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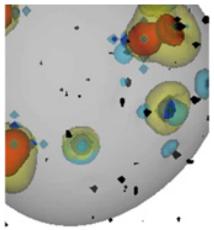

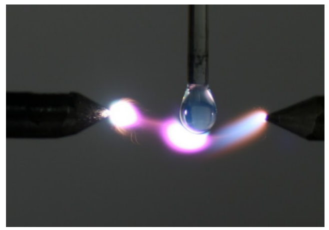

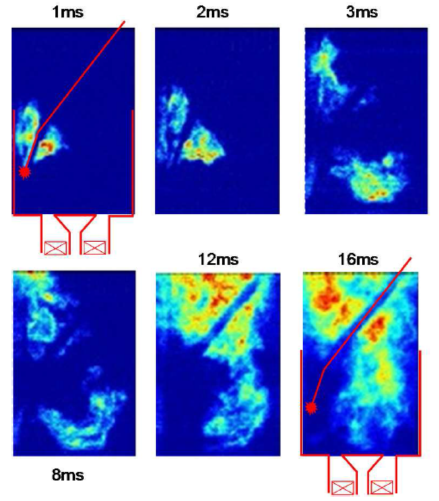

Ignition of gas turbines

MUSAF-II, 19 September 2013

Epaminondas Mastorakos

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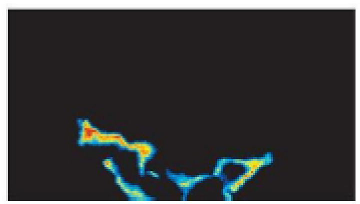
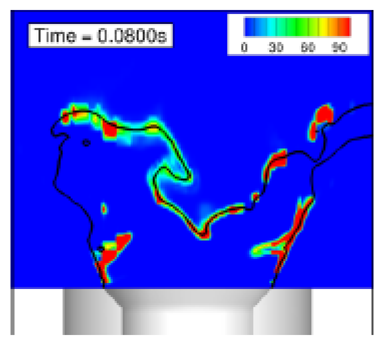
Department of Engineering





Acknowledgements

- Drs. S. Ahmed, C. Letty, A. Neophytou, A. Tyliszczak, J. Kariuki, D. Cavaliere, E. Richardson, A. Triantafyllidis, A. Garmory

- Profs. R.S. Cant (Cambridge - DNS); A. Masri (PLIF – Sydney); N. Chakraborty (Newcastle – DNS); Prof. J.R. Dawson (Trondheim – exp)

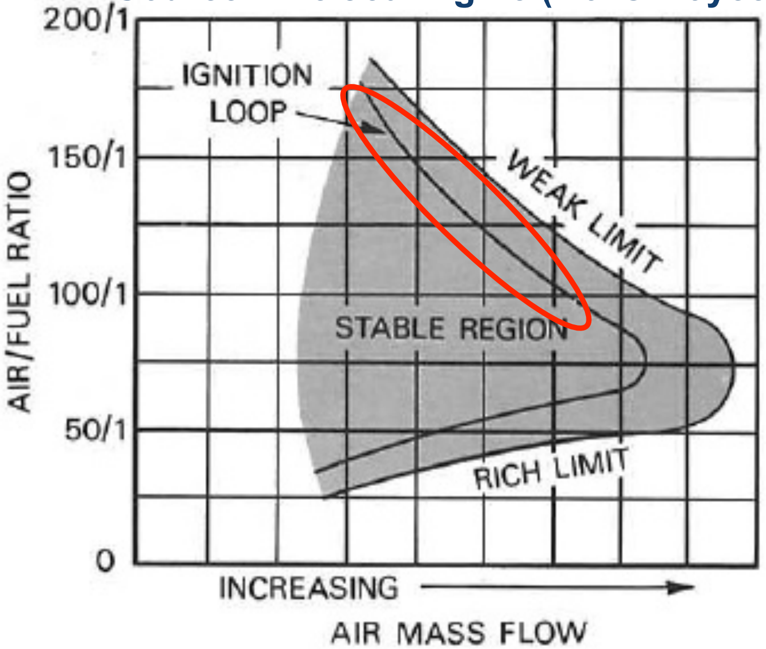
- Funding by EC (projects TIMECOP, TECC), EPSRC (studentships), Rolls-Royce Group

Outline

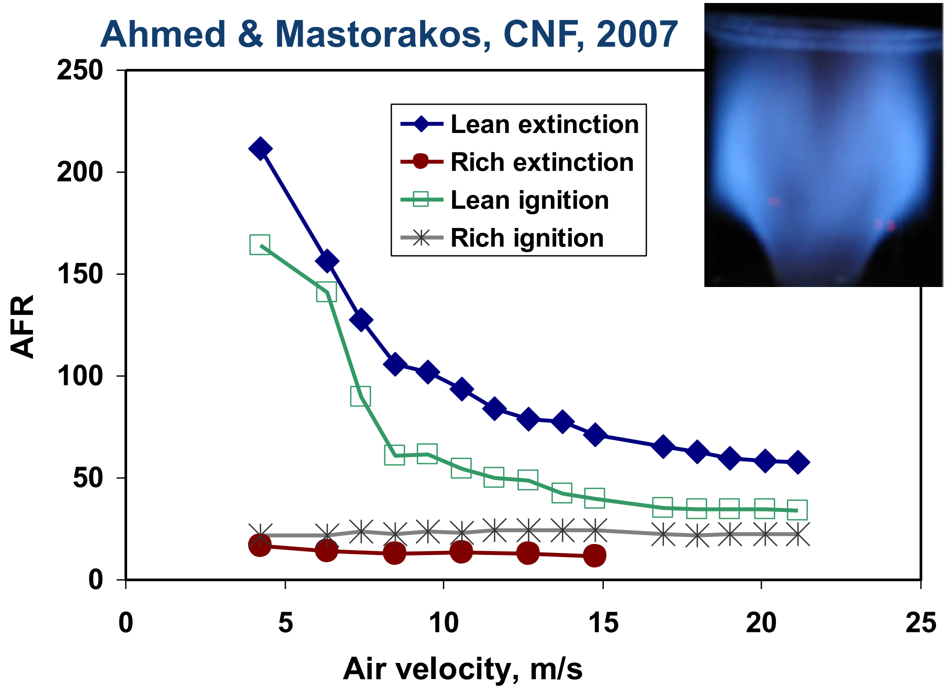
- Limits of operation of gas-turbine flames
- Some basics of spark ignition for non-premixed systems
- Experiments and simplified modelling to assist design
- Conclusions

The practical ignition/blow-off loop

Source: The Jet Engine (Rolls-Royce)



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 in gas turbines

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

Phase 2: kernel grows and flame spreads (S_T in sprays, flow); o(10) ms

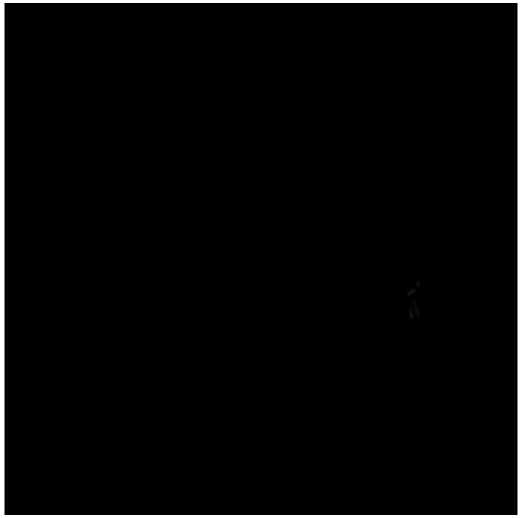
Phase 3: burner ignites (sometimes failure ⇔ global extinction); o(100) ms

Phase 4: burner-to-burner propagation (lightround); o(1000) ms

Turbulence, heat transfer, and multi-phase flow affect all the above (randomness, range of scales, dispersion, intra-droplet mixture)

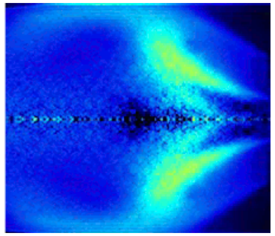
Phase 5: engine "pullaway" (power increases); o(10) s

