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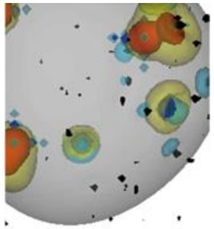

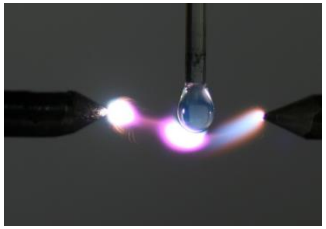

Gas turbine combustor ignition: experiments and simulations

ECM 2015, Budapest

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Acnowledgements

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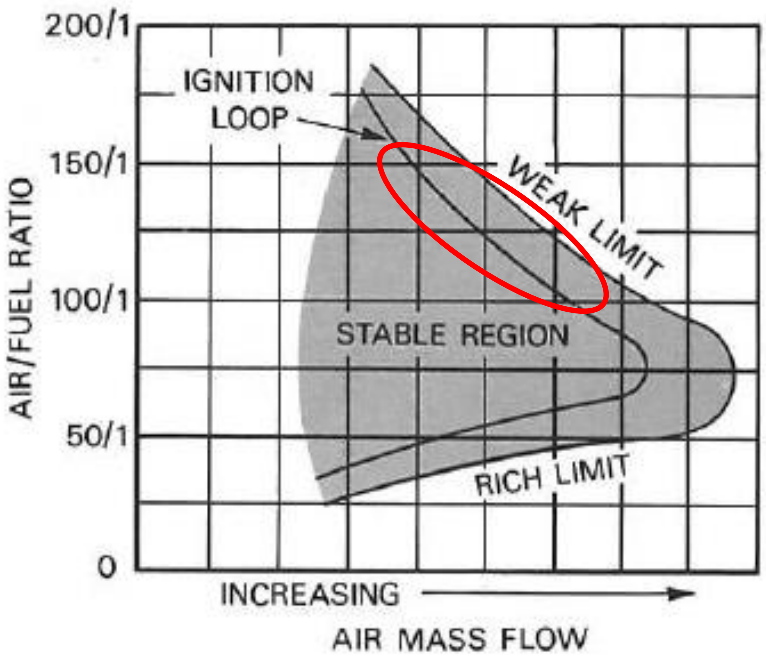
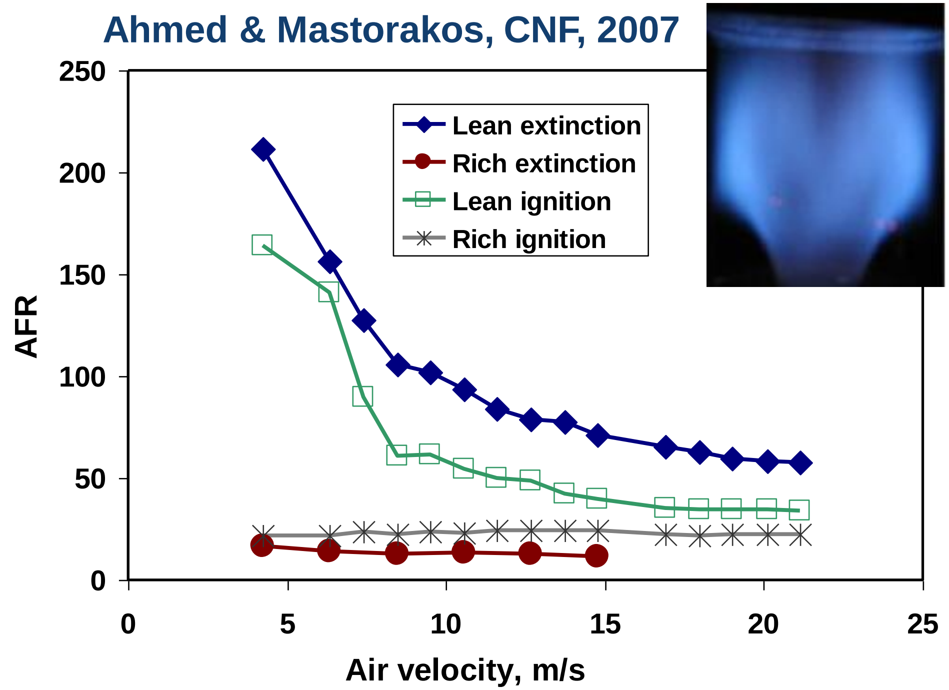
Outline

- Limits of operation of gas-turbine like flames
- The four phases of combustor ignition
- Experiments, DNS, LES
- Simplified modelling to assist design
- Conclusions

The practical ignition/blow-off loop



Ahmed & Mastorakos, CNF, 2007



Why this shape? What factors determine the distance between loops? How are flame patterns related to this curve? *Can we predict it?*

Knowledge on extinction is useful to understand ignition and vice versa.

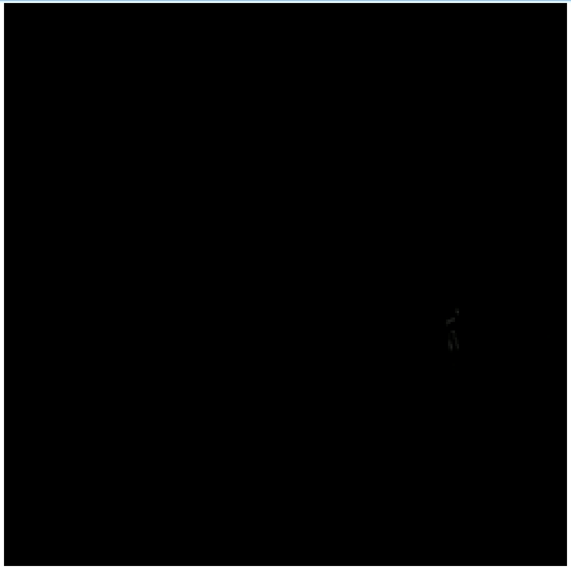
Shape and extinction/ignition loop separation visible also in lab-scale flames

Spark ignition of non-premixed and spray systems

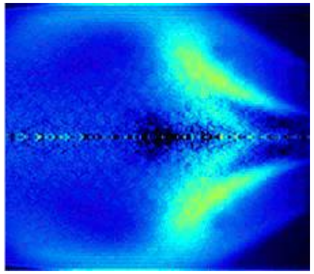
- Spark ignition: High-altitude relight of aviation gas turbines; Ignition in gasoline direct injection engines (GDI); Safety (leaks from cracked pipes etc). Very complex problem, not well studied, in contrast to fully premixed that is better studied.
- Need to go beyond global correlations.
- Predictive capability based on CFD needed.
- Physics-based, easy to use ("low-order") models needed.
- Stochasticity and transient behaviour are important. Fast diagnostics and LES help.

THE FOUR PHASES AND BASIC CONCEPTS

Spark ignition of Rolls-Royce combustor



OH*



FAILURE

SUCCESS

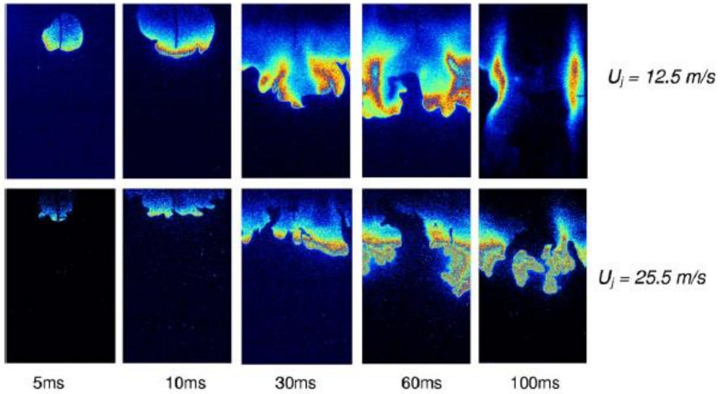
Ignition experiments at 0.4bar, 250K (Read, Rogerson, Hochgreb, AIAA J, 2011; Mosbach et al., ASME, 2011):

- Variability: not each spark is successful
- Success: tends to be associated with RZ ignition
- Spark is large relative to flame, unlike in automotive applications

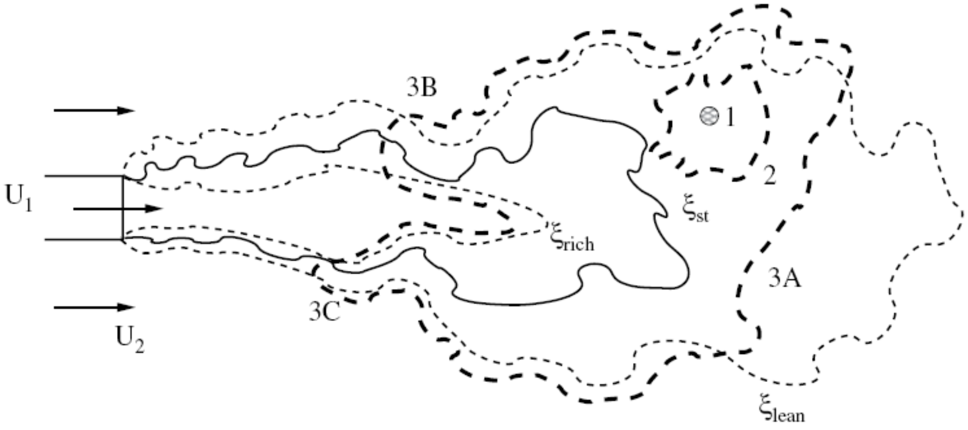
Movies thanks to S. Hochgreb

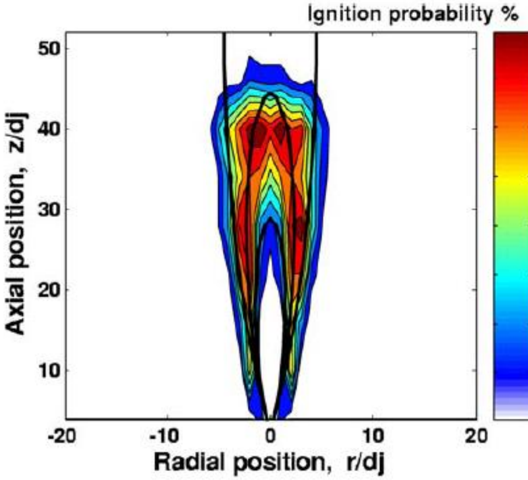
Spark ignition of non-premixed systems: axisymmetric fuel jet

JET, SUCCESS



OH-PLIF





Ahmed & Mastorakos, Comb. Flame, 146 (2006) 215–231

IGNITION PROBABILITY

Spark ignition in gas turbines

Phase 1: create a kernel (failure ⇔ local extinction)

Phase 2: kernel grows and flame spreads (S_T in non-premixed & sprays, flow)

Phase 3: burner ignites (sometimes failure ⇔ global extinction)

Phase 4: burner-to-burner propagation (lightround)

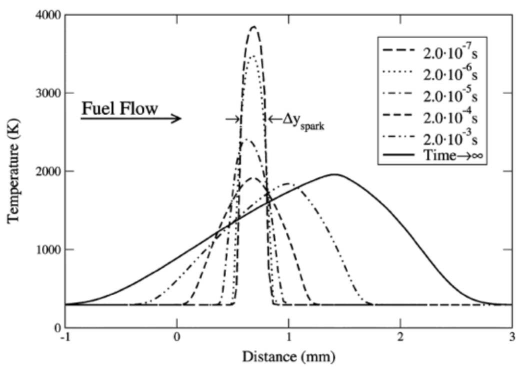
Phase 1: Kernel generation – premixed

- To ignite *laminar* premixed flame, one needs E > E needed to raise volume $o(\delta_L^3)$ to T_{ad}; this leads to MIE=f(fuel,ϕ,P,T) (Lewis & von Elbe, textbooks etc). Some recent explorations with laminar flame codes & analytics (Chen, Ju, etc) for Lewis number & radiation effects.
- To ignite *turbulent* premixed flame, MIE_turb > MIE_lam (experiments by Lefebvre & Ballal, mid 70's-80s; DNS by Poinsot & Veynante, Klein, Cant, Chakraborty etc). MIE may increase suddenly as u'/S_L increases much (Shy, Renou – "ignition transition").

