Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-mixed E85 SI Engine Operation

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Abstract

It is well known that well-mixed lean or dilute SI engine operation can provide improvements of the fuel economy (FE) relative to that of traditional well-mixed stoichiometric SI operation. However, the potential is limited by the onset of unstable combustion for low fuel/air-equivalence (ϕ) ratios. This work examines the use of two methods for improving combustion stability for lean operation, namely multi-pulse transient plasma ignition and intake air preheating. These two methods are compared to standard SI operation using a normal inductive ignition system without intake air preheating. E85 is the fuel chosen for this study.

The experimental results from single-cylinder testing show that the FE improvement for lean operation with the regular spark system without intake air preheating amounts to 12% for ϕ = 0.67. Using a combination of intake air preheating and multi-pulse ignition, the engine can be operated stably at lower ϕ, enabling a larger improvement of FE, amounting to 17% for ϕ = 0.59. This enhanced lean operation is attributed to a more stable flame initiation offered by both the increased charge temperature and the multi-pulse transient plasma ignition. The multi-pulse plasma ignition utilizes a specialized spark-plug geometry with a semi-open ignition cavity. High-speed flame imaging in the same engine reveals that this combination of multi-pulse ignition and special spark-plug geometry results in a very fast transition to fully turbulent deflagration, which is beneficial for stable combustion. The emissions measurements show that the combination of multi-pulse ignition and heated intake improves the trade-off between NO_x emissions and combustion instability, reaching a fairly low indicated specific NO_x ($ISNO_x$) of 0.63 g/kWh at ϕ = 0.48.

Analysis of the data for even leaner operation with ϕ down to 0.45 shows that it is possible to propagate a flame under these conditions, but that a reduction of cycle-to-cycle variability is required. Statistical analysis of the available IMEP data suggests that FE improvements of at least 20% are possible for stabilized ultra-lean SI operation.

Acknowledgement

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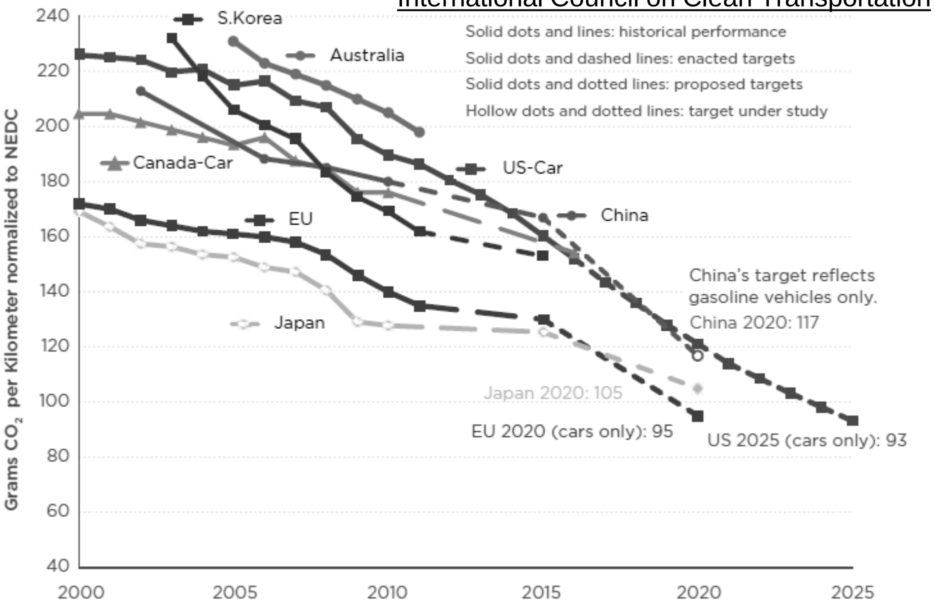
Introduction

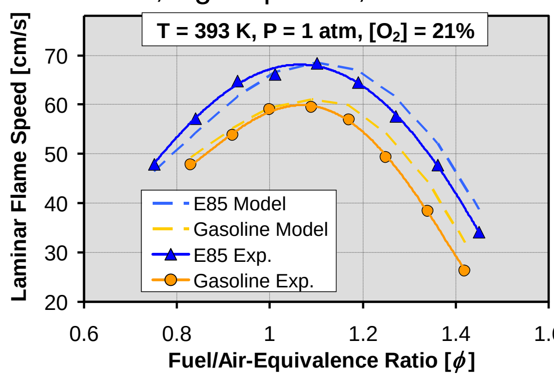
- Automotive industry is under strong pressure to reduce CO_2 emissions.
- Improved engine efficiency is one key factor for accomplishing this.
- Well-mixed stoichiometric SI operation is standard for gasoline-type engines.

International Council on Clean Transportation



- **Lean and/or dilute well-mixed SI operation** can improve fuel economy.
- Combustion stability is one key issue.
- The higher flame speeds of high-ethanol fuels are beneficial for lean operation.

Zhao, Egolfopoulos, Mehl & Pitz



Objectives / Scope

- Examine lean well-mixed SI operation in terms of:
  - Its potential for improved engine efficiency.
  - Limitations due to combustion variability and combustion inefficiency.
- Examine two factors that have potential to improve the stability of lean operation relative to that of regular spark (RS) operation.
  - Multi-pulse (MP) transient plasma, in collaboration with USC-LA.
  - Intake charge heating.
- Combine:
  - All-metal performance testing with emissions measurements.
  - High-speed imaging of ignition and flame development.
- Four main data sets that sweep fuel/air-equivalence ratio (ϕ):

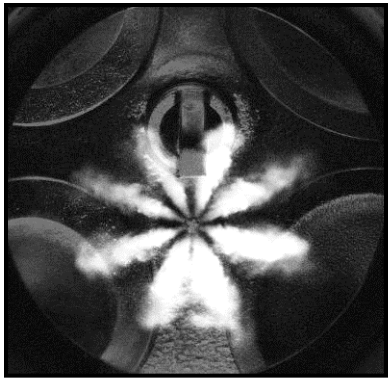
Data set	Ignition Type	Intake Air Temp.	Imaging?
RS	Inductive	30°C	Yes
RS Heated	Inductive	100°C	
MP	Multi-pulse	30°C	Yes
MP Heated	Multi-pulse	100°C	

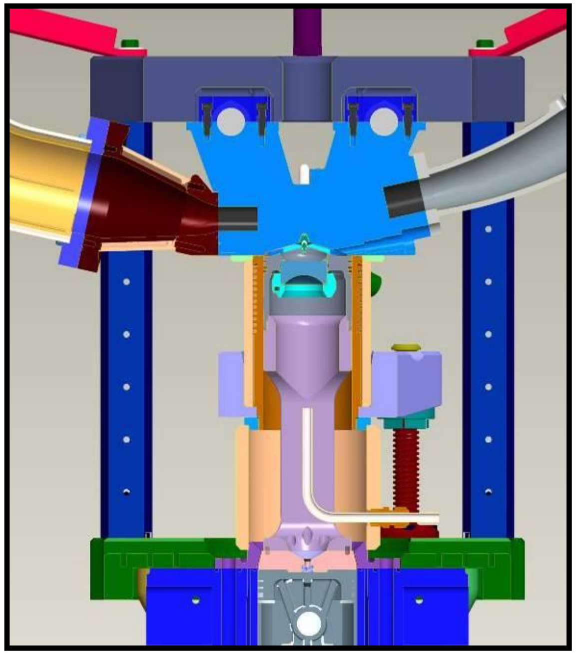
Approach / Research Engine

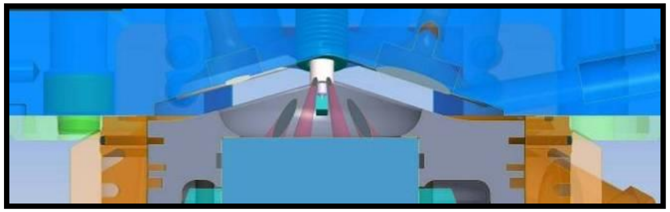
Two configurations of drop-down single-cylinder engine.

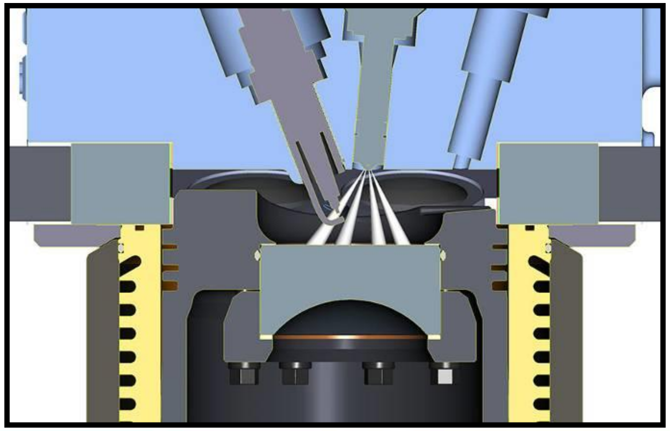
Bore = 86.0 mm, Stroke = 95.1 mm, 0.55 liter swept volume.

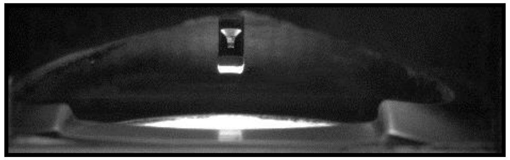
- All-metal: Metal-ring pack and air/oil-jet cooling of piston.
- Optical: Pent-roof window, piston-bowl window, and 45° Bowditch mirror.
- Identical geometry for both configurations.
- 8-hole injector with 60°included angle ⇒
  22° between each pair of spray center lines.
  Spark gap is in between two sprays.

