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SAND2020-1559PE

Ignition Mechanism of Low-Temperature Transient Plasma

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Sandia National Laboratories, February 3 – 6, 2020

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

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Hardware support: Mark Musculus
Chemical Mechanism support: Marco Mehl

Major PACE Outcomes to Support Dilute/Lean PURPOSE

- **Better efficiency and reduced emissions through design-of-mixture and superior ignition**

  stoic ~~> 12%~~ efficiency gain [UNDER REVIEW]

  lean > 25% efficiency gain (higher risk)

Major Outcome 6: Develop viable advanced igniters and control methods that expand existing dilution limits

Proposed success measure: Prototype igniters and control strategies 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.

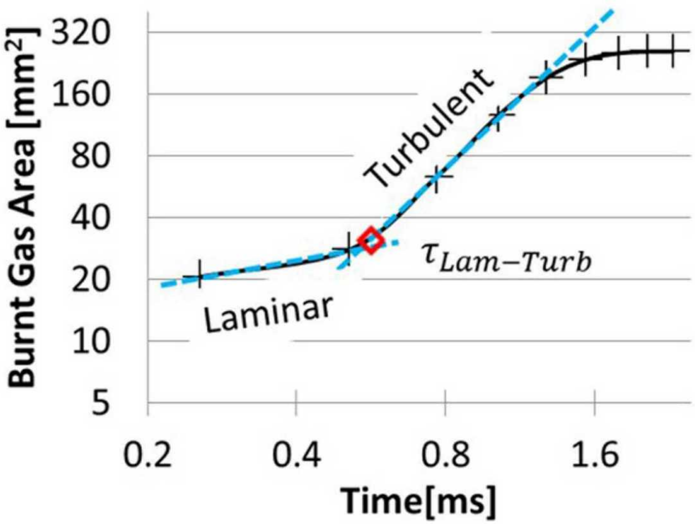
Condition(s): ACEC 3 bar/1300 rpm test point.

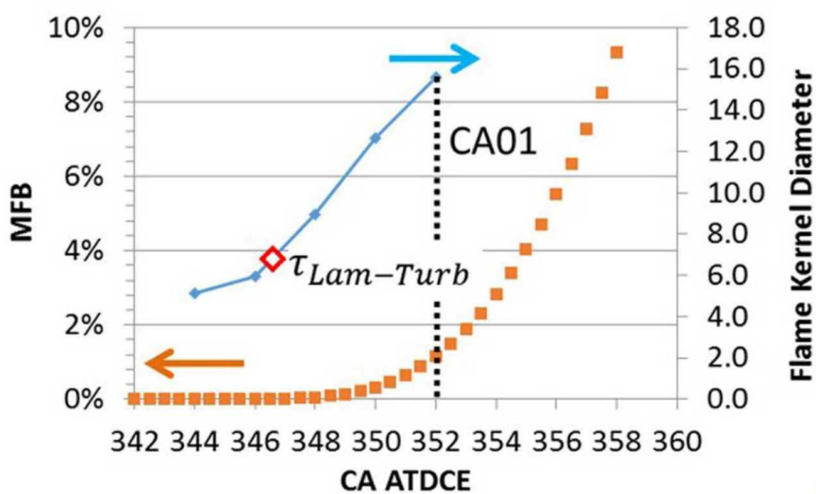
Owner – Ignition Team Leads, due FY21Q2.

The ignition team under the PACE initiative

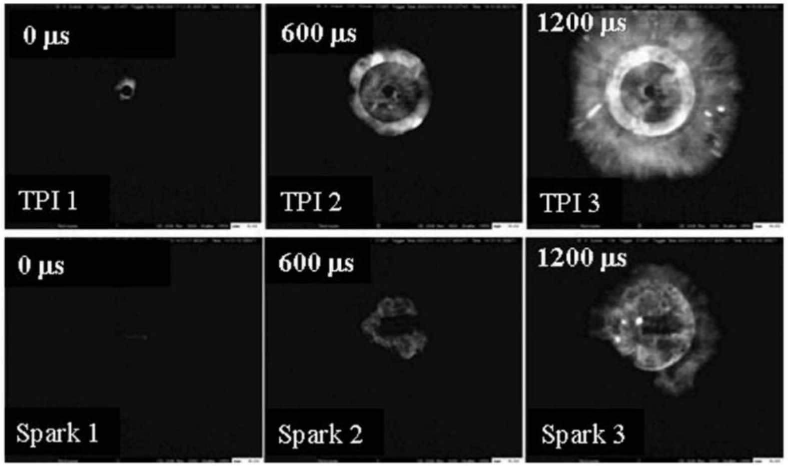
Scarcelli R. (ANL)	Plasma and CFD ignition modeling
Ekoto I. (SNL)	Fundamental ignition experiments (optical diagnostics)
Chen J. (SNL)	DNS of kernel evolution
Nguyen T. (SNL)	Physics based ignition submodel development
Grout R. (NREL)	ML based ignition submodel development
Rockstroh T. (ANL)	Metal engine experiments
Pitz W. (LLNL)	Surrogates and kinetics for ignition

Breakdown/arc free low-temperature plasma (LTP) igniters are advantageous for high-efficiency mixed-mode engine combustion





Schiffmann, Reuss, and Sick
Intl. J of Engine Research, 2018.

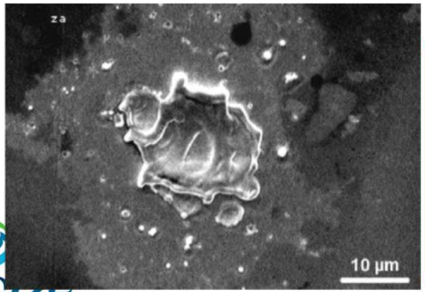


C.D. Cathey et al., *IEEE Transactions* 35 (2007).

PROS

- Large volume
- Accelerated flame speeds
- Potentially avoids breakdown
- Plasma species generation

Electrode Erosion



Soldera et al, IEEE Trans
Vehicular Tech, 53(4), 2004.

CONS

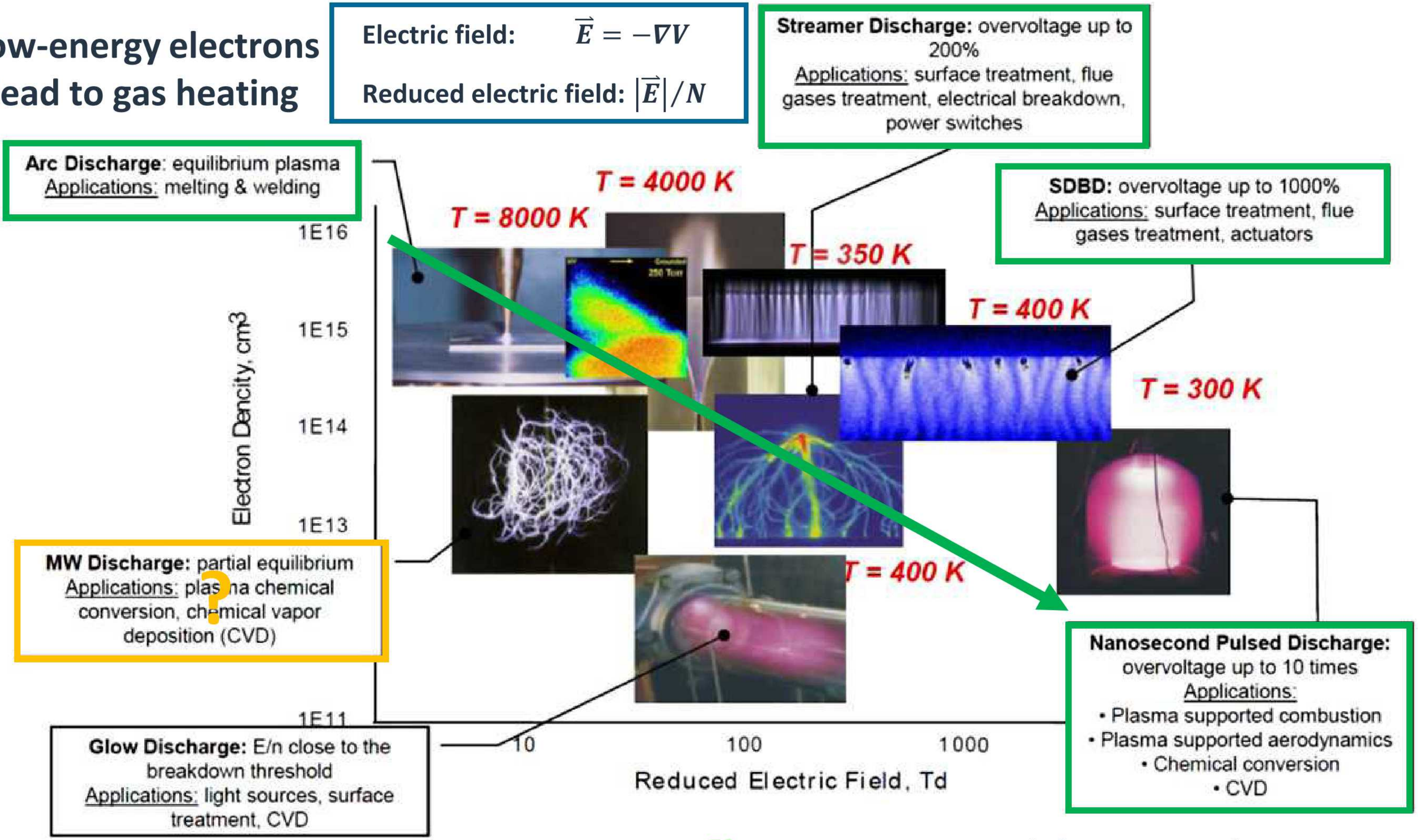
- Pulse reflections can cause breakdown
- Breakdown events cause severe erosion
- Confined ignition

Low-Temperature Plasma (LTP) facilitates radical driven ignition w/o electrode corrosion

Low-energy electrons lead to gas heating

Electric field: $\vec{E} = -\nabla V$

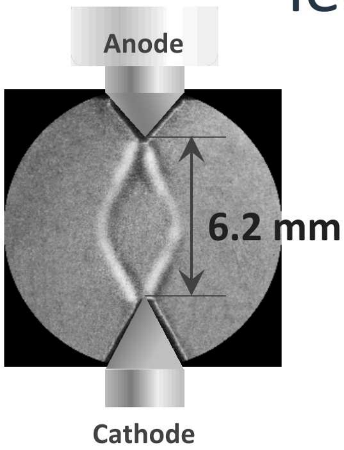
Reduced electric field: $|\vec{E}|/N$



Starikovskiy & Aleksandrov, Prog Energy & Combust Sci, 39, 2013.