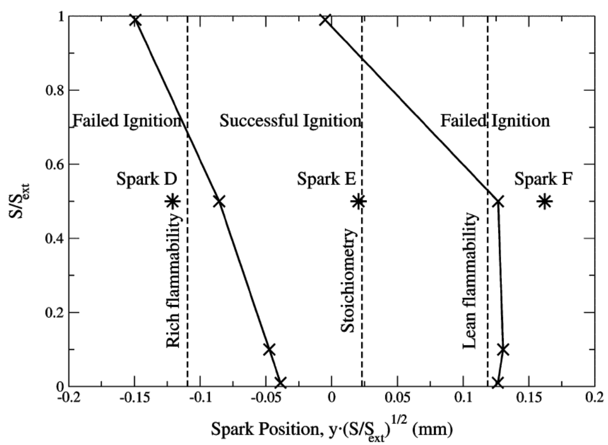
- Numerical simulations based on thermal description; *plasma chemistry and interactions not usually captured*.
- Electrical vs. laser spark
- "Overdrive effect" (Bradley, DNS)

Phase 1: Kernel generation – non-premixed

- **To ignite *laminar* non-premixed flame, MIE additionally depends on spark position and strain rate. *Need experiments!***
- **To create kernel in *turbulent* non-premixed flame, u' & mixture fraction important (from DNS & experiment).**

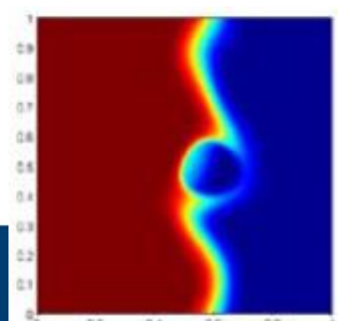


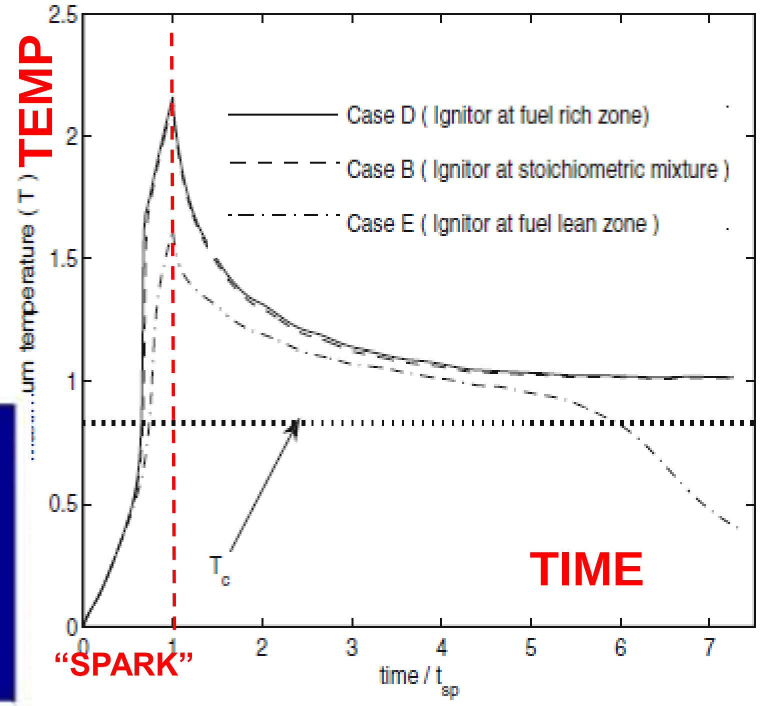
COSILAB, high T in a narrow zone at t=0; Richardson & Mastorakos CST 2007



DNS with power source in mixing layer (Chakraborty et al, FTC, 2008)

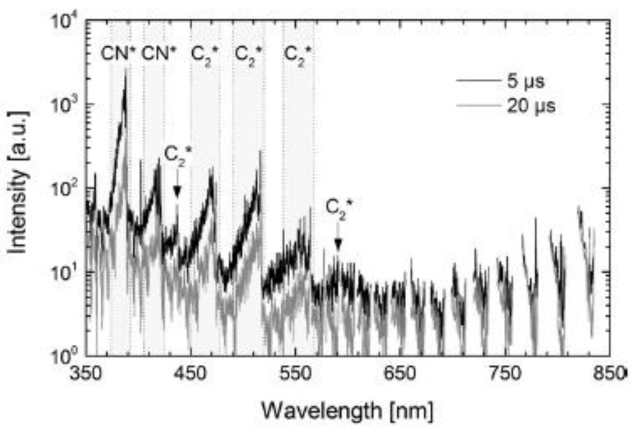
FUEL

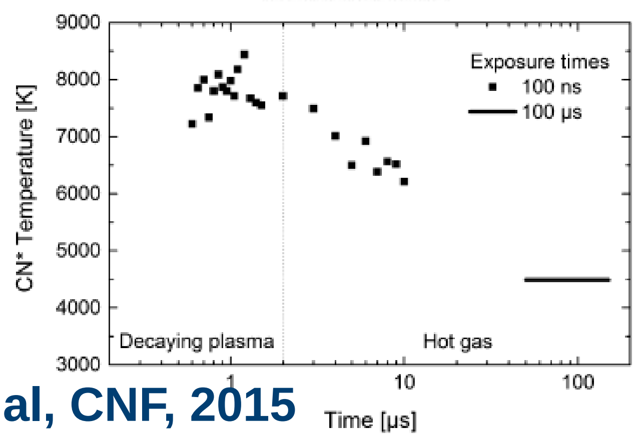




Phase 1: Kernel generation – spray

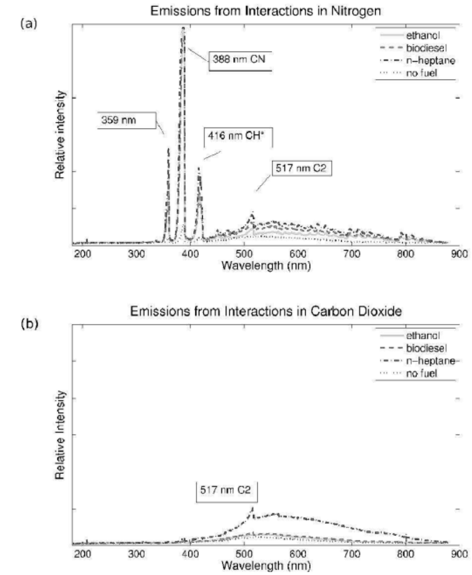
- **To create kernel in *sprays*, MIE additionally depends on droplet size, spray volatility, and degree of pre-evaporation (Ballal & Lefebvre, mid 80s, Agarwal 1998 PECS). *Need more experiments!***

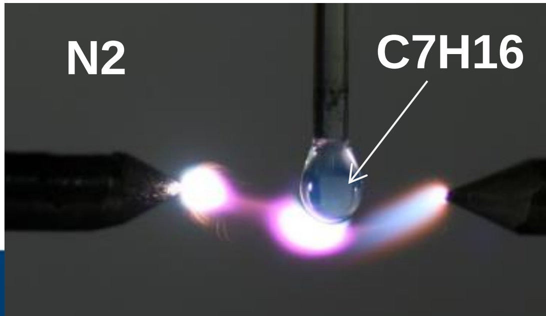




Gebel et al, CNF, 2015

Plasma-combustion transition begins to receive attention

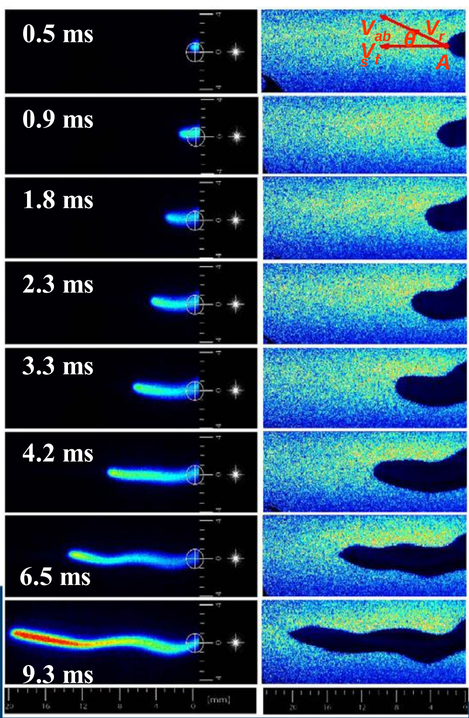




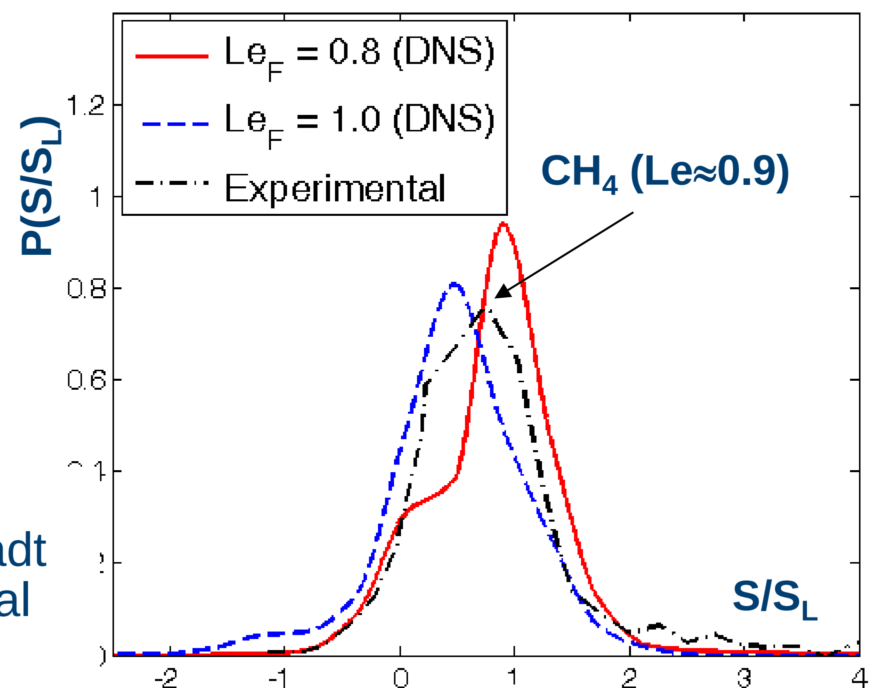
Farrow, MENG project

Phase 2: Flame growth – gas

- If mixture fraction fluctuations are small, flame grows as ***stratified flame*** (e.g. Renou & Cessou); established flame studied by many (Hochgreb, Barlow, Dreizler, TNF Workshop etc).
- If mixture fraction fluctuations are large, flame becomes edge flame. ***Turbulent edge flames*** not studied too well, but enough to tentatively conclude that average speed is low. Turbulence does not make it faster.



DNS vs. experiment – collaboration with Darmstadt (Hesse et al &, Heeger et al PROCI 32)

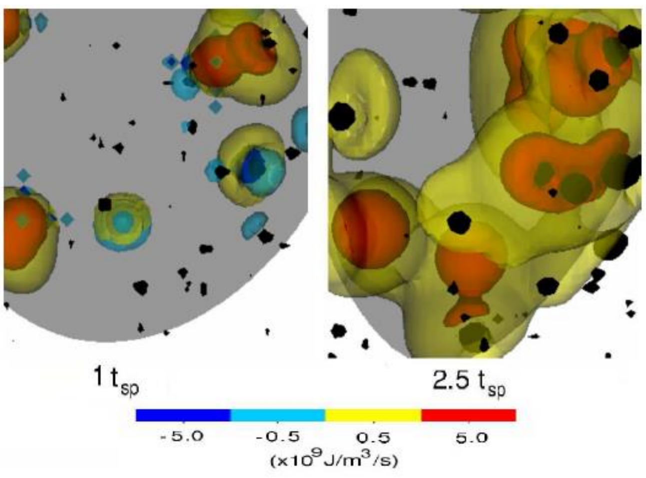


Phase 2: Flame growth – spray

- **Sprays add stratification at the small-scale, and in combustors we have large-scale droplet number density inhomogeneities.** ***Turbulent flame speed & extinction in sprays has been studied very little.***

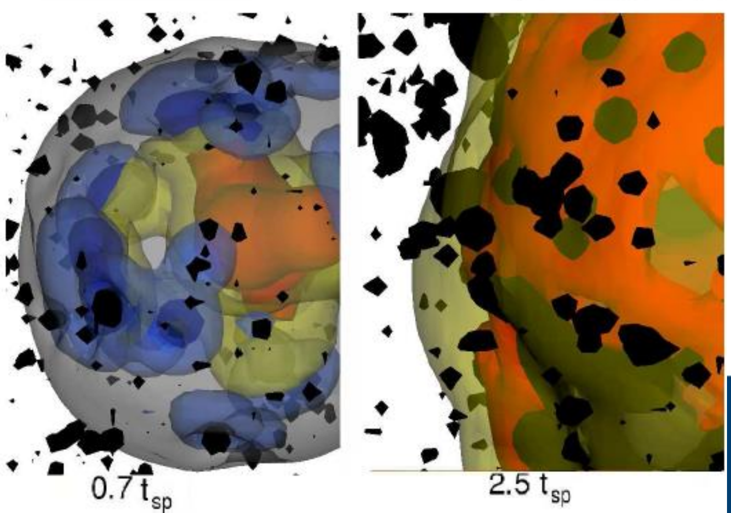
- **DNS of spark ignition in *uniform* dispersions: droplet-scale flame vs. cloud flame depending on Group number; very rich overall Φ possible to ignite.**

