SAND2022-14118C

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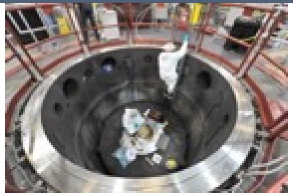
Helical deformation of 3D defects in a premagnetized Z-pinch liner

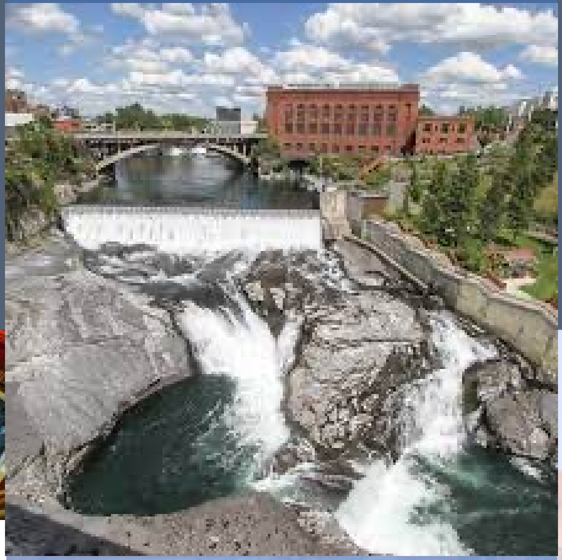




E. Yu, T. Awe, K. Cochrane, M. Hatch*, K. Peterson, T. Hutchinson**, K. Yates, K. Tomlinson°, W. Tatum°, B. Bauer◊, B. Hutsel, D. Sinars, G. Shipley

2022 APS DPP

Spokane, Washington

Sandia National Laboratories
*University of New Mexico
**Lawrence Livermore National Laboratory
°General Atomics
◊University of Nevada at Reno




This research was supported by the Sandia Laboratory Directed Research and Development Program under Projects 178661 and 200269

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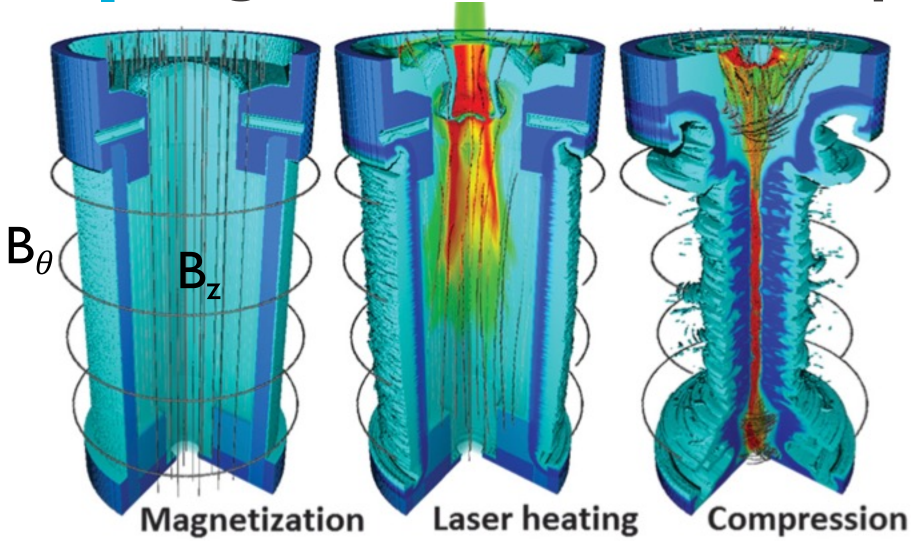
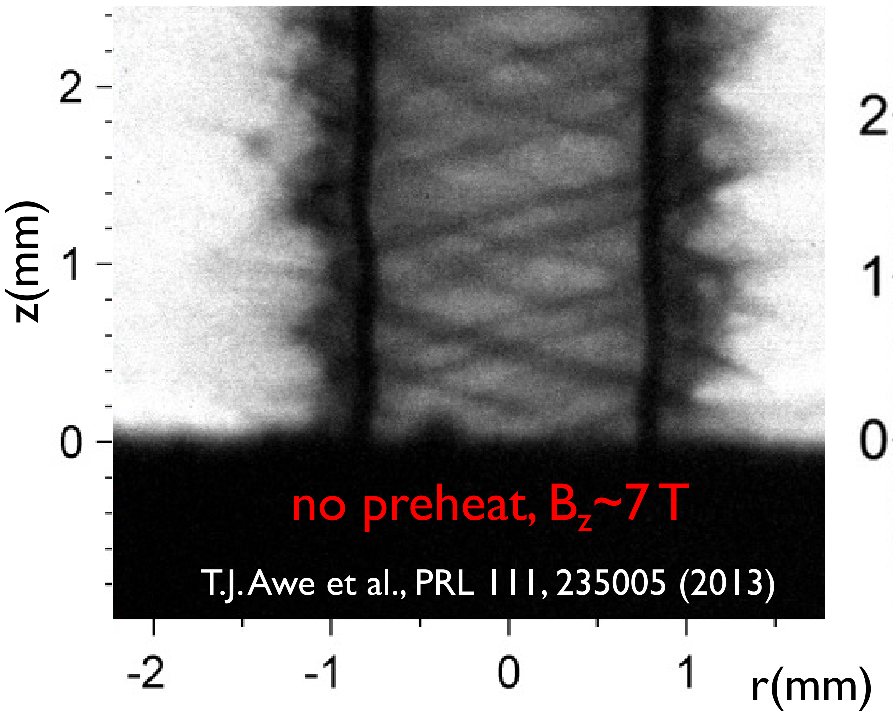
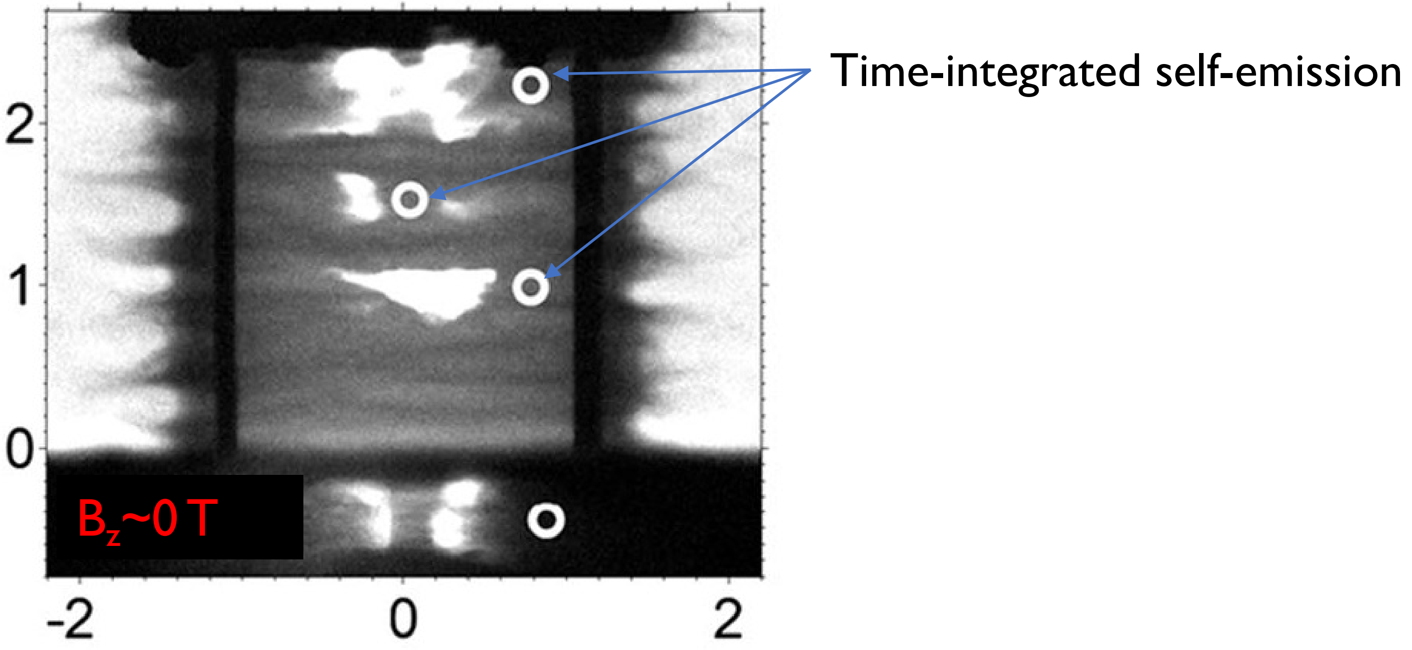
Magnetized liners develop helical structures



MagLIF: azimuthal magnetic field (B_θ) compresses liner filled with premagnetized (B_z) fusion fuel.

S.A. Slutz et al., Phys. Plasmas 17, 056303 (2010)
M.R. Gomez et al., PRL 125, 155002 (2020)

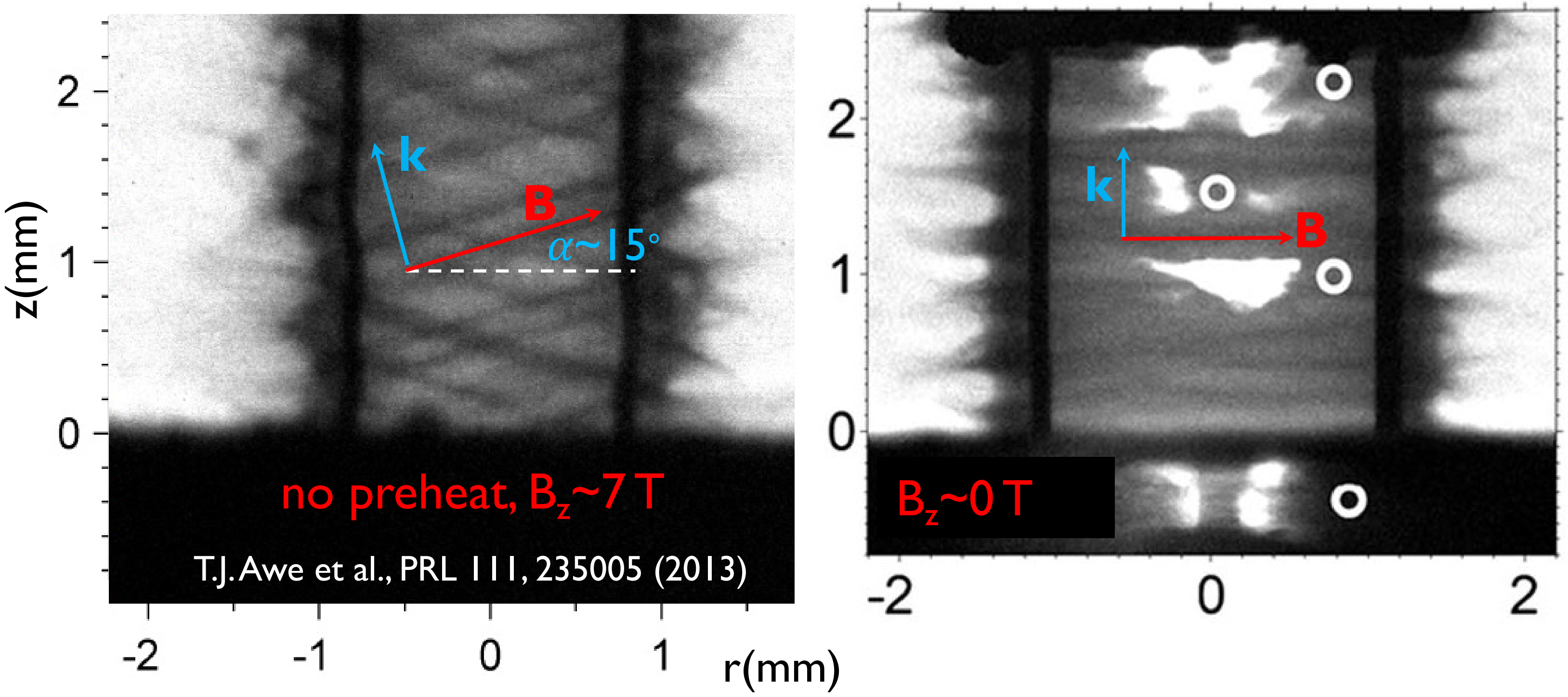




The origin of the helical mode remains an open research question

From instability theory, $\mathbf{k}\cdot\mathbf{B}=0$ minimizes the (stabilizing) **B** field line bending

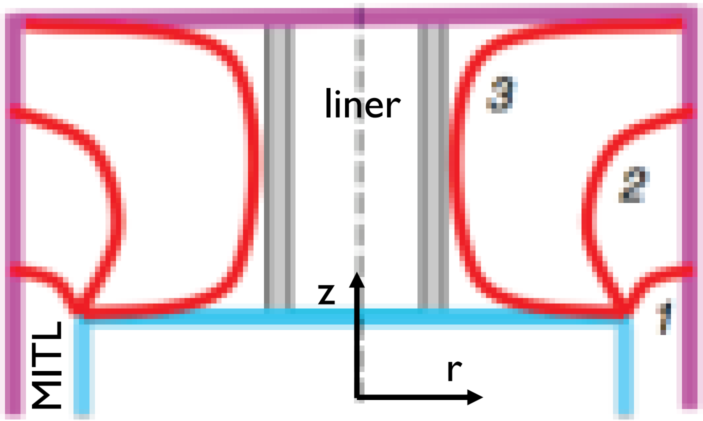
However, this condition implies a much larger B_z than the expected value:
$\mathbf{k}\cdot\mathbf{B}=0 \Rightarrow B_z=B_\theta \tan(\alpha)=700\ \mathrm{T} \gg 7\ \mathrm{T}$



The origin of the helical mode remains an open research question

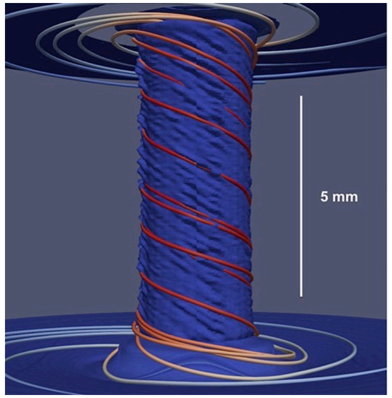
Low-density plasma from MITL (magnetically insulated transmission line) sweeps up, compresses, and amplifies B_z at liner surface

D. D. Ryutov et al., AIP Conf. Proc. 1639 (2014)



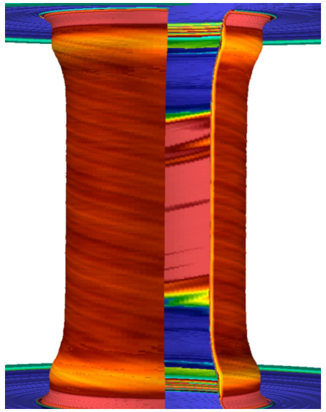
3D simulations demonstrate viability of flux compression hypothesis and importance of Hall term in modeling this effect

C.E. Seyler, M.R. Martin, and N.D. Hamlin, PoP 25, 062711 (2018)
J.M. Woolstrum et al., PoP 27, 092705 (2020)



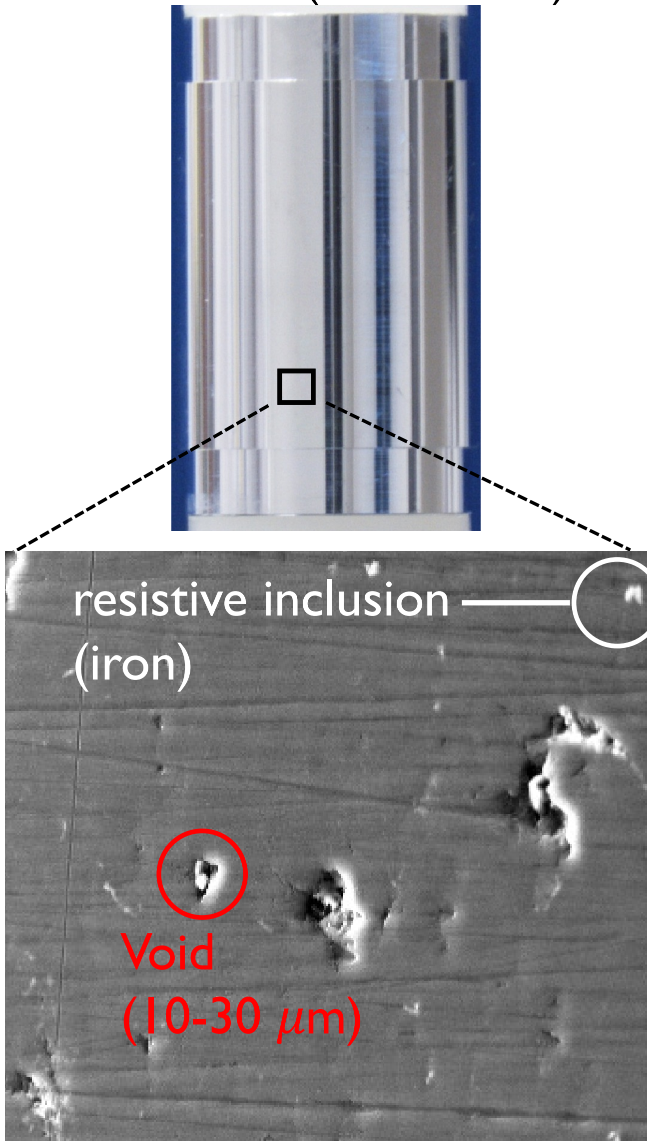
Plasma particles from MITL are helically oriented and bombard the liner, creating a helical temperature perturbation

