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*H_2 Internal Combustion Engine Research**

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2008 DOE Merit Review
Bethesda, Maryland

February 25th 2008

DOE-Sponsor: Gurpreet Singh

****** This presentation does not contain any proprietary or confidential information***

Purpose of work

- Develop a combustion concept that
  - Offers excellent fuel conversion efficiencies
  - Produces virtually zero emissions
  - Achieves power density levels of modern gasoline engines
  - Reduces the dependence on foreign oil
  - Decreases green house gas emissions

Purpose of work

- Evaluate potential of hydrogen internal combustion engines
  - Investigate hydrogen combustion concepts for additional efficiency and emissions improvements
    - *Analyze influence of injector location*
    - *Evaluate impact of injector nozzle design*
  - Apply/develop diagnostic tools that allow deeper understanding of hydrogen combustion engines
    - *Develop correlation of chemiluminescence measurement with engine-out NO_x emissions*
  - Feed information forward to multi-cylinder hydrogen engine and vehicle level application

Relevant DOE goals and objectives

- 45% Brake Thermal Efficiency
- 0.07 g/mile NO_x
- Power density similar to gasoline
- $45/kW by 2010 and $30/kW in 2015

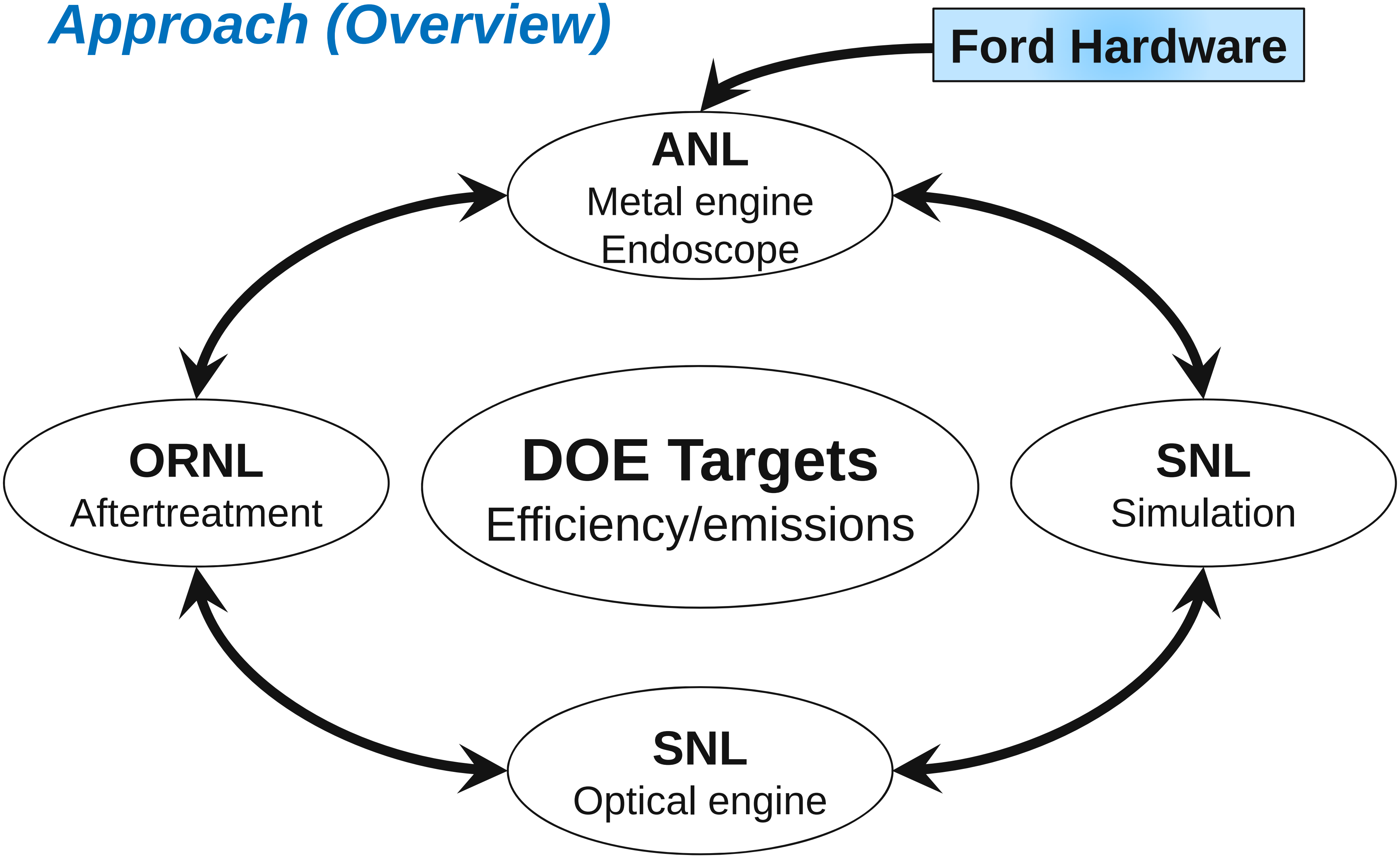
Previous Review Comments and Actions Taken

