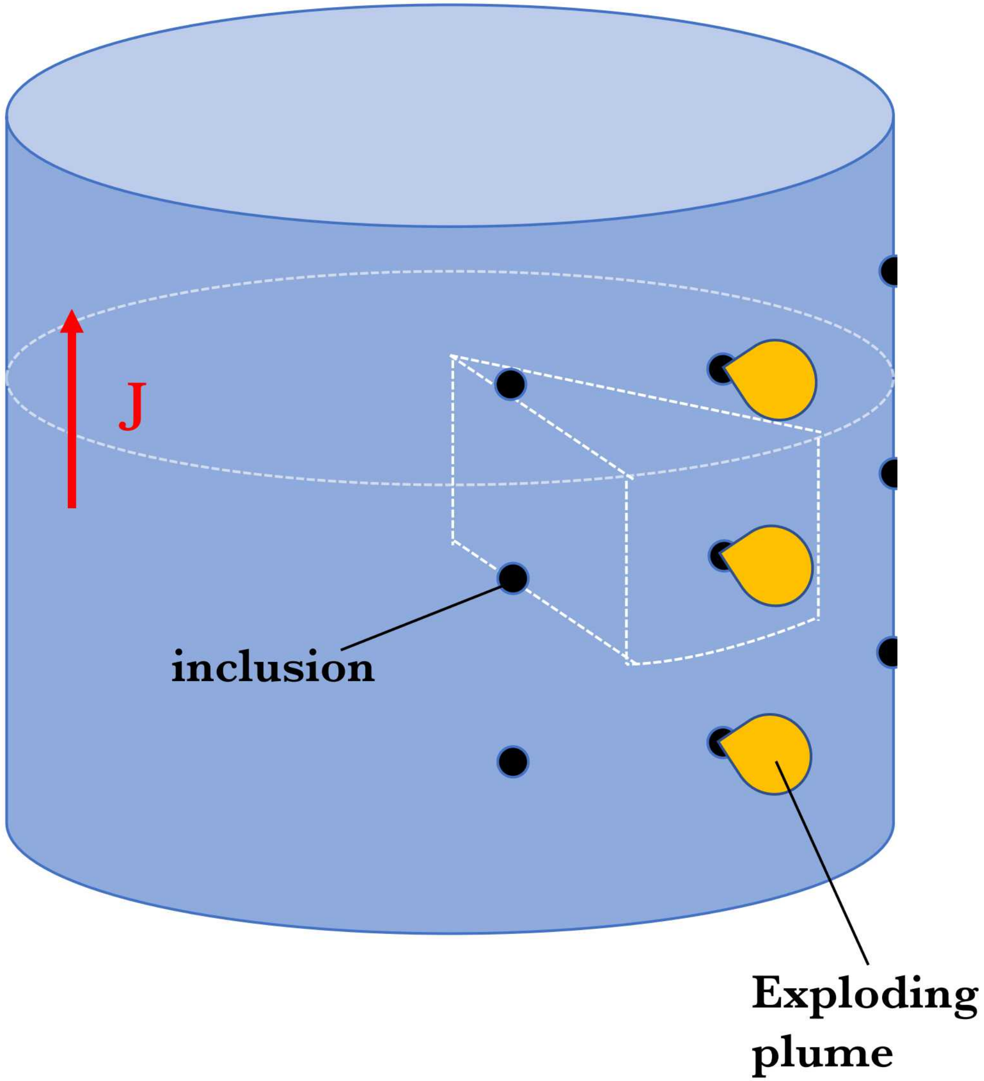




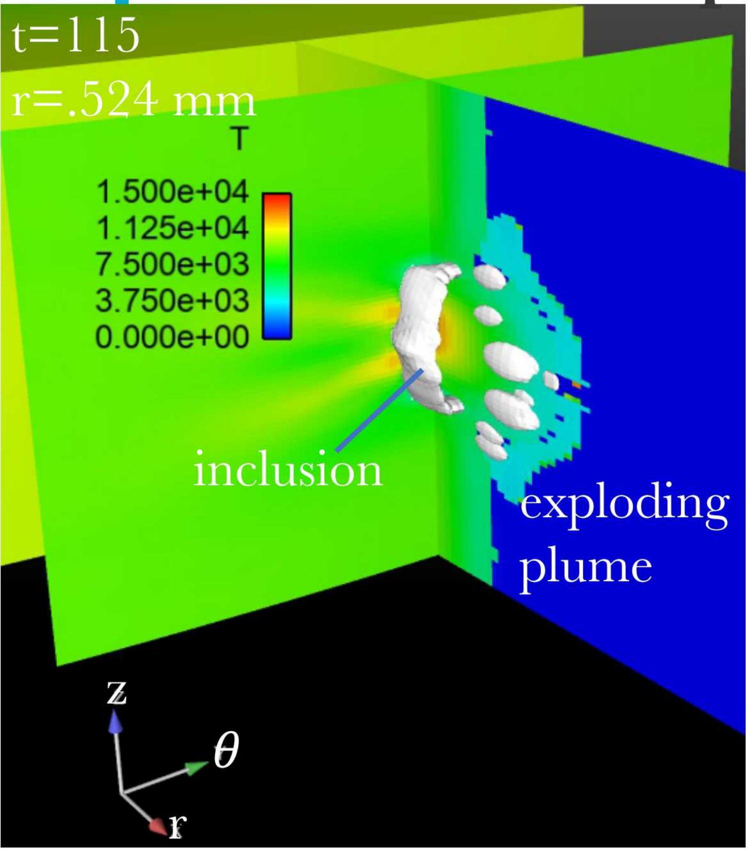
The striation explodes

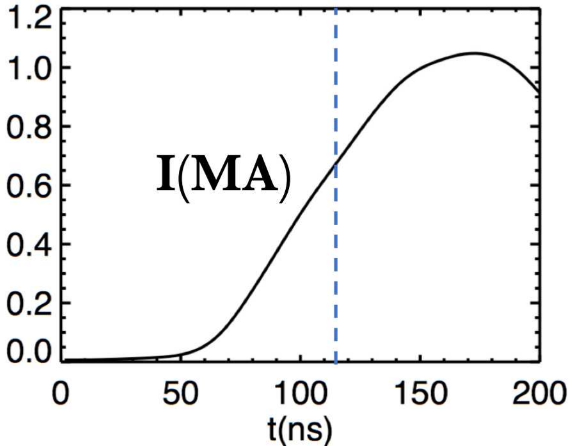


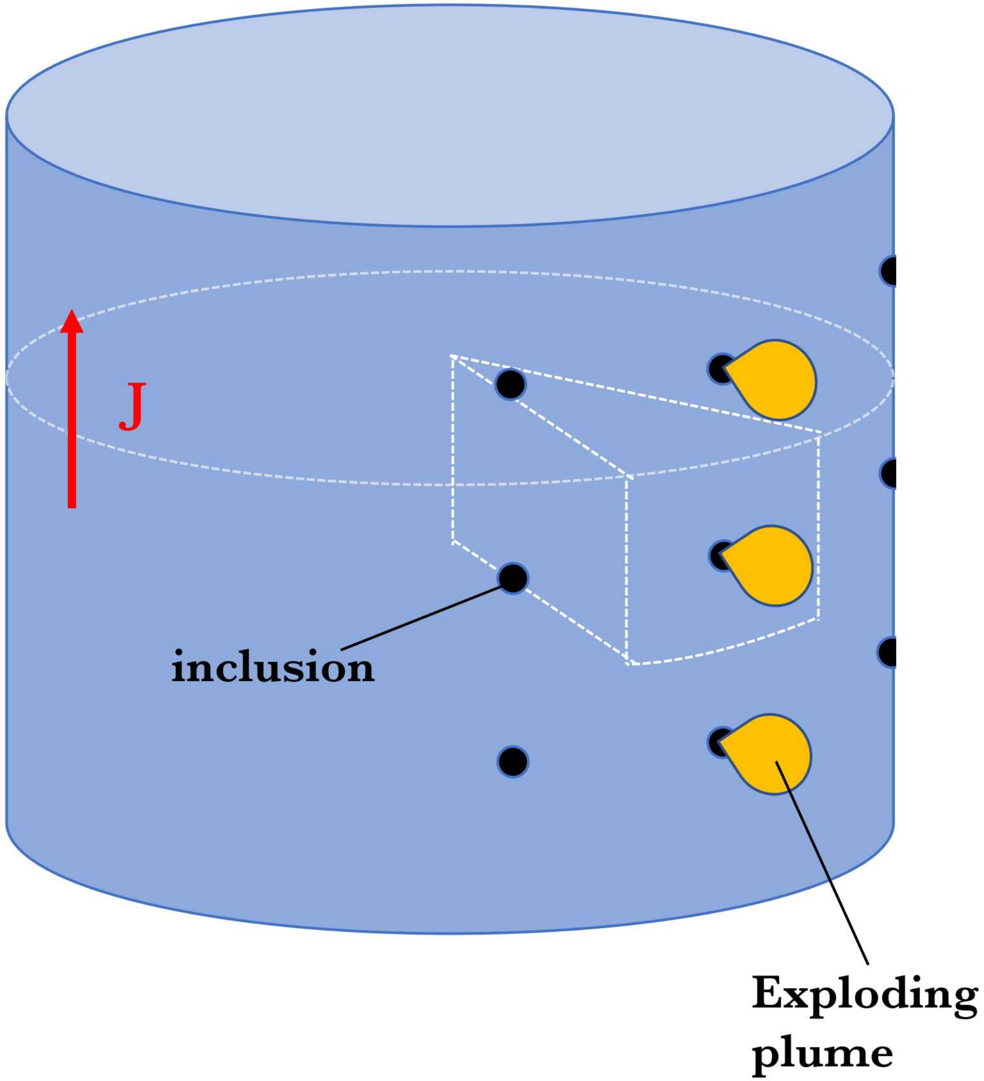




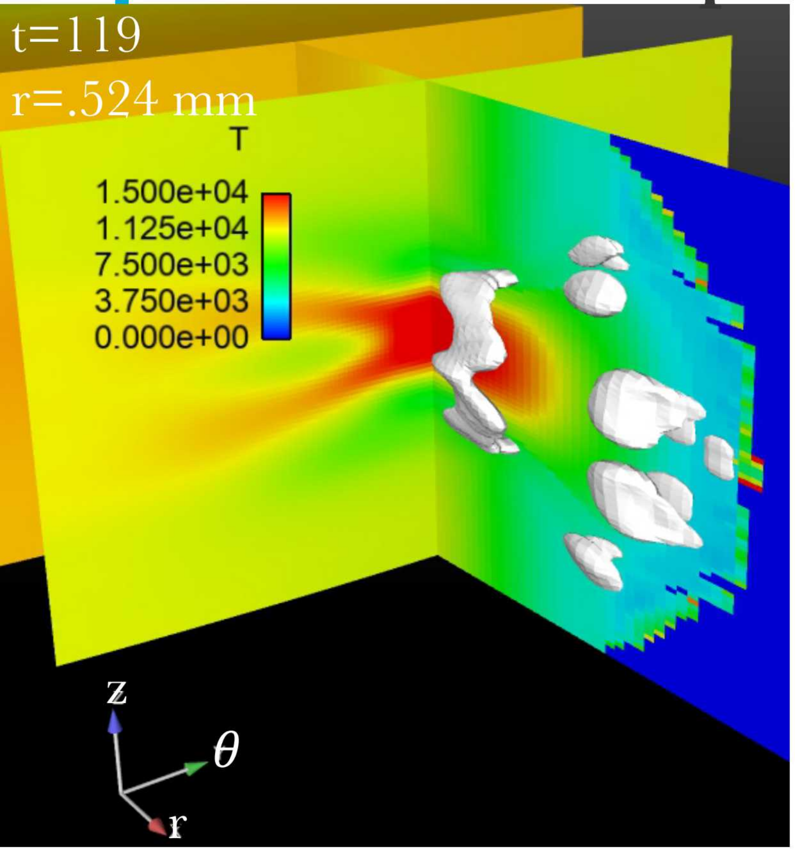
The striation explodes

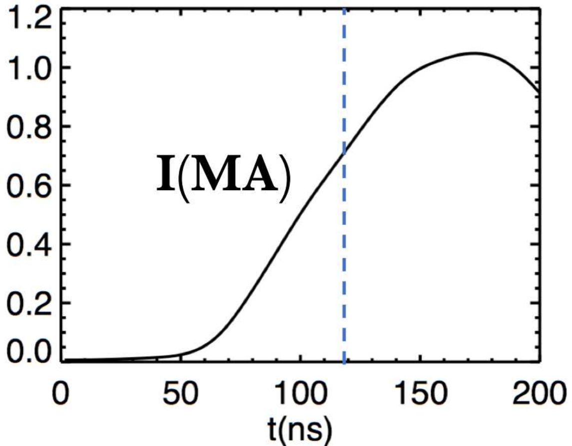


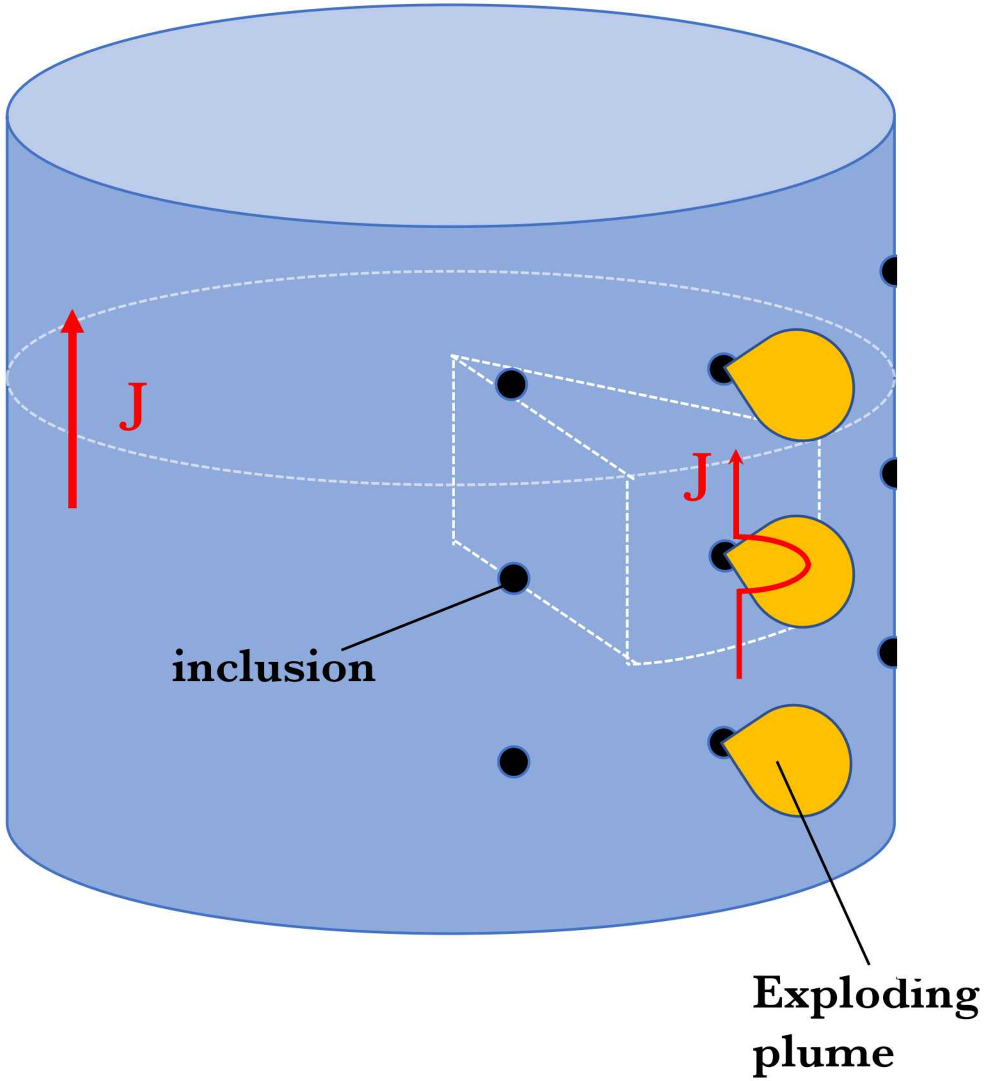




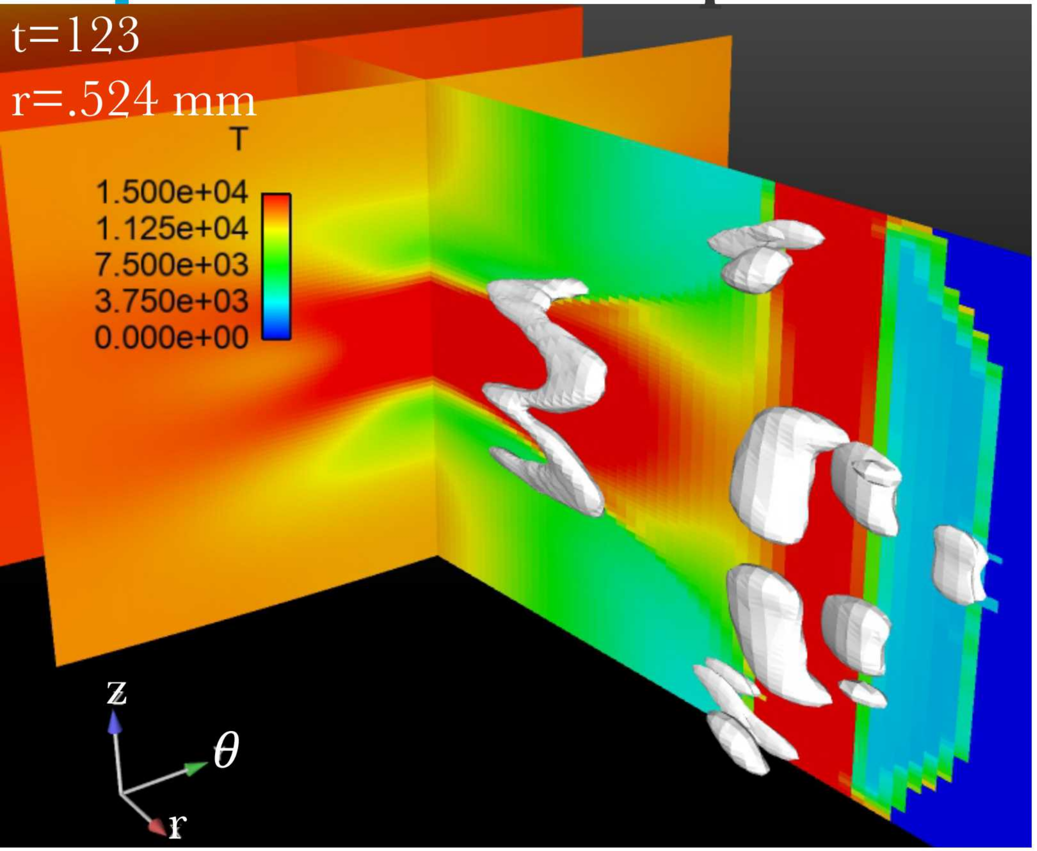
The striation explodes

