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Title: (U) Multi-Scale Friction Model in FLAG

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(U) Multi-Scale Friction Model in FLAG

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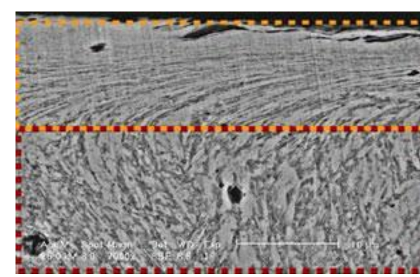
Outline

- Introduction
- The model
- FLAG input syntax
- Results
- Summary, Conclusions and Future work

Introduction

- In extreme loading regimes "friction" between metals is complex
  - Sticking: Static friction forces keep materials from sliding and materials are strong enough to withstand those forces
  - Sliding: Static friction is exceeded and Coulomb friction forces exist along with dry friction heating at the interface (rub your hands together to warm them up), materials are strong enough
  - Smearing: Sticking condition, but material strength exceeded by Coulomb forces, material plastically deforms and produces plastic work heating
  - All cases: heat conduction
- Plasticity is localized at the surface in a thin boundary layer
  - Too expensive to resolve the boundary layer
- Heat from plastic work and dry friction thermally soften the metals which can melt

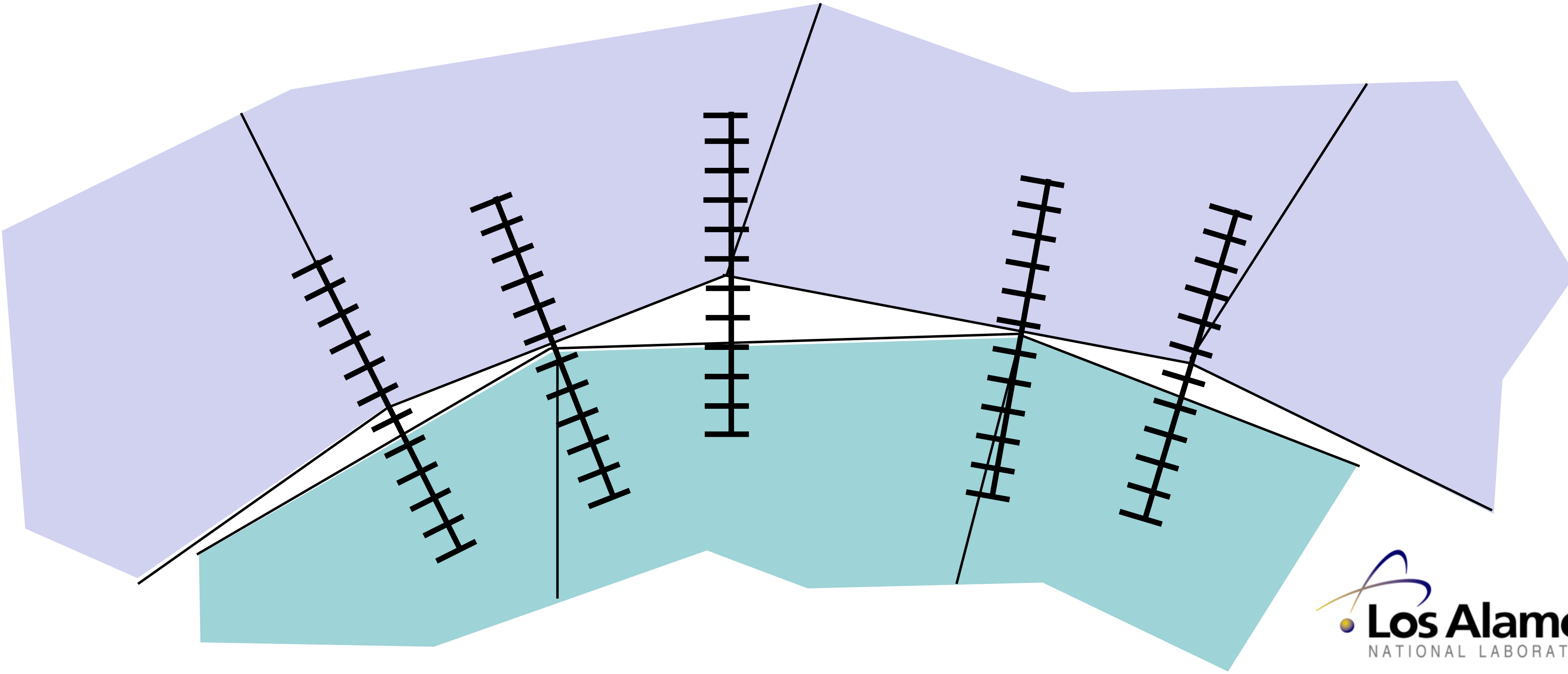


Introduction

- Thin plastic boundary layer and high relative sliding velocity means large strain rates and huge range of strain rates
  - $O(10^8)$ s^{-1} at the interface
- At small length scales, conduction time scales matter
- Plastic work deposits heat locally that conducts away
- Coulomb dry friction heating at the surface conducts into both materials
- Complicated.
- Want a practical model that captures much if not all of the physics

The Model

- Coupled multi-scale friction model
  - Macro-scale = Computational mesh
  - Micro-scale = 1D boundary layer mesh at <u>each</u> surface point
    - Spans both contacting materials
    - Micro-scale conduction and plasticity
  - Based on similar approach by Dambakizi



The Model: Micro-scale conduction

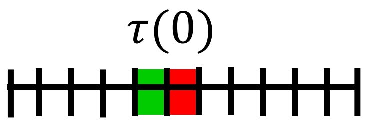
- Solves the non-steady heat equation on a 1D mesh using Crank-Nicholson time integration. Implicitly evolves temperature field by macro-scale Δt
- Coupled to macro-scale
  - Macro-scale temperature used as Dirichlet BC at each end of the 1D mesh
  - Heat flux in/out the ends of the 1D mesh coupled to macro-scale as macro-scale internal energy source/sink
  - Macro-scale heating (PdV, radiation-electron coupling, etc.) deposited uniformly into 1D micro-scale thermal field
  - Macro-scale sliding velocity and friction force provide Coulomb dry friction heat source, deposited at the center of the 1D mesh at the contact interface
- Coupled to micro-scale plasticity
  - Micro-scale plastic heating deposited into thermal field

The Model: Micro-scale plasticity

- Quasi-static assumption (Boo!!)
  - Quasi-uniform strain and strain rate
- Steinberg-Cochran-Guinan (SCG) strength (Boo!!)
  - Thermal softening with melt (Yay!!)
  - Not rate-dependent (Boo!!)
- Quasi-static assumption and rate independent strength enable a numerical "trick"

The Model: Micro-scale plasticity

- Compute yield stress of each material in 1D zones connected to contact interface using SCG model
- Take minimum of the two (weaker material)