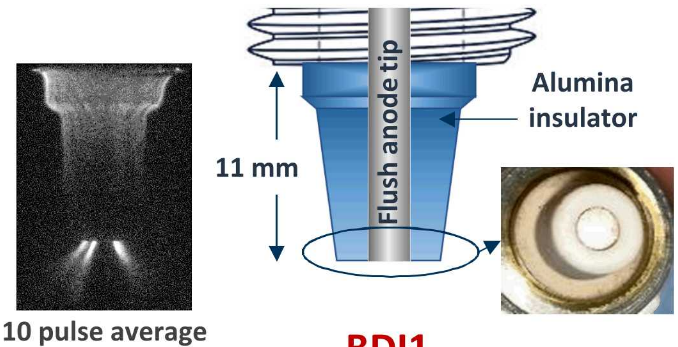
High-energy electrons promote radical formation

Previous: Transient plasma igniters have ability to extend lean/dilute ignition limits

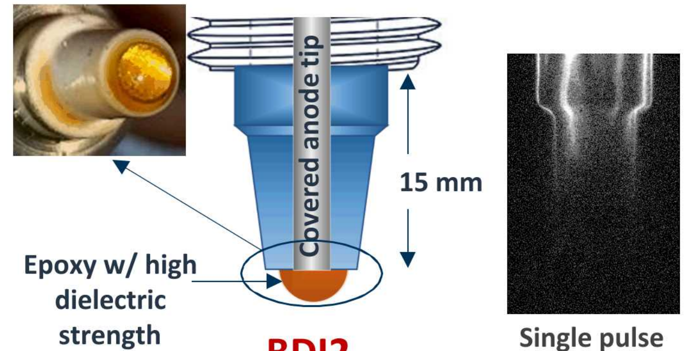


Pin-to-pin (P2P)

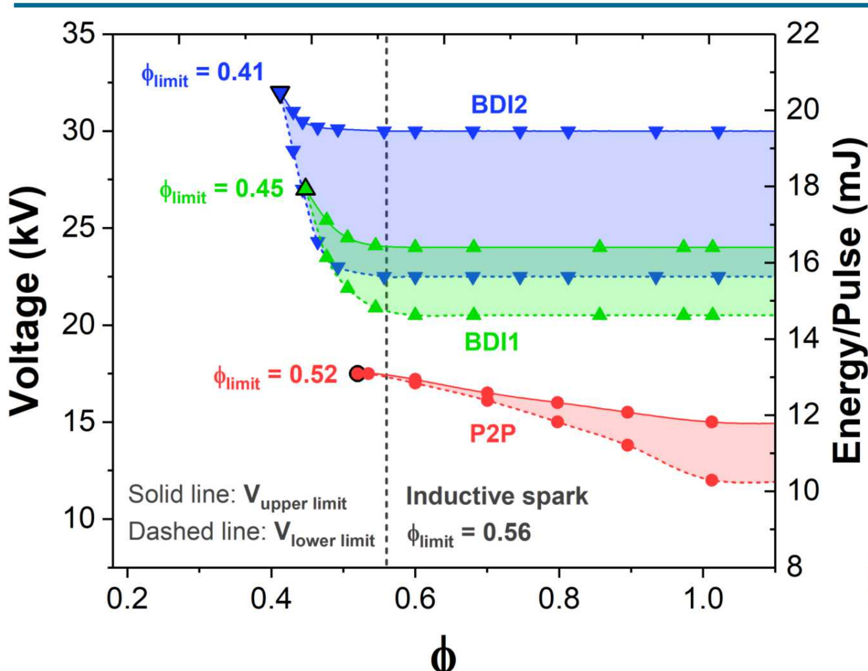
Barrier discharge igniter (BDI)

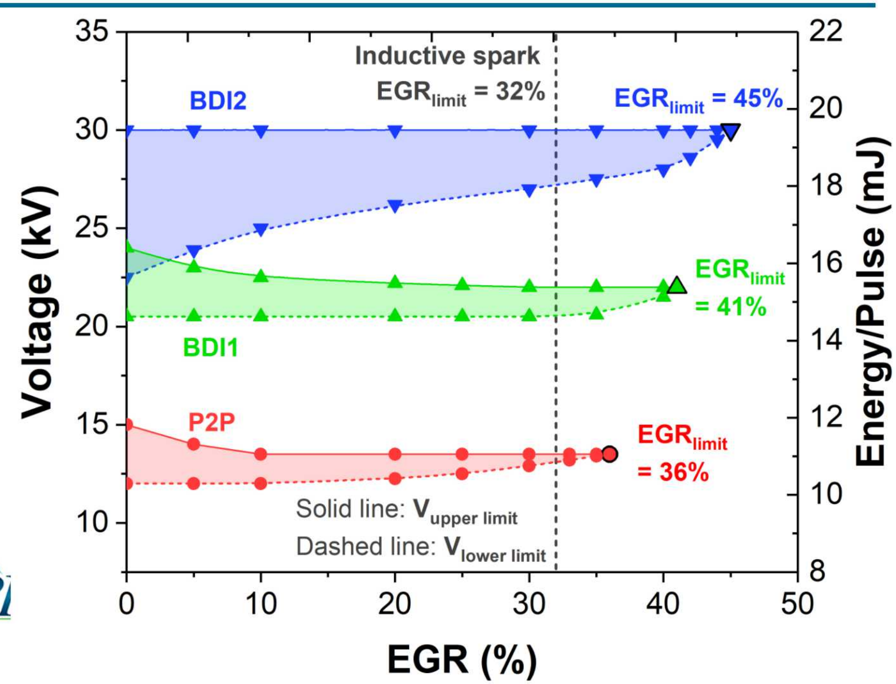


BDI1



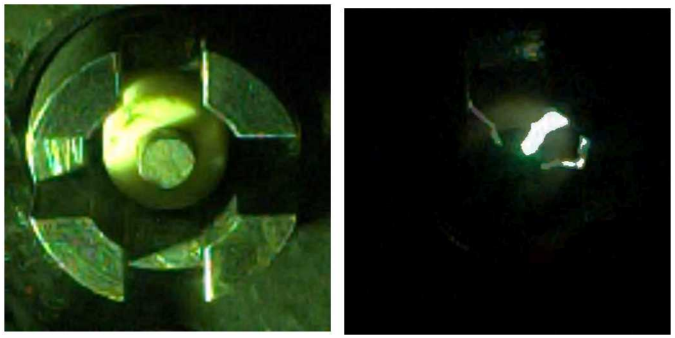
BDI2





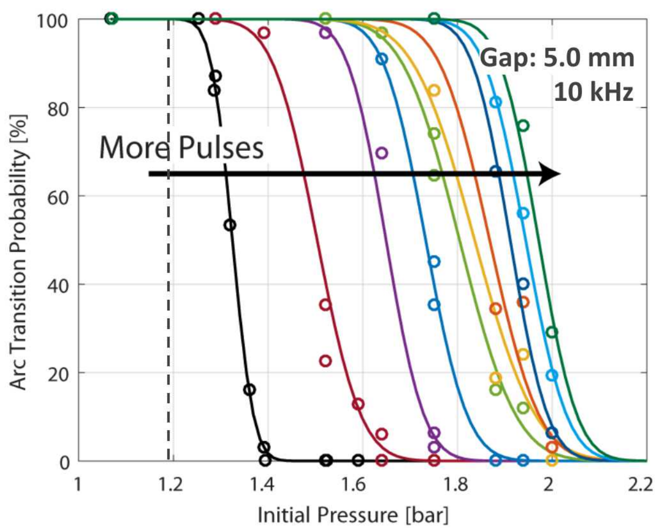
Previously observed multi-pulse LTP to arc transition

Sjöberg et al, *SAE Int J Engines*, 2014



Arcs with multi-pulse – no arc with single-pulse

$\Longrightarrow$ a thermal or chemical pre-conditioning mechanism



Wolk & Ekoto, IAV Conference on Ignition Systems, 2016.

