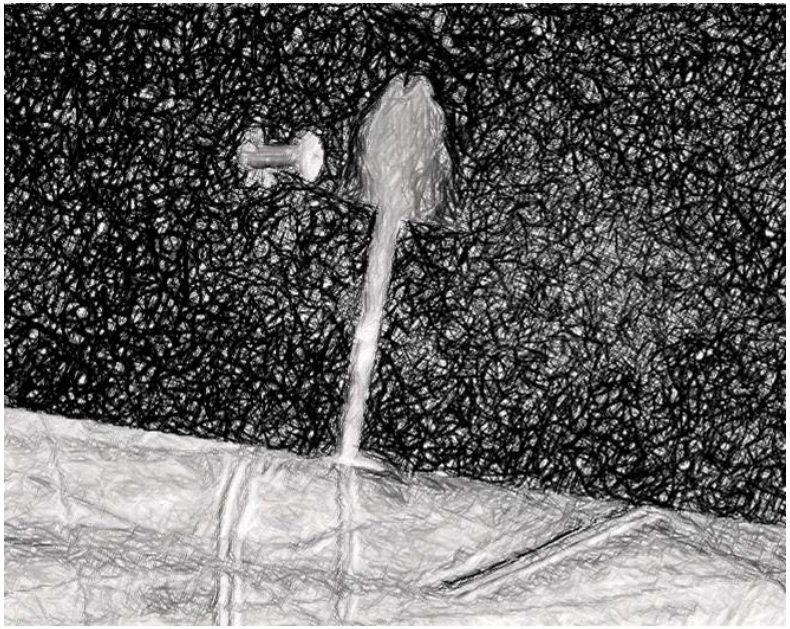
High Rate, Low Temperature Testing and Modeling of Water Ice for High Speed Ballistic Probes



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Background

- Europa is a target of high interest for Planetary Science because it could contain a liquid water ocean capable of supporting life beneath its icy shell.
- Two main questions that need to be answered:
  - How much energy is available to support life?
  - Are the necessary chemical components available to support life and if so, are indications of life present?
- These questions can be answered using ballistic penetrators
- Penetration into cryogenic ice introduces some technical challenges that we have begun addressing

Ballistic Penetrator Concepts

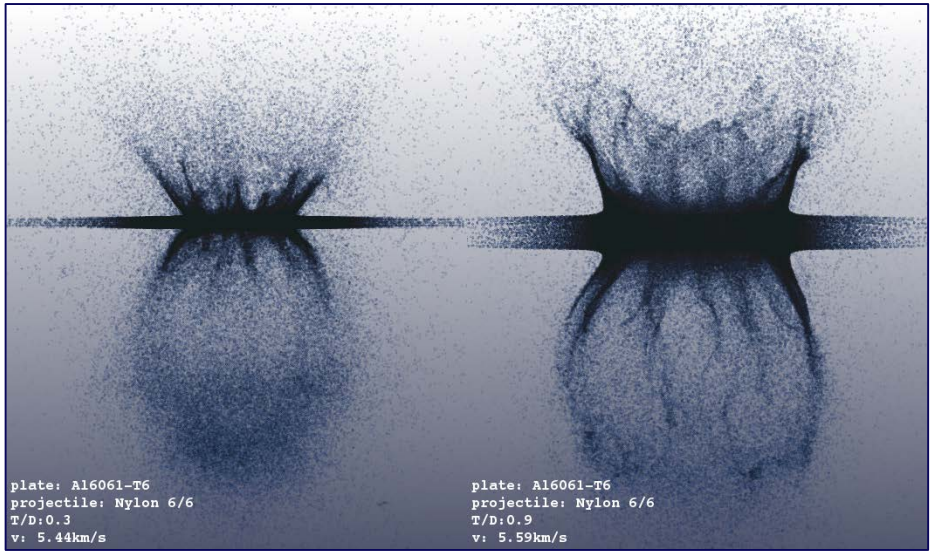
- Instrumented penetrators
  - Robust power source
  - On-board instruments for measuring organic content, seismic activity
  - Communication device for transferring data to an orbiter
- Non-instrumented penetrators
  - Capable of producing a controlled ejecta stream that can either be sampled by the orbiter for analysis, or analyzed using remote instruments on the orbiter
- Design of either type of device requires understanding of the dynamic properties of ice at cryogenic temperatures and the ability to model penetration into cryogenic ice at very high speeds

Research Objective

- Develop and utilize advanced impact analysis methods for modeling the penetration process and transport of ice ejecta
- Measure the dynamic material properties of ice over a wide range of temperatures and strain rates
- Conduct penetration experiments into cryogenic ice to investigate penetrator-nose shape effects and for model validation