Φ=1, d=20μm



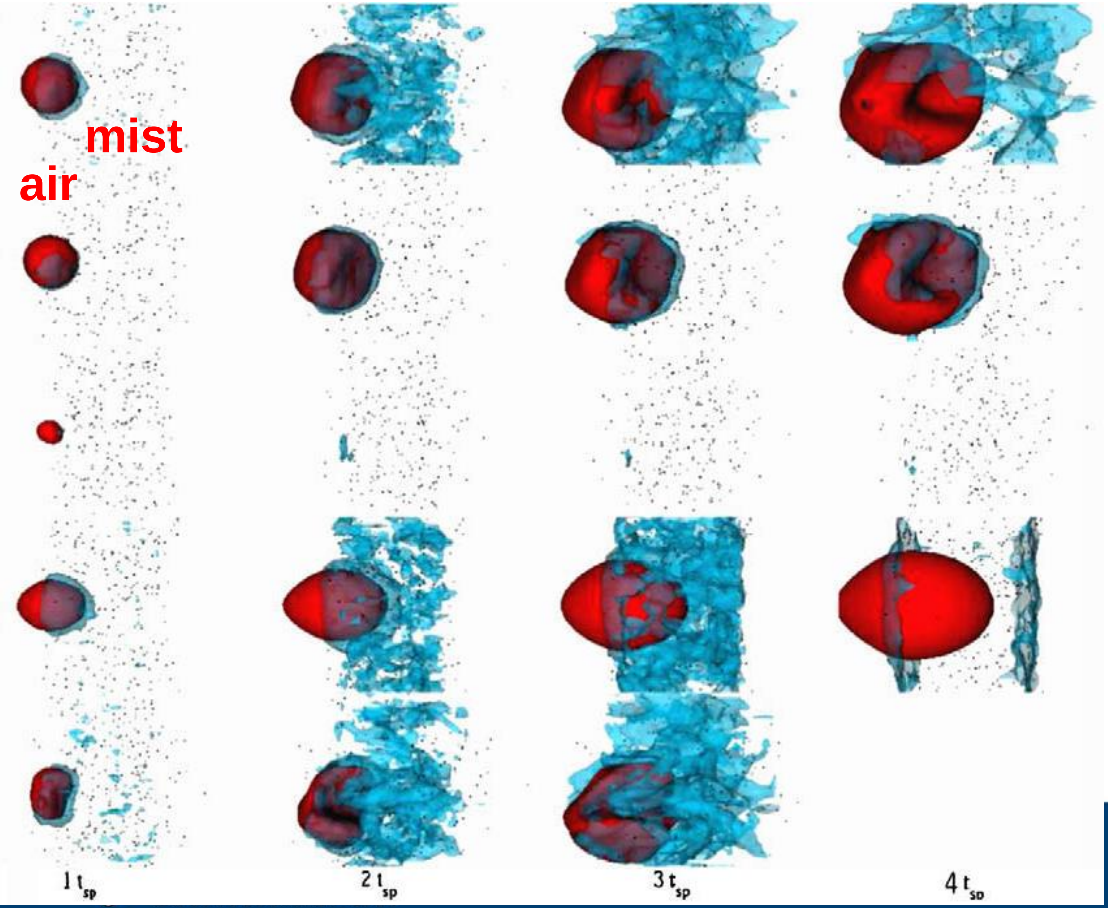
DNS, 128^3, 32-species, heptane, power source in uniform dispersion (Neophytou et al, CNF 2012, PROCI 33)

Φ=8, d=20μm



Phase 2: Flame growth – spray

- **DNS of spark ignition in *non-uniform* dispersions: flame growth or not depends on spark position, fuel volatility, turbulence (Neophytou et al., CNF 2010). Displacement speed proved useful concept.**



Standard

Less volatile

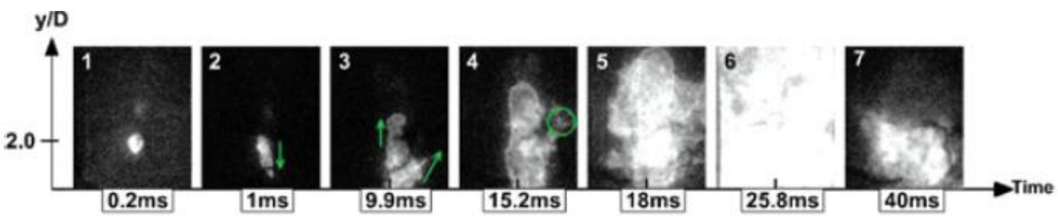
Less volatile, air side

Laminar

Higher u'

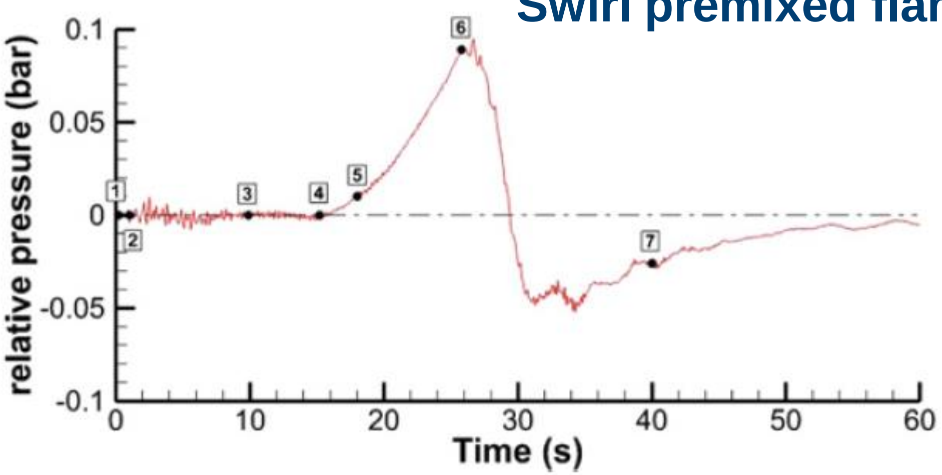
Phase 3: Burner ignition

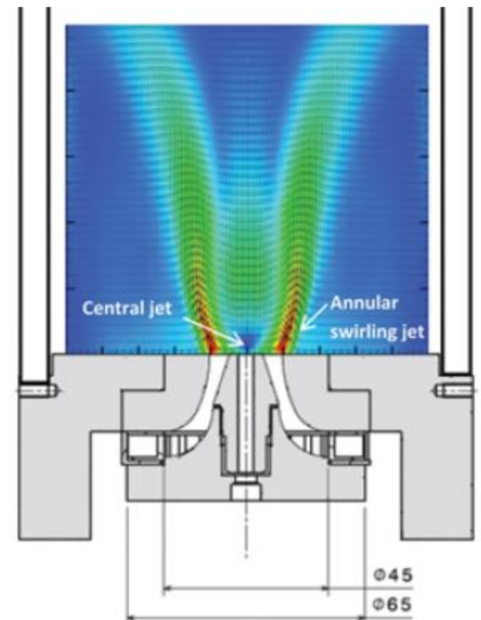
- *Flow pattern important*: **flame must grow in the right direction**
- *Recirculation zone critical*: **flame must be captured in RZ**
- **Premixed, non-premixed, spray have been studied (more later)**
- **LES simulations useful (more later)**
- **Failure to establish flame can be related to blow-off physics**



Cordier et al, CST 2013

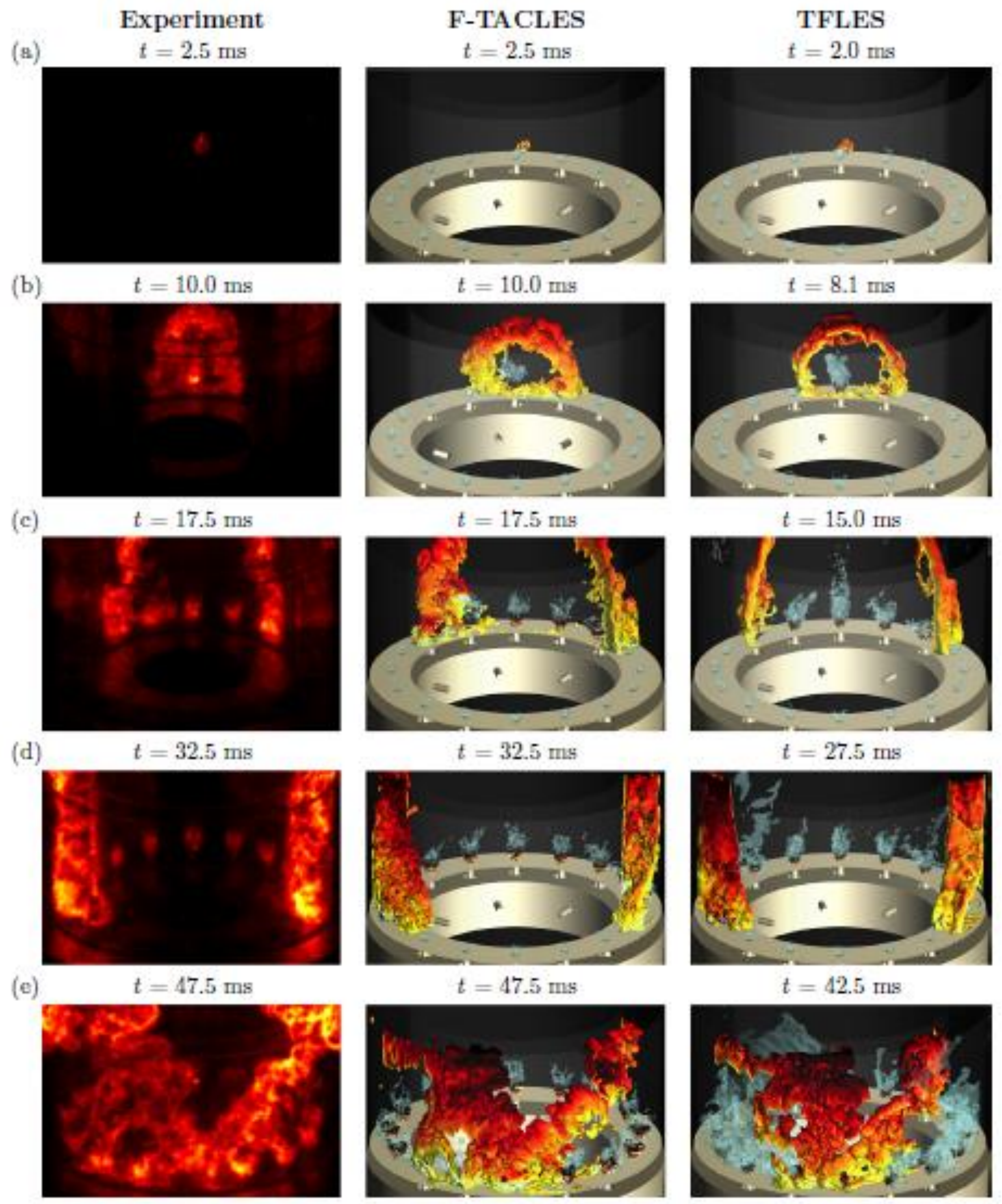
Swirl premixed flame





Phase 4: Lighround

- Little studied so far
- Experiments at Ecole Centrale, Rouen, Cambridge; simulations at CERFACS
- Dilatation seems important
- Mostly premixed systems studied so far (more later)

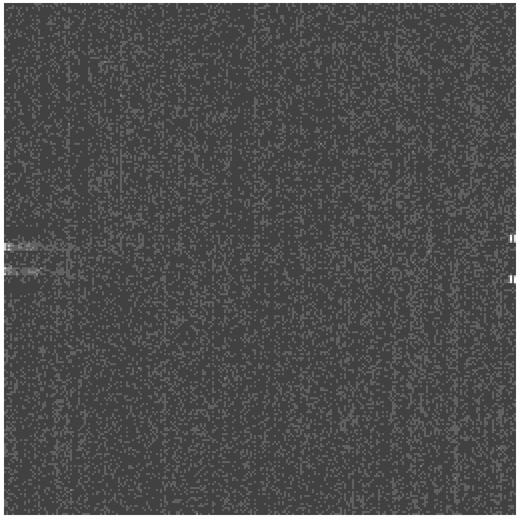


Bourgouin et al, PROCI 35

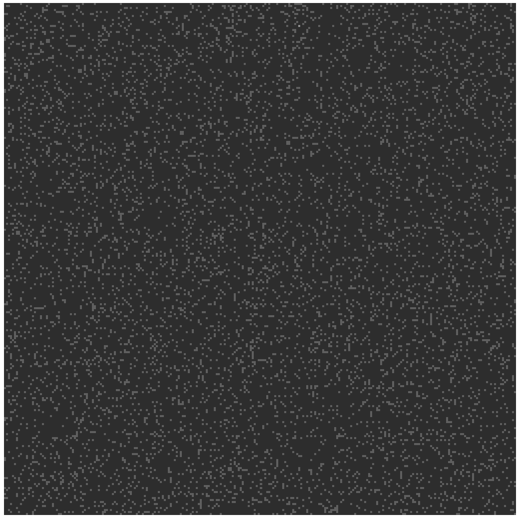
Spark ignition in gas turbines

RECIRCULATING FLAMES

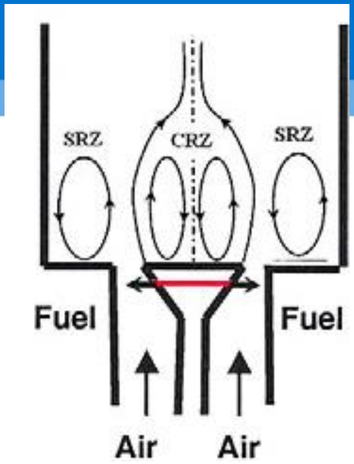
Spark ignition of non-premixed bluff-body flame: ignition probability

