Modeling and Optimization of Trajectory-based Combustion Control

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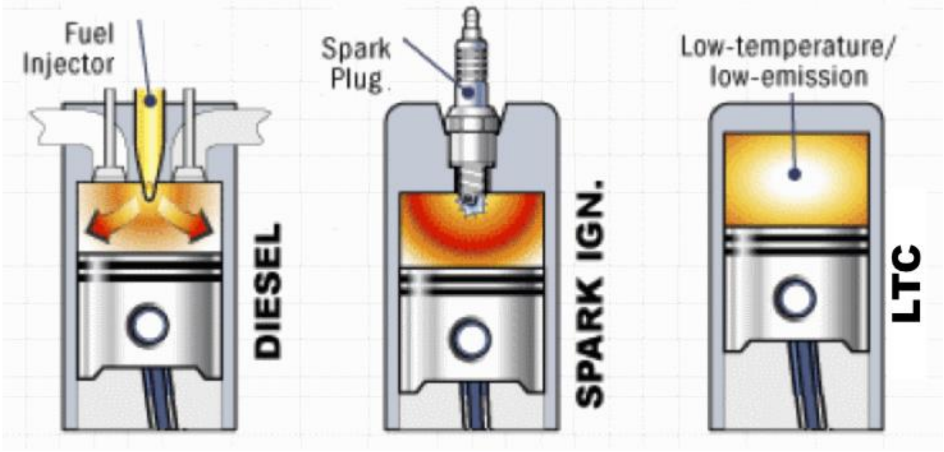
Presentation Outline

- Motivation, Background and Objective
- Trajectory based Combustion Control
  - *Previous Work: Modeling and Optimization Framework*
- Approach for experimental validation
  - *A novel instrument Controlled Trajectory Rapid Compression and Expansion Machine (CT-RCEM)*
  - *Unique capabilities of CT-RCEM*
  - *Experimental characterization of CT-RCEM*
- Conclusions

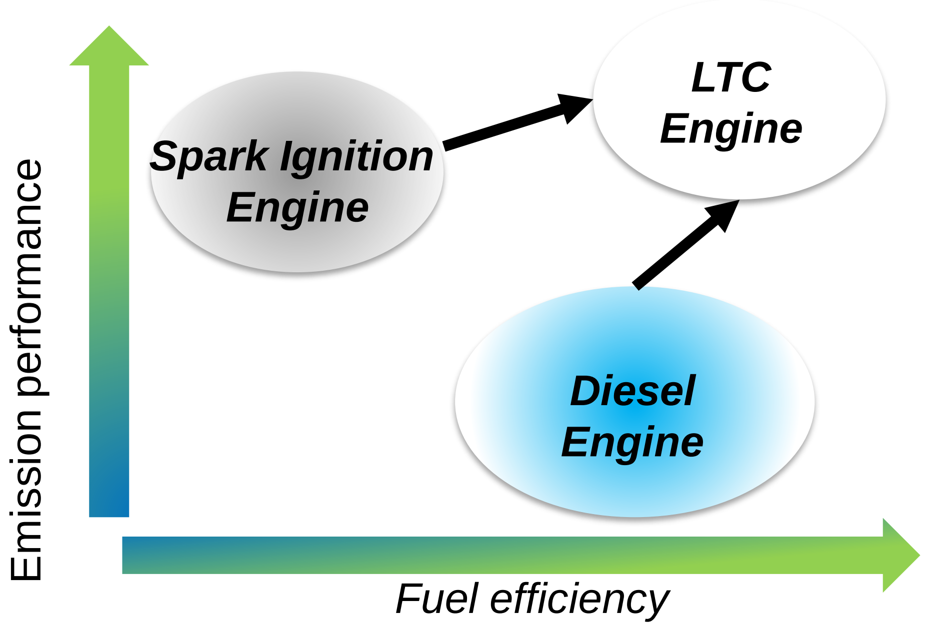
Background – Advanced Combustion Modes



Global trend - tighter regulations for fuel efficiency and emissions

Low Temperature Combustion (LTC) modes are kinetically modulated

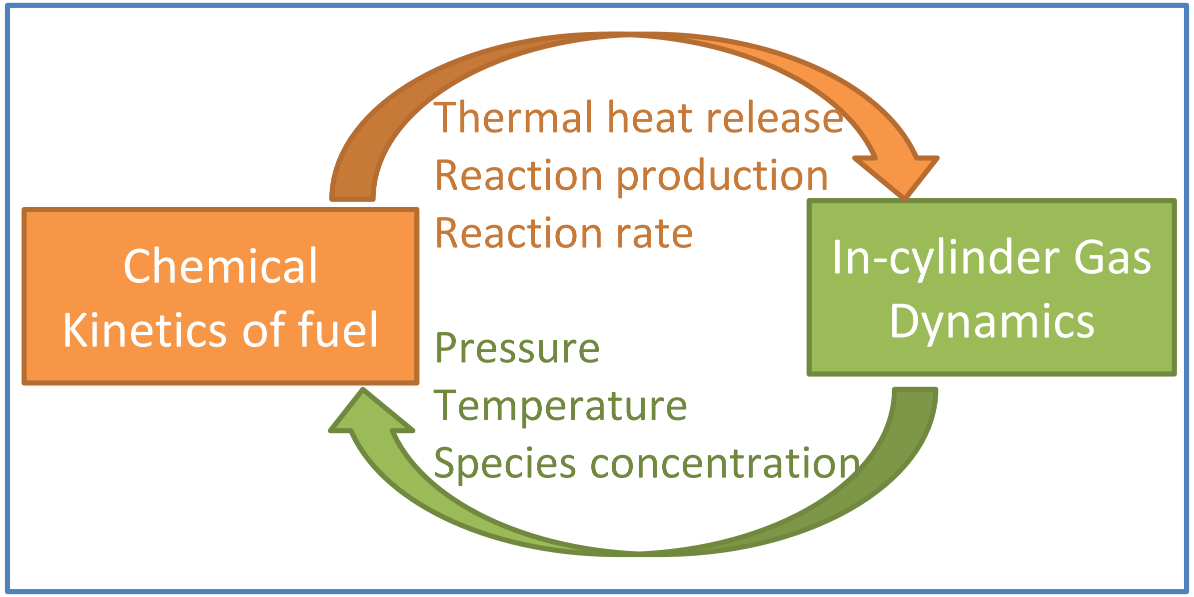
- ✓ Extremely fuel-lean operation leading to *high fuel efficiency*
- ✓ High CR operation and faster heat release leading to *higher fuel efficiency*
- ✓ Low peak temperature leading to *lower NOx*



Background – HCCI Combustion

Challenge - Combustion phasing

Control of ignition timing to achieve continuous operation is extremely difficult in conventional ICE

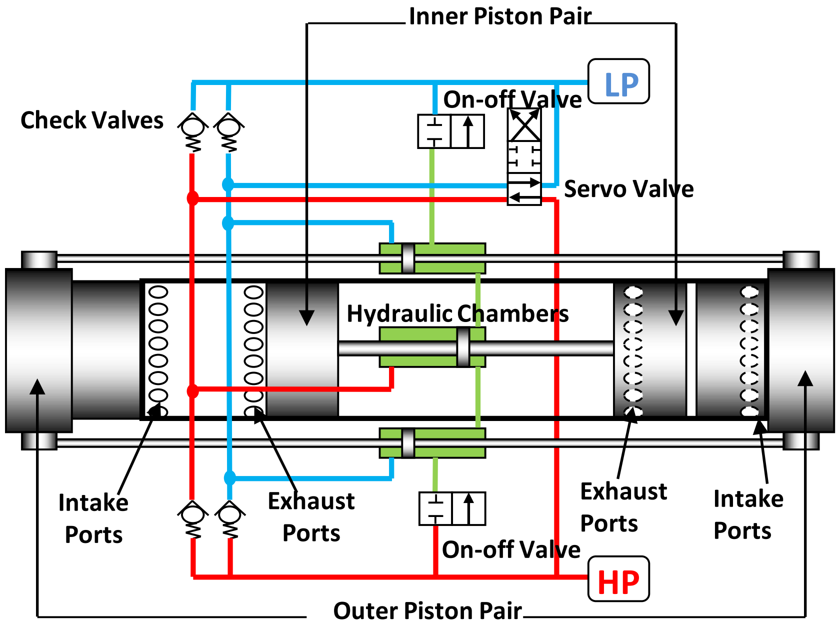


Existing control methods include

- Exhaust gas recirculation (EGR)
- Varying valve timing and
- Charge stratification

Control input is provided at a single time instant during the cycle

Background – FPE at UMN



- ❖ Opposed Piston Opposed Cylinder Engine
- ❖ No mechanical crankshaft
- ❖ Direct Fuel Injection

