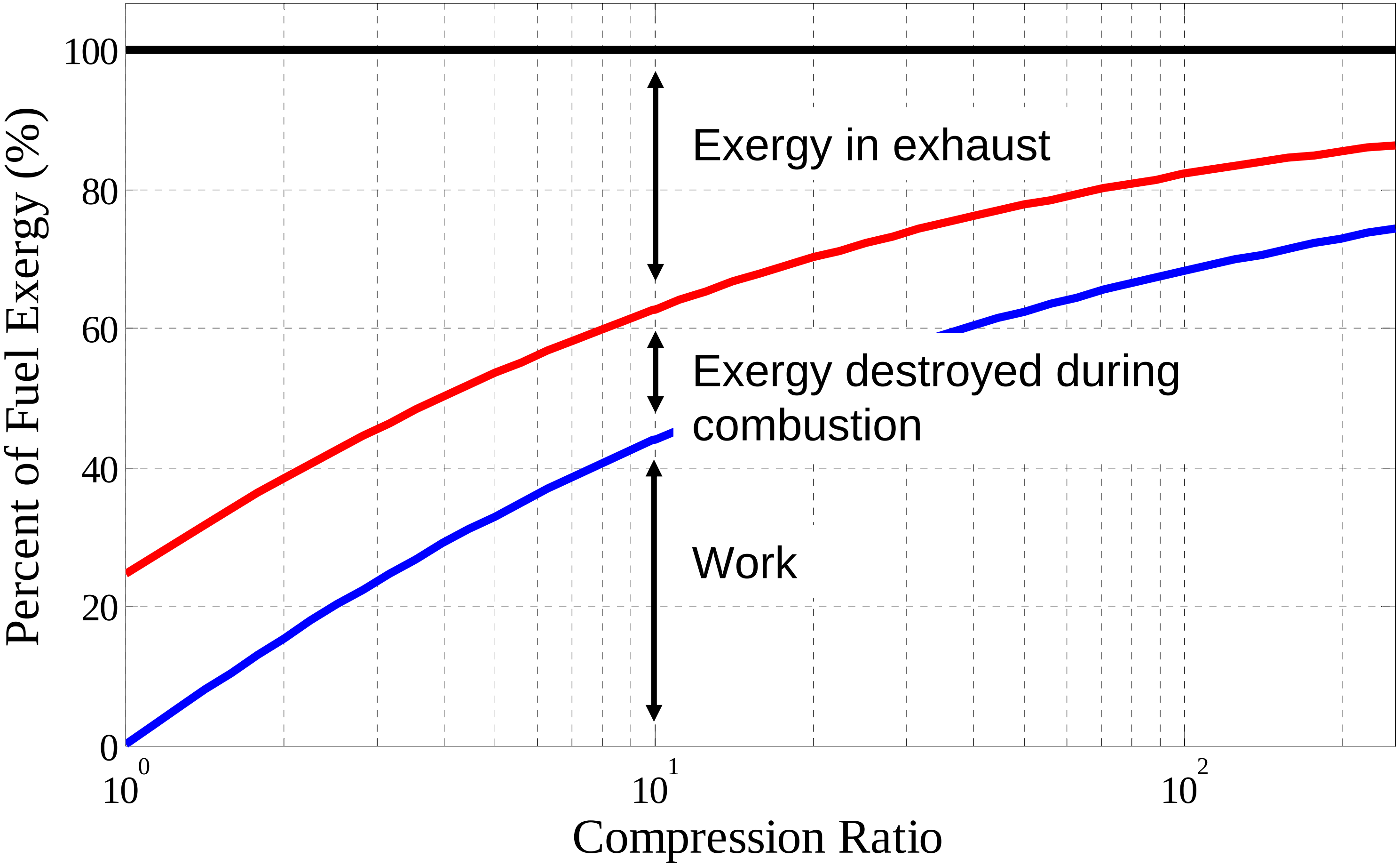
Development of Low-Exergy-Loss, High-Efficiency Chemical Engines

Chris Edwards,
Shannon Miller, Matthew Svrcek,
Sanakaran Ramakrishnan, Kwee Yan Teh,
Olivier Lacroix, Joe Wilson

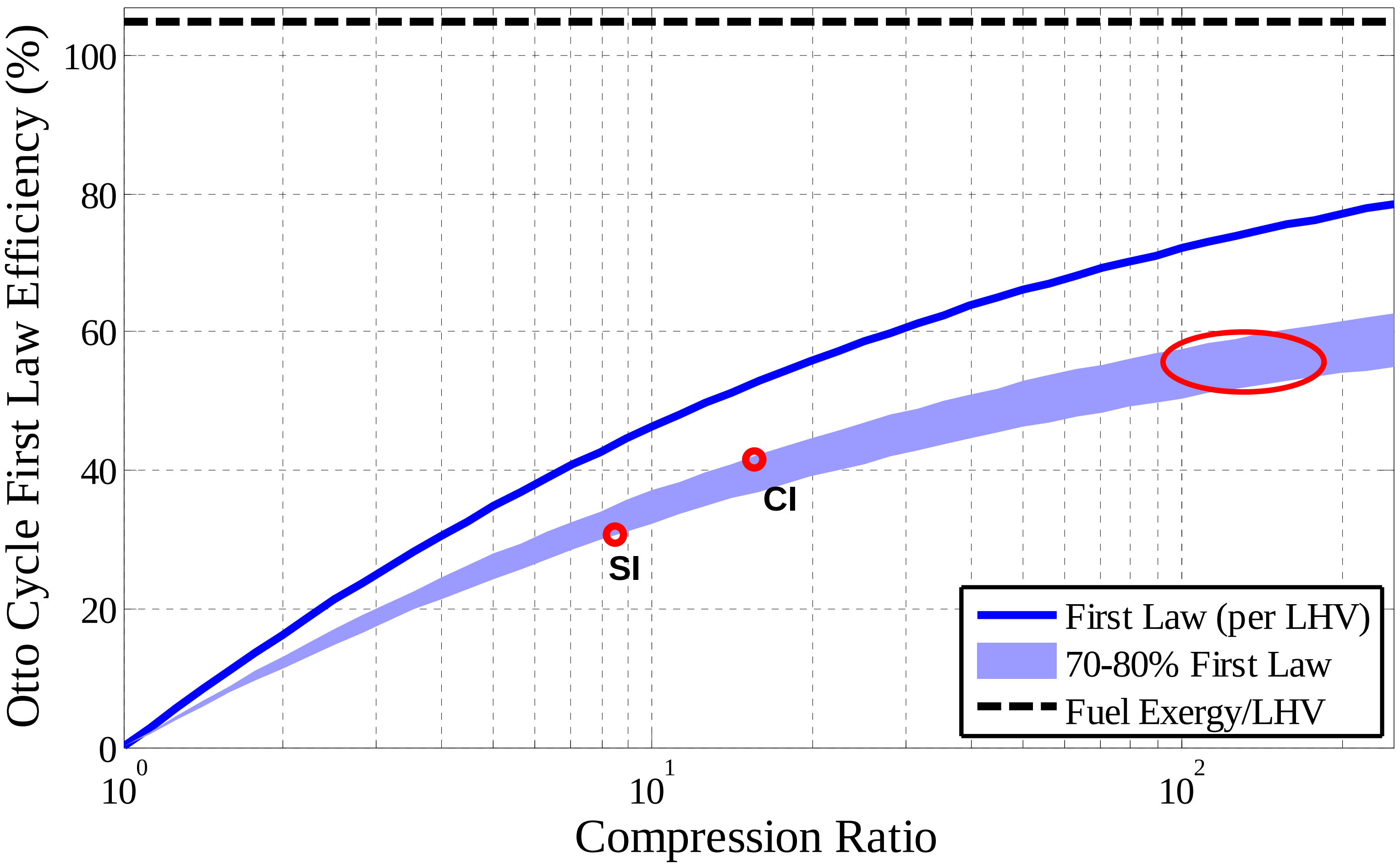
Department of Mechanical Engineering
Stanford University

Fuel Exergy Distribution for Reactive Otto Cycle



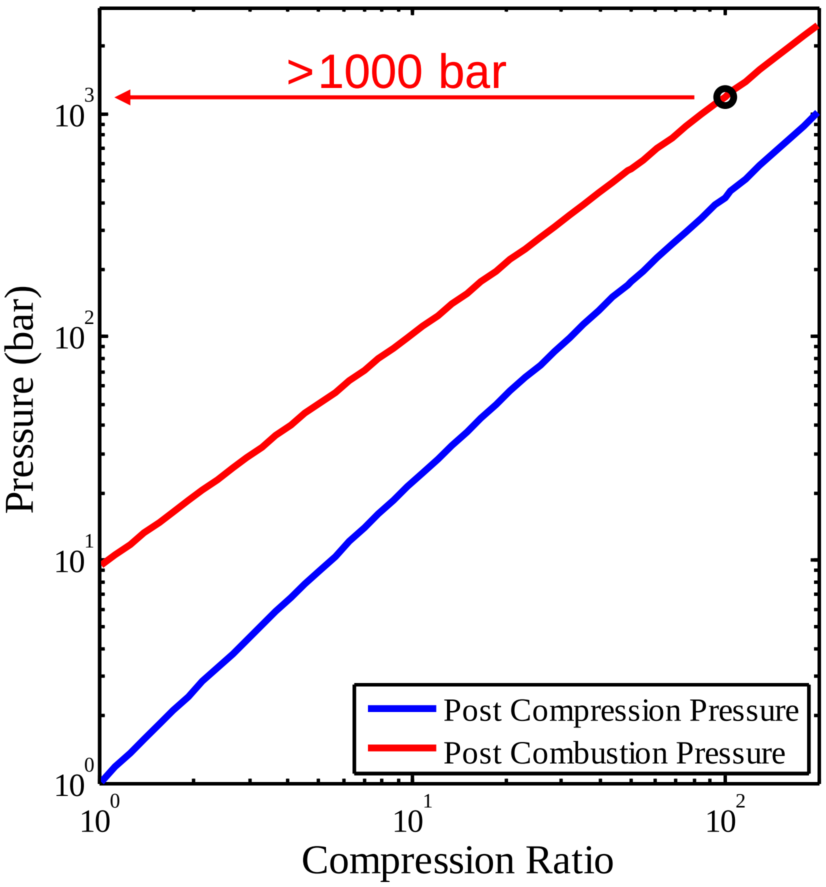
Stoichiometric propane/air modeled as ideal gases.

