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, Vehicle Technologies Office. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2021-5967PE

PACE PARTNERSHIP TO ADVANCE COMBUSTION ENGINES

ACE141: Advanced Ignition System Fundamentals

Isaac Ekoto, Sayan Biswas, James MacDonald, Francisco Di Sabatino (SNL)
Toby Rochstroh, Taehoon Han, Riccardo Scarcelli, Vyaas Gururajan (ANL)

FY21 DOE Vehicle Technologies Office Annual Merit Review, June 21-24, 2021

Overview

Timeline

- PACE start: Q3, FY19
- PACE end: Q4, FY23 (46% complete)
- Focus and objectives of individual tasks will be continuously adjusted
- Overall PACE work plan discussed in **ACE 138**

Budget

Task	Description	FY20	FY21
A.M.03 PI: Scarcelli	Advanced Ignition Modeling Tools	400k*	370k*
A.E.03 PI: Rockstroh	Fundamental Ignition Experiments	380k	342k
S.E.03.01 PI: Ekoto	Advanced Ignition to Enable Alternative Combustion Modes	420k	420k

*Listed funding also supports research presented in **ACE 142**

Barriers

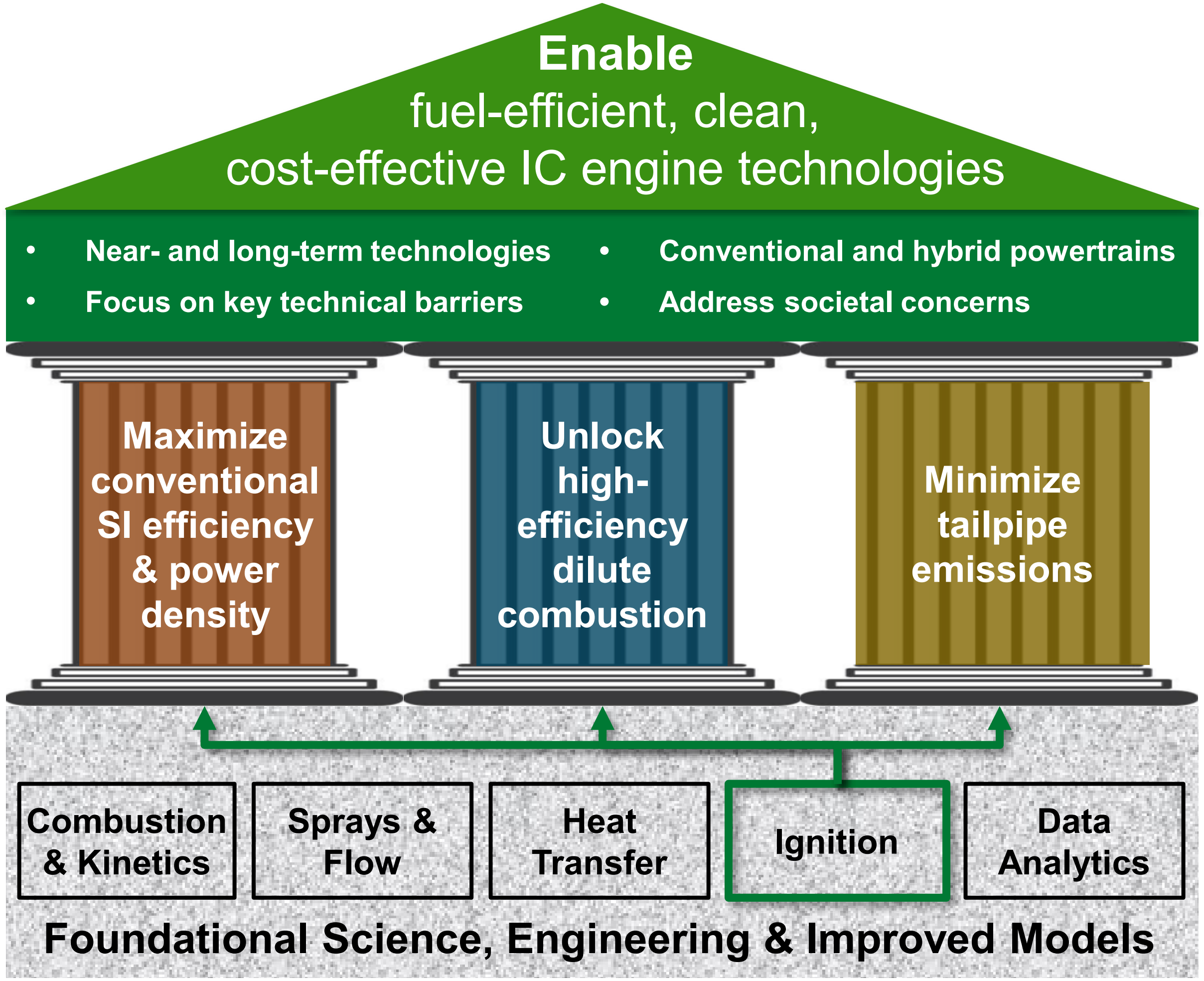
- Addresses PACE Major Outcomes 6 and feeds directly into Major Outcomes 4, 5, & 8
- More robust ignition systems for part-load dilute†
- Technologies to reduced combustion variability at boosted high-load†

†ACEC TT Roadmap

Partners

- **PACE is a DOE-funded consortium of 5 National Laboratories working towards a common goal (ACE 138)**
  - Kinetics (**Wagnon, ACE 139**)
  - Ignition modeling (**Scarcelli, ACE 142**)
  - Cold-start modeling/experiments (**Edwards, ACE 145**)
- **Partners include:**
  - Plasma ignition collaboration with Tenneco and TPS
  - Plasma kinetics/physics with U. Auburn, U. Texas
  - Pre-chamber research with CMT-Motores, Mahle Powertrain
  - Pre-chamber modeling – Gamma Technologies

Relevance



Overall Relevance of PACE: (ACE 138, McNenly)

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

Major Outcome 6

Develop viable advanced igniters and control methods that expand existing dilution limits and enable stable catalyst heating operation

Success measure

Prototype igniters and control strategies ignition control methods enable stable ignition for EGR dilution rates of up to 40% or air dilution rates of up to 50% with no adverse impact on pollutant emissions relative to the stock OEM configuration.

Demonstrate ignition system can maintain stable combustion at high exhaust heat flux conditions seen during cold start. ACEC 3 bar/1300 rpm test point*

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

Milestones

- **Task A.M.03: Advanced Ignition Modeling Tools**

Date	PI	Milestone	Status
FY22 Q2	Scarcelli	Model LTP flammability limits with a combination of plasma and CFD simulations	50% Complete
FY22 Q4	Scarcelli	Develop engineering models for pre-chamber	25% Complete
FY22 Q4	Scarcelli	Develop pulsed plasma ignition models to include O3 generation	25% Complete

- **Task A.E.03: Fundamental Ignition Experiments**

Date	PI	Milestone	Status
FY21 Q4	Rockstroh	Demonstrate stable operation 40% EGR dilution with PC ignition for ACEC 1300 rpm, 3 bar BMEP	75% Complete
FY22 Q3	Rockstroh	Demonstrate comparable PC performance for cold-start protocol relative to conventional SI	0% Complete
FY22 Q3	Rockstroh	Develop 1-D model PC mixing and jet-exit momentum model – New task	25% Complete

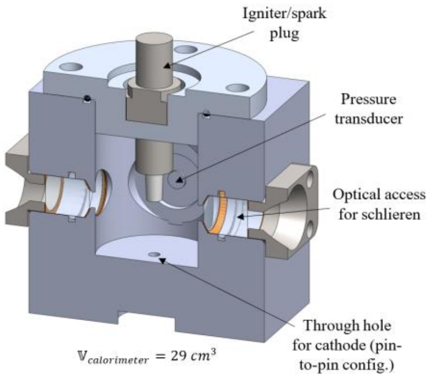
- **Task S.E.03.01: Advanced Ignition to Enable Alternative Combustion Modes**

Date	PI	Milestone	Status
FY21 Q1	Ekoto	Improved SACI cyclic stability w/ O_3 addition for EGR dilute charge at ACEC 1300 rpm, 3 bar BMEP	75% Complete
FY21 Q1	Ekoto	Demonstrate LTP plasma ignition 40%+ EGR tolerance under stoichiometric conditions	100% Complete
FY22 Q3	Ekoto	Demonstrate improved performance with BDI cold-start protocol relative to conventional SI	0% Complete
FY20 Q3	Ekoto	Passive PC engine testing with conventional igniter and BDI	50% Complete

Approach: Fundamental Plasma Experiments & Modeling

A.M.03
S.E.03.01

Facilities:



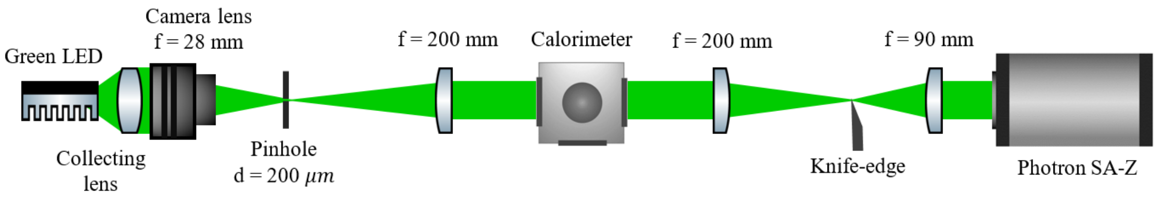
Static Ignition Tester

Crossflow Facility

- Initial Press/Temp:10 bar (30 bar discharge only)/373 K
- Oxidizer Stream: Air/CO_2/N_2/H_2O
- Gaseous & Liquid Fuels

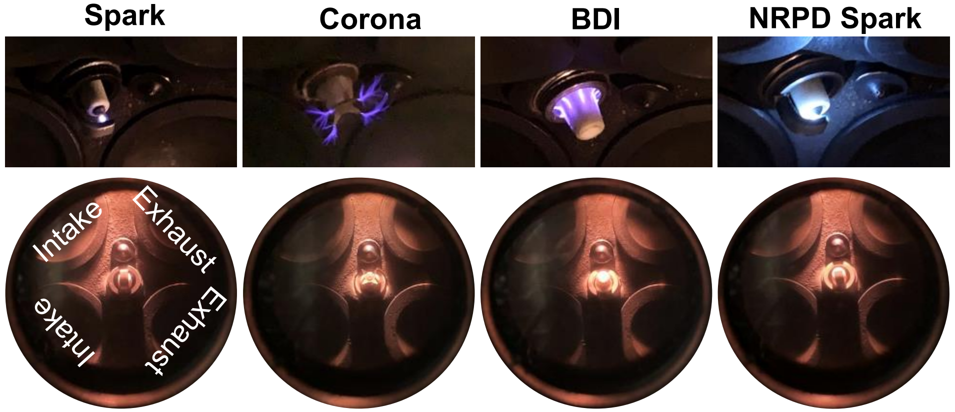
Diagnostics:

- Heat release & Calorimetry – not simultaneously
- High-frequency voltage/current monitoring
- High-speed schlieren/intensified imaging – 60+ kHz



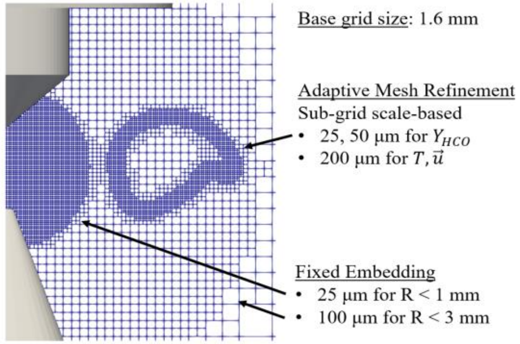
Non-equilibrium Plasma Igniters:

- Specific focus on nanosecond repetitive pulses (NRPD)
- Combination of high-energy ***streamer*** and ***spark*** discharges

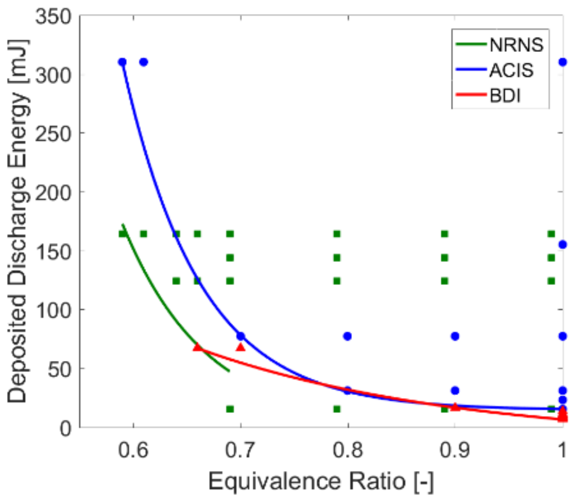


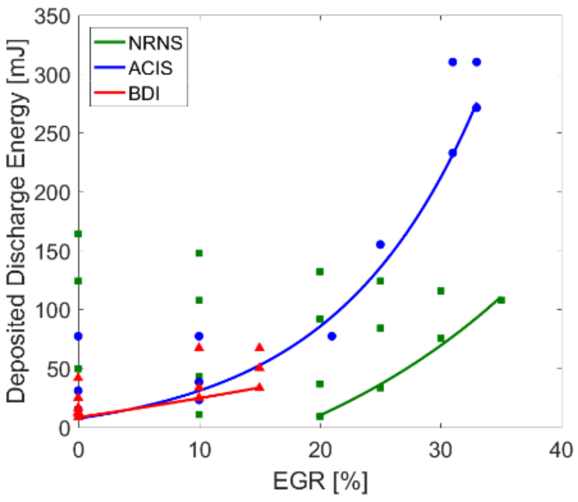
Non-equilibrium Plasma Ignition Modeling :

