EFC Topic 4.1
Measurements for Simulation benchmarking

Presented by Brian Peterson (TU Darmstadt)

Objectives of 4.1

Contents:

- Engine participants to EFC
- Summarize available data
- Scope and uniqueness of data
- EFC subtopics addressed by data

Contributions

1. **Transparent Combustion Chamber Engine,** **TCC (GM/UM)**
   David Reuss, dreuss@umich.edu

2. **Spark-Ignited Direct-Injection Engine,** **SIDI (TU Darmstadt)**
   Brian Peterson, peterson@csi.tu-darmstadt.de

3. **SGEmac Experimental Database,** **SGEmac (IFP)**
   Cecile Pera, cecile.pera@ifpen.fr

4. **Sandia H_2 Direct-Injection Engine,** **H2ICE (SNL/U DuE)**
   S. Kaiser, sebastian.kaiser@uni-due.de

1. TCC (GM/UM)

TCC Engine Measurements and LES Working Group

Simulations:

Tang-Wei Kuo, Xiaofeng Yang, General Motors Company, Sponsor

Chris Rutland, University of Wisconsin

Daniel Haworth , Pennsylvania State University

Measurements:

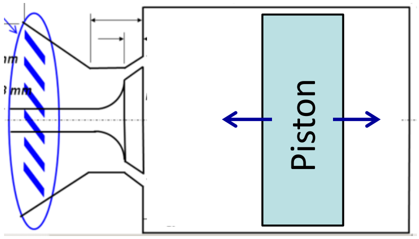
Volker Sick, Dave Reuss, University of Michigan

Scope:

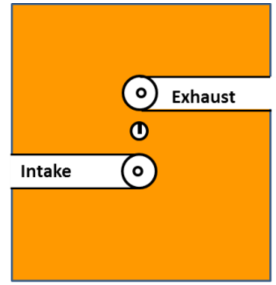
- Provide accurate and repeatable data base for RANS and LES model validation.
- Identify sources and mitigate CCV.

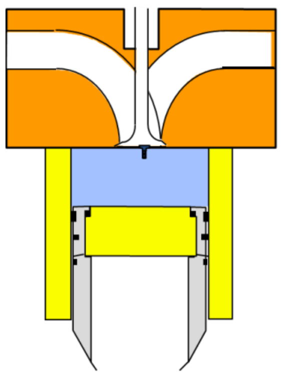
Imperial College, 1978

Morse, Whitelaw, Yianneskis

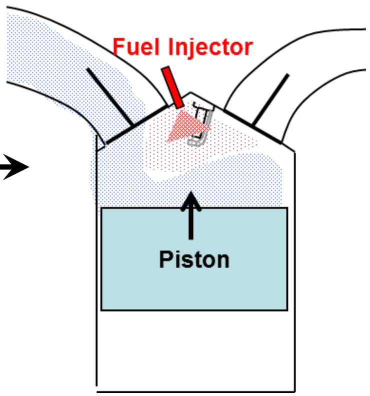


GM TCC-0, 1990





Modern 4-V Pent Roof



<u>Design Intent</u>:

- Transition from Imperial College analogue for simulation benchmarking circa 1990.
- Platform for fundamental, empirical studies of CCV.
- Simulation Grid Friendly
  - Geometrically simple
  - Efficient multi-cycle simulation*
- Optically accessible for measurements.

- Features to exaggerate fluid mechanics
  - “Pancake” chamber & Undirected port → high CCV
  - Small D_{valve}/D_{bore} → high shear @ low rpm

* Haworth, OGST, 1999

History of experimental installations

TCC - 0 GM R&D, 1995 – 2002 publications

- GM Intake and Exhaust systems, single-angle valve seat
- PIV, RANS, LES development in reciprocating ICE
- Motored and fired data

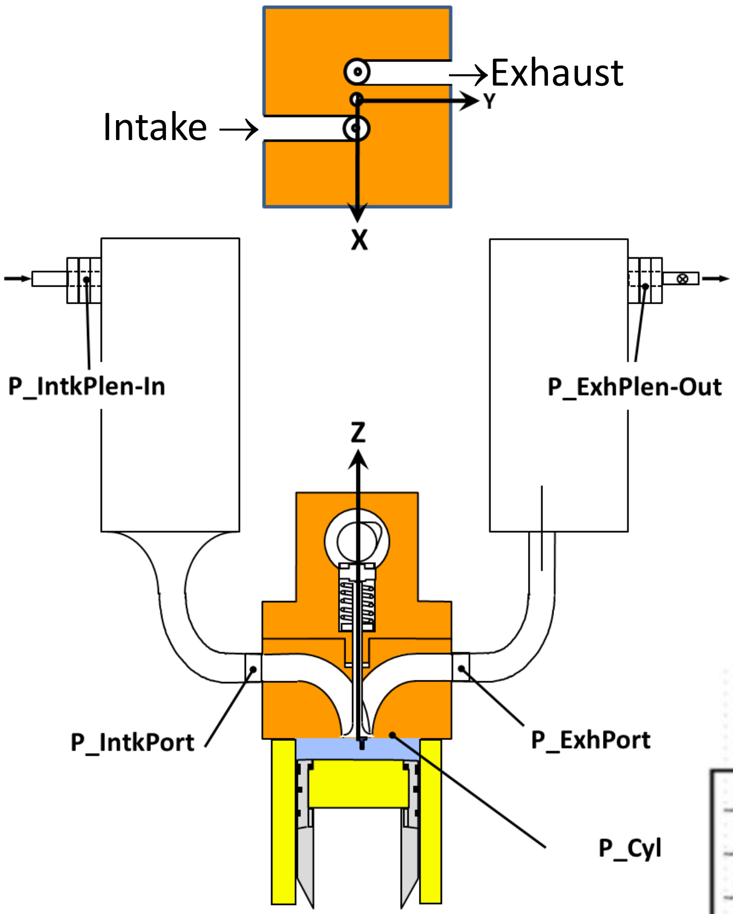
TCC – II University of Michigan, 2010 – 2014 publications & posted data

- UM intake and exhaust systems
- Full quartz cylinder, improved piston ring, two-angle valve seats
- Motored data

TCC – III University of Michigan 2013 -

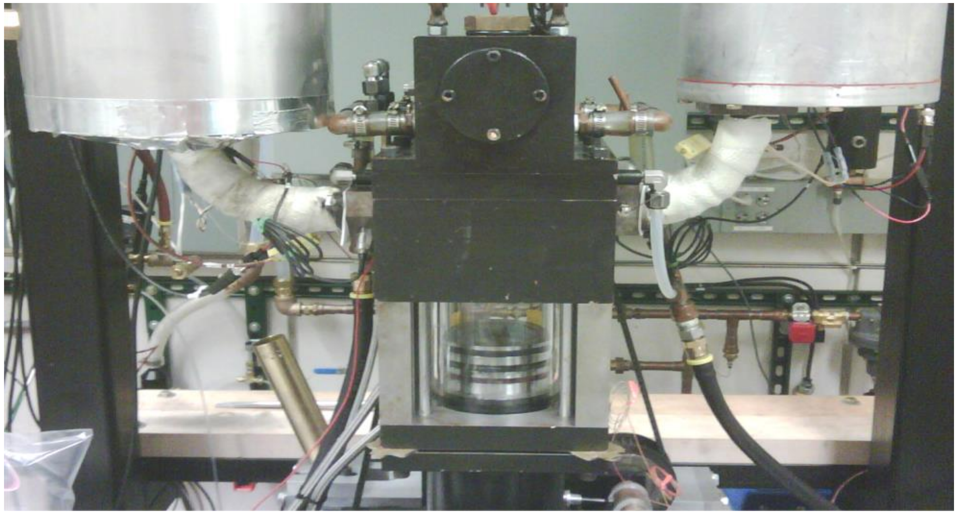
- Added: fuel (C_3H_8), N_2 dilution, flame arrestors $\rightarrow$ new GT Power model
- Refurbish valve train, (four-angle seats)
- Motored and fired data

TCC-II



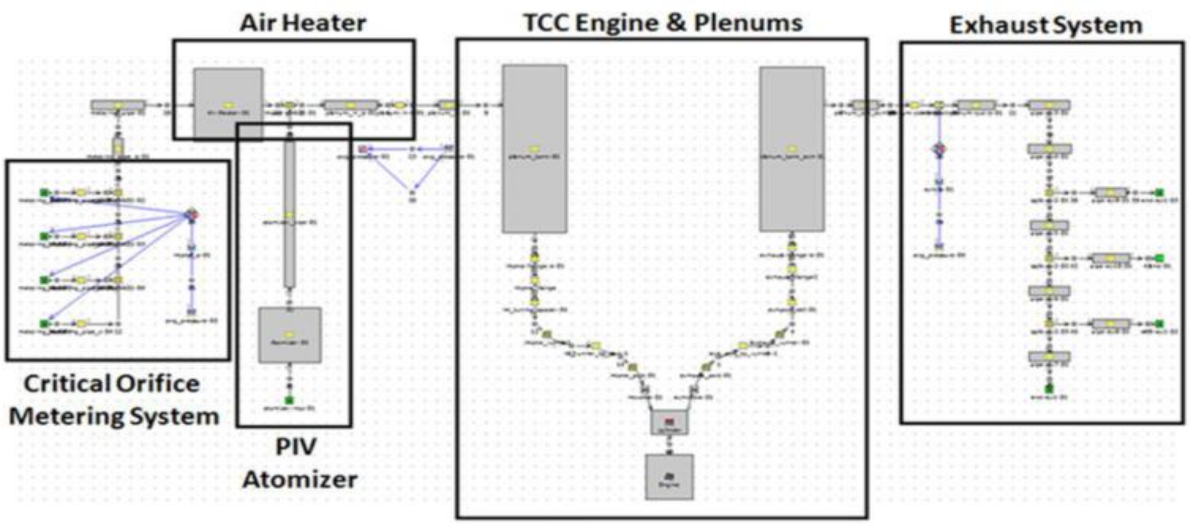
5 Measured Pressures

92mm x 86mm BxS, 10:1 CR



"Closed" & heated intake-air metering system

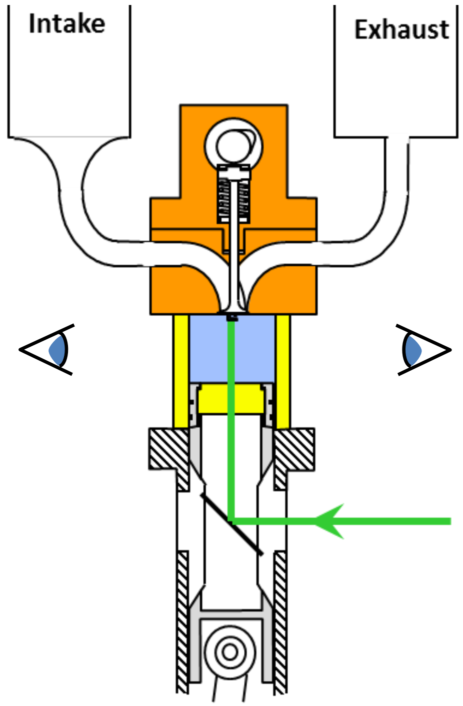
GT Power model available



TCC-II Engine Conditions for PIV Acquisition

Engine Operation

- Motored at 400, 800 & 1600 rpm
- each 5 ca deg, 70 continuous cycles
- 3000 cycles at 100 & 300 ca aTDCexh
- 2 and 3 component PIV measurements