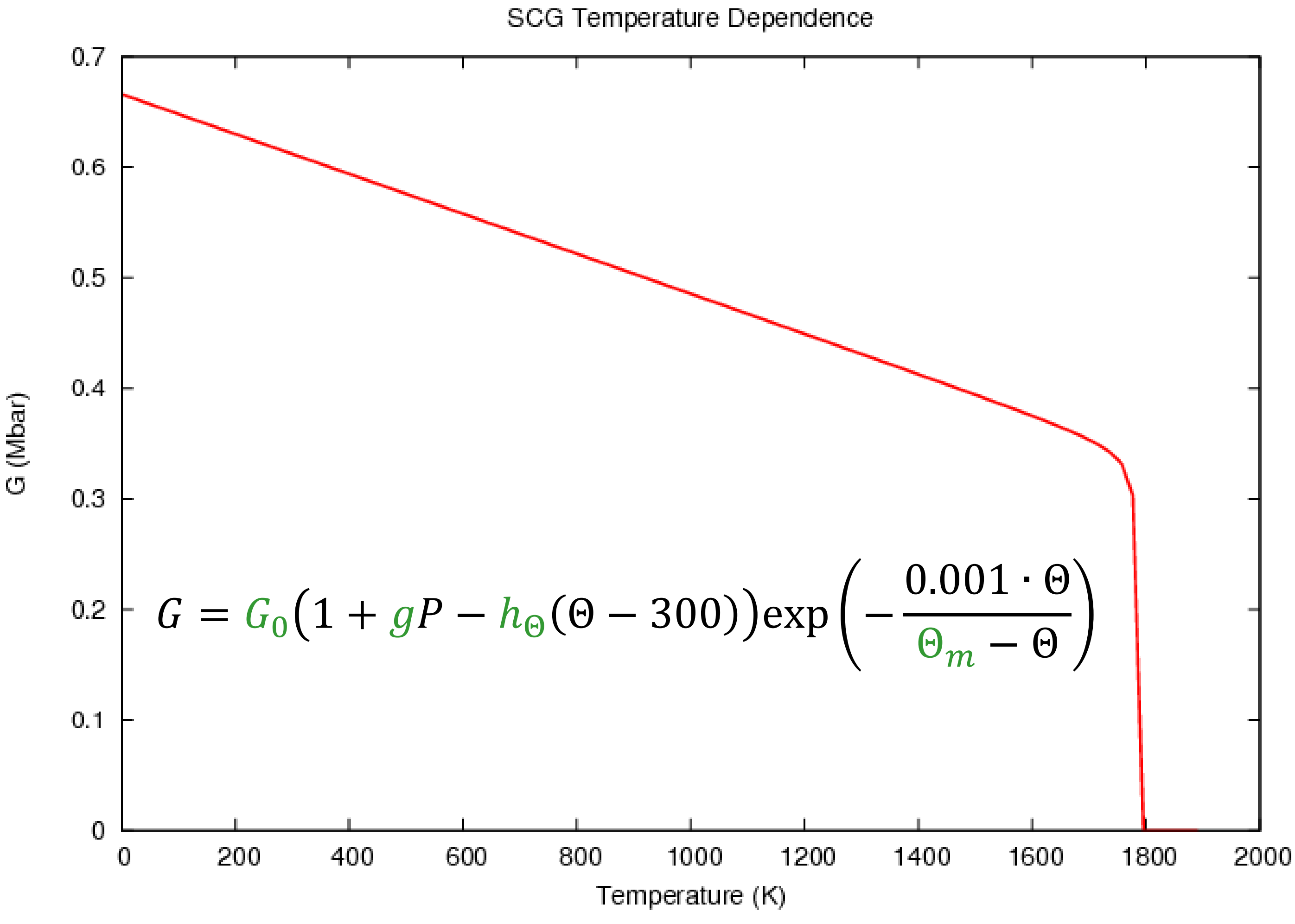
- Apply this stress to the entire 1D mesh
  - Requires quasi-static assumption
- Calculate strain increments in each 1D zone
  - Solve SCG stress-strain relation for strain increment and rate (divide increment by Δt to get strain rate)
  - Requires rate-independent strength model

$$Y = \sqrt{3}\tau(0) = Y_0\left(1 + \beta\epsilon_p\right)^{\eta}\frac{G(P,\Theta)}{G_0} \qquad G = G_0\left(1 + gP - h_\Theta(\Theta - 300)\right)\exp\left(-\frac{0.001\cdot\Theta}{\Theta_m - \Theta}\right)$$

$$\epsilon_p^n = \epsilon_p^{n-1} + \Delta\epsilon_p \qquad \Delta\epsilon_p = \frac{1}{\beta}\left[\left(\frac{\sqrt{3}\tau(0)G_0}{Y_0 G(P,\Theta)}\right)^{\frac{1}{\eta}} - 1\right] - \epsilon_p^{n-1}$$

$$\dot{\epsilon_p} = \Delta\epsilon_p/\Delta t$$

The Model: Micro-scale plasticity



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The Model: Micro-scale plasticity

$$Y = \sqrt{3}\tau(0) = Y_0\left(1 + \beta\epsilon_p\right)^{\eta}\frac{G(P,\Theta)}{G_0}$$

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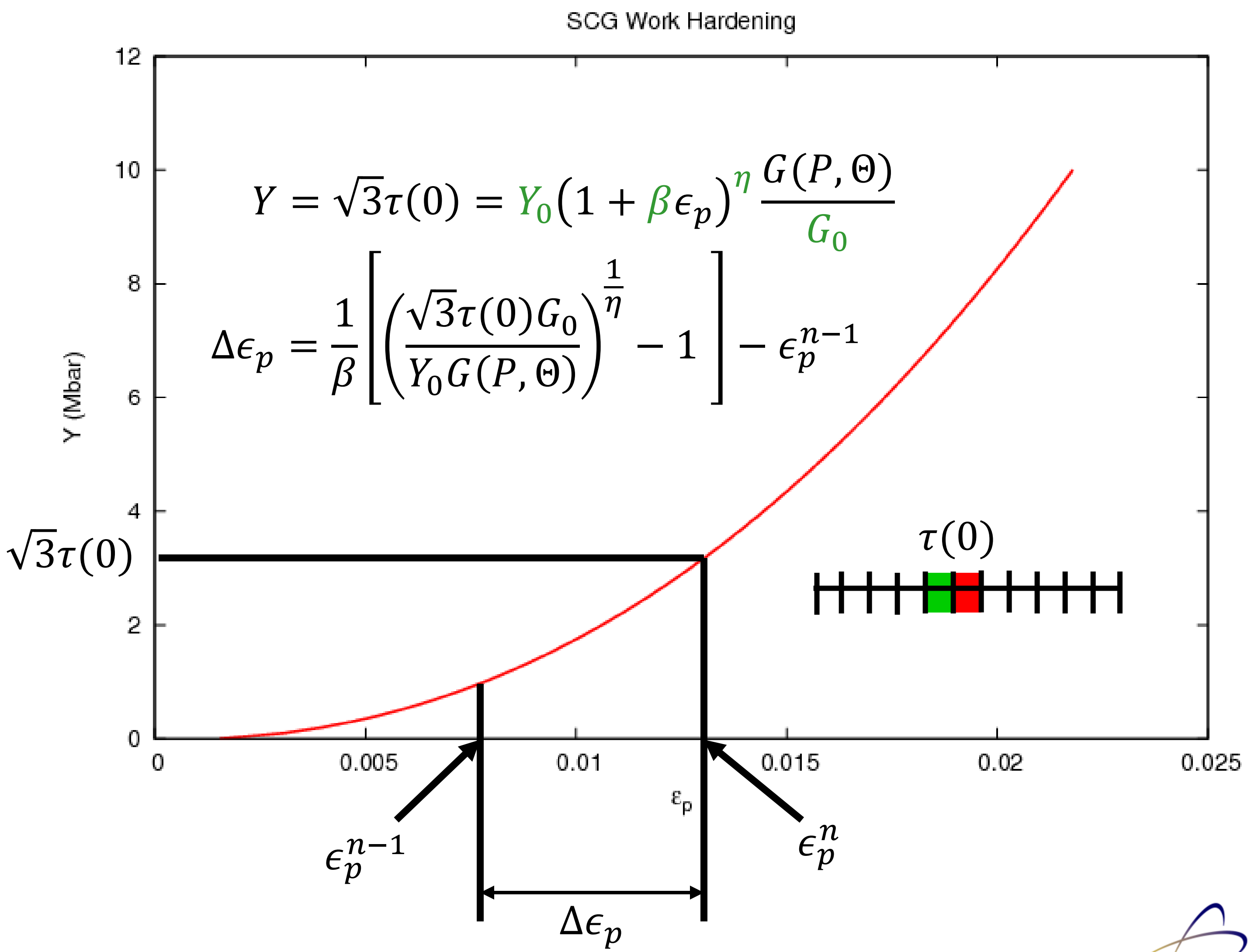

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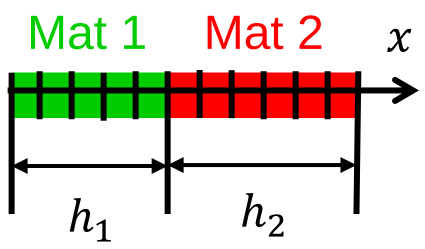
The Model: Micro-scale plasticity

- Integrate strain rate across 1D domain
  - Gives micro-scale relative sliding velocity
  - $\Delta u_{12} = \sqrt{3}\int_{-h_1}^{h_2} \frac{\Delta\epsilon_p(x)}{\Delta t} dx$



- Get macro-scale sliding velocities U_1 and U_2
- Get macro-scale relative sliding velocity
  - $\Delta U_{12} = U_2 - U_1$
- Scale strain increments so integral matches macro-scale relative sliding velocity
  - $\Delta\epsilon_p^{new} = \max\left(0, \frac{|\Delta U_{12}|}{\Delta u_{12}} \Delta\epsilon_p\right)$
- Deposit heat into 1D model based on scaled strain increments
- Evolve 1D plastic strain field based on scaled strain increments
- $\tau_t = \mu_t \cdot \tau(0)$ is the Tresca (smearing) friction force