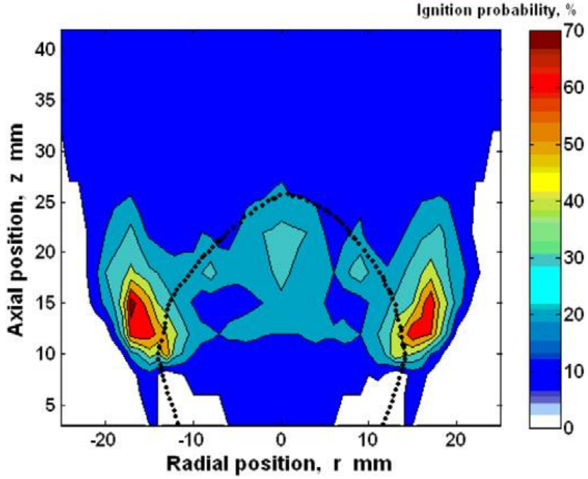


Successful spark



Failed spark





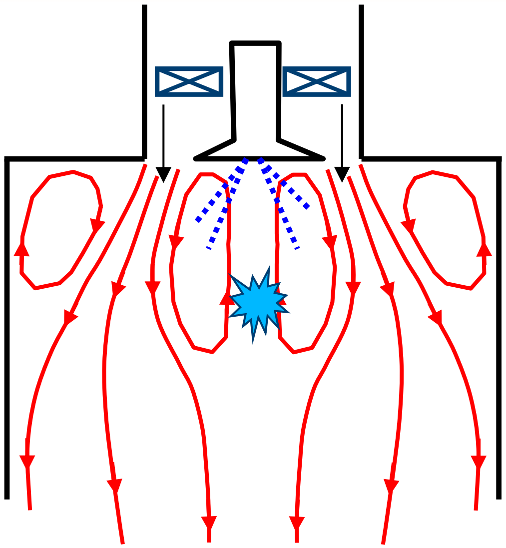
Ignition probability

$$\text{Result}: F = \int_{\xi_{lean}}^{\xi_{rich}} P(\eta)\, d\eta \neq P_{\text{ker}} \neq P_{\text{ign}}$$

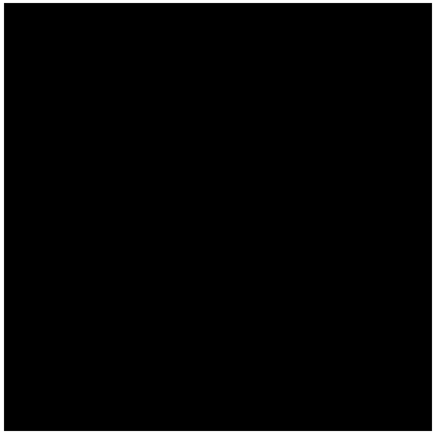
"Flammability factor" (Birch et al, 80s)

Ahmed et al., CNF, 151 (2007) 366–385

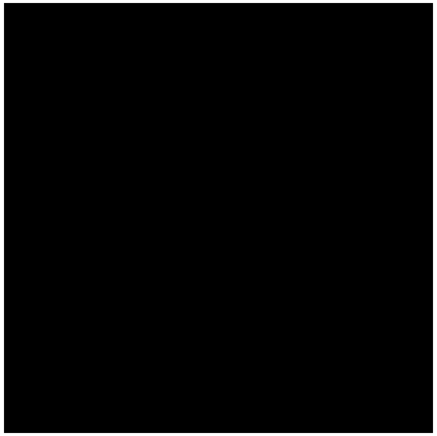
Spark ignition of non-premixed systems: spray flame (Marchione et al., CNF 2009)

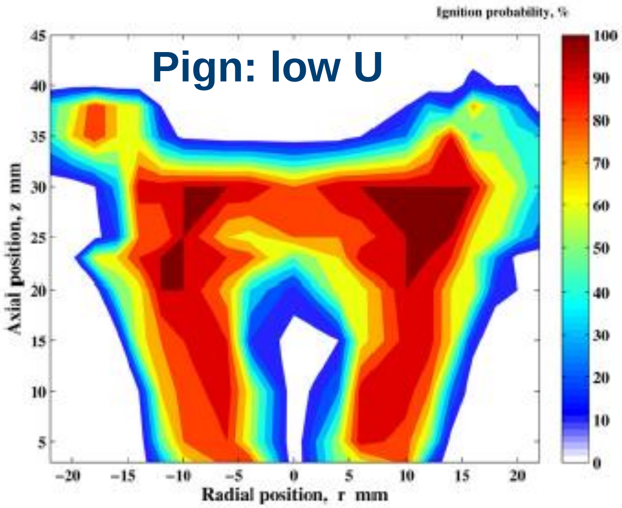


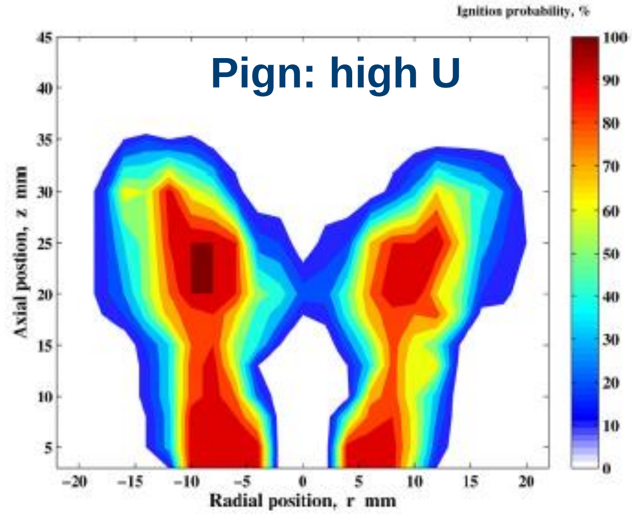
FAIL



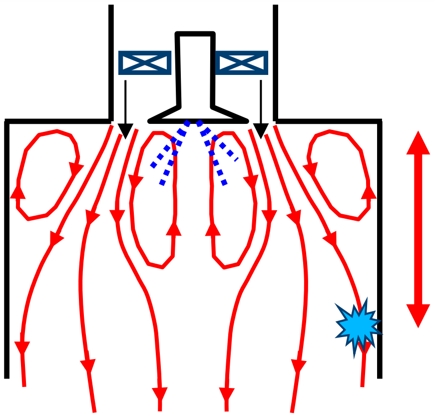
SUCCESS

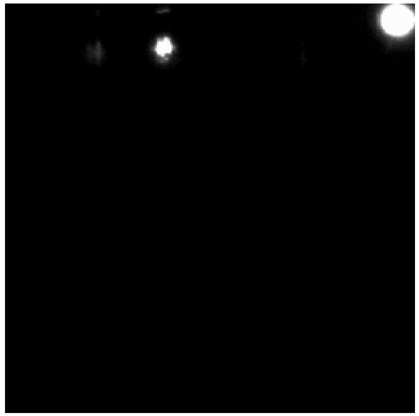


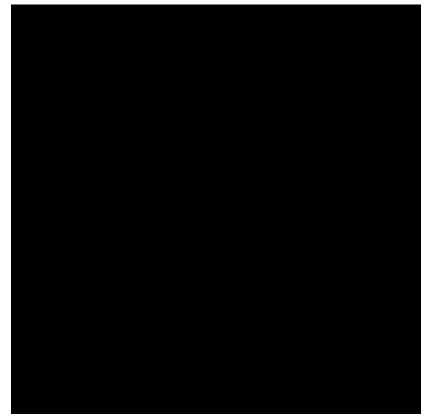


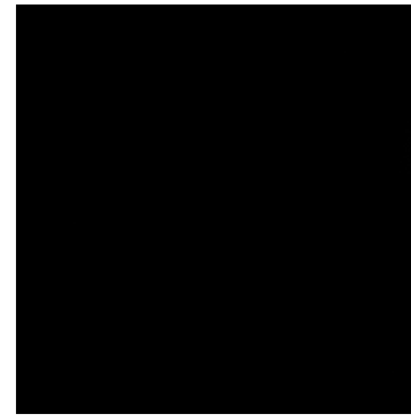


Spark ignition of non-premixed systems: spray flame with 100 Hz spark at wall (Marchione et al., CNF, 2009)





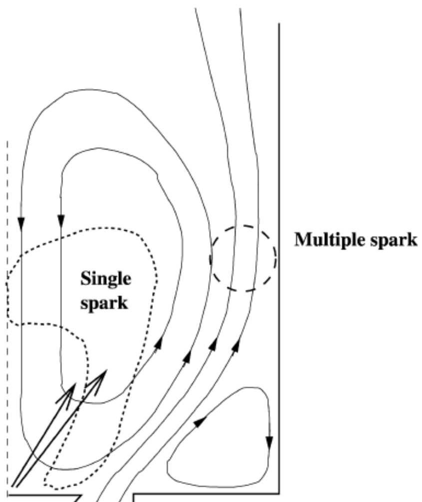




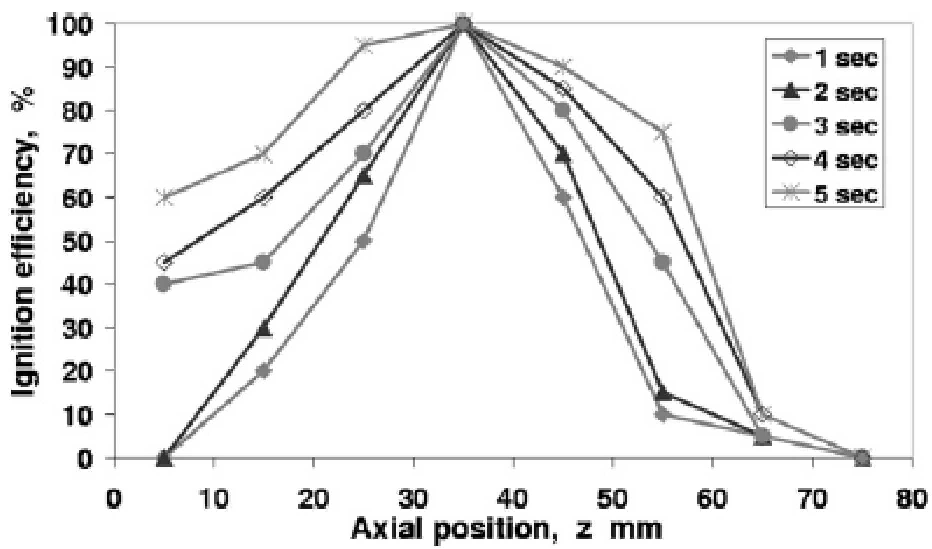
5 mm

15 mm

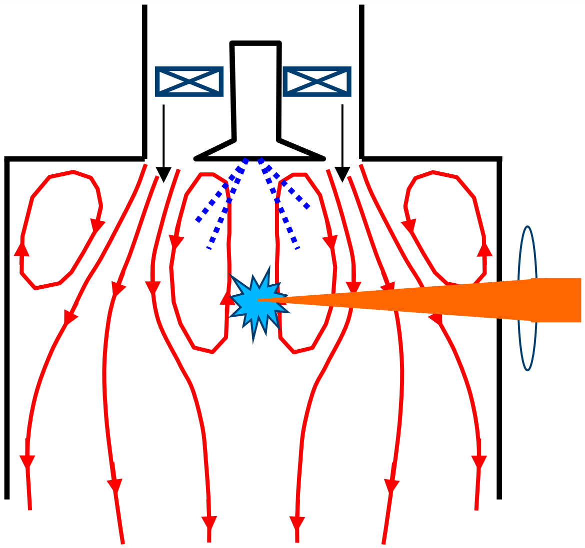
35 mm

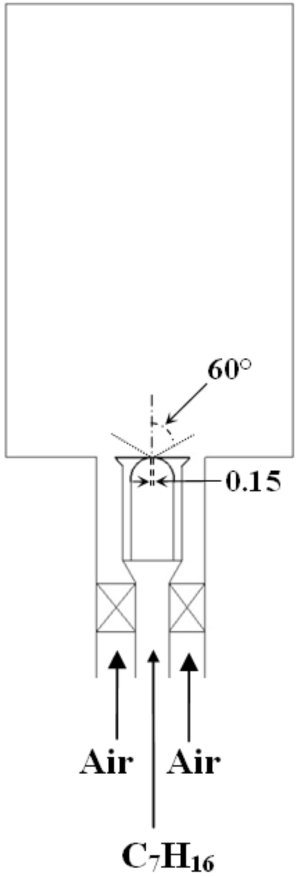


BEST SPARK LOCATION



Spark ignition of non-premixed systems: spray flame, close to blow-off point (Letty et al, ETFS 2012)



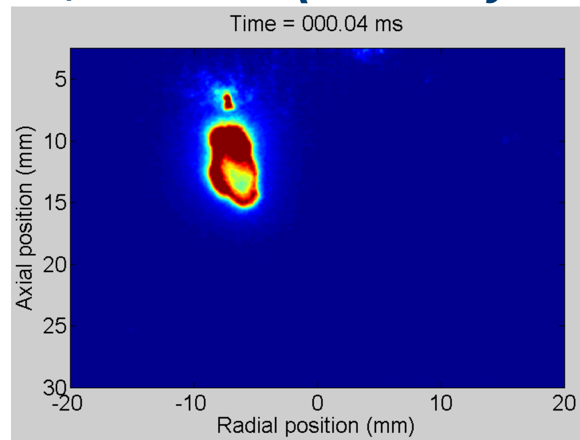


- Square section: 95mm x 95mm x 150mm
- Ignition by laser (Nd:YAG laser at 1064 nm (dichroic mirrors to purify l), f=10Hz, fl=150 mm converging lens, E ∊[40;370] mJ/pulse.
- Heptane fuel, ambient conditions

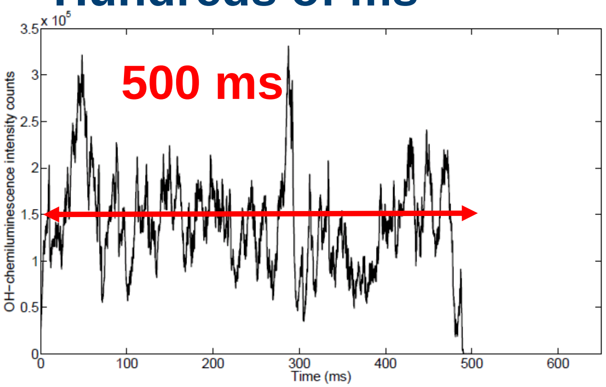
Spark ignition of non-premixed systems: spray flame, close to blow-off point (Letty et al, ETFS 2012)