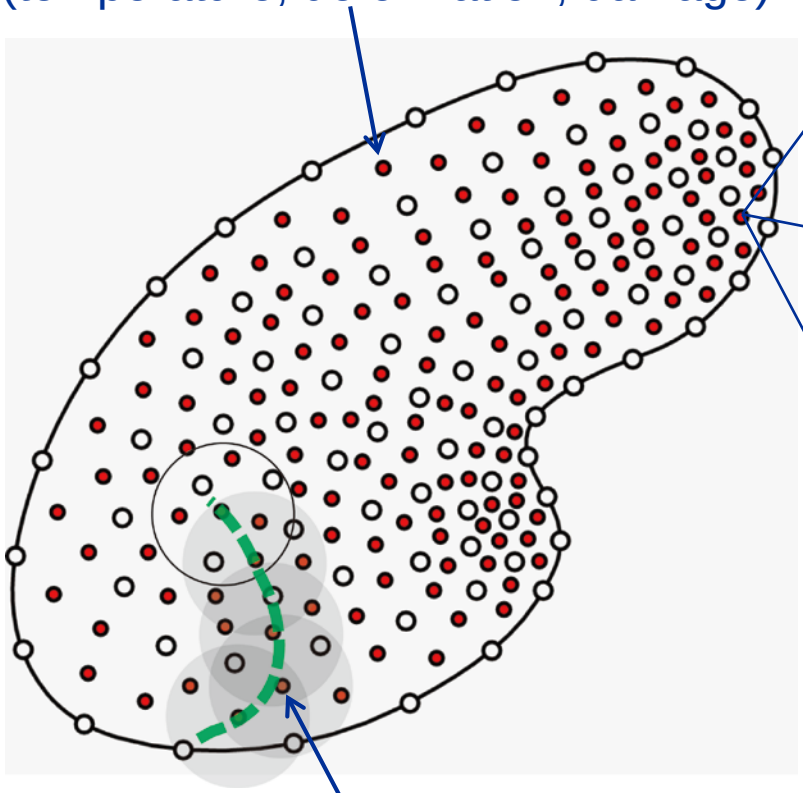
Computational Modeling

- The Optimal Transportation Meshfree (OTM) method for high- and hypervelocity impact
  - Meshfree method, no mesh entanglement, suitable for the simulation of extremely large deformation, multiphase transition and mixing (solid, liquid, gas), fragmentation and debris clouds
  - Local Max-Ent interpolation, no extra treatment for essential boundary conditions, efficient and robust solution
  - Material point sampling, numerical integration and history-dependent material responses
  - Hybrid MPI/Pthreads massively parallel implementation, perfect scalability up to $O(10^5)$ threads

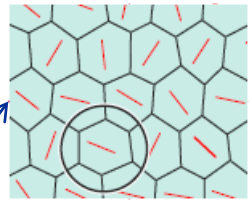


The Eigenerosion Algorithm and Micromechanics-Based Material Model for Ice

Material points
(temperature, deformation, damage)

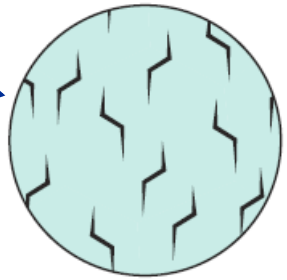


Failed material points



Intact ice :
Equation of state + shear + temperature-dependent viscosity

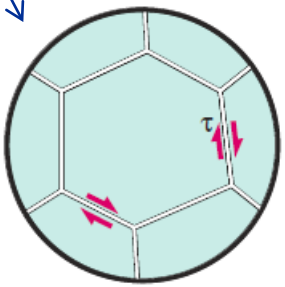
crack propagation



Microcracking
($0 < D < 1$)

Damaged ice:
Equation of state + partial shear + partial viscoplasticity (sliding friction) + temperature-dependent viscosity