- *'…would like to see more analysis of the in-cylinder measurements to understand more details of the combustion.'*
  - Detailed analysis of in-cylinder pressure measurements
  - Correlation between OH* chemiluminescence and engine-out NO_x emissions derived
- *'…the project should include modeling.'*
  - Meetings with project partners; Simulation at Ford/Sandia
  - Post-doc candidate with hydrogen engine modeling experience identified
- *'NO_x levels seem very high…what the plan for NO_x control was.'*
  - In-cylinder measures
    - Multiple injection data presented at last review
    - Optimized injector location and nozzle design
    - Additional measures (EGR, water injection…)
  - Lean NO_x aftertreatment (Ford, ORNL)

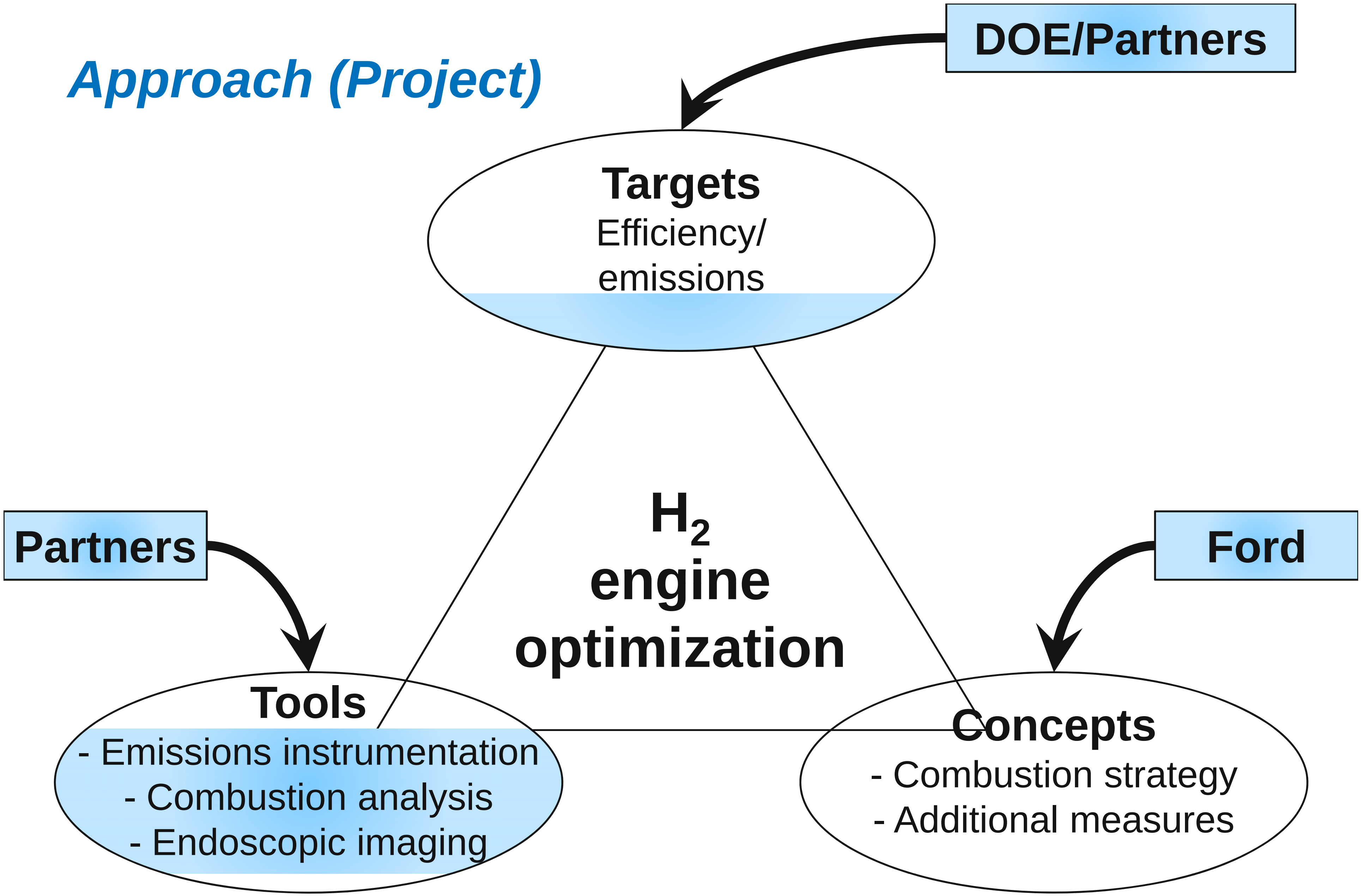
Barriers

- Operation with hydrogen port injection
  - Combustion anomalies (knock, pre-ignition) prevent extension of high efficiency regimes towards higher engine loads
  - Low power density
- Operation with hydrogen direct injection
  - Trade-off between NO_x emissions and power density
  - Trade-off between NO_x emissions and engine efficiency at low engine loads

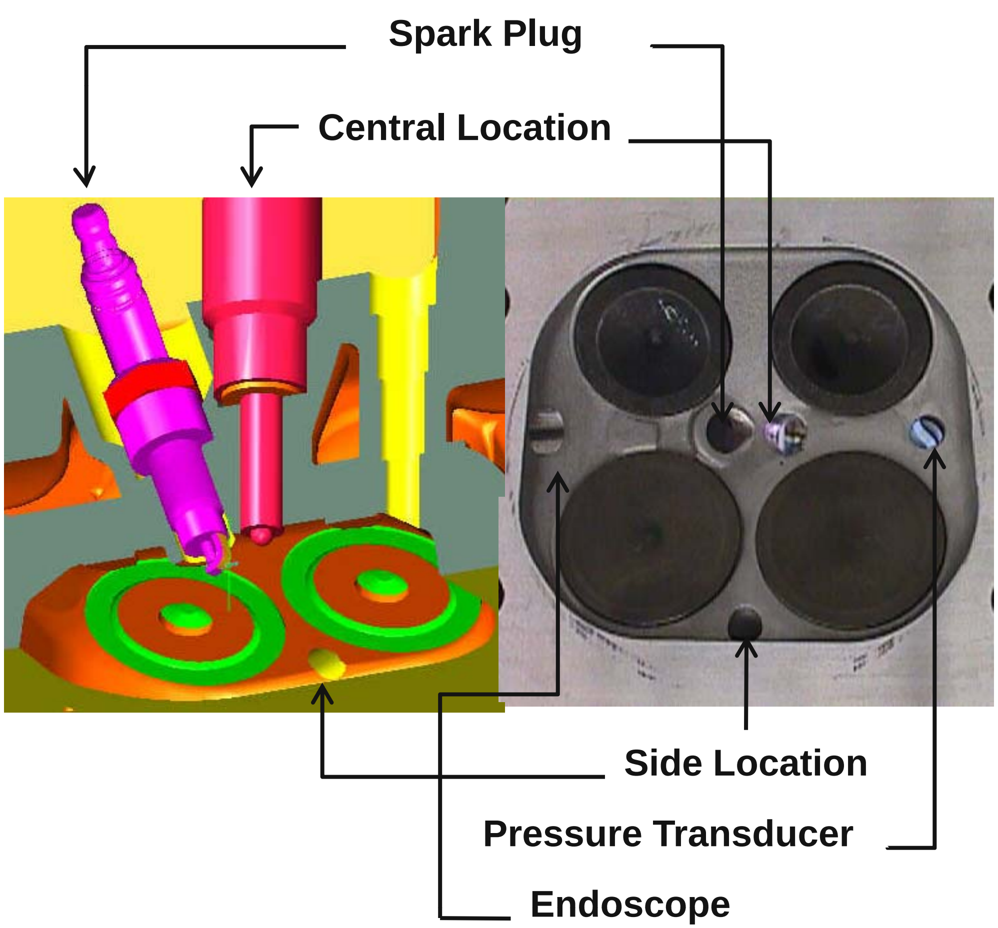
Approach (Overview)