5kHZ OH*, intermediate failure

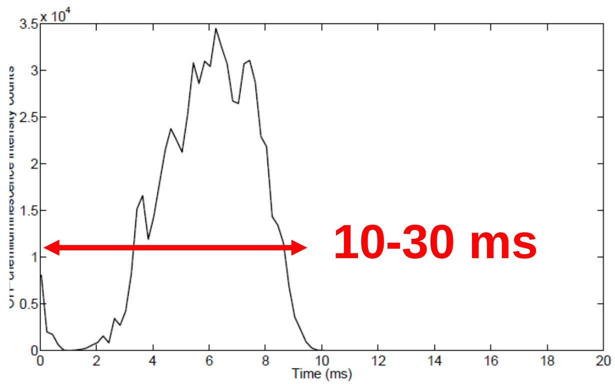
5kHZ OH-PLIF, success (with USydney, A. Masri)



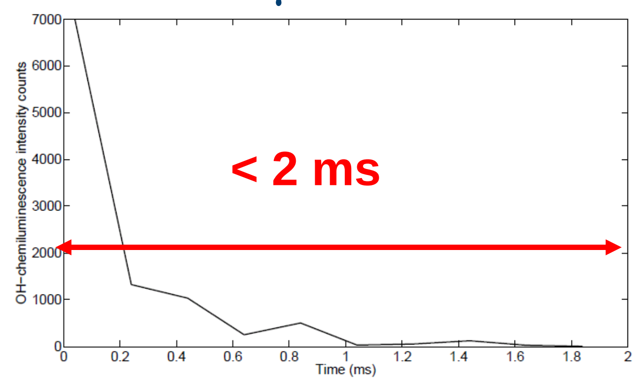
***Long* failure mode:**
Hundreds of ms



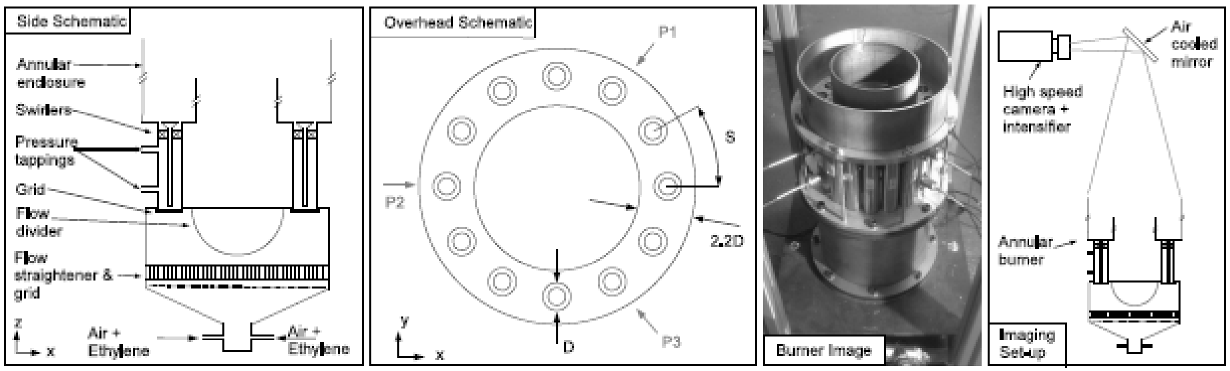
***Intermediate* mode:**
A few tens of ms

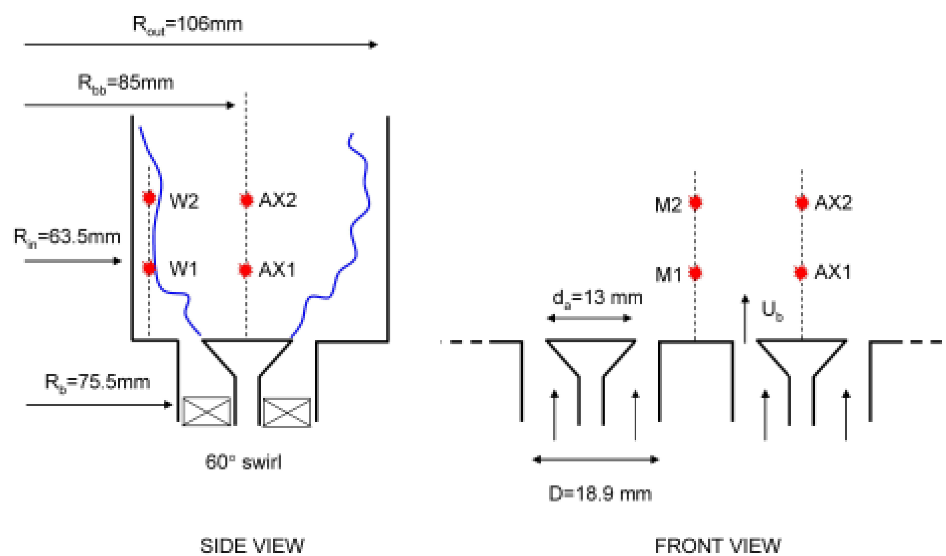


***Short* failure mode:**
From a few μs to a few ms

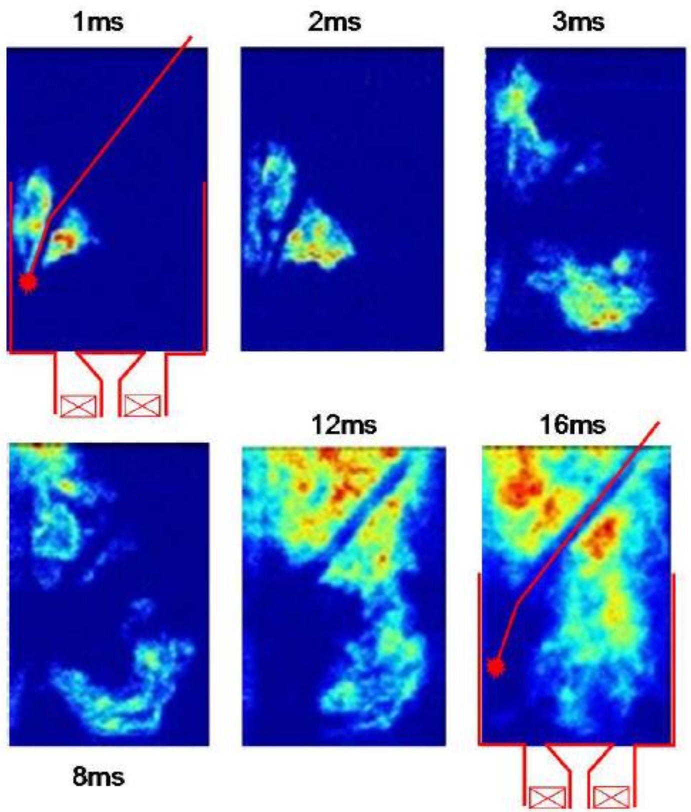


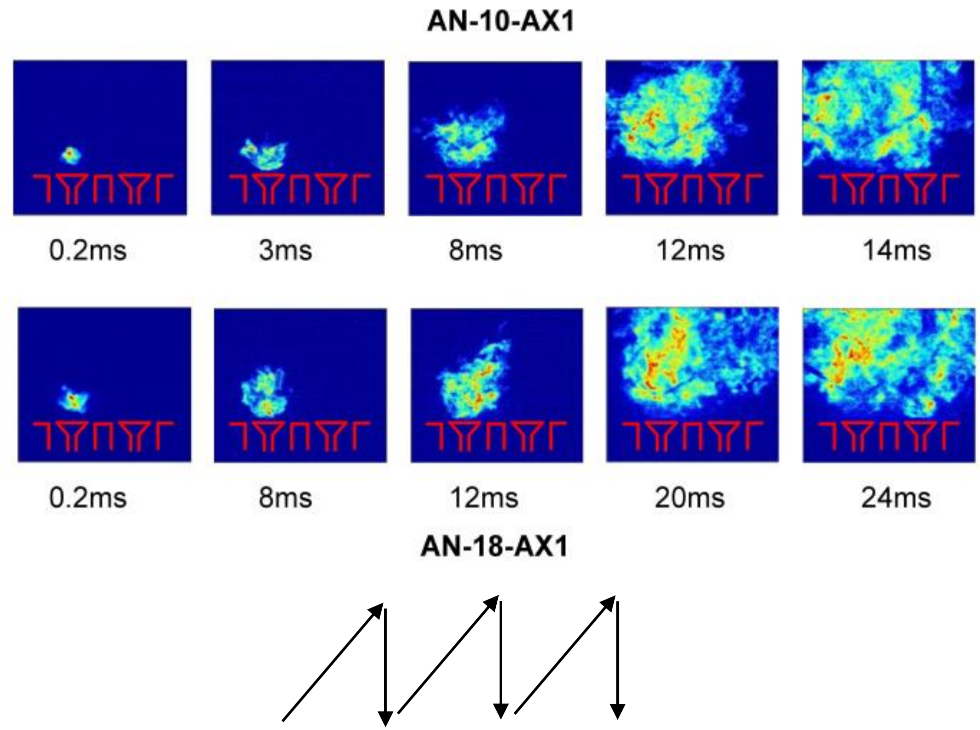
Spark ignition of annular combustor (Cambridge, ECP)





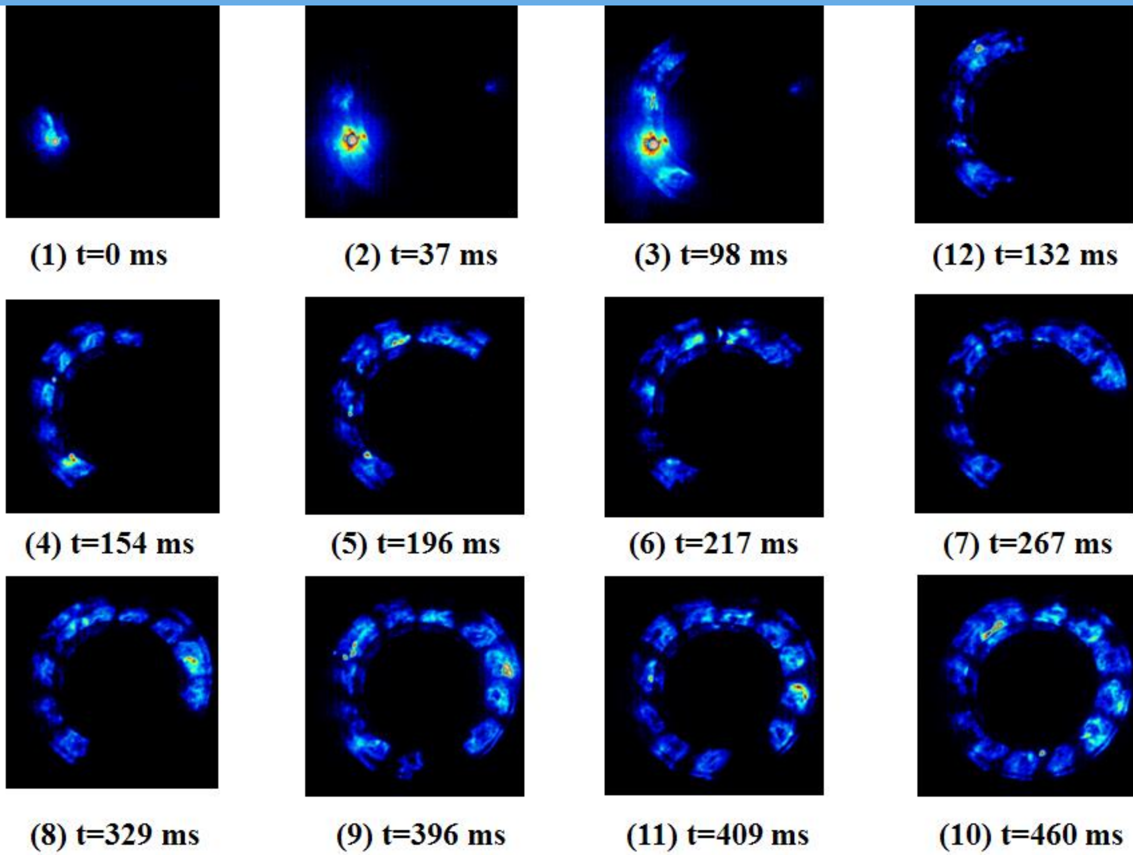
Spark ignition of annular combustor: burner-to-burner flame expansion

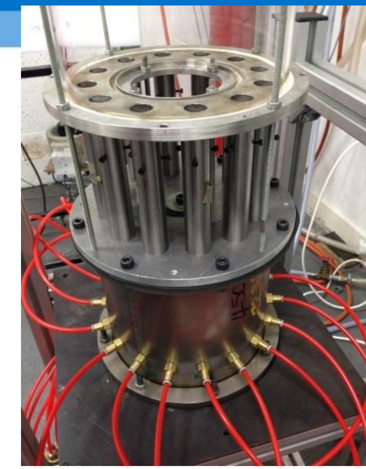




"Sawtooth" burner-to-burner propagation

Spark ignition of annular combustor: non-premixed flames (Machover & Mastorakos, MCS-2015, Rhodes)

