AIAA Propulsion & Energy Forum
August 24th, 2020

The work was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Financial support was provided by the U.S. Department of Energy, ... nal Technology and Engineering Solutions of Sandia, ... urity Administration under contract DE-NA0003525.

SAND2020-8166C

Automotive Nanosecond Repetitively Pulsed Discharge Research at Sandia National Laboratories

Isaac Ekoto and Sayan Biswas

Sandia National Laboratories, Livermore CA

Acknowledgements
Technical support: Alberto Garcia, Keith Penney, Aaron Czeszynski
DOE Program Managers: Michael Weismiller, Gurpreet Singh

Despite vehicle fleet electrification advances, internal combustion engine vehicles will likely dominate global fleets until at least 2050

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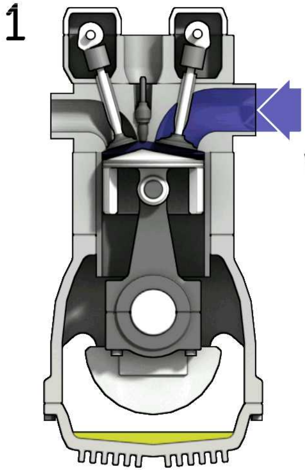


We assume:

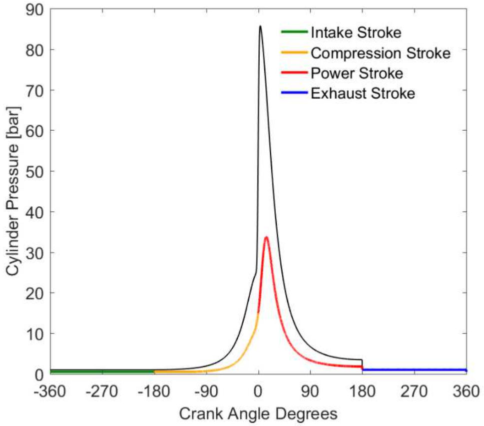
$$\eta_{Otto} = 1 - \frac{1}{CR^{\gamma-1}}$$

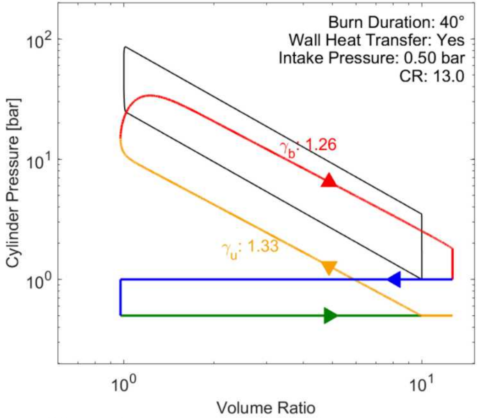
CR: Compression Ratio
γ: specific heat ratio

But we actually get:

$$\eta_{th} = \frac{\int pdV}{Q_{fuel}}$$

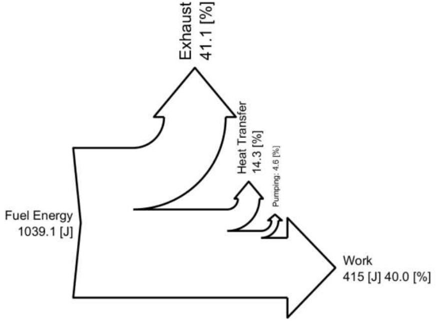
Q_{fuel}: Fuel energy



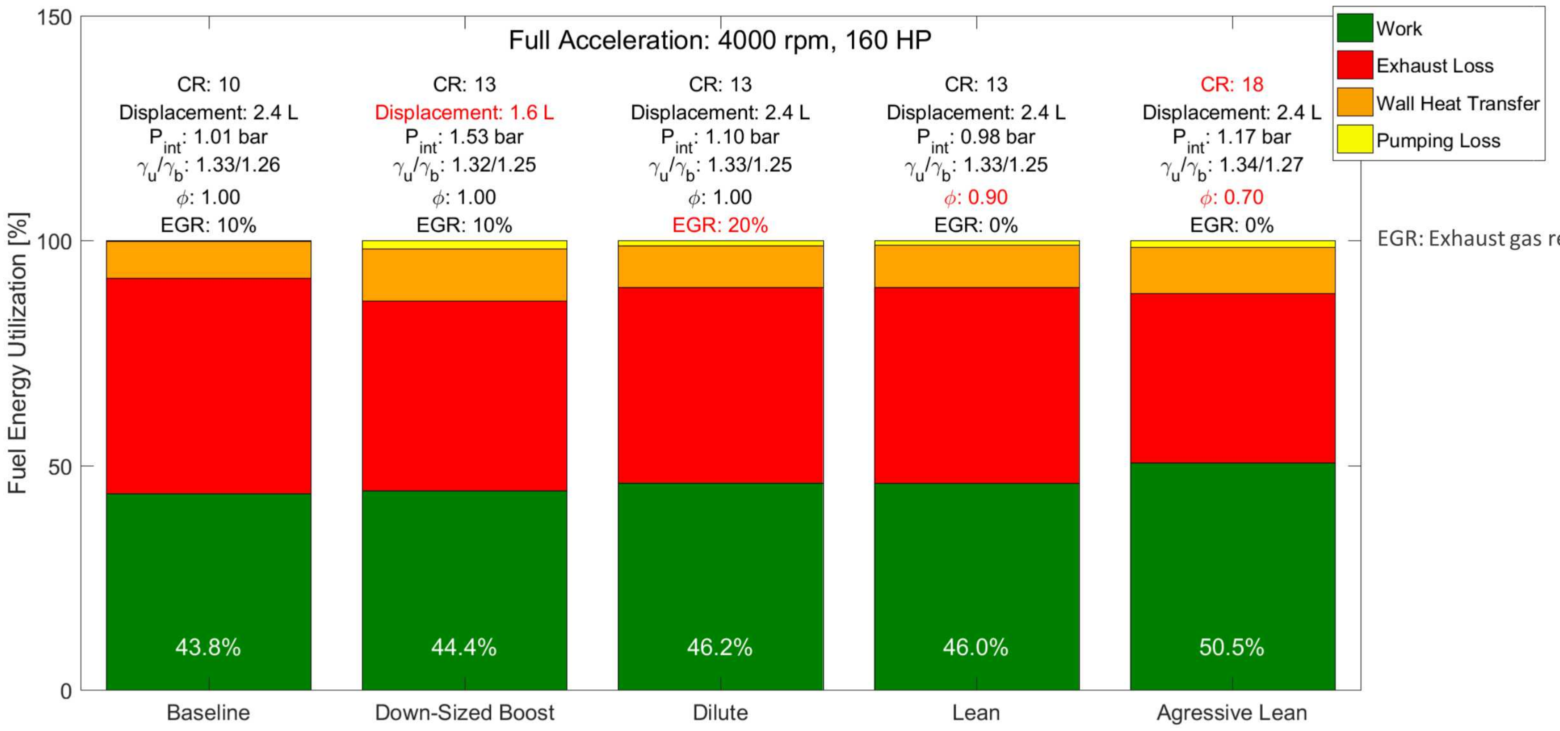


We also must account for:

- Real γ (unburned and burned)
- Long burn durations
- Wall heat transfer
- Pumping losses
- Delayed exhaust valve closure
- Also: friction, gas exchange, blow-by, incomplete combustion



We can extend this analysis a bit further to examine the impact of various combustion strategies on efficiency



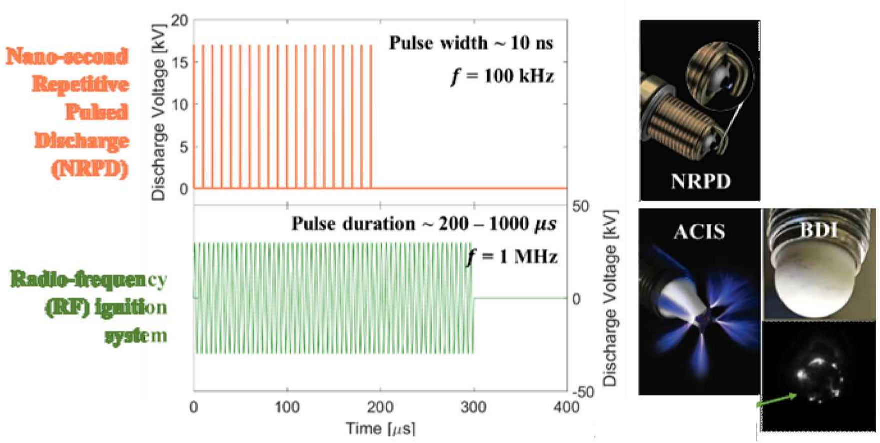
EGR: Exhaust gas recirculation

Pollutant emissions are perhaps even more important

Advanced plasma igniters evaluated in custom ignition test vessels and optically accessible engines

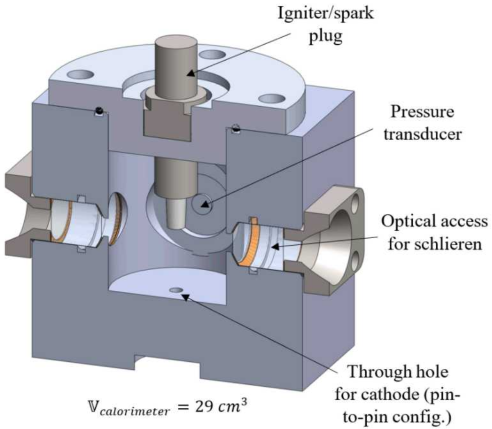
Third party igniters evaluated

- Advanced Corona Ignition System (ACIS)
- Barrier Discharge Igniter (BDI)
- Nanosecond Repetitively Pulsed Discharge (NRPD) pin-to-pin (P2P)



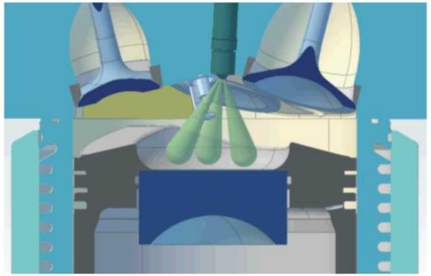
Fundamental NRPD research is focused on corona, glow, arc, and surface discharge ignition

