Van der Waals loops or Maxwell constructs?

Assessing EOS applicability using PDV of electrically thick metal driven by high lineal current density

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The evolution of a conductor driven by intense current is of broad interest

Fundamental radiation-MHD (and beyond):

Challenging interplay of magnetic diffusion, hydrodynamics, and radiative energy transfer

- **Liner compression**
- **Magneto-inertial fusion**
- **Magnetically accelerated flier plates**
- **Ultrahigh magnetic field generators**
- **Magnetically insulated transmission lines**
- **Wire-array z-pinches**
- **High-current fuses**
- **Astrophysics**

Simulations and underlying models need experimental validation

Magnetohydrodynamic (MHD) modeling requires accurate material properties models

- **Equation of state, electrical conductivity, thermal conductivity,…**

Material properties models depend on approximations

- **Atomic potentials, tunable parameters,…**

Experiments are important for calibrating & validating material properties models and MHD simulations

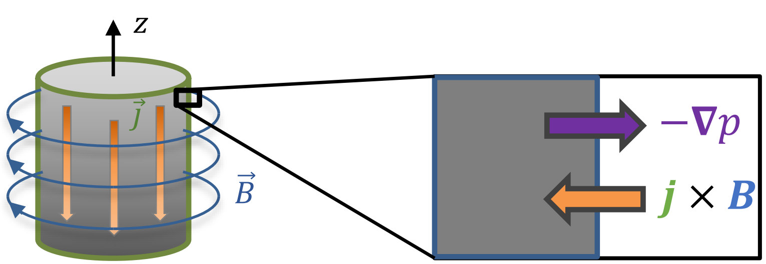
SESAME EOS tables for Al vary considerably below solid density

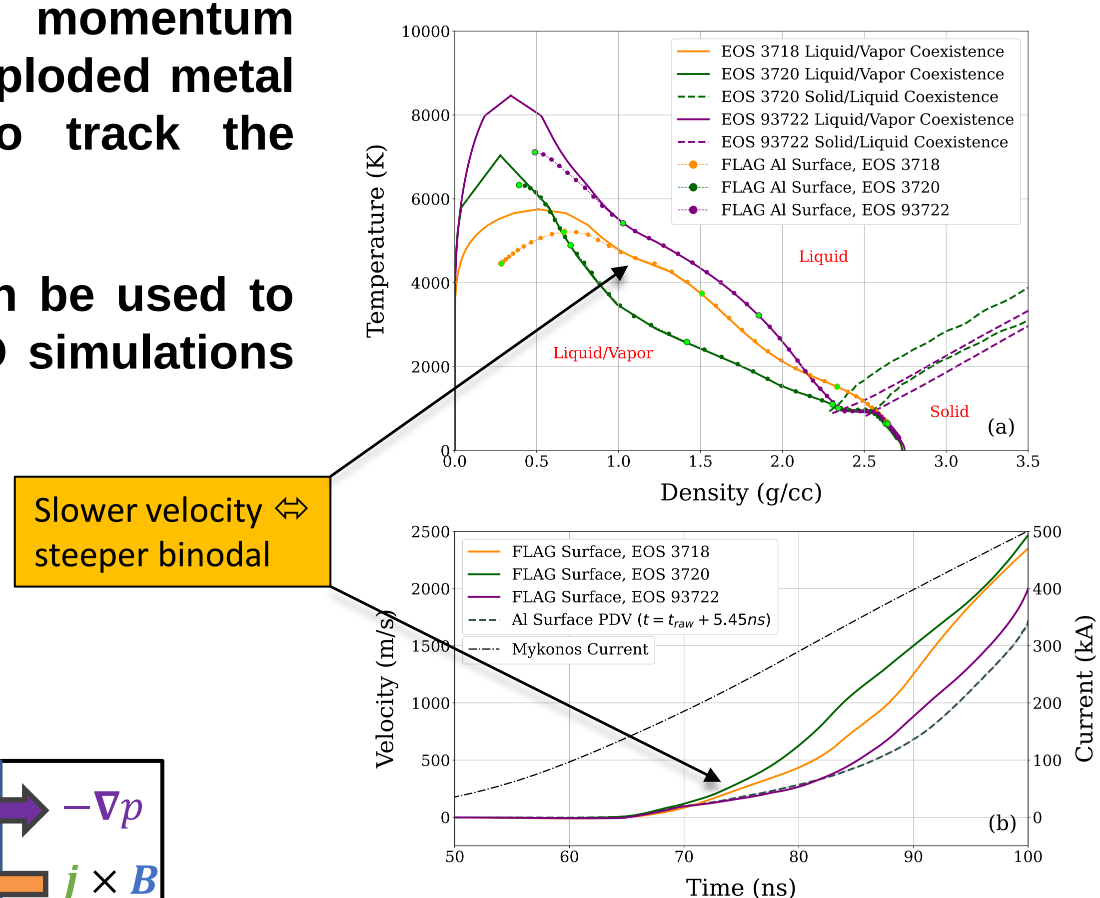
(LANL-FLAG modeling by S.E. Kreher)

Local balance in MHD momentum equation on an Ohmically exploded metal rod causes the surface to track the vaporization phase boundary.

Experimental velocimetry can be used to validate EOS models in MHD simulations for metals in expansion.

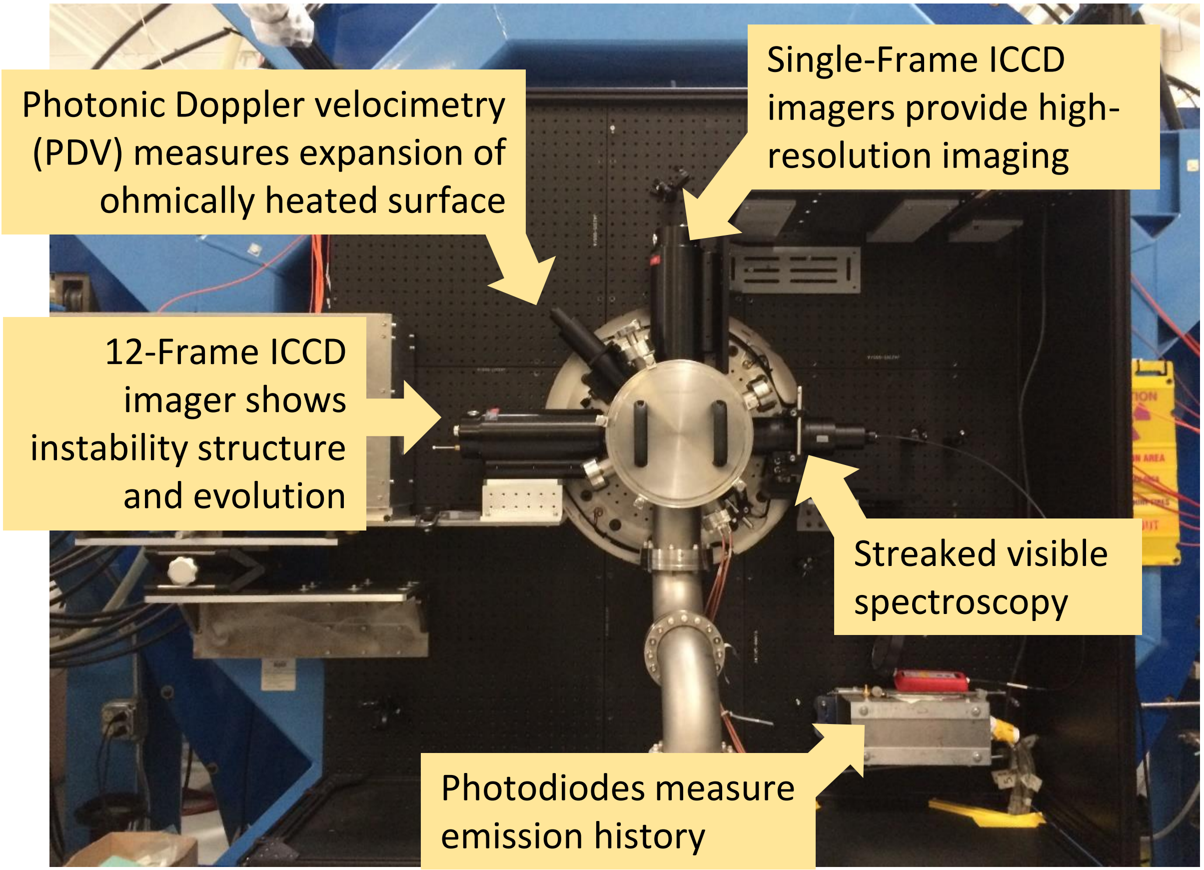
$$\rho \frac{D(\boldsymbol{u})}{Dt} = -\boldsymbol{\nabla} p + \boldsymbol{j} \times \boldsymbol{B}$$