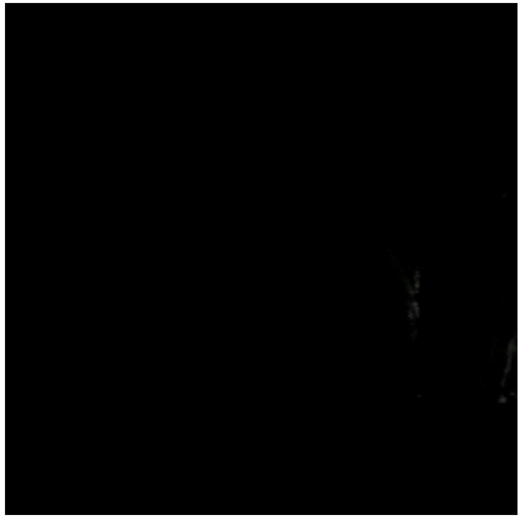
Spark ignition of Rolls-Royce combustor



FAILURE

OH*





SUCCESS

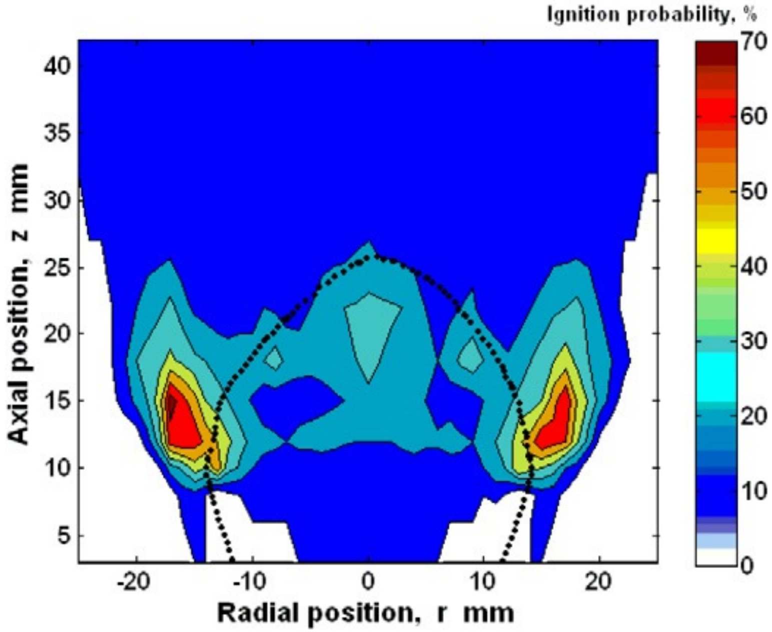
Ignition experiments at 0.4bar, 250K (Read, Rogerson, Hochgreb, AIAA J, 2011; Mosbach et al., ASME, 2011):

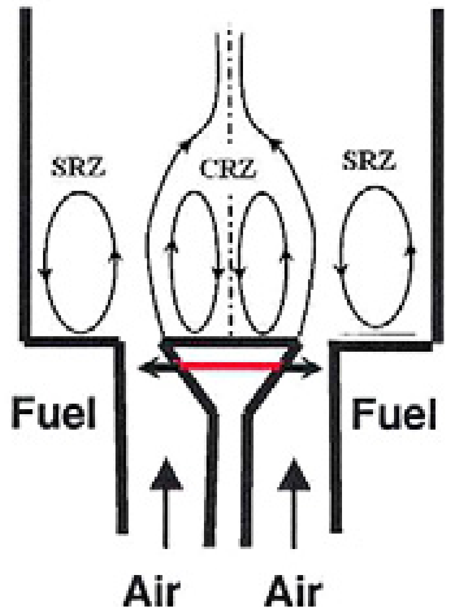
- Variability: not each spark is successful
- Success: tends to be associated with RZ ignition
- Is “Phase 1” always OK due to the high spark energy?

Movies courtesy of S. Hochgreb

Spark ignition of non-premixed bluff-body flame: ignition probability & flammability factor

Ignition probability

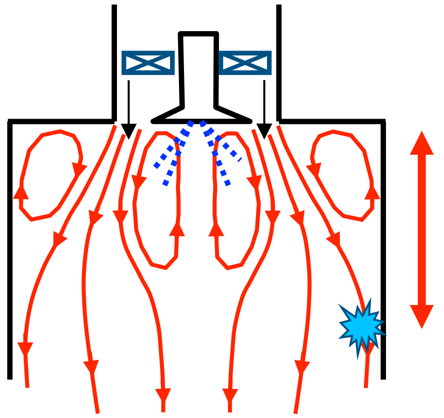


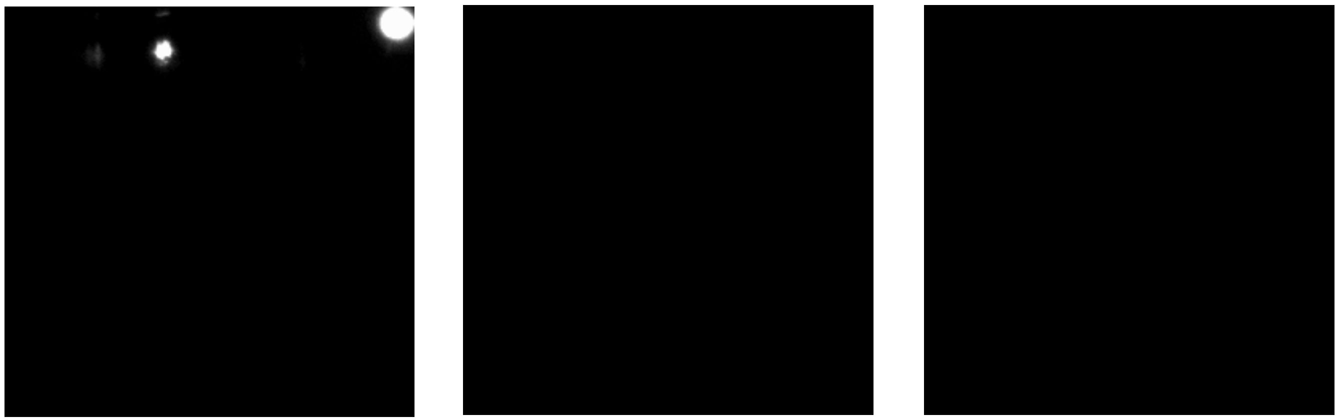


$$\text{Result}: \ F = \int_{\xi_{lean}}^{\xi_{rich}} P(\eta) d\eta \neq P_{\text{ker}} \neq P_{\text{ign}}$$

