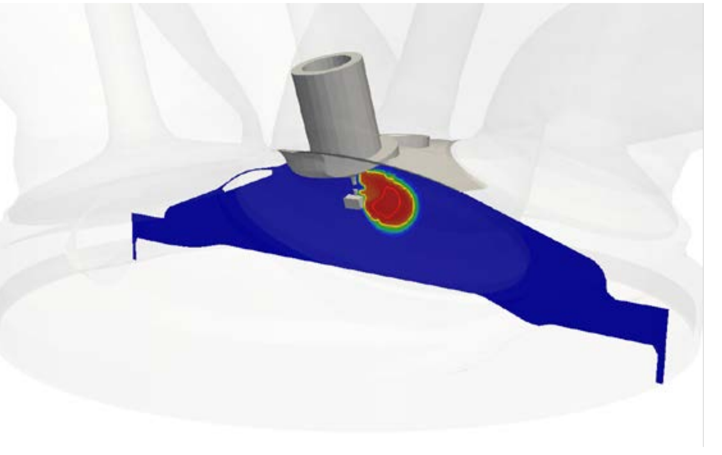
ADVANCED IGNITION SYSTEMS FOR GASOLINE DIRECT INJECTION (GDI) ENGINES



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Argonne National Laboratory

DOE Technology Manager: Leo Breton

Project ID: ACS084

June 6, 2017

OVERVIEW

Timeline

- Project start: FY 2017
- Project end: FY 2019
- Percentage complete: 20%

This is a specific task of a large ANL research project addressing the VTO Lab Call 2017 *"Towards Improved Understanding and Modeling Capabilities for Advanced Combustion Engines"*

Budget

- Funding in FY16: $485k*
- Funding in FY17: $370k**

* High-Efficiency GDI Engine Research (ended FY2016)

** Funds for FY17 reflect a reduced spending rate

Barriers

Lack of robust SI dilute combustion technology:

- Limited engine dilute operation
- Limited understanding of advanced ignition mechanisms enabling SI dilute combustion
- Limited availability of modeling tools for the development of advanced ignition systems

Main Partners

- Ford Motor Company
- Sandia National Laboratory
- Convergent Science, Inc.
- Esgee Technologies, Inc.
- Michigan Technological University

RELEVANCE

Ignition is a key enabler technology for highly dilute, efficient combustion

- **Current ignition technology in production is still based on conventional spark**
  - Challenges exist at dilute and boosted operation
  - High required energy leads to durability issues
  - Spark models are not predictive under challenging conditions
- **Non-conventional ignition technologies are heading towards production**
  - In-house development and optimization at suppliers
  - Absence of CFD models for engine optimization
- **Several promising technologies still at research stage**
  - Limited understanding → Slow development
  - Absence of CFD models for ignition/engine optimization

OBJECTIVES

Improve basic knowledge and analysis of advanced ignition systems to enable dilute SI combustion

- **Understand** the fundamentals of ignition, in particular for non-conventional ignition technologies that show the potential to extend the engine dilution tolerance
- **Build** novel ignition models and combustion modeling best-practices that allow accurately simulating the ignition process from advanced ignition systems under dilute operation
- **Demonstrate** the efficiency increase potential of advanced ignition systems by understanding the trade-offs and interactions between the ignition source and key engine features (flow, thermodynamics, etc.)

APPROACH

Image: TPS

Image: BorgWarner

Ignition technologies

Image credits: SNL

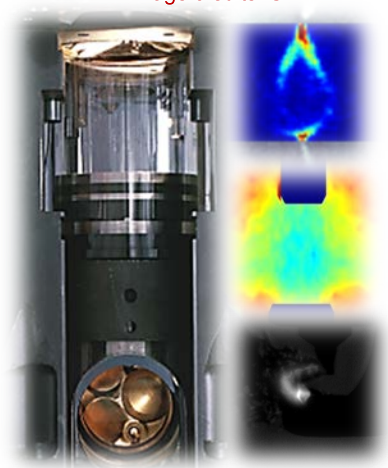
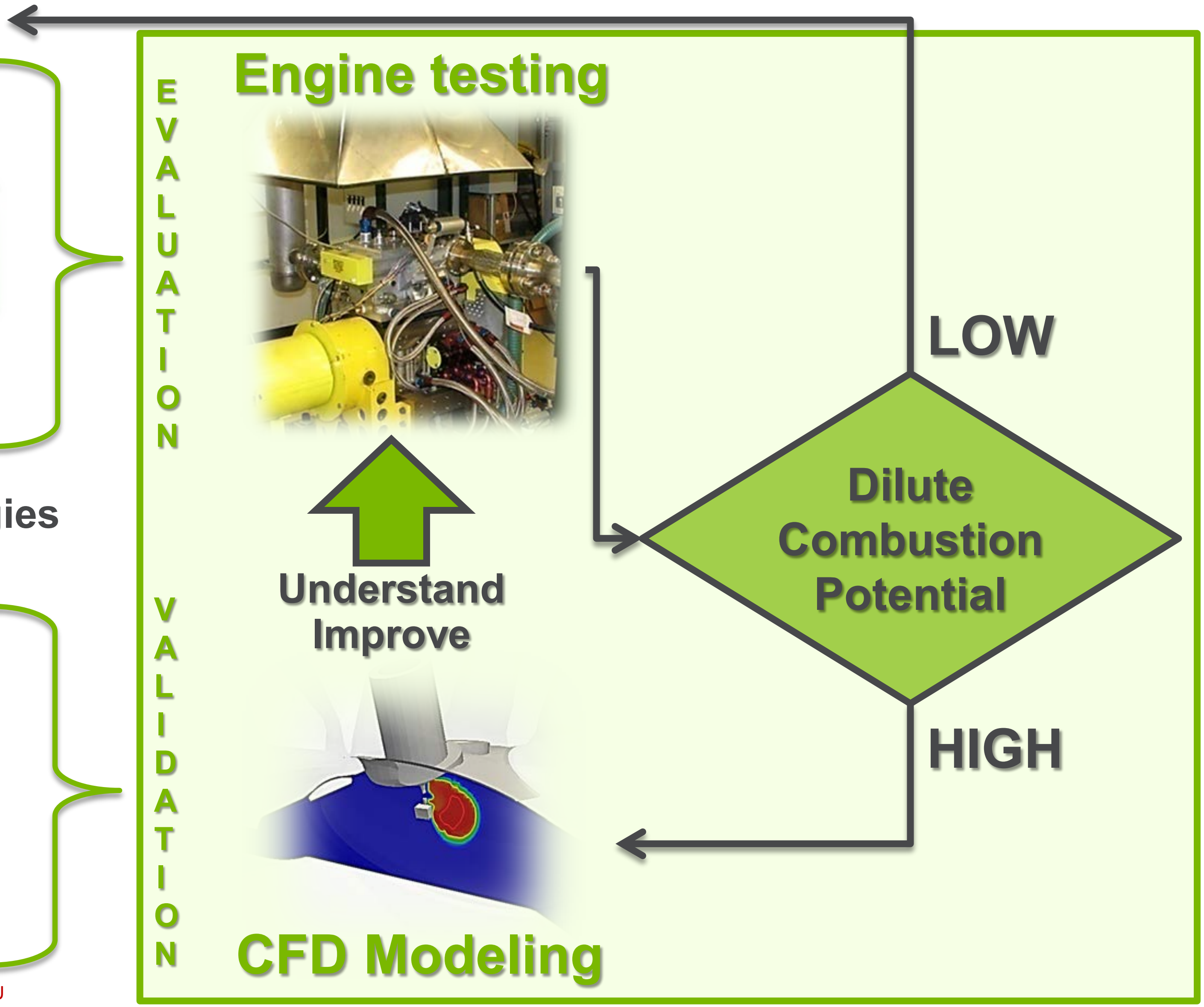


Image credits: MTU

Advanced diagnostics



MILESTONES

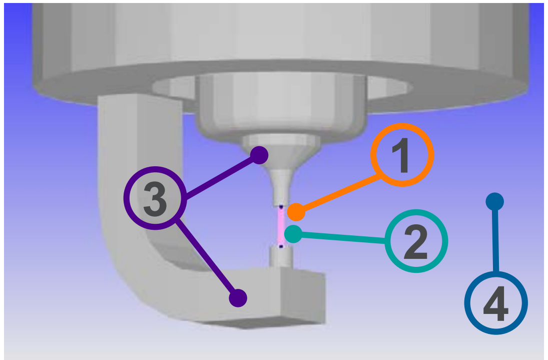
Mo./Year	Description	Status
FY16 - High Efficiency GDI Engine Research with Emphasis on Ignition Systems		
06/2016	Develop and validate conventional ignition model	Completed
09/2016	Evaluate effect of laser ignition location on EGR dilute tolerance	Completed
FY17 - Advanced Ignition Systems for GDI Engines		
12/2016	Improve plasma characterization by leveraging advanced diagnostics	Completed
03/2017	Use endoscope to evaluate ignition behavior at engine operation	Completed
06/2017	Expand the ignition model to simulate non-conventional ignition	On-Track
09/2017	Evaluate the effect of plasma composition on CFD ignition results	On-Track