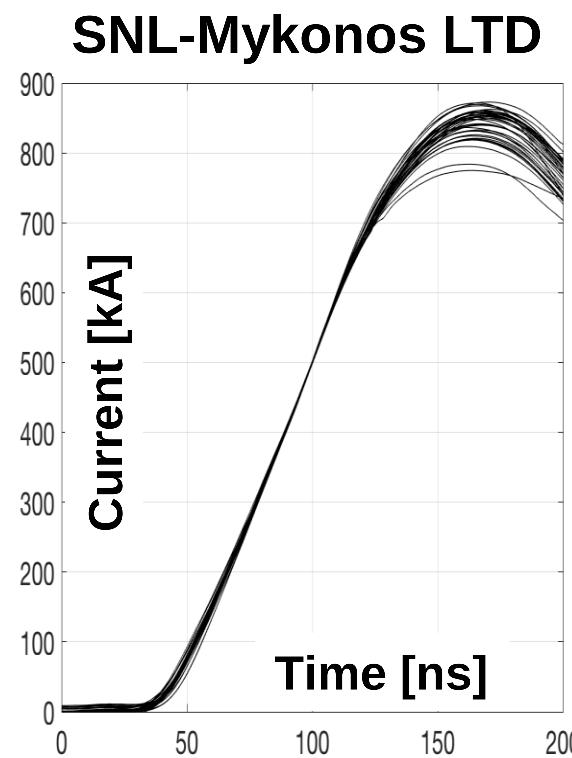




SEK, BSB

To study ETI, 0.8 MA are driven through 0.8-mm-diameter metal rods on Mykonos



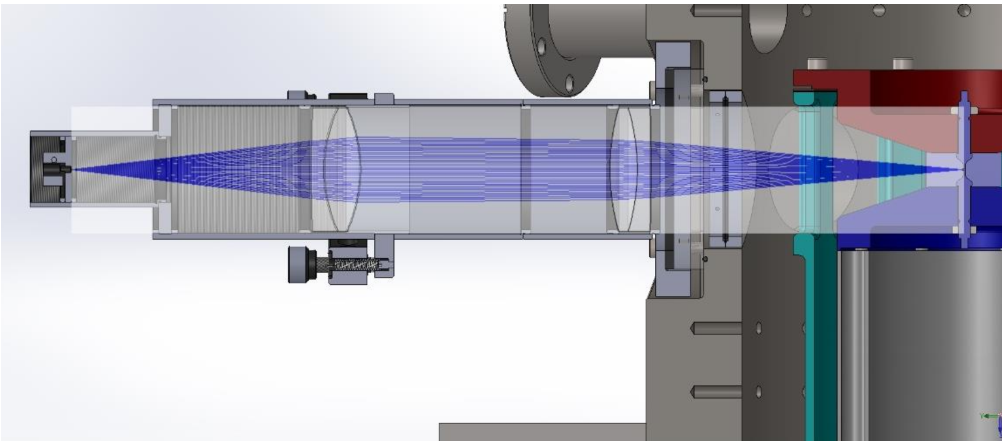


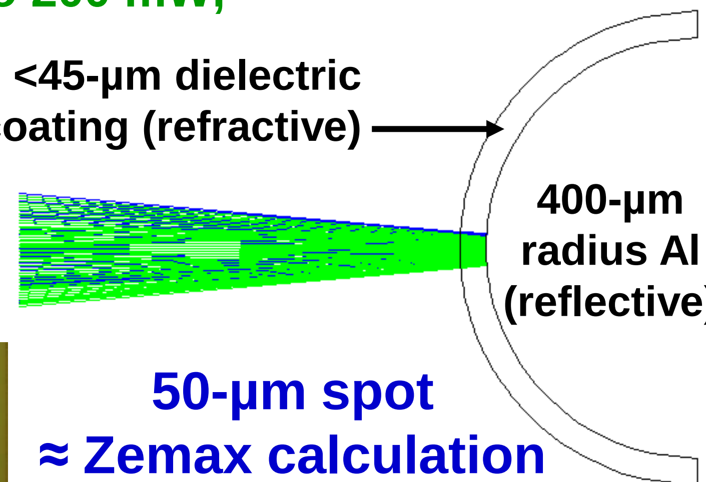
- **Al-5N, Al-6061, Cu-5N, Ni-4N rod radii >> electrical skin depth**
- **Parylene-N coated (5, 17, 41 μm thick) & uncoated rods**
- **Surface defects, inclusions, and machining periodicity varied**

TMH, BSB

Al surface motion was measured with photonic Doppler velocimetry (PDV)

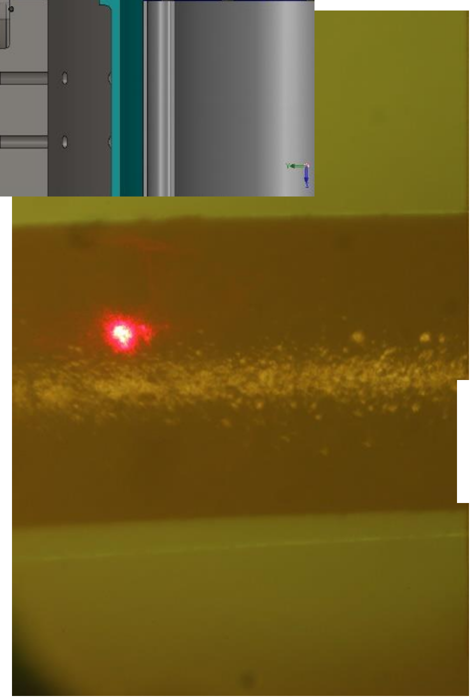
CW 1550-nm probe laser, upgraded from 35 mW to 200 mW, fiber-coupled to achromatic imaging system

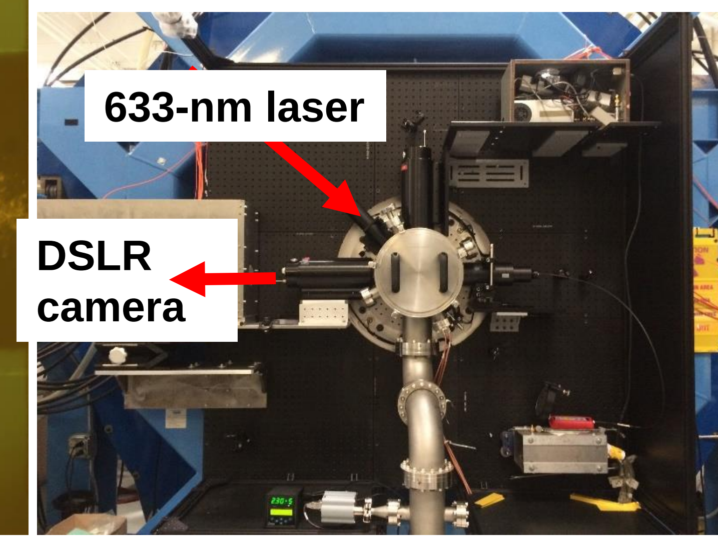




50-μm spot ≈ Zemax calculation

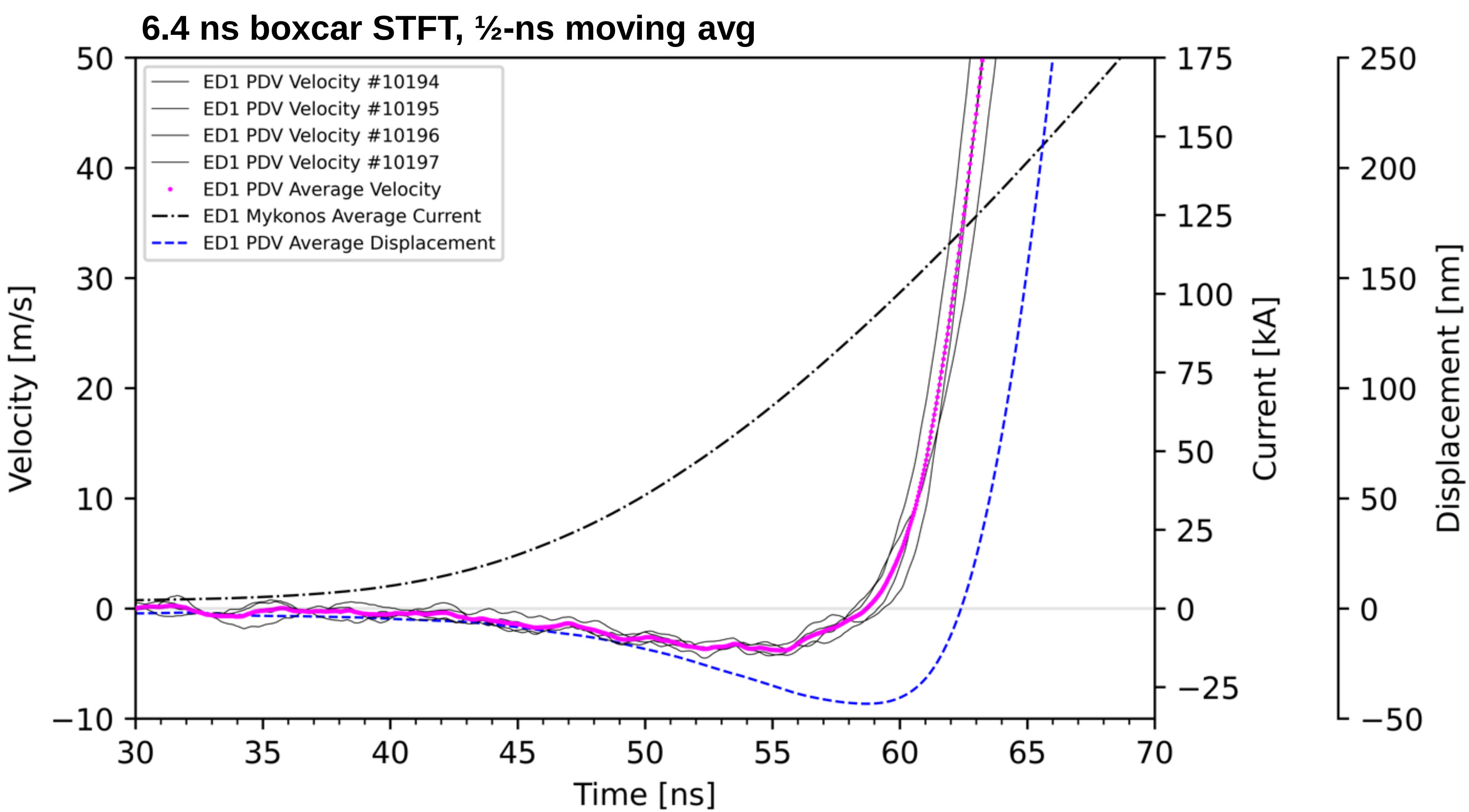
193.416-THz probe laser nonlinearly mixed with 193.414-THz reference laser ⇒ scope signal of (2 GHz)+(Doppler shift) ⇒ Doppler shift $\bar{f}$ using Short-Time Fourier Transform ⇒ Apparent velocity $v^* = \frac{\lambda_0}{2}\bar{f}$