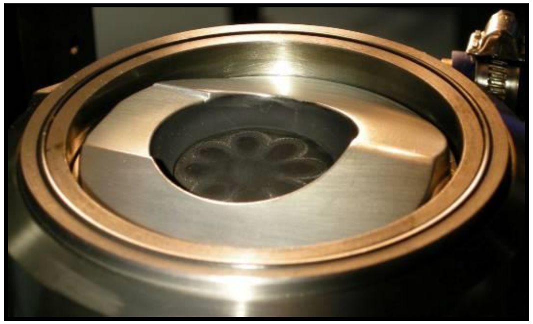












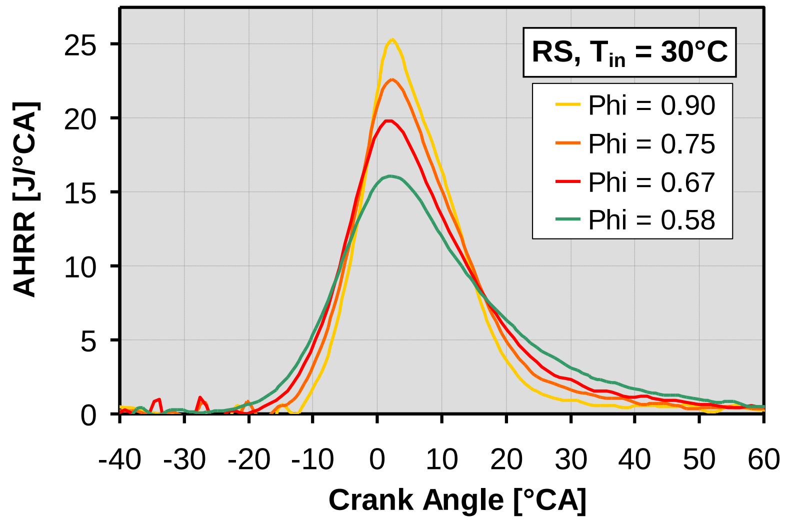
Parameter Space

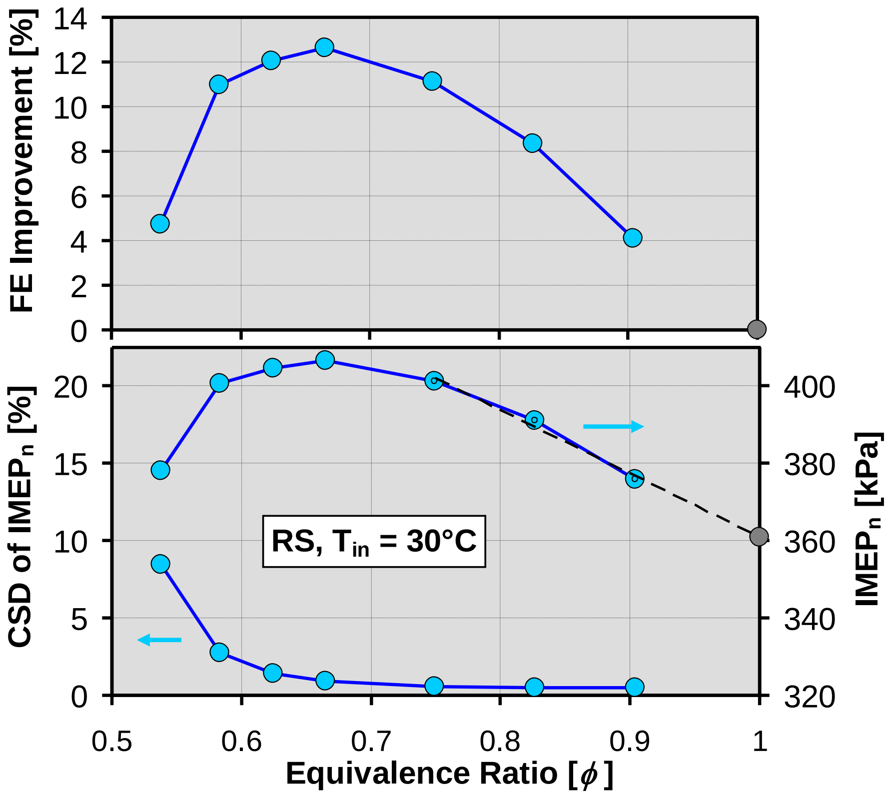
- Grouped as hardware, static parameters & operating variables.
- Low residual gas level, 5 – 6% by mass.
- Constant E85 fuel mass.
- Increase air flow to lean out mixture.
- Target CA50 = 5°CA, as a compromise.
- Adjust spark timing to maintain CA50.

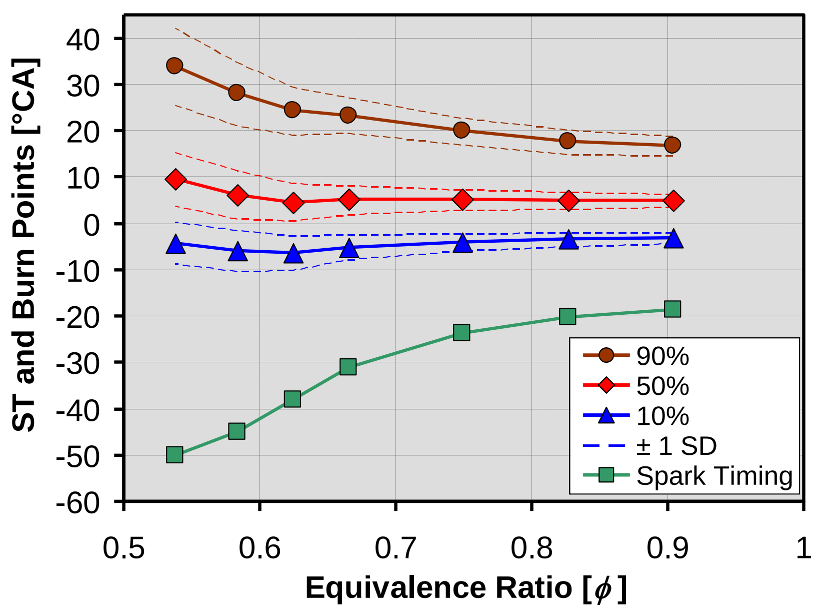
Parameter	This Presentation
CR	12
Piston Bowl	∅ 46 mm
Valve Timings	For Minimal Residual Level
Injector & Spray Targeting	Bosch 8 x 60° Straddling Spark
Swirl Index	2.7
Tumble Index	0.62
Engine Speed	1000 rpm
Injection Pressure	170 bar
# of Injections	Single
Fuel Type	E85
Fuel Mass	21.6 mg/cycle
EGR / $[O_2]_{in}$	No EGR / 21% O_2
$P_{exhaust}$	100 kPa
$T_{coolant}$	75°C
CA50	5°CA
Spark Timing	-58 to -15°CA
T_{in}	30°C or 100°C
ϕ	0.91 - 0.45
Intake Pressure	47 - 96 kPa

ϕ - Sweep, Regular Spark

- $IMEP_n$ increases by 12% at $\phi = 0.67$.
- Unacceptable cycle-to-cycle variability for lower ϕ.
- Spark – CA10 induction period becomes excessive.