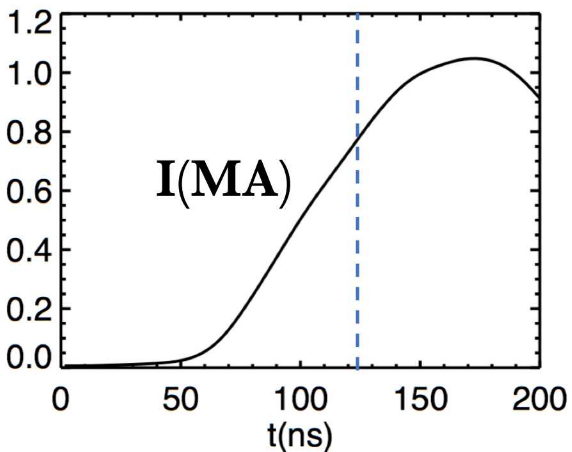


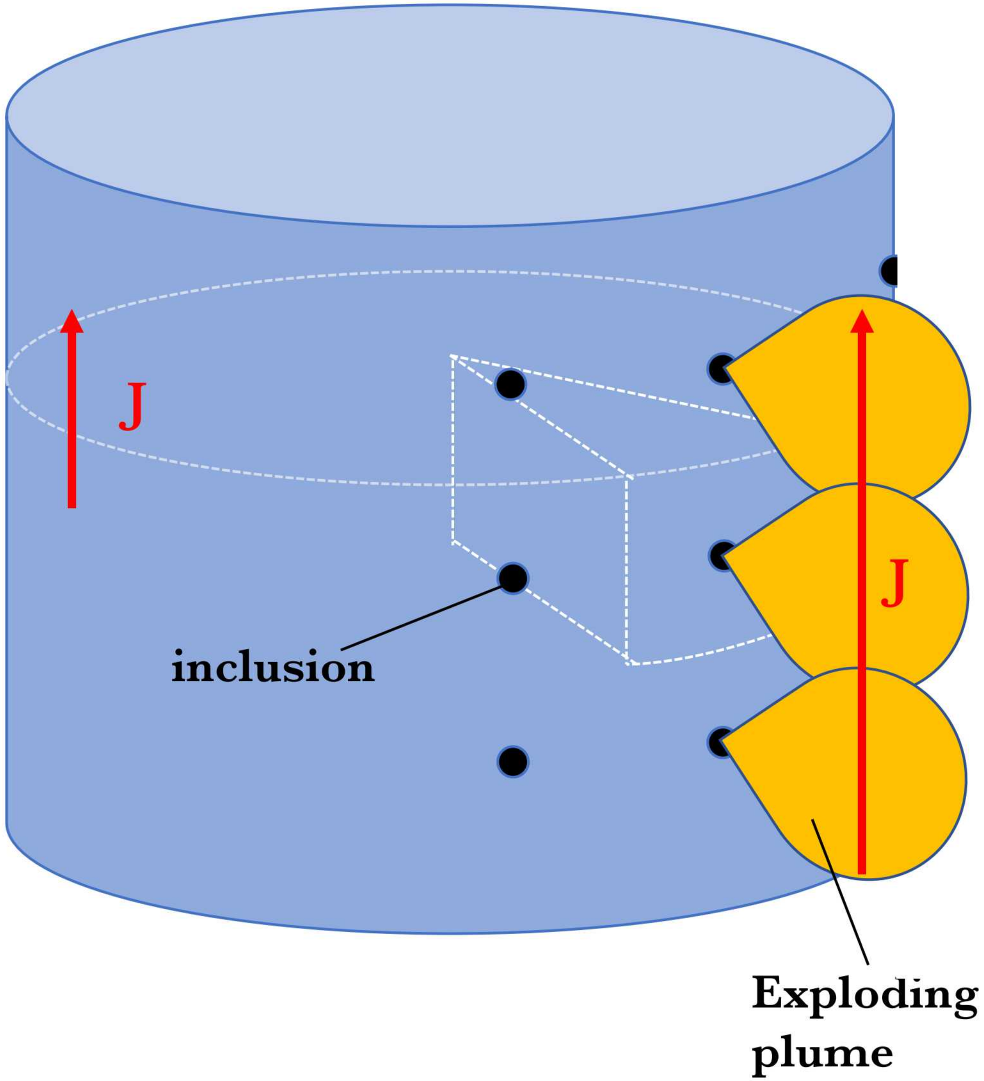




The striation explodes

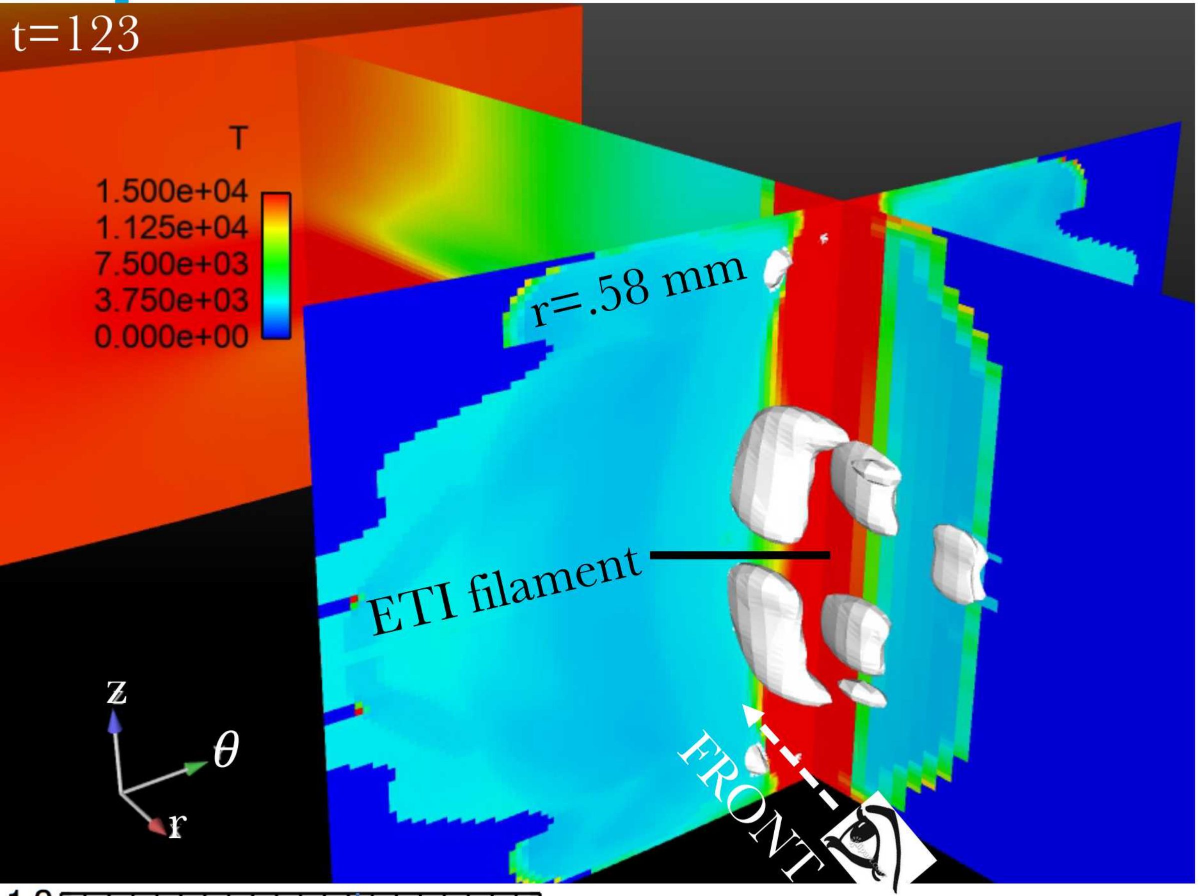


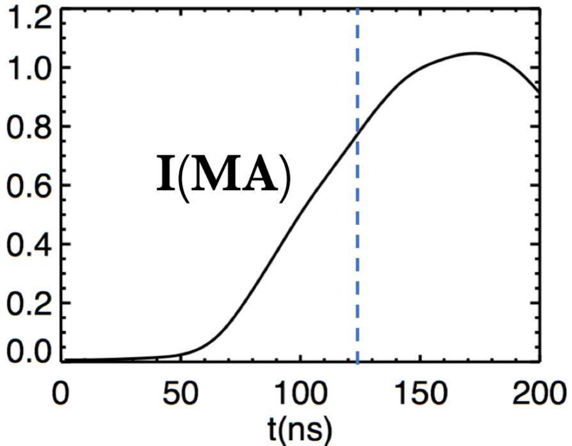




The exploding plume spans the mesh, allowing **J** to "reconnect" through the plume. (Recall periodic BCs in z)

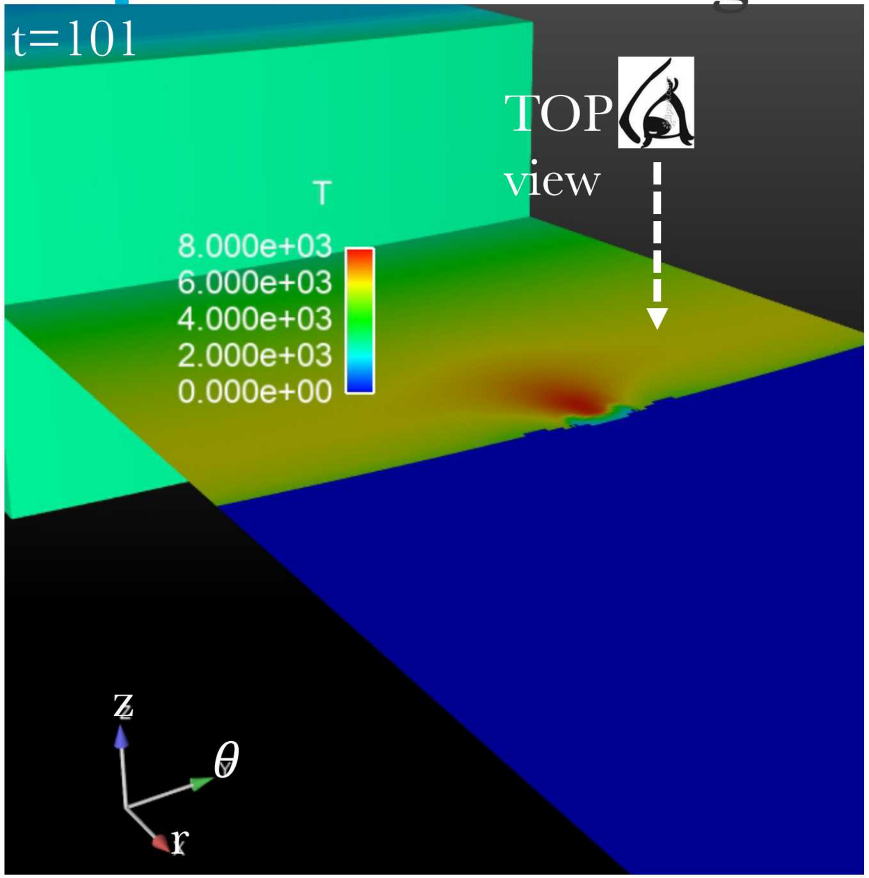
The ETI filament has formed in the exploding plume