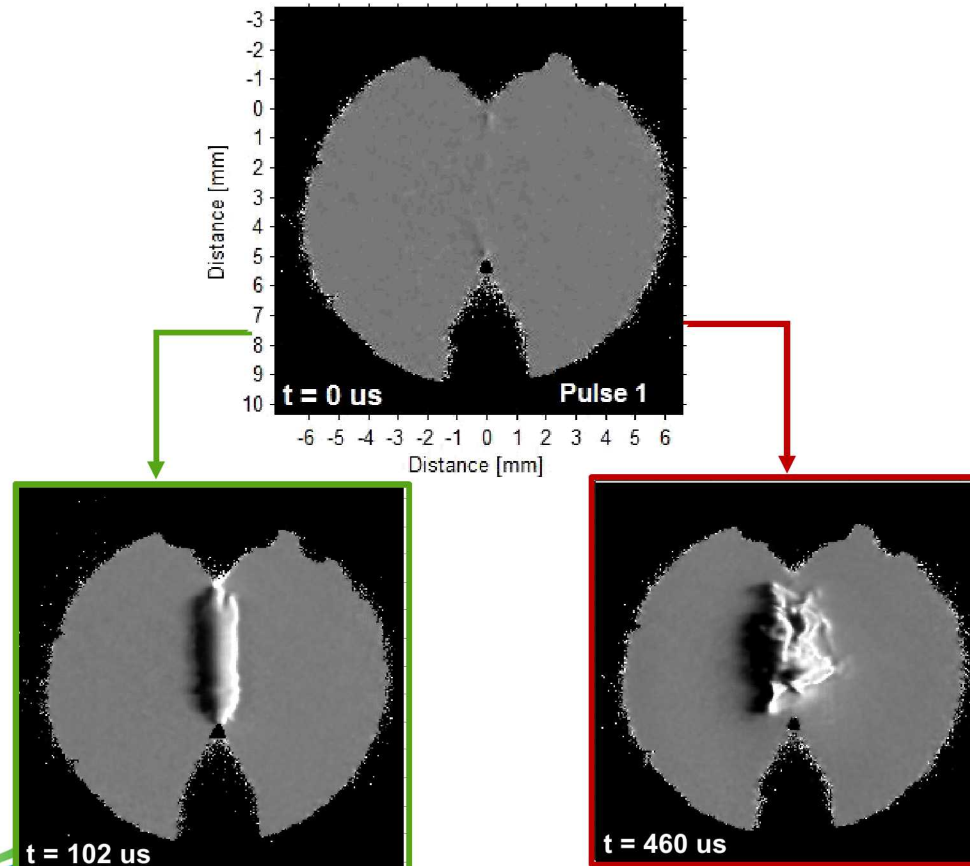
Engine results confirmed by calorimetry

Temperature rise after each pulse

Calorimetry

$$\Delta T = \frac{E_{Thermal}}{\rho c_p V}$$

Streamer volume



Inductive Spark

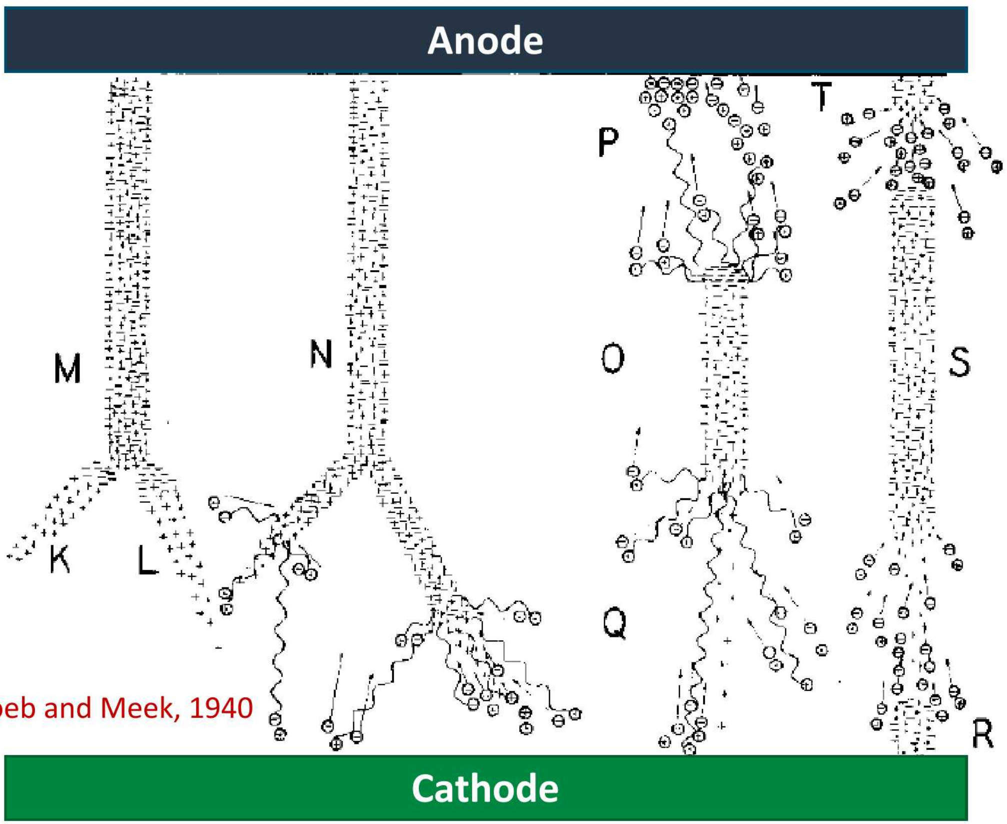
Laminar expansion

Nanosecond Discharge

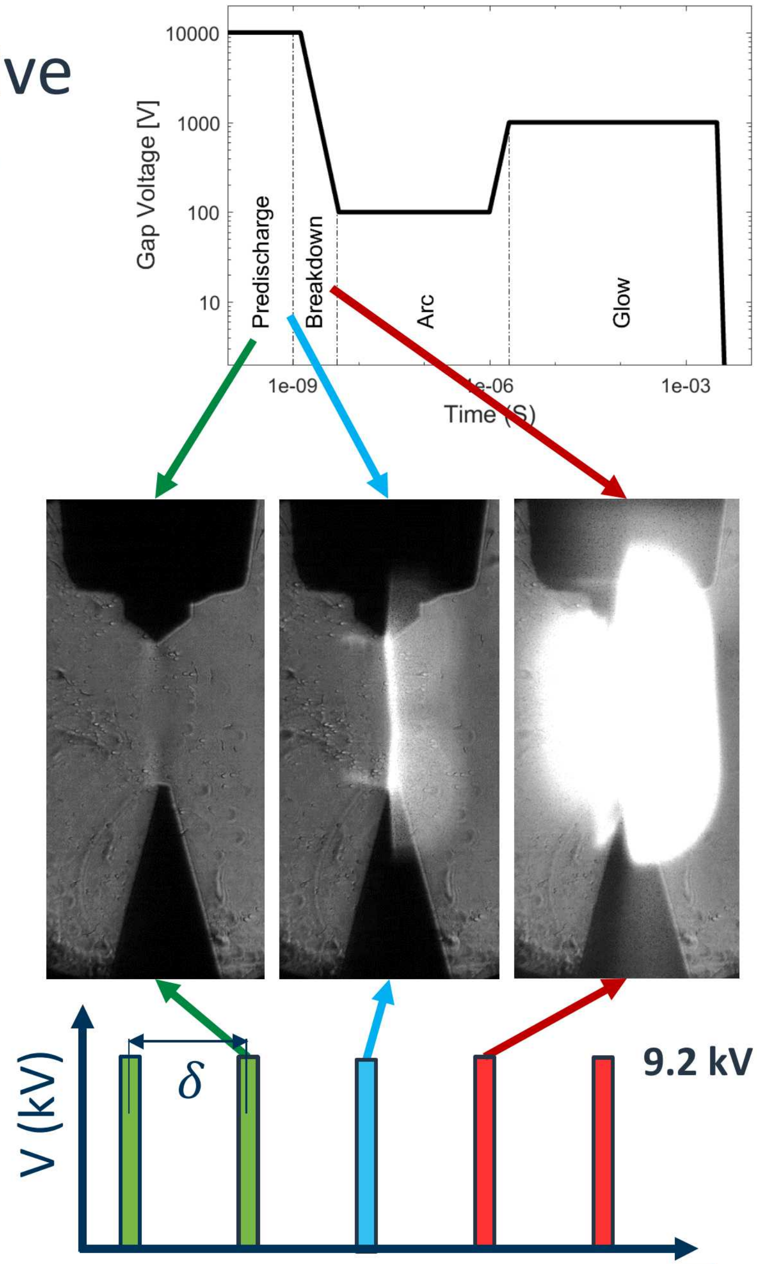
Turbulent expansion

Transition from LTP to arc is sensitive to # of pulses and inter-pulse time

Streamer branching phenomena

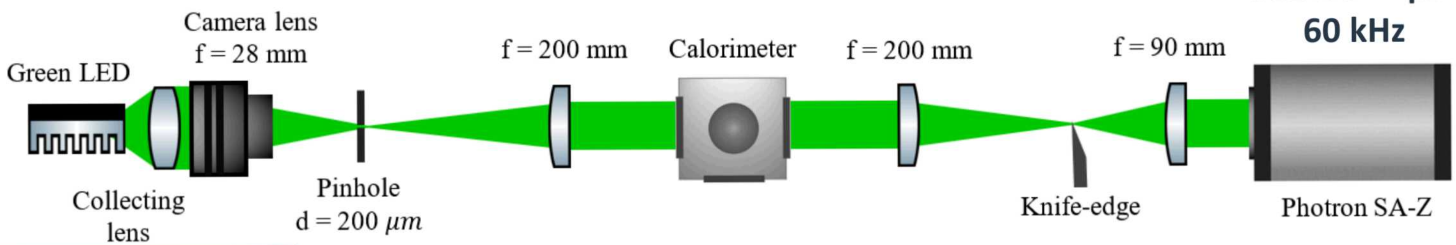


Loeb and Meek, 1940

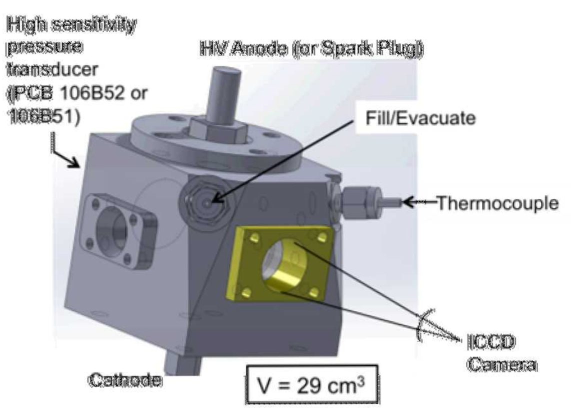


Diagnostics & facilities to explore TPI

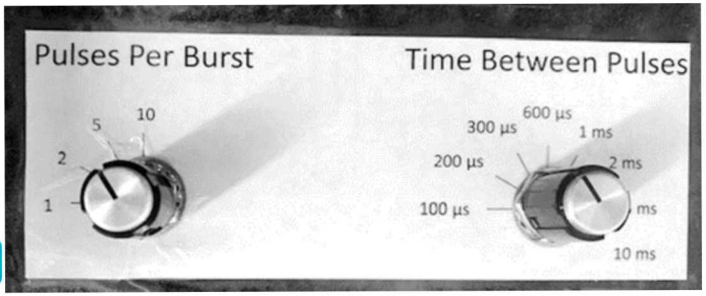
512 x 512 px^2
60 kHz



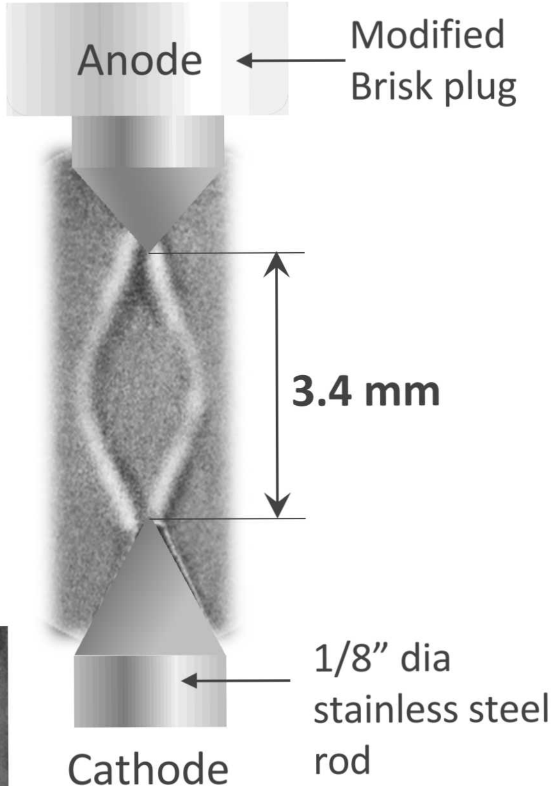
Optical Ignition Calorimeter



Control box for # of pulse, inter-pulse delay



Transient Plasma Systems



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 – 15 kV
- Pressure 1.3 – 4 bar

Smaller gap size can be used to reduce peak voltage and # of pulses, at expense of longer inter-pulse delay, and lesser margin of error

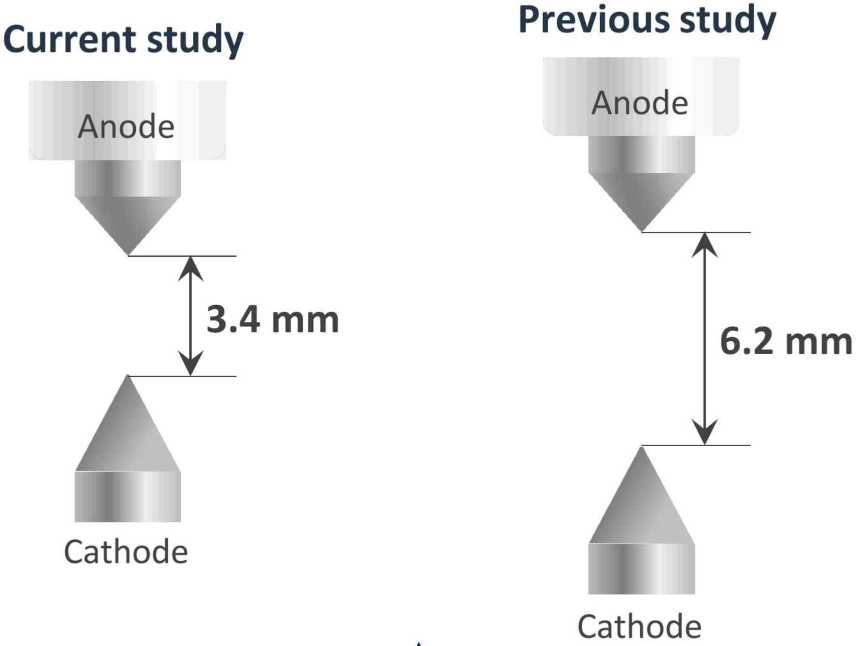
Gap size	3.4 mm	6.2 mm
# of pulses, N	2	10
Dwell, δ (μs)	300	100
V_{peak} (kV)	14.1	17.5
E_{total} (mJ)	17	86

