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Assessment of Spark, Corona, and Plasma Ignition Systems for Gasoline Combustion

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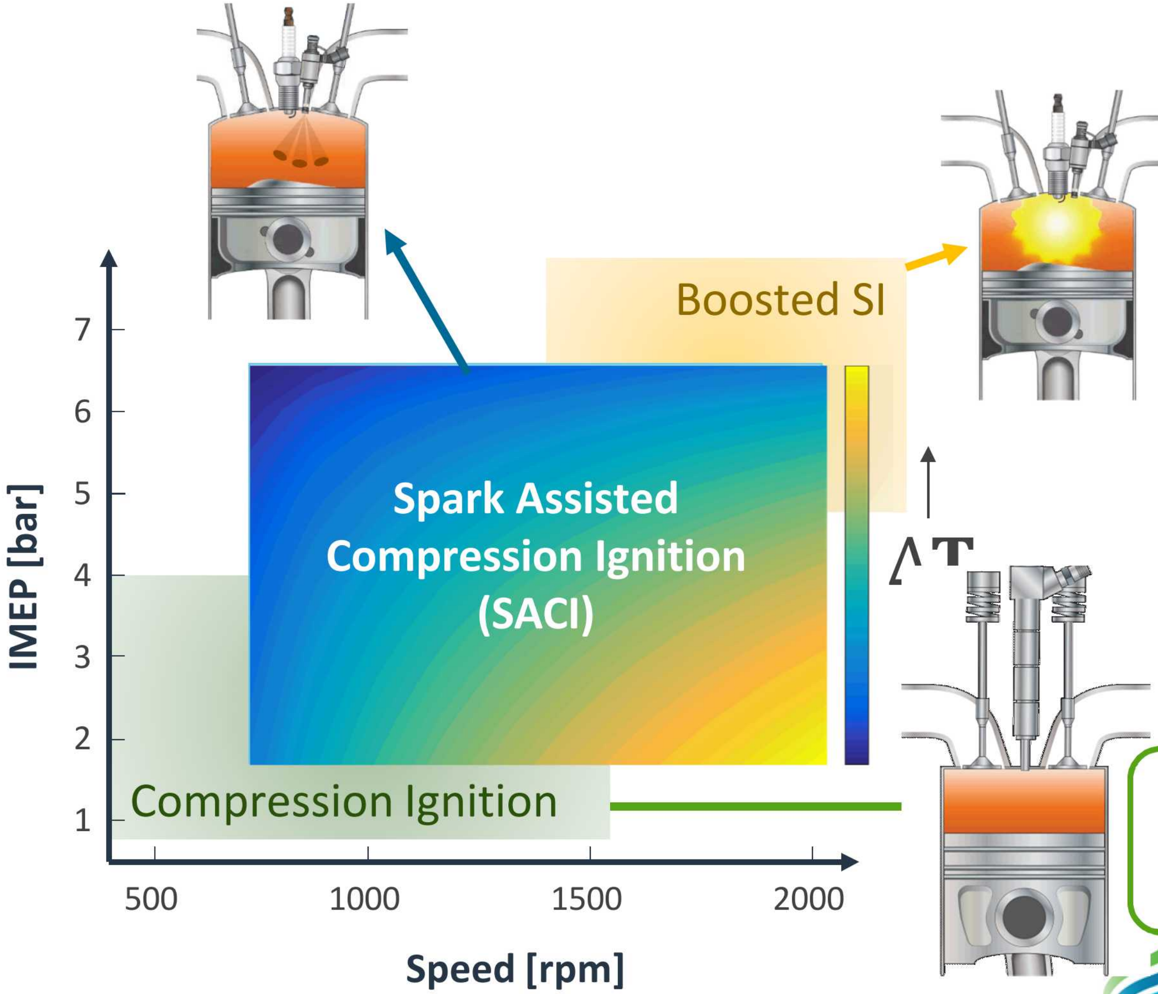
Advanced low-temperature plasma (LTP) and corona ignition can be a key enabler of multi-mode combustion strategies



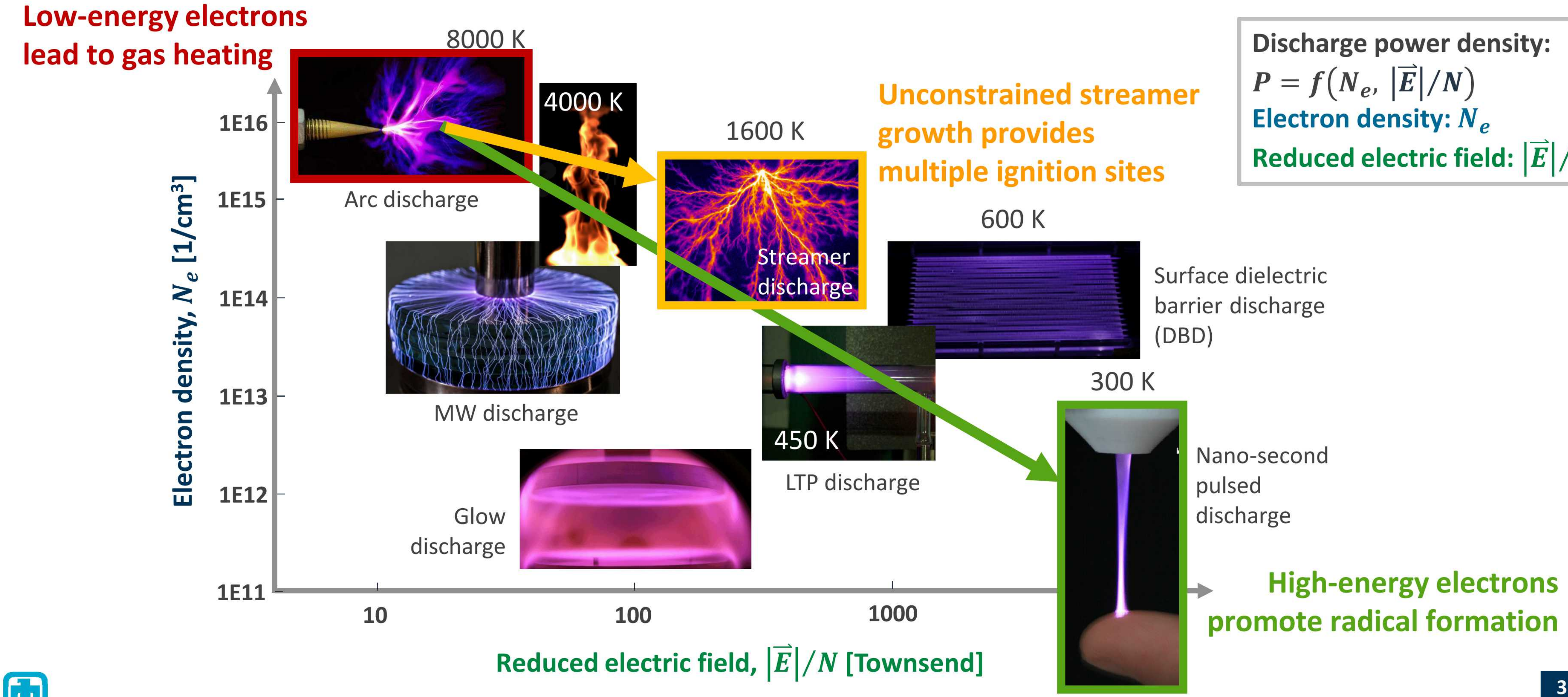
Late LTP: Higher flame speeds from LTP-generated O-atom leads to enhanced SI flame propagation rates (i.e., higher dilution tolerance)

Plasma & Corona Ignition System

- Produces reactive species (O, O_3) and increases mixture reactivity
- Enhances ignition kernel growth and flame propagation rate

Early LTP: O_3 from LTP-generated O-atom enables controllable compression ignition

Nanosecond repetitive pulsed discharge promote radical formation and unconstrained streamer discharge produces multiple ignition sites