Optical Ignition Calorimeter

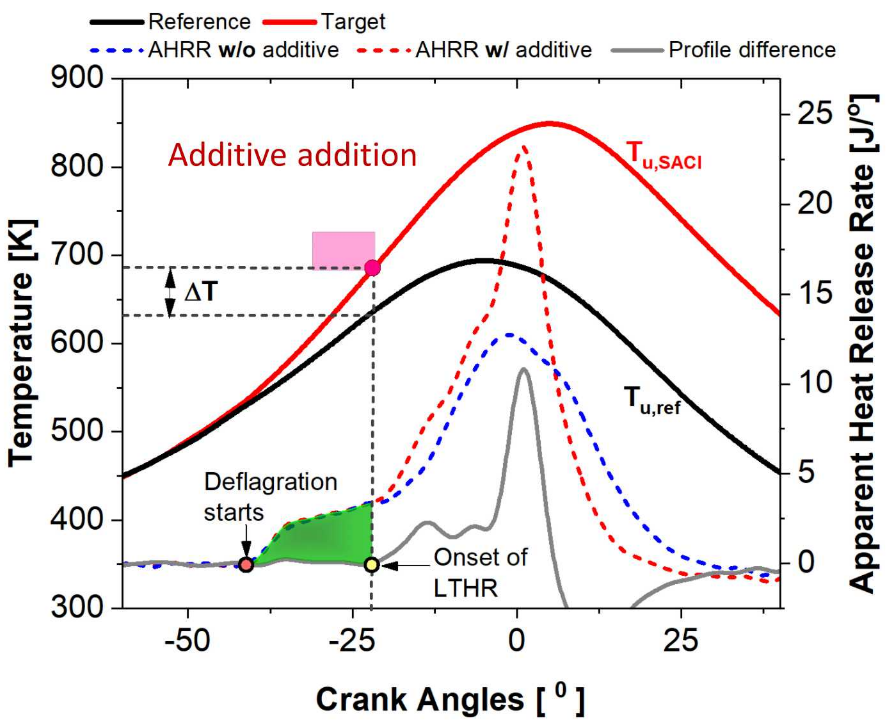


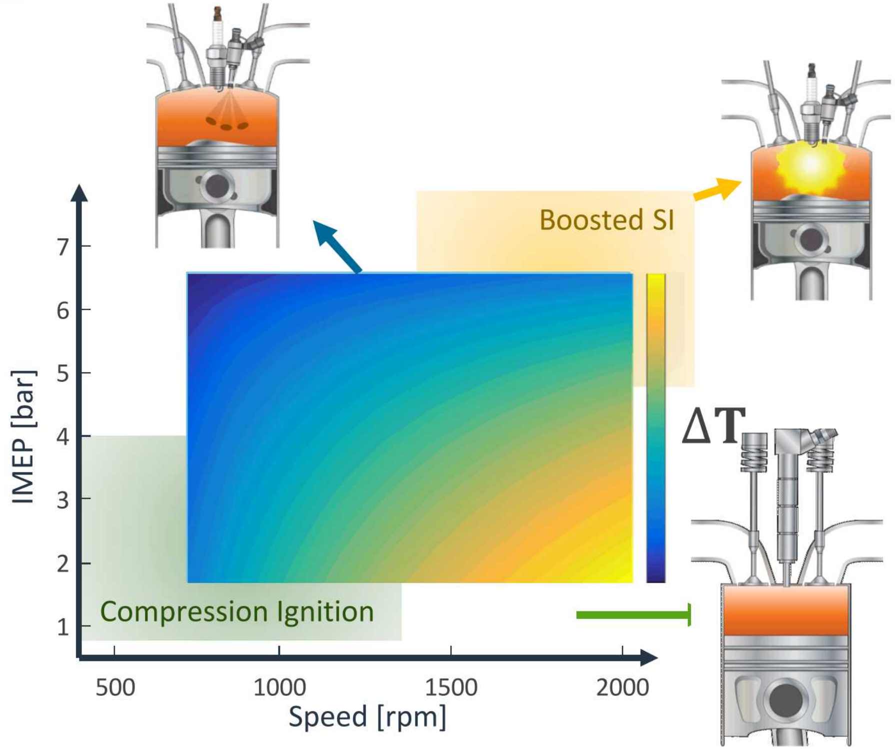
GM SG2 single-cylinder optical engine

- 0.55 L displacement
- 13:1 compression ratio
- Piston & pent-roof windows



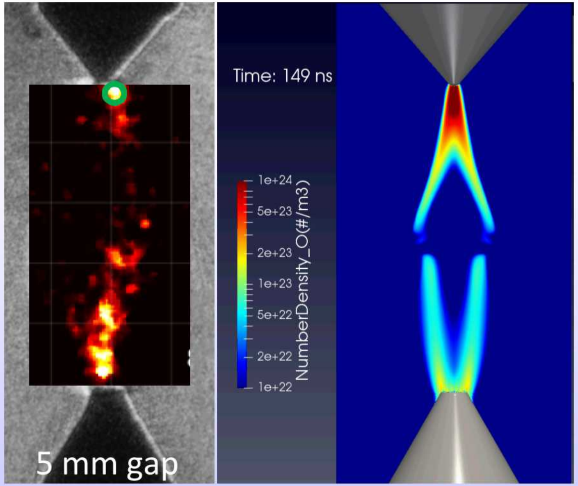
The lean-burn, mixed mode combustion strategy maximizes efficency while minimizing pollutant emissions



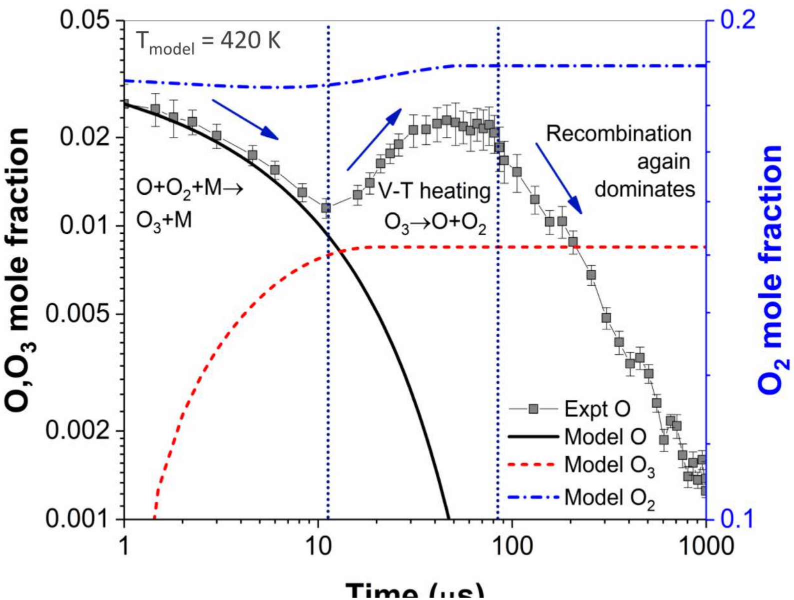


The additive we are interested in is ozone (O_3)

Atomic oxygen – a necessary building block for O_3 – was measured for a pin-to-pin configuration at engine relevant densities

