COMBUSTION RESEARCH FACILITY

FREE-PISTON ENGINE

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Project ID: ACE008

Overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects.
- Project currently scheduled for completion this calendar year

Budget

- Project currently funded by DOE/VT
- FY11: $300K (ACE) and $300K (FT)
- FY12: $50K (ACE) and $50K (FT)

Barriers

- Increased thermal efficiency (>50%) via high compression ratio
- Petroleum displacement : multi-fuel capability via variable compression ratio (hydrogen, ethanol, biofuels, natural gas, propane)
- Reduced emissions: lean, premixed combustion (LTC/HCCI)
- Low cost and durability: port fuel injection, uniflow port scavenging

Partners

- General Motors/Univ. of Michigan CRL
- Ronald Moses (LANL)

RELEVANCE

Goals of the Free-Piston Engine Research Prototype

- Study the effects of continuous operation (i.e. gas exchange) on indicated **thermal efficiency and emissions** of an opposed free-piston engine utilizing HCCI combustion at high compression ratios (~20-40:1)
- Concept validation of passively synchronizing the opposed free pistons via the linear alternators, providing a **low cost and durable design**
- Proof of principle of electronic variable compression ratio control, allowing optimized combustion timing and **fuel flexibility**, by means of mechanical control of bounce chamber air pressure
- Provide a research tool to explore the free-piston engine operating envelope across multiple inputs, such as boost level, equivalence ratio, and alternative fuels
- Explore the potential thermal efficiency of an HCCI engine approaching the ideal Otto cycle at high compression ratio by removing constraints typically imposed due to mechanical concerns (e.g. limiting compression ratio and heat release rate)

APPROACH

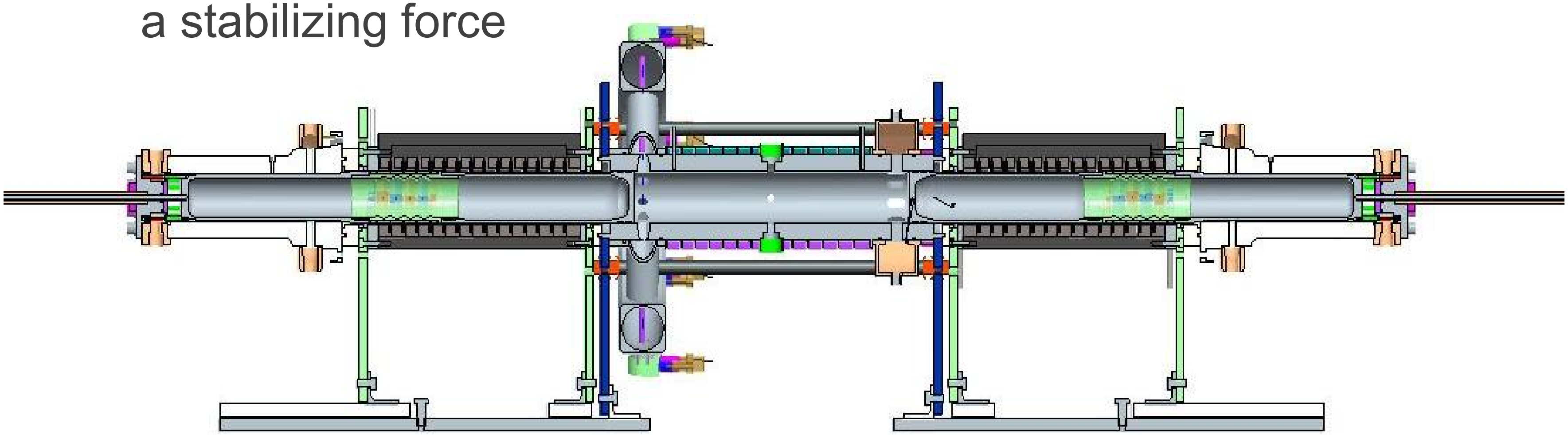
Unique opposed piston design enables high efficiency with low complexity

Opposed Free-Piston Engine

- Mechanically-simple control of compression ratio
- Port fuel injection, two stroke configuration minimize cost
- Uniflow scavenging and potential for boosted intake to improve power density

Piston Synchronization through Passive Coupling of Linear Alternators

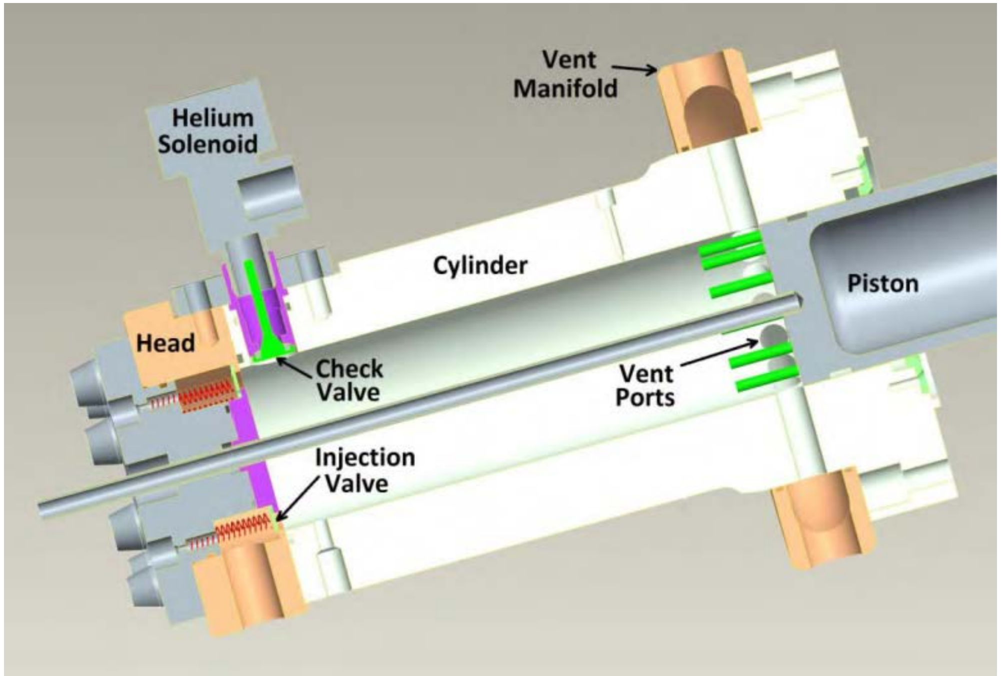
- Load devices also serve to synchronize pistons, reducing complexity and cost
- Stators on either side of center are tied to a common load, providing a stabilizing force



