SAND2019-0132C

A free-piston driven shock tube for generating extreme aerodynamic environments: design and first shots

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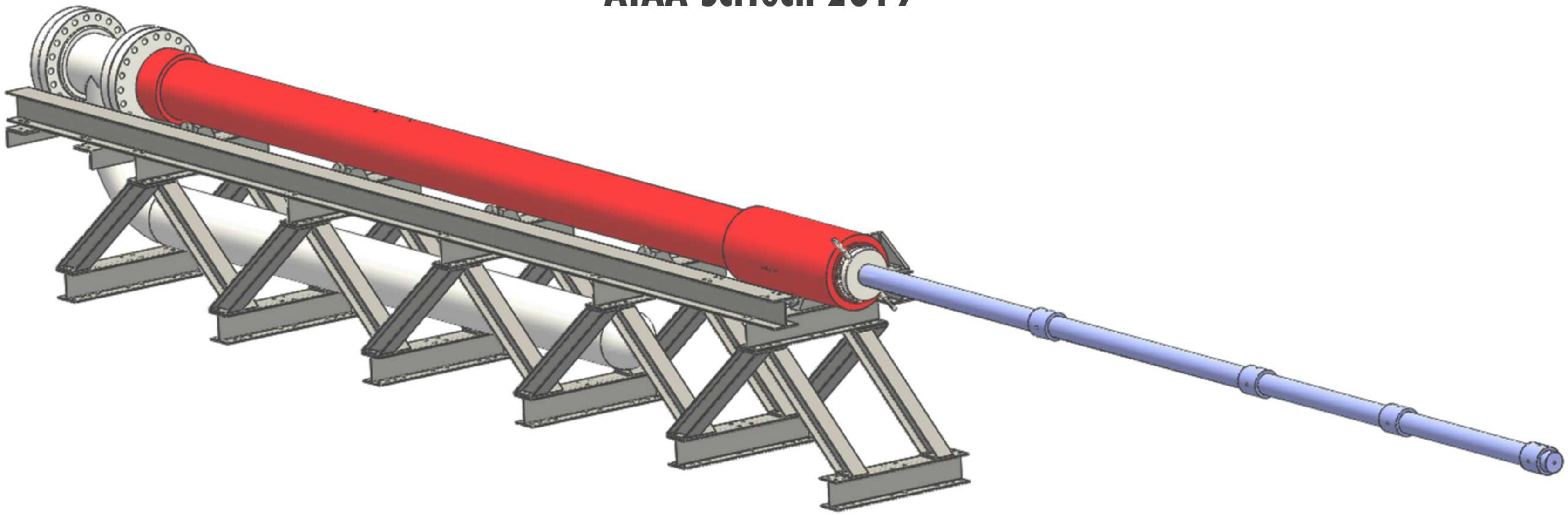
AIAA SciTech 2019



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Motivations

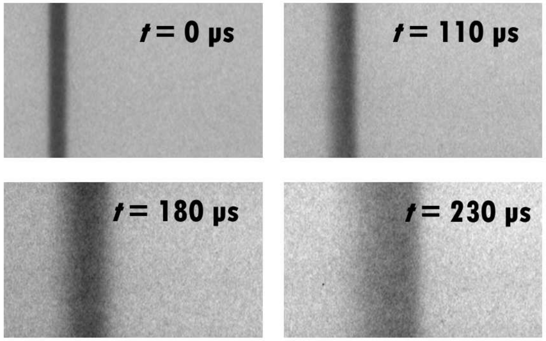
- **Previous work: *1-D Shock-particle interactions in inert* gas-solid flows having *dense volume fractions***
- **Sandia Multiphase Shock Tube (MST) generates shock Mach numbers M_s up to 2.0**
- **Gate valve, large hopper, nozzle inserts deliver dense ‘curtain’ in test section**

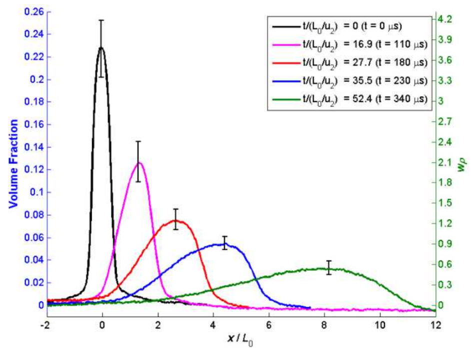
Quantifying the interaction of shock wave and induced flow with the dense curtain is the primary scientific goal

Motivations

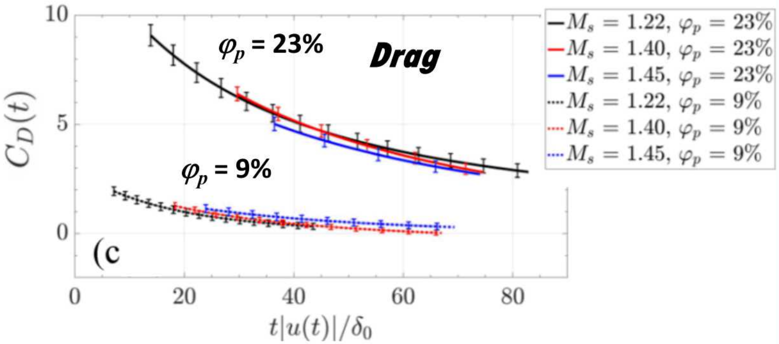
Unsteady Drag and Curtain Spread From PIV and Schlieren

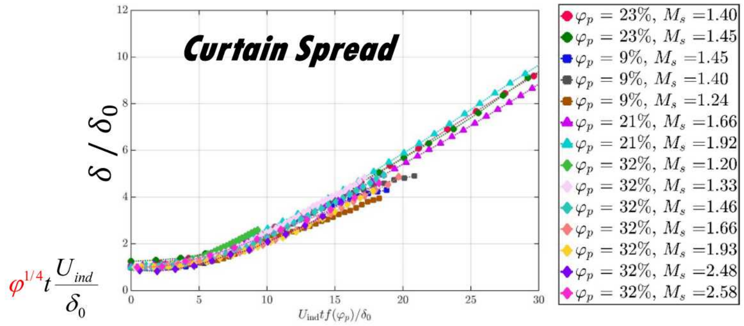
Volume Fraction From X-Ray





Scaling Correlations

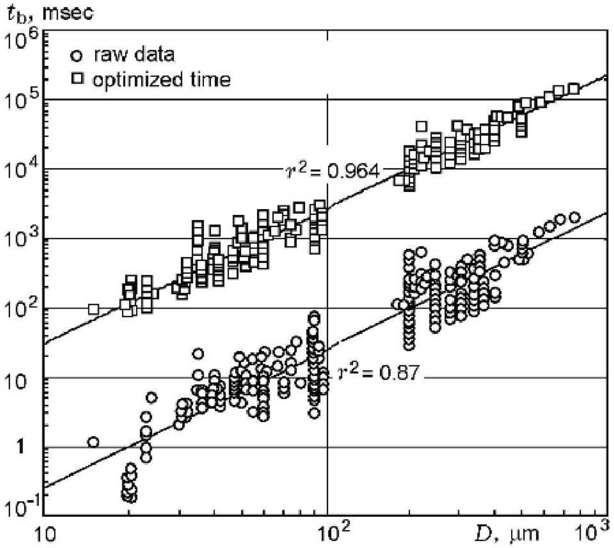




Motivations

- **Driving scientific question:** ***What scalings apply for reacting particles?***
- ***Many*** **open questions on particle burn in** ***convecting*** **flow and** ***high volume*** **fraction.**

Al Burn time vs Particle Size[1]