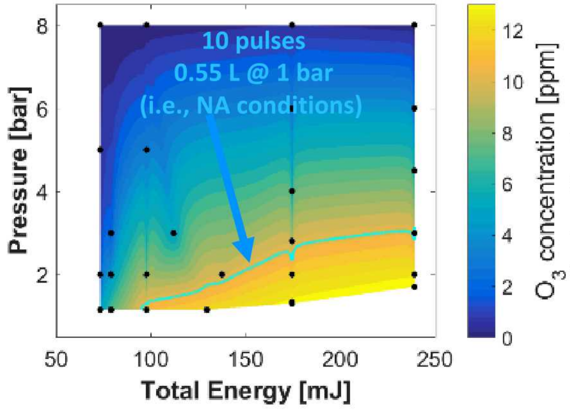


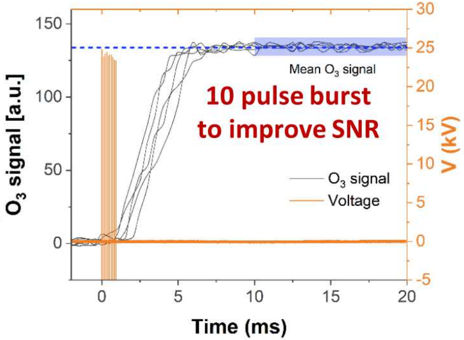
VizGlow Simulations
Riccardo Scarcelli (ANL)



Low global O formation and potential O_3 destruction from V-T heating makes this pathway unviable

Ozone can be generated in-cylinder by early-cycle BDI that use NRPD





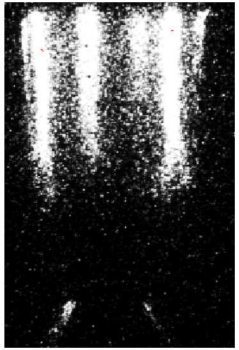
Highest O_3 yields with lowest pressures & highest pulse energies

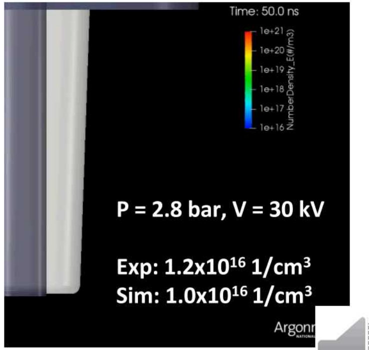
- 30 ppm created with 0.3 to 0.7 J (~30 pulses)
- 30% ↘ when T increased from 22 to 85° C
- 40% ↘ when EGR increased from 0 to 30%

Complementary plasma discharge simulation results agree well with measurements

- Most O_3 forms along insulator surface – minimal streamer contribution

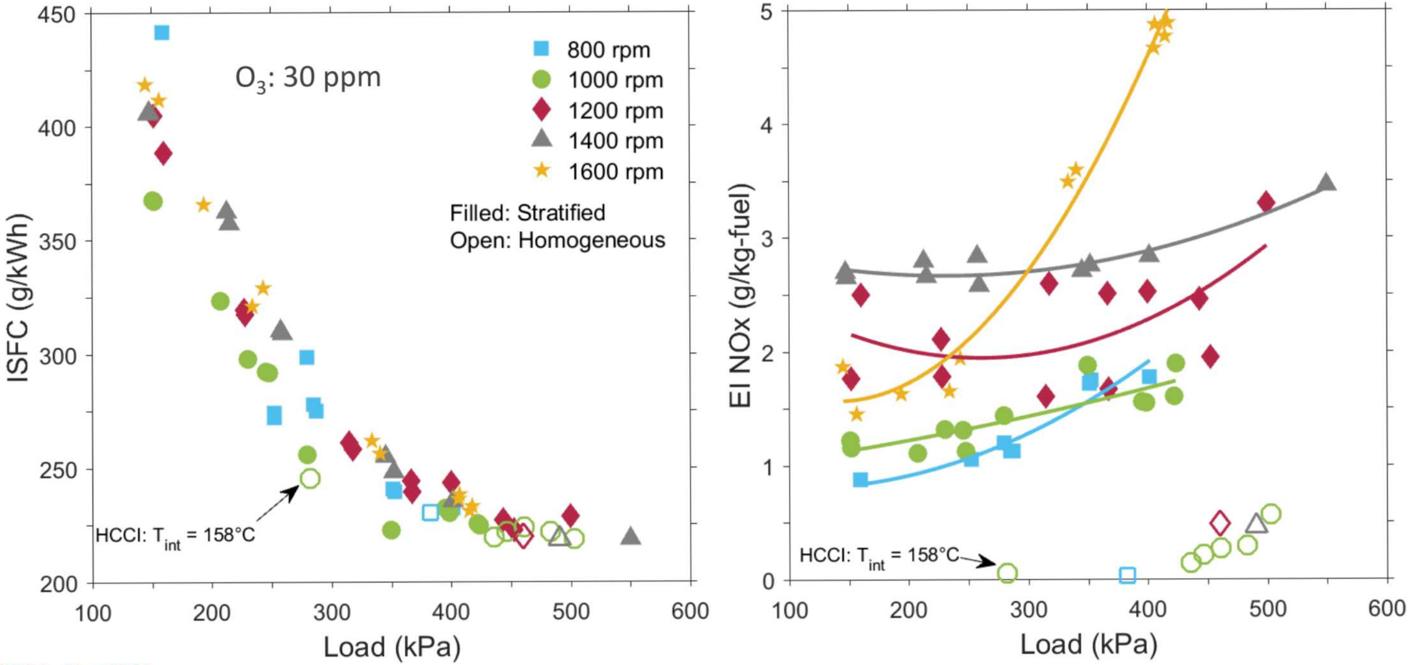
Results offer a viable path to in-cylinder O_3 generation with the igniter





Scarcelli & Gururajan (

Ozone addition increases efficiency by 6 – 9% with a roughly 20% reduction in nitrogen oxide (NOx) emissions