An air-driven dynamometer will be used to initiate combustion tests

Air-Driven Dynamometer

- First cycle initiated by high pressure injection of helium through solenoid valves and check valves in each head
- Motoring of engine accomplished by air injection into bounce chambers through valves actuated by each piston
- Control of air injection pressure and vent pressure allows adjustment of compression ratio while motoring
- As fuel is introduced, vent pressure is increased with injection pressure held constant, reducing the energy input by dynamometer

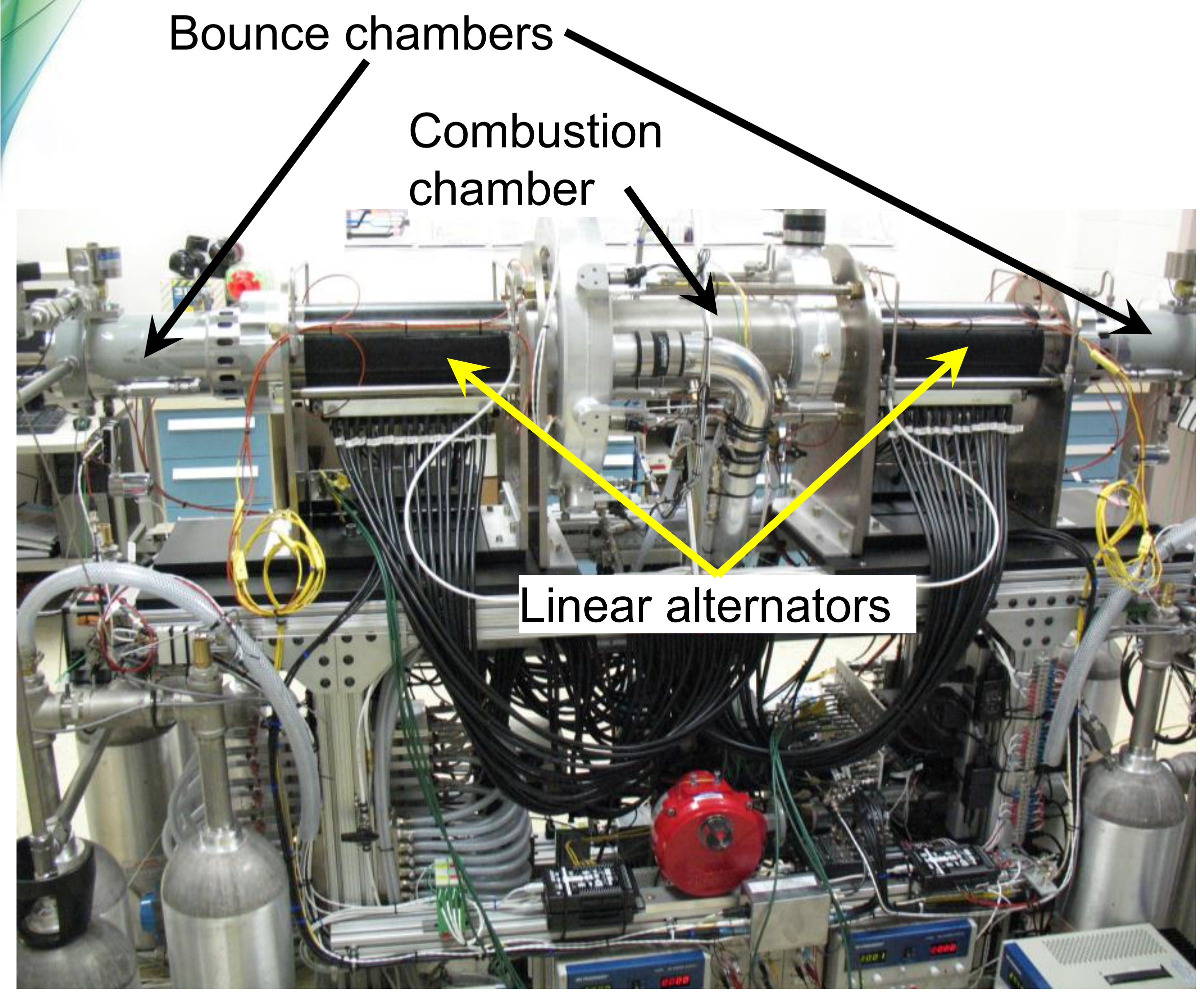


FY11 and FY12 Milestones

Time	Milestone or Go/No-Go Decision
Mar- May 2011	Bounce chamber cylinders, air injection valves, and pistons obtained and assembled
June–Aug 2011	He starting system demonstrated synchronous start w/o magnets. Piston friction model developed.
Sept–Oct 2011	He start tests showed deficiency in bounce chamber venting. Validated thermodynamic model successfully used to redesign vent ports.
Nov 2011 – Jan 2012	Procedures developed and magnets bonded onto backirons. Completed pistons installed in engine.
Feb-Mar 2012	Fluid dynamics model used to redesign bounce chamber vent manifolds. Hardware designed and contract placed for fabrication.
Feb-Mar 2012	He start tests performed with magnets. Analysis of electrical current and piston position data showed evidence of passive synchronization.
April-May 2012	Modifications to enable air motoring: new bounce chamber vent manifolds, increase air pressure/flow capability, reduce piston friction
June-July 2012	Perform air motoring experiments to demonstrate continuous synchronized operation.
Aug-Sept 2012	Perform first combustion experiments and assess controlled operation.
Oct-Dec 2012	Demonstrate fuel flexibility, thermal efficiency, and reduced emissions.