The Model: Other stuff

- In addition to the micro-scale aspects:
- Sticking traction is computed
- Coulomb traction is computed
  - $\tau_c = \mu_c \cdot P$
- Tresca (plasticity/smearing) traction τ_t is computed
- Minimum traction is determined
  - If Coulomb, no plasticity, but we must solve the conduction problem with a dry friction heat source
  - If Sticking, no plasticity, just conduction without a dry friction heat source
  - If Tresca, evolve plasticity, deposit plastic work, no dry friction heating
- Can change throughout a simulation

The Model: Recap

- Handles sticking, Coulomb and Tresca friction automatically
- Coupled multi-scale model
- Micro-scale plasticity and heat conduction
- Coupled to macro-scale internal energy, velocity and stress fields
- Some big warts in the micro-scale plasticity

FLAG Input Syntax

- Must indentify “material 1 side” vs “material 2 side”
  - Each has different SCG parameters, mesh depths, conductivities
- Must specify thermal and mechanical properties
- Only true knobs are the friction coefficients μ_t and μ_c
- Calibrating rate-independent SCG model parameters for higher rates would probably be considered knobs

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FLAG Input Syntax

Add this to your typical slideline definition:

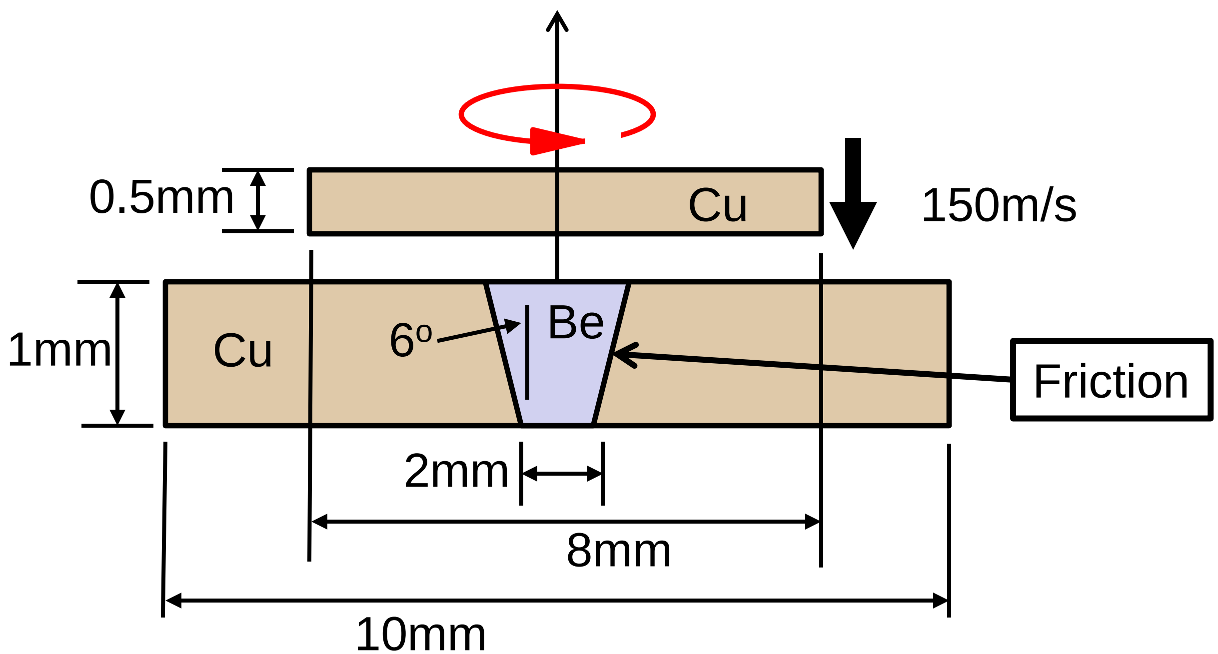
```
mk /global/mesh/hydro/lhydro/kbc(SlipFrict)/slide/enforcement/friction/multi_scale
   alias pffrict      pffrict      $Friction forces
   alias p_tau        p_tau        $Friction tractions
   alias p_taustick   p_taustick   $Sticking tractions
   alias p_taucoulomb p_taucoulomb $Coulomb tractions
   alias p_tautresca  p_tautresca  $Tresca tractions
   alias p_relvel     p_relvel     $Relative sliding velocities
   alias p_x0temp     p_x0temp     $Temperature at 1D interface
   alias p_maxtemp    p_maxtemp    $Maximum temperature on "my" side of 1D mesh
   alias p_maxeps     p_maxeps     $Maximum effective plastic strain on my side
   alias p_pressure   p_pressure   $Contact pressure
   alias p_heatflux   p_heatflux   $Heat flux through my end of 1D mesh
   alias kp_frictype  kp_frictype  $Friction type (0=none, 1=stick, 2=Tresca, 3=Coulomb

   bdy1 = "Be_Contact_Bdy"         $kbdy node name identifying side 1 (Beryllium)
   map_opt = 2                     $Project onto z-axis when mapping across interface
   gap_max = 0.01                  $In contact if gap is less than this

   rmu_c   = 0.3                   $Coulomb friction coefficient
   rmu_t   = 0.9                   $Tresca friction coefficient
```

FLAG Input Syntax (cont'd)

```
$ 1D mesh specs
   h1      = 1.0e-3       $1D mesh depth into material 1
   h2      = 1.0e-3       $1D mesh depth into material 2
   nz      = 40           $1D zones in each material (80 zones total)
$ Be is side 1
   rk1     = 2e-11        $Conductivity of material 1
   g01     = 1.51         $G_0 SCG initial shear modulus of material 1
   y01     = 3.3e-3       $Y_0 SCG initial yield stress of material 1
   ymax1   = 1.31e-2      $Y_max SCG maximum yield stress of material 1
   beta1   = 26.0         $SCG work hardening coefficient of material 1
   eta1    = 0.78         $SCG work hardening exponent of material 1
   g1      = 1.54         $SCG P-dependent shear modulus coefficient for mat 1
   htheta1 = 2.58e-4      $SCG T-dependent shear modulus coefficient for mat 1
   tmelt1  = 1820.0       $Melt temperature of material 1
$ Cu is side 2
   rk2     = 4.01e-11     $Conductivity of material 2
   g02     = 0.477        $G_0 SCG initial shear modulus of material 2
   y02     = 1.2e-3       $Y_0 SCG initial yield stress of material 2
   ymax2   = 6.4e-3       $Y_max SCG maximum yield stress of material 2
   beta2   = 36.0         $SCG work hardening coefficient of material 2
   eta2    = 0.45         $SCG work hardening exponent of material 2
   g2      = 2.83         $SCG P-dependent shear modulus coefficient for mat 2
   htheta2 = 3.77e-4      $SCG T-dependent shear modulus coefficient for mat 2
   tmelt2  = 1790.0       $Melt temperature of material 2
```