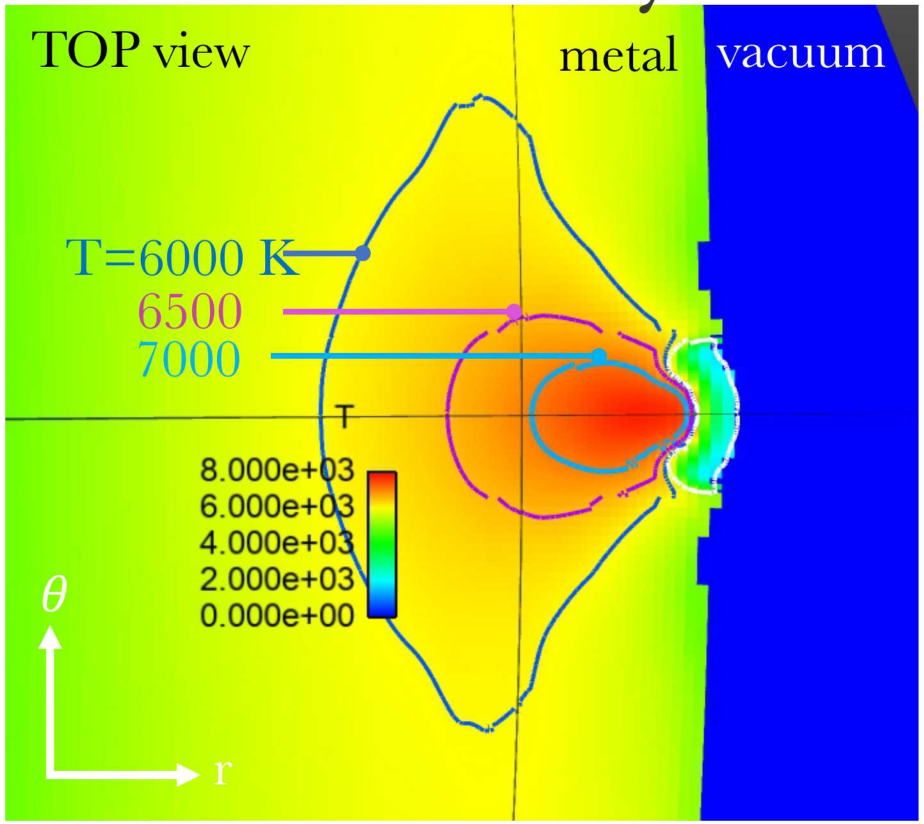


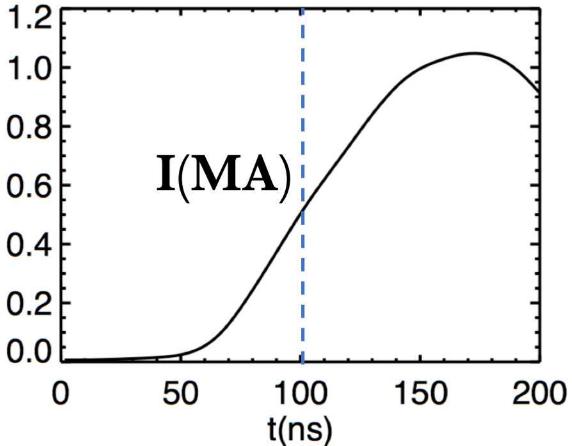


Q: But where did it come from?

ETI filament originates from an azimuthally focusing flow

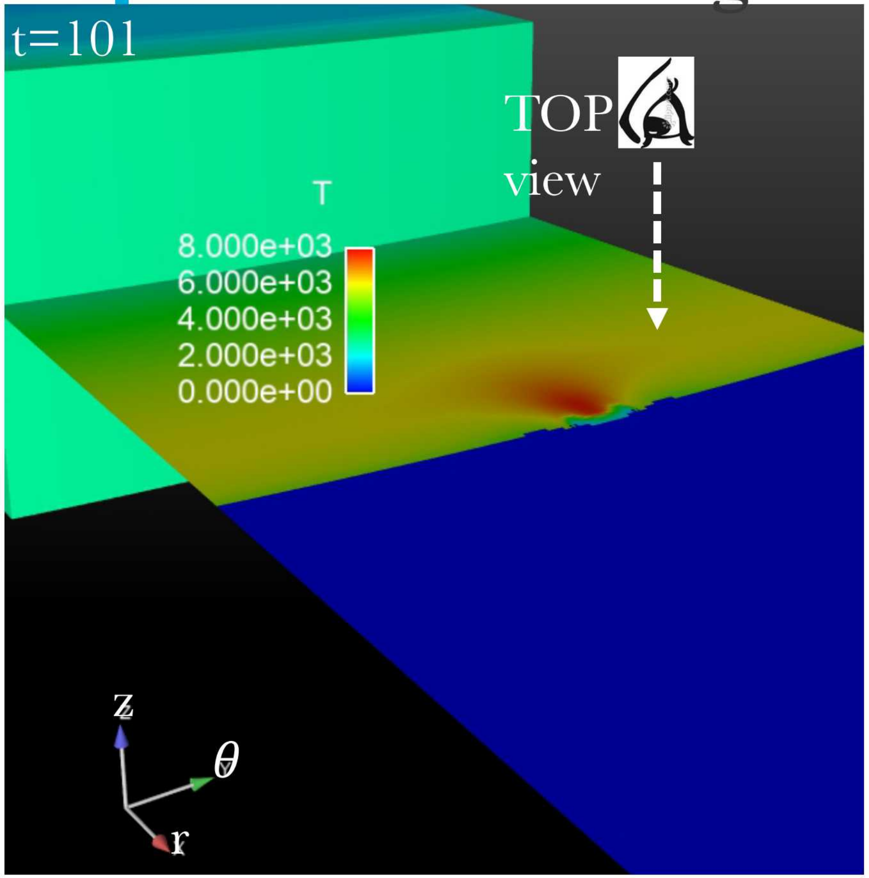


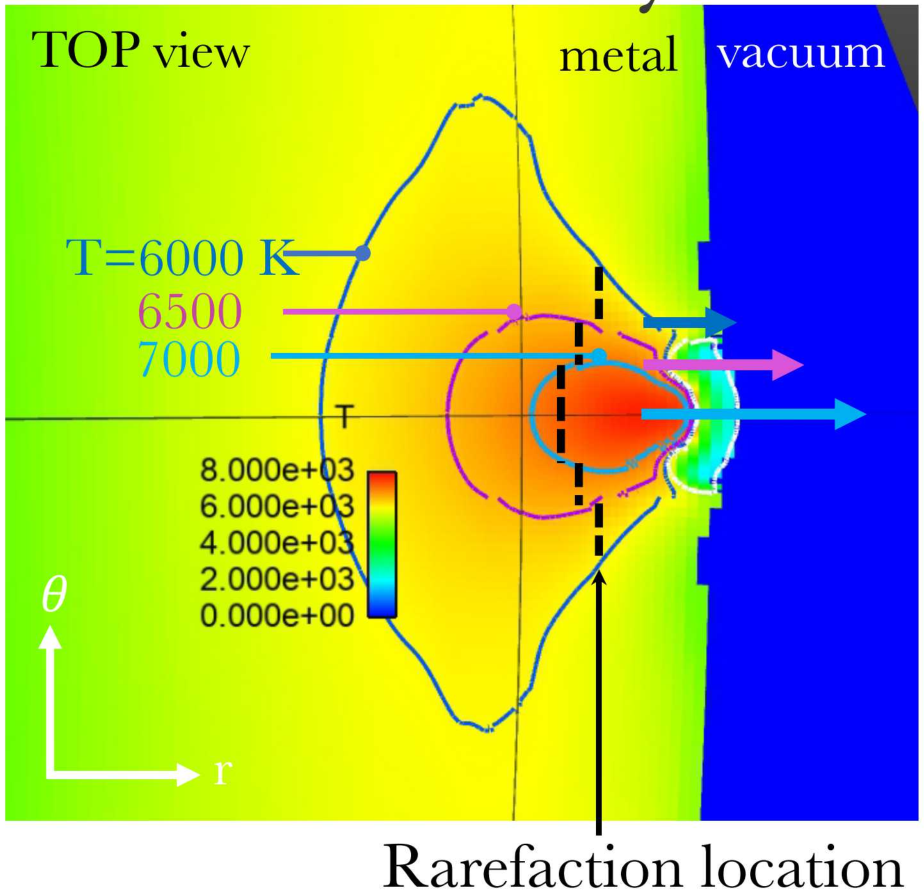


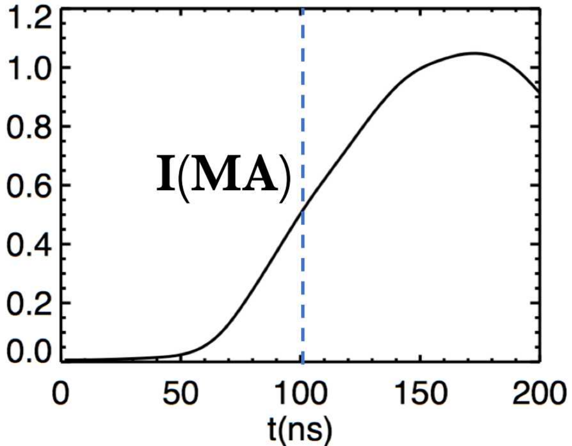


Right before the inclusion explodes, T is hottest closest to the inclusion.

ETI filament originates from an azimuthally focusing flow

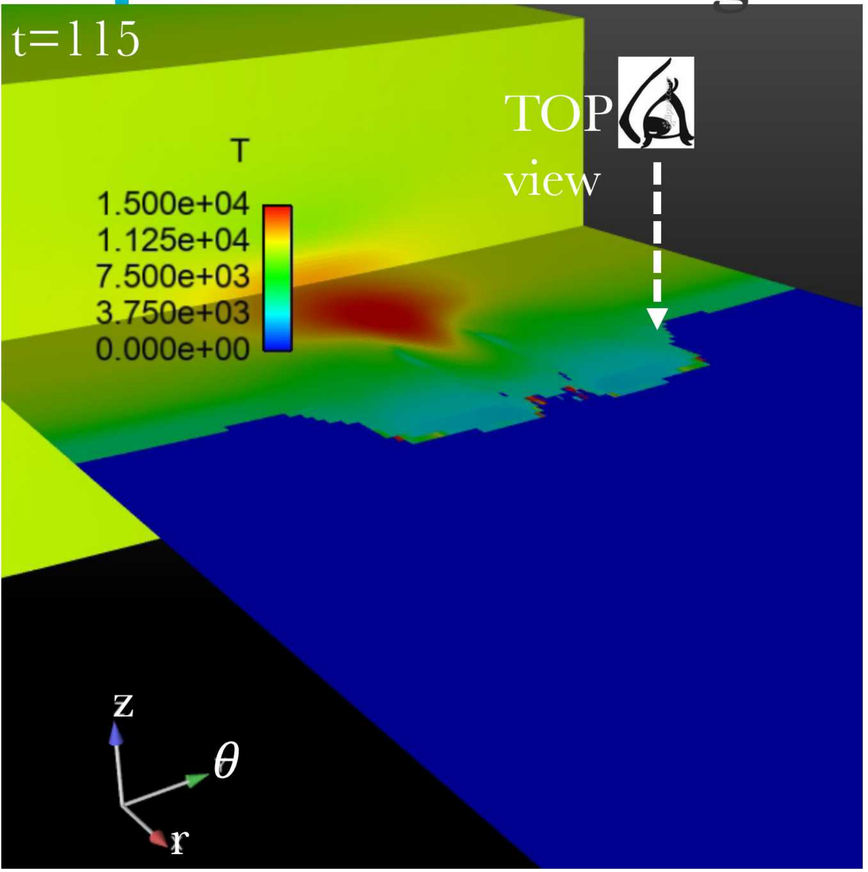


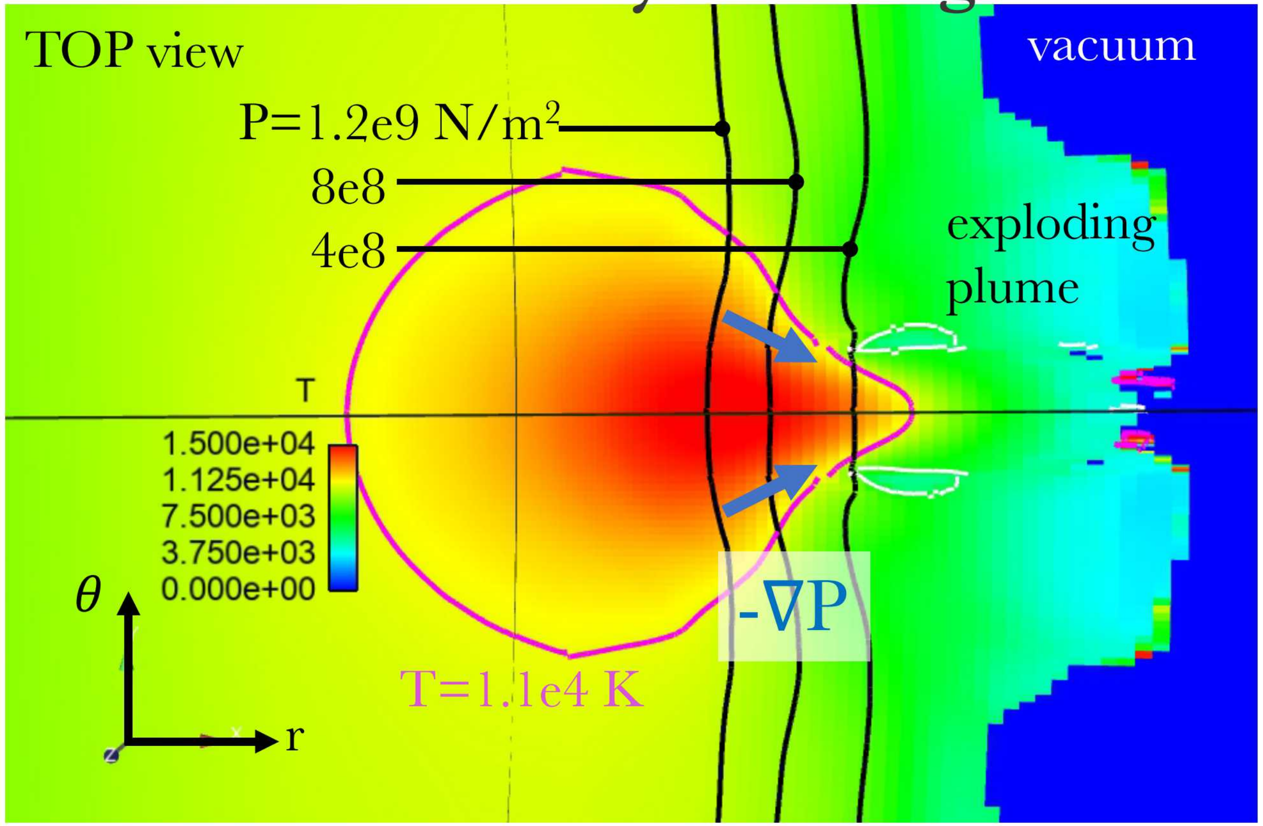


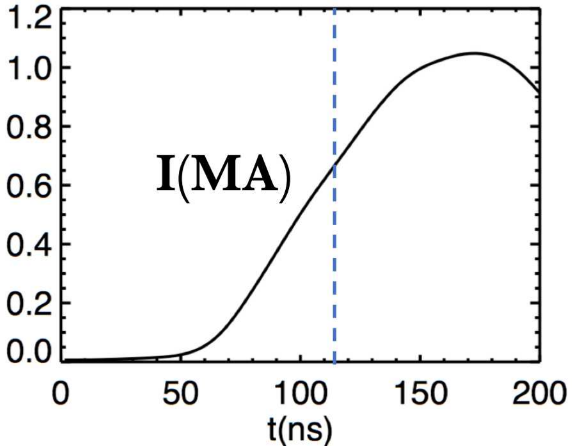


Rarefaction will penetrate deepest in hottest regions, leading to <u>concave</u> P contours