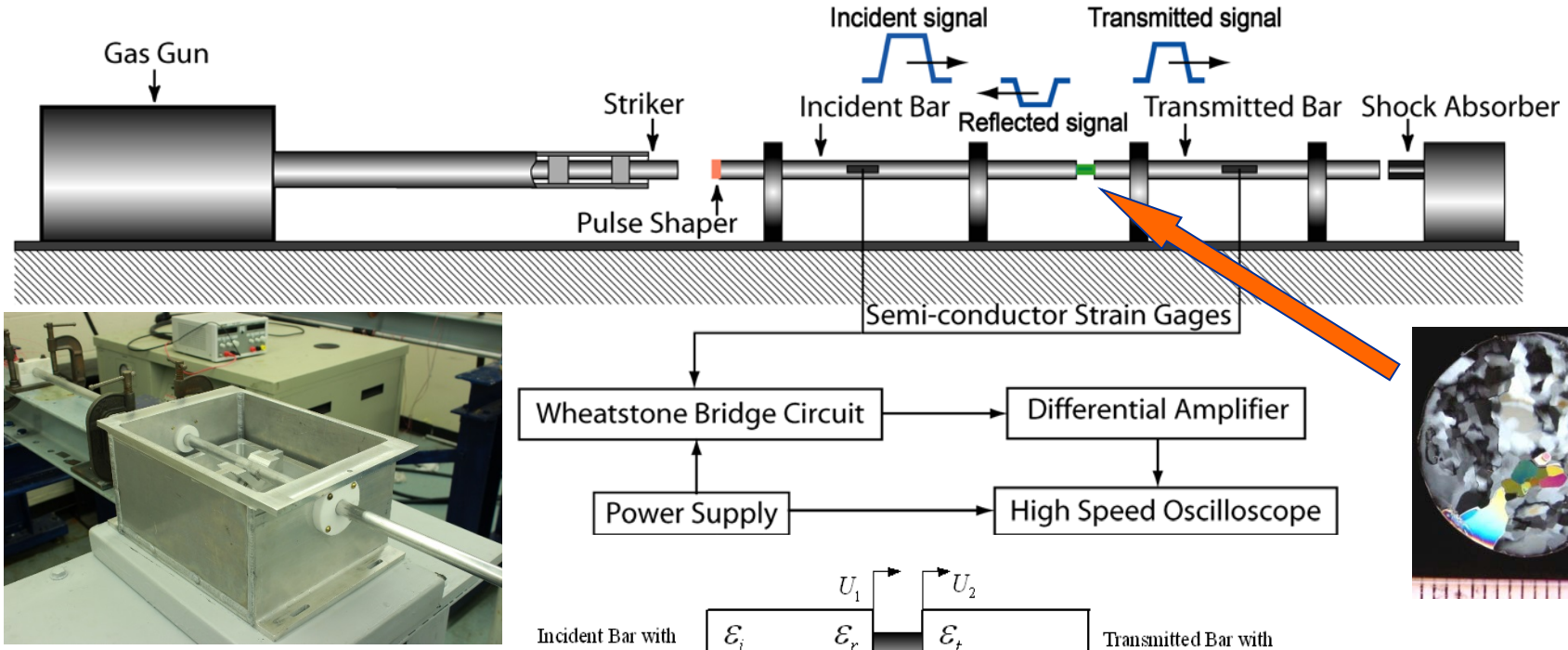
crack propagation

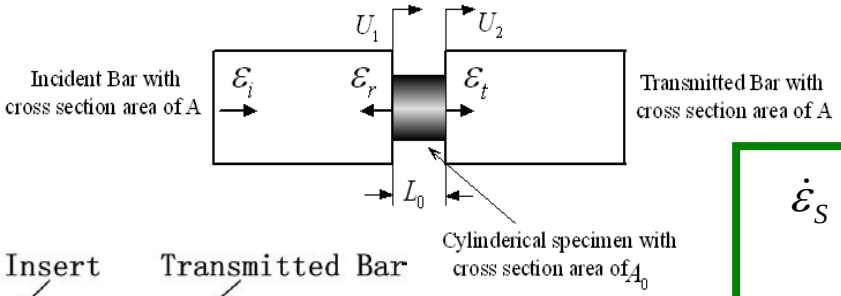


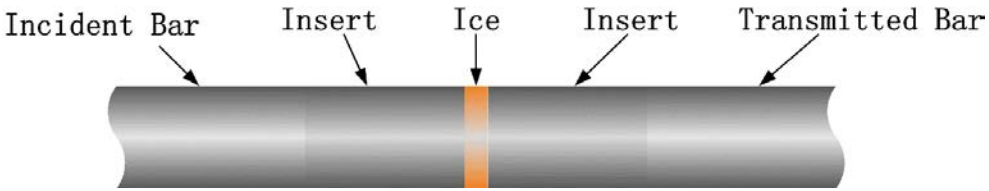
Granular plasticity
($D = 1$)

Comminuted ice:
Equation of state (tensile free) + viscoplasticity (sliding friction)

Mechanical Property Measurement







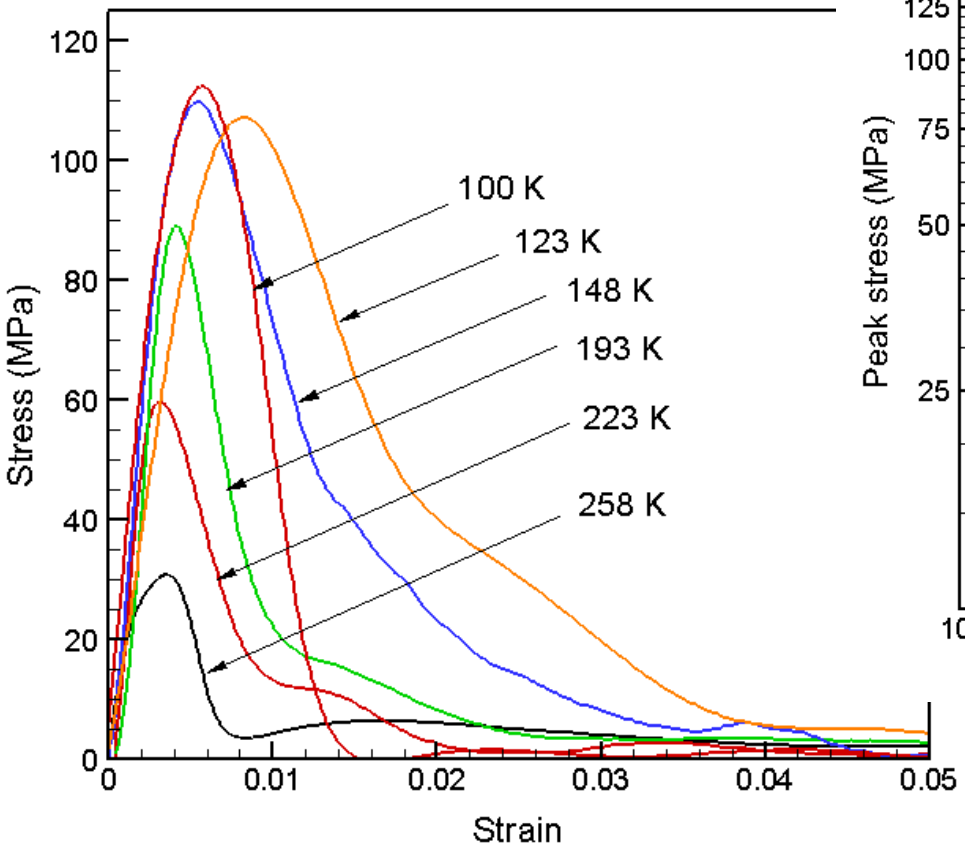
$$\dot{\varepsilon}_S = -2\frac{c_0}{L}\varepsilon_r(t)$$