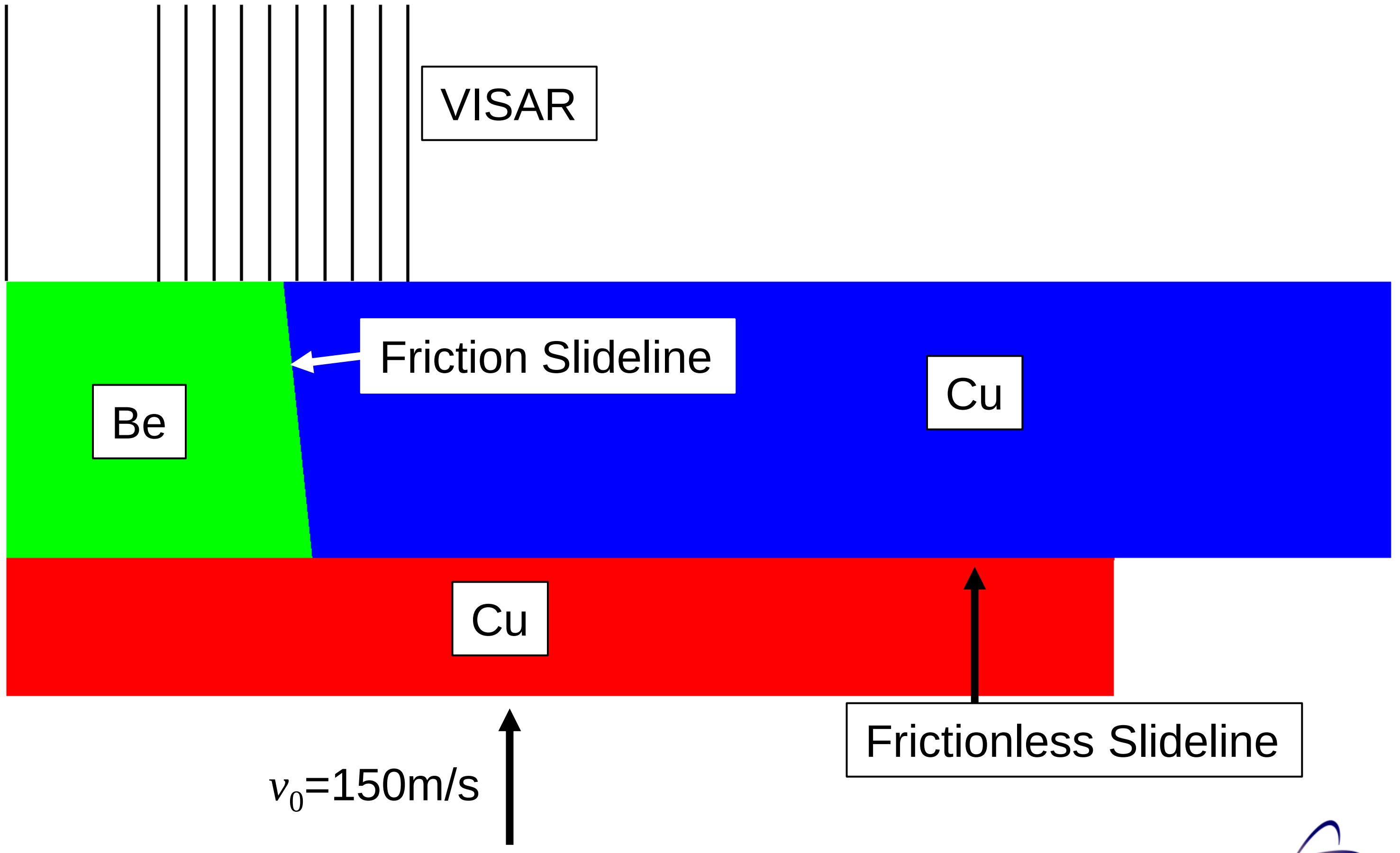
Results

- LANL laser-driven flyer Cu/Be friction experiment
- ~150m/s Cu flyer velocity
- Composite Cu/Be target
- Point and line VISAR diagnostics and TIDI on the back surface of the target



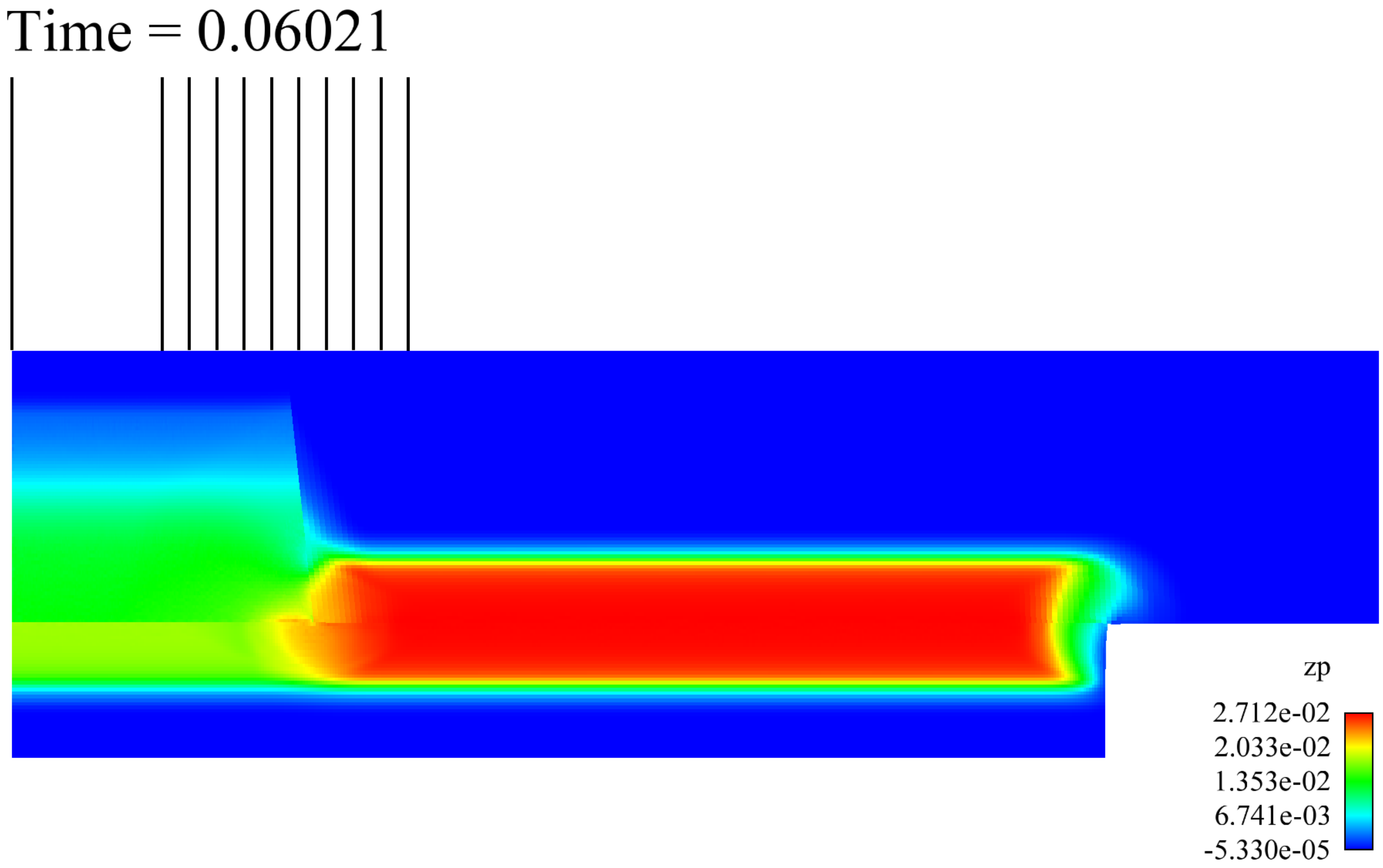
Results: The Model

- PTW' for all materials
- 2 slidelines, one frictionless, one with friction
- Cu and Be SCG friction parameters from Steinberg compendium
- 11 VISAR probes



