Exploring Blast-Structure Aerodynamics and Response in a Shock Tube

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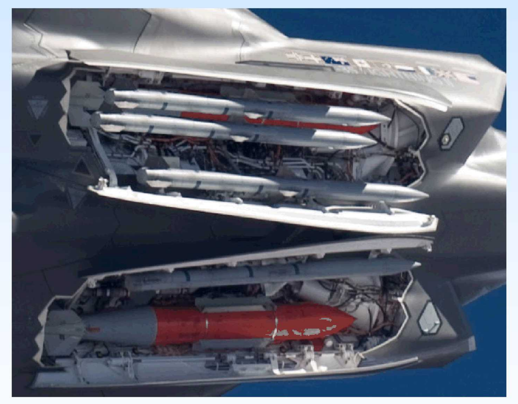
1: SNL, Org. 1515
2: SNL, Org. 1512
3: SNL, Org. 1556

Motivation of Project

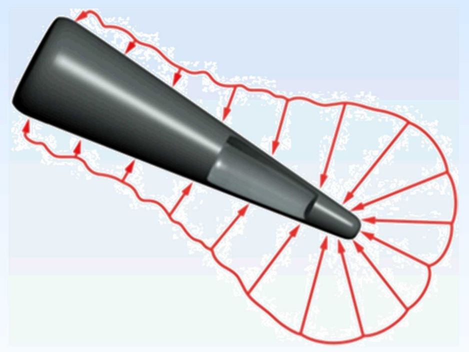
Predicting how energy is transferred from the flowfield throughout the structure in our blast-structure and fluid-structure interaction (BSI and FSI) simulations remains quite challenging.

Modeling Applications

Cavity resonances in weapons bays



Loading during hypersonic reentry

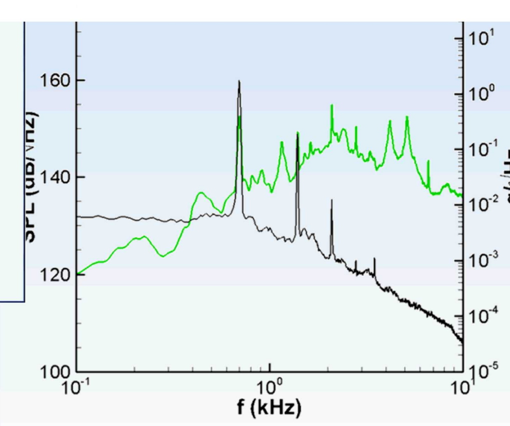


Numerous challenging modeling issues…

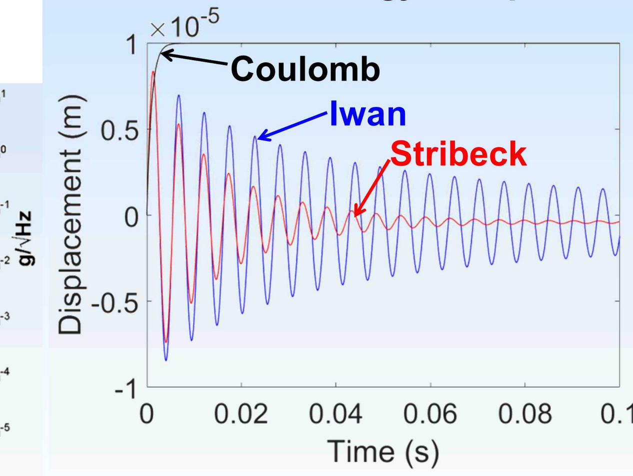
1. Response of structures to fluid dynamic loading
2. Response of structures to blast loading
3. Energy dissipation in jointed structures

Current Limitations

Flow-structure resonances amplify structural responses



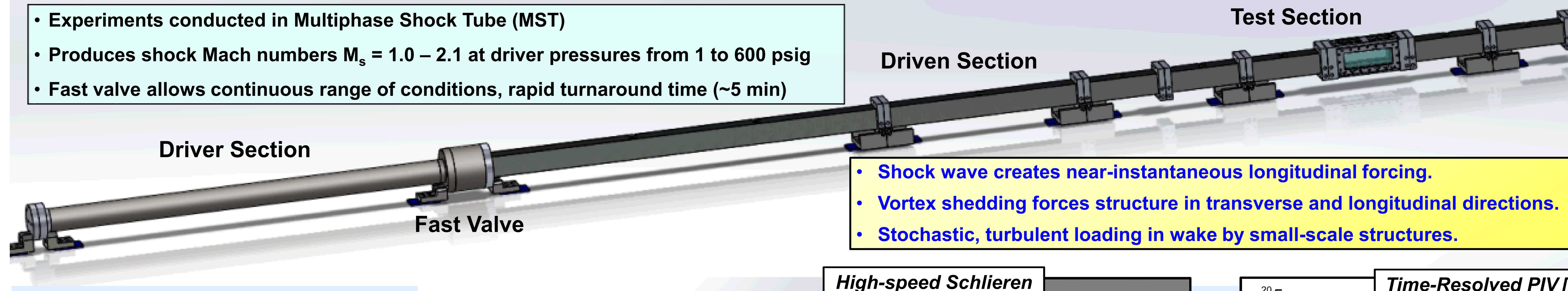
Different joint models yield wildly different energy dissipation



Hypothesis: Well-controlled experiments with diagnostics that spatially and temporally capture the underlying fluid dynamic and structural physical phenomena are required to reduce model form error

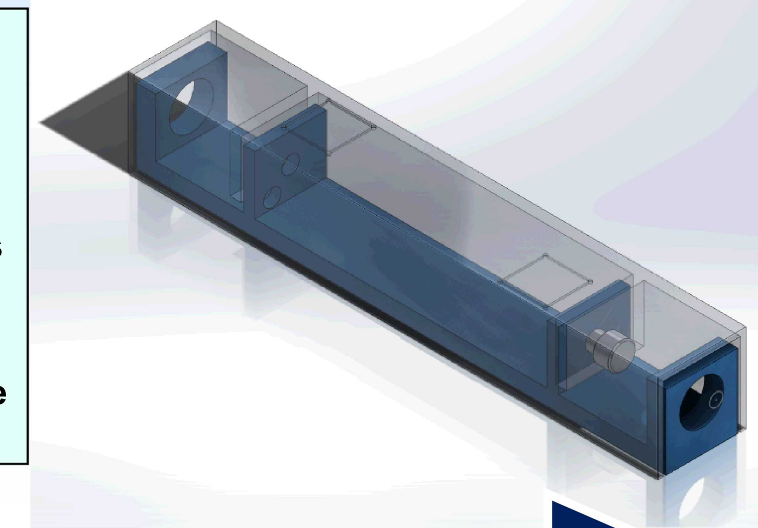
Shock Tube and Test Models

- Experiments conducted in Multiphase Shock Tube (MST)
- Produces shock Mach numbers M_s = 1.0 – 2.1 at driver pressures from 1 to 600 psig
- Fast valve allows continuous range of conditions, rapid turnaround time (~5 min)

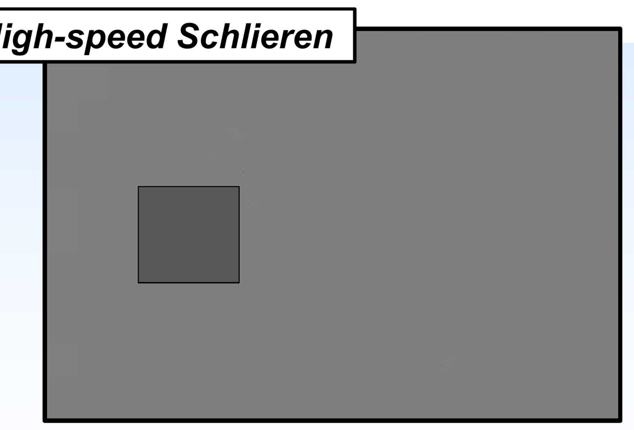


- Shock wave creates near-instantaneous longitudinal forcing.
- Vortex shedding forces structure in transverse and longitudinal directions.
- Stochastic, turbulent loading in wake by small-scale structures.