✓*Variable compression ratio*

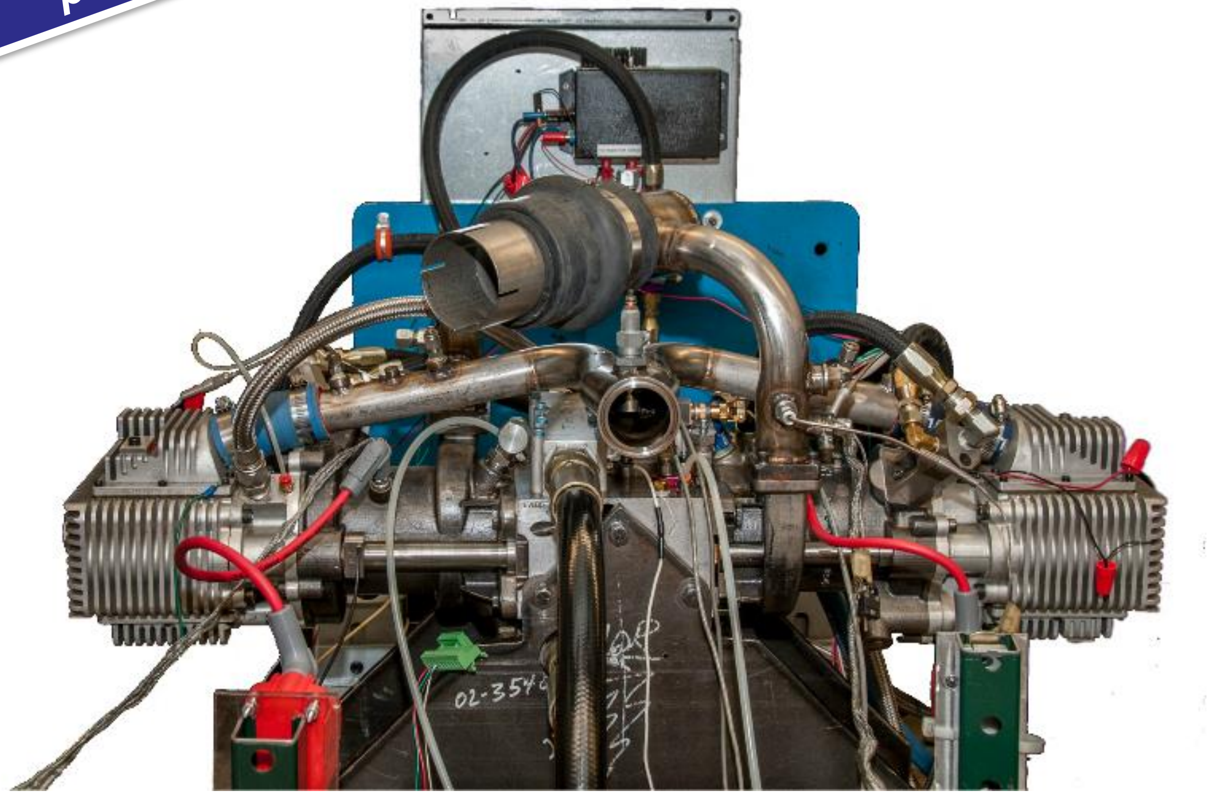
- *Advanced combustion strategy*
- *Multi-fuel operation*

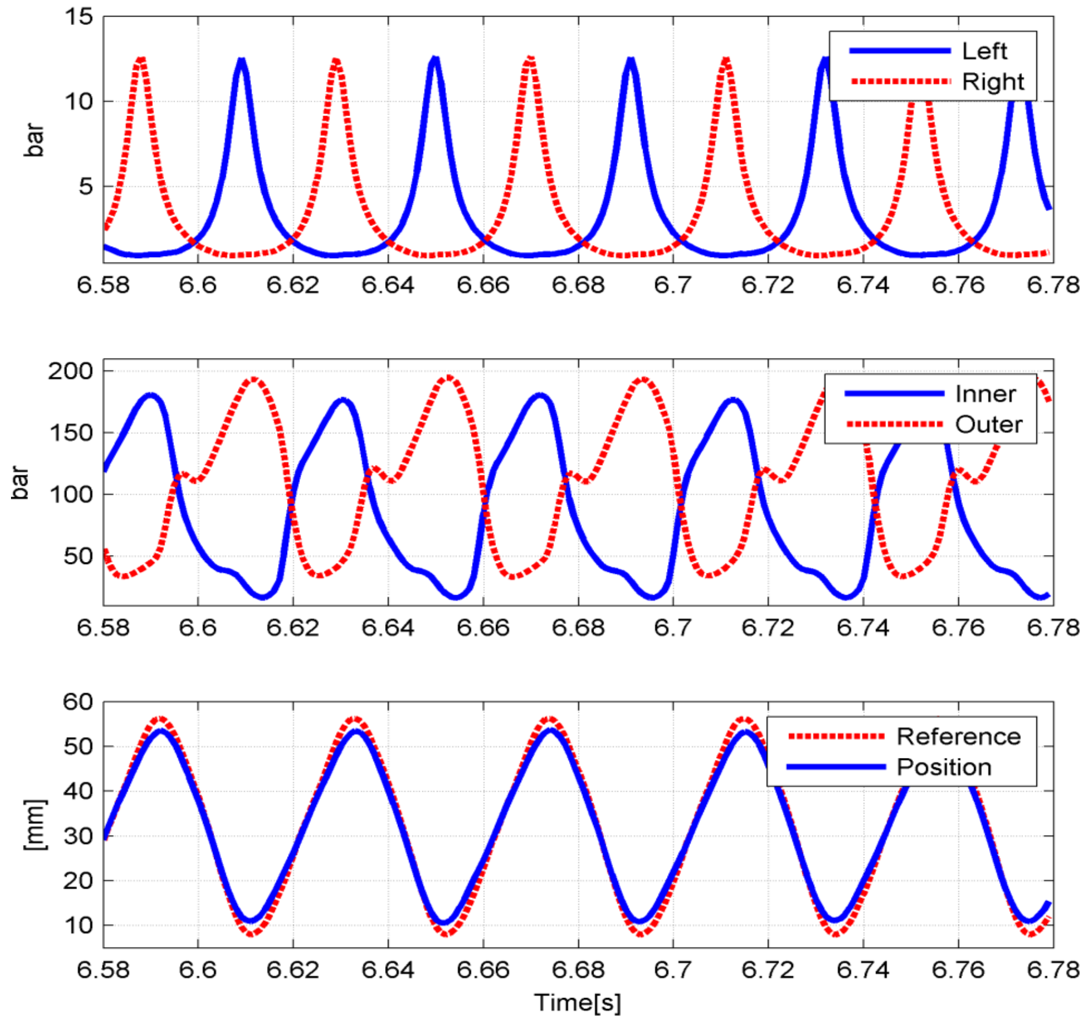
✓*Reduced frictional losses*

✓*Faster response time*

Background – FPE at UMN

Virtual crankshaft mechanism enables the FPE pistons to precisely track the prescribed piston trajectory





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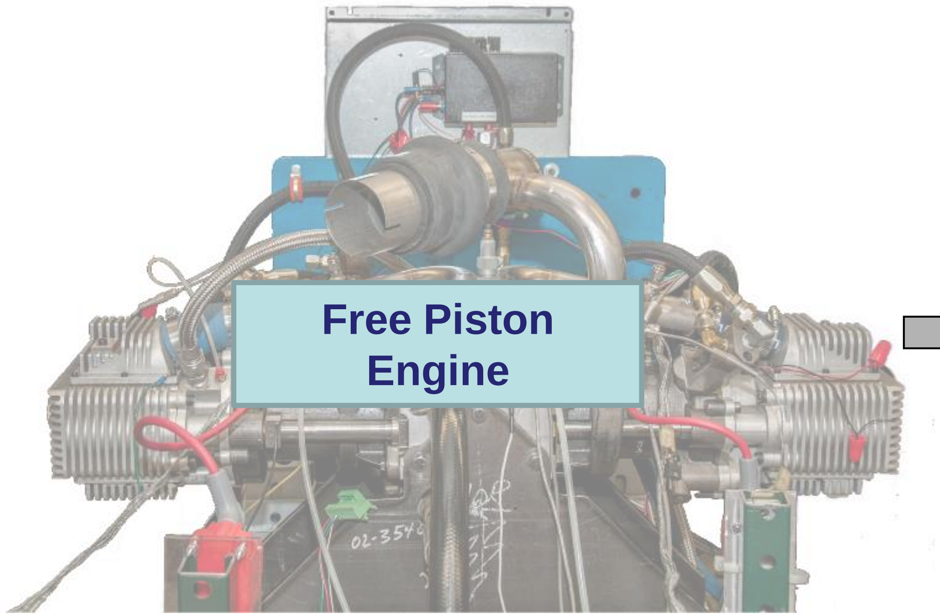
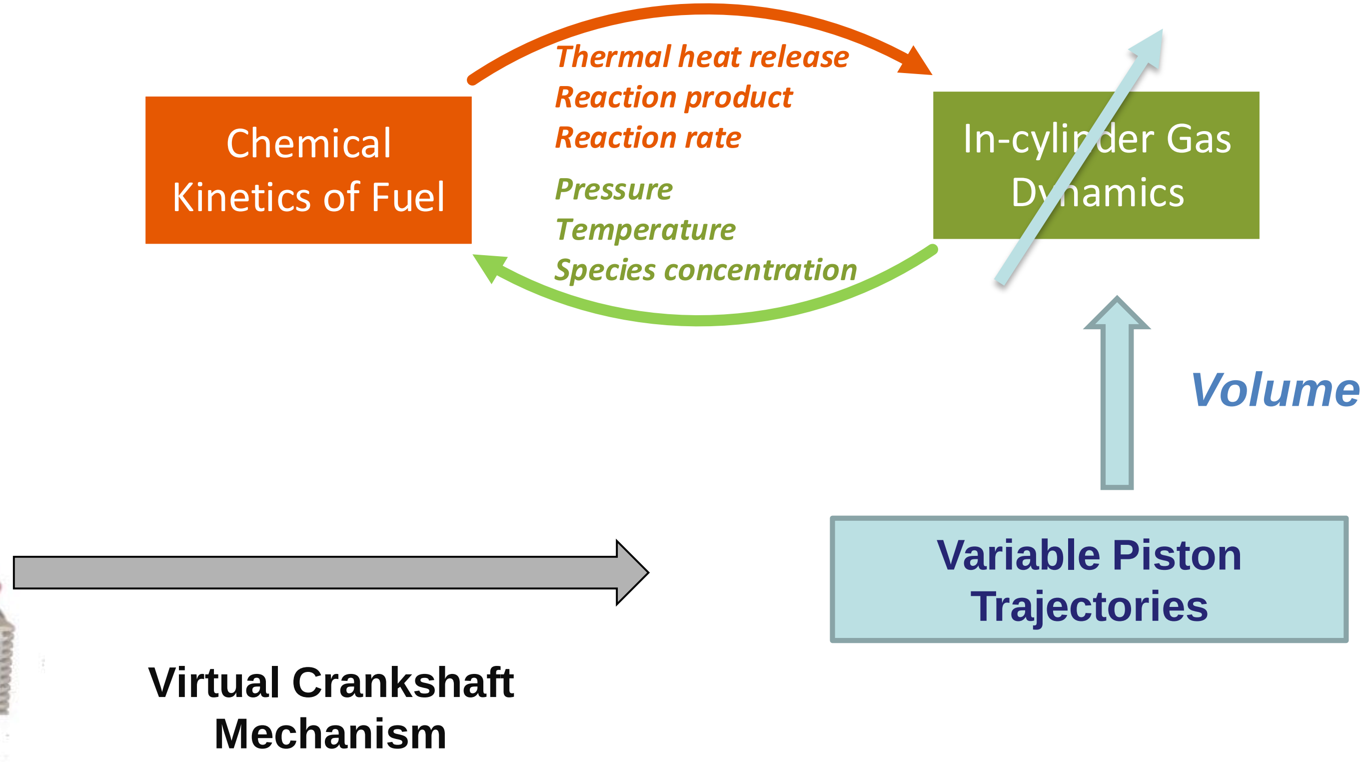
What is Trajectory-based Combustion Control