A.B. Sefkow, Bull. Am. Phys. Soc. 61, 373 (2016)



Metallic liners are inhomogeneous

Be liner (50 nm rms)

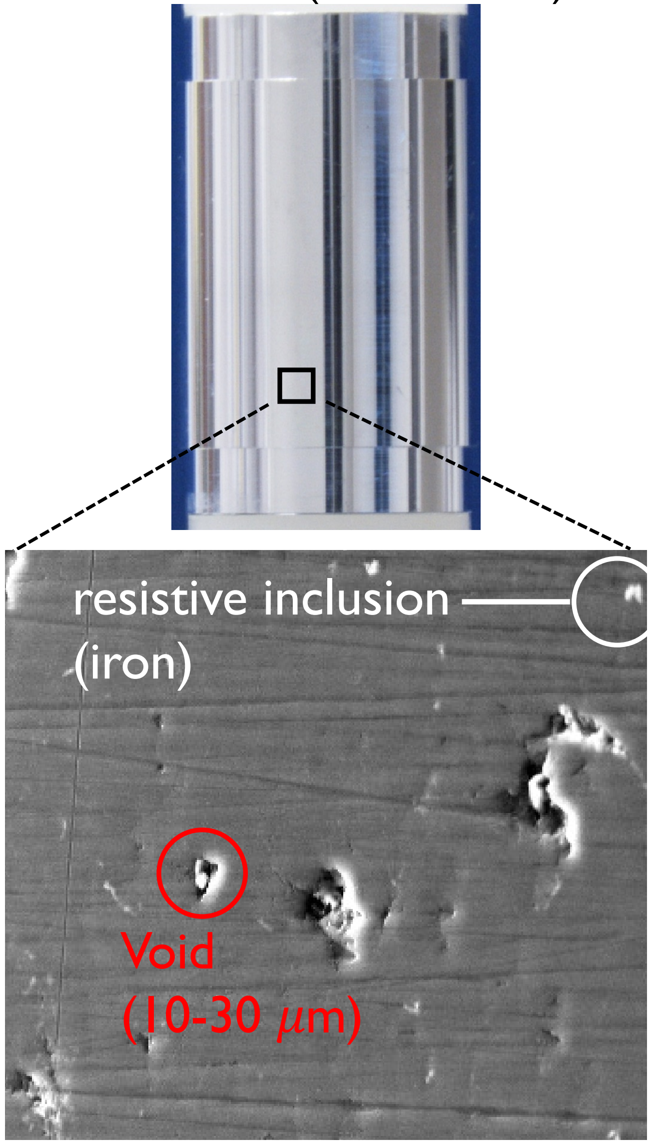


Characterization of Be rod surface
(E. Harding, K. Tomlinson)

Q: Do defects really matter?

3D defects constitute nonlinear perturbations to current density j

Be liner (50 nm rms)



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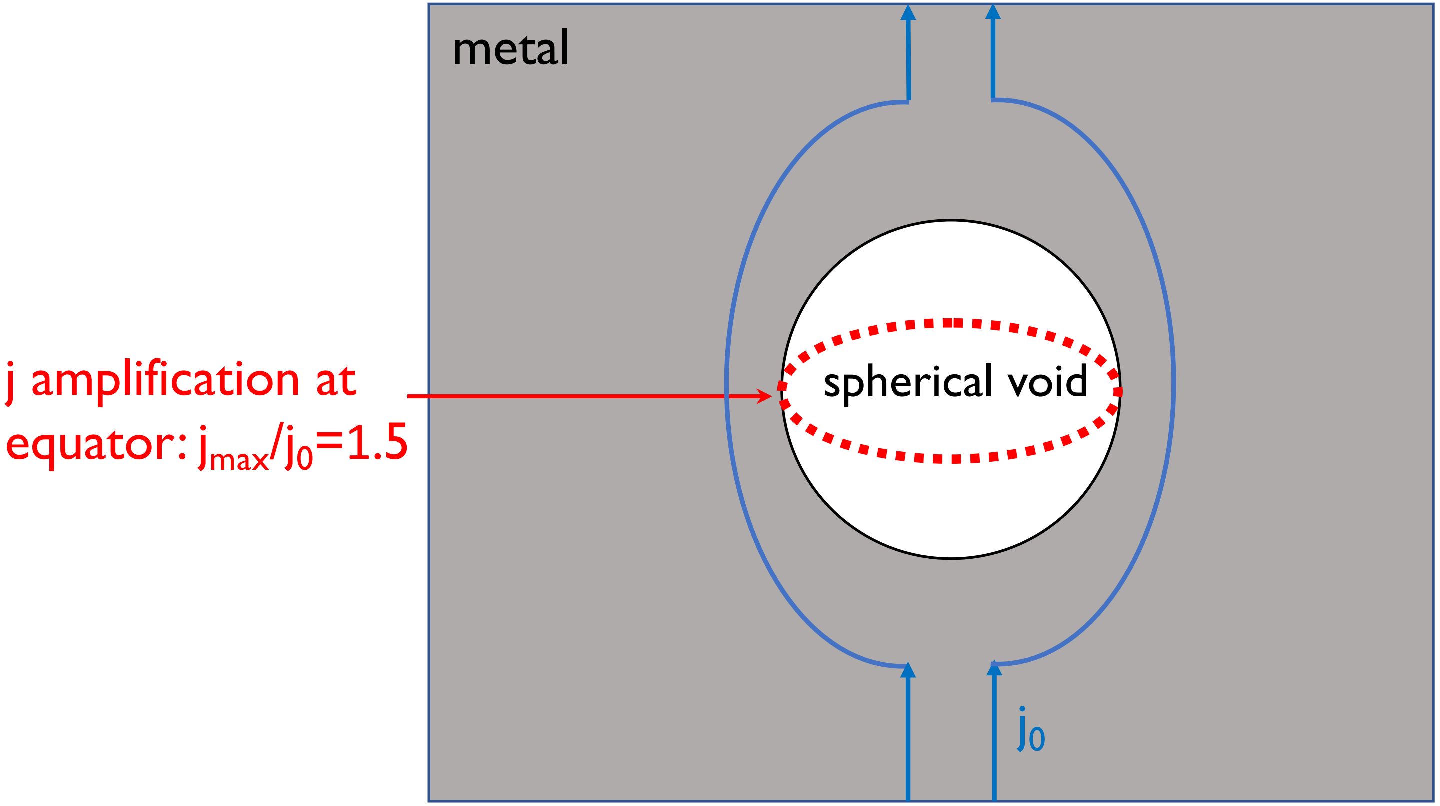
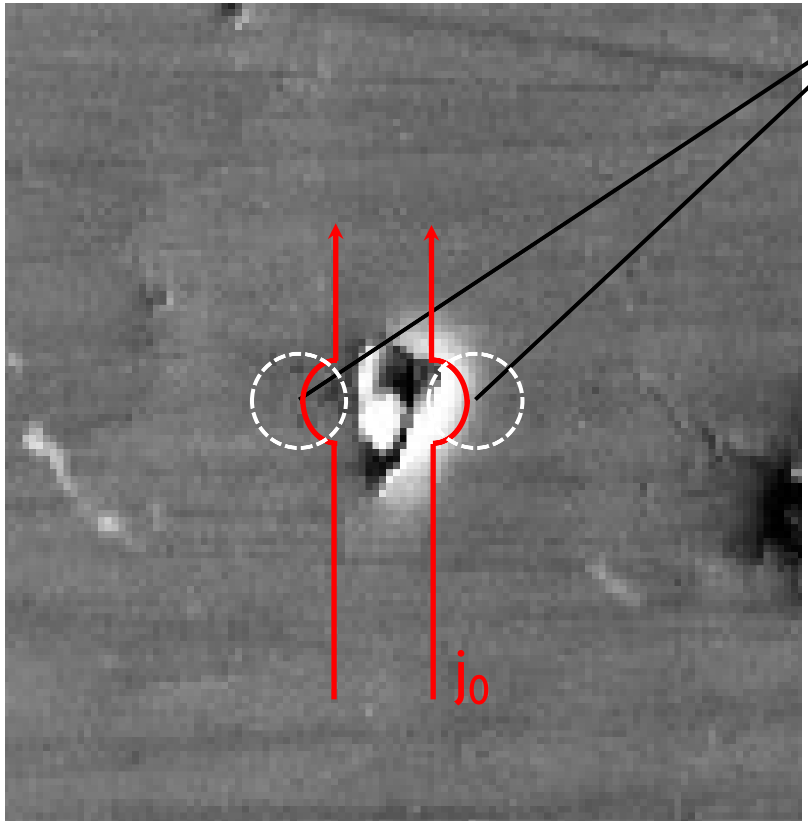


- $\delta j = j_{max} - j_0$ depends on shape, not size

Hydrodynamic analogy with electrical current flow
E.P. Yu, T.J. Awe, K.R. Cochrane et al., Phys. Plasmas **27**, 052703 (2020)

Nonlinear δj initiates a feedback loop unique to current-driven metal

$\delta j > 0 \Rightarrow \delta(j^2/\sigma) > 0 \Rightarrow \delta T > 0 \Rightarrow \delta\sigma < 0$



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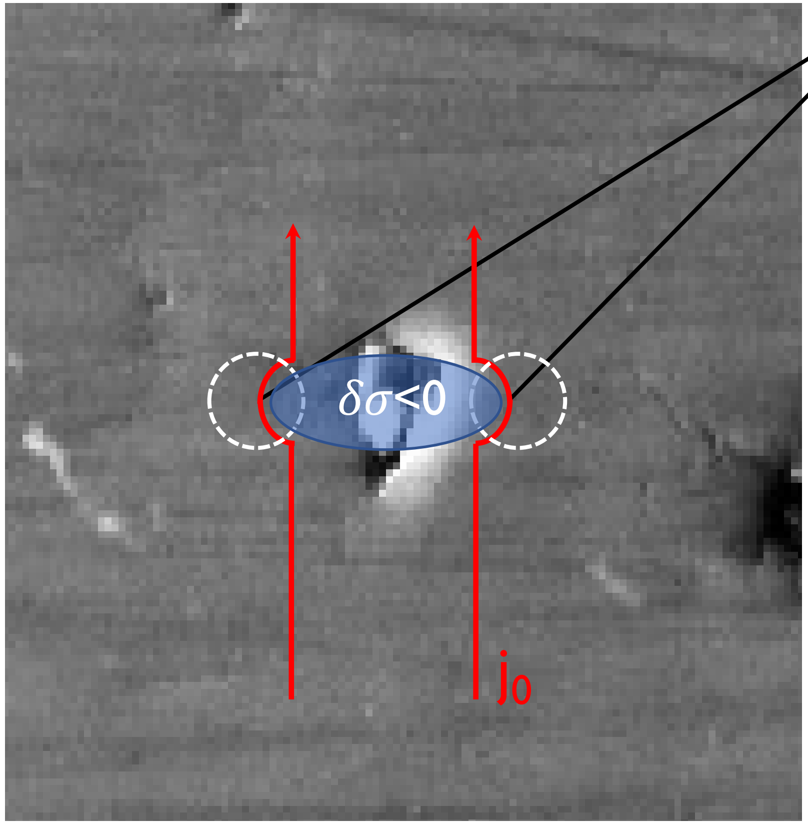
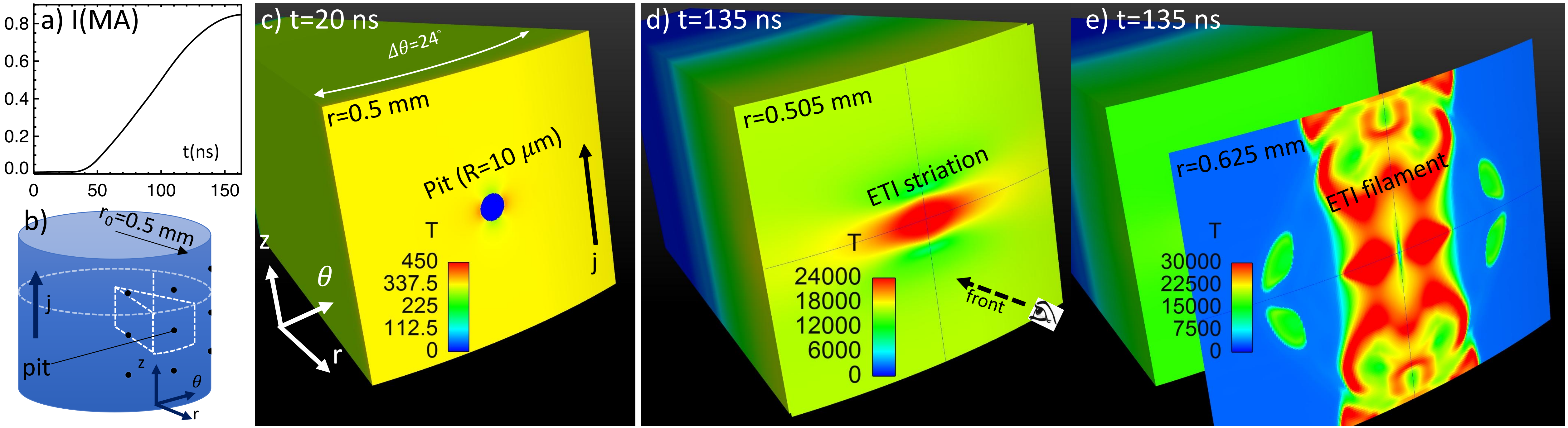


$$\delta j>0 \Rightarrow \delta(j^2/\sigma)>0 \Rightarrow \delta T>0 \Rightarrow \delta\sigma<0$$

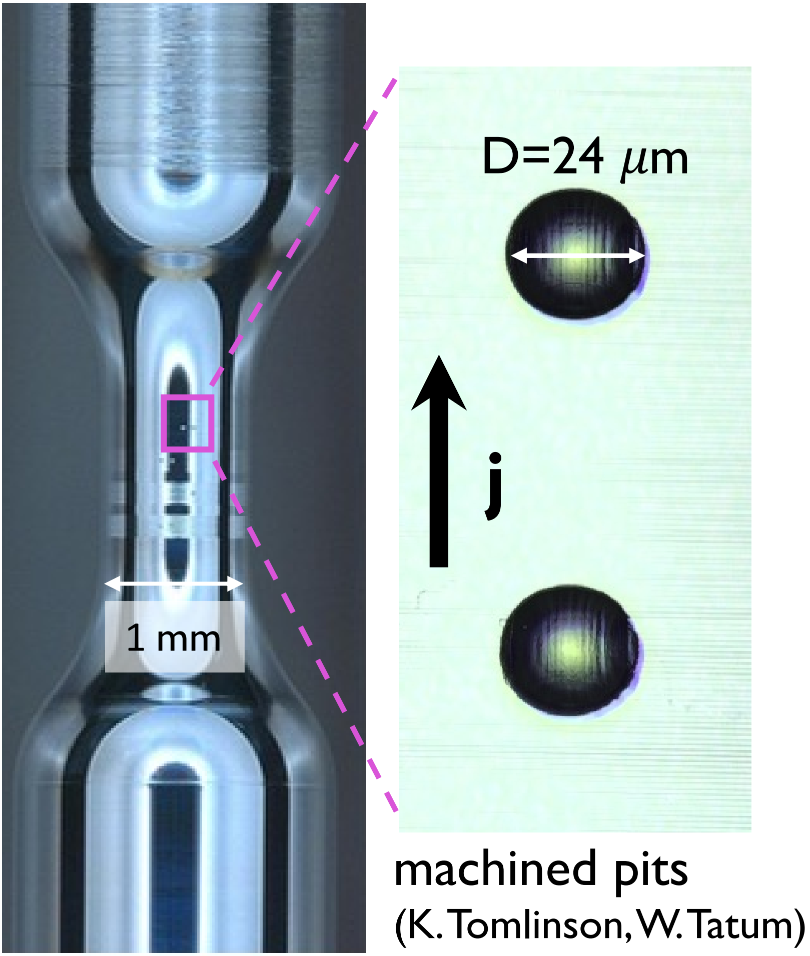
This feedback loop is studied in the electrothermal instability (ETI), which describes how small defects can grow into larger structures.