TMH, BSB

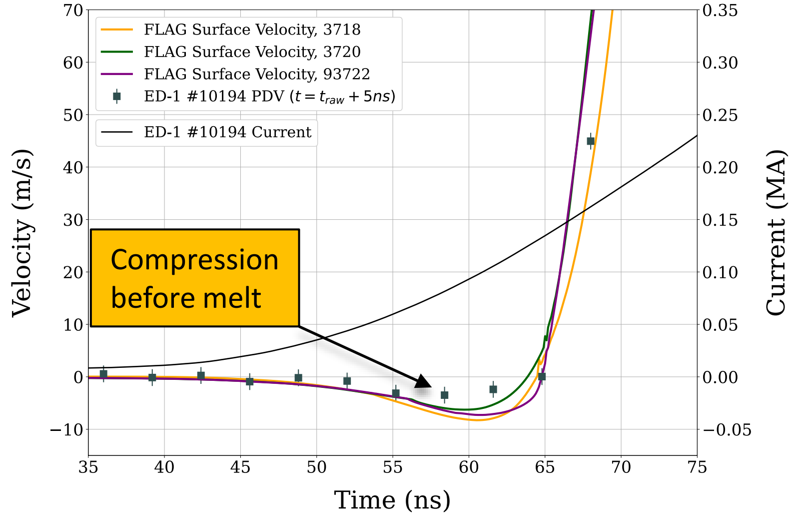
First PDV measurement of radially inward motion of solid-filled Al rod

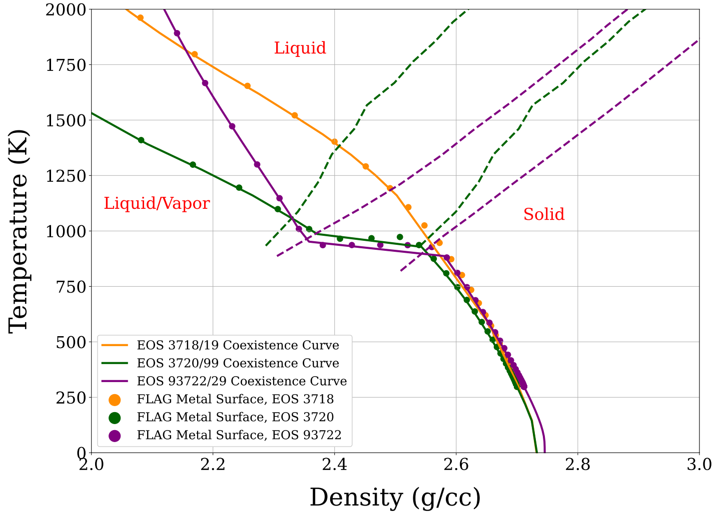


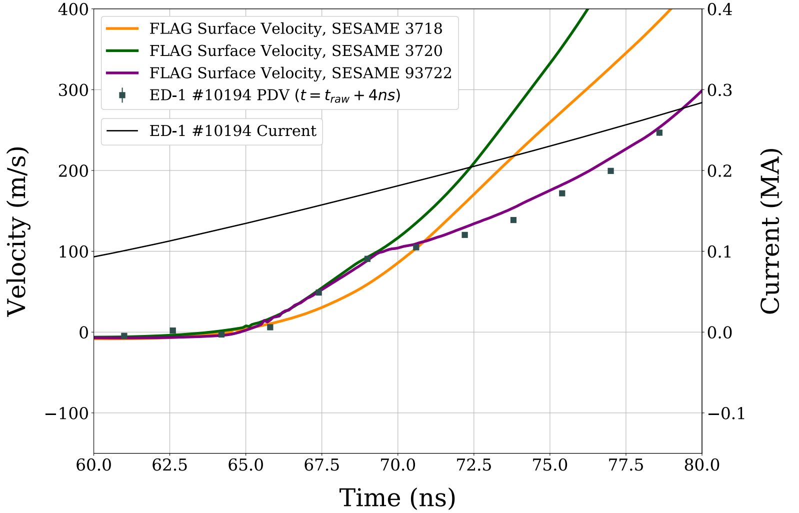
AWK, BSB

Early PDV features validate EOS

Prior to surface melting, the $\vec{j} \times \overrightarrow{B}$ Lorentz force slightly dominates thermal expansion and compresses the rod