- VizGlow non-equilibrium plasma discharge simulations
- Source term modeling with coupling to CONVERGE



Accomplishments: Fundamental Plasma Experiments



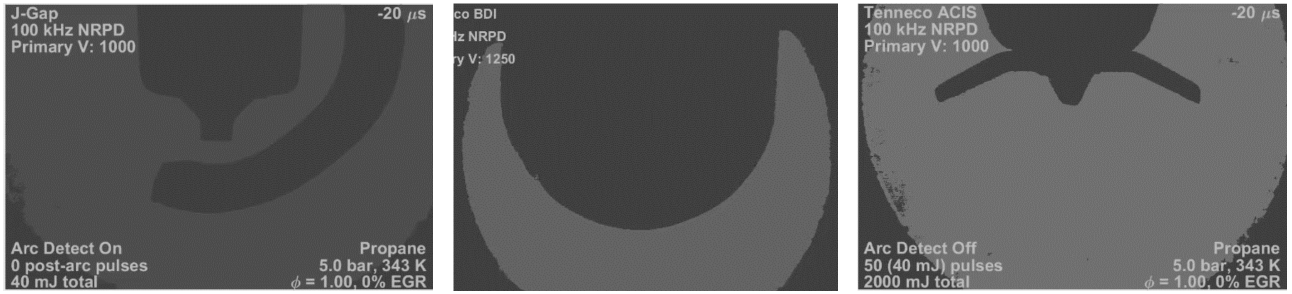


Dilution ignition limits measured for multiple spark and non-equilibrium plasma igniters

- Baseline spark ignition lean limit: ϕ =0.59 (93 mJ)
- Nanosecond spark igniters improve lean and dilution ignition limits
  - Greater extension for EGR dilution
- Spark igniters also use a lot less energy
  - Calorimetry performed to measure deposited energy (see Backup 1)
  - Streamer & spark energy use more consistent

Complementary schlieren imaging reveals ignition physics

- Early ignition kernel supported by additional discharges
  - Spark igniters supply expansion energy
  - Streamers form on ignition kernel – kernel grows along streamer front
- Excess discharge energy disrupts ignition due to localized extinction

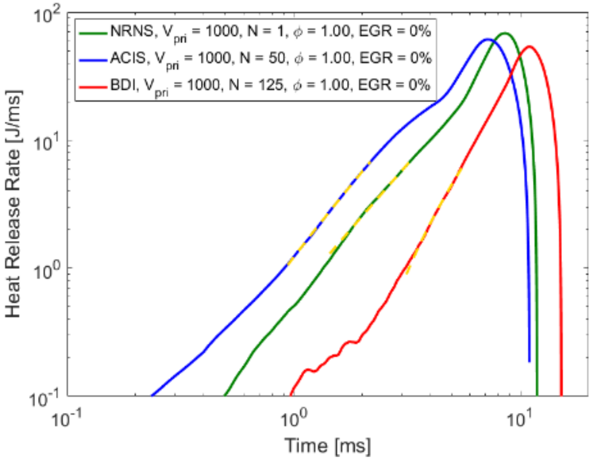


Need to characterization growth rates via heat release data

Accomplishments: Fundamental Plasma Experiments

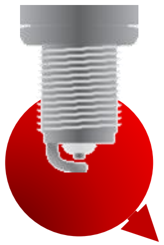
S.E.03.01

- **Large differences in flame development**
  - Does not always correlate with ignition limits



- **Only interested in first 10% of heat release period**
  - $\dot{Q}_{Work} = 4\pi LHV \cdot Y_{fuel}\rho S^3 (t - t_0)^2 - \dot{Q}_{Heat\ Loss}$

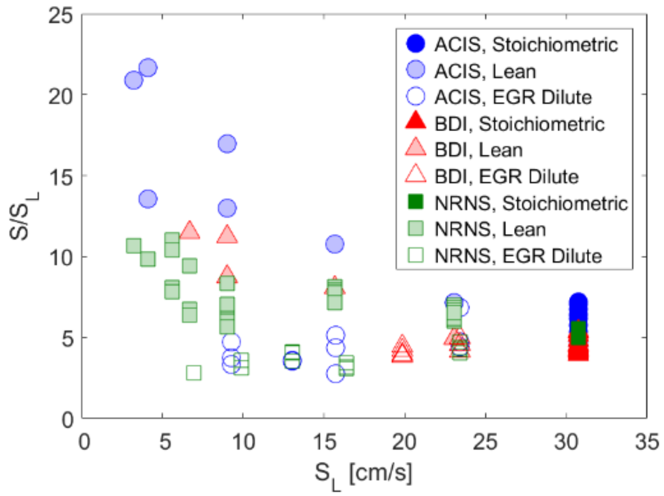
    Unknowns



  - Fit applied using the heat release data to get S and t_0
  - Values well-match with imaging data of kernel growth

S

- **Large differences in flame propagation rate for lean ignition**
  - Lean ignition readily accelerated by additional discharge energy – More so for streamer igniters
  - Dilute ignition not dependent on added discharge energy or discharge type

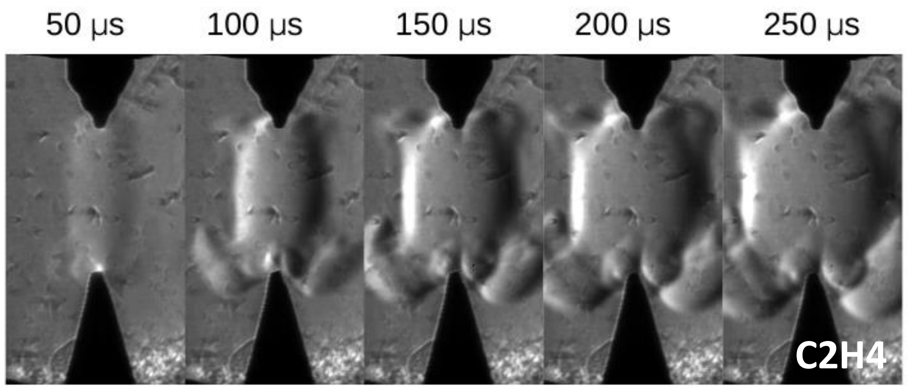


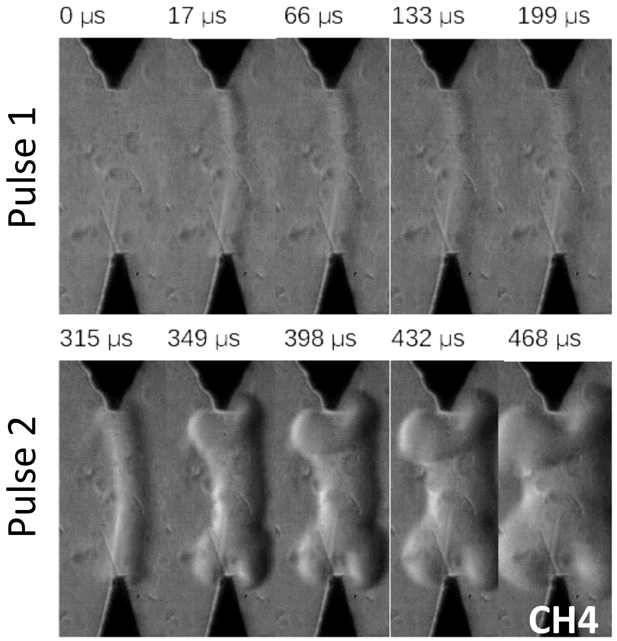
Streamer igniters seem best suited for lean combustion strategies

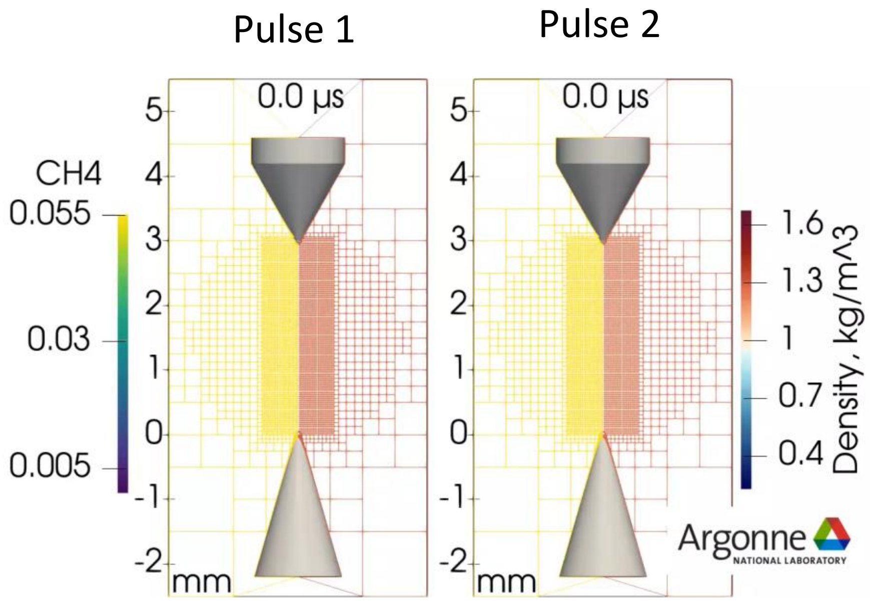
Accomplishments: Fundamental Plasma Ignition Modeling

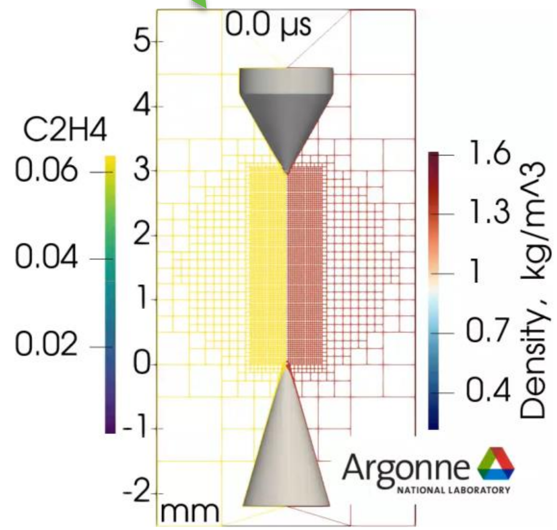
A.M.03

- **Ignition initialized via VizGlow discharge simulation outputs**
  - Used to create a temporally & spatially resolved energy source term: S_{LTP} (See Backup Slide 3)
  - S_{LTP} converted to a User Defined Function & used to initialize flame kernel
- **LTP ignition simulations qualitatively match experiments**
  - Methane-air (φ=1) required at least two pulses
  - Ethylene-air (φ=1) ignited with a single pulse
- **Simplified discharge models under development**