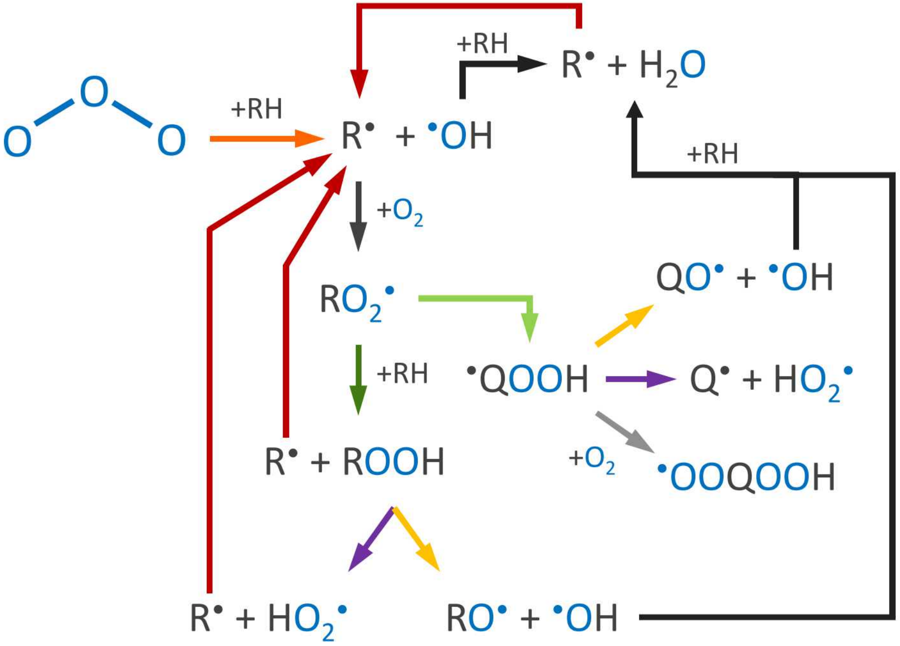
Biswas & Ekoto, SAE PF&L, Aug 2019
Biswas & Ekoto, SAE WCX, Apr 2019
Ekoto & Foucher, *SAE Int J Fuels Lubr* 11(4), 2018

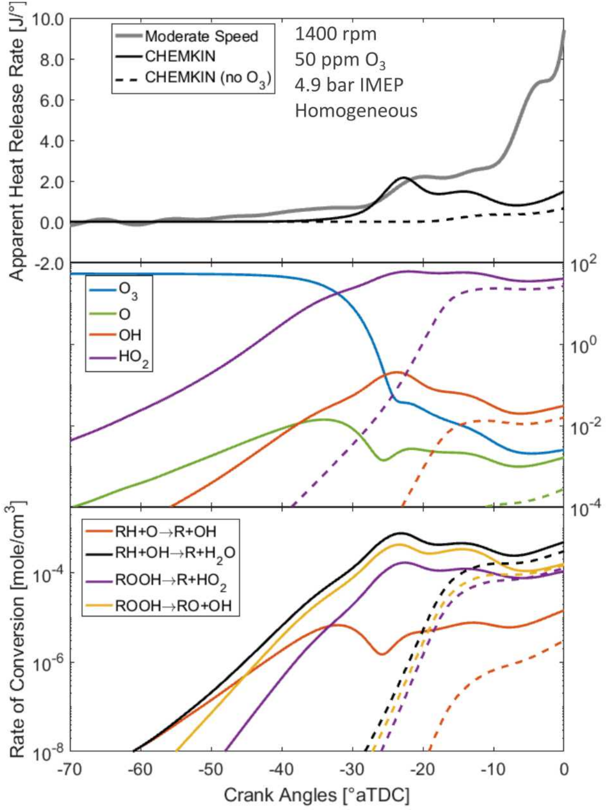
A further order reduction of NOx is possible if mixture stratification is eliminated

Ozone improves fuel reactivity by altering low-temperature heat release (LTHR) pathways

Ozone decomposition @ ~625 K

Masurier et al, *Energy & Fuels*, 2013

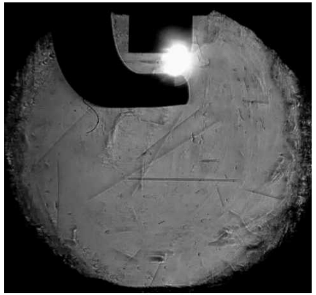




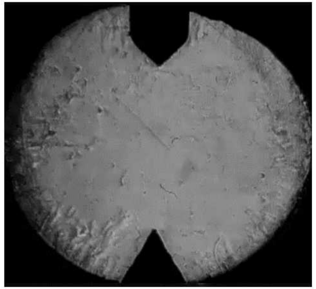
Biswas & Ekoto, SAE WCX, 2019-01-0966

NRPD discharges likewise extend lean ignition limits for various igniter configurations