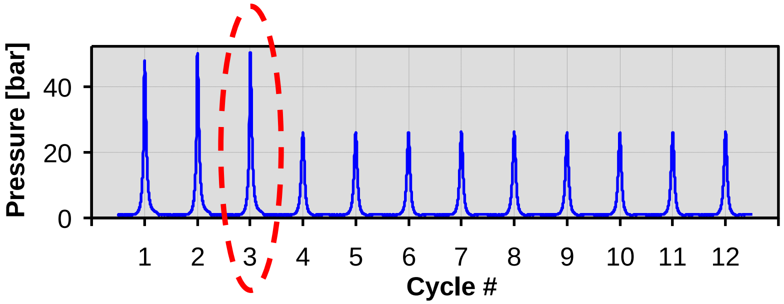


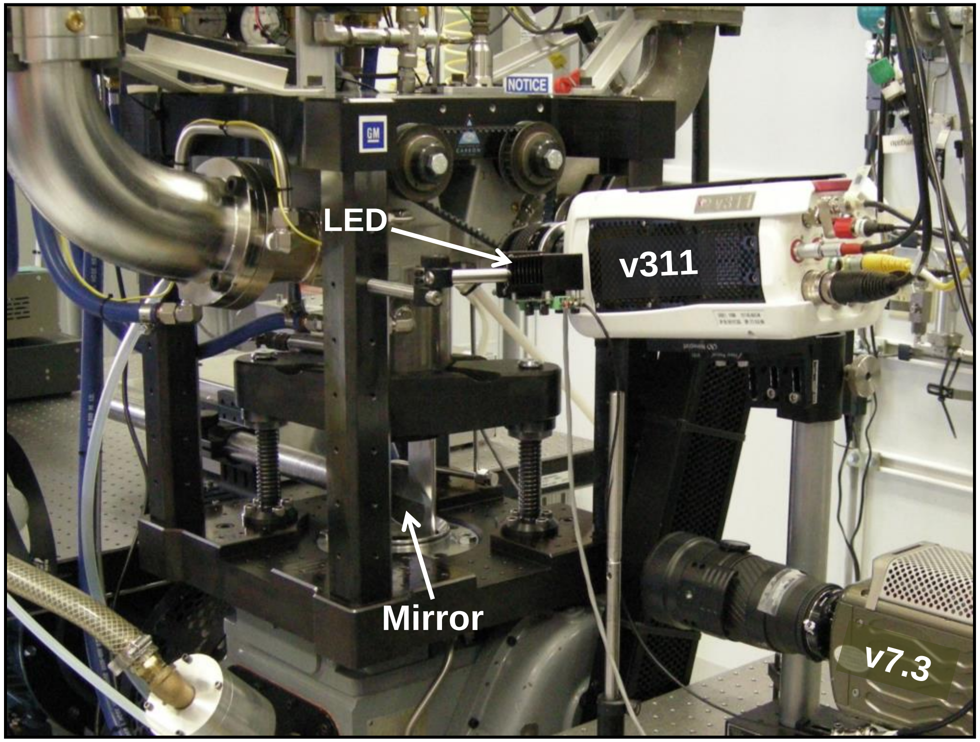




Optical Diagnostics Setup

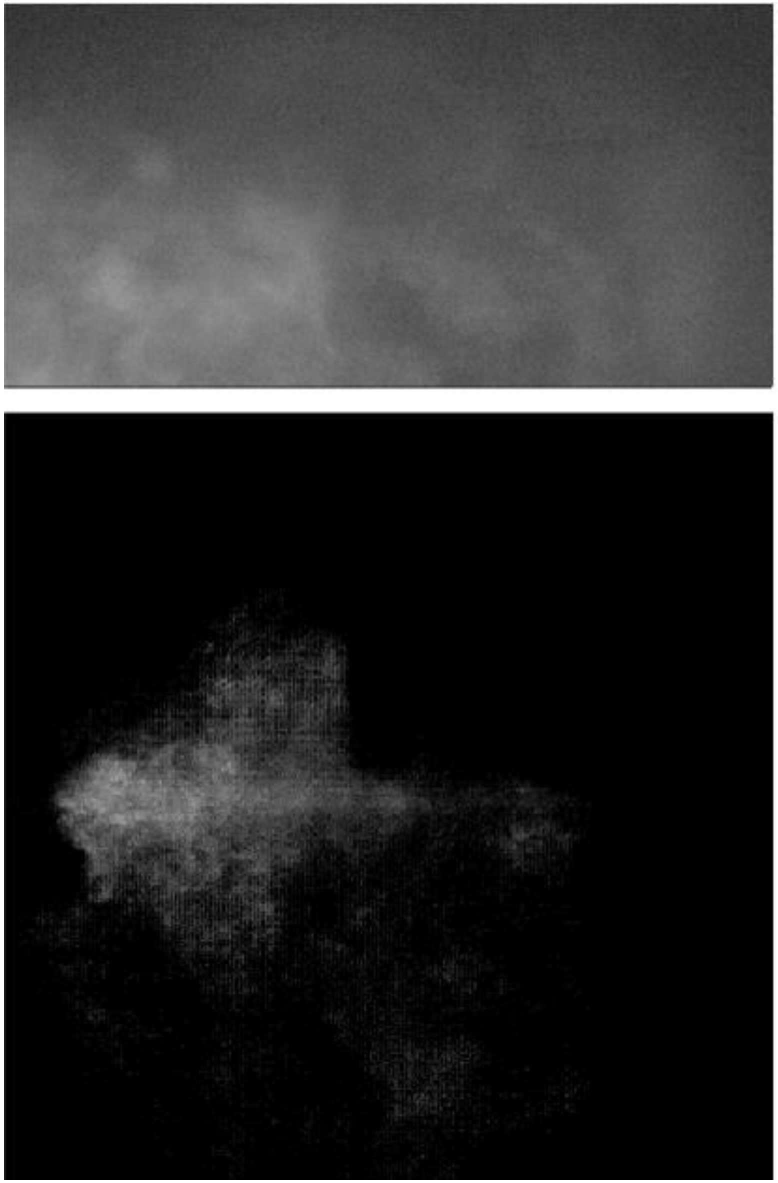
- Dual-camera setups with Phantom v7.3 & v311
- High-intensity LED light pulse as TDC marker/timing-check.
- 3/12 - skipfire operation for realistic residuals.



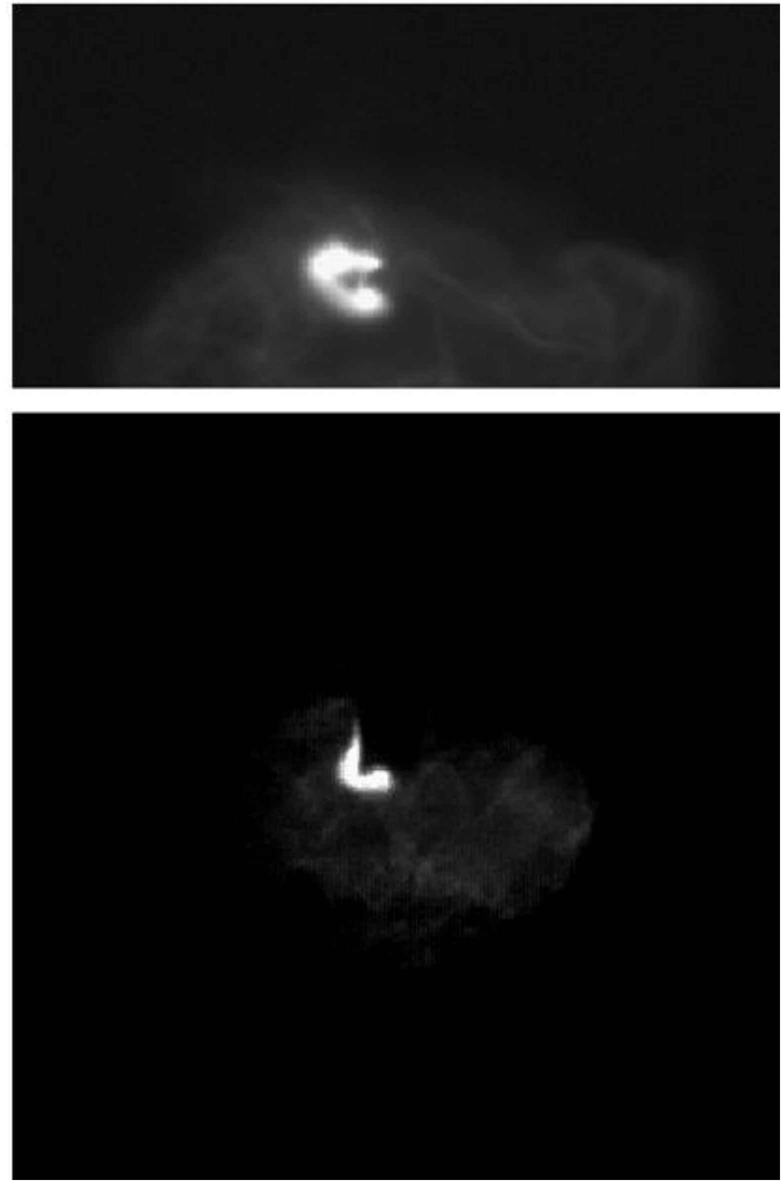


High-Speed Imaging, Regular Spark

$\phi = 0.63$

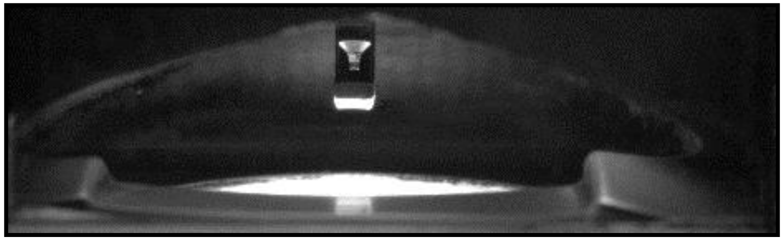


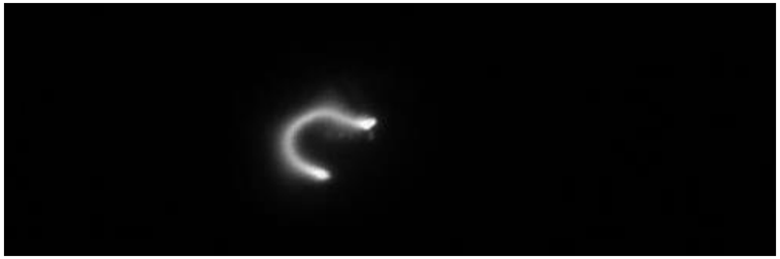
$\phi = 0.90$



Spark Discharge Variations

- Flow field near spark-plug gap has cycle-to-cycle variability.
- Evidenced by plasma-channel variations.
- Example for spark timing = -48°CA.

