High Pressure Turbulent Flame *Initiation (Ignition)* and Propagation at Large Reynolds Number

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High Pressure Turbulent Premixed Combustion

CH_4, $\phi = 0.9$

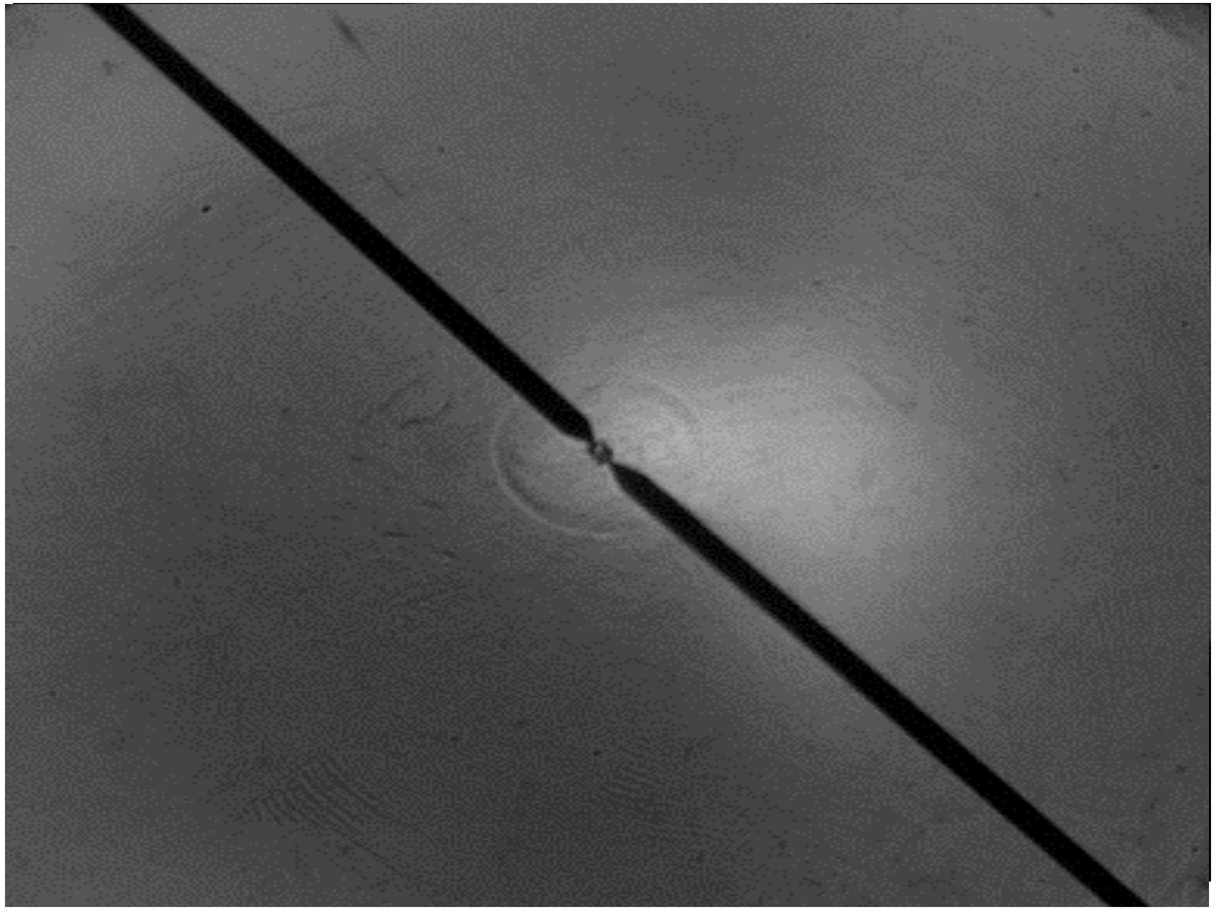
5 atm

$u'/S_L \approx 8$

Field of view

12 x 12 cm^2

Minimum Ignition Energy (50%)



Go: successful ignition

(1) Spark

(2) Shock wave (a few μs)

(3) Flame kernel (hundreds μs) → Expanding flame

No Go: (1) No breakdown (no spark); (2) Spark→ Small kernel → Quench; (3) Spark→ Kernel→ Small flame→ Quench

Outline of the Talk

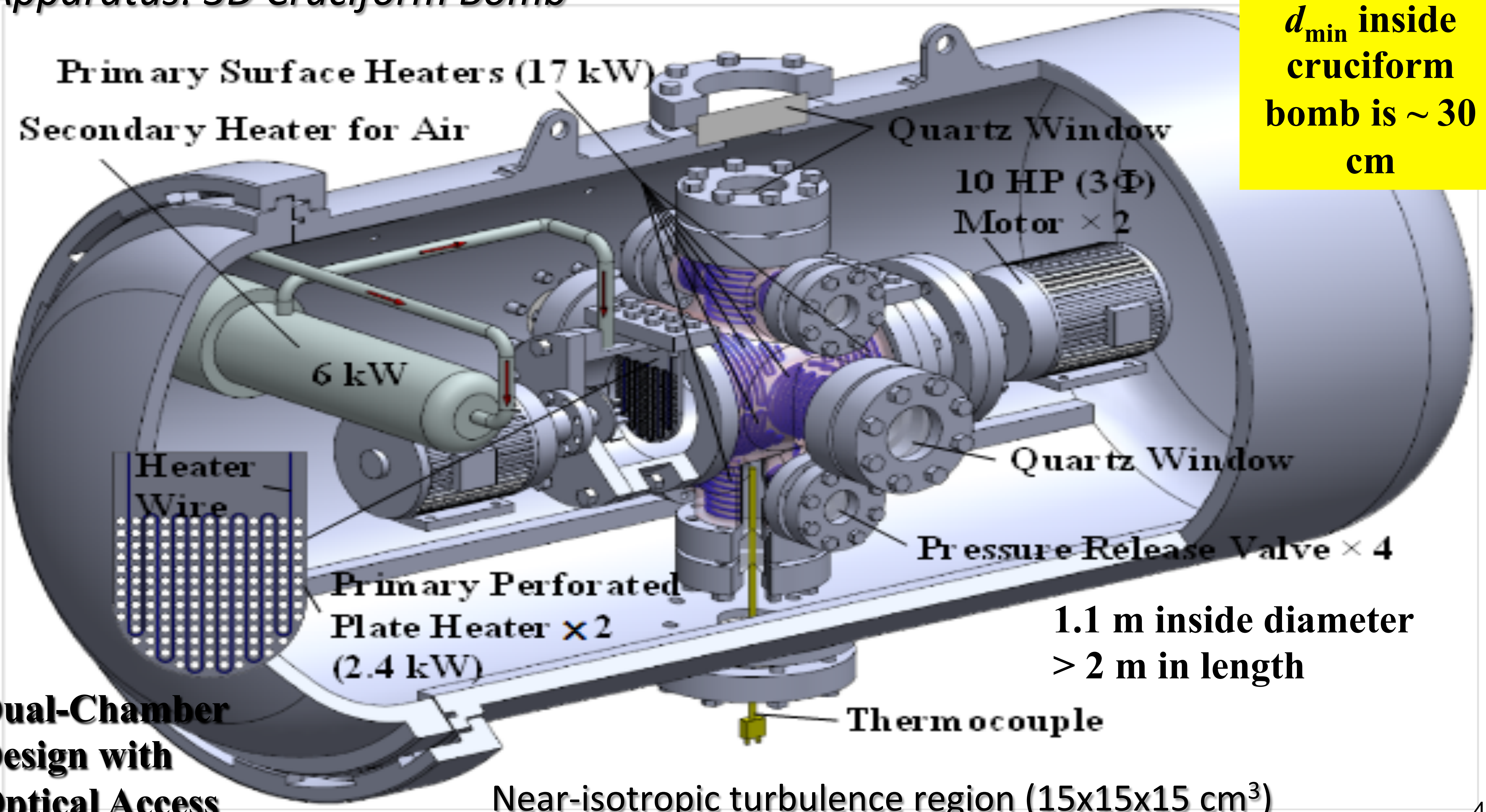
(1) Give a brief review on Minimum Ignition Energy (MIE) Transition of turbulent spark ignition up to 5 atm over a wide range of u'/S_L [Shy et al. PCI 36 (2016) 1785-1791].

(2) Discuss an unexpected result: "Turbulent facilitated ignition (TFI) through differential diffusion discovered by Law and co-workers [PRL 113 (2014) 024503].

(3) TFI only occurs for Le >> 1 flame and is restricted at rather small spark gap which is much smaller than the quenching distance [Shy et al. CnF 185 (2017) 1-3].

(4) Propagation will not discuss here (ICDERS, TF 1, Tue)

Apparatus: 3D Cruciform Bomb



d_{min} inside cruciform bomb is ~ 30 cm

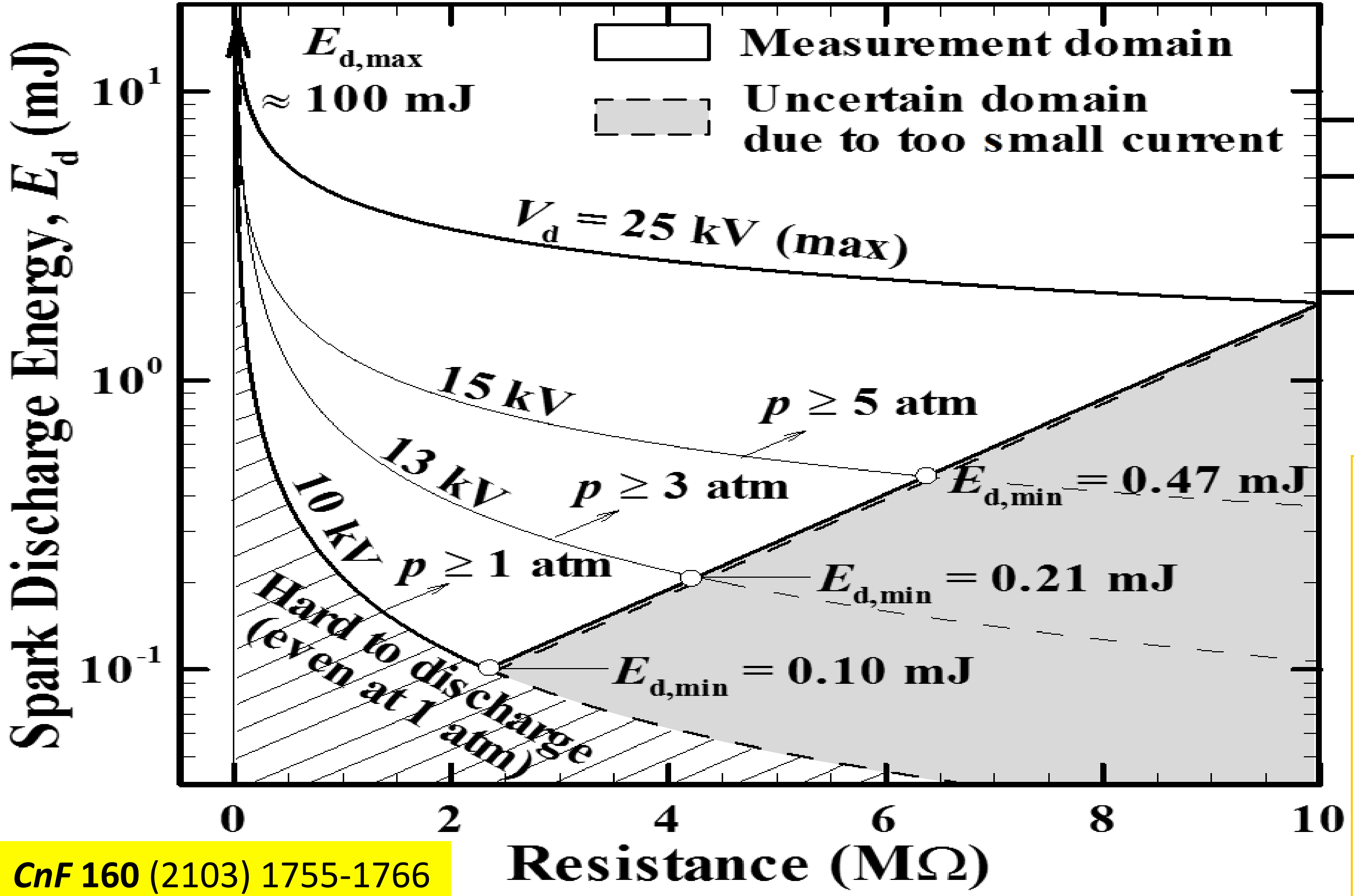
1.1 m inside diameter
> 2 m in length

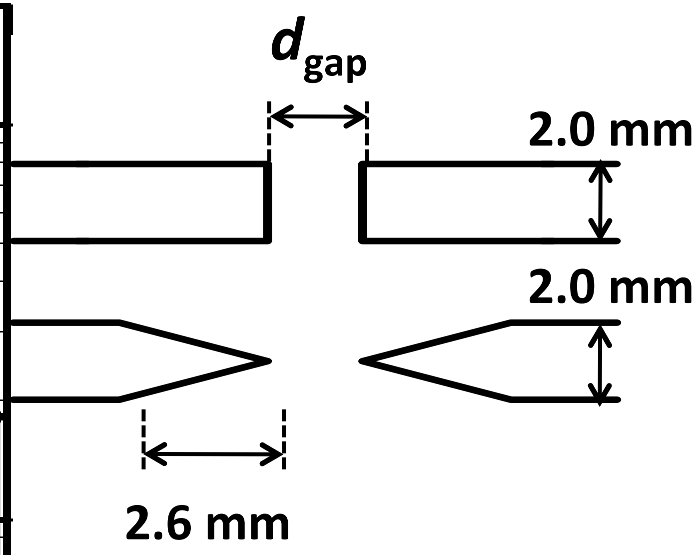
Dual-Chamber Design with Optical Access

Near-isotropic turbulence region (15x15x15 cm^3)

Many parameters can influence spark ignition (Minimum Ignition Energy, MIE): (1) ***electrical breakdown characteristics*** *i.e. type of discharge, discharged voltage/current, pulse duration time*; (2) ***electrode characteristics*** *i.e. material, geometry, size, gap*; (3) ***flow characteristics*** *i.e. type of flow, turbulent velocity/length scales, pressure, temperature*; (4) ***mixture characteristics*** *i.e. equivalence ratio, phase of fuel*. For accurate reproduction of a spark ignition experiment, ***these aforesaid parameters as well as the discharged*** E_{ig} ***are needed***.

