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TO ADVANCE
COMBUSTION
ENGINES

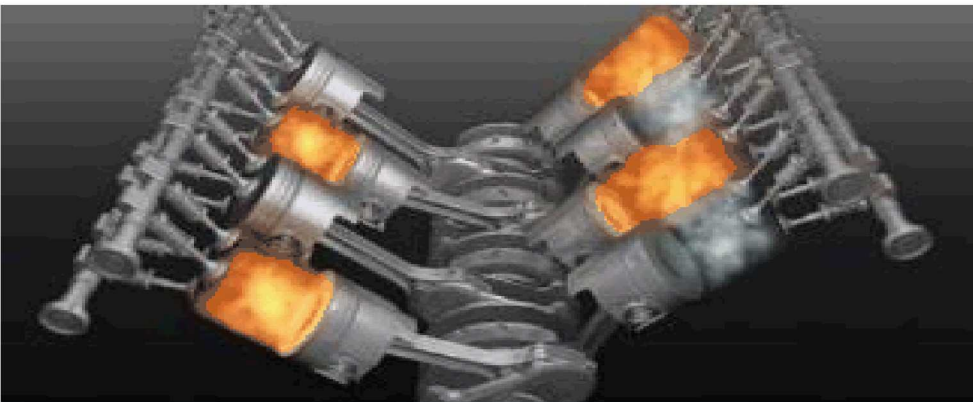
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ACE141: Advanced Ignition System Fundamentals

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VTO Annual Merit Review, June 1-4, 2020



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This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- PACE started in Q3, FY19
- PACE will end in FY23 (~25% complete)
- Focus and objectives of individual tasks will be continuously adjusted
- Overall PACE work plan discussed in ACE138

Budget

Results from three FY20 PACE tasks*

Task		Lab	PI	FY19	FY20
C.01.01	Advanced ignition for alt. combustion modes	SNL	Ekoto	\$370k	\$420k
C.01.02	Fundamental ignition exp.	SNL	Ekoto	\$100k	\$420k
F.01.01	Remove barriers to pre-chamber ignition	ANL	Rockstroh	\$600k	\$600k

*Funding levels split between multiple projects

Barriers

PACE Major Outcome 4: Improved high-load ignition modeling

PACE Major Outcome 5: Predictive lean/dilute combustion modeling

PACE Major Outcome 6: Develop advanced igniters & controls

PACE Major Outcome 7: Improved SI/ACI combustion control

PACE Major Outcome 8: Reliable cold-start

PACE Major Outcomes developed from USCAR feedback on research priorities

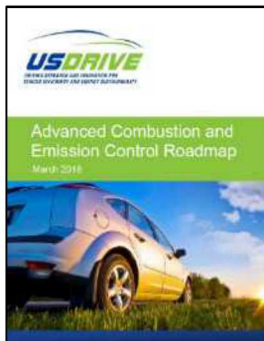
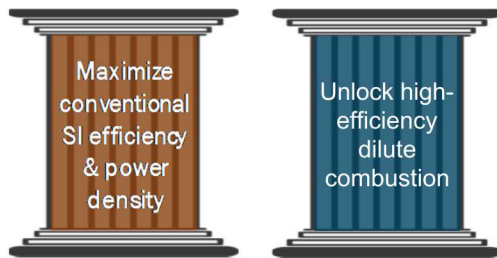
Partners

- **PACE is a DOE-funded consortium of 6 National Laboratories working towards a common goal (ACE138)**
 - Goals and work plan developed considering input from stakeholders including DOE, ACEC Tech Team, CFD code developers, and more
- **Specific partners on this work include:**
 - Plasma ignition collaboration with Tenneco and TPS
 - Plasma kinetics/physics with U. Auburn, U. Texas, and Argonne
 - Pre-chamber research with Argonne and CMT-Motores

Relevance



PACE Purposes in ACE138



Overall Relevance of PACE:

PACE combines unique experiments with world-class DOE computing and machine learning expertise to speed discovery of knowledge, improve engine design tools, and enable market-competitive powertrain solutions with potential for best-in-class lifecycle emissions

Presentation Specific Relevance: PACE Major Outcomes 4, 5, 6 & 7

Major Outcome 4: Improved ignition modeling enabling improved igniter high-load performance
→ *Acquire data on spark deflection and restrike at high specific power density conditions*

Major Outcome 5: Predictive modeling of dilute engine efficiency and emissions
→ *Fundamental experiments into ignition processes used to inform complementary modeling efforts*

Major Outcome 6: Advanced igniters and control methods that expand existing dilution limits
→ *Evaluate ignition technologies that enable extended dilution tolerance*

Major Outcome 7: Next-cycle phasing and stability control for gasoline SI/ACI combustion
→ *Explore influence of plasma generated radicals on combustion phasing control*

Major Outcome 8: Predictive modeling combustion phasing and engine-out cold-start emissions
→ *Probe physics relevant to ignition at cold-start*

*https://www.energy.gov/sites/prod/files/2018/03/f49/ACEC_TT_Roadmap_2018.pdf

Milestones

■ Task C.01.02: Fundamental experiments into the mechanisms of ignition

Date	PI	Milestone	Status
FY20 Q1	Ekoto	Characterization of early flame kernels	100% Complete
FY20 Q2	Ekoto	Develop ignition cross-flow test facility (up to 30 m/s with densities up to 20 g/liter)	50% Complete
FY20 Q4	Ekoto	Time-resolved spark deflection/re-strike imaging with complementary spark calorimetry	Not yet started

■ Task C.01.01: Advanced Ignition to Enable Alternative Combustion Modes

Date	PI	Milestone	Status
FY19 Q3	Ekoto	Static cell quantification of BDI generated ozone	100% Complete
FY19 Q4	Ekoto	Lean limit engine testing with advanced plasma igniters	100% Complete
FY20 Q1	Ekoto	Engine testing of ozone-enhanced SACI with BDI ozone generation	Delayed - FY20 Q4
FY20 Q3	Ekoto	Prototype and test BDI with custom insulator properties	25% Complete

■ Task F.01.01: Remove barriers to pre-chamber ignition

Date	PI	Milestone	Status
FY19 Q4	Rockstroh	Design/implement active pre-chamber ignition (PCI) system	100% Complete
FY20 Q2	Ekoto	Prototype and test passive pre-chamber that uses BDI to expand dilution tolerance	100% Complete
FY20 Q2	Ekoto	Static cell and engine ignition limit testing of passive BDI PC	50% Complete
FY20 Q3	Rockstroh	Pre-chamber product sampling and characterization	Delayed - FY21 Q1
FY20 Q4	Rockstroh	Evaluate potential of an active pre-chamber systems for multi-mode engine	25% Complete

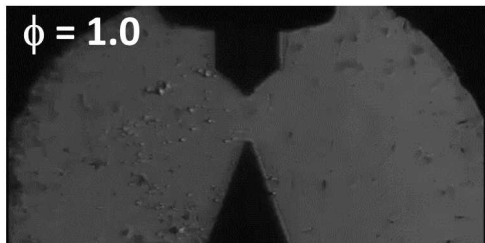
All direct ignition can be divided into 3 basic processes:

1. Local electrical energy deposition as plasma
 - Rapid energy deposition quickly heats gas
 - Complex plasma dynamics form reactive species
 - Plasma channels can deflect, re-strike, blow-off
 2. Plasma-to-kernel transition
 - Kernels form in high temp. & radical regions
 - Minimum kernel size needed to avoid quench
 - $f(\text{fuel, dilution, heat loss, plasma energy, ...})$
 - Plasma/combustion chemistry interactions
 3. Kernel-to-flame transition
 - Kernel growth, shedding, and merging
 - Instabilities/turbulence distort flame front
 - Sustained turbulent flame propagation
- Approach:
 - Develop ignition process model
 - Ignition kernel & discharge measurements (SNL)
 - Plasma discharge modeling (ANL)
 - DNS flame kernel propagation (SNL)
 - ML mining of DNS statistics (NREL)
 - Sub-model development (ANL/SNL/NREL)
 - Common experiment/modeling condition
 - 5 bar, 343 K, propane/air, lean/dilute limit
 - Liquid fuels once PACE surrogate finalized
 - Single-pulse nanosecond spark
 - Goal: Decouple plasma from kernel development
 - Experiments
 - High-speed kernel image
 - Out years: Turbulence, crossflows, plasma-flame

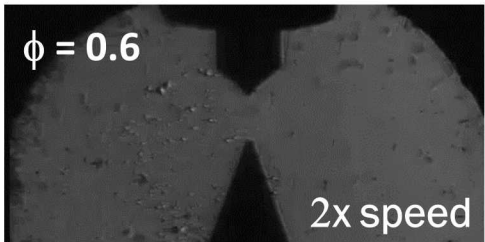
Characterization of early flame kernels at engine relevant densities for complementary ignition modeling efforts

C.01.02: Accomplishments (SNL/ANL)

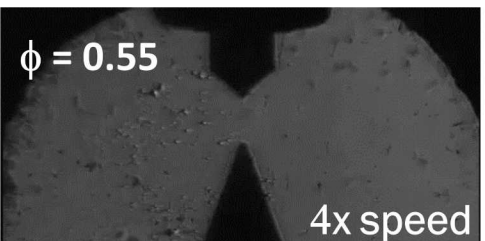
- Single-pulse nanosecond spark experiments (SNL)
 - Pulse energy minimized to limit hydrodynamic forces
 - High temporal resolution (60 kHz)
 - Goal: Decouple plasma from kernel development
- Two discharge modeling methods evaluated (ANL)
 1. Spatially constant line energy deposition (ED)
 2. VizSpark plasma solver coupled with CONVERGE
 - Goal: Create DNS discharge boundary condition



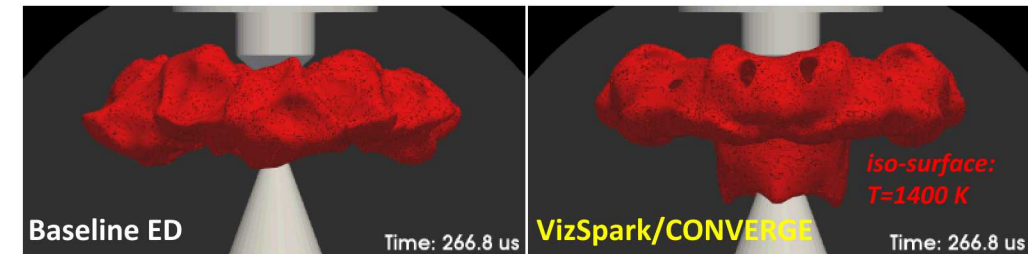
- Stoichiometric
 - Strong hydrodynamics observed despite limited pulse energy
 - Both models well-capture effects



- Lean limit
 - Similar kernel distortion from plasma blast wave
 - Very slow early kernel growth
 - Models capture early discharge behavior, but predict kernel quench