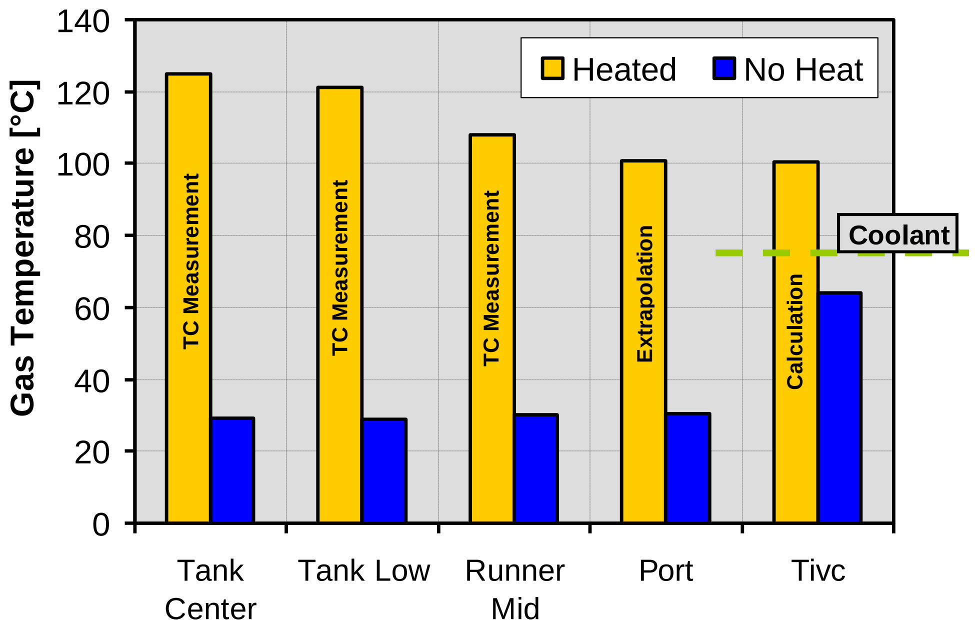


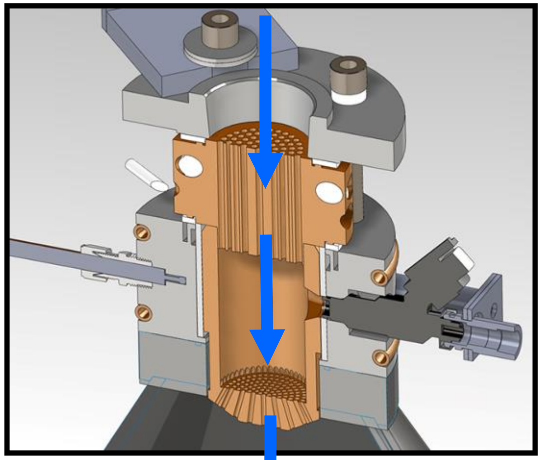


- Contributes to cyclic variability for lean operation.
  - Long induction time from spark to CA10.

Intake Air Heating

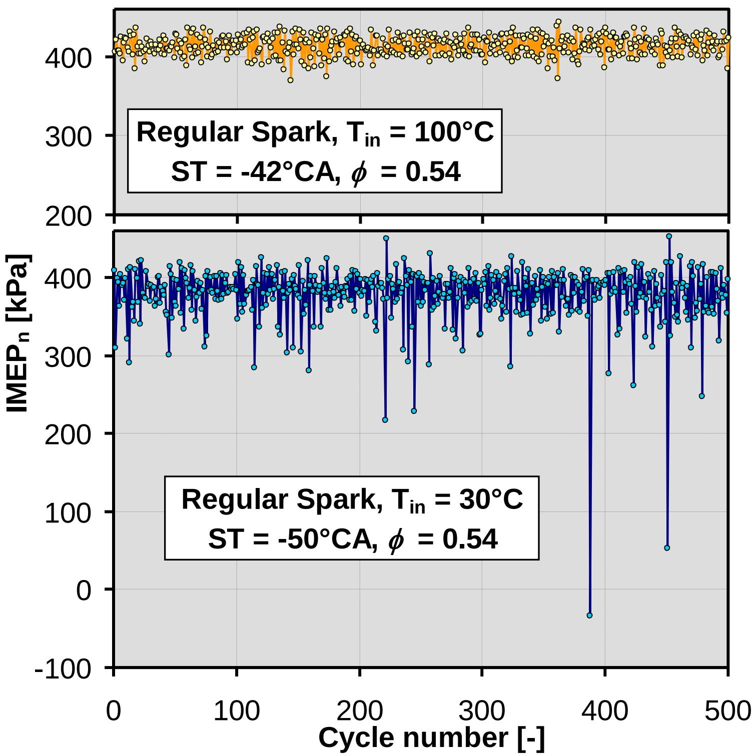
- Installed a new copper intake air heater.
- Air temperature in port estimated from three thermocouples.
- Temperature rise in-cylinder only ≈40K.
  - Calculated following SAE Paper 2004-01-1900.
  - Heat-transfer during intake stroke.
  - Mixing with residuals (≈5%).

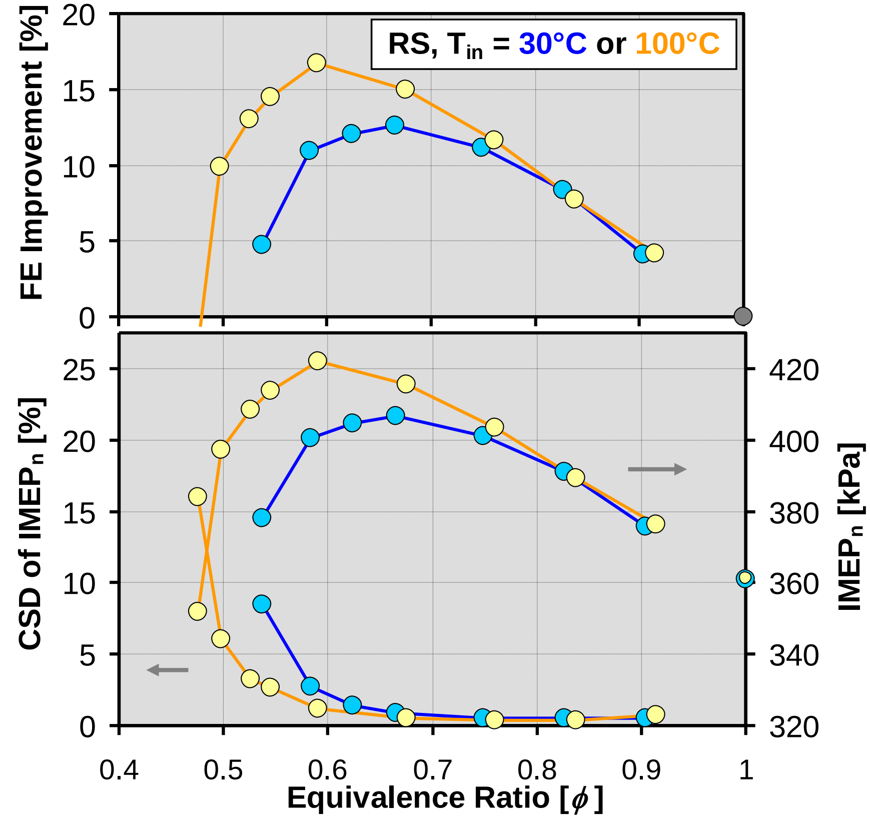




Regular Spark, T_{in} Effect

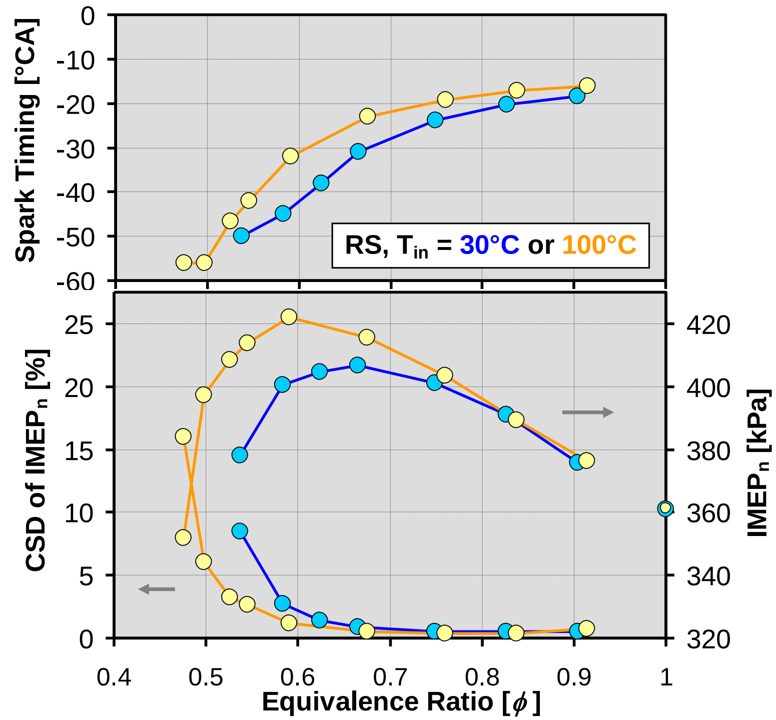
- Higher T_{in} provides substantial improvement of lean operation.
- Example of IMEP variations at $\phi = 0.54$.
- Remarkable improvement for only 40K higher charge temperature at IVC.

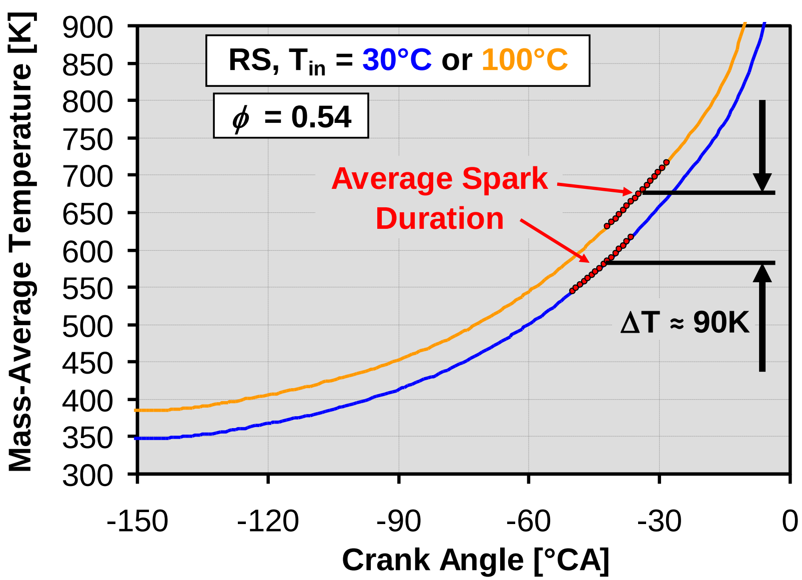




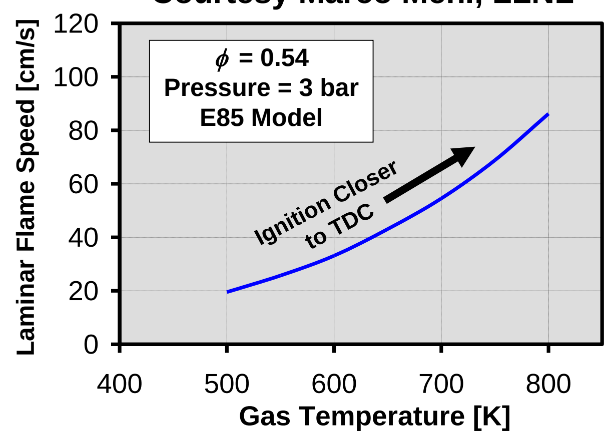
Combined ST & T_{in} Effects

- Higher T_{in} allows later spark.
- Enhances effect of higher T_{in}.
- Difference in charge temperature during spark event is ≈90K.
- 90 K leads to large relative increase of S_L near flammability limit.