Effect of increasing pressure on spark discharge energy

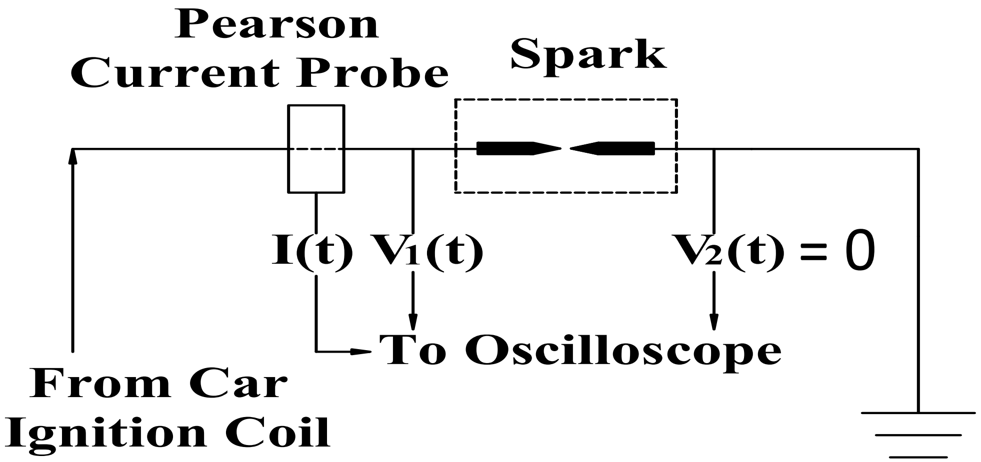




CnF **160** (2103) 1755-1766

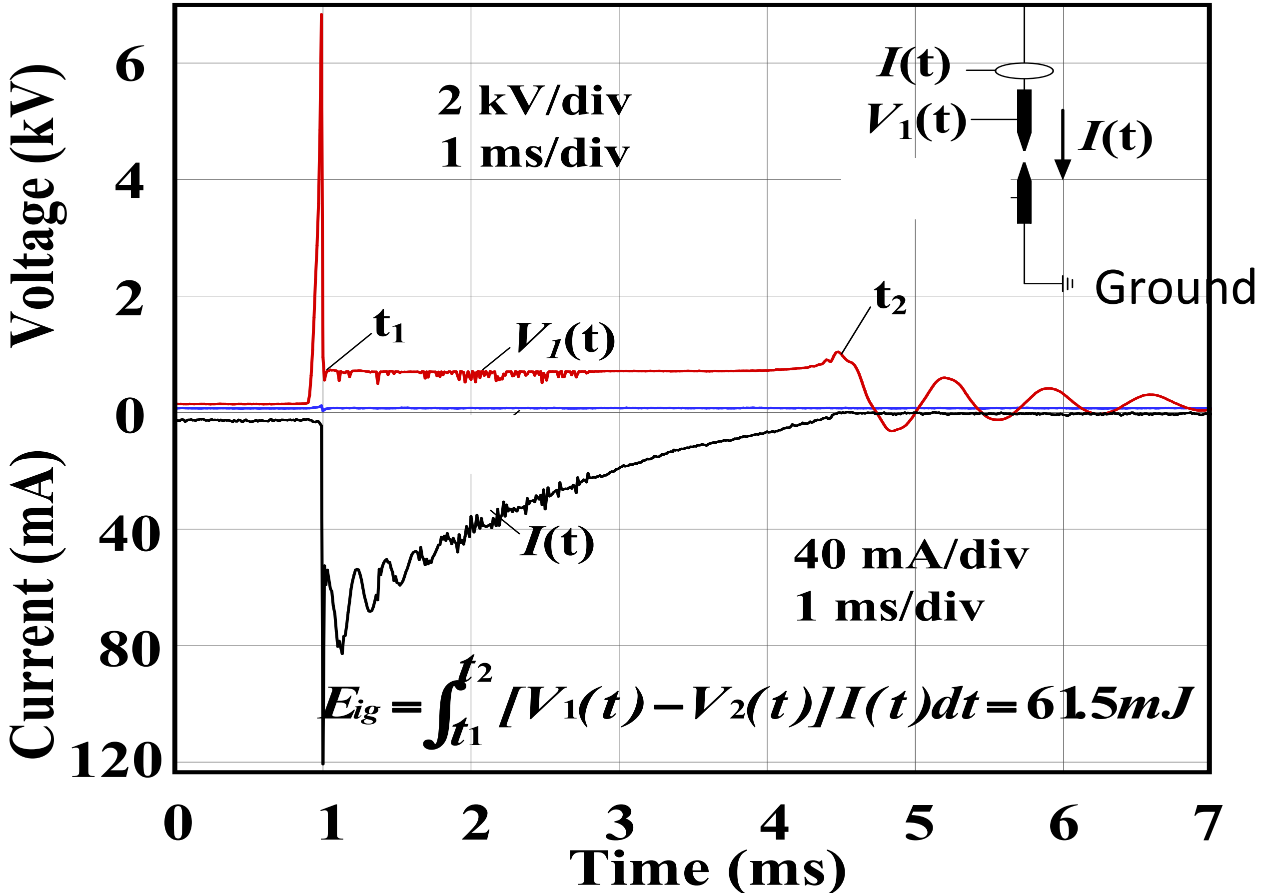
- Independence on electrode geometry
- t_d = 100 μs
- 3 domains
- p ↗, V_d ↗

How accurate can we measure E_{ig}?

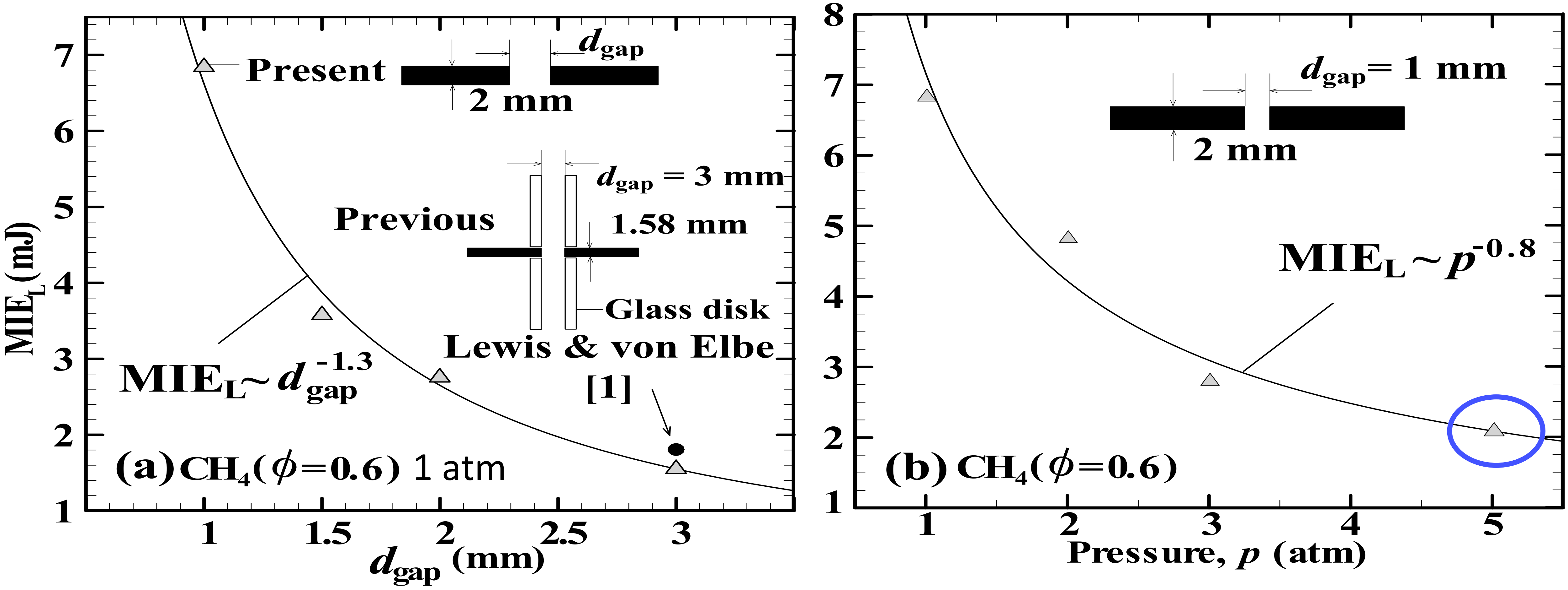


Car Ignition Energy

E_{ig} Measurement



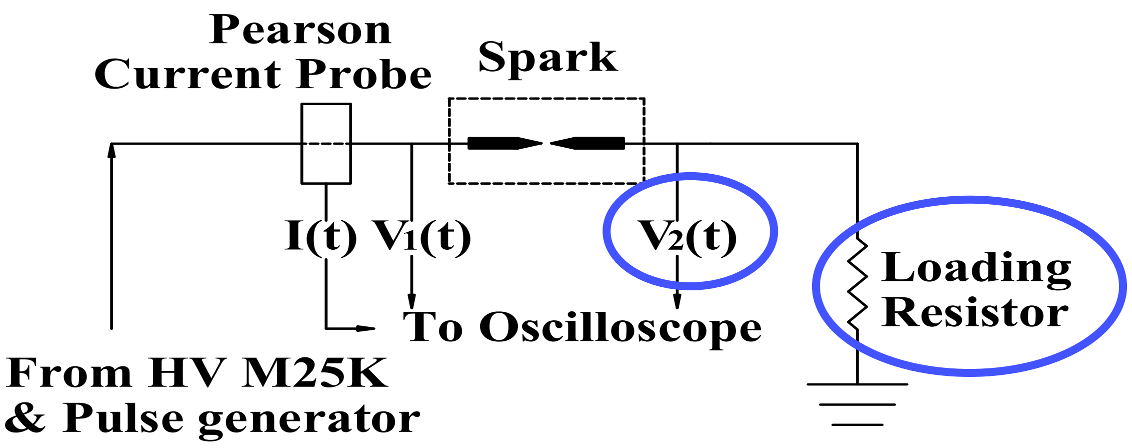
Peaks, Oscillations on V(t) & I(t), large uncertainties



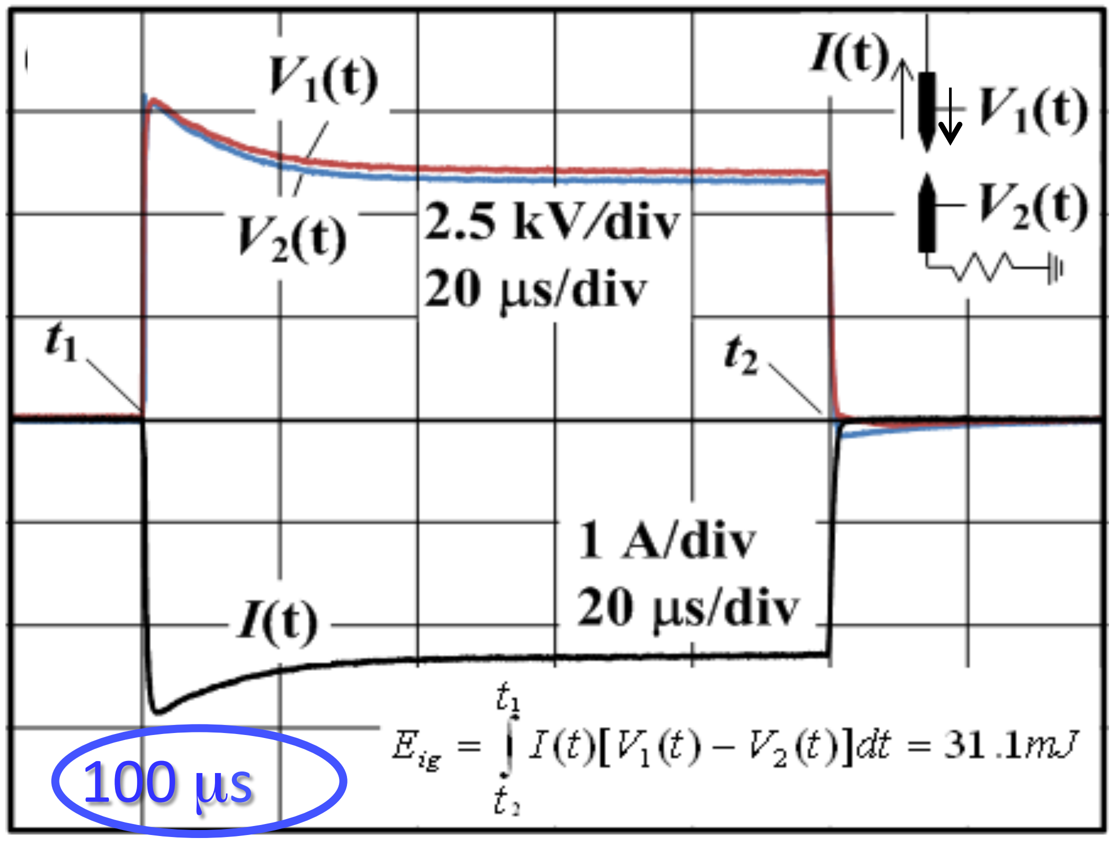
(a) MIE_L ↓ noticeably w/ d_{gap} from 1 to 3 mm.