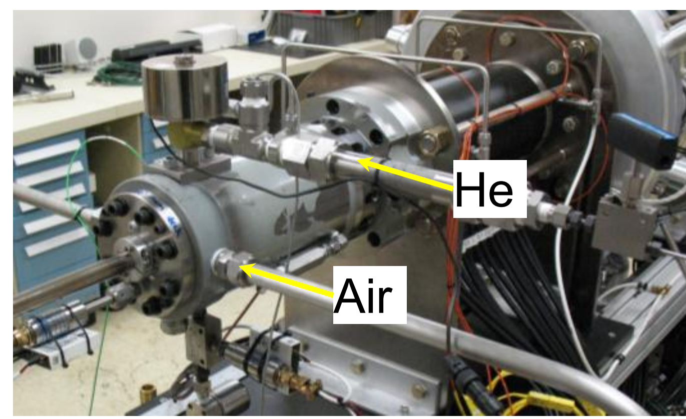
TECHNICAL ACCOMPLISHMENTS

Engine fully assembled and operated with air and He injection

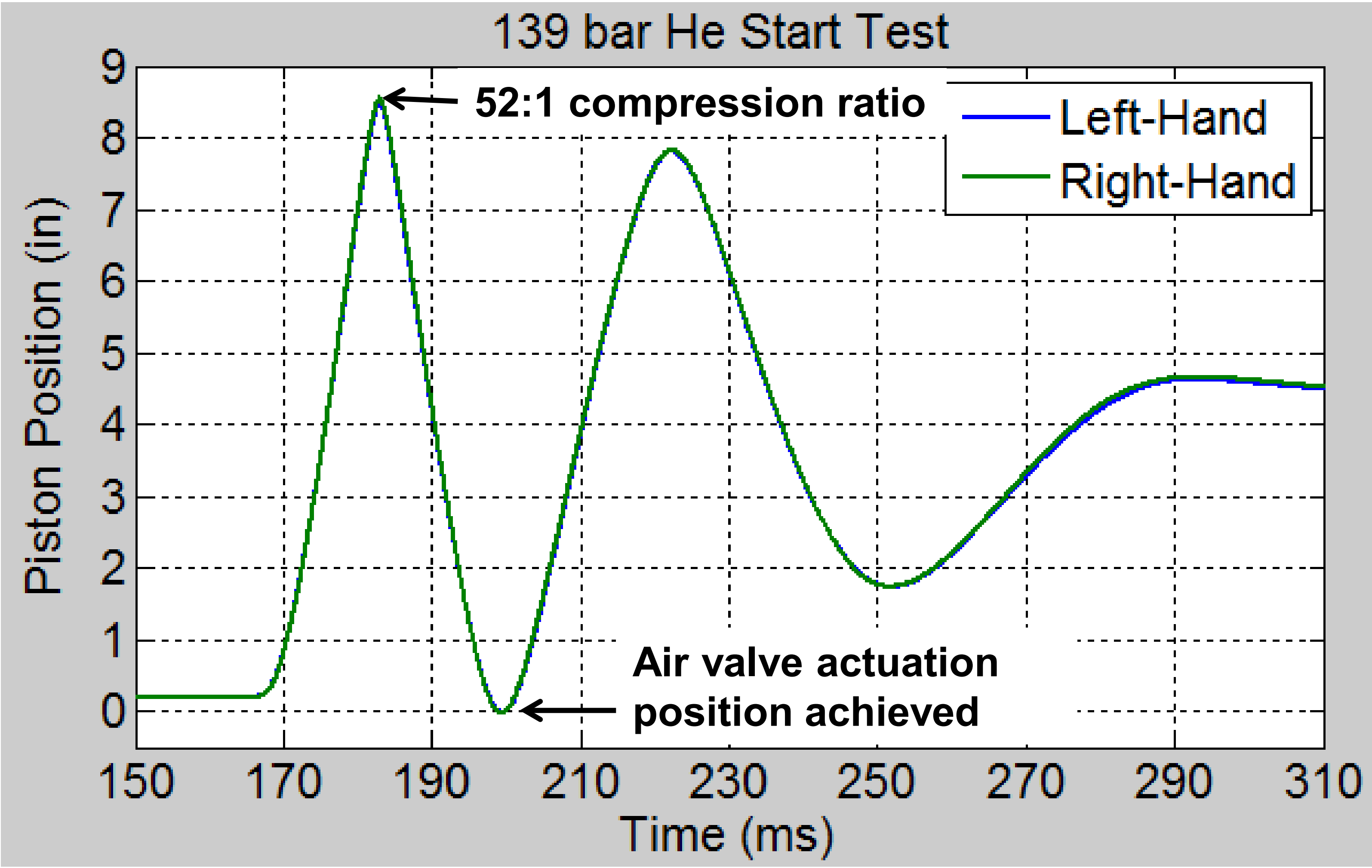


Fully assembled piston with magnets