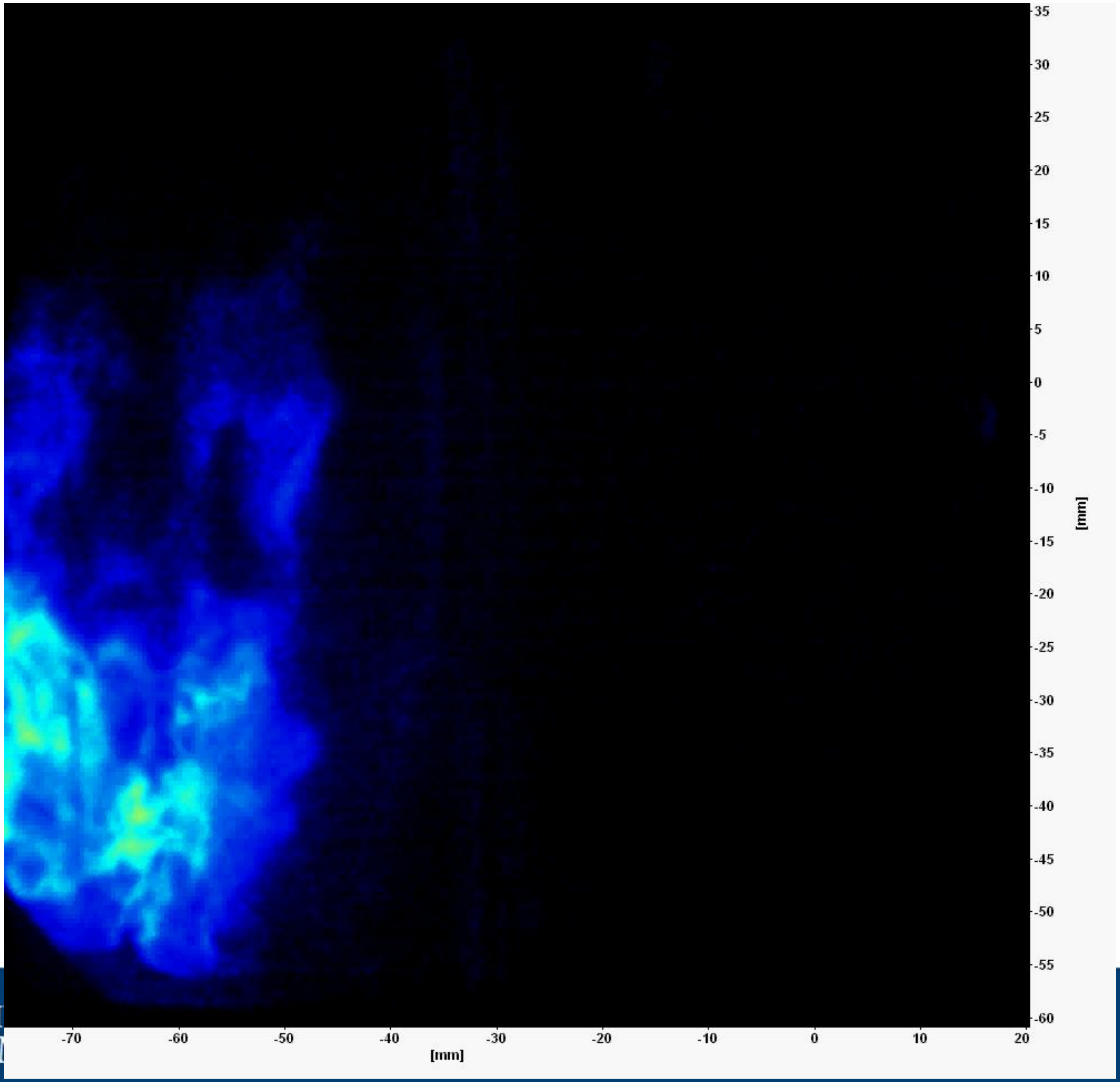




Top view, 5kHz OH*

Speed of lightround: very slow compared to premixed

Spark ignition of annular combustor: non-premixed flames (Machover & Mastorakos, MCS-2015, Rhodes)



"Saw-tooth" propagation more pronounced than in premixed

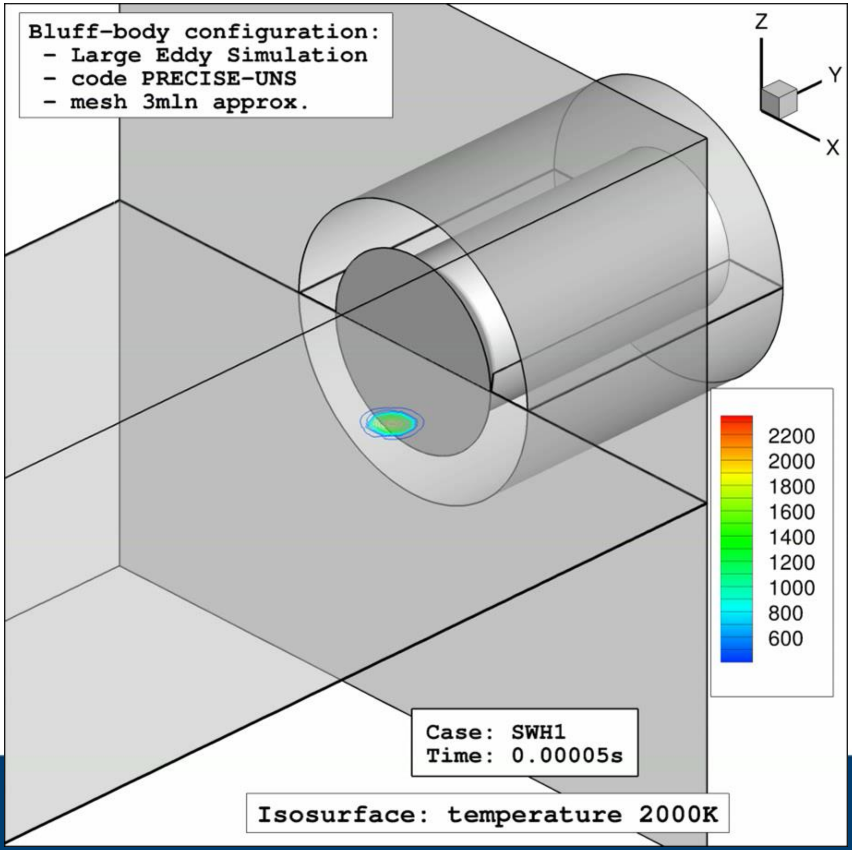
Side view, OH*

SIMULATIONS WITH LES AND LOW-ORDER MODELS

LES/CMC of spray flame ignition (Tyliszczak & Mastorakos, AIAA 2013)

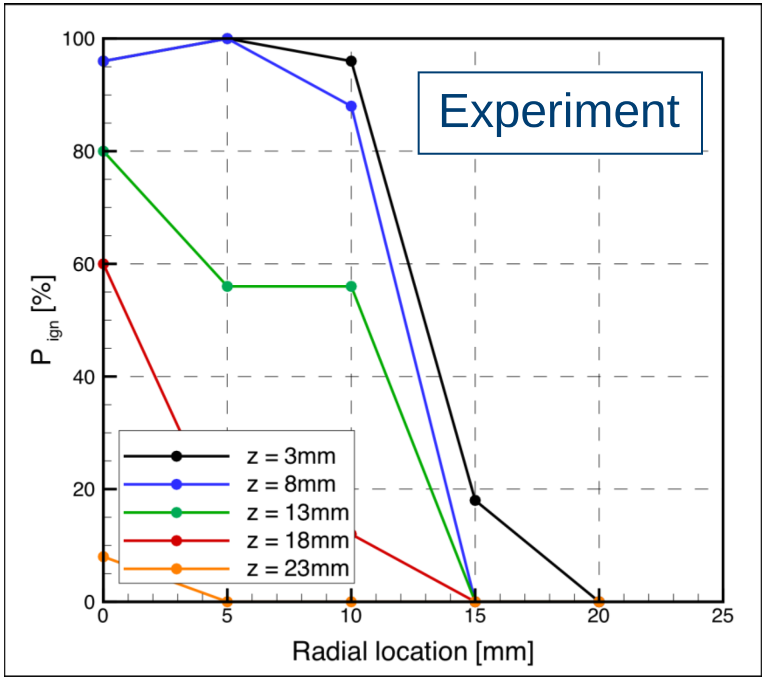
LES: mixture-fraction, Lagrangian spray, Smagorinsky

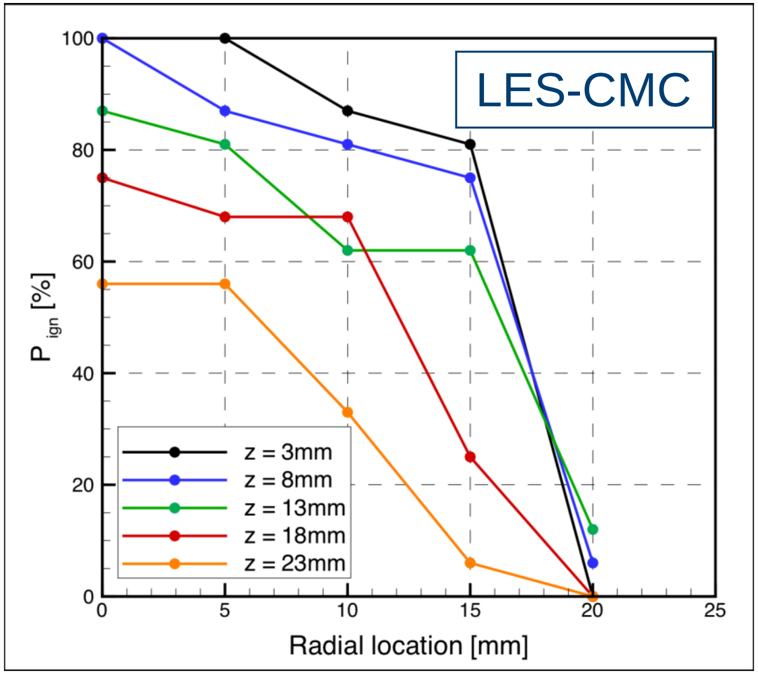
Conditional Moment Closure: sub-grid combustion model incl. detailed chemistry. Developed over range of flows (gas, spray, far from and close to extinction)



Ignition probability from LES/CMC of spray flame ignition (Tyliszczak & Mastorakos, AIAA 2013)

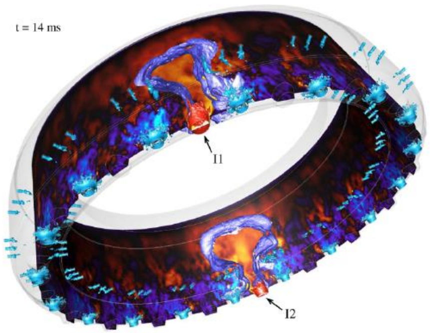
Probability of ignition shows reasonable agreement with experimental trend: Pign decreases as we go downstream and outwards in the radial direction. LES based on 16 simulations with spark at each of 20 points.



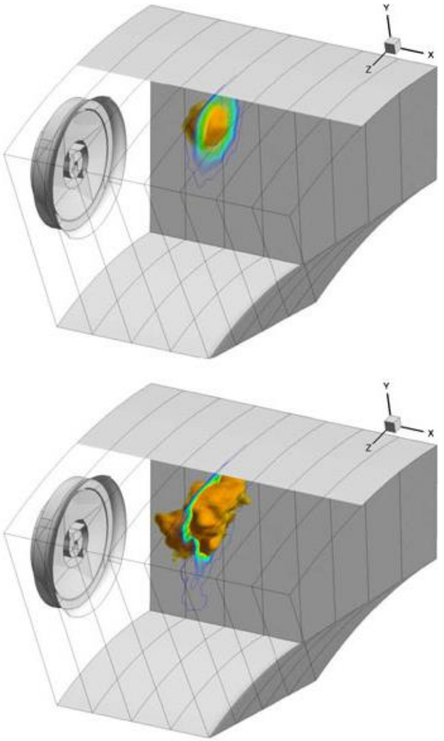


Work in many labs

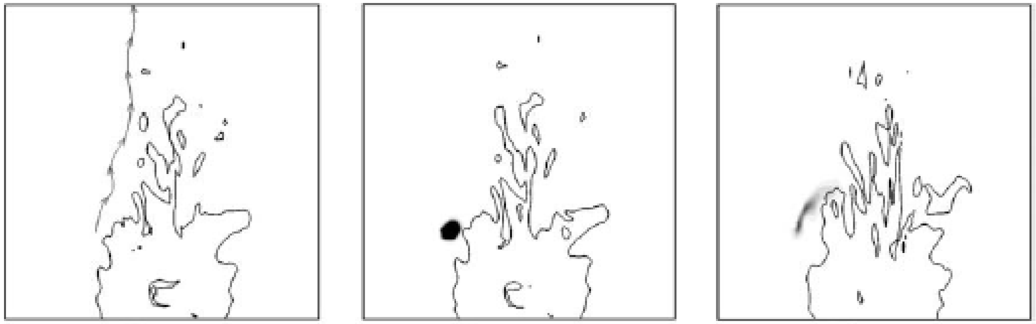
- CERFACS, DLR, Rouen, Imperial College, Univ. of Chestochowa.
- EU projects: TECC, KIAI, etc.