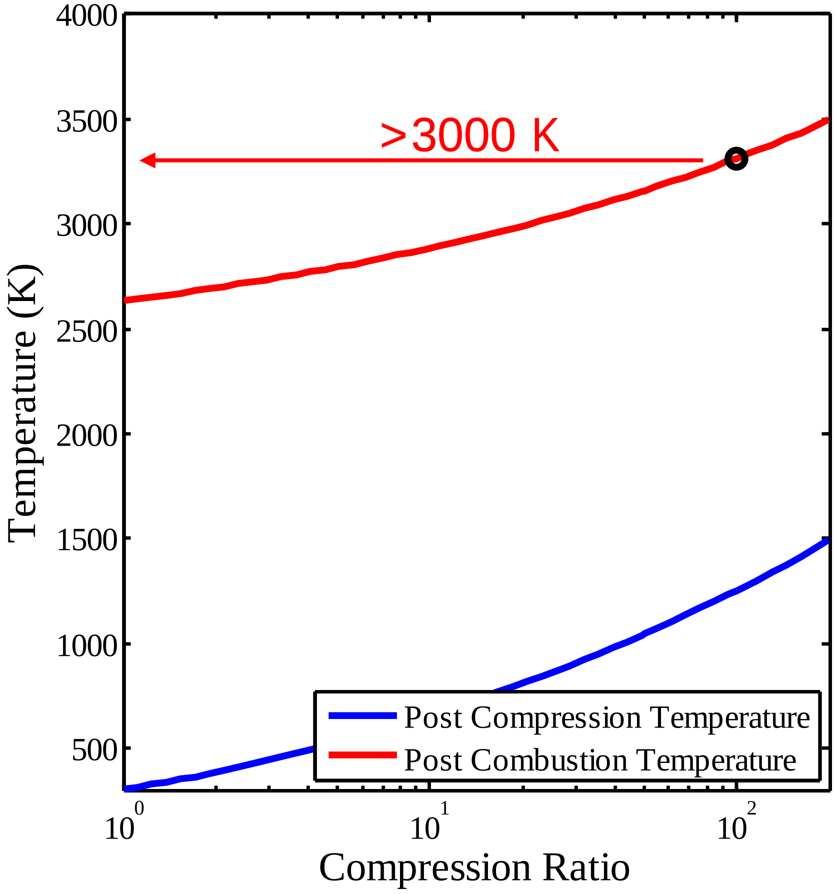
What fraction of theoretical efficiency might be achieved?



Stoichiometric propane/air modeled as ideal gases.

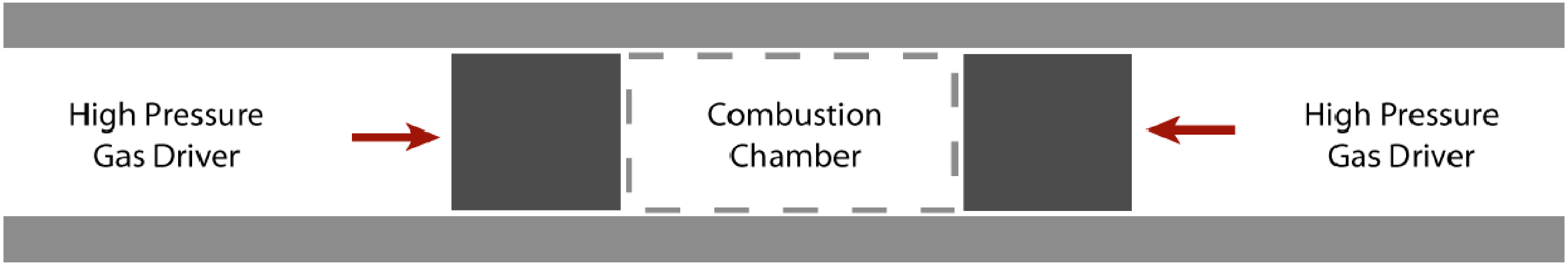
Extreme Compression Conditions





Stoichiometric propane/air mixture modeled as ideal gases.
Adiabatic, isentropic compression followed by adiabatic constant volume combustion

Achieving Extreme Compression



Basic Requirements:

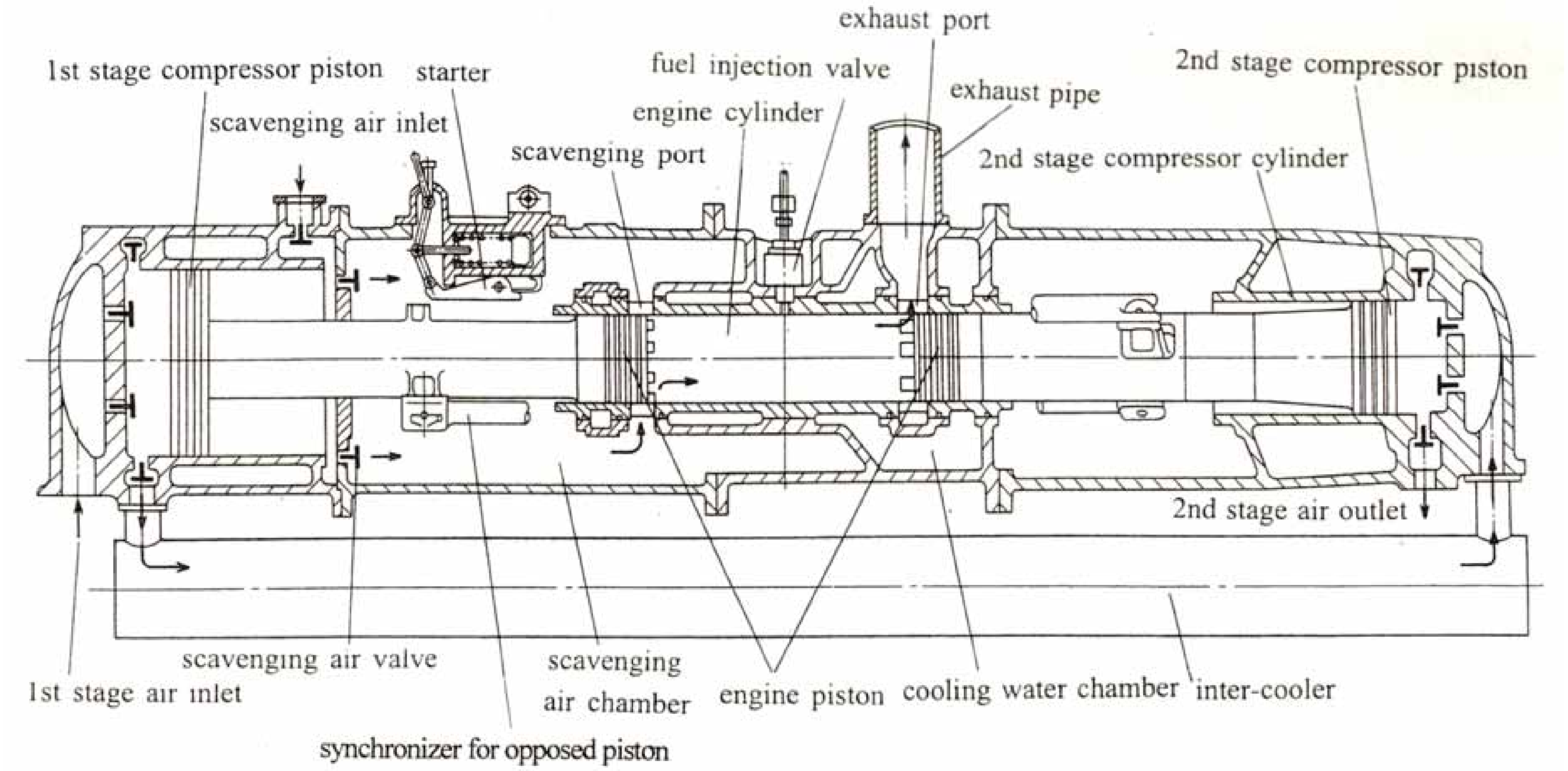
- High compression ratio (100:1 and higher)

- Approach for reducing heat transfer
  - Large TDC volume to reduce heat transfer
  - High piston speeds to reduce time available for heat transfer