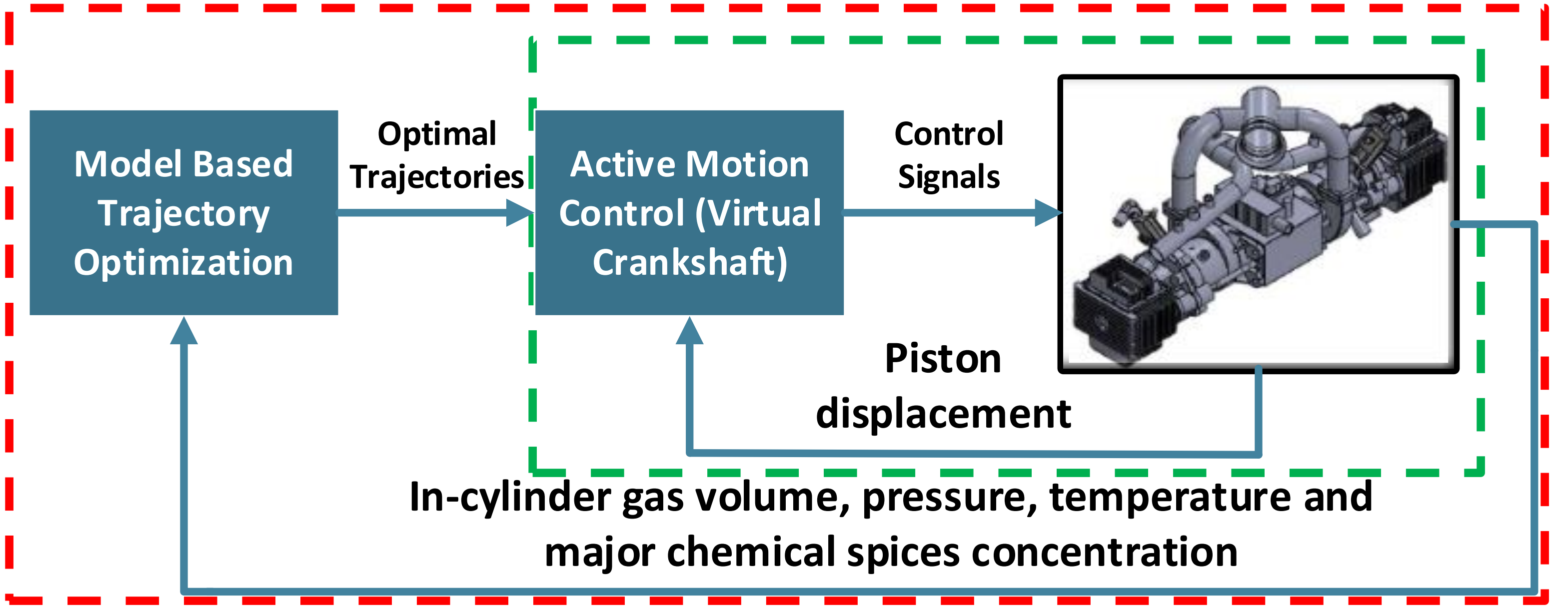




Use complete piston trajectory as control input to modulate in-cylinder gas dynamics

Basic Framework - Trajectory-based Combustion Control

Overall architecture for implementation of trajectory based combustion control



- ***Inner Loop:*** piston motion control - virtual crankshaft
- ***Outer Loop:*** Trajectory-based combustion control

Find piston trajectory which minimizes emissions & maximizes work output

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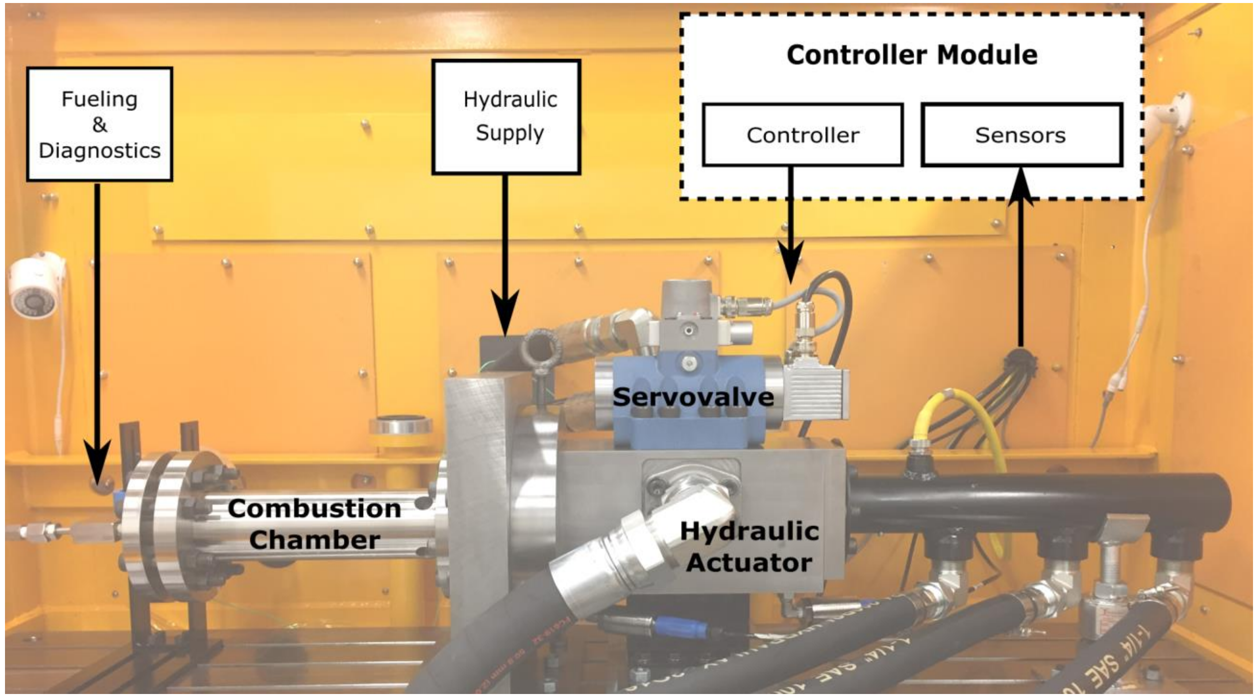
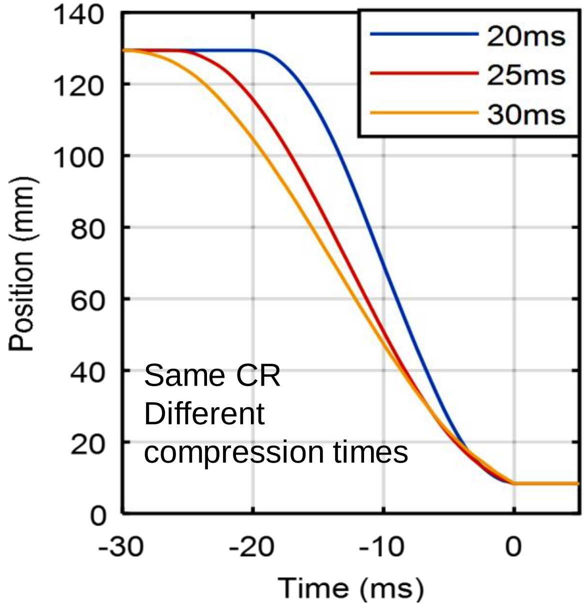
Controlled Trajectory Rapid Compression and Expansion Machine