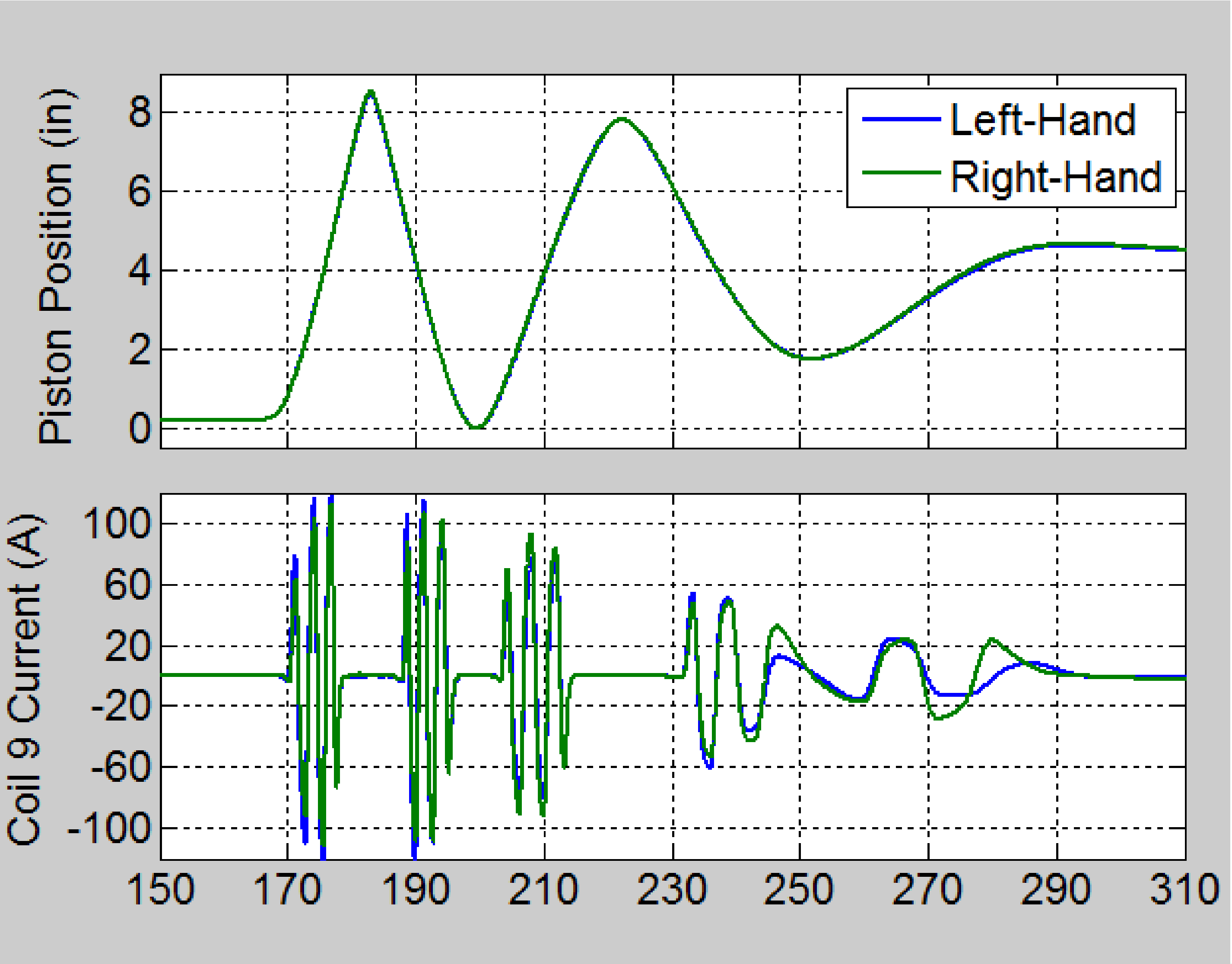
Bounce chamber with He start system and air motoring system attached



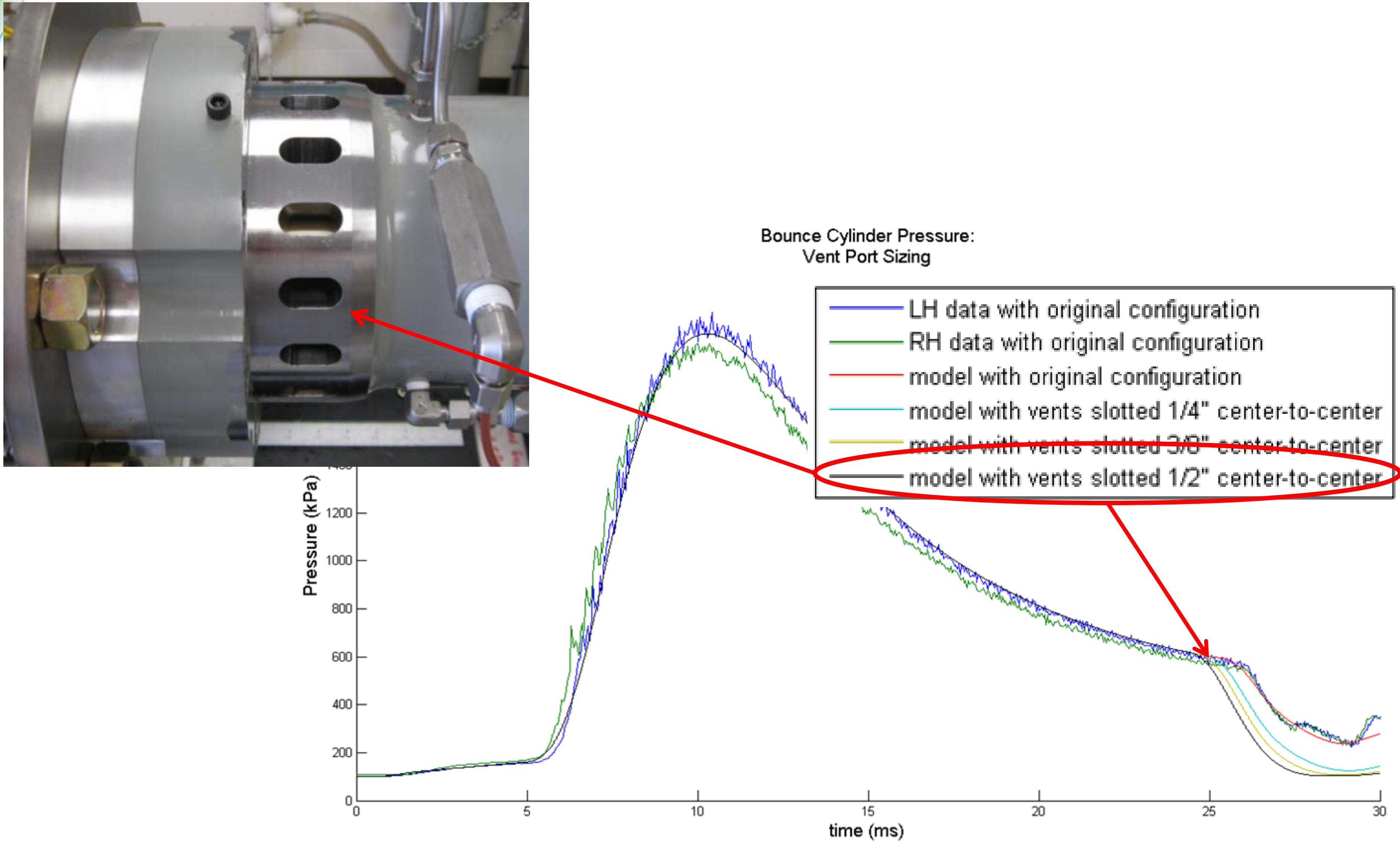
He start tests show that desired travel and good synchronization can be achieved