Modeling of non-equilibrium plasma initiated and compared to experimental observations

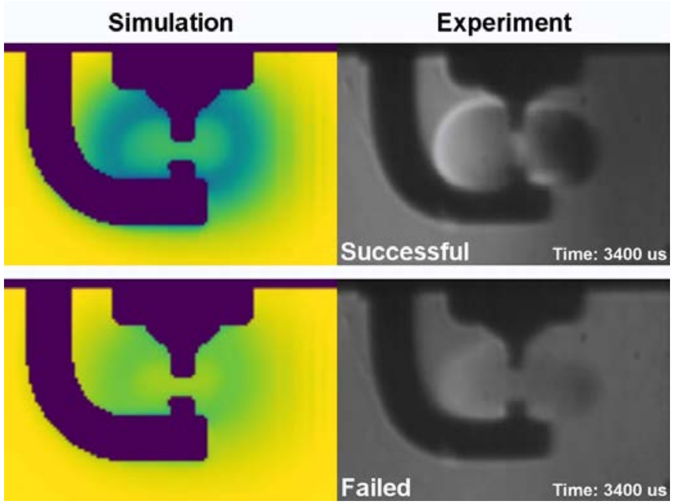
ACCOMPLISHMENTS FY16

Detailed energy deposition (ED) model developed at ANL (selected for the 2016 US DRIVE Highlights)

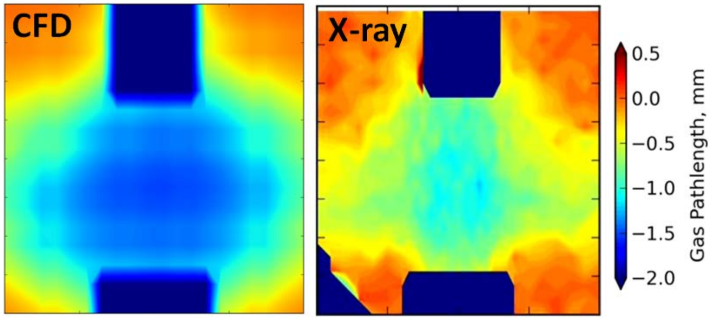
Eulerian ED ignition model implemented in CONVERGE and used with realistic inputs



1. Accurate energy release
2. Line-shaped energy source
3. Conjugate heat transfer
4. Detailed chemistry



1. Predicts ignition success/failure



2. Captures plasma thermal properties

Validated at quiescent conditions

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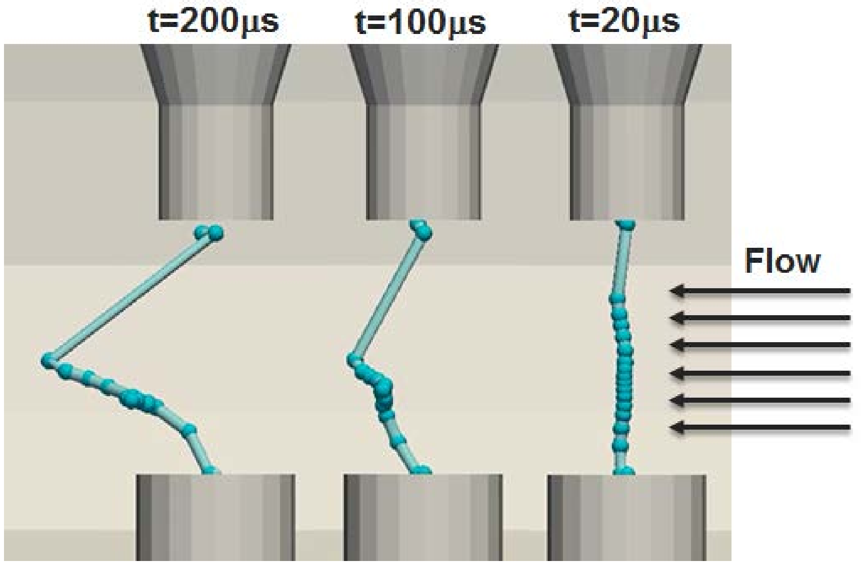
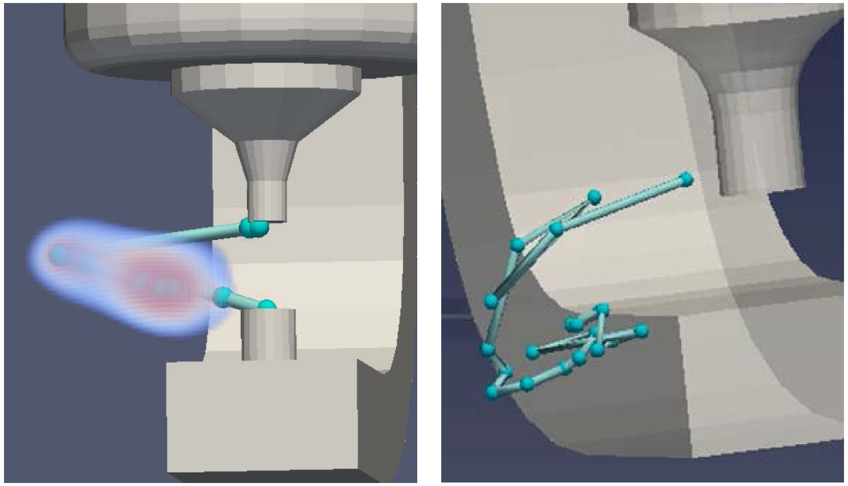
ACCOMPLISHMENTS FY17

ED model evaluated at non-quiescent conditions

Default source motion settings in CONVERGE are simplistic

- Line source represented by a list of points
- **Fixed number of points** for the line source
- **Even amount of energy** for each point
- Source points can move with the flow
- **No restrictions** except max displacement
- Breakdown **shock wave** introduces a **strong perturbation** of the channel shape



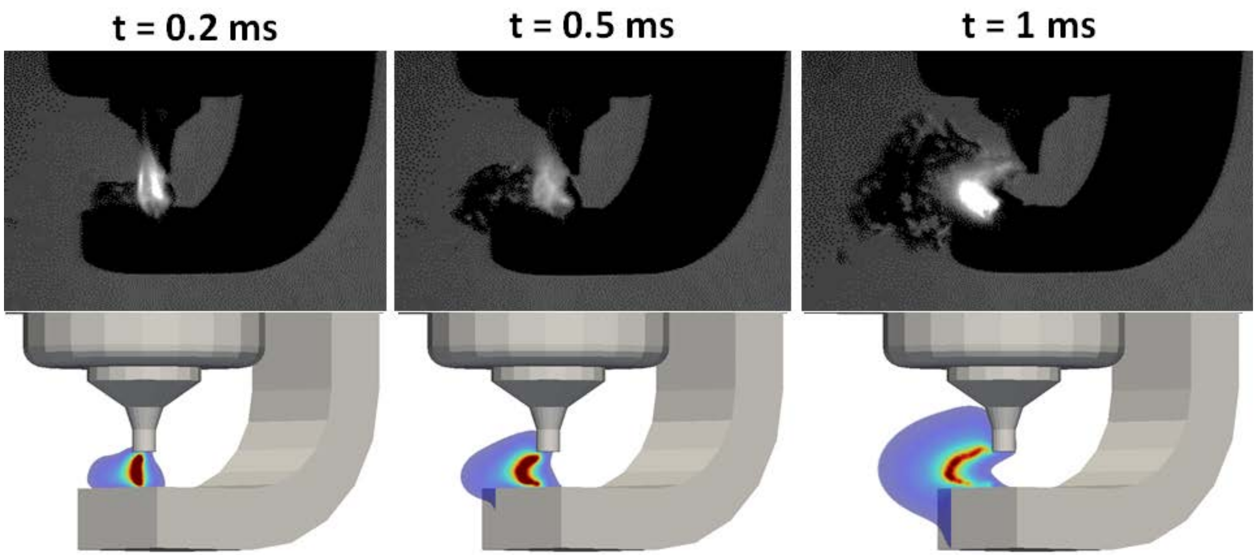


- Spark channel **elongation not accurately described**
- Channel can easily detach from electrodes
- Spatial **energy deposition** is essentially **unrealistic**

ACCOMPLISHMENTS FY17

ED model developed in CONVERGE (UDFs) to describe spark channel elongation at non-quiescent conditions

1. Breakdown (BD) induces shock wave → Points are hold right after BD
2. Energy deposition affects the local flow → Neighbor points move together
3. Points are added when channel elongates to keep nicely shaped channel
4. Energy is deposited evenly along the spark channel
5. End points can freeze or keep moving along the electrodes



Schlieren images are a courtesy of S.Y. Lee (MTU)

CFD results qualitatively match Schlieren data from MTU for similar flow conditions

More work is planned on lean/dilute ignition and combustion in a combustion vessel (MTU) and DISI optical engine (SNL)