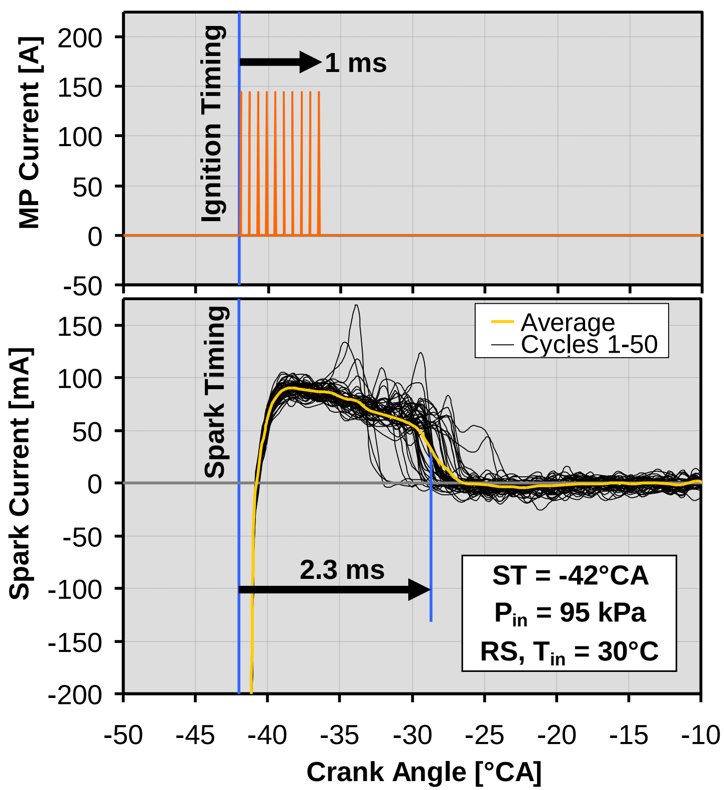


Courtesy Marco Mehl, LLNL



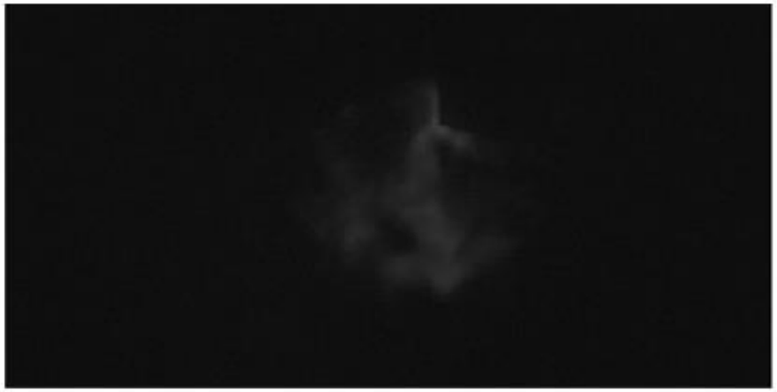
Multi-pulse Transient Plasma

- Modified spark plug. 4 grounding arms.
  - Allow fuel to enter.
  - Form an semi-open cavity.
- 10 ultra-short high-current pulses over 1 ms.
  - Ignition duration does not vary.
- Spark duration varies for inductive system.

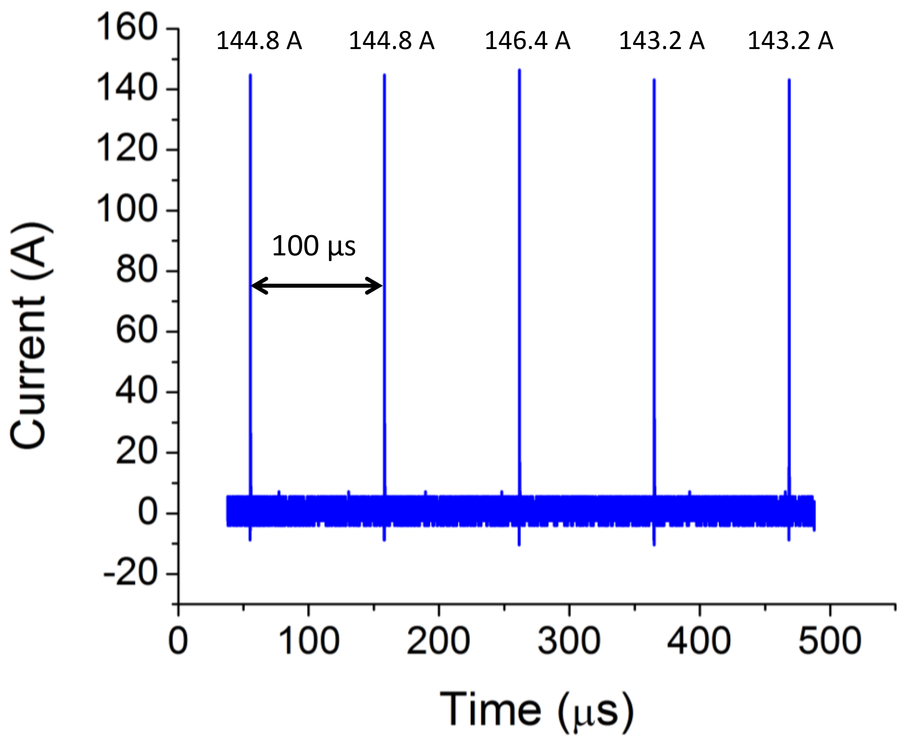


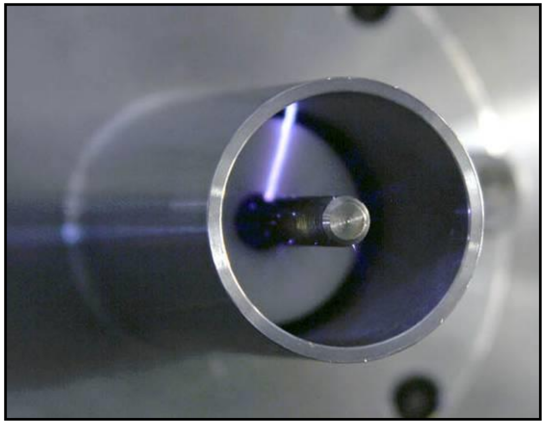
MP Example at $\phi = 0.90$.

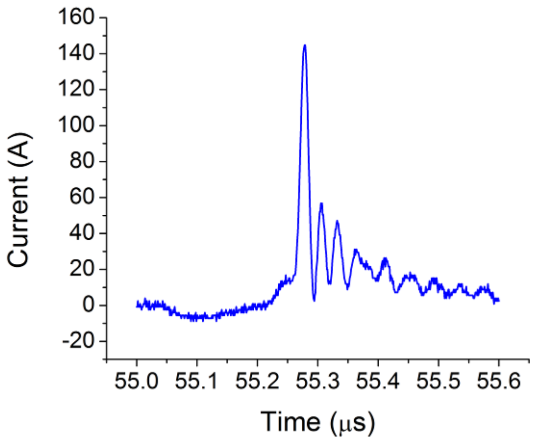
- Example for $\phi = 0.90$.
- Typically only one or two anodes show strikes.
  - Seldom all four are active in one particular cycle.
- Downward jet-effect is typically generated.



Pulse Train at 10 kHz



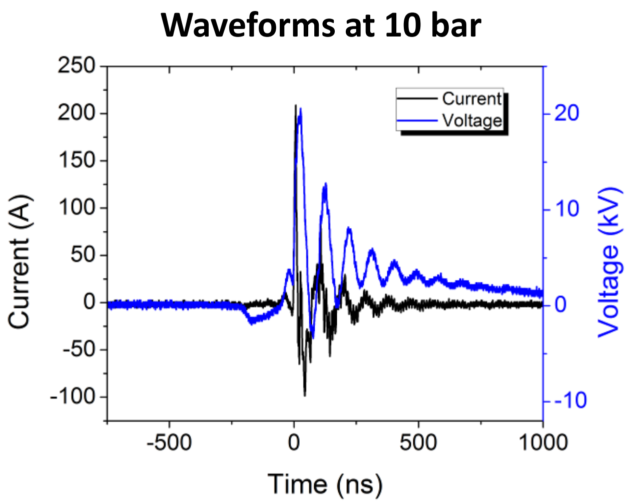




Zoomed-in view shows first pulse in the train.