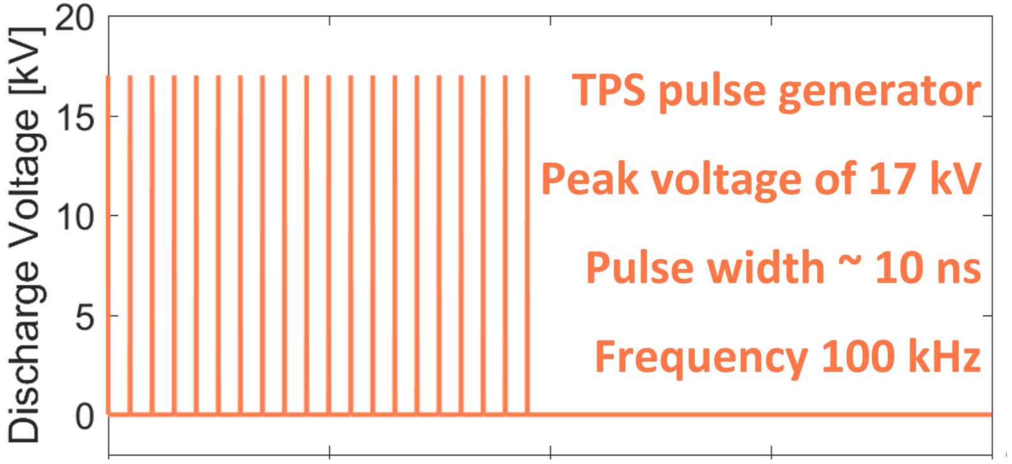


Discharge power density:
$P = f(N_e, |\vec{E}|/N)$
Electron density: N_e
Reduced electric field: $|\vec{E}|/N$

Current focus is on 3 distinct ignition systems: **Spark, Corona**, & **LTP**

NRPD: **N**ano-second **R**epetitive **P**ulsed **D**ischarge
ACIS: **A**dvanced **C**orona **I**gnition **S**ystem
BDI: **B**arrier **D**ischarge **I**gnition

Nano-second repetitive pulsed ignition system



Transient Low-temperature Plasma:
Short-pulse glow-phase ignition

Image: TPS

Inductive Coil Spark:
Localized thermal plasma

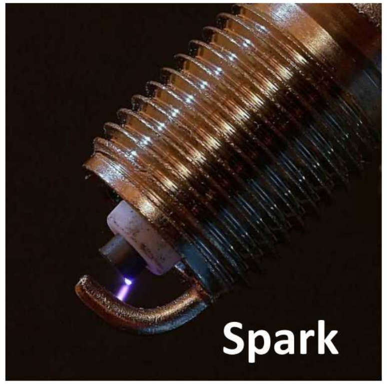


Image: Wikipedia

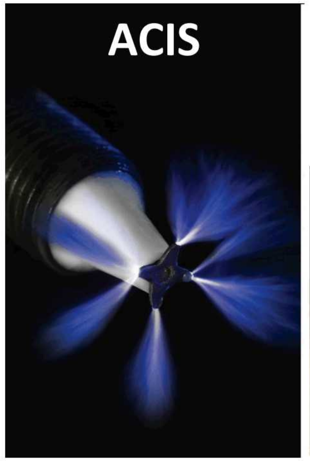
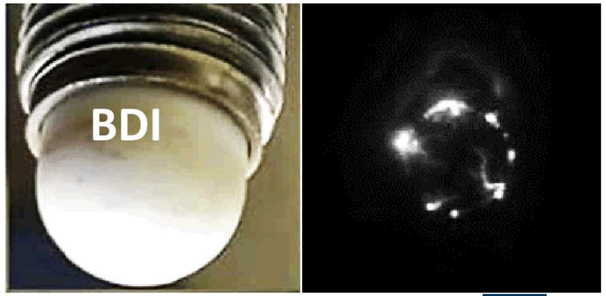


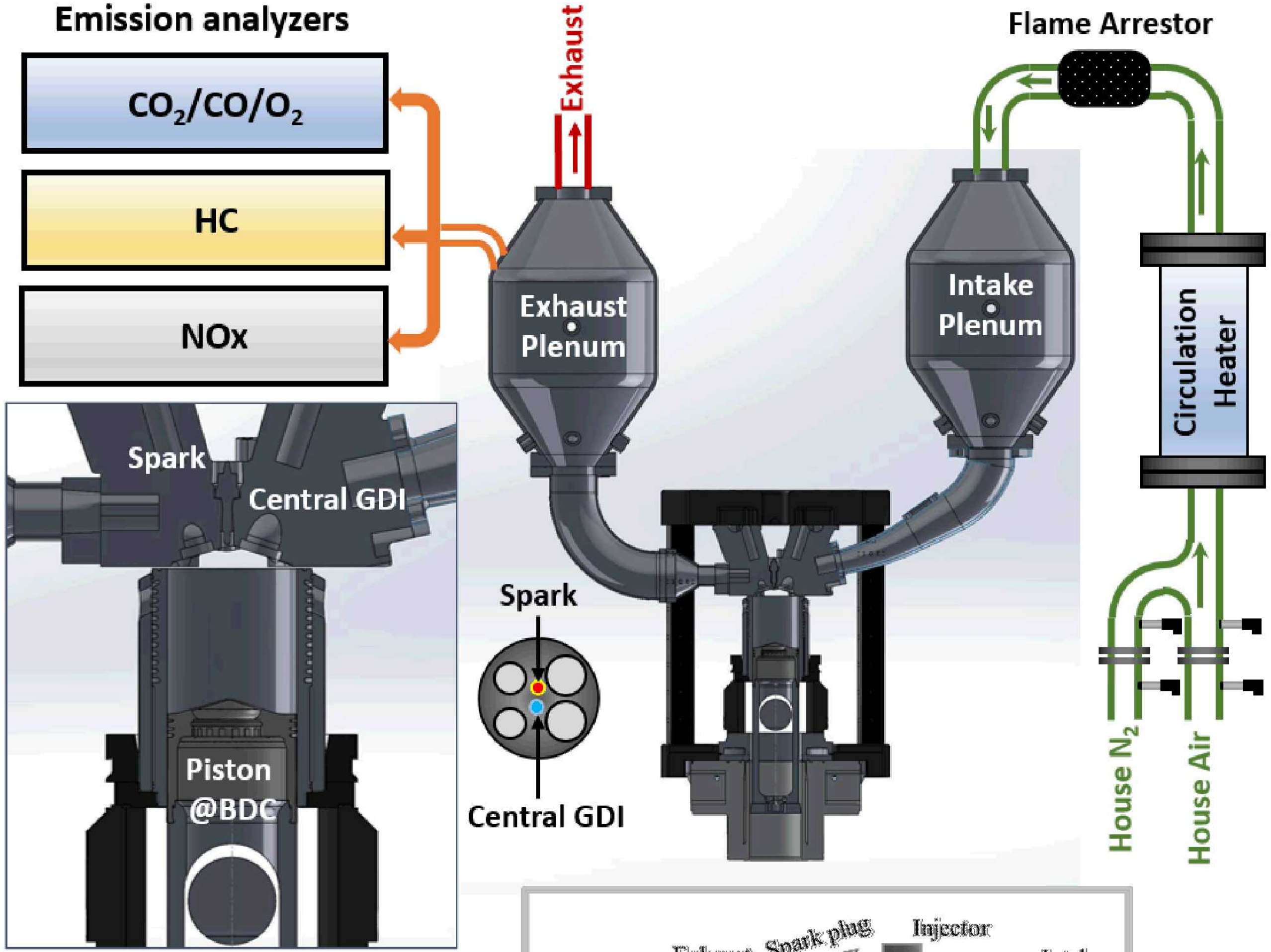
Image: Tenneco

RF Corona: High-energy, repetitive multi-point streamers initiate gas heating



Hardware & operating conditions

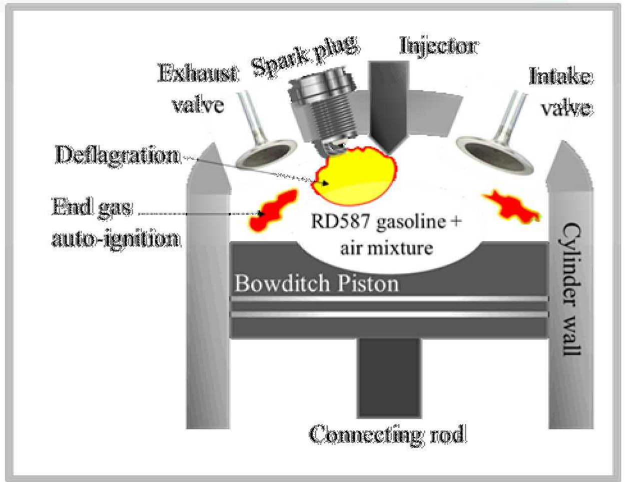
Ignition system	Spark, plasma, corona
Engine Speed [rpm]	**1300**
IMEPg [bar]	**3.5 bar**
Displaced volume [liter]	0.55
Compression Ratio	13:1
Intake Pressure [kPa]	53 – 78
Exhaust Pressure [kPa]	105
Intake Temperature [°C]	42
Equivalence ratio	0.59 – 1
Residual gas fraction [%]	17.5 – 22.3
Spark Timing	-52 – -15
Main SOI [CA]	-330



Fuel RD587 gasoline

- RON 92.1
- Octane sensitivity 7.3

Liquid Density @15 °C [g/L]	748
LHV [MJ/kg]	41.9
H/C ratio	1.972
O/C ratio	0.033
Research Octane Number	92.1
Octane Sensitivity	7.3