- Ignition quench
 - Strong mixing rapidly cools kernel

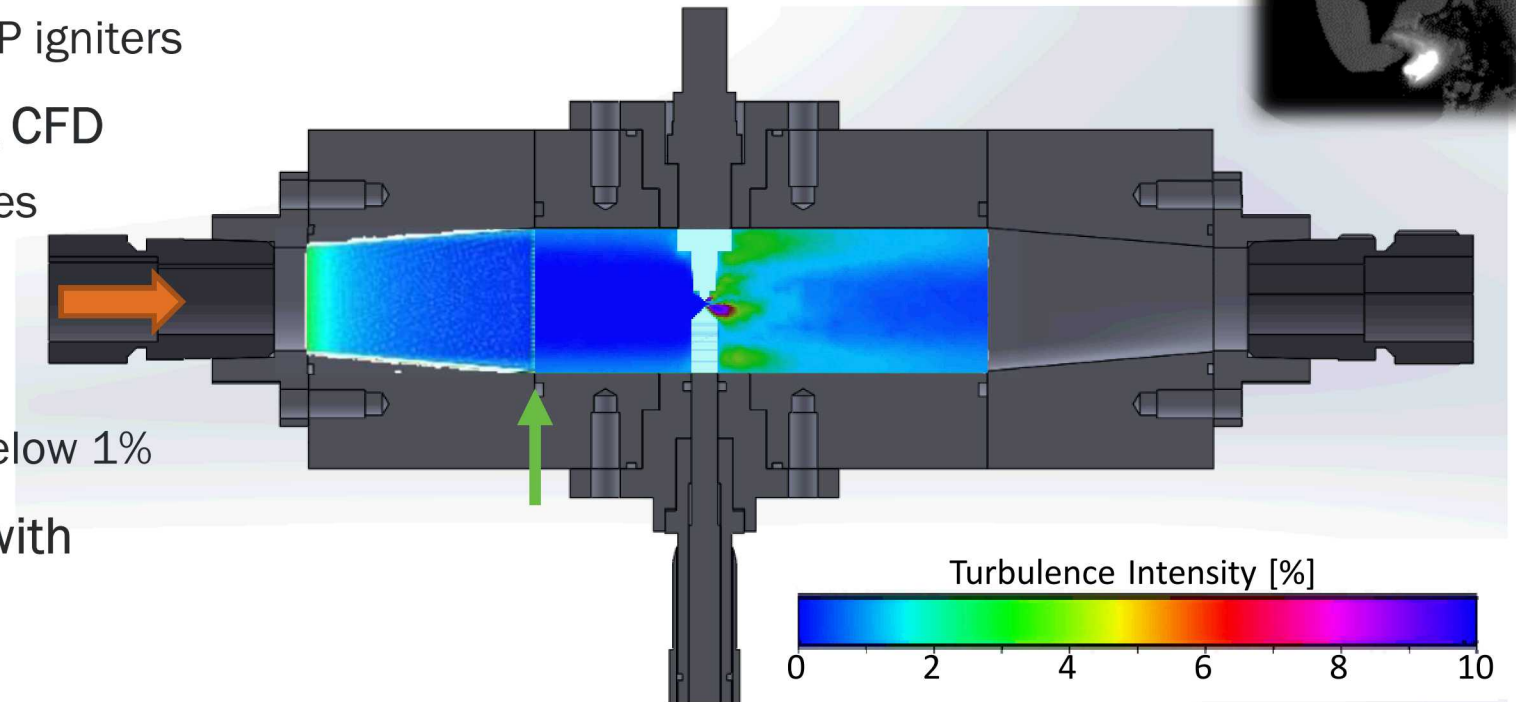


Early results suggest both ED & VizSpark models well-capture discharge, but poor ignition prediction result from the combustion models – DNS will help here

Designed cross-flow ignition test facility that reproduces relevant in-cylinder densities (30 g/L) and velocities (30 m/s)

C.01.02: Accomplishments (SNL)

- Cross-flow velocities achieved using high flow rate axial fan & variable speed AC motor.
 - Gases supplied by upstream bank of high-pressure mass flow controllers, with liquid fuels pre-vaporized and mixed upstream using a purchased liquid fuel vaporizer (see Technical Backup Slide 4 for further details)
 - Integrated optical access for in situ measure of discharge/ignition phenomena (e.g., PIV, schlieren, emission)
 - Imbedded cartridge heaters enable up to 400 K temperatures (for H₂O and full boiling point liquid fuels)
 - 35 bar peak design pressure for spark channel deflection experiments (10 bar for combustion)
 - Facility accommodates spark and LTP igniters
- Flow characteristics optimized using CFD
 - Contoured nozzle & test-section edges use to minimize wall vorticies and boundary layer interference
 - Upstream woven mesh used to limit free-stream turbulence intensities below 1%
- Construction delayed until Q3FY20 with initial testing planned for Q4FY20



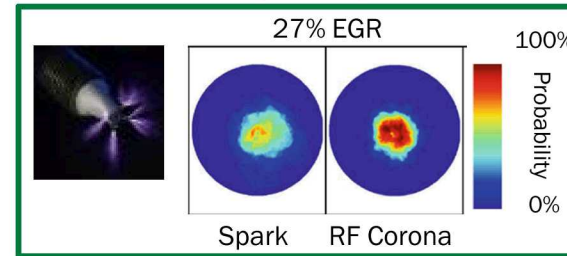
Advanced Ignition to Enable Alternative Combustion Modes

C.01.01: Approach (SNL)

Tenneco Advanced Corona Ignition System (ACIS)

- High-frequency (MHz+) & voltage (20 kV+) discharges
- High-energy corona streamers
- Large and repeatable ignition volumes

Marko et al (Daimler), IAV ISGE, 2016.

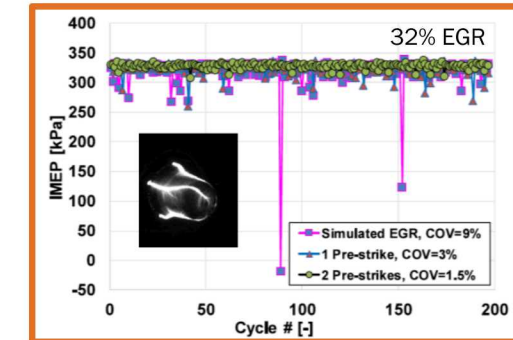


Approach

- NRPD static-cell ignition-limit & early flame kernel measurements
 - Igniters:
 - Pin-to-pin (P2P): streamers
 - Barrier discharge igniter 1 (BDI1): Exposed anode tip flush with surface
 - BDI2: Completely encapsulated anode
 - BDI generated ozone (O_3) generation to improve combustion stability
 - Complementary modeling (ANL, Scarcelli – ACE142)
- GM SG2 single-cylinder optical engine
 - ACEC operating point: 3.5 bar IMEP; 1300 rpm; single early injection
 - Igniters:
 - ACIS: 4-prong; primary voltage 20 – 35 V; 500 – 2000 μ s
 - BDI: primary voltage 50 – 75 V; duration 500 – 1000 μ s
 - NRPD: secondary voltage up to 20 kV; pulse repetition: 100 kHz

Tenneco Barrier Discharge Igniter (BDI)

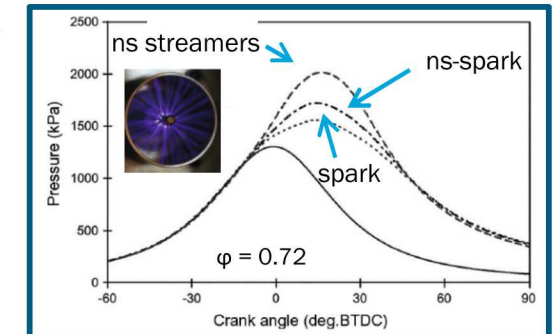
- Same ACIS pulse hardware
- Radical formation from surface discharges



Idicheria et al, IAV ISGE, 2018.

Nanosecond Repetitive Pulse Discharge (NRPD)

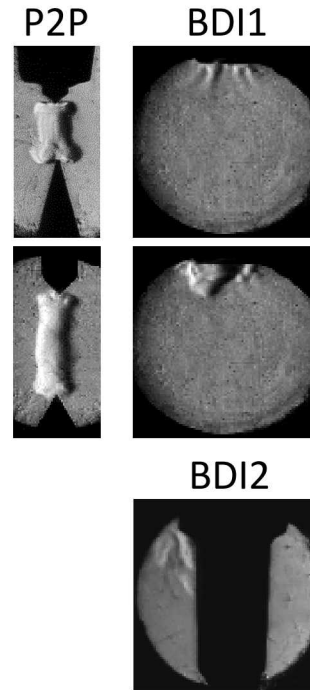
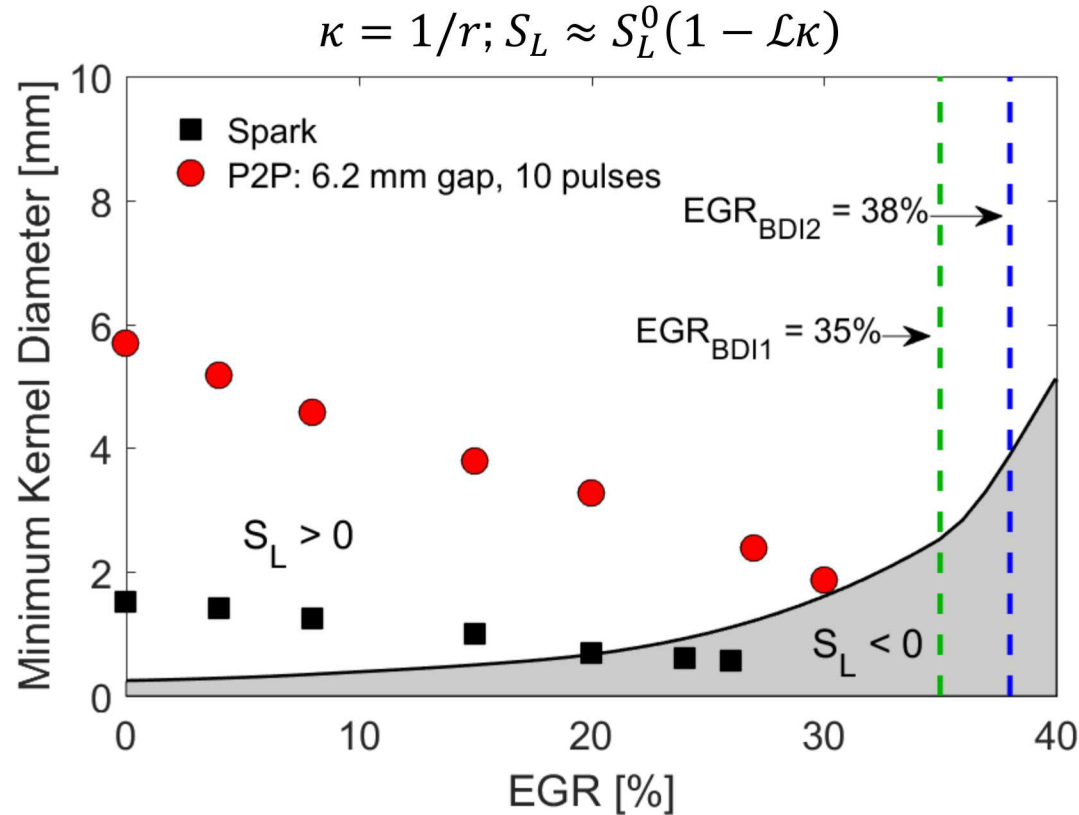
- Repetitive (10 KHz+), high-voltage (15 kV+) DC
- Strong LTP between pin-to-pin electrodes
- BDI also possible



Cathey et al, IEEE Trans, 35, 2007.