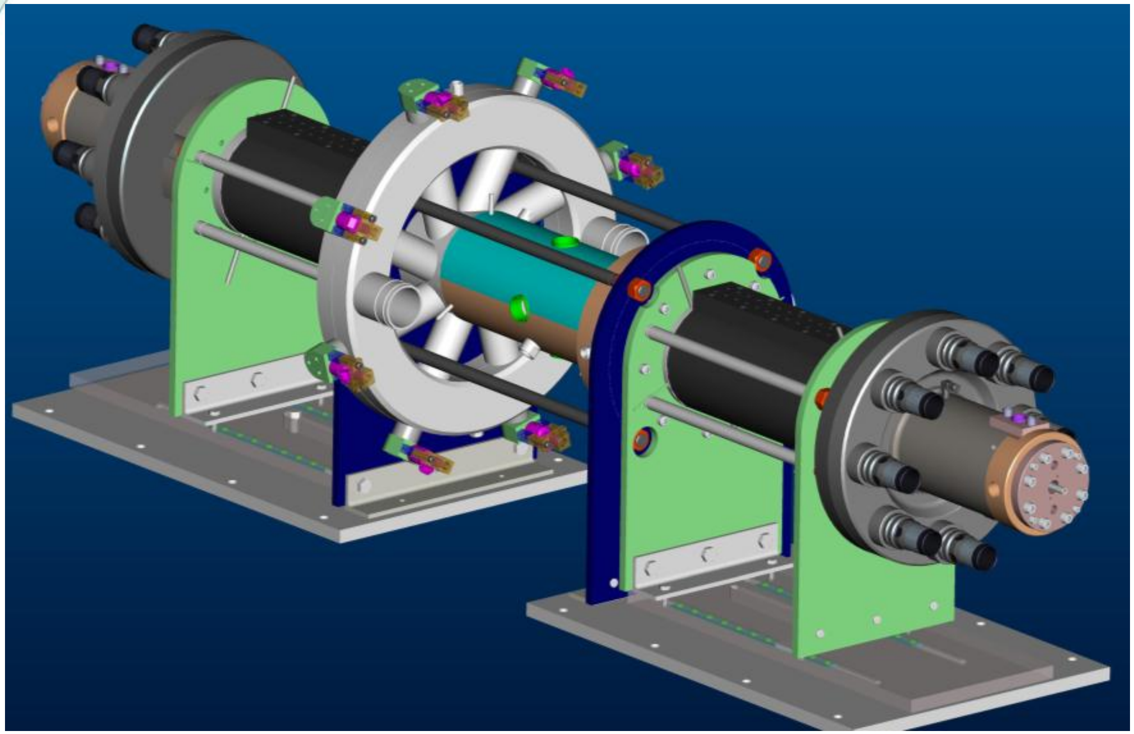
Tests have generated coil currents comparable to model predictions

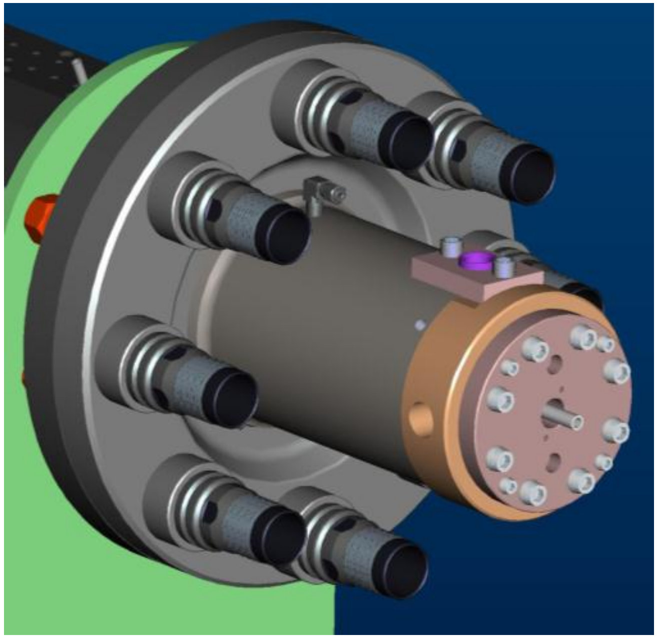


Modeling used to redesign bounce chamber vent ports for sufficient venting



Conceptual design for new bounce chamber vent manifolds completed

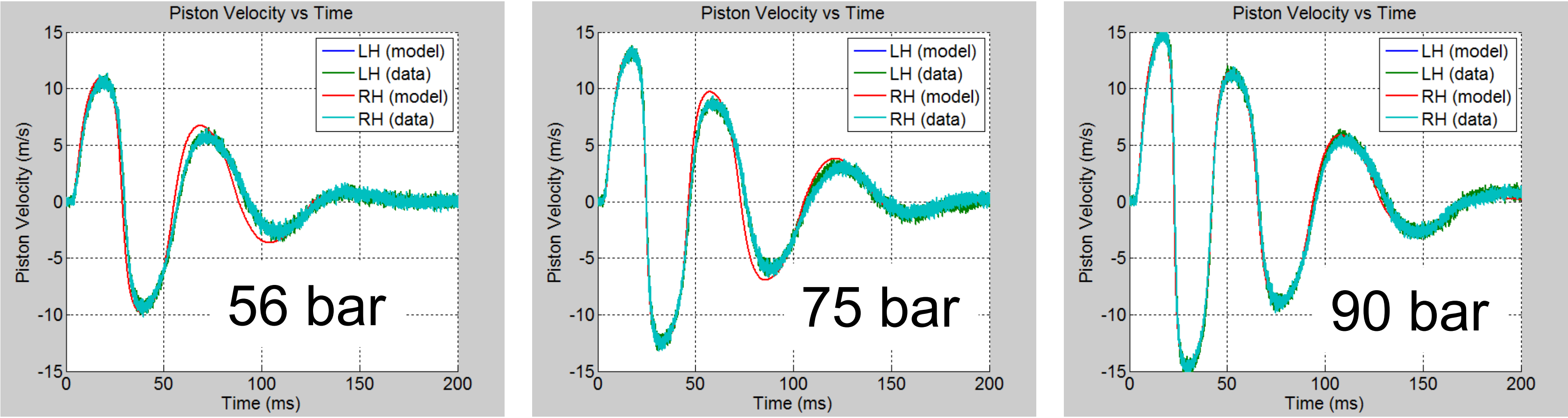




- Original manifolds were too small; didn't allow for full venting
- New design has ~2L volume and much larger flow area to vent tanks
- Manifold design based on fluid dynamics modeling results