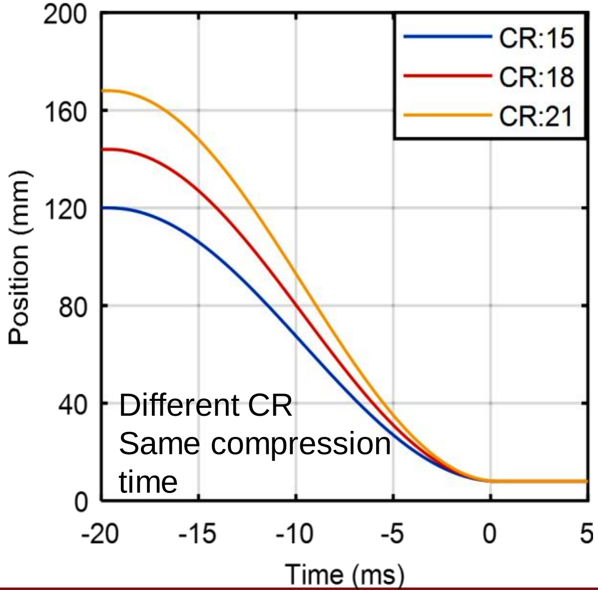


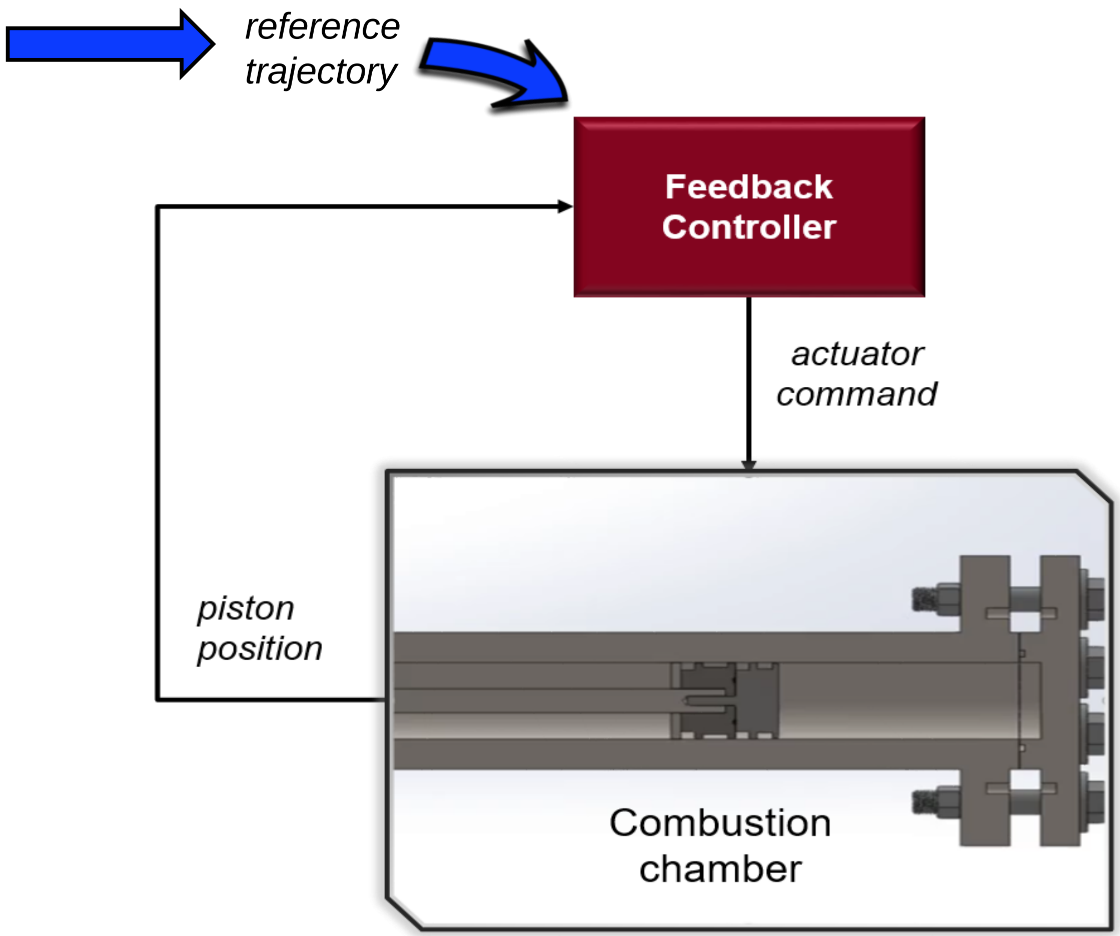
CT-RCEM is new instrument that uses fluid power to enable unique experimental capabilities for fundamental and applied combustion research

- Developed at University of Minnesota under 3 year NSF-MRI Grant
- High throughput and extreme operational flexibility
- Ability to control the piston trajectory inside the combustion chamber

CT-RCEM – What's unique?



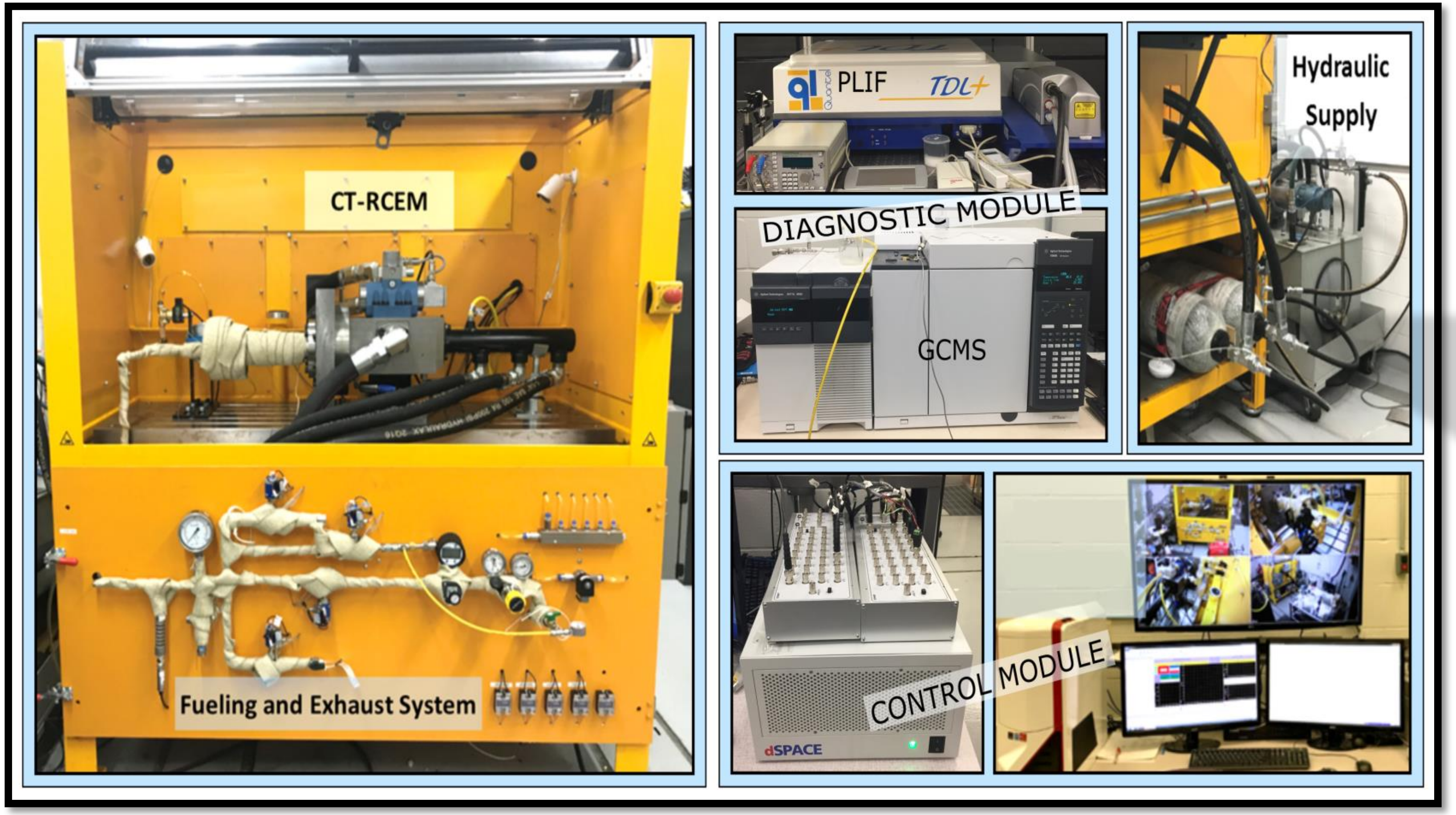




CT-RCEM uses an electro-hydraulic actuator with feedback control to drive the piston