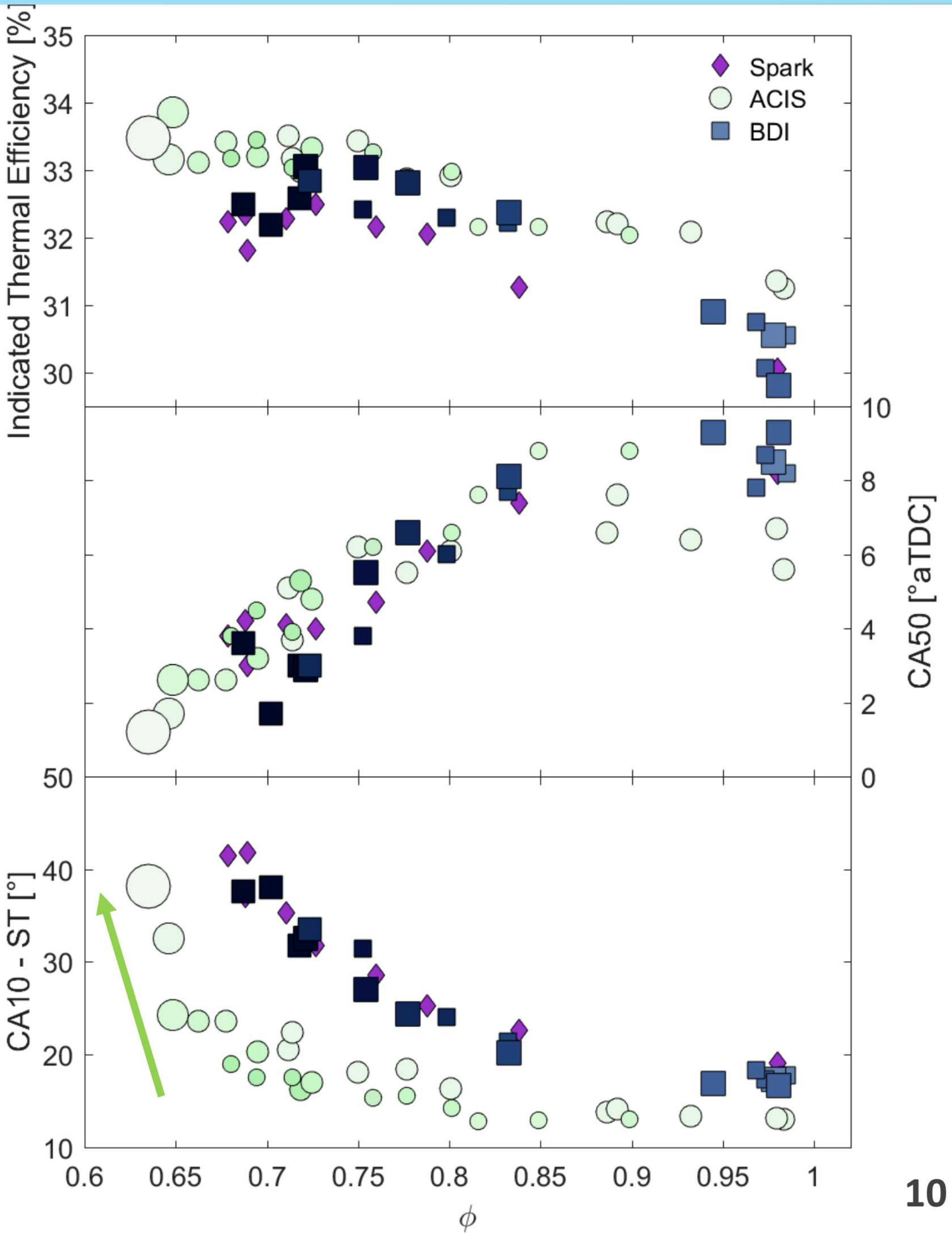
Engine performance @3.5 bar IMEPg, 1300 rpm: **ACIS, BDI**

No notable lean-limit extension with BDI

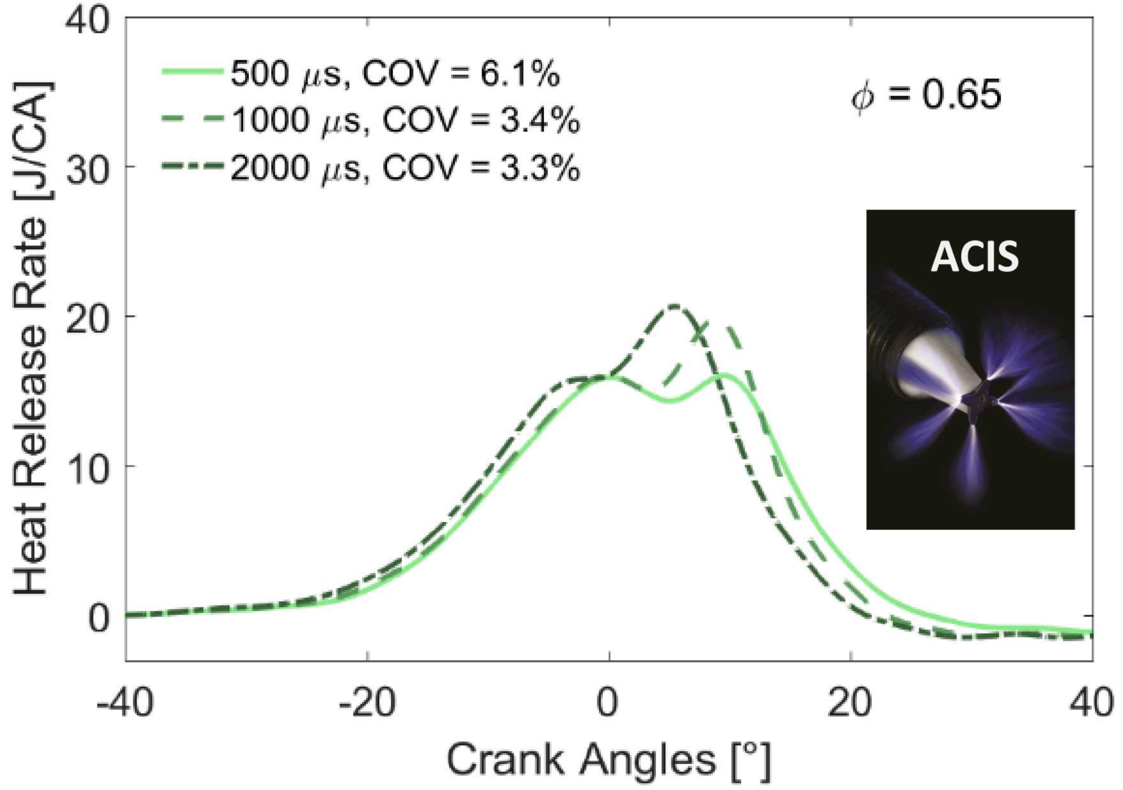
- Intake pre-strikes not used (others observed these improve stability)

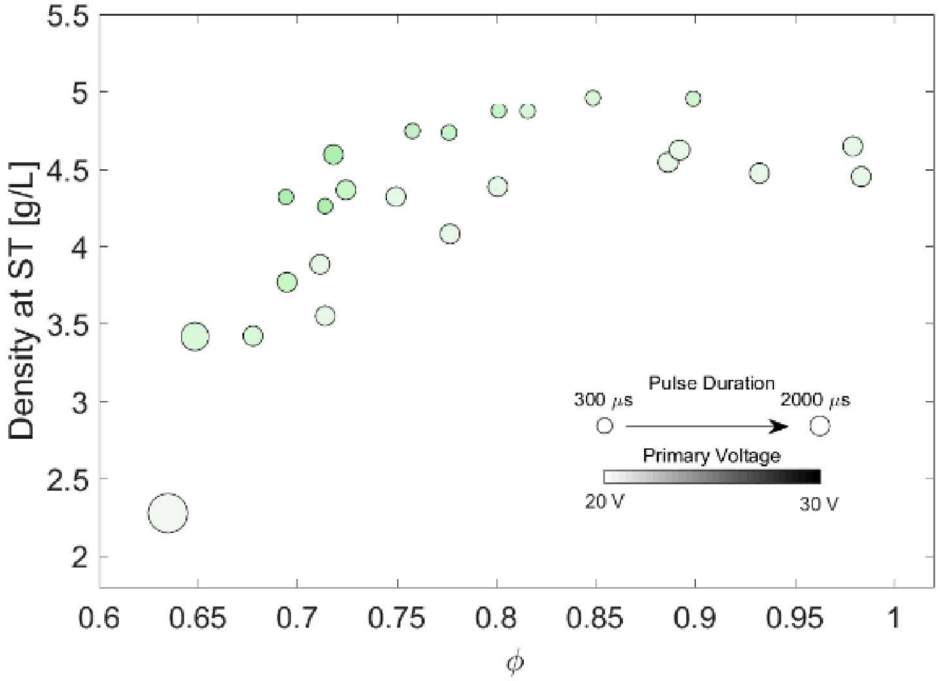
ACIS lean-limits extended from $\phi = 0.73$ to $\phi = 0.68$