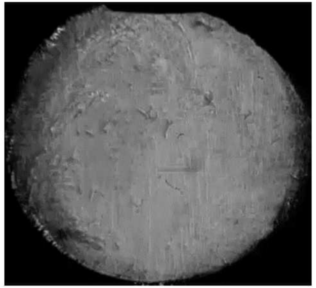
Propane/air, T = 343 K, P = 1.3 bar



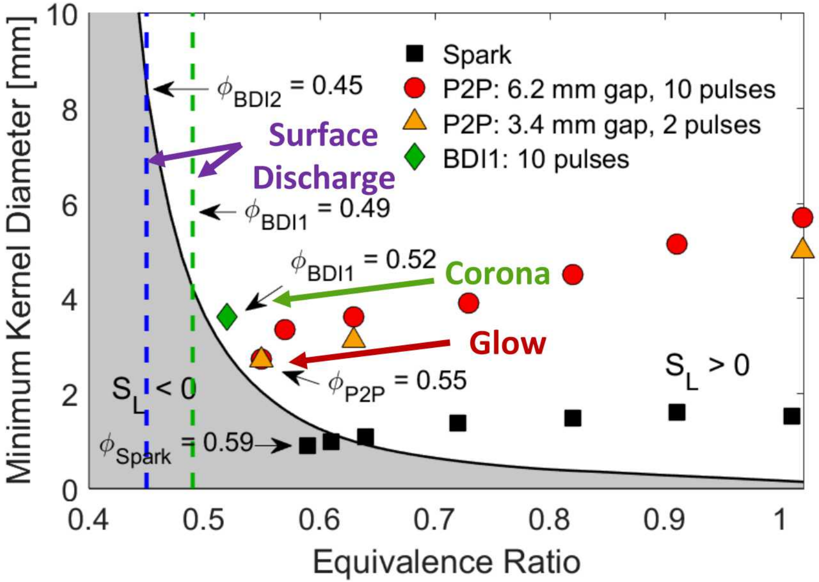
$\phi = 0.59$
93 mJ



$\phi = 0.55$; 87 mJ
10 pulses; 17.5 kV_{peak}

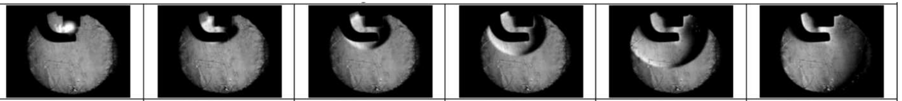
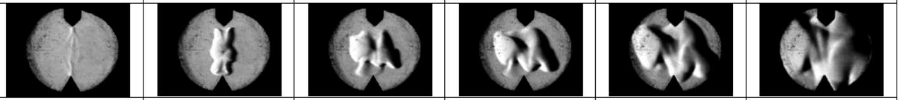
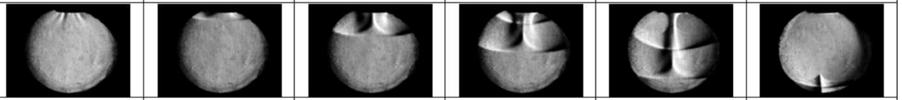
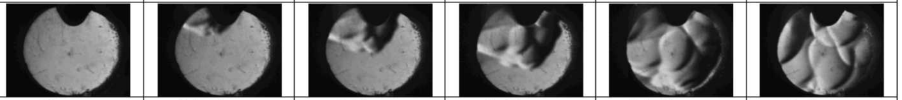


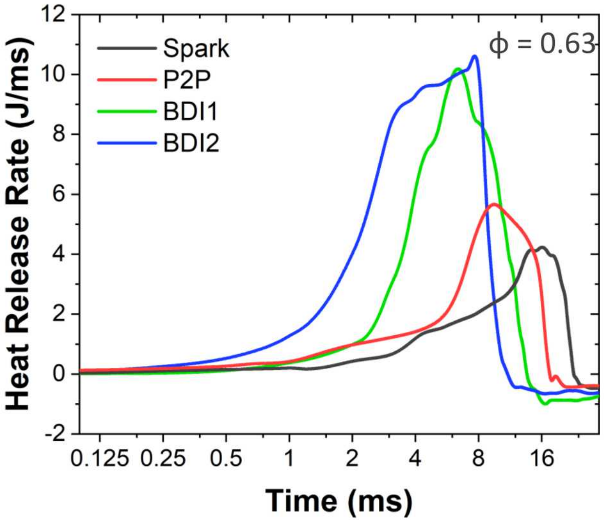
$\phi = 0.52$; 148 mJ
10 pulses; 27 kV_{peak}



Early burn rates are likewise significantly enhanced with NRPD

- Laminar burning phase substantially increases with dilution
- Relative to spark, NRPD severely shortened laminar-to-turbulent flame kernel transition
  - P2P: Initial hydrodynamic induce flame-front corrugation
  - BDI: Near elimination of laminar burning phase accelerates burn rates

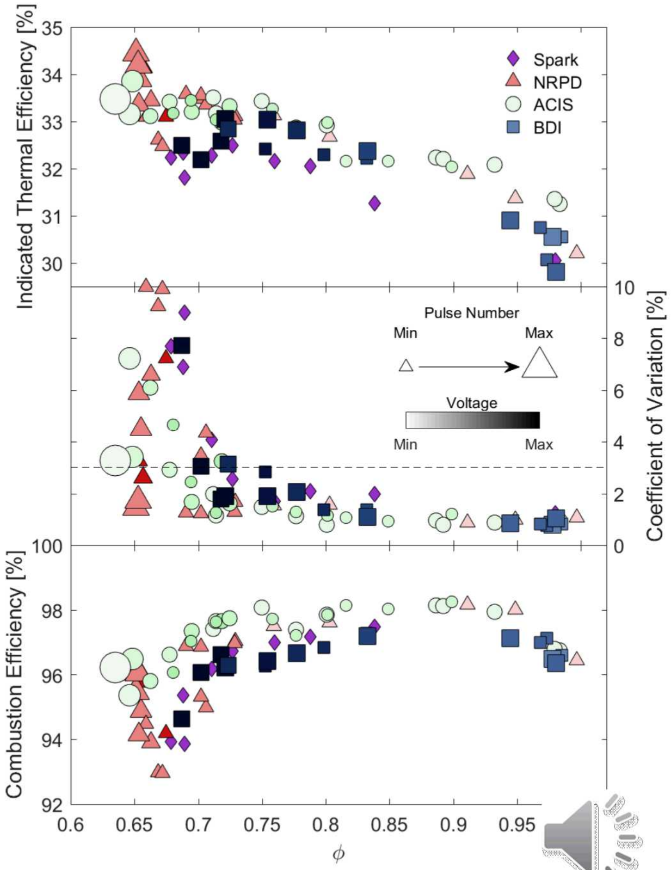
Spark						
	0 ms	1.75 ms	3.5 ms	4.75 ms	6.75 ms	9.5 ms
P2P						
	0 ms	0.75 ms	1.75 ms	3.0 ms	5.0 ms	6.75 ms
BDI1						
	0 ms	1.0 ms	2.0 ms	3.0 ms	4.5 ms	6.25 ms
BDI2						
	0 ms	0.75 ms	1.5 ms	2.5 ms	3.75 ms	5.0 ms
Burn fraction	**0%**	**3%**	**5%**	**10%**	**25%**	**50%**