Ahmed et al., CNF, 151 (2007) 366–385

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

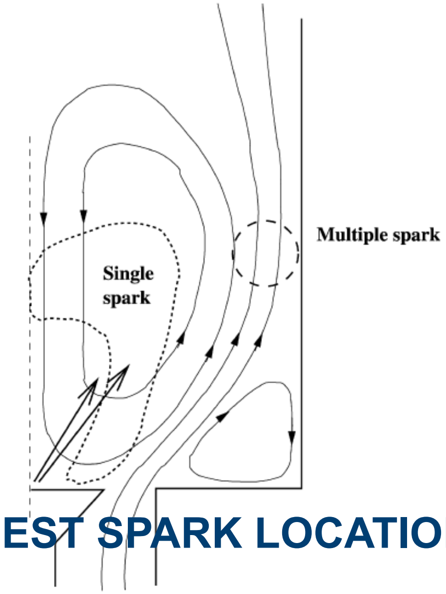




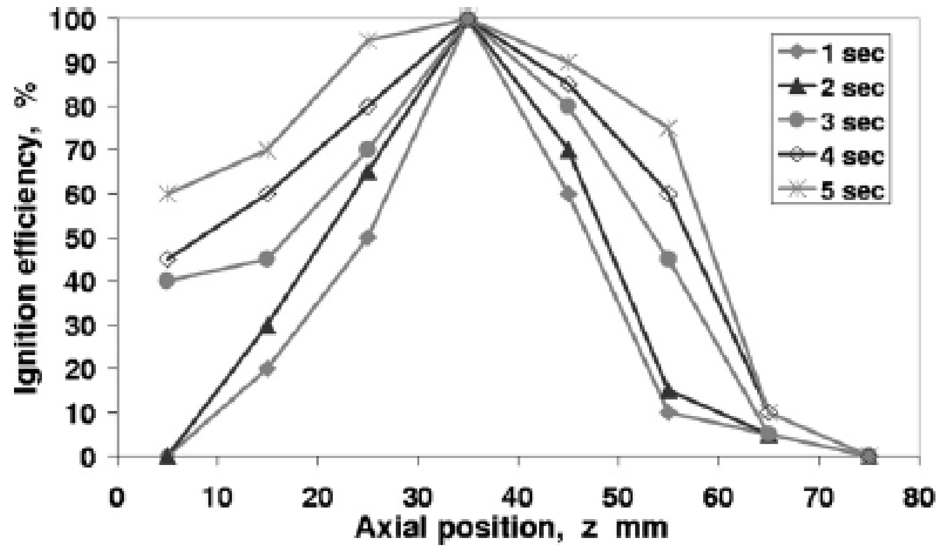
5 mm

15 mm

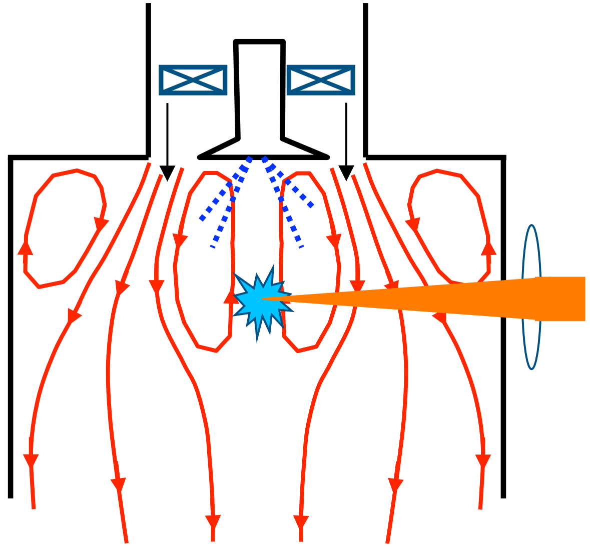
35 mm

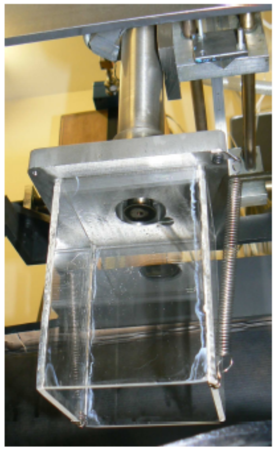


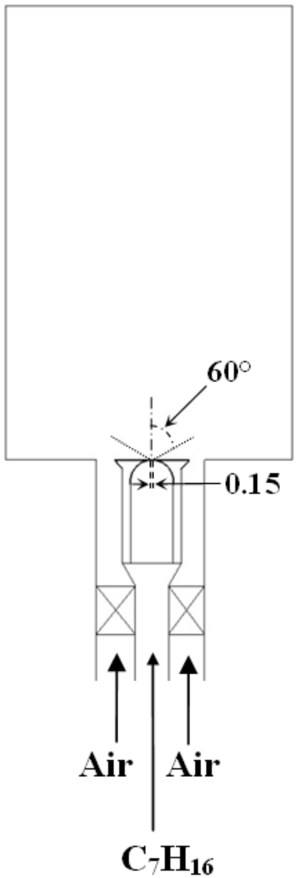
BEST SPARK LOCATION



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

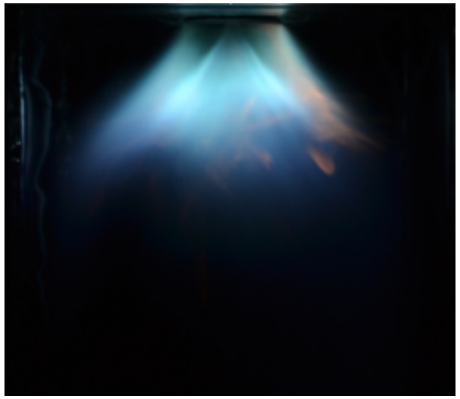






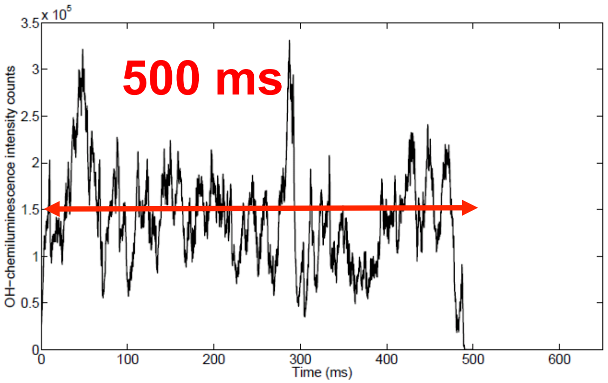
- Square section: 95mm x 95mm x 150mm
- Ignition by laser (Nd:YAG laser at 1064 nm (dichroic mirrors to purify I), f=10Hz, fl=150 mm converging lens, E ∈[40;370] mJ/pulse.
- Heptane fuel, ambient conditions

Types of spark failure: spray flame, close to blow-off point (Letty et al, ETFS 2012)