Approach (Project)

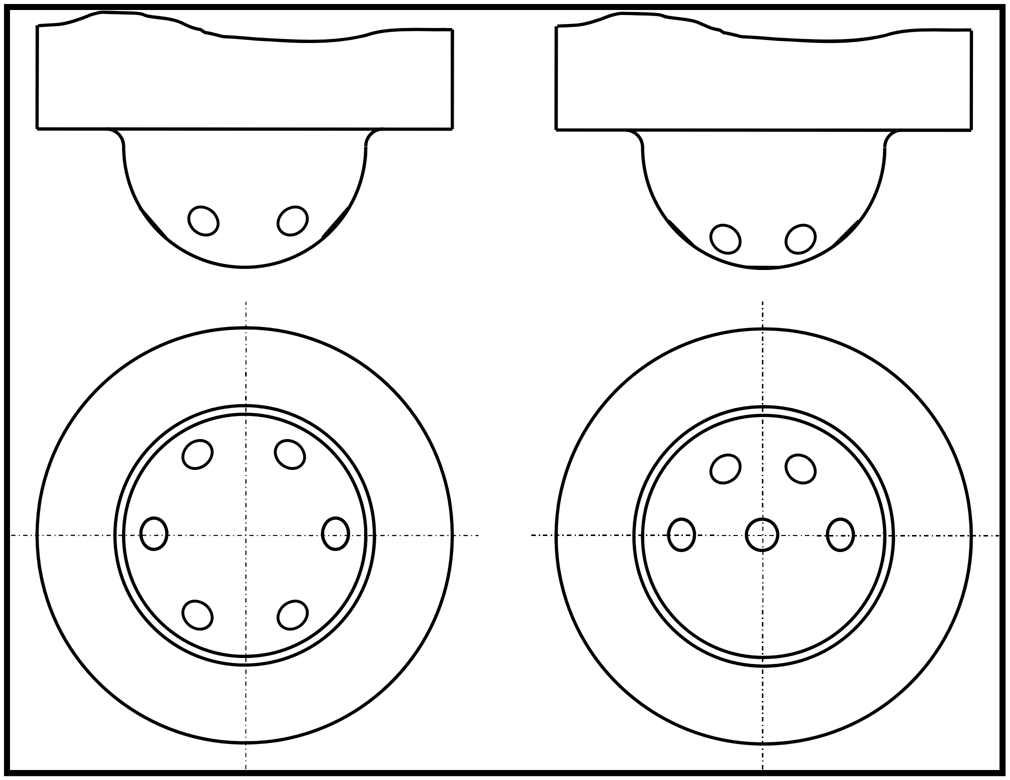


Progress
Hardware upgrade



- New cylinder head installed with
  - Central and side injector location for Direct Injection
  - Endoscope access