ETI filament originates from an azimuthally focusing flow

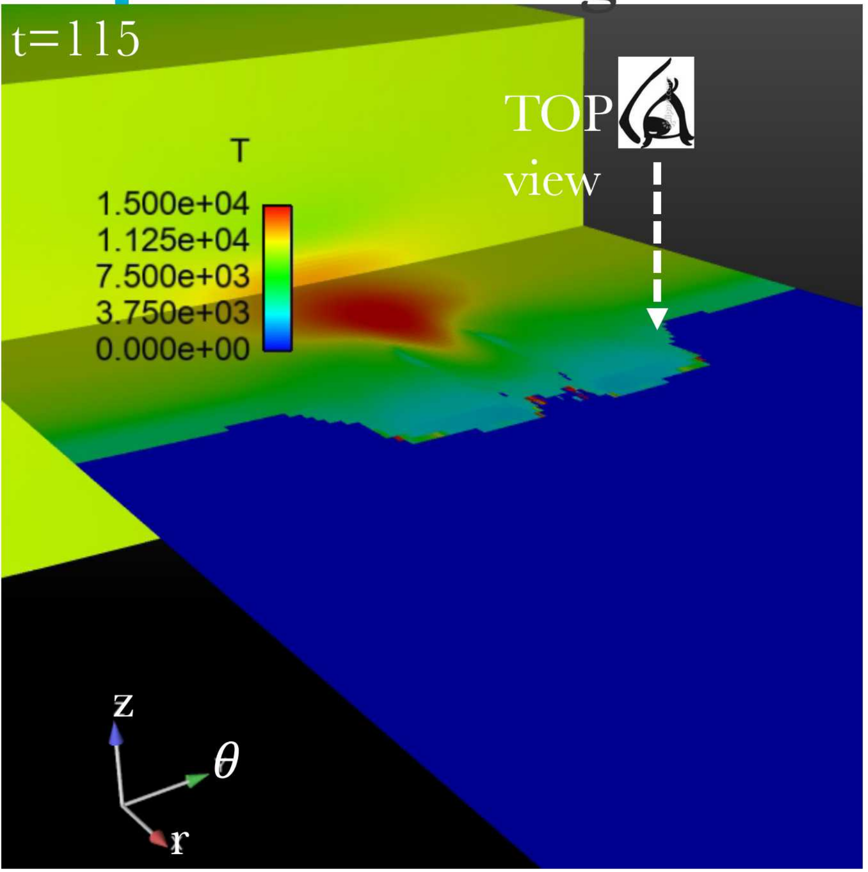


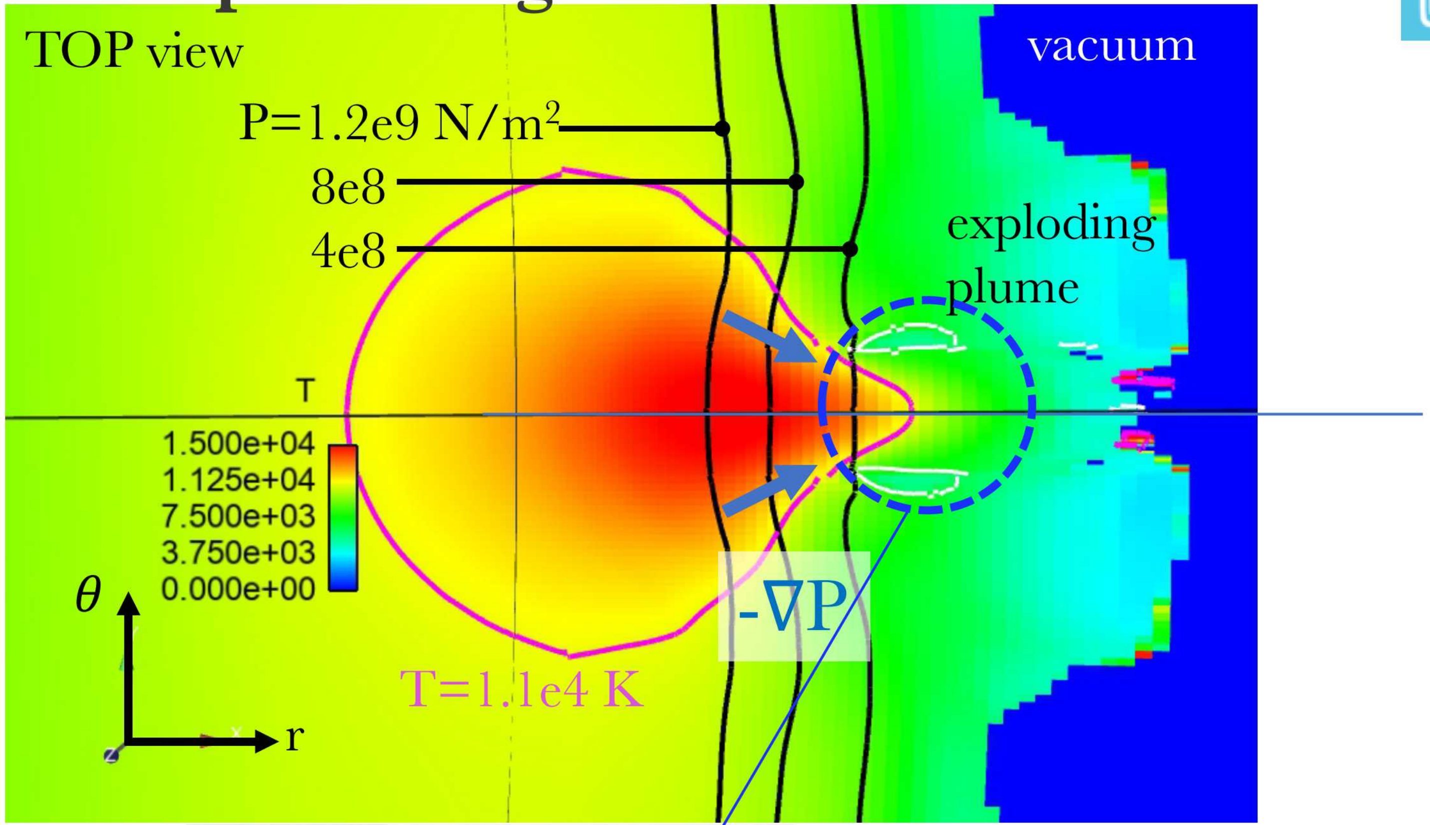


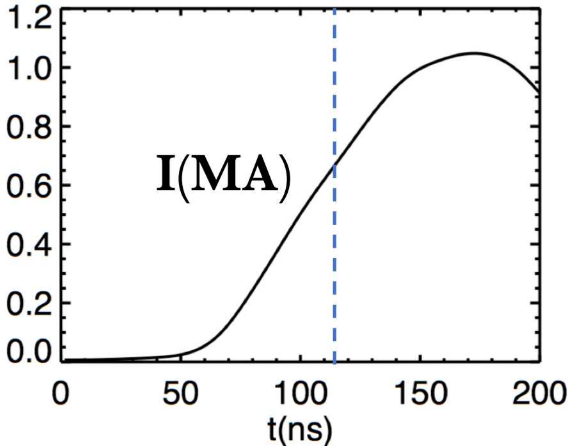


Concave P <u>focuses</u> the flow azimuthally, at least initially

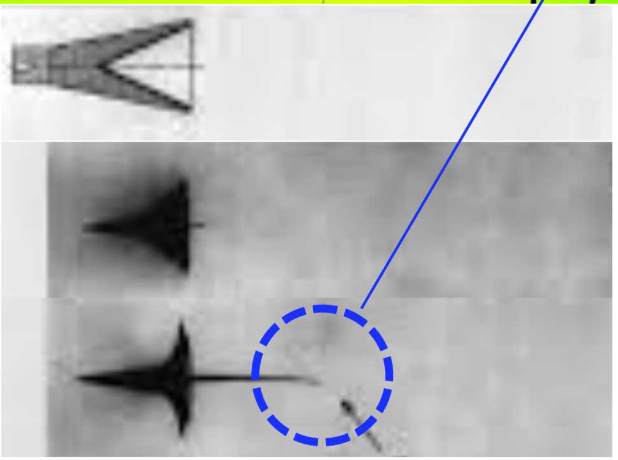
This focusing is similar to "shaped charge" effect



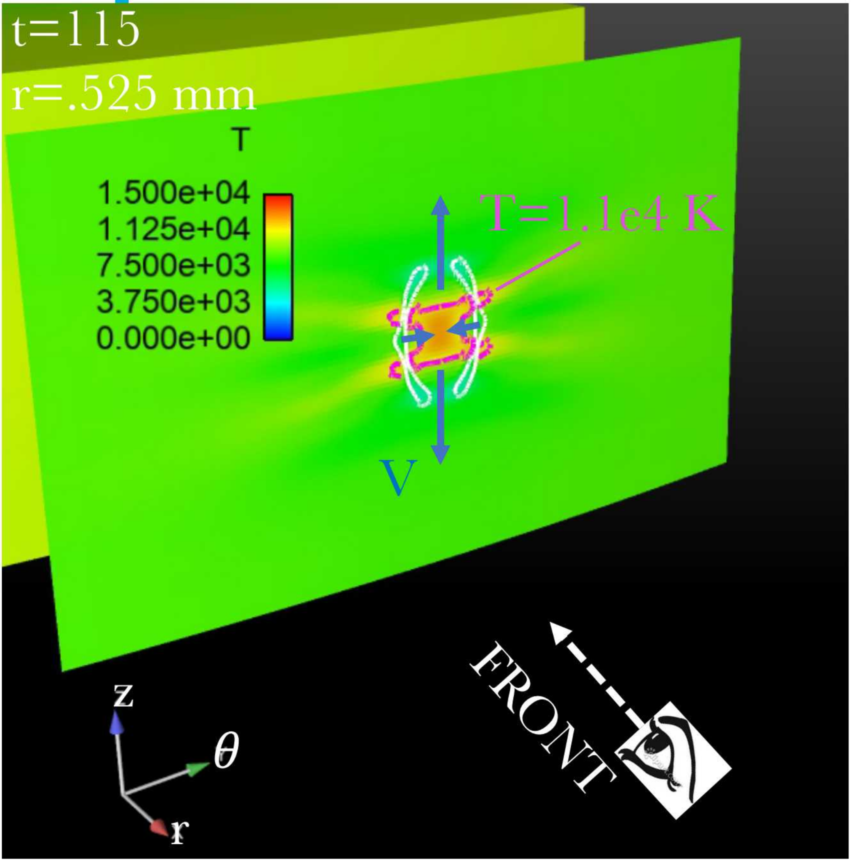


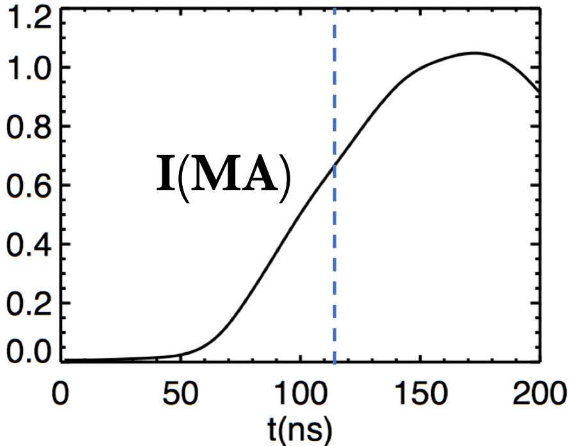


explosive



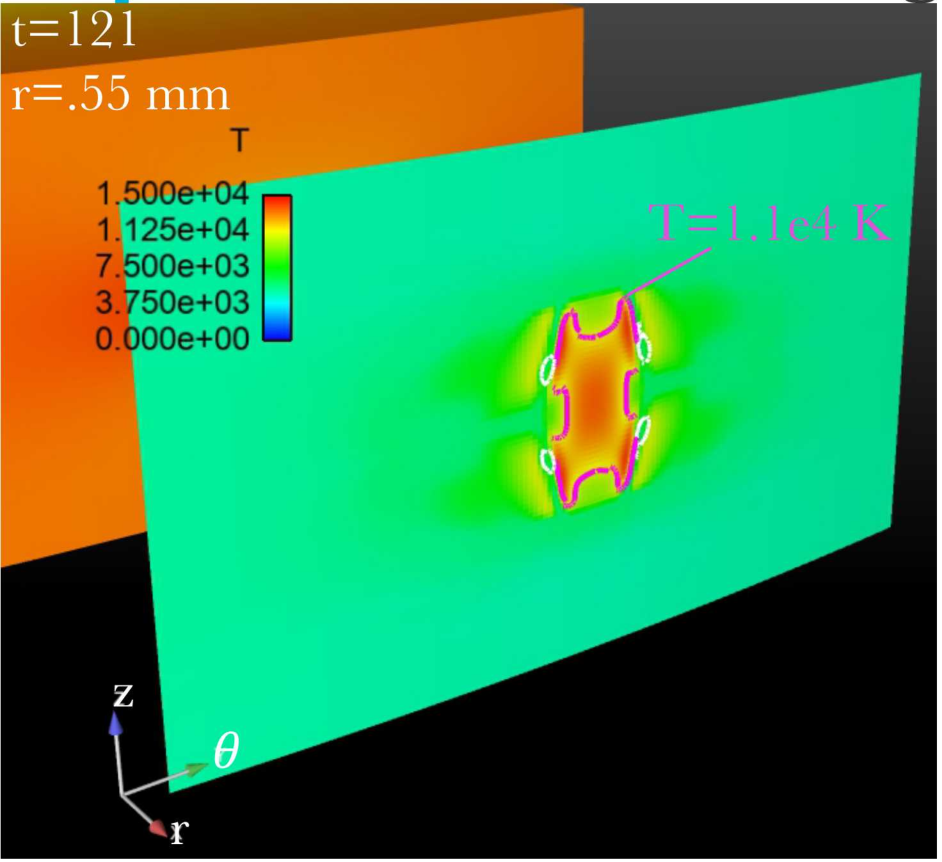
Filament forms through azimuthal focusing and axial expansion