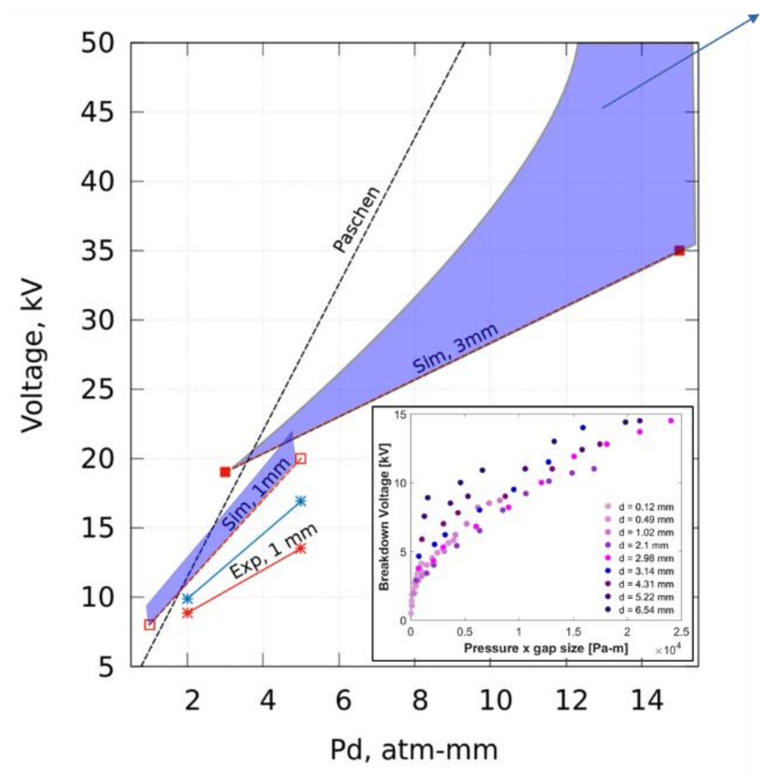


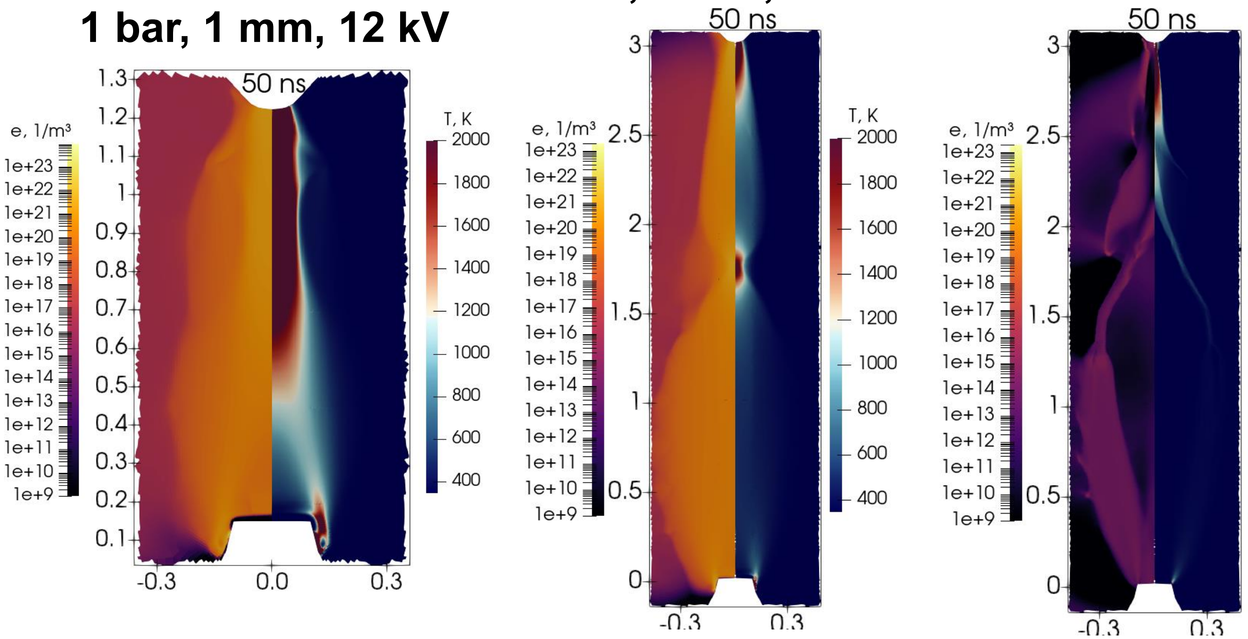
CONVERGE

Accomplishments: Fundamental Plasma Ignition Modeling

A.M.03
S.E.03.01

- **Development of predictive for streamer-arc transition capability**
  - *Major design constraint for streamer igniters*
  - VizGlow simulations correlated to experiments at a wide range of pressure/gap-size/voltage





- **Simulations capture previous experimental observations, and provide additional detail**
  - Streamer widths decrease with pressure
  - Branching increases with pressure
  - Gas heating decreases with pressure
  - Breakdown voltage increases with pressure and gap size but the rate of change decreases

Approach: Engine Testing

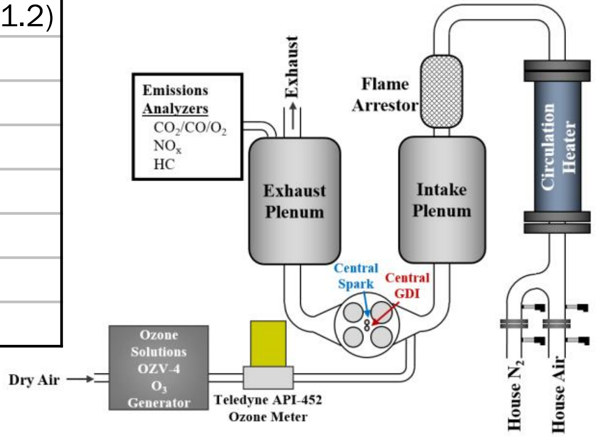
Homogeneous lean/dilute w/ plasma & passive PC (SNL):

- EGR (N2 only) and air dilution sweeps
- Heat release, emissions, and ignition imaging
- ***2 streamer & 3 spark-type plasma igniters evaluated***
- Passive pre-chamber with either spark or plasma igniters
- Multiple tip geometries (hole area, tangential angle)

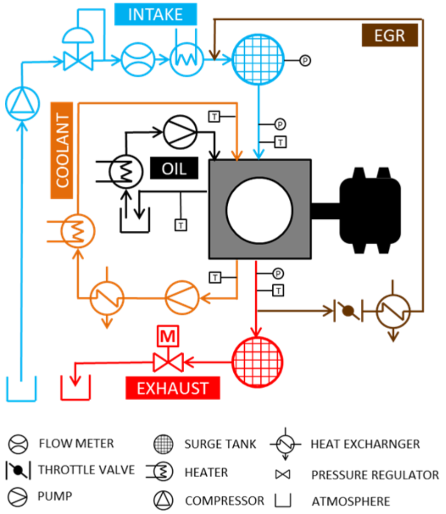
Homogeneous dilute w/ active/passive PC (ANL):

- EGR dilution sweeps
- Heat release and emissions measurements
- Instrumented pre-chamber
- Single tip geometries (4-hole)
- ***Companion modeling of PC residuals & jet momentum***
- ***Active PC: premixed fuel/air vapor***

SG2 Central DI/SI	
Injector	8-hole solenoid (HDEV 1.2)
Stroke/Bore	1.11
CR	13 (12.6 w/ PC)
Displacement [L]	0.55
Intake press. [bar]	0.5 – 0.7
Engine Speed [rpm]	1300
EGR [%]	0 – 27%
IMEP [bar]	3.5



EcoBoost Central DI/SI	
Injector	6-hole solenoid
Stroke/Bore	1.13
CR	11.3 (10.9 w/ PC)
Displacement [L]	0.63
Intake press. [bar]	0.5 – 0.7
Engine Speed [rpm]	1300, 1500
EGR [%]	0 – 32%
IMEP [bar]	3.5, 5.0

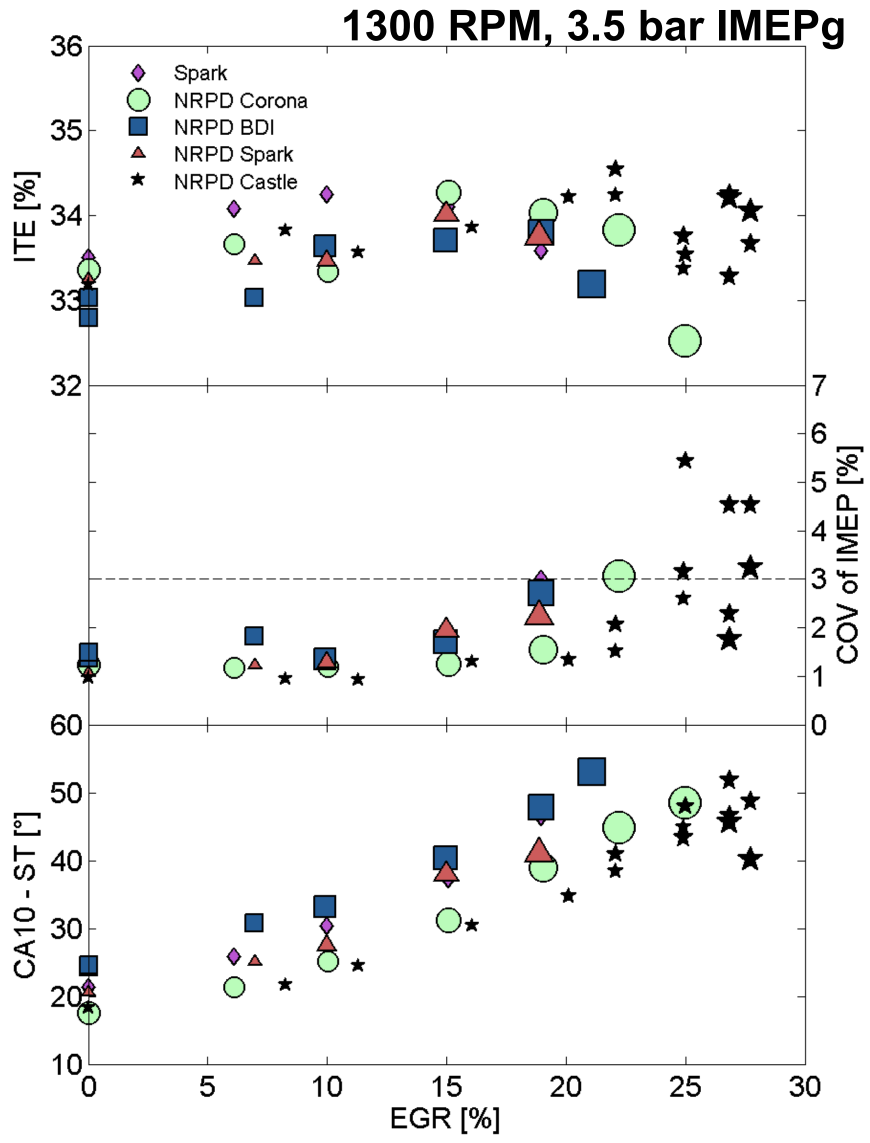


Additional lean-stratified work with ozone addition at SNL (see Backup slide 4)

Accomplishment: Homogeneous Plasma Ignition

S.E.03.01

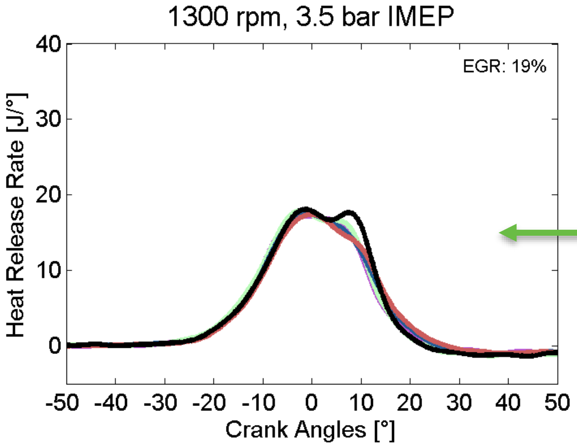
- **FY20: Demonstrated RF corona & NRPD spark extended lean limits and increased ITE relative to spark**
  - Spark: ϕ = 0.73, ITE: 32.5%
  - ACIS: ϕ = 0.68, ITE: 33.8%
  - NRPD Spark: ϕ = 0.65, ITE: 34.4%
- **NRPD igniters further extend lean limits increase ITE**
  - Peak ITE: 36.0% (NRPD Castle), 35.7% (NRPD Corona)
  - Strongest NOx reduction with NRPD castle (71% reduction)
  - Corona igniter limited by arcing but still had fastest early burn rates – consistent with static cell measurements
- **Little difference in igniter type on dilution limits or peak efficiency – confirms static-cell experiments**
  - Marginal benefit with NRPD Castle igniter but requires high energies that result in rapid electrode erosion
  - Corona igniter limited by increased arc propensity with higher dilution rates that restricted applied voltage that could be used



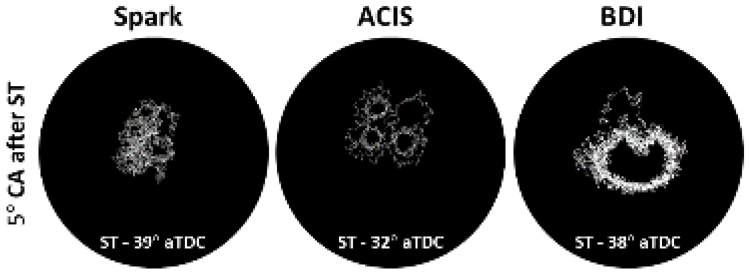
Accomplishment: Homogeneous Plasma Ignition