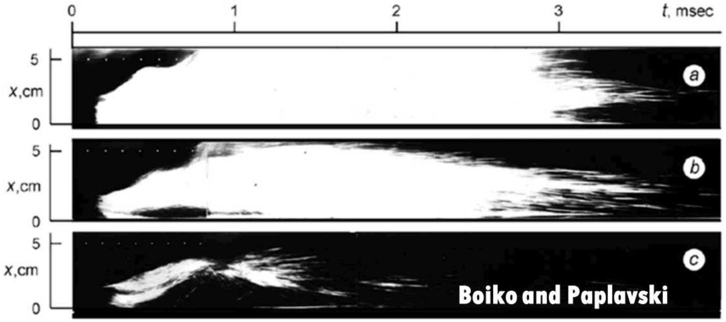
- **Aluminum combustion well characterized with ignition by gas burner, *reflected* shock waves, lasers.**
- **Combustion in quasi-static conditions**
- **D>20 µm, burn time t_b scales ≈ $D^{1.8}$ [1]**
- **D<10 µm t_b behavior more nuanced [2]**

Convection Effects

- **"The effect of convection on the burning rate and ignition delay is unknown, but remains of significant concern." -Lynch *et al.* 2009**
- **Detonation tube experiments of Tanguay *et al.* (2009) suggest $D^{0.5}$**
- **Lab-scale aluminized explosives experiments by Glumac *et al.* (2013) suggest blast-driving effects from aluminum inconsistent with D^2**

Volume Fraction Effects?

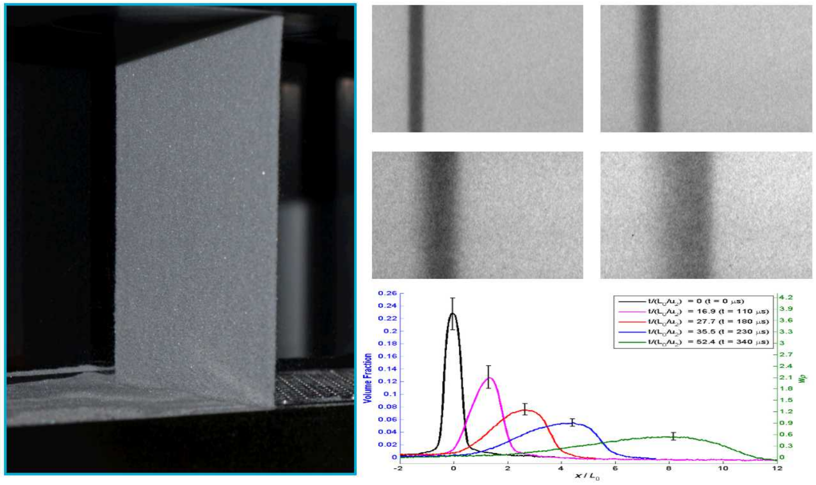
"A high concentration of the gas-dust mixture is one of the conditions causing low-temperature ignition" - Boiko and Paplavski 2002

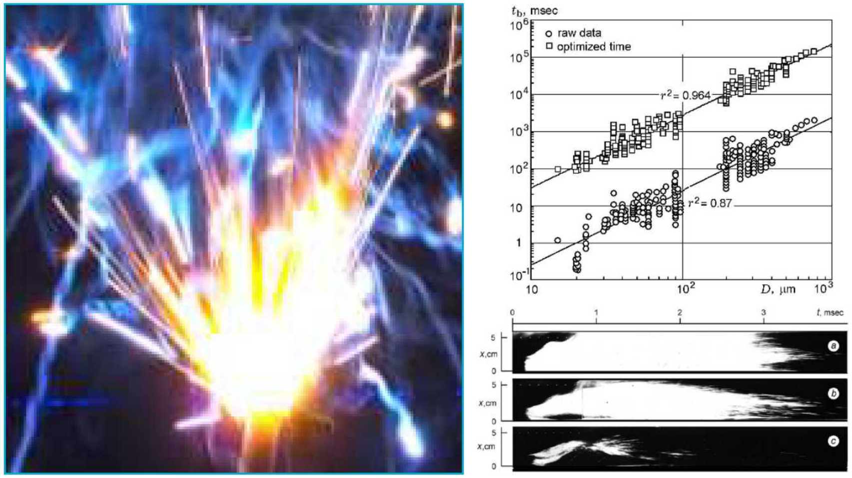


Turbulent Mixing Effects?

- **Turbulence in low-speed (Dreizin et al. 2014) and high-speed flows (Glumac et al. 2014) decreases burn time.**

Facility Objectives





Dense particle volume fractions and dispersal

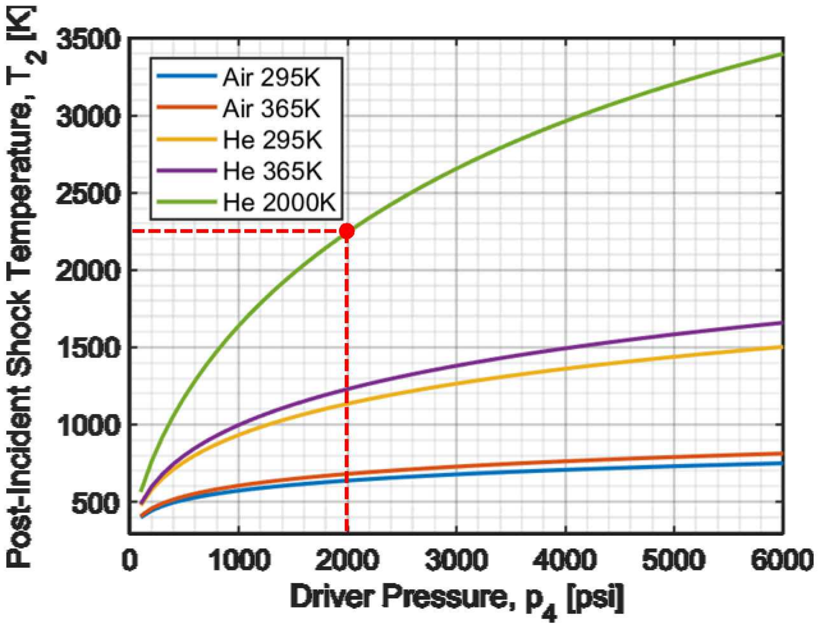
Ignition of reacting particles

A shock tube facility is required with following operating characteristics:

1. **Post-incident shock temperatures > 2300 K (Melt of AlO)**
2. **Post-incident shock velocities > 2 km/s**
3. **Test times > 0.5 ms**
4. **Initial driven gas at atmospheric pressure**

Design Study

- **How to produce very strong shocks?**
- **Traditional shock tube with air driver unable to generate req. temperatures.**
- **Unheated/moderately heated helium driver only able at extreme pressures**
- **Heating helium driver to 2000 K achieves req. at modest pressures.**
- ***How to superheat helium at high pressure? Use concepts from hypersonic ground test!***



Combustion Driver

- Hydrogen/oxygen mixture combusts, increases temperature
- Limit up to combustion temperature
- Flammable gas handling required, difficult safety analysis.
- Residual unburned oxidizer/fuel possible after contact surface.