Reference trajectory is fed electronically to the controller

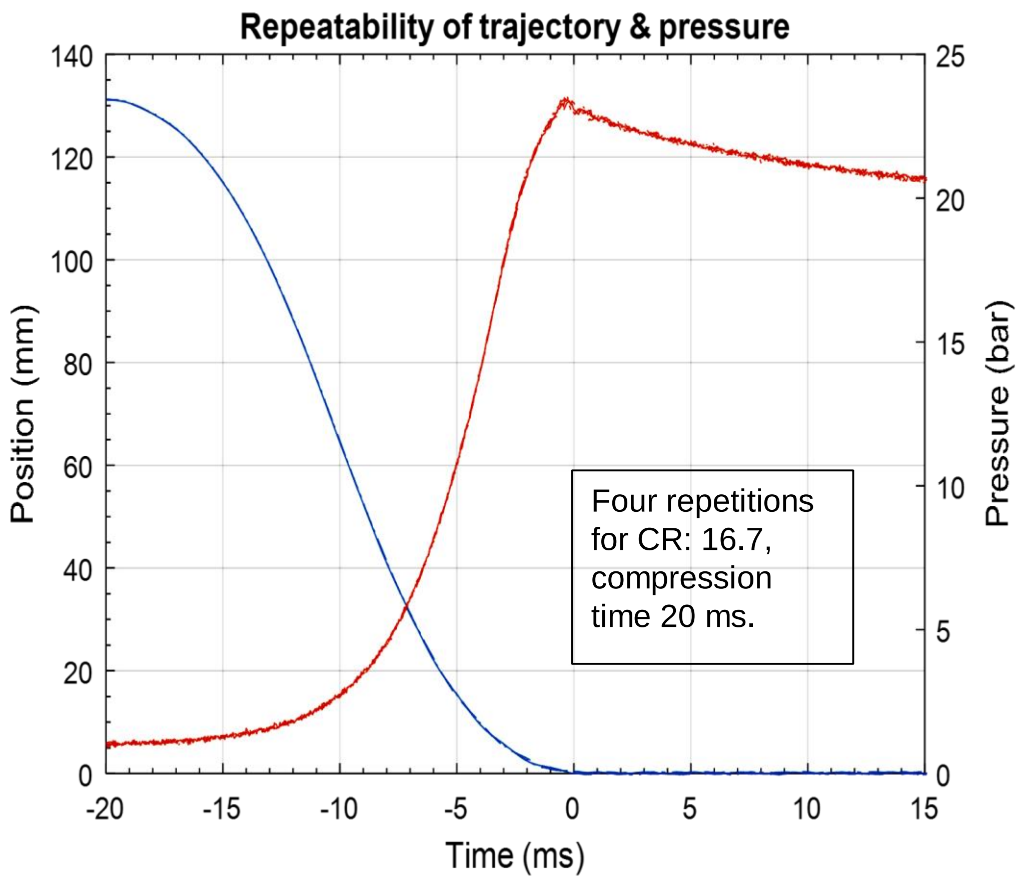
Setup and Specifications



Maximum Combustion Pressure	250 bar
Minimum Compression Time	20 ms
Maximum Compression Ratio	25
Combustion Chamber Bore	50.8 mm
Maximum piston travel	192 mm
TDC clearance	8 mm
Hydraulic Working Pressure	350 bar
Hydraulic Piston Bore	40 mm
Mass of Piston Assembly	1.7 kg

Key requirement:
High-force and high-speed actuation

Repeatability of CT-RCEM

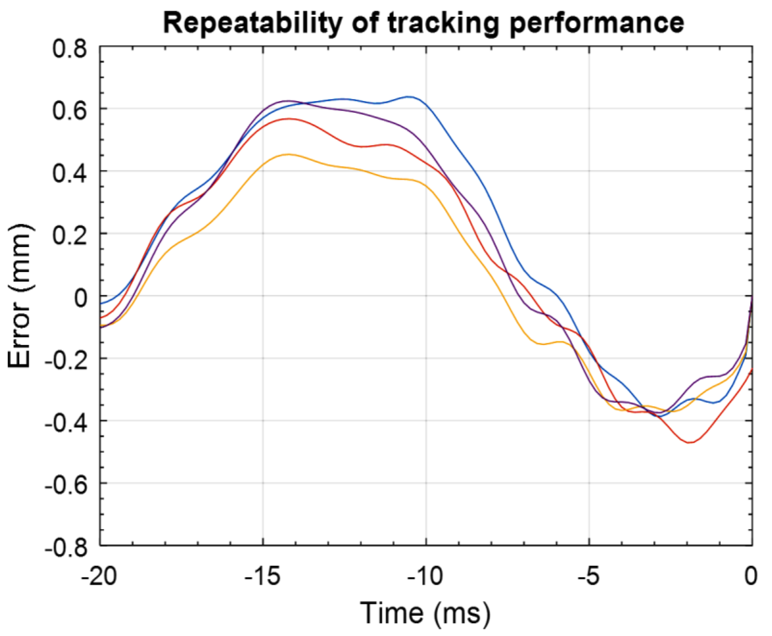


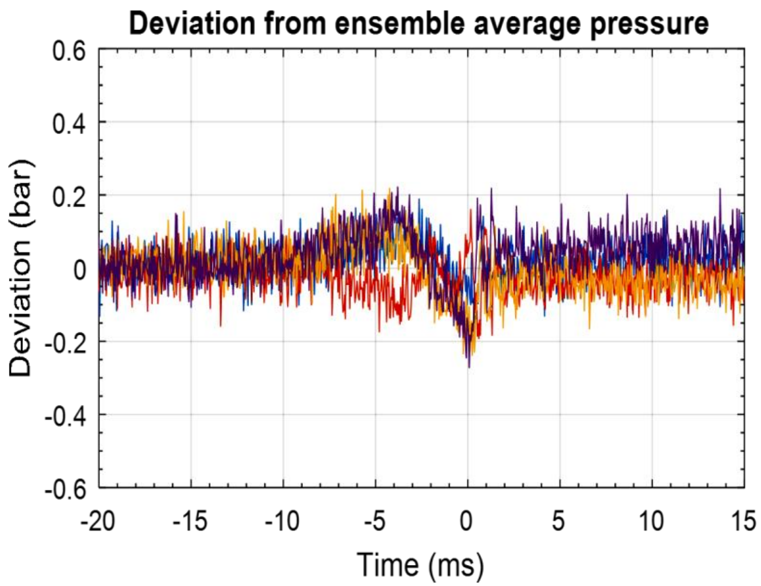
Tracking accuracy is the key to repeatability

Repeatability Analysis for Compression ratio 16.7

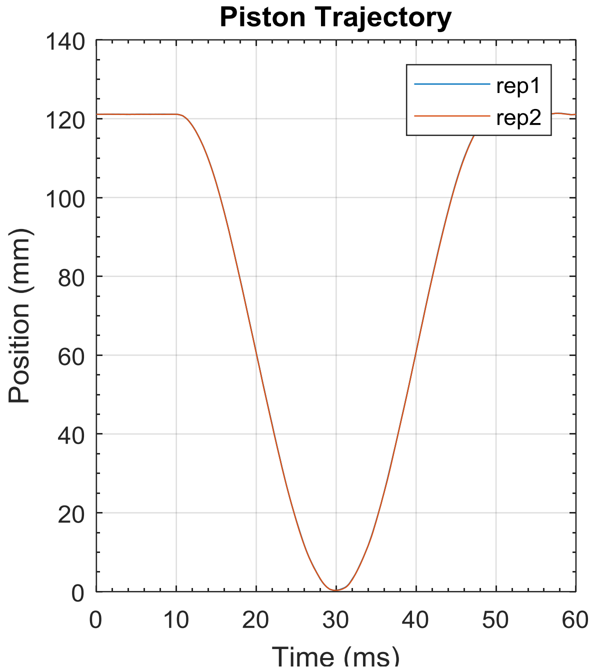
Stroke	**131 mm**
Compression time	**20 ms**
Peak velocity	**12.5 m/s**
Peak tracking error	**0.6 mm**
Average velocity	**7 m/s**
Peak flow rate	**920 l/min**
Peak instantaneous power	**0.4 MW**

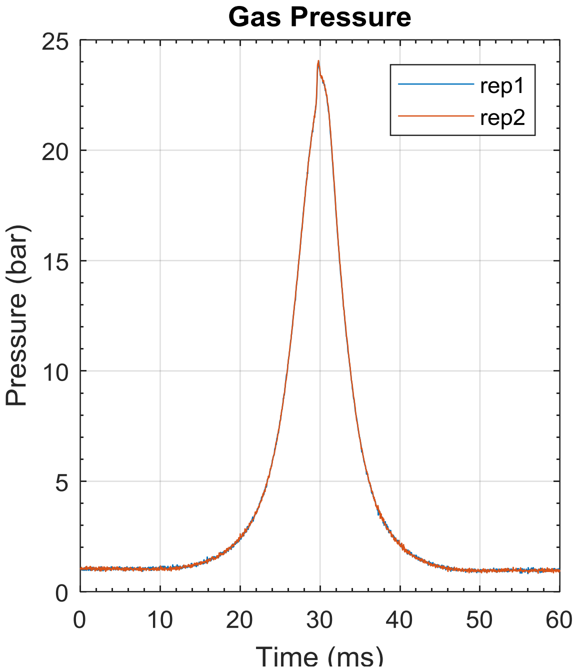
Maximum deviation of individual pressure profiles from ensemble average of repetitions ≈ ***0.2 bar***