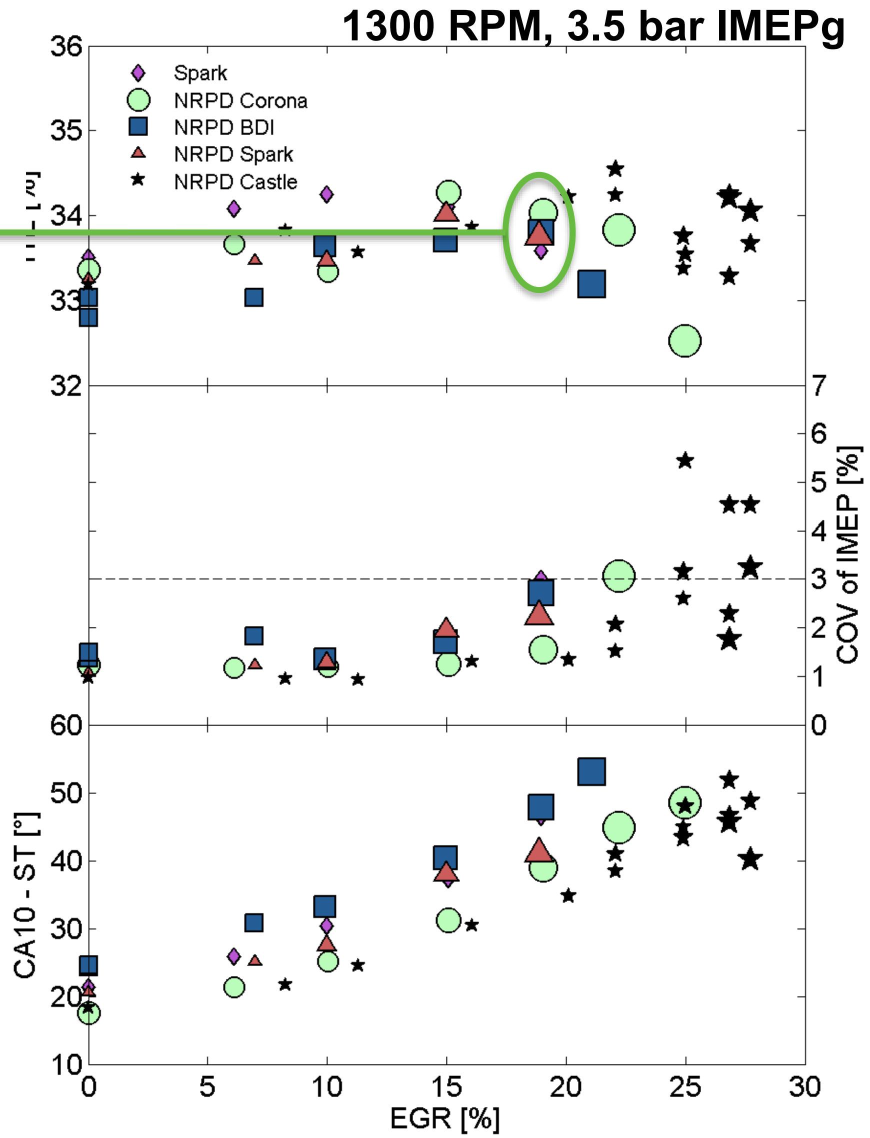
S.E.03.01

- **Auto-ignition inhibited by slow early flame development**
  - Exception is NRPD Castle igniter
    - Auto-ignition phasing highly variable



- **Imaging reveals better stability due to more repeatable early flame development for plasma igniters**
  - Corona stability limited by arc propensity w/ increase dilution
  - BDI stability limited by poor discharge energy deposition

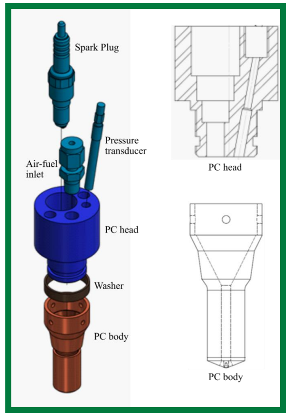




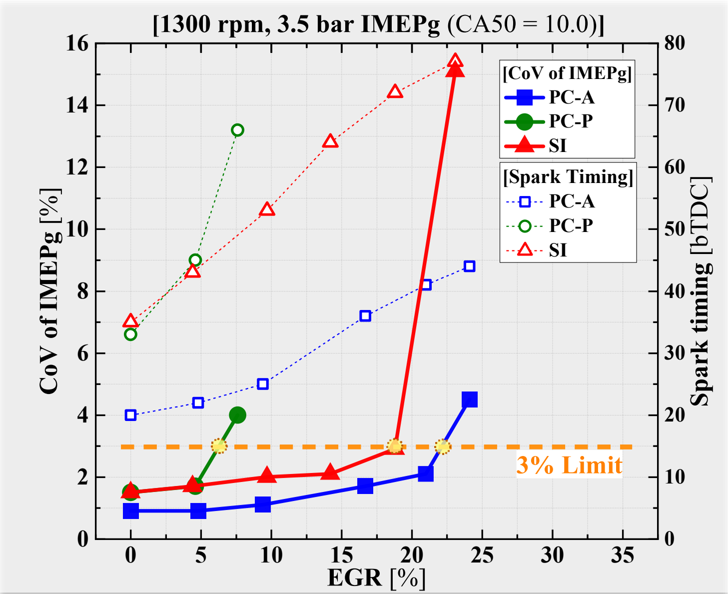
Given high discharge energies, plasma igniters likely cannot do better with current engine platform

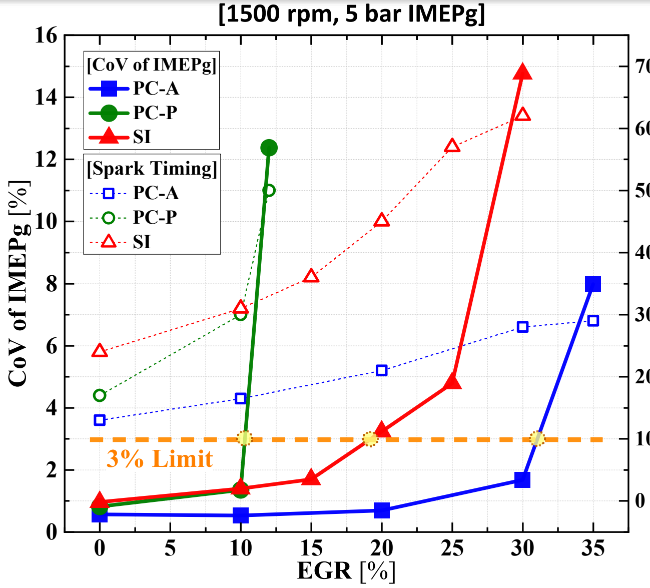
Accomplishment: Pre-Chamber Engine Ignition Testing

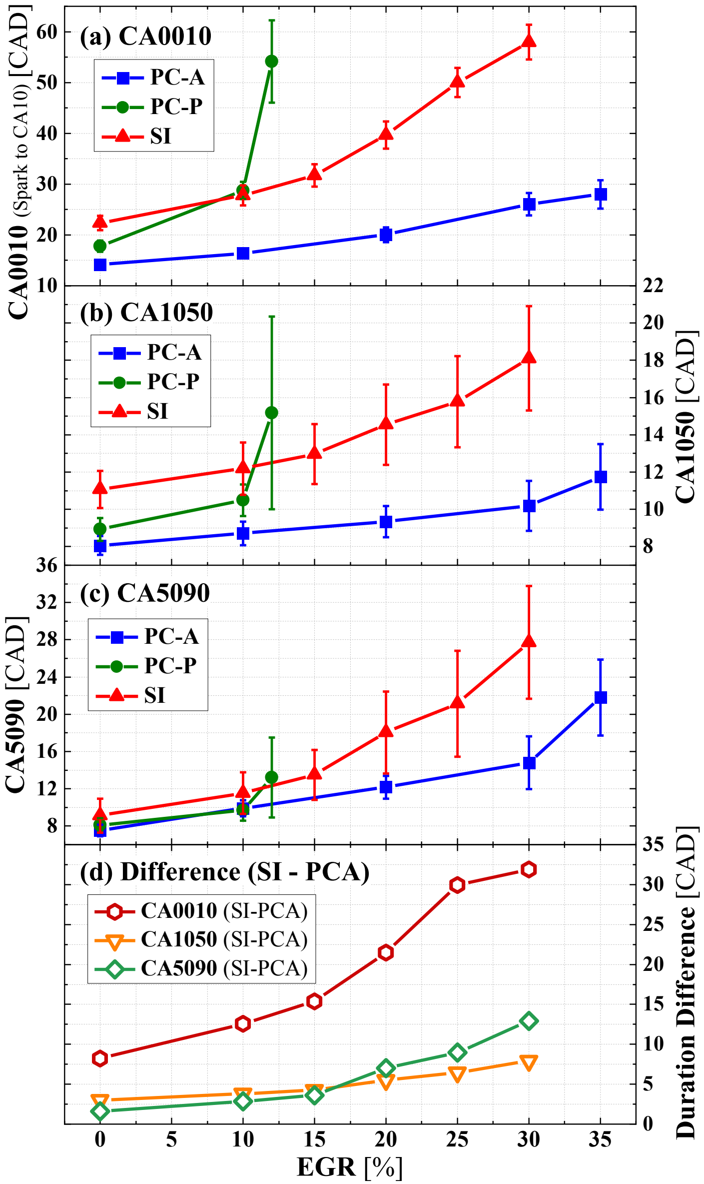
- **ANL developed active pre-chamber**
  - Funnel-throat concept
  - Pre-vaporized air/fuel
  - 3% of clearance volume
  - 4-nozzles – no swirl
  - Working with Tier 1s for production concepts



- **ACEC TT low-load (3.5 bar / 1300 rpm): 18% EGR SI baseline**
  - 7% EGR tolerance for Passive PC (PC-P)
  - 22% EGR tolerance for Active PC (PC-A)
- **Moderate load/speed (5 bar / 1500 rpm): 19% EGR SI baseline**
  - 10% EGR tolerance for PC-P
  - 32% EGR tolerance for PC-A
  - **Close to EGR tolerance goal**



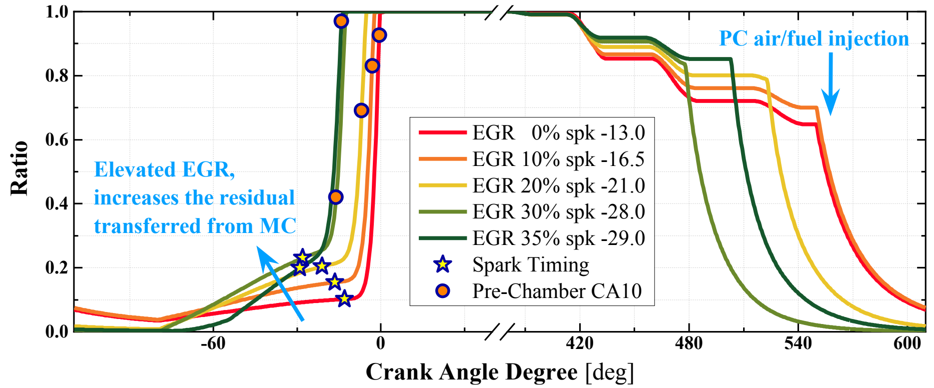


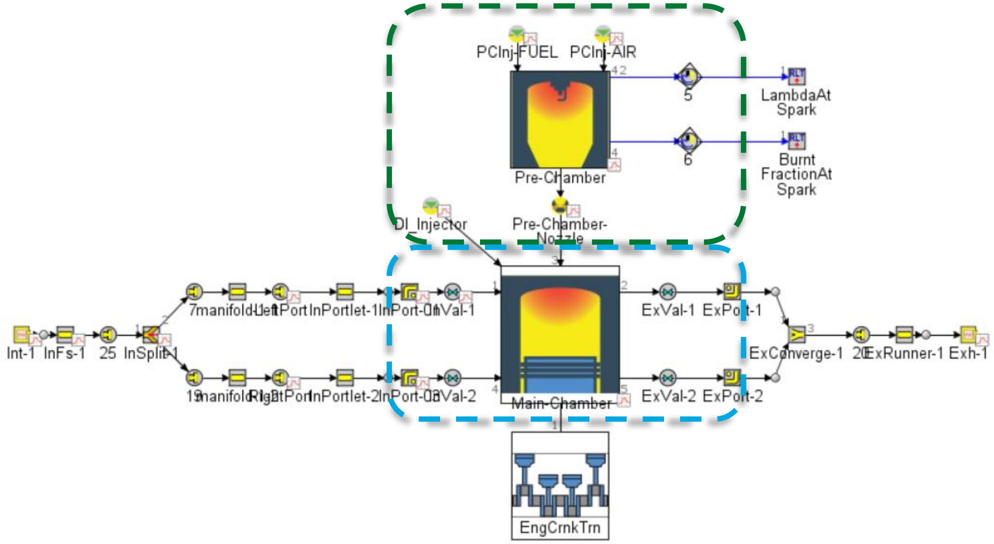


Accomplishment: 1D Pre-Chamber Tool Development

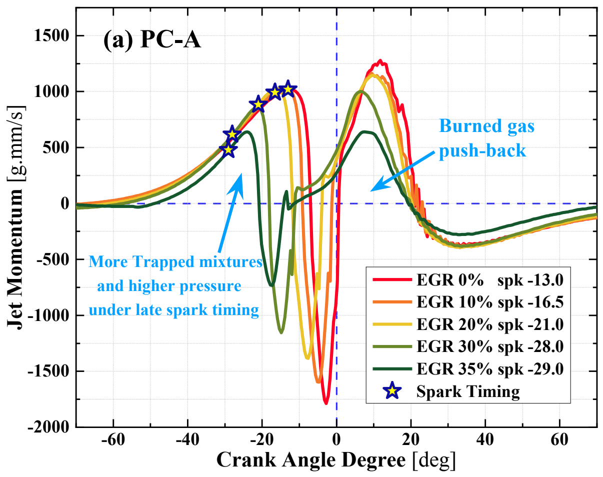
A.E.03

- **GT Power Model MC to PC gas exchange**
  - 1D gas exchange solved via energy & mass conservation using measured PC and MC pressure data
  - Estimates pre-chamber residual gas fraction at spark timing