Statistics: Mean: 144.5 A; Std Dev: 1.34 A; Variance: 1.79 A

Discharge Energy



Energy Calculation Procedure

- Pulse Energy is calculated by numerically integrating the instantaneous power

$$E_{Pulse} = \int v(t) * i(t)\, dt$$

- The general trend is that the discharge energy decreases with increasing pressure

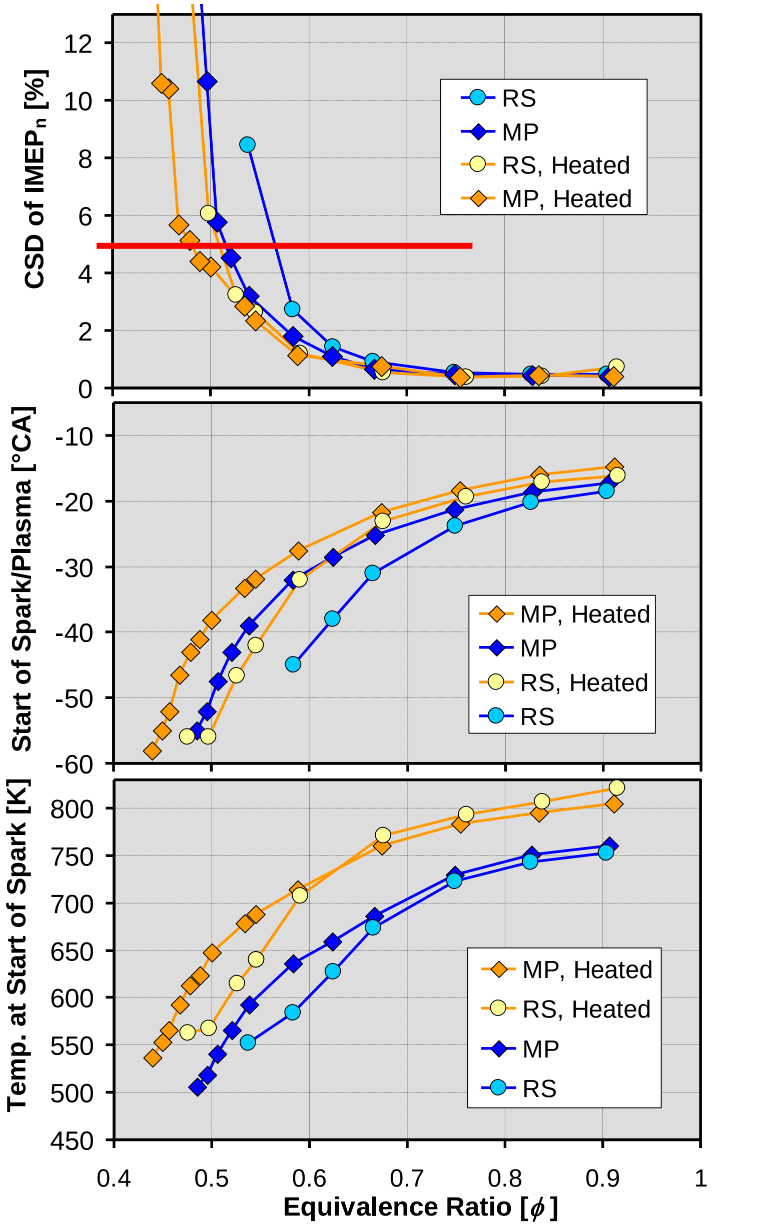
Pressure (bar)	Discharge Energy (mJ)	Number of Discharges	Total Energy of 10 kHz Pulse Train (mJ)
10	1.37	10	13.7
11	1.16	10	11.6
12	1.26	10	12.6
13	1.47	10	14.7
14	1.56	10	15.6
15	1.00	10	10.0

ϕ - Sweep, Multi-Pulse

- Multi-pulse transient plasma provides more stable lean operation.
- With 5% variability limit:

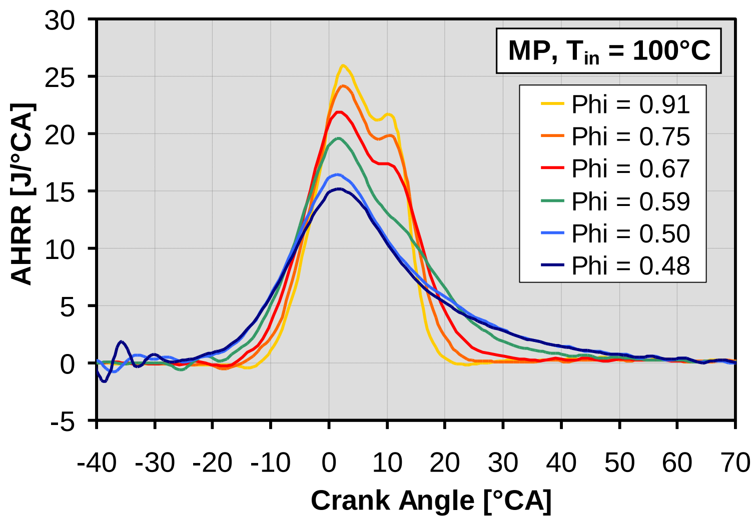
Operation	Lean Limit
RS	$\phi = 0.565$
MP	$\phi = 0.515$
RS Heated	$\phi = 0.508$
MP Heated	$\phi = 0.480$

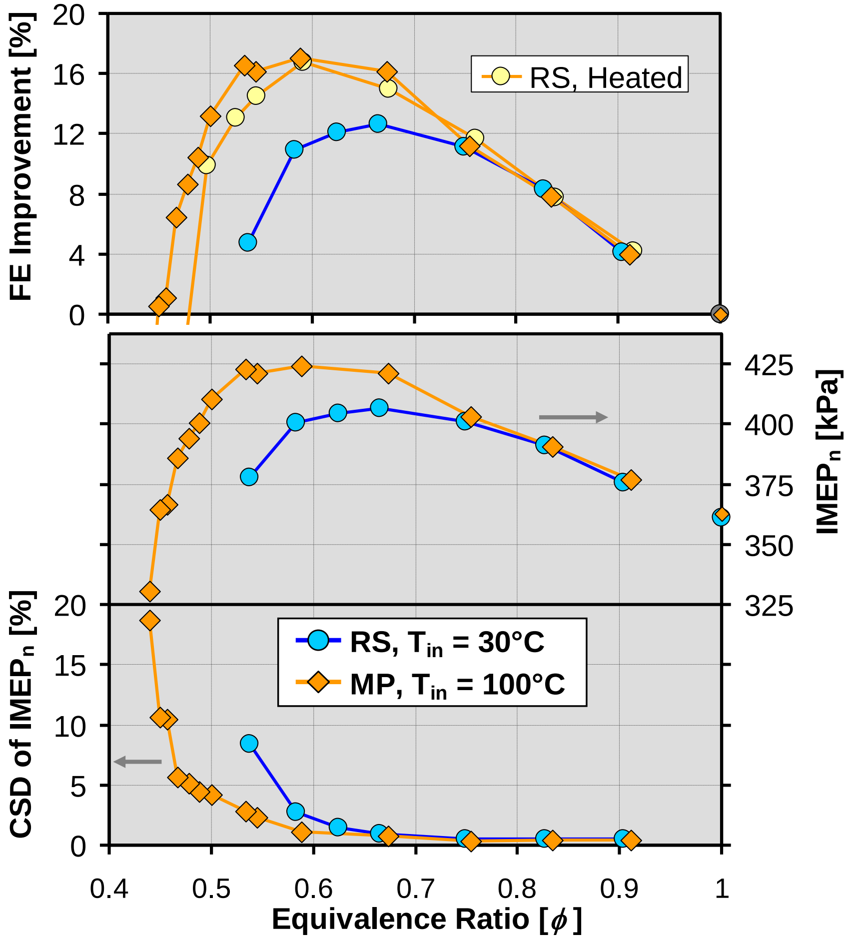
- Relative regular spark unheated: Improvement with MP is equivalent to intake air heating.
- **Spark timing** and **gas temperature at spark timing** explain instability trends.



ϕ - Sweep, Multi-Pulse

- Combination of heated MP provides best lean operation relative non-heated RS.