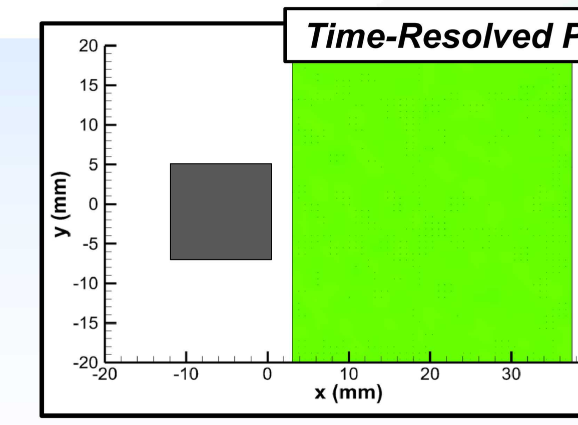
- Model design proposed by structural modeler Adam Brink (1553)
- Two parts: Rigid inner support, C-shape outer shell
- Bolted connection on flanges creates contact patch for interaction.
- Simulations indicate experimental structure exhibits nonlinear response when subjected to shock loading



High-speed Schlieren



Time-Resolved PIV [1]



Physically rich loading with greater strength than simple impact hammer or shaker table testing

Enables

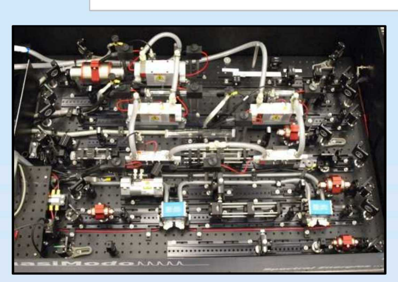
Novel Diagnostic Development

1. Flowfield with Tomographic PIV

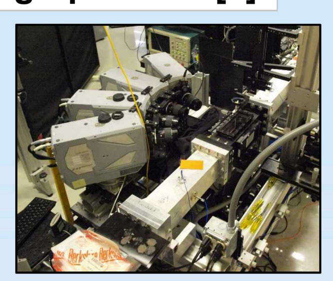
- Extend *planar* particle image velocimetry to a *volume*
- Uses multiple views to perform tomographic reconstruction of particles
- Cross-correlation in 3-D: correlates small regions of reconstructed volumes
- Captures all velocity components, full velocity gradient tensor

Generally limited to *small volumes and low speeds* due to limited laser energy…

Pulse-Burst Tomographic PIV [2]

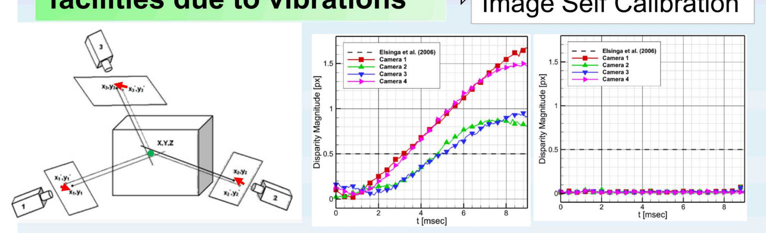


Spectral Energies Pulse-Burst Laser

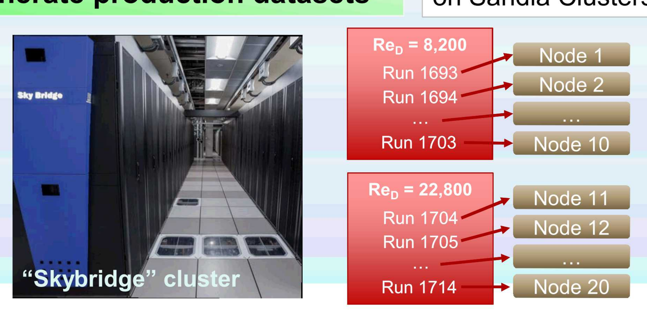


4 x Photron SA-Z Cameras

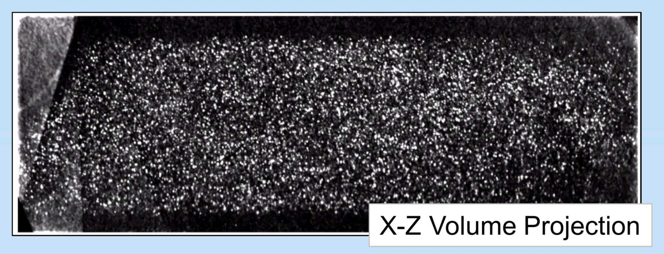
Rarely applied in industrial facilities due to vibrations ⇨ Implemented Single-Image Self Calibration



Computationally heavy, can't generate production datasets ⇨ Scalable Parallelism on Sandia Clusters

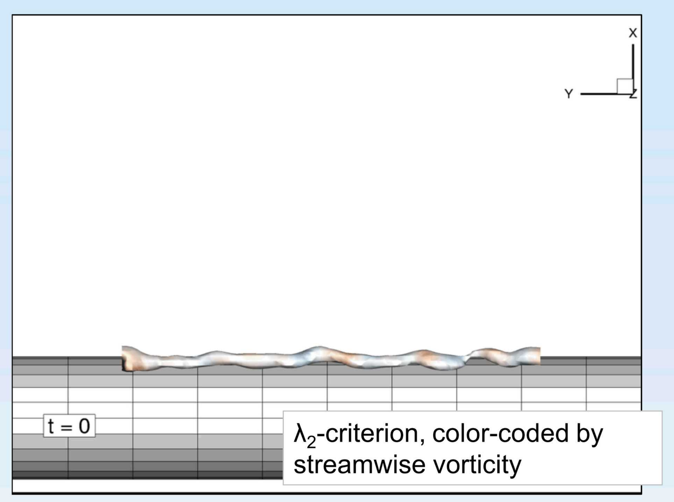


Particle volumes successfully reconstructed in presence of significant facility vibrations!



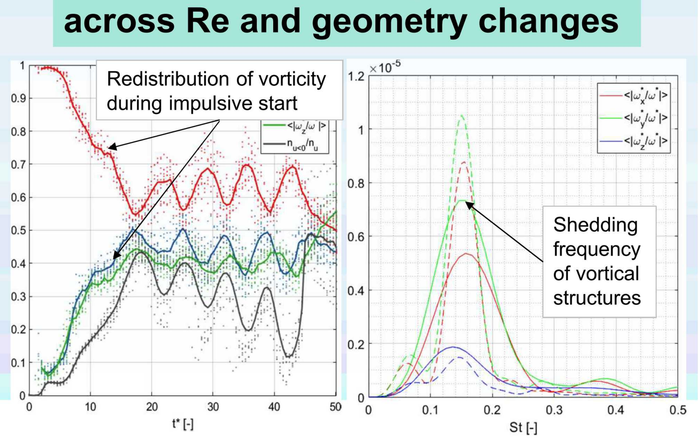
X-Z Volume Projection

Ful vorticity vector: vortex detection criteria visualize impulsive flow development



λ_2-criterion, color-coded by streamwise vorticity

Big data sets: identify important trends in flow development, across Re and geometry changes



2. Loading with Fast PSP

- Use fast-response pressure sensitive paint to characterize unsteady, asymmetric loading on the structure
- PSP is critical: extremely difficult to fully instrument small models with traditional transducers (Kulites, PCBs)

Traditional fast-PSP degrades quickly, has low brightness, and high temperature sensitivity