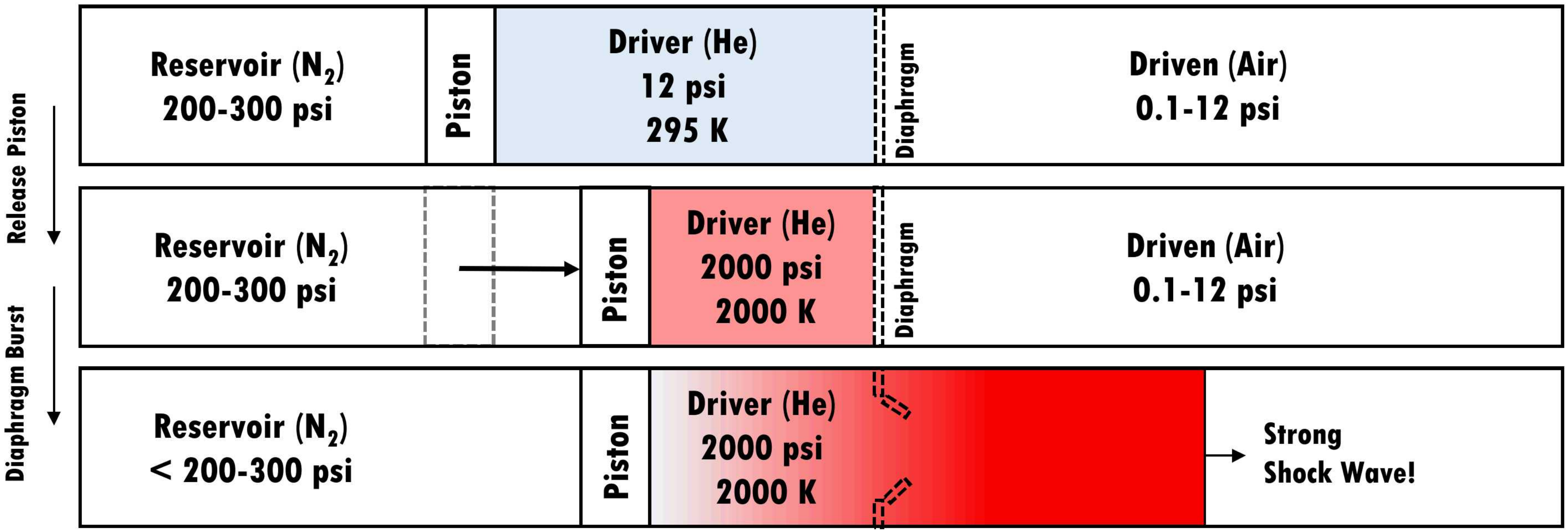
Electric-Arc Driver

- High-voltage electric arc deposits energy in driver gas.
- Requires substantial electrical infrastructure.
- Challenging safety analysis, unique hazards such as arc flash.

Free-Piston Driver

- Isentropic compression and heating of gas yields highest potential performance.
- Any driver gas can be used, including inert gases such as helium.
- No specialized gas handling or electrical requirements.
- Safety analysis straightforward using mechanical stress analysis.

Free-Piston Principles



- **Long compression tube: Provides required volume ratio for pressure and temperature rise of the driver gas, according to isentropic compression**

$$\frac{V_1}{V_2} = \left(\frac{p_2}{p_1}\right)^{1/\gamma} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$$

- **Heavy piston: acquires and maintains sufficient momentum to compress driver gas far above reservoir pressure.**
- **Long compression tubes/heavy pistons used by T4, T5, HEG, HIEST, etc.**
- ***Short* compression tubes, *lightweight* pistons also used for space-constrained setups, typically lower performance, e.g., X2 facility. *The HST uses this concept.***

Preliminary Design

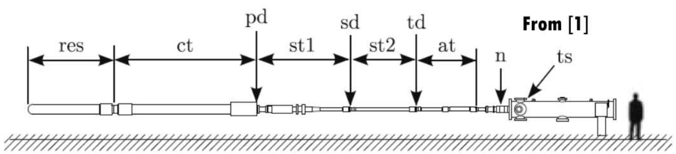
Design constraints:

1. Test section diameter at least 3 in.
2. Standard pipe sizes to reduce cost.
3. Shock tube L/D 60-100 for test time.
4. Compression tube max weight 4000 lbs
5. Compression tube not to exceed 20 ft.

Design similar to Queensland X2

Special thanks to David Gildfind and UQ team for hosting us in September 2017.

From [1]



Queensland X2 Facility

Facility Comparison

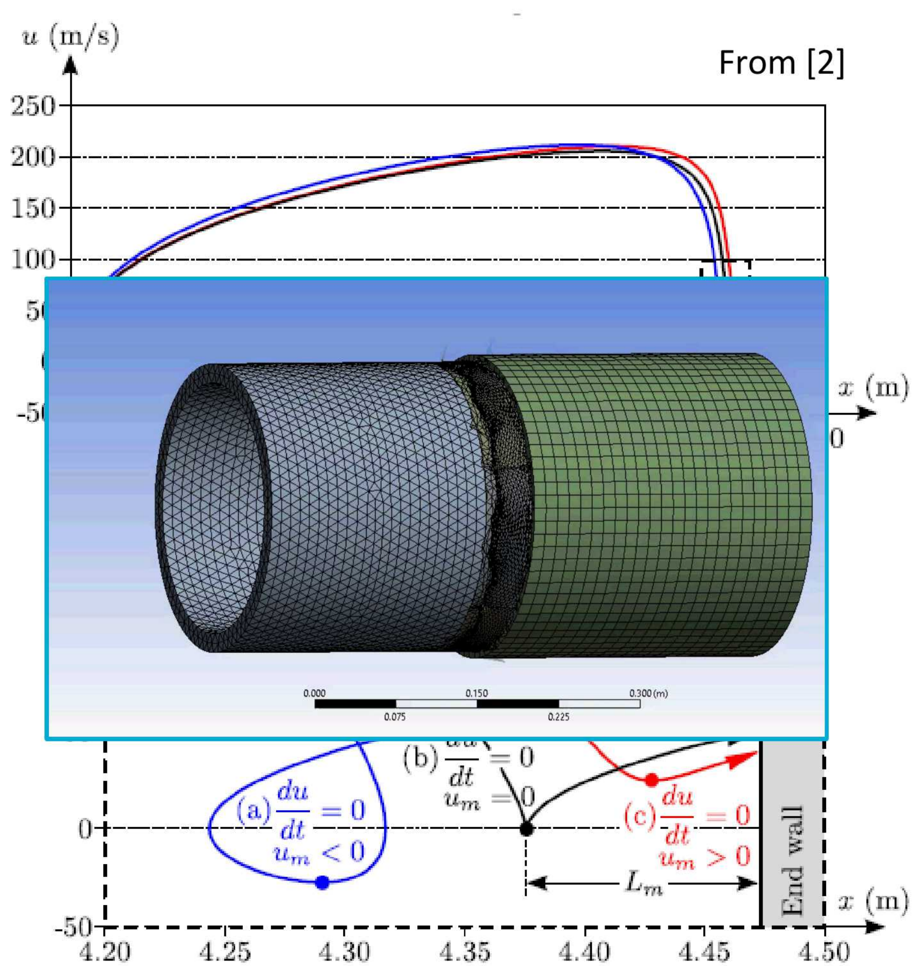
	HST	X2
Compression Length	17 ft (5.2 m)	14.3 ft (4.37 m)
Compression Diam.	10.5 in (0.267 m)	10.1 in (0.257 m)
Driven Tube Length	30.2 ft (9.2 m)	29.5 ft (9 m)
Driven Tube Diam.	3.44 in (8.74 cm)	3.34 in (8.5 cm)
Piston Mass	26.2 lbs (11.9 kg)	23.1 lbs (10.5 kg)

- HST is purely a shock tube; no acceleration tube section or catch tank test section.
- Lower burst pressure ratings of 3000 psi, compared to > 5200 psi for X2.