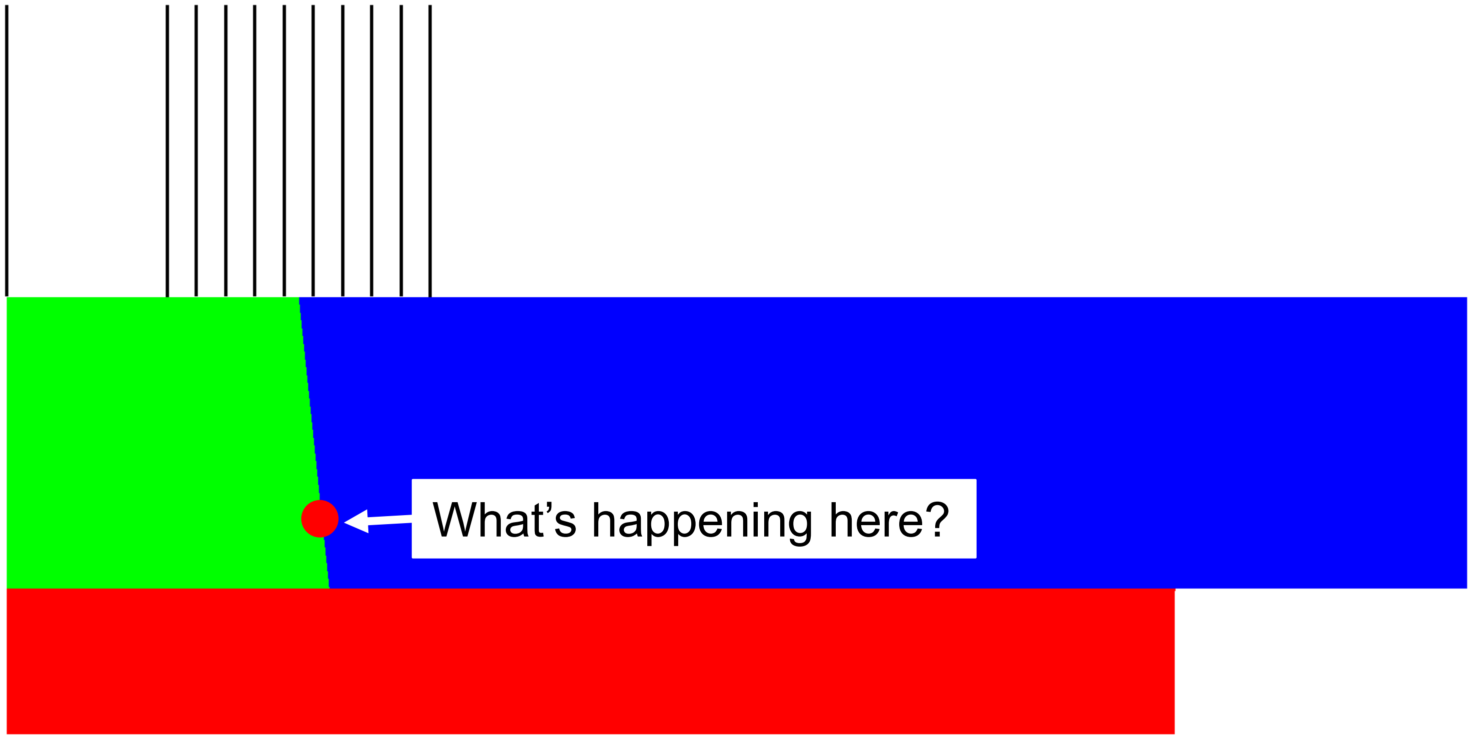
Results: Pressure at 60ns

- Be sound speed higher than Cu
- Velocity difference at interface causes sliding
- Cone angle increases contact pressure



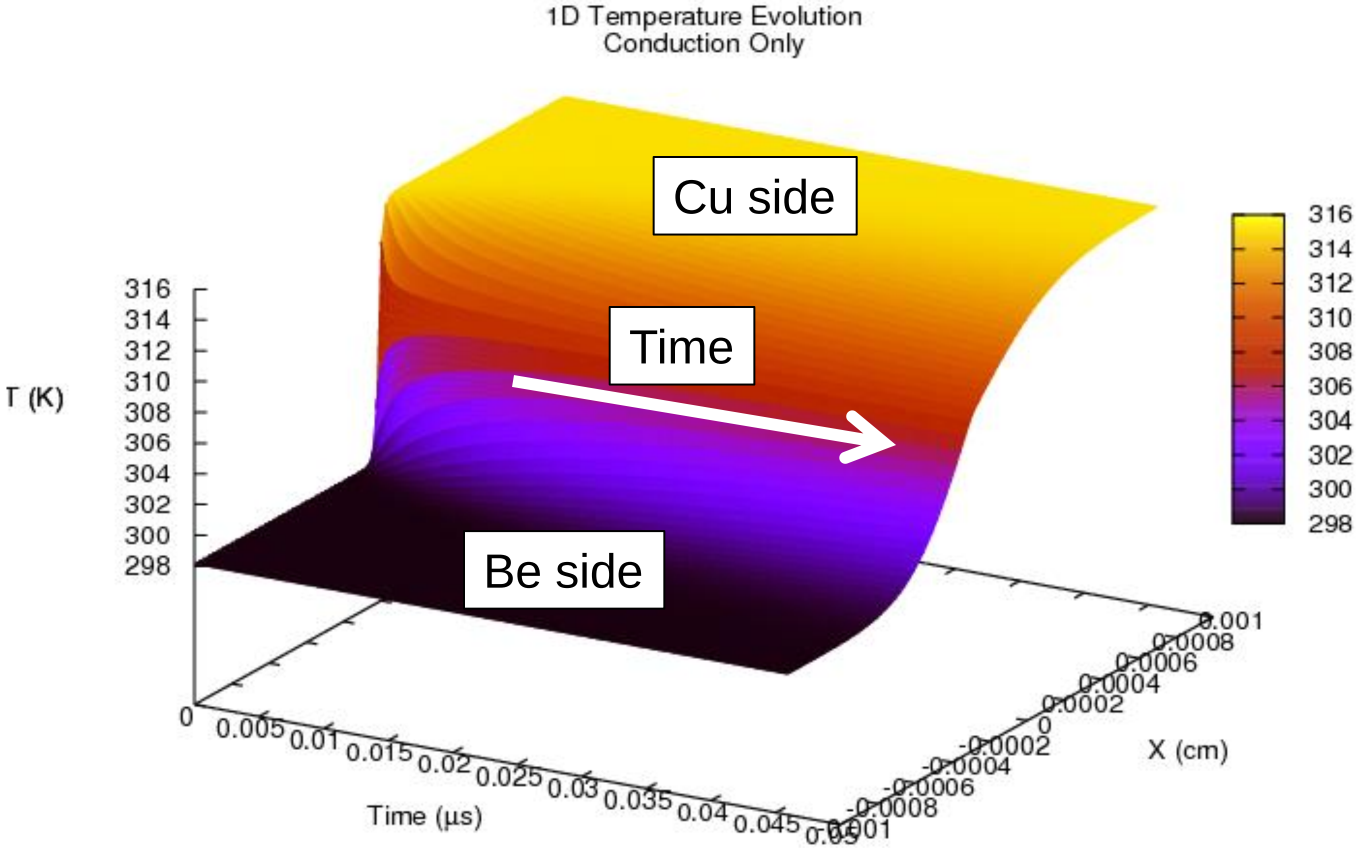
Results: Micro-scale behavior

- Will evaluate each aspect of the model at one point on the interface
- Demonstrate increasingly coupled effects



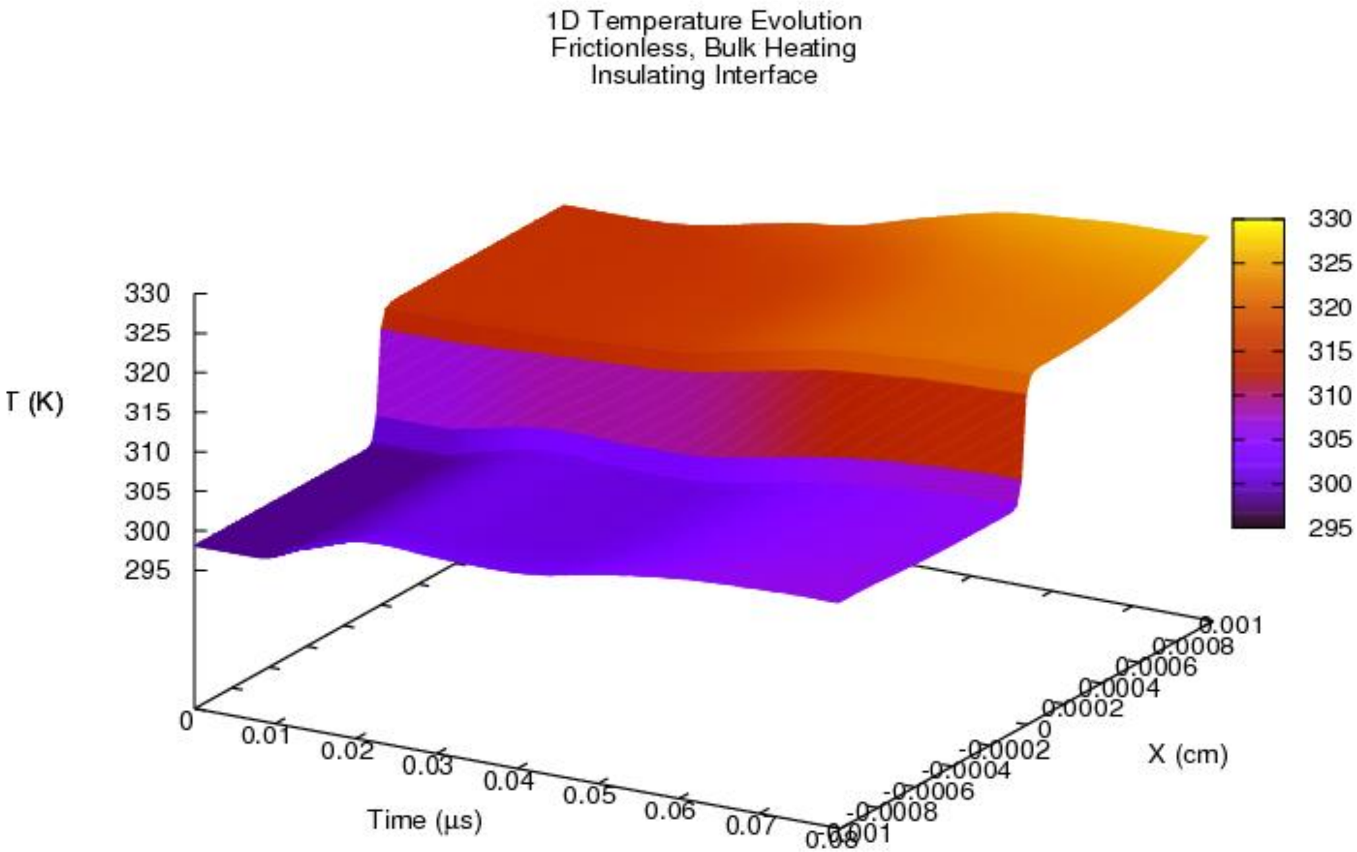
Results: Pure Conduction

- Set impact velocity to 0
- Only conduction
- Cu and Be initialize to different temperatures