- **Pre-chamber combustion**
  - Genetic optimization of Wiebe function anchor angle, burn rate & exponent using experiment data
  - Estimates jet-exit momentum



- **Main Chamber combustion**
  - Imposed burn rate from experiment data & Three Pressure Analysis
  - Start of combustion set by PC 50% MFB point
  - Refinement ongoing

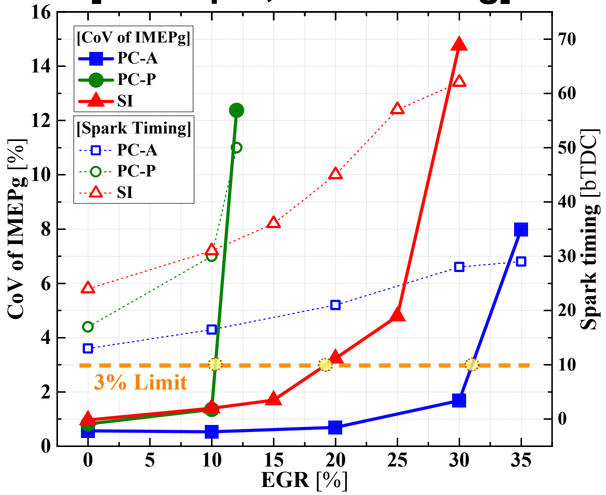
Accomplishment: Pre-Chamber Combustion Analysis

A.E.03

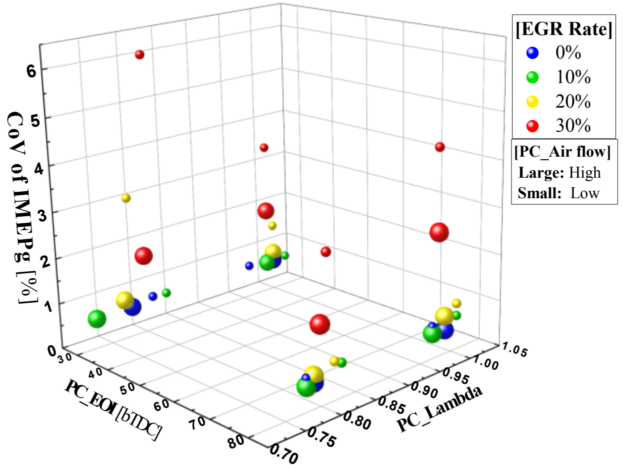
PC-A injection control parameters (λ_{PC}, EOI_{PC}, and m_{PC}) investigated to identify influence on different PC and MC combustion properties

- **MC Combustion CoV**
  - Higher m_{PC} improves stability
  - **Rich** PC mixtures produce good stability regardless of EOI_{PC}
  - **Stoichiometric** PC mixtures only stable for late EOI_{PC}

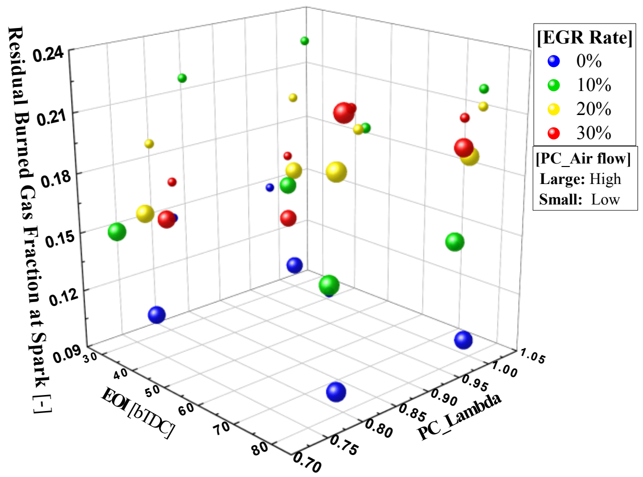
[1500 rpm, 5 bar IMEPg]



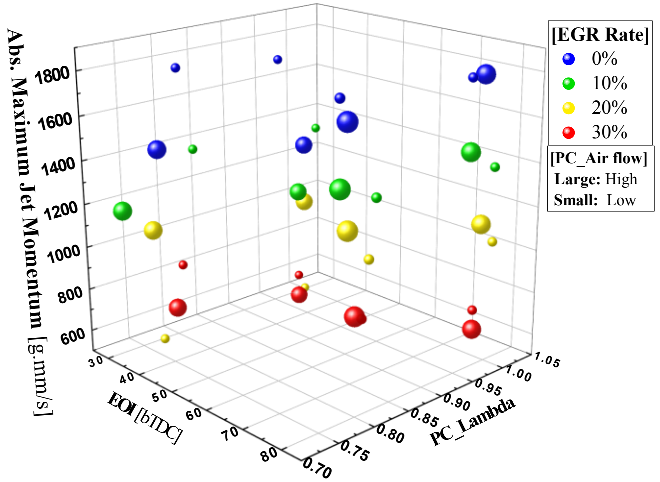
COV



PC Residual Gas Fraction



Max Jet Momentum

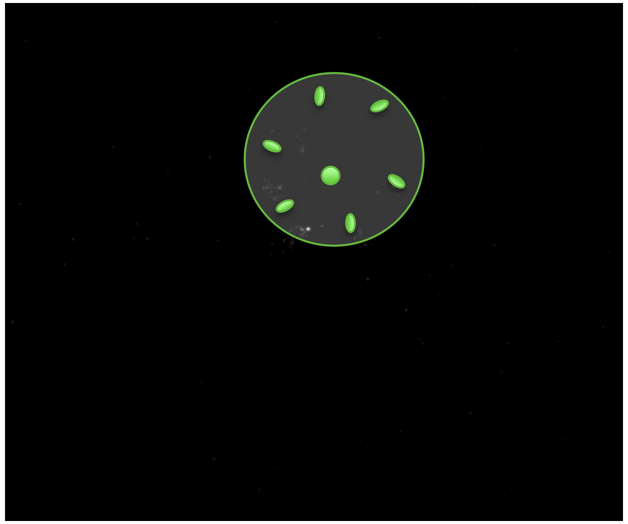


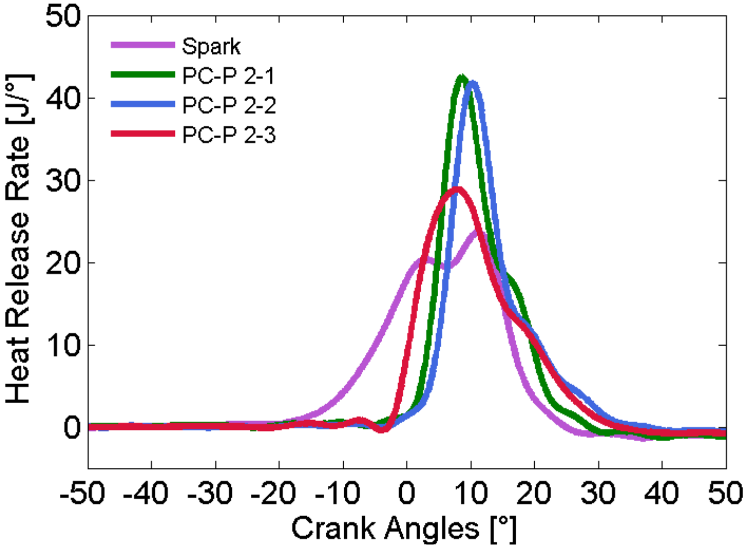
- **PC Residual Gas Fraction:**
  - Improved scavenging with increased m_{PC}
  - Reduced residuals with late EOI_{PC}
- **Jet Momentum:**
  - Late EOI_{PC} reduces jet momentum
  - Higher jet momentum with lower λ_{PC}
- **1D modeling needed to link jet exit momentum and energy to MC combustion (see future work)**

Accomplishment: Pre-Chamber Imaging Experiments

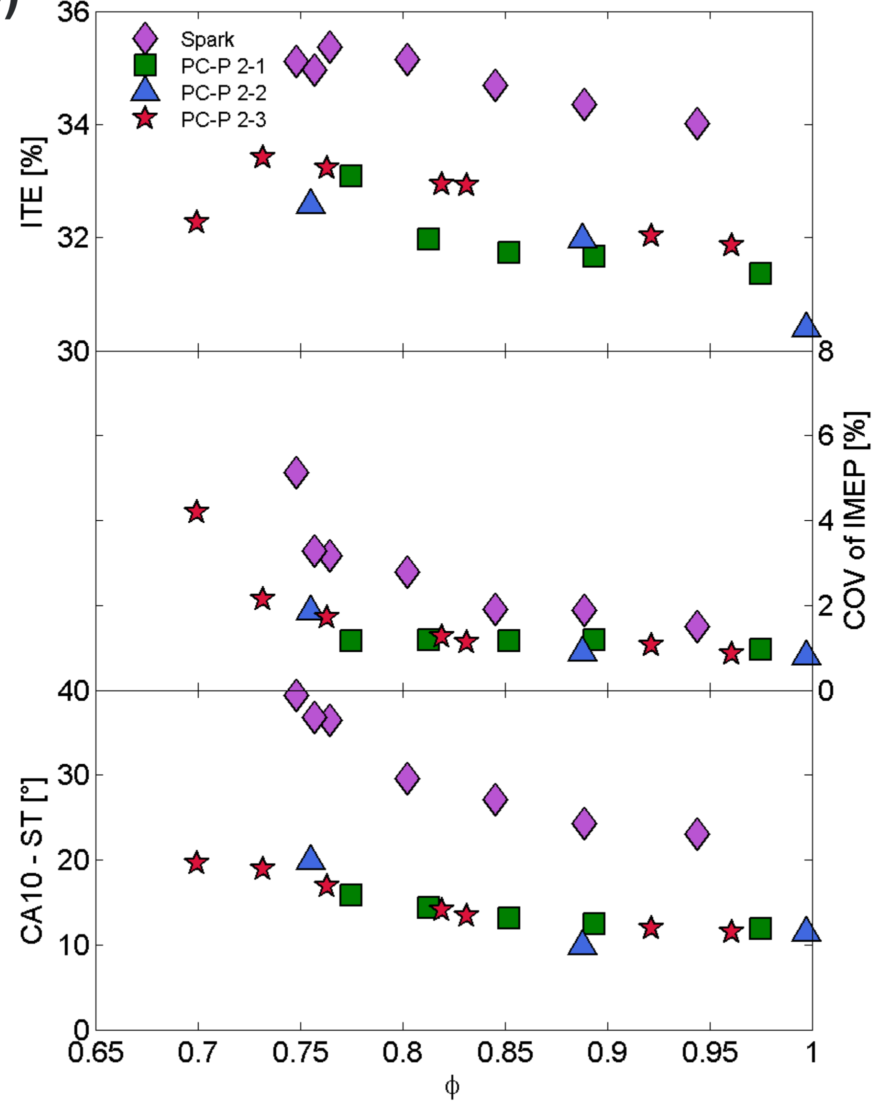
S.E.03.01

- **Similar passive PC with 6 x tangential nozzles (See Backup 5)**
  - All PC demonstrated improved lean limit relative to SI
  - PC-P 2-1: Added center hole nozzle, larger PC volume (2.0 cc)
    - Early central ignition followed by 2nd stage radial ignition
    - CMT simulations well-matched to the data
  - PC-P 2-2: Same hole arrangement, smaller PC volume (1.7 cc)
    - Virtually identical ignition characteristics as PC-P 2-1
  - PC-P 2-3: no center hole nozzle, smaller PC volume (1.7 cc)
    - Radial ignition followed by combustion in the core

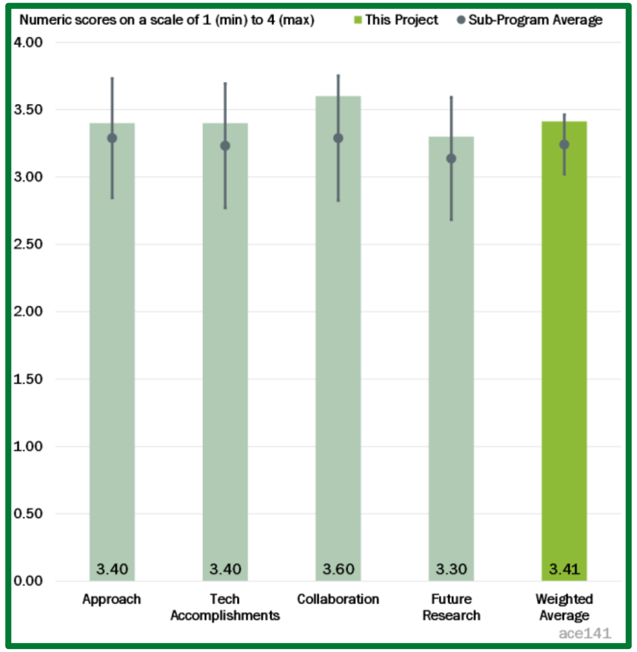




1300 RPM, 3.5 bar IMEP



Response to Reviewer Comments



Approach/Relevance

- **R3: … effort is needed to understand the mechanisms [of the jet] ignition process ...**
  - **Agreed!** In FY21 we leveraged CFD and 1D engine models to evaluate different nozzle hole arrangements with select variants tested in thermodynamic/optical test engines. Imaging and heat release data are being used to identify ignition mechanisms and improve the predictive capability of the modeling approaches.
- **R4: … can [you] narrow options to one ignitor path?**
  - We have already down-selected laser and rail plug igniters. Our current focus is on streamer, nanosecond spark, and active/passive pre-chamber igniters. These igniters have favorable features for advanced combustion concepts under consideration by various OEMs (e.g., high-tumble, mixed-mode). No igniter is optimal for every advanced combustion strategy.
- **R5: … more measurements of ignition energy - primary and secondary - should be made and reported. / R2: … compare results between new ignition systems and current ignition systems with equal energy input**
  - We agree this was lacking. As such we reported extensively the primary and deposited energy each plasma igniter.