(b) $MIE_L \sim \delta_{RZ}^3$ (Zeldovich) $\sim (\alpha_{RZ}/S_L)^3 \sim p^{-0.9}$ ($\alpha_{RZ} \sim \rho^{-1} \sim p^{-1}$; $S_L \sim p^{-0.7}$)

Measurements of Controllable Ignition Energies

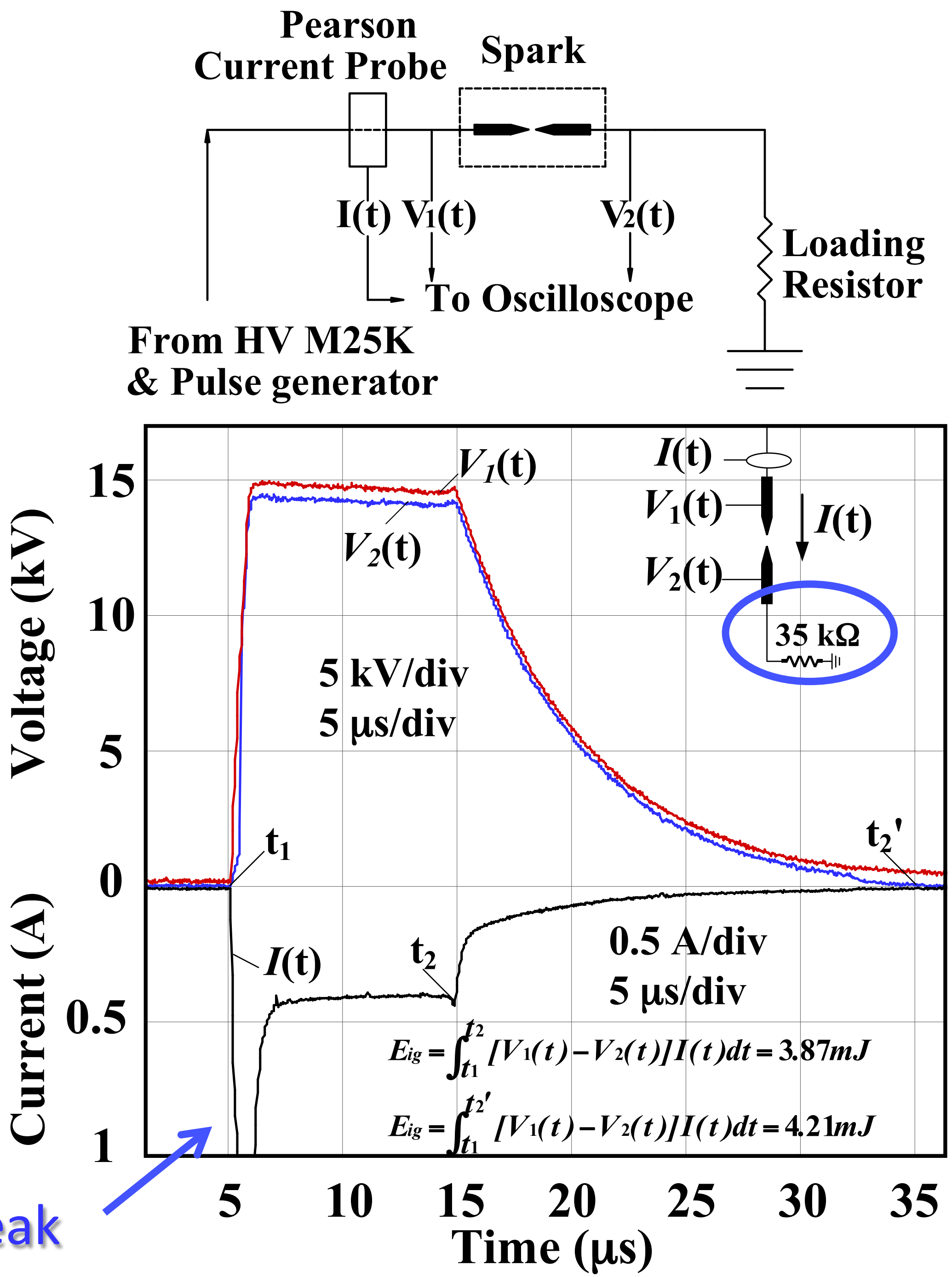


Good pulse generator & appropriate circuit



A typical voltage and current waveforms directly measured across the electrodes for calculating E_{ig}. Yes, we can measure E_{ig} accurately provided that we must know:

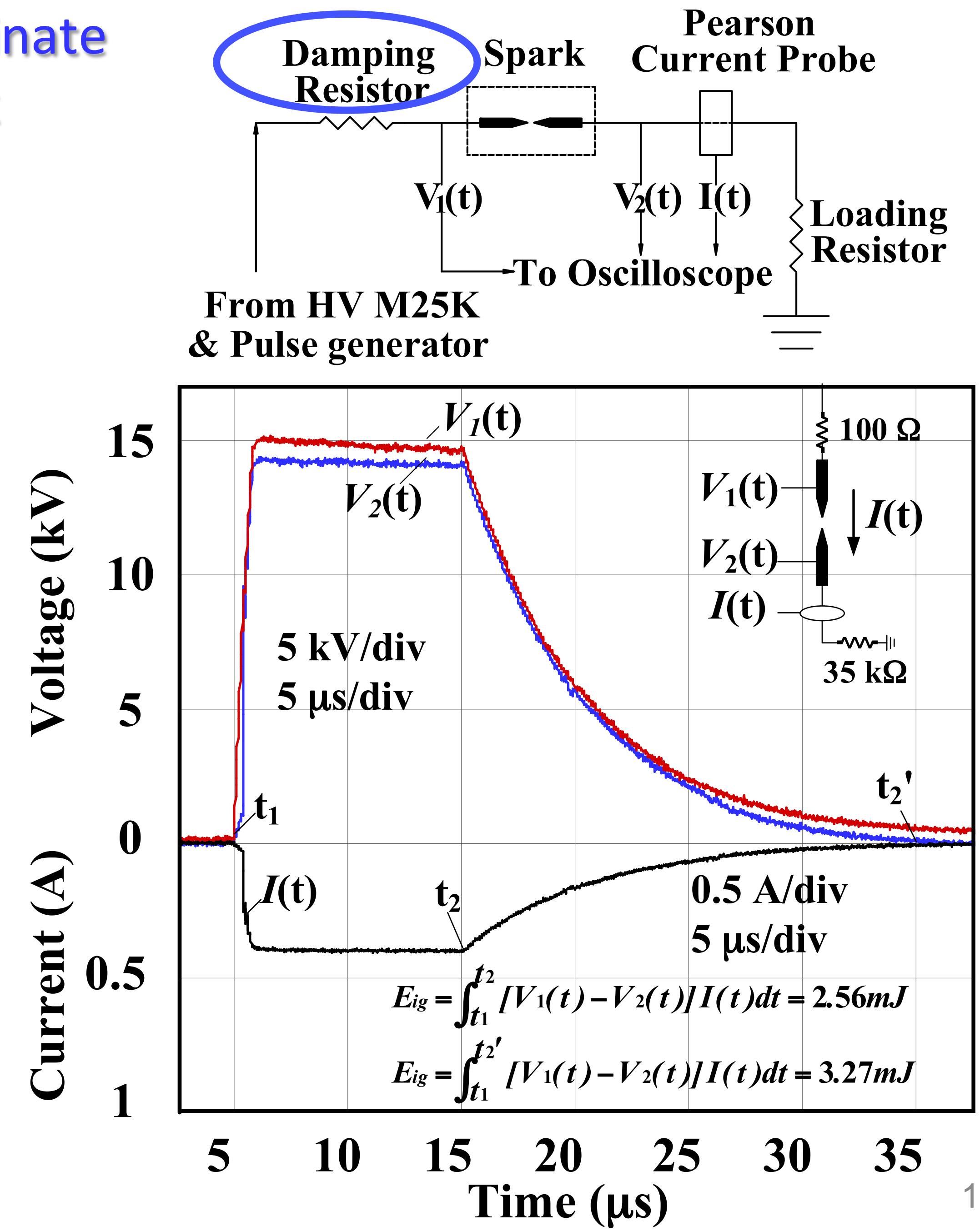
<u>Precise pulse duration time</u>, <u>discharge voltage & current</u>.



Peak

Eliminate peak

10 µs pulse

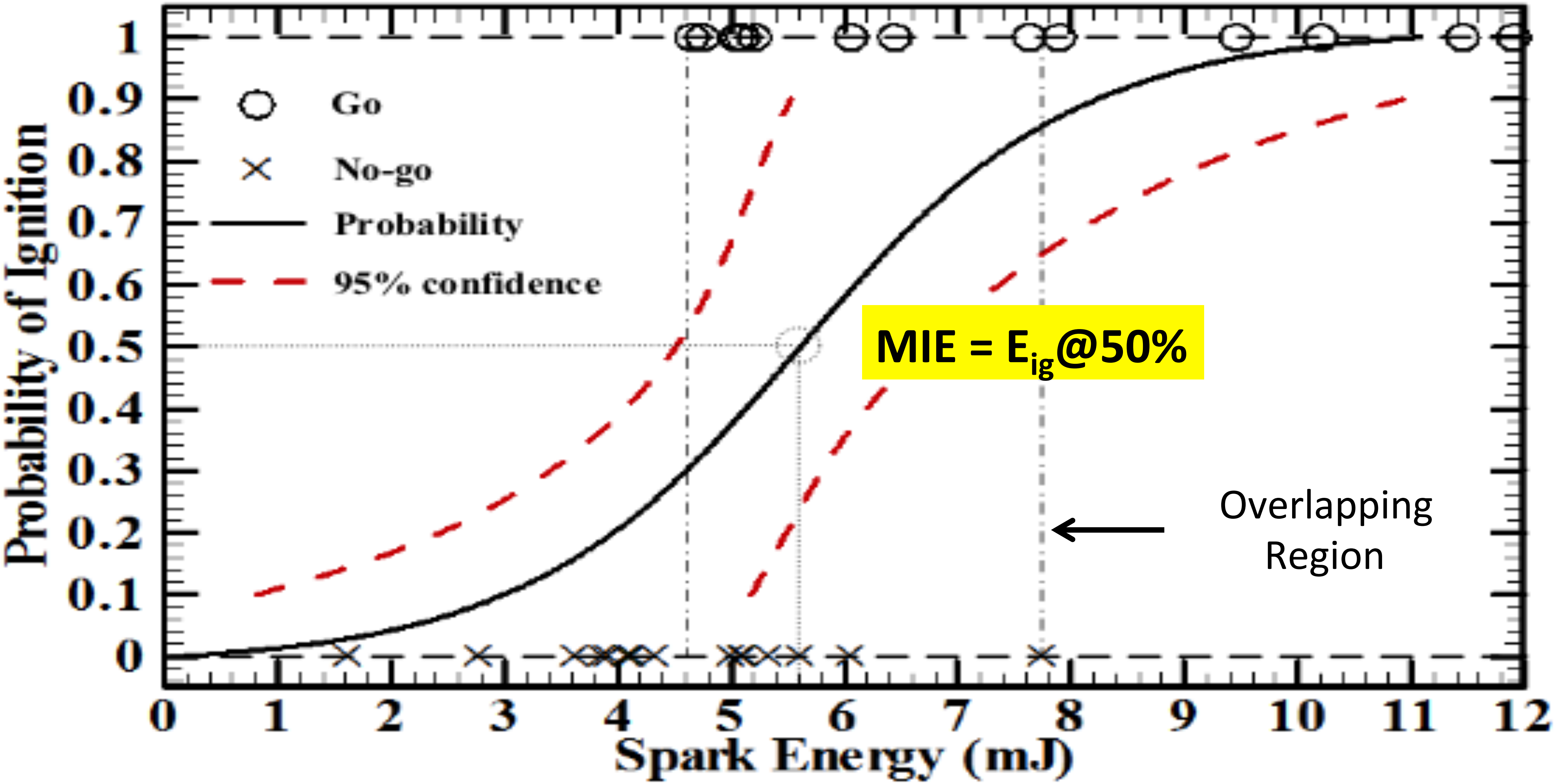


MIE is a statistical property, not a threshold value. An overlapping region of E_{ig} exists having "<u>Go</u>" or "<u>No Go</u>".