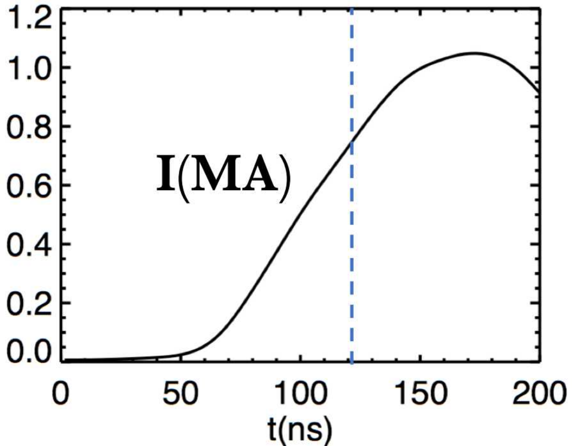




The hot spot focuses azimuthally (initially), but expands axially

Filament forms through azimuthal focusing and axial expansion

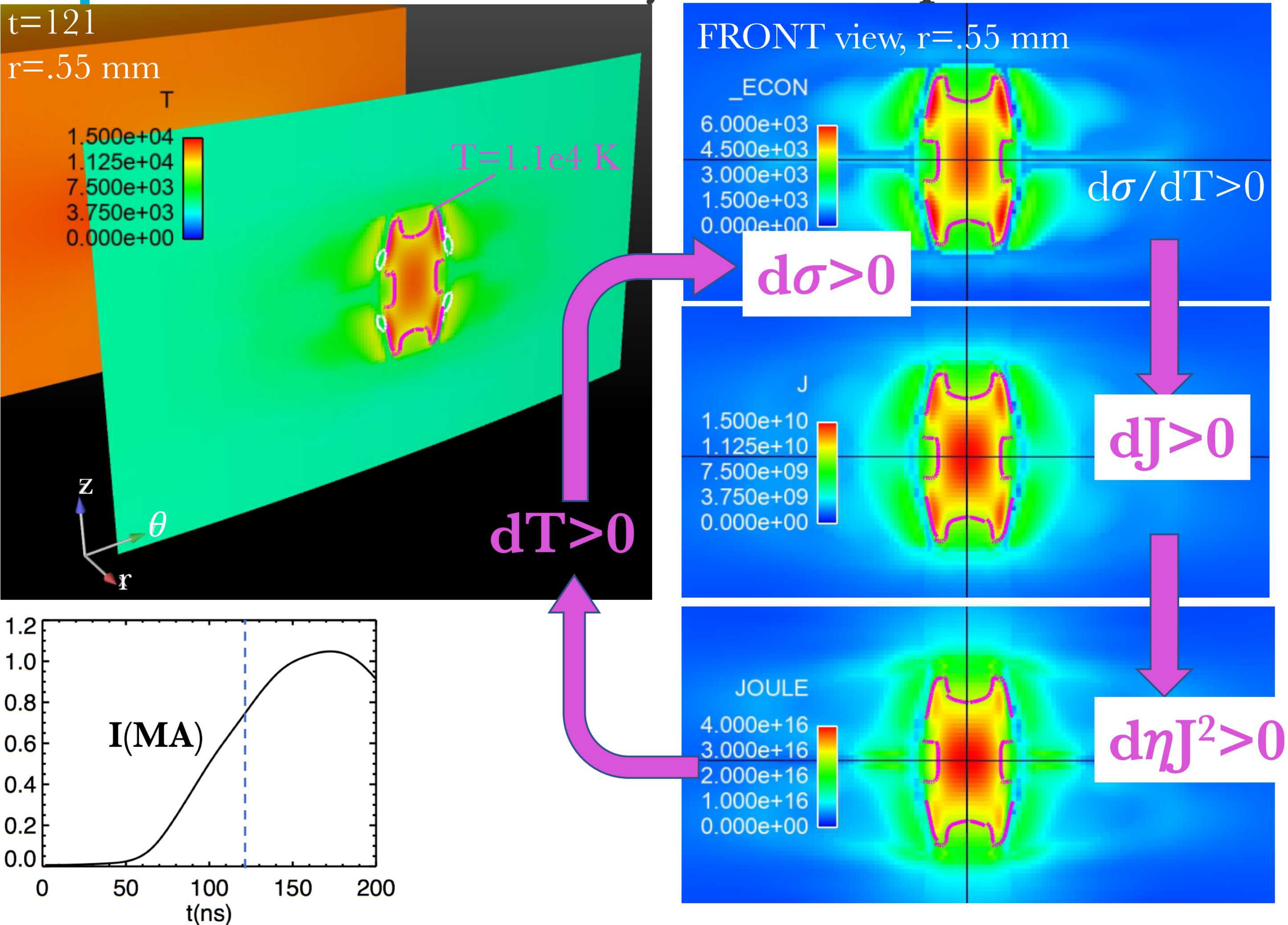




Following the hot spot in a Lagrangian sense, it has elongated axially, 6 ns later; it is transforming into a filament.

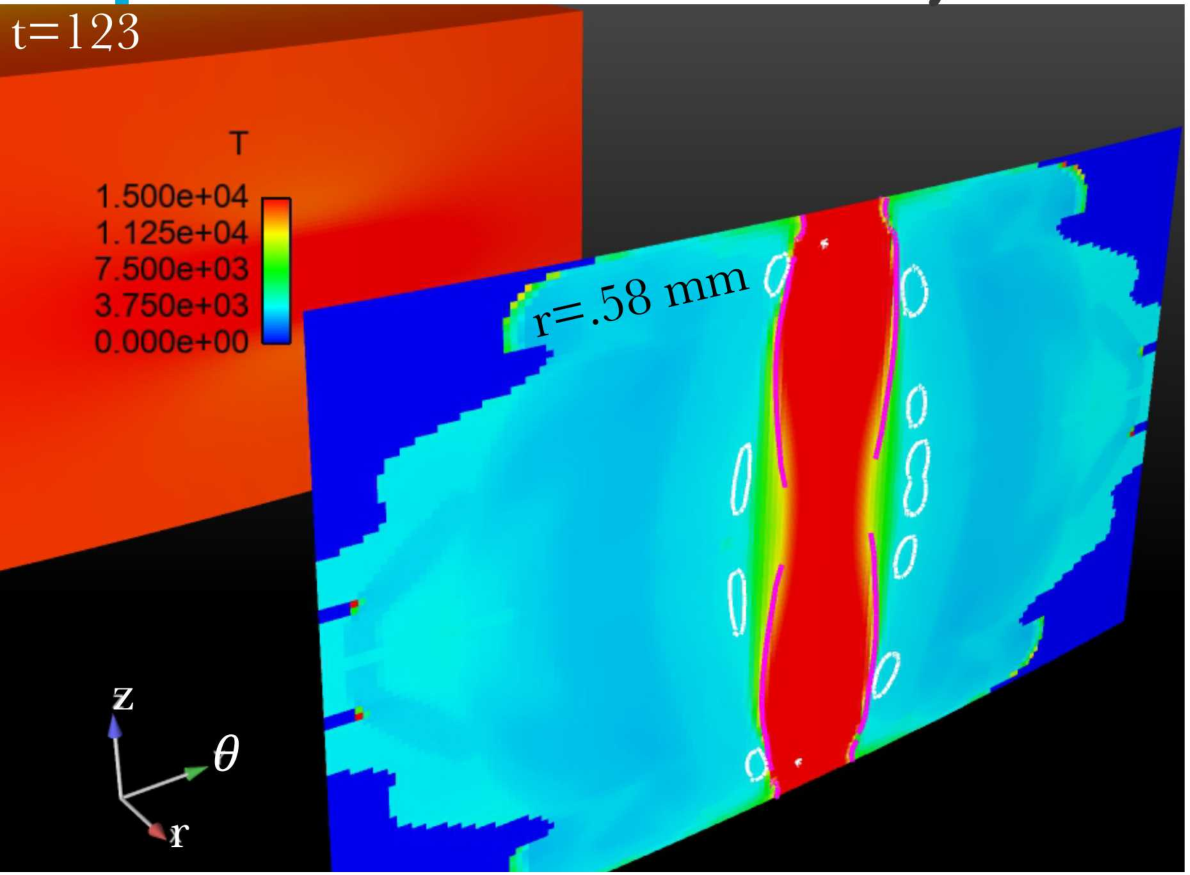
Also, despite the strong pdV expansion cooling, the hot spot has heated.

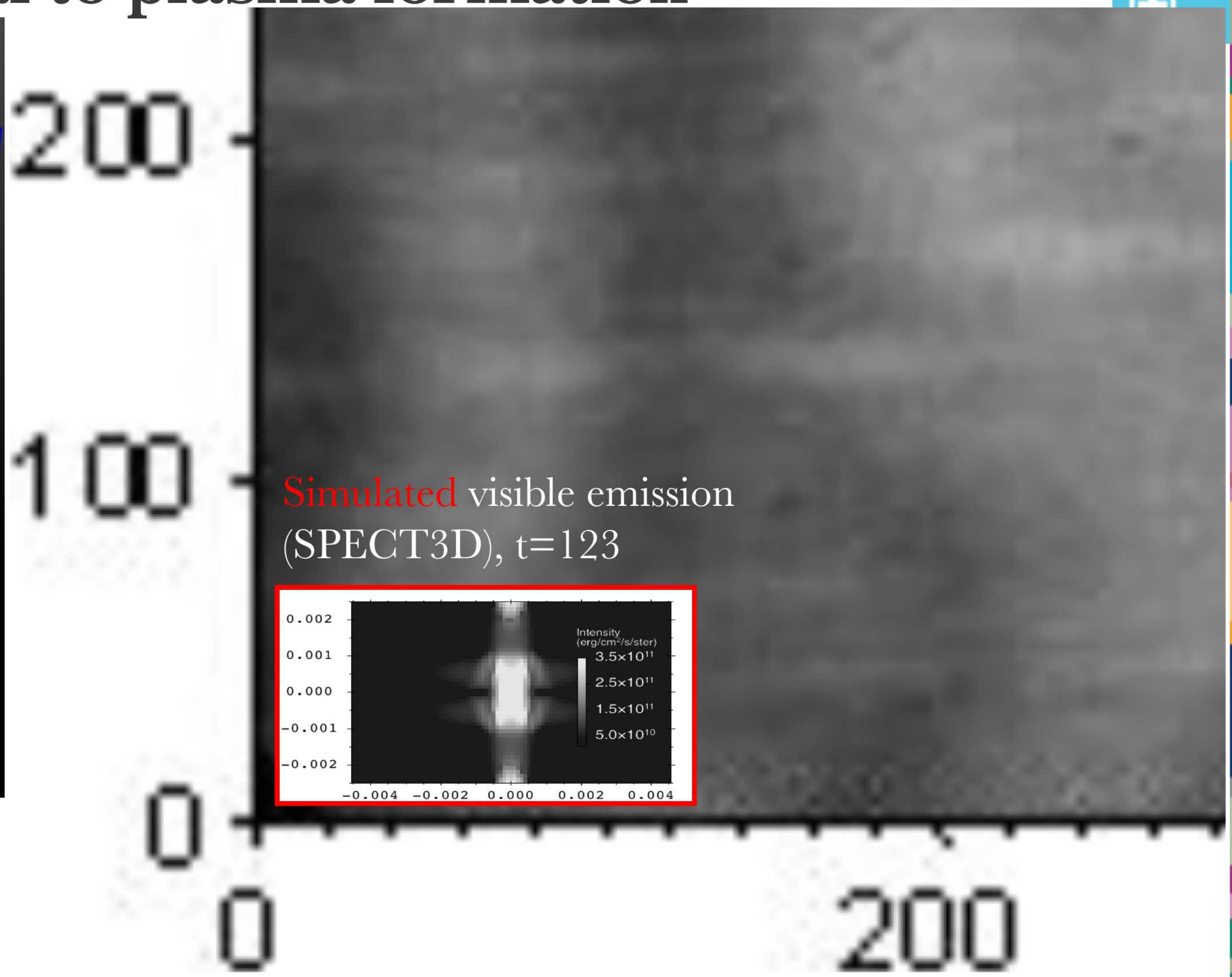
ETI filament instability is vital to plasma formation

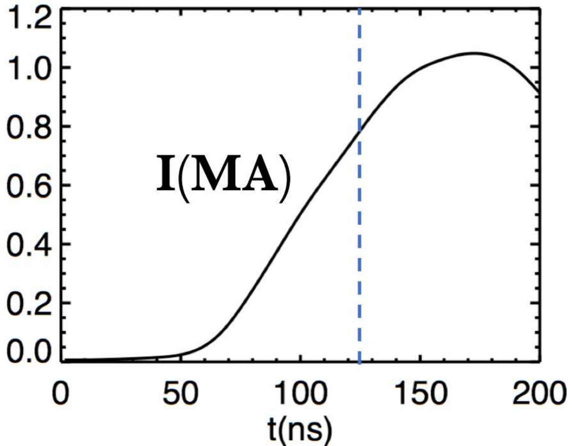


The hot spot continues to heat, despite pdV cooling, due to the ETI filament instability (i.e. **J** concentration)