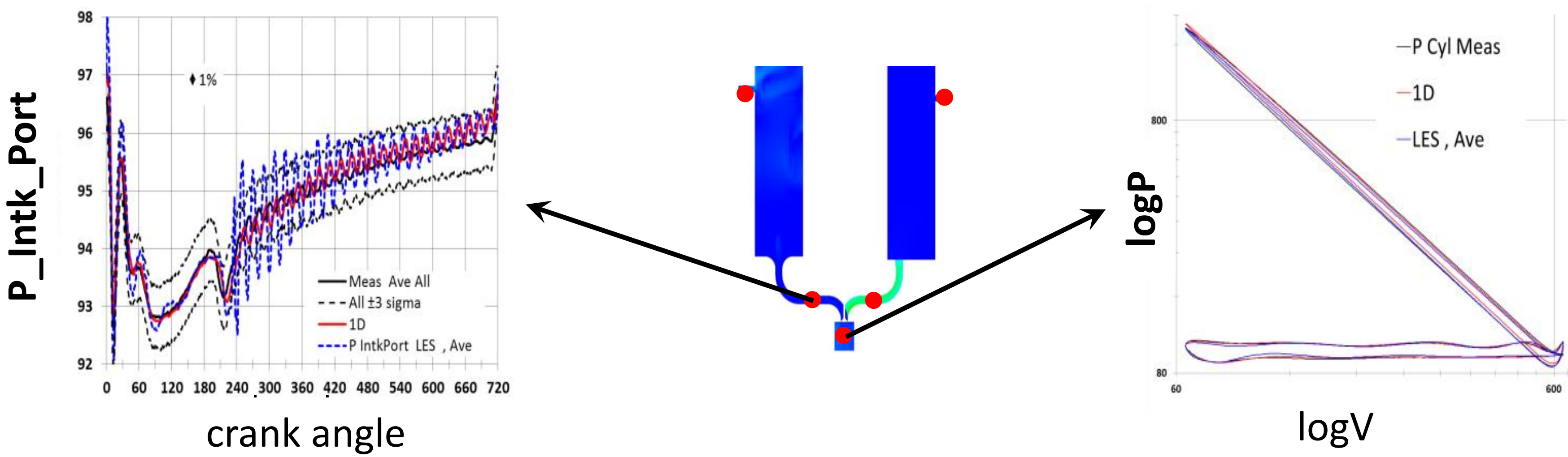
- 1.6 & 2.9 mm resolution, recorded simultaneously

Data Integrity

- Dynamic measurement of Instrumentation timing:
  - encoder–piston TDC timing
  - valve lift & open/close ramps.
- Optical-engine compression-ring design → blowby < 1% at 95 kPa
- Pressure & Velocity Measurement range, noise, & uncertainty documented.
- Test-to-test engine operation repeatability
  - Operation protocols
  - Redundant transducers & daily calibration
  - Operation control-charting & post-test evaluation

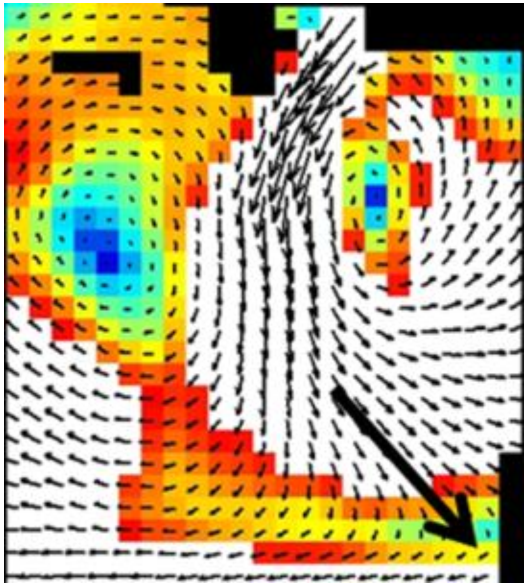
Data Integrity (continued)

- Extensive intake, exhaust, and cylinder-pressure comparative analysis

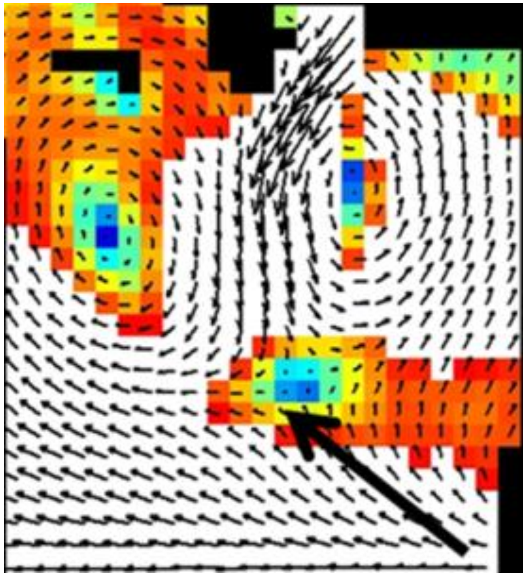


Data and Analysis Focus

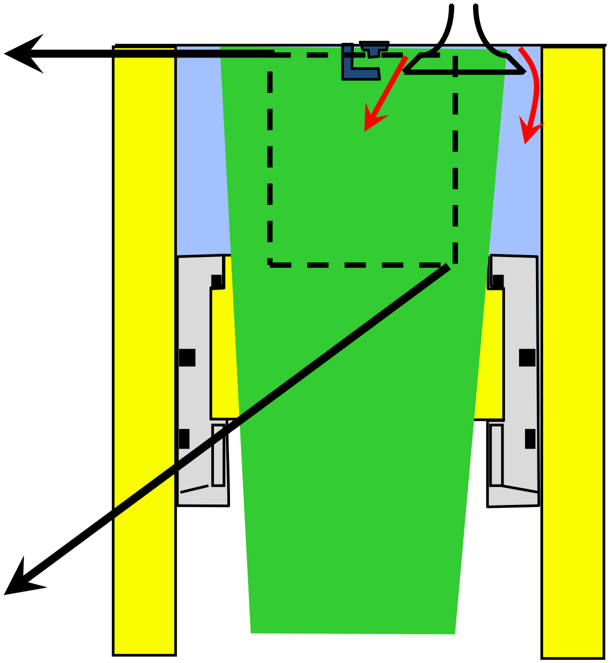
Intake Jet, 100 CAD aTDC$_{exhaust}$



Test 1
(70 cycle average)



Test 2
(70 cycle average)



Undirected TCC Intake Flow Exhibits:

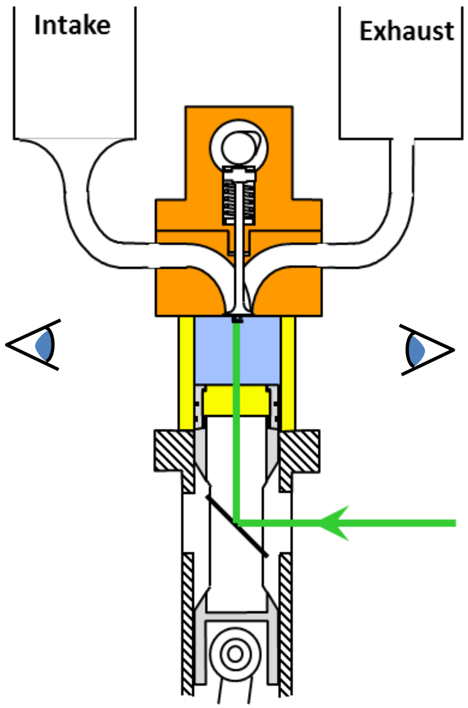
- Large CCV of intake jet
- CCV yields averaging-sample dependency

Details in Topic 4.4

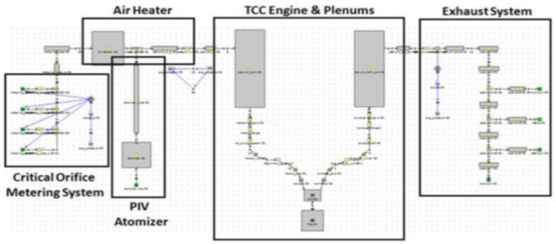
Posted Data*, TCC-II

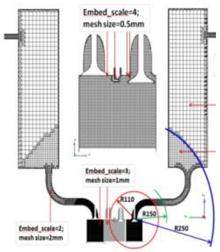
- Test averages and StdDev
- Per-cycle parameter averages & StdDev: measured values, cycle-integrated parameters
- Per-crankangle measurements: in-cylinder , runners, & plenum pressures; rpm

- Velocity: - 2-component velocity, 2-D grid
  - PIV measurement plane through valve centers
  - 1.6 & 2.9 mm resolution, simultaneously
  - each 5 ca deg, 70 continuous cycles



- Geometry: GT Power model, geometry (.STL)

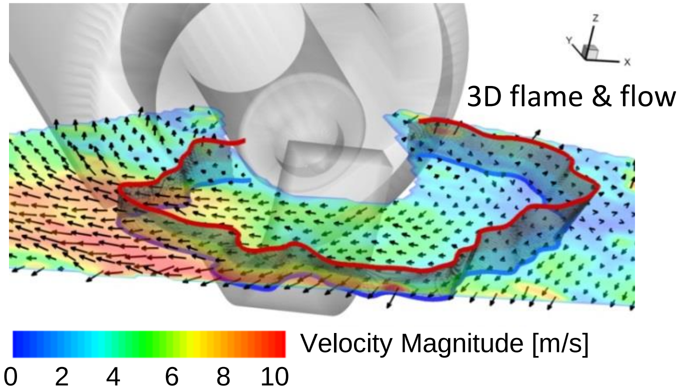




* ECN: http://www.sandia.gov/ecn/engines/engineFlows/TCCEngine.php
Data located on UM server. Contact Volker Sick: vsick@umich.edu

2. SIDI (TU Darmstadt)

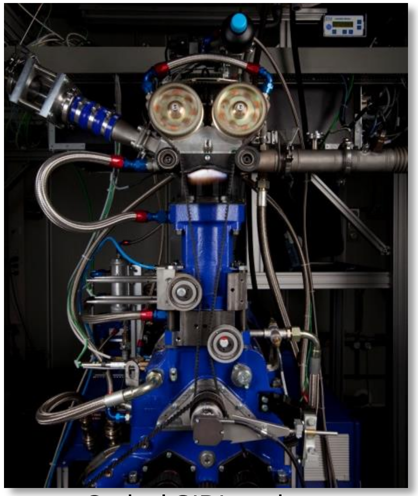
TU Darmstadt Measurement-Simulation Efforts

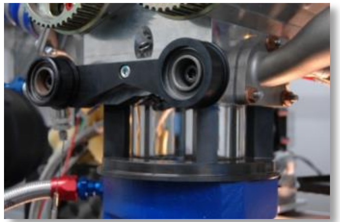


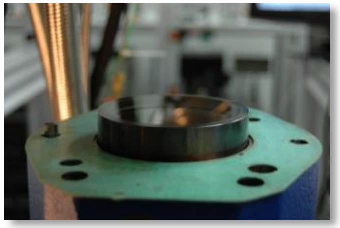
- Scope of Investigations
  - Sub-processes of turbulent-combustion in engines
  - Provide established database for model validation
- Experiment Group
  - TU Darmstadt (A. Dreizler)
  - Data availale upon request:
    - Brian Peterson (peterson@csi.tu-darmstadt.de), Benjamin Böhm (bboehm@ekt.tu-darmstadt.de)
- Modeling Groups
  - TU Darmstadt (J. Janicka, S. Jarkirlic)
  - TU Freiberg (C. Hasse)
  - U. Duisburg-Essen (A. Kempf)
  - RWTH Aachen (H. Pitsch)
  - Cambridge (N. Swaminathan)