- Peak ITE increased from 32.5% to 33.8%
- Longer discharges & higher voltages needed for lean mixtures
- ~ 1.0-point ITE improvement from shorter initial burn durations



ACIS pulse duration affects heat release rate (HRR) behavior but limits the primary voltage to avoid breakdown





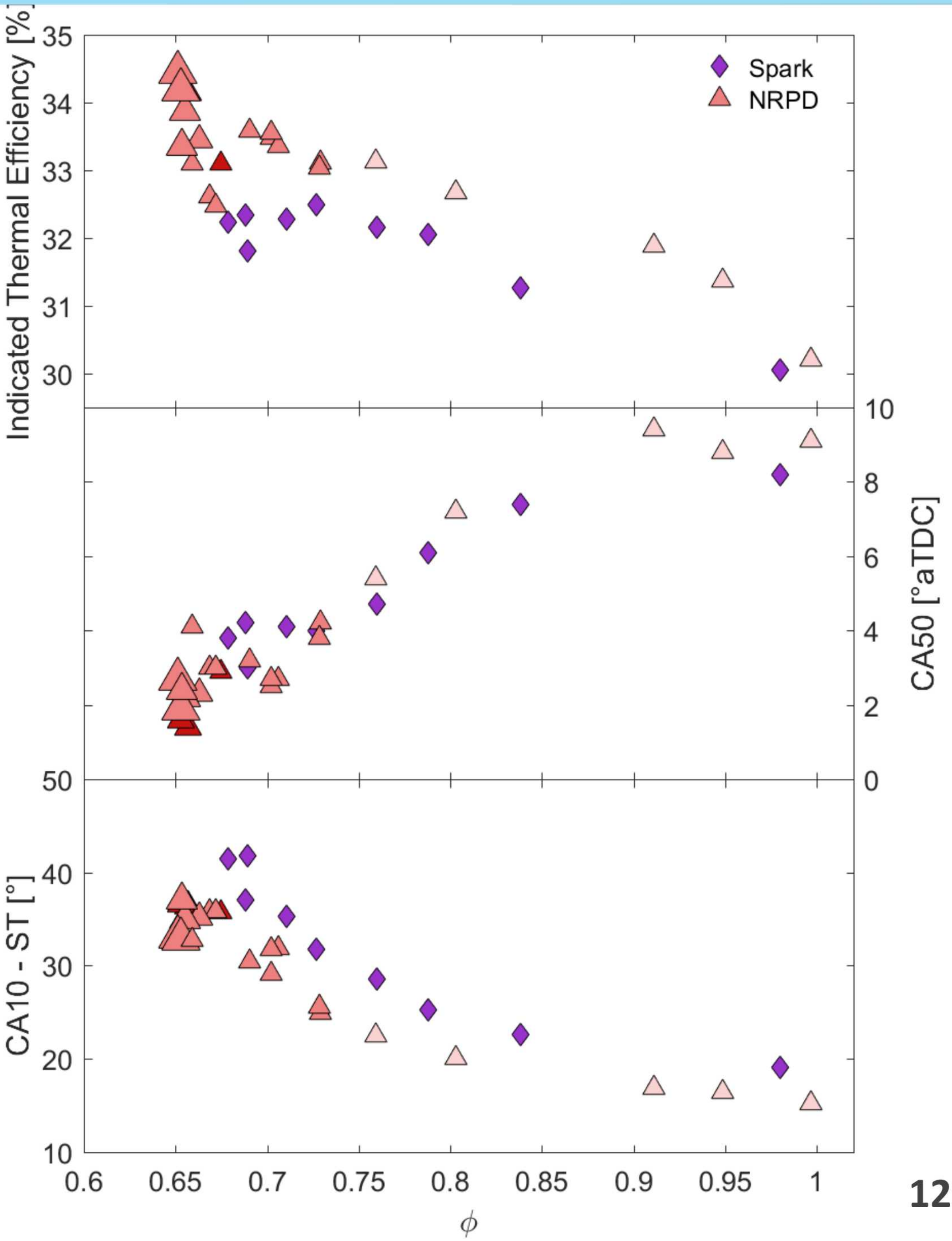
- ST depends on cylinder density
- To accommodate longer pulse durations, the pulse voltage must accordingly be lowered to avoid breakdown/arcing due to lower in-cylinder density

Engine performance @3.5 bar IMEPg, 1300 rpm: **NRPD**

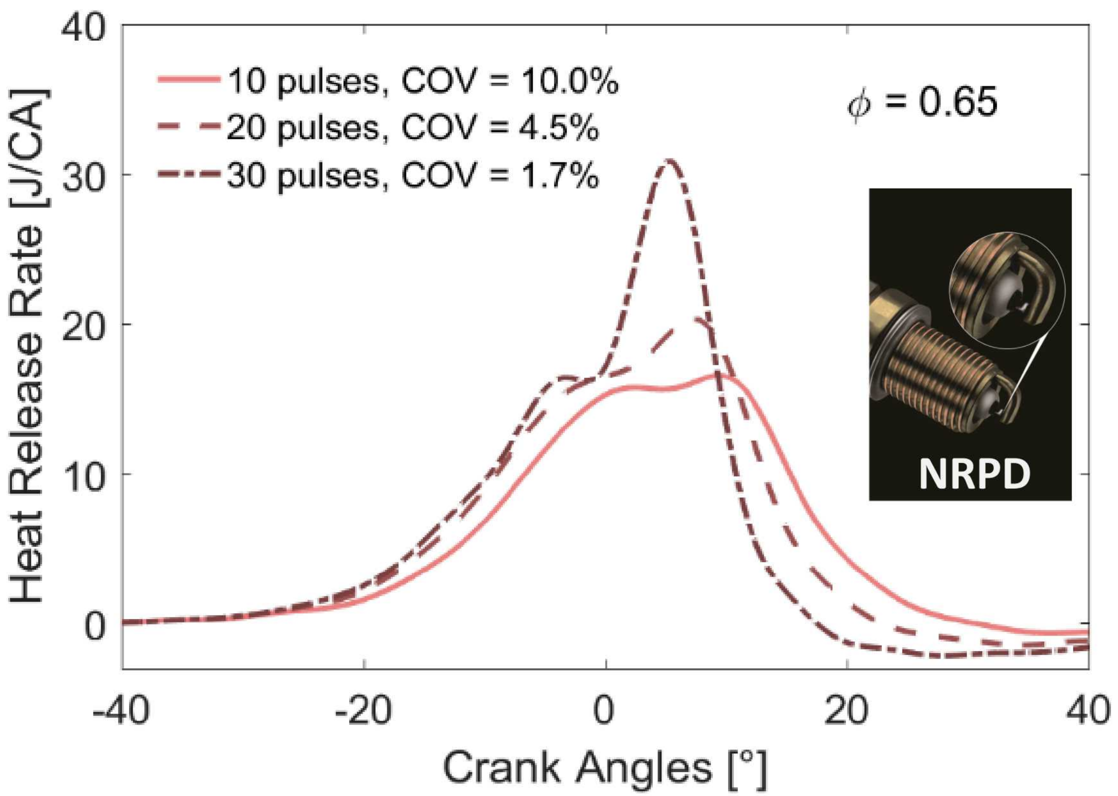
NRPD lean-limit never reached (best value: $\phi = 0.65$)

- Igniter was a non-resistor spark plug
- Peak ITE increased from 32.5% to 34.4%
- Lean-stability limit was never reached during the limited test window
- For leanest mixtures, stability improved w/ increased pulse number
- ~ 0.5-point ITE improvement from shorter initial burn durations

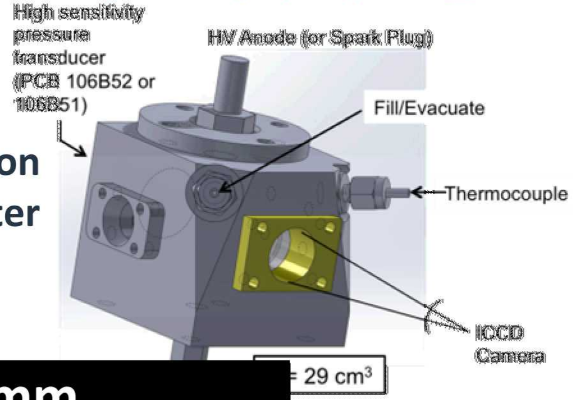
Faster initial burn rates with LTP ignition translated into extended lean stability limits relative to spark