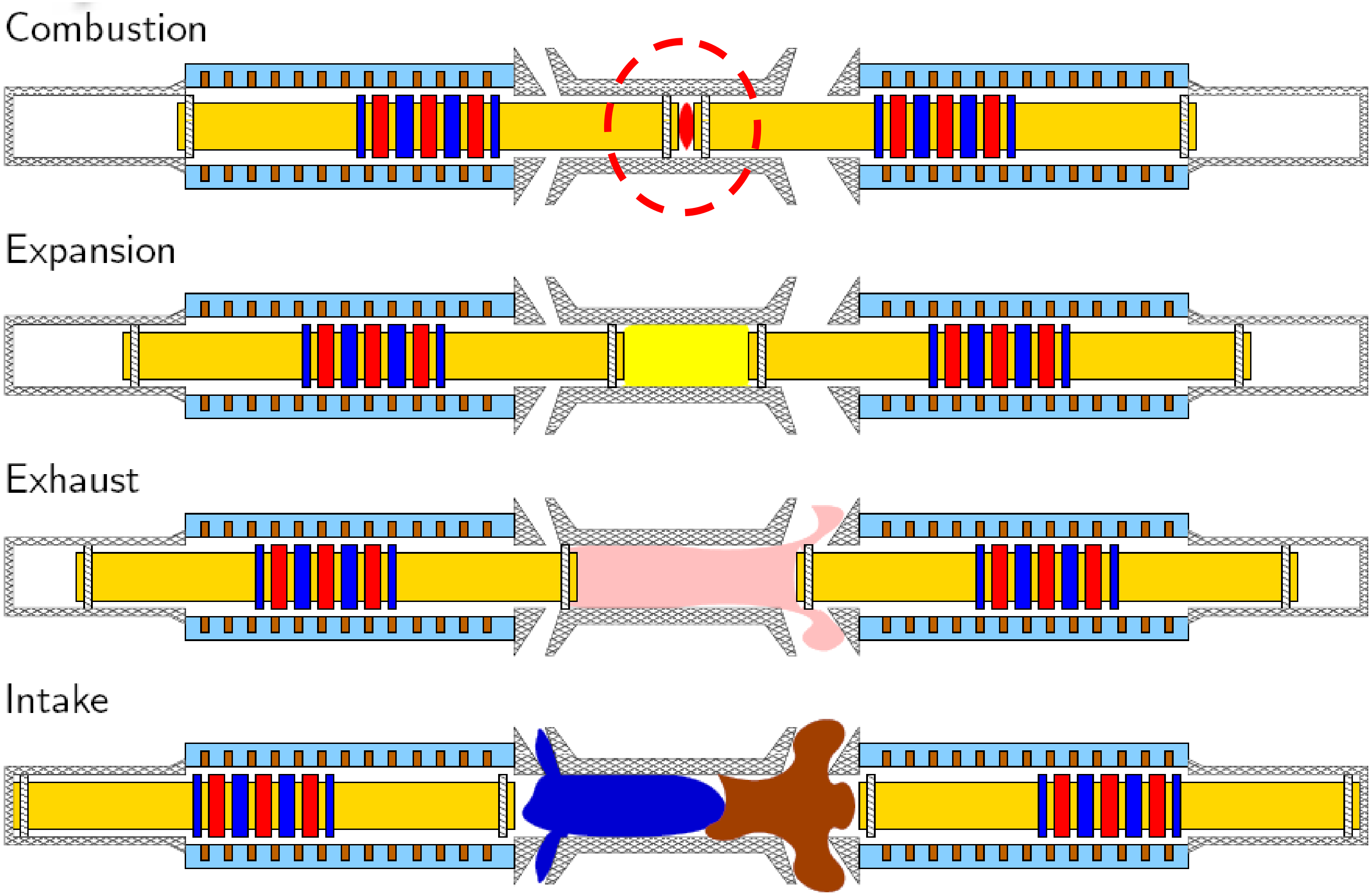
- Approach for high forces
  - Free pistons
  - Multiple pistons

Design apparatus for testing the Critical Questions

Junkers Free-Piston Compressor



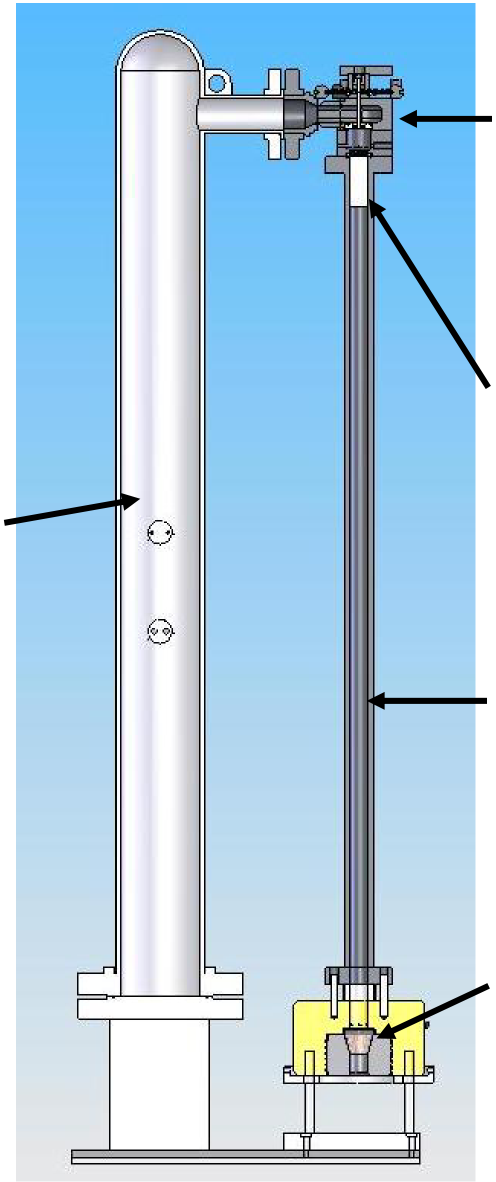
Van Blarigan/Aichlmayr Linear Alternator Concept



Critical Questions

1) Can an engine handle the high temperatures and pressures required for extreme-state combustion?
    1) Material stress
    2) Wall temperatures and heat transfer
    3) NOx
2) Can the rings withstand the pressure and piston speed?
    1) Seal survivability
    2) Sealing ability: Can we achieve <1% blowby?
3) Can we implement and control combustion?
    1) Ignition phasing
    2) Combustion control
    3) Rate and efficiency

Experimental Design



A fast-acting poppet valve for initiating compression

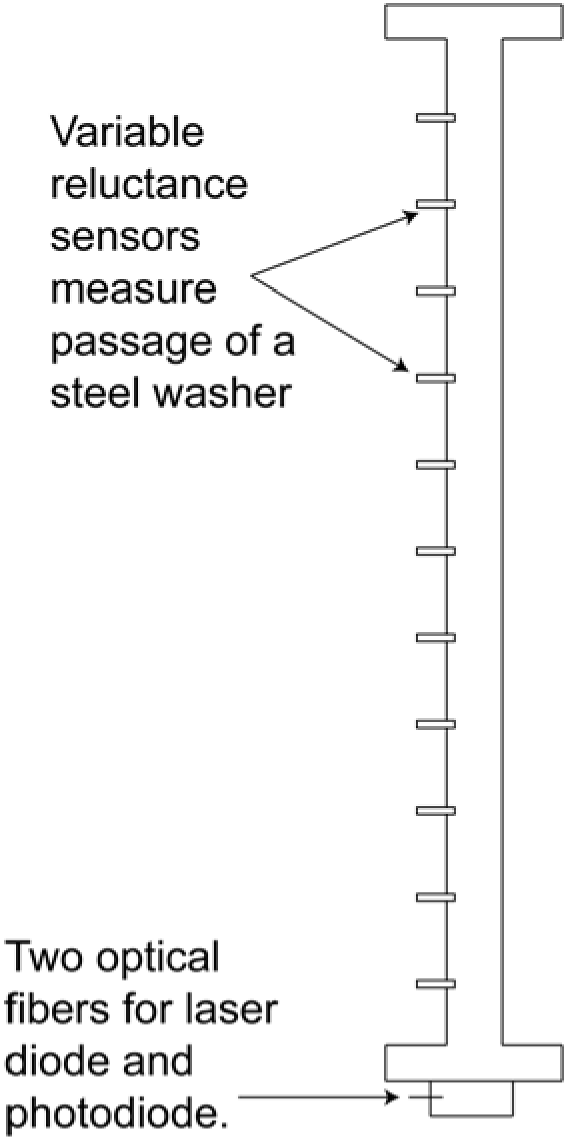
A single, free-piston design with the forces distributed over a large area

A large, high-pressure reservoir, capable of pressures up to ~70 bar

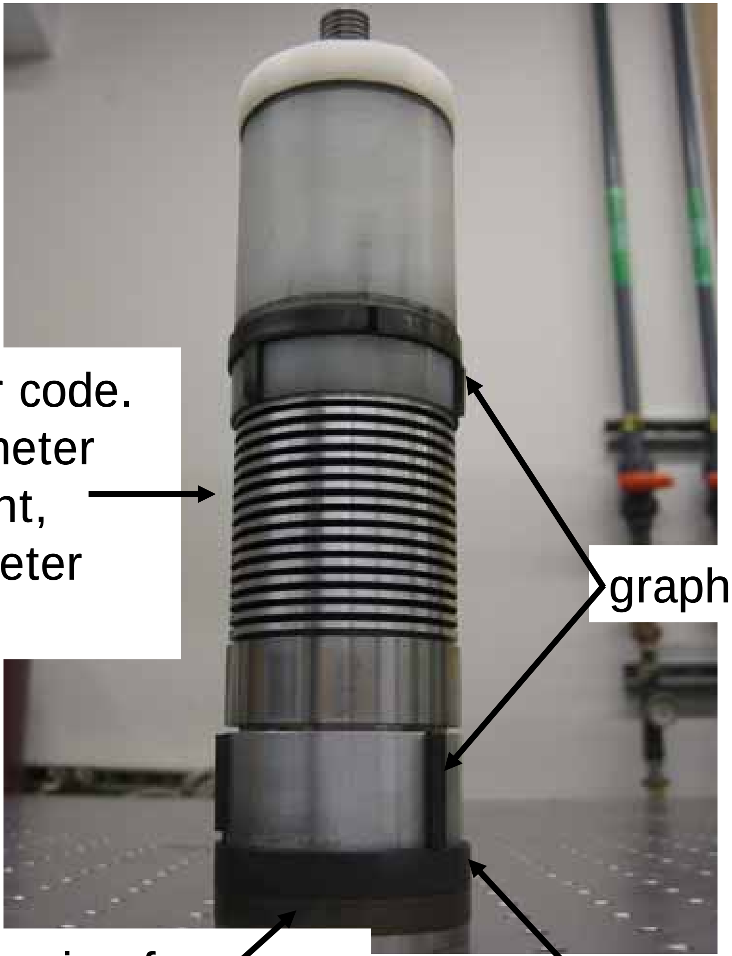
~2.5m cylinder for a low surface to volume ratio at TDC (~ 1:1 aspect ratio at CR = 50)

Optical access through a sapphire window in a high-strength, forged, steel combustor

Piston Position Sensing



Current Piston Design



Optical bar code. Outer diameter reflects light, inner diameter does not.