⇩

RTV-based Fast PSP

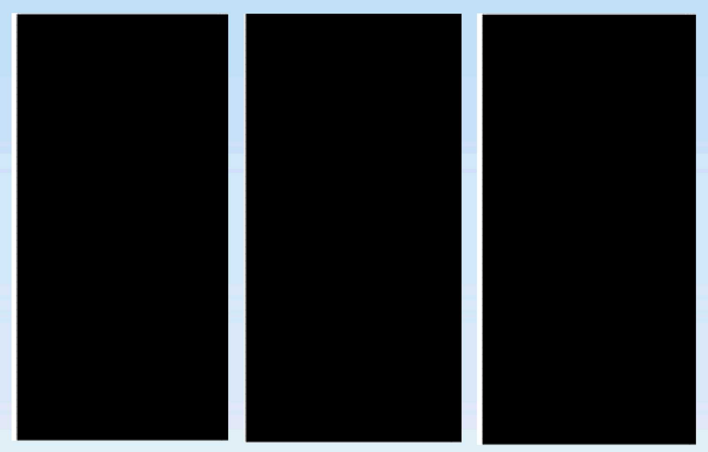
- New paint formulation from Prof. Egami (Japan) being tested for use in shock tubes and wind tunnels

Ratiometric PSP highly sensitive to model vibrations due to reference image misalignment

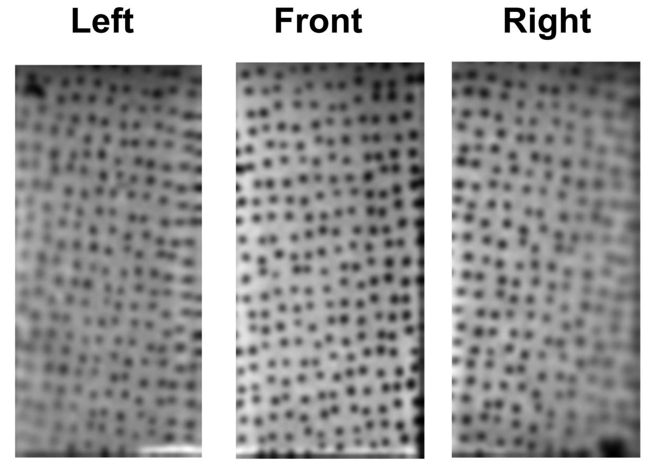
⇩

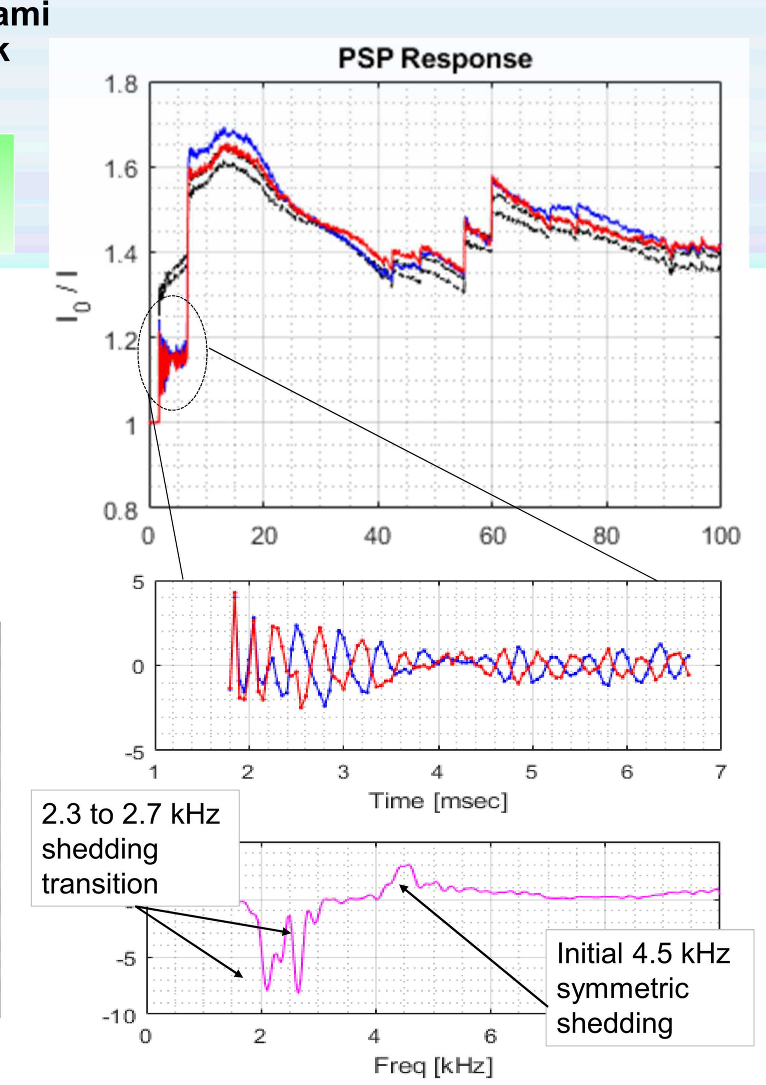
DIC Speckle Image Registration for Ratiometric PSP

- Corrects for misalignments to reference image. *Simultaneously* allows for a DIC measurement.



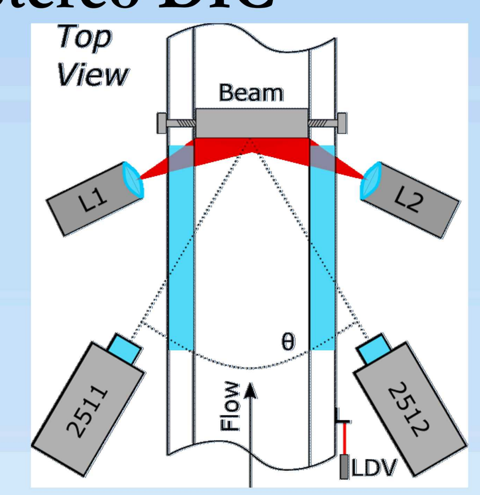
Left Front Right



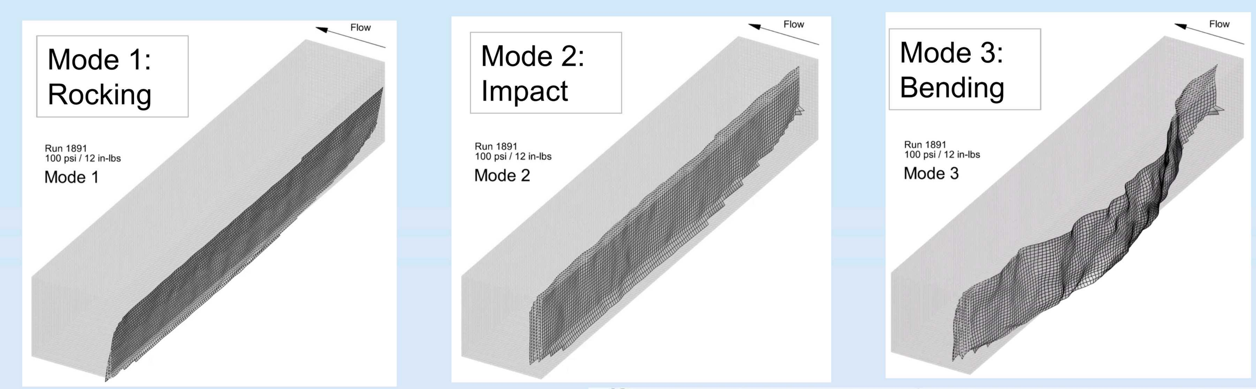


3. Response with Stereo DIC

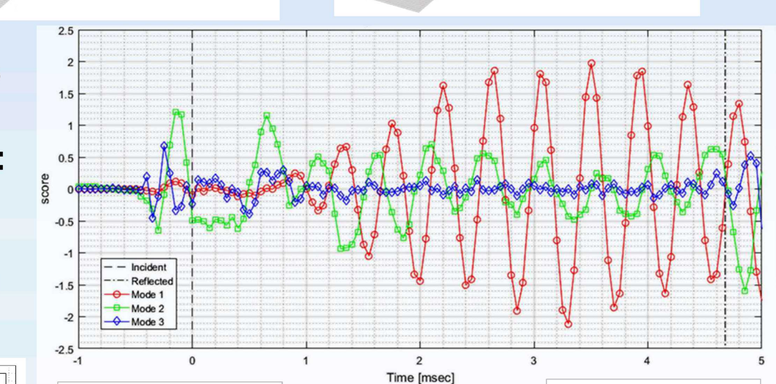
- Structural response measured using Stereo DIC on front face of beam
- 2 x Phantom v2511s used with Schiempflugs to optimize signal at high frame rates
- Cavitar supercontinuum lasers used for monochromatic pulsed illumination