Simulations show 3D feedback loop transforms pit into larger structures: ETI striation and filament (B_z=0)



Periodic wedge simulation of aluminum rod + pit, driven by ~1 MA (Mykonos driver)

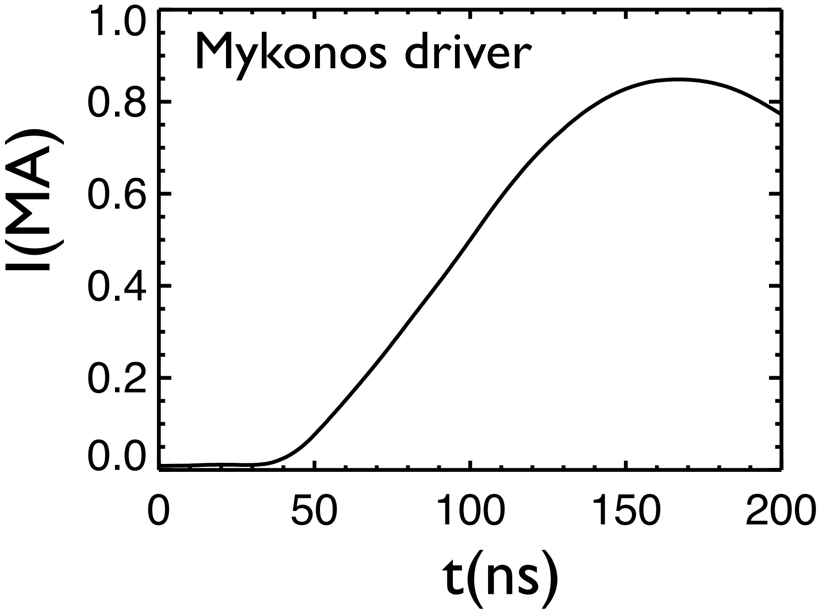
Ultrapure aluminum rods driven by ~1 MA current allow us to explore the feedback loop and test simulation predictions (B_z=0)



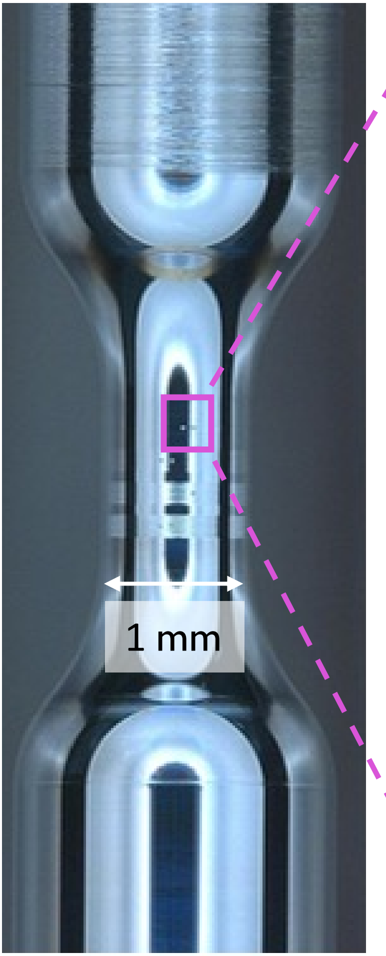
machined pits
(K. Tomlinson, W. Tatum)

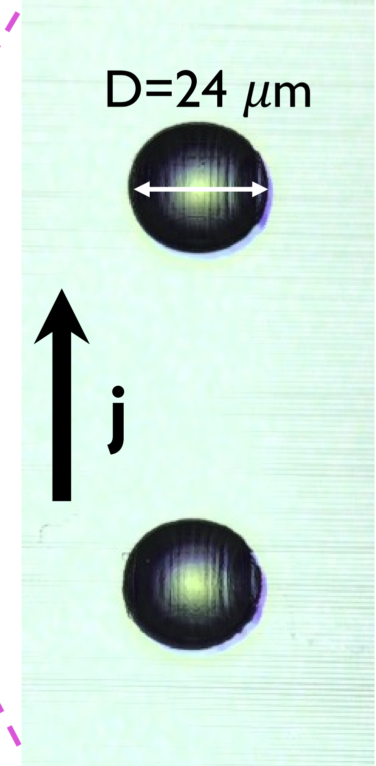
Al 5N rod (99.999% pure)

- Ultrapure metal provides a "clean" background (no native inclusions/voids)
- Machined pits play the role of voids.



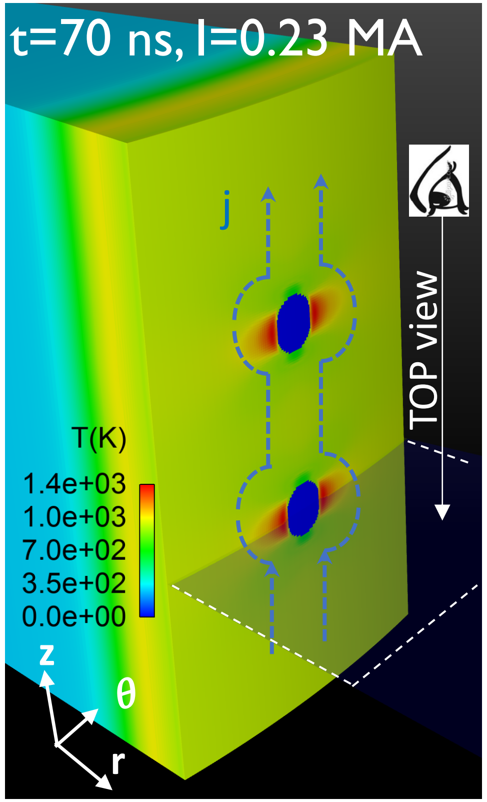
j redistribution causes overheating at the pit equator

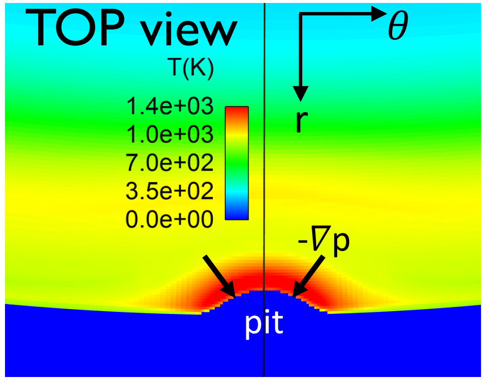




machined pits

3D MHD simulation

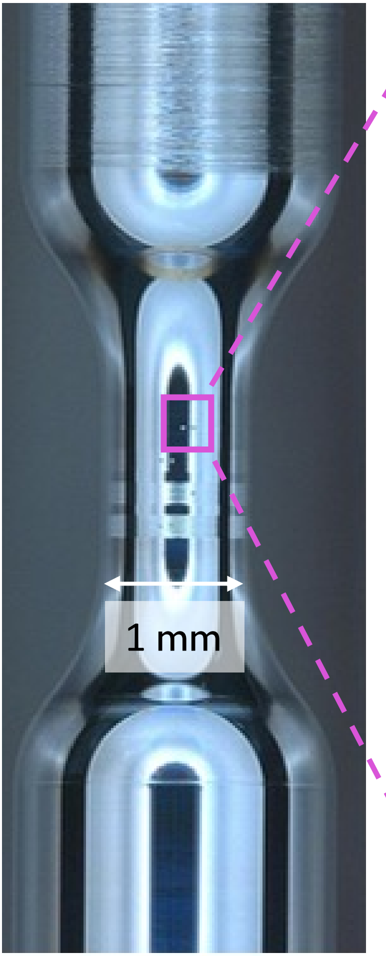


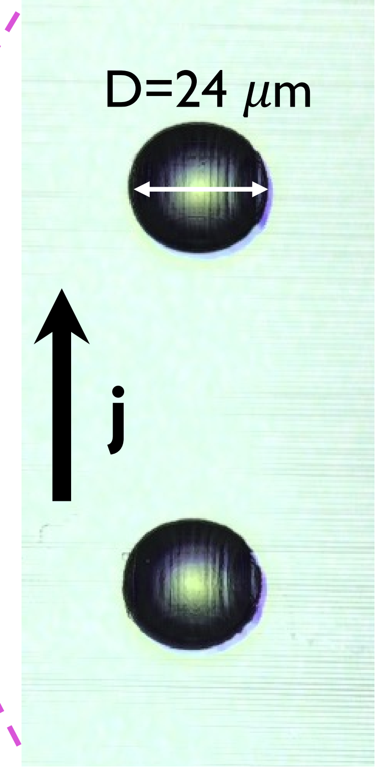


Periodic wedge simulation

Expansion azimuthally <u>focuses</u>, due to shaped charge effect

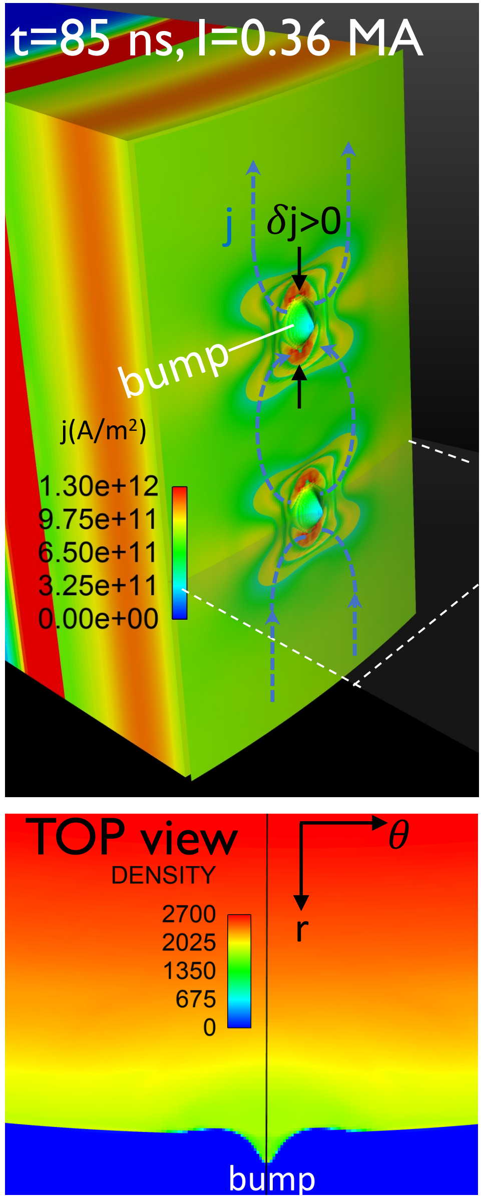
Pit expands and transforms into a bump





machined pits

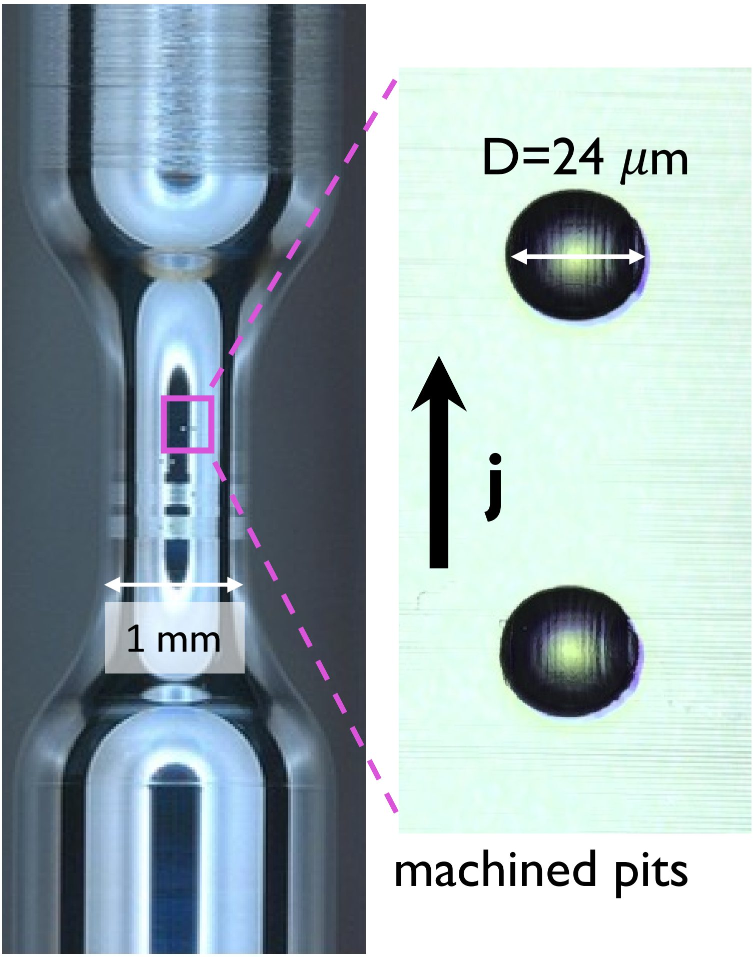
3D MHD simulation



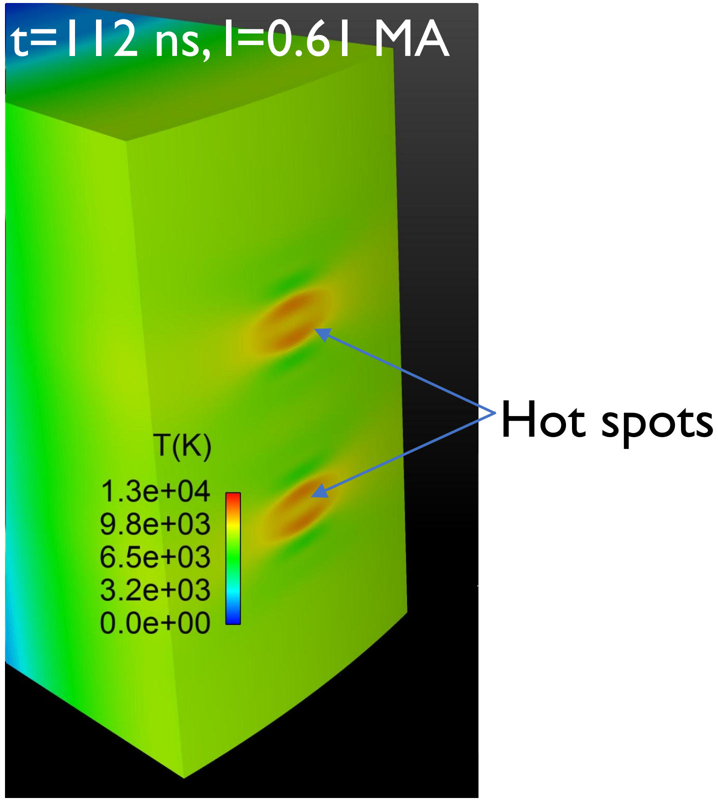
j changes qualitatively from flow around pit to flow over a bump.

j focuses at the top and bottom of the bump, creating hot spots there.

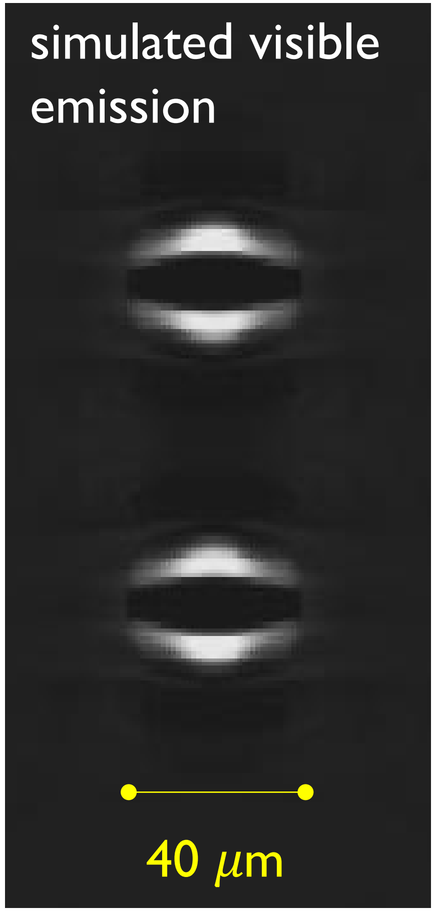
Simulations predict distinctive, testable patterns