graphite skis

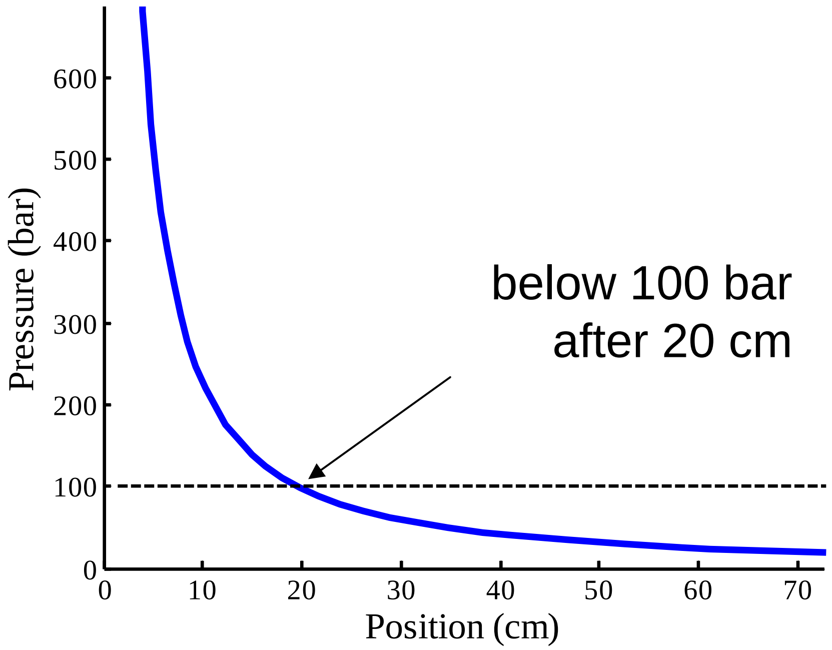
copper ring for thermally protecting the rings

graphite ring

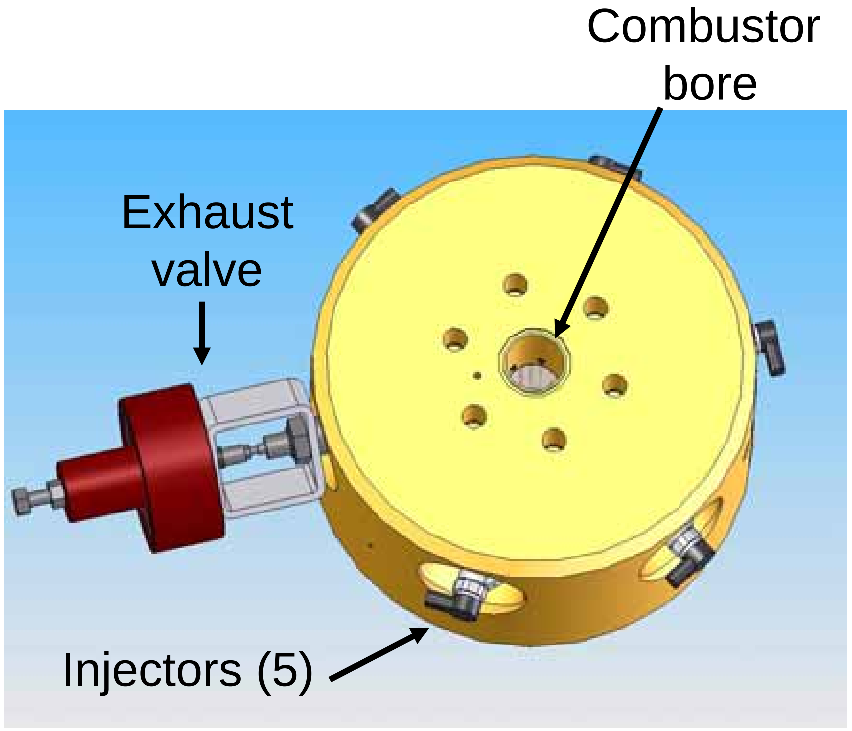
Combustor Design

Material stress strategy: Use pressure profile to our advantage

Injection strategy: Five Bosch high-pressure diesel injectors



below 100 bar
after 20 cm



Combustor
bore

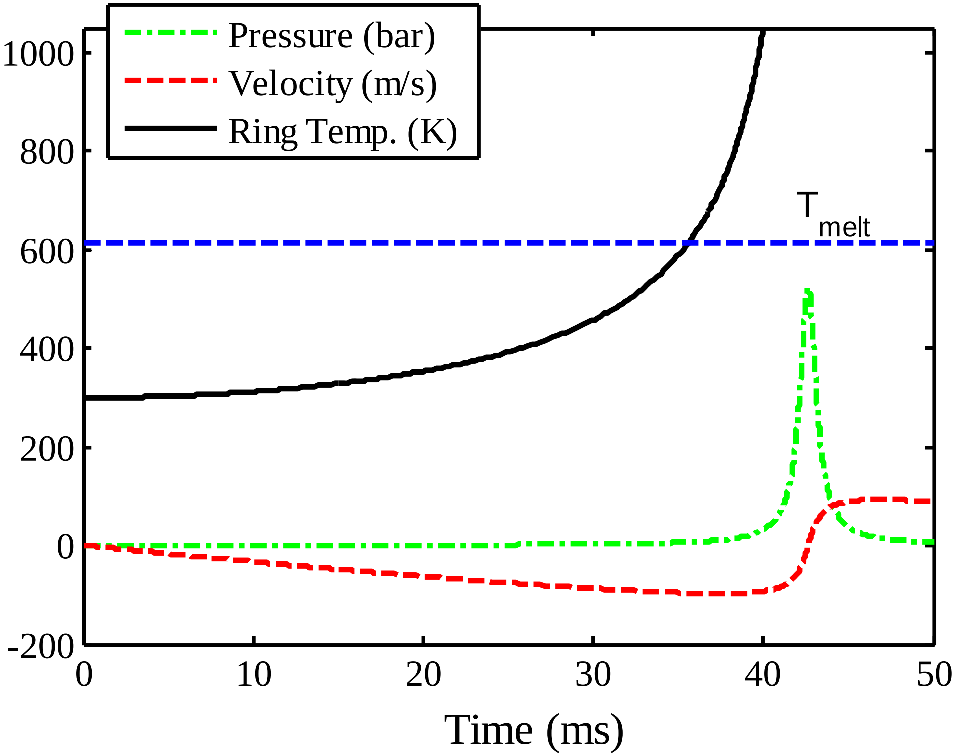
Exhaust
valve

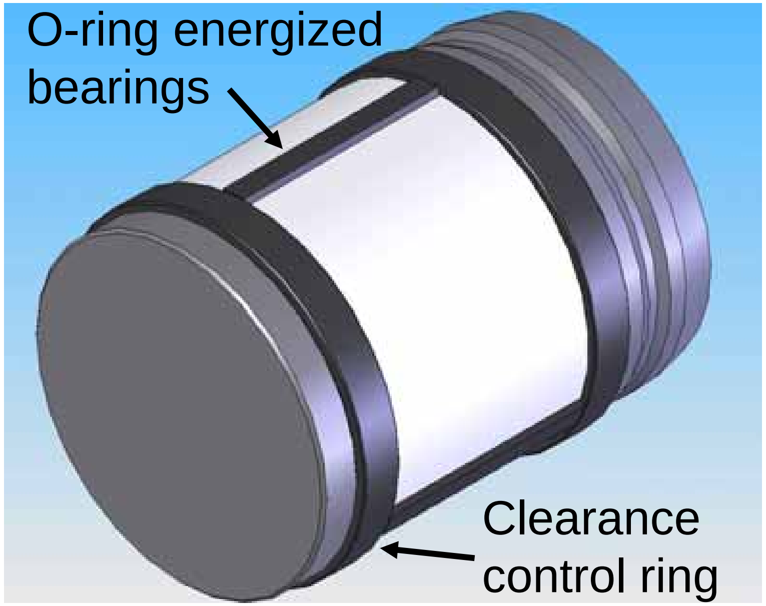
Injectors (5)

Combustor with 2000 bar
working pressure

Piston Design

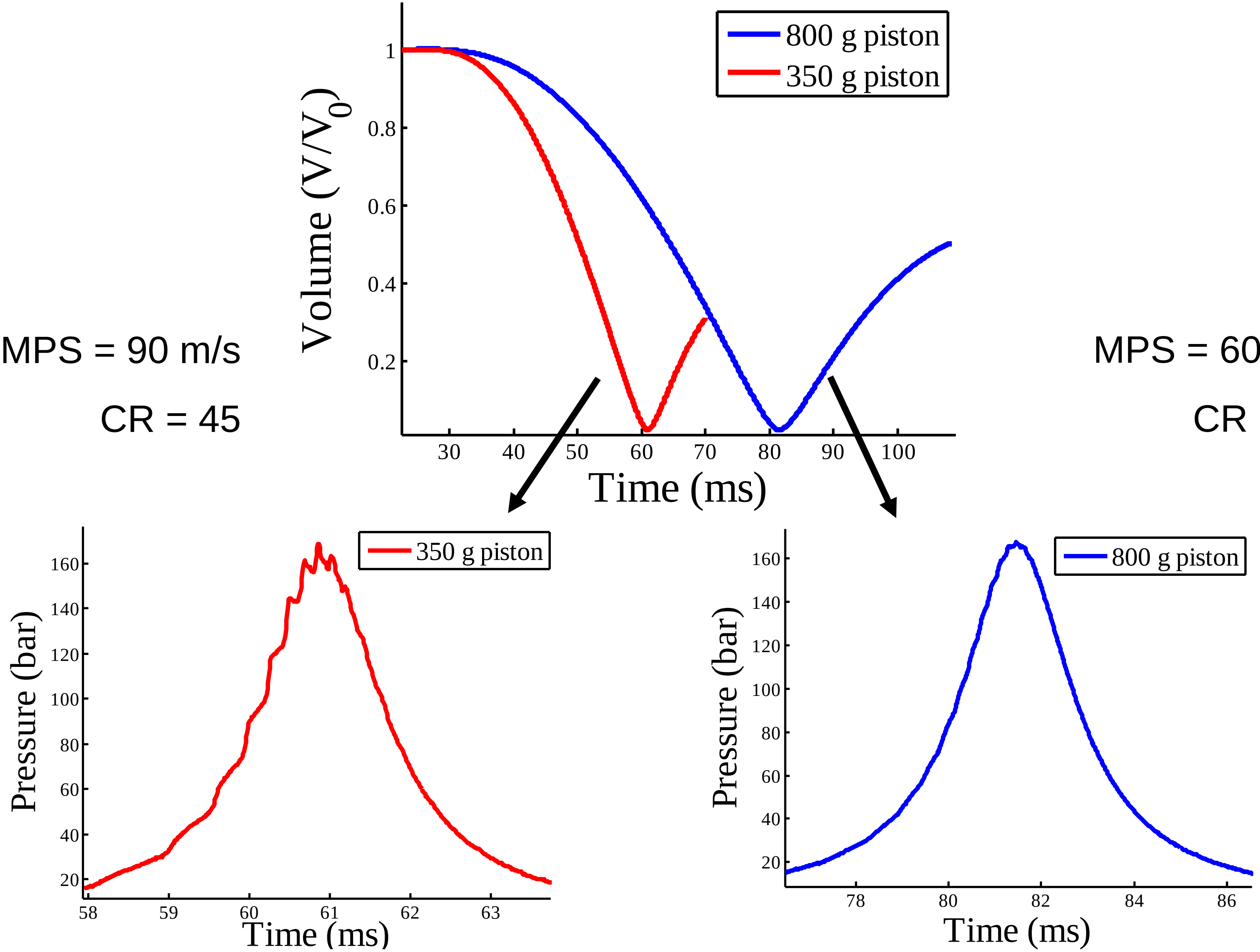
Sealing strategy: Use clearance control, rather than conventionally energized rings to reduce ring temperatures





This low friction strategy also gives high experimental repeatability.