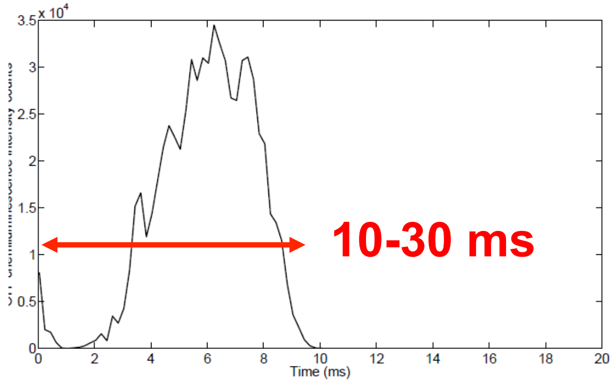


5kHZ OH*

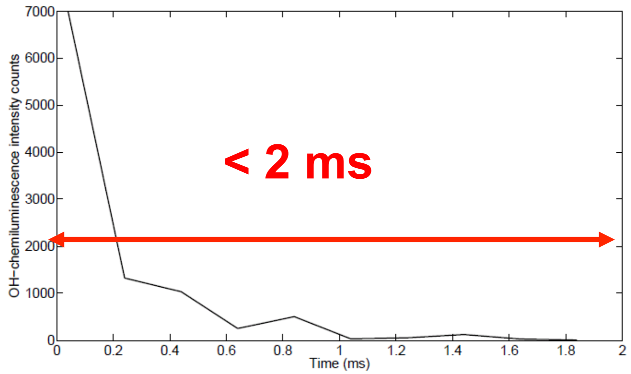
Intermediate failure



Long **failure mode (Phase 3)**

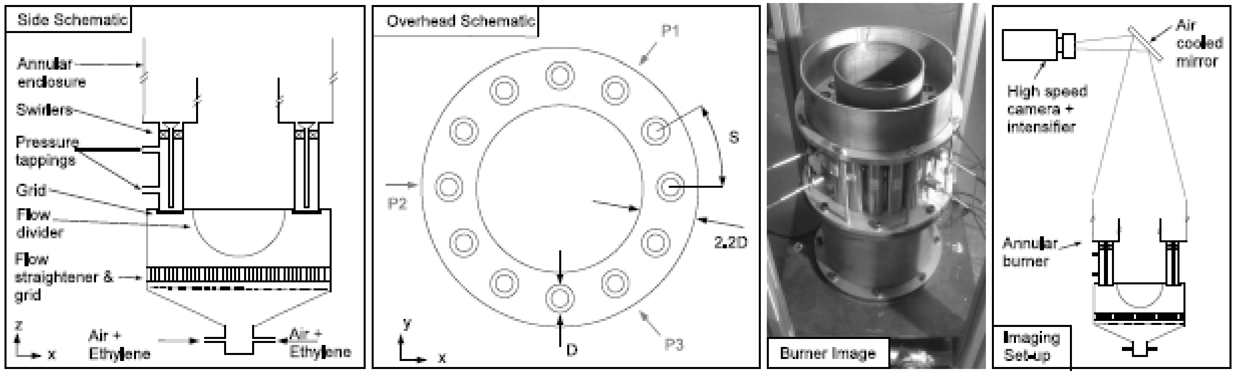


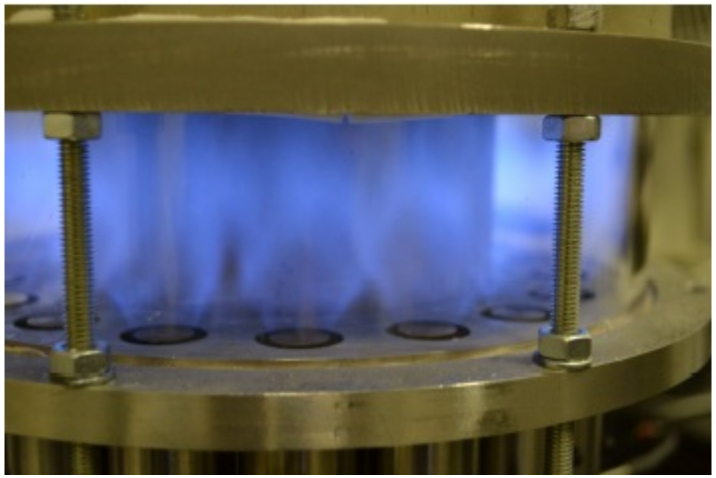
Intermediate **mode (Phase 2/3)**

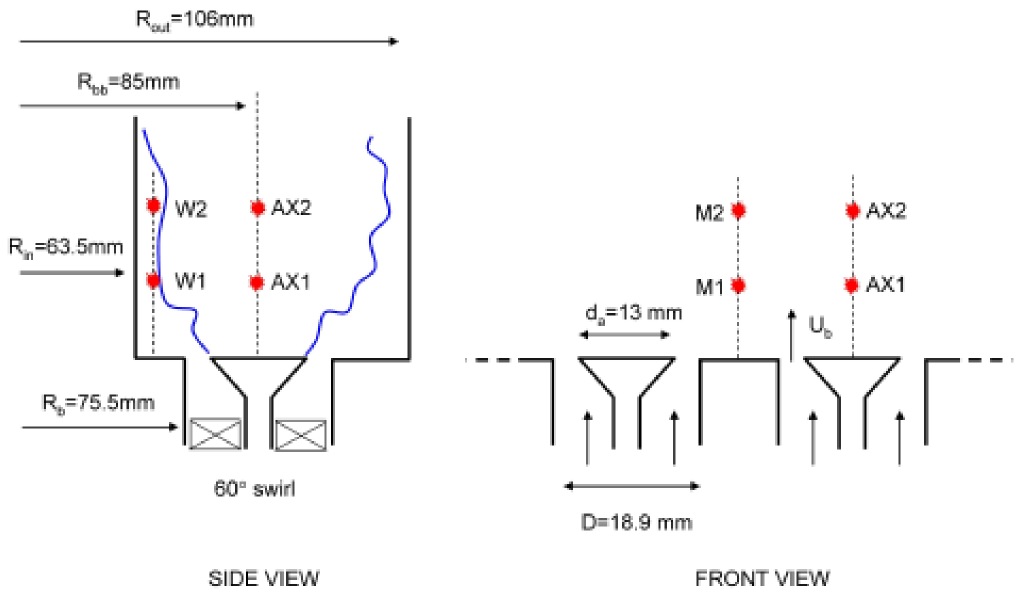


Short **failure mode (Phase 1)**

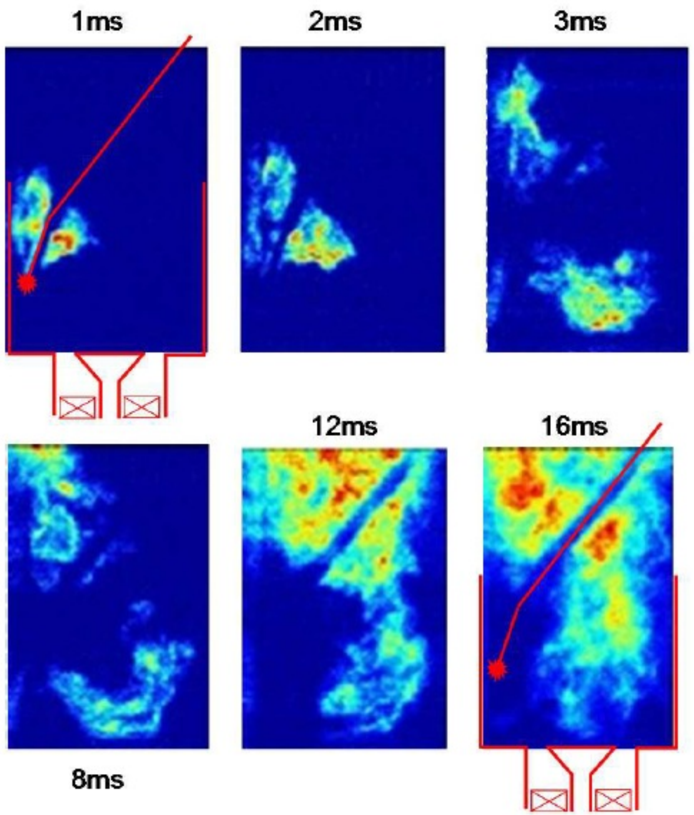
Phase 4: spark ignition of annular premixed combustor (Bach et al., AIAA ASM, Jan 2013)

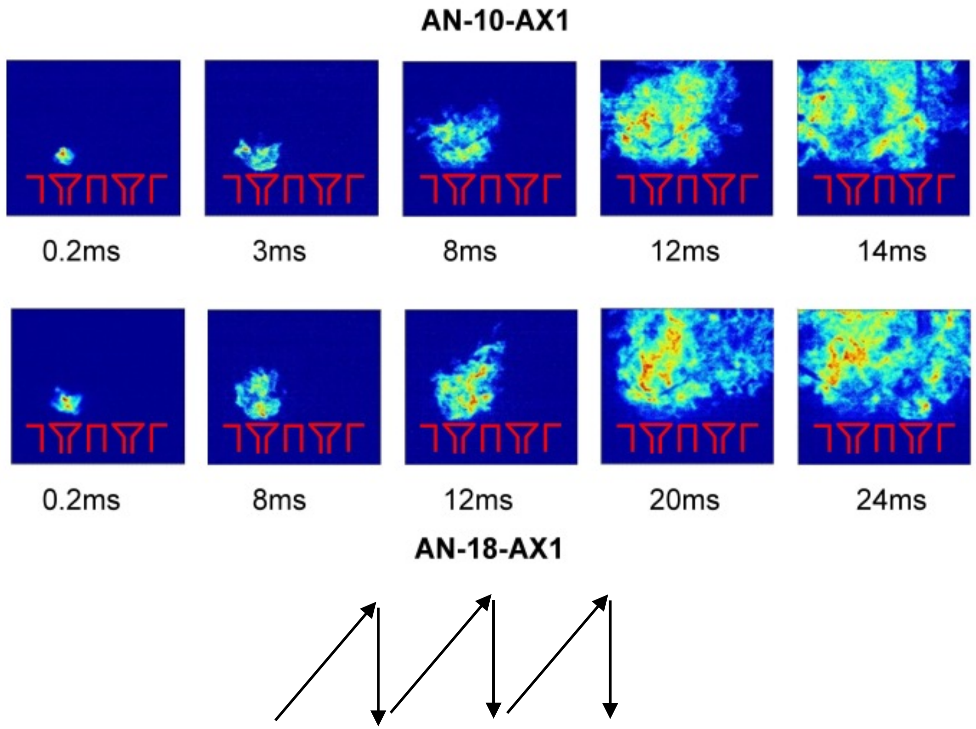






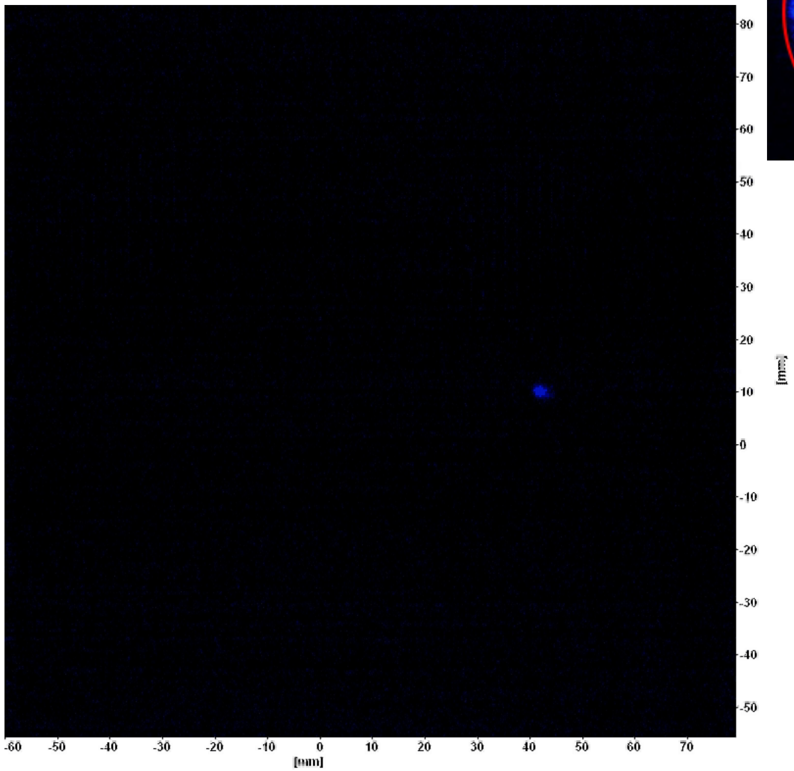
Spark ignition of annular combustor: burner-to-burner flame expansion