ACCOMPLISHMENTS FY17

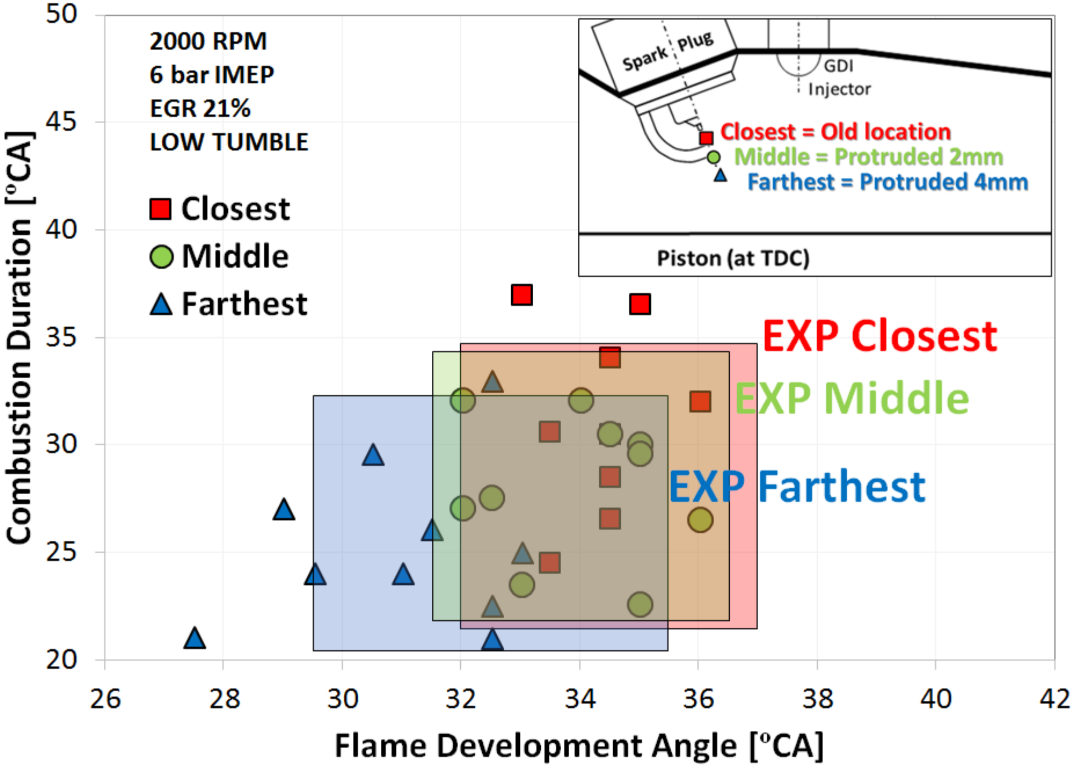
Simulation evaluated the effect of laser ignition location

FY2015 Results

- Experiments showed that laser ignition cannot match performance of conventional spark.
- Simulations showed that laser ignition flexibility (location) could be exploited (multi-point).

FY2016 Results (Q4)

- Simulation and experiments evaluated **effect of ignition location** for **single-point** laser.
- A **simplified ED model was used**. Dedicated laser ED model has not been developed.



Multi-cycle CFD results show:

☺ Combustion metrics improve when ignition point is protruded

☺ ITE increase up to 1%

☹ **Lowest COV_{IMEP} for middle point** (Protrusion = 2mm)

Engine results show:

☺ Combustion metrics improve when ignition point is protruded

☺ ITE increase up to 0.5%

☹ **Lowest COV_{IMEP} for closest point** (Not protruded)

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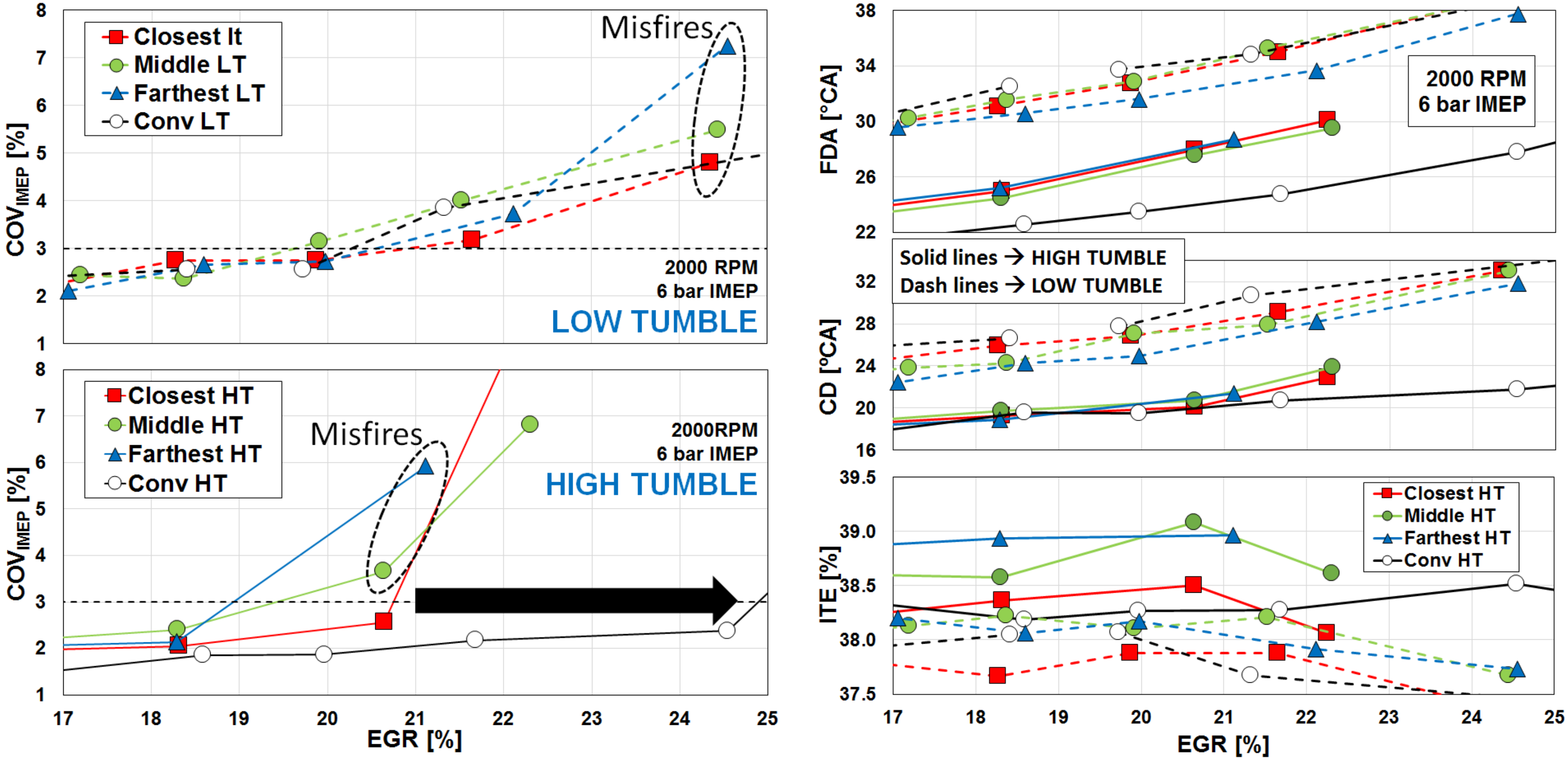
ACCOMPLISHMENTS FY17

Experiments evaluated the effect of laser ignition location



- **Misfires occur easier** (i.e. at lower EGR) with **high tumble** and **more protrusion**
- This is a single-pulse laser → Short duration → Very sensitive to the local flow
- FDA/CD with laser are good at low tumble. ITE with laser always better than conventional
- Our **laser ignition model** is too simplistic and **not predictive**

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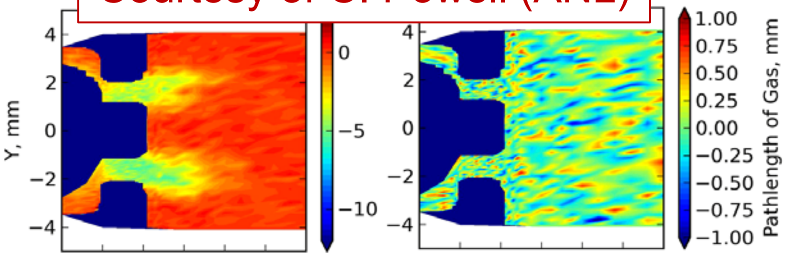
ACCOMPLISHMENTS FY17

* I. Ekoto, ACS006

Improved understanding of non-equilibrium plasmas

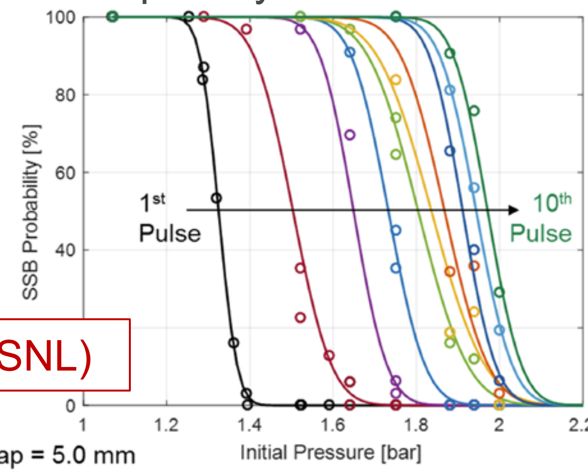
Courtesy of C. Powell (ANL)