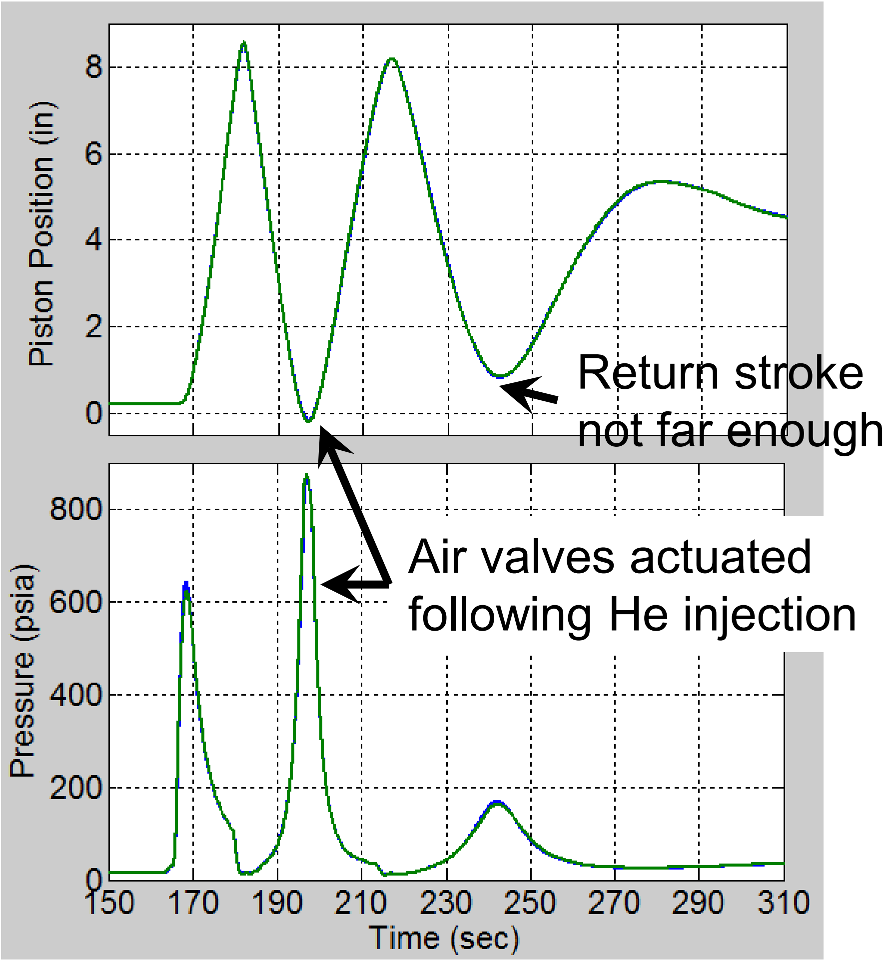
A friction force model was developed and fit to open circuit He start data

- Model was parameterized by comparing to three different helium start tests.
- Tests were performed with coils disconnected to isolate friction force
- The equation, $F_f\ (N) = (50+390*(abs(vel))^{0.25})*sign(vel)$, was found to work reasonably well for all cases.



Simulations and experiments indicate air motoring may be limited by piston friction

- Air motoring simulations indicate 900-1000 psi required for continuous operation; very high flow rates
- Recent tests validate simulation results
  - 60 bar (875 psi) in air tanks
  - 155 bar He start pressure
  - Air valves appropriately actuated, but not enough pressure increase to get a second actuation on piston return



We are pursuing friction reduction options in parallel with air system enhancements to enable motoring

Friction reduction options:

- Change to gapped vespel rings
  - New rings designed for current groove dimensions
- Reduce ring width
  - Friction reduced through lower normal force and lower surface area
- Redesign piston ends
  - Increase piston-to-cylinder clearance
  - Add rider rings

Air system enhancements

- New regulator to increase accumulator pressure
  - Old regulator limited to 1000 psi
  - New regulator extends to 1500 psi
- Large accumulator volume to allow extended run times
  - Buffers feed from compressor to allow 5-10 min experiments
- High pressure gas system to extend or replace compressor
  - 6000 psi N2 cylinders
  - Larger compressed air or N2 systems