$$\sigma_s(t) = E\frac{A_0}{A}\varepsilon_t(t)$$

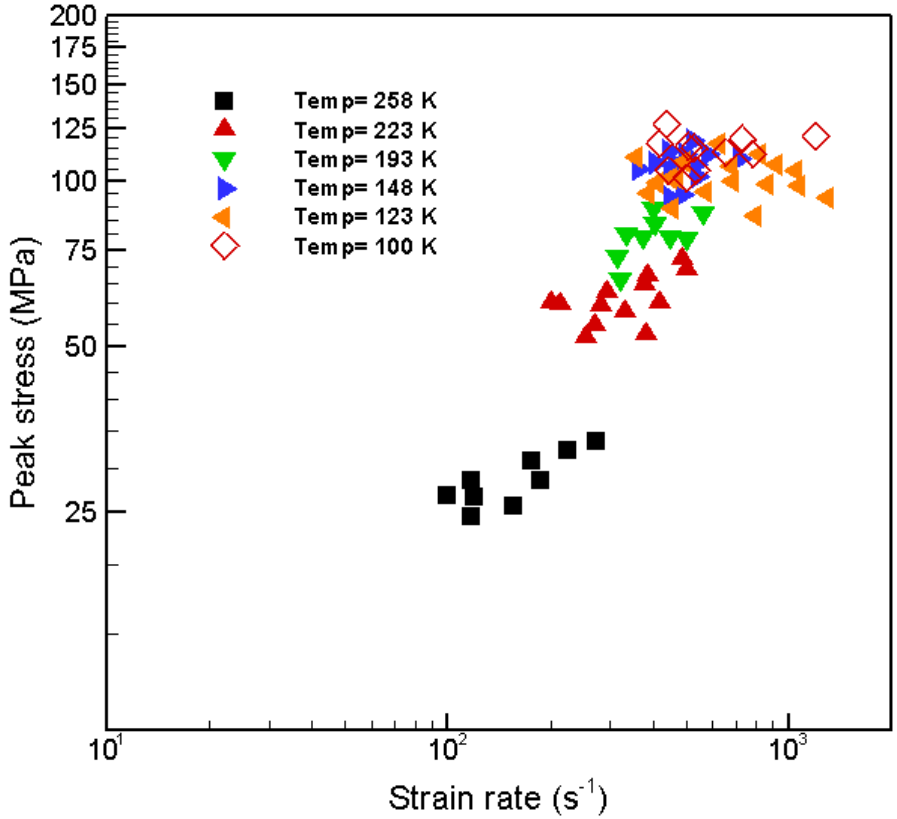
$$\varepsilon_s(t) = \int_0^t \dot{\varepsilon}_s(t)\,dt$$