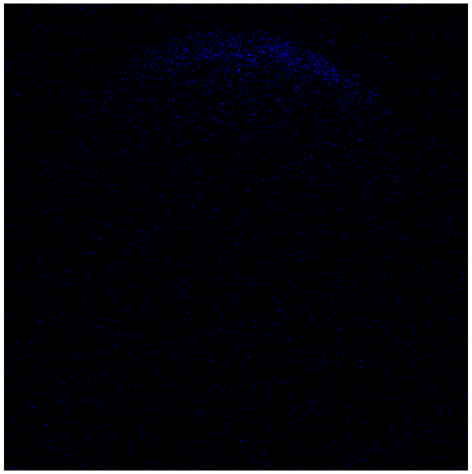
Progress
Novel nozzle designs



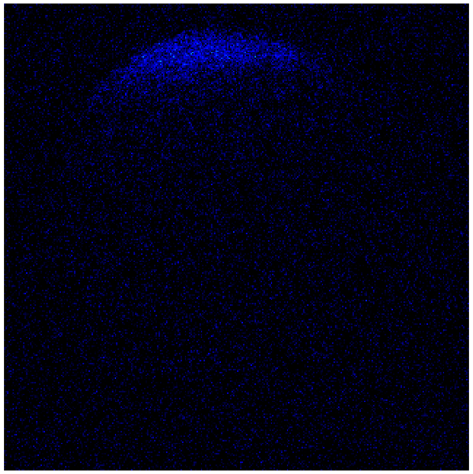
- Symmetric 6 hole nozzle for central injection
- Asymmetric 5 hole nozzle for side injection
- 4 configurations tested:
  - Symmetric 6 hole central
  - Symmetric 6 hole side
  - Asymmetric 5 hole side jets up
  - Asymmetric 5 hole side jets down

Experimental results
Sample images (2000 RPM 8 bar IMEP)

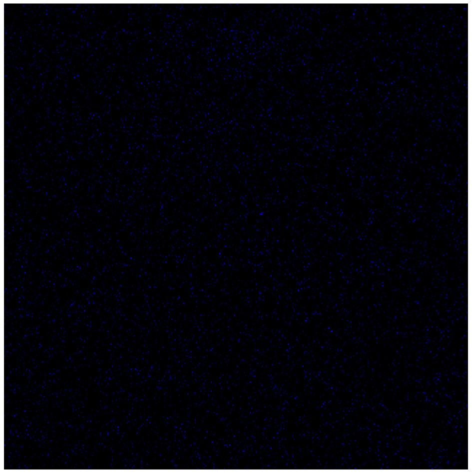
6-hole central
SOI=80



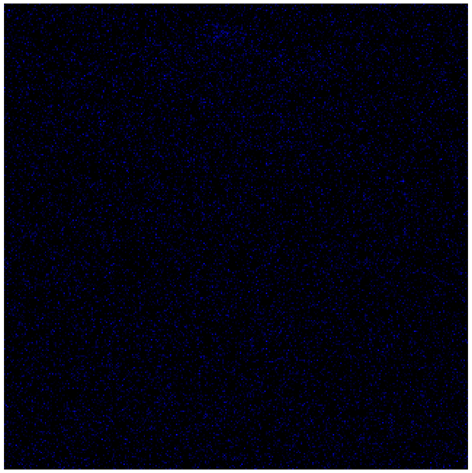
6-hole side
SOI=80



5-hole side up
SOI=80



5-hole side down
SOI=80



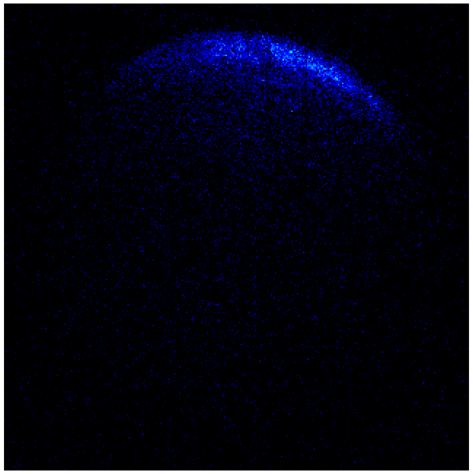
10 deg CA ATDC

0 500

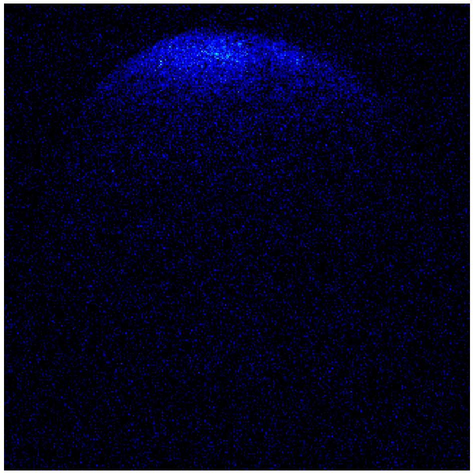
OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