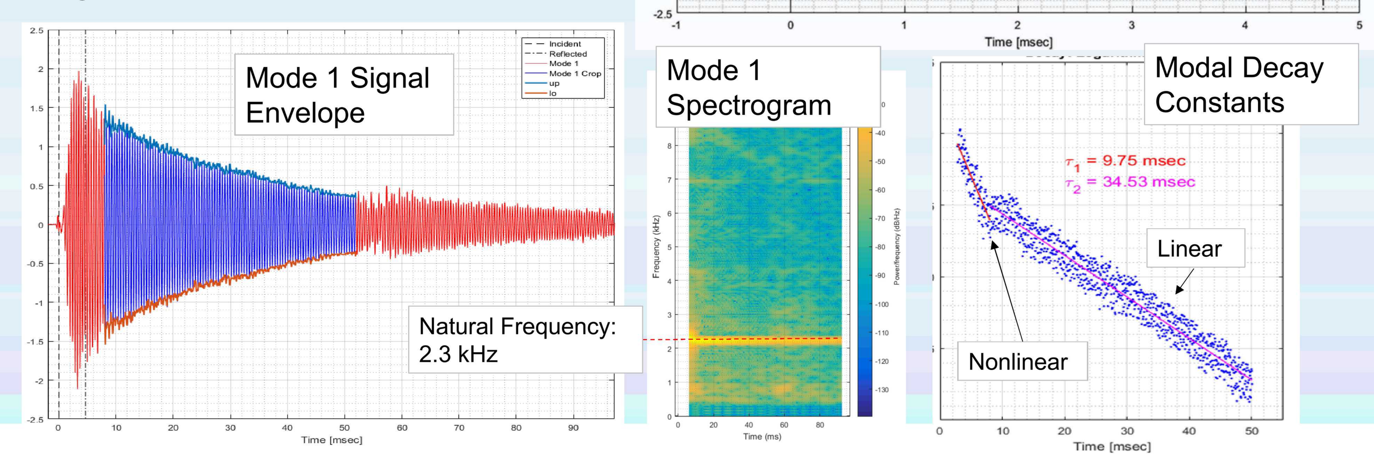


Principal Components Analysis (PCA) extracts dominant displacement modes



- Time-dependent mode coefficients illustrate varying mode dynamics
- Effective dimensionality reduction: reduce large, complex full-field dataset to simple time traces
- Analyze structural ringdown using only modal coefficients!

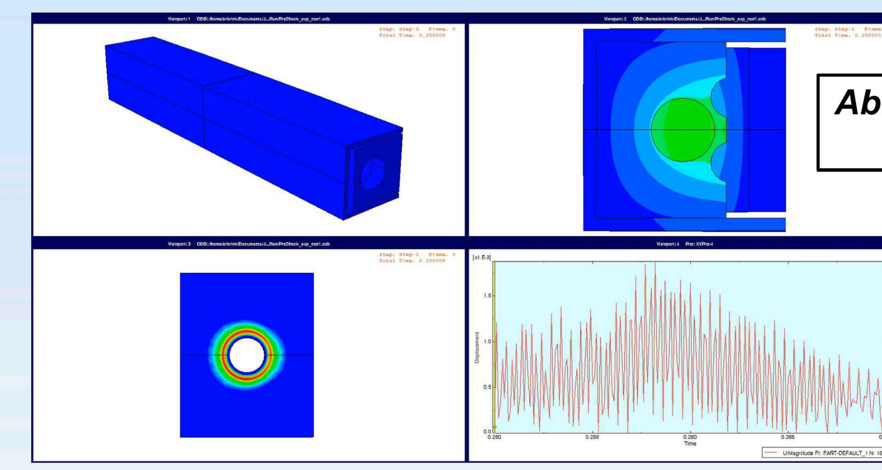




Model Development

- Modeling effort together with Dane Quinn (Univ. Akron)
- Improved models incorporated into Abaqus FE: joints use four-parameter Iwan ROM.
- Incorporates nonlinear stiffness and damping of jointed connection.

$$F(t) = \int_0^\infty \bar{\rho}(\bar{\phi})k[u(t) - \bar{x}(t,\bar{\phi})]\,d\bar{\phi}$$



Abaqus Simulation of Beam

Model parameters ϕ are user-specified: PSP + Stereo DIC data provide dataset for proper tuning.

Journal and Conference Papers

1. JL Wagner, EP DeMauro, KM Casper, SJ Beresh, KP Lynch, BO Pruett (2018) Pulse-burst PIV of an impulsively started cylinder in a shock tube for Re > 10^5. Accepted for publication in *Experiments in Fluids*.
2. KP Lynch, JL Wagner (2018) Time-resolved pulse-burst tomographic PIV of impulsively-started cylinder wakes in a shock tube. AIAA SciTech Conference.
3. EC Quintana, EMC Jones, PL Reu, J Wagner. X-Ray based Digital Image Correlation for Fluid-Structure Interactions. International Digital Image Correlation Society. Barcelona, Spain November 2017.

Acknowledgements

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Sandia National Laboratories

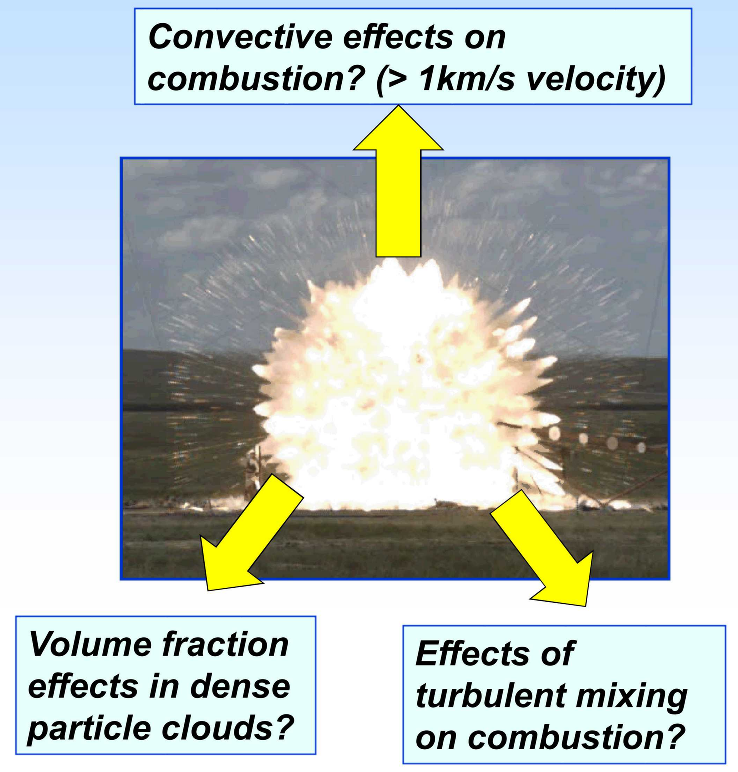
A High-Temperature Shock Tube for Creating Extreme Environments