[1] Gildfind et al. Expansion Tubes in Australia. Experimental Methods of Shock Wave Research pp 399-431

Preliminary Design

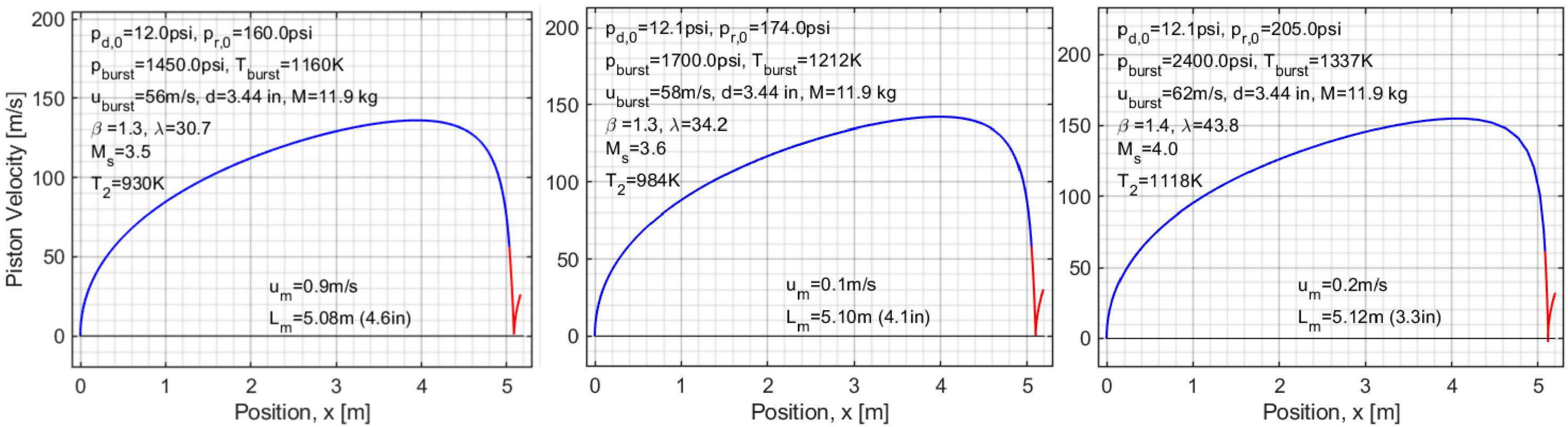
- **With the facility dimensions set, what parameters are required to achieve safe operation?**
- **Aiming for a 'soft landing' operation; piston reaches zero velocity before end of tube**
- **Long nylon 'buffer' rods extend to catch the piston at this location.**
- **Two functions: prevention of a hard rebound, safety during a direct impact. Verified by FEA.**
- **These behaviors can be evaluated using the ODE-based analysis of Hornung [1].**
- **Also allows estimation of resulting shock strength by knowing burst pressure, temperature.**



[1] H. G. Hornung, "The piston motion in a free-piston driver for shock tubes and tunnels," GALCIT, 1988.
[2] Gildfind et al. (2015) Free-piston driver performance characterization using experimental shock speeds through helium. *Shock Waves* 25.

Preliminary Design

- **ODE analysis of Hornung [1] provides 'first cut' of operating parameters.**
- **Identifies *realistic* shock strengths compatible with safe piston dynamics, i.e.: maximum performance without direct impacts.**
- **For *air* driver, p_{burst} of 2400 psi, p_{shk} of 12 psi yields $M_s = 4.0$, $T_2 = 1120$ K**
- **For *helium* driver, p_{burst} of 2400 psi, p_{shk} of 12 psi yields $M_s = 6.9$, $T_2 = 2590$ K** ✓

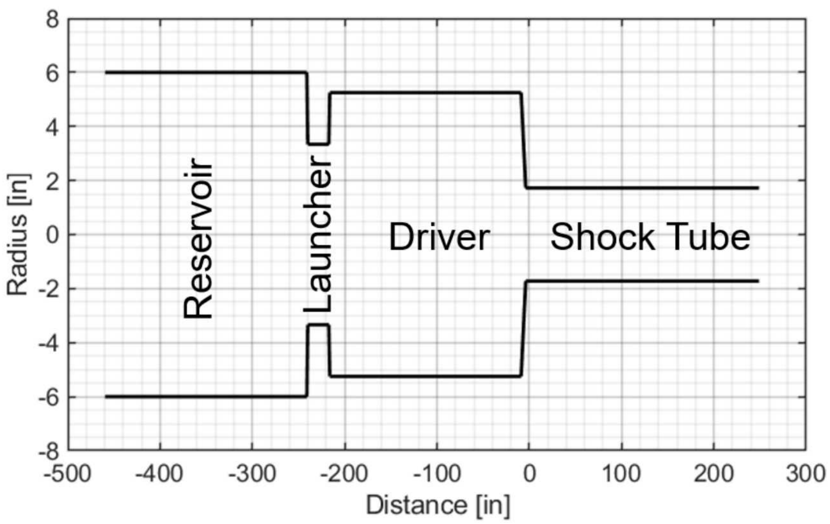


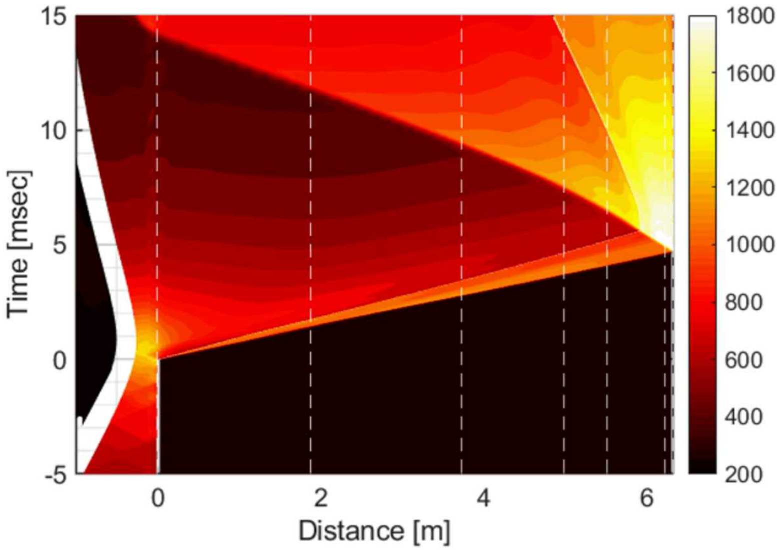
Achieving a post-incident shock temperature of > 2300 K is feasible using a helium driver at safe burst and reservoir pressures

[1] H. G. Hornung, "The piston motion in a free-piston driver for shock tubes and tunnels," GALCIT, 1988.

Detailed Analysis with L1D

- **Previous ODE analysis does not account for the shock propagation into the shock tube, and has simplified post-burst piston dynamics**
- **Analysis using Queensland L1D code evaluates higher fidelity piston dynamics *and* flow uniformity/test time for a given condition.**
- **L1D is a quasi-one-dimensional flow solver which includes a real gas model (NASA CEA), piston friction modeling, and shock tube viscosity modeling [xx].**
- **HST modeled as a series of area changes representing major components**
- **Provides full x-t history of shock/piston dynamics.**





[xx] P. A. Jacobs, "Shock Tube Modelling with L1d," University of Queensland, 1998.