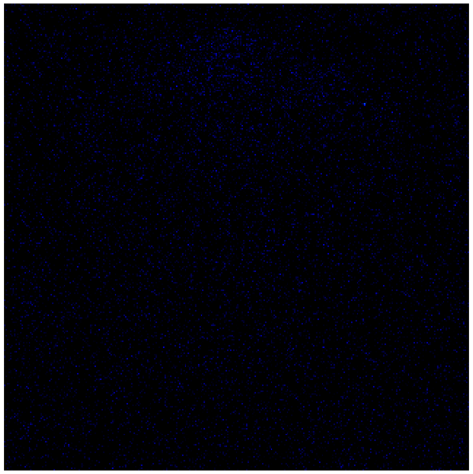
6-hole central
SOI=80



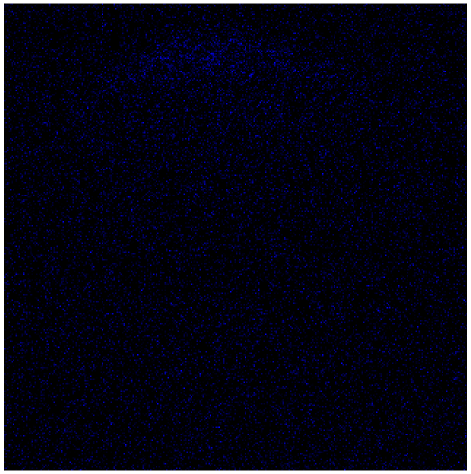
6-hole side
SOI=80



5-hole side up
SOI=80



5-hole side down
SOI=80



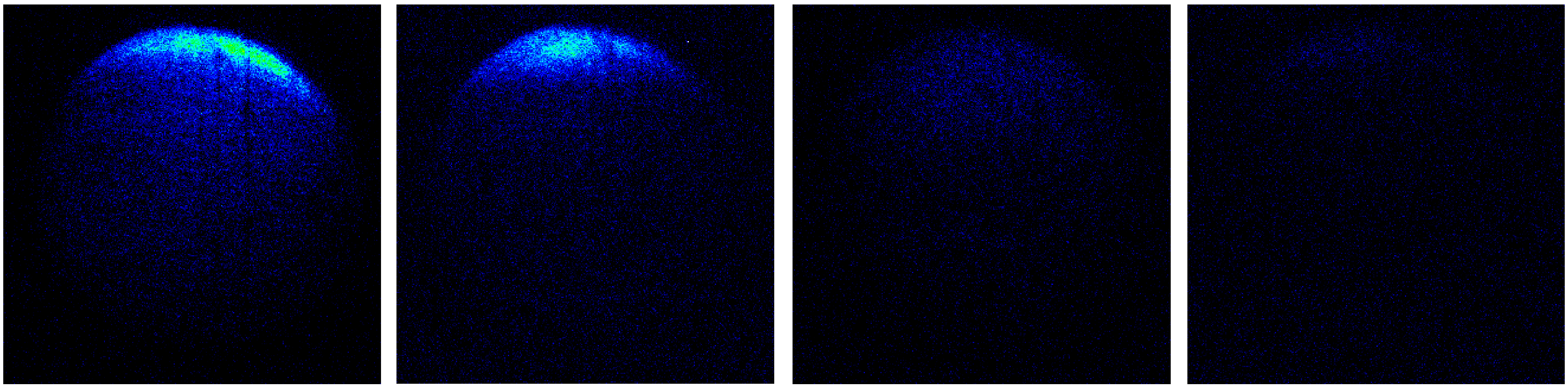
12 deg CA ATDC

0 500

OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central SOI=80	6-hole side SOI=80	5-hole side up SOI=80	5-hole side down SOI=80