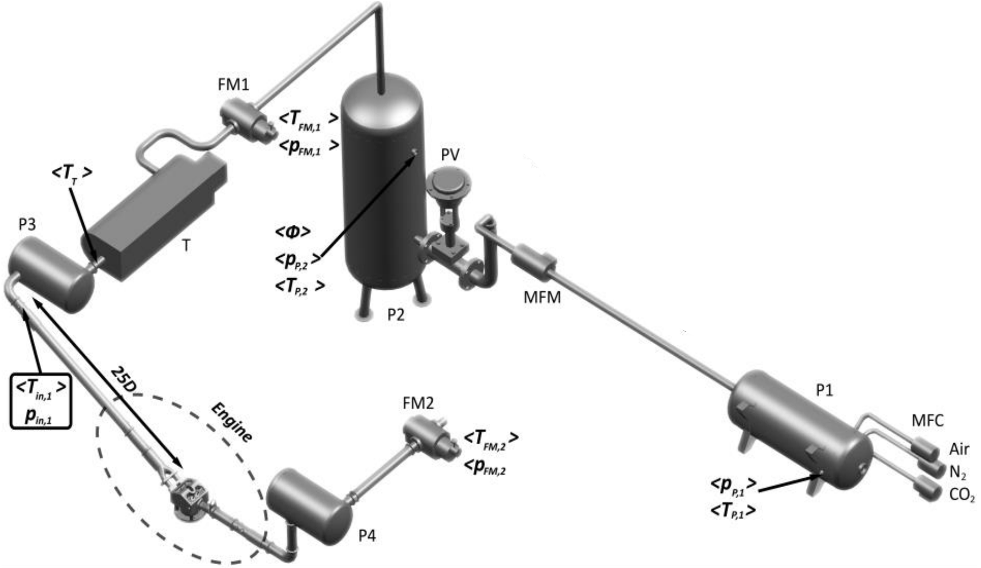
TU Darmstadt Optical Engine

- Single-cylinder SIDI engine
  - 4-valve, pentroof head
  - Bore, Stroke: 86 mm
- Designed for model validation
- Engine Test Bench
  - Well-characterized BCs
    - Flow, T, P, rel. humidity, EGR, fuel (DI, PFI), λ, spark (V,I)
  - Repeatable, reliable operation and BCs


Optical SIDI engine


Quartz glass cylinder


Quartz glass piston



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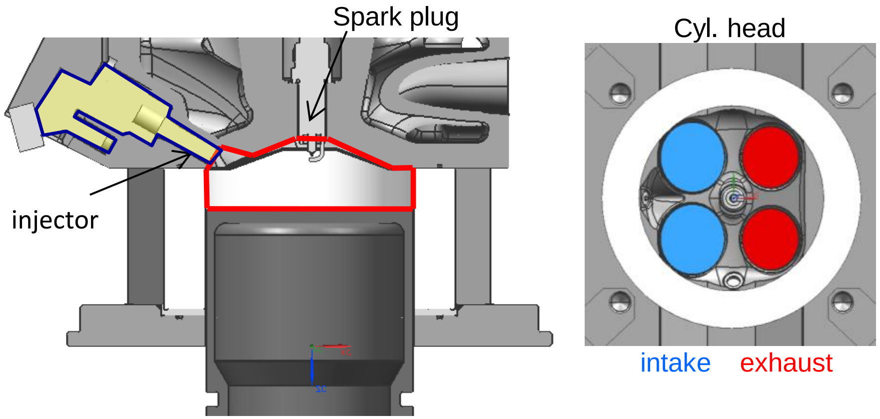
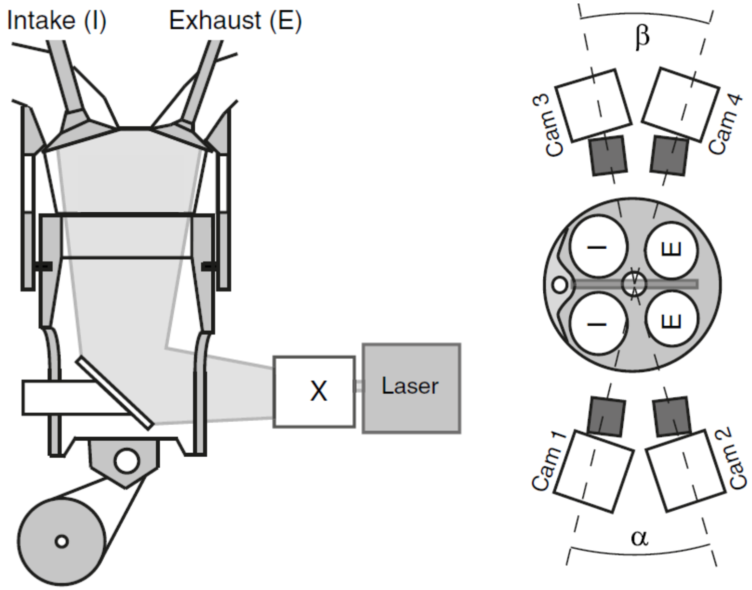
Optical Engine: Available Cylinder Heads

Wall-guided

- Side mounted injector
- Valves
  - Intake: 33 mm dia.
  - Exhaust: 31 mm dia.
- Clearance Volume: 66.5 cm^3
- CR: 8.5



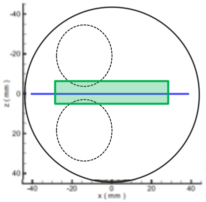
Experimental Setup: Example

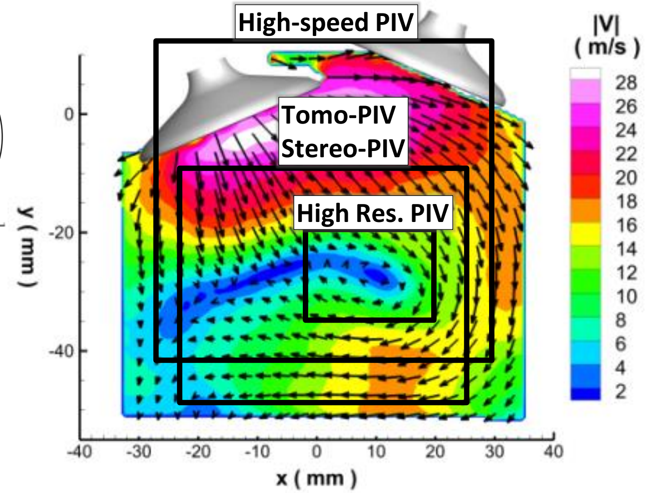


1) Baum et al.: *Flow Turbulence Combust* (2014) 92: 269-297
2) Baumann et al. *Flow Turbulence Combust* (2014) 92: 299-317
3) Peterson et al.: *Appl. Phys B* (2014) *DOI: 10.1007/s00340-014-5815-0*
4) Peterson et al.: *Proc. Combust. Inst.* (under review 2014)
5) Freundenhammer et al. *Exp. Fluids* (2014) DOI:
6) Baum et al.: *Proc. Combust. Inst.* 34, 2903-2910 (2013)
7) Peterson et al.: *Proc. Combust. Inst.* 34, 3653-3660 (2013)
8) Peterson et al. *11th Int. Congress Engine Combust. Processes,* Ludwigsburg (2013)
9) Baum et al. *16th Int. Symp. Laser Techniques to Fluid Mechanics,* Lisbon (2012)

Non-Reacting Flow

- Fundamentals of engine flows
  - Multiple diagnostic approaches
- Comprehensive flow database

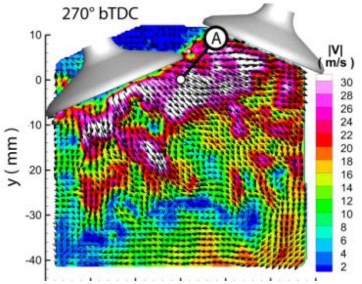


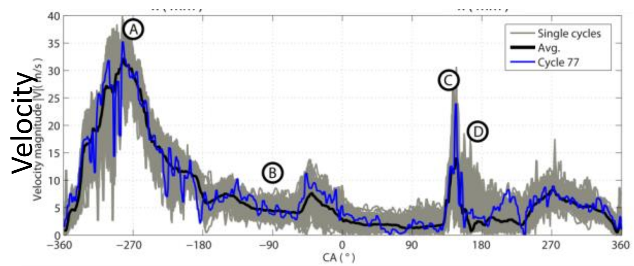


High-statistic PIV (up to 2700 cycles)

- Statistical moments of flow
- Convergence
- Conditioned statistics

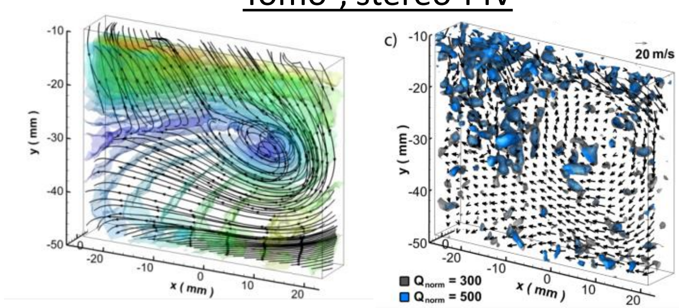
High-speed PIV





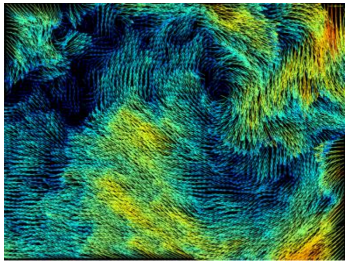
- Evolution of flow
- Intra-cycle & cyclic flow dynamics

Tomo-, stereo-PIV



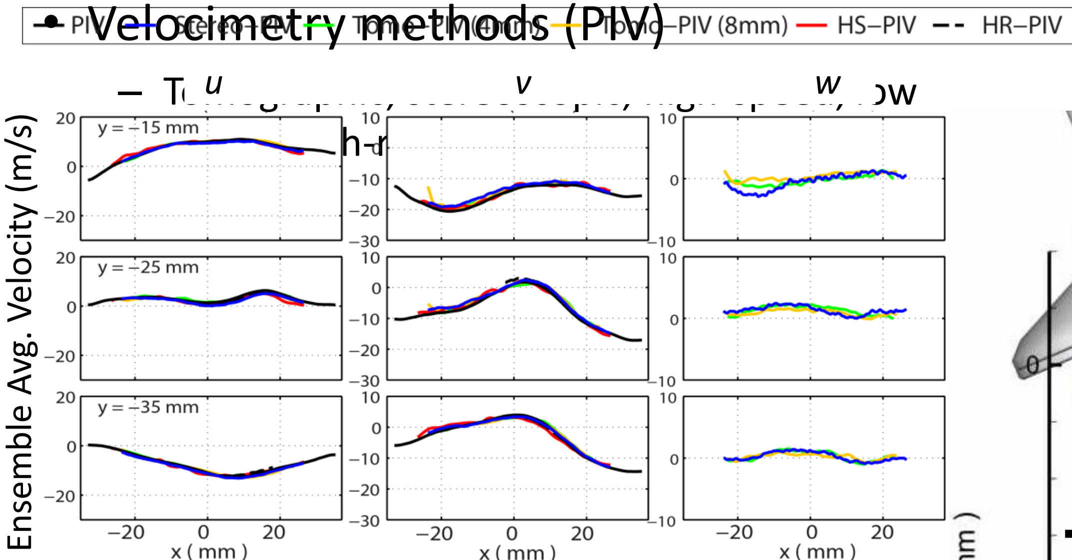
- 3D flow
- *All* gradient tensor components
  - Reynolds Stress
  - Anisotropic invariants