Detailed Analysis with L1D

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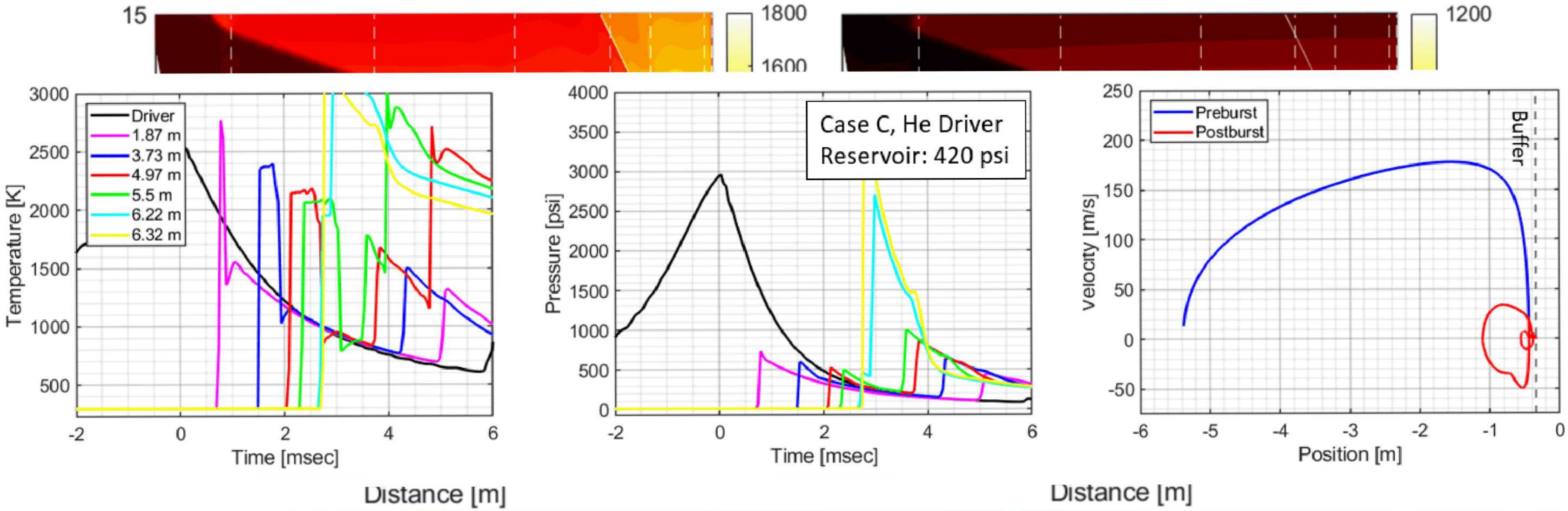
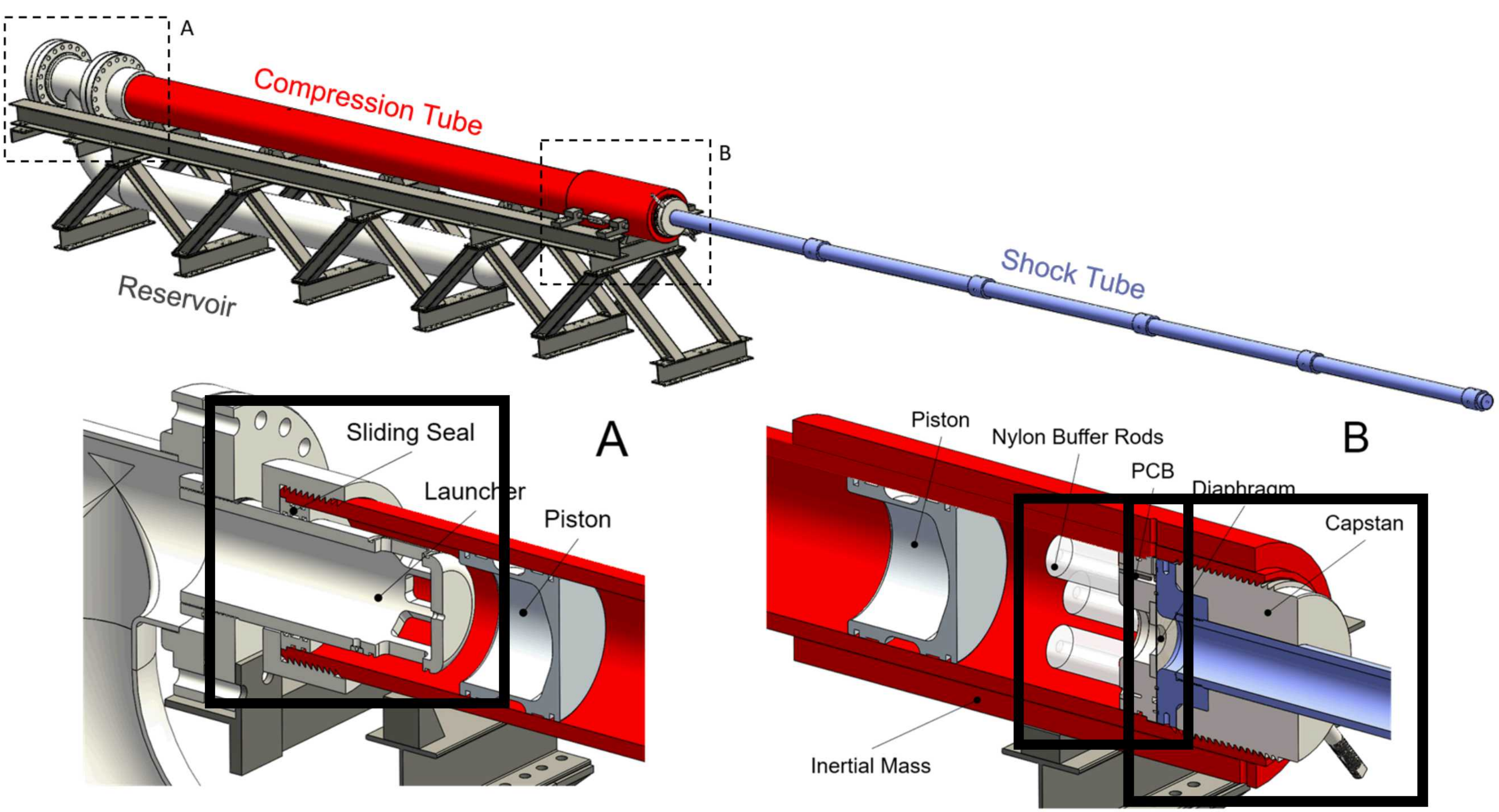
- **Repeating the ODE analysis in L1D provides more refined estimate of conditions**
- **U, T, P traces extracted at sensor locations (dashed lines), test section at 5.5 m.**
- **For *air* driver, p_{burst} of 2400 psi, p_{shk} of 12 psi requires p_{res} of 332 psi, yields a max T_2 = 1120 K for approx. 2 msec, with significant piston rebound but no impact.**
- **For *helium,* driver, p_{burst} of 2400 psi, p_{shk} of 12 psi requires p_{res} of 420 psi, yields max T_2 = 2300 K for approx. 1.5 msec, with reduced rebound and no impact.**



Achieving a T_2 of >2300 K using ambient shock tube fill and test time >0.5 msec is feasible using a helium driver at safe burst and reservoir pressures

Mechanical Design

- **Many concepts of the X2 and X3 facilities incorporated into the HST design:**
  - **Capstan-style breech mechanism for diaphragm installation.**
  - **Sliding reservoir seal to decouple compression tube recoil from reservoir.**
  - **Removable pressure plate and orifice plates for maintenance and piston tuning**



Fabrication

- Manufactured through early 2018 at Springs Fabrication, Colorado.
- Compression tube honed by Scot Industries, Texas.