Boileau et al,
CNF 2008



Tyliszczak & Jones,
FTC 2010

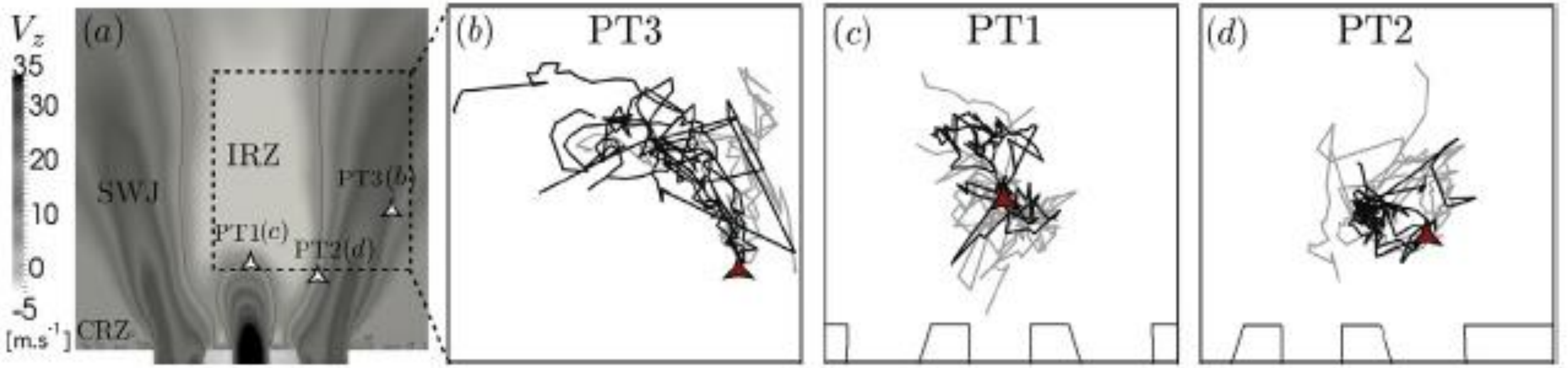


(a) 0 ms (b) 0.15 ms (c) 1 ms

Subramanian et al, CNF 2010

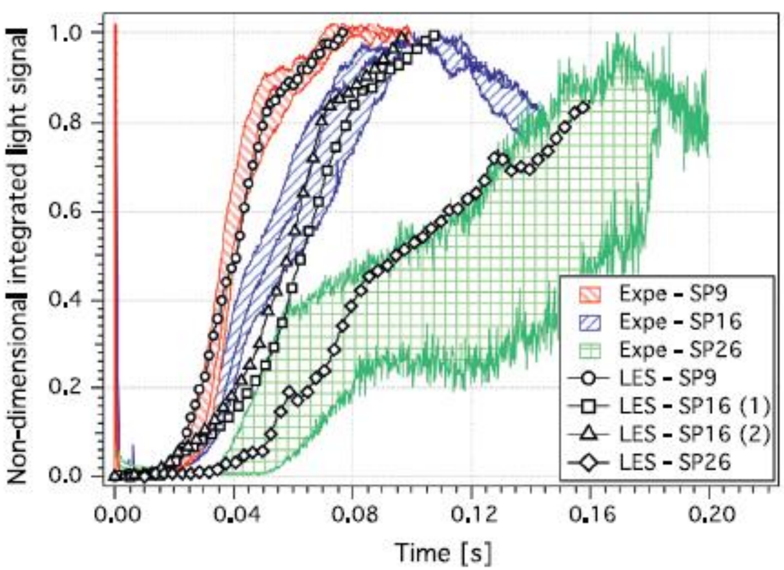
Work in many labs

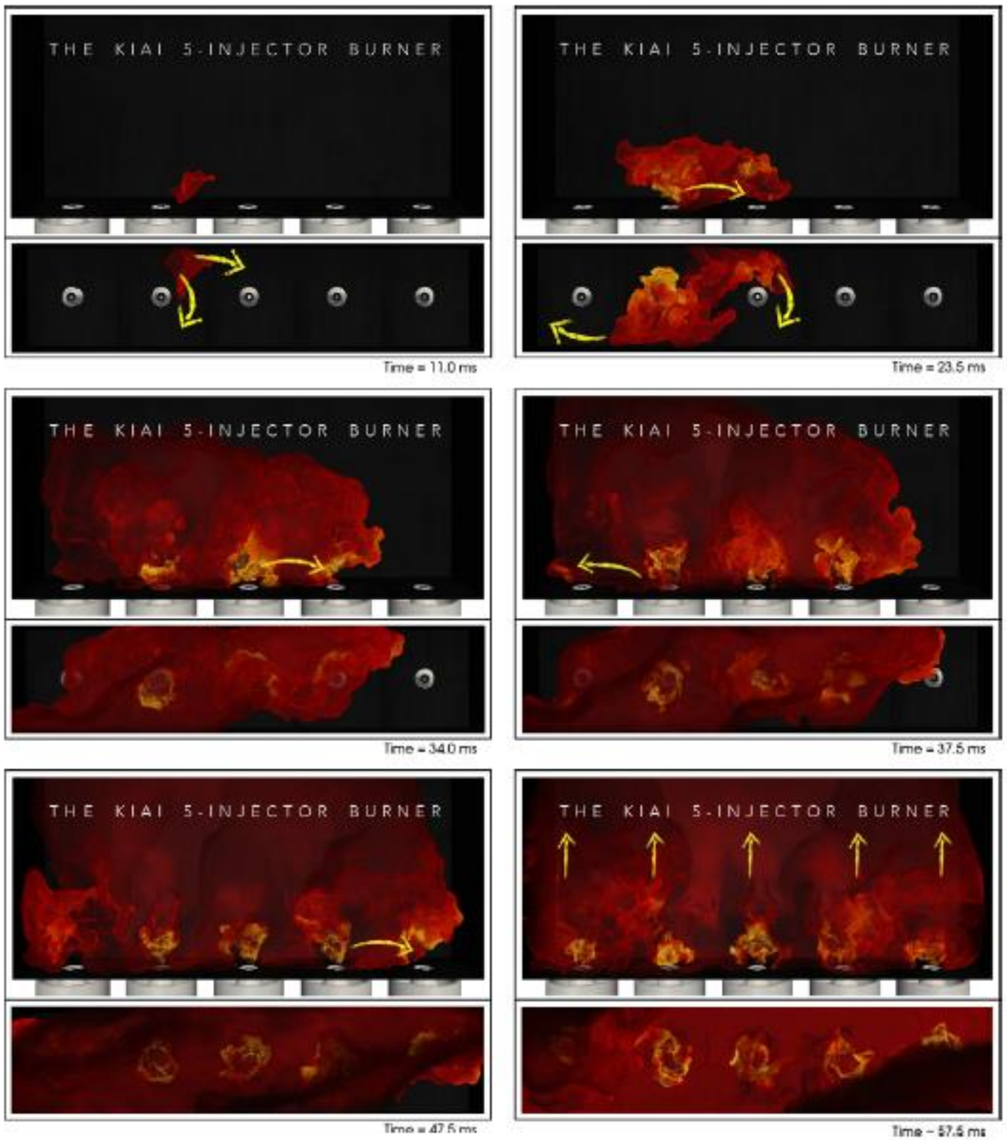
- Ignition probability based on multiple LES (Esclapez, Riber, Cuenot, PROCI 35): successful ignition means generation of kernel and radially-inwards movement and no quenching.



Work in many labs

- Linear burner (Rouen, CERFACS; Barre et al., CNF 2014)
- Sideways vs. axial expansion





Simplified model for ignition of combustors (Neophytou et al, Comb. Flame 159 (2012) 1503-1522)

- Optimum design process: take decisions on ignitability early on
- New designs (lean, new fuels, mixing patterns) put "existing wisdom" and empirical correlations in question
- Physical approach:
  - Distill fundamental knowledge from experiments, DNS & LES
  - Simple to use, quick
  - "Interrogate" a CFD solution of the inert (un-ignited) flow to provide an educated guess about success
- Code SPINTHIR (Stochastic Particle INTegrator for HIgh-altitude Relight).

SPINTHIR: a synthesis of most physical findings

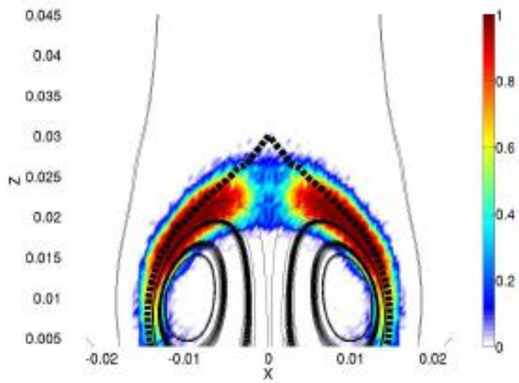
1. Track virtual "flame elements" using a random walk with mean & stochastic velocity component from the CFD solution.
2. If local Karlovitz number < critical value, particle remains alive and new particle is launched from this position. (Ka depends on local ξ.)
3. For sprays, laminar burning velocity for ***sprays at relight conditions*** is used (Neophytou & Mastorakos, Comb. Flame 156 (2009) 1627–1640).
4. If local Ka > critical value, forget this particle.
5. Count volume of combustion visited by flame: this is the "ignition progress factor" π_{ign}.
6. Continue for a long time.
7. Repeat for many times to compile statistics (sample space: individual spark events).

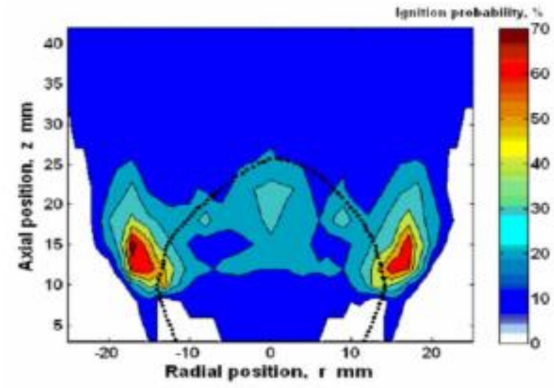
SPINTHIR: a synthesis of most physical findings

- Validation: Ignition probability compares well experiment

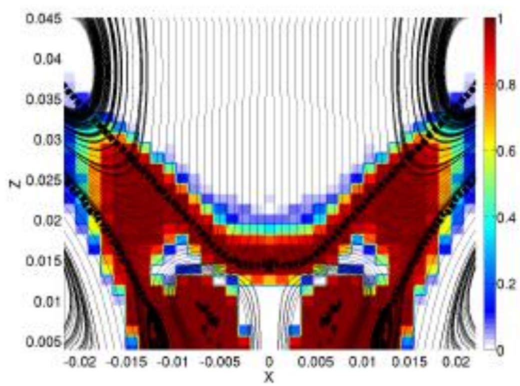
MODEL | EXP

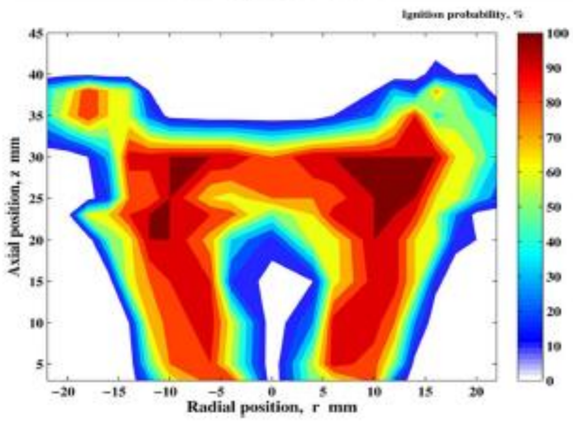
CH4





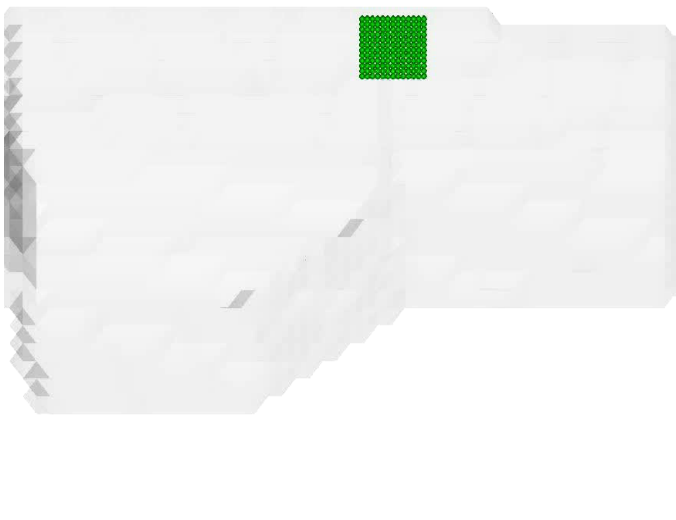
Spray





SPINTHIR for Rolls-Royce combustor

- Builds insight on ignitability of combustor as a function of flow pattern, size of spark, variability between spark events etc.