High Res. PIV (0.4 mm)



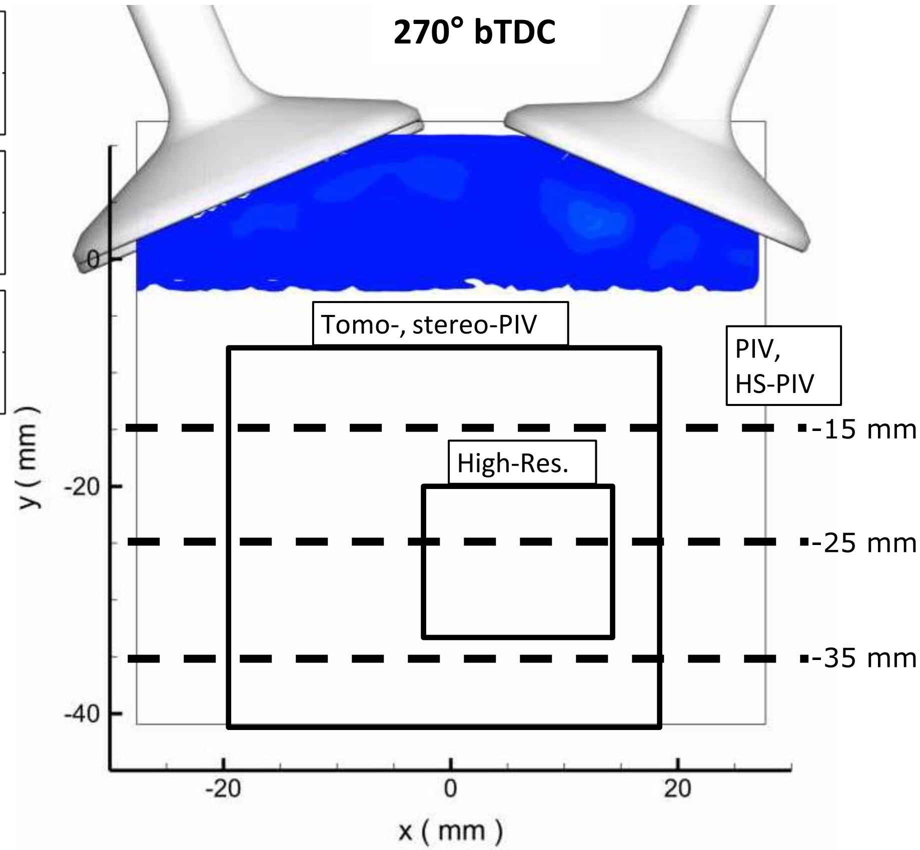
- Spatial scales
- Gradients
- Energy spectra

Coherence of Measurements



- Velocimetry methods (PIV)
  - Tomographic, stereoscopic, high-speed, low-speed, high resolution
- Data integrity
  - Validated, reliable, repeatable

Experimental Comparisons



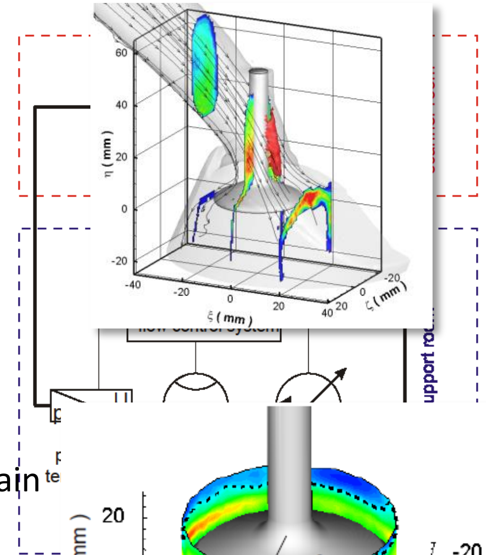
Ensemble Average Velocity field in Central Axis

Steady-State Flow Bench

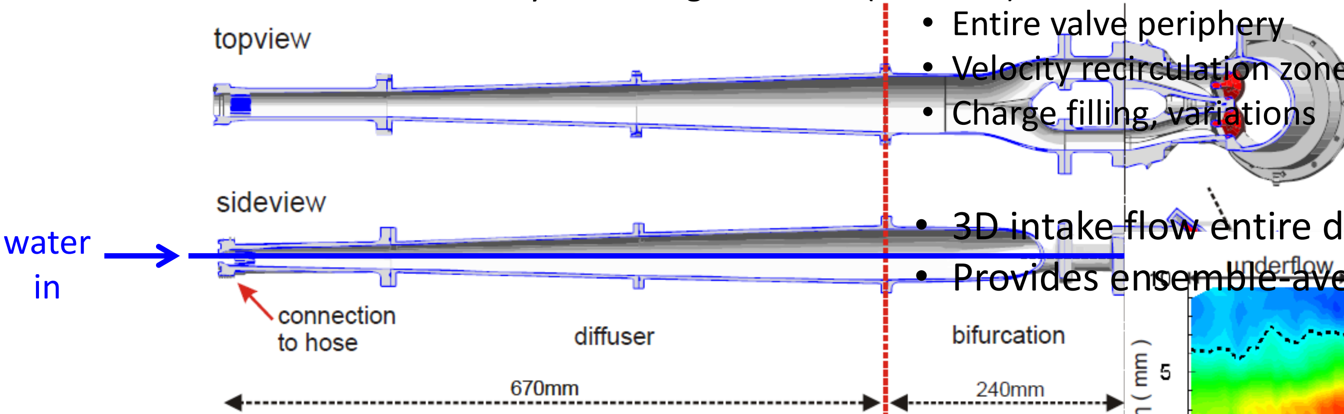
- Magnetic Resonance Velocimetry*
  - Water with Gadolinium-based agent
  - Conducted in MRI machine

*Collaboration with Sven Grundmann, Aeronautical Engin. TU Darmstadt

Exp. Fluids (2014) awaiting proofs

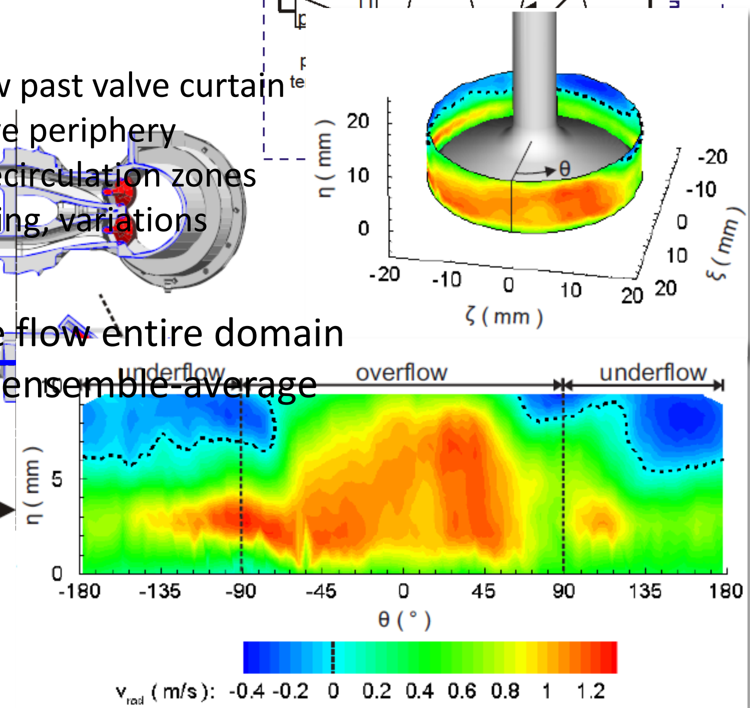


Polyamide engine model (1:1 scale)



- Radial flow past valve curtain
- Entire valve periphery
- Velocity recirculation zones
- Charge filling, variations

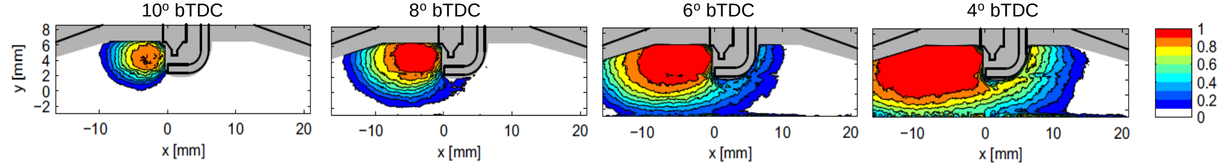
- 3D intake flow entire domain
- Provides ensemble-average



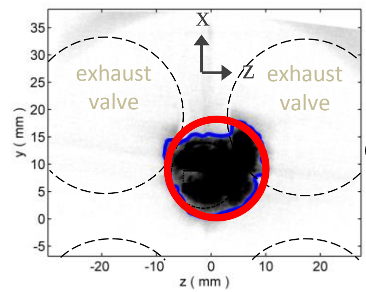
Combustion Characterization

- Flame Propagation
- Mie scattering
  - PDF of enflamed region

2D probability of enflamed region, spark timing 16° bTDC

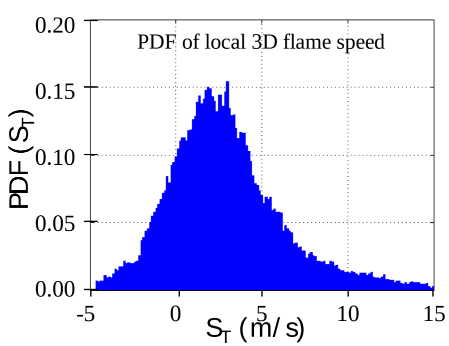


- Chemiluminescence
  - Spherical flame growth approximation

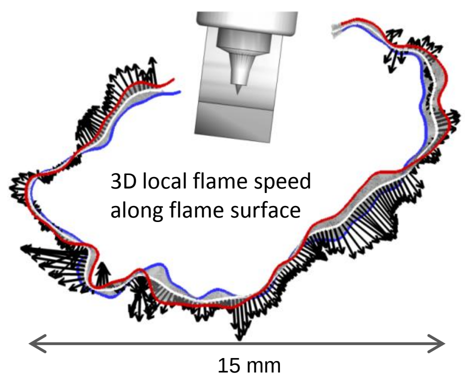


Chemiluminescence

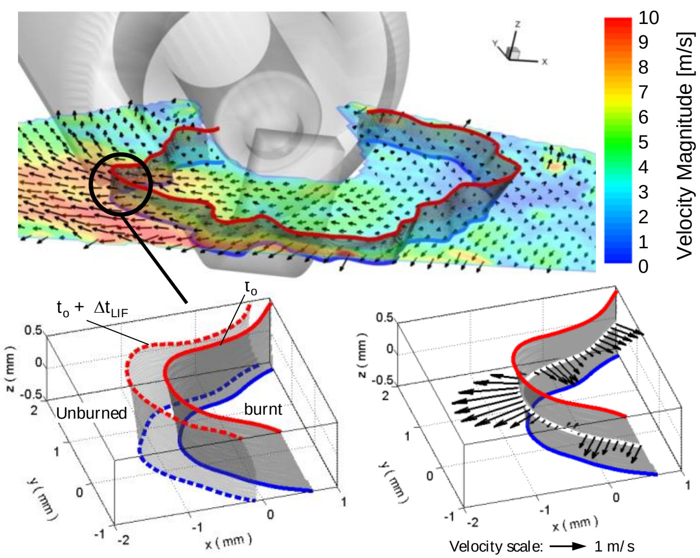
- Simultaneous dual-plane OH-LIF & stereoscopic PIV
  - 3D reconstruction of flame surface
  - *u,v,w* convection velocity
  - 3D local flame speed