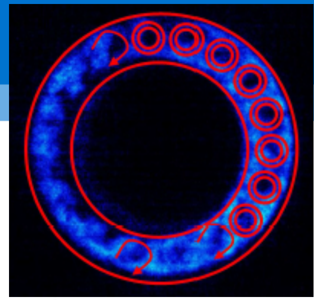


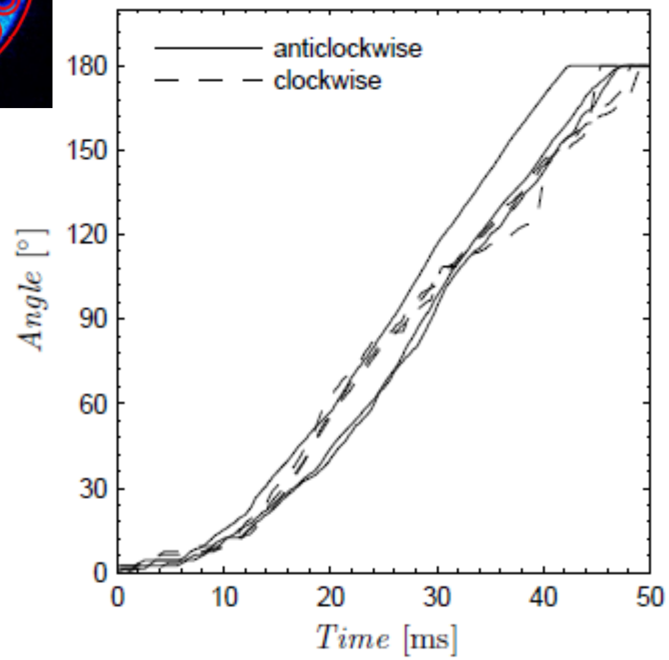


"Sawtooth" burner-to-burner propagation

Spark ignition of annular combustor: speed of lightround







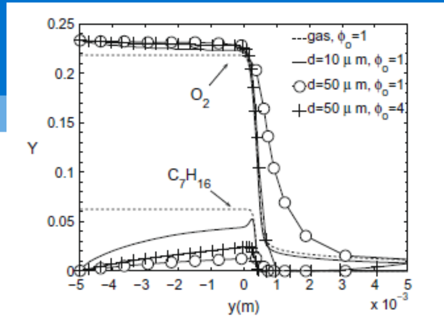
Top view, 5kHz OH*

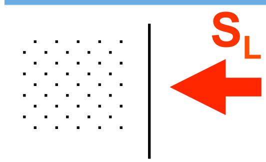
Speed of lightround: ~7 m/s

Similar experiment in Ecole Centrale de Paris (Candel, Durox et al., CNF, 2013)

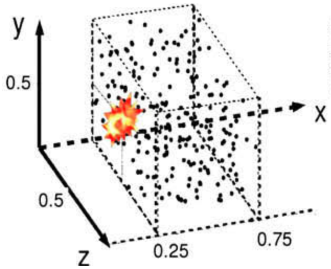
Simulation hierarchy

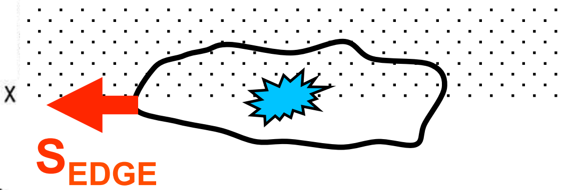
- Opposed-jet non-premixed spark, laminar flame speed in sprays



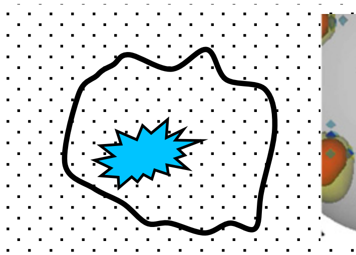


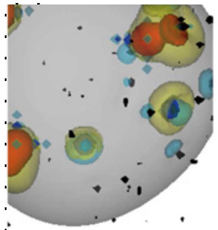
- Turbulent mixing layer (DNS)



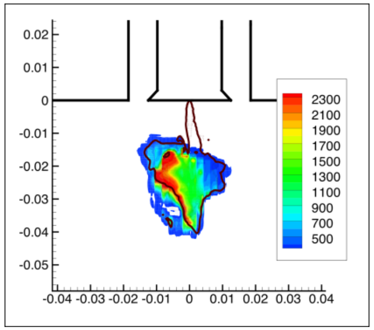


- Kernel in turbulent spray (DNS)

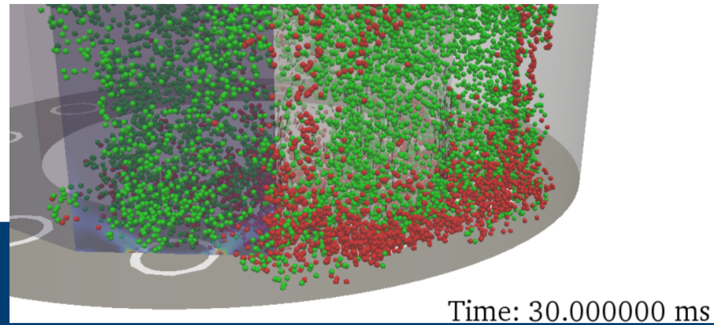




- LES/CMC of spark ignition

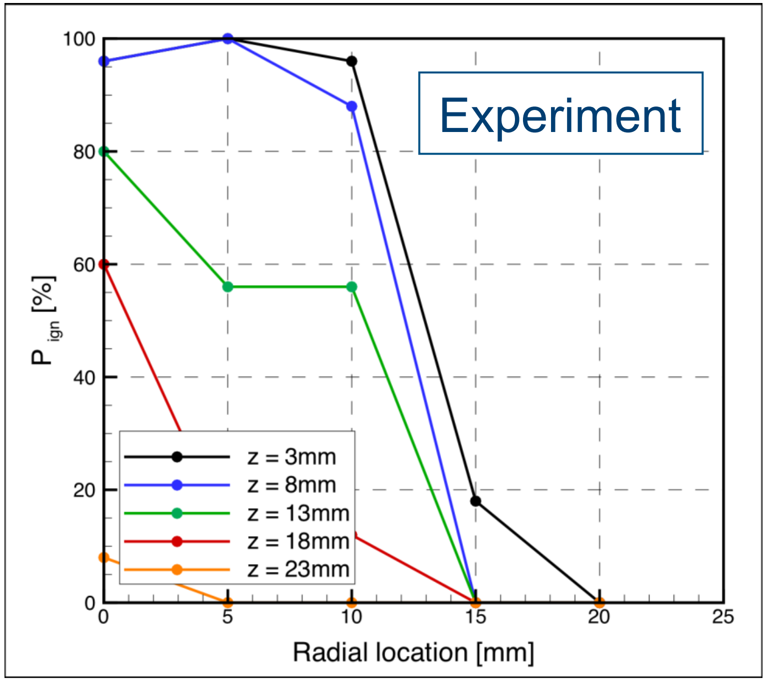


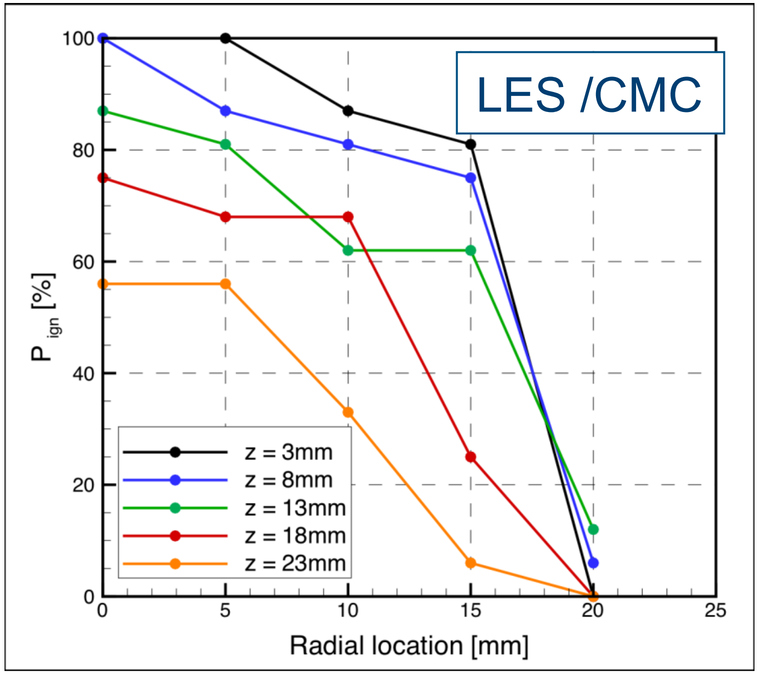
- SPINTHIR



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

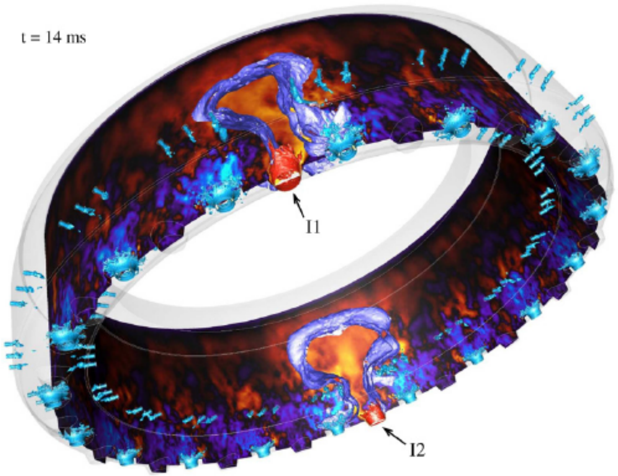
Probability of ignition shows reasonable agreement with experimental trend: Pign decreases as we go downstream and outwards in the radial direction. LES based on 16 simulations with spark at each of 20 points. But LES failure is mostly “Phase 1”.