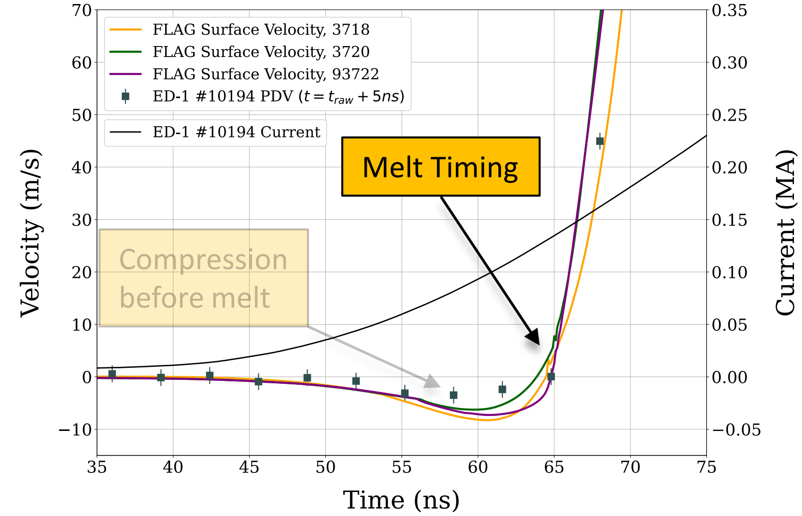


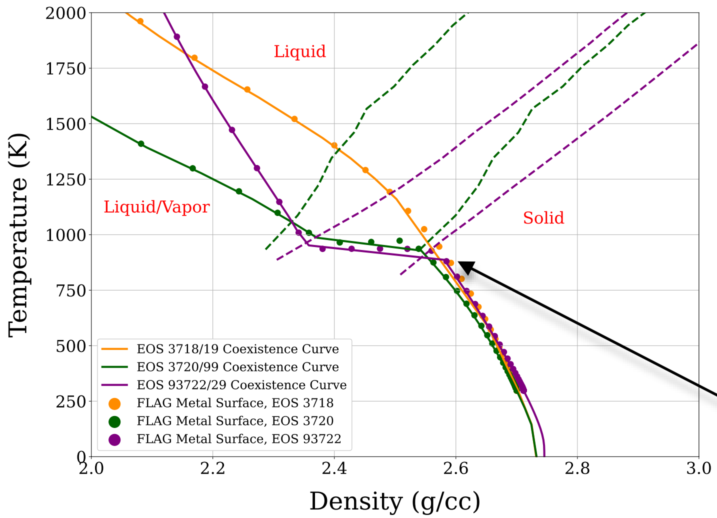


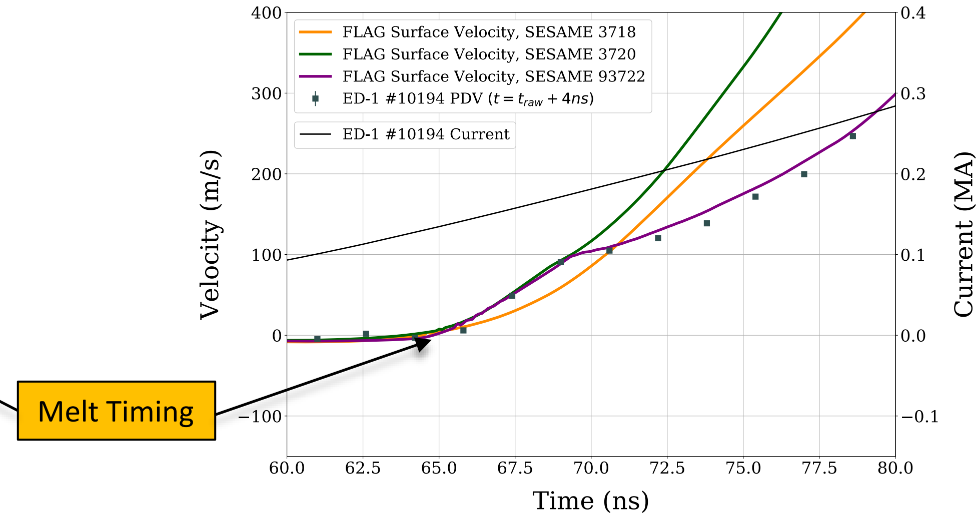


Early PDV features validate EOS

@ *t* ~ 64 ns
the surface begins to melt
and starts to expand rapidly

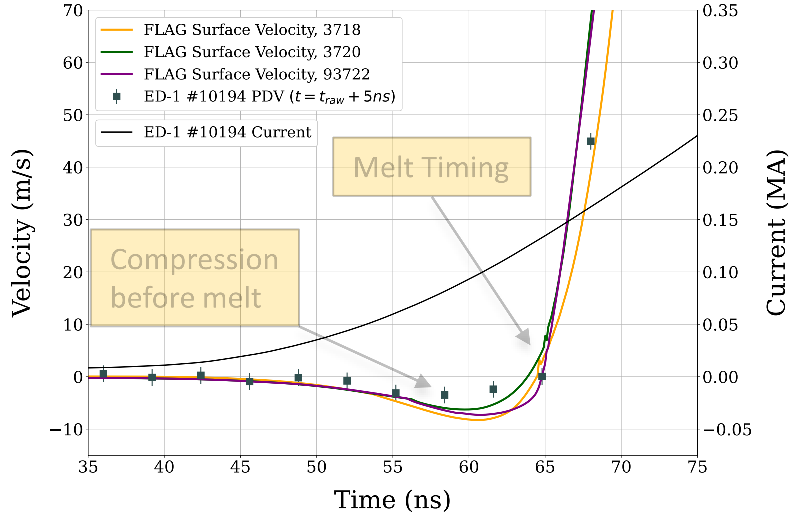


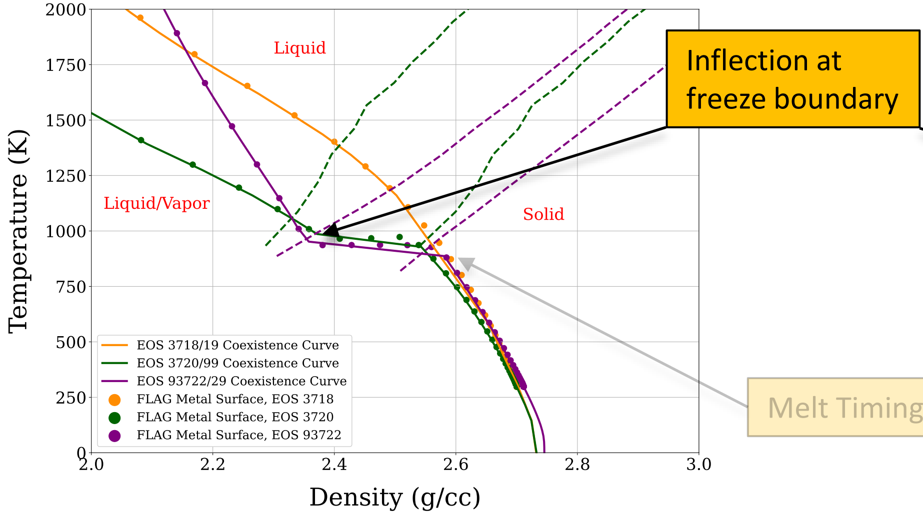


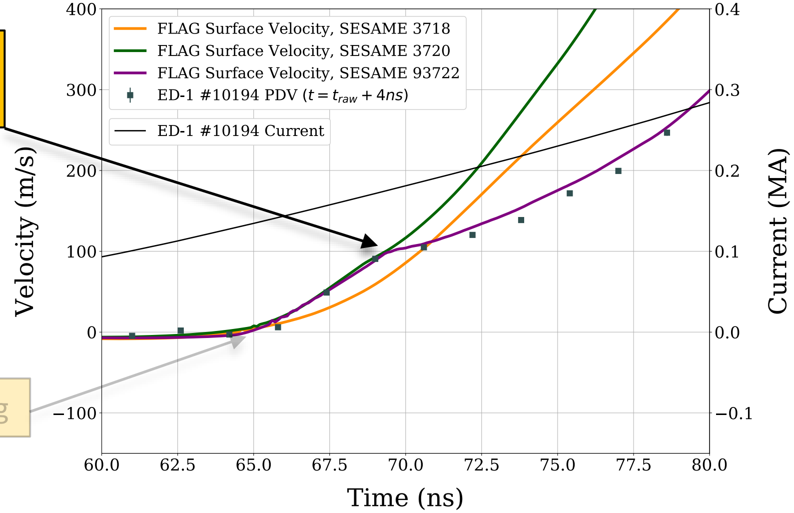


Early PDV features validate EOS

@ *t* ~ 69 ns
the surface finishes melting;
binodal slope increases drastically at freeze/ liquidus phase boundary
=> sharp decrease in acceleration

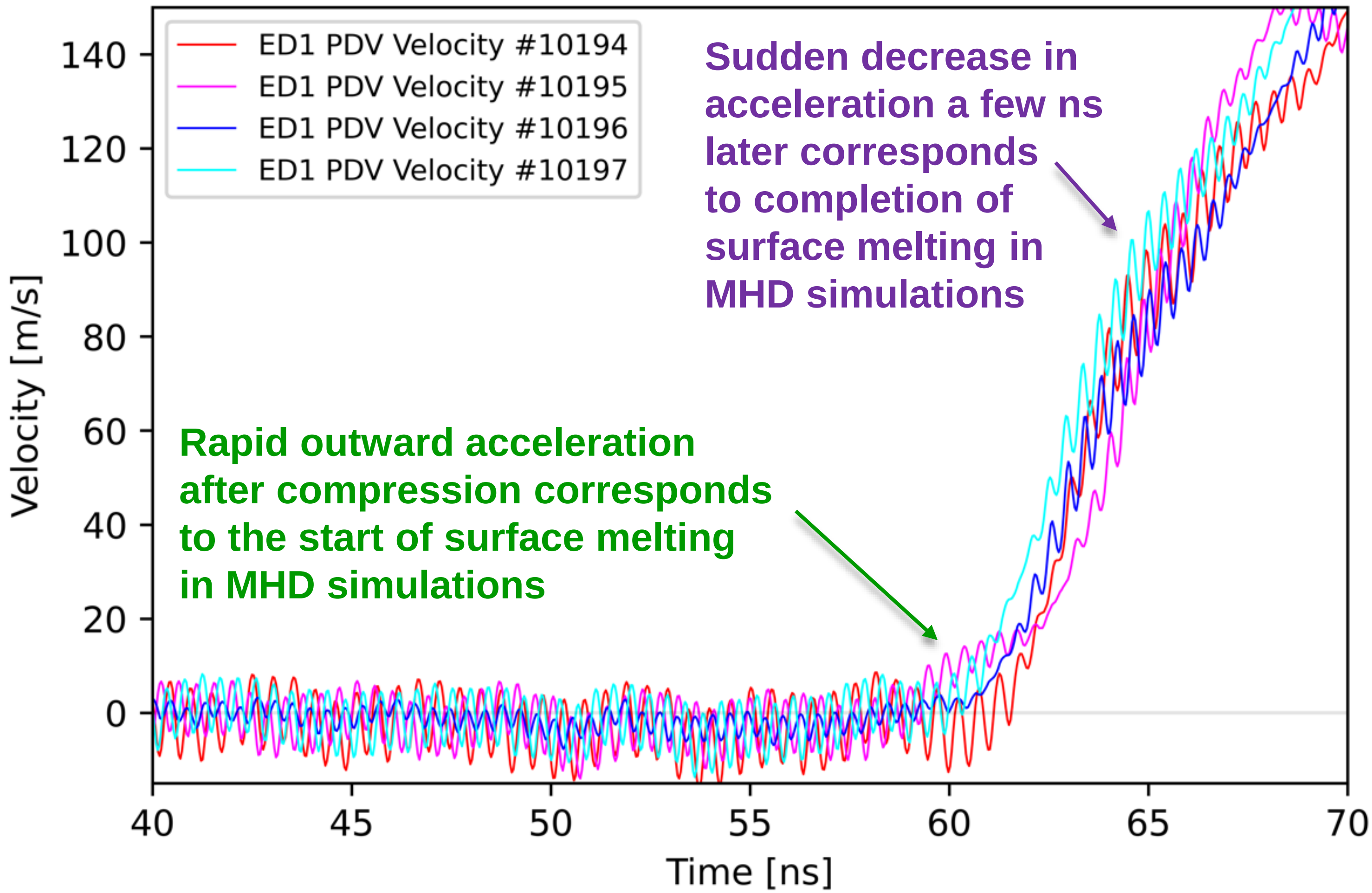






Inflection points of $v'(t)$ will give first measurement of duration of surface melting on a current-driven rod