Peterson et al. ProCI (2014)



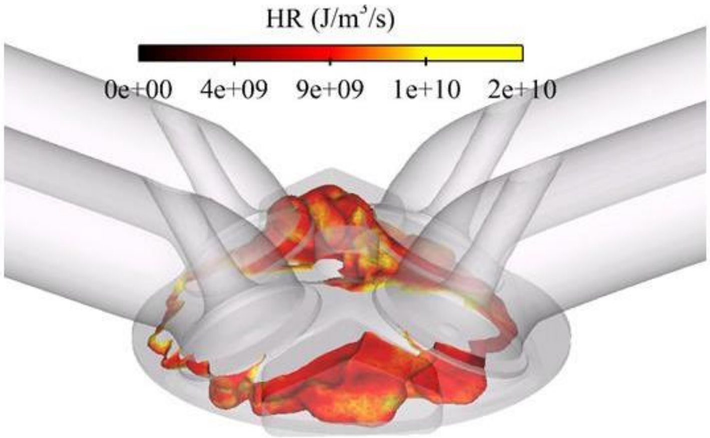
3D reconstructed flame surface and 3C turbulent flow field

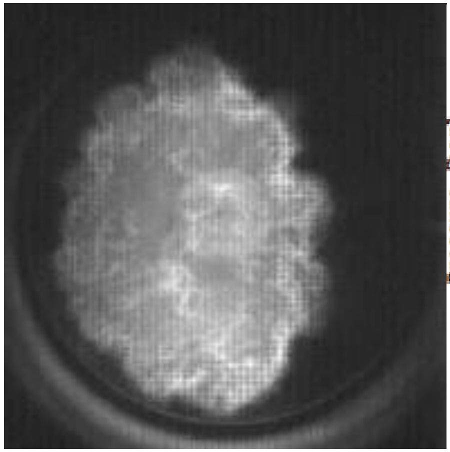


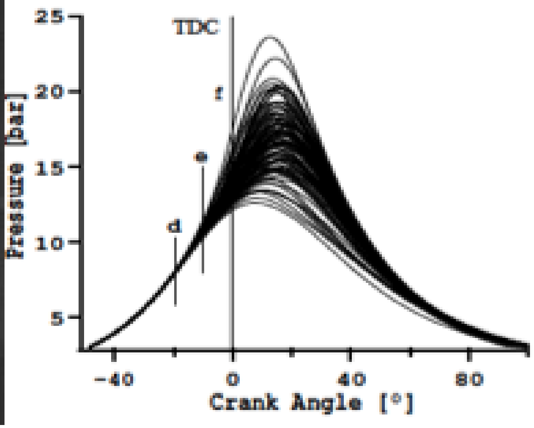
3. SGEmac (IFP)

Introduction

- Experimental database for validation and development of LES modeling
- Objective: study of cycle-to-cycle variations using LES supported by experiments
- Uniqueness:
  - Modern engine geometry
  - Experiments with LES
  - 1D Simulations

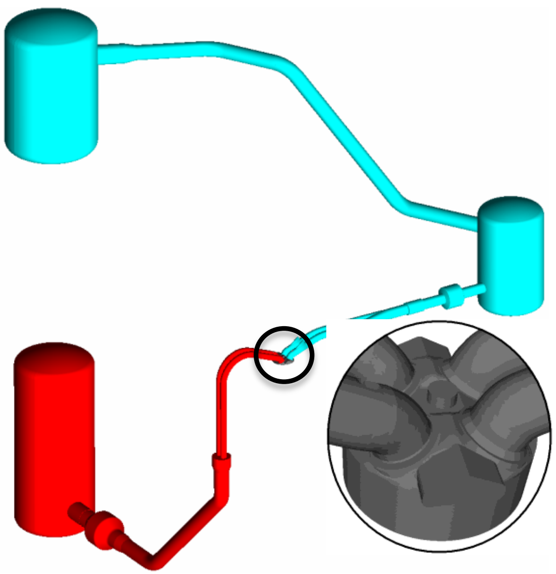


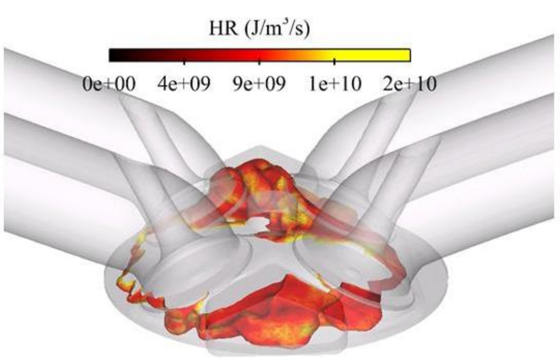




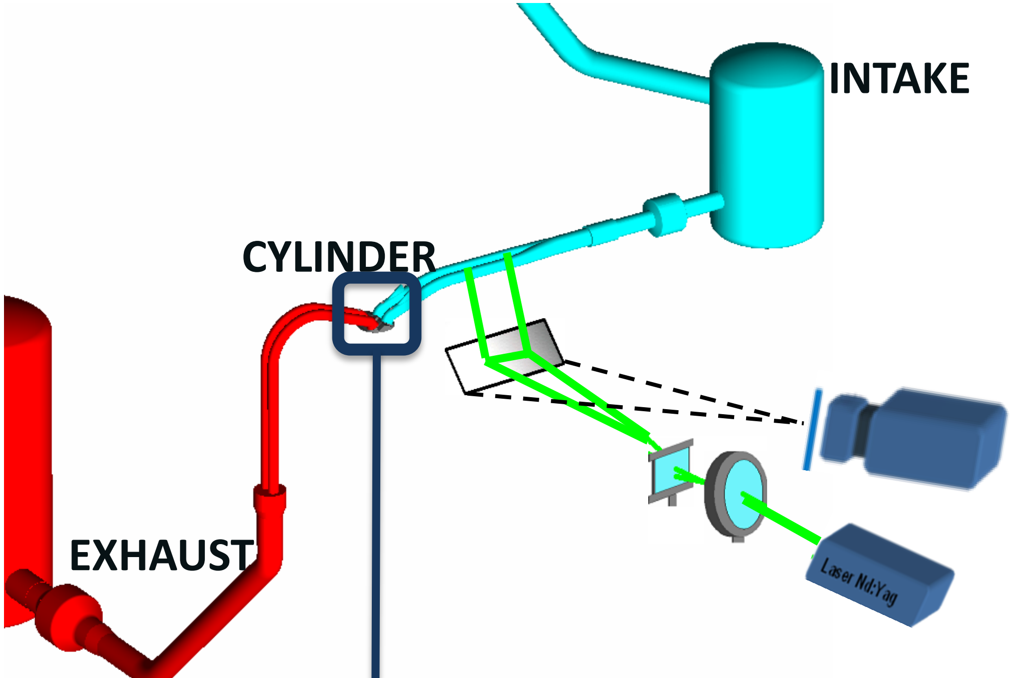
Details

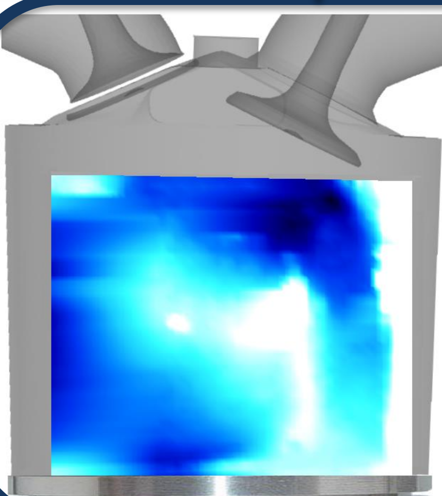
- Complete geometry available
  - 4-valve, pentroof
  - Based on Renault F7P
- Well characterized BCs
  - CA° resolved
  - Cycle resolved
- Operation
  - Homogeneous C_3H_8 / air
  - Direct-injection (iso-octane)
  - Low CCV operating points
  - Large CCV operating points
    - Lean, diluted
- System Simulation Support

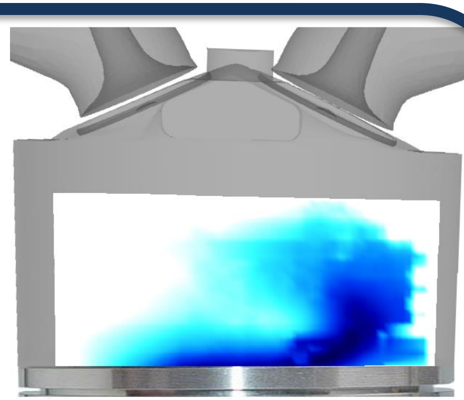




Topic 4.1 : Measurements for Simulation Benchmarking

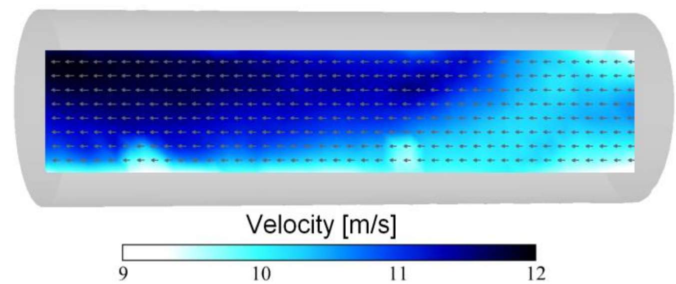


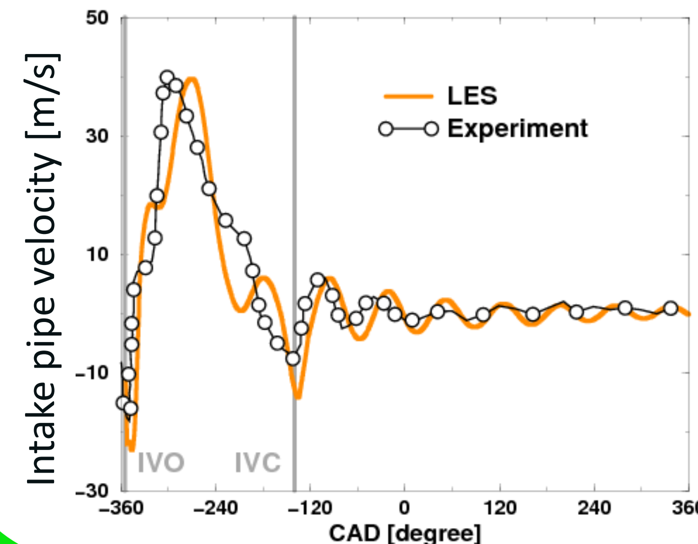




In-cylinder PIV (100 cycles)