Arcing event (High V, low P)

Non-arcing event (Low V, High P)

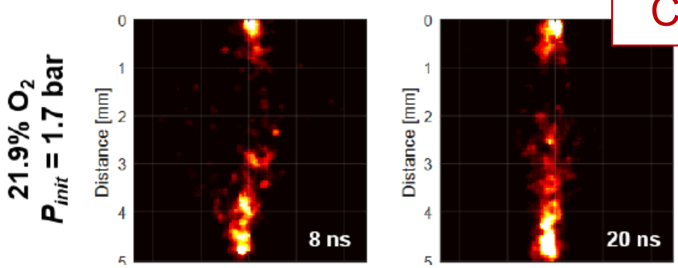
- Nano-pulse delivery can result in arcing event depending on voltage, density, composition, etc.
- X-Ray diagnostics quantifies thermal properties (density)
- Arcing (**SSB***) shows low density. Non-arcing (**LTP***) difficult to quantify



Gap = 5.0 mm

- Calorimetry experiments evaluated the transition **LTP→SSB*** (I. Ekoto, ACS006)
- Arcing occurs easier with more pulses. Thermal pre-conditioning claimed as the main cause

Courtesy of I. Ekoto (SNL)

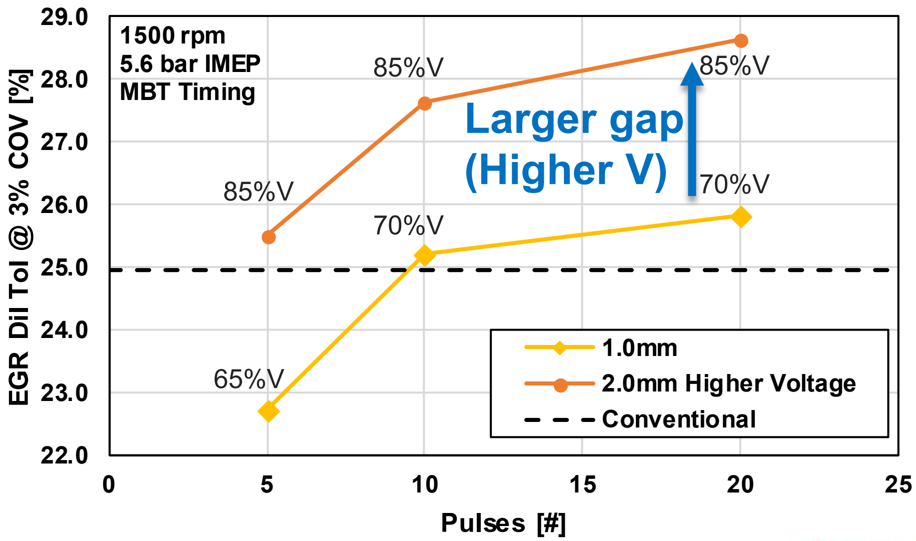


- O* measurements complement thermal analysis
- Streamer characteristics (branching, etc.) are shown

SNL-ANL coordinated effort to characterize non-equilibrium plasmas and provide data for qualitative/quantitative model validation

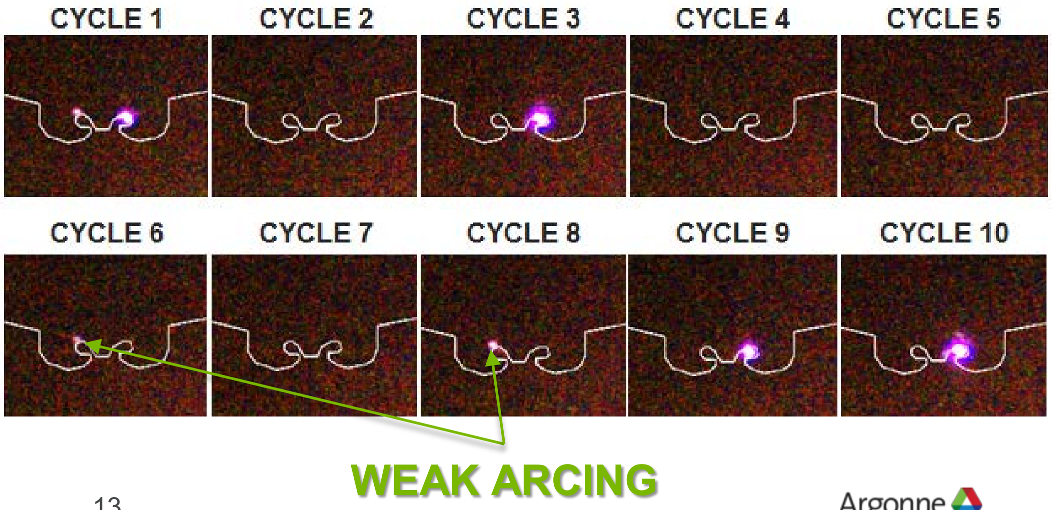
ACCOMPLISHMENTS FY17

Non-equilibrium plasma ignition evaluated at engine operation (1/2)



- High Voltage and multiple pulses can **extend dilution tolerance** but **increase the chance of arcing**
- Engine performance testing at stoichiometric, lean, and EGR dilute operation **coupled with endoscope images** for arcing detection

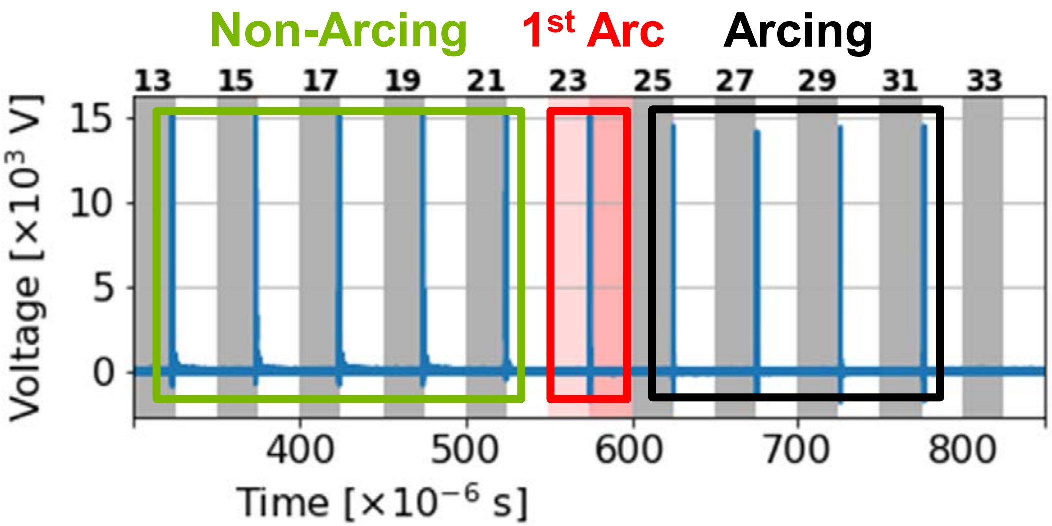
- Cyclic variability of the arcing occurrence was observed
- Arcing location can change from a cycle to the next
- Arcing could happen but not be visible due to the electrodes

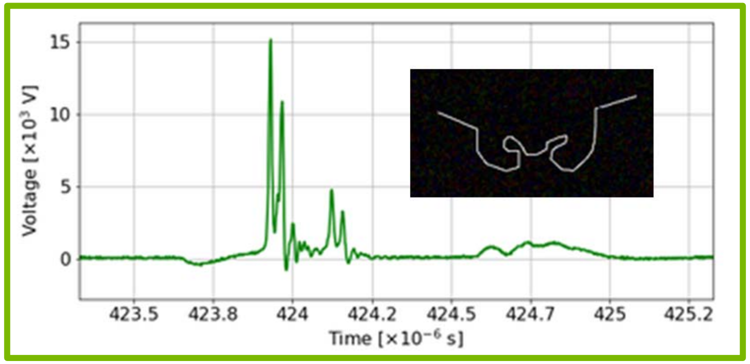


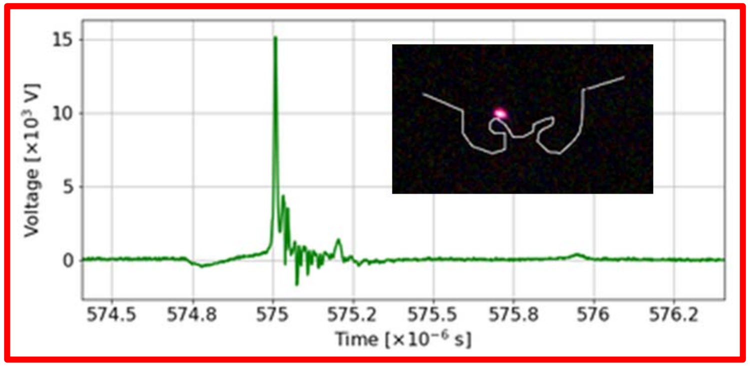
ACCOMPLISHMENTS FY17

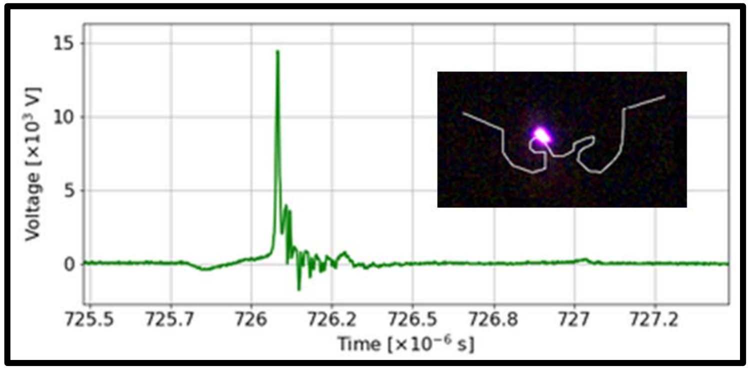
Non-equilibrium plasma ignition evaluated at engine operation (2/2)