Kyle Lynch[1] and Justin Wagner[1]

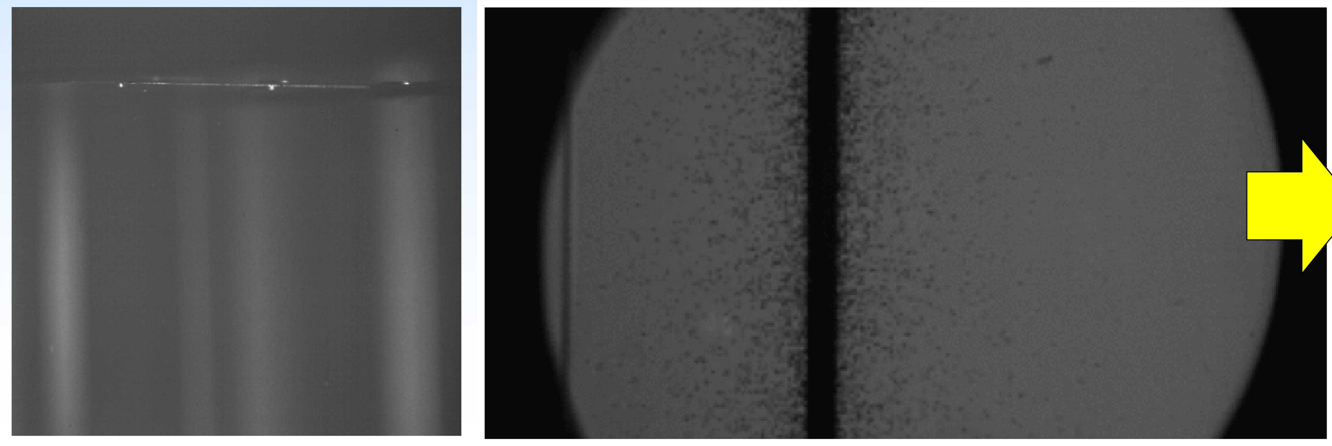
1: SNL, Org. 1515

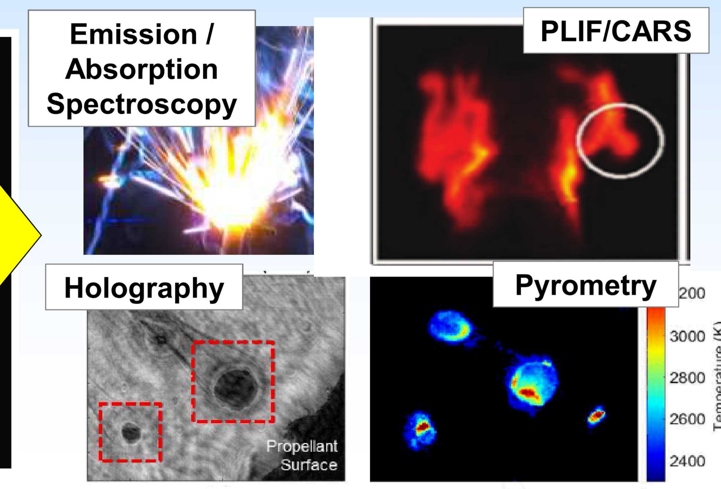
Motivation of Project

Create a lab-scale facility to generate *extreme environments* representative of explosives. This enables fundamental study of physical processes occurring in convective, reacting, multiphase flows.



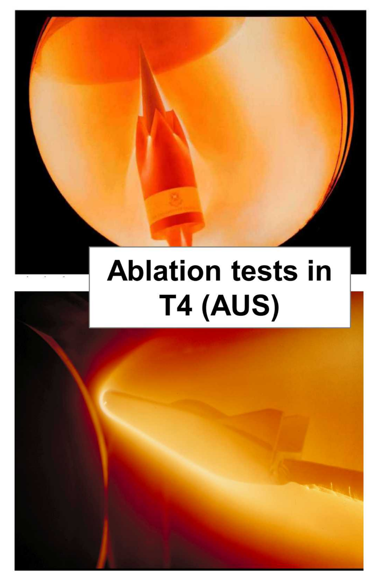
Extend work on inert particles (glass/steel) to reactive mixtures (Mg/Al). Characterize reacting products using particle and gas-phase diagnostics.