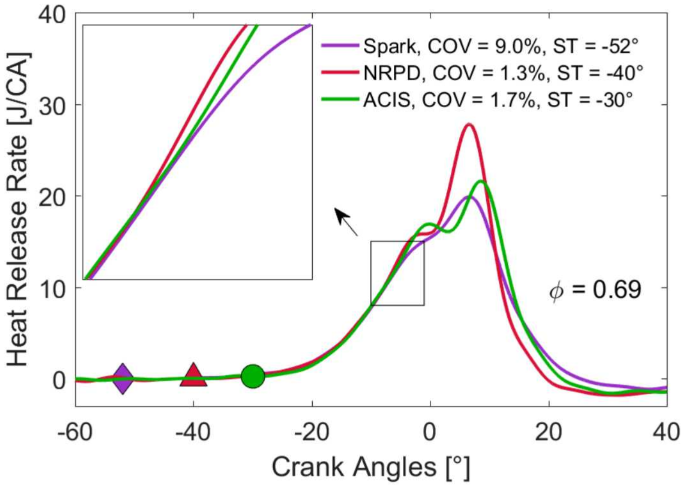
Since laminar-to-turbulent kernel period has the most variability, shorter periods are expected to benefit engine combustion stability

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

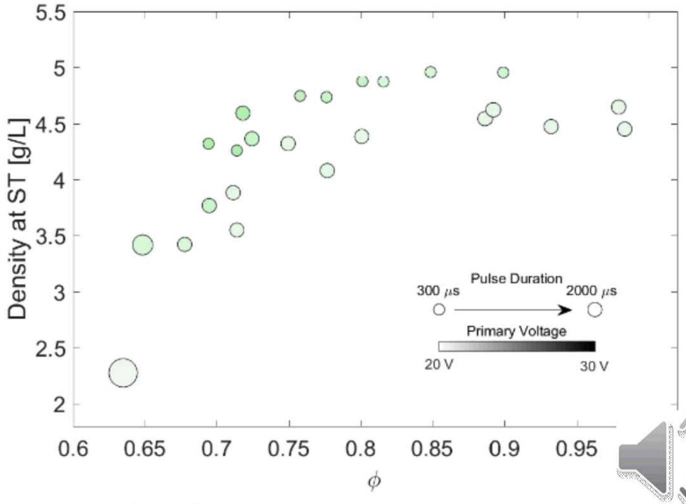
- **No notable lean-limit extension with RF BDI**
  - No intake pre-strikes
- **RF ACIS lean-limits extended from $\phi = 0.73$ to $\phi = 0.68$**
  - Peak efficiency increased from 32.5% to 33.8%
  - Longer discharges & higher voltages needed for lean mixtures
  - ~1.0 point efficiency improvement from shorter initial burn
- **NRPD P2P lean-limit never reached (best value: $\phi = 0.65$)**
  - Non-resistor spark plug
  - Peak ITE increased from 32.5% to 34.4%
  - Increased pulse number needed leaner mixtures
  - ~0.5 point efficiency improvement from shorter initial burn



Faster early burn rates observed with ACIS and P2P NRPD ignition

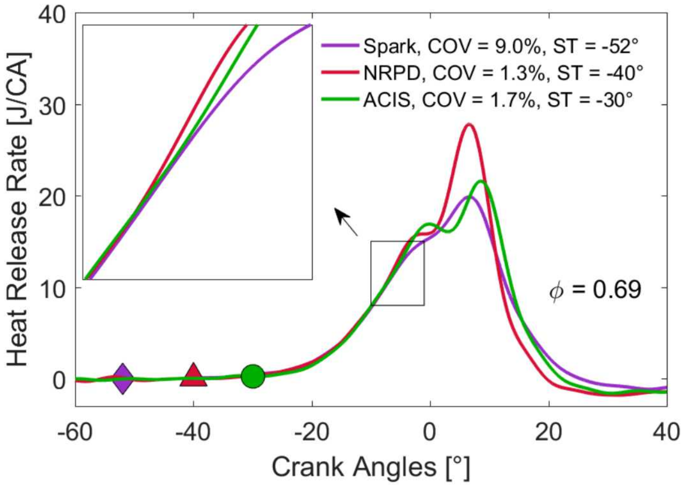


- **Despite later ignition timings relative to spark, ACIS and P2P NRPD heat release is well-matched by -10°**
  - End-gas auto-ignition caused by residual charge heating from valve overlap
  - More consistent early burn led to more repeatable end-gas auto-ignition



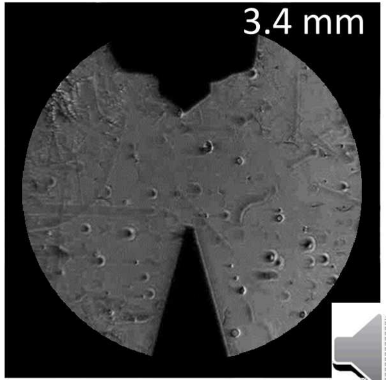
- **RF corona (ACIS) pulse duration and voltage was limited by arc transition for lean mixtures**
  - Lower charge densities due to earlier ignition timing

Faster early burn rates observed with ACIS and P2P NRPD ignition



- **Despite later ignition timings relative to spark, ACIS and P2P NRPD heat release is well-matched by -10°**
  - End-gas auto-ignition caused by residual charge heating from valve overlap
  - More consistent early burn led to more repeatable end-gas auto-ignition