ETI filament instability is vital to plasma formation



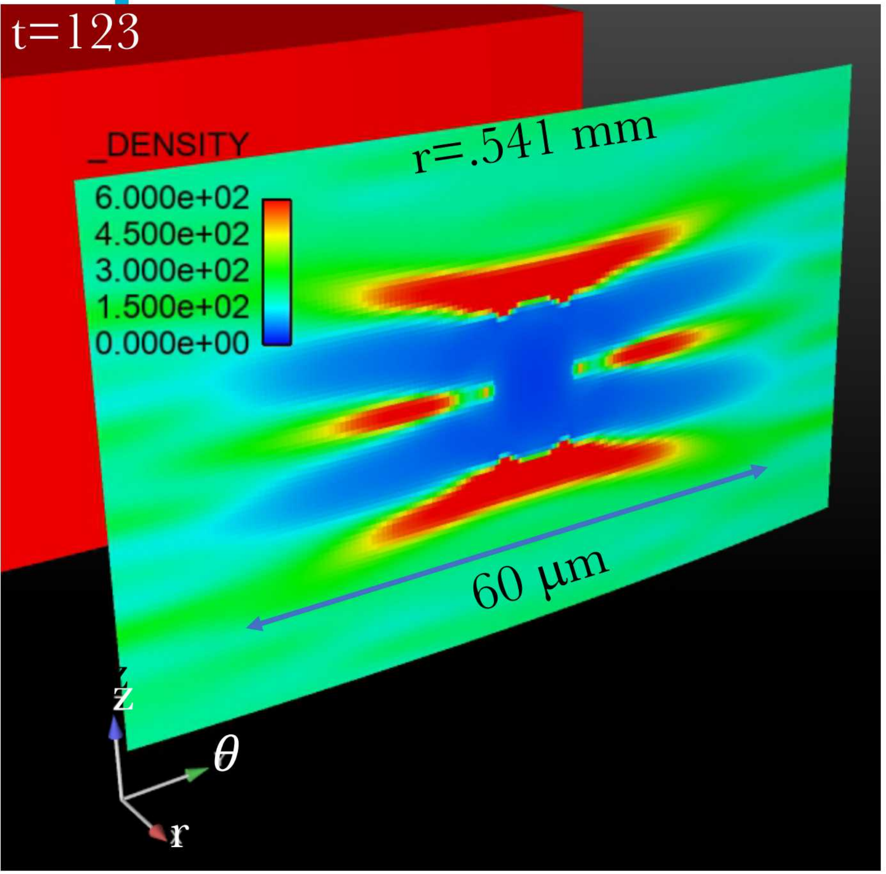


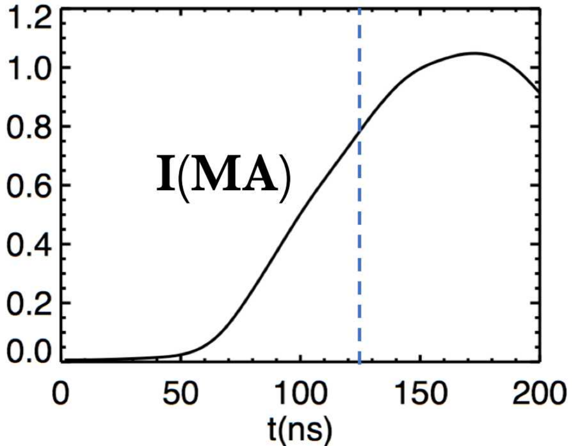


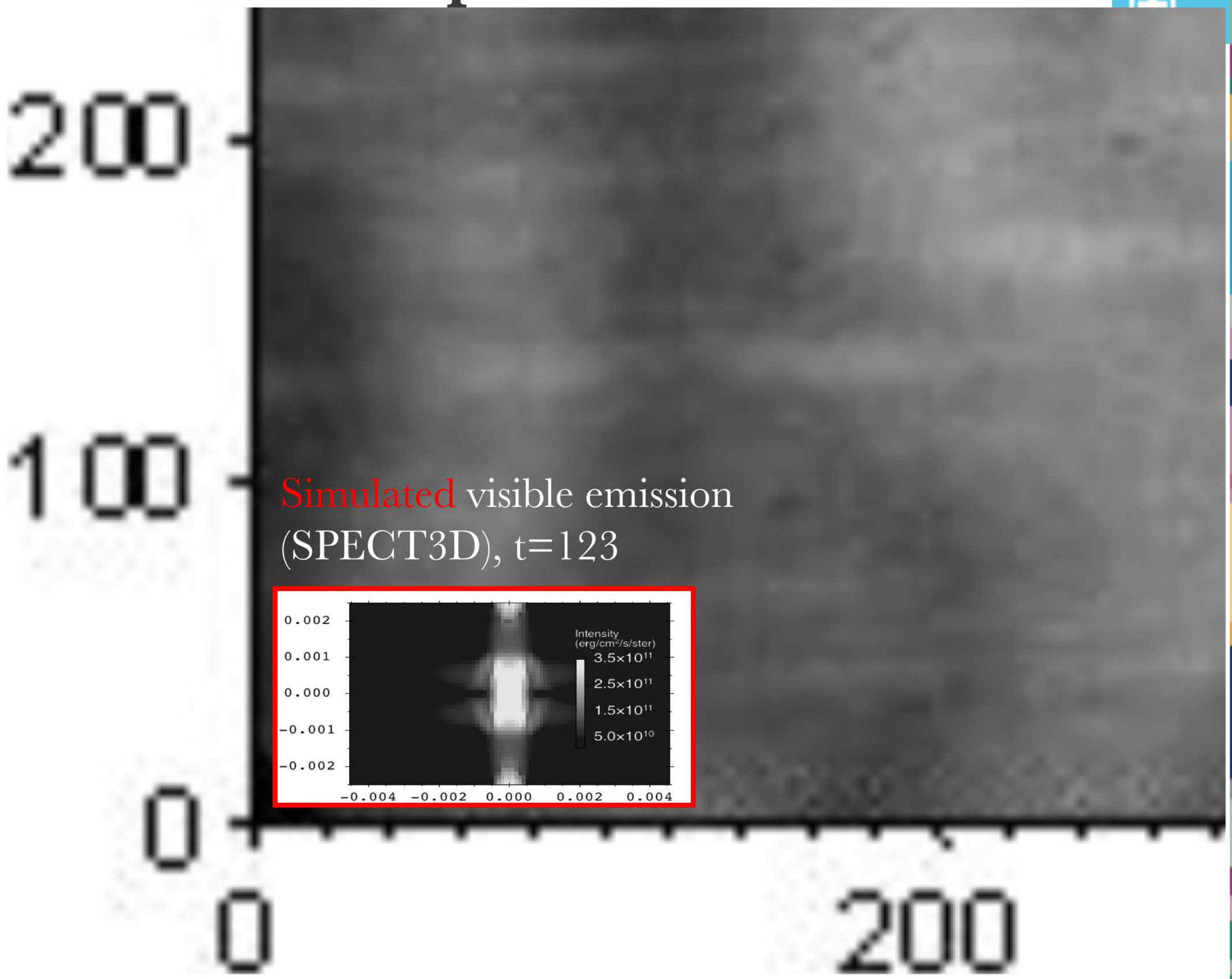
Once the hot spot spans the mesh axially, **J** "reconnects", driving explosive heating.

Plasma formation is a 3D process. In an equivalent 1D simulation, which can't model the ETI filament, plasma forms ~25 ns later.

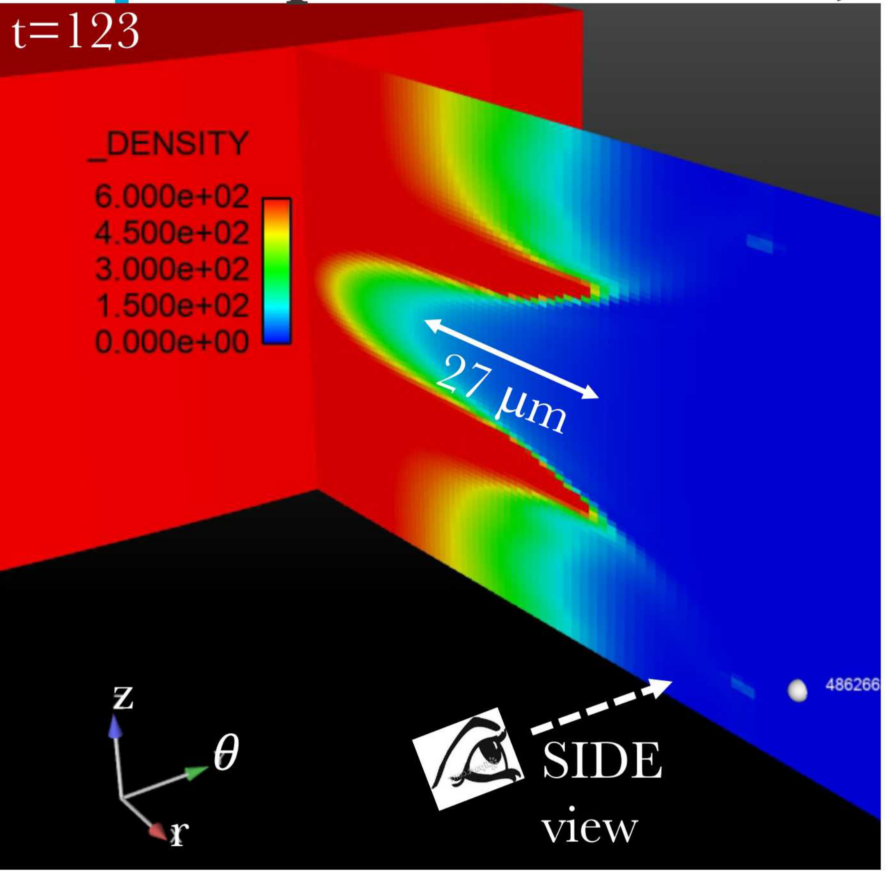
Deeper in the metal, the striation has developed into a crater

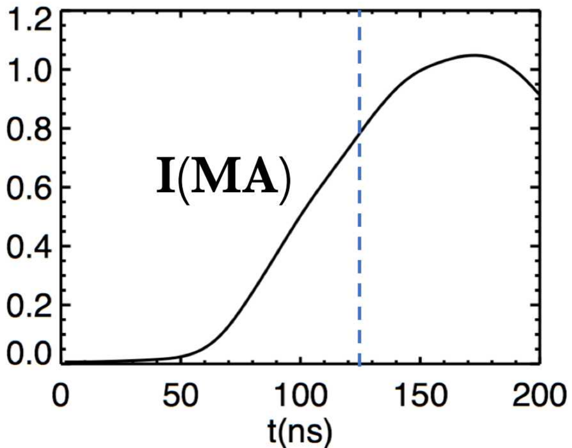






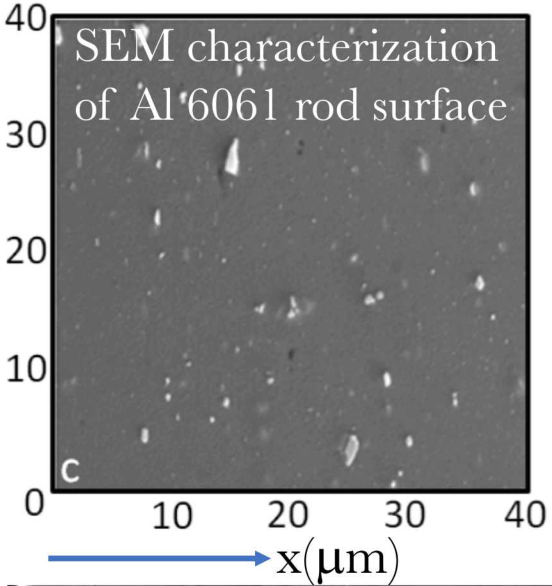
Deeper in the metal, the striation has developed into a crater

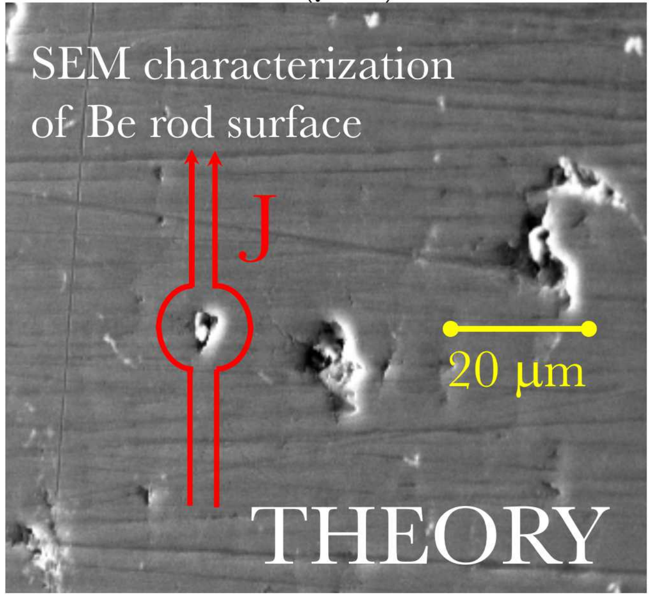


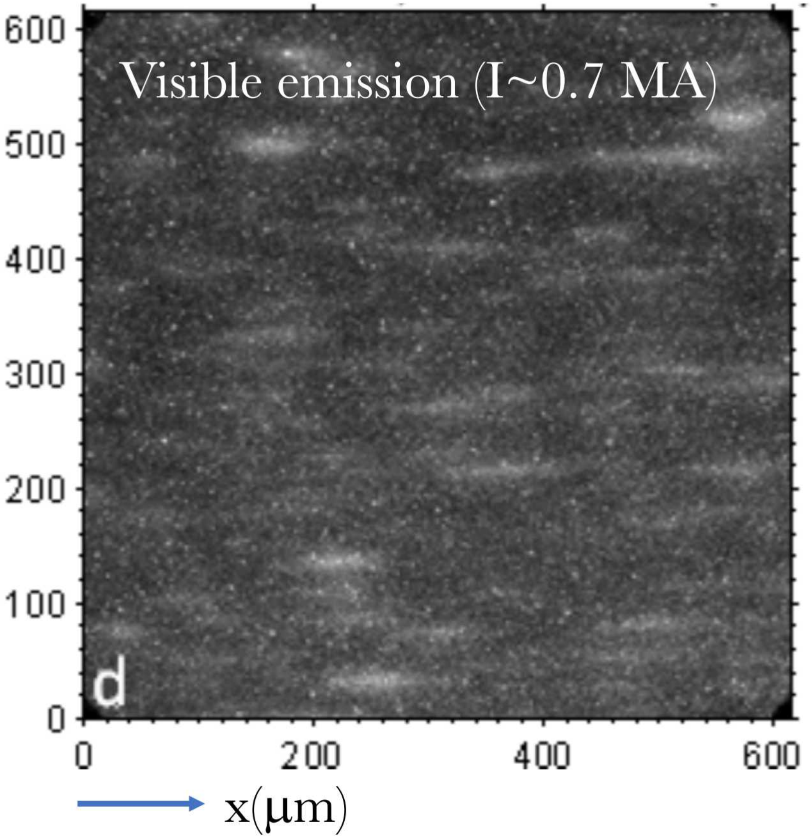


The crater is ~10X wide and deep as the original inclusion, important for MRT.