Compression Tube

Inertial Mass

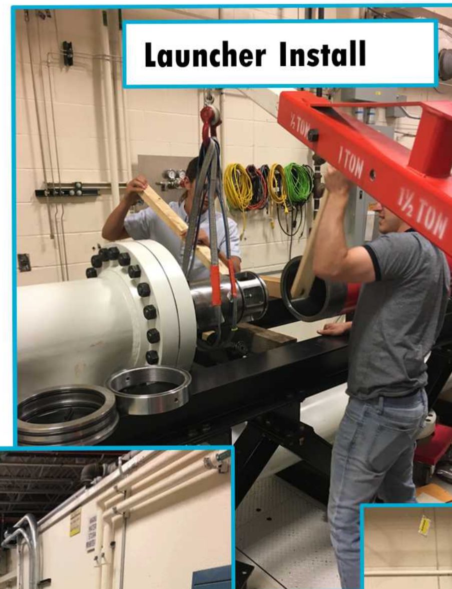
Shock Tube Sections

Couplers

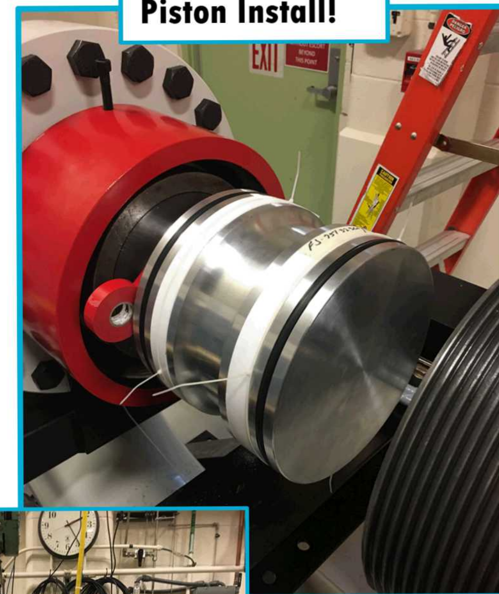
Coupler Fitting

Construction

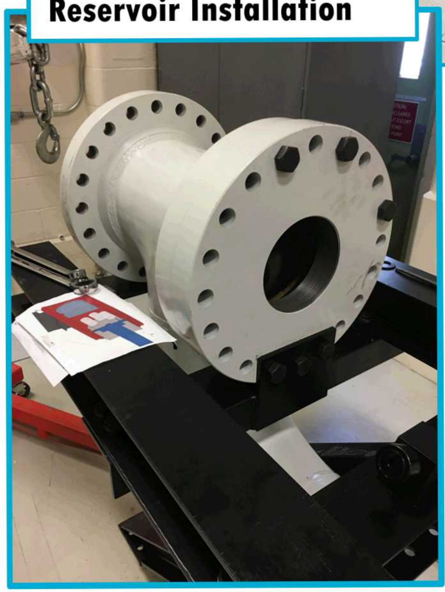
- **July through September 2018, assembly in Albuquerque.**



Launcher Install



Piston Install!