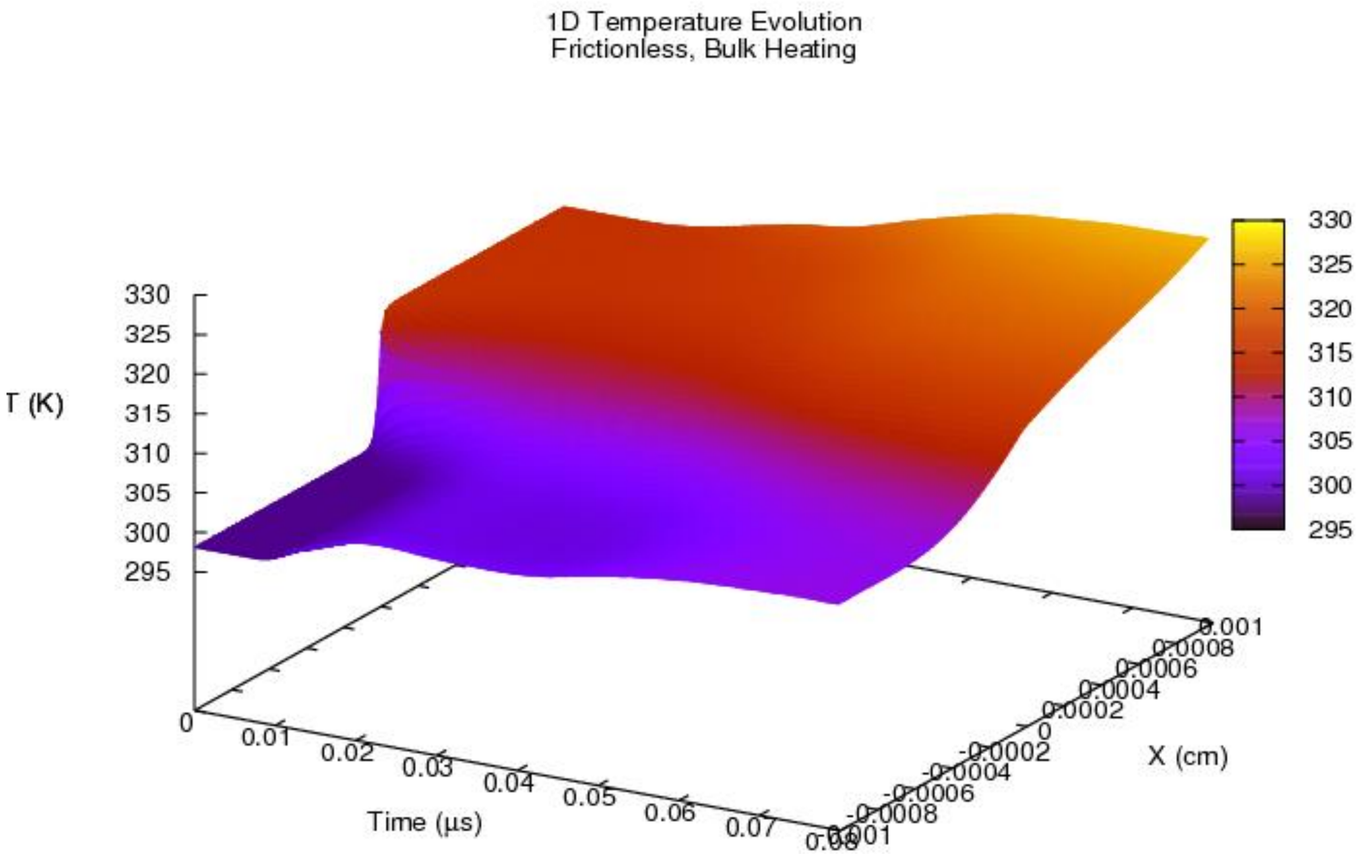
Results: Bulk Heating

- Set impact velocity to 150m/s
- Frictionless (set Coulomb friction coefficient to zero)
- Force insulating condition at contact interface
- Cu and Be heating due to macro-scale PdV work and Dirichlet BC