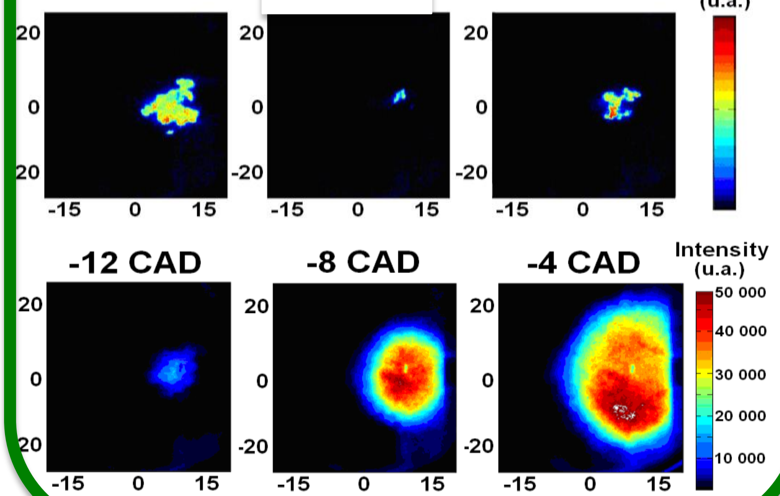
PIV (100 cycles) in the transparent intake pipes for acoustic LES boundary condition definitions





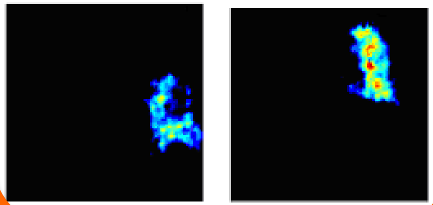
Combustion characterisation

OH-LIF and OH*: Flame kernel structure and location

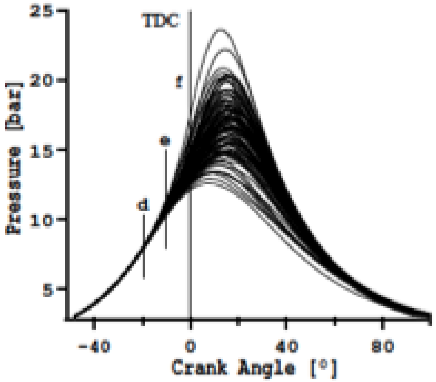


Chemiluminescence

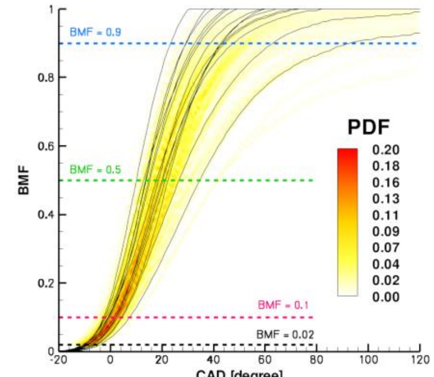
Reactive zone characterization



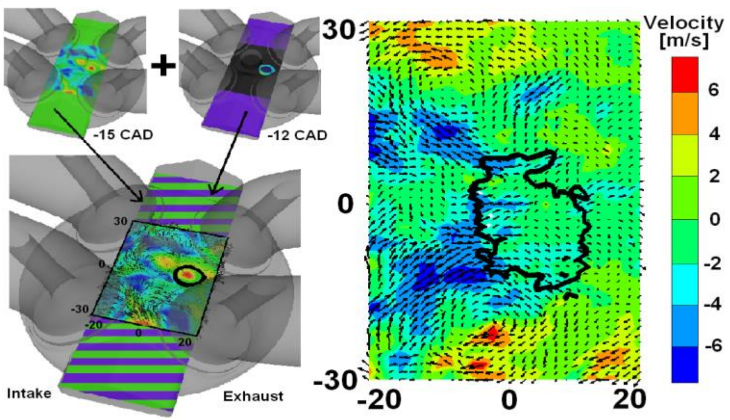
1D Analysis



P_{cyl} for low and large CCVs



Statistics on combustion (BMF, CA_{XX}, …)



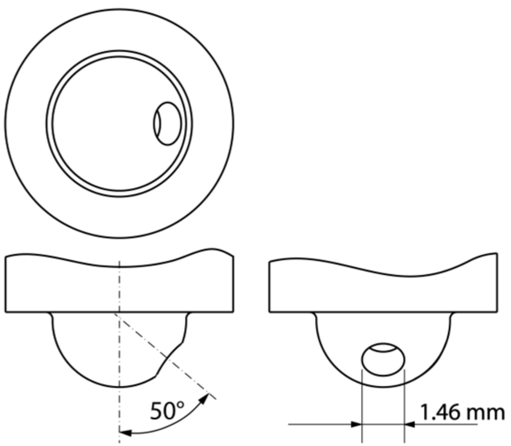
Simultaneous PIF and OH-LIF:

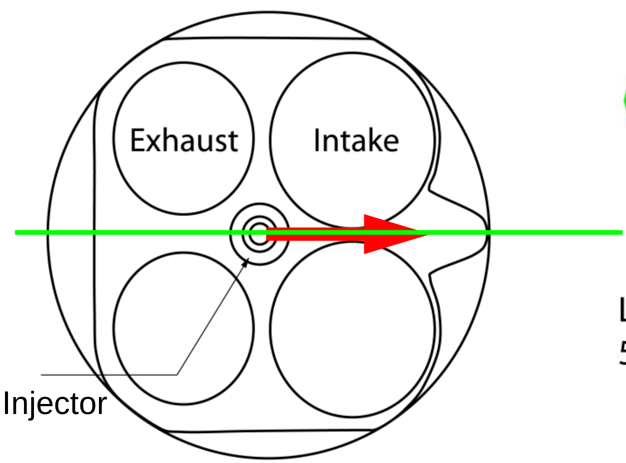
Turbulent flame propagation models

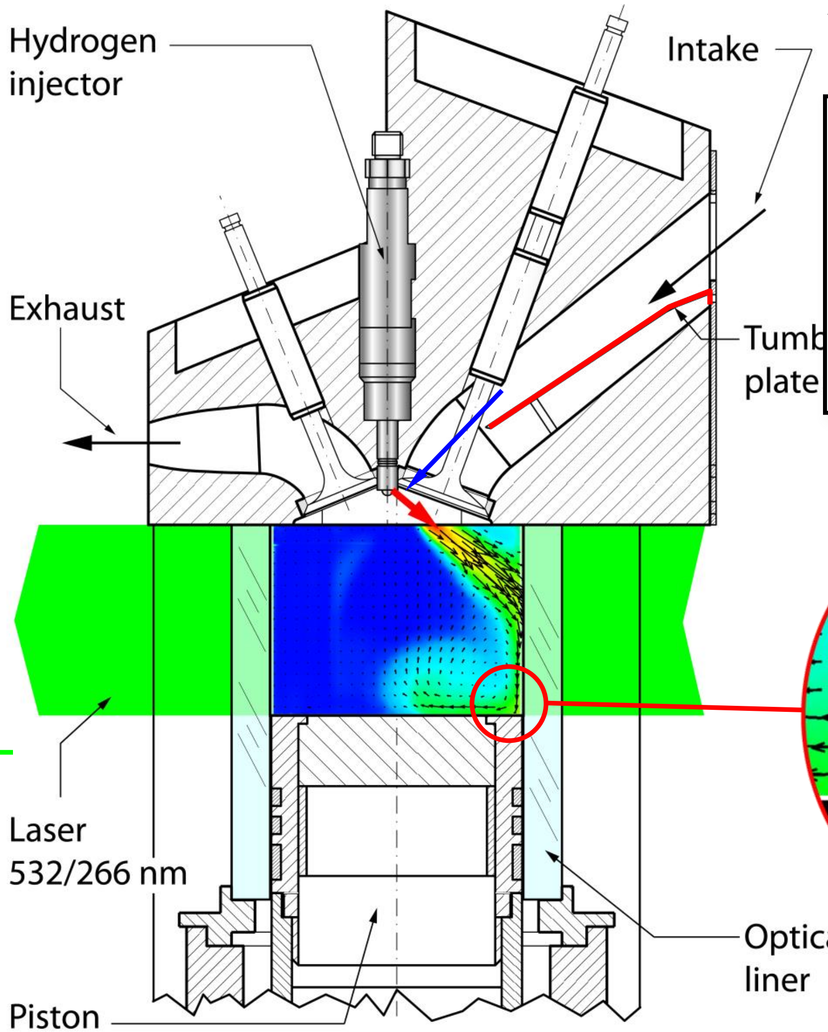
4. H2ICE (SNL/U DuE)