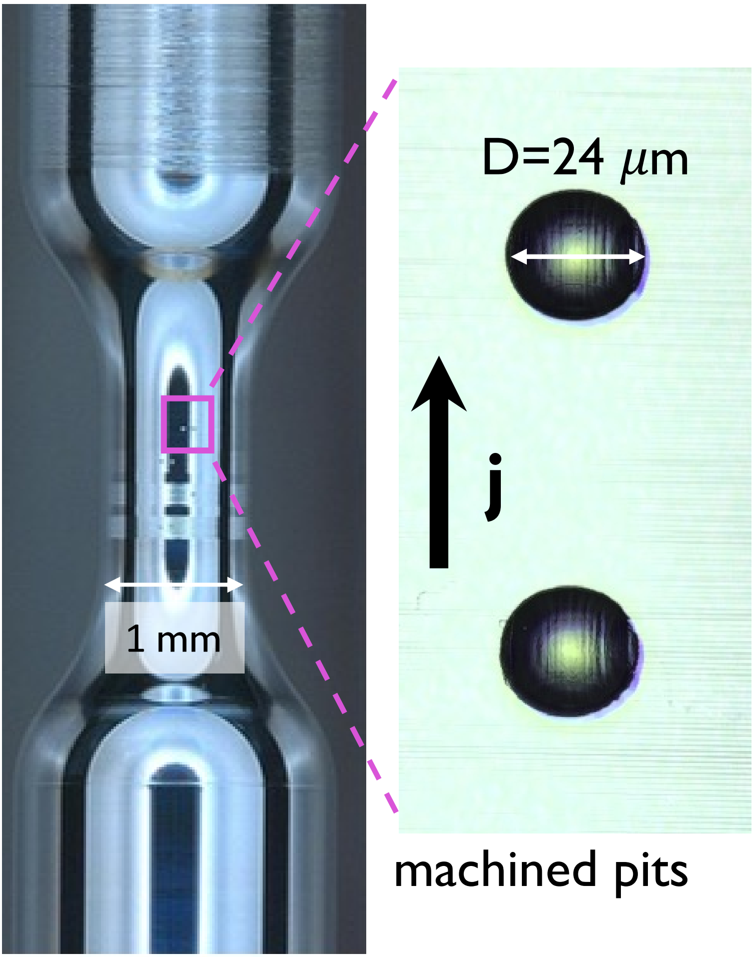
3D MHD simulation

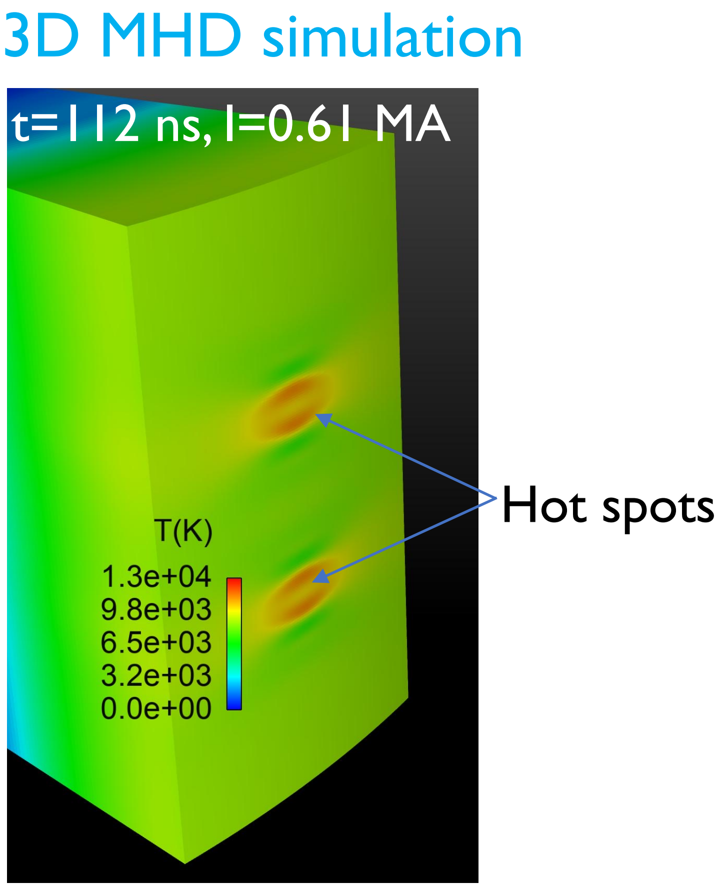


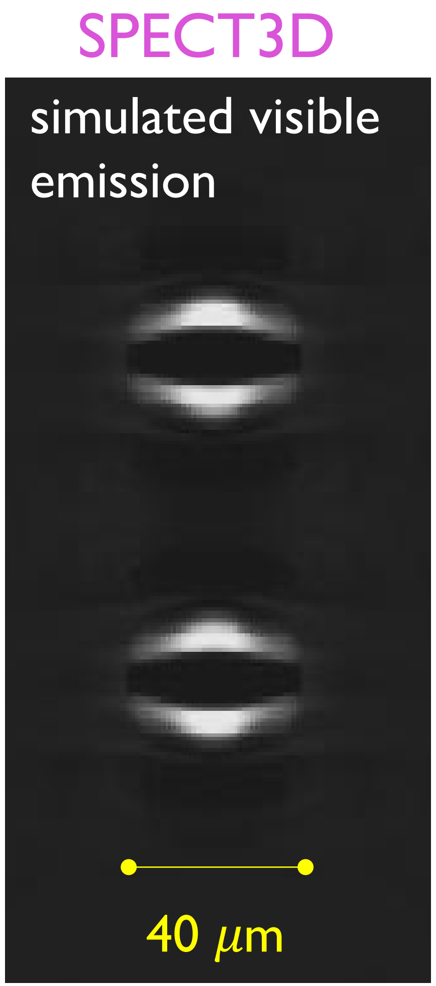
SPECT3D

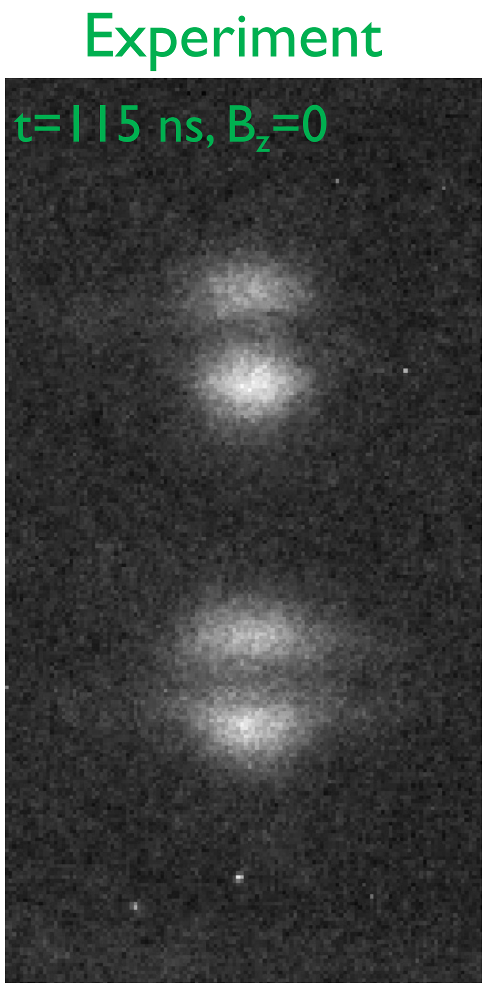


Experimental validation provides confidence in simulation



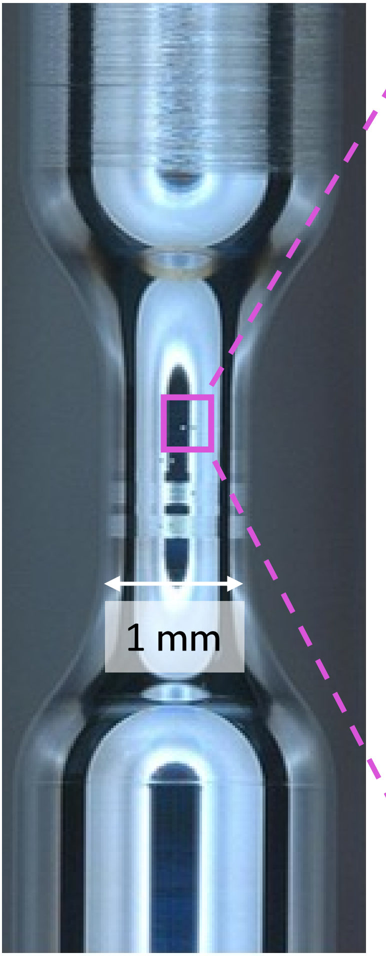


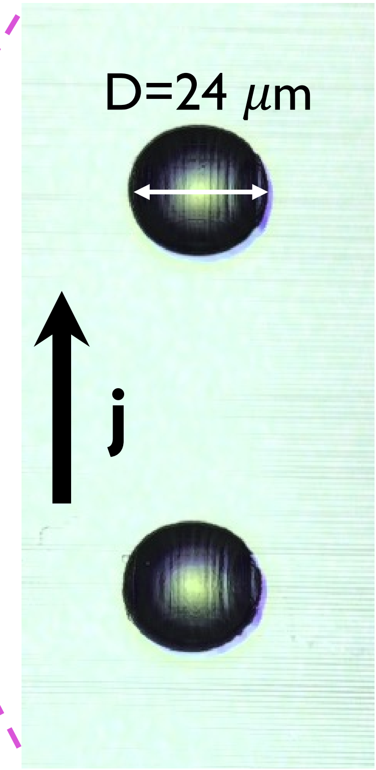




T.J. Awe, E. P. Yu, M.W. Hatch, T. M. Hutchinson, K. Tomlinson, W.D. Tatum, K.C. Yates, B.T. Hutsel, and B.S. Bauer, Phys. Plasmas **28**, 072104 (2021)

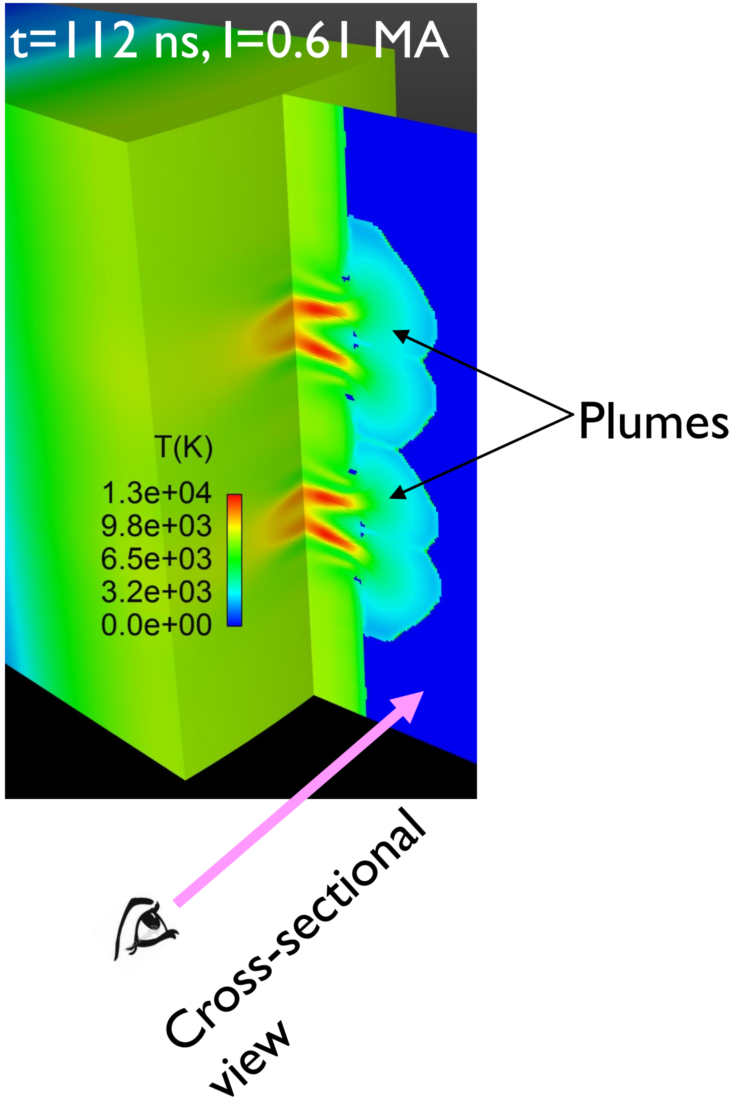
Hot spots explode, creating plumes and craters



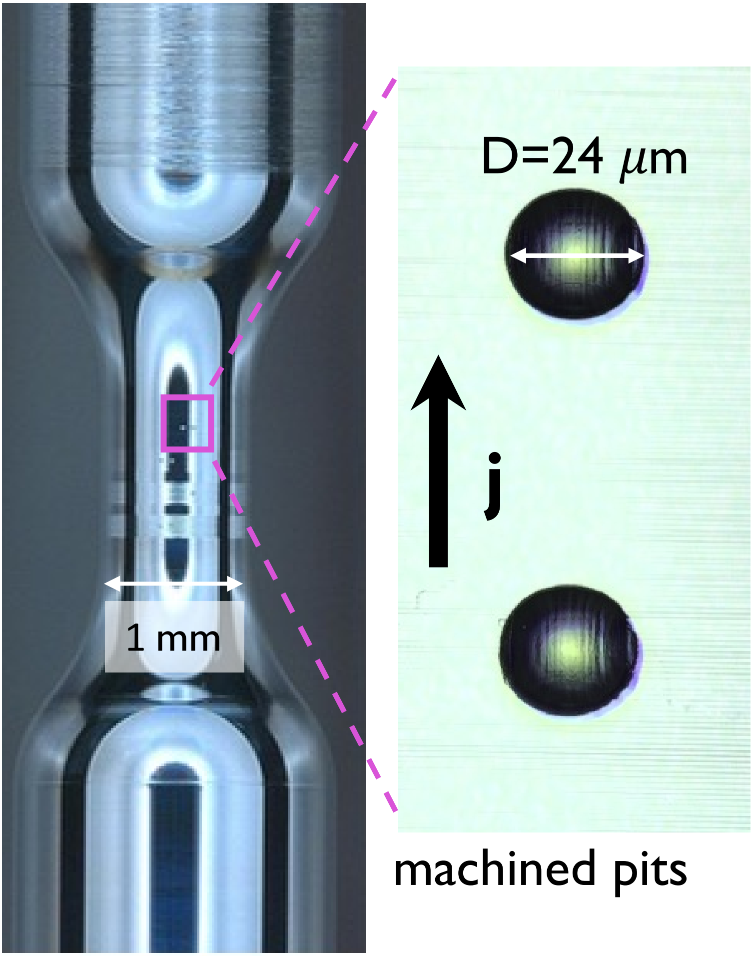


machined pits

3D MHD simulation

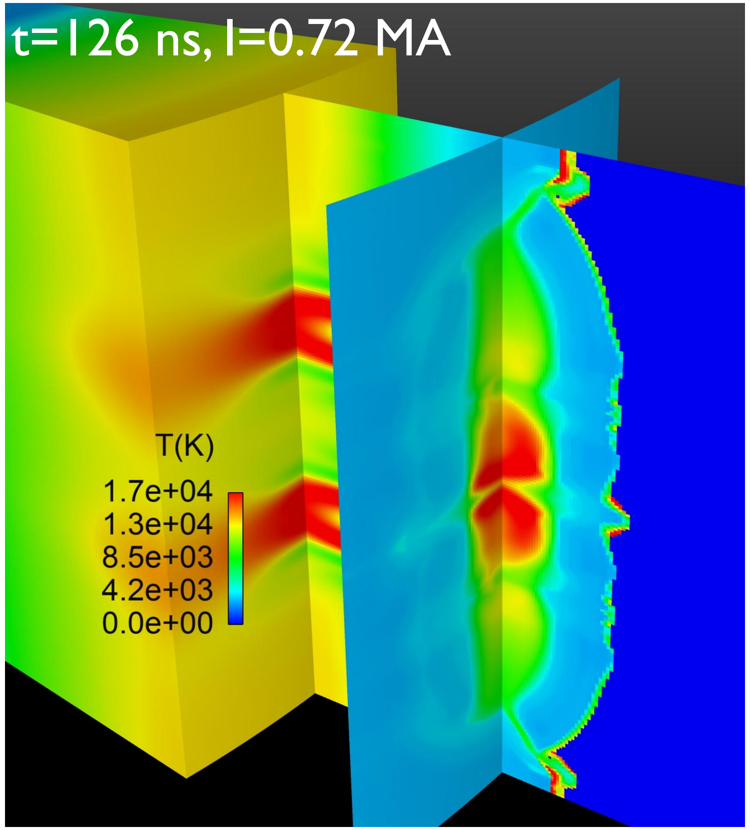


Pits seed the ETI filament

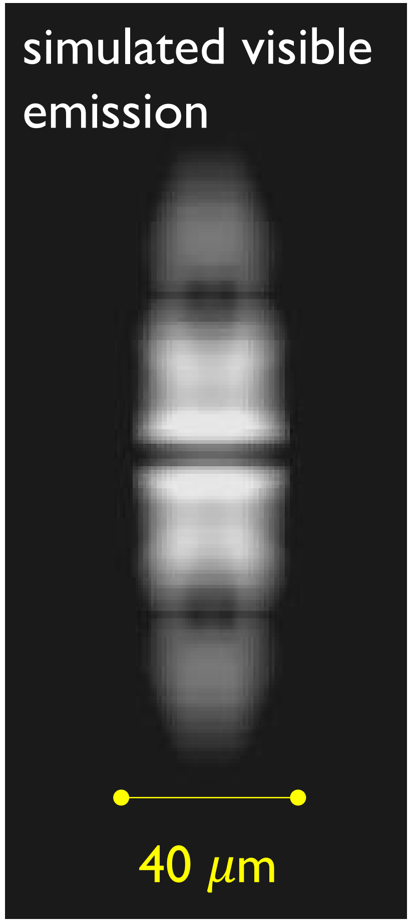


machined pits

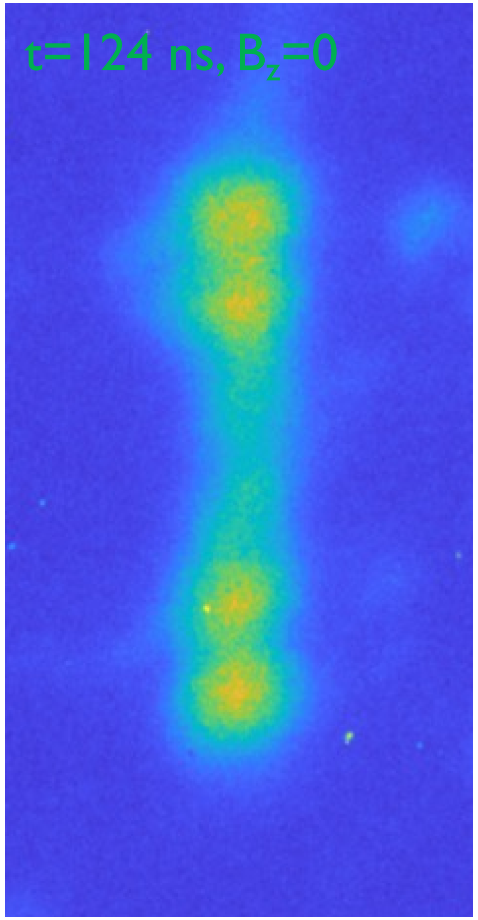
3D MHD simulation



SPECT3D

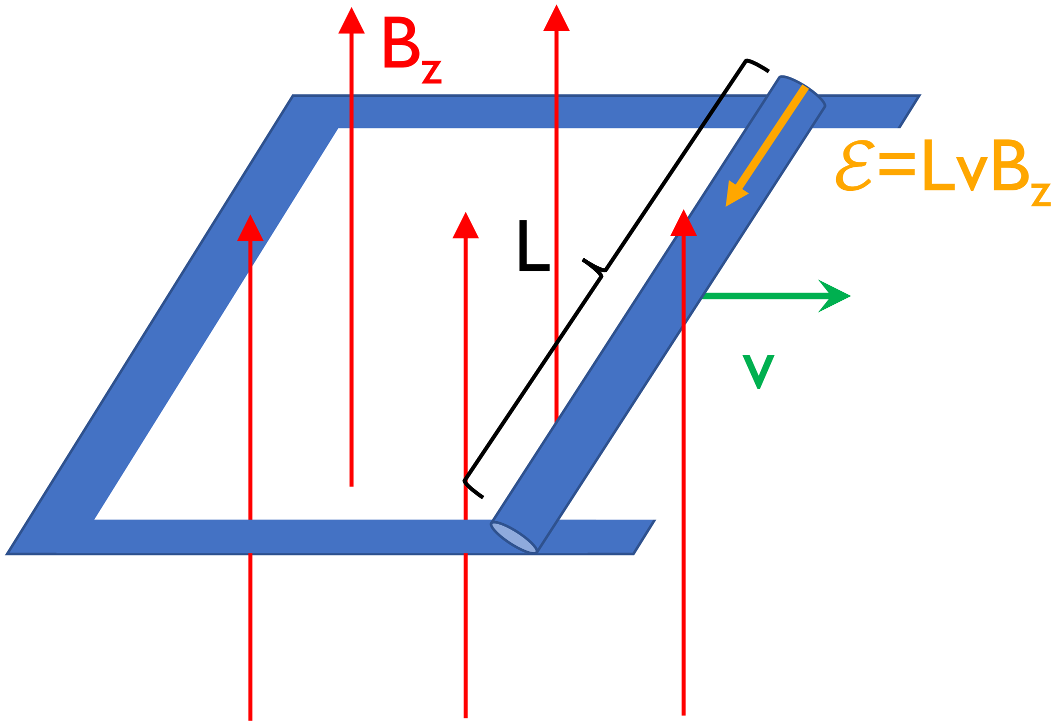


Experiment



Q: how does this picture change when $B_z>0$?