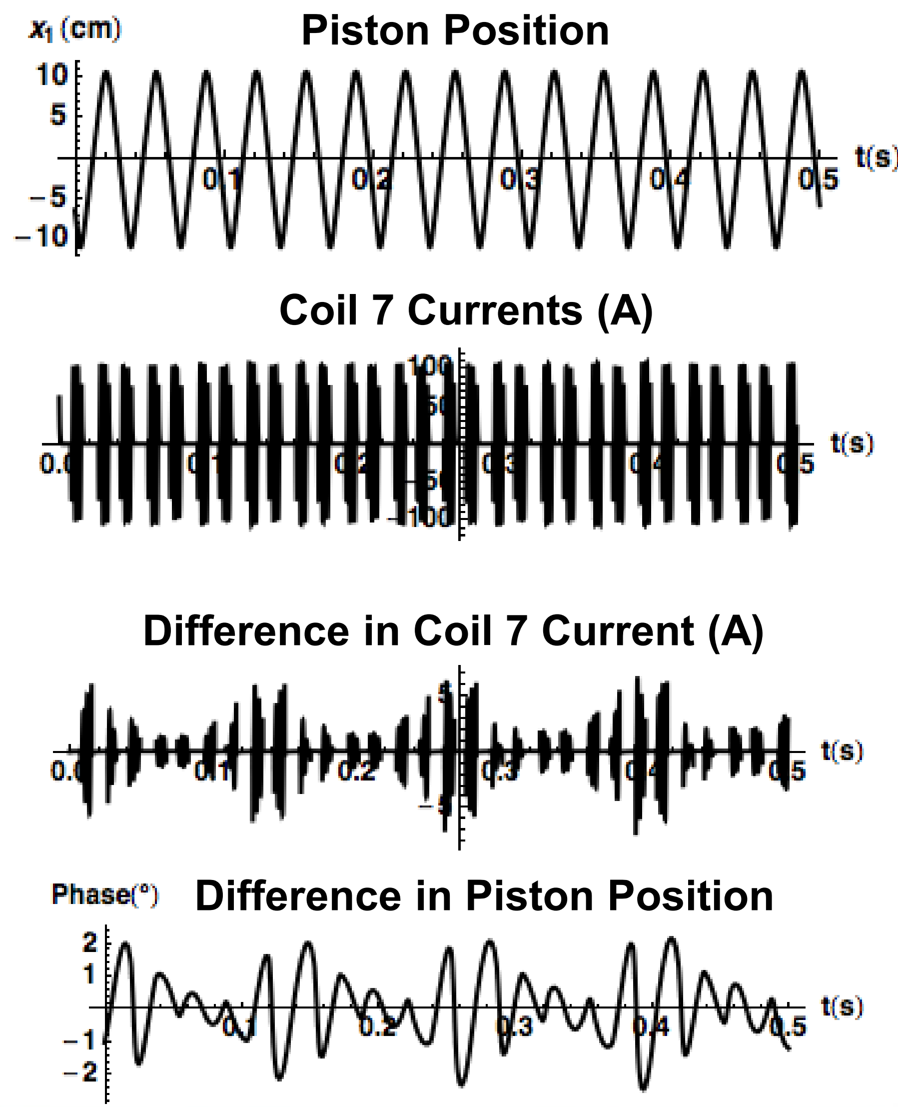
Electromagnetic model of FPLA demonstrates passive stabilization

Model includes:

- Adiabatic air drive through bounce chambers
- Experimentally-based friction model
  - 10% difference imposed between left and right-hand pistons
- Newtonian mechanics of piston motion
- Electrodynamics of individual coil pairs connected in parallel to 14 separate resistors; with coils, cables, and resistors based on experimentally measured resistances and inductances.

Model does not include:

- Gas flow dynamics
- Heat transfer effects back on driving air



Phase of 360°represents piston offset of 44mm

COLLABORATION AND COORDINATION

We have been collaborating with GM and U of M since May 2009

General Motors / University of Michigan

- A new phase of collaboration with the GM/UM CRL began in May 2009.
- GM/UM CRL will assess Sandia free-piston engine (FPE) potential with a model built in a MATLAB/Simulink framework featuring 0-D thermodynamics, a linear alternator model, a bounce chamber air control model, and dynamic force balance.
- The model will be validated with respect to Sandia FPE experimental data and used to explore conditions outside the experimental matrix.

FUTURE WORK

The final milestones for this project are scheduled to be completed within the calendar year

- **Motor the engine using air injection system**
  - Test the stabilizing capability of the linear alternator coupling and assess control of compression ratio

- **Perform combustion experiments**
  - Evaluate the free-piston linear alternator concept
  - Attempt to approach ideal Otto cycle operation at high compression ratio to explore the limits of thermal efficiency
  - Operate with different fuels at a variety of compression ratios and equivalence ratios to demonstrate the engine's fuel flexibility

Summary

- Free-Piston Engine (FPE) research prototype completely assembled
- Helium-powered starting system successfully demonstrated
- Bounce chamber vent manifold redesigned and fabrication partially complete
- Efforts to reduce piston friction and improve air supply system to enable continuous air motoring ongoing
- Collaboration with GM/UM CRL on modeling of the Sandia FPE prototype engine is ongoing.
- Combustion experiments expected by late summer/early fall

BACKUP SLIDES

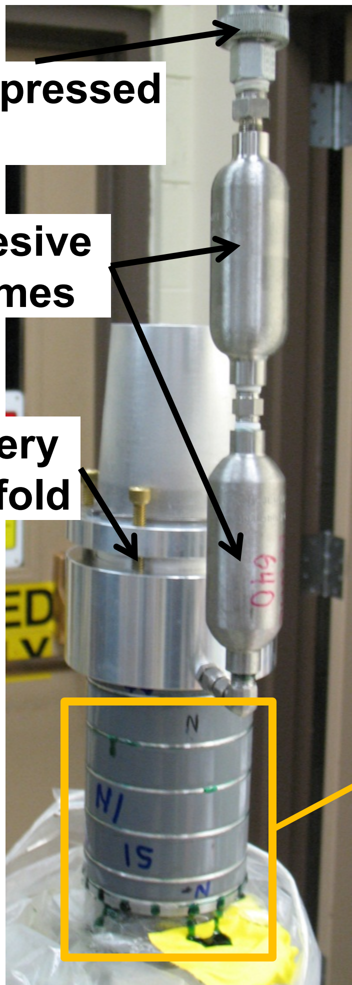
Pistons assembled with magnets and installed in the system