Air Compression: Initial Findings



MPS = 90 m/s

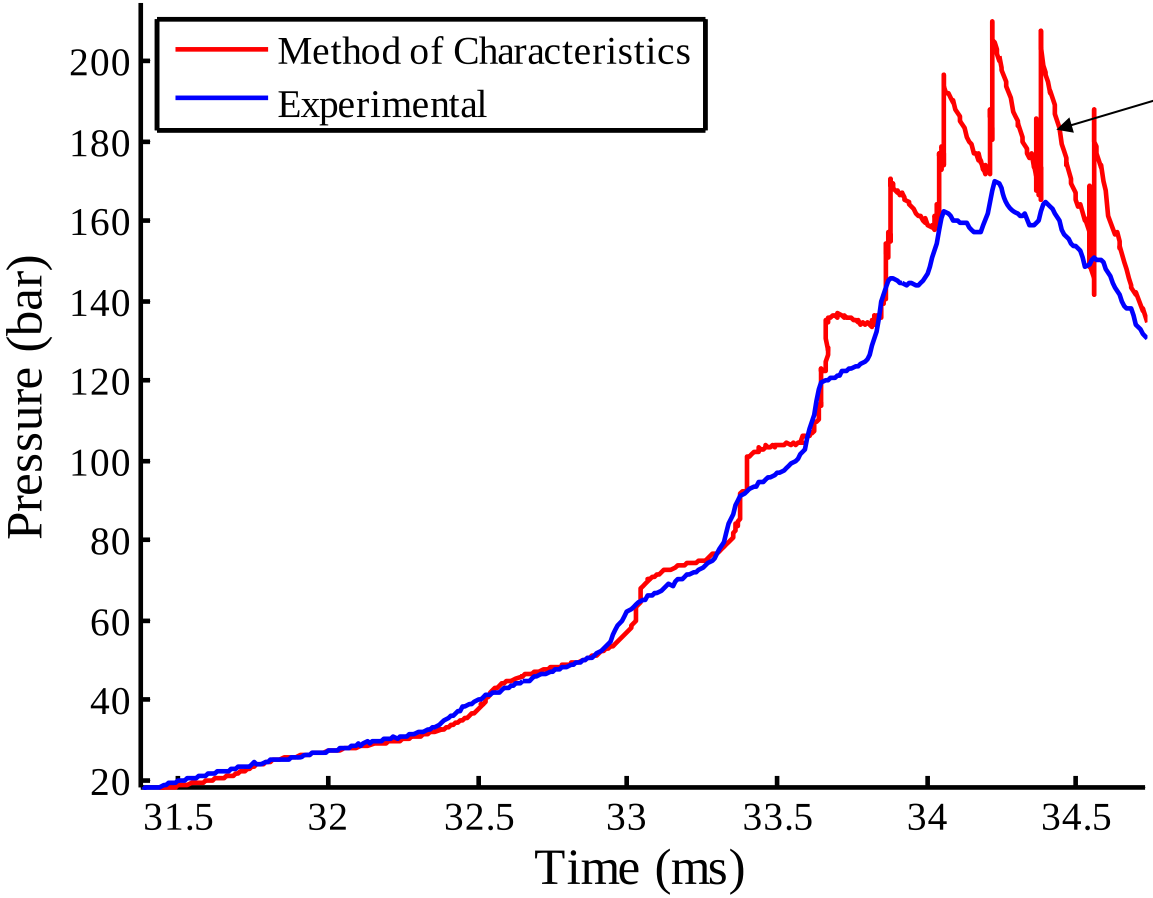
CR = 45

MPS = 60 m/s

CR = 45

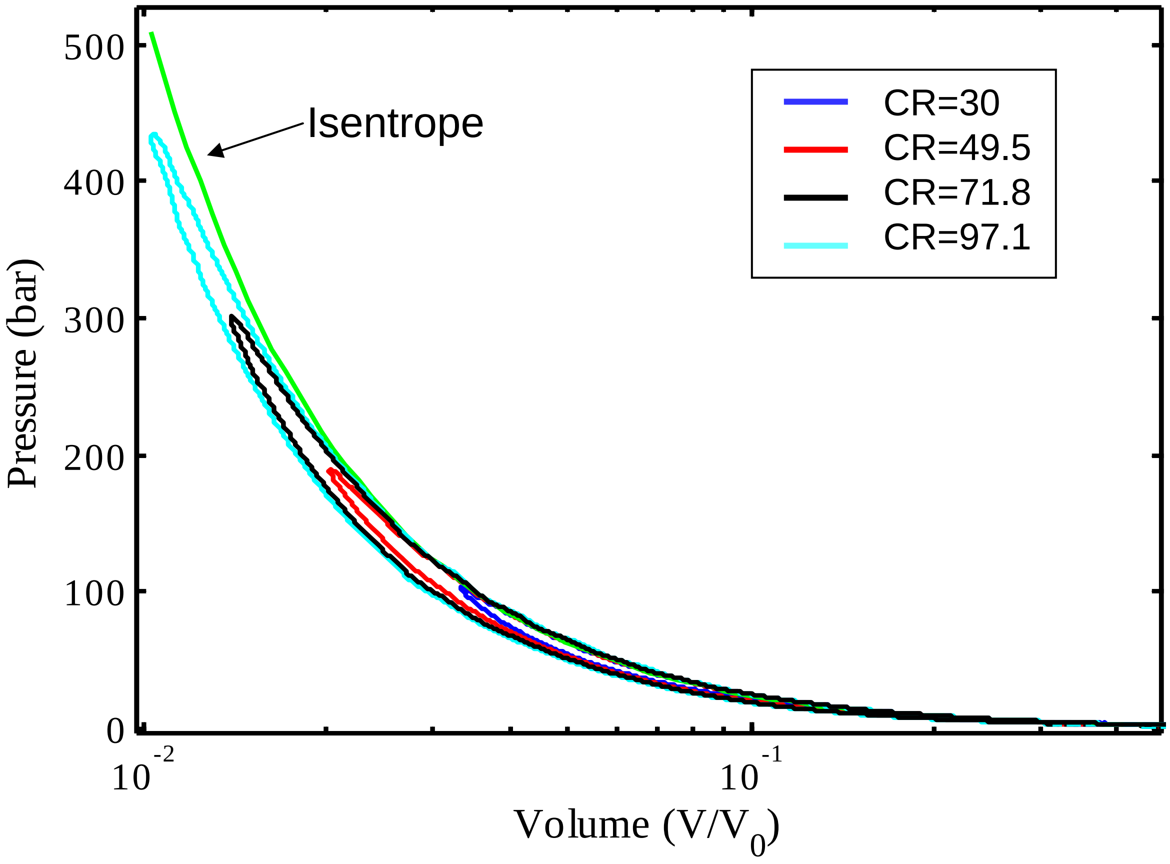
Acoustic Waves

Method of characteristics simulations show that high piston accelerations cause acoustic waves.