Sandia H2ICE on the ECN – data and simulation

Acetone PLIF + PIV

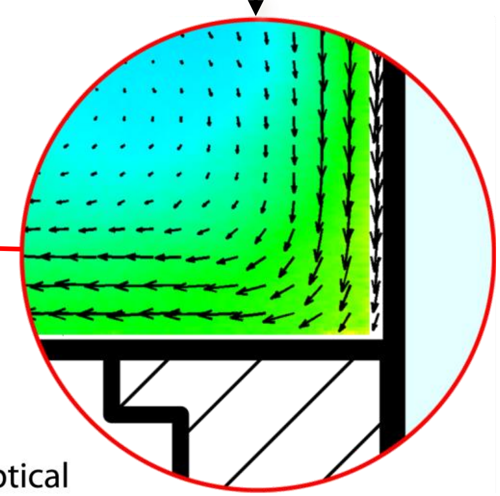




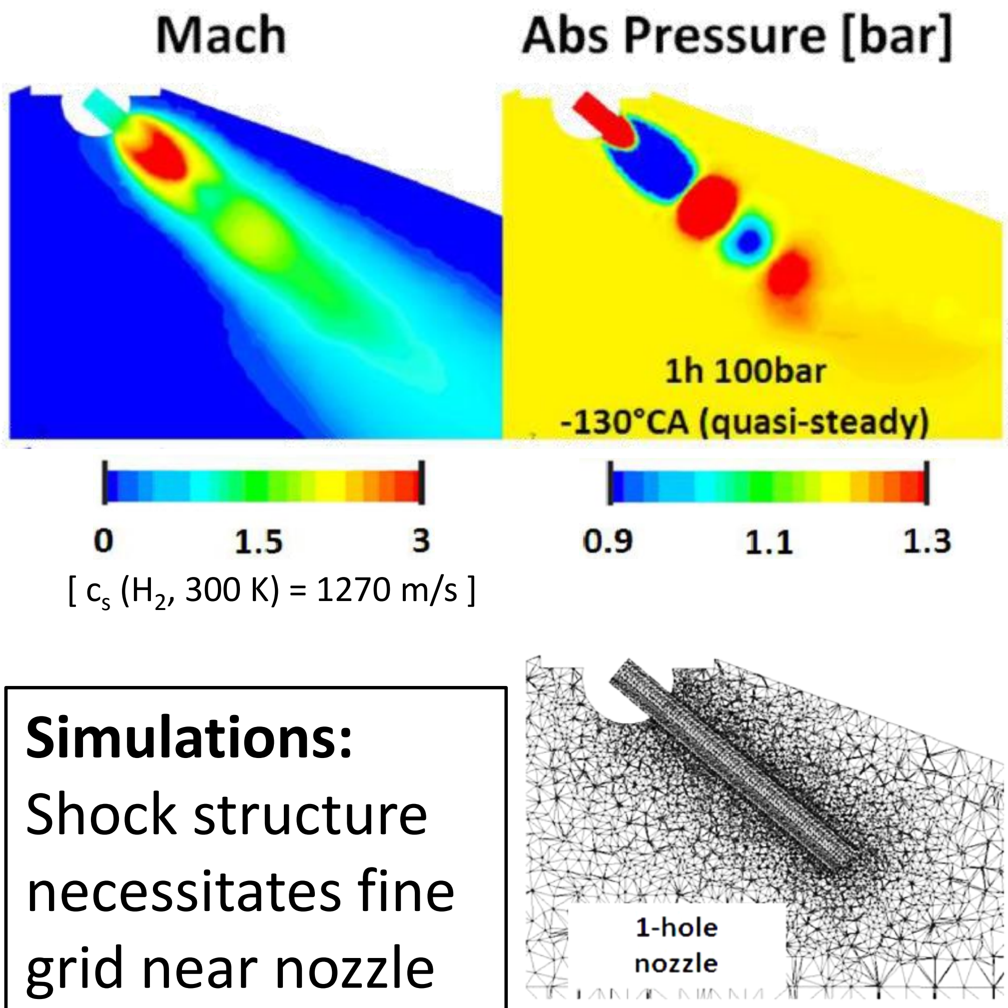


Unique measurements

- full bore & stroke
- almost to walls
- quantitative



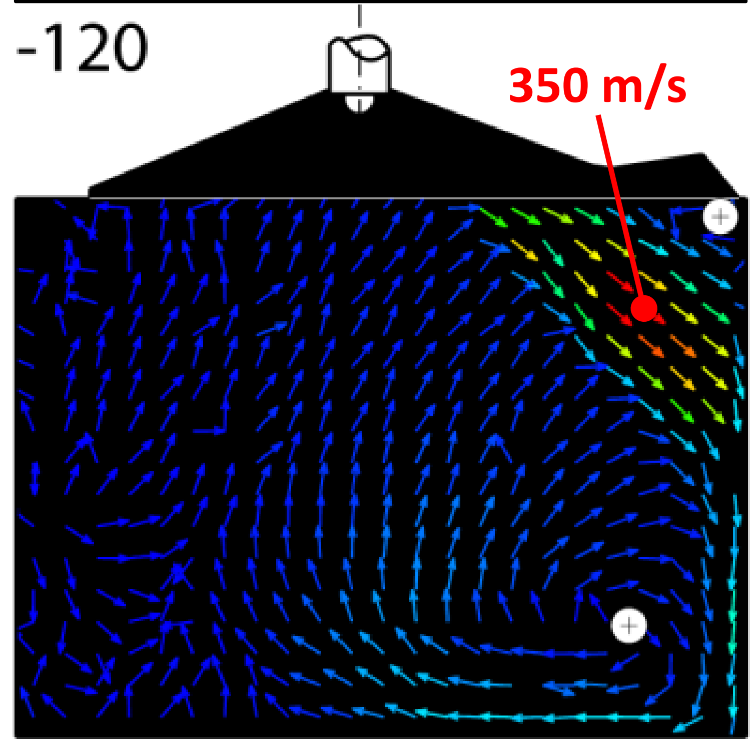
Hydrogen DI : a single-phase, fully gaseous, highly underexpanded jet



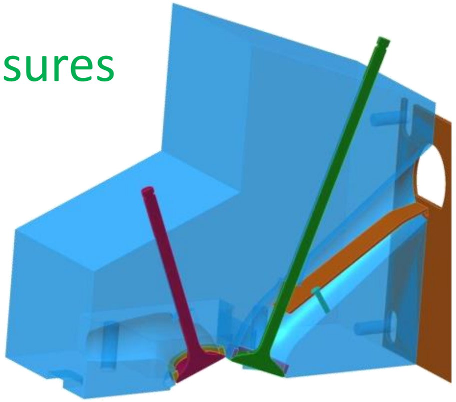
[c_s (H_2, 300 K) = 1270 m/s]

Simulations:
Shock structure necessitates fine grid near nozzle

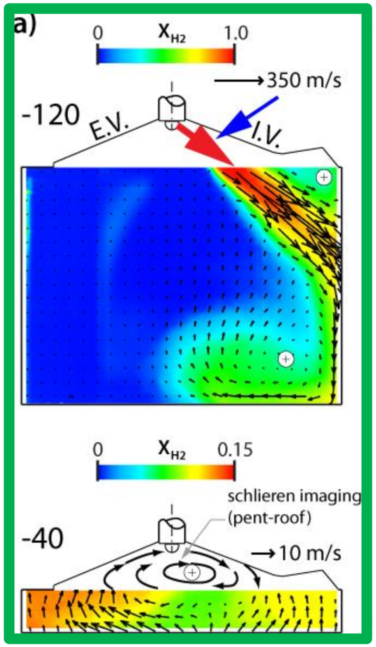
Experiment
PIV underestimates centerline mean velocity during injection

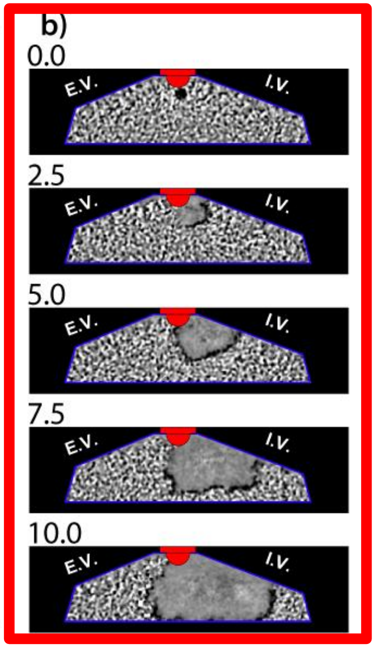


Green: On the ECN web page *Red: Measured but not on ECN page*



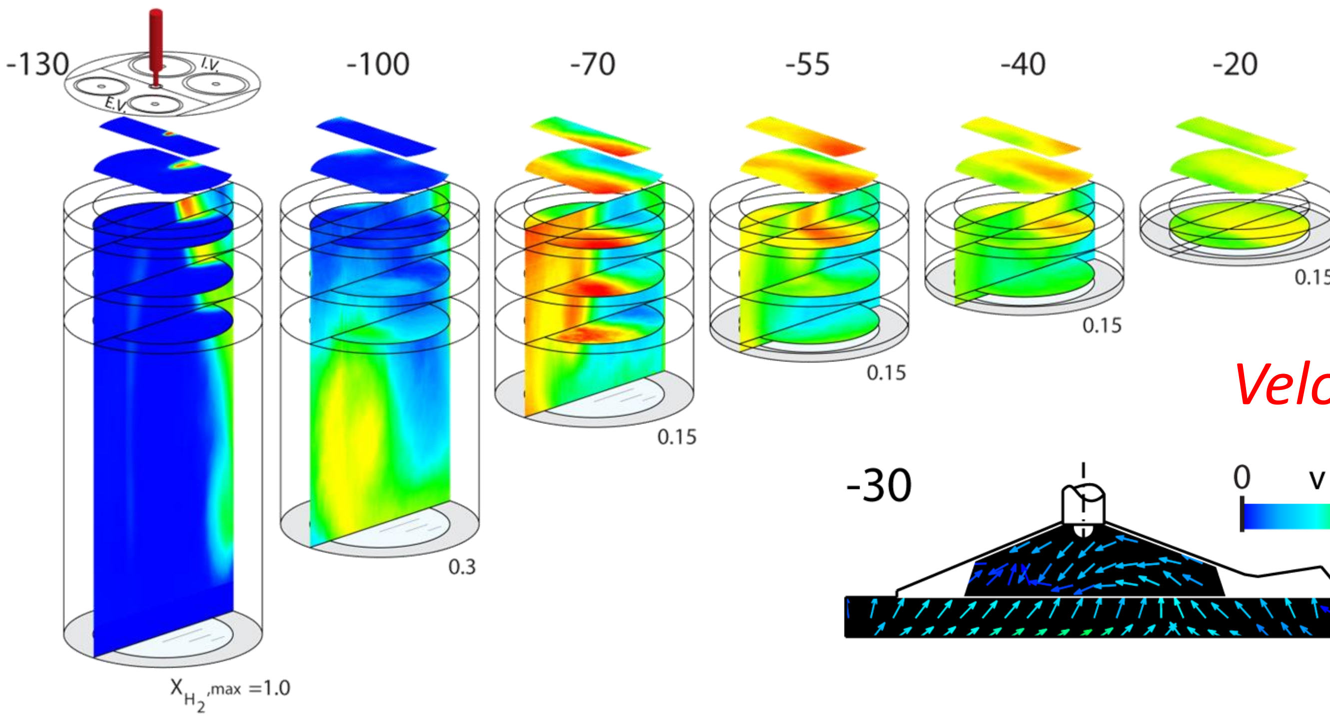
- Geometry, boundary conditions, intake, cyl., exhaust pressures *(valve lifts unintentionally missing on the web)*
- Tumble-plane velocity during compression
  - With and without injection
  - For neutral and tumble-enhanced intake
  - In complete cylinder *and pent-roof*
- Tumble-plane fuel mole-fraction during compression
  - Angled single-hole nozzle, Inj. at IVC
  - *Other injectors and injection timings*
- Ensemble-means available, *single shots missing*
- *Flame propagation*
  - *High-speed Schlieren movies in pent-roof*
  - *Single-cycle correlated pressure traces and AHRR*
- *Schlieren movies of early jet penetration*



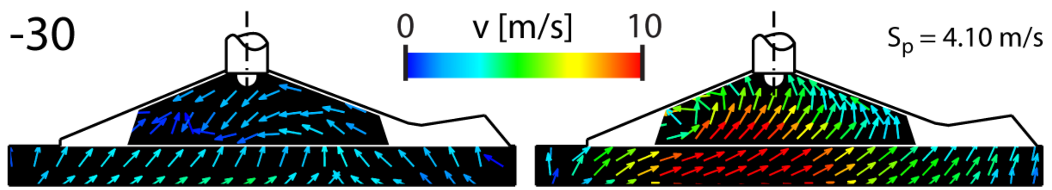


Measured, but currently not on the ECN web page

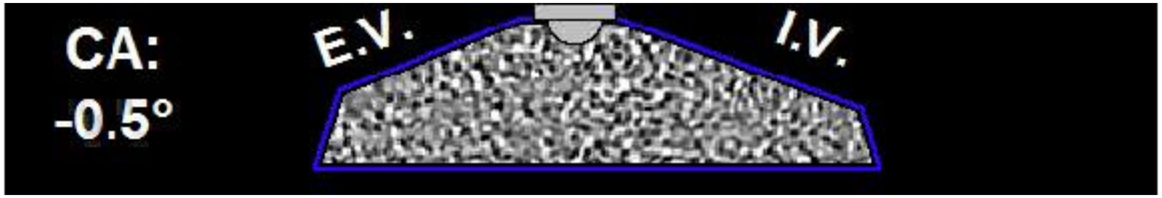
Multiple-cross-plane imaging (in the mean)