- High resolution endoscope images coupled with simultaneous measurement of voltage and current for arc detection









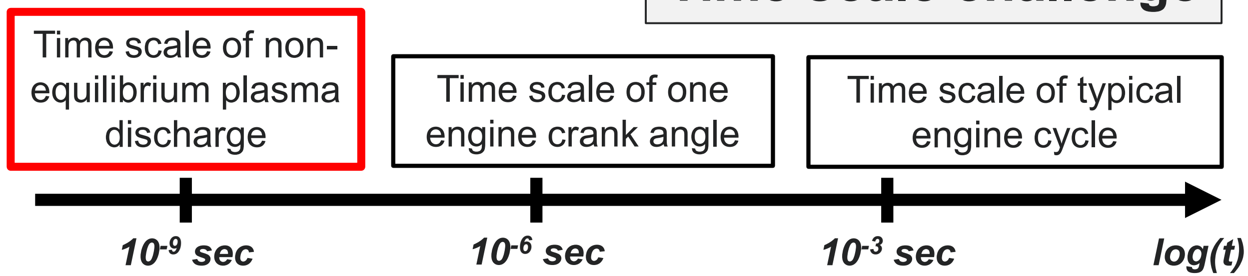
- After the 1st occurrence of arc, keeps arcing in the same location
- Consistent with other observations and with the assumption of thermal pre-conditioning

ACCOMPLISHMENTS FY17

Non-equilibrium plasma modeling initiated

- Non-equilibrium plasma ignition systems aim to deliver the energy into gases in a volumetric fashion **WITHOUT gas breakdown**. Fuel-air mixture ignition is induced by excited species (radicals, electrons, etc.) at low temperatures.

Time scale challenge



Modeling strategy

- Ignition source as combination of thermal energy and active species
- Separate plasma and flow/combustion time scales based on short deposition
- **Requires detailed understanding** of non-equilibrium plasma characteristics

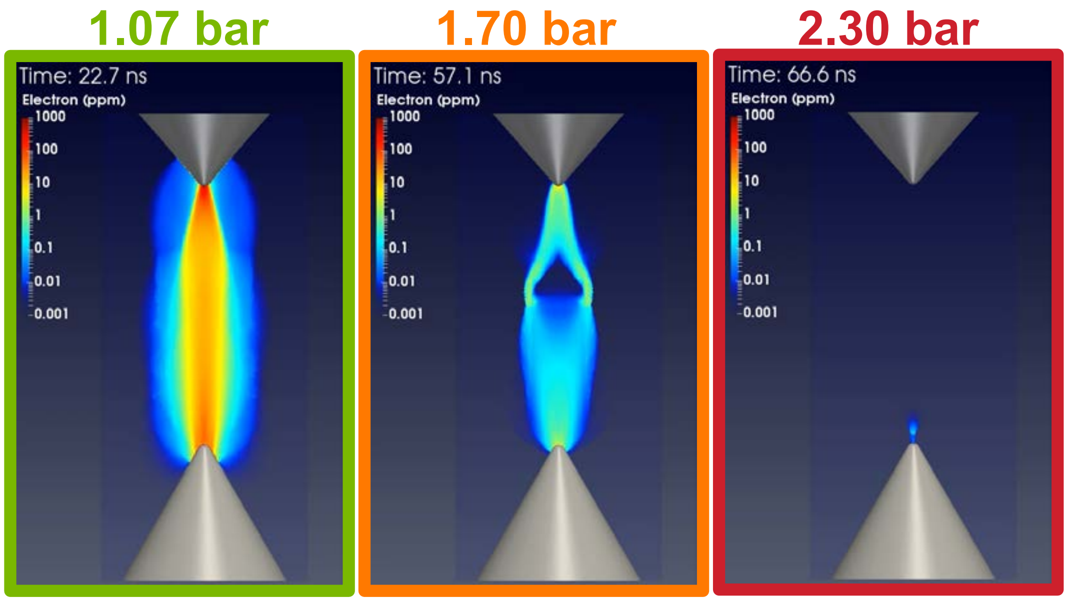
VizGlow

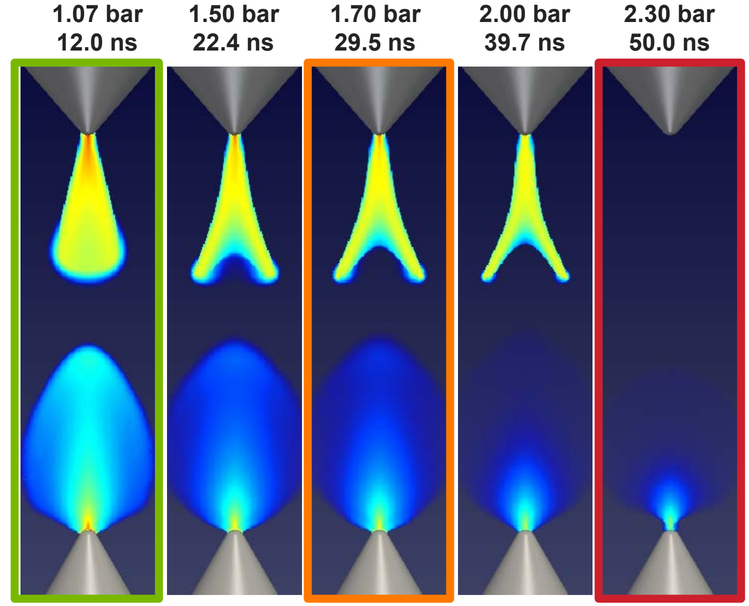
EsgeeTechnologies Inc.
Analysis and Design through High-Fidelity Simulations

- High-fidelity, self-consistent plasma code for non-equilibrium plasma
- Bulk gas heating and photoionization are modeled by the code
- 2D simulations are performed

ACCOMPLISHMENTS FY17

Non-equilibrium plasma modeling tentatively validated

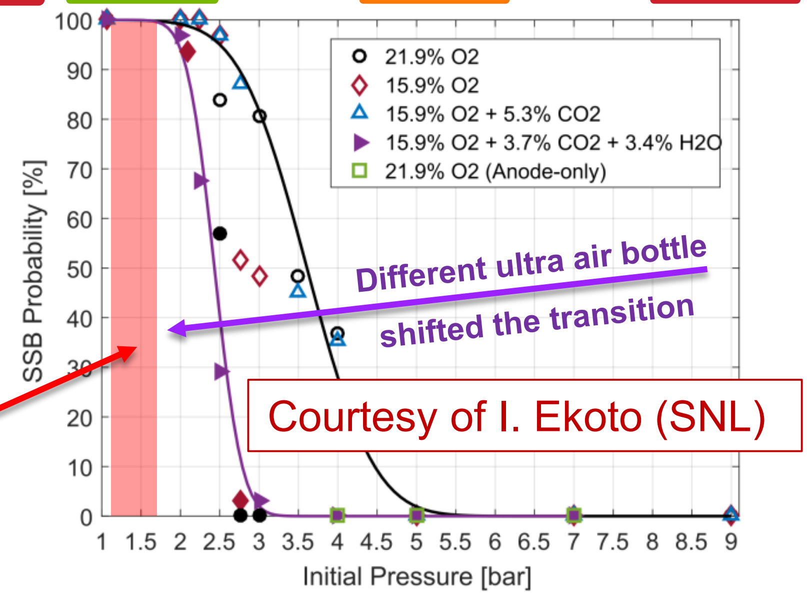




Top electrode: anode, bottom electrode: cathode

- Pressure dependency behavior of the plasma are consistent with experimental observations
- Increased ambient pressure leads to delayed plasma formation, reduced streamer thickness, higher tendency to branch