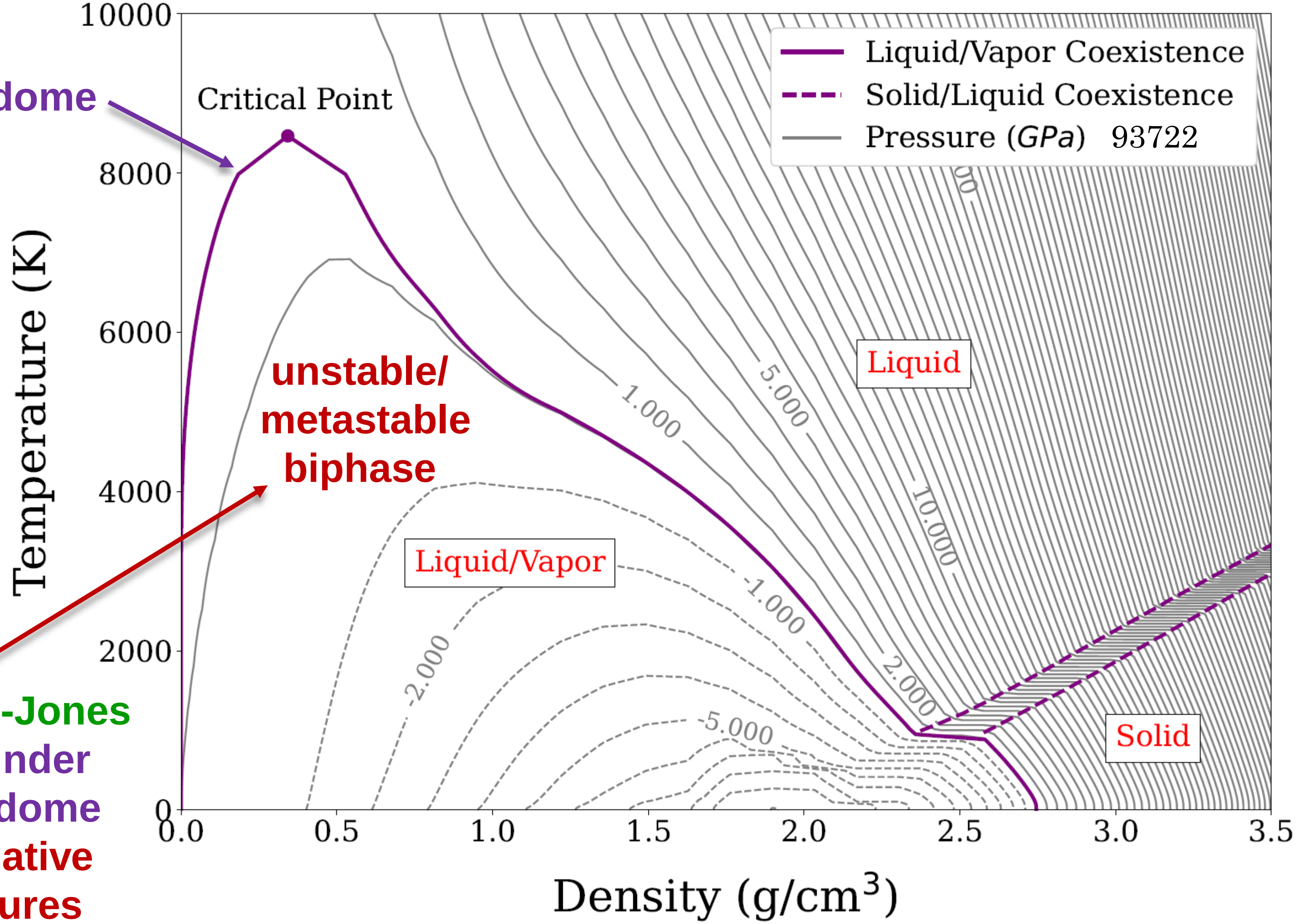
ED1 PDV comparison: Boxcar windowing function, Gaussian peakfinding, 3.2 ns tau, no smoothing



AWK, BSB

Under vapor dome, unmodified Al EOS has $p<0$ van der Waals (VdW) loops

vapor dome



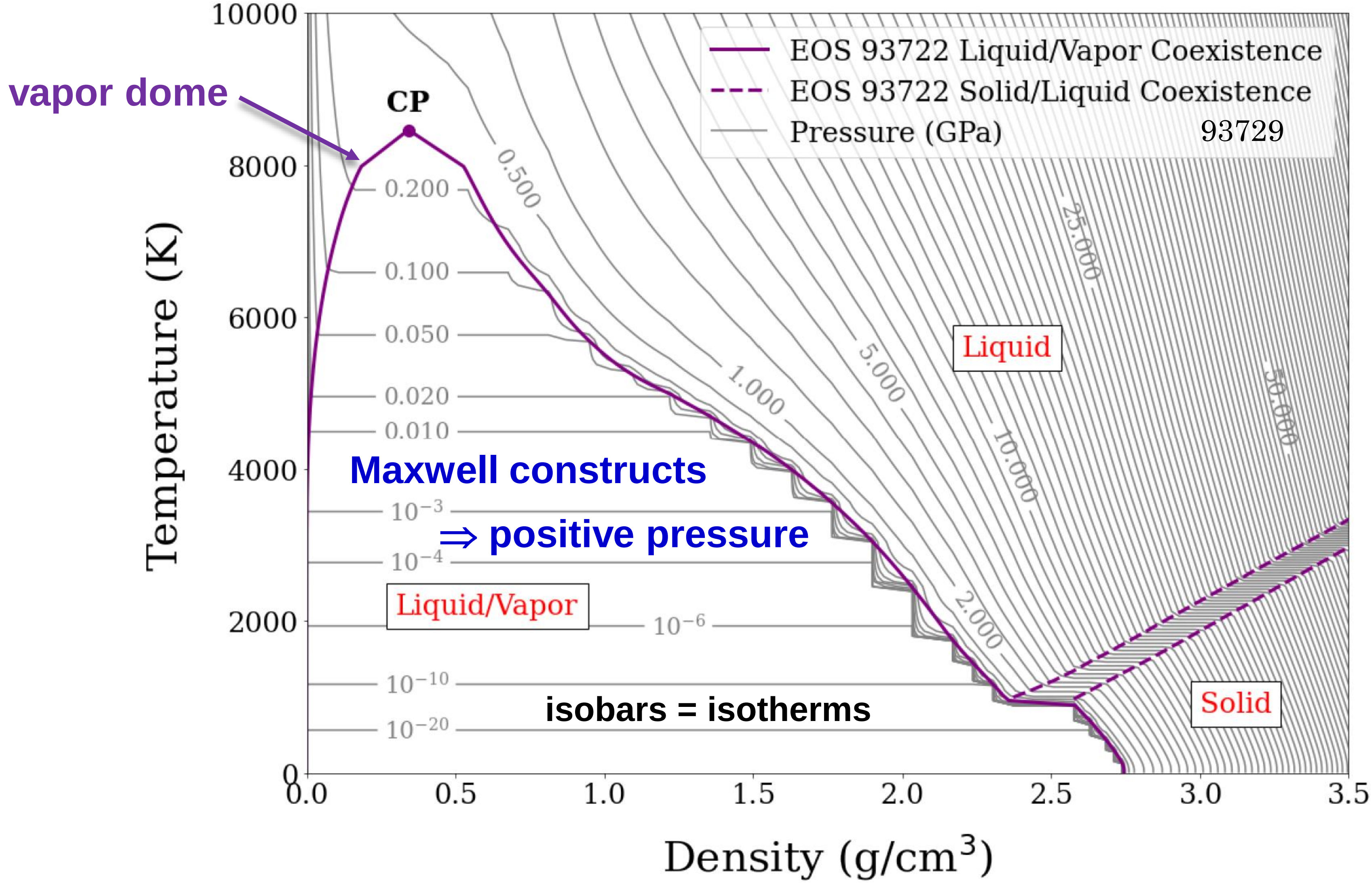
Lennard-Jones EOS under vapor dome ⇒ negative pressures

T. Sjostrom et al., Phys. Rev. B 94, 144101 (2016)

S.E. Kreher, PhD dissertation, Univ. of Nevada, Reno (2023)

SEK, BSB

Under vapor dome, Al EOS modified with Maxwell constructs has $p>0$



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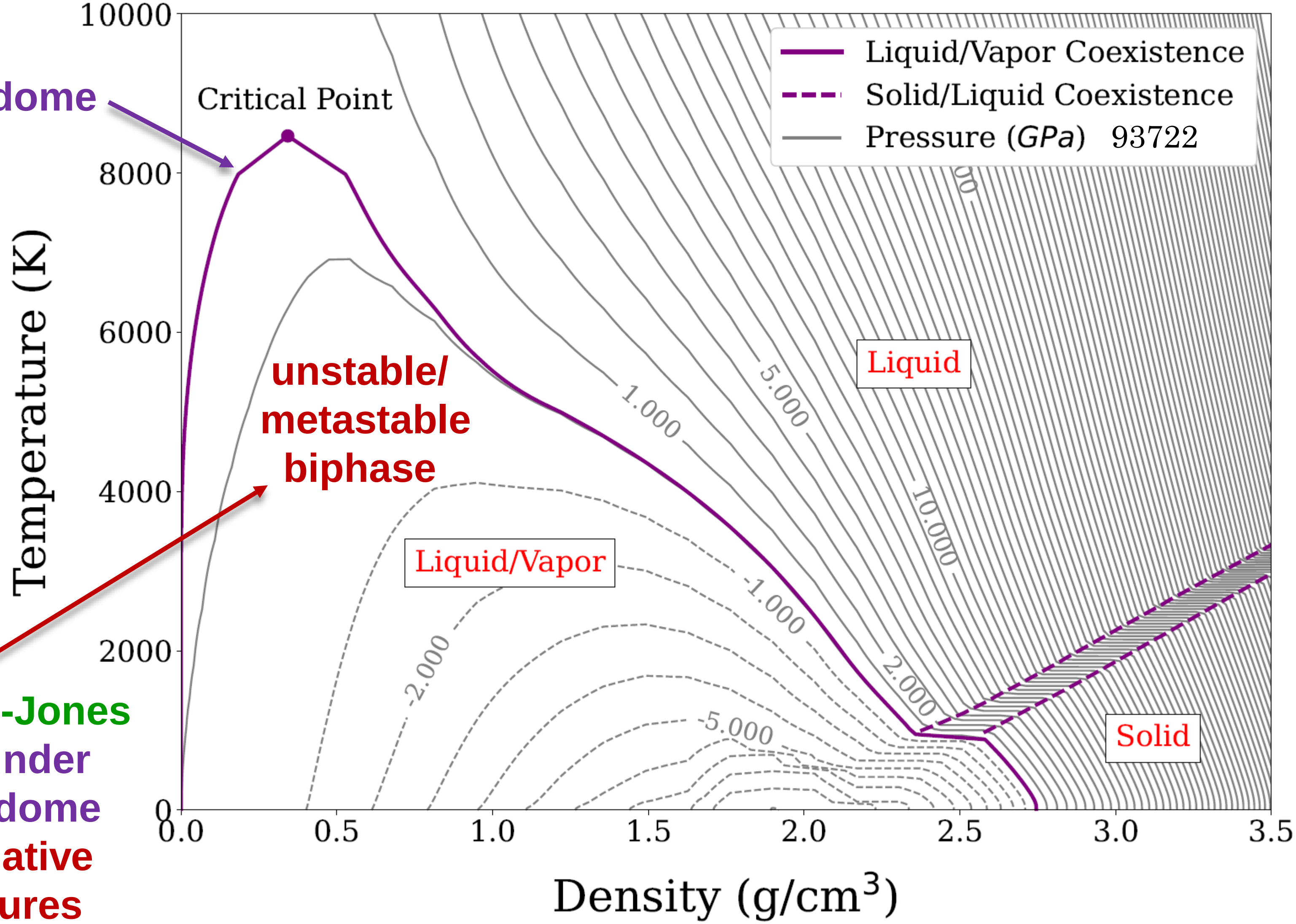