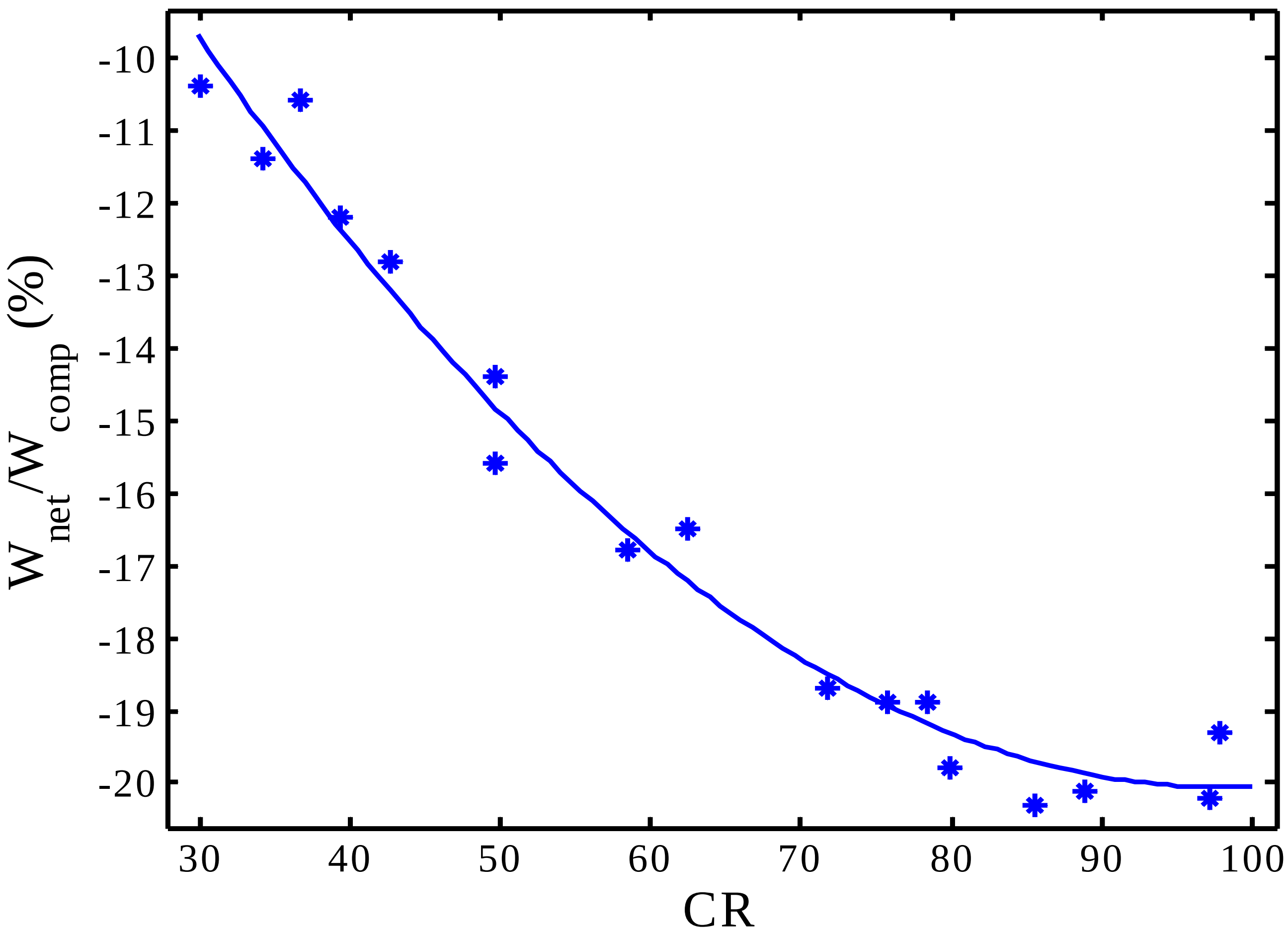


Shock forms
(no dissipation)

P-V Plots: Air Data

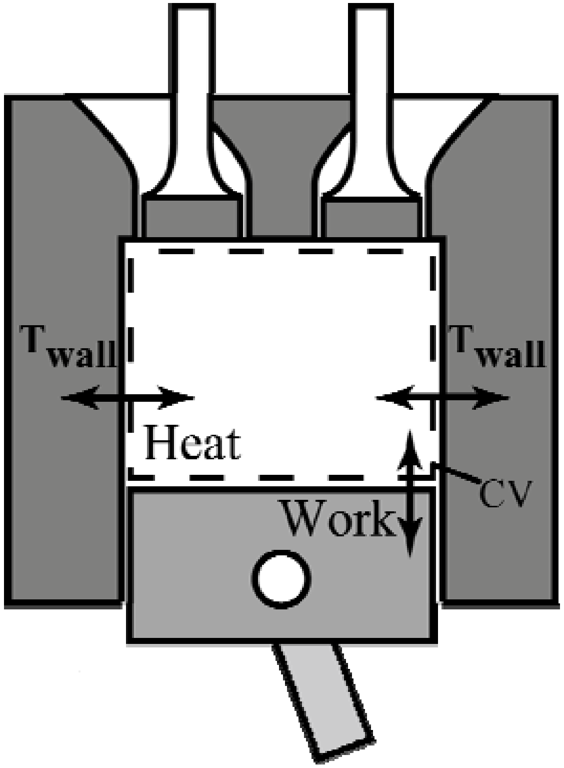


Total Losses Over an Air Cycle



Losses consist of heat and mass transfer.

Heat Loss on Compression



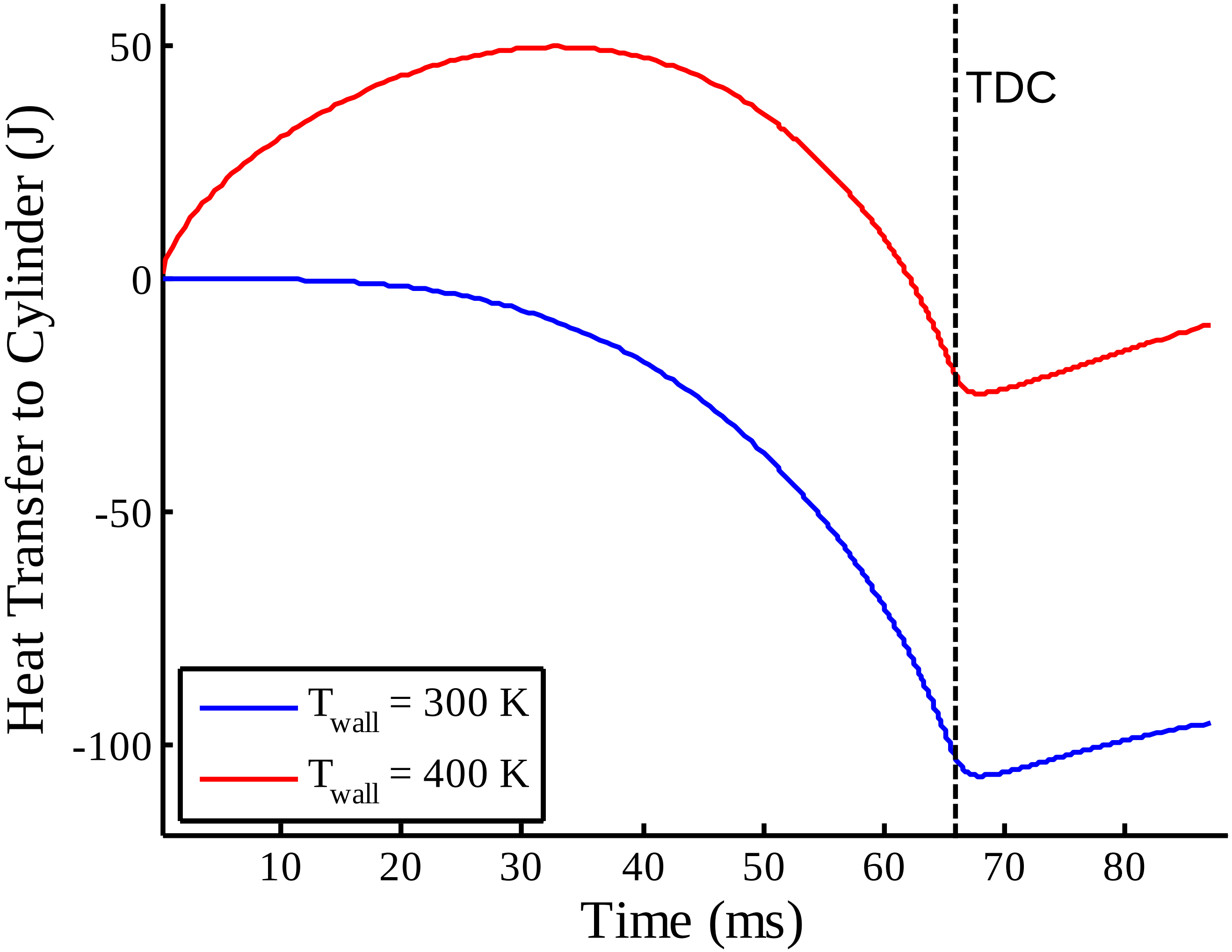
Model Assumptions

- simulates boundary layer formation assuming conduction as only form of heat transfer
- one dimensional
- constant wall temperature
- uniform pressure

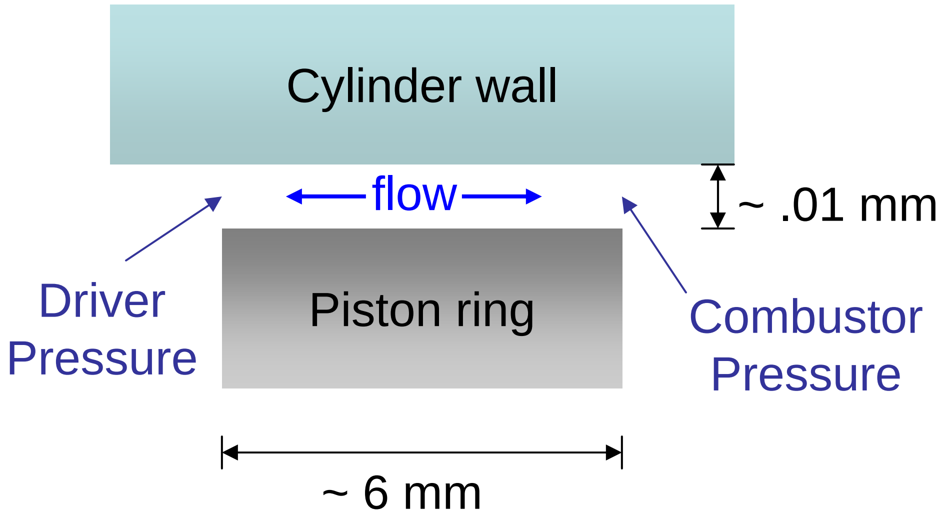
Modeled heat transfer losses for CR = 50 air data:

300 K → ~2% compression work lost to HT
~3% drop in peak pressure from isentropic
400 K → ~0.2% compression work lost to HT
negligible pressure drop from isentropic

Heat Transfer to Cylinder



Mass Loss Past Rings



Model Assumptions

- 1D, isothermal flow through ring-wall gap driven by pressure drop and piston motion
- Viscous effects included via a friction factor
- Pressure and piston motion from experimental runs