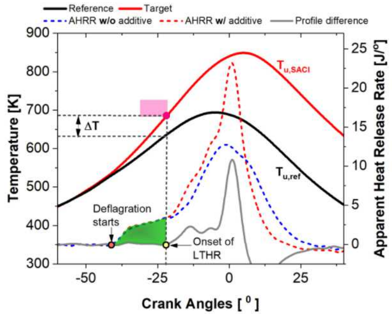
- **Static-cell tests indicate multiple pulses with NRPD help kernel expansion**
  - Additional pulses can also cause arc due to the lower inter-electrode gas density, which could lead to electrode wear

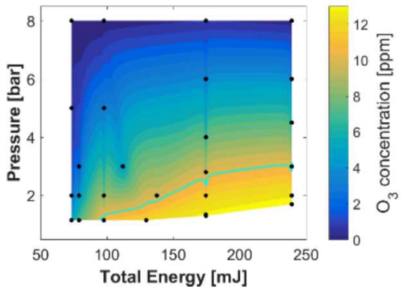


Summary:

A promising path to improved engine efficiency is the use of lean-burn, mixed-mode combustion provided the igniter:

- Creates early-cycle ozone to increase end-gas reactivity
- Generates strong deflagrations in lean mixture



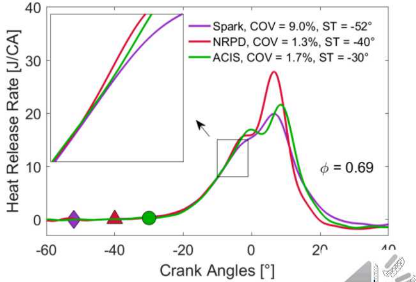


NRPD BDI is effective at generating sufficient O_3 quantities via early-cycle discharges

- Optimal O_3 generation requires lower combustion residuals and charge temperatures

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

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



NRPD BDI appears to be the most viable igniter

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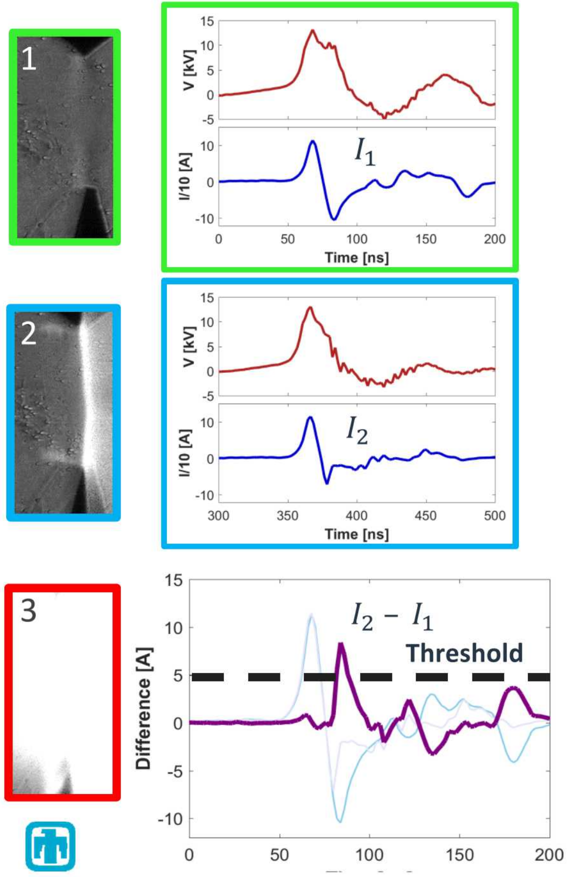
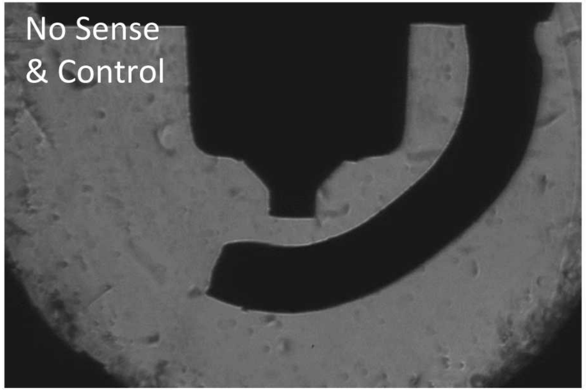
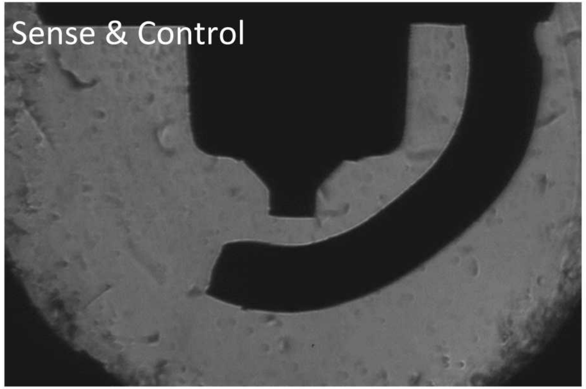
Future work:

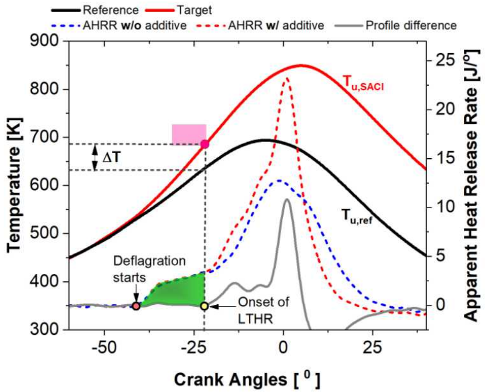


Project with Transient Plasma Systems Inc.





Evaluate lean mixed mode with NRPD BDI



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EI1 Ekoto, Isaac, 8/5/2020

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