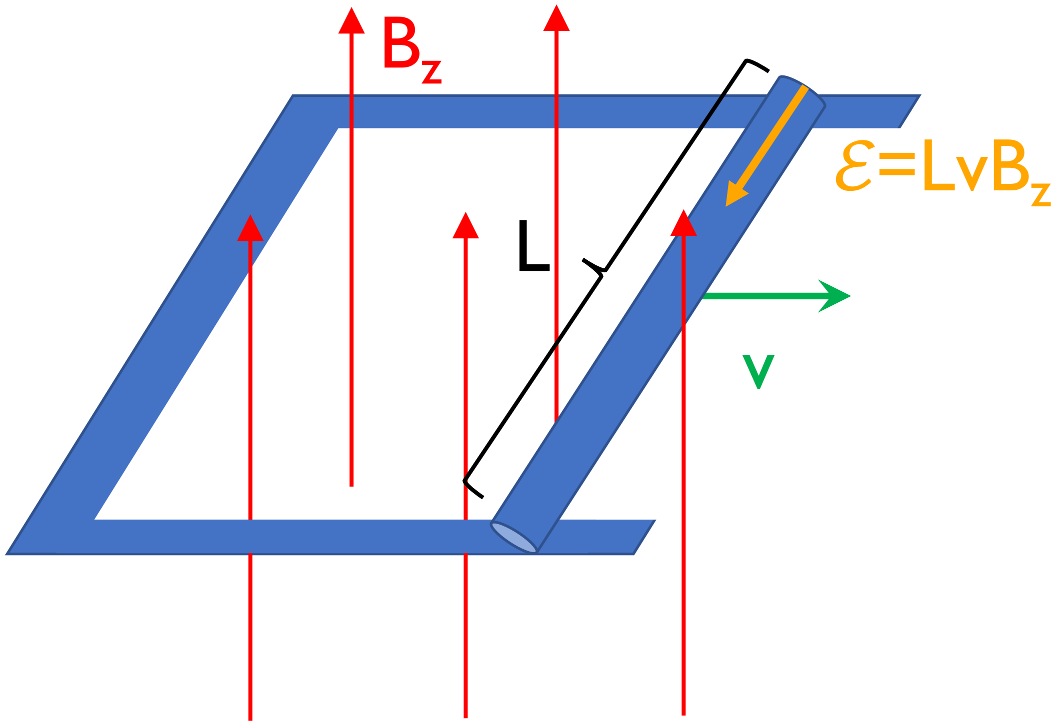
Motional EMF term in Ohm's law drives helical asymmetry in ETI