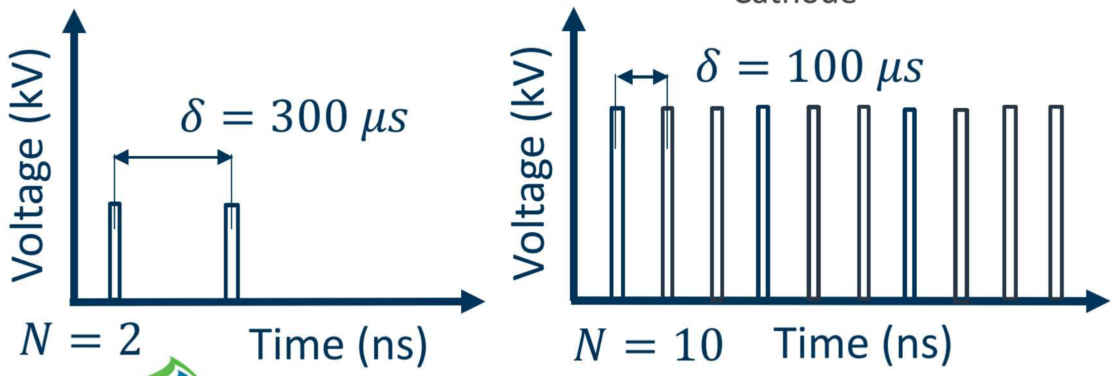
Benefits of smaller gap

- Lower peak voltage
- Lesser # of pulses
- Reduced ignition energy

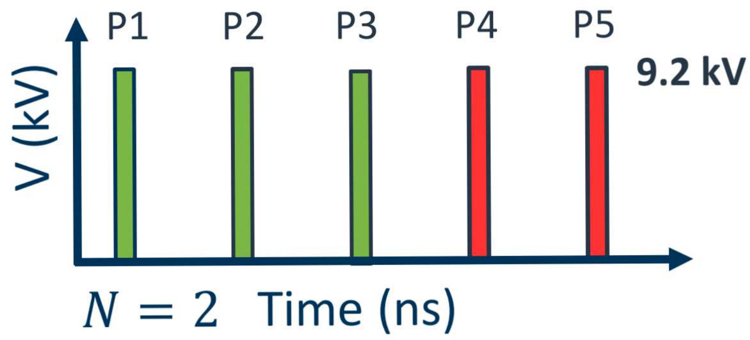
Challenges of smaller gap

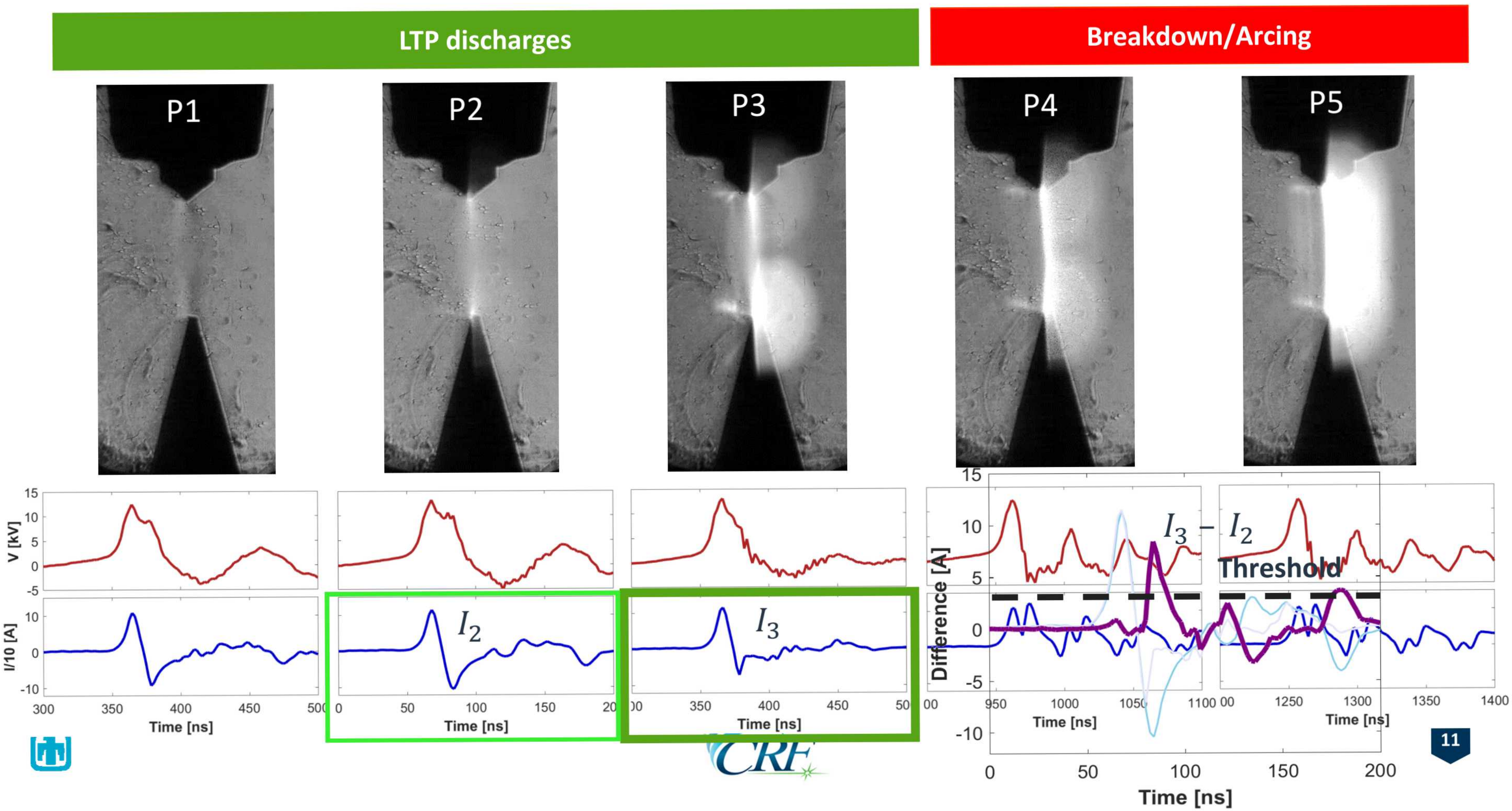
- Longer dwell
- Less margin of errors
- Arc-free ignition ?





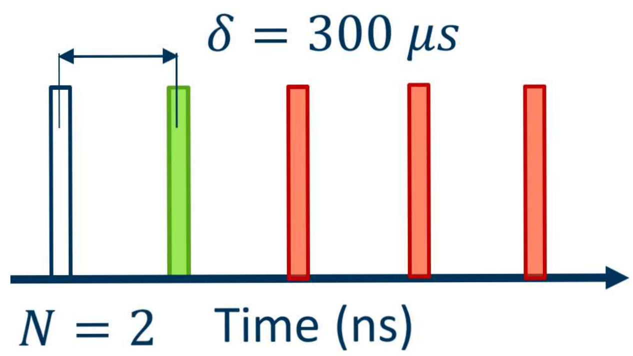
Current traces can help detect LTP to breakdown transition

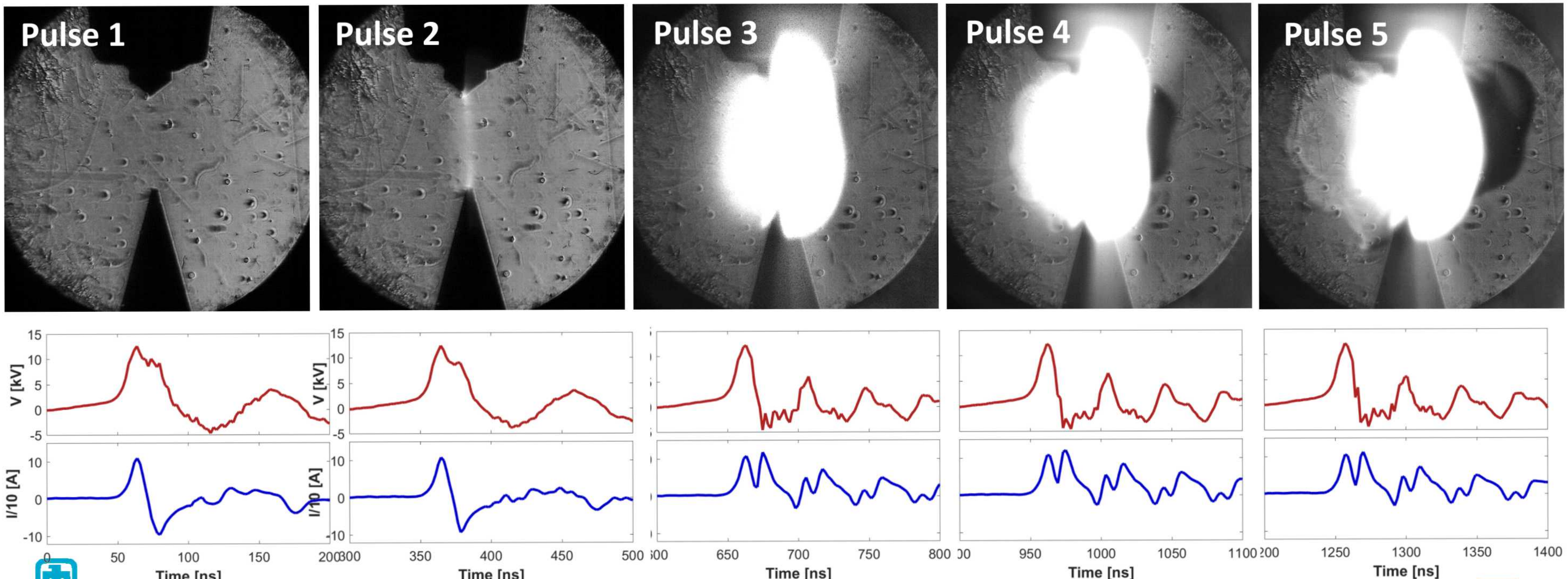




Breakdown/arcing occurs after ignition via LTP pulses

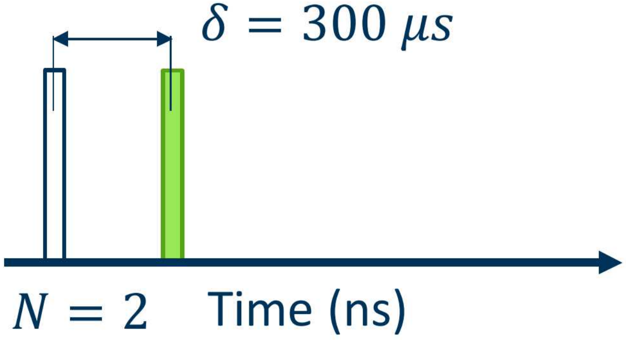
ϕ	1
# of pulses, N	5
Dwell, δ	300 μs
V_{peak}	12.3 kV