Extended lean/dilute ignition limits are achieved by creating larger early flame kernel volumes

C.01.01: Accomplishments (SNL)



- Kinetic modeling performed to clarify ignition mechanisms
 - Calculated minimum diameters from Markstein lengths (San Diego Mech)
 - Additional P2P experiments with more gap sizes & higher 60 kHz frame rate
 - Larger gaps more forgiving for arc avoidance but require more energy
- Lean-limit extension correlates most strongly with increased kernel size

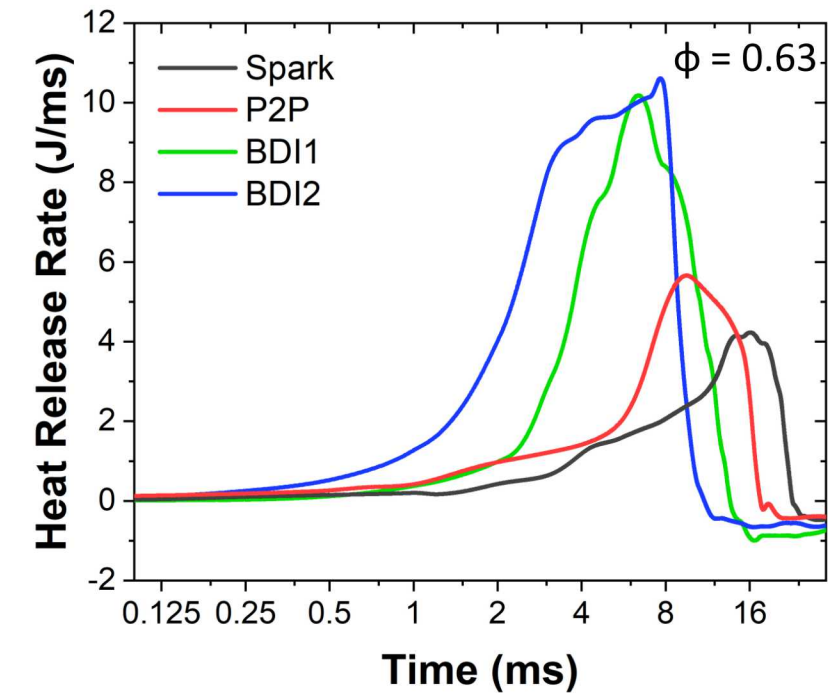
- NRPD with P2P extended ignition limits further due to the larger initial ignition kernel diameter
- Multiple streamers at BDI1 tip merge to former large initial kernel
- BDI2 ignition occurs along insulator surface (~7 mm diameter)

Surface NRPD has extended ignition limits to the most extreme value possible

Slow initial laminar burning phase is a key source of combustion variability for lean/dilute mixtures

C.01.01: Accomplishments (SNL)

- Laminar burning phase substantially increases with dilution
- Relative to spark, NRPD severely shortened laminar-to-turbulent flame kernel transition
 - P2P: Initial hydrodynamic induced corrugation transitions to turbulence
 - 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%

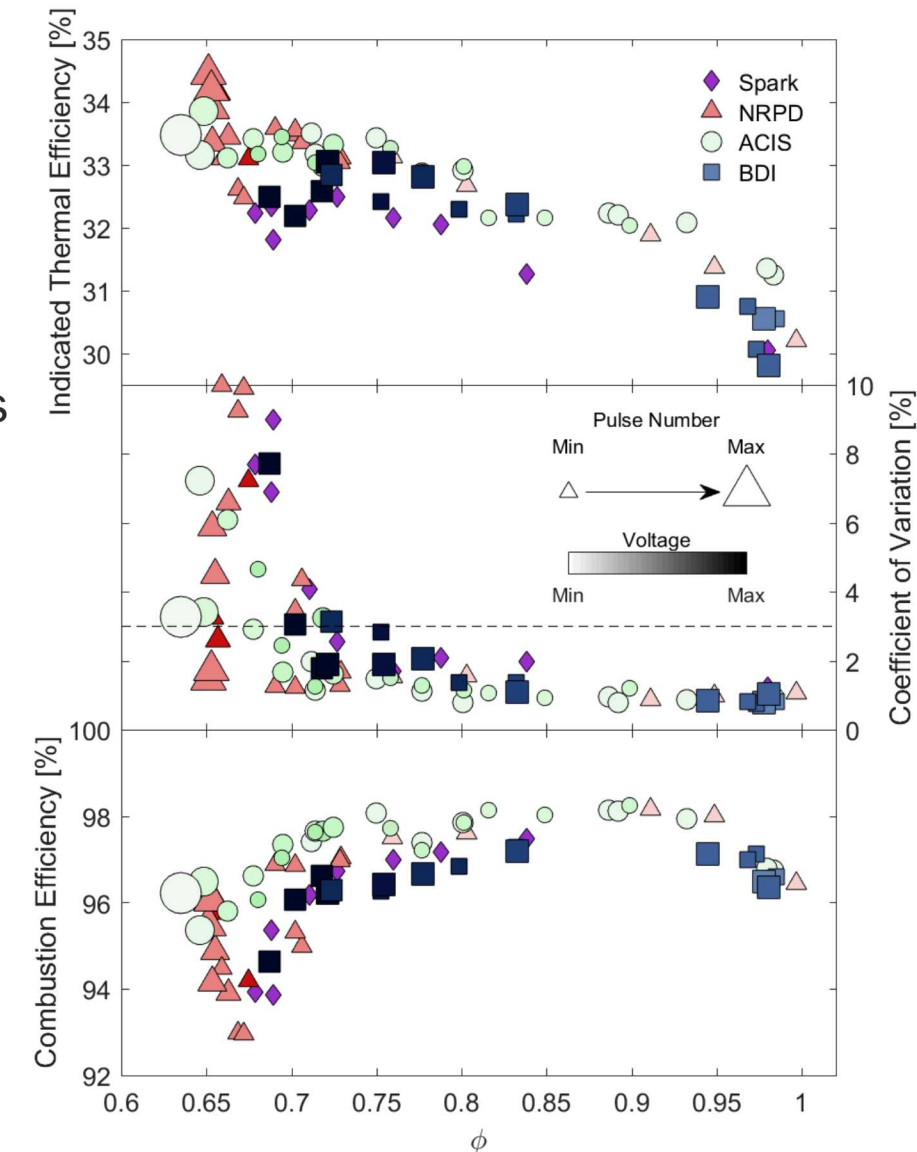
Since laminar-to-turbulent kernel period has the most variability, shorter periods are expected to benefit engine combustion stability

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

C.01.01: Accomplishments (SNL)

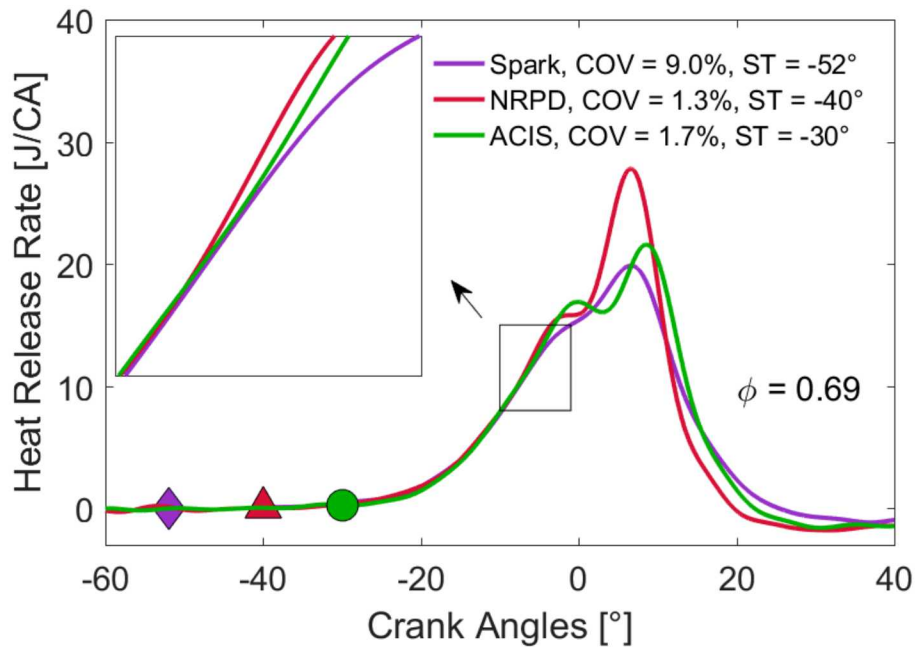
- No notable lean-limit extension with BDI
 - Intake pre-strikes *not* used (others observed these improve stability)
- ACIS lean-limits extended from $\phi = 0.73$ to $\phi = 0.68$
 - Peak ITE increased from 32.5% to 33.8% (NOx decreased by 30%)
 - Longer discharges & higher voltages needed for lean mixtures
 - ~1.0 point ITE improvement from shorter initial burn durations
- 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% (NOx decreased by 30%)
 - For leanest mixtures, stability improved w/ increased pulse number
 - ~0.5 point ITE improvement from shorter initial burn durations

Planned EGR sweeps and complementary flame kernel imaging were interrupted by the lab shutdown and will be completed once work resumes



Faster early burn rates observed with ACIS and NRPD ignition

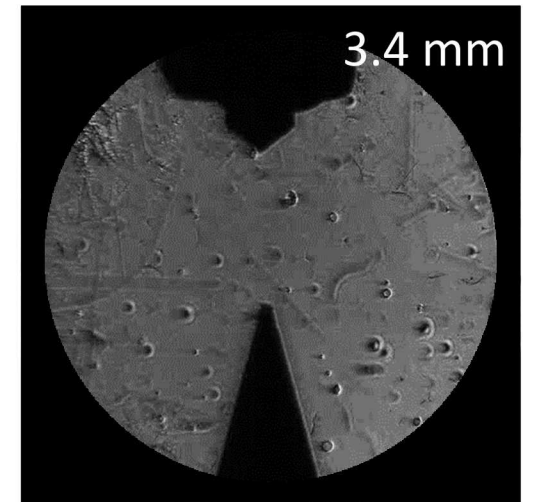
C.01.01: Accomplishments (SNL)



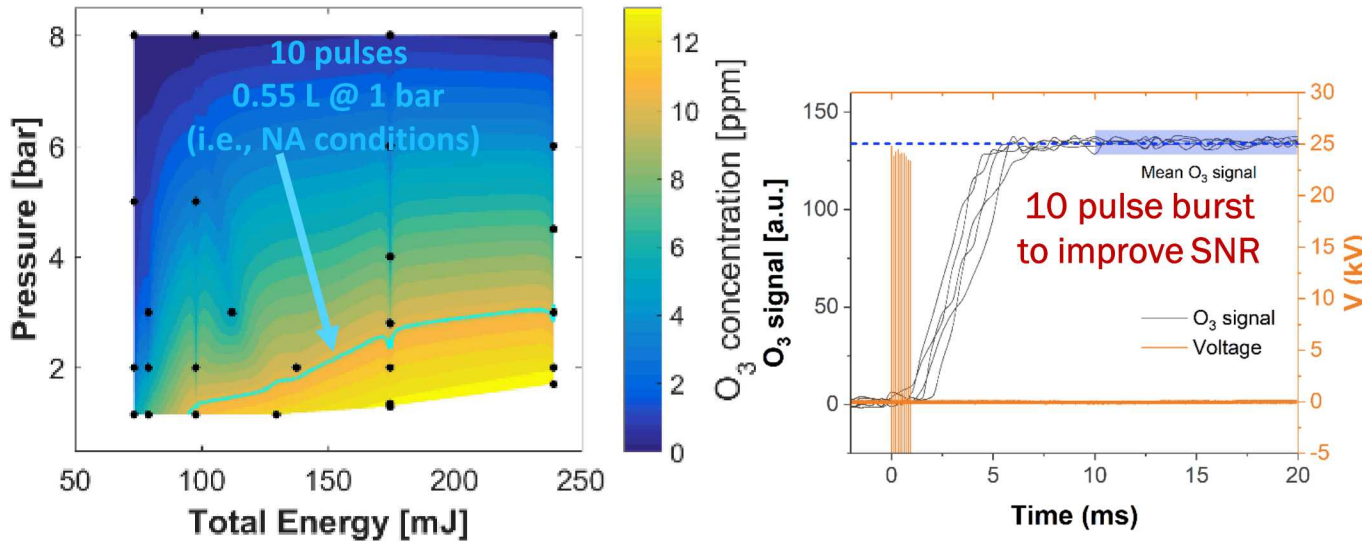
- For all igniters, end-gas auto-ignition was observed due to residual heating from modest positive valve overlap (~34°)
 - As expected from static-cell ignition tests, more consistent early burn periods led to a more repeatable end-gas auto-ignition event
 - Despite substantial ST retard for the ACIS/NRPD igniters relative to the spark, heat release rates were roughly equivalent by -10° aTDC
- ACIS is expected to produce largest kernel volumes due to multiple ignition sites and unconstrained streamer growth
 - Will verify with engine ignition kernel imaging in Q3FY2020

- 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
 - Pulse monitoring/modulation strategies under investigation as a potential arc mitigation method – see Technical Backup slide X

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



Static cell quantification of BDI generated ozone

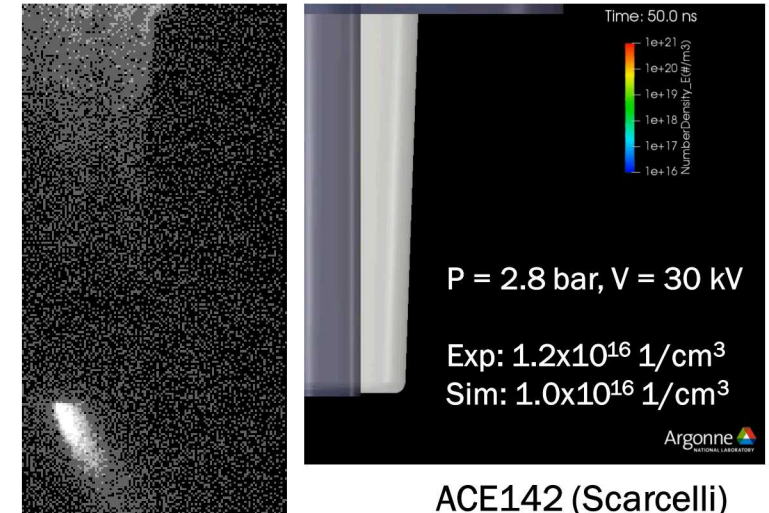


- BDI formed O₃ (NRPD) measured for range of discharge voltage, pressure, temperature & EGR.
 - Highest O₃ yields with lowest pressures & highest pulse energies (i.e., discharge voltages)
 - 30 ppm O₃ can be created with under 30 pulses and 0.3 to 0.7 J/cyc of total cycle energy
 - For SACI, 10 - 30 ppm O₃ significantly altered charge reactivity – more had diminishing returns
 - O₃ yields decrease w/ higher temperature & EGR
 - 30% O₃ decrease when T increased from 22° to 85° C
 - 40% O₃ decrease when EGR increased from 0 to 30%

- Complementary single- and double-pulse discharge plasma discharge simulation results agree well with measurements

- Simulations indicated most O₃ forms along the insulator surface, with minimal contribution from the streamers
- Arc events destroy formed O₃ which occurs if surface streamers reach the anode – limits applied voltage, and thus O₃ yield
 - Arc can be avoided by larger anode protrusions or full BDI configurations

- Engine tests with BDI generated O₃ planned for Q4FY21 for EGR dilute ACEC 3 bar, 1300 rpm test point – compared to O₃ seeded benchmark

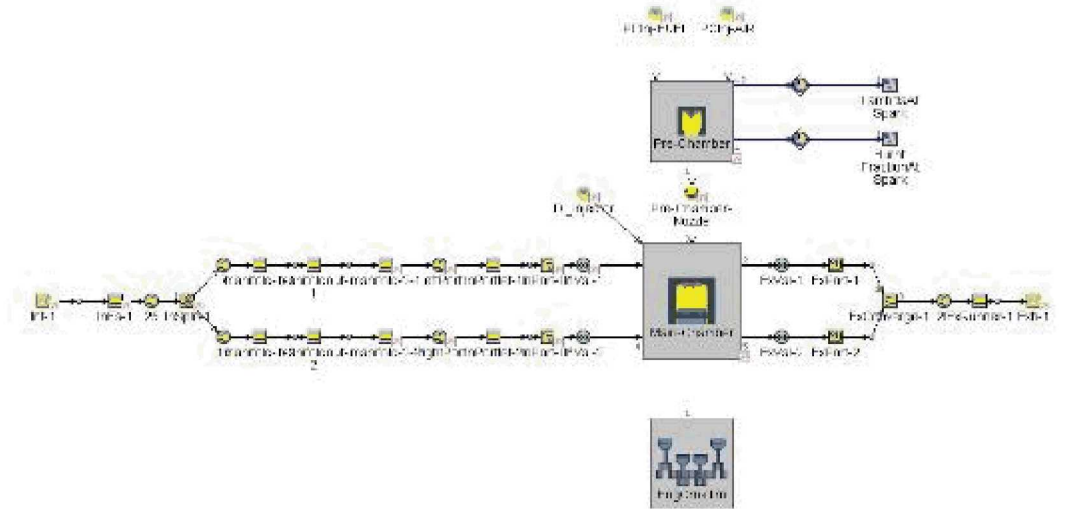


ACE142 (Scarcelli)

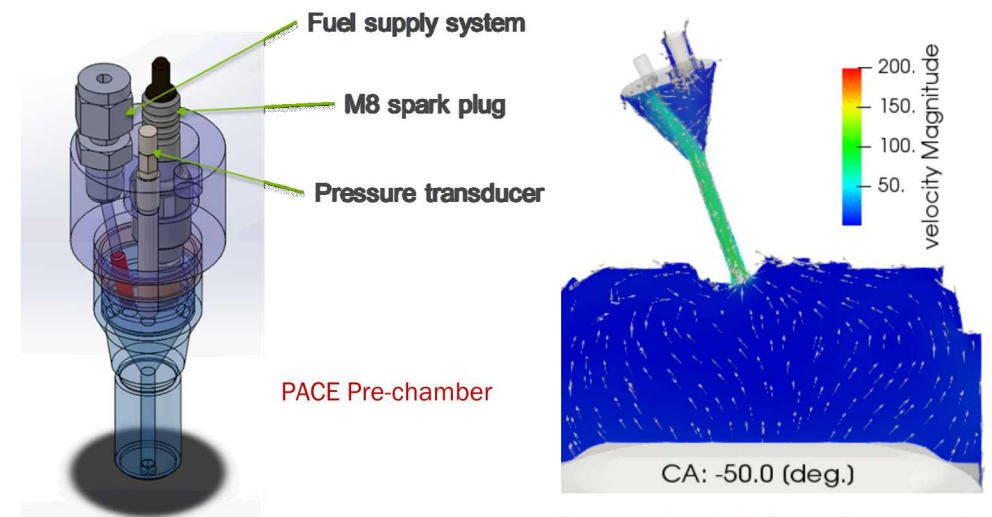
Remove barriers to pre-chamber ignition

F.01.01: Approach (ANL/SNL)

- Approach
 - Modular active pre-chamber (ANL/SNL)
 - Variable PC volume/nozzle geometry
 - Air/fuel supply system
 - Ford SCE GDI engine; central DI/SI; single inj. (ANL)
 - 1D GT-Power model development
 - Complementary CFD (Scarcelli, ANL – ACE142)
 - EGR dilution sweep
 - Active vs. passive pre-chamber ignition
 - GC sampling of pre-chamber products (ANL/SNL)
 - Optical vessel imaging of PC ignition
 - NRPD BDI in a passive pre-chamber (SNL)
 - Goal: make a passive pre-chamber perform like an active pre-chamber
 - Joint project with SNL/ANL & CMT – See Technical Backup Slide 5



1D GT-Power Model of FSC engine with PCI



PACE Pre-chamber CFD - PI: Scarcelli

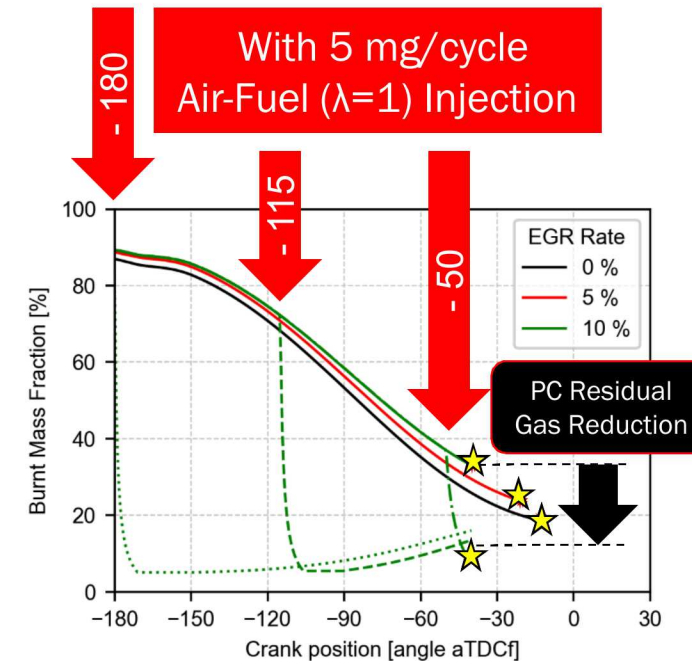
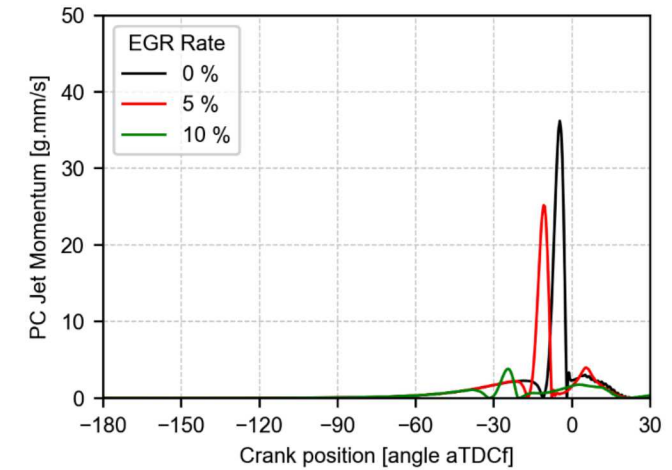
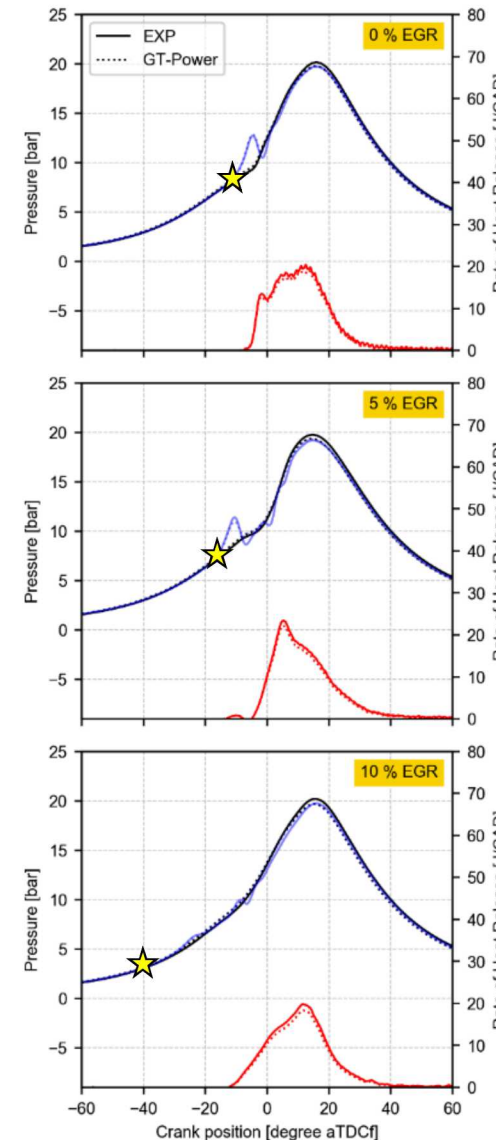
Technical Accomplishments

F.01.01: Accomplishments (ANL)

Experimental data/GT-Power simulations

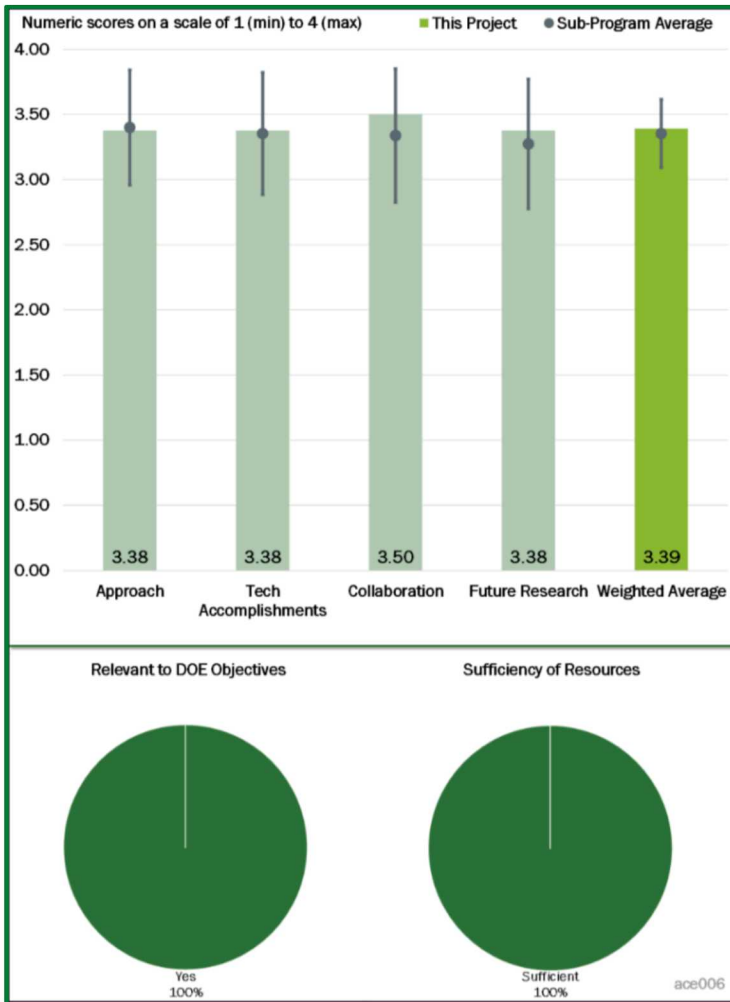
- EGR sweep at 1500 rpm/ 3.7 bar IMEP
- GT-Power model developed and calibrated
 - PC Jet Momentum
 - Burnt Mass Fraction in PC
- EGR dilution limit of passive pre-chamber
 - High residual mass fraction in pre-chamber
 - Diminishing PC heat release
 - Longer main chamber burn rate necessitates earlier SA => higher residual in PC
- GT-Power simulations of air-fuel injection for active pre-chamber operation
 - Scavenging of pre-chamber reduces PC residuals below 0 % EGR case
 - Later air-fuel injection beneficial

GT Power simulations explain higher EGR tolerance with active PC – testing in Q4FY20



RESPONSE TO REVIEWER COMMENTS

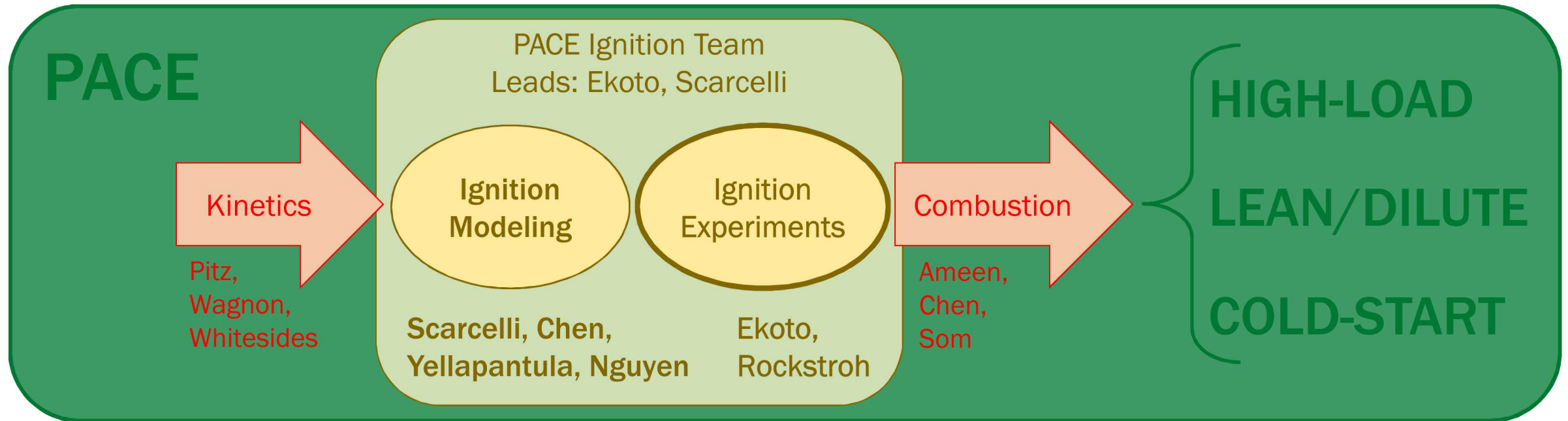
ACE006 (Ekoto, SNL) was the only project reviewed in FY19



“... estimating ... primary energy requirement is key... to show (energy balance is) a net positive. “

- Transient Plasma Systems indicates that worst case primary-to-secondary energy conversion is 50%
 - Most ignition cases use 10 pulses at 10 mJ/pulse or less (secondary); accordingly secondary energy use is under 400 mJ per ignition event
 - For lean limit ACIS/NRPD, 7.5 J reduction in fuel energy use → ~19:1 increase in energy recovered vs energy used (again which is the worst case)
- **Reviewers consistently wanted to see more data on stoichiometric EGR dilute conditions.**
 - Additional static-cell data presented for EGR dilution tolerance
 - Shutdown interrupted planned engine & static-cell experiments with EGR, but those will proceed soon
- **Reviewer wants a better understanding of material properties for BDI that lead to failure**
 - It is beyond our capability/expertise to understand the BDI material failure
 - Experiments were adjusted to focus on discharge properties that result in material failure, so that those measurements can be used by other groups

COLLABORATION AND COORDINATION



EXTERNAL COLLABORATORS

Convergent Science (CSI) – *CFD model development*
Esgee Technologies – *plasma model development*
Tenneco, Transient Plasma Systems (TPS) – *ignition hardware*
Michigan Tech, U-Perugia (*optical diagnostics*), U-Texas,
Auburn (*plasma chemistry*), Purdue (*combustion modeling*)
CMT Motores – *Pre-Chamber development*

CONNECTION WITH OTHER DOE PROGRAMS

DOE HPC4Mfg – TPS, plasma modeling
DOE TCF – CSI, LESI model in CONVERGE
DOE VTO FT – ANL/SNL/NREL/ORNL, pre-chamber
ignition modeling for MD/HD NG engines
DOE VTO FT – Co-Optima, Multimode/pre-chamber
ignition modeling with focus on fuel properties

REMAINING CHALLENGES AND BARRIERS

■ Predictive ignition modeling serves multiple purposes in PACE

- Prioritization needed, depending on current state-of-the-art and available test time.
- Impact of ignition on lean/dilute combustion is well-know, while cold-start issues are unclear

■ Conventional vs. non-conventional ignition systems

- Can only afford a limited number of fundamental ignition studies given the resources available
- PC or LTP igniters likely to remain at the engineering level in FY21-23

■ High-load ignition conditions are difficult to reproduce experimentally

- High turbulence, pressures/temperatures, and convective flows are challenging mimic in combustion vessels

■ How do we leverage current understanding for electrode wear?

- SNL lacks material science expertise for discharge-to-wear processes
- Fundamental discharge phenomena modeling provides complementary data

Future Work

START	END	PI	MILESTONE
Q3FY20	Q1FY21	Pitz & Wagnon	Improved ozone kinetics for with different fuels and EGR constituents
Q3FY20	Q4FY21	Ekoto	Fundamental measure of ignition phenomena in controlled test vessels (e.g., flame speeds, initial kernel sizes, pulse characteristics, calorimetry)
Q1FY21	Q4FY21	Ekoto & Rockstroh	Demonstrate 40% EGR tolerance & 50% excess-air tolerance with PC and LTP ignition in a single-cylinder engine for ACEC 1300 rpm / 3 bar condition
Q1FY21	Q2FY22	Scarcelli	Model impact of LTP on flammability limits numerically evaluated with a combination of plasma and CFD simulations
Q3FY21	Q3FY22	Ekoto & Rockstroh	Demonstrate comparable cold-start performance for PC and LTP ignition relative to conventional spark ignition for the ACEC cold-start protocol in a single-cylinder engine
Q1FY22	Q1FY23	Curran & Prikhodko	Demonstrate 40% EGR tolerance & 50% excess-air tolerance and comparable cold-start performance with PC and LTP ignition in a multi-cylinder engine for ACEC 1300 rpm / 3 bar condition

	FY20				FY21				FY22				FY23			
PI(s)	FY20 Q1	FY20 Q2	FY20 Q3	FY20 Q4	FY21 Q1	FY21 Q2	FY21 Q3	FY21 Q4	FY22 Q1	FY22 Q2	FY22 Q3	FY22 Q4	FY23 Q1	FY23 Q2	FY23 Q3	FY23 Q4
Pitz																
Ekoto																
Ekoto & Rockstroh																
Scarcelli																
Ekoto & Rockstroh																
Curran & Prikhodko																

Relevance

- Overall goals of PACE are to speed discovery of knowledge, improve engine design tools, and enable market-competitive powertrain solutions with potential for best-in-class lifecycle emissions
- These tasks directly address USDRIVE research priority 1: Dilute Gasoline Combustion and priority 3: Low-Temperature Combustion (LTC)
 - Expanded dilution tolerance with advanced igniters
 - Creation of radicals that favorably impact auto-ignition processes
- Measurements will enable better understanding of ignition processes that will be leveraged by PACE modeling groups to develop improved ignition models at lean/dilute and cold-start conditions

Approach

- Targeted experiments on ignition processes that are leveraged by complementary PACE modeling efforts to develop improved ignition models for lean/dilute conditions
- Develop hardware and test facilities needed to interrogate relevant ignition phenomena
- Use combination of static-cell and single-cylinder engine testing to better understand mechanisms of ignition for both conventional and advanced ignition systems
- Develop ignition system platforms that can be used to identify methods necessary to remove barriers to igniter viability

Accomplishments

- Attributed improvement of LTP ignition to larger early kernel volume rather than plasma chemistry
- Demonstrated extension of lean limit with ACIS & NRPD igniters and elucidated impact of pulse-control strategy
- Measured ozone generation from pre-strikes at engine relevant intake conditions
- Developed prototype pre-chamber ignition system and performed initial
- Used 1D modeling to describe effectiveness of passive vs. active pre-chamber ignition for stoichiometric dilute conditions

Collaborations

- PACE is a collaboration of 6 national laboratories; work plan developed considering input from ACEC TT, code developers, and more
- PACE projects presented at AEC semi-annual program review meeting
- External collaborations with Tenneco, TPS, CMT, U. Auburn, U. Texas, and other university partners

Future Work

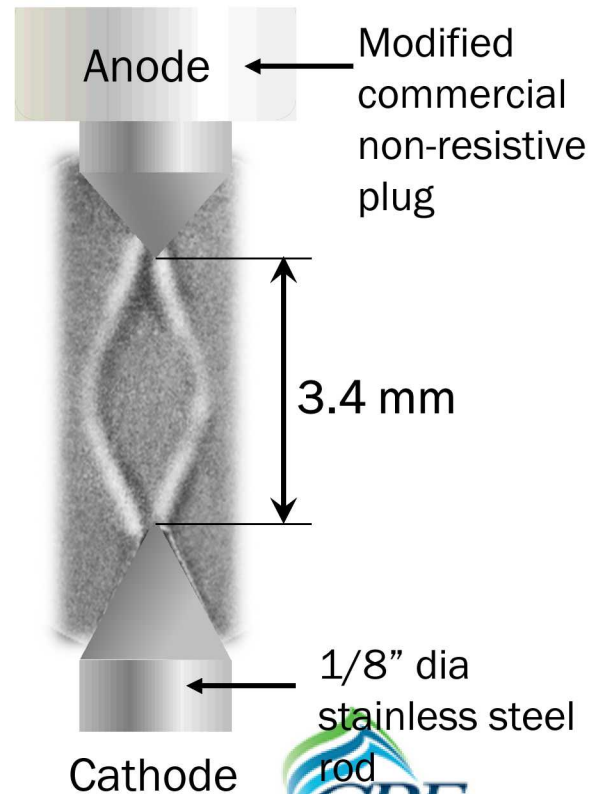
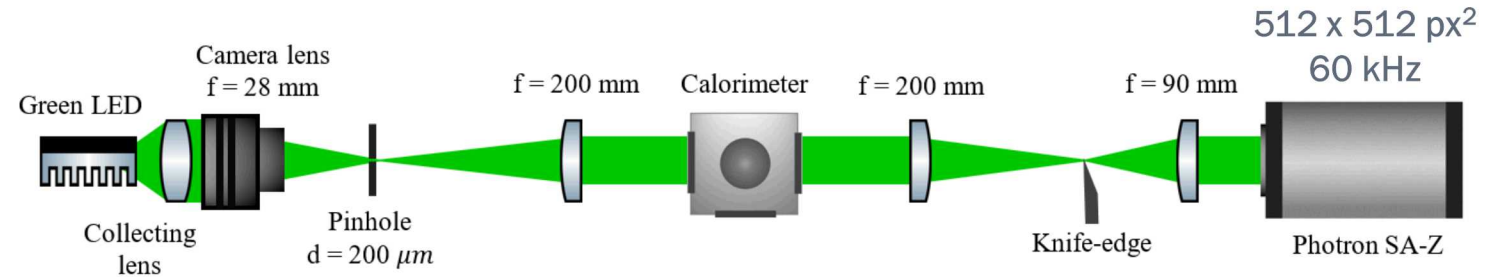
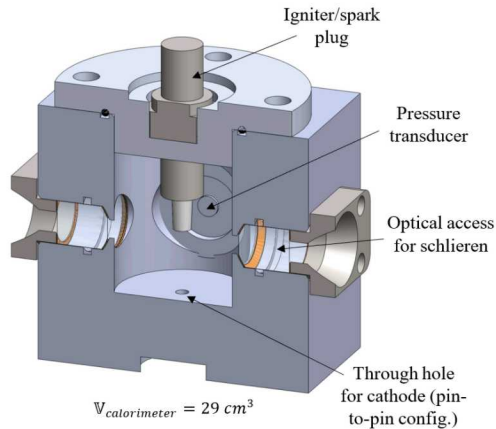
- Perform ACIS, BDI, and NRPD testing in the engine for EGR dilute conditions with complementary imaging of the flame kernel development
- Couple BDI with pre-chamber, to explore BDI pre-strikes to improve performance; flame kernel imaging and multi-cylinder engine tests for igniters
- Develop a better understanding of how ozone influences combustion stability
- Continuously refine igniter hardware for engine relevant conditions for lean/dilute mixtures

BACKUP SLIDES

SNL static-cell experiments

C.01.02: Technical backup (SNL)

Optical Ignition Calorimeter



Schlieren Imaging

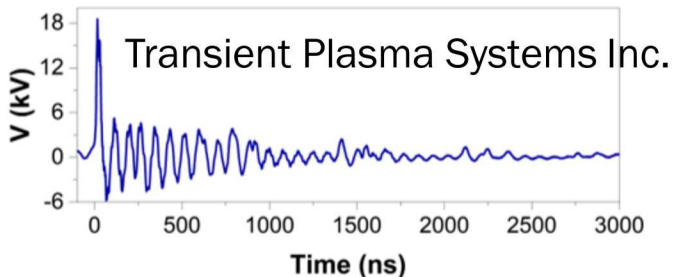
- Discharge volume
- Channel temperature (with calorimetry)
- Flame kernel growth

Experimental Conditions

- Propane/air
- $\phi = 0.52 - 1.0$
- EGR 0 – 34%
- Voltage 8 – 14.1 kV
- Pressure 1.3 – 4 bar

Pin-to-Pin (P2P)

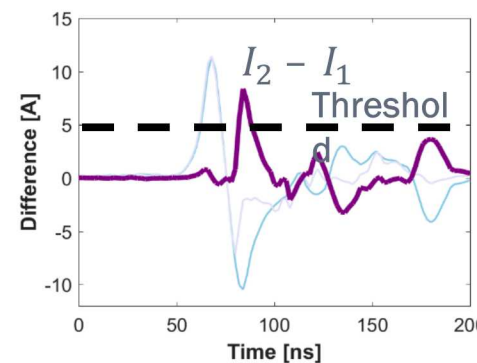
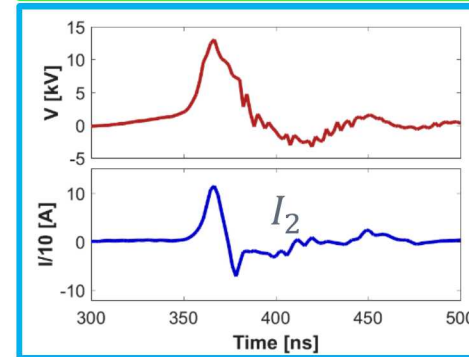
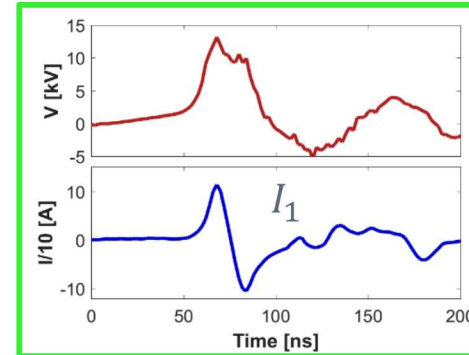
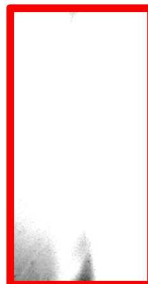
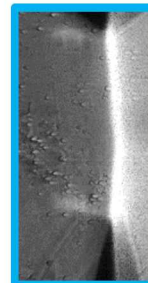
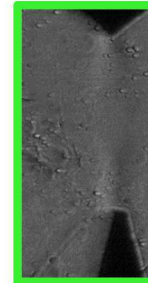
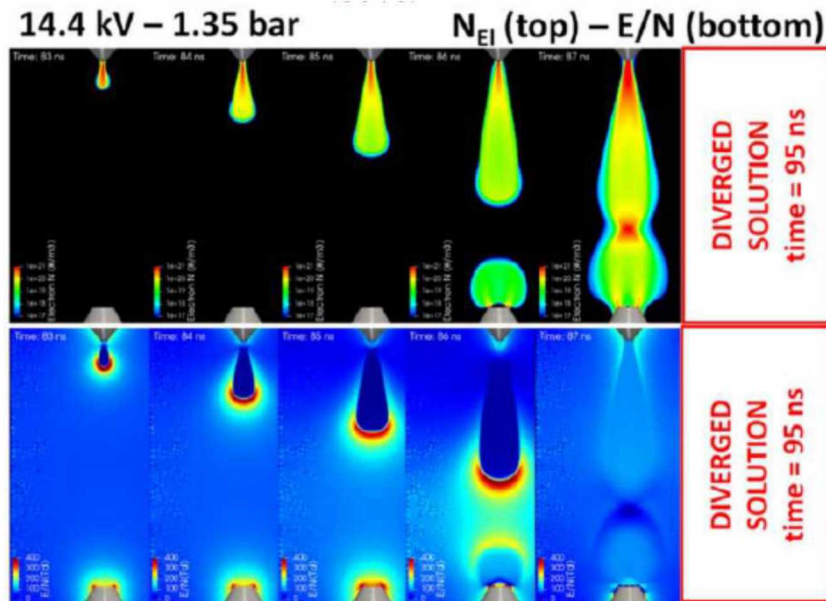
- Strong electric fields at electrode tips
- Concentrated pulse energy and wide gap lowers flame kernel heat loss
- *Ignition primarily thermally driven?*



LTP-to-breakdown transition sensitive to pulse # and inter-pulse time

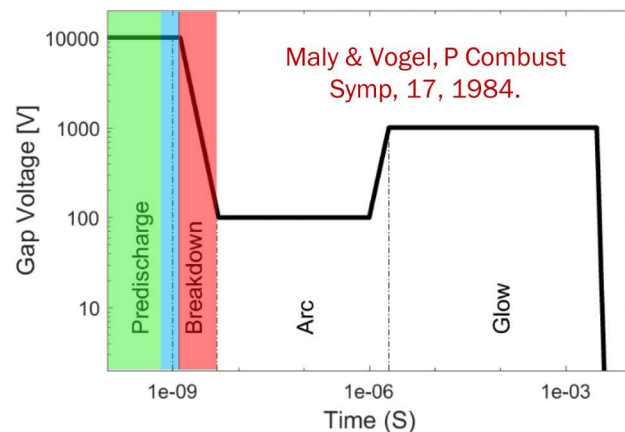
C.01.02: Technical backup (SNL)

Scarcelli et al., Plasma Sources Sci. Technol. 27



Breakdown: Plasma ionization makes the gas electrically conductive, which causes current flow between electrodes

- Breakdown cause electrode erosion from plasma ablation
- Discharge voltage/current are different for LTP discharge, ignition, and breakdown due to a change in impedance from the inter-electrode gases
- Transition from LTP to ignition can be detected through pulse monitoring and a threshold monitor
- Pulse voltage or dwell between pulses can then be adjusted to expand the kernel without breakdown transition

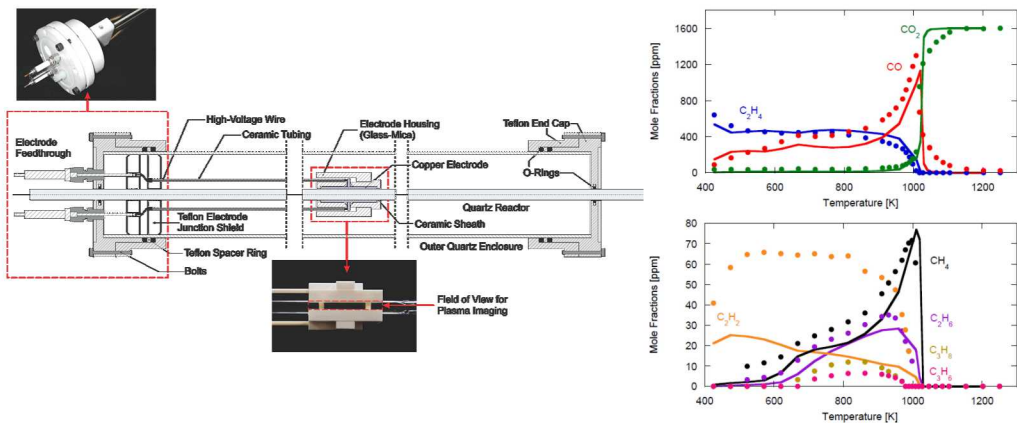


Multi-laboratory collaboration to understand LTP chemistry and physics

C.01.02: Technical backup (SNL/ANL)

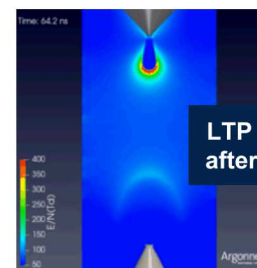
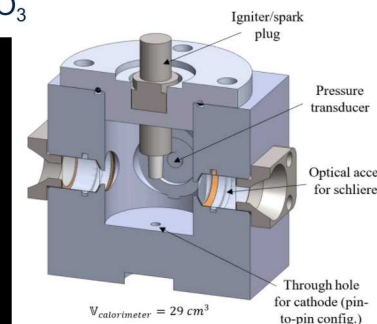
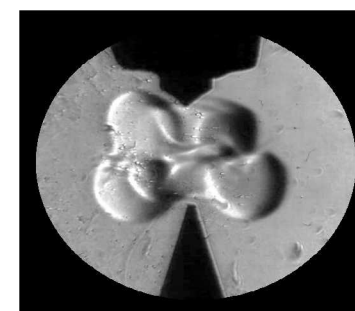
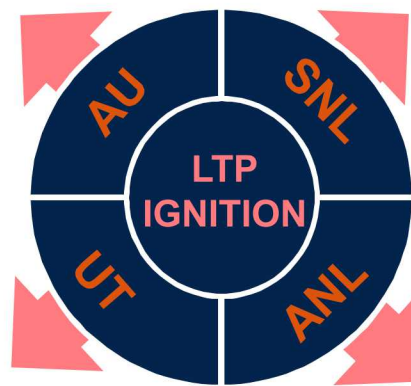
LTP Kinetic Model Development via Plasma Flow Reactor

- Purposed-built flow reactor with nanosecond-duration LTP perturbation for LTP kinetic studies
- Ex-situ diagnostics for species identification/quantification – GC-MS
- 0D plasma kinetic model for LTP-specific kinetic mechanism development

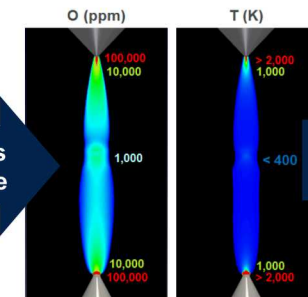


Measuring LTP Ignition Characteristics via Ignition Cell

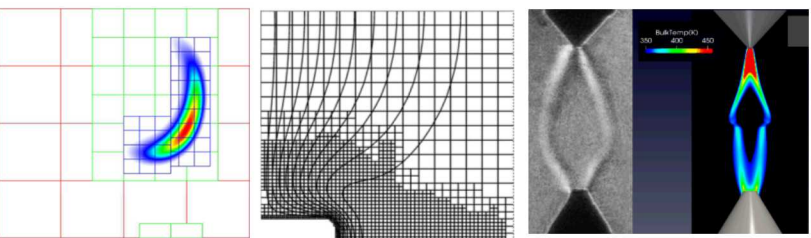
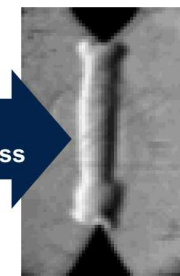
- Purpose built ignition test vessel for LTP ignition studies
- Experimental measurements/diagnostics include:
 - Pressure rise calorimetry – bulk energy deposition
 - High-Speed Schlieren and OH* measurements – flame propagation measurements
 - Direct measurements of active radicals O* and O₃



LTP properties after discharge



Impact on ignition process



- Exascale solver build on AMReX (Lawrence Berkeley National Lab)
 - Hierarchy of meshes and resolution near electrodes
 - Efficient temporal integration
 - Ready for high-performance computing on massively-parallel DOE computers
- Development of reduced skeletal mechanisms for LTP ignition of hydrocarbon fuels

- Commercial solver use: VizGlow (Esgee Technologies)
- Validation carried out by looking at:
 - Discharge regime (glow or spark)
 - Bulk gas temperature estimates and/or active species [O, O₃] direct measurements
 - Impact on ignition described by CFD combustion tool (CONVERGE CFD) and validated against Schlieren from SNL

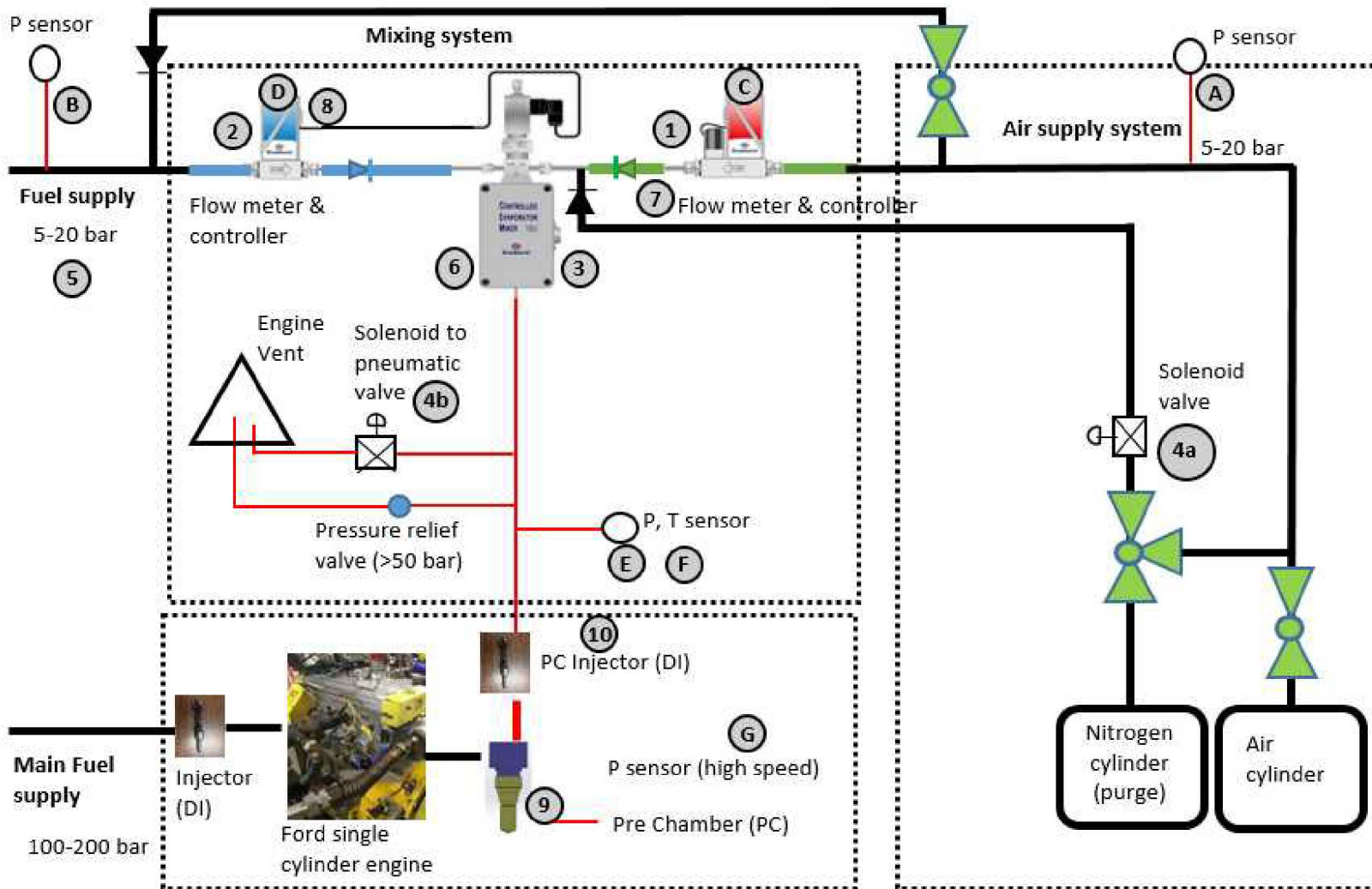
Development of LTP Ignition Exascale-Ready AMR Software

Appraising Existing Commercial LTP Modeling Software

Pre-chamber fuel system

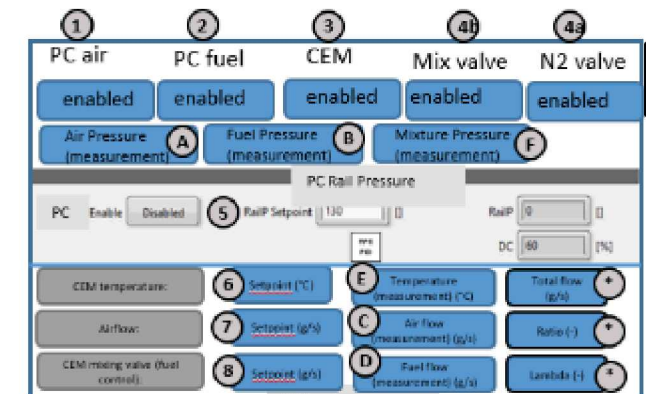
F.01.01: Technical backup (ANL)

Detailed PC schematic



PC controls

#	Requirement	Details
Control		
1	Energize air flow meter	24 V from NI module
2	Energize fuel flow meter	24 V from NI module
3	Energize CEM	Logical bit – enable heater control Safety switch – digital input
4	Operate NO valve	24 V from NI module
5	Fuel Pressure Ctrl – Re-Sol	MODBUS tbd
6	Set CEM temperature	Analog output to SS relay Digital input for 208 V relay PID temp. control loop (temp before PC)
7	Set airflow meter	0 – 10 V analog
8	Set CEM mixing valve	0 – 10 V analog
9	Spark plug	Peak and hold (existing)
10	PC Injector	Existing
11	E-stop loop	Logic control to shut off flow meter, turn on E-solenoids and open CEM mixing valve
Measurements/ Outputs		
A	Air pressure (before CEM)	0-10 V output [bar]
B	Fuel pressure (before CEM)	0-10 V output [bar]
C	Air flow	0-10 V output [g/s]
D	Fuel flow	0-10 V output [g/s]
E	Mixed temperature	NI card [°C]
F	Mixed pressure	0 – 10 V output [bar]
*	Mass based lambda	Air/mass flow based

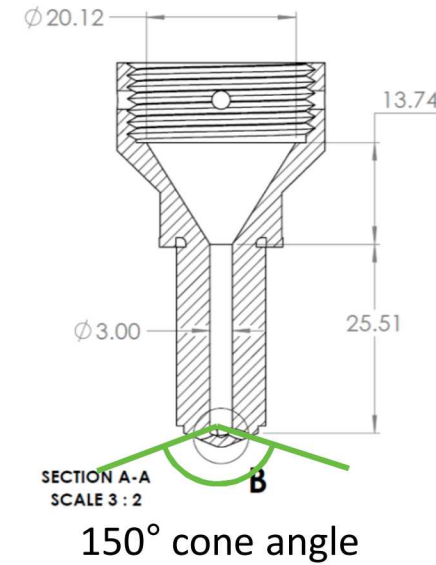
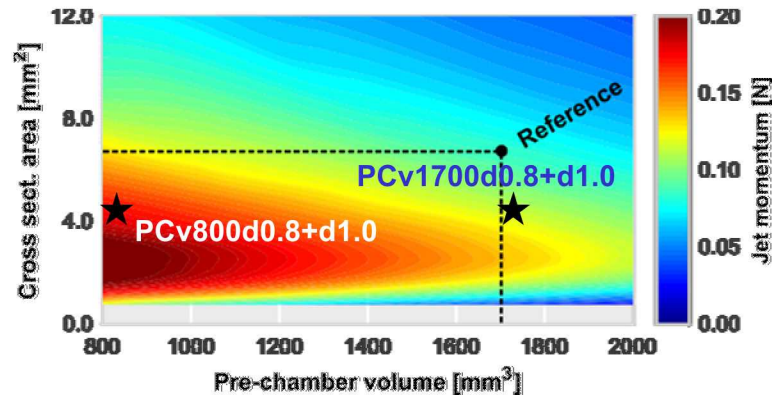


PC GUI

Collaboration with ANL and CMT to develop passive pre-chamber igniter with improved EGR dilution tolerance by using BDI

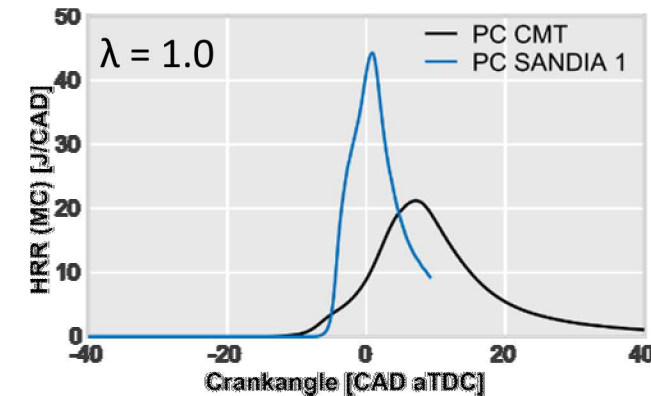
F.01.01: Technical backup (SNL)

- 1D GT-Power model results used to estimate volume and hole area parameters that maximize jet-exit momentum
 - Smaller hole area and chamber volume leads to better pre-chamber pressurization
 - Model does not account for heat transfer
 - Single point optimization (ACEC 1300 rpm, 3 bar)



12° tangential angle

150° cone angle



PC ID	Volume [mm ³]	Radial Holes	Holes Diam. [mm]	Axial Holes	Holes Diam. [mm]
Baseline	1700	6	1.2	0	-
Small Area	1700	6	0.8	1	1.0
Small Area & Volume	800	6	0.8	1	1.0



Preliminary CFD indicates the funnel and throat design improves pre-chamber-mixing and jet-exit momentum

REVIEWER-ONLY SLIDES

Critical assumptions and issues

Issue: Fundamental understanding of ignition processes is lacking.

Ignition system optimization requires a deep understanding of the underlying physical and chemical ignition mechanisms, along with the associated development of accurate, high-fidelity simulation capabilities. These cannot happen unless high-quality data are acquired using advanced in situ diagnostics in well-controlled test facilities that reproduce relevant engine combustor conditions.

Assumption: Cost-effective multi-mode engines will meet future emissions/efficiency standards.

Next-generation multi-mode engines will achieve comparable or superior efficiency relative to an emissions compliant diesel engine through a reduction of heat transfer and throttling losses, but without the need for costly emissions aftertreatment or high-pressure injection systems.

Assumption: Advanced ignition systems will further improve multi-mode engine performance.

Advanced ignition systems will improve multi-mode engine operation across the load-speed map through:

- Low load/speed: Controllable LTC via in-cylinder radical generation & local charge heating
- Moderate load/speed: Distributed ignition sites to extended SI dilution tolerances
- High load: Faster flame speeds that improved knock resistance for boosted SI

Advanced igniters will enable the use of higher compression ratios, facilitate transient mode switching, and reduce charge-heating requirements; features that will improve performance while reducing system cost & complexity.

Assumption: The most critical parameter for plasma discharge studies to match is gas number density.

Accurate reproduction of the exact thermodynamic state in combustion vessels is not feasible because of hardware constraints, and the propensity of fuels to auto-ignite

Assumption: Performance of optical engines is similar to commercial engines.

Design compromises such as a piston notch that enables optical access or the use of quartz windows that do not match metal thermal conductivity properties need to be made to enable optical experiments. However, experience has shown that underlying trends are well-reproduced relative to commercial engines; this assumption requires continual reassessment.

Assumption: Surrogate fuels can mimic the performance of commercial fuels.

Single-component fuels or multi-component fuel blends are often used to isolate particular fuel effects, enable optical measurements, and facilitate subsequent modeling efforts. Fuel characteristics can be related to those of conventional gasoline fuels through engineering parameters such as the octane sensitivity index.

Publications and Presentations

Publications:

1. Biswas, S, and Ekoto I, 2019. "Spark Assisted Compression Ignition Engine with Stratified Charge Combustion and Ozone Addition." SAE 2019-01-2253.
2. Seignour, N, Ekoto I, Foucher F, and Moreau B, 2019. "Measurements and Modeling of Ozone Enhanced Compression Ignition in a Rapid Compression Machine and Optically-Accessible Engine." In 2019 JSAE/SAE Powertrains, Fuels and Lubricants International Meeting, Kyoto, Japan, 2019-01-2254.
3. Biswas, S, and Ekoto I, 2019. "Detailed Investigation into the Effect of Ozone Addition on Spark Assisted Compression Ignition Engine Performance and Emissions Characteristics." SAE 2019-01-0966.
4. Biswas, S, Ekoto I, and Scarcelli R., 2019. "Transient Plasma Ignition (TPI) for Automotive Applications." Proceedings of IAV Ignition Systems for Gasoline Engines - 4th International Conference, Berlin, Germany.

Presentations:

- Feb 2020: "Ignition Mechanism of Low-Temperature Transient Plasma," Advanced Engine Combustion Program Review Meeting, Sandia National Laboratories, Livermore, CA.
- Nov 2019: "How Novel Low-Temperature Plasma Ignition Systems Can Enable Sustainable Transportation," U. Georgia Engineering Lecture Series, Athens, Georgia
- Aug 2019: "Static Cell Measurements of Lean/Dilute Limit Extension with Barrier Discharge Ignition," 11th U. S. National Combustion Meeting, Pasadena, CA.
- Aug 2019: "Spark Assisted Compression Ignition Engine with Stratified Charge Combustion and Ozone Addition," 2019 JSAE/SAE Powertrains, Fuels and Lubricants International Meeting, Kyoto Japan. – **Best Paper**
- Aug 2019: "Measurements and Modeling of Ozone Enhanced Compression Ignition in a Rapid Compression Machine and Optically-Accessible Engine," 2019 JSAE/SAE Powertrains, Fuels and Lubricants International Meeting, Kyoto Japan.
- Apr 2019: "Detailed Investigation into the Effect of Ozone Addition on Spark Assisted Compression Ignition Engine Performance and Emissions Characteristics," SAE World Congress Experience, Detroit, MI.
- 2019-2020: Multiple in-person and web meetings with GM, Ford, Transient Plasma Systems Inc.