MHD: $j=\sigma(E + v\times B)$

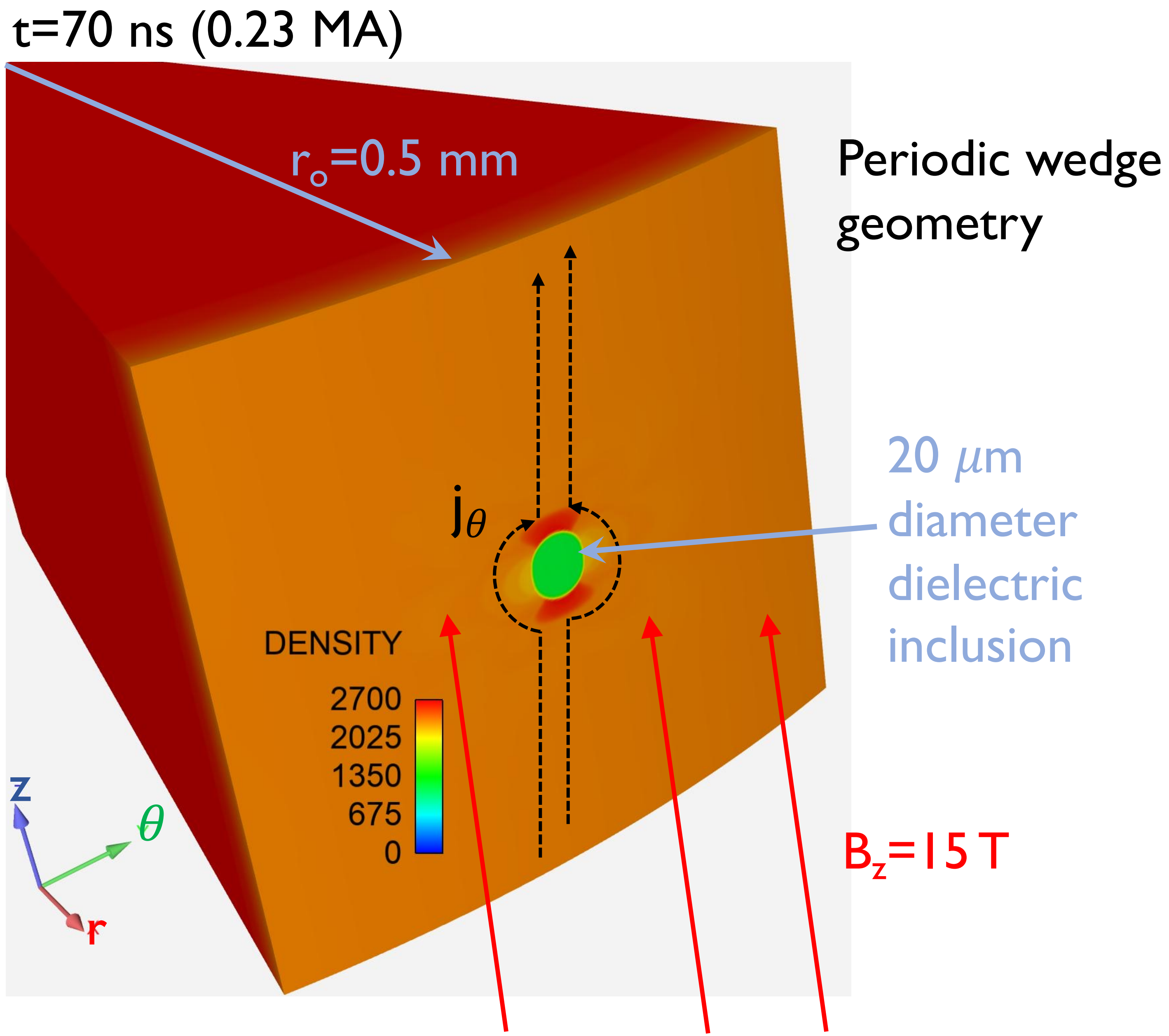
Motional EMF

3D simulation of aluminum rod with resistive inclusion, B_z=15 T

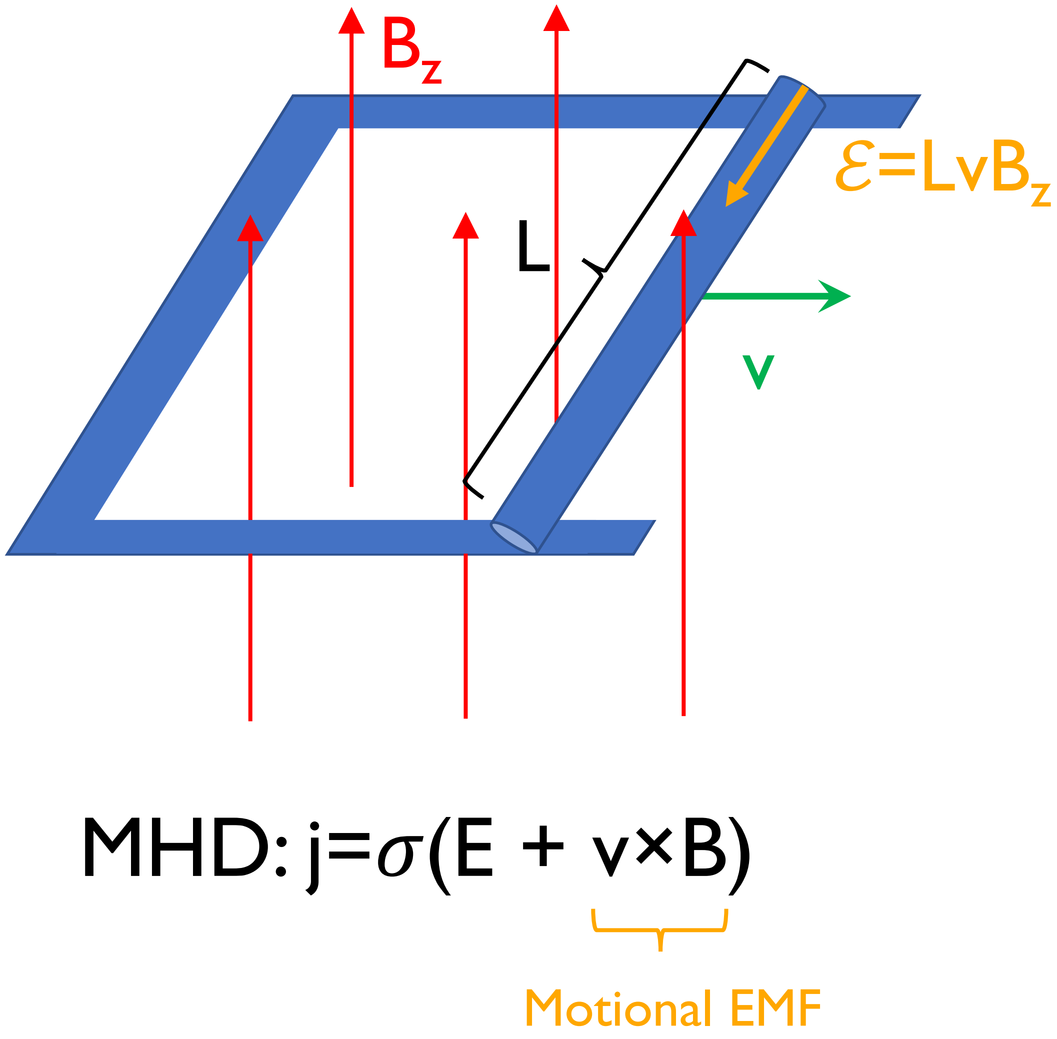


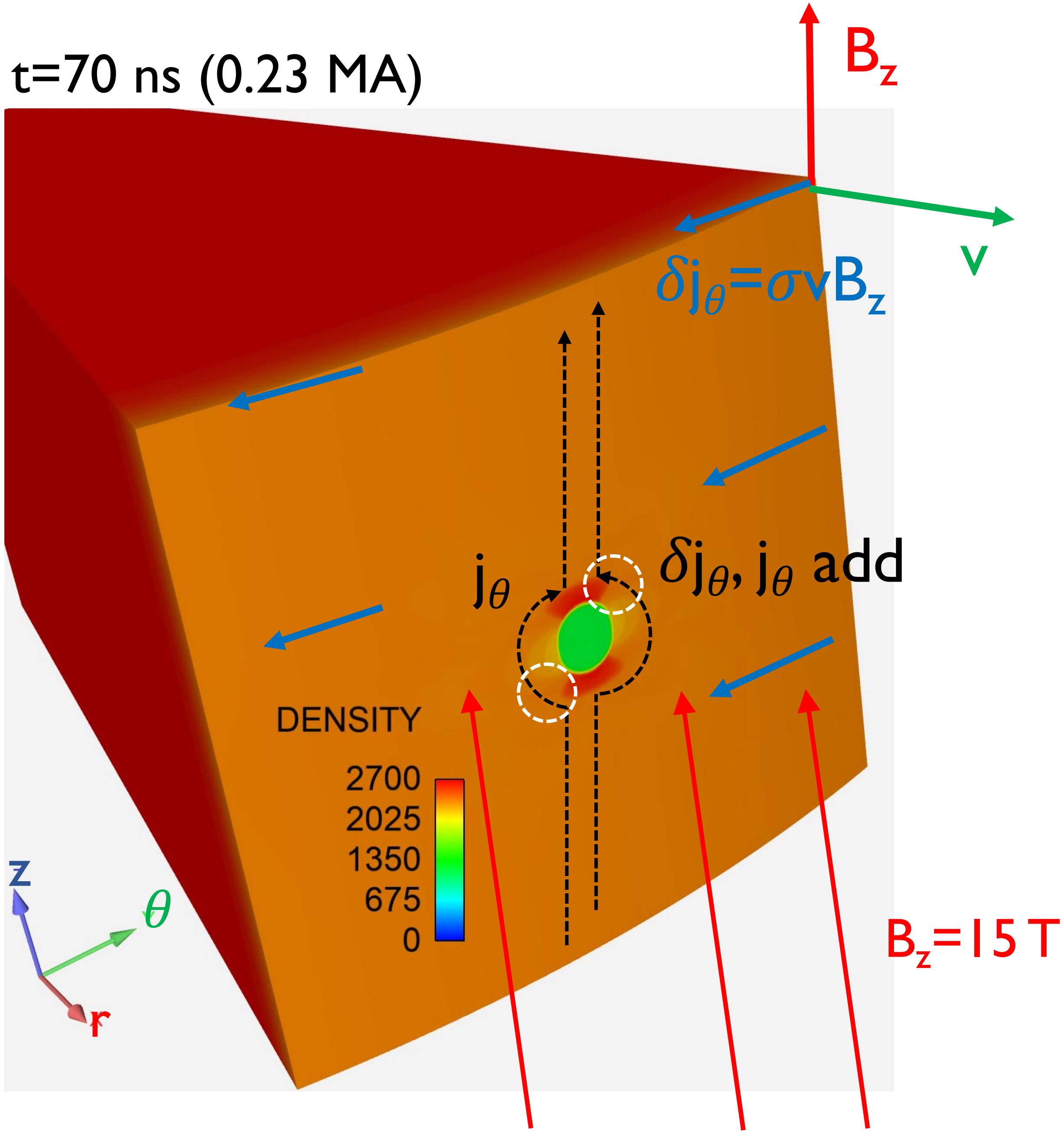
MHD: $j=\sigma(E + v \times B)$

Motional EMF



Induced δj introduces asymmetry at NE/SW corners

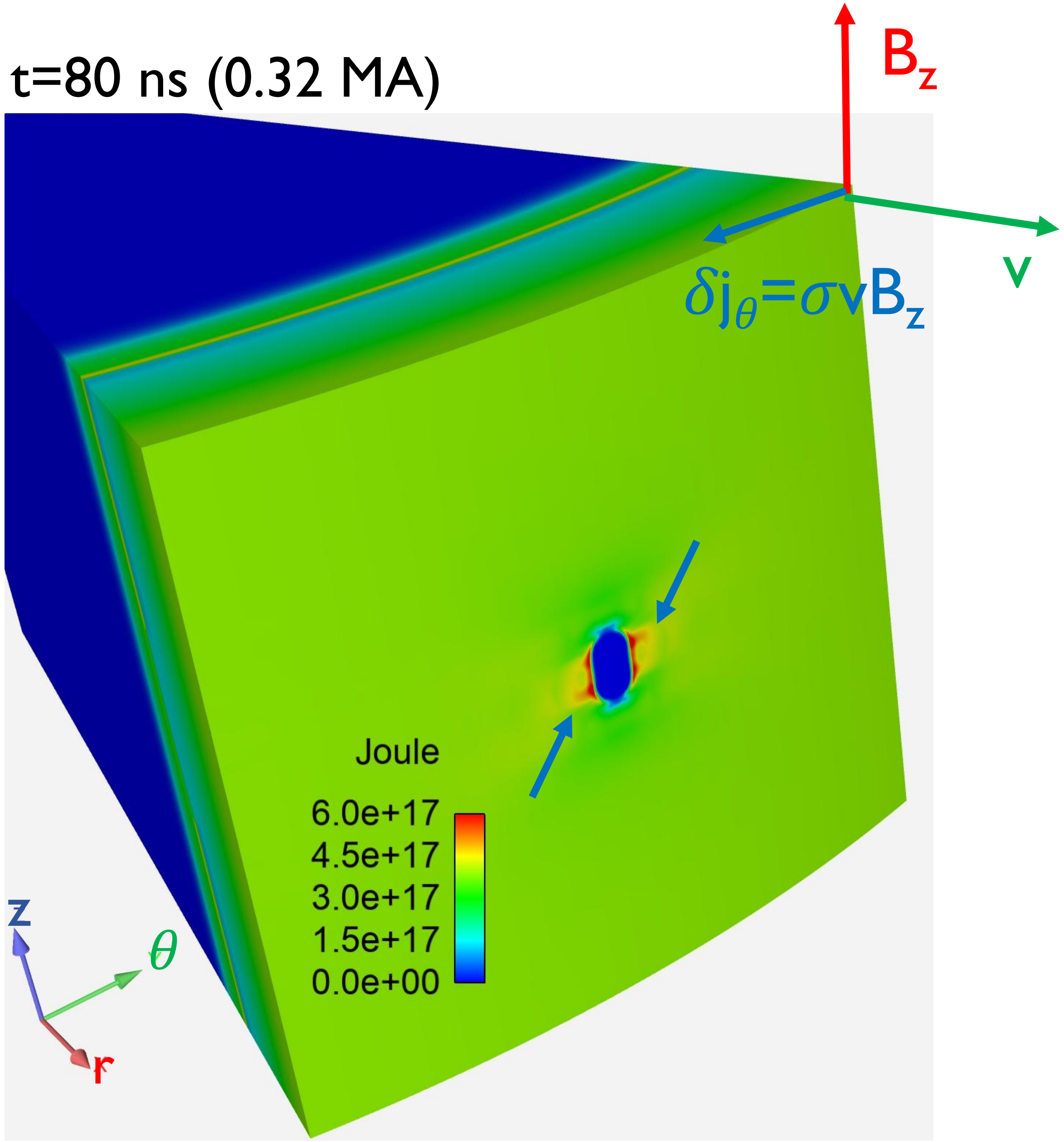




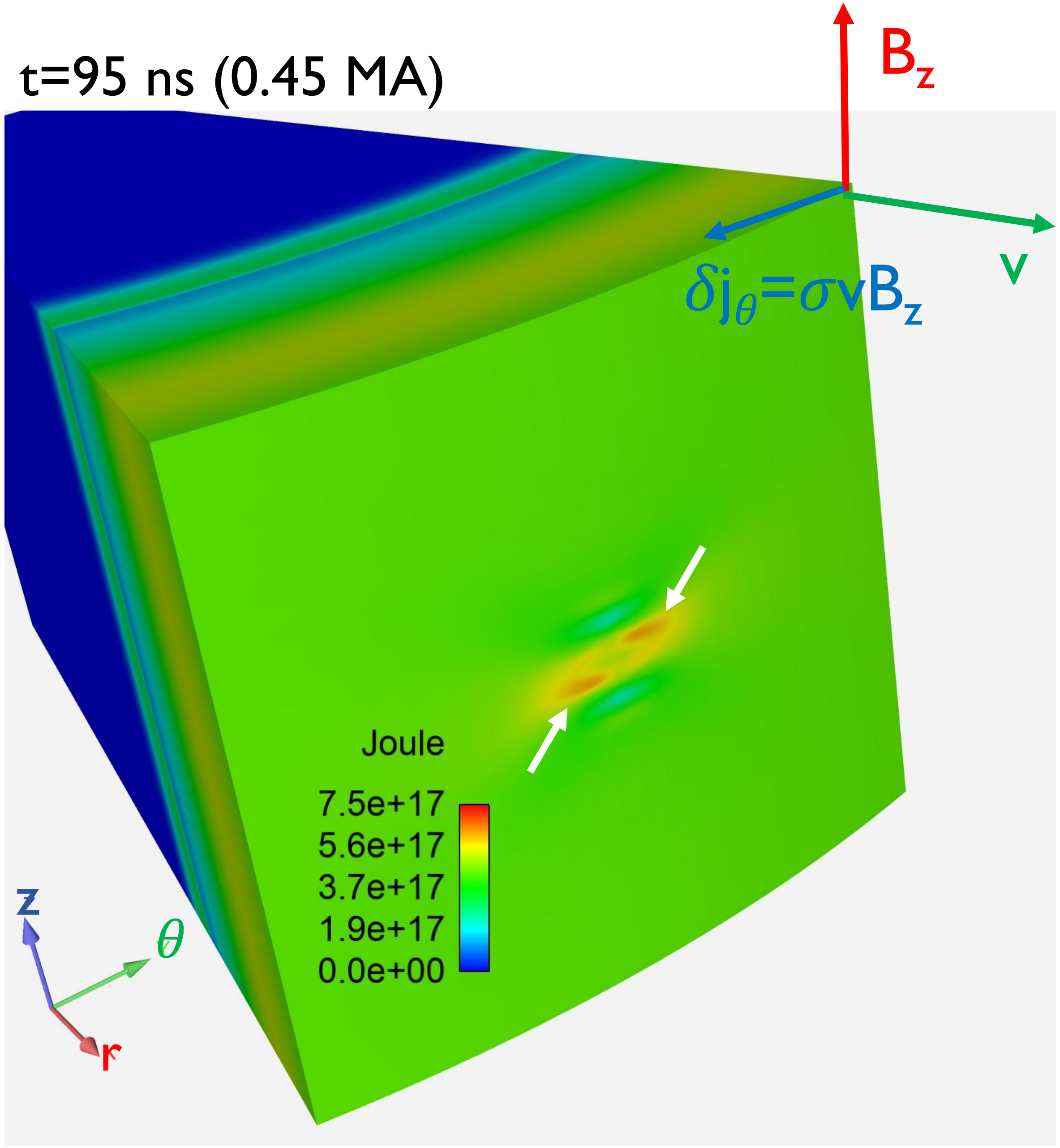
Induced δj introduces asymmetry at NE/SW corners

$\delta j_\theta / j_\theta$ is small (~10%) but results in asymmetry

t=80 ns (0.32 MA)



Asymmetry at NE/SW corners amplifies with time



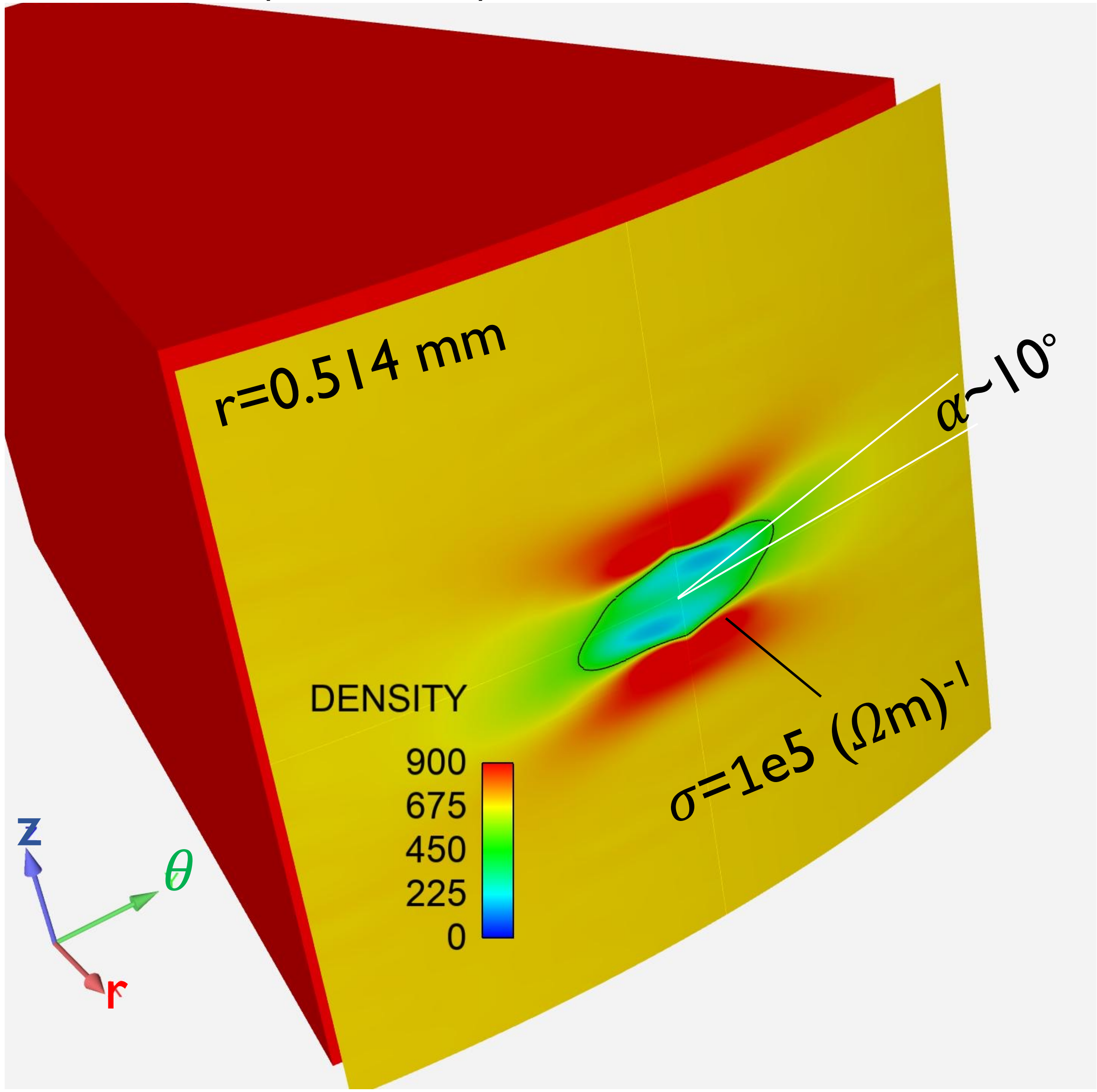
Angle of helical perturbation does not agree with k·B=0 condition

Asymmetric Joule heating results in asymmetric density perturbation with α~10°.

This angle is determined by the interaction between δj_θ and j_θ, rather than the condition **k**·**B**=0.

k·**B**=0 predicts a pitch angle arctan(B_z/B_θ)=3.5°

t=115 ns (0.63 MA)

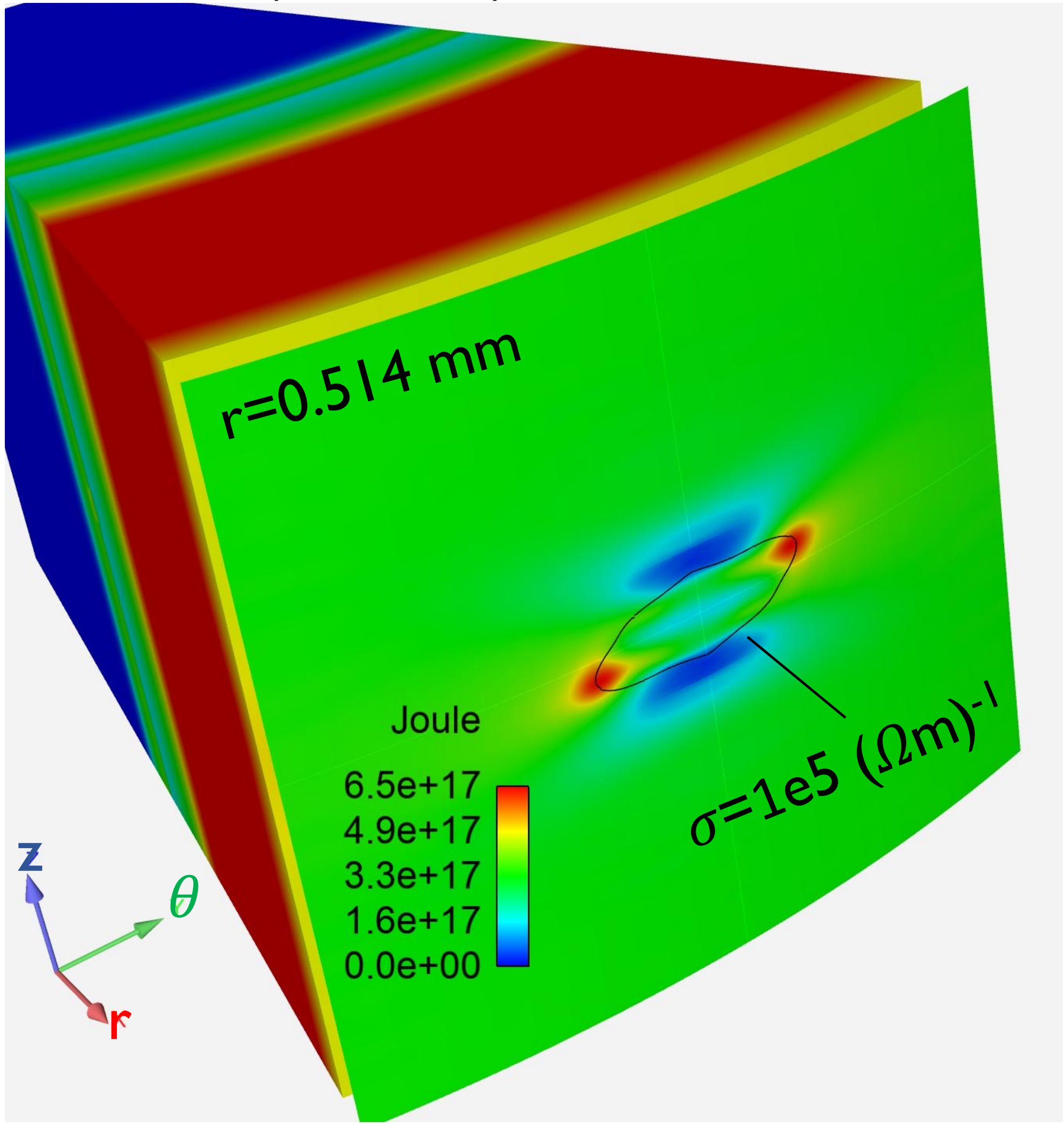


Asymmetric Joule heating will grow density perturbation helically

This mechanism provides a means for helically-oriented striations to form.

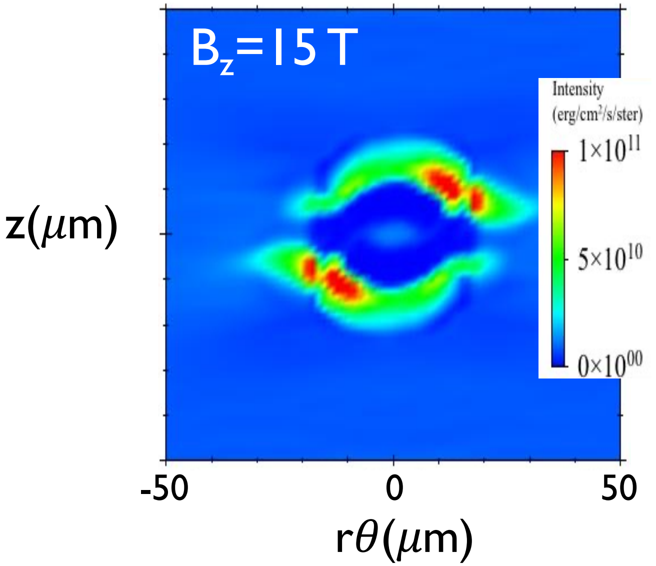
However, physics in an aluminum rod driven by 1 MA will be different from beryllium liner driven by 20 MA.