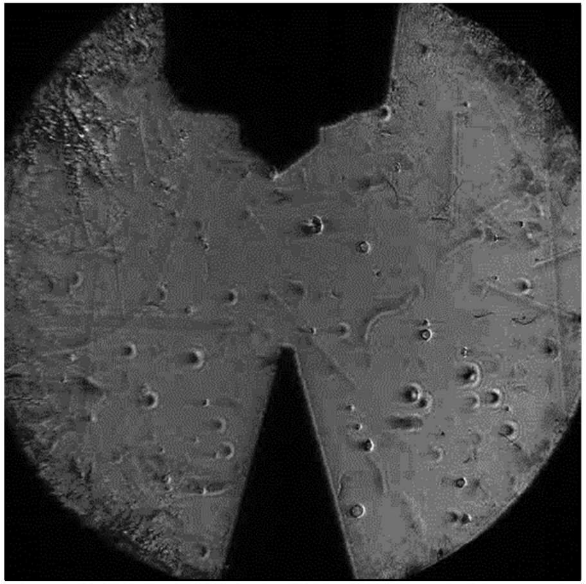


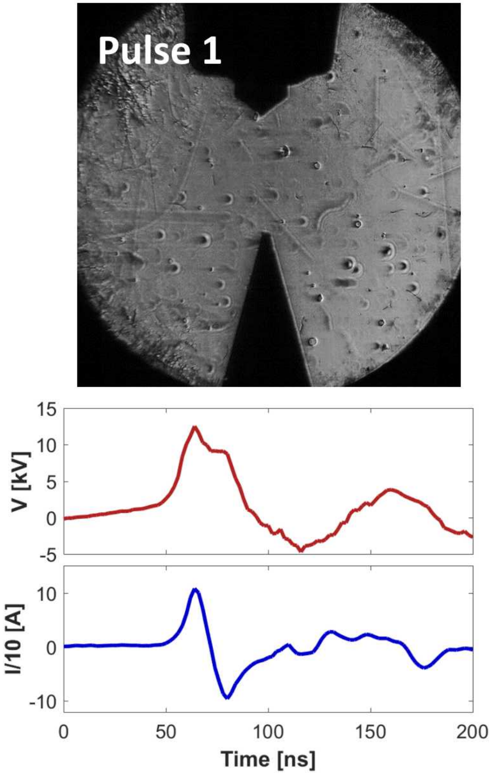


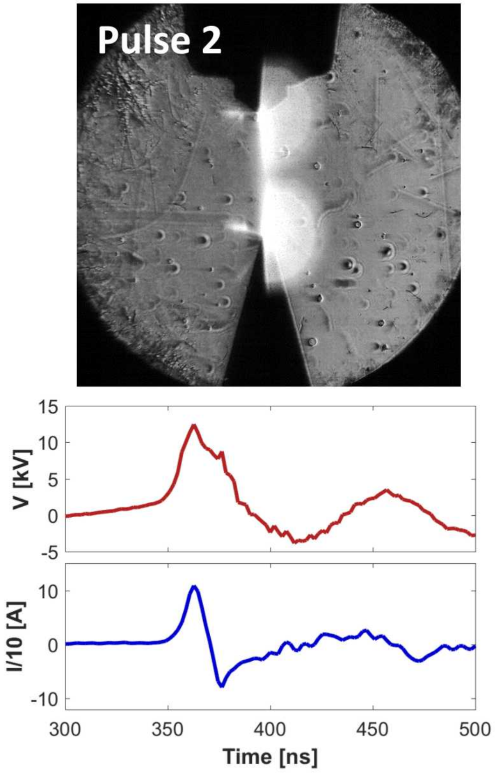
Reducing # of pulse eliminates breakdown: Ignition via LTP

$\boldsymbol{\phi}$	1
# of pulses, N	**2**
Dwell, $\boldsymbol{\delta}$	300 μs
$\boldsymbol{V_{peak}}$	12.3 kV



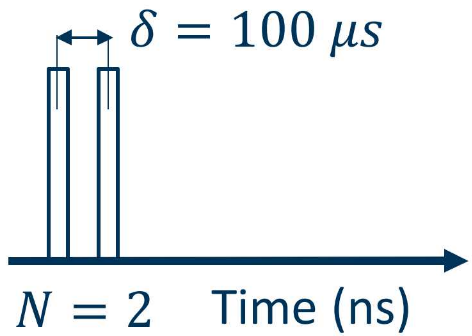


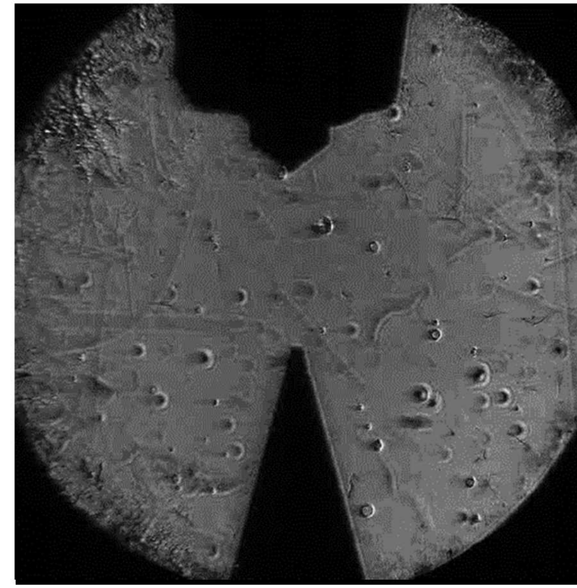




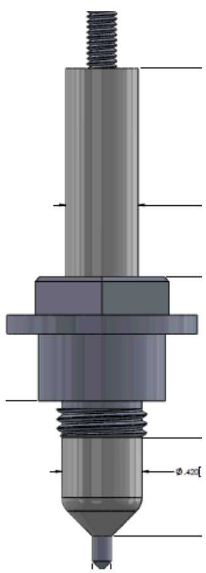
Reducing dwell leads to ignition kernel quenching

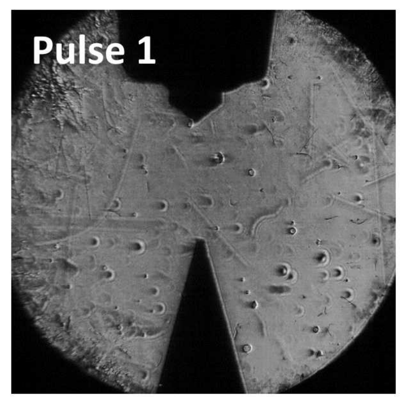
ϕ	1
# of pulses, N	2
Dwell, δ	100 μs
V_{peak}	12.3 kV

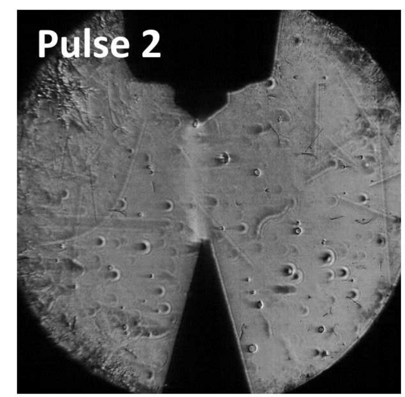




Our failed attempt to make non-resistive igniter in-house

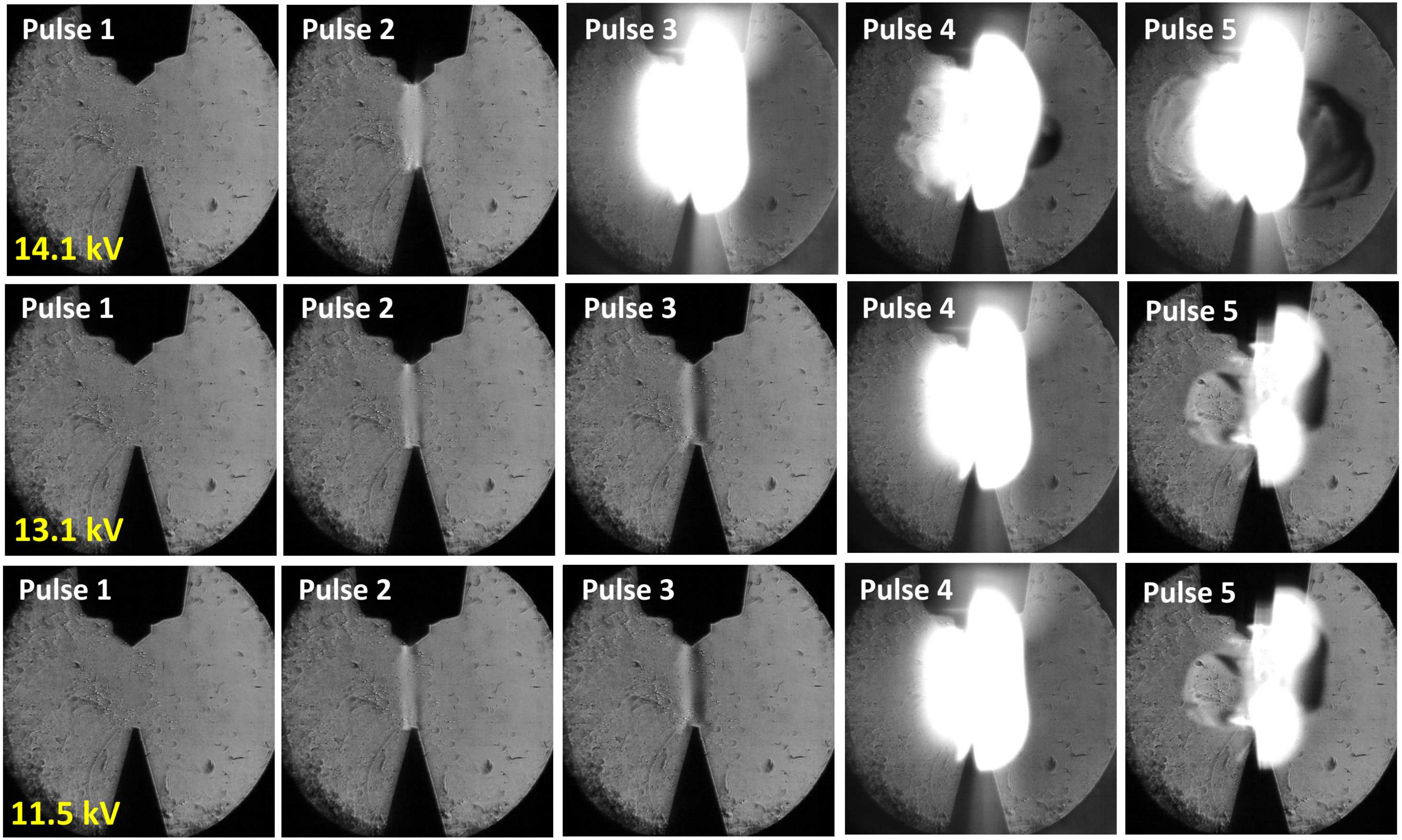




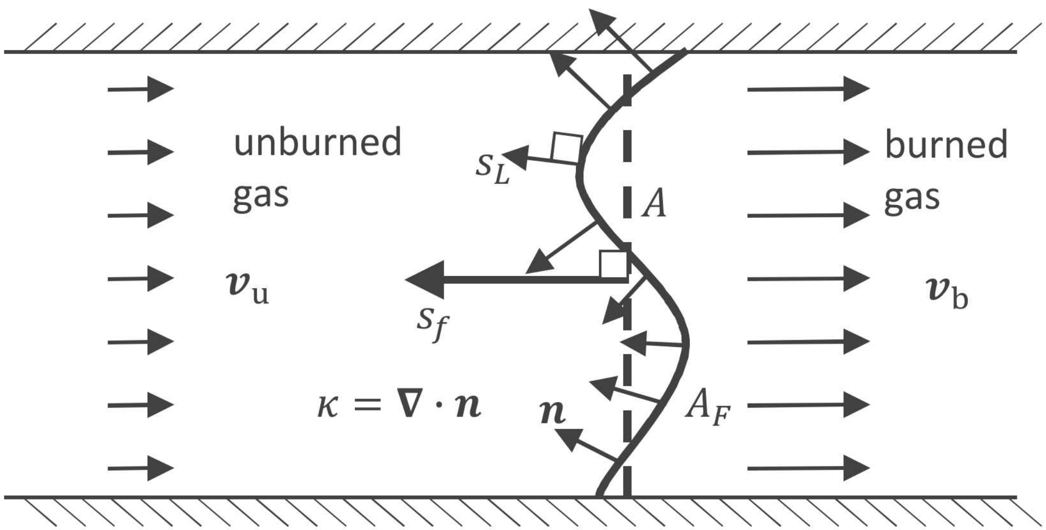


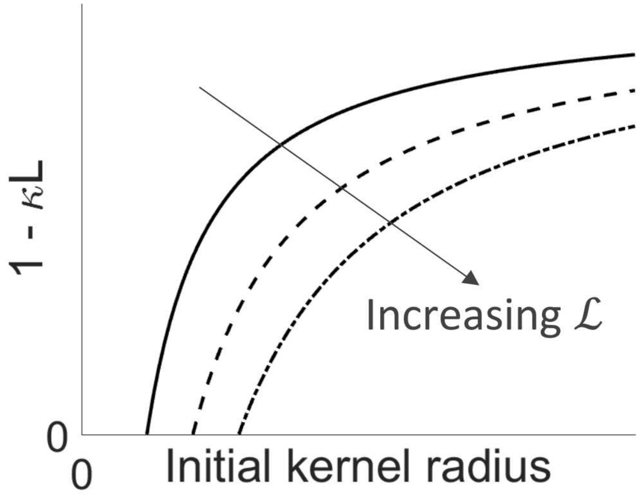
Decreasing voltage reduces the # of breakdown pulses

$$\phi = 0.52, N = 5, \delta = 300\ \mu s$$



Slower flame speeds at lean conditions can be overcome in part by increased flame front turbulence