Adhesive Delivery System

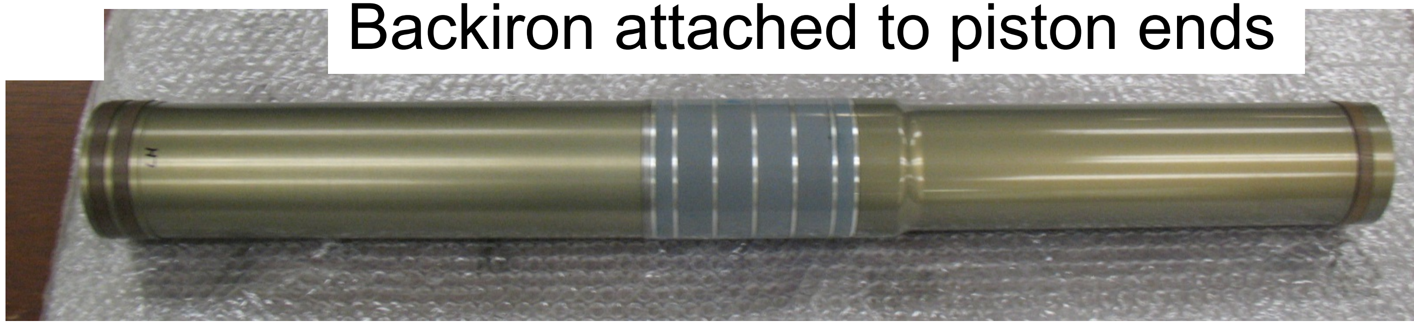
Compressed air

Adhesive volumes

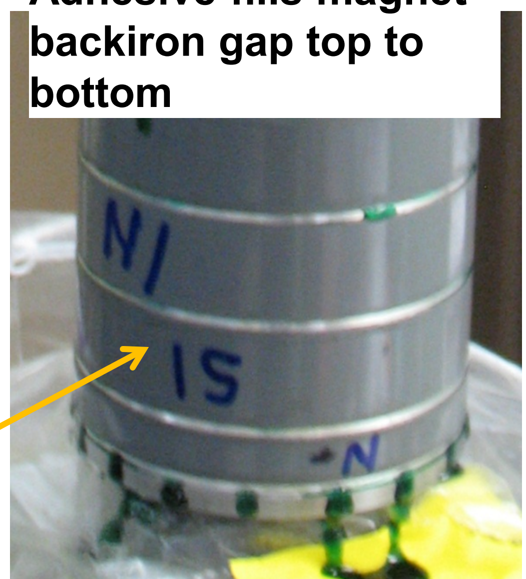
Delivery manifold



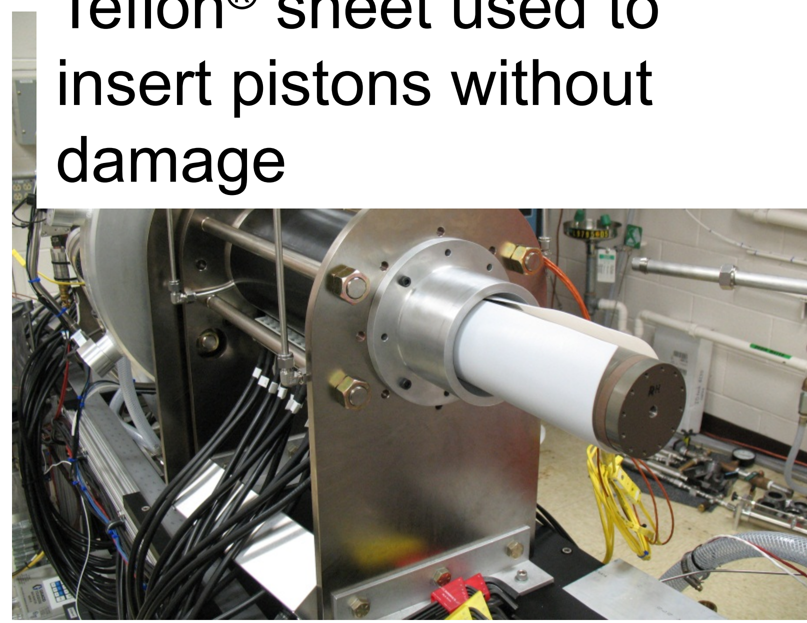
Backiron attached to piston ends



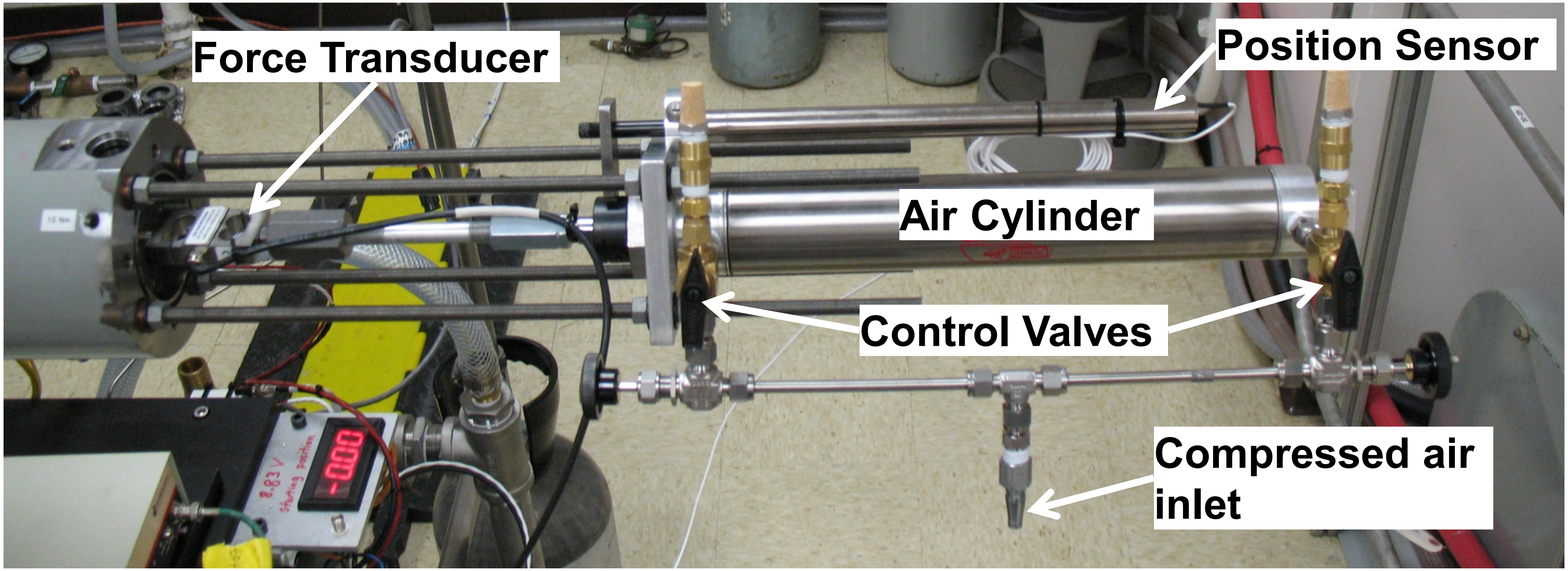
Adhesive fills magnet-backiron gap top to bottom



Teflon® sheet used to insert pistons without damage



Piston forces measured up to ~1 (m/s) velocity with custom test rig



Forces measured with and without electrical load connected isolate effects