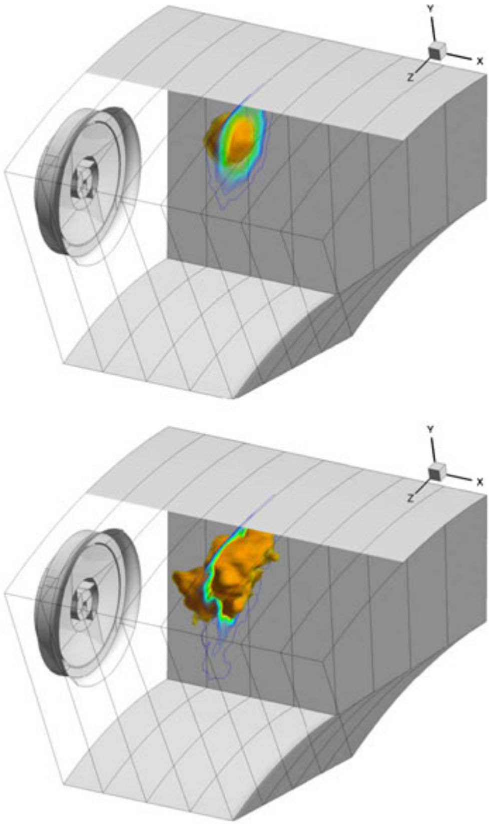


Work in many other labs

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



CERFACS



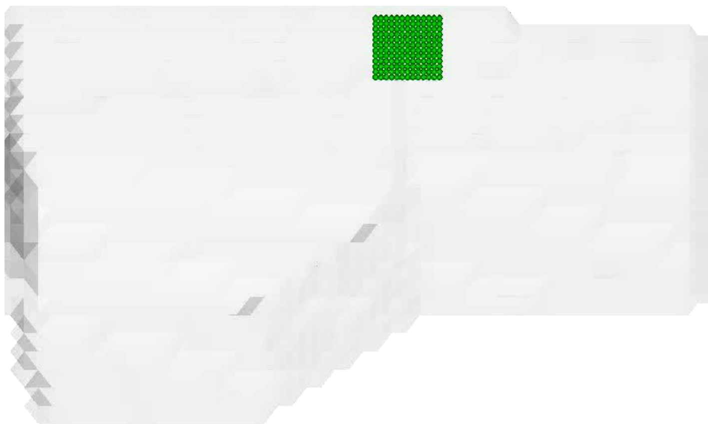
ICL/Chestochowa

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

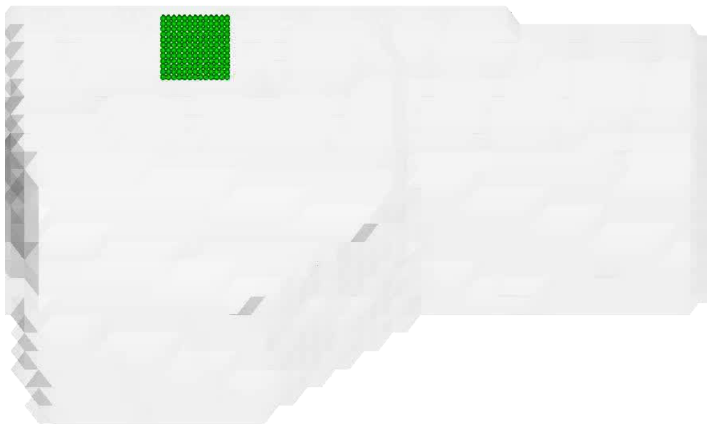
- Optimum design process: take decisions on ignitability early on
- New designs (lean, new fuels, mixing patterns) put "existing wisdom" and empirical correlations in question
- Our approach:
  - Distill fundamental knowledge from experiments, DNS & LES
  - Simple to use, quick
  - "Interrogate" a CFD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

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.



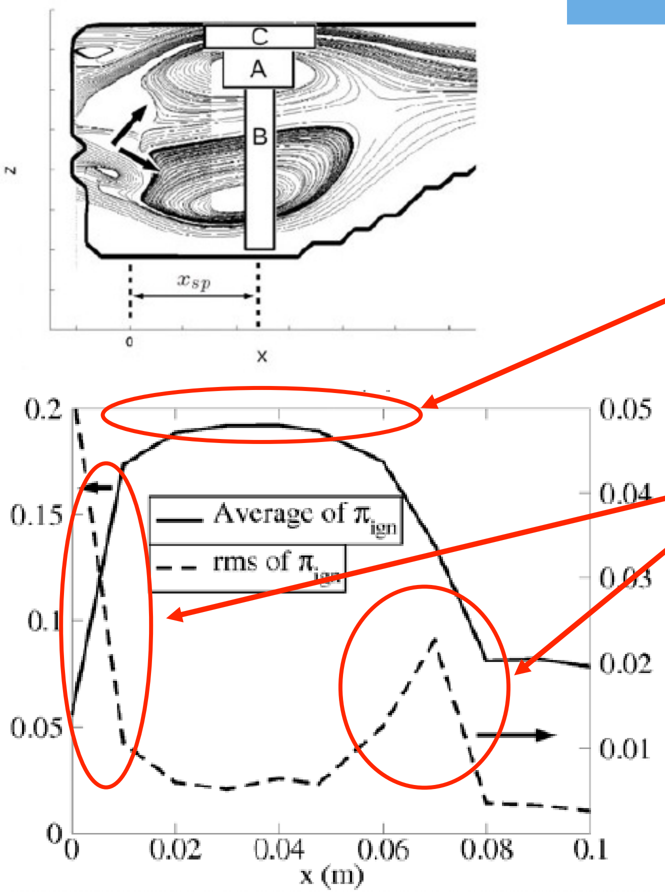
Bad spark location



Good spark location

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

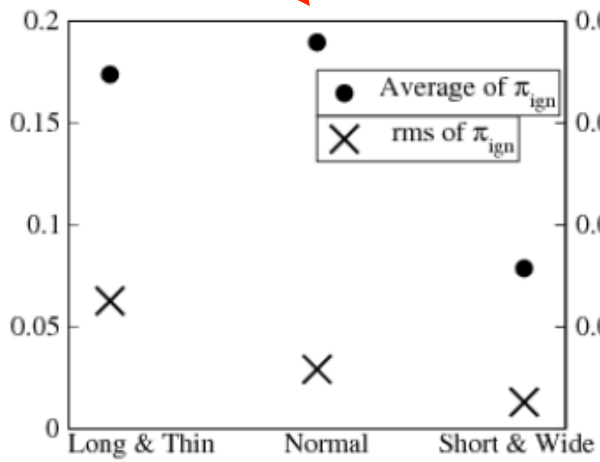
Spark variability and effect of shape and location



The best ignitor location – agrees with experience

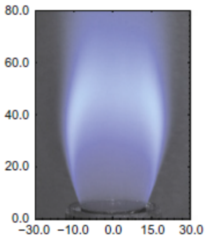
Large variability

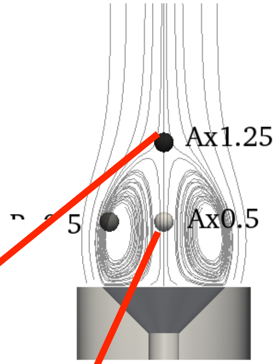
The best ignitor shape – agrees with experience