unstable/ metastable biphase

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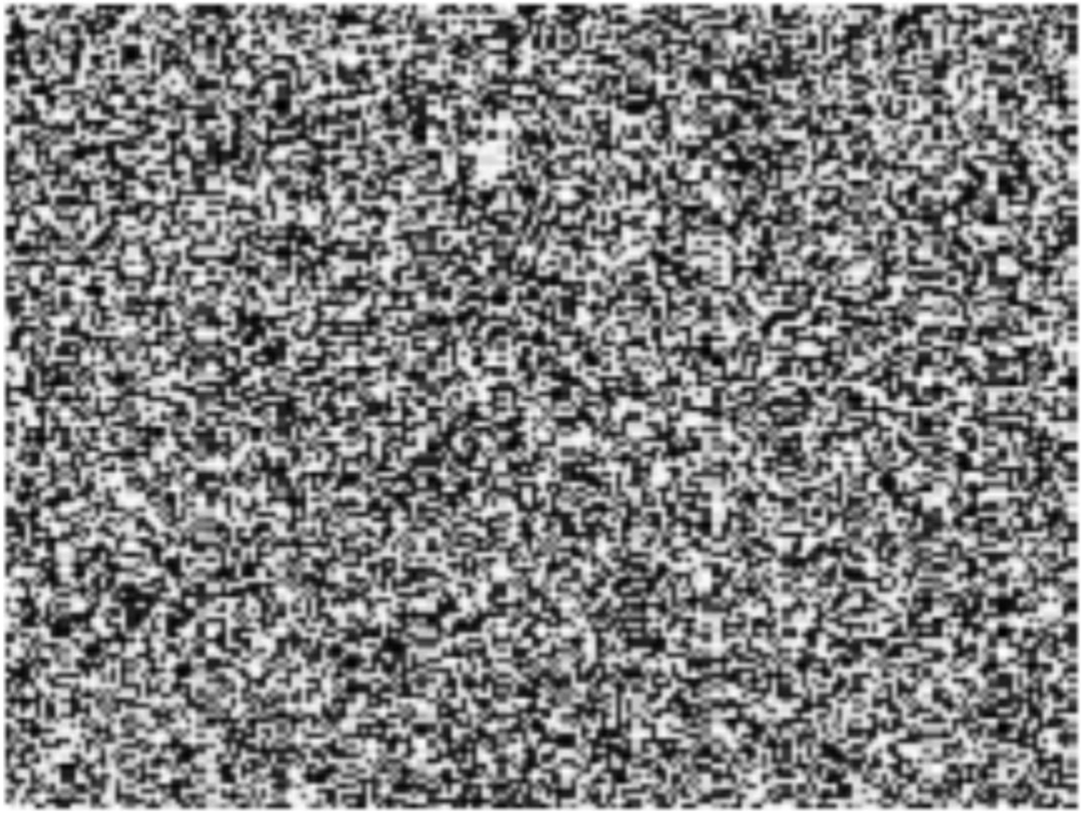
If enough time for spinodal decomposition and/or nucleation, unstable/metastable biphase dissociates into liquid & vapor $\Rightarrow$ use Maxwell constructs



Spinodal Decomposition

Microstructural evolution under the Cahn–Hilliard equation, demonstrating distinctive coarsening and phase separation.

Yonatan Oren, Wikimedia Commons, 2007,
commons.wikimedia.org/wiki/File:CahnHilliard_Animation.gif

BSB

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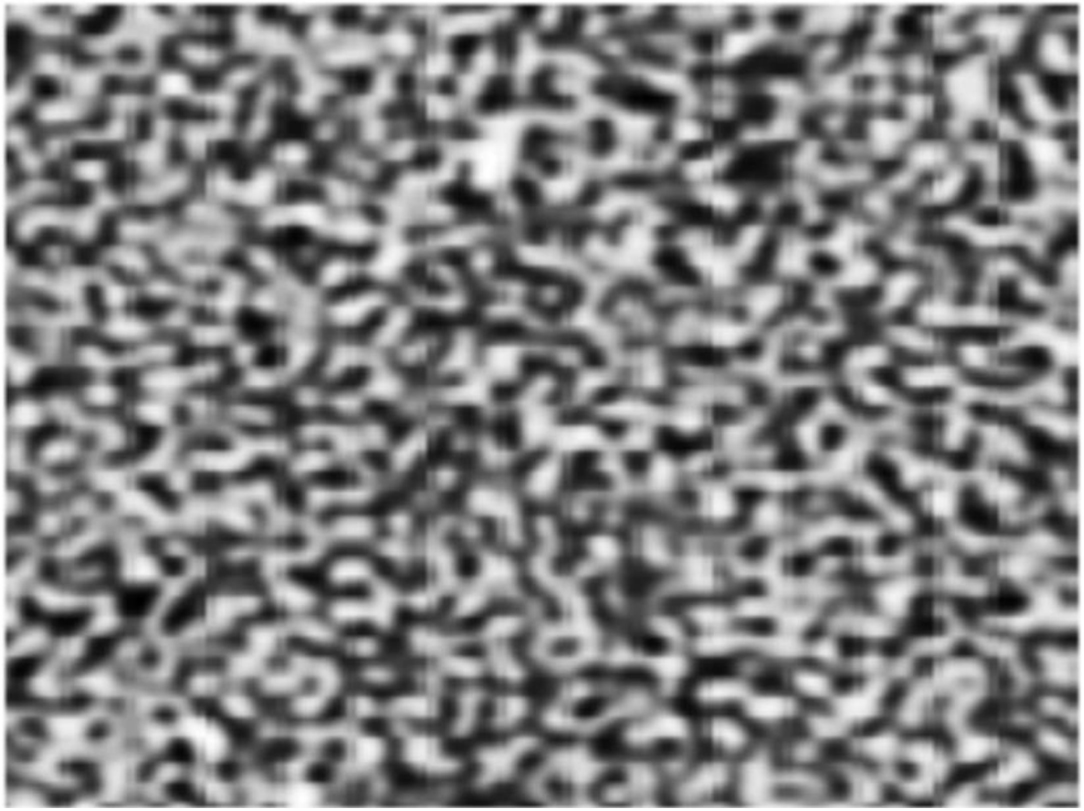

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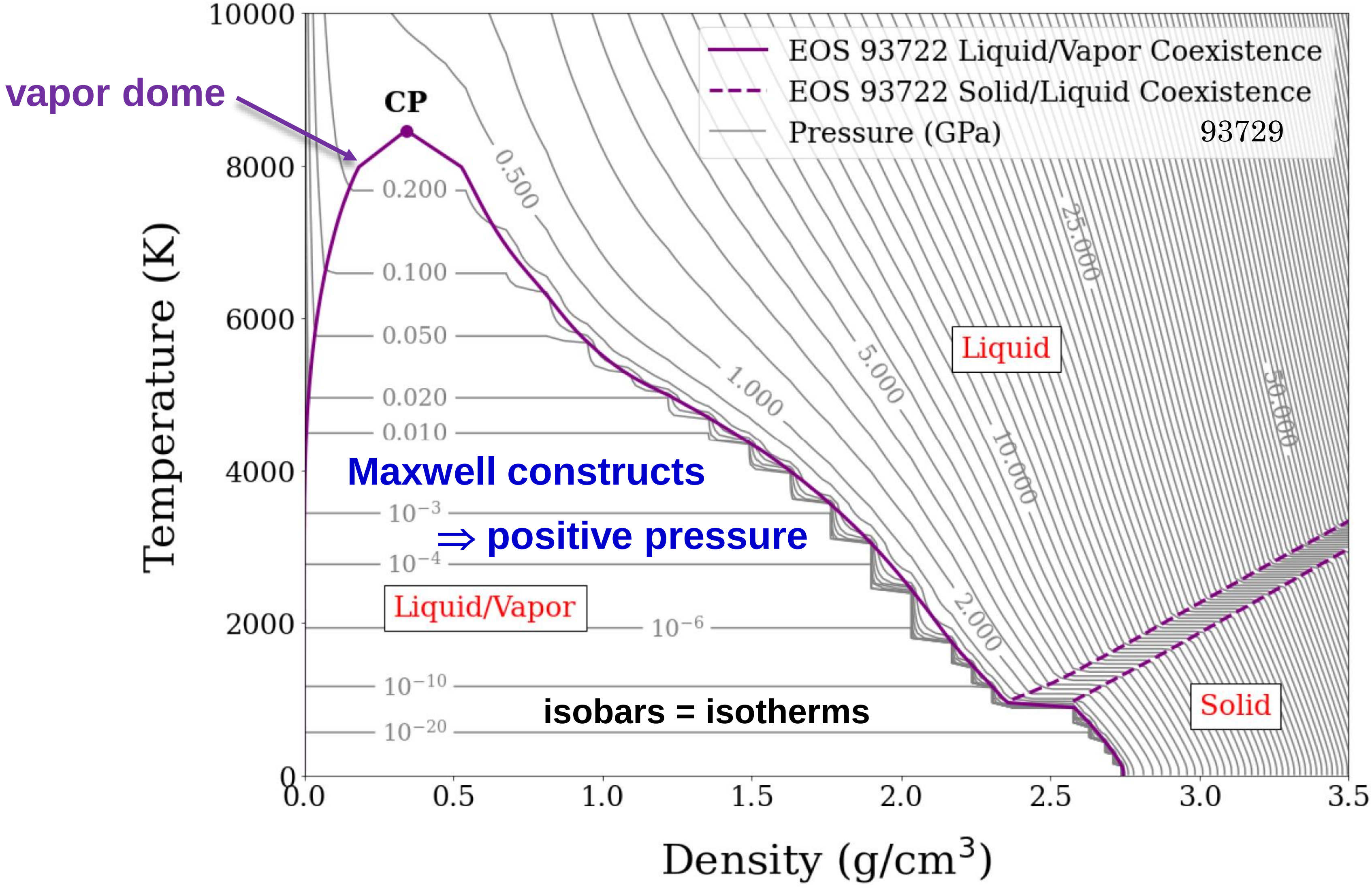