Rate and Temperature Compression Testing

Typical Dynamic Stress vs. Strain Curves as a Function of Test Temperature



Peak Stress vs Strain Rate at Various Test Temperatures

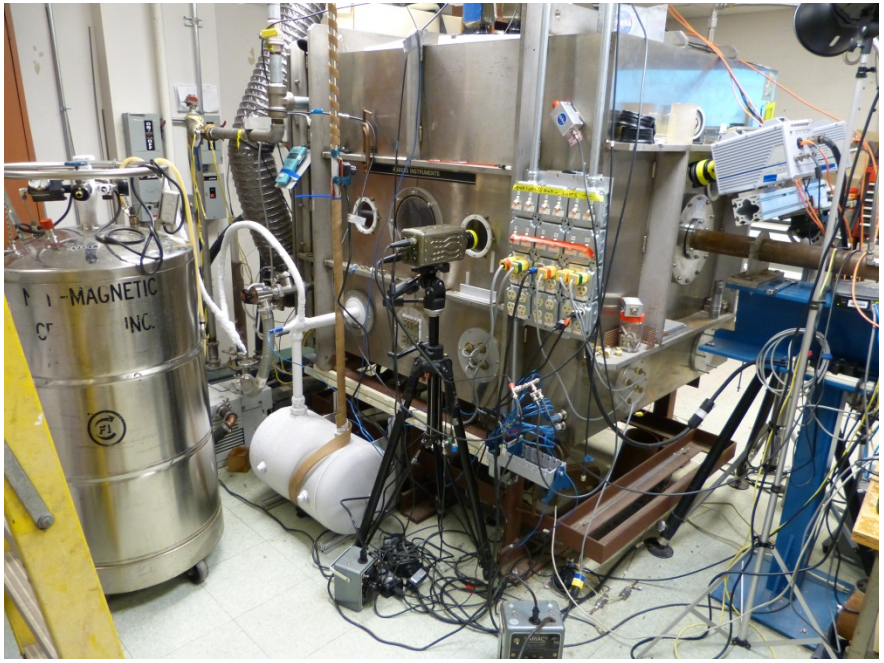


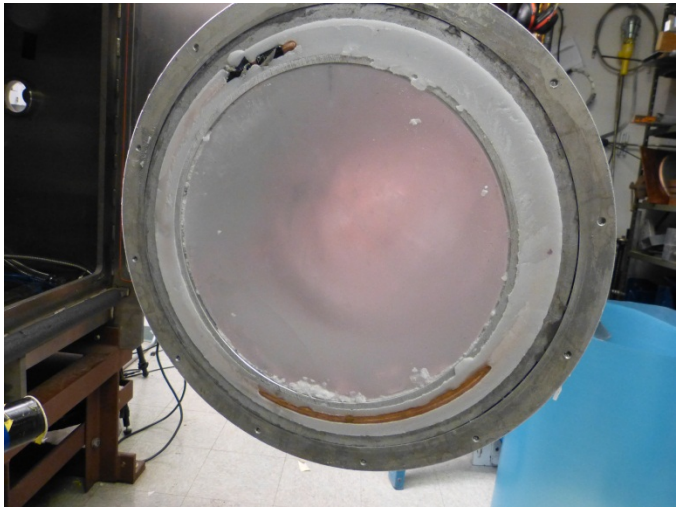
Penetration Testing

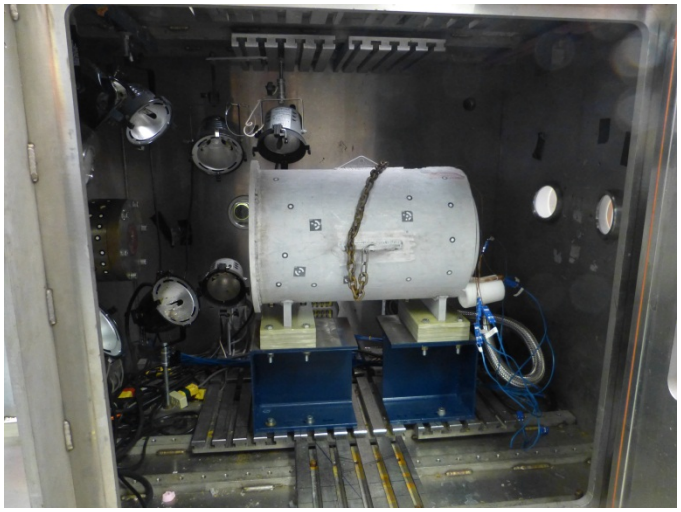
- Objective was to impact projectiles of different shapes into large blocks of ice cooled uniformly to 100K
  - Provide data for model validation
  - Explore effects of shape and a concept for generating a controlled ejecta stream
  - Hardened S2 tool steel
  - 0.5 inch (12.7 mm) diameter
  - 3-4 inches (75-100 mm) long
  - Mass: 75.4-75.8 gm
  - 79-236 m/sec impact vel

Penetration Testing

- Ice Targets:
  - Diameter 12 inches (30 cm)
  - Length 24 inches (60 cm)
  - Clear water ice
  - Uniform 100K temperature