Traditionally, it is known that laminar MIE (MIE_L) data increase drastically when $d_{gap} < d_q$, where d_q is a critical d_{gap} called the quenching distance that may be related to the critical radius of the developing flame kernel (R_c) for successful flame initiation in the classic thermal-diffusion theory (e.g., Lewis & von Elbe book; Law et al.; Ju et al.). Flame critical radius concept is important, but it has a …

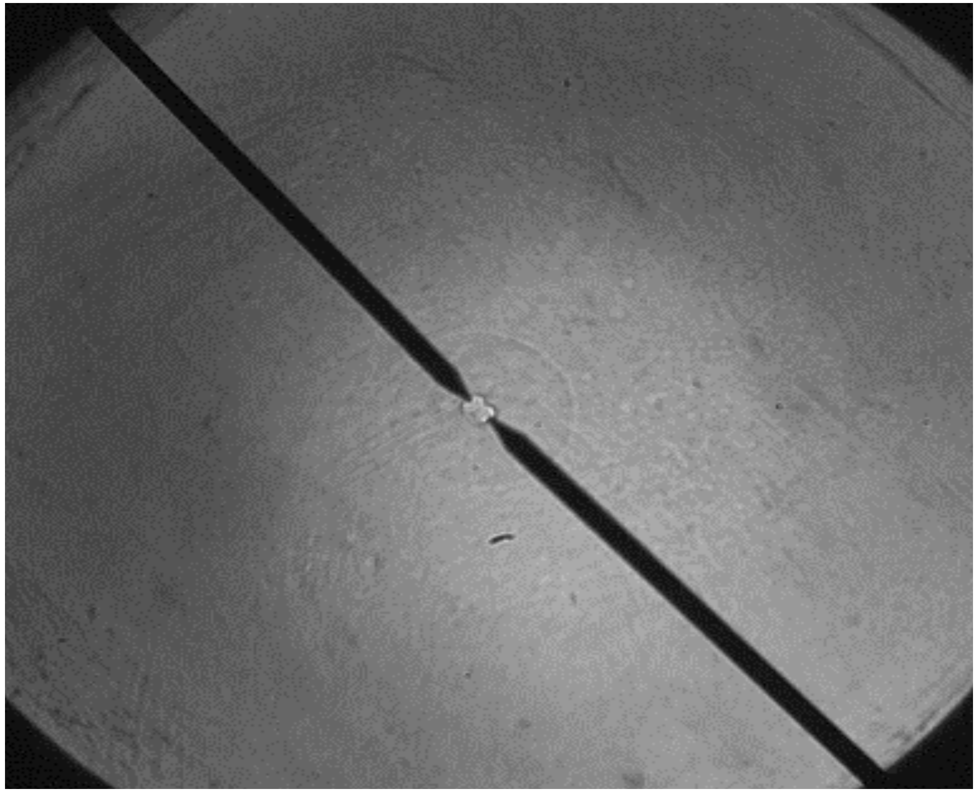
Problem: *Same discharged E_{ig} cannot always produce the same R_c* because of electrical spark breakdown perturbations.

Logistic Regression Method (18 ~ 30 runs)



Laminar case: Iso-octane/air mixture (φ = 0.8) at 1 atm and 373K (100℃)

No Go



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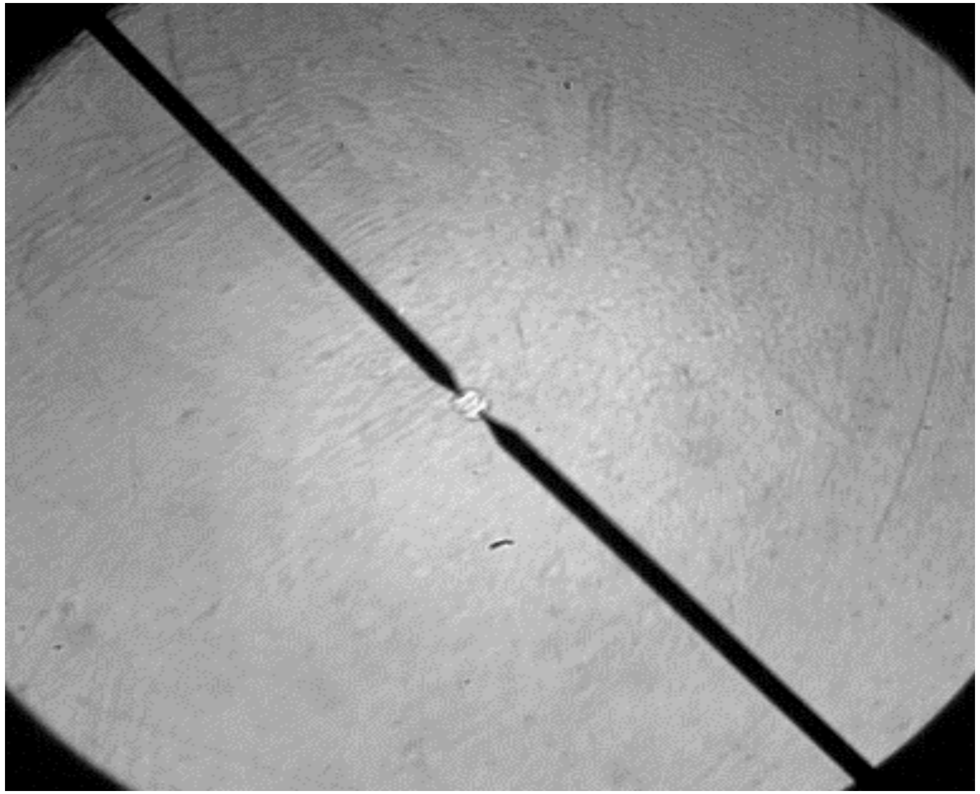
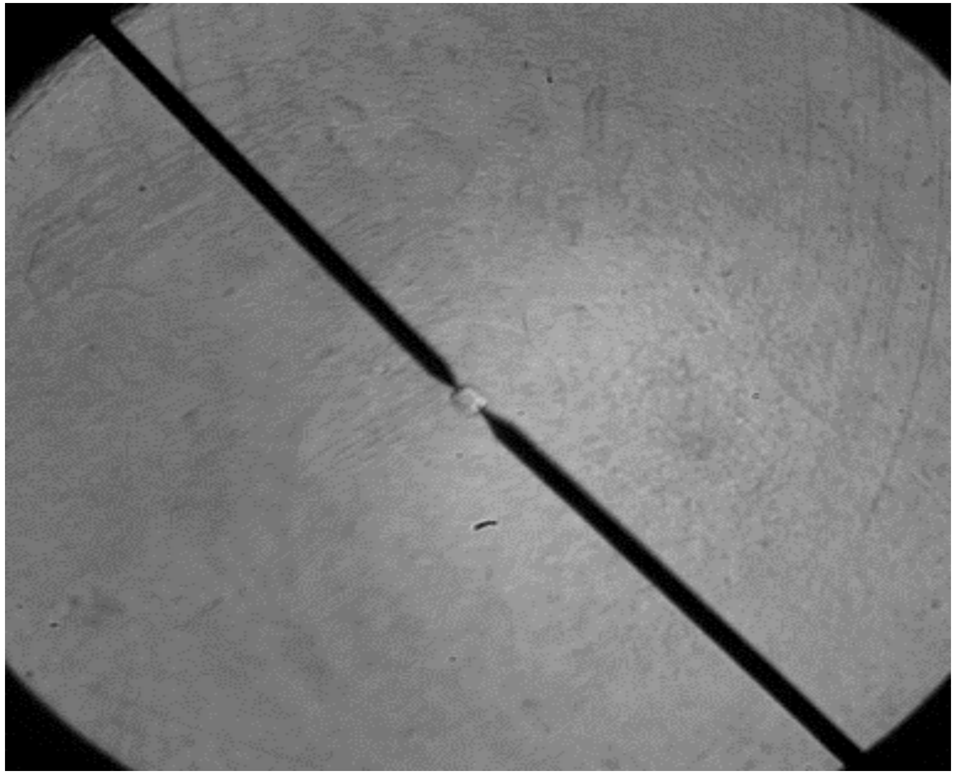


Laminar case: $E_{ig} \approx 7.7$ mJ (overlapping region)

Iso-octane/air at $\phi = 0.8$, $T = 373$ K, $p = 1$atm

Field of view: 11×11 cm^2

No Go



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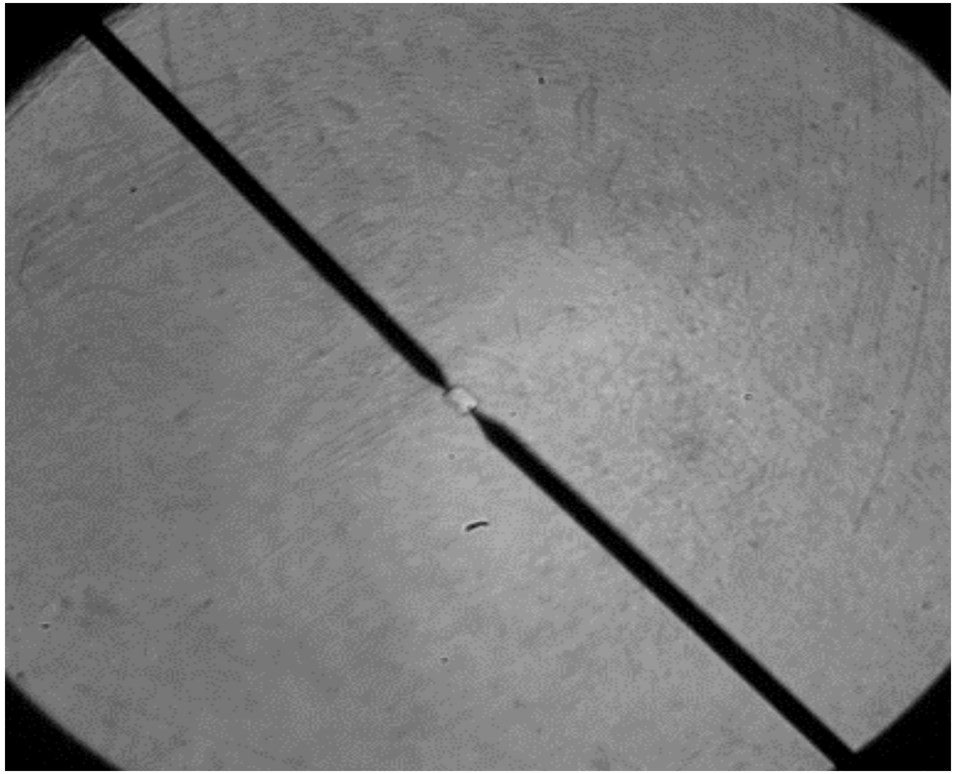
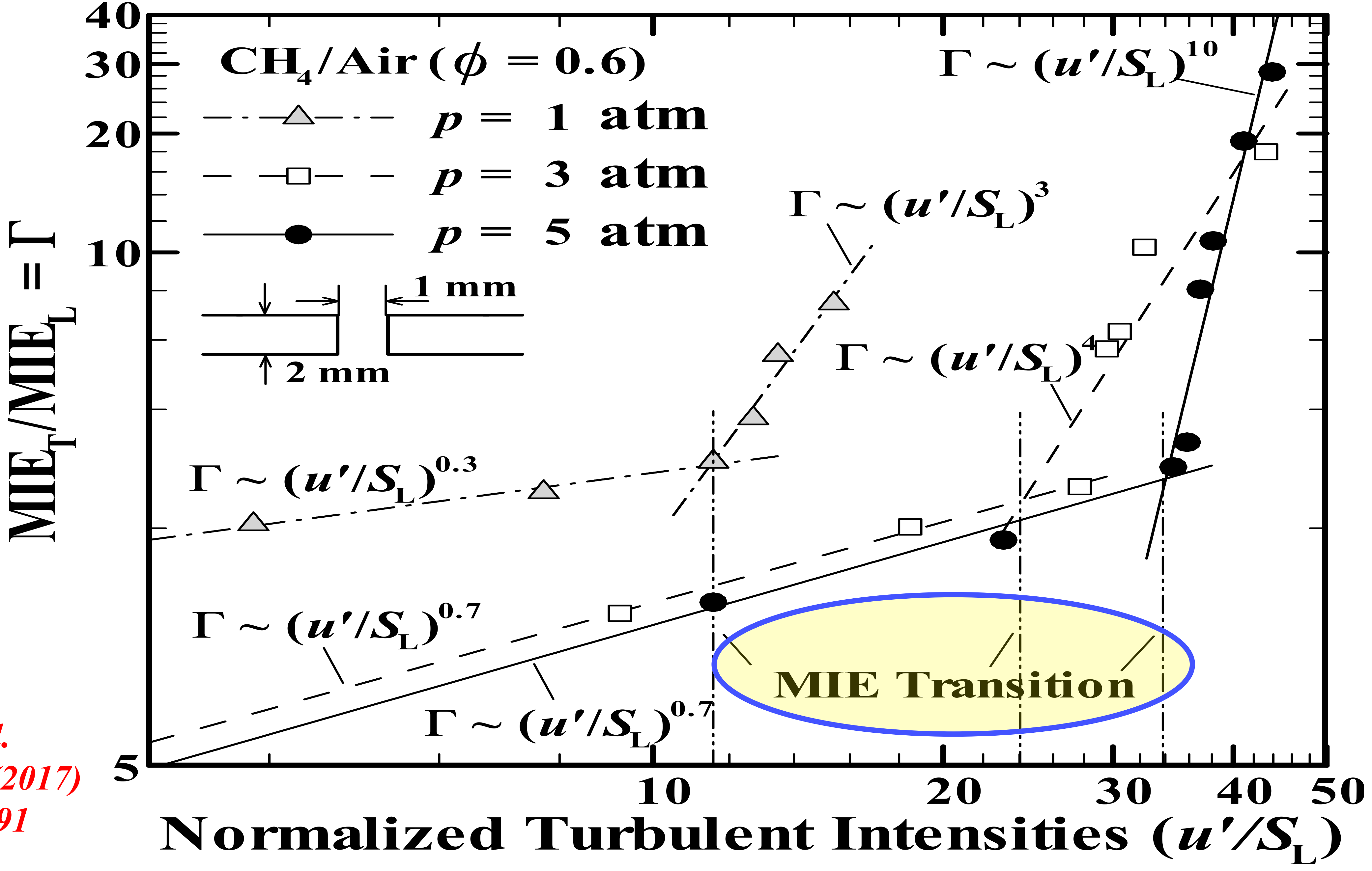


Turbulent case: $E_{ig} \approx 24$ mJ (overlapping region)