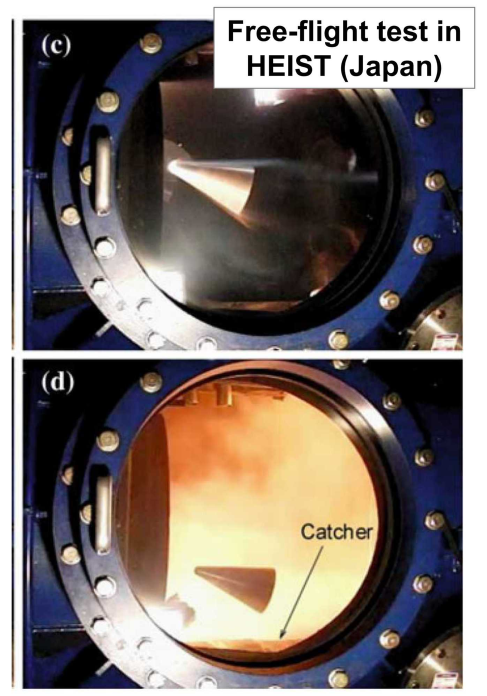


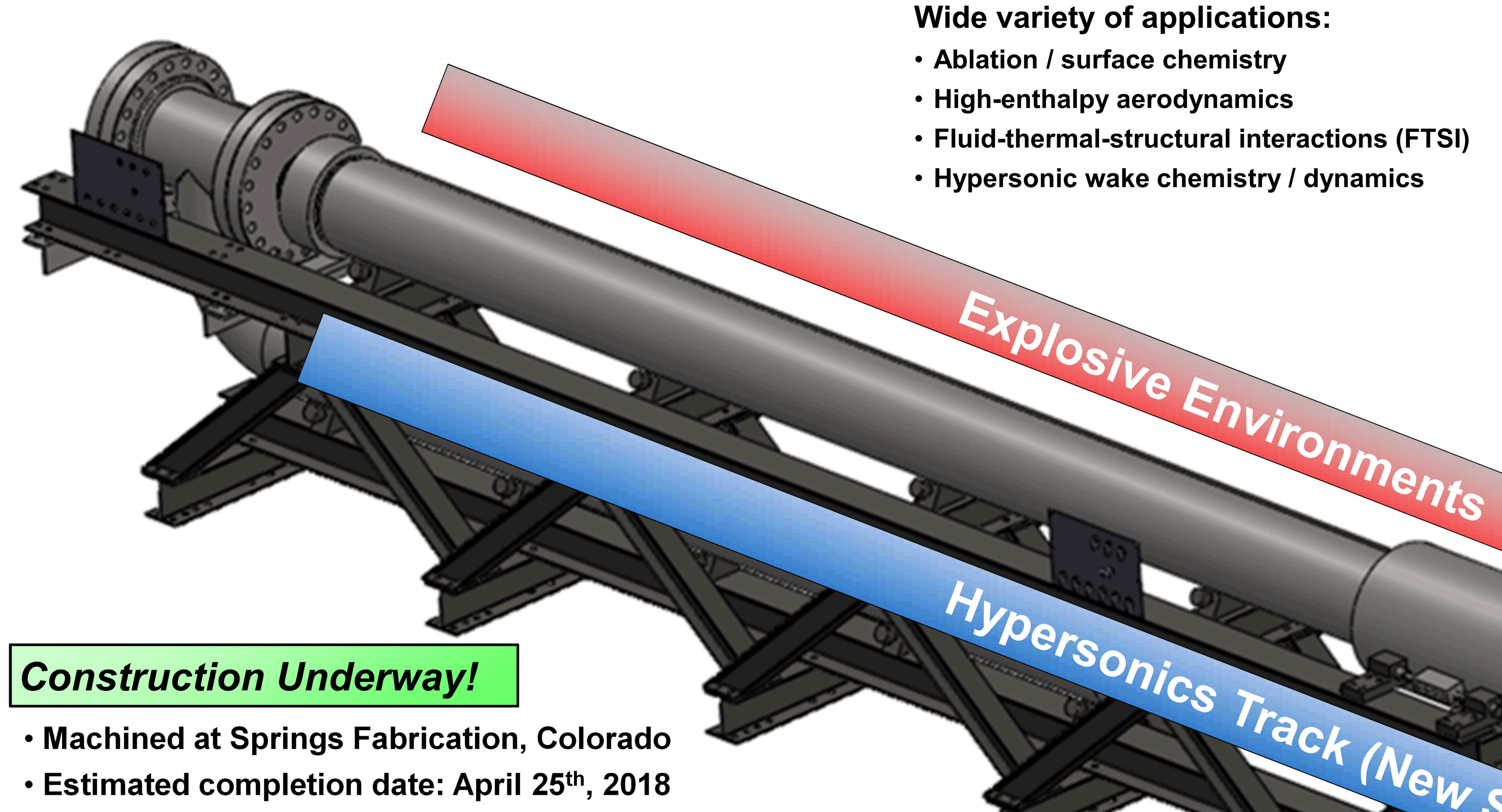
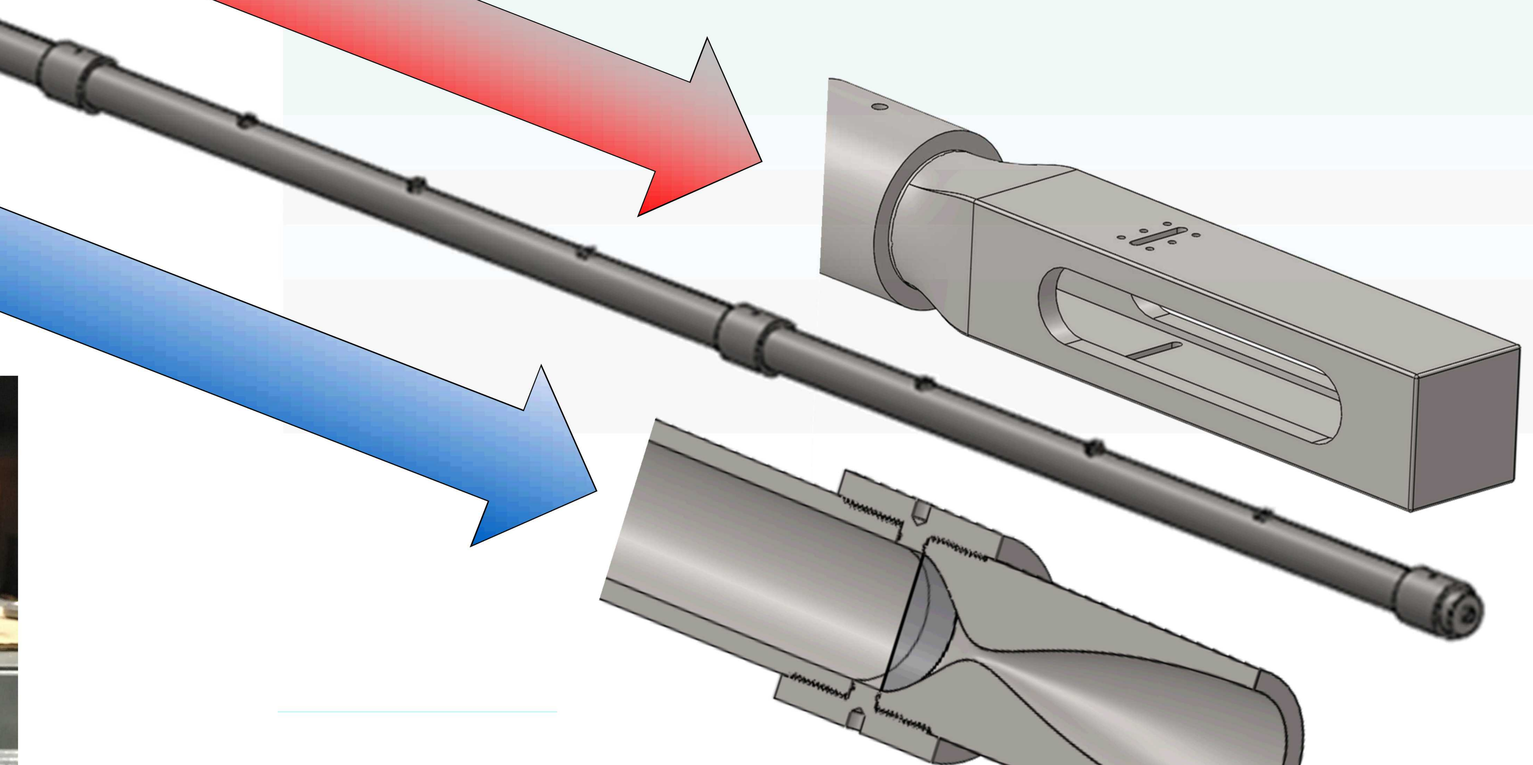


Generate high-enthalpy reentry environments of reentry through the entire flight profile

Wide variety of applications:
- Ablation / surface chemistry
- High-enthalpy aerodynamics
- Fluid-thermal-structural interactions (FTSI)
- Hypersonic wake chemistry / dynamics

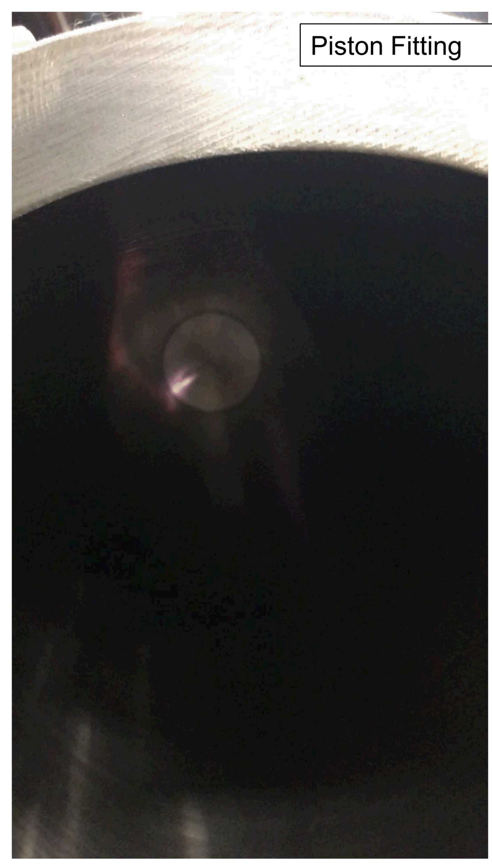


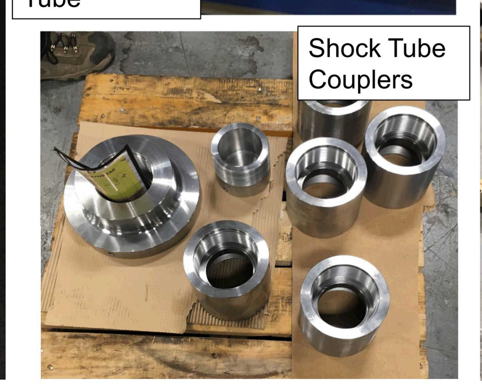


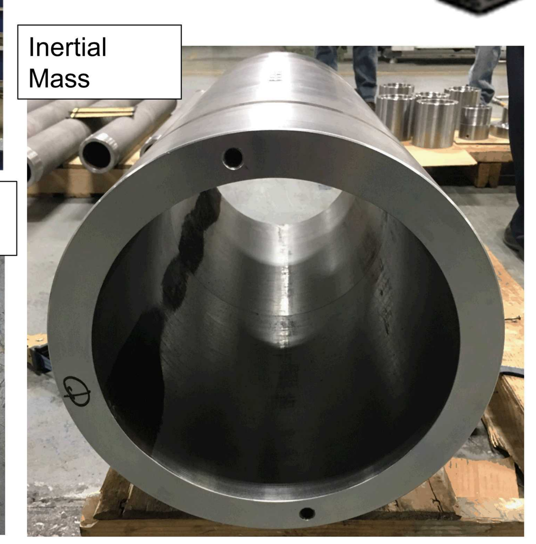




Construction Underway!