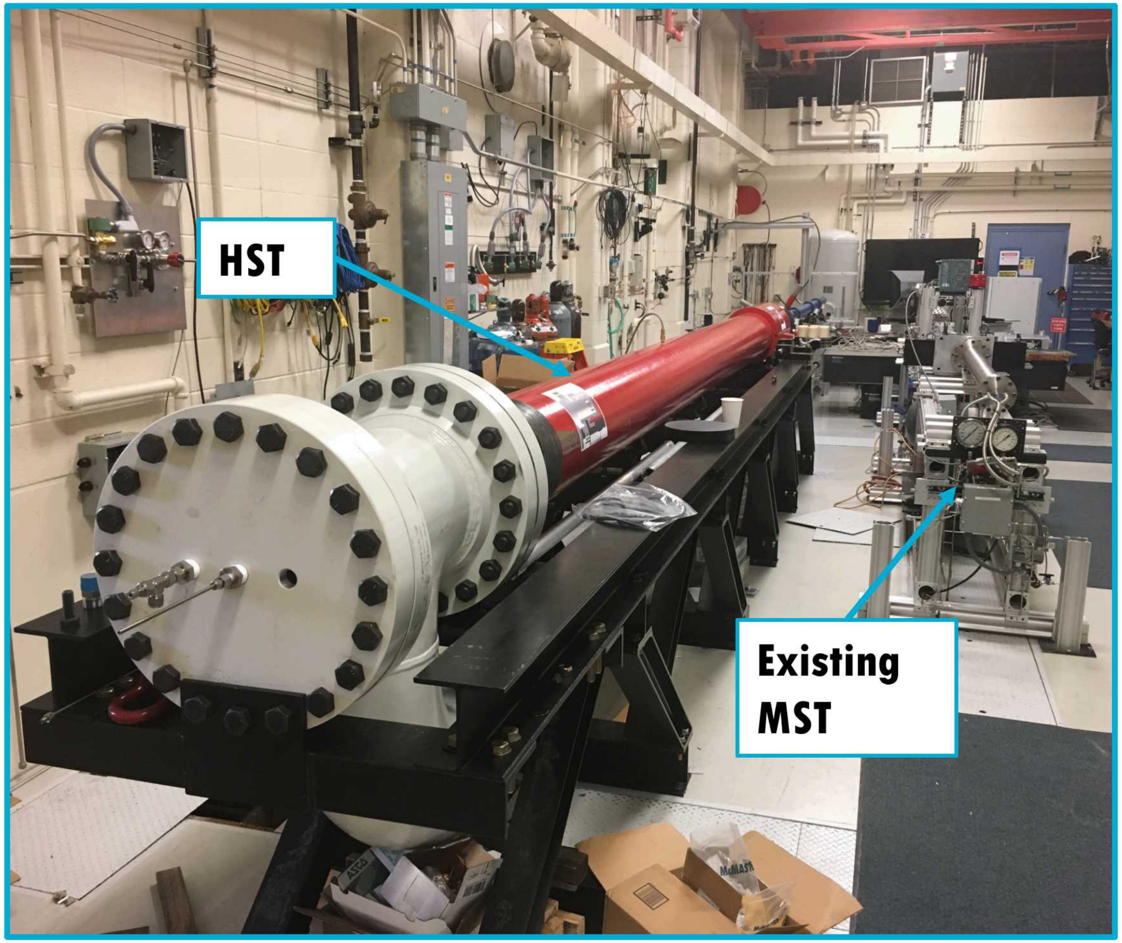
Reservoir Installation

Compression Tube Lift

Capstan Install

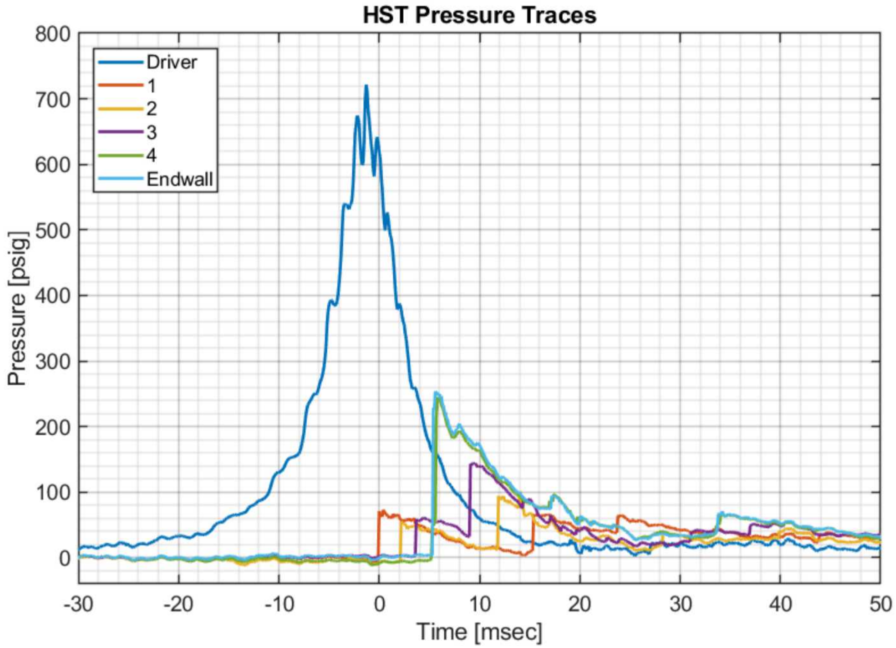
Construction

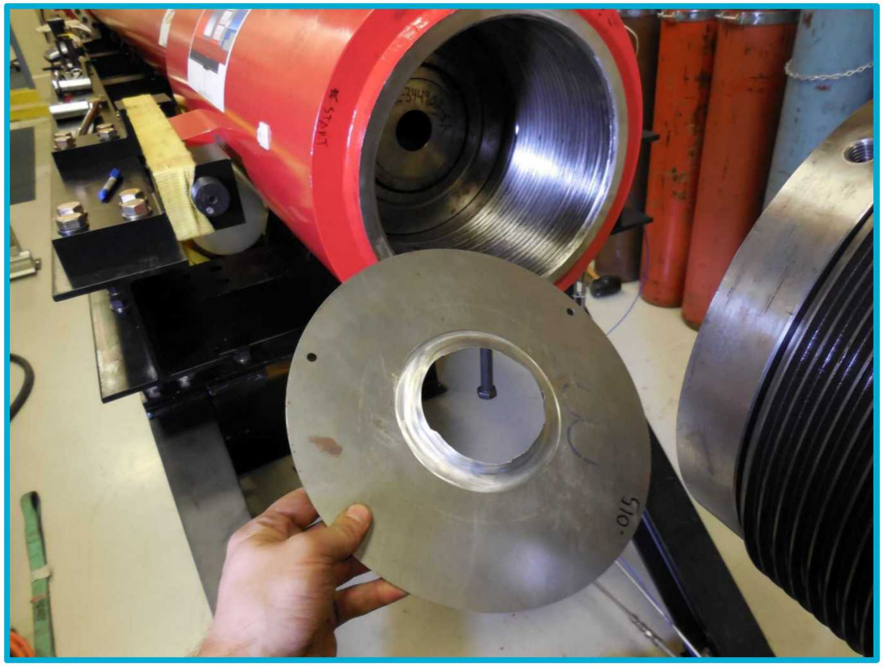
- Finally completed early September 2018
- Operating together with existing multiphase shock tube (MST)



First Shot

- **September 9th, 2018: First shot of HST!**
- **Used a very thin diaphragm (0.015 in/0.38 mm) and small orifice plate for safe operation.**
- **Shock Mach of 2.4, post-incident temperature 600 K.**

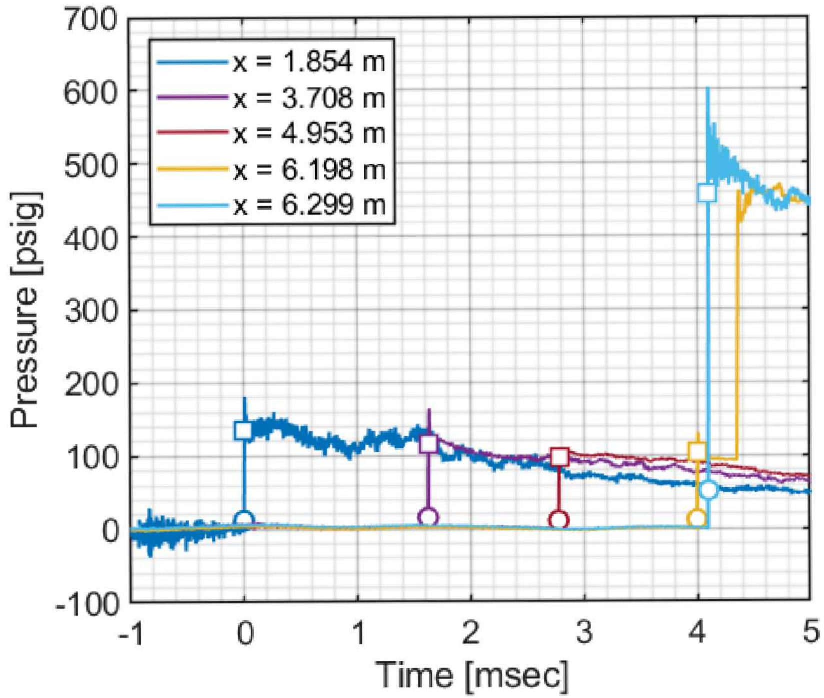


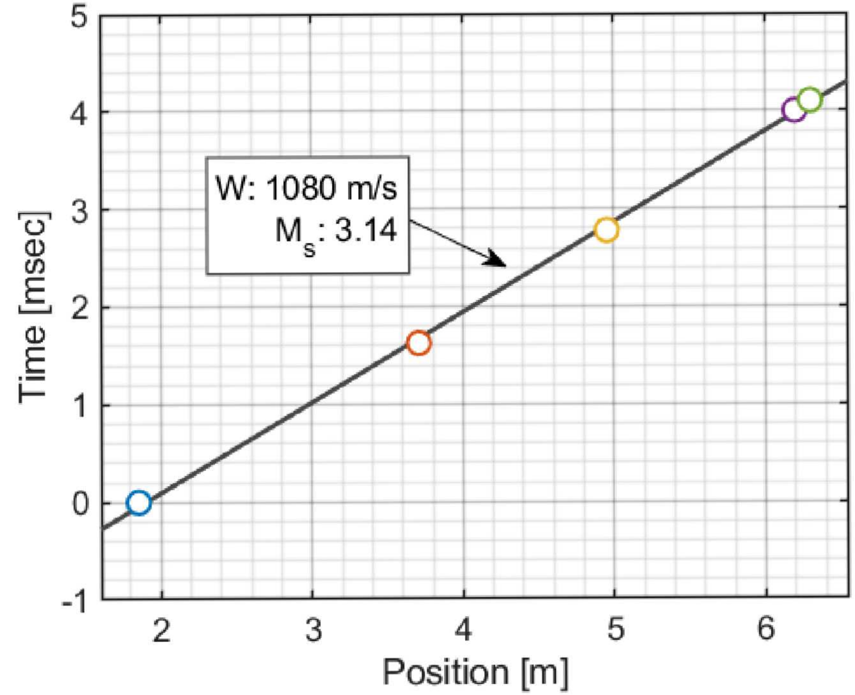


Max. Driver Pressure	**720 psi (5.0 MPa)**
Shock Mach, M_s	**2.4**
Post-Incident Temp, T_2	**600 K**