Technical Accomplishments

- **R2: … emphasize EGR tolerance at stoichiometric conditions / R4: … pursue stoichiometric dilute combustion / R5: ... [results that extend] the EGR tolerance of stoichiometric gasoline combustion have not been met**
  - Stoichiometric dilute combustion research comprised roughly half of all work performed for plasma ignition, and more than half of work performed for pre-chamber related research. This includes evaluation of active pre-chamber igniters with air addition.

Collaboration and Coordination

- **R5: … more collaboration with conventional ignition system suppliers is required to keep the project at a practical level**
  - For this project we worked closely with advanced ignition system suppliers with engagement of conventional ignition system suppliers reserved for for ACE 142.

Future Research

- **R3: … looking forward to active pre-chamber research. Are catalyst heating conditions sufficiently represented in the future plans? / R5: More work on pre-chamber ignition and high-load ignition should be conducted as these are important to the OEMs.**
  - In FY21, we evaluated active pre-chambers at Argonne and passive pre-chamber igniters at Sandai. At both labs, the dilute ignition testing is nearly complete, and we will transition to evaluation of catalyst heating conditions in Q3/Q4. High-load ignition tests are planned for FY22.
- **R4: How do we leverage current understanding for electrode wear?**
  - While direct prediction of electrode wear is largely beyond our expertise and capability, predictive capability for arc propensity discussed here is essential for associated electrode wear calculations. We are accordingly working with modeling groups that specialize in wear prediction to ensure compatibility with our discharge prediction methods.

Collaboration and Coordination

- **PACE Coordination**
  - Internal pre-chamber spark ignition modeling (***Scarcelli, ACE 141***)
  - Ignition prediction at lean/dilute part-load and boosted high-load (***Ameen, ACE 146***)
  - Associated auto-ignition characteristics from BDI generated ozone (***Wagnon, ACE 139***)
  - Catalyst warm-up operation during cold-start (***Edwards, ACE 145***)
- **Connections to other DOE projects**
  - **DE-EE0008874:** Development of a High-Fidelity LTP Model for Predictive Simulation Tools
    PIs: Nick Tsolas (U. Auburn), Fabrizio Bissetti (U. Texas – Austin)
  - **DE-SC0013824:** SBIR Phase IIB, Low-energy nanosecond pulsed ignition system
    PI: Dan Singleton (Transient Plasma Systems Inc.)
  - HPC for manufacturing FOA: Modeling of Non-equilibrium Plasma for Automotive Applications
    PI: Dan Singleton (Transient Plasma Systems Inc.)
- **External Collaborations**
  - ***Tenneco / Transient Plasma Systems Inc.***: Plasma igniter development and testing
  - ***Mahle Powertrain***: Integration of active pre-chamber igniter into PACE engine
  - ***Gamma Technologies***: Development of 1D pre-chamber ignition modules
  - ***CMT Motores***: Passive pre-chamber testing with plasma ignition
  - ***Esgee Technologies***: High-fidelity plasma discharge modeling

Remaining Challenges and Barriers

- **Streamer plasma ignition works best for lean combustion, but is less effective at dilute conditions**
  - Most discharge energy (95%+) is reflected back to the pulse generator. Methods for improved energy deposition via improved impedance matching are needed.
  - Simplified methods for modeling streamer discharges are needed that capture the streamer growth using rules-based 1D growth and branching with minimal computational time
  - A comparative study of discharge voltage and insulator thickness for BDI is needed along with an evaluation of best-practice manufacturing methods and dielectric material properties.
- **NRPD BDI do not produce ozone concentrations observed during static-cell testing**
  - Temperature is the likely culprit, so lower intake temperature conditions need to be evaluated.
- **Equilibrium plasma from nanosecond sparks result in significant electrode erosion**
  - Electrode configurations that minimize applied voltage while maximizing deposition efficiency are needed
- **Pre-chamber ignition performs poorly at idle & cold-start conditions due to excess PC residual gases**
  - It is unclear what nozzle hole patterns work best for different conditions and importantly what works well across the load/speed map. Validated methods for rapid hole patternation evaluation are needed.
  - Improved ignitability of internal PC fuel/air/residual gas mixtures via high-energy ignition concepts need evaluation
    - Still unclear what turbulence model is best (WSR?, G-Eqn?, ECFM?) and how to treat heat transfer (e.g., conjugate heat transfer?)
  - Quantitative characterization of PC jet-exit products needed for better understanding of ignition mechanisms
  - PC heat losses are a major efficiency challenge. Thermo swing coatings are needed to minimize these losses

Future Work

- **Nanosecond pulse BDI ozone formation experiments**
  - Evaluate why engine generated ozone does not match static cell or modeling results
    - Switch to RF BDI if NRPD BDI continues to fail
- **Pre-chamber ignition**
  - Perform direct sampling within PC to evaluate 1D model performance
  - Implement/calibrate 1D jet-ignition combustion model that matches burn rates & observed combustion behavior
- **Catalyst light-off during cold-start experiments (PC and plasma)**
  - Demonstrate comparable or superior performance to baseline spark testing
  - ACEC TT Cold-Start Protocol
    - 1300 rpm, 2 bar IMEP, 20°C coolant & intake temperature
    - Exhaust Heat Flux: 3 – 10 kW/liter (stoichiometric)
- **High-load crossflow facility and engine testing: 80% peak load @ 2000 rpm**
  - Measure burn rates with varying crossflow velocities
  - Demonstrate improved high-load KLSA due to faster early burn rates with PC & NRPD plasma ignition
- **Reduced order plasma streamer modeling**
  - Develop simplified rules-based plasma streamer ignition model that can be implemented as a UDF in an engineering-level combustion solver

Summary

Relevance

- PACE goals speed discovery of knowledge, improve engine design tools, and enable market-competitive powertrain solutions with potential for best-in-class lifecycle emissions
- Tasks directly address USDRIVE research priority 1: Dilute Gasoline Combustion and priority 3: Low-Temperature Combustion (LTC)
    - Removes barriers to advanced ignition

Approach

- Experiment facilities developed to replicate relevant conditions at dilute, high-load, and cold-start; with companion diagnostics to identify relevant ignition phenomena
- High-fidelity discharge and ignition modeling capability developed to identify dominant ignition mechanisms that can then be used for reduced order model development
- Combination of thermodynamic and optical engine experiments performed using custom igniter hardware to evaluate ignition mechanisms and benchmark performance

Accomplishments

- Demonstrated that streamer igniters have low deposited-to-discharge energy efficiency due to poor impedance matching of the voltage pulse
- Developed a method to evaluate igniter induced early flame growth rates using heat release data – validated with flame kernel growth imaging

Accomplishments (Cont.)

- Successfully modeled multi-pulse streamer ignition using a combination of high-fidelity discharge simulations and a newly developed LTP energy source model
- Demonstrated increased dilution tolerance with active PC
- Used developed 1D PC gas exchange & ignition models to evaluate the influence of active PC parameters on engine performance
- Demonstrated improved lean ignition limit with passive PC relative to high-energy spark through nozzle hole optimization

Collaborations

- PACE is a collaboration of 5 national laboratories; work plans are developed considering input from ACEC TT, code developers, and industry users
- PACE projects presented at AEC MOU program review meeting
- External collaborations with Tenneco, TPS, CMT, U. Auburn, U. Texas, and other university partners

Future Work

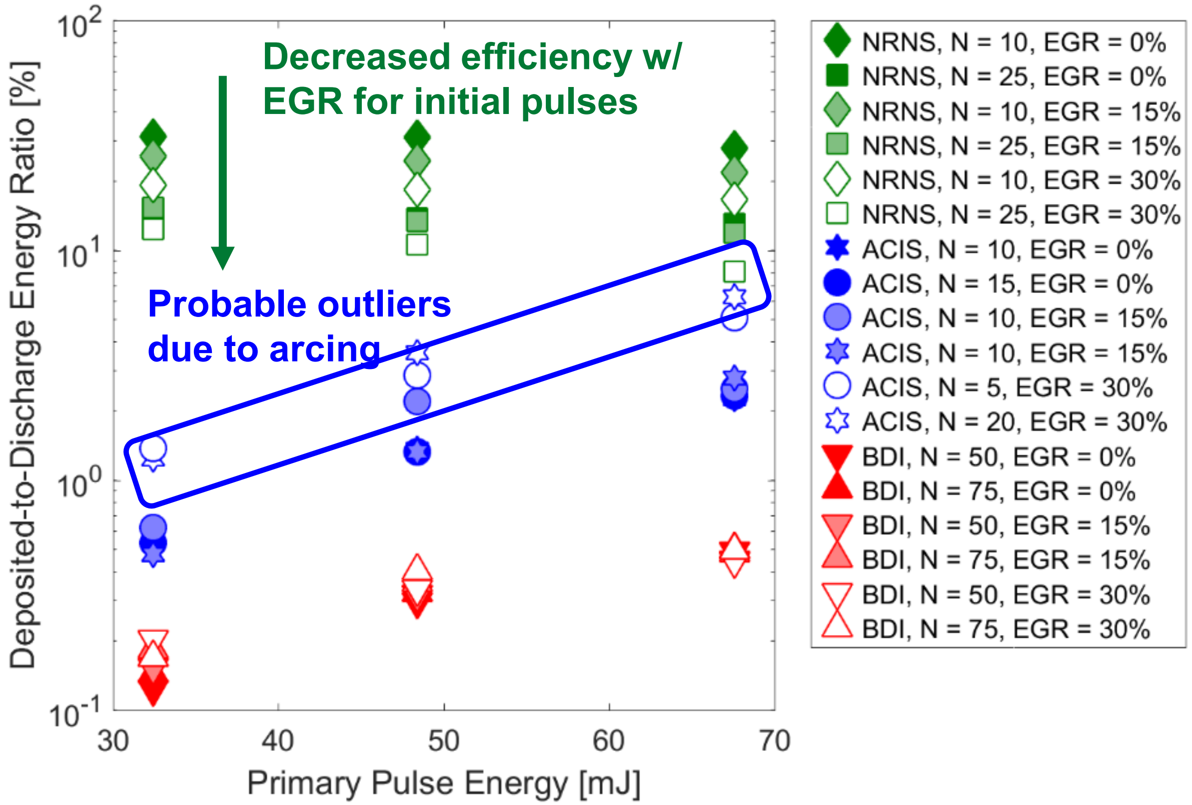
- Nanosecond pulse BDI ozone formation experiments
- Pre-chamber ignition 1D jet ignition mode development
- Catalyst light-off during cold-start experiments (PC and plasma)
- High-load crossflow facility and engine testing:
- Reduced order plasma streamer modeling