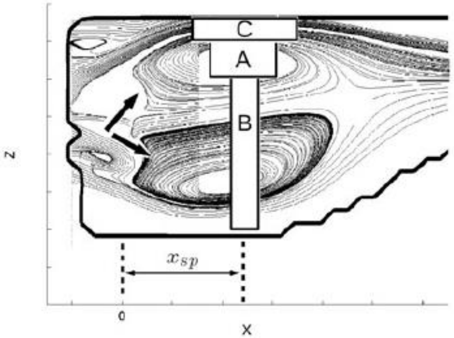


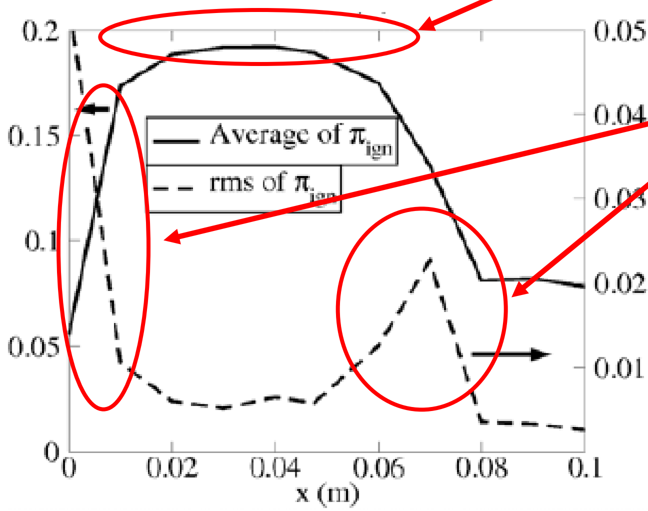
Bad spark location

Good spark location

Neophytou et al., Mediterranean Combustion Symp. Sept 11
CFD solution from S. Stow, RR

SPINTHIR for Rolls-Royce combustor

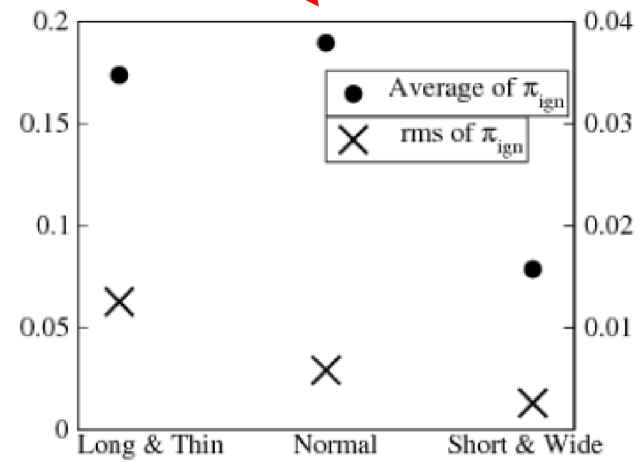




The best ignitor location – agrees with experience

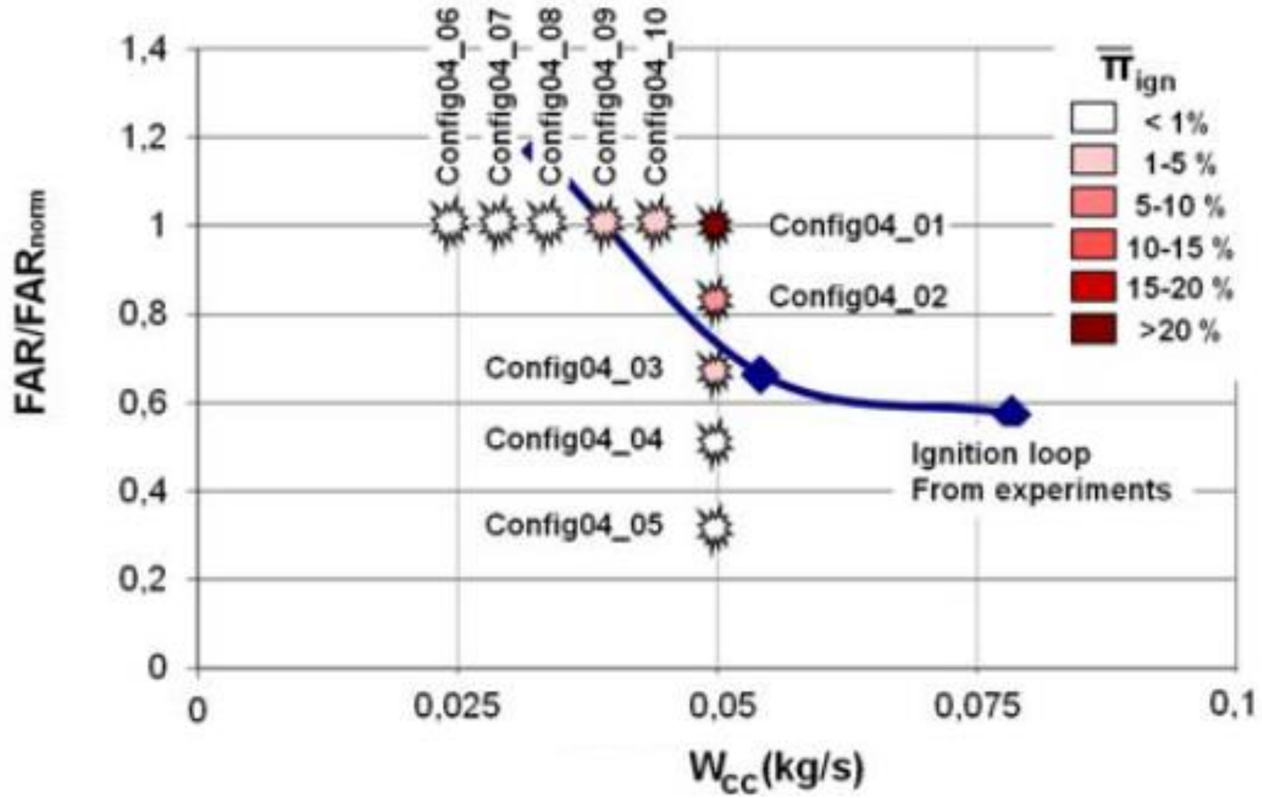
Large variability

The best ignitor shape – agrees with experience



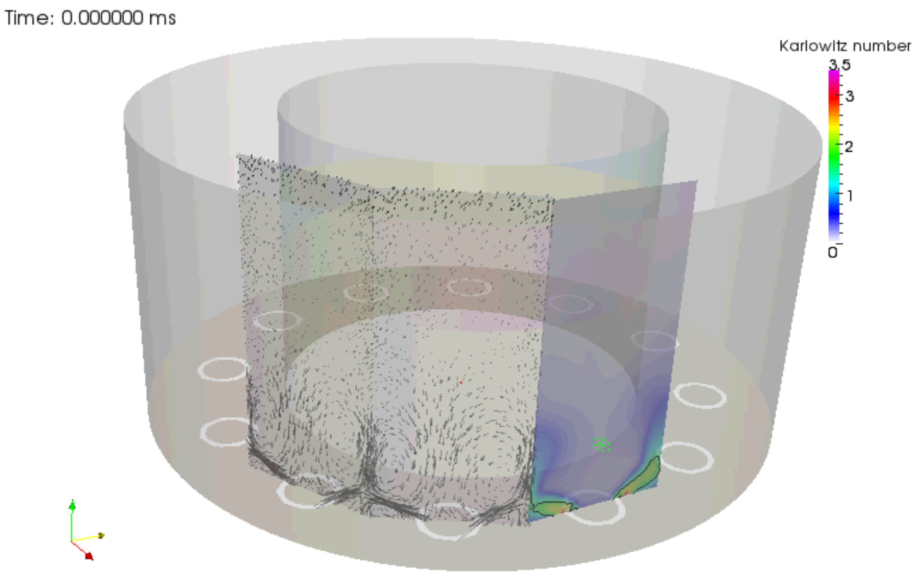
- Statistics of π_{ign}: assist designer decide spark location and shape

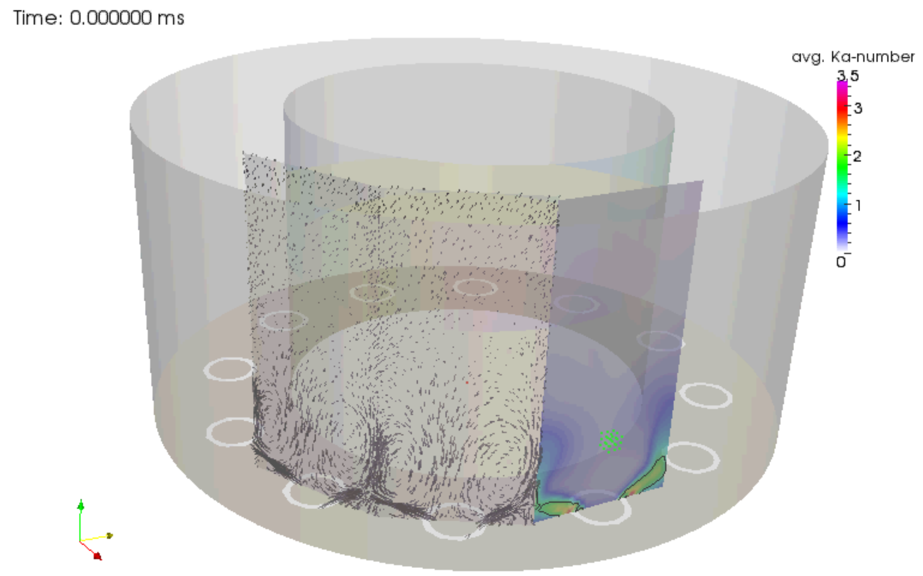
SPINTHIR for Rolls-Royce combustor



Statistics of π_{ign}: high values consistent wtith good ignition behaviour in real combustor at relight conditions (Sowork et al, ASME Turbo Expo 2014)

SPINTHIR for annular combustor - lightround





Good ignition, ϕ=0.70

Bad ignition, ϕ=0.55

Sitte, MPhil thesis, 2013

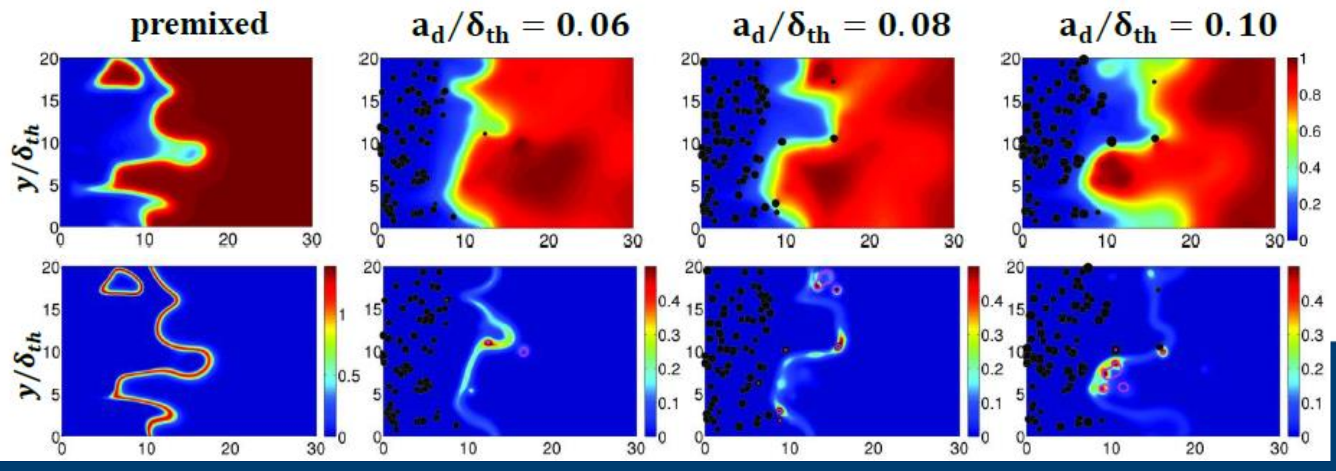
Conclusions

- Spark ignition of non-premixed systems is very challenging and rich in phenomena. Experiments in progressively more complicated geometries have revealed key features: stochasticity, quenching, good spark locations.
- Laminar and turbulent simulations (DNS) have been instrumental at identifying trends and flame speed.
- LES with a good combustion model (e.g. CMC, thickened flame, PDF, ξ-c flamelet) can be used to predict individual ignition events & Pign.
- Simplified model (e.g. code SPINTHIR) has been developed and used by gas turbine designers.

Next steps

- Plasma – combustion interactions: transition from plasma to combustion chemistry (Ecole Polytecnique, Princeton, Georgia Tech etc)
- Turbulent flame speed in sprays (TCS Workshop, DNS, modelling, exp.)
- LES sub-grid models for small-kernel growth and local extinction with sprays
- Four-dimensional measurements (e.g. Darmstadt, Lund)

Wacks & Chakraborty, submitted



Spark ignition of non-premixed systems: experimental & numerical work at UCAM

Variety of geometries and results (Ignition probability; Timescale of expansion; Flame structure; Statistics of edge flame speed):

- Jet (CNF, 146 (2006) 215–231)
- Opposed-jet (Ahmed et al., PROCI, 31st, 32nd)
- Planar mixing layer (AIAA 2009-238860)
- Bluff-body non-premixed (CNF, 151 (2007) 366–385)
- Swirling spray (CNF, 156 (2009) 166–180; ETFS, 43 (2012) 47-54)
- Premixed bluff-body, annular (AIAA 2013)

- Statistics of edge flame speed in mixing layers (FTaC (2010) 84:125–166; PROCI 32 (2009) 1399–1407)
- Statistics of edge flame speed in sprays (CNF, 157 (2010) 1071–1086)
- 5kHz OH-PLIF of spray spark ignition (ETFS, 43 (2012) 47-54)
- DNS, LES (CNF papers 2010,11,12; FTaC 2013)

Review: E. Mastorakos, Prog. Energy Combust. Sci., 35:57-97 (2009)
Conceptual model: Neophytou et al., CNF, 159:1503-1522 (2012)