This is our SSB→LTP transition

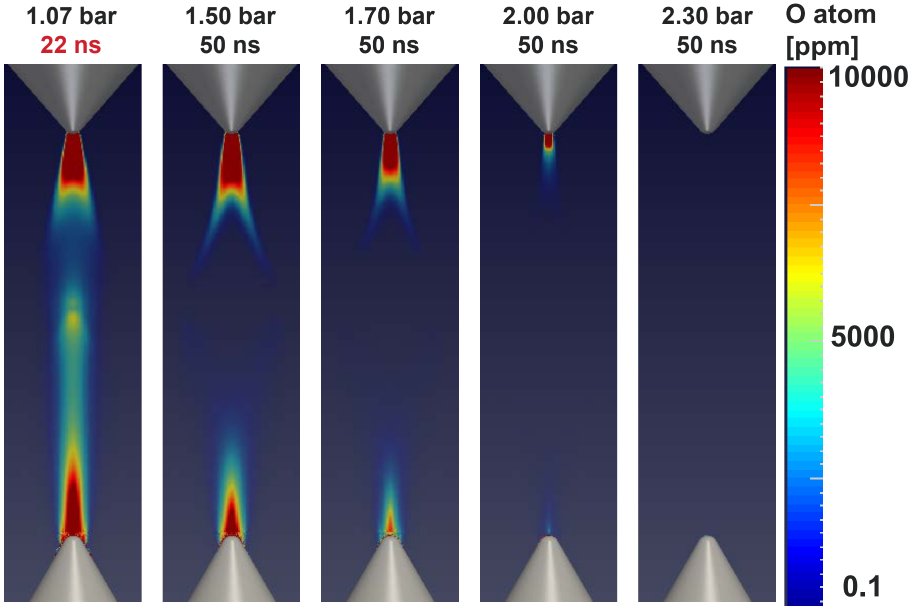


ACCOMPLISHMENTS FY17

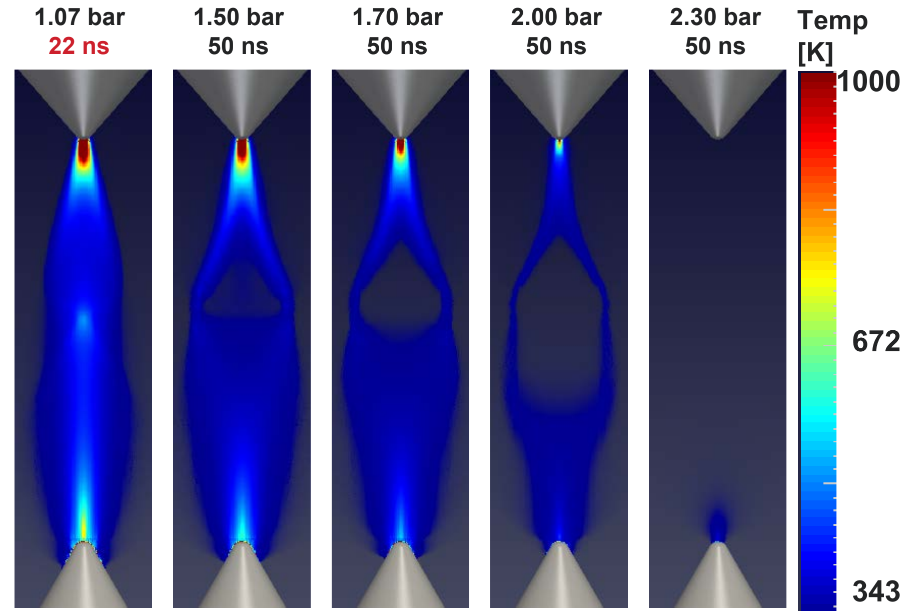
Non-equilibrium plasma characteristics investigated

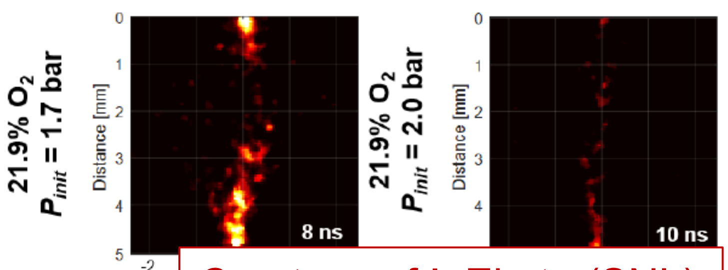
- Active species formation and local gas heating are two major factors that will impact ignition and combustion

Atomic O distribution



Temperature distribution





Courtesy of I. Ekoto (SNL)

O and Temperature distributions **qualitatively capture experimental observations at Sandia**

RESPONSE TO REVIEWER COMMENTS

- "...goal of 20% over a stoichiometric GDI engine with production spark is incorrect..."
  - ✓ Acknowledged during Q&A discussion at last Annual Merit Review.
- "…**much of this experimental work has been done and reported**. The reviewer questioned what more the project could hope to contribute…**the focus should be on understanding the mechanism of ignition…**and improving the process to gain dilution tolerance"
  - ✓ This project has been **re-scoped to provide in-depth understanding and build advanced modeling tools.** Such features can be of vital importance for industry to improve the dilute combustion process.
- "…The **modeling work supports the main experimental evaluation but cannot justify the project**.."
  - ✓ We will keep providing experimental evaluation of advanced ignition systems. However, we believe that building **proper understanding** and **reliable modeling tools** is of **high priority** for industry.
- "…**More optical engine experiments** should be conducted"
  - ✓ **No optical work is done at Argonne, but we have strategic partners (Sandia/MTU)** in that field. We also coupled performance testing with endoscope imaging to improve our experimental approach.
- "Better guidance from an OEMs needed…Collaboration should not occur for the sake of collaboration"
  - ✓ Please check our next slide on collaboration and coordination.

COLLABORATION AND COORDINATION

Experiments

Transient Plasma Systems, Inc.
BorgWarner
Princeton Optronics, Inc.
Knite, Inc.
Ignition systems
SBIR/SBV programs

Ford Motor Company
OEM support
Technical guidance

USCAR
Coordination
Ranking
Guidelines

Modeling

Convergent Science, Inc.
Ignition model development
Best-practices for GDI/CCV

Egsee Technologies, Inc.
Non-equilibrium plasma modeling
Code validation and development

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Diagnostics

Sandia NL
Optical data for validation
Ignition setup sharing
Coordination through USCAR

Michigan Tech
Optical data for validation

…Not to forget ANL internal key collaborations…

Advanced Photon Source (X-Ray diagnostics)

Distributed Energy Research Center (Laser ignition technology)

REMAINING CHALLENGES AND BARRIERS

- **Computational challenge**: Bridging the gap between basic (ignition) and applied (engine modeling) research
  - Non-equilibrium plasma modeling uses expensive chemistry and nanosecond timescales
  - Combustion engine modeling uses less expensive chemistry and millisecond timescales
  - Detailed ignition needs to be coupled with combustion modeling
  - Turbulence modeling has a key role to predict combustion stability
- **Practical challenge**: Engine development is required to maximize the benefits from advanced ignition technologies
  - We provide in-depth understanding and the proper analysis tools

PROPOSED FUTURE WORK

- **Use improved knowledge to expand current models (FY17)**
  - Develop CFD engine codes to handle non-conventional ignition
  - Reduced plasma chemistry integrated with fuel chemistry
- **Build/validate advanced computational framework (FY18)**
  - Comprehensive ignition model accounting for different plasma technologies/characteristics
  - Couple advanced ignition models with CFD best-practices for the simulation of GDI engines combustion and cyclic variability
- **Use modeling to identify potential development areas (FY19)**
  - Basic analysis of discharge characteristics and geometry of the igniters
  - Interaction between ignition source and engine flow/thermodynamics

Any proposed future work is subject to change based on funding levels

SUMMARY

Advanced Ignition Systems for GDI Engines

Relevance

- Ignition is a key enabler technology for highly dilute, efficient combustion
- CFD tools are not predictive when testing conventional ignition at challenging conditions
- Limited or absent CFD models to handle non-conventional ignition technologies

Approach

- Basic and applied research to understand physics, build and apply models, demonstrate potential, and support development
- External and internal collaborations to leverage core capabilities and key expertise

Technical accomplishments (1/2)

- Detailed energy deposition (ED) developed and validated at non-quiescent conditions
- Effect of laser ignition location on engine performance evaluated using both simulations and experiments

Technical accomplishments (2/2)

- Improved characterization of non-equilibrium plasmas through coordinated effort at Argonne and Sandia using advanced diagnostics
- Non-equilibrium plasma ignition behavior evaluated at engine operation
- Non-equilibrium plasma modeling initiated and tentatively validated against experimental data from advanced diagnostics

Remaining barriers

- Convey the improved physical understanding of non-conventional ignition systems (small timescales, complex chemistry) into a CFD engine tool (large timescales, reduced chemistry) to be practically used for development and optimization

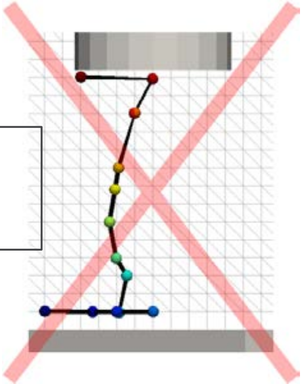
Future work

- Build and validate comprehensive ignition and combustion models
- Look at main interactions between engine parameters (flow, thermodynamics) and ignition characteristics (discharge, geometry)