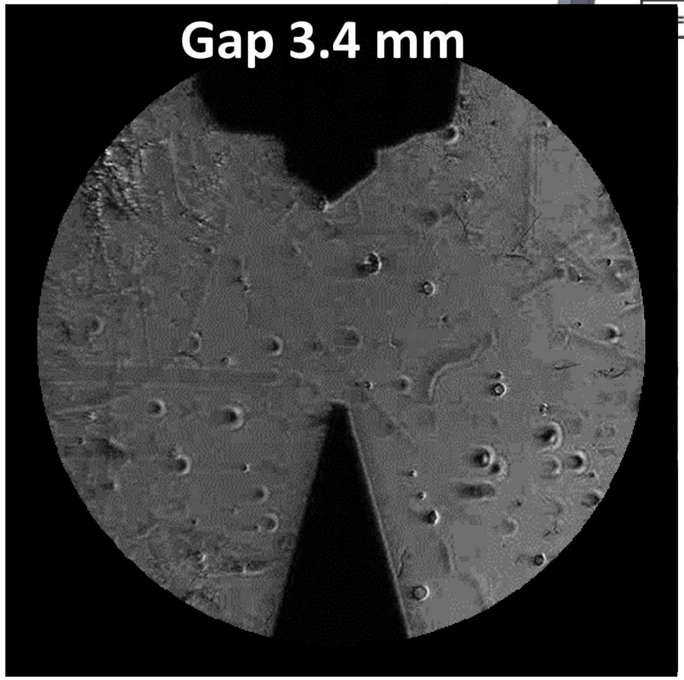


Higher NRPD pulse numbers facilitate early heat release by supplying additional energy that help in kernel expansion



Optical Ignition Calorimeter

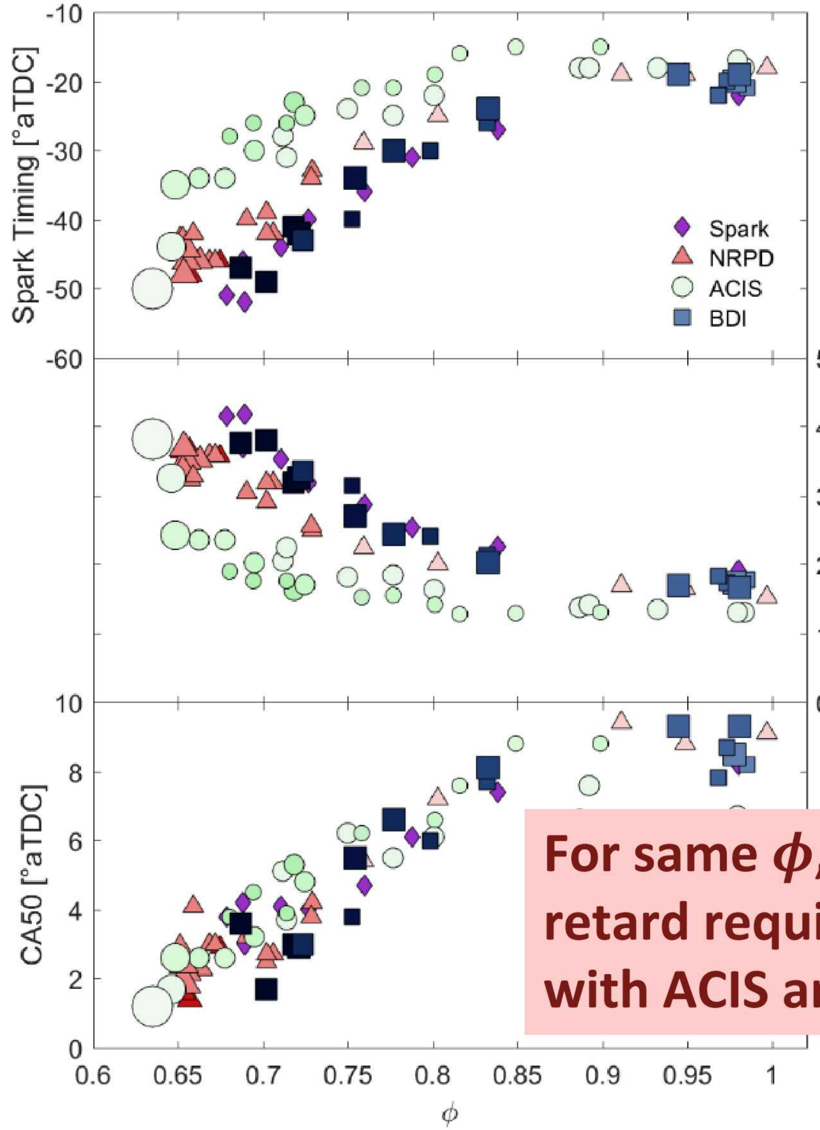




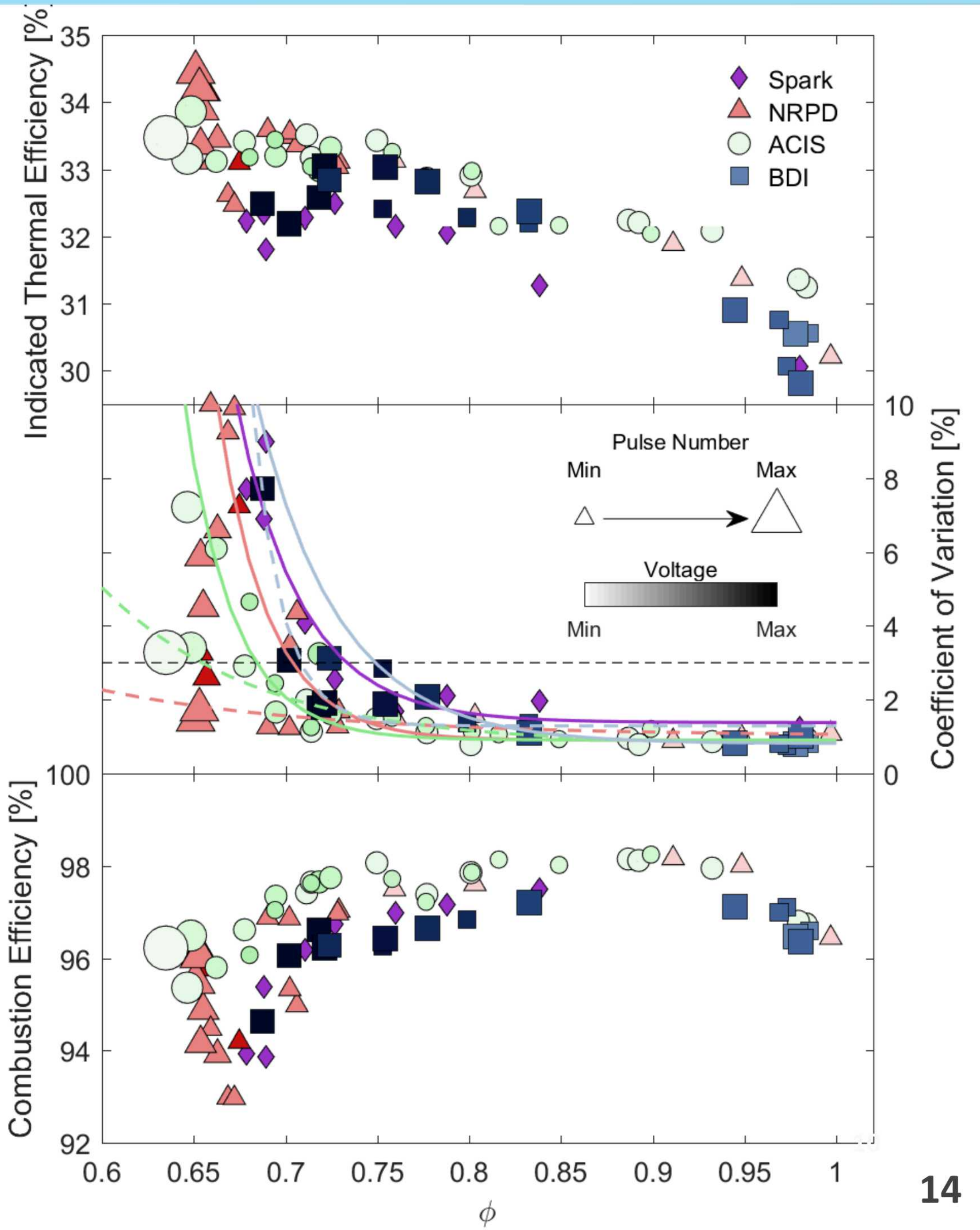
Engine tests reinforce static-cell observation that the most critical ignition parameter is the initial kernel size and not plasma chemistry