- Machined at Springs Fabrication, Colorado
- Estimated completion date: April 25th, 2018



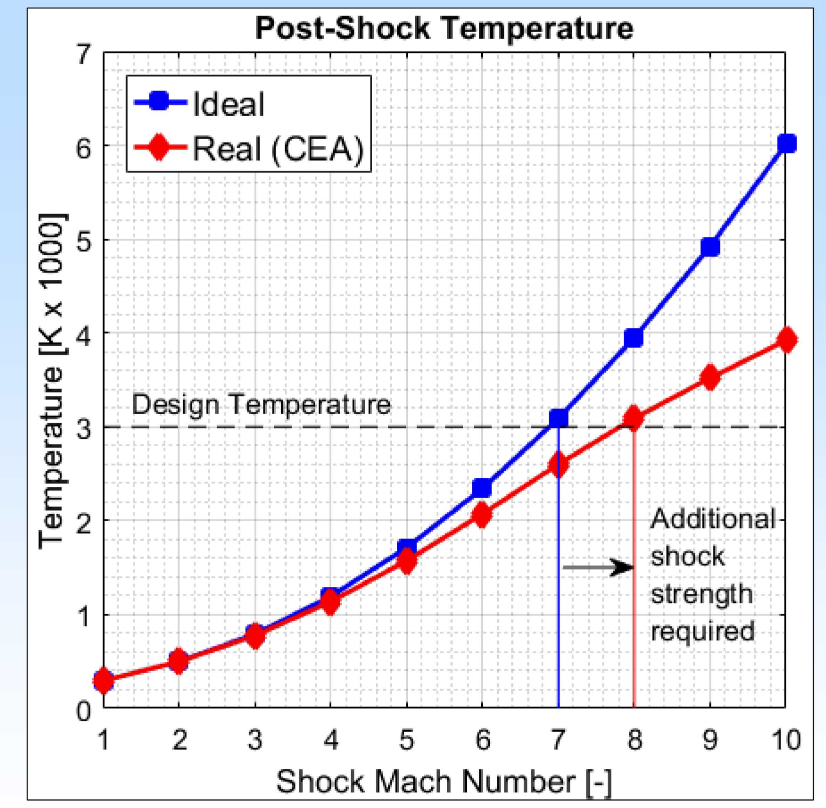


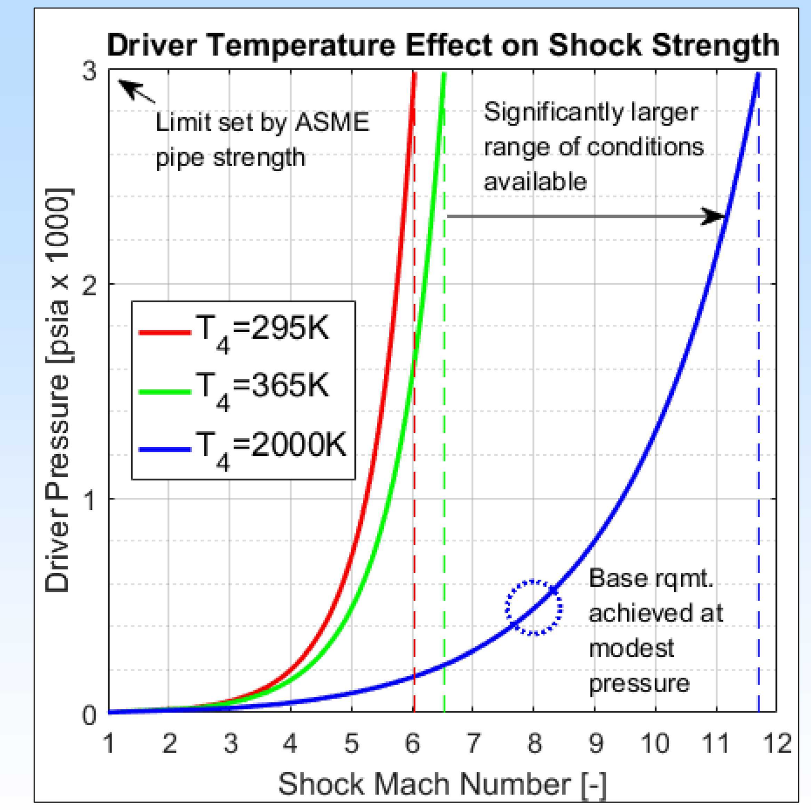


Design Study

- At high temperatures, specific heats are no longer constant. Chemical equilibrium calculations show that for required T, stronger shock needed compared to ideal value.
- Reviewed many techniques for high M_s design: Helium driver, driver-driven area ratio, electrical resistance heating, driven section at vacuum.
- Challenging to achieve high M_s with traditional designs: Need to heat the driver gas to thousands of degrees.

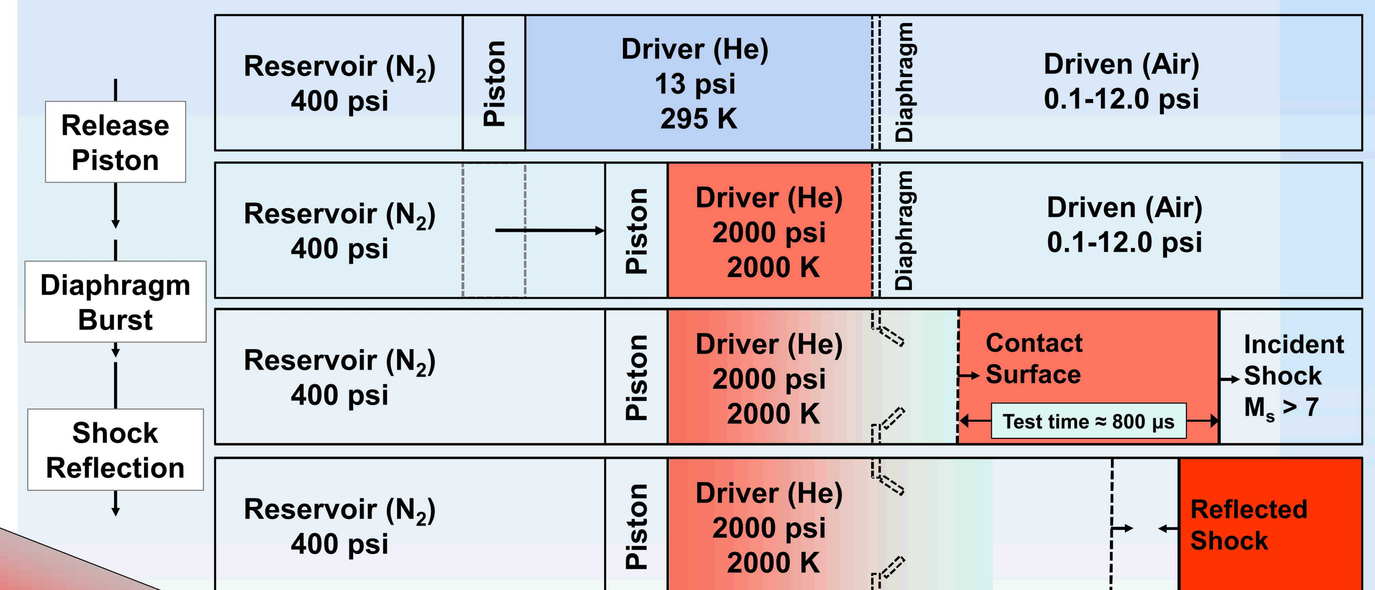
Simultaneous extreme pressurization and heating is the fundamental principle of high-enthalpy hypersonic impulse facilities such as free-piston shock tunnels