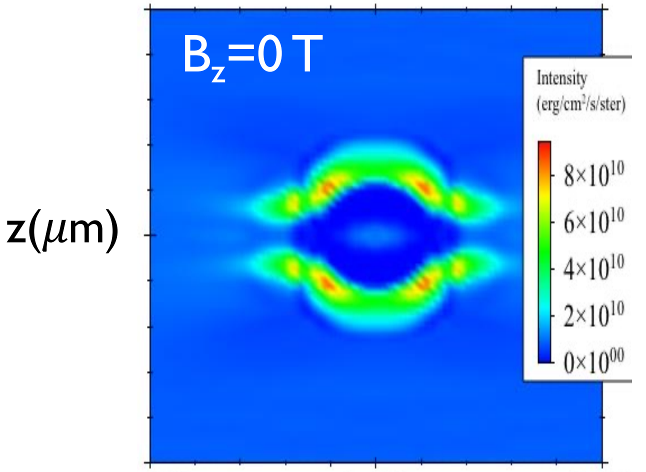
t=115 ns (0.63 MA)



Asymmetric heating due to B_z should be experimentally verifiable

simulated visible emission (SPECT3D)





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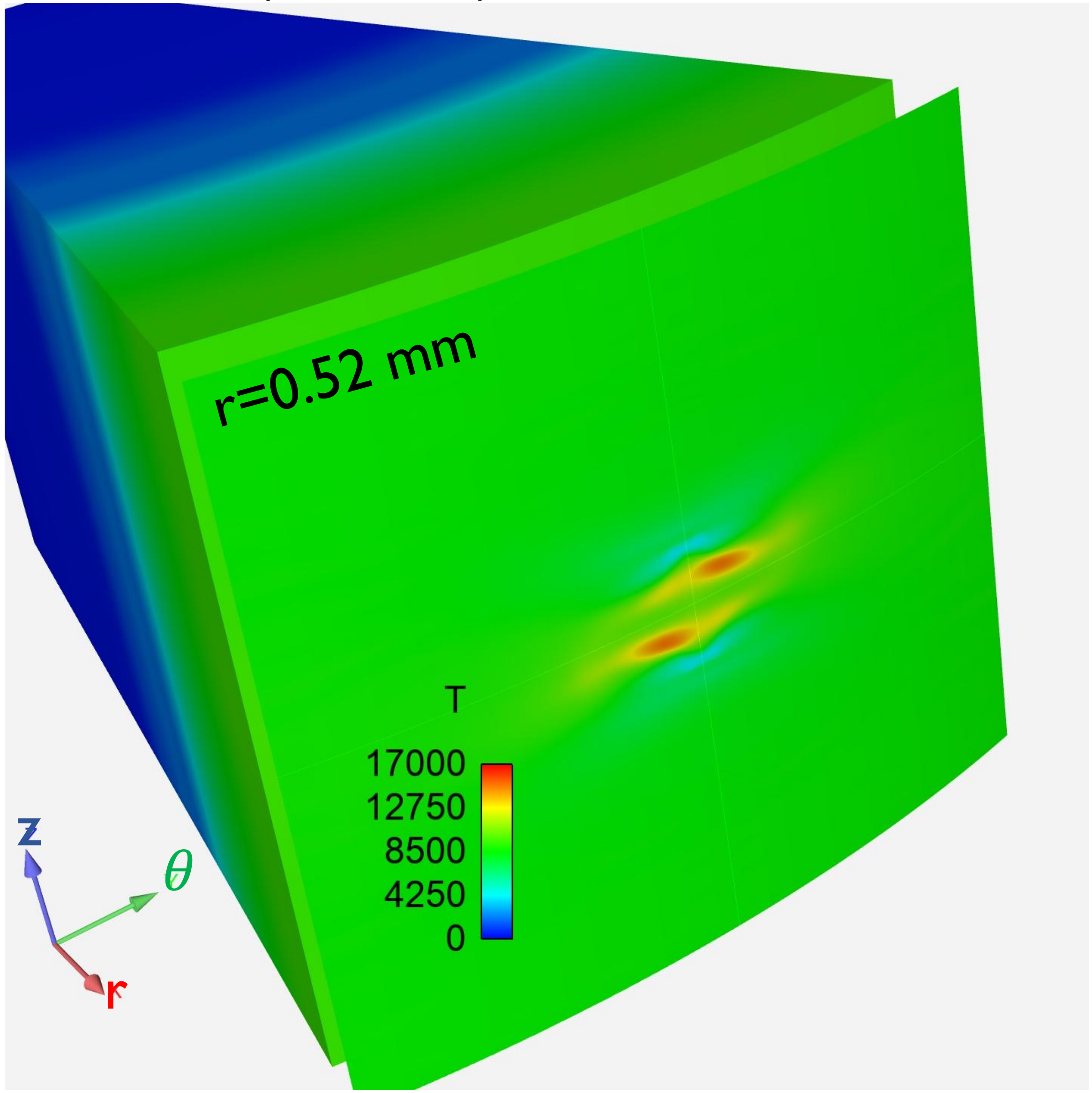
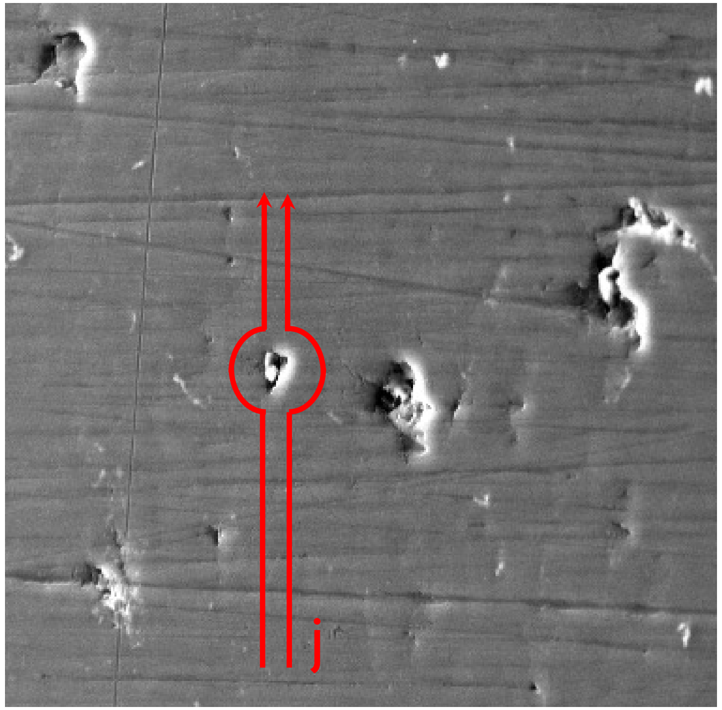


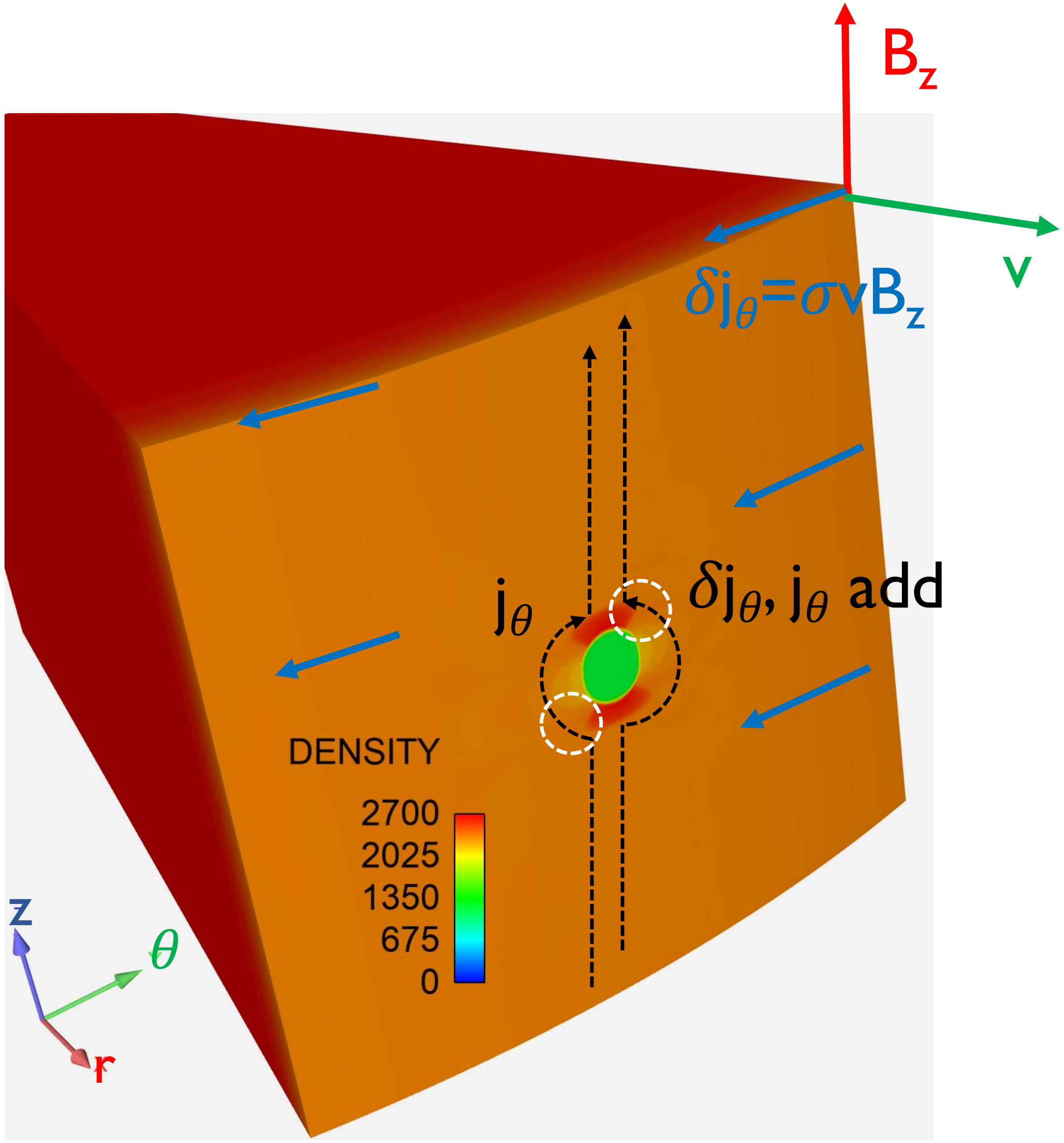
Summary

- Metals are full of defects which seed a feedback loop connecting **j** and σ (ETI)



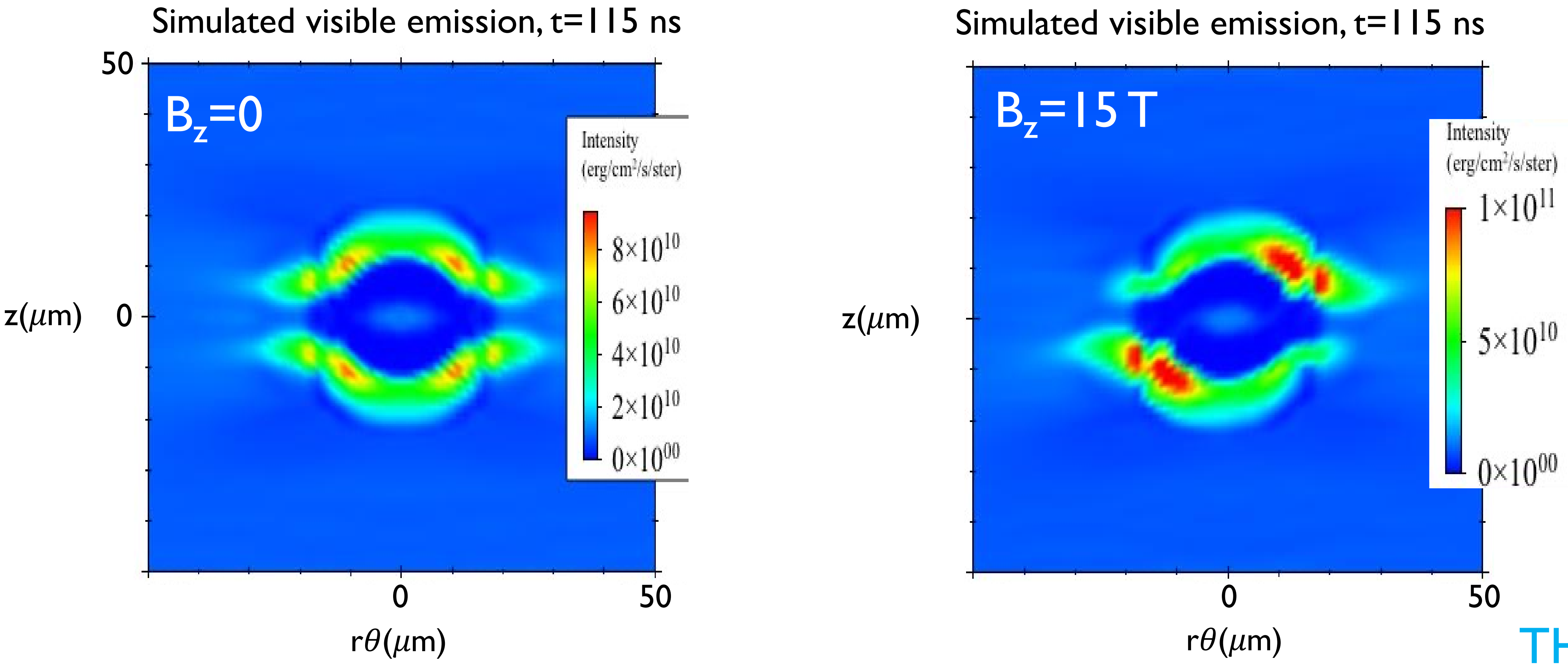
Summary

- B_z creates small perturbations in **j** around the defect, driven by $\delta j=\sigma(v\times B)$, which will amplify due to ETI



Summary

- Simulations predict B_z creates an asymmetric emission pattern. We plan to experimentally verify this prediction on the Mykonos driver.



THANKS!

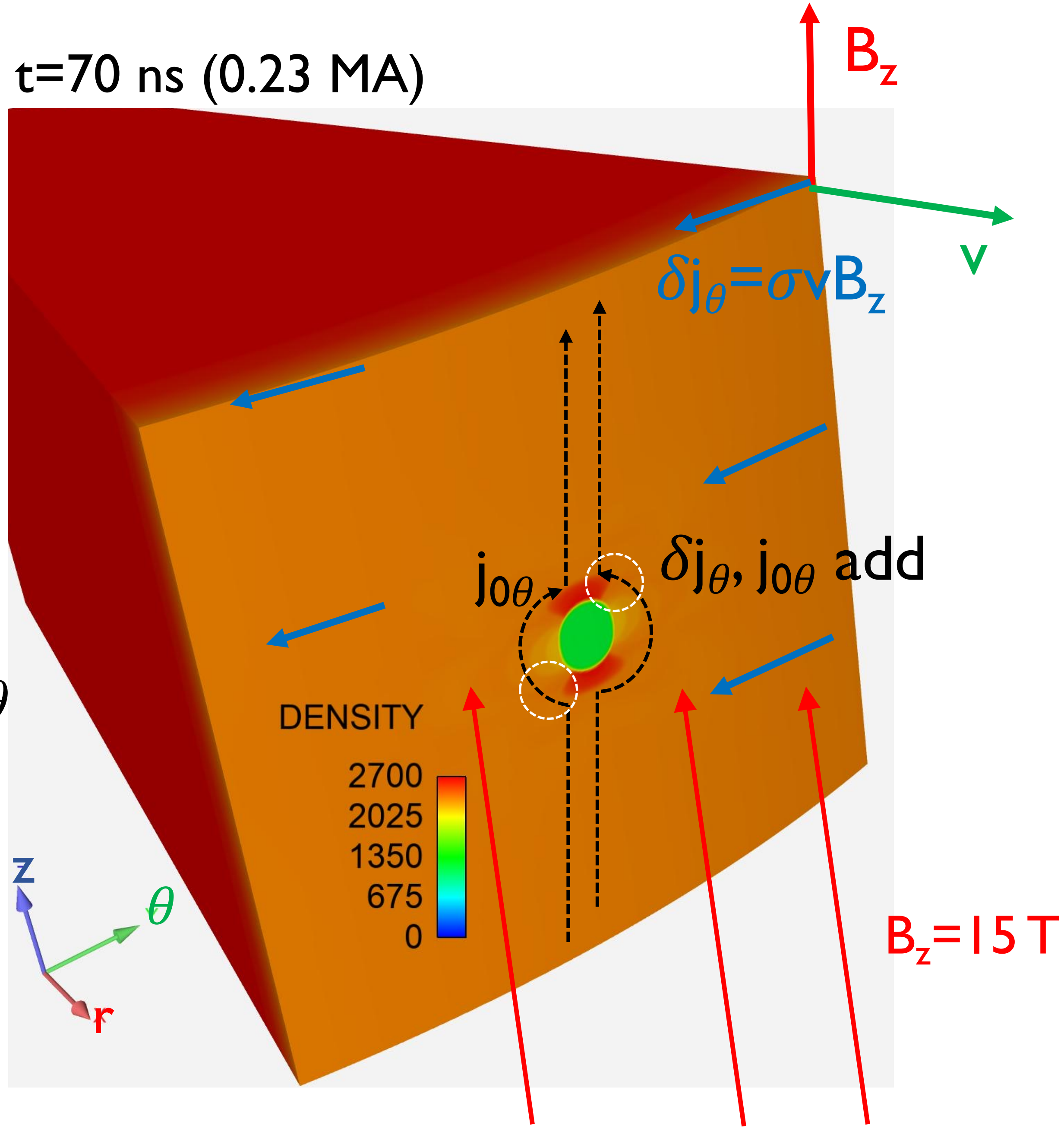
Backup: δj introduces asymmetry at NE/SW corners

$$\mathbf{j} = \underbrace{\mathbf{j}_0}_{\text{j when } B_z=0} + \delta\mathbf{j}$$

$$j^2 = j_0^2 + 2\mathbf{j}_0 \cdot \delta\mathbf{j} + \delta j^2$$

$$j^2 - j_0^2 \simeq 2\mathbf{j}_0 \cdot \delta\mathbf{j} = 2 j_{0\theta} \delta j_\theta$$

Maximum perturbation in j^2 is where $j_{0\theta}$ is largest i.e., NE/SW corners.