Static-cell tests indicate multiple pulses with NRPD help in kernel expansion

Engine performance @3.5 bar IMEPg, 1300 rpm: **ACIS, BDI, NRPD**

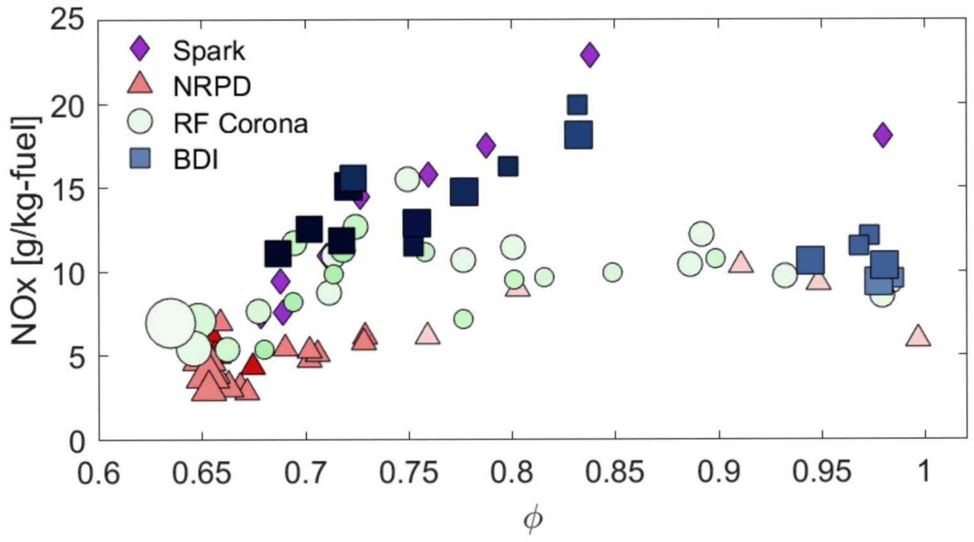


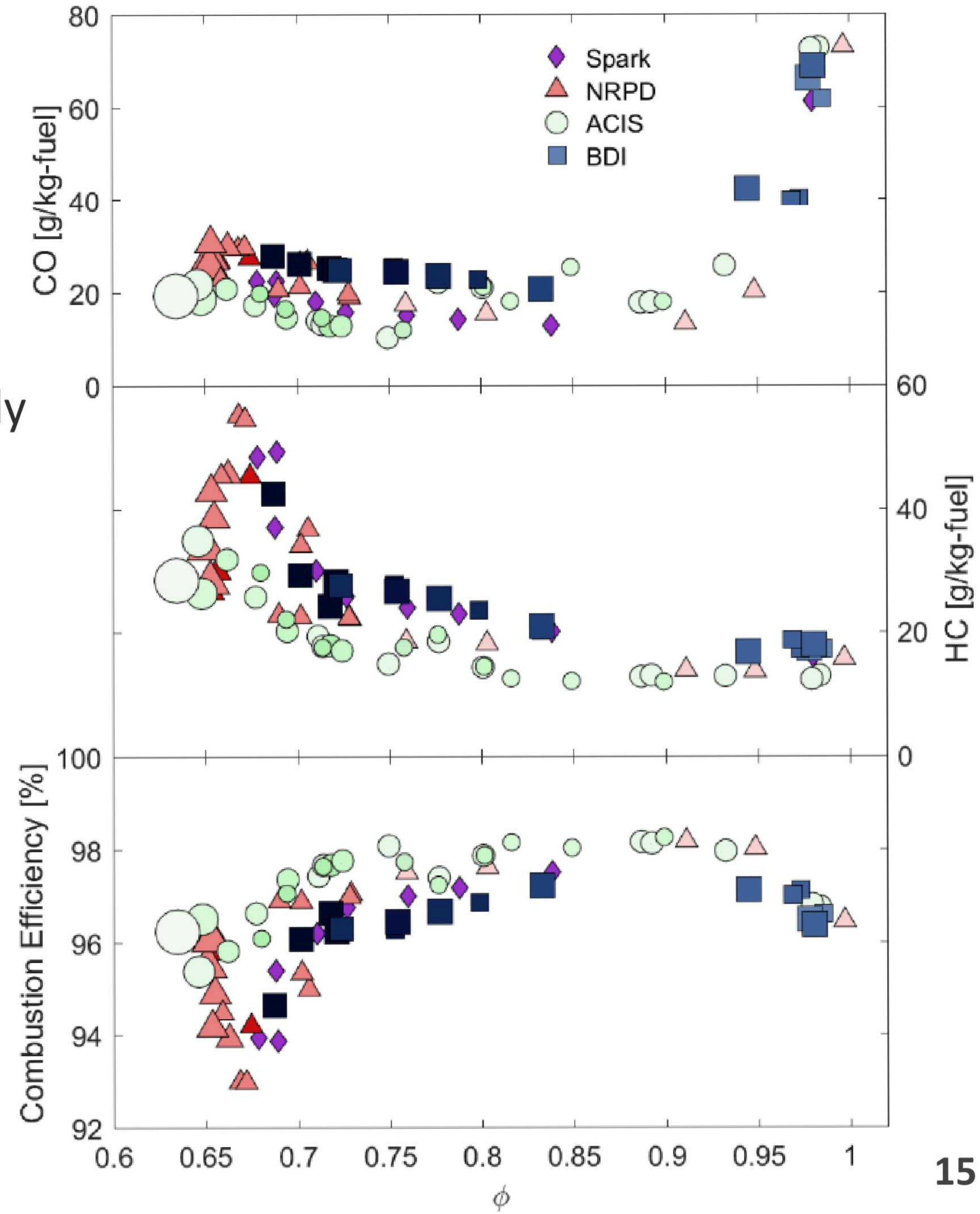
For same ϕ, spark retard required is less with ACIS and NRPD



Emissions @3.5 bar IMEPg, 1300 rpm: **ACIS, BDI, NRPD**

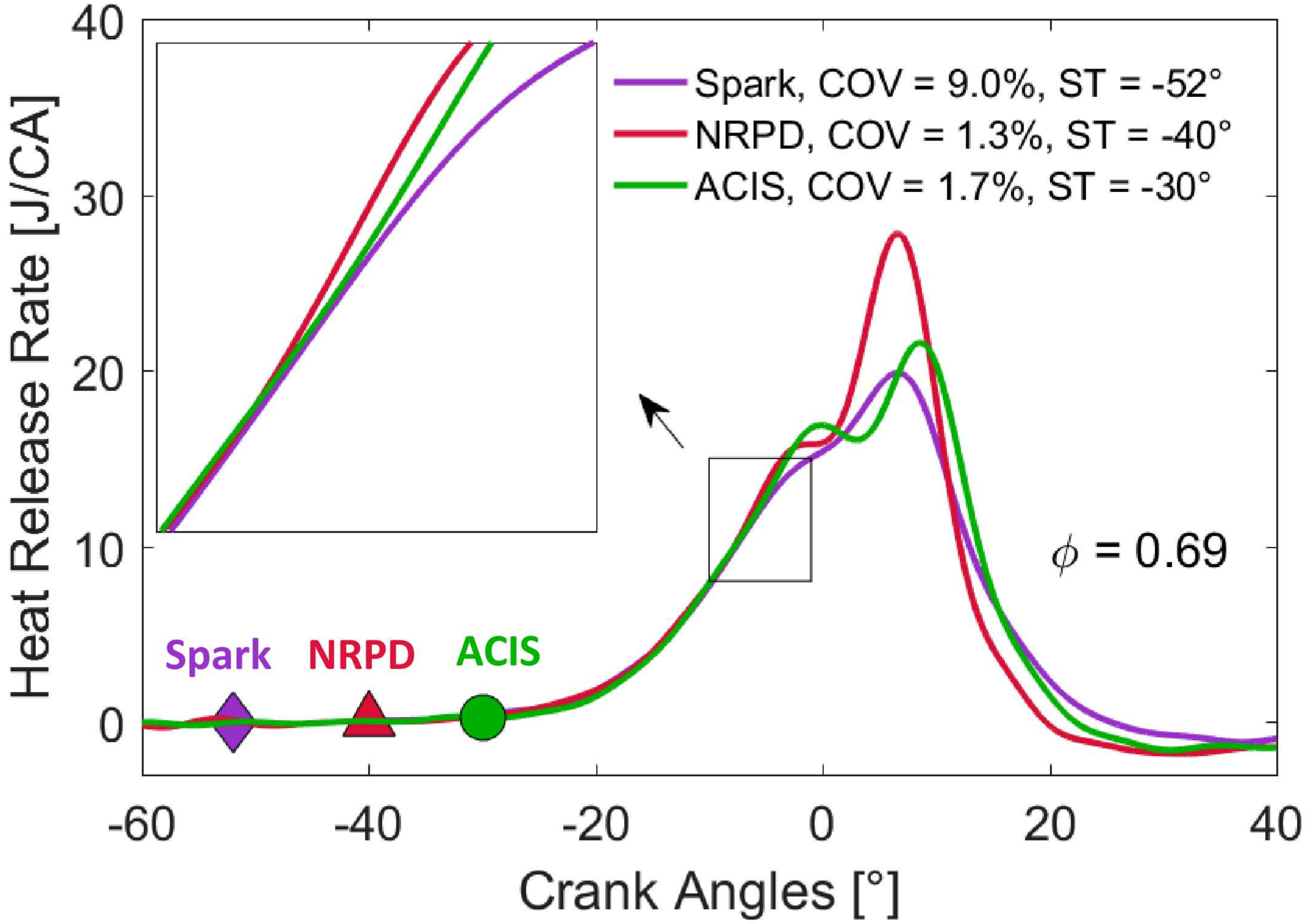
- HC emissions slightly increases for NRPD at lean limit
- Similar CO and HC emissions irrespective of ignition systems, except for the ACIS resulting from faster early burn rates
- Overall NOx reduced from NRPD and ACIS by 30%