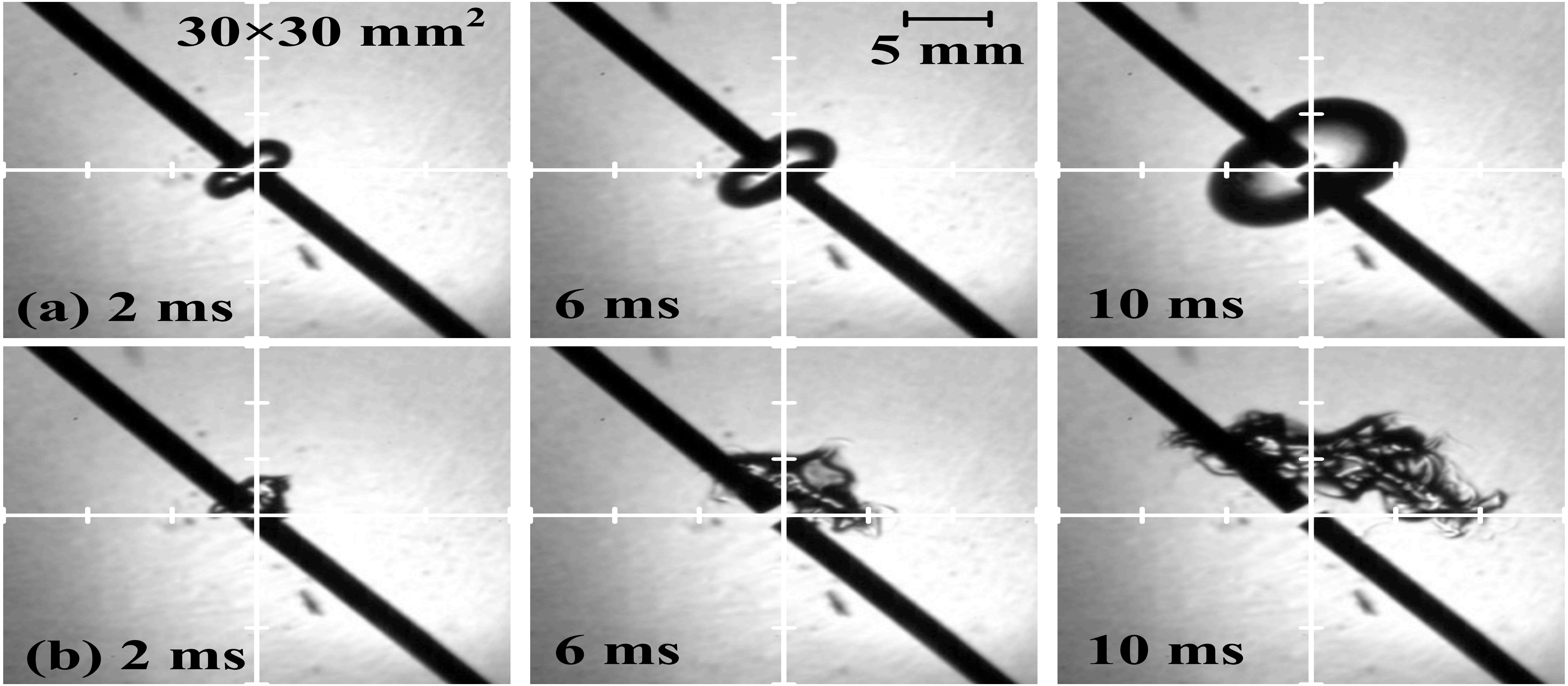
Iso-octane/air at $\phi = 0.8$, $T = 373$ K, $p = 1$atm, $u'/S_L \approx 5$

Field of view: 11×11 cm^2

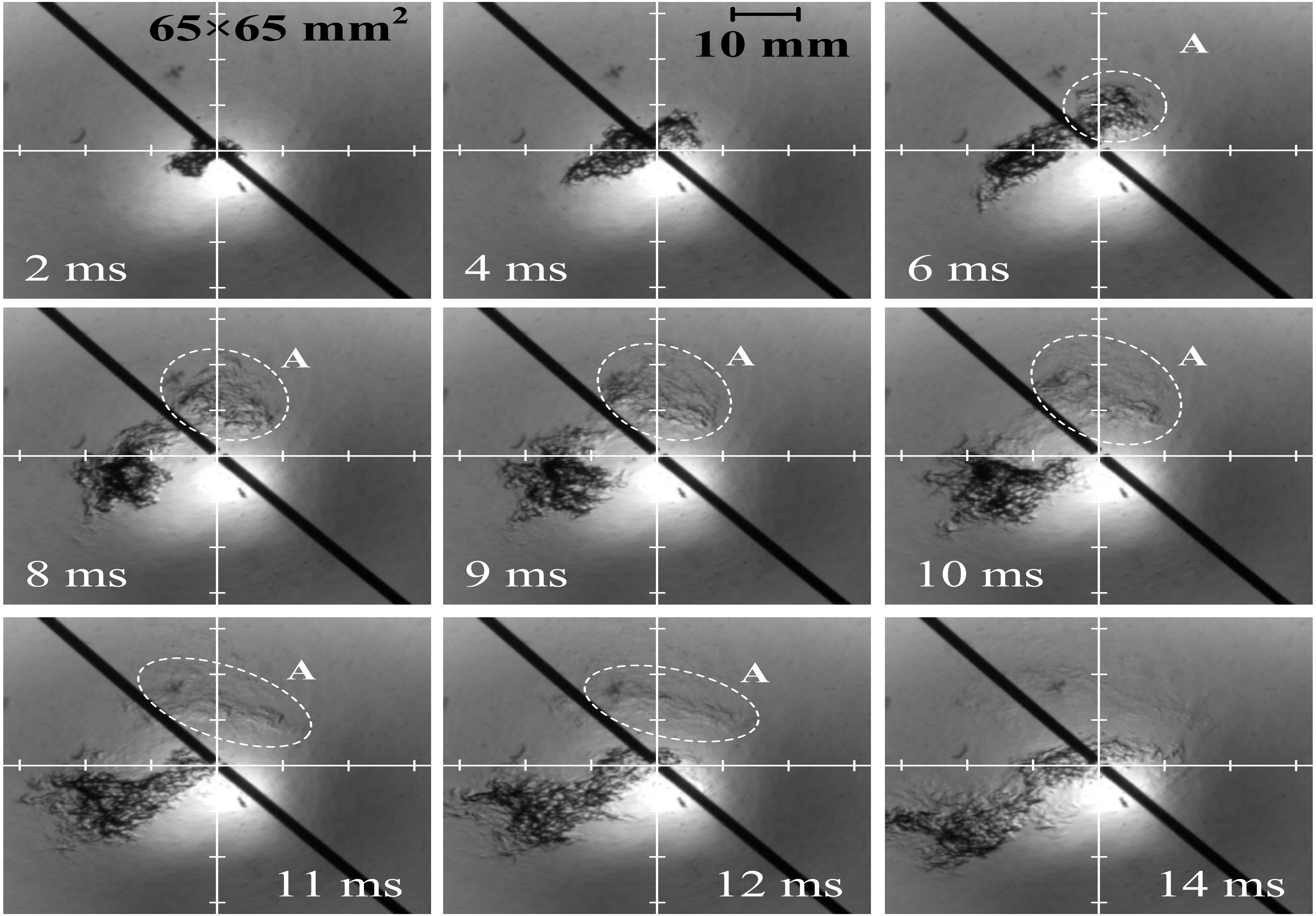


Shy et al.
PCI 36 (2017) 1785-1791

Schlieren images at *p = 5 atm*: Before Ignition Transition



(a) Laminar case ($E_{ig} \approx 2.30$ mJ); (b) turbulent flamelet case ($u'/S_L \approx 12$; $Ka \approx 8 > 1$; $E_{ig} \approx 5.85$ mJ)



After TIT Distributed-like kernel at 5 atm:

$u'/S_L \approx 40$

Ka ≈ 40

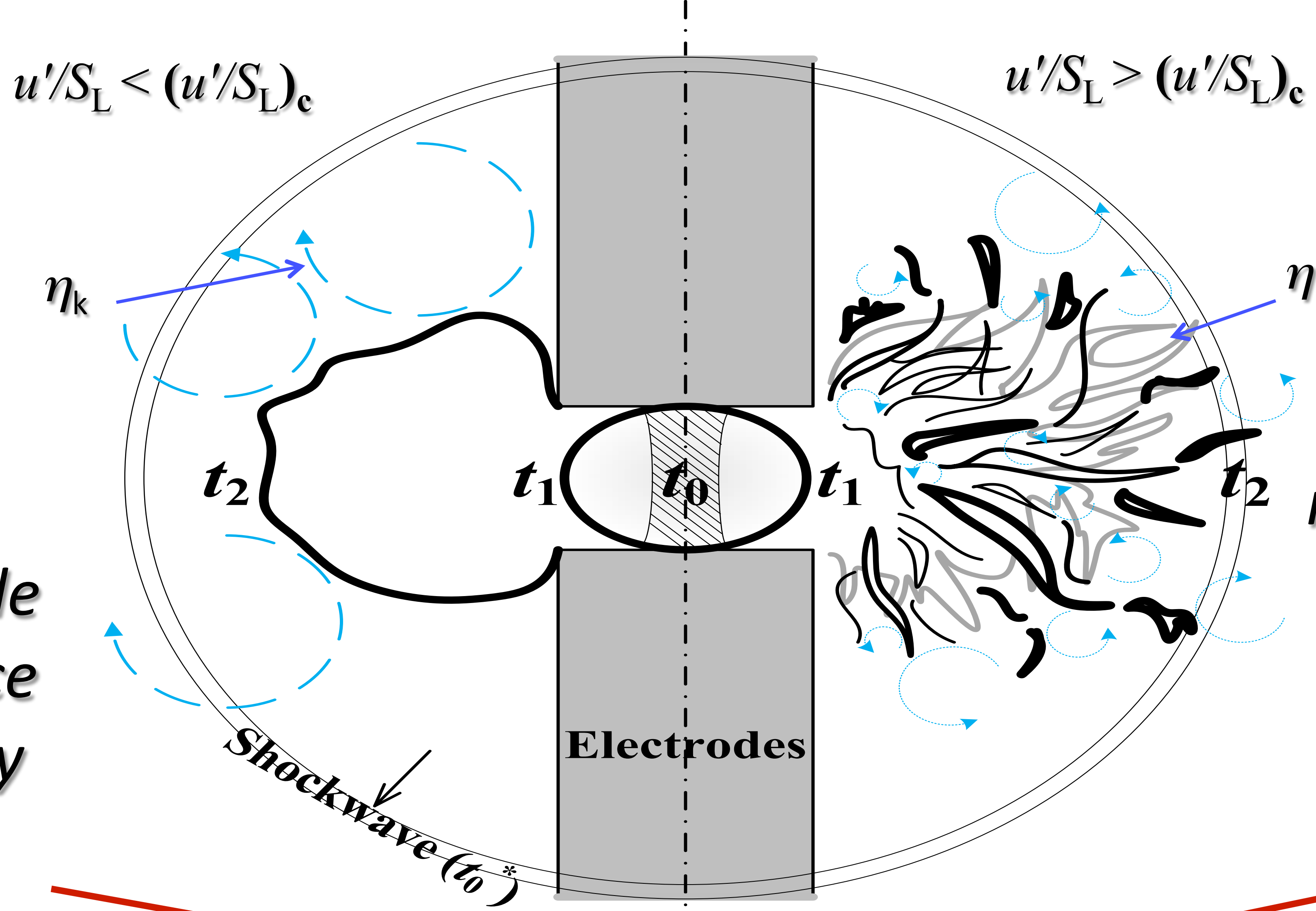
$E_{ig} \approx 42$ mJ

Island formation

Broken RZ

"A" island quenching

Shy et al. PCI 36 (2017) 1785-1791



small scale turbulence diffusivity $u'\eta_k$

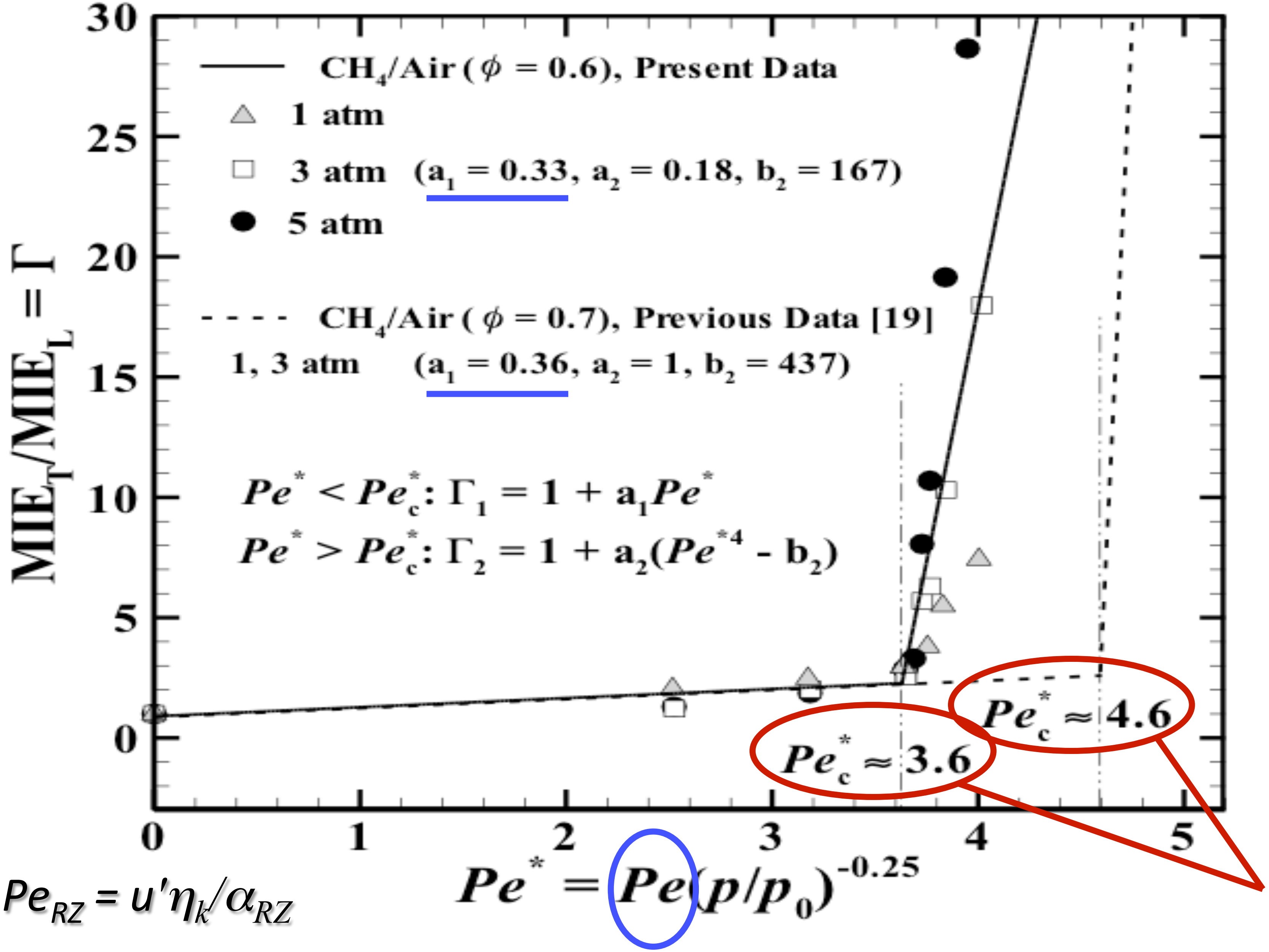
reaction zone thermal diffusivity α_{RZ}

$$Pe_{RZ} = u'\eta_k/\alpha_{RZ}$$

MIE transition occurs at different $(u'/S_L)_c$

$(u'/S_L)_c \approx$ 12 (1 atm), 24 (3 atm), 34 (5 atm)

Spark ignition seems self-similar



$Pe_{RZ} = u'\eta_k/\alpha_{RZ}$

Ignition Chemistry?

when using Pe^* with pressure correction to minus 1/4 power. All data at different u' and p are collapsed to a single curve with two different slopes, showing ignition transition.

Karlovitz and Peclet numbers estimated at the instant of the formation of spark kernel (RZ)

$$Ka = \tau_c/\tau_k;\ Pe_{RZ} = u'\eta_k/\alpha_{RZ}$$

Ignition transition depends on the surface diffusivity ratio between small scale turbulence and chemical reaction, not their time ratio.

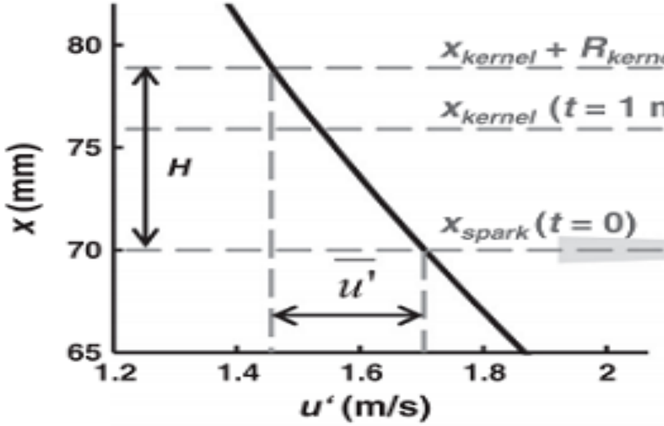
$$\Gamma = MIE_T/MIE_L \sim Pe^{*} \text{ before transition}$$

$$\Gamma = MIE_T/MIE_L \sim Pe^{*4} \text{ after transition}$$

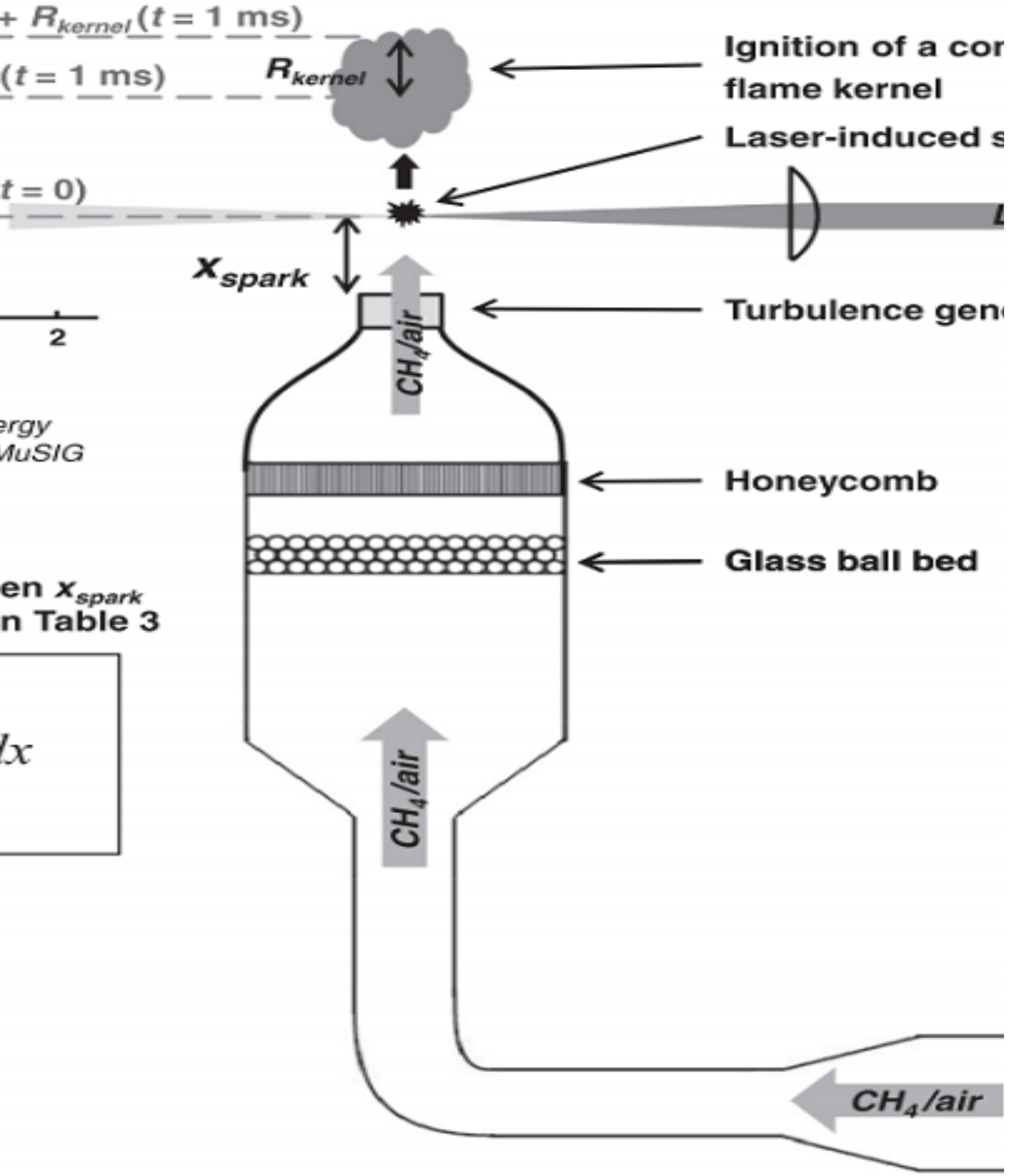
It seems that spark ignition is self-similar

Is ignition transition a possible universal phenomenon?

Laser Spark Ignition of Lean Methane/Air Mixtures Using Wind-Tunnel Turbulence by Cardin et al. *Combustion and Flame* 160 (2013) 1414-1427.

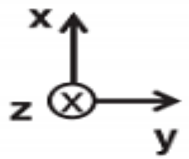


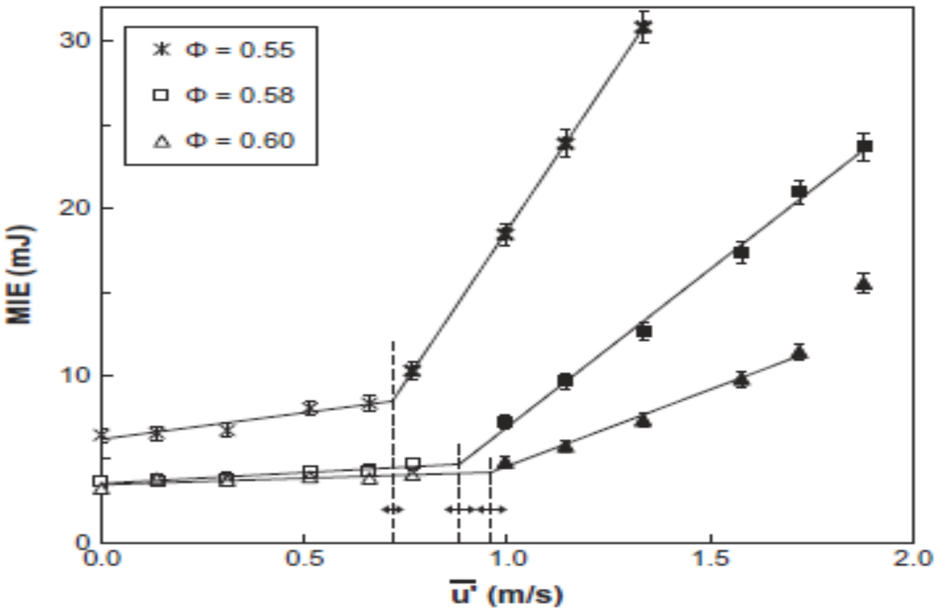
Spatial evolution of u', for an energy deposition at 70 mm above the MuSIG

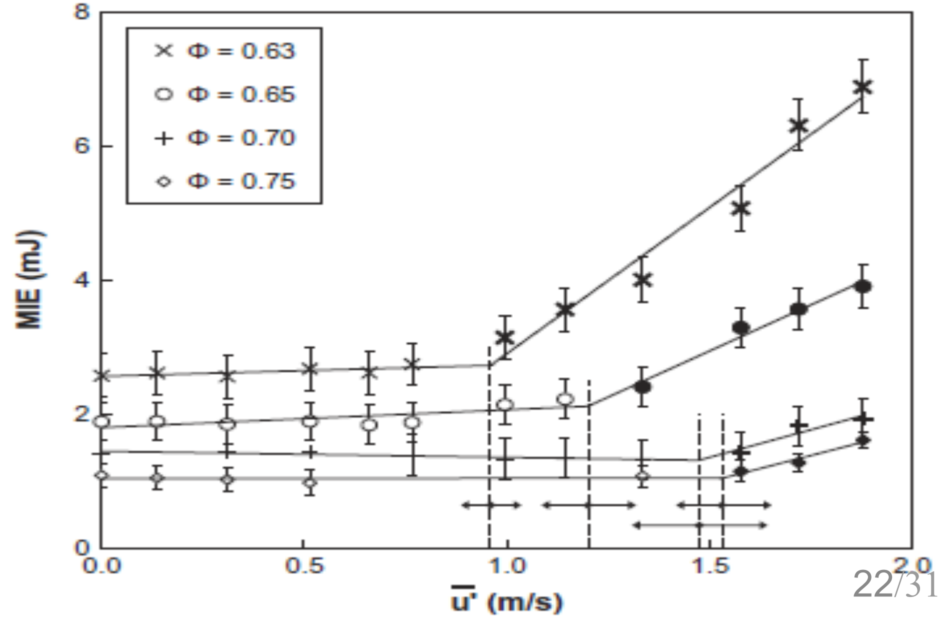


Spatial average of *u'* between x_{spark} and $x_{spark} + H$, as reported in Table 3