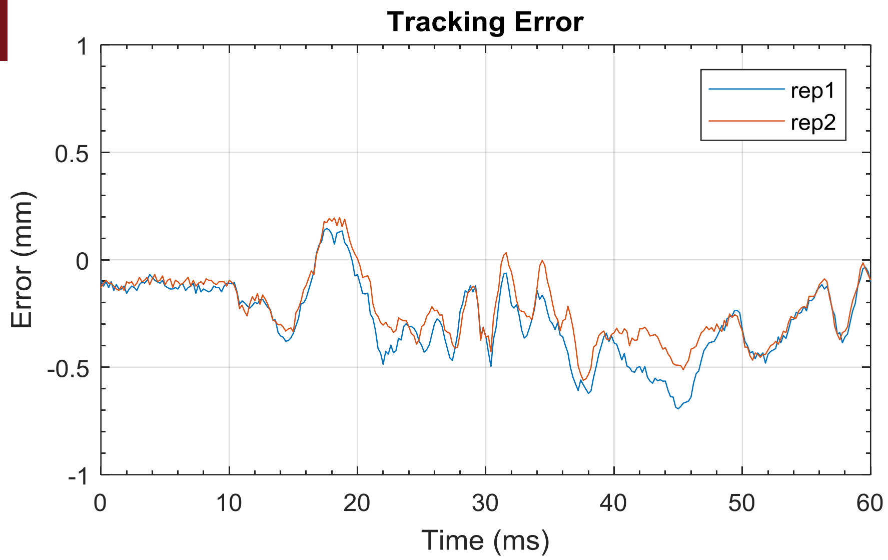




Mimicking Engine Operation in CT-RCEM

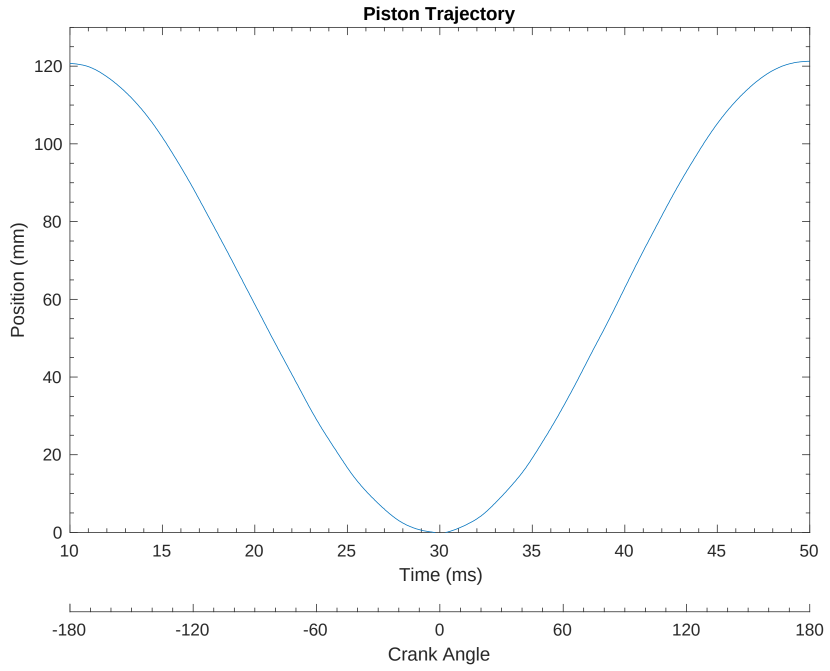


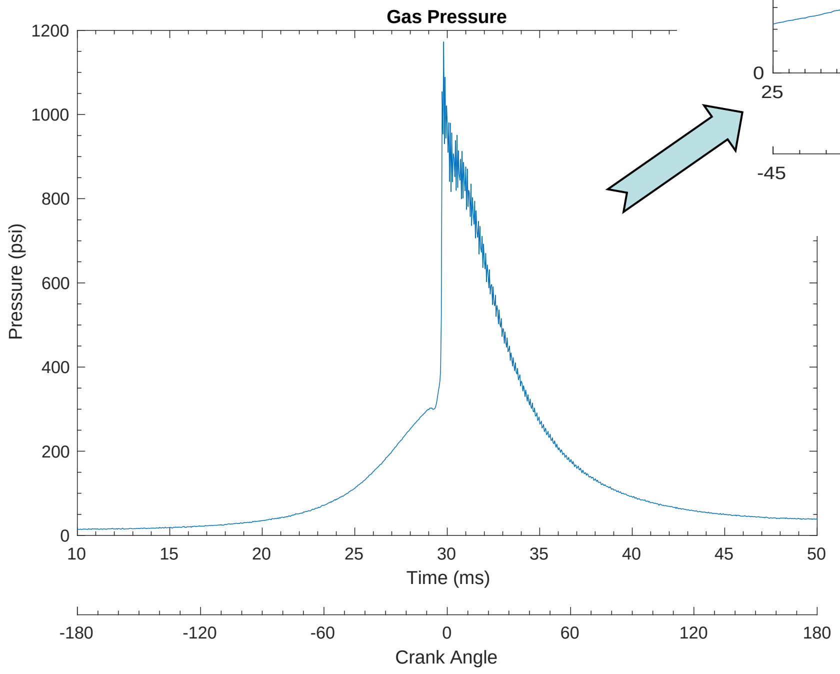


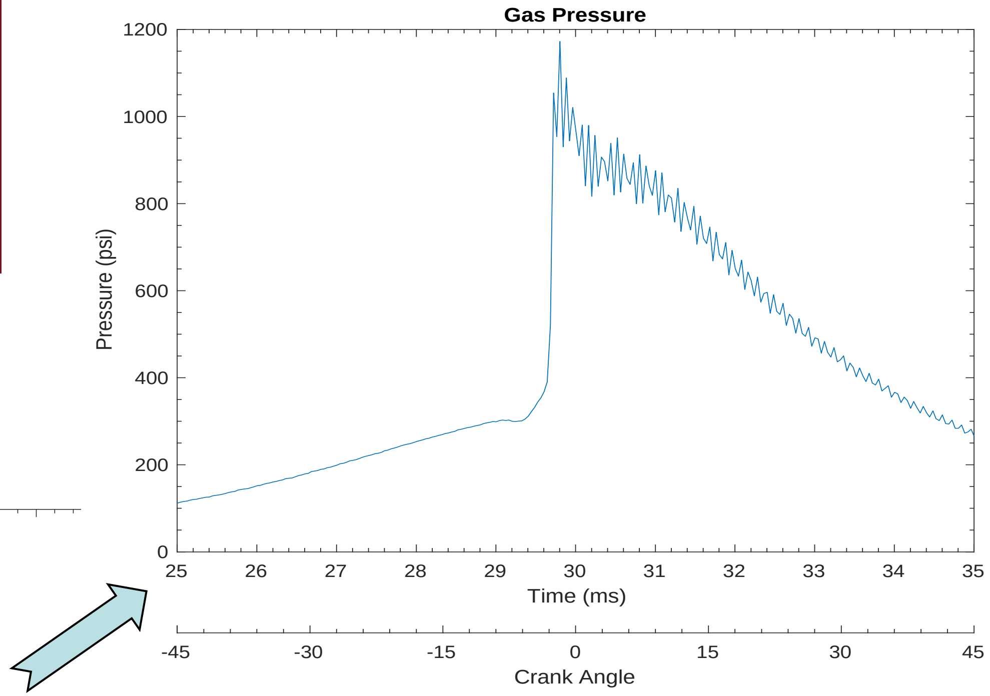


- Investigating partial ignition of DME for engine-like sinusoidal trajectory
- Fuel mixture – DME:O_2:N_2 = 1:4:40 (lean and diluted with extra nitrogen)
- Stroke: 121 mm, CR: 15.5, RPM: 1500
- Creviced piston to trap boundary layer