BACKUP SLIDES

Technical Backup 1: Plasma discharge calorimetry

S.E.03.01

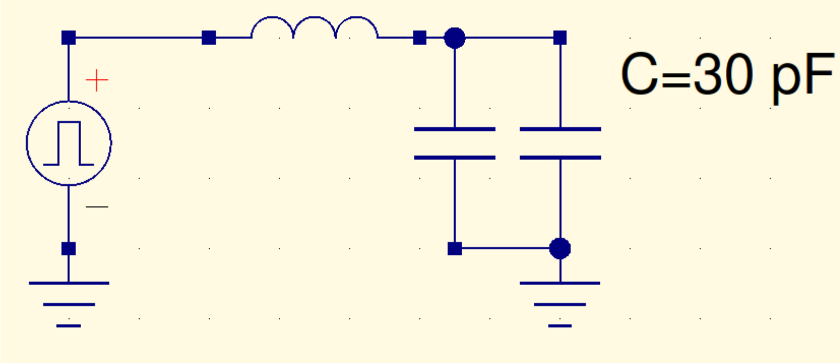
- **Measured energy deposition for nanosecond spark and streamer igniters**
  - Specified discharge energy with pressure-rise calorimetry used to measure deposited energy
  - Evaluated impact of **discharge number** and **EGR composition**
  - Inert mixtures only
- **Nanosecond spark energy deposition More efficient**
  - Efficiency drops with successive pulses
  - EGR decreases deposition efficiency
- **Corona deposition efficiency drops by an order of magnitude (Max 5%)**
  - Linear increase with pulse voltage (i.e., energy)
  - Invariant to EGR
- **BDI deposition efficiency less than 1%**
  - Linear increase with pulse voltage (i.e., energy)
  - Invariant to EGR



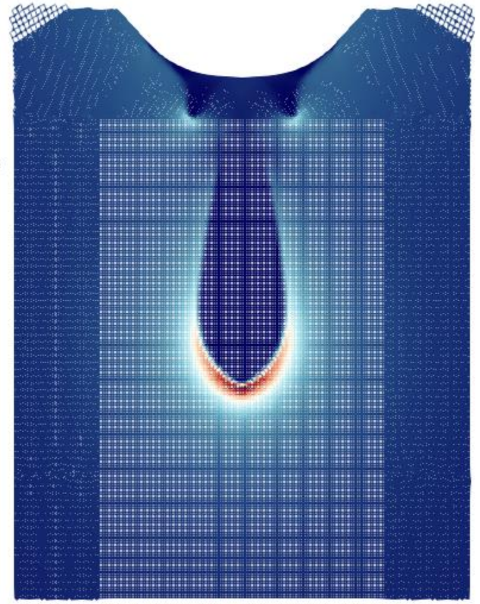
Technical Backup 2: Simulation Circuit & Discharge Model

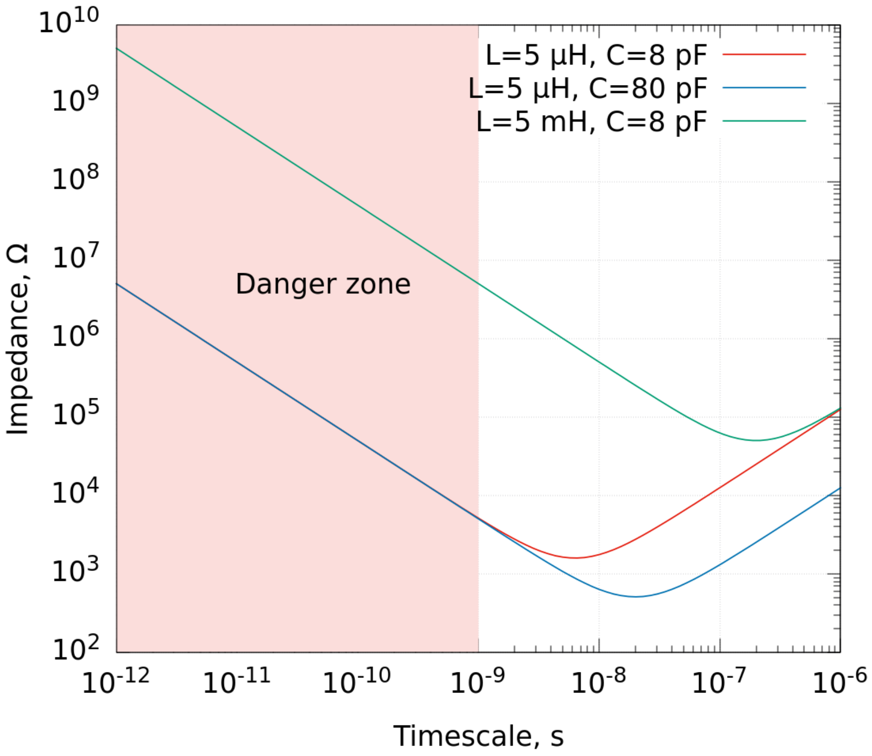
A.M.03

- **Circuit impedance (and thus current) controlled by adjusting upstream capacitance and inductance**



- **VizGlow simulations are run for a 2μm mesh in the streamer vicinity**
  - Photoionization neglected
  - No fluid dynamics
  - No surface electron emission





Technical Backup 3: Combustion Discharge Source Term

A.M.03

- **Converge setting**
  - No turbulence model
  - AMR with a minimum 31.25 µm cell size
  - Chemistry solved using Foundational Fuel Chemistry Model (FFCM-1) http://nanoenergy.stanford.edu/ffcm1
  - Source term due to Low Temperature Plasma, S_{LTP} given by

$$B(t) = \left(1 + fl(\frac{t}{\tau_p} - 1) - fl(\frac{t}{\tau_p} - \hat{\tau})\right) \times H(t - fl(\frac{t}{N\tau_p}))$$

$$f(x,y,z) = e^{-\left(\frac{x^2+y^2}{2\sigma_g^2} + \frac{(z-m(z))^2}{2\sigma_f^2}\right)}$$

where $m(z)$ results in heating close to z_a, z_c, and z_i via:

$$m(z) = \begin{cases} z_a & z \geq \alpha z_i \\ z_i & \alpha z_i < z < \beta z_i \\ z_c & z \leq \beta z_i \end{cases}$$

$$S_{LTP}(x,y,z,t) = AB(t)\left(f(x,y,z) + g(x,y)(h_a(z) + h_c(z))\right)$$

$$g(x,y) = e^{-\left(\frac{x^2+y^2}{2\sigma_g^2}\right)}$$

$$h_a(z) = \begin{cases} 0 & z \geq z_a \\ a_a z^2 + b_a z + c_a & z_i \leq z \leq z_a \\ 0 & z \leq z_i \end{cases}$$

where

$$a_a = 4(1-H_a)/d_a$$
$$b_a = 4\left(H_a(z_i+z_a) - z_i - z_a\right)/d_a$$
$$c_a = \left(2z_i z_a(1-2H_a) + z_i^2 + z_c^2\right)/d_a$$
$$d_a = z_i^2 - 2.0 z_i z_a + z_a^2$$

$$h_c(z) = \begin{cases} 0 & z \leq z_c \\ a_c z^2 + b_c z + c_c & z_c \leq z \leq z_i \\ 0 & z \geq z_i \end{cases}$$

where

$$a_c = 4(1-H_c)/d_c$$
$$b_c = 4\left(H_c(z_i+z_c) - z_i - z_c\right)/d_c$$
$$c_c = \left(2z_i z_c(1-2H_c) + z_i^2 + z_c^2\right)/d_c$$
$$d_c = z_i^2 - 2.0 z_i z_c + z_c^2$$

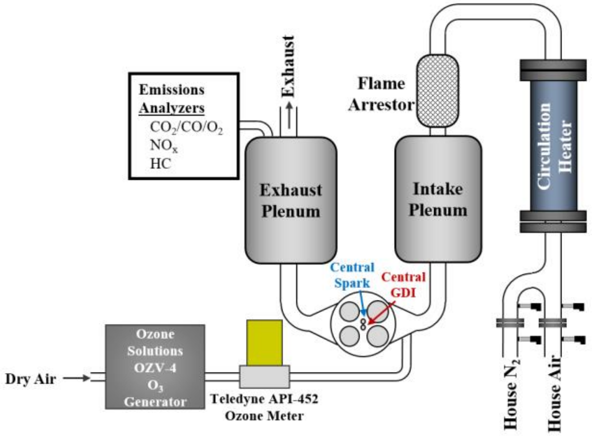
Technical Backup 4: Lean-Stratified with Ozone Addition

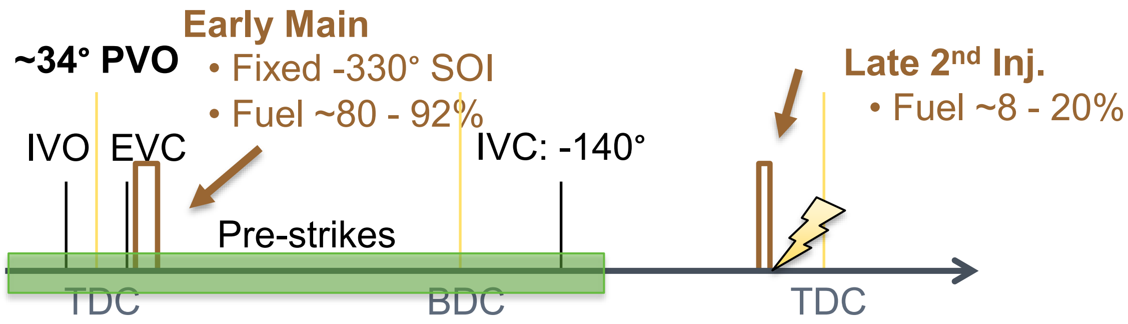
S.E.03.01

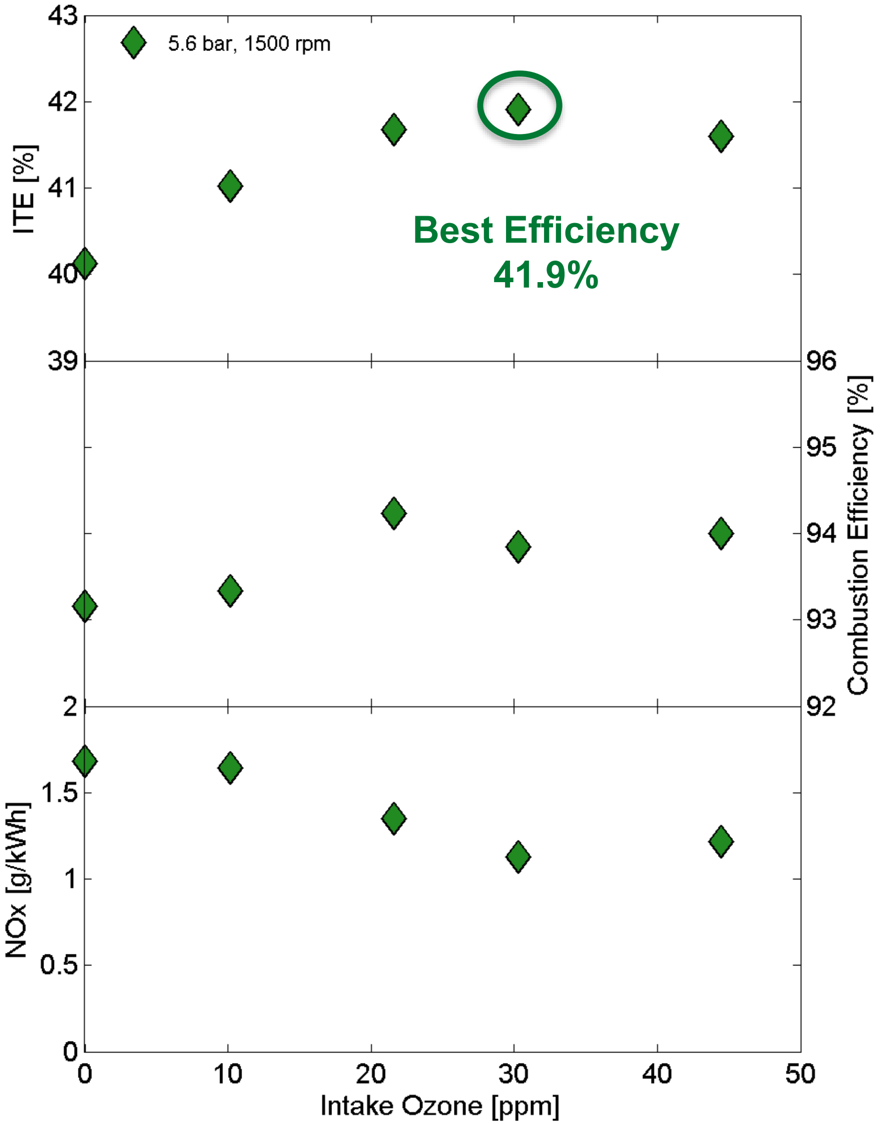
O_3 Enhanced Mixed-Mode:

- Intake seeded ozone with conventional spark - baseline
- ***BDI formed ozone and ignition - ongoing***
- Discharge and ignition imaging
- ***Ozone absorption measurements***

SG2 Central DI/SI	
Injector	8-hole solenoid (HDEV 1.2)
Stroke/Bore	1.11
CR	13 (12.6 w/ PC)
Displacement [L]	0.55
Intake press. [bar]	1
Engine Speed [rpm]	800, **1300**, 1500
phi	**0.36**, 0.48
Intake O_3 [ppm]	0 - 110
IMEP [bar]	1.0, **3.5**, 5.6