Results: Bulk heating with conduction

- Same as before, but conduction enabled across interface



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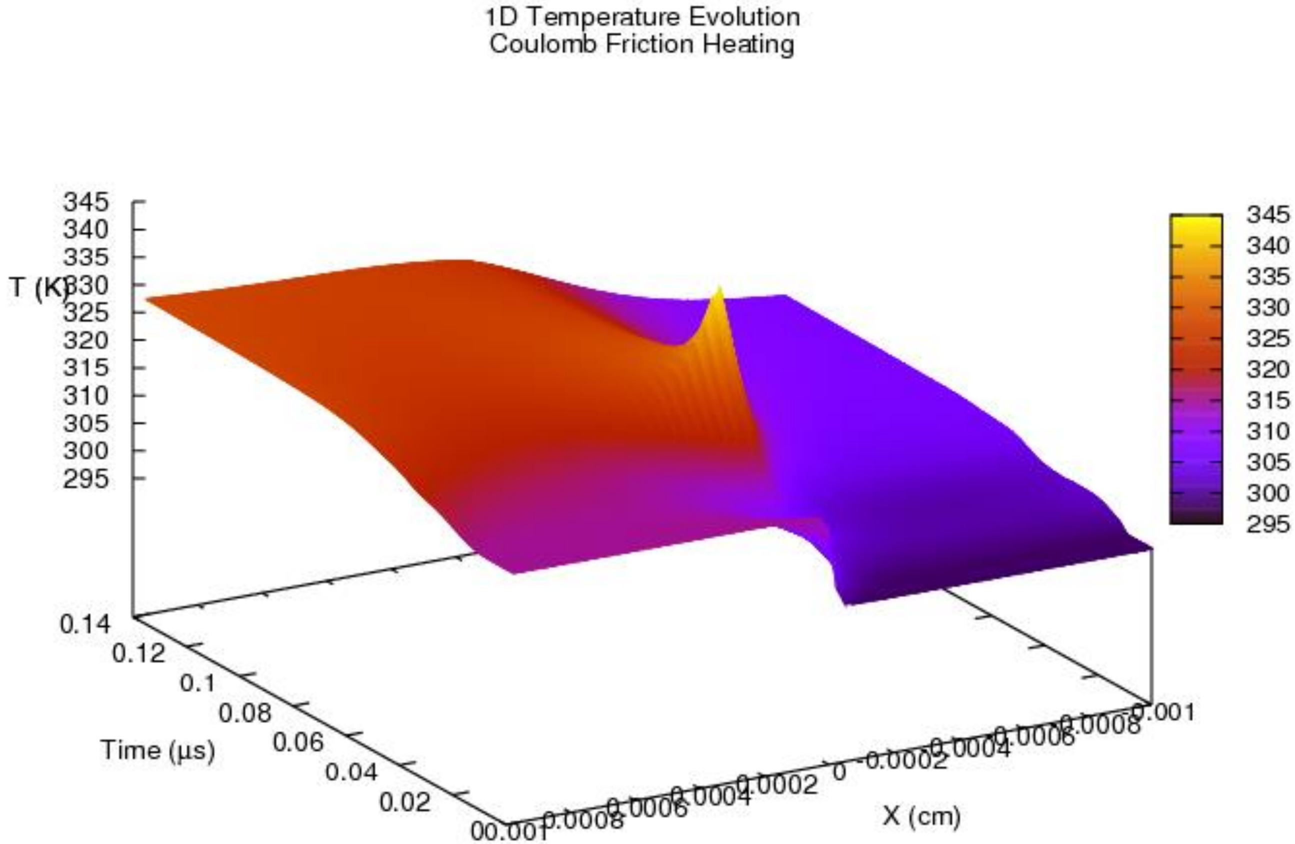
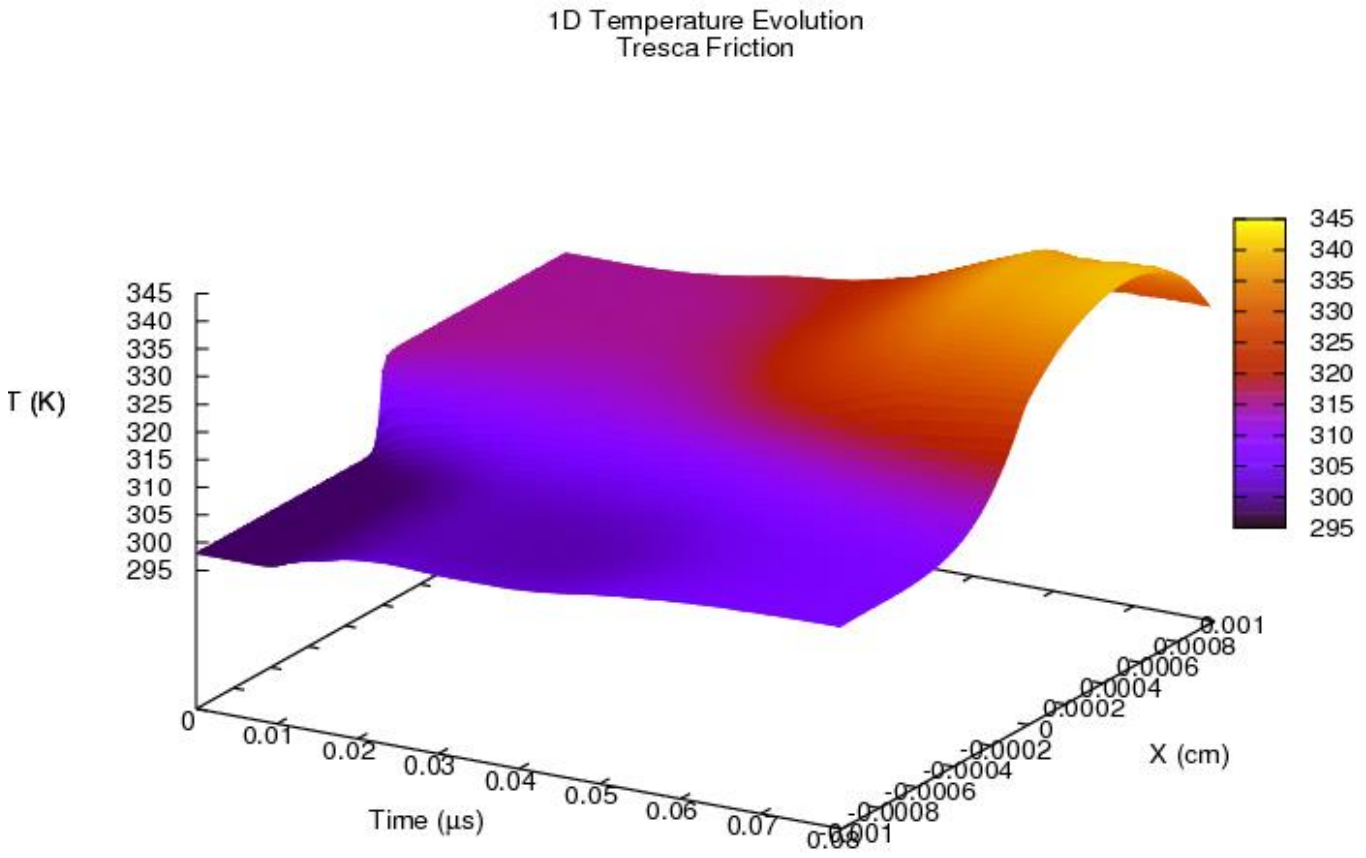
Results: Bulk and Coulomb heating

- Turn on Coulomb friction
- Set SCG Y_0 to a large number so smearing friction is disabled
- Coulomb dry friction heat source at interface until sticking condition occurs



Results: Smearing friction

- Turn off Coulomb friction (set coefficient to large value)
- Use correct SCG parameters
- Plastic work heating in Cu



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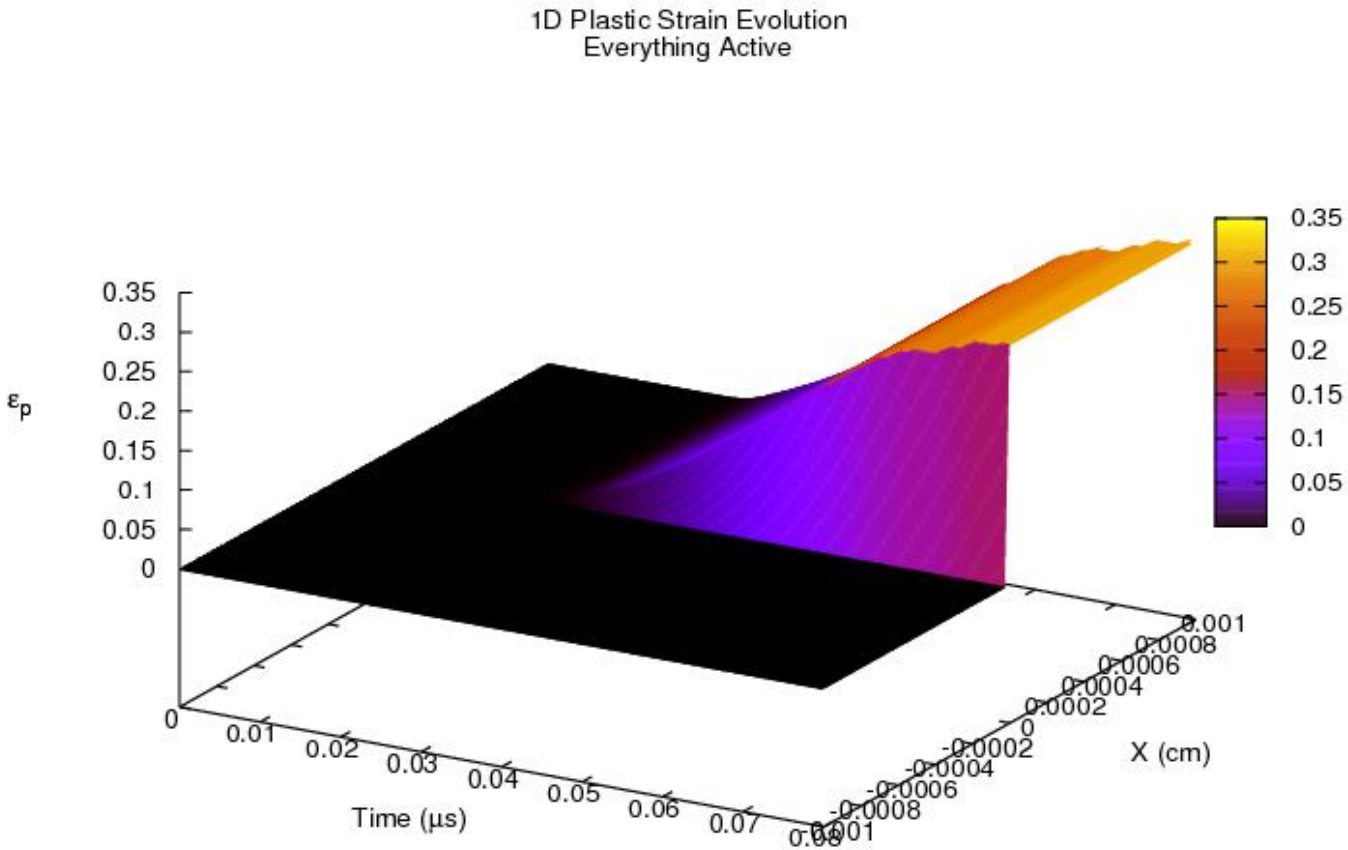
Results: Smearing friction

- Cu plastic strain field essentially constant
- Temperatures not high enough for much thermal softening
- Not much temperature difference to see strength differences