HCCI Combustion for an FPE Trajectory

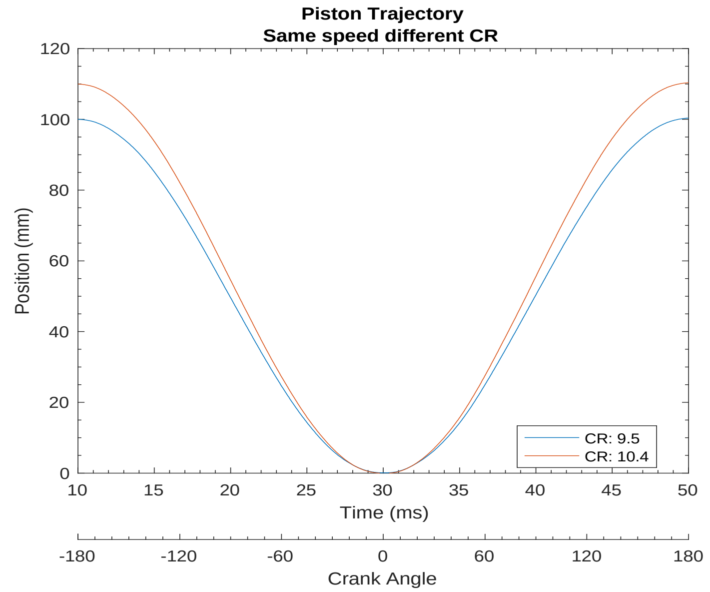


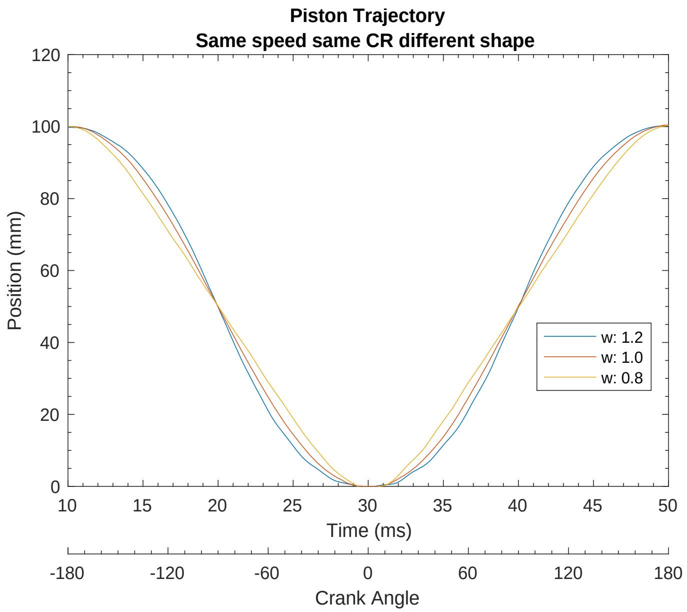


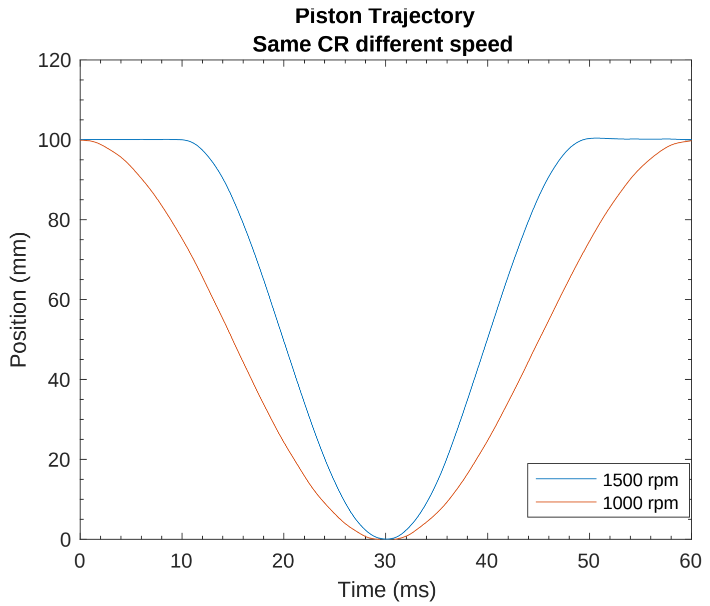


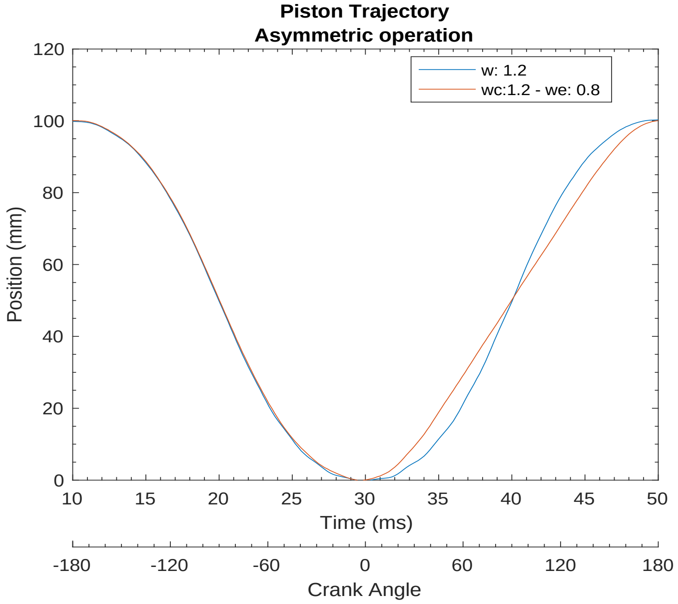
- Autoignition test for DME
- Fuel-air equivalence ratio (ϕ) 0.75
- Initial temperature 50°C
- Initial pressure 15 psi
- Ambient pressure 14.15 psi
- Stroke: 121 mm, flat piston
- CR: 11.3, 1500 rpm

Producing different FPE Trajectories









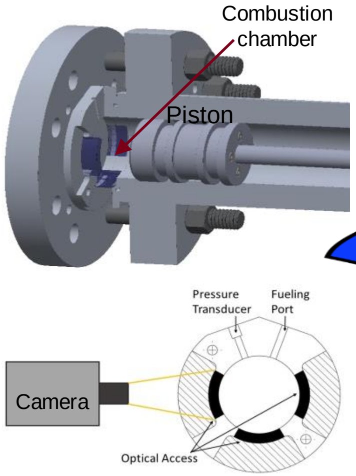
Unique ability to electronically change CR, speed and shape of piston trajectory allows reproduction of any FPE trajectory

Further development is underway to demonstrate the intake and exhaust stroke, and spark ignition

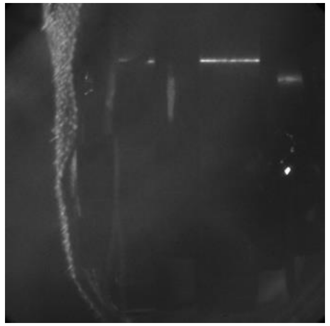
CT-RCEM for Engine Applications – FPE and Conventional ICE

- Scope to incorporate multi-cycle testing
- Flexibility to accurately pre-set initial conditions (charge pressure and temperature)
- Flexibility to accommodate in-situ or ex-situ species diagnostics through optical (chemiluminescence, LIF) or gas sampling methods (GCMS)
- Replaceable head design to incorporate direct injection, spark plug, or intake manifold as required
- Uniquely suited for investigating turbocharged combustion modes
- Replaceable piston crown to enable evaluation of piston crown geometries
- Flow field and turbulence studies by using various piston designs, changing piston trajectories or even including an intake stroke

Optical Diagnostics – Accessing Chemical Kinetics Information

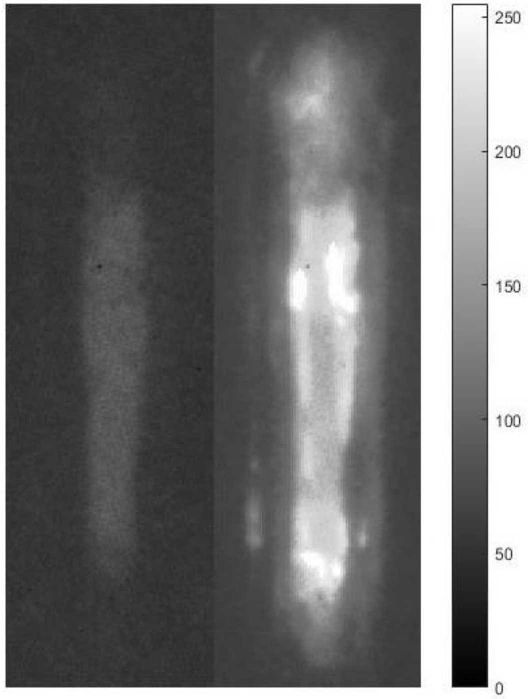


30 ms compression



20 ms compression

- Optical measurement work by capturing the fluorescence of intermediate species
- Chemiluminescence or Laser induced fluorescence
- Measurement of intermediate species such as OH*, CH*, CH2*
- Comparing image intensities gives a quantitative estimate of species concentration