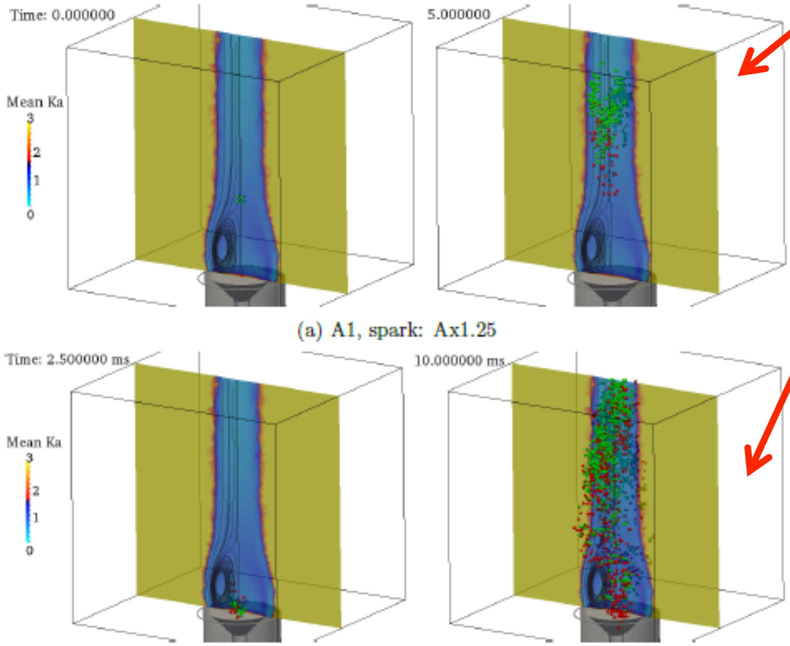


Statistics of π_{ign}: assist designer decide spark location and shape

Extension to premixed: single premixed burner (Sitte, MPhil thesis, 2013)



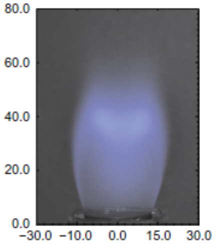


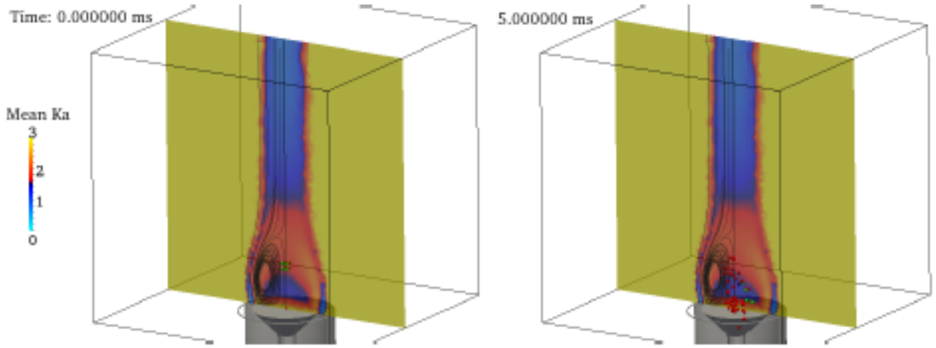


(a) A1, spark: Ax1.25

(b) A1, spark: Ax0.5

ϕ=0.75





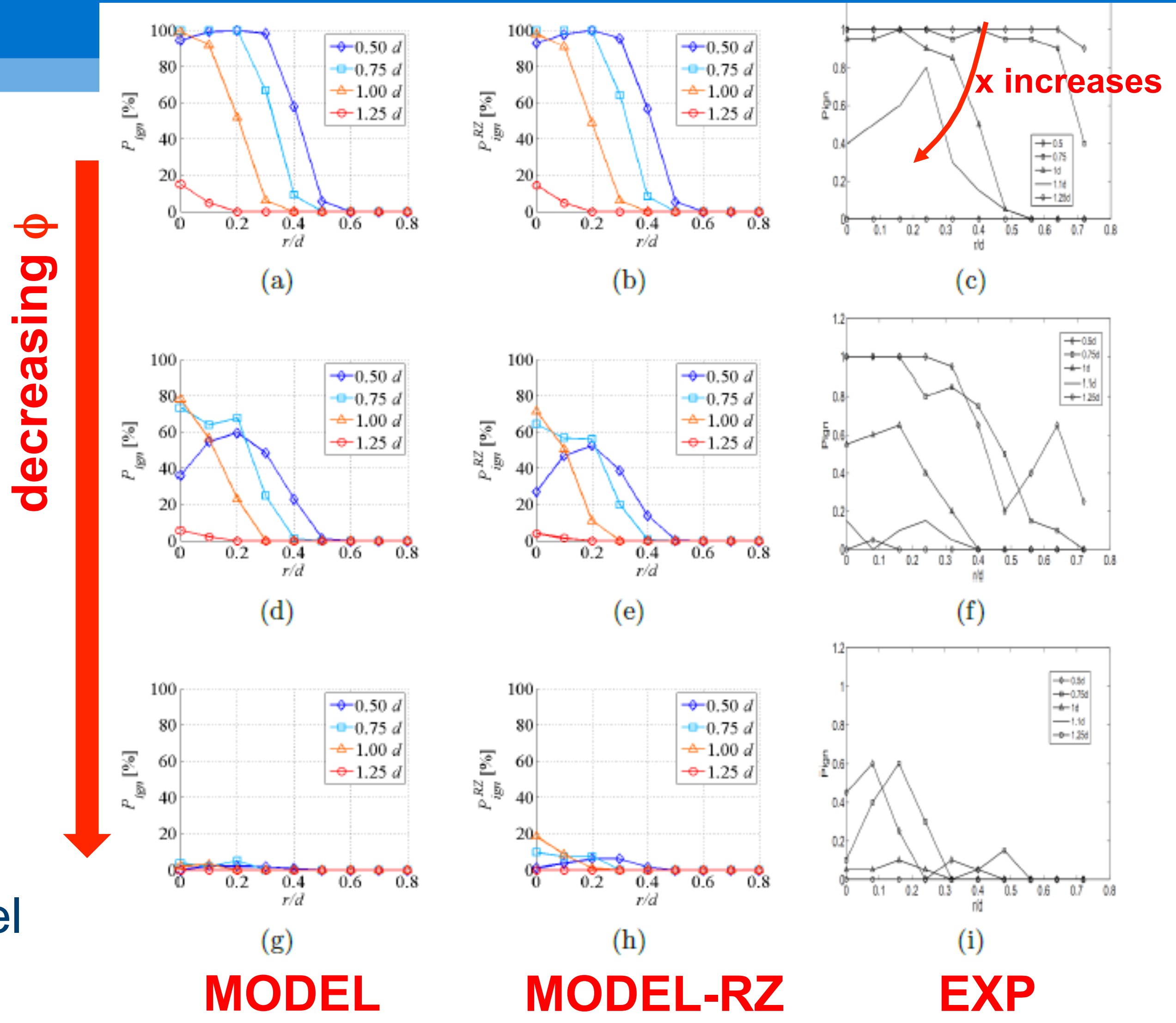
(c) A4, spark: Ax0.5

ϕ=0.68
Experiment shows no ignition

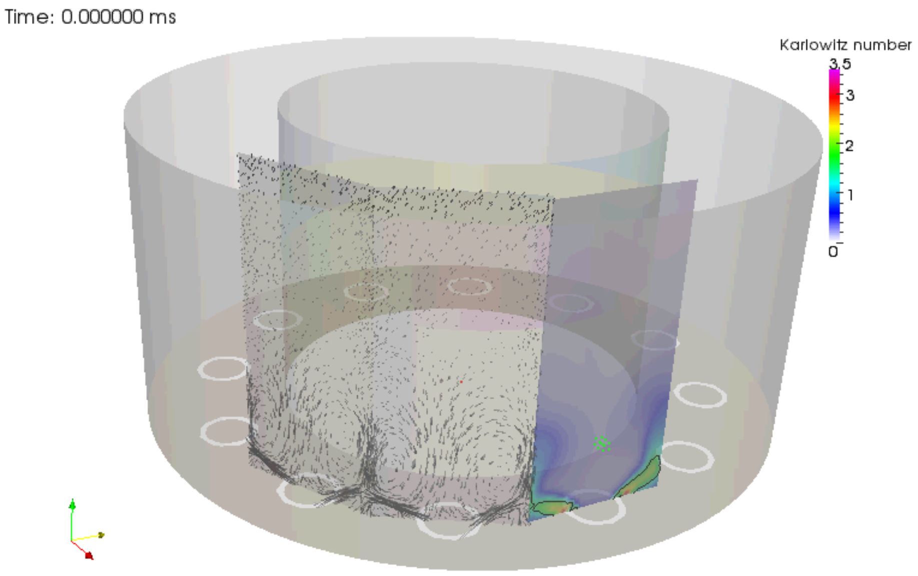
Single premixed burner: ignition probability