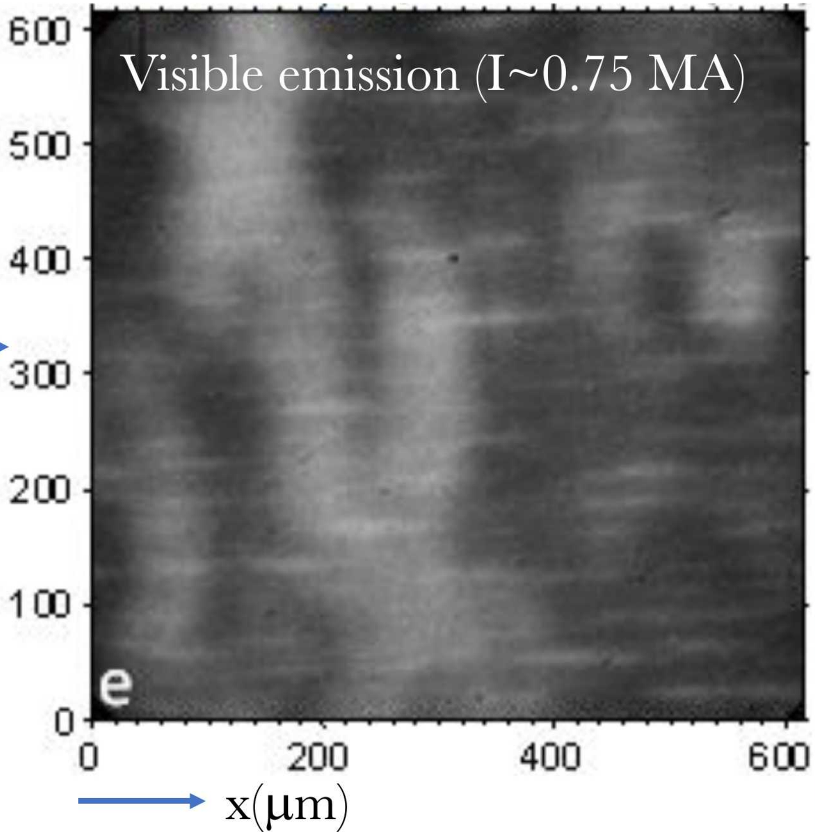
Can resistive inclusions or voids seed striations/filaments?







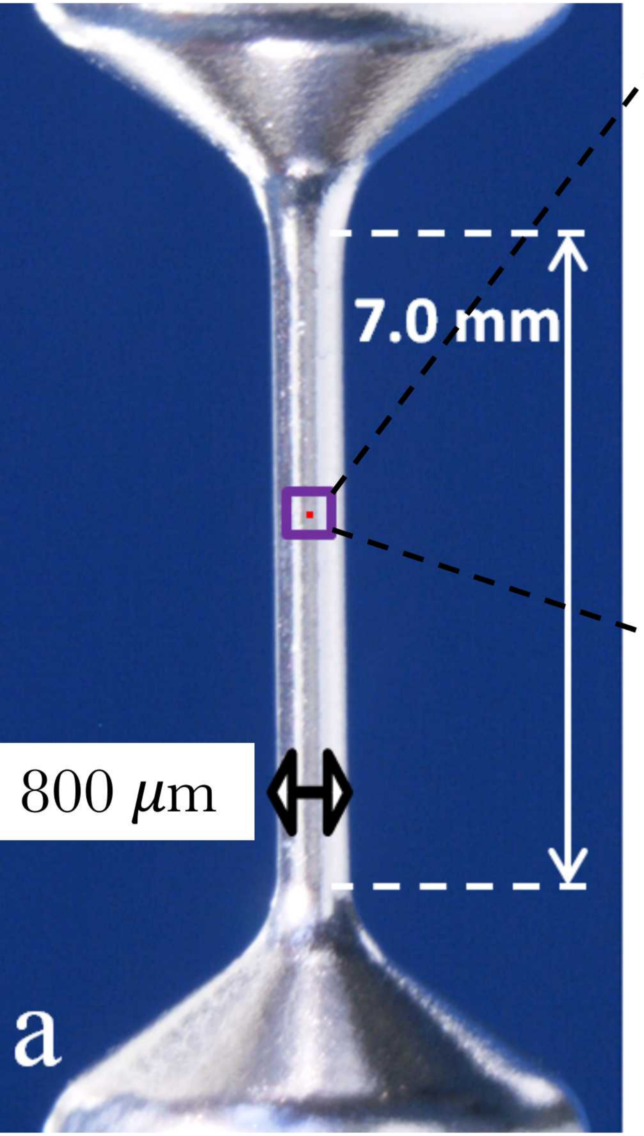
3D MHD simulation



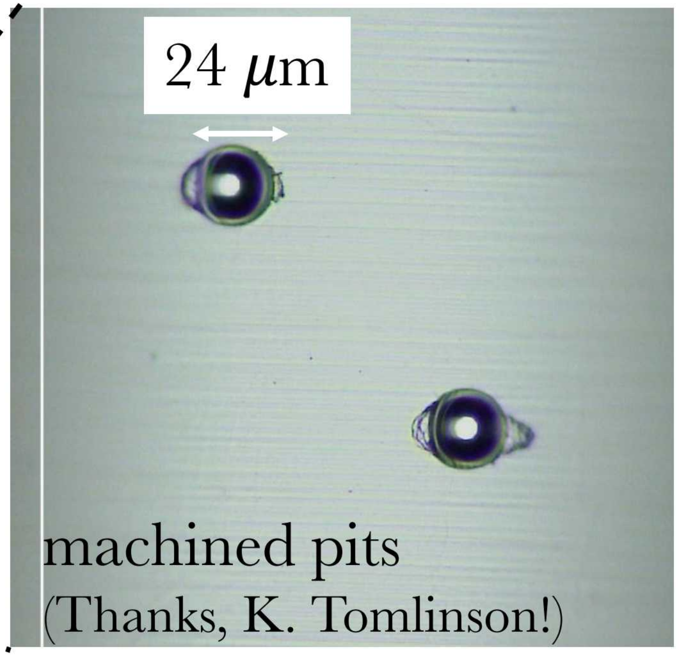
Q: How much can we really believe simulations?

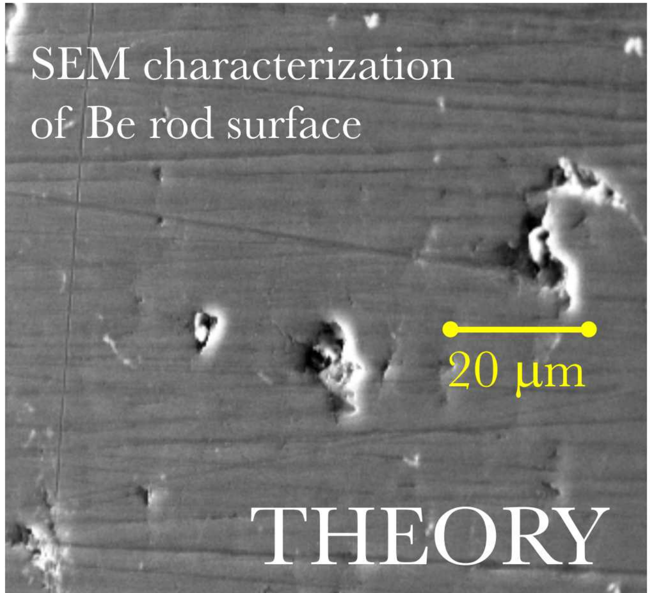
Need experiment!

Experiments with pre-machined perturbations on 99.999% pure Al provide a known initial condition for 3D MHD simulations



Al 5N rod (99.999% pure)
i.e. no inclusions





Large pits are easier to diagnose

M. Hatch (CP10.00051): Development of a novel dual view, 4-frame imaging system to study ETI
S. Kreher(JP10.00090): Magnetohydrodynamic calculations of resistively exploding aluminum rods

First experiments did not match simulation prediction

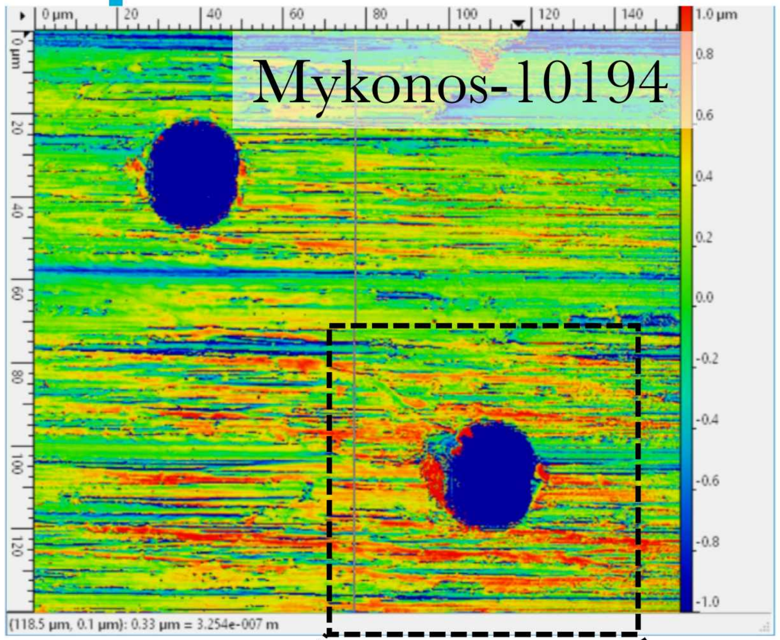
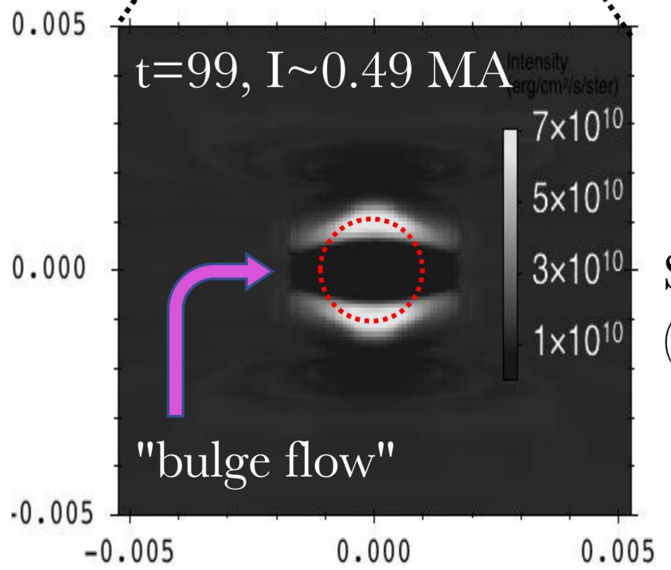
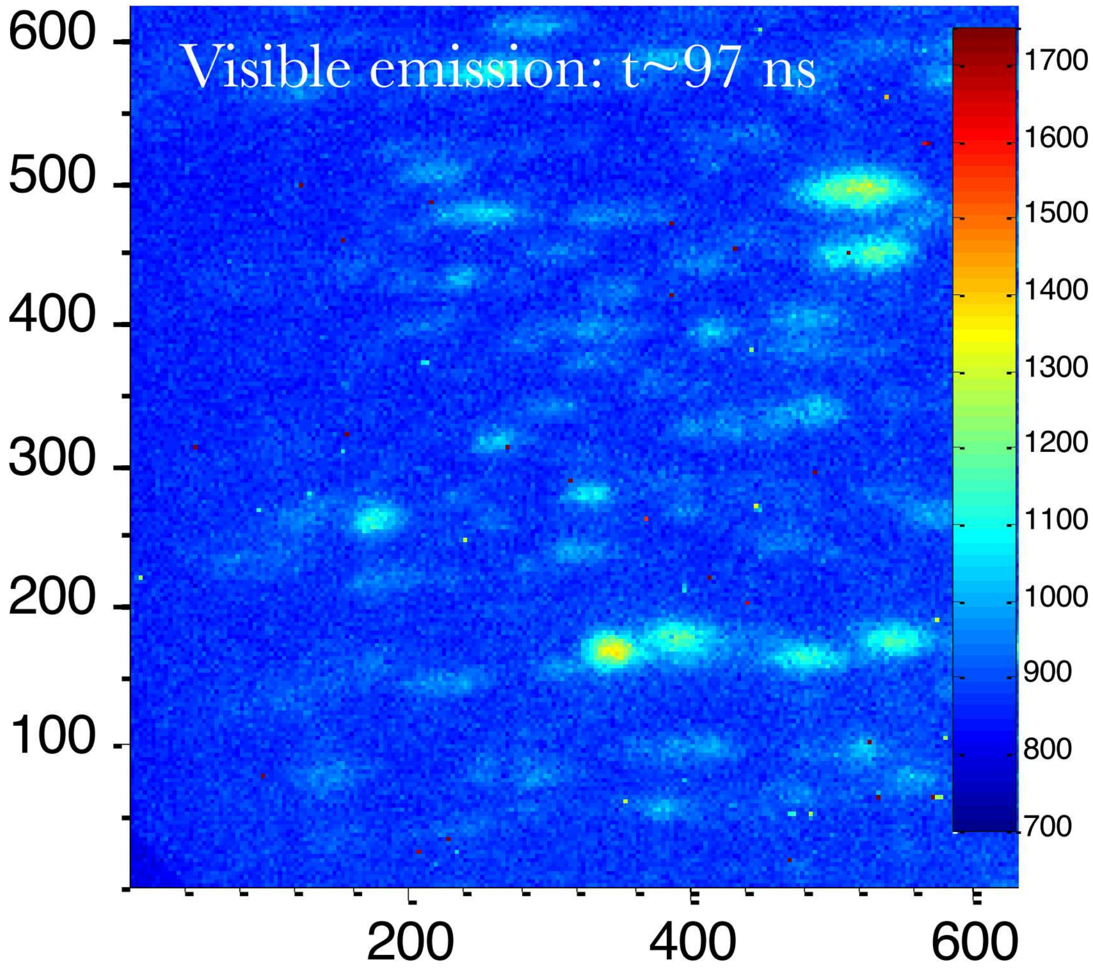


Figure 6-9. **Ra=397 nm**



Simulated emission of single pit (SPECT3D)



No evidence of the predicted pit emission! Looks like standard "pitless" case.