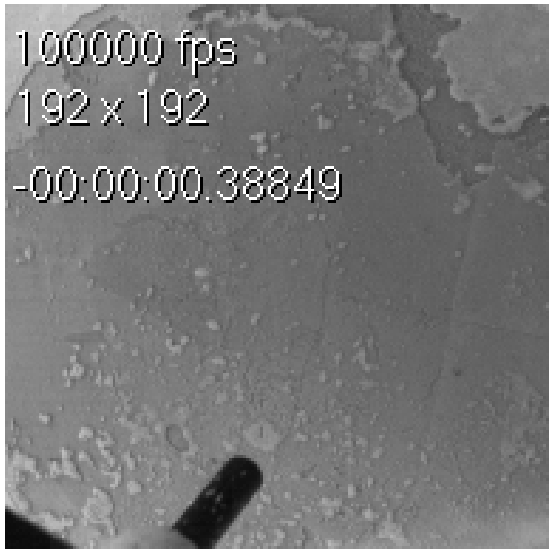


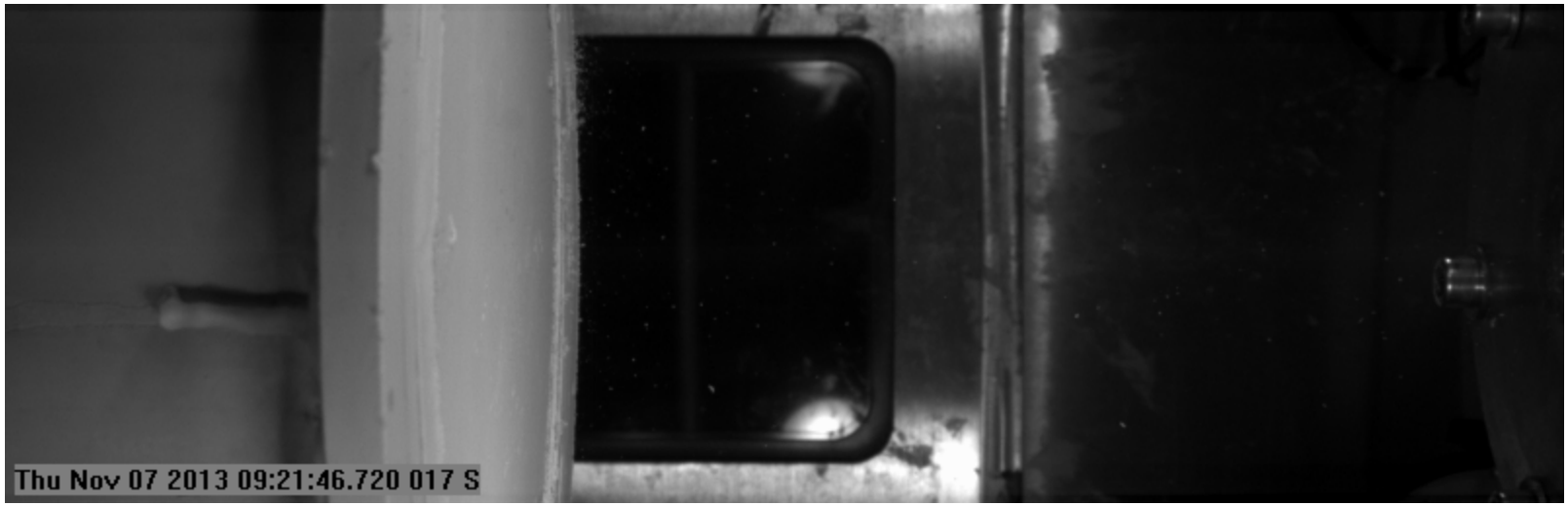




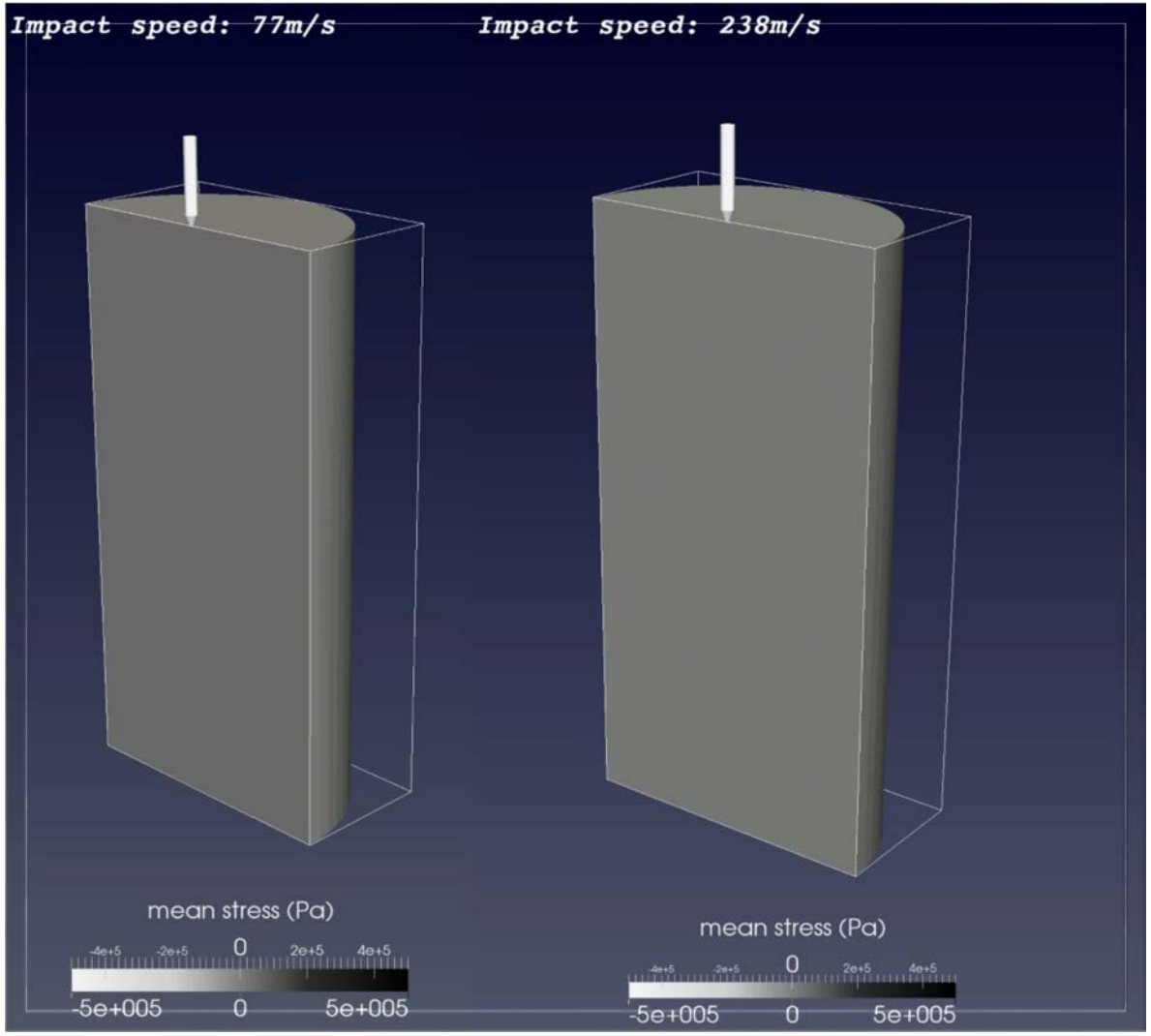
Penetration Testing

- Little difference was observed between the conical nose and flat nose projectiles (right)
- The annular projectile produces a high velocity concentrated ejecta stream (bottom)