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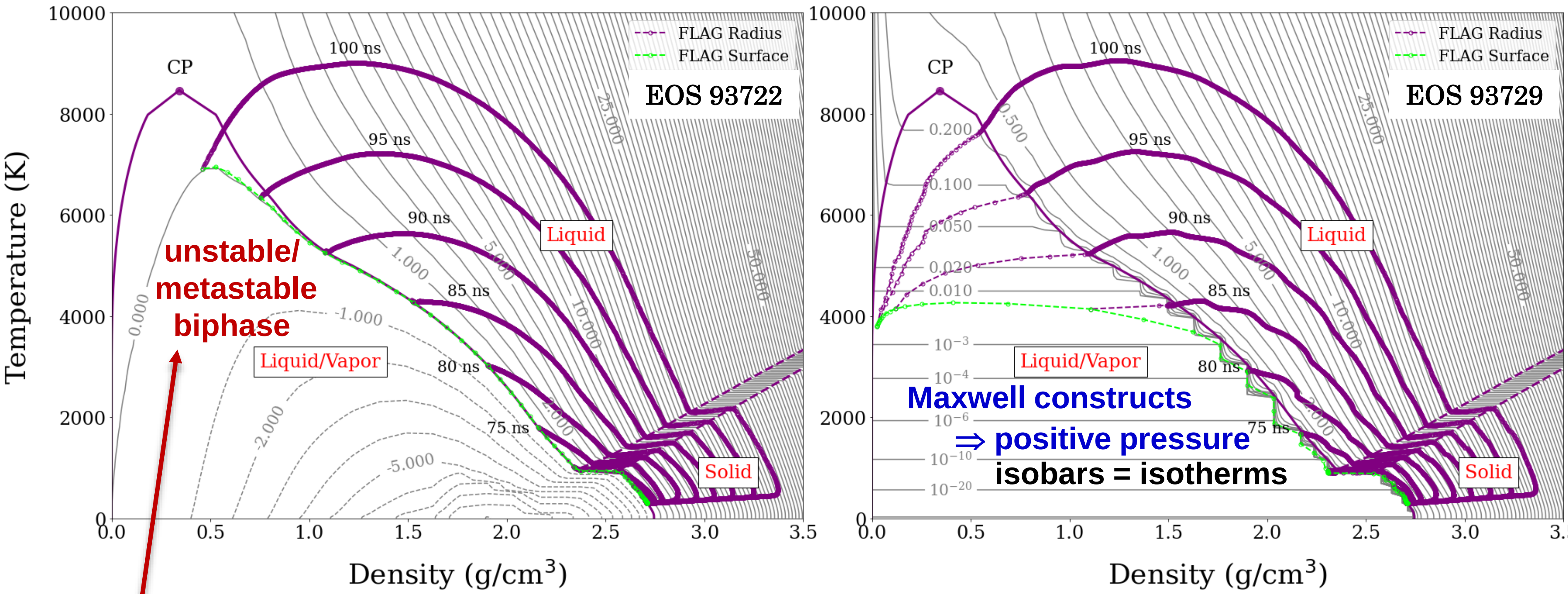
Maxwell constructs cause surface to vaporize earlier vs unmodified EOS tables with van der Waals loops



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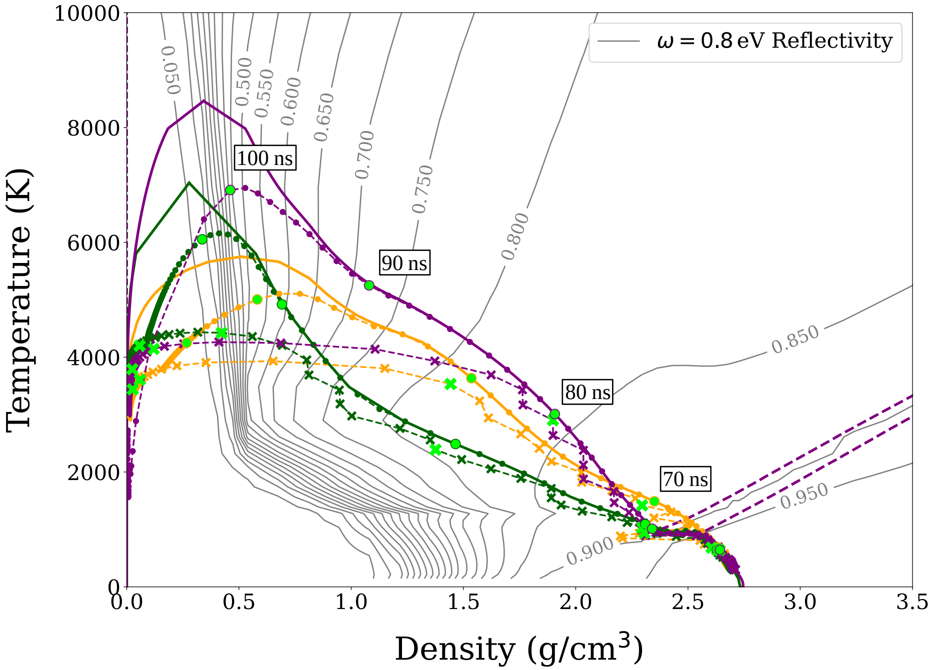
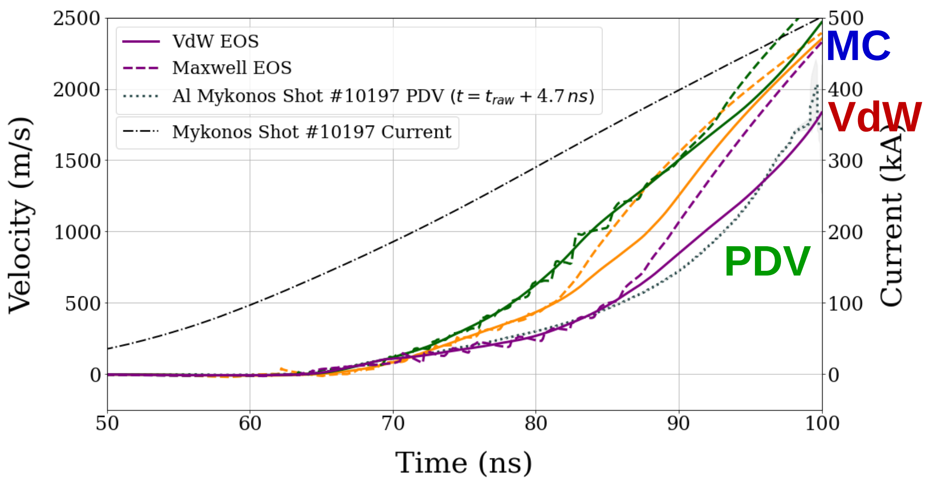
Maxwell-construct earlier vaporization
⇒ rapid acceleration of Al surface
but VdW prediction better matches PDV





Al reflectivity to 0.8 eV PDV laser from DFT calculations suggests rod surface is reflective for both VdW & MC EOS in RHS of vapor dome

SEK, BSB

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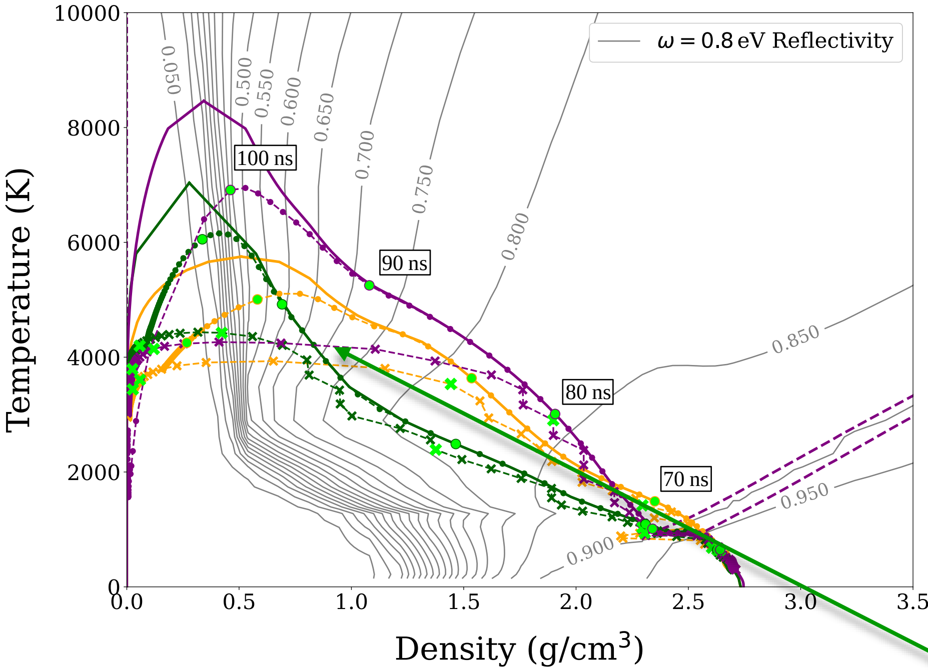