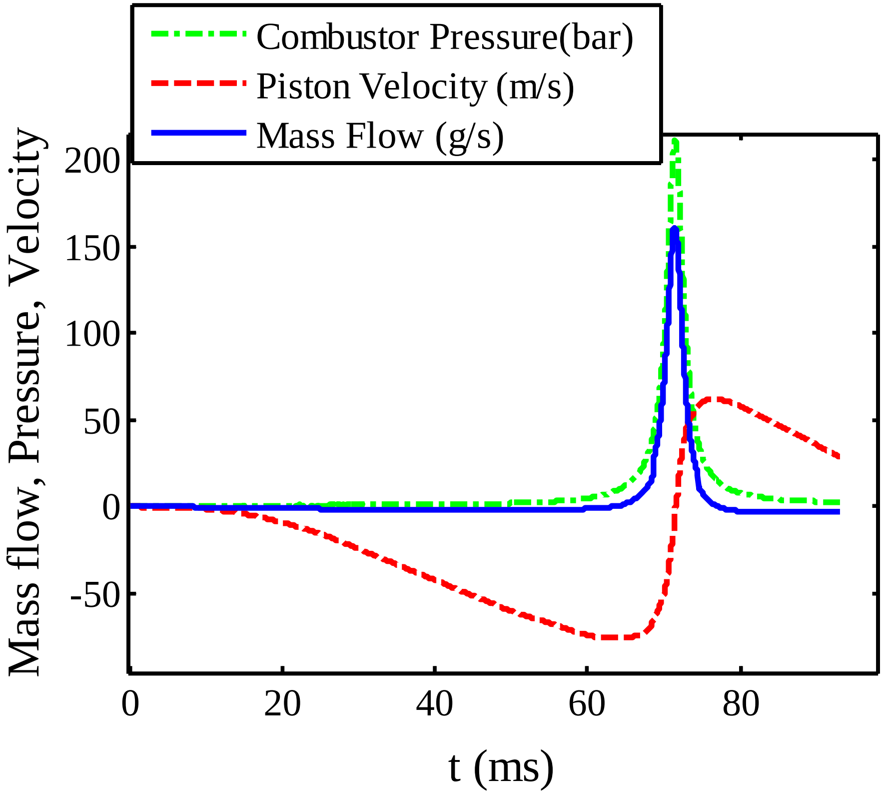
Modeled losses for the CR = 50 air data:

8% of compression work (W_{net} / W_{comp})

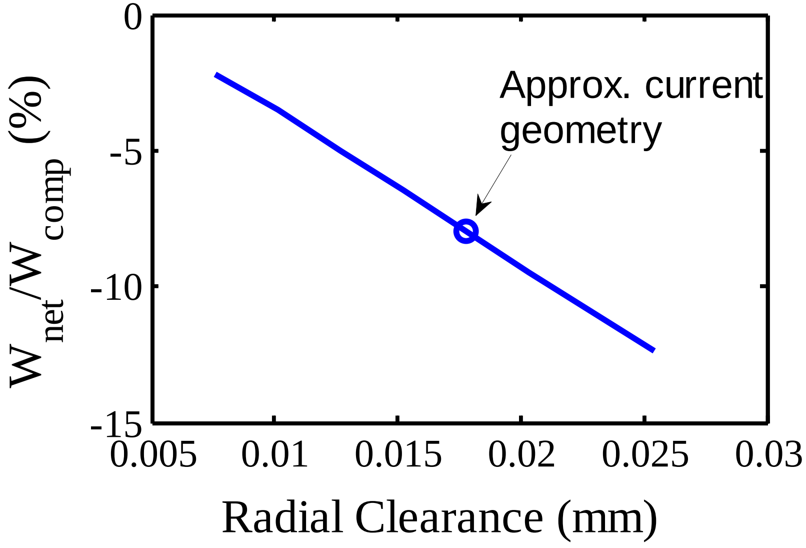
4% of peak pressure (P / P_S)

Mass Transfer to Cylinder

Mass flow profile for CR = 50



Effect of clearance gap on work loss for CR = 50

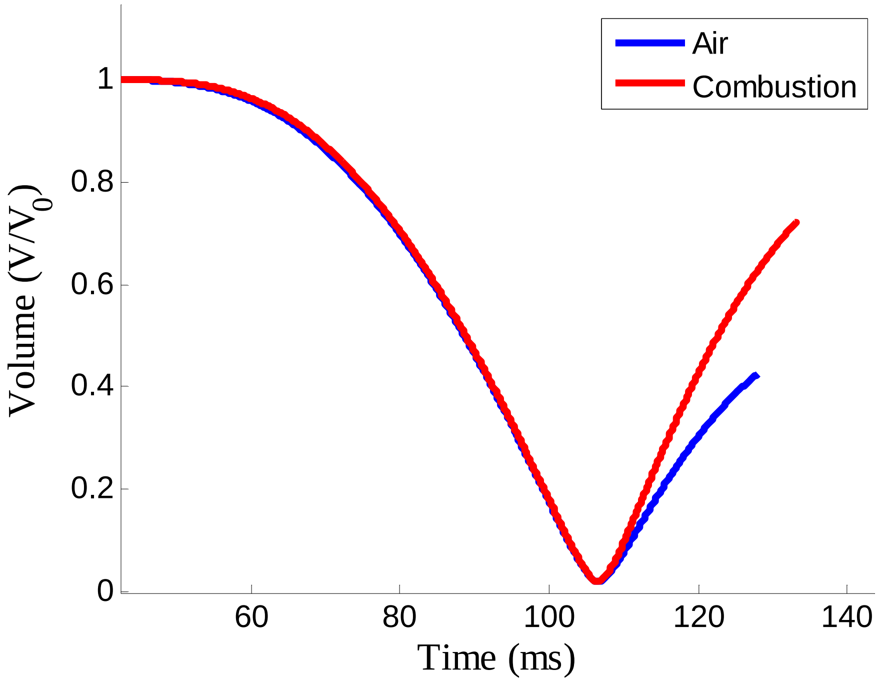


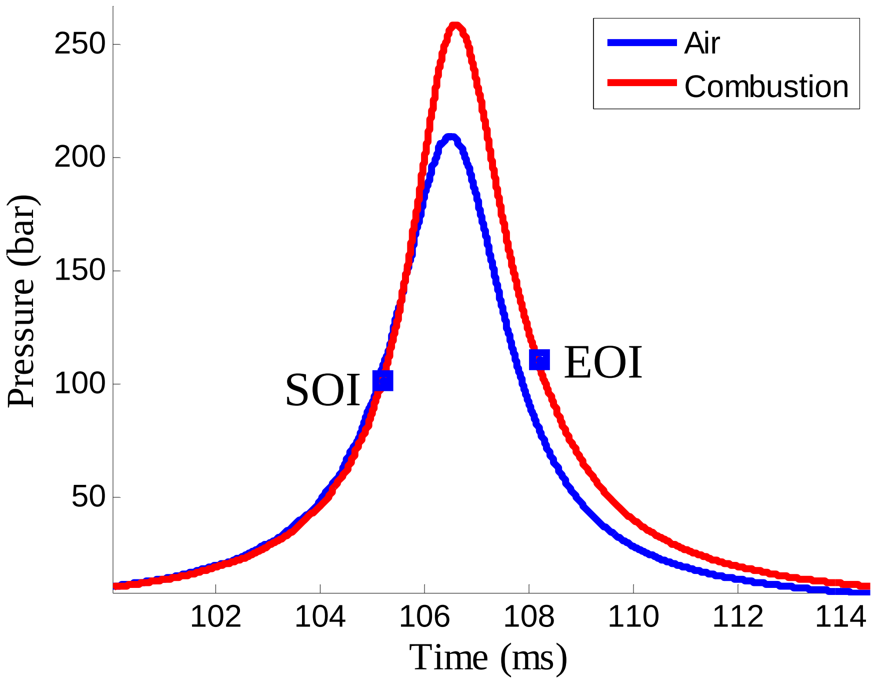
Radial bore tolerances:

combustor ± .0015 mm

cylinder ± .007 mm

Combustion Data: CR = 50





MPS ~ 40 m/s

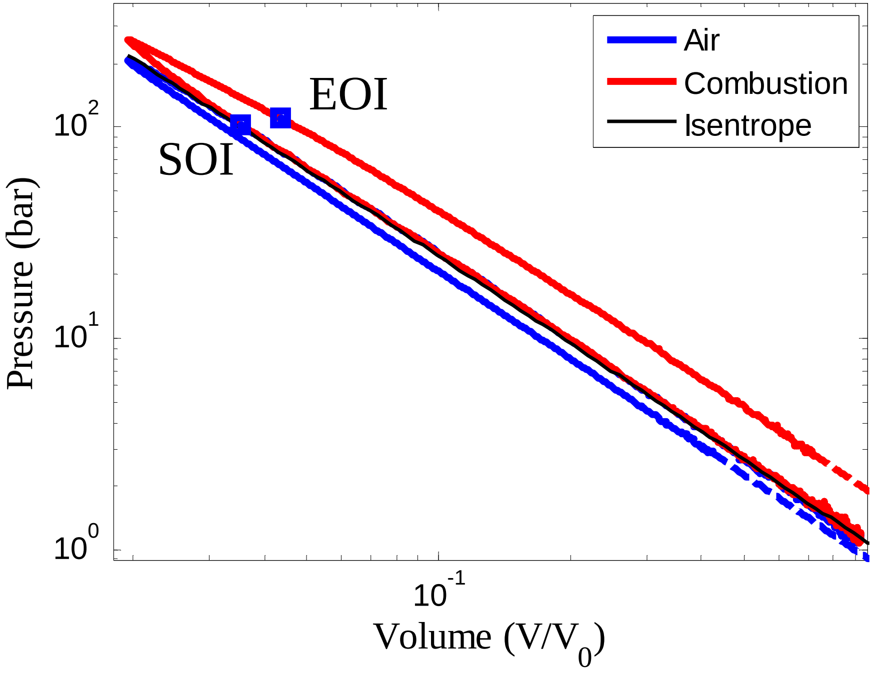
Peak Speed ~ 75 m/s

Piston mass = 1.03 kg

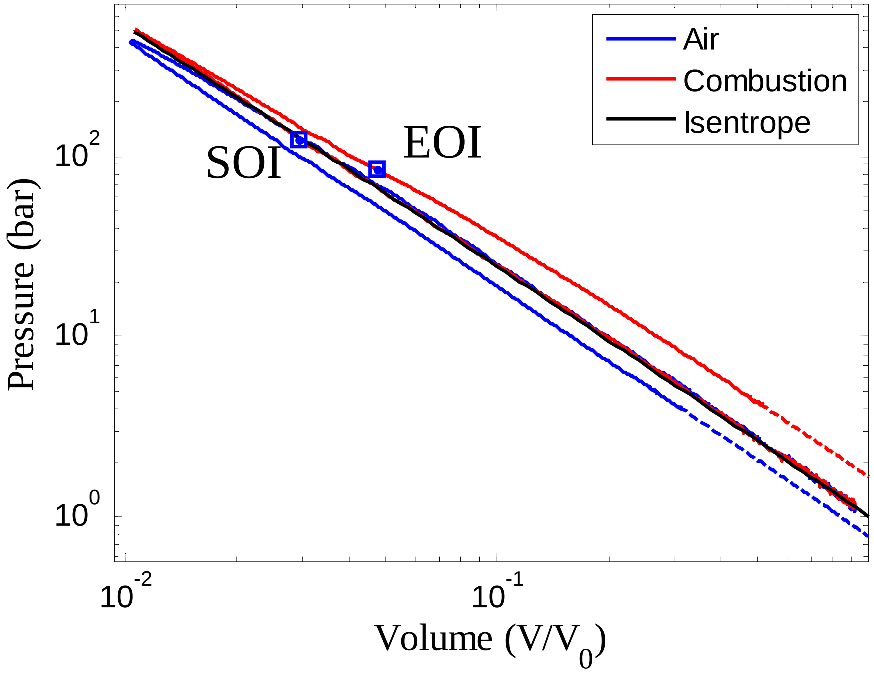
CR = 51.4

Driver Pressure = 10.2 bar

Comparison to Higher Compression

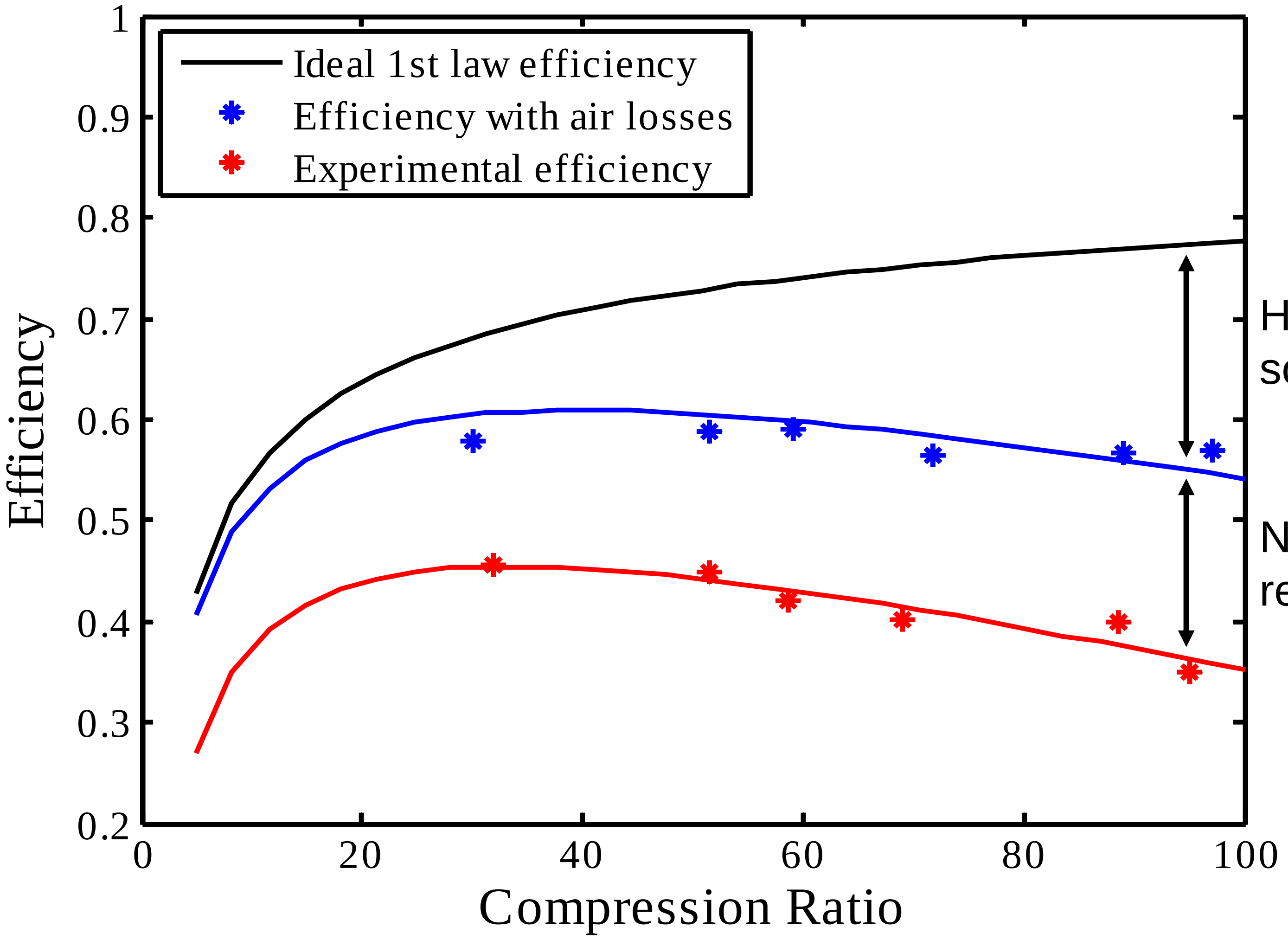


CR = 51.4 (Combustion)



CR = 95 (Combustion)

1^{st} Law Efficiency vs. CR



Hardware solutions

Next area of research

Critical Questions Revisited

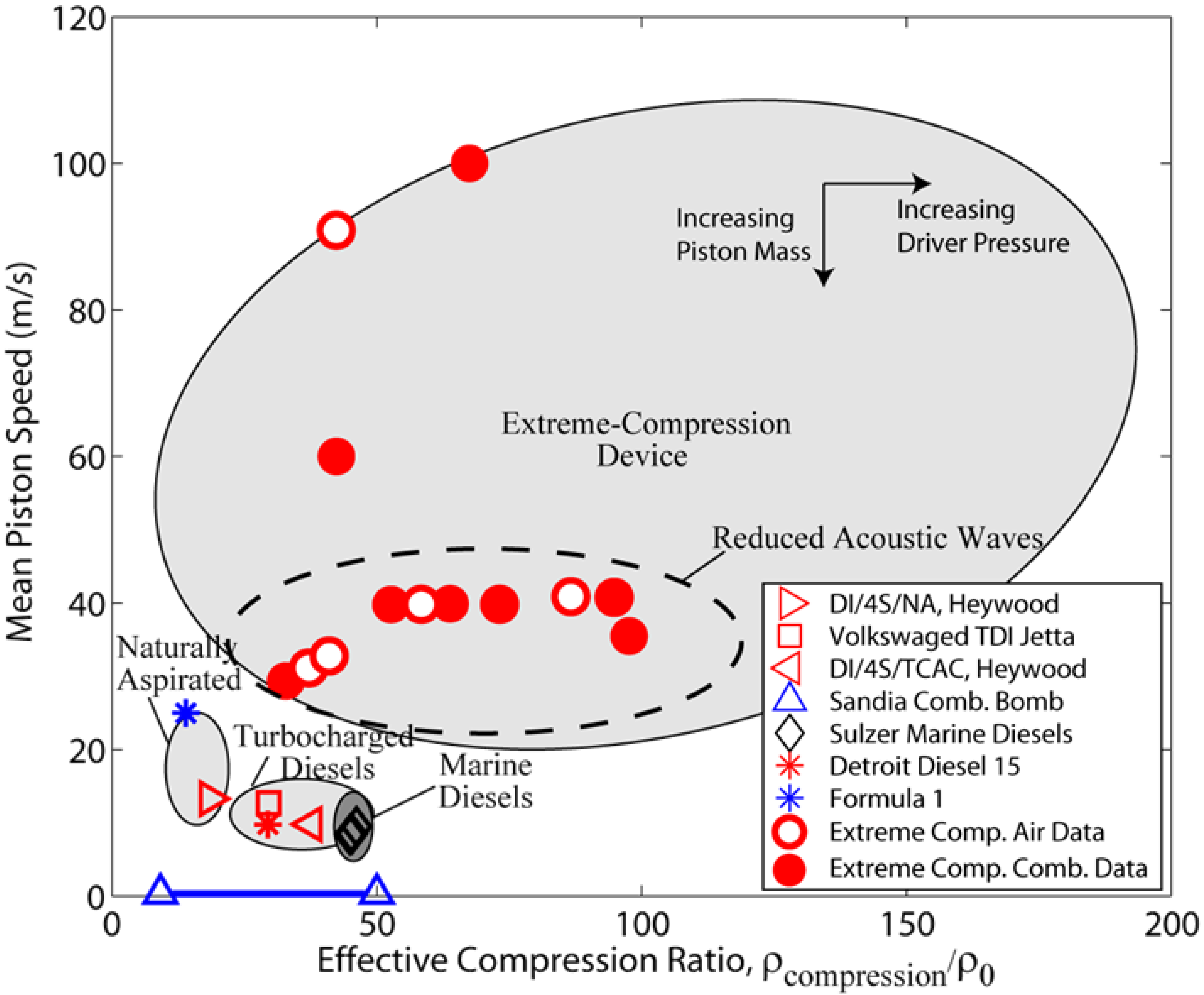
Critical Question	**Extreme Compression Apparatus**	**Extreme Compression Engine**
Material stress	✓	✓
Wall temperatures and heat transfer	🟩	🟩
NOx	🟩	🟩
Seal survivability	✓	🟩
Sealing ability	🟩	🟩
Ignition phasing	✓	✓
Combustion control	●	●

✓ solutions available and understood

🟩 more research required, but no obvious barriers

● high priority for research

Operating Space



Next Steps

- Assess Combustion Performance
  - Injection performance at high densities
  - Ignition delay timing
  - Ability to generate turbulent mixing
  - Combustion efficiency
  - Implications for heat loss
- Install window to visualize spray dynamics and combustion
- Analysis and experimental testing of ring design to quantify and reduce blowby
- Install exhaust gas analysis system for measuring NOx and combustion efficiency

Posters

- *Increasing Engine Efficiency through Extreme Compression:* S.L. Miller, M.N. Svrcek, K.-Y. Teh, O. Lacroix, J. Wilson, C.F. Edwards

- *Optimal Architecture for Efficient Steady-Flow Engines: S*. Ramakrishnan, K.-Y. Teh, S.L. Miller, C.F. Edwards