Accordingly: $s_f \approx s_L \cdot \frac{A_F}{A}$

A caveat is that s_L is also influenced by flame front curvature (κ)

$$s_L = s_L^0(1 - \kappa\mathcal{L})$$

$\mathcal{L}(Le, \ell_f^0)$: Markstein length

Le: thermal-to-mass diffusivity ratio (Le_{CH_4}: 0.91, $Le_{C_3H_8}$: 1.63, $Le_{C_8H_{18}}$: 2.55)

ℓ_f^0: unstretched laminar flame thickness

Where $\uparrow Le$ & $\uparrow \ell_f^0$ lead to $\uparrow \mathcal{L}$

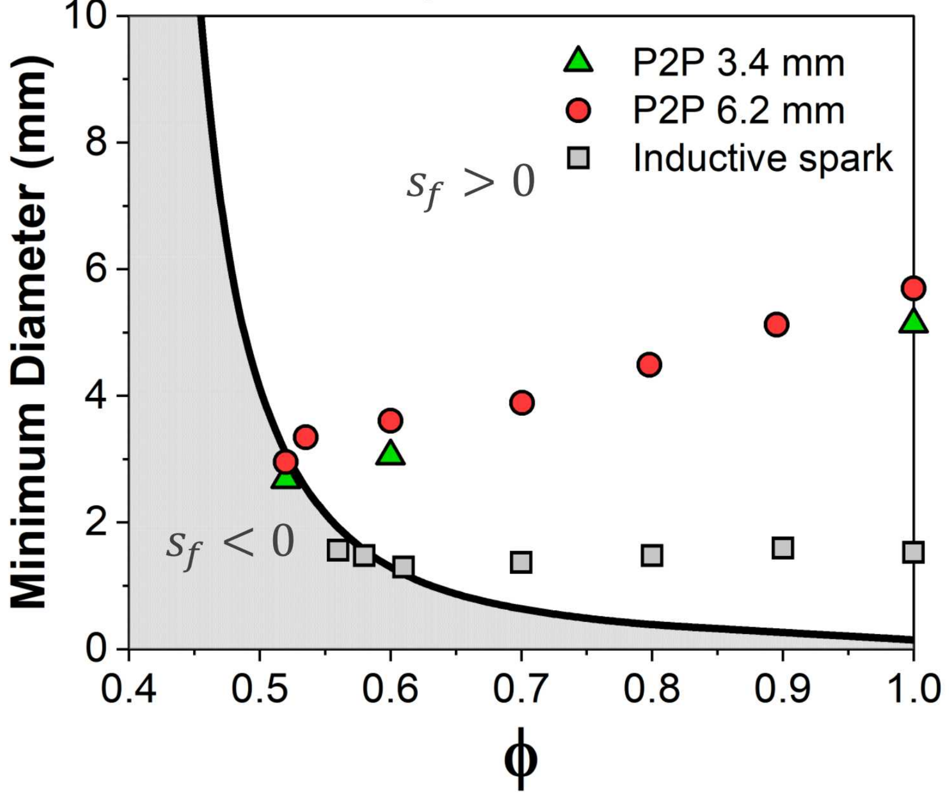
Increased EGR increases ℓ_f^0 while decreased ϕ increases both ℓ_f^0 and Le, which sets a limit for turbulence flame front enhancement

Plasma-to-Kernel-to-flame transition depends on kernel radius, flame speed, and Markstein length

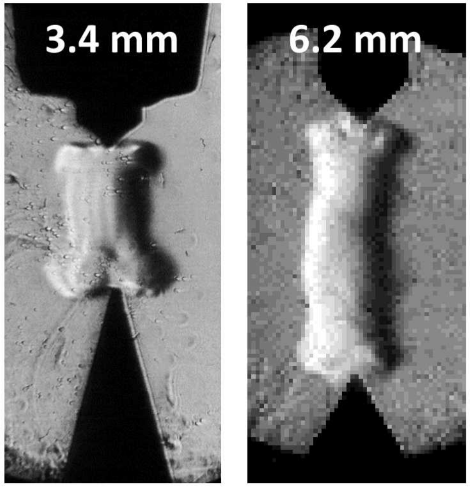
Kernel-to-flame transition

- Formed kernels are initially laminar
- Minimum size needed to sustain kernel (i.e., $2r > \mathcal{L}$)
- Increased EGR dilution or ϕ increases required initial r

$$\kappa = 1/r$$
$$s_f \approx s_L(1 - \mathcal{L}\kappa)$$



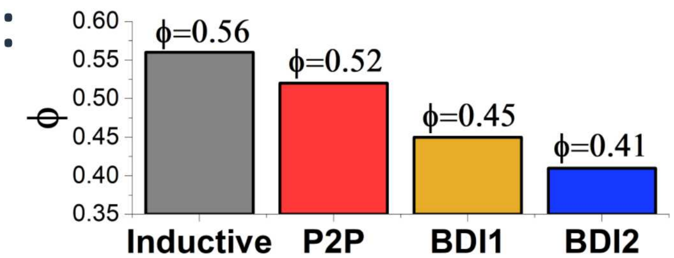
Lean limit
$\phi = 0.52$



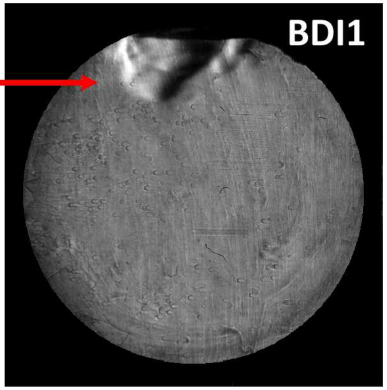
Average ignition kernel diameter **2.7 mm** **3.0 mm**

Small gap sizes for conventional spark ignition limit EGR dilution rates and ϕ

BDI1 & BDI2 can extend the lean limit: Effect of plasma chemistry?

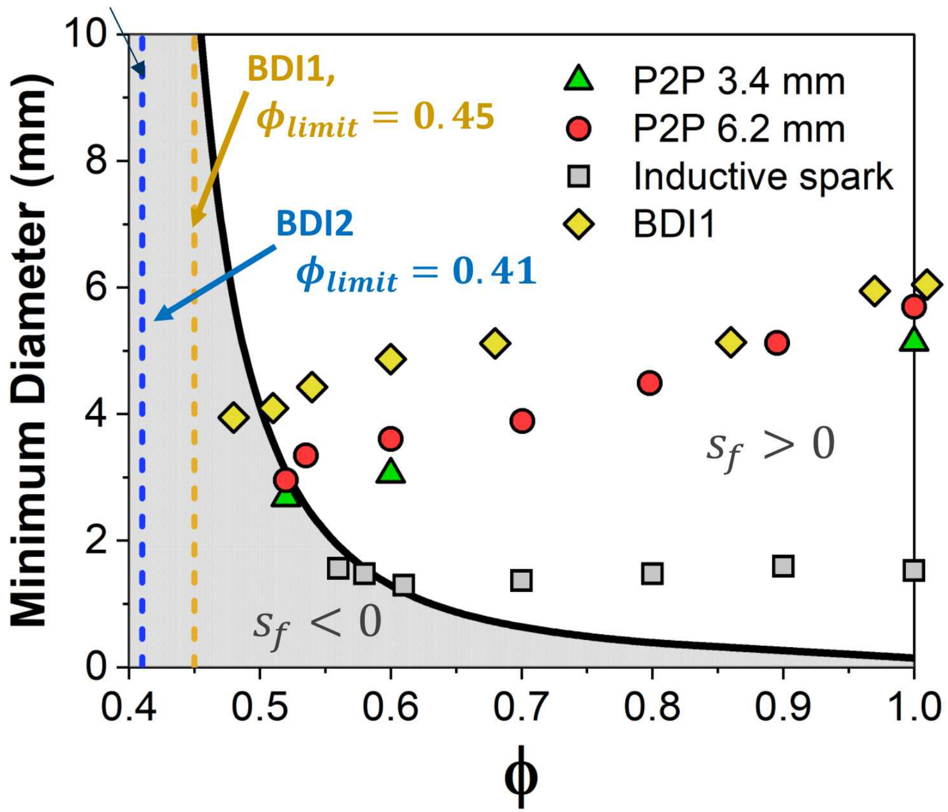


Ignition kernel



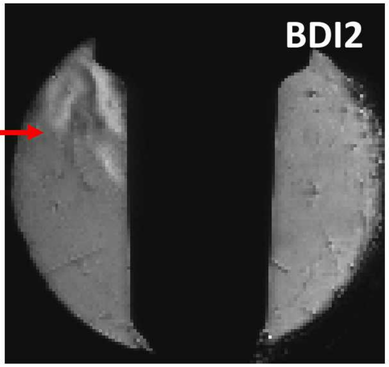
$\phi = 0.48$

Average ignition kernel diameter **2.7 mm**



For BDI1 $\phi = 0.45$ and for all BDI2 cases ignition started from the electrode side

Difficult to calculate an accurate ignition kernel



$\phi = 0.45$

BDI discharges produce radicals and intermediate species, unlike P2P

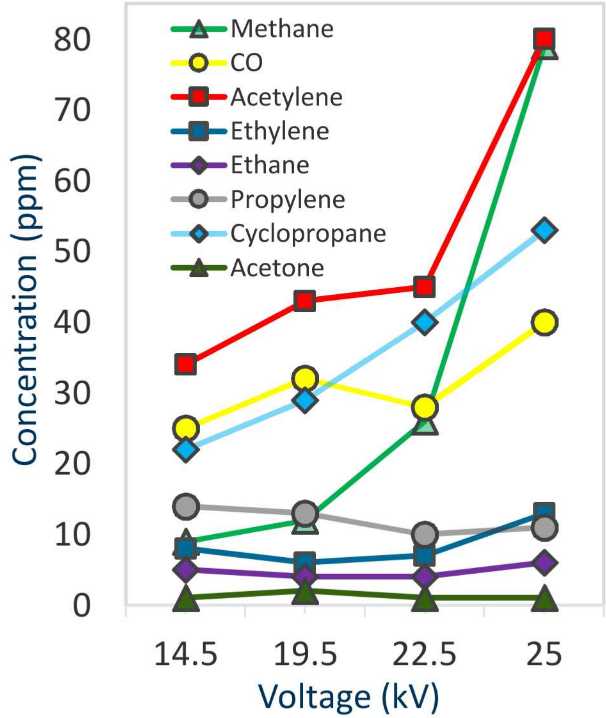
Presence of intermediate products from BDI1 discharges enhances flame speed