Theory predicts grooves dominate pits

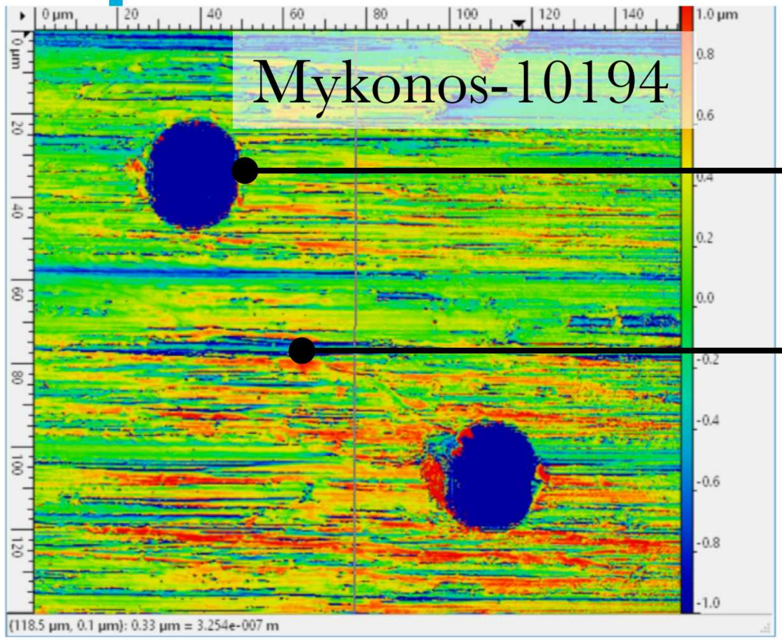


Figure 6-9. **Ra=397 nm**

$J_{pit}=1.5J_0$

$J_{groove}=J_0(1+2\pi A/\lambda)$

For A~1 μm, λ~7 μm,
$J_{groove}=1.9J_0$

Need a smoother rod!

In smoother rods, pits should dominate grooves

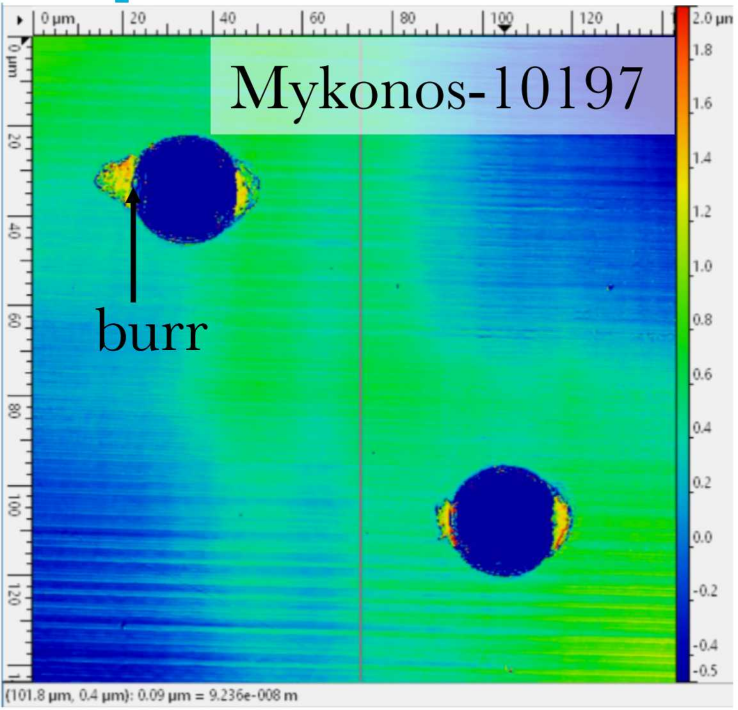
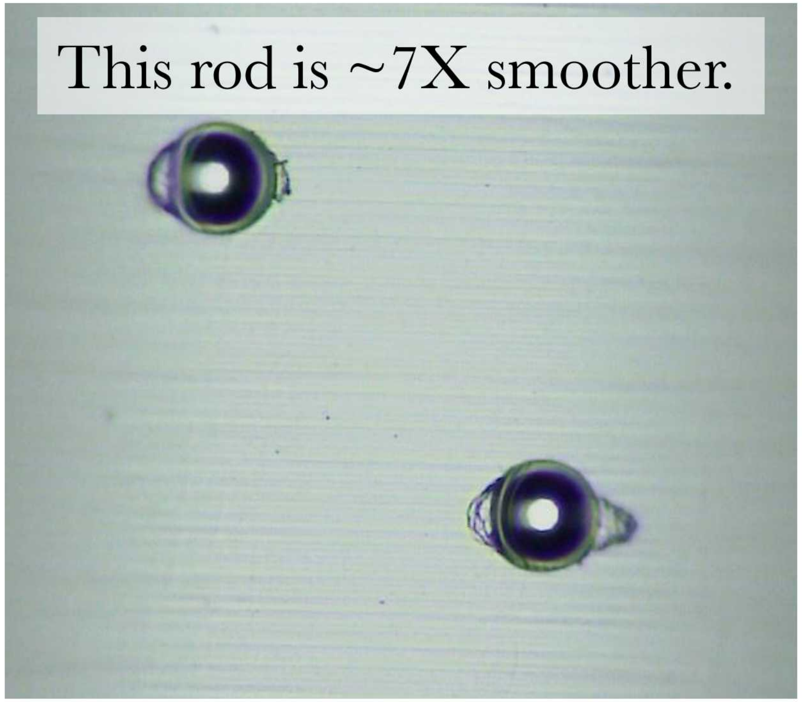
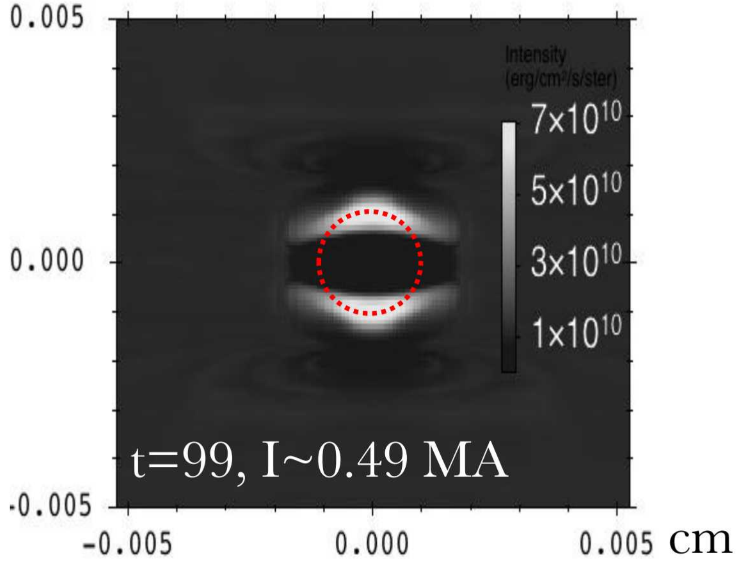


Figure 6-12. **Ra=57 nm**





Simulated emission of single pit (SPECT3D)

Simulation prediction is similar to experiment, for smooth rods

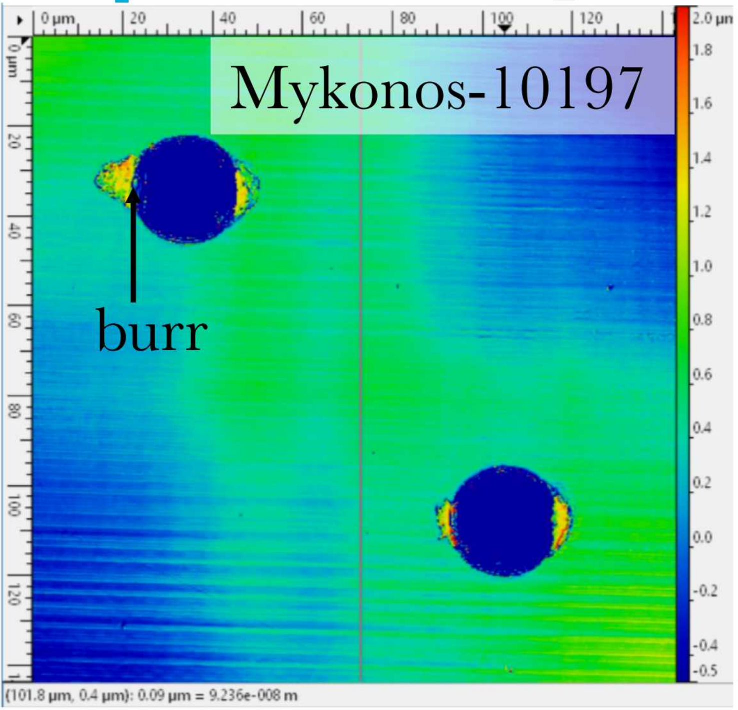
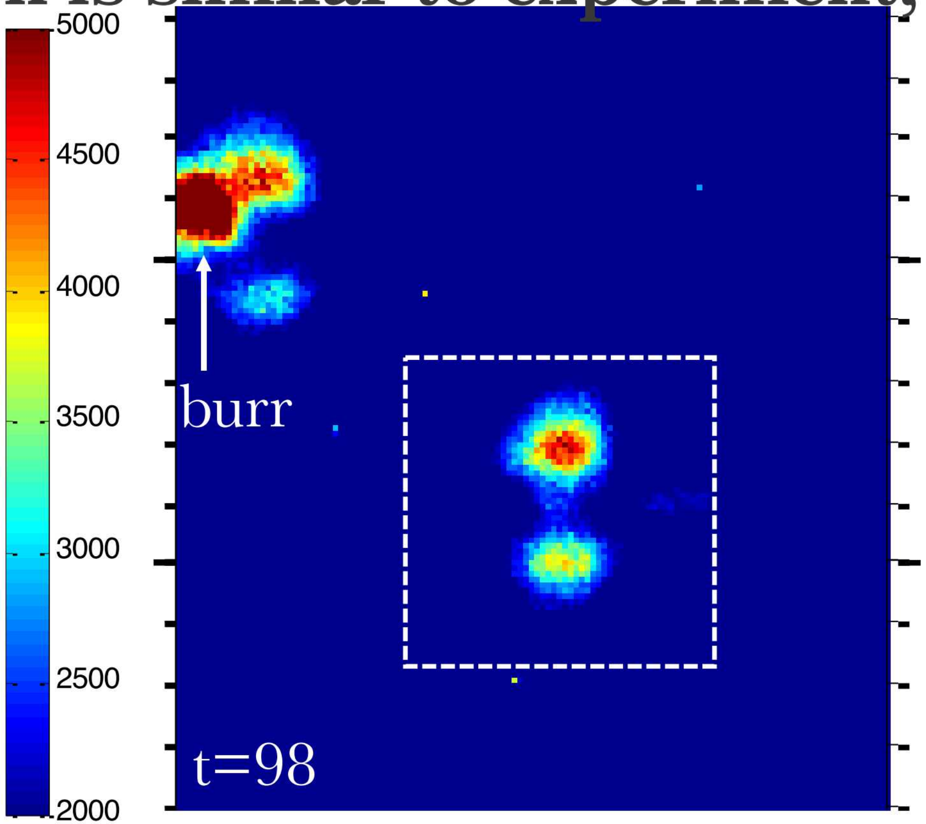
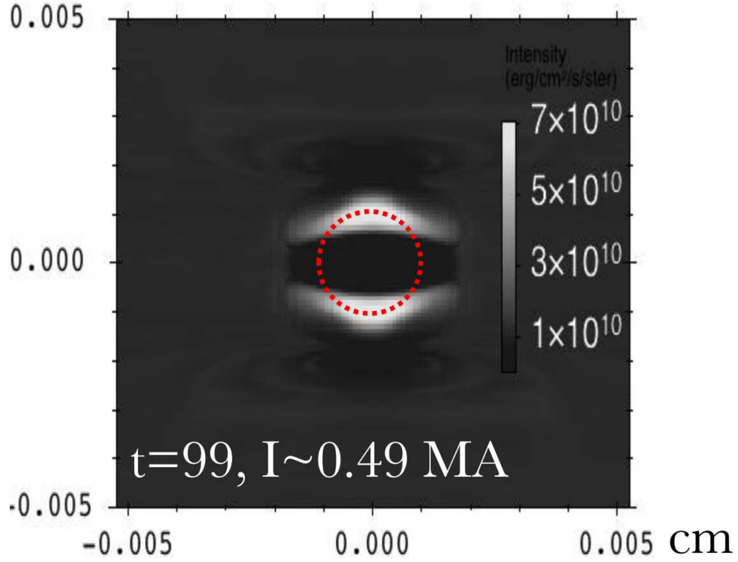


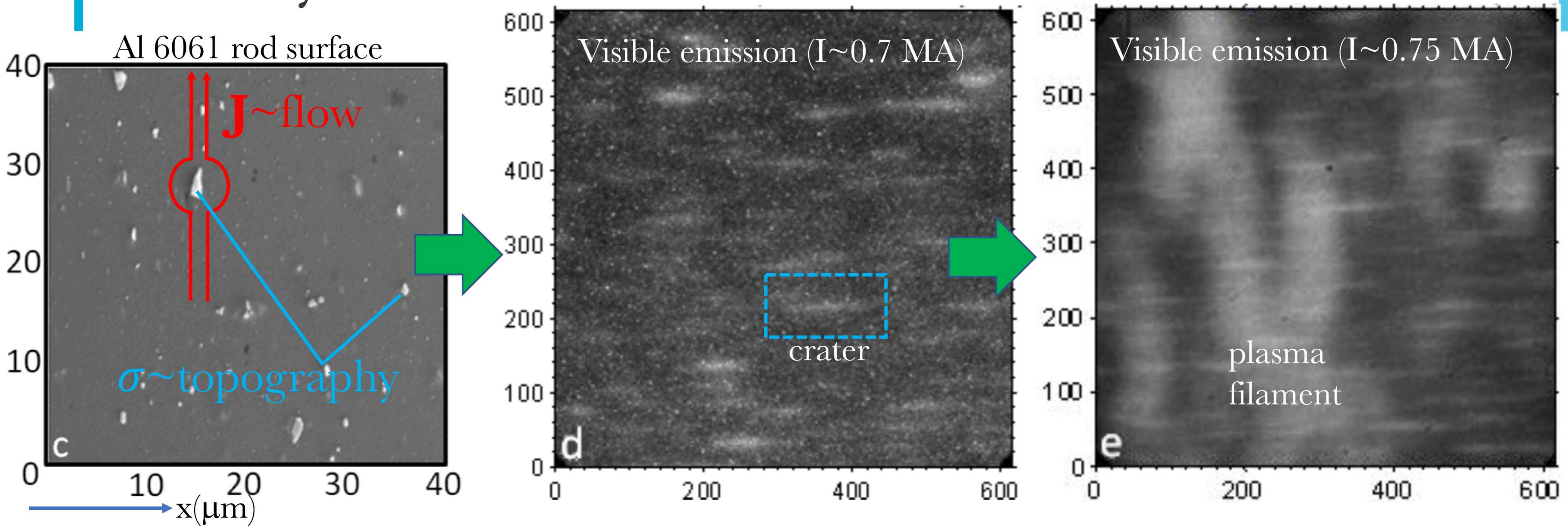
Figure 6-12. **Ra=57 nm**





- 3D MHD <u>can</u> model metal explosion
- A first step towards a <u>controlled</u> metal explosion

Summary



- Micron-scale resistive inclusions can transform into ~10X wider, deeper craters, important for later magneto Rayleigh-Taylor instability development
- Inclusions seed plasma formation, which is a 3D effect.
- We are using the new understanding of MRT seeding mechanism to devise stabilizing strategies (e.g. pure, void-free metal coating).

THANK YOU!