$$\overline{u'} = \frac{1}{H}\int_{x_{spark}}^{x_{spark}+H} u'(x)dx$$







Concluding Remarks and A Puzzle

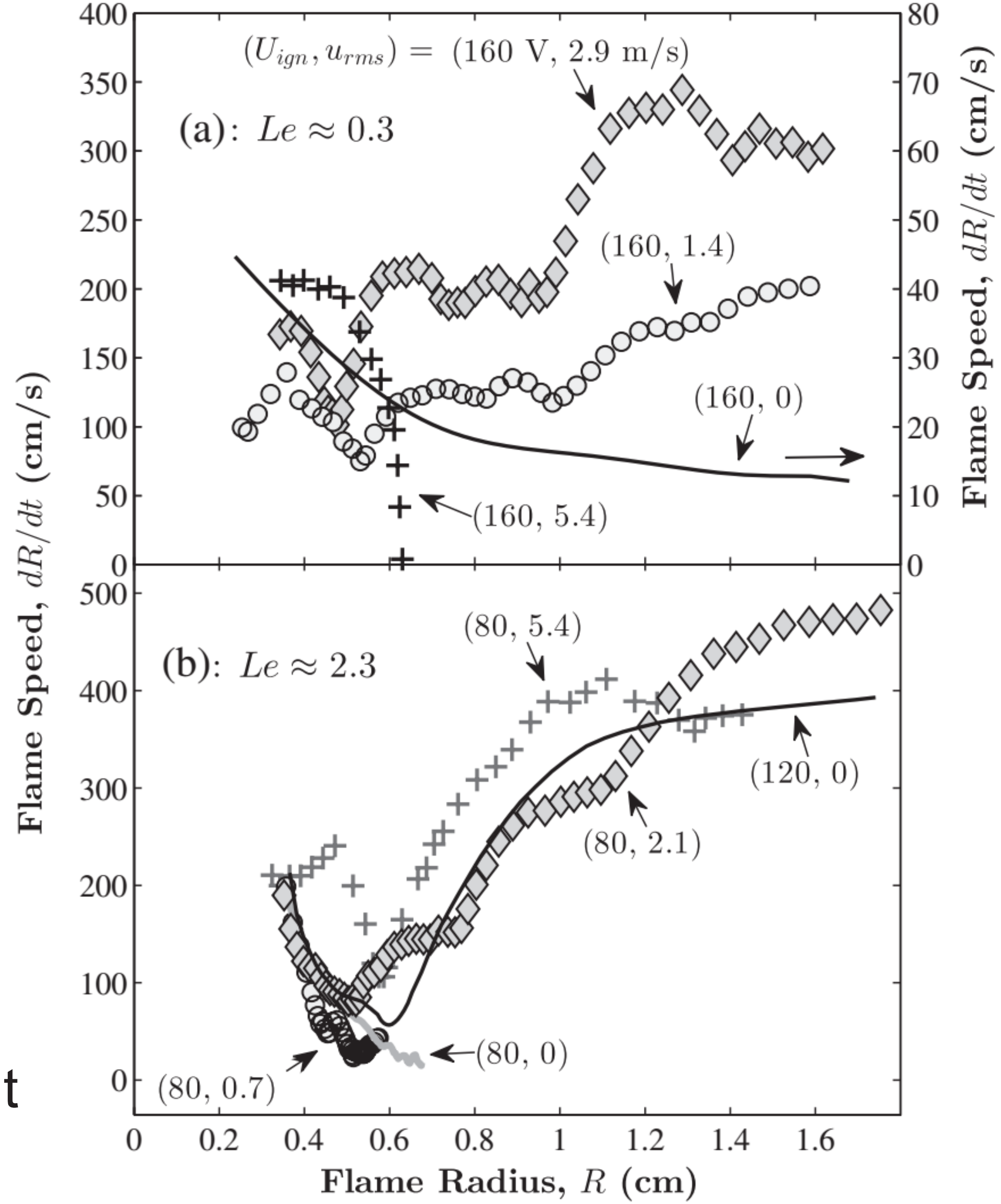
(1) It seems that ignition transition could be a universal phenomenon, because both electrode & laser sparks found similar IT phenomenon regardless of different ignition systems & different flow configurations used.

(2) Spark ignition may be self-similar, which is characterized by a spark kernel surface diffusion ratio between small scale turbulence and chemical reaction.

(3) Contrarily, Law and co-workers (PRL 2014) found that turbulence can facilitate ignition for Le >> 1 flames.

Why???

TFI: Law and co-workers discovered ***that turbulence can facilitate ignition through differential diffusion when the effective Lewis number (Le) of mixtures is sufficiently greater than unity, where a pair of thin cantilever electrodes of 0.25-mm in diameter with small electrode gaps (d_{gap} ≤ 0.8 mm)*** was applied in near-isotropic turbulence generated by a fan-stirred burner.



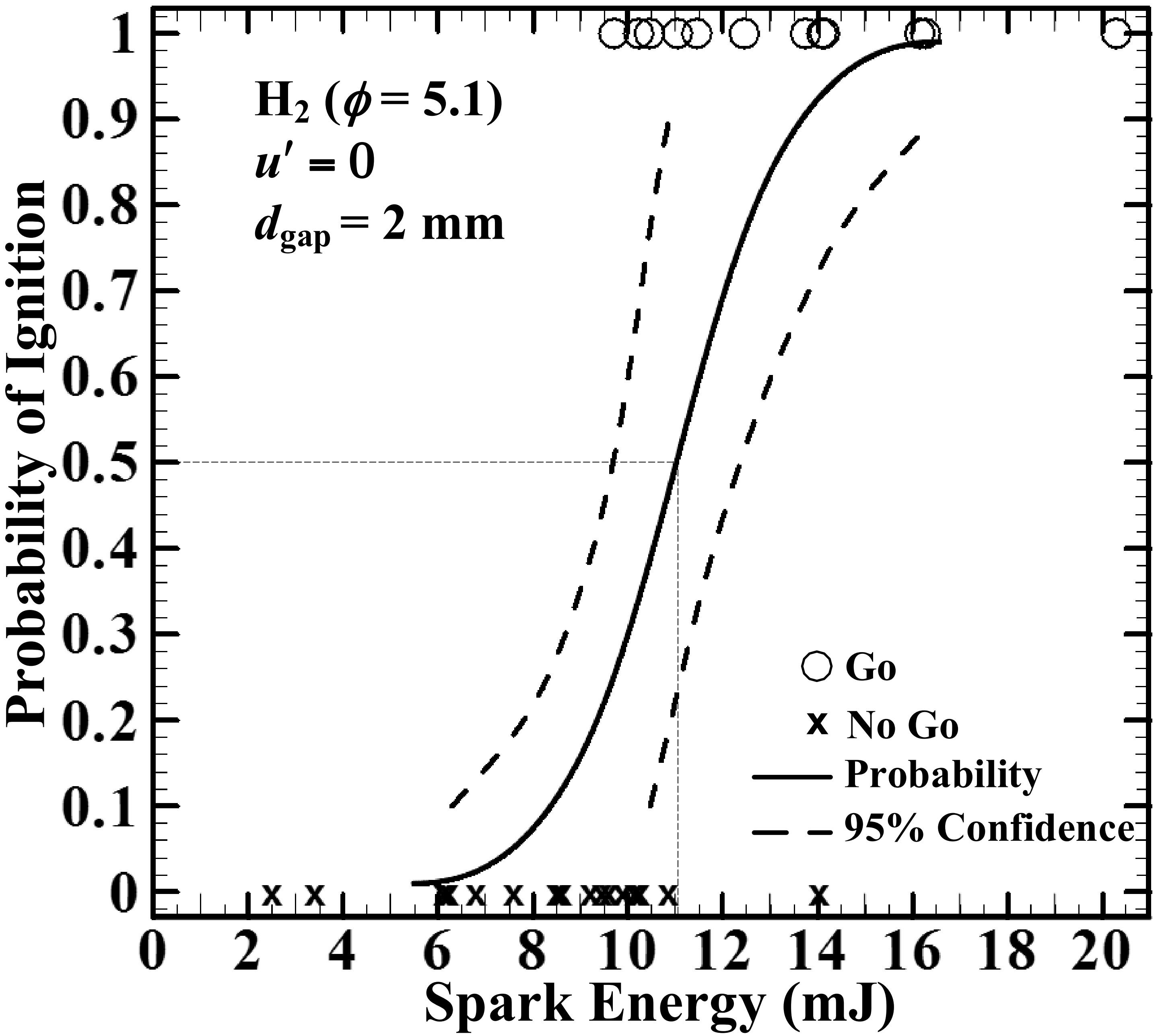
Flame speed versus flame radius for (a) lean H2/air at ϕ = 0.18 and (b) rich H2/air at ϕ = 5.1, at different ignition voltages and turbulent levels (**Phys. Rev. Lett 113 (2014) 024503).**

Question:

Is the aforesaid TFI for Le >> 1 dependent on d_{gap}?

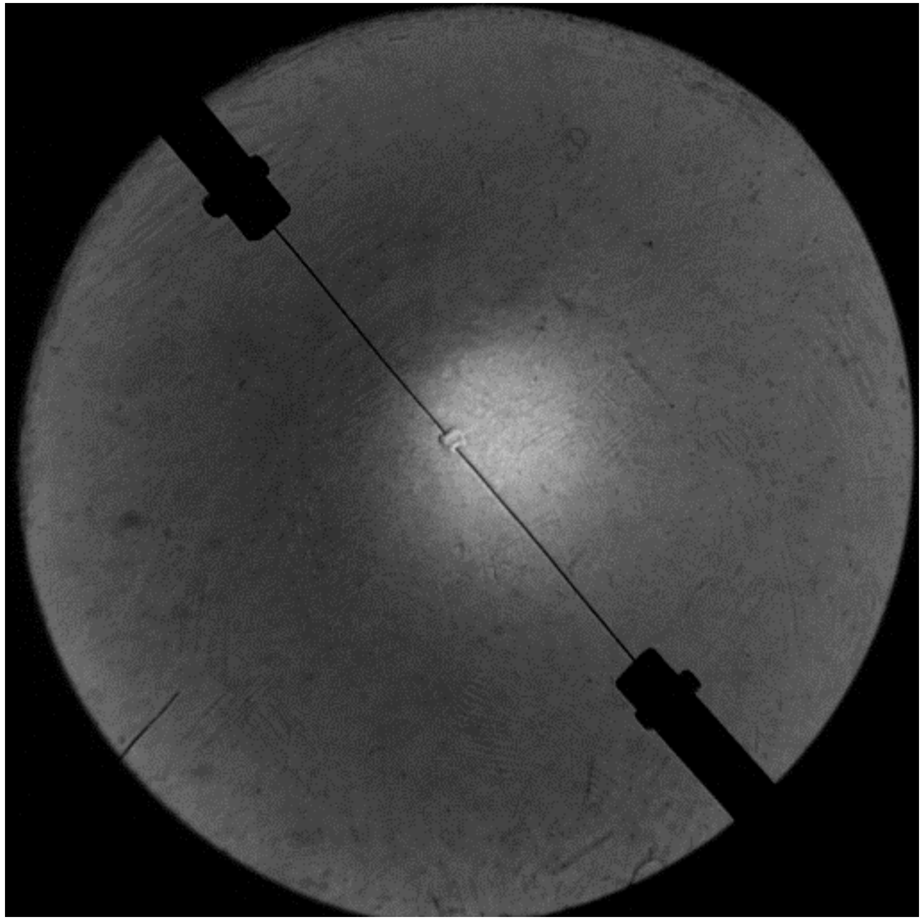
Effect of spark gap on TFI?

Approach: Using the same rich and lean H_2/air mixtures and electrodes as that used by Law and co-workers in our cruciform bomb together with the well-established ignition system allows measuring E_{ig} here of high accuracy and/or minimum ignition energy (MIE) as a function of d_{gap} at both quiescence ($u' = 0$) and intense turbulence ($u' = 5.4$ m/s) conditions, which reveals the subtle detail of spark ignition phenomena.



This figure shows a typical case for the statistical determination of MIE ≡ $E_{ig(50\%)}$ using the logistic regression method, where the hydrogen/air mixture at $\phi = 5.1$ with $Le \approx 2.3$ is applied in quiescence.

Go



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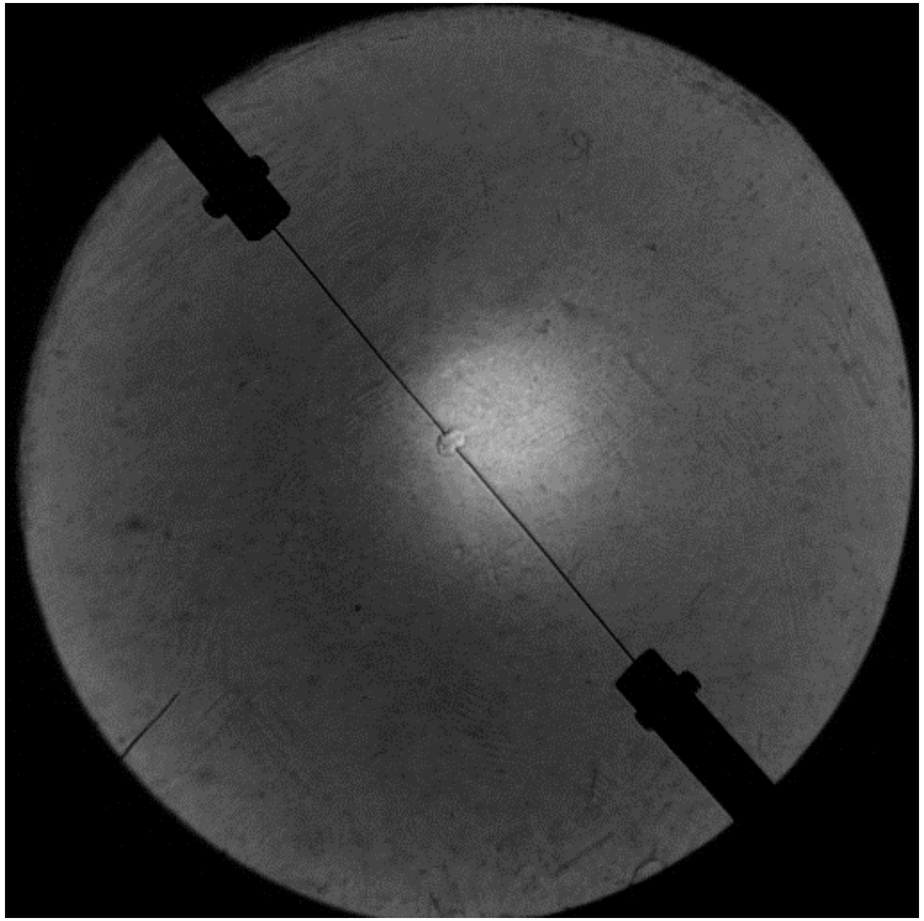

Laminar case: $E_{ig} \approx 10.2$ mJ (overlapping region)
Hydrogen/air at $\phi = 5.1$, $T = 298$ K, $p = 1$atm.
Field of view: 11×11 cm^2