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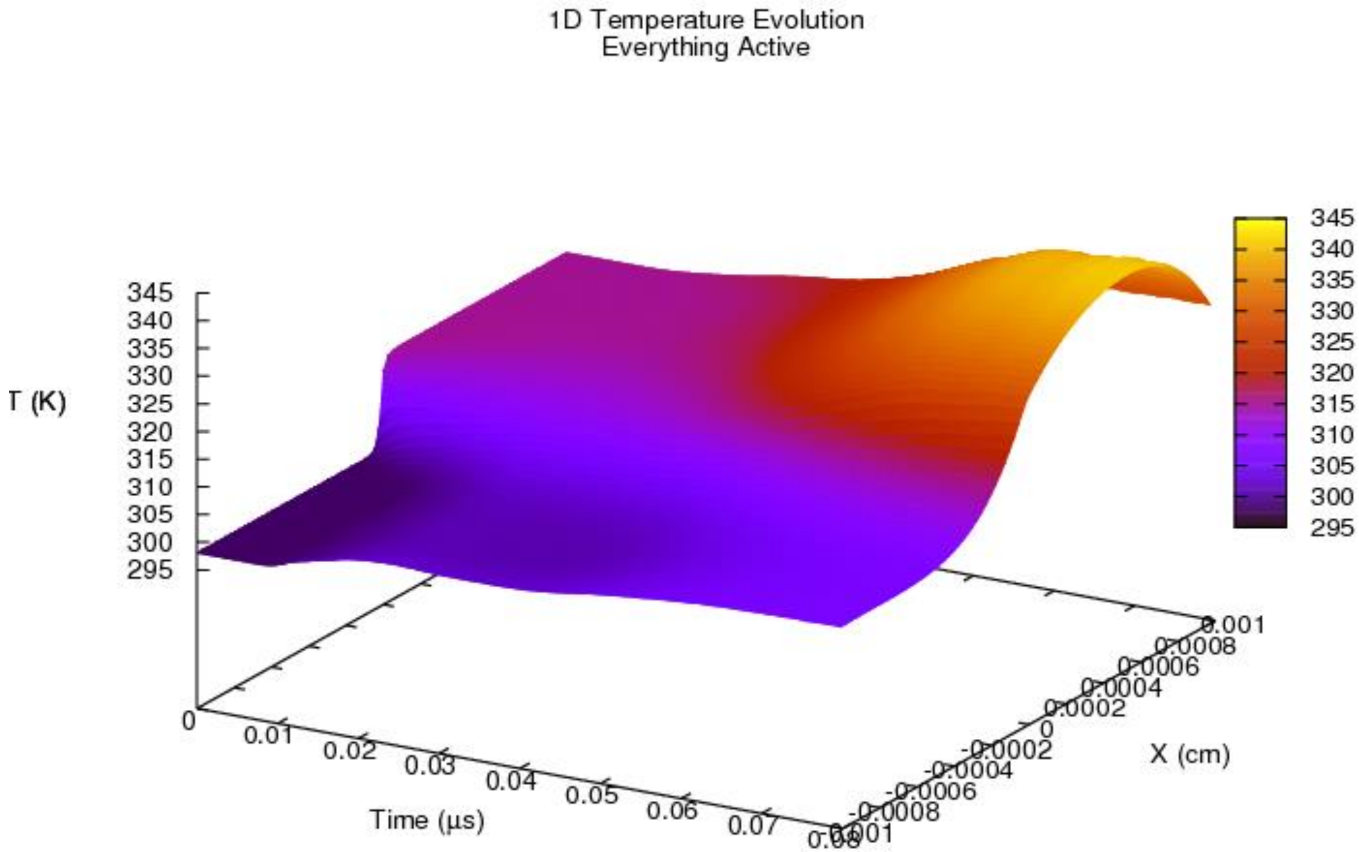
Results: Whole tamale

- Set everything to proper values
- Essentially no Coulomb friction or sticking, purely smearing



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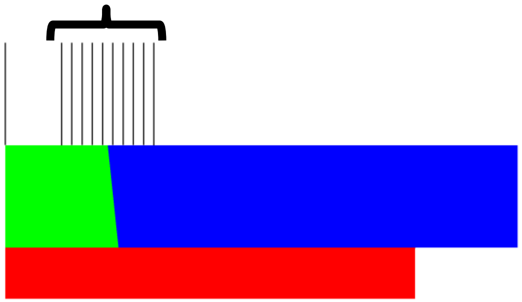
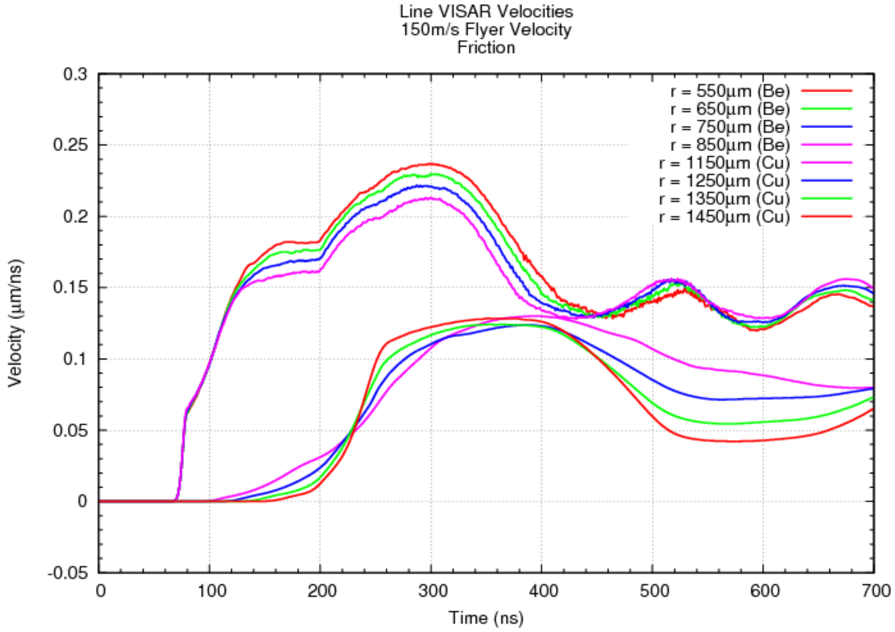
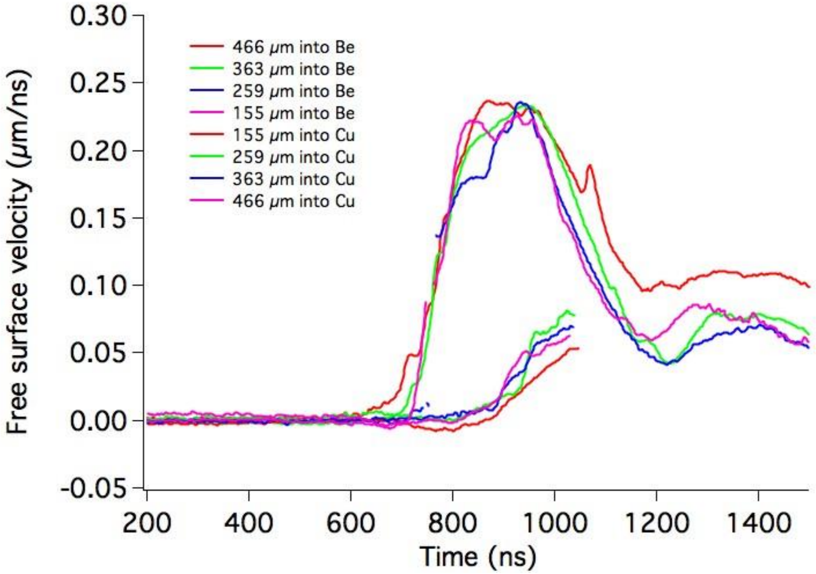
Results: Line VISAR

- Don’t understand experimental results
- Don’t follow expected trends
- Suspect experiment warrants more complicated initial conditions
- Need to simulate AWE/CEA Al/SS friction experiments







Summary

- Coupled multi-scale friction model is in FLAG
- 1D micro-scale thermal conduction coupled to macro-scale and 1D micro-scale plasticity
- Sticking, Coulomb and Tresca conditions
- Plasticity model assumes quasi-static conditions and is rate-independent
  - Biggest concern with the current model

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Conclusions

- Much of the individual aspects of the model have been tested independently and in increasingly coupled cases, works as designed
- Plasticity assumptions are invalid, but may be "sufficiently valid"?
- Friction has an effect, but better experiments need to be simulated for validation testing

Future Work

- Simulate AWE Al/SS friction experiments
- Test on integrated applications
- Replace plasticity model
  - 1D implicit elastic/visco-plastic hydrodynamics solver (velocity field, momentum equation, etc.)
  - 1D pure shear (xy) assumption
  - PTW' (or multiple) plasticity model(s)
    - Rate dependence, thermal softening, work hardening, etc.
- $\kappa(\rho, \Theta)$ for more accurate conduction