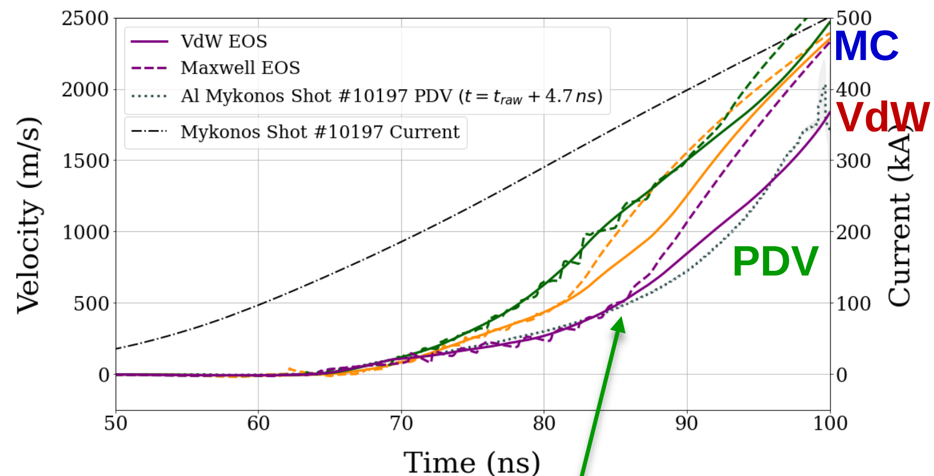

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Velocity inflection @ 85-86 ns should still be 70-75% reflective for MC calculation

SEK, BSB

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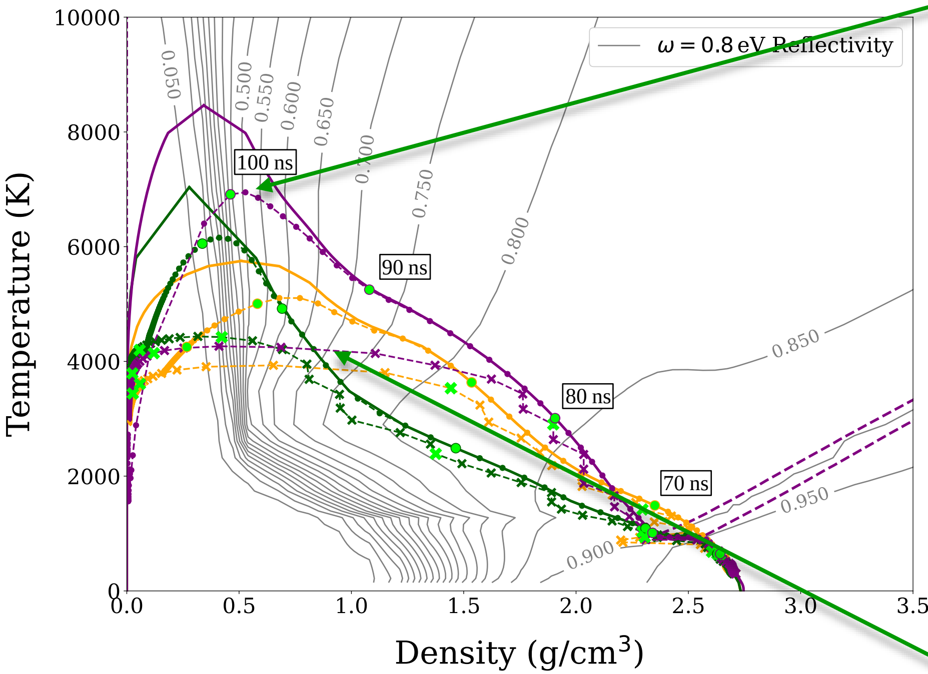
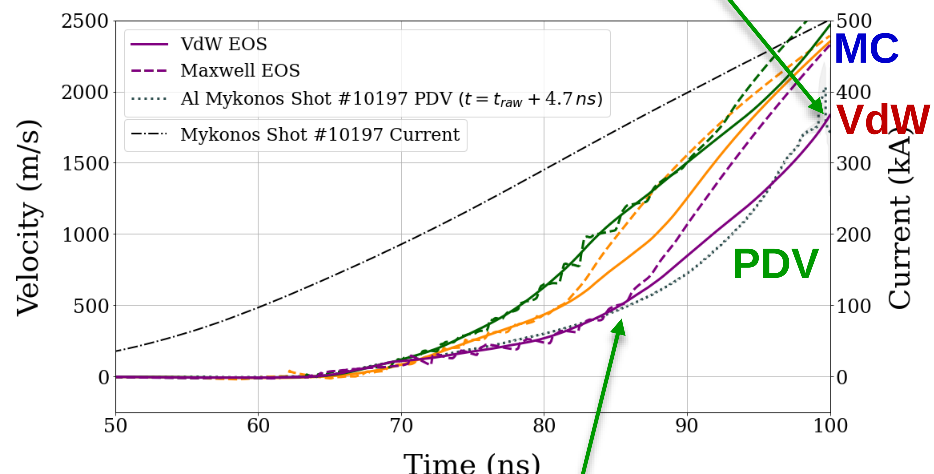


PDV signal cutting out @ 98 ns correlates with reflectivity cliff for VdW calculation



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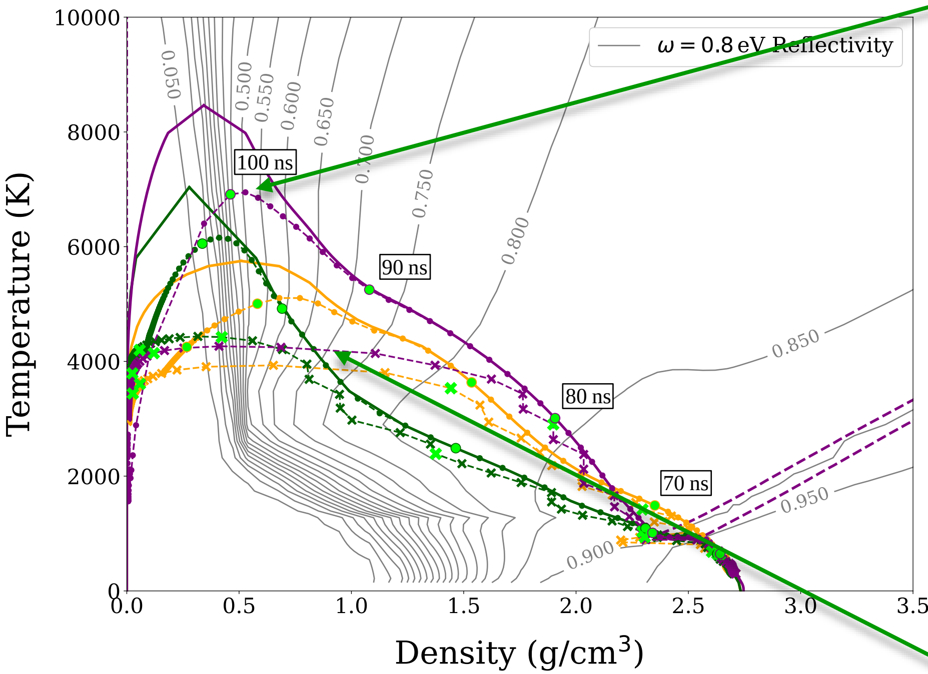

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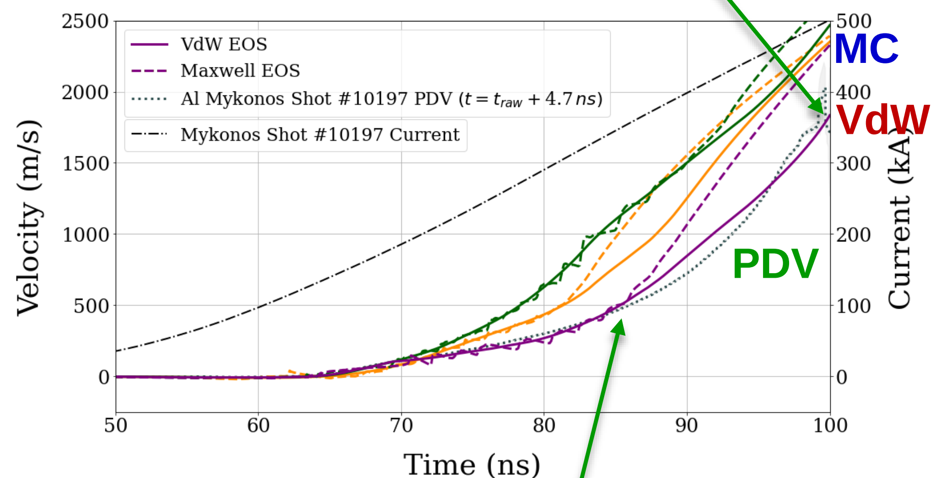

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Effect of energetic electrons/photons from magnetically insulated transmission line?

SEK, BSB

Conclusions

- ✓ PDV from diamond-turned, 0.8-mm-diameter, Al-5N rods driven by 860-kA, 71-ns-risetime, SNL-Mykonos LTD
- ✓ First PDV measurements of radially inward motion and duration of surface melting on a current-driven rod
- ✓ PDV compared with FLAG MHD modeling: After melt, the phase-space trajectory of the reflective surface follows liquid-vapor boundary until surface vaporizes
- ✓ Maxwell constructs cause surface to vaporize earlier than unmodified EOS with van der Waals (VdW) loops
- ✓ MHD with SESAME EOS 93722 (VdW) agrees with PDV best; vital knowledge for device modeling