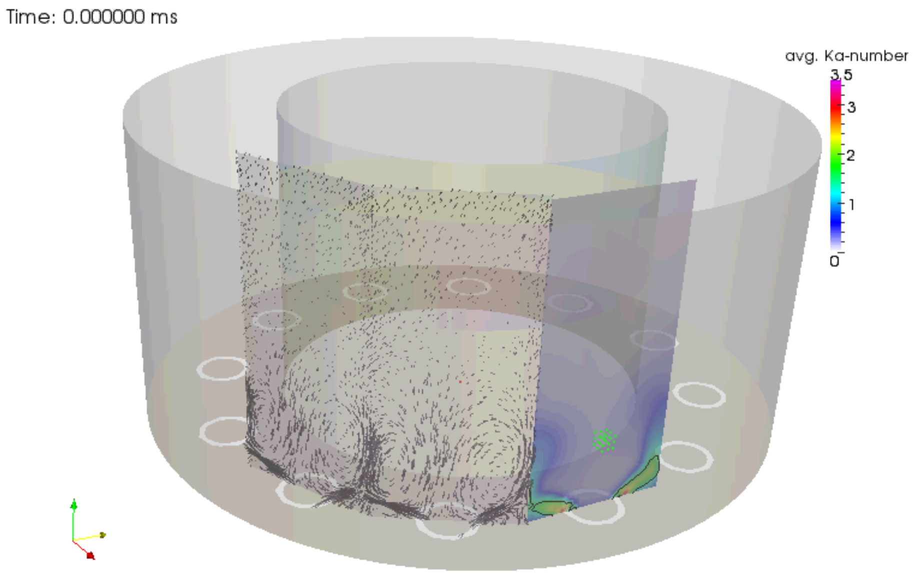
- Experimental trends reproduced

- Numerical agreement depends on some model inputs



SPINTHIR for annular combustor - lightround



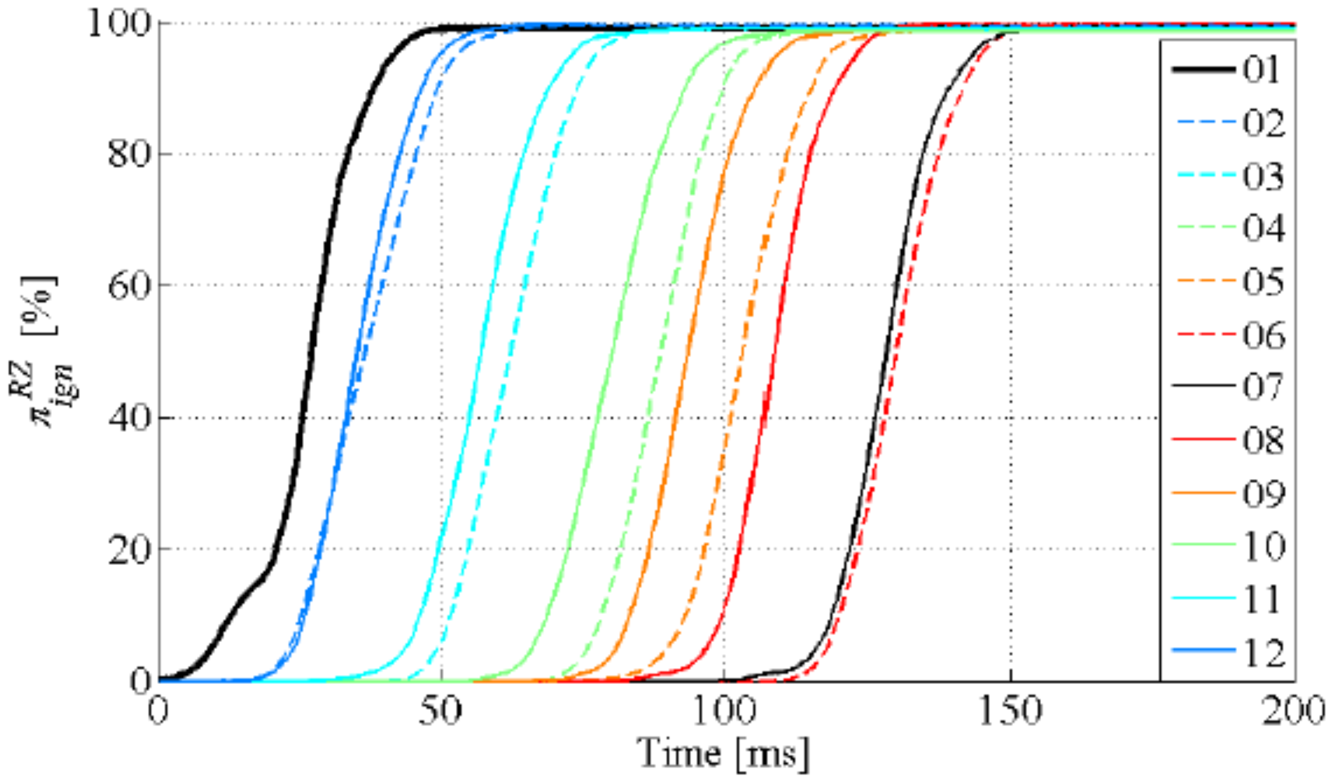


Good ignition, ϕ=0.70

Bad ignition, ϕ=0.55

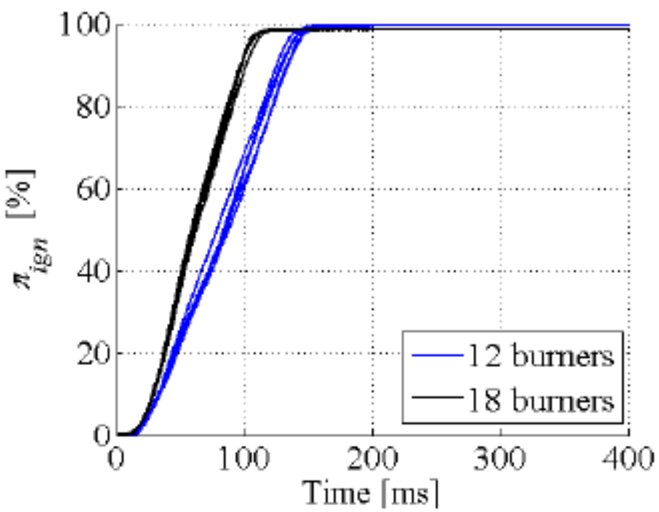
Sitte, MPhil thesis, 2013

Structure of lightround

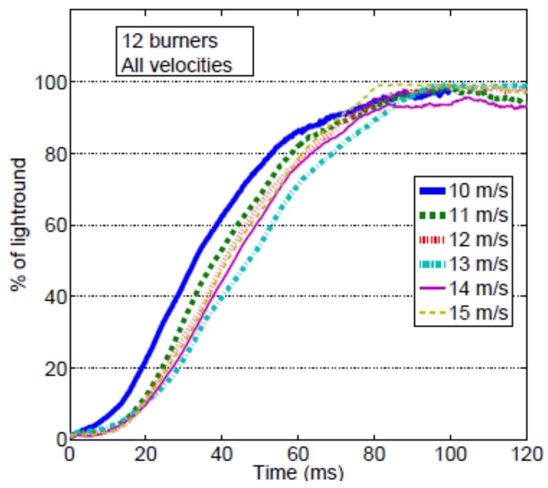


- Each burner's RZ needs to be ~50% ignited for neighbour to ignite
- Seems consistent with experiment, qualitatively

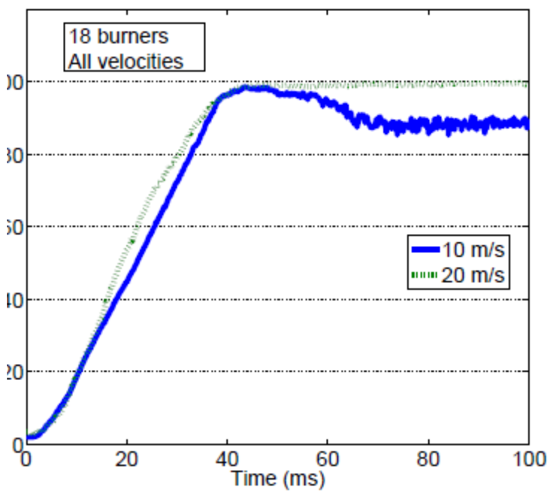
Speed of lightround



MODEL



EXPERIMENT-1
2 burners



EXPERIMENT-
18 burners

- Distance between burners increases lightround time
- Velocity has small effect (faster propagation balanced by quenching)

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. Annular rig used for lightround.

- Laminar and turbulent simulations (DNS) have been instrumental at identifying trends and flame speed.

- LES with a good combustion model like CMC can be used to predict individual ignition events.

- Simplified model (code SPINTHIR) has been developed and used by gas turbine designers. Trends consistent with experiment.

- Next steps: Turbulent flame speed in sprays; model refinements; spark plasma; fuel effects