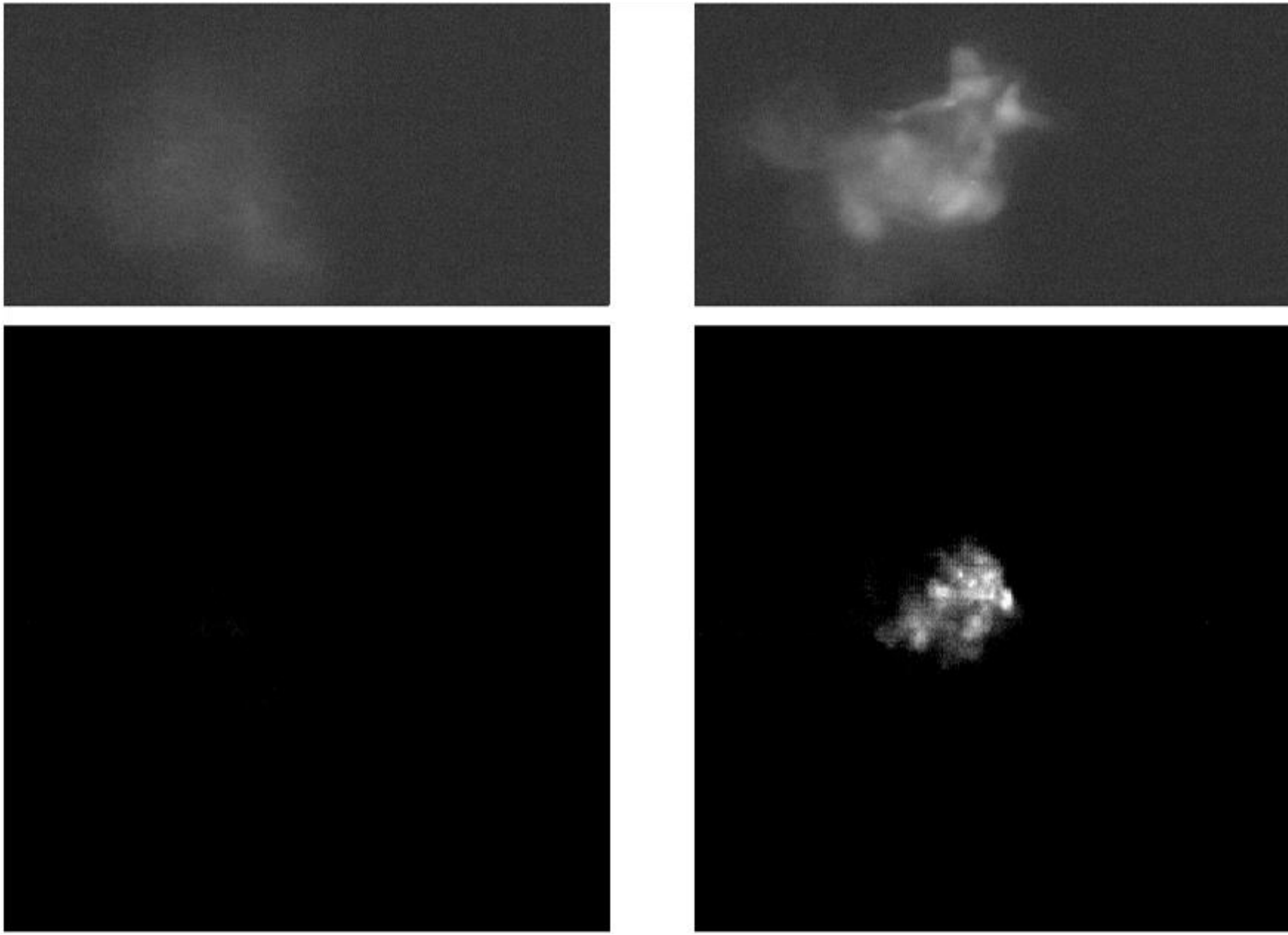




- Peak FE improvement with heated MP operation is similar to heated RS.
- But MP tolerates leaner operation.

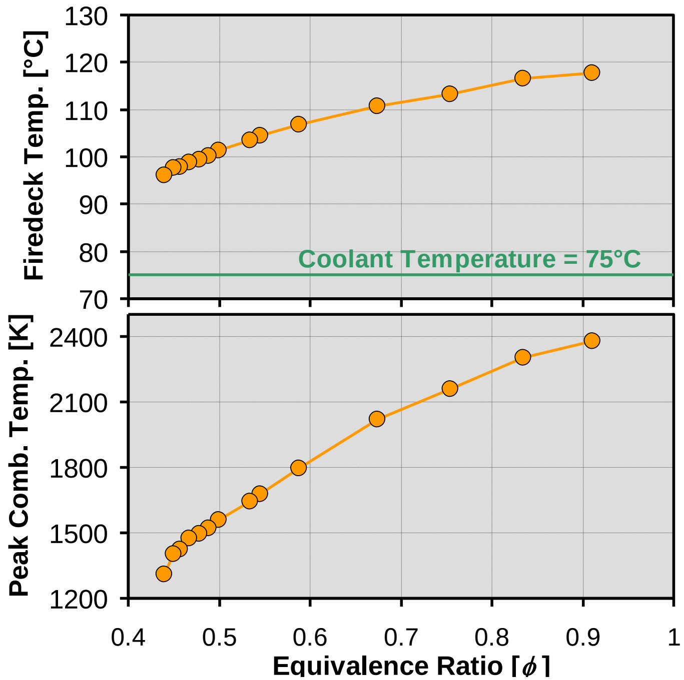
Dual-views at $\phi = 0.63$

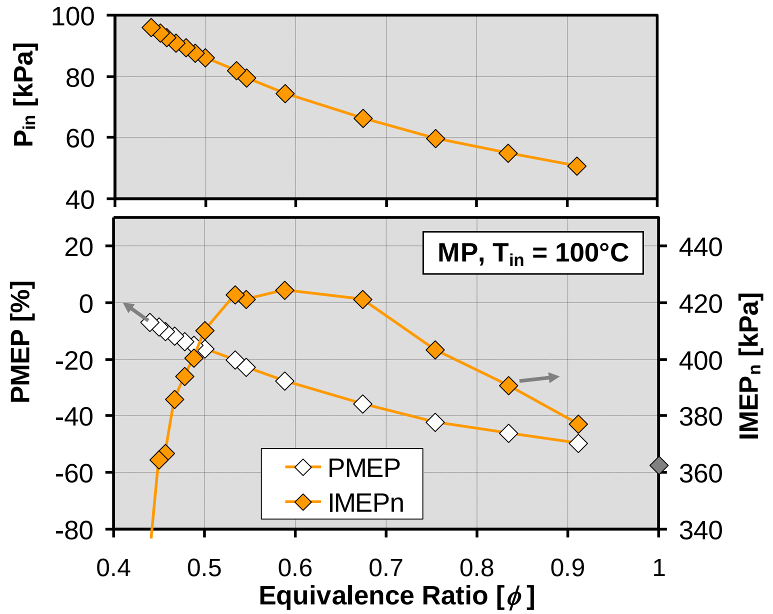
Regular Spark | **Multi-pulse**



Factors for Improved Efficiency

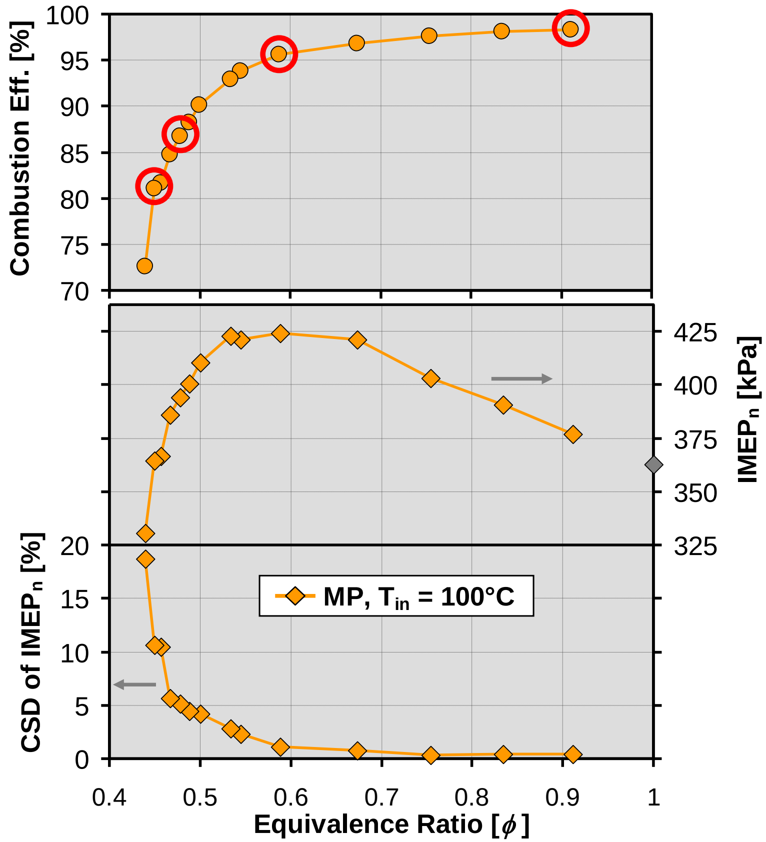
- Why does IMEP rise initially on the lean side?
- Less pumping losses due to higher P_{in}.
  - 30% contribution to increased efficiency.
- Lower combustion temperatures lead to:
  - Higher γ .
  - Lower heat-transfer losses.