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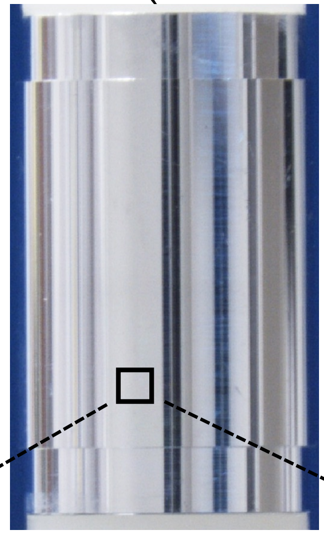

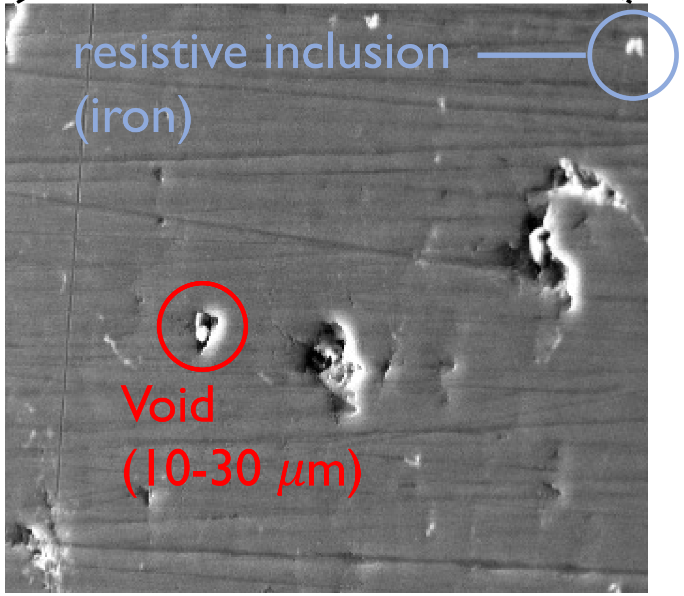

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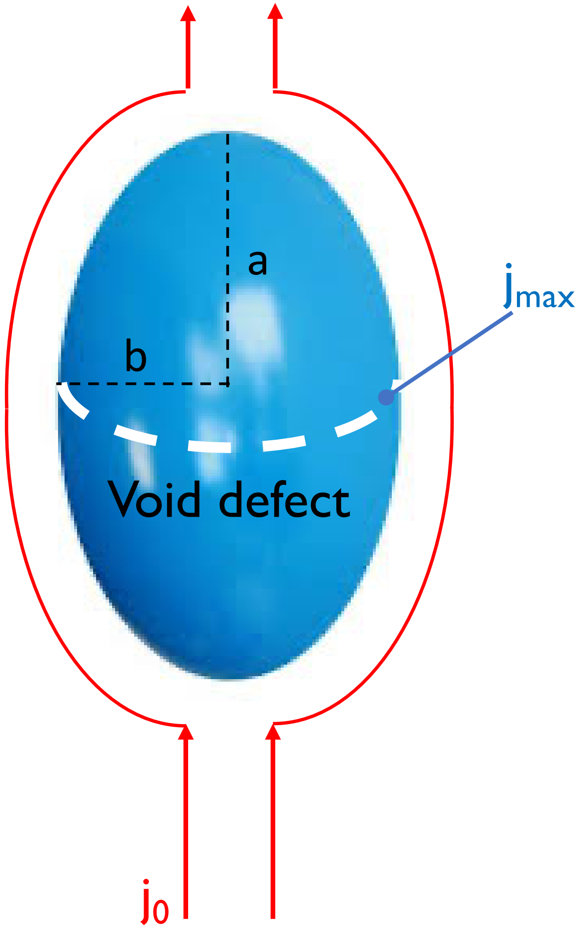

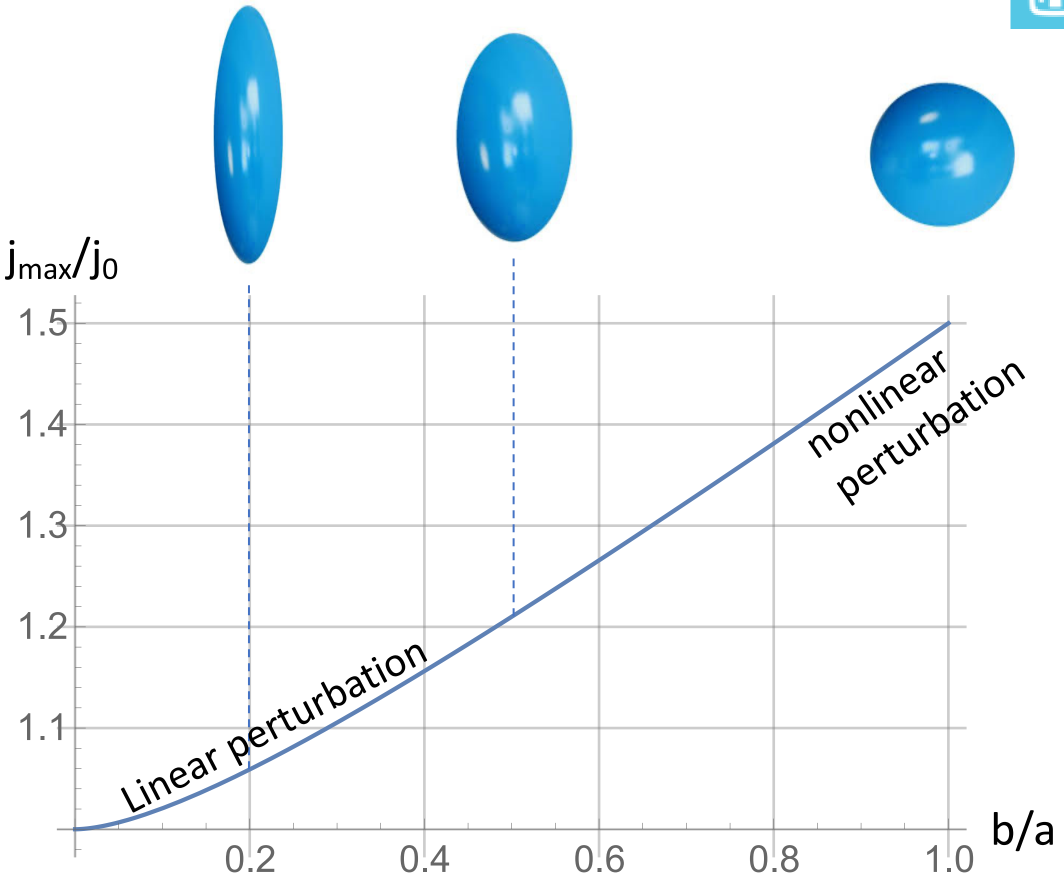

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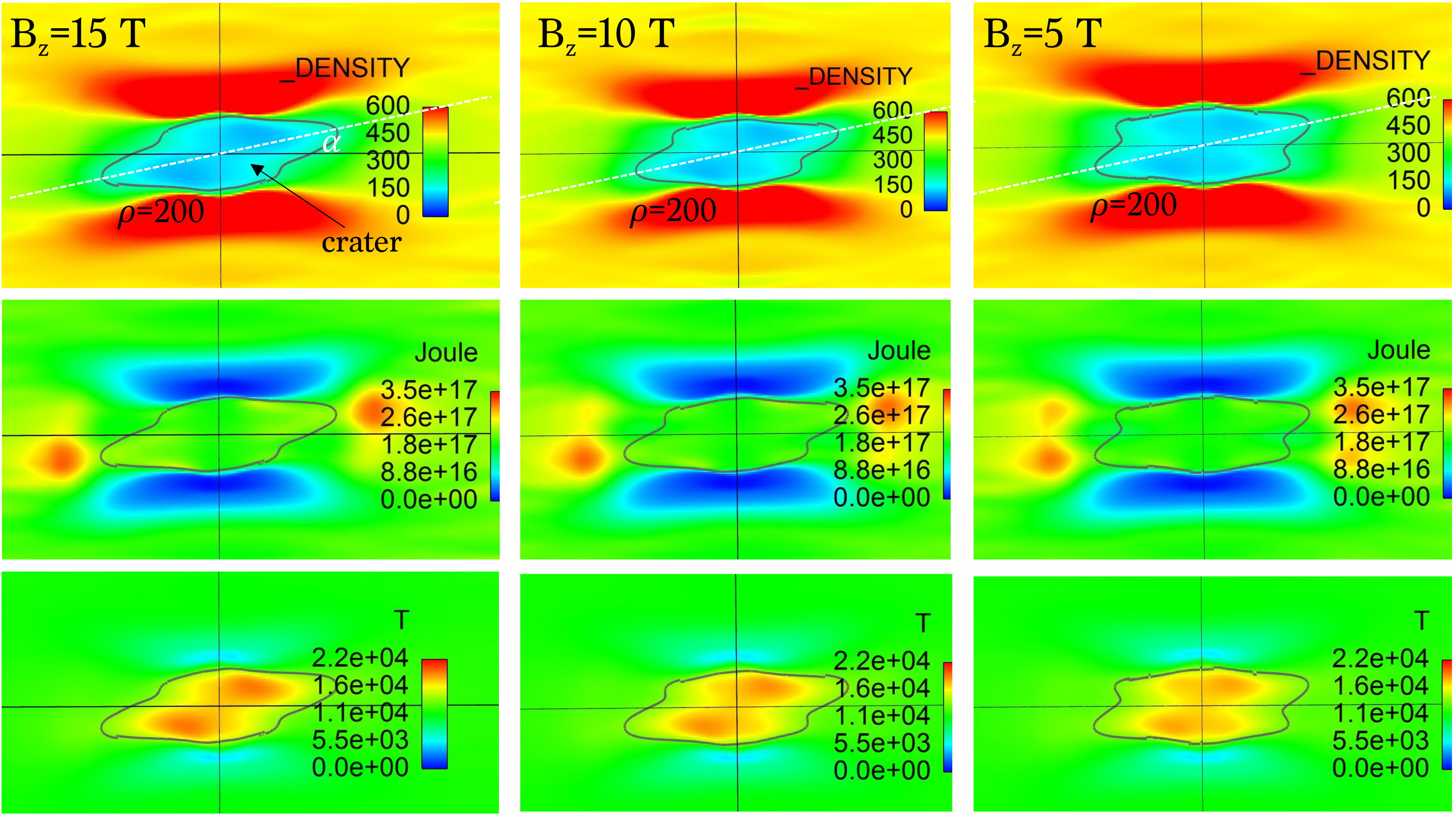
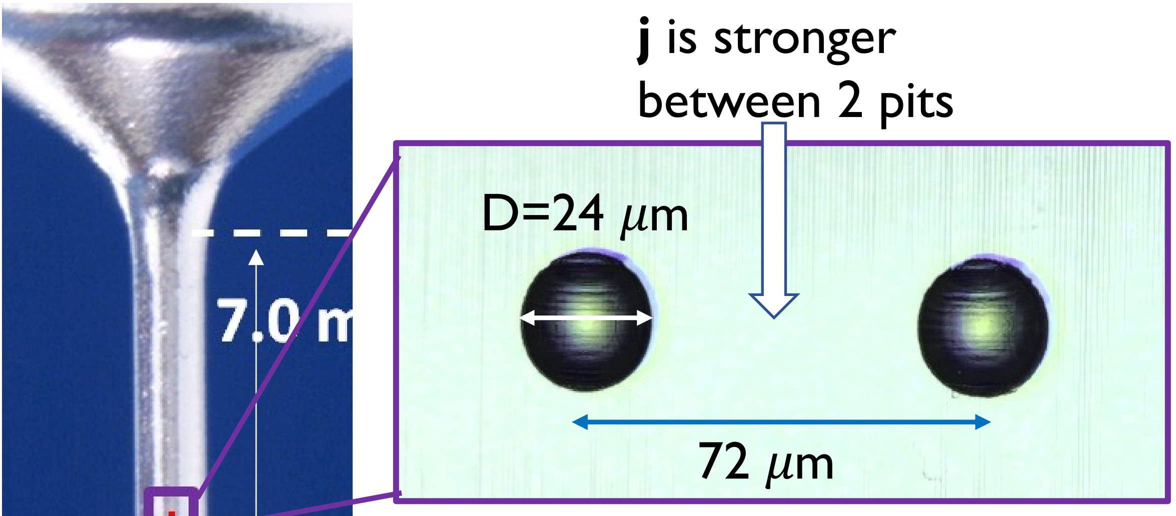
Hydrodynamic analogy with electrical current flow
E.P. Yu, T.J. Awe, K.R. Cochrane et al., Phys. Plasmas **27**, 052703 (2020)

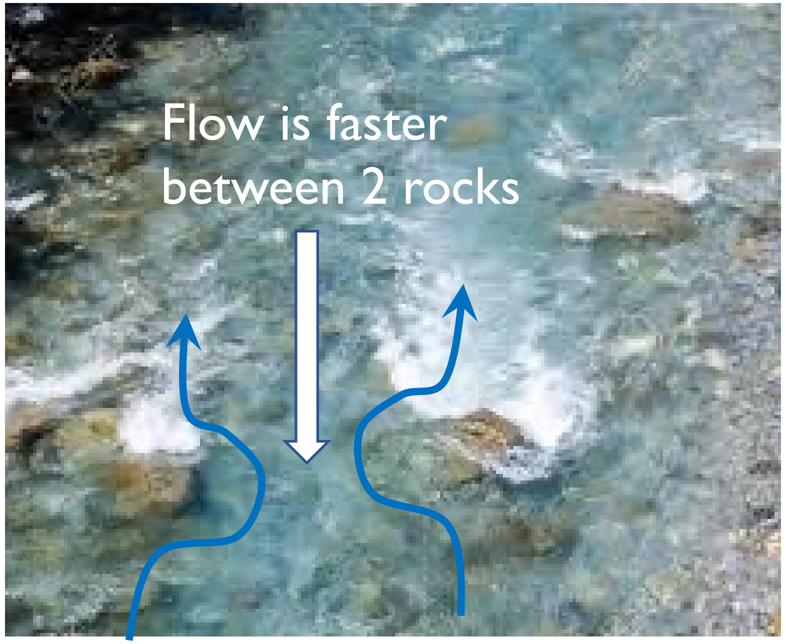
Backup: B_z scan at t=125 ns, R=5.26e-4

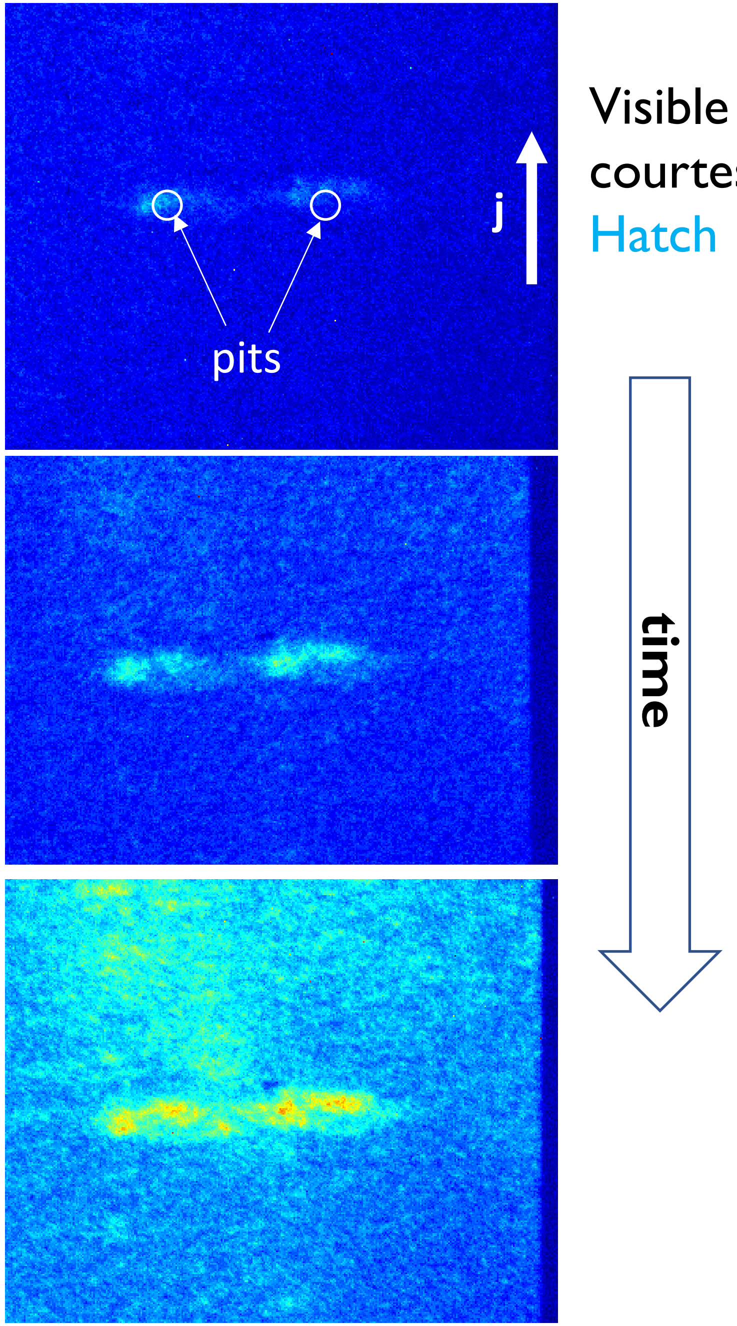


Backup: horizontal pits on coated, ultrapure Al rods show azimuthal correlation



j is stronger between 2 pits





Visible emission, courtesy of Maren Hatch