NRPD and ACIS could reduce NOx significantly

Faster early burn rates observed with ACIS and NRPD ignition



End-gas auto-ignition from all igniters

Residual heating from modest positive valve overlap (~34°)

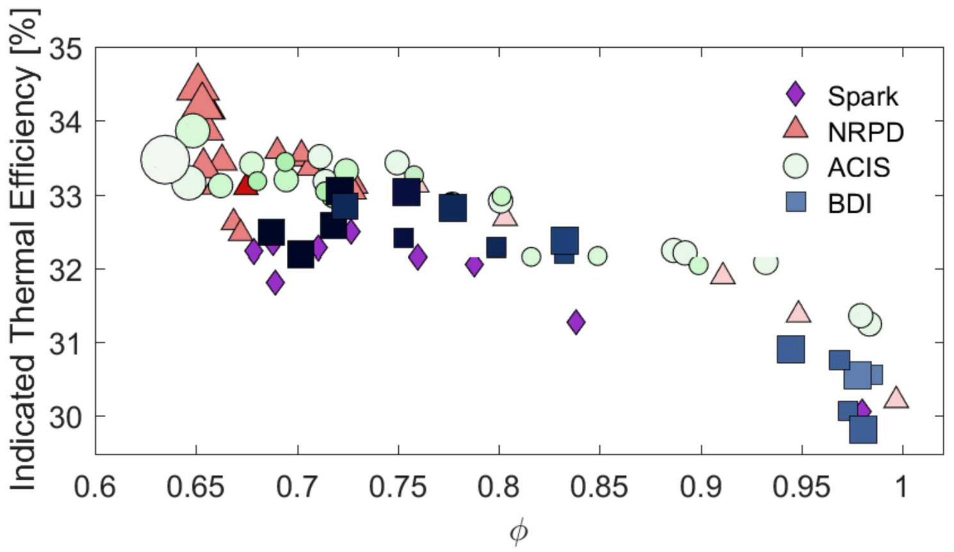
Similar heat release rate until -10° aTDC despite substantial variation in ST

4-prong ACIS offers unconstrained streamer growth with multiple ignition sites

- ACIS produces largest ignition kernel volumes
- Need to validate using ignition kernel imaging

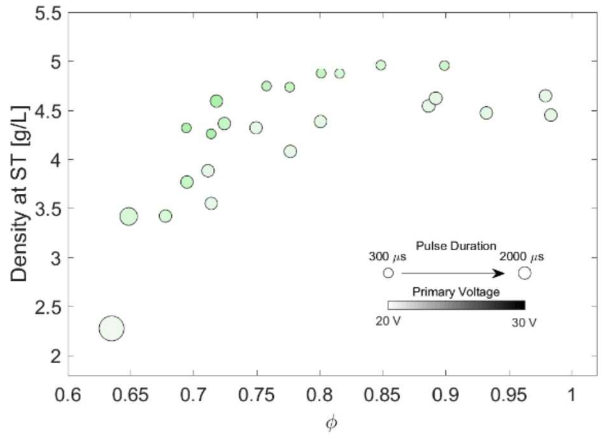
Higher number of NRPD pulses supplied additional energy for kernel expansion

Summary



ACIS and NRPD extends lean limit

- Both ACIS ($\phi = 0.68$) and NRPD ($\phi = 0.65$) extend lean stability limit compared to inductive spark ($\phi = 0.73$)
- Peak ITE increases from 32.5% for spark ignition to 33.8% for ACIS and 34.5% for NRPD
- Lean stability limit was not reached during the limited test window for NRPD, suggests possibility of improvement

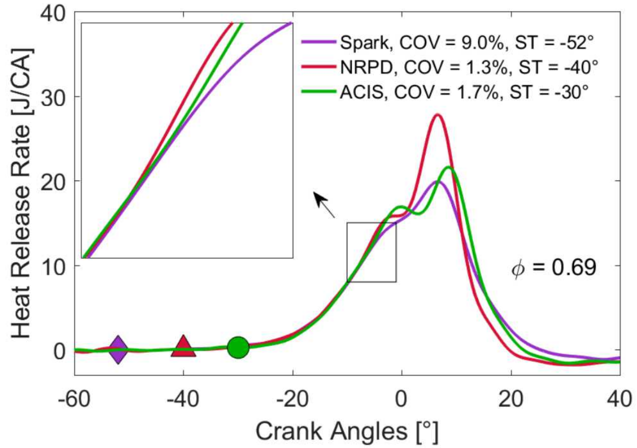


Engine operation heavily relies on optimum pulsing strategy

- Increased pulse number for NRPD and increased pulse duration for the ACIS was highly effective for improving cyclic stability for the leanest mixtures ($\phi < 0.7$)
- In-cylinder density limits the use of longer pulse durations for ACIS

Larger ignition volumes produce the fastest early kernels, while continual discharges sustain early kernel flame fronts

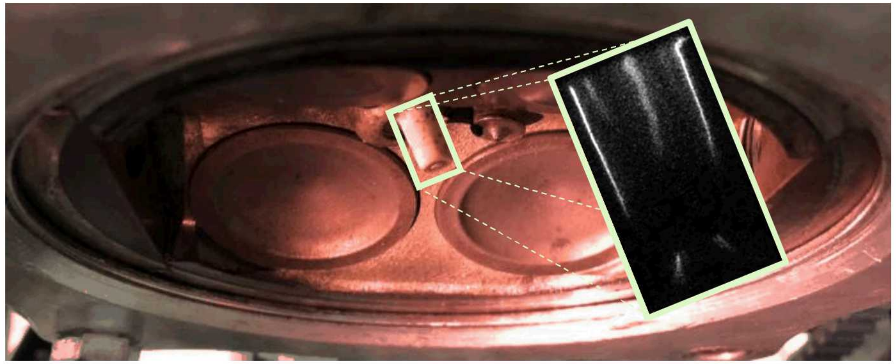
- ACIS discharges produce large early flame kernel volumes
- NRPD effectively add discharge energy to the kernel volume



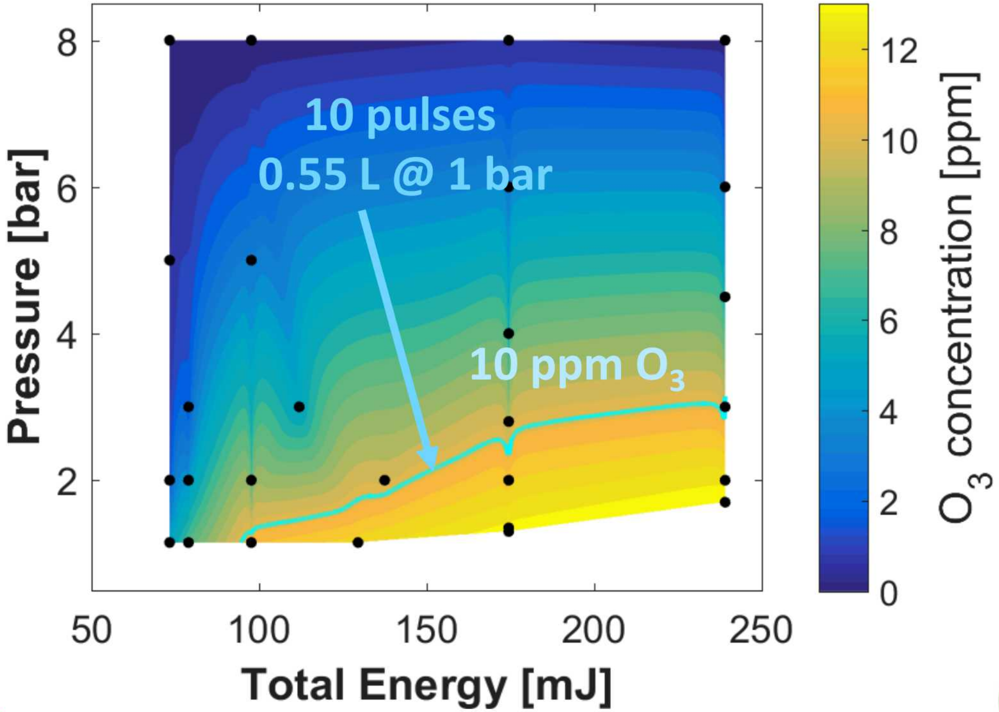
Future work

Optical imaging of ignition kernels

- Crank angle resolved intensified imaging of spark, plasma, and corona ignition to better understand the ignition physics
- Explore the effect of EGR dilution tolerance
- Compare different pulsing strategy