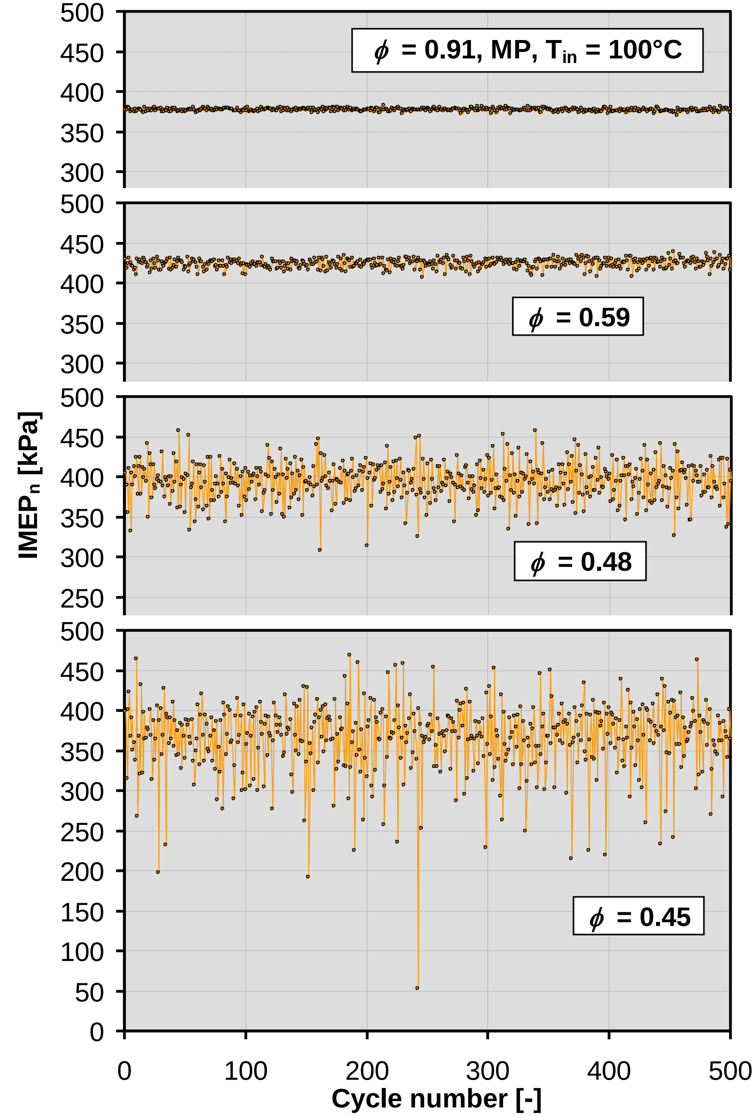




Lean Limit Issues

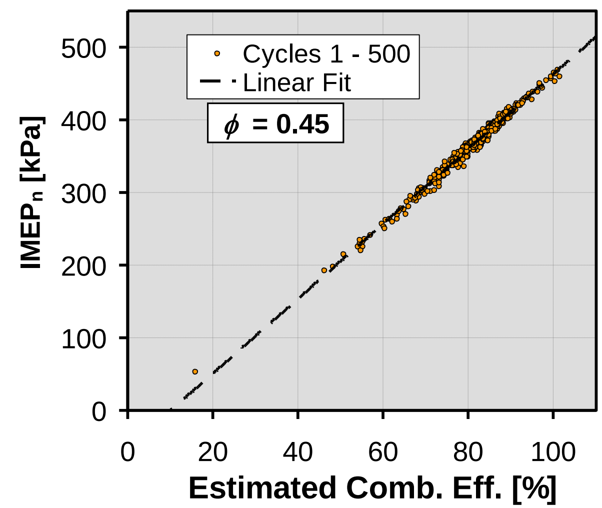
- Why does not IMEP keep rising on the lean side? Low-IMEP cycles appear.
- Low IMEP because of late burn or incomplete burn?
- Drop in CE suggests incomplete burn.

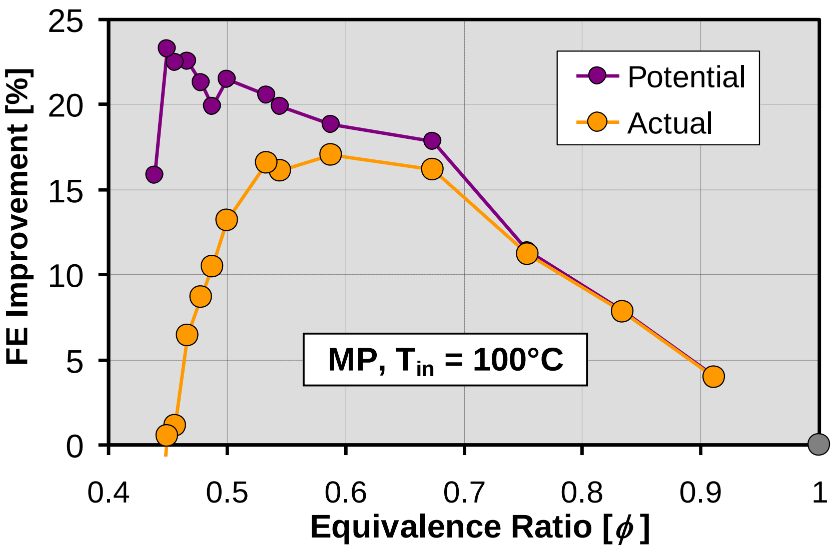


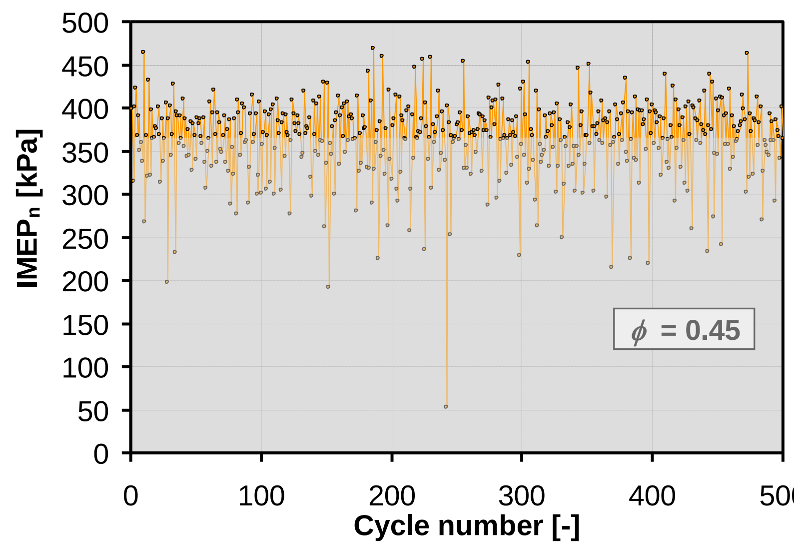


Potential of Lean Operation

- HR analysis supports hypothesis that low-IMEP cycles are partial burns.
- Examine IMEP statistics for potential of lean operation.
- Many cycles burn well, some too well!
- Low IMEP cycles leave unburned fuel for next cycle ⇒ very high IMEP.
- Exclude cycles that are preceded by lower-than-average IMEP.

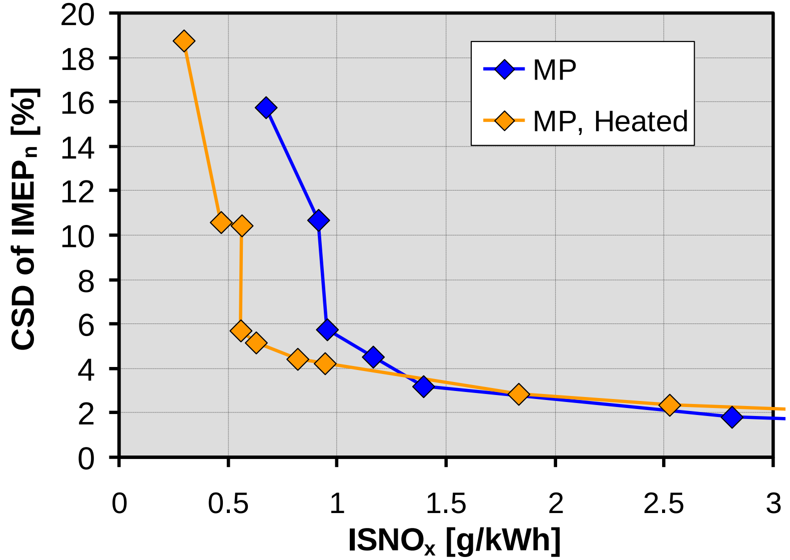


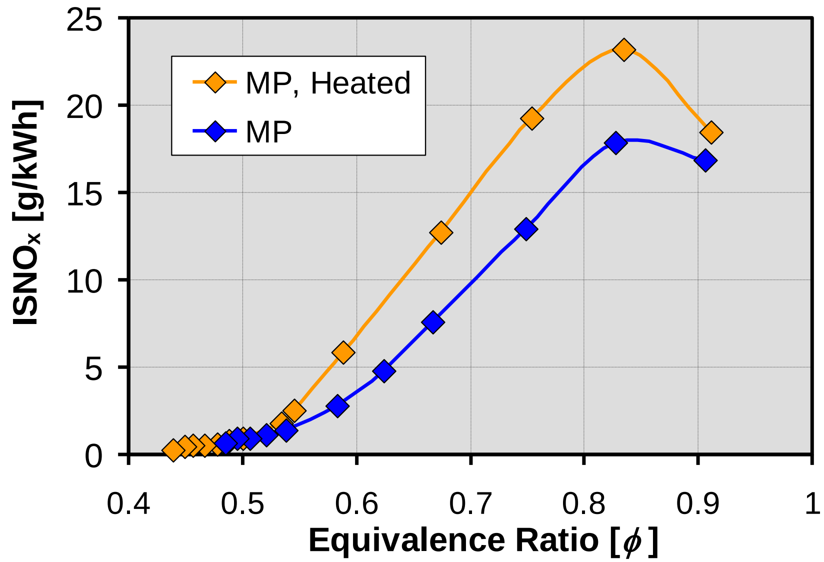




NO_x Emissions

- Heated MP operation leads to more NO_x at moderately lean conditions.
  - Higher peak temperatures.
- Lower specific NO_x can be reached with heated MP operation.
- Better trade-off between NO_x and combustion instability.
  - More stable operation allows leaner operation with lower peak temperatures.





Conclusions

- Lean well-mixed operation has potential for ≈20% fuel-economy improvement.
- Observed improvement is less due to unstable combustion and onset of partial-burn cycles.
- Heated intake air and multi-pulse ignition both improve stability of lean operation.
- For a given target CA50, stable combustion is promoted by:
  - Late spark timing.
  - High charge temperature at the time of spark.
- Heated intake provides more stable lean combustion by:
  - Allowing a later spark, due to shorter spark – CA10 induction time (higher S_L).
  - Increasing the charge temperature for a given spark timing.
- Multi-pulse transient plasma ignition with a semi-open spark geometry provides more stable lean combustion by:
  - Ensuring a constant 1 ms time with plasma.
  - Creating a turbulent jet of ignition products that quickly deflagrates into unburned gas, thereby shortening the induction time from ignition to CA10.