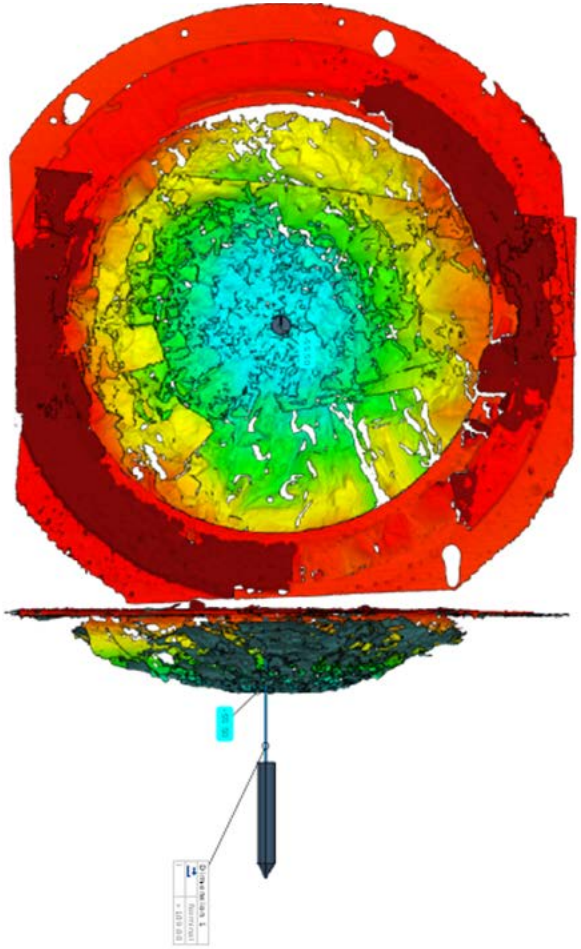




OTM Simulations of Ballistic Impact on Ice Target



Laser scan of experimental impact test on ice at 236 m/s and 100K



Next Steps

- Determine mission feasibility and costing.
- Obtain additional mechanical properties that are needed for the impact model.
  - Effects of composition (dust, salt, ammonia…)
  - Low temp., high rate fracture (G_{1C}) and friction properties
- Perform higher speed impact tests for model validation at speeds representative of a Europa impact, as determined by the mission study.
- Use the model to design a high velocity Europa penetrator.

Thank you.

I would like to thank everyone involved in this work.

At GRC:

Dr. Mike Pereira, Dr. Kelly Carney,

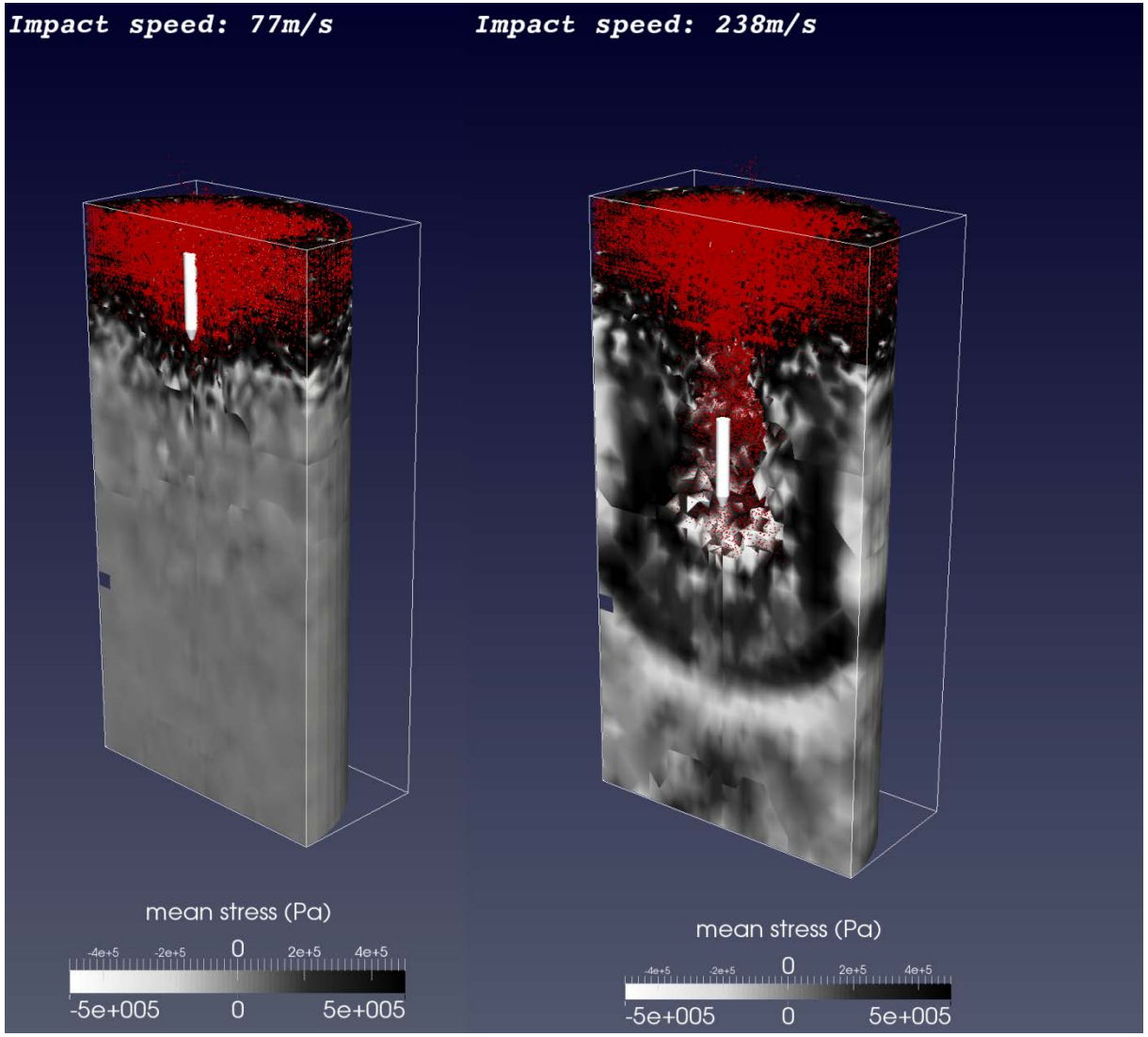
Dr. Chuck Lawrence, Duane Revilock, Chuck Ruggeri,

Jeff Hammel and Tibor Kremic

At Case Western Reserve University:

Dr. Bo Li, Dr. Vikas Prakash, Dr. Xianqian Wu

Simulation Results



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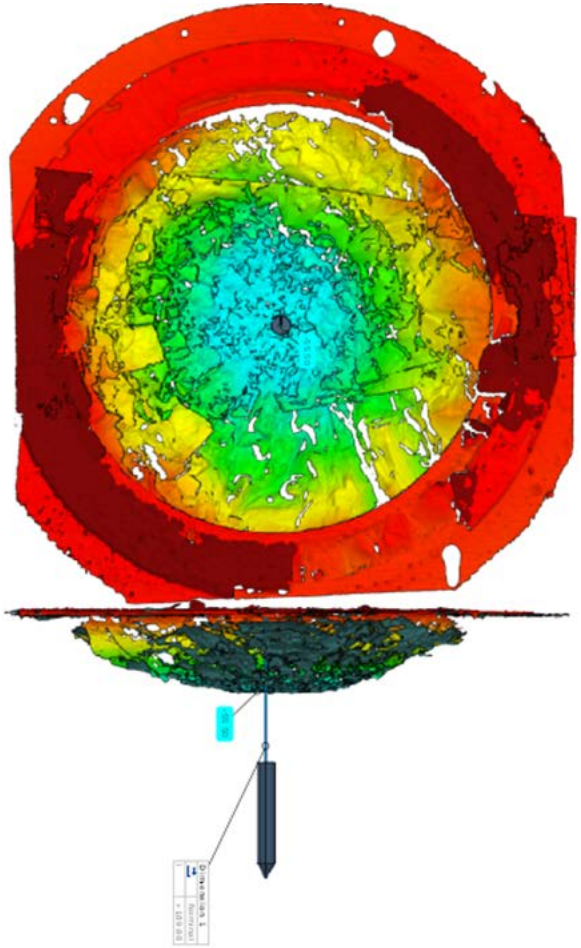
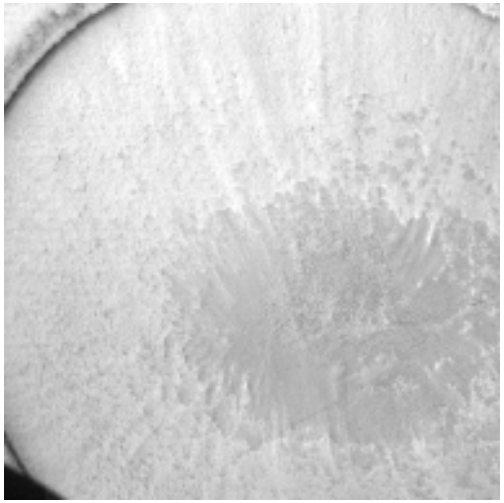
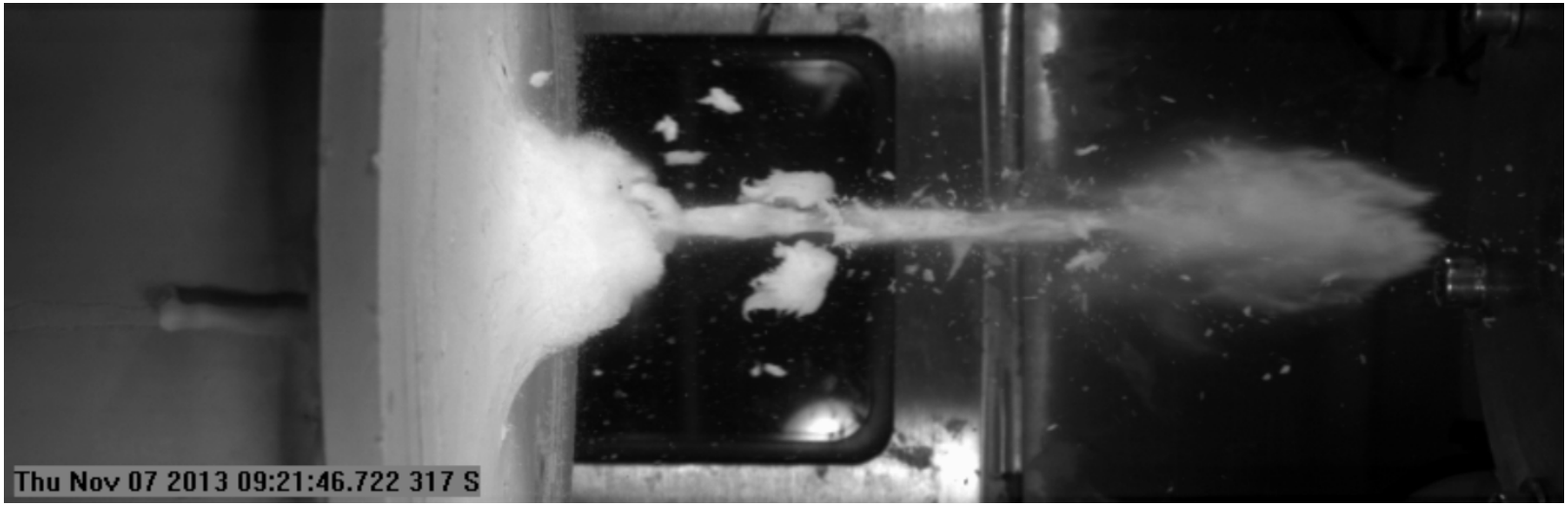


Penetration Testing Results

Projectile	Mass (g)	Impact Velocity (m/sec)	Penetration Depth (mm)	Comments
Conical Nose	75.8	79	50	Projectile produced a large crater in the ice, but bounced back
Conical Nose	75.8	234	190	Projectile produced a large crater and remained embedded in the ice
Flat Nose	75.4	236	180	Projectile produced a large crater and remained embedded in the ice
Annular	75.4	236	163	Projectile produced a large crater and remained embedded in the ice. A stream of ice particles exited back through the annular hole of the projectile at a speed of 455 m/sec (double the impact velocity)

Extra

- Annular projectile impact, front view
- Still image of side view