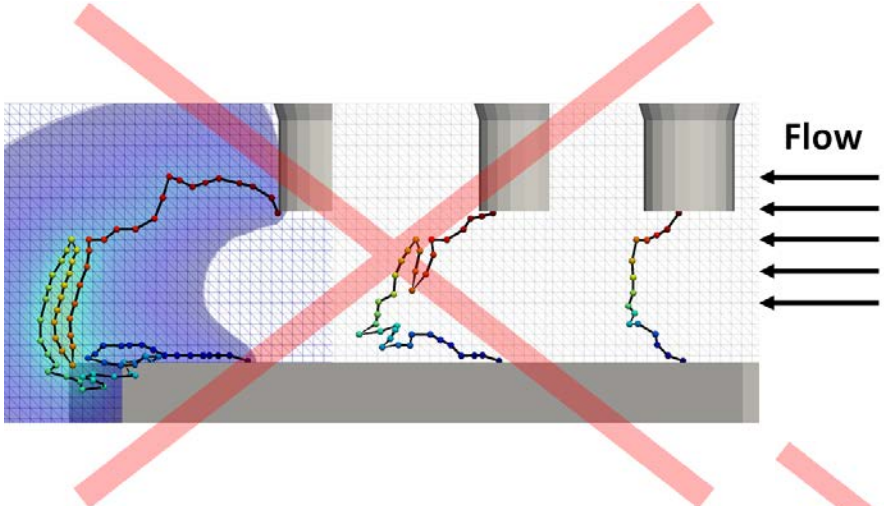
BACKUP SLIDES

TECHNICAL BACKUP SLIDES

ED model development at non-quiescent conditions



Breakdown introduces strong flow perturbations
→ Points frozen until shockwave is gone

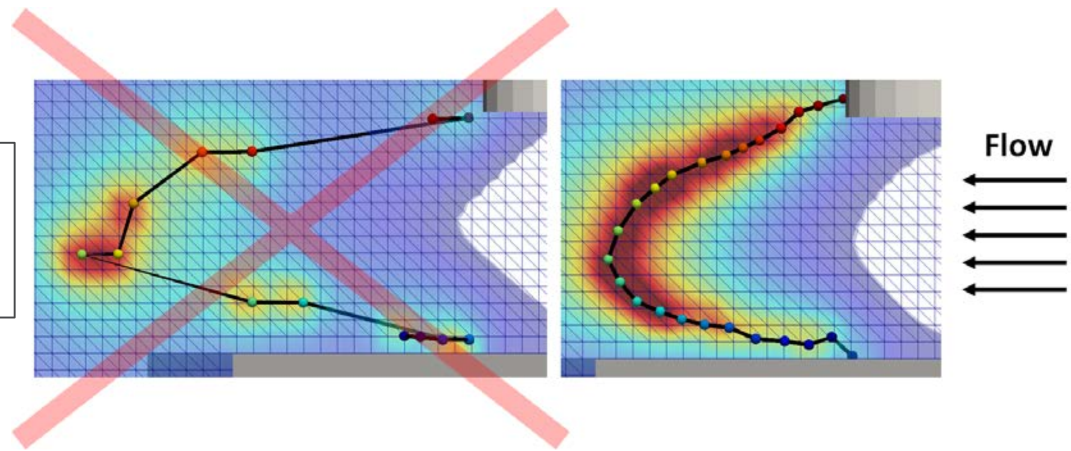


New points added when channel elongates to deliver nice shape

Points do not move independently from neighbors to avoid folding

Consistent energy deposition

End points can freeze or keep moving along the electrodes



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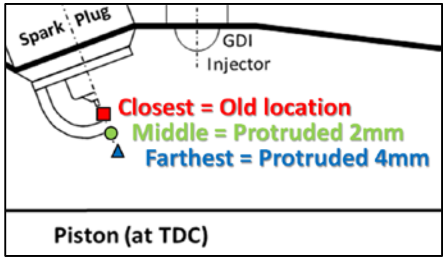
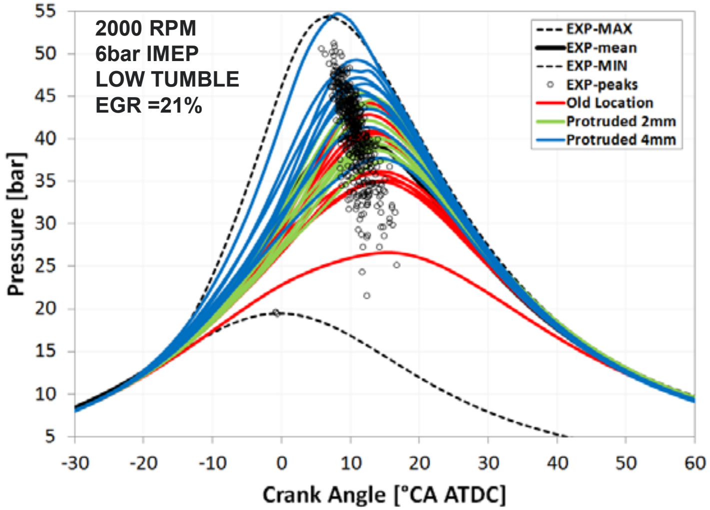
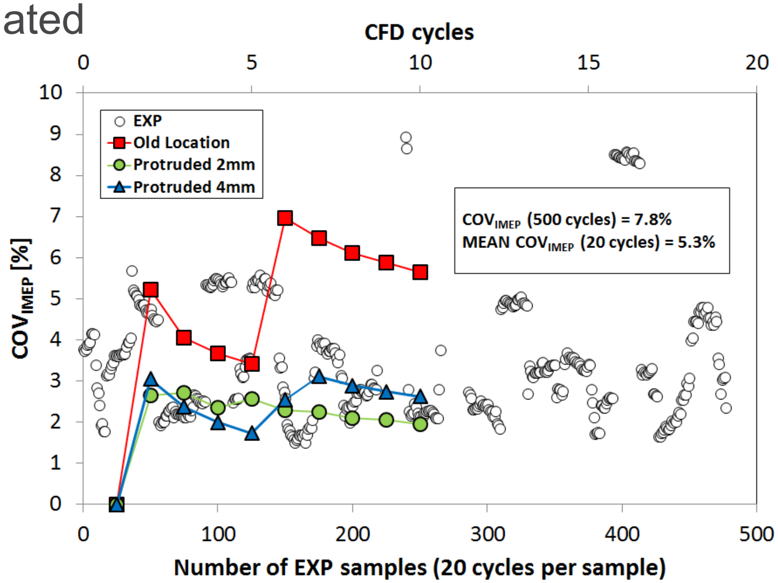
TECHNICAL BACKUP SLIDES

Laser ignition modeling setup



- **Simplified ED ignition model to simulate laser ignition**
  - Spherical kernel shape
  - Size should be very small, but we are limited by the MIN mesh size (0.125 mm)
  - Energy deposition lasts nanosecond. Our assumption is 1 μs duration
  - These assumptions have never been validated against optical data
  - Simulations were run for 10 consecutive cycles at fixed BCs and spark timing
  - Low tumble configuration was simulated





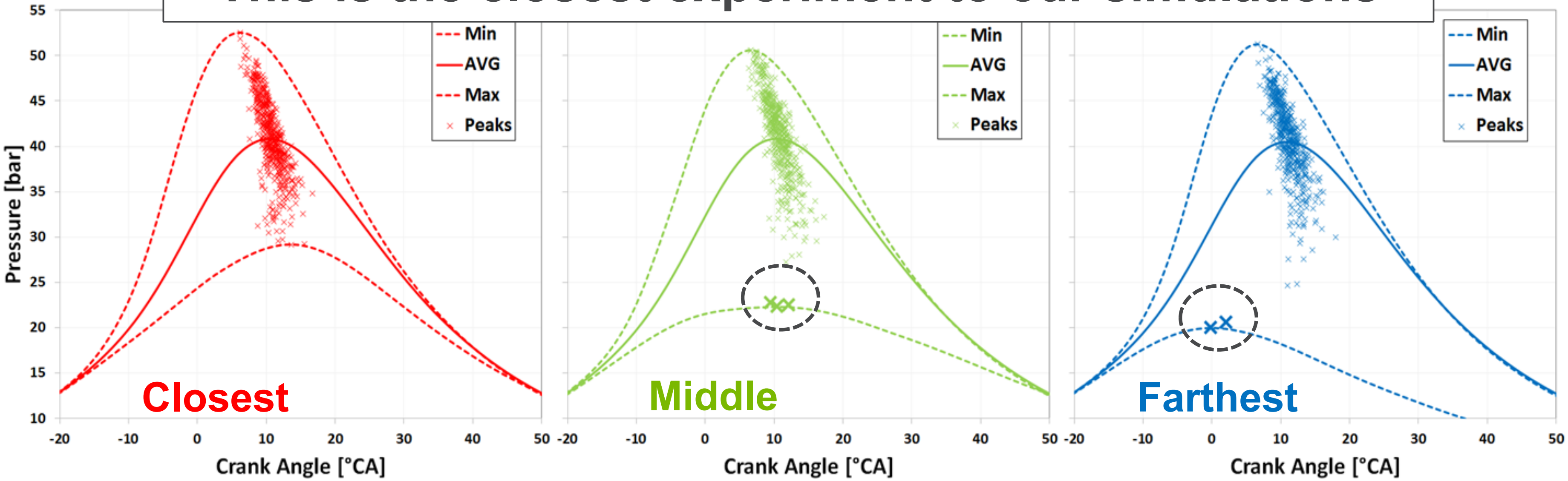
Our assumption is that the model does not take into account the negative effect of flow (flame quenching) on misfires and severe partial burns