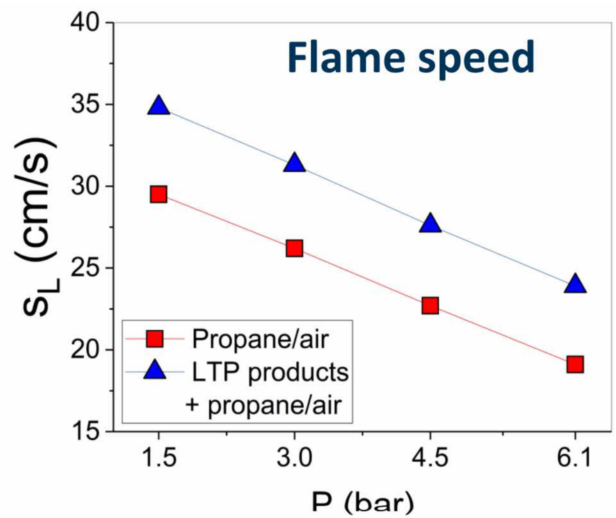
Ignition gas chromatography

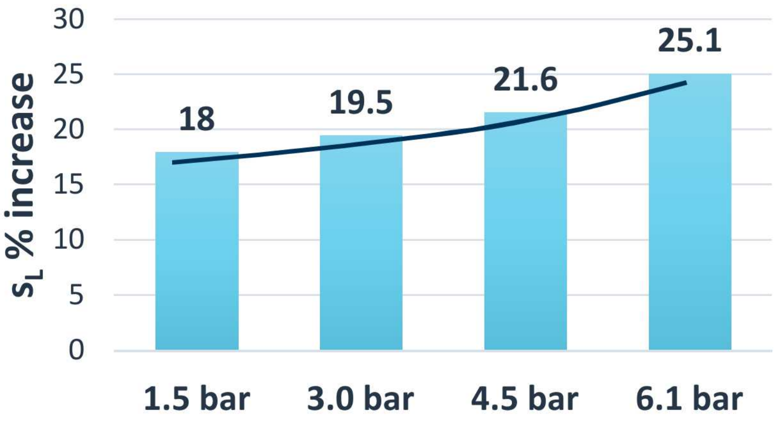
- BDI1 discharge in Propane/air mixture below lean flammability limit (LFL)
- Sampled discharge generated intermediates, fuel fragments, etc.
- Computationally add propane to make the mixture stoichiometric

Composition of BDI1 discharge products versus original propane/air mixture

% by Vol.	BDI1 products + propane/air	Propane/ air
O2	20.2	20.2
N2	75.8	75.8
Propane	2.5	4
Methane	0.26	
CO	0.22	
Acetylene	0.51	
Ethylene	0.1	
Propylene	0.12	
Cyclopropane	0.26	
Acetone	0.03	

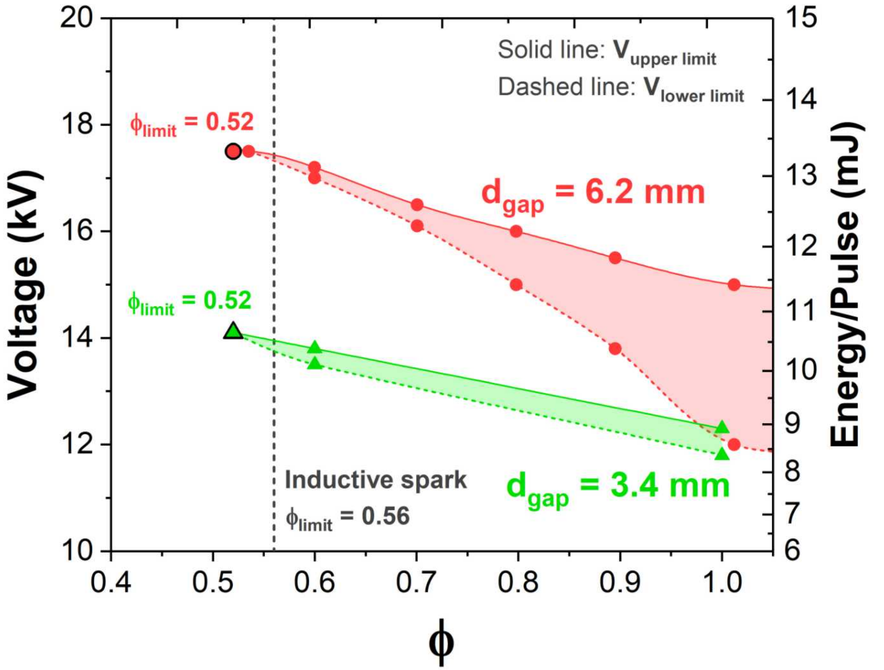


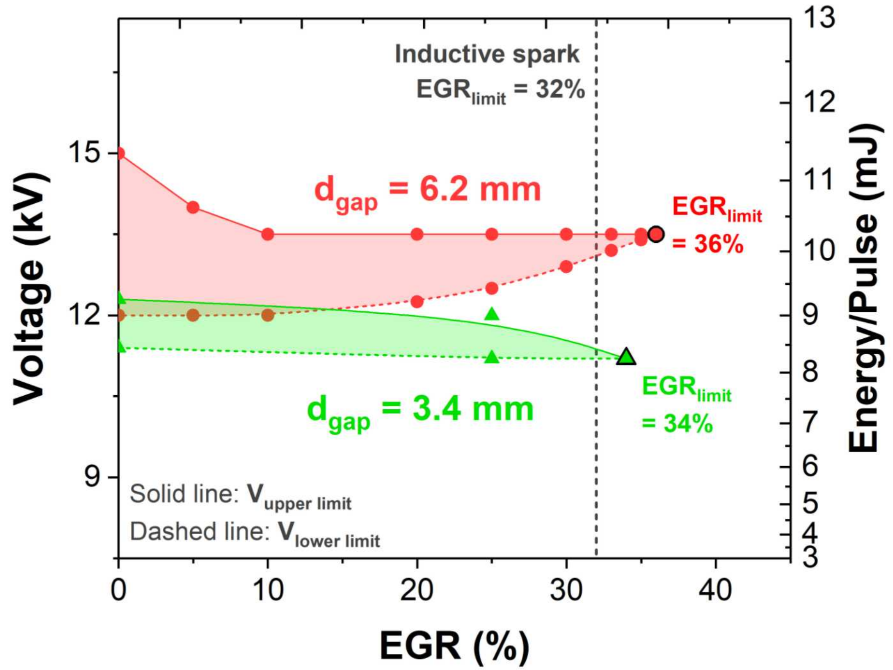




Pressure ↑ Flame speed ↑

Lean limit remains unchanged and dilution limit drops slightly w/ smaller gap size; but the operating range shrinks





Gap size	3.4 mm	6.2 mm
# of pulses	2	10
Dwell (μs)	300	100
V_{peak} (kV)	14.1	17.5
E_{total} (mJ)	17	86

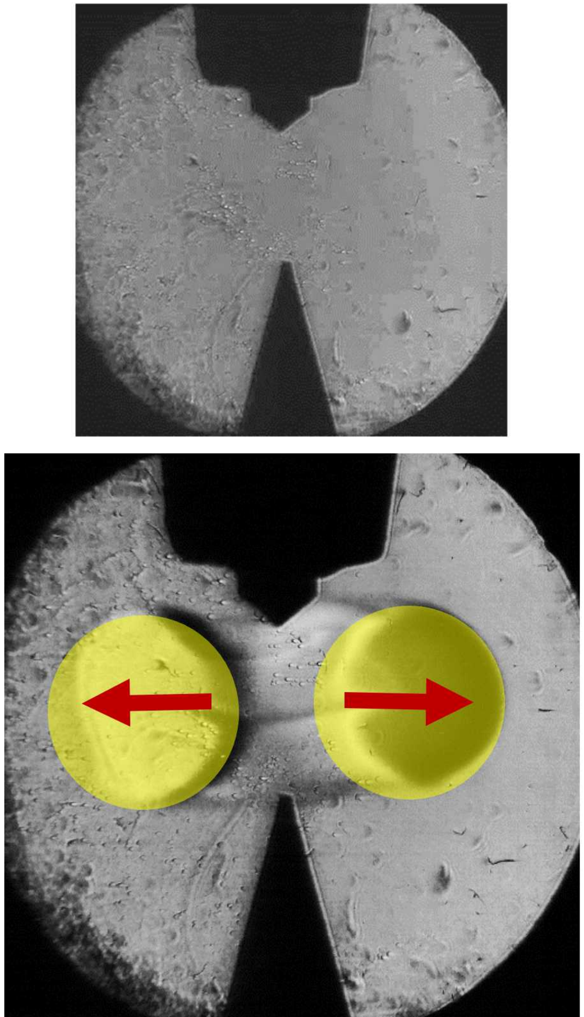
P2P 3.4 mm compared to 6.2 mm gap size

Benefits:
- Lean limit unchanged
- Dilution limit nearly unchanged
- Total energy requirement reduces 5 folds

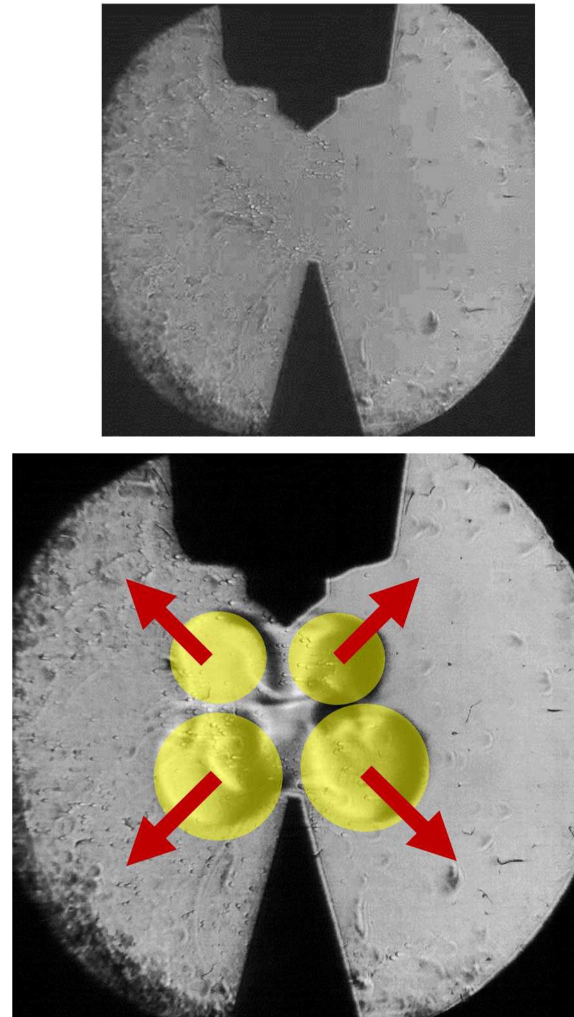
Challenges:
- Narrow voltage range
- Less forgiving

Ignition kernel shape and propagation is very different for TPI versus breakdown/arc ignition