Barrier discharge electrode in engine



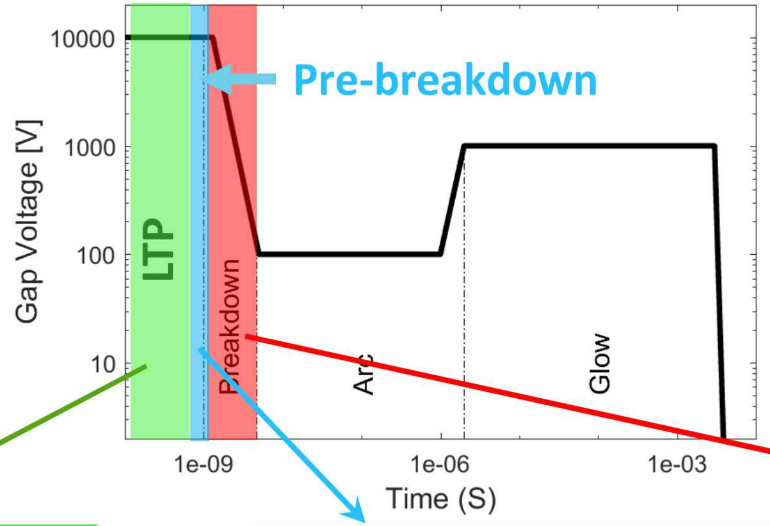
Preliminary study shows BDI produces adequate O_3 necessary for stable combustion

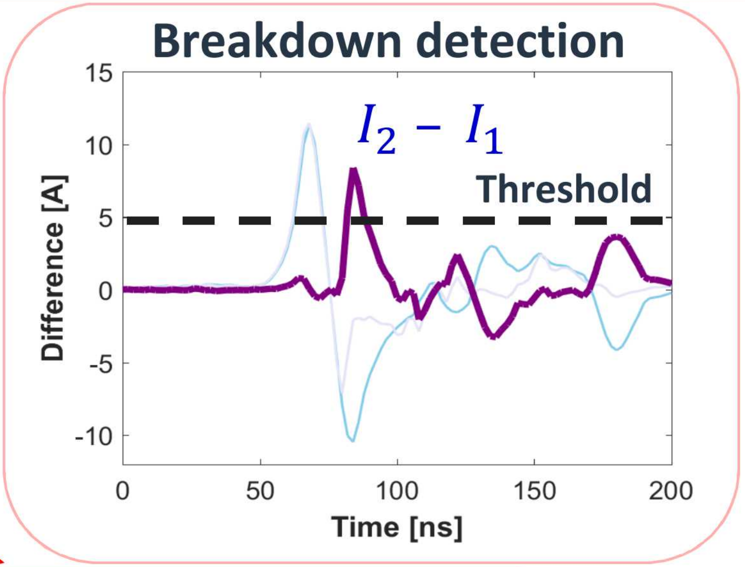
- O_3 generation depends on cylinder pressure and applied voltage
- Small amount, 10 – 30 ppm O_3, could significantly alter charge reactivity
- **Target 30 ppm O_3 = 30 pulses = 3 bursts of 10 pulses**

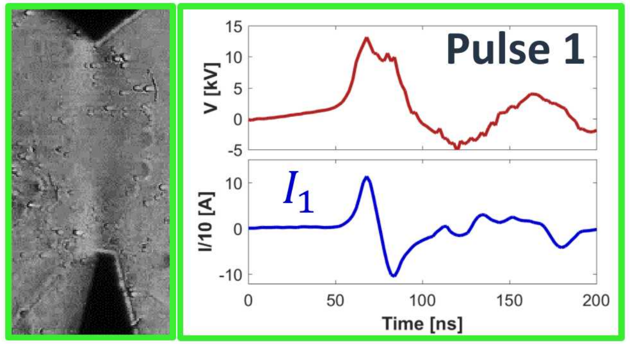
Future work

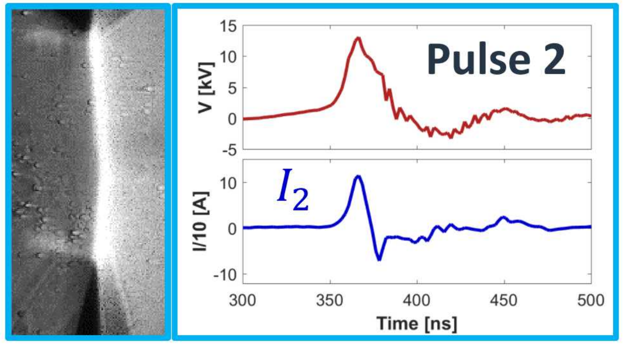
Current monitoring can detect onset of arcing/breakdown

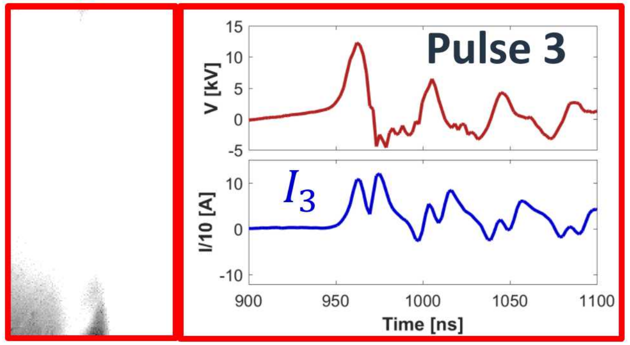
Maly & Vogel, P Combust Symp, 17, 1984.





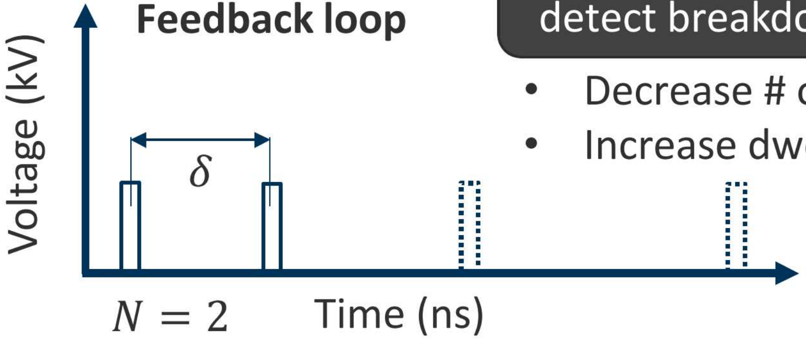






Pulsing strategy to avoid arcing

Strategy # 1
Feedback loop

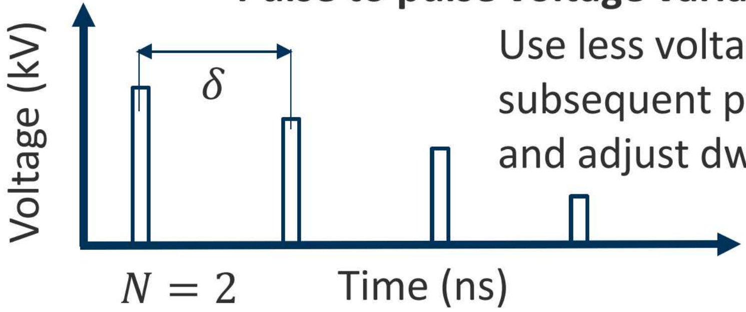


Active V/I monitor to detect breakdown/arcing

- Decrease # of pulses
- Increase dwell

Strategy # 2
Pulse to pulse voltage variation

Use less voltage in subsequent pulses and adjust dwell



Thank You!

Questions?

ICEF2020-3034