First Shots

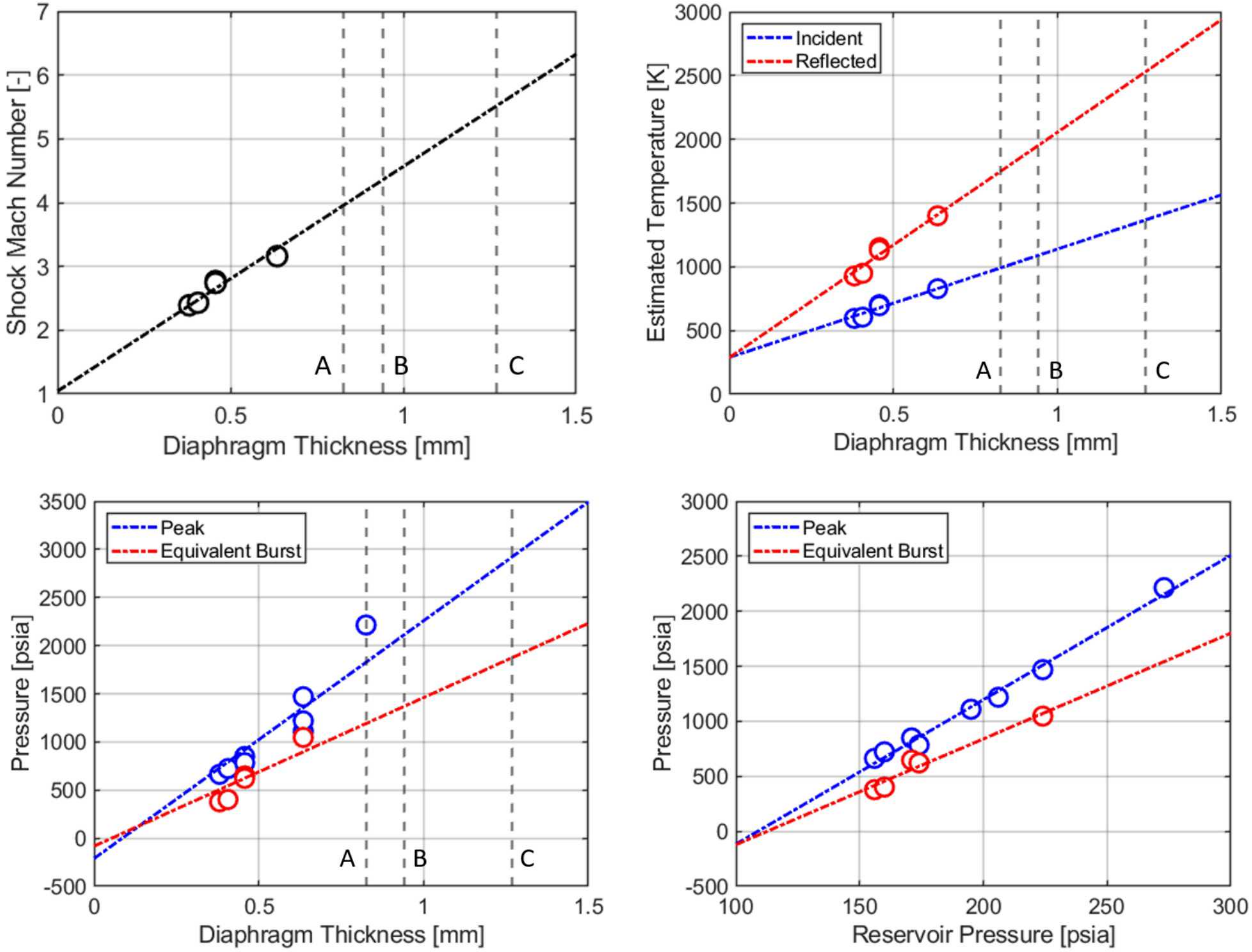
- **Shot 11 is current highest-condition shot, 0.6 mm thick diaphragm**
- **Continuing to use air driver during commissioning process**
- **Current maximum shock Mach number, 3.14 with ambient shock tube fill.**





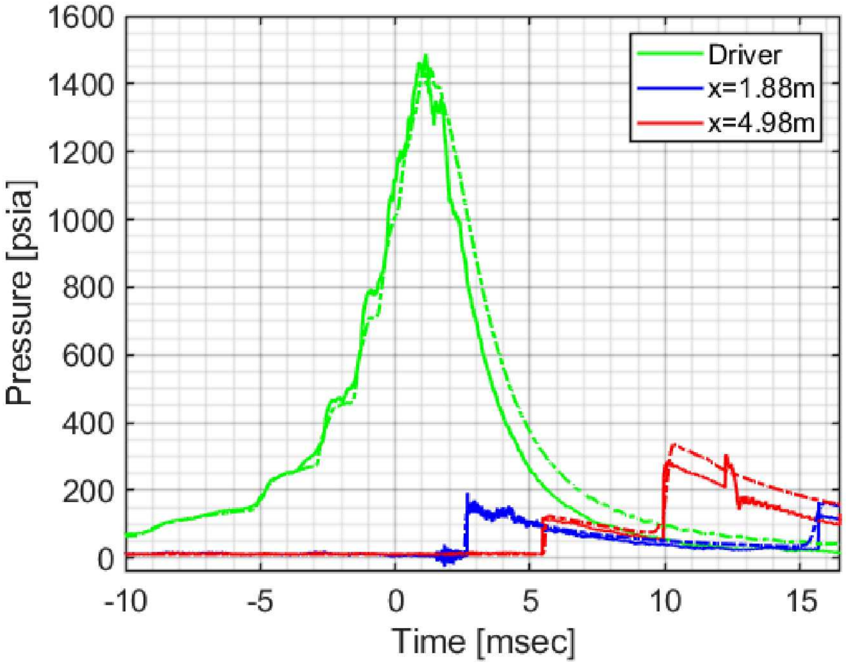
First Shots

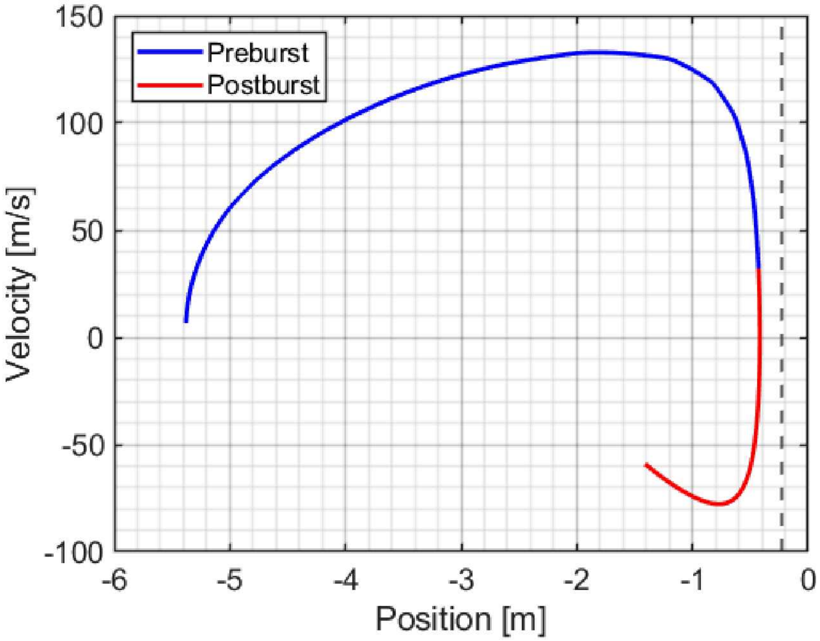
- Shots to-date compiled to establish trends for upcoming high-power shots.
- A, B, and C are current cold-rolled diaphragms ready for use.
- Note, low temperatures due to use of *air* driver rather than helium.



Simulation Comparison

- **Calibrate the L1D simulation to currently available shot data.**
- **Primary variables: launcher and diaphragm pressure loss factors, piston friction, effective reservoir length, and reservoir temperature (due to fast fill process).**
- **'Blank-off' tests with solid, 0.5 in thick diaphragm calibrates driver pressure traces. Critical for tuning the reservoir and launcher parameters/piston friction.**
- **Dashed curves are simulations, solid are experimental measurements.**
- **Excellent agreement on driver and incident shock traces.**





Conclusions and Future Work

- **A new free-piston shock tube is now operating and in the commissioning process.**
- **A design study indicates target $T_2 > 2300$ K is possible with safe operating characteristics and with margin if necessary.**
- **First shots conducted through September to November using air drivers to calibrate diaphragm thicknesses and simulation parameters.**
- **Current maximum conditions using air driver and ambient shock tube fill, shock Mach number $M_s = 3.14$, post-incident temperature $T_2 = 900$ K.**
- **Throughout 2019 the focus is on improving turnaround time, switching to helium driver gas, and using diaphragms for design conditions A, B, and C.**
- **Particle curtain test section design underway, to be built mid-2019.**

Special thanks to the University of Queensland Hypersonics group, including David Gildfind and Richard Morgan, for their help and hosting us in September 2017!