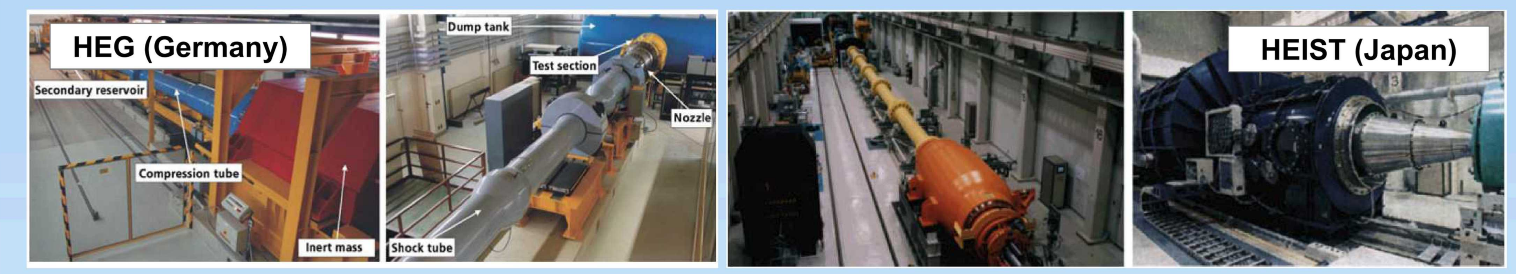


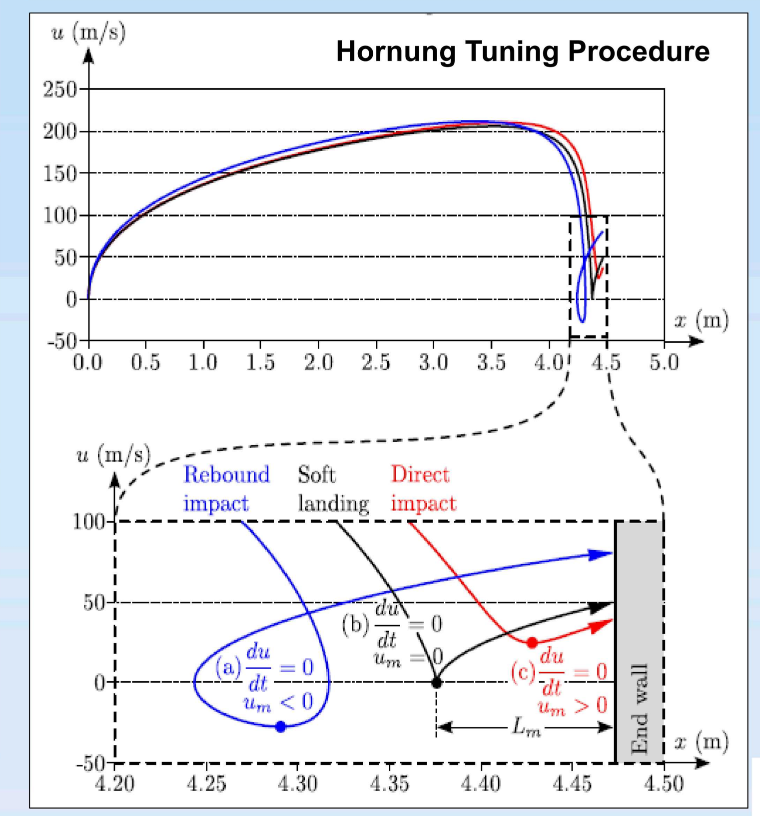


The Free-Piston Shock Tube

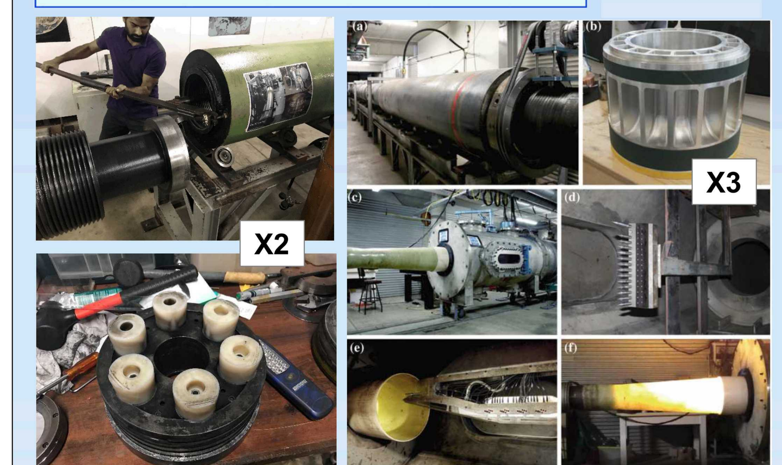
- Apply free-piston shock tunnel concept to create range of extreme environments. *Readily adaptable to hypersonic reentry.*
- Free-piston driver concept: High-speed piston isentropically compresses and heats driver gas before diaphragm rupture.
- Tuning procedure slows piston before reaching end-wall.
- Concept invented in 1962 by R. J. Stalker (Univ. Queensland, AUS). Only 1 other free-piston facility in US (T5, Caltech).



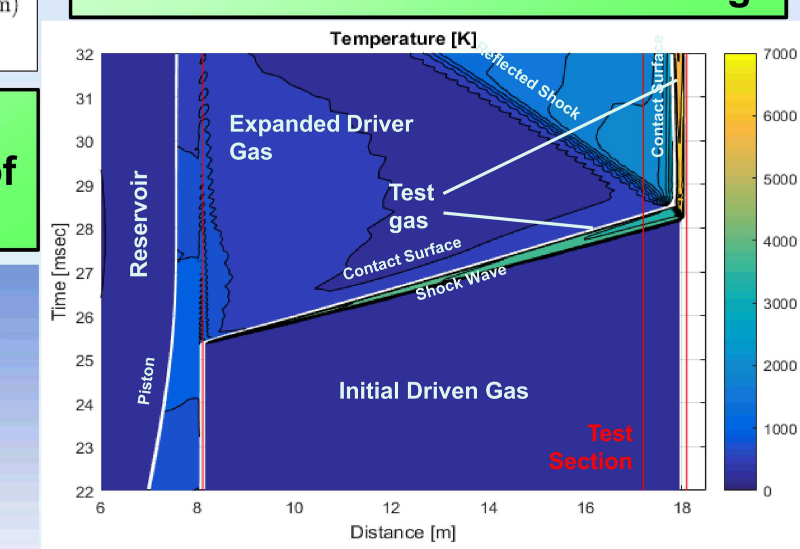




Travelled to AUS in 2017 to learn principles of free-piston design and operation



1-D Lagrangian Flow Solver used for tube simulation and fine-tuning



ANSYS explicit FE and transient thermal analyses evaluate safety of fast piston, superheated gases