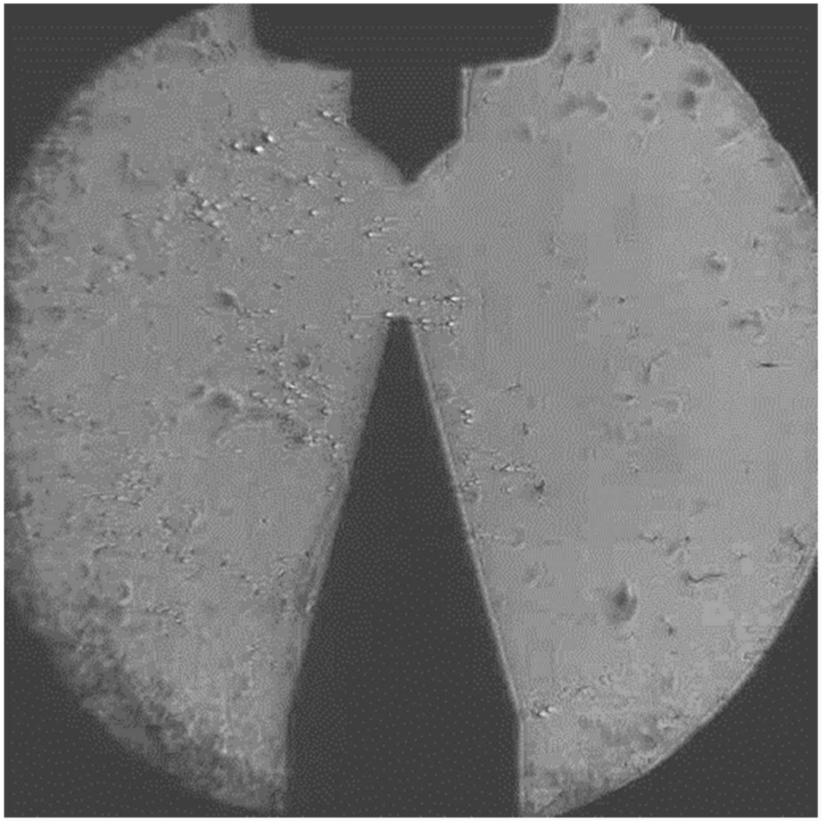
Breakdown at ignition



No breakdown at ignition



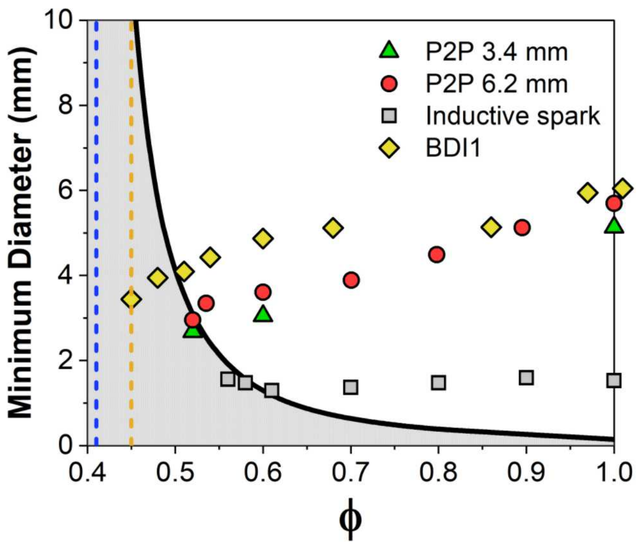
Preliminary investigation of TPI at high-pressure always resulted in breakdown



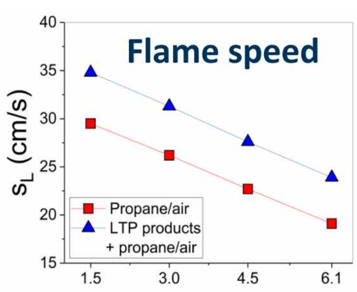
Experimental conditions
- Gap size 1.9 mm
- Propane/air $\phi = 1.0$
- Pressure 2.3 bar
- Voltage 13 kV
- Number of pulses 5
- Dwell time 300 μs

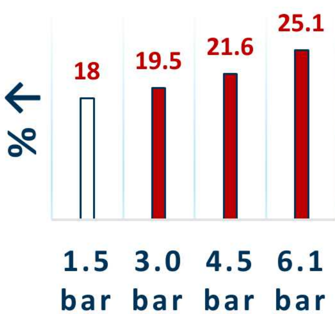
Future steps
- Different pulsing strategy
- Dwell time adjustment
- Better igniter

Summary



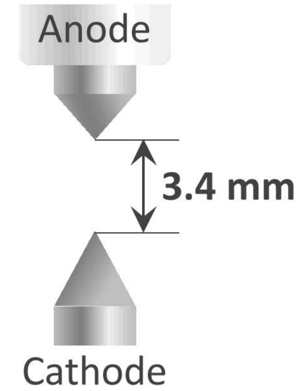
- For **pin-to-pin**, plasma-to-Kernel-to-flame transition depends on kernel radius, flame speed, and Markstein length
- For **barrier discharge igniters** produce radicals and intermediate species and can extend the lean limit further

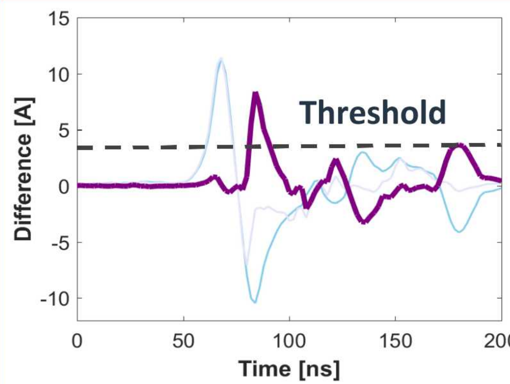


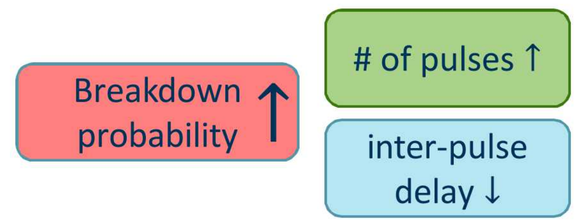


For pin-to-pin configuration

Gap size	3.4 mm	6.2 mm
ϕ_{limit}	0.52	0.52
EGR_{limit}	34%	36%
E_{total}	17	86



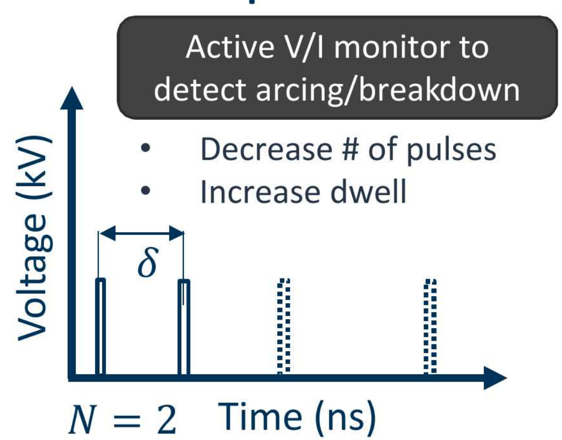




Current traces can help detect LTP to breakdown transition

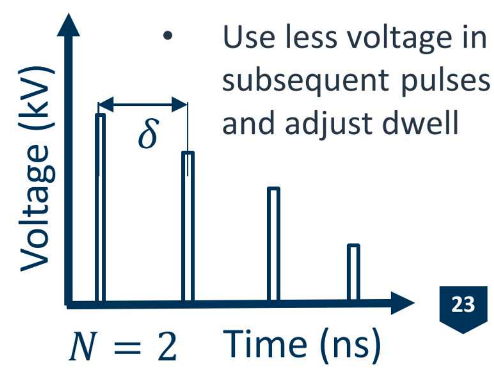
Pulsing strategy # 1

Feedback loop



Pulsing strategy # 2

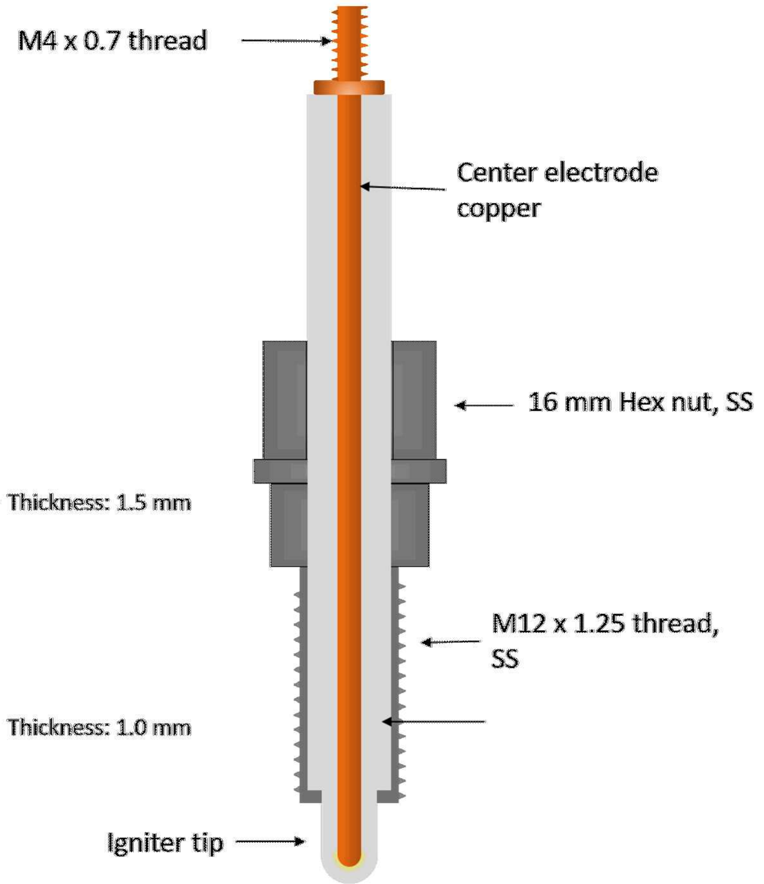
Pulse to pulse voltage variation

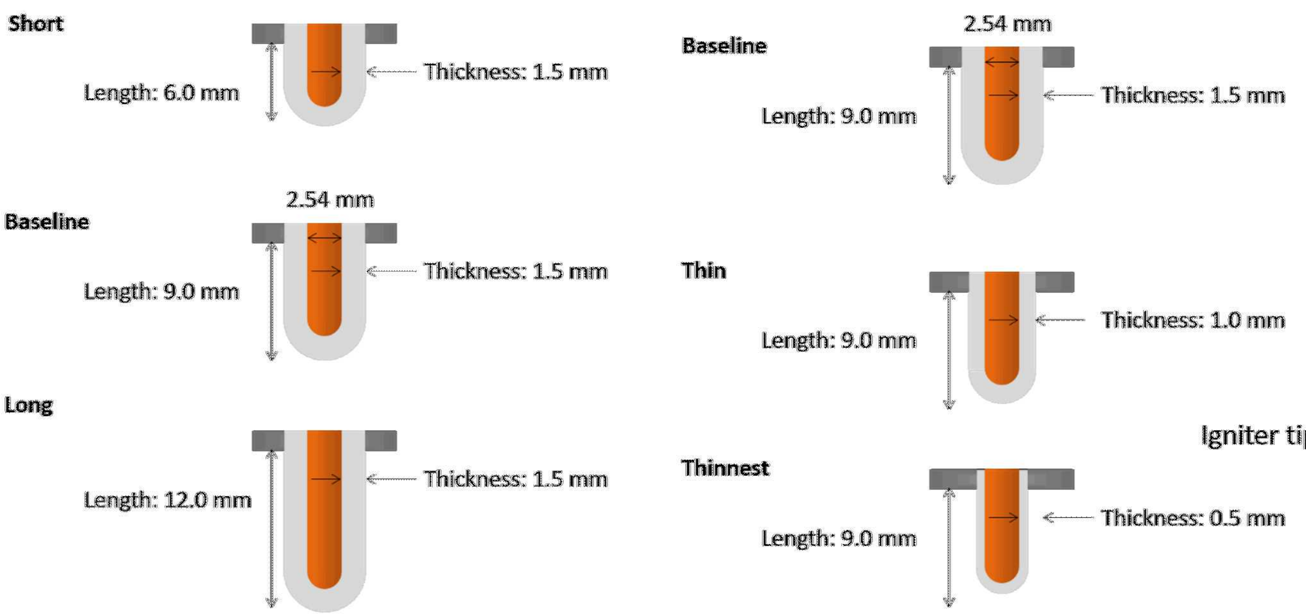


Next steps

New BDI igniter by IJ research Inc.

- BDI without exposed anode
- Embedded insulator prongs
- Active/passive pre-chamber with TPI





Thank You!