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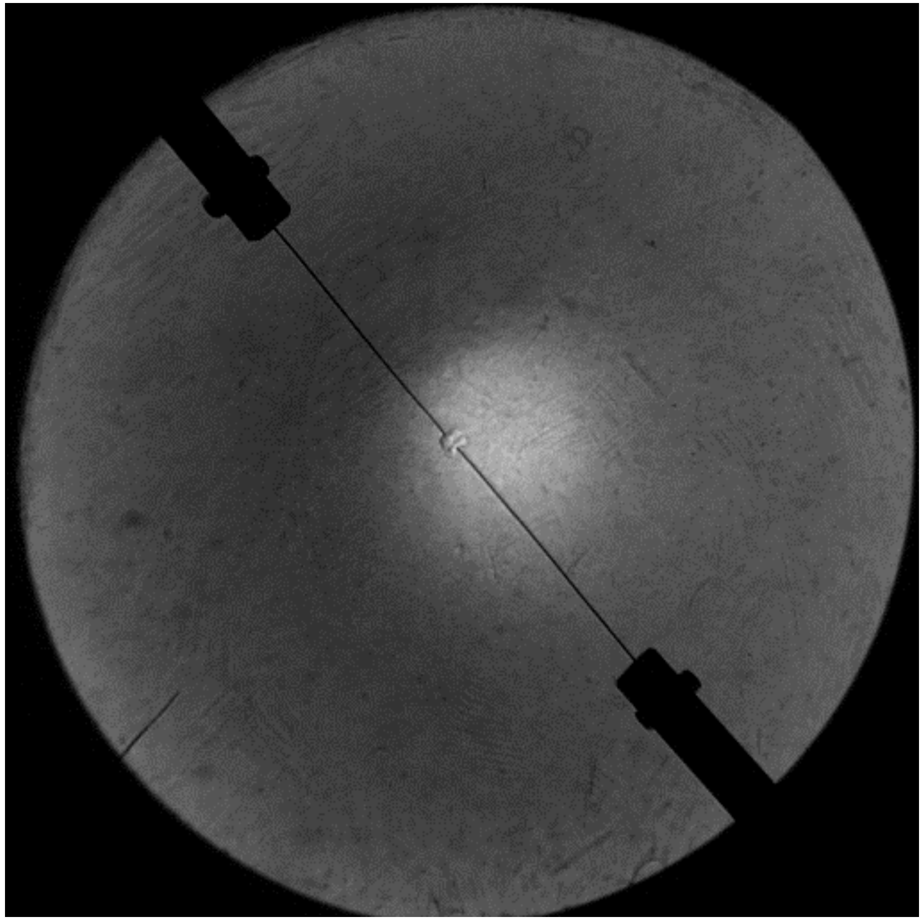

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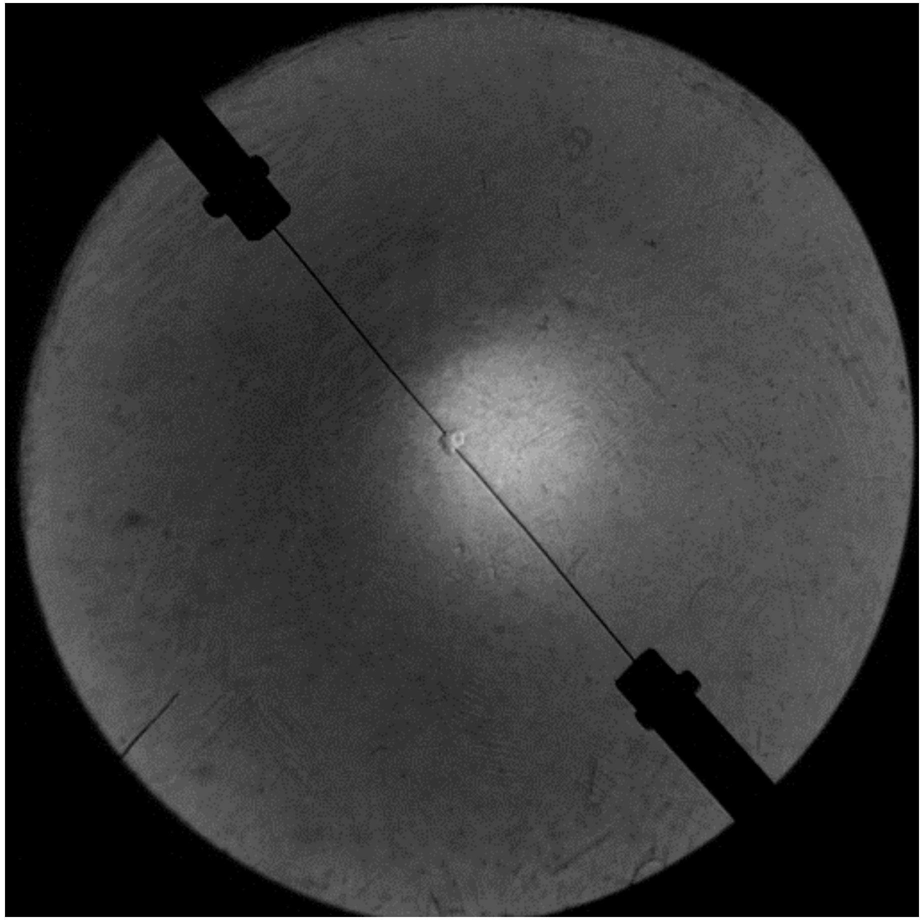
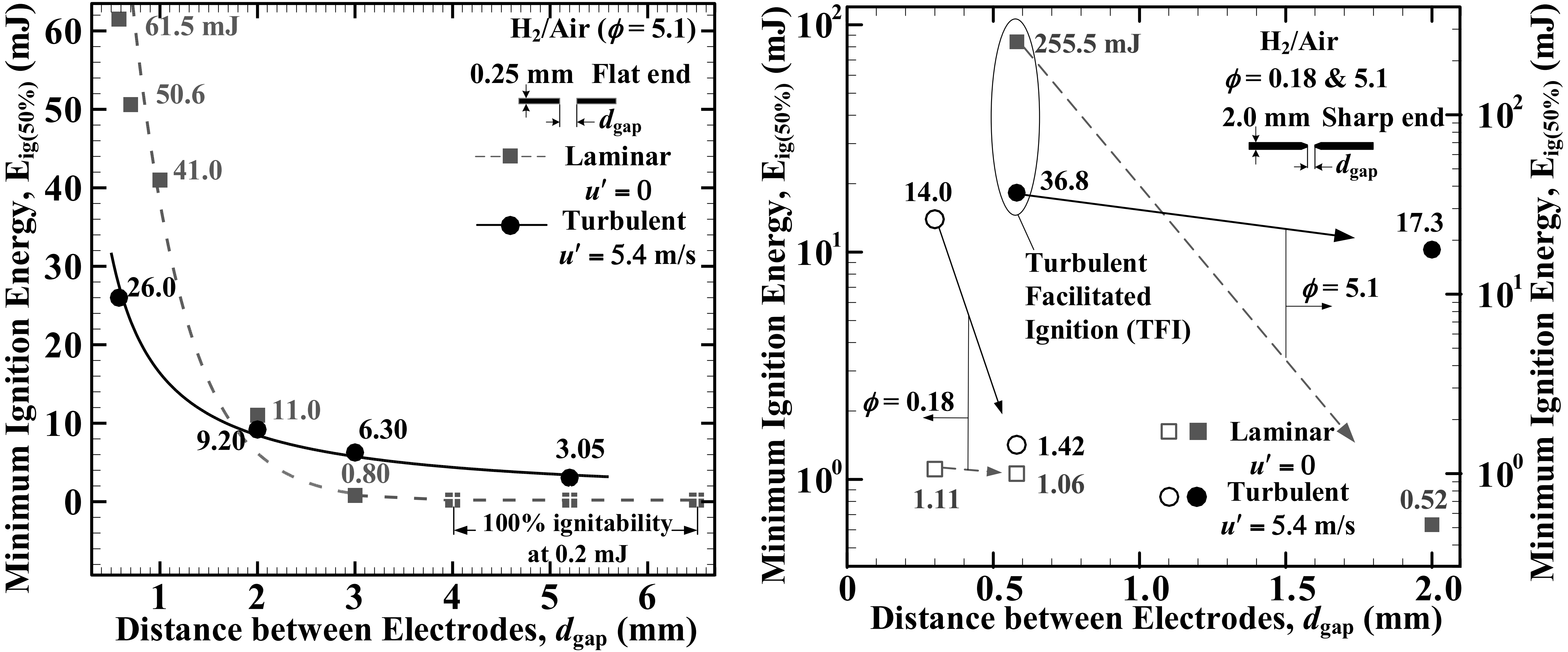


Turbulent case: $E_{ig} \approx 9.3$ mJ (overlapping region)

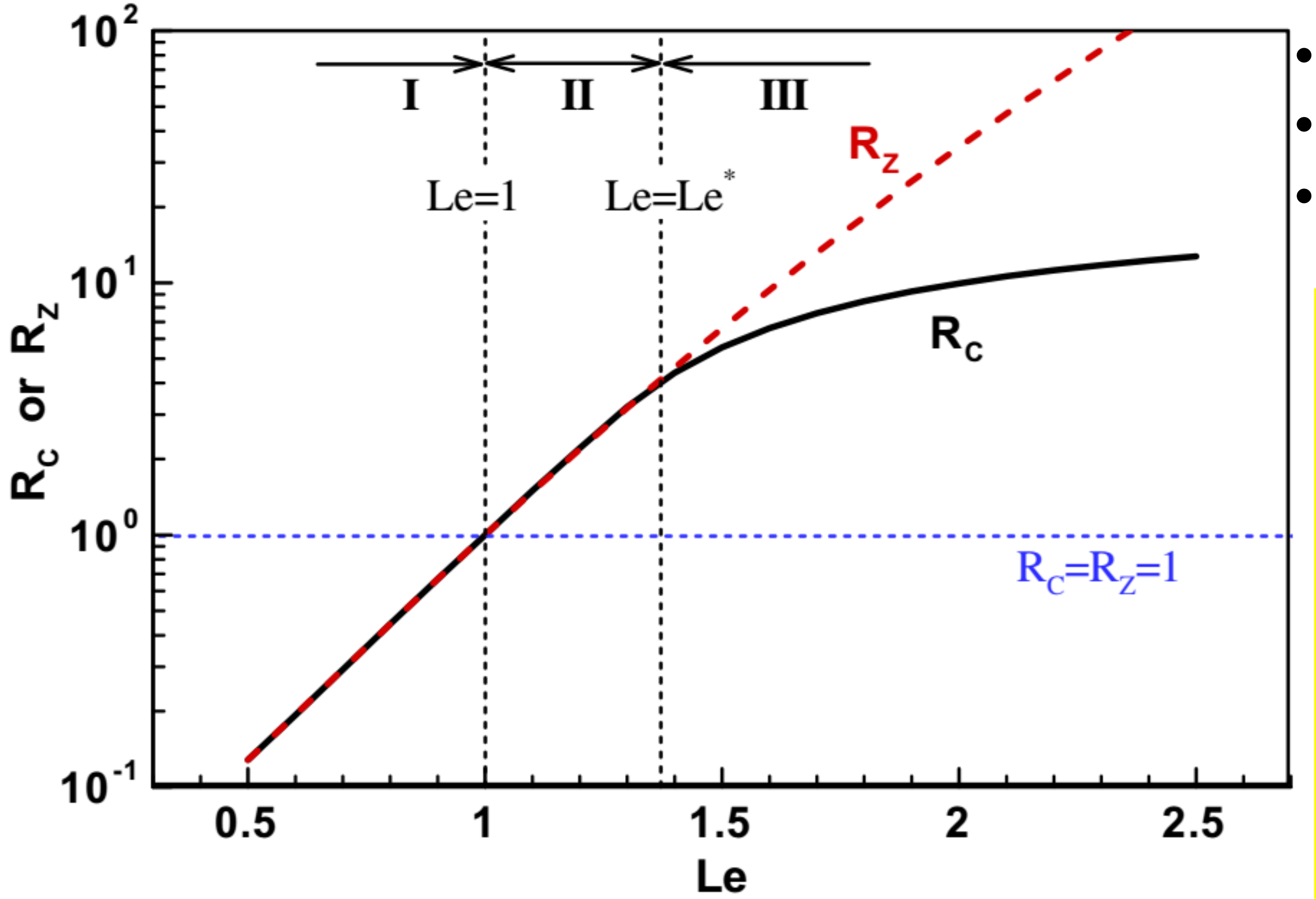
Hydrogen/air at $\phi = 5.1$, $T = 298$ K, $p = 1$atm, u′ = 5.4 m/s

Field of view: 11 × 11 cm^2

Key Results: Effect of Spark Gap on TFI [Shy et al. CnF 185 (2017) 1-3]



Turbulence can facilitate ignition through differential diffusion for Le >> 1 mixture, but such peculiar phenomenon is restricted at small d_{gap}.



Change of the critical flame radius R_c and the flame ball radius R_z with the Lewis number.

- **Regime I (Le < 1.0):** $R_c = R_z < \delta_F$
- **Regime II (1 < Le < Le*):** $R_c = R_z > \delta_F$
- **Regime III (Le > Le*):** $\delta_F < R_c < R_z$

We use the numerical finding of critical flame radius R_c as a function of Le found by Ju & co-workers to explain these results. Please see a recent brief communication [CnF 185 (2017) 1-3].

Ref: Z. Chen, M.P. Burke, Y. Ju, On the critical flame radius and minimum ignition energy for spherical flame initiation, Proc. Combust. Inst. 33 (2011) 1219-1226.

Thank you for your attention!

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