TECHNICAL BACKUP SLIDES

Laser ignition testing details (Low tumble)

- Engine test were performed at fixed IMEP (6 bar) and adjusting intake pressure
- **Engine results are shown at MBT spark timing**:
  - Closest 39 °CA BTDC
  - Middle 40 °CA BTDC
  - Farthest 37 °CA BTDC → Combustion is faster (consistent with simulations)
- Conversely, simulations were run at fixed spark timing (40 °CA BTDC)

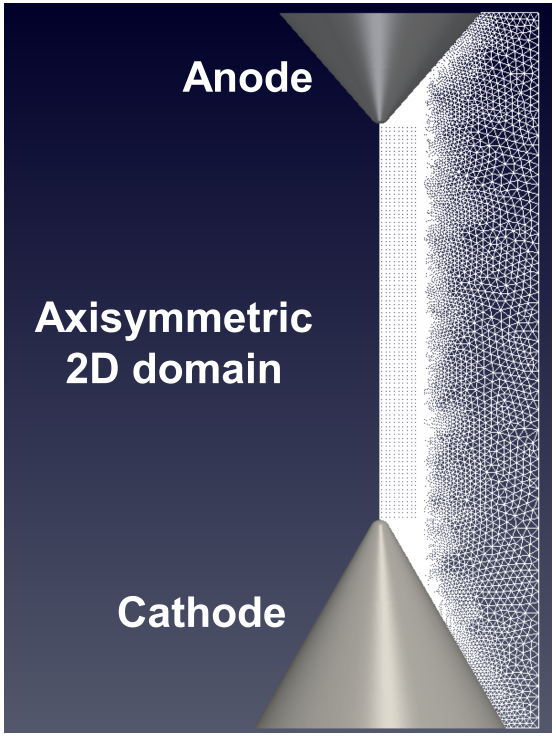
This is the closest experiment to our simulations



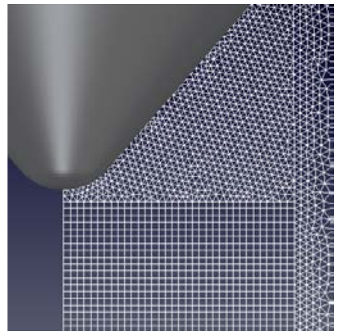
Protruding the ignition point progressively into the cylinder improves FDA/CD but increases the number of misfires/partial burns

TECHNICAL BACKUP SLIDES

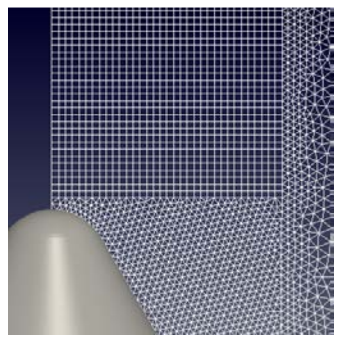
VizGlow setup



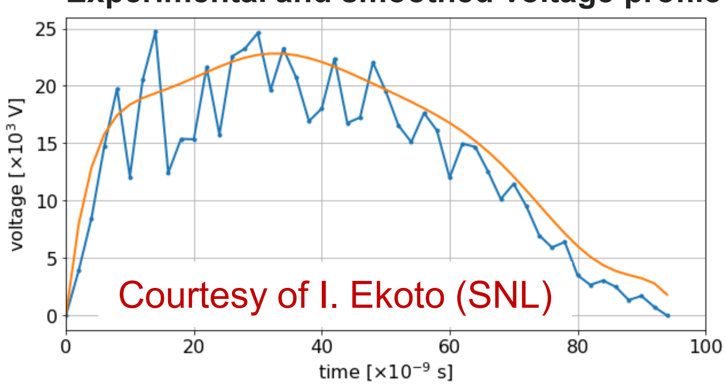
Anode details



Cathode details



Experimental and smoothed voltage profile



Plasma model highlights

- Electrostatic potential is computed using Poisson's equation
- O2-N2 plasma chemistry for high pressure applications with 18 species: E, O2, O2*, O2a1, O2b1, O2+, O2-, O, O-, O4+, O2+N2, N2, N2a1, N2A, N2B, N2C, N2+, N4+
- Photoionization and bulk energy are modeled

Boundary and initial conditions

- 5 mm gap between rounded electrode tips
- Mixture: 15.9% O2, 84.1% N2 @ 70K with multiple pressure levels
- Experimental voltage profile applied to the anode
- External circuit modeled with 100 ohm resistance

Mesh configuration

- Mixed quad/tri mesh with 15 μm min size
- Uniform quad cells in the center gap
- Total cell count ~27,000

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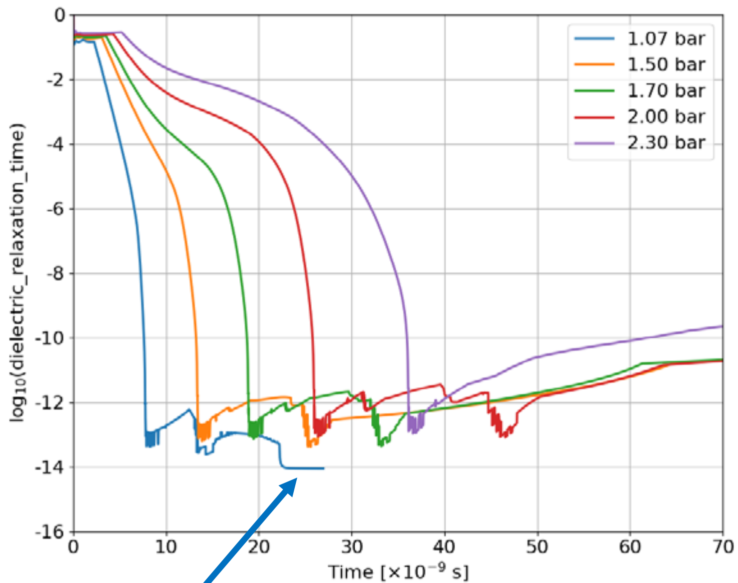
TECHNICAL BACKUP SLIDES

VizGlow simulation details

Identify Arcing in Simulation

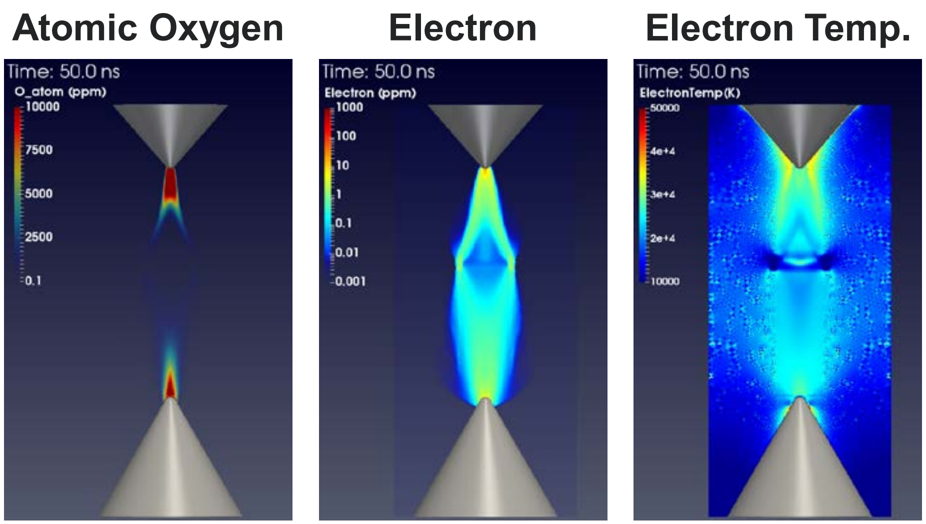
- VizGlow is a code suitable for non-equilibrium (bulk temperature is much lower than electron temperature) plasma
- A characteristic dielectric relaxation time is tracked numerically during simulation
- When arcing occurs, bulk temperature increases and the dielectric relaxation time drops to a very small value



Arcing occurs at 1.07 bar

Atomic oxygen vs. excited state oxygen

- Qualitative comparison was carried out between atomic oxygen (simulation) and excited state oxygen O* (experiment)
- O* is not a direct output from the simulation, and three factors affect O* formation: concentration of ground state oxygen, concentration of electrons, and energy of electrons
- High atomic oxygen concentration is found to reside at locations with high electron numbers and sufficient electron temperature



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