30 ms ***20 ms***

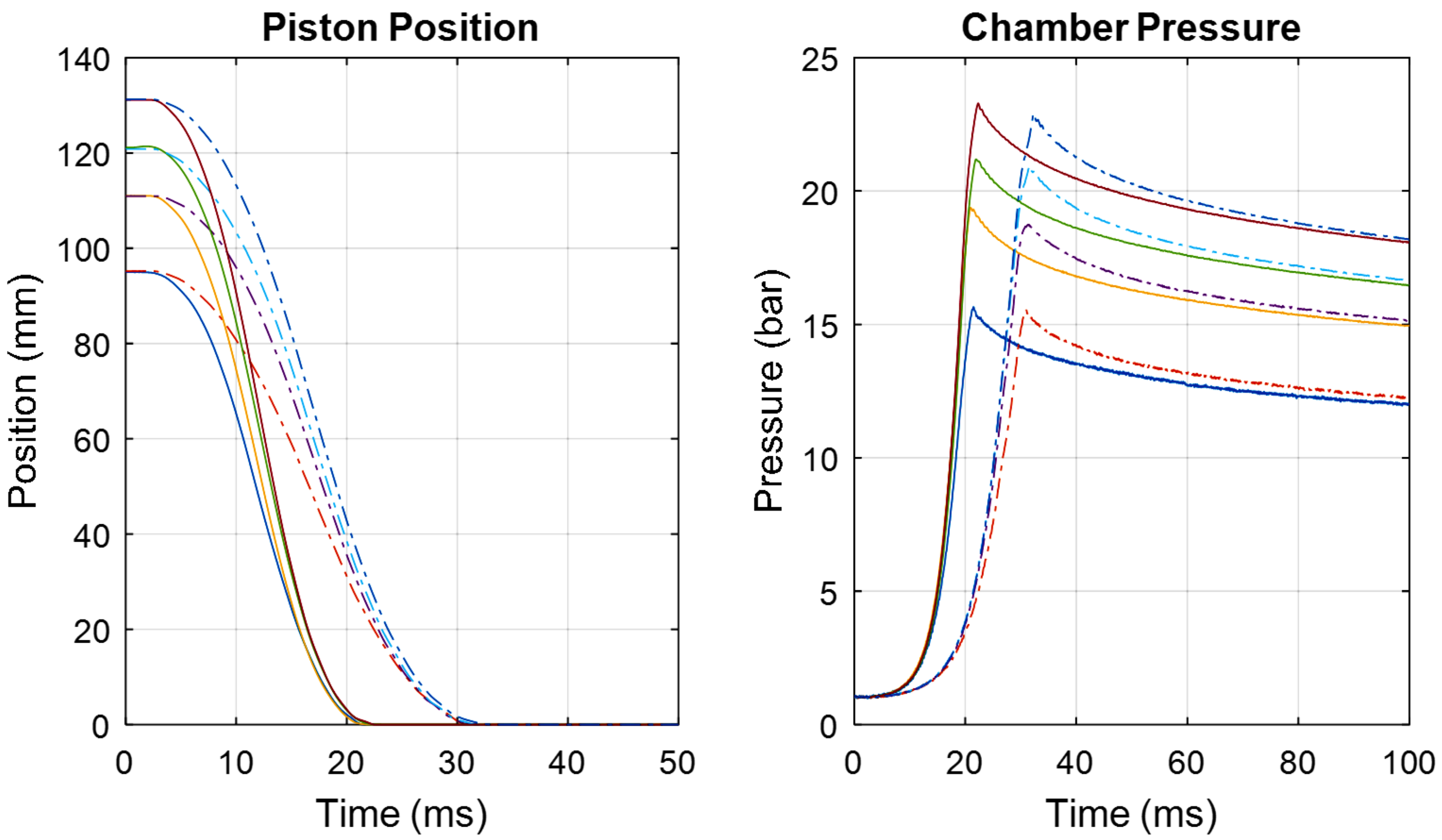
Conclusions

- A controlled trajectory rapid compression and expansion machine has been developed at UMN for addressing the research needs of fundamental and applied combustion investigation
- The exceptional flexibility and the novel capabilities have been demonstrated
- CT-RCEM offers a unique opportunity to experimentally validate the concept and framework of trajectory based combustion control
- We are looking for opportunities to collaborate to further develop and demonstrate the capabilities of the CT-RCEM.

Backup Slides

Operational Flexibility of CT-RCEM

'Floating' BDC allows the stroke to be changed electronically



Inert mixture testing

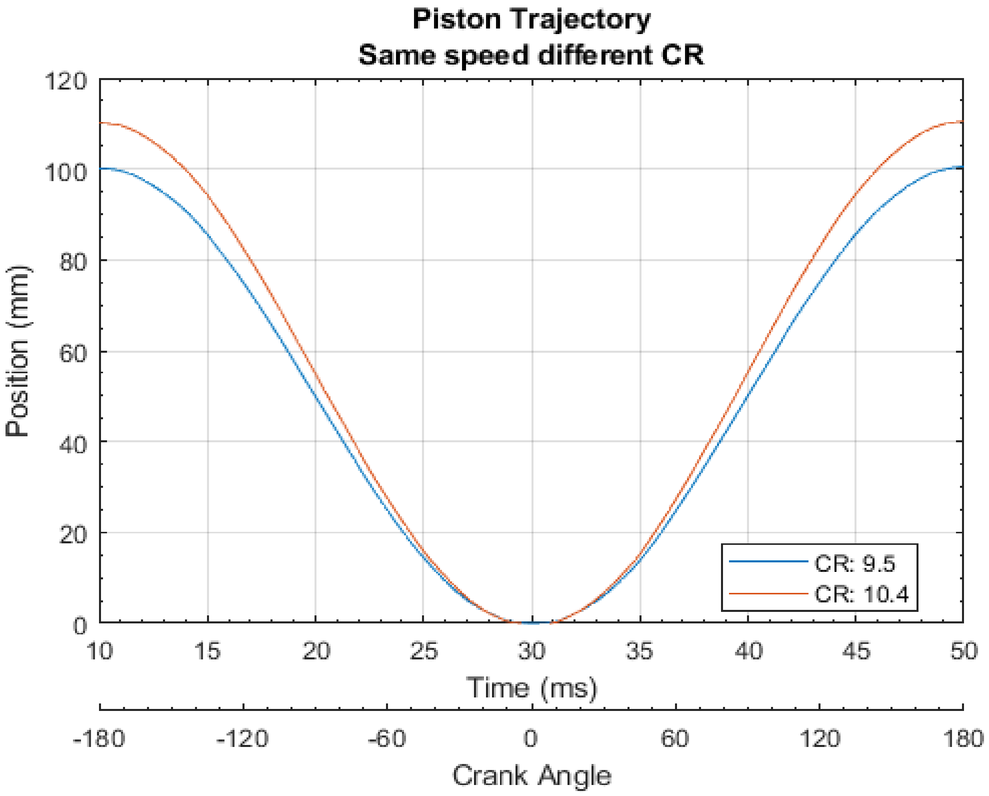
Ensemble average for four repetitions of compression of Air-CO_2 mixture

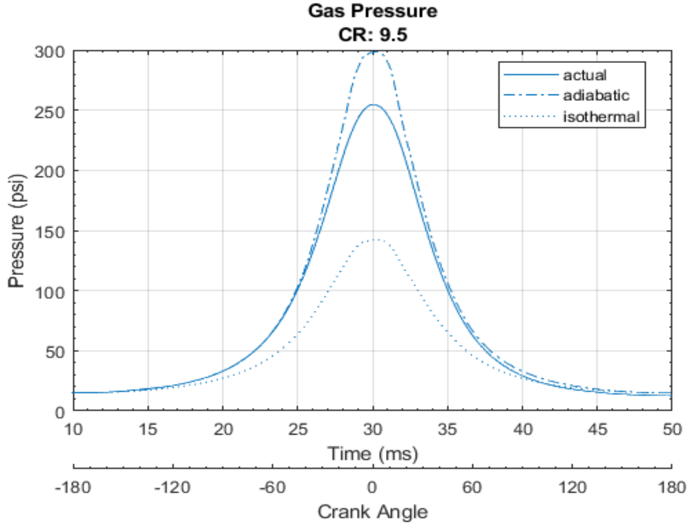
- Compression ratio: 12.4, 14.2, 15.5, 16.7
- Compression time: 20 ms & 30 ms

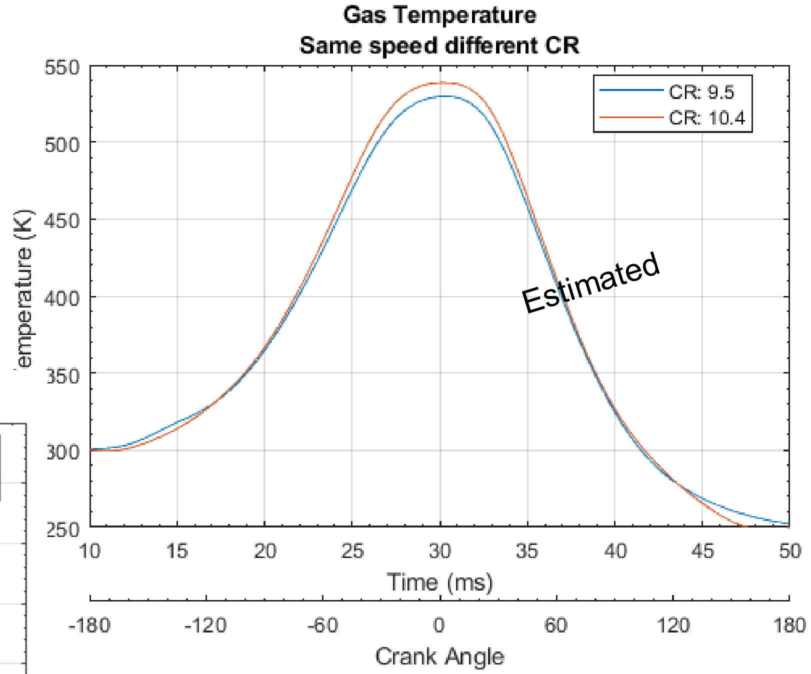
Enables calibration of heat transfer models using experimental data over a wide range of operating conditions

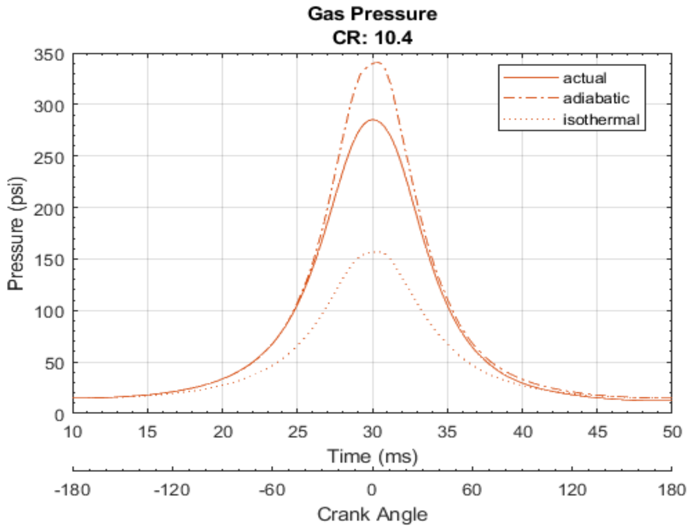
Uniquely suited for experimental validation of trajectory based combustion control

Simulating FPE Operation









- Piston position and actual pressure shown here is measured data
- Adiabatic pressure, isothermal pressure, and temperature traces are estimated