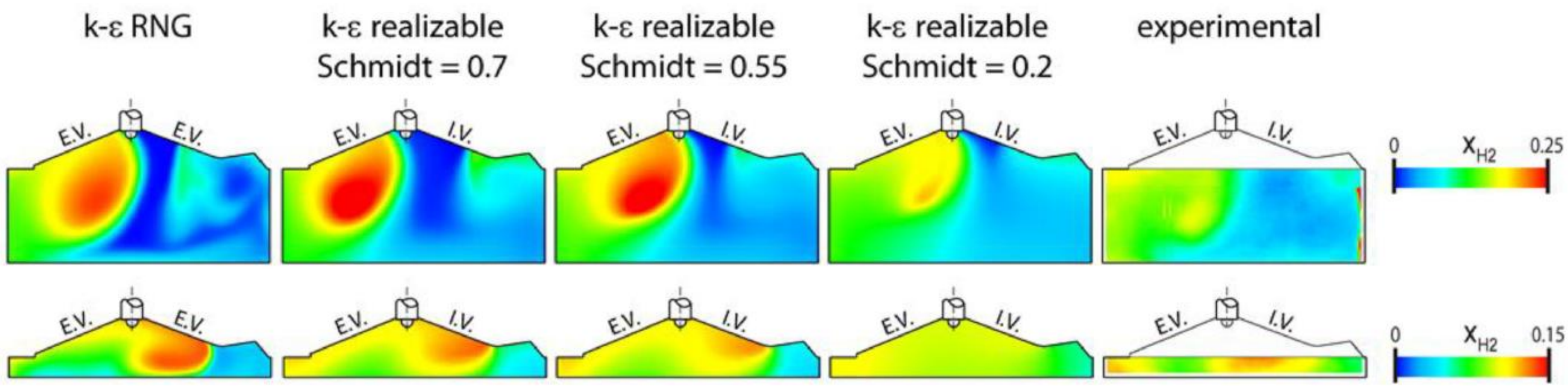
Velocity in the pent roof



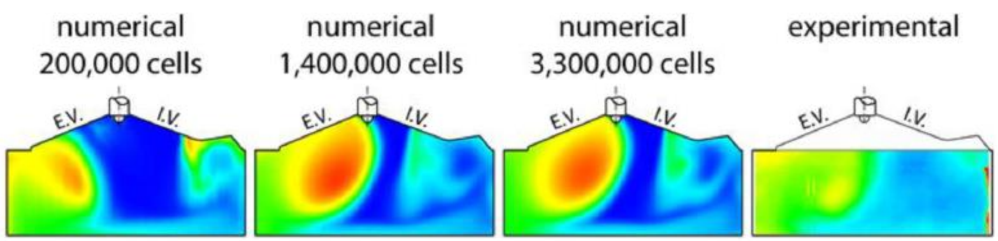
Early flame propagation



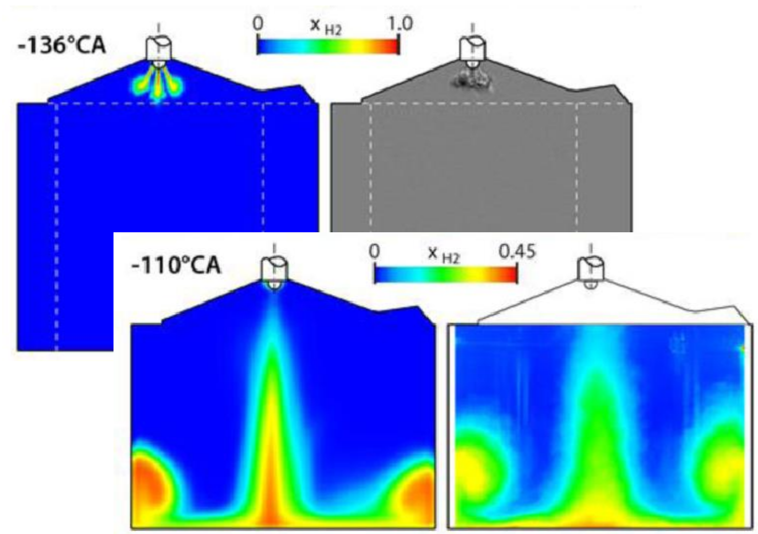
Collaboration between Sandia and Argonne (2009 – 2011)



Turbulence models and tuning



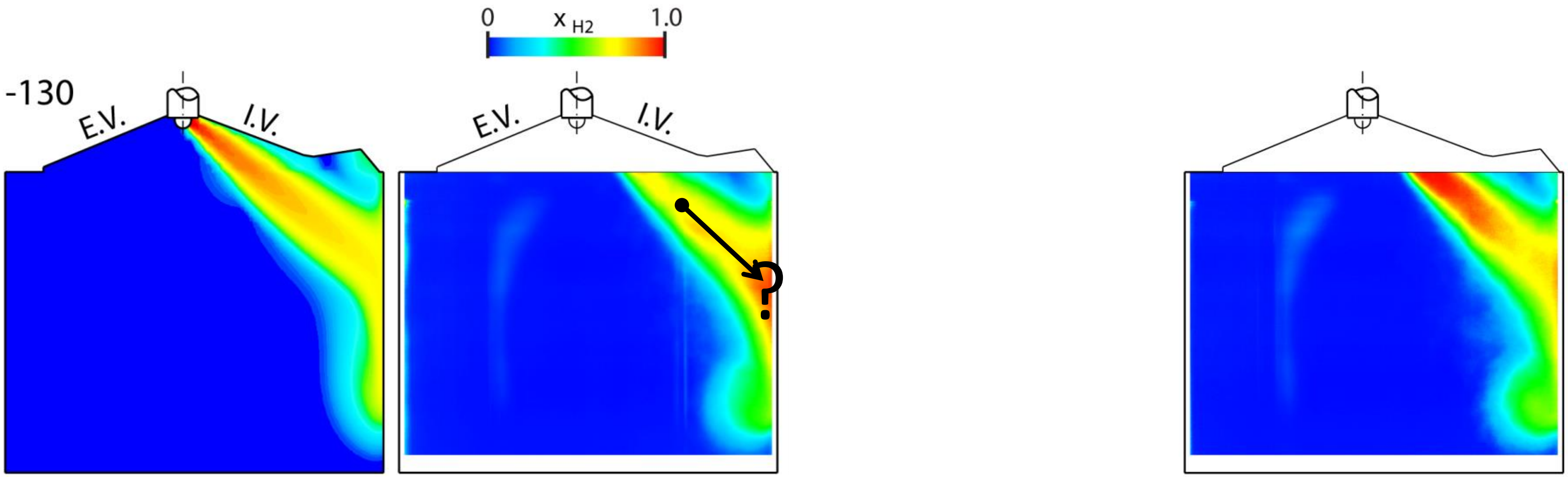
Grid convergence



Multi-hole nozzles

Simulation helped the experiment in fixing mistakes

numerical | experimental (N_2) | experimental (corrected)



Fluorescence (ns)
+ phosphorescence
(μs - ms)

(at 300 m/s:
100 μs = 30 mm)

Fluorescence (ns)
phosporesence
quenched by O_2

More accurate calibration (corrected for fuel lost into intake in flat-field calibration)

Comparisons of/with different RANS-simulations

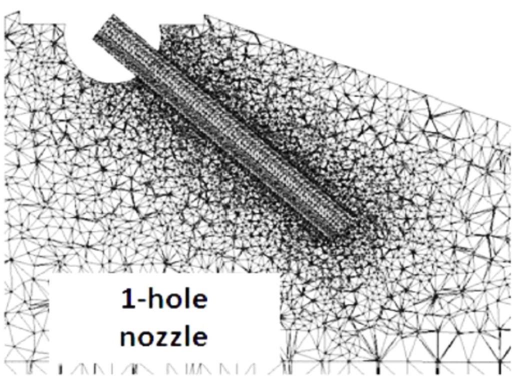
Argonne Nat'l lab (R. Scarcelli)

- FLUENT
- All k-*e* models found to perform similarly well

SAE 2011-24-0096

SAE 2011-01-0675

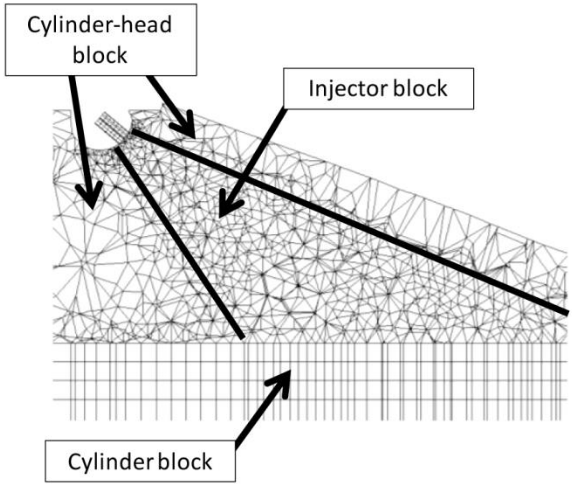
SAE 2009-24-0083



Poli. Milano (T. Lucchini)

- OpenFOAM
- Standard and RNG k-*e* found to perform best

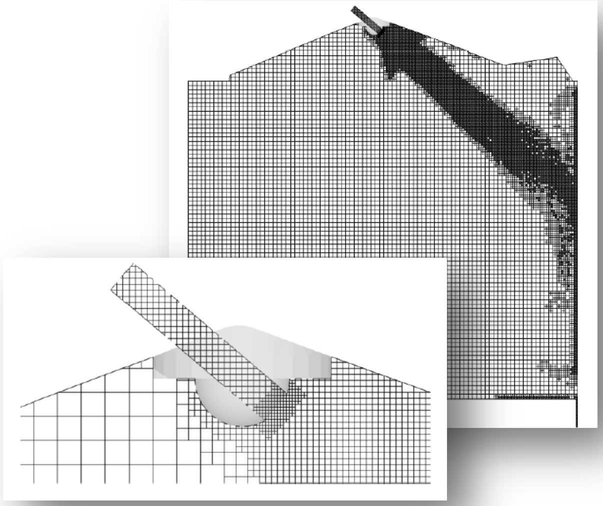
SAE 2011-24-0036



Convergent Science (J. LeMoine)

- CONVERGE
- RNG k-*e*

ASME ICEF2014-5610 (submitted)



Status DI-H2ICE

- Engine and lab still usable but unused at Sandia
- No dedicated support for any further experimental activities
- More of the existing data, e.g., velocity in pent-roof and flame-propagation movies could be put online
- Data may be moved to Duisburg server for better site maintenance

- Victor and Sebastian receive and support 2 - 3 requests / year from researchers starting simulations of this engine

Fuel dispersion in different simulations

ANL (FLUENT) Low-tumble case		P. Milano (OpenFOAM) Low-tumble case		Conv. Science (CONVERGE) High-tumble case	
Simulation	Experiment	Simulation	Experiment	Simulation	Experiment