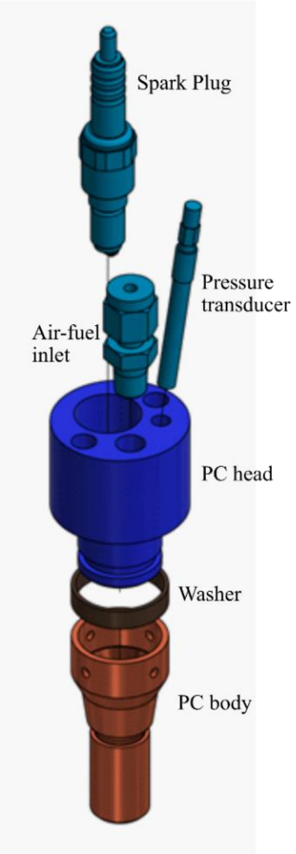


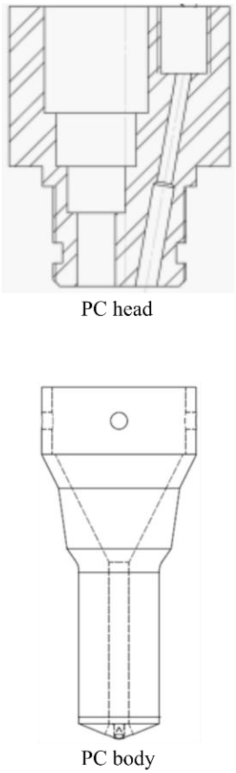
Technical Backup 5: Pre-chamber geometry

A.E.03
S.E.03.01

ANL

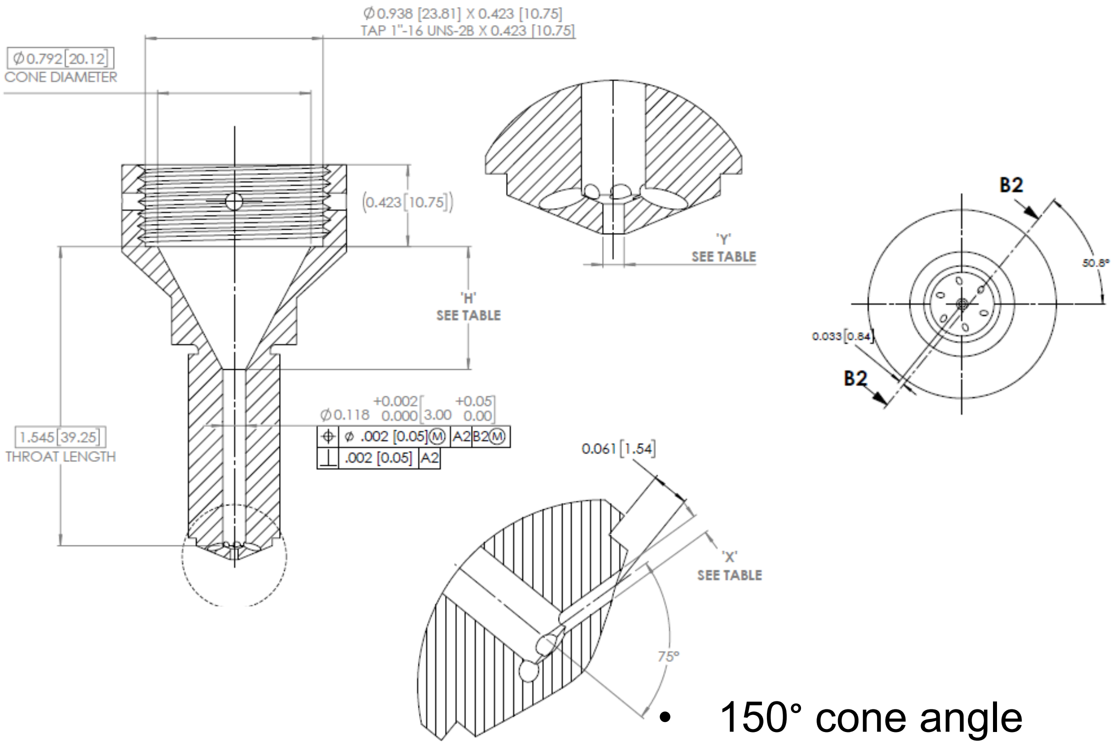
Igniter	Hole (#/diam. [mm])	PC Volume [cc]	Cone Angle [°]	Throat Diam. [mm]
ANL 1	4 / 2.0	2.0	80°	7.0





SNL

Igniter	Radial Hole (#/diam. [mm])	Center Hole (#/diam. [mm])	PC Volume [cc]
PC 2-1	6 / 0.8	1 / 1.0	2.0
PC 2-2	6 / 0.8	1 / 1.0	1.7
PC 2-3	6 / 1.2	1 / 1.0	1.7



- 150° cone angle
- 12.5° tangential angle
- Throat diameter: 3 mm

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.

High-dilution engines can achieve comparable 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 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., Ekoto, I., Singleton, D., Mixell, K., “Nanosecond Pulsed Ignition for Automotive Applications: Performance and Emissions Characteristics of Gasoline Combustion in an Optical Engine,” SAE WCX, SAE 2021-01-0475.
2. Biswas, S., Ekoto, I., Singleton, D., Mixell, K., Ford, P, “Assessment of spark, corona, and plasma ignition systems for gasoline combustion,” ICEF 2020 -3034.
3. Rohwer, J., Han, T., Shah, A., Rockstroh, T., “Investigations into EGR dilution tolerance in a pre-chamber ignited GDI engine,” IJER (under internal review)
4. Gururajan, V., Scarcelli, R., Biswas, R., Ekoto, I., “CFD modeling of low temperature ignition processes from a nanosecond pulsed discharge at quiescent conditions,” ASME ICEF 2021 (under review)
5. Gururajan, V., “Numerical simulations of point-to-point electrical breakdown at engine relevant conditions,” Journal of Applied Physics-D (under preparation)
6. Gururajan, V., “Numerical Computation of Minimum Ignition Energies for Low Temperature Plasma discharges,” Combustion and Flame (under preparation)
7. MacDonald, J., Di Sabatino, F., Biswas, S., Ekoto, I., Singleton, D., “Comparison of nanosecond streamer and arc ignition characteristics at engine combustor relevant conditions,” Combustion and Flame (under preparation).

Presentations:

Apr 2021: Rohwer, J., Han, T., Shah, A., Rockstroh, T., “EGR dilution tolerance for stoichiometric operation in a pre-chamber ignited GDI engine”, Oral only presentation at SAE WCX2021

Ap 2021: Scarcelli, R., Ekoto, I., Moderator: Advanced Ignition Concepts: Technical Challenges and Opportunities - Roundtable Discussion, SAE WCX2021

Feb 2021: Ekoto., I., “Comparison of Discharge and Ignition Characteristics for Nanosecond Pulsed Corona, Barrier Discharge, and Spark Igniters ,” Advanced Engine Combustion Program Review Meeting, Remote.

Feb 2021: Ekoto., I., “Initial Evaluation of Part-Load Engine Performance and Emissions with the Use of Prototype Nanosecond Pulsed Igniters”,” Advanced Engine Combustion Program Review Meeting, Remote.

Feb 2021: Gururajan, V., “Progress on Modeling Streamer Discharges and Non-Equilibrium Plasmas,” Advanced Engine Combustion Program Review Meeting, Remote.

Aug 2020: Biswas, S., “Assessment of Spark, Corona, Barrier Discharge, and Nanosecond Pulsed Discharge Ignition Systems for Gasoline Combustion for a Common Part-Load Operating Point,” Advanced Engine Combustion Program Review Meeting, Remote.

Aug 2020: Biswas, S., “Assessment of Spark, Corona, Barrier Discharge, and Nanosecond Pulsed Discharge Ignition Systems for Gasoline Combustion for a Common Part-Load Operating Point ,” Advanced Engine Combustion Program Review Meeting, Remote.

2020-2021: Multiple in-person and web meetings with GM, Ford, Transient Plasma Systems Inc, Tenneco, CMT

Complete PACE Budget FY21

Code and Work Flow Development

		Lab	PI	FY20	FY21
A.M.05.01	Spray and Combustion model implementation	ANL	Ameen	350k	340k
A.M.05.02	Gridding, validation, and workflow development	ANL	Ameen	350k	300k
A.M.05.04	MO1 Integration	ANL	Som		75k
A.M.05.05	MO5 Integration	ANL	Scarcelli		75k
L.M.05.01	Accelerated multi-species transport in engine simulations	LLNL	Whitesides	275k	250k
L.M.05.02	Improved chemistry solver performance with machine learning	LLNL	Whitesides		250k
L.M.05.04	Scalable performance and CFD integration of ZERO-RK	LLNL	Whitesides	275k	75k
L.M.05.06	Mechanism Reduction	LLNL	Whitesides		75k
L.M.05.07	Accelerate Mechanism Reduction Tools	LLNL	Whitesides		75k

Cold Start

		Lab	PI	FY20	FY21
O.E.07	Multi-cyl Cold Start & surrogate testing	ORNL	Curran	350k	350k
S.E.07	Engine experiments characterizing wall films & PM formation	SNL	Sjoberg	270k	270k

Combustion and Emissions

		Lab	PI	FY20	FY21
O.E.02	Effectiveness of EGR to mitigate knock throughout PT domain	ORNL	Szybist	220k	175k
S.E.02	Experiments supporting particulate modeling -- wall film & pyrolysis	SNL			400k
L.M.01	Improved Kinetics for Ignition Applications	LLNL			
S.M.02.01	DNS and modeling of turbulent flame propagation & end gas ignition	SNL	Chen	50k	50k
S.M.02.02	Flame wall interactions	SNL	Nguyen	150k	50k
S.M.02.03	Engineering PAH Model Development	SNL	Hansen		100k

Partially Funded

Fully Funded

Data Analytics

		Lab	PI	FY20	FY21
O.E.08	Machine Learning and Nonlinear Dynamics	ORNL	Kaul	200k	200k

Flows and Heat Transfer

		Lab	PI	FY20	FY21
O.E.06.01	Neutron diffraction for in situ measurements in an operating engine	ORNL	Wissink	100k	100k
O.E.06.02	Neutron Imaging of Advanced Combustion Technologies	ORNL	Wissink	200k	200k
O.M.06	Conjugate heat transfer	ORNL	Edwards	350k	350k
LA.M.06.01	Heat Transfer through Engine Metal - - -	LANL	Carrington	200k	
LA.M.06.02	Heat Mass Transfer in Liquid Species - - -	LANL	Carrington	200k	

Flows and Heat Transfer

		Lab	PI	FY20	FY21
O.E.06.01	Neutron diffraction for in situ measurements in an operating engine	ORNL	Wissink	100k	100k
O.E.06.02	Neutron Imaging of Advanced Combustion Technologies	ORNL	Wissink	200k	200k
O.M.06	Conjugate heat transfer	ORNL	Edwards	350k	350k
LA.M.06.01	Heat Transfer through Engine Metal - - -	LANL	Carrington	200k	
LA.M.06.02	Heat Mass Transfer in Liquid Species - - -	LANL	Carrington	200k	

Fuel Kinetics and Surrogates

		Lab	PI	FY20	FY21
A.E.01	Measurements of autoignition fundamentals at dilute gasoline conditions	ANL	Goldsborough	280k	252k
L.M.01	Surrogates and Kinetic Models	LLNL	Pitz	500k	425k
L.M.01.02	Models for improved prediction of PAH/soot	LLNL	Kukkadapu	200k	200k

Ignition

		Lab	PI	FY20	FY21
A.M.03	Advanced Ignition Modeling Tools	ANL	Scarcelli	400k	370k
N.M.03	ML based LES ignition model	NREL	Yellapantula	275k	275k
S.M.03.01	DNS of early ignition kernel development	SNL	Chen	100k	100k
S.M.03.02	Physics based flame-kernel LES modeling	SNL	Nguyen	100k	100k
A.E.03	Fundamental Ignition Experiments	ANL	Rockstroh	380k	342k
S.E.03.01	Advanced Ignition to Enable Alternative Combustion Modes	SNL	Ekoto	420k	420k
S.E.03.02	Fundamental ignition experiments	SNL	Ekoto	420k	420k

LSPI

		Lab	PI	FY20	FY21
O.E.09.01	Fuel spray wall wetting and oil dilution impact	ORNL	Splitter	220k	220k

Sprays

		Lab	PI	FY20	FY21
A.E.04	X-Ray Studies of Fuel Injection and Sprays	ANL	Powell	490k	441k
O.E.04.01	Injector Characterization & Distribution	ORNL	Wissink		125k
S.E.04	Spray Experiments	SNL	Pickett	380k	380k
S.E.04.03	GDI sprays leadership & data sharing	SNL	Pickett	140k	140k
A.M.04	Towards Predictive Simulations of Sprays in Engines	ANL	Torelli	300k	220k
A.M.04.01	Improved free spray and spray-wall interaction modeling	ANL	Torelli		125k
LA.M.04.01	Simulate free sprays in chamber and engines - - -	LANL	Carrington	200k	
S.M.04.01	Free spray modeling	SNL	Nguyen	50k	50k
S.M.04.02	Free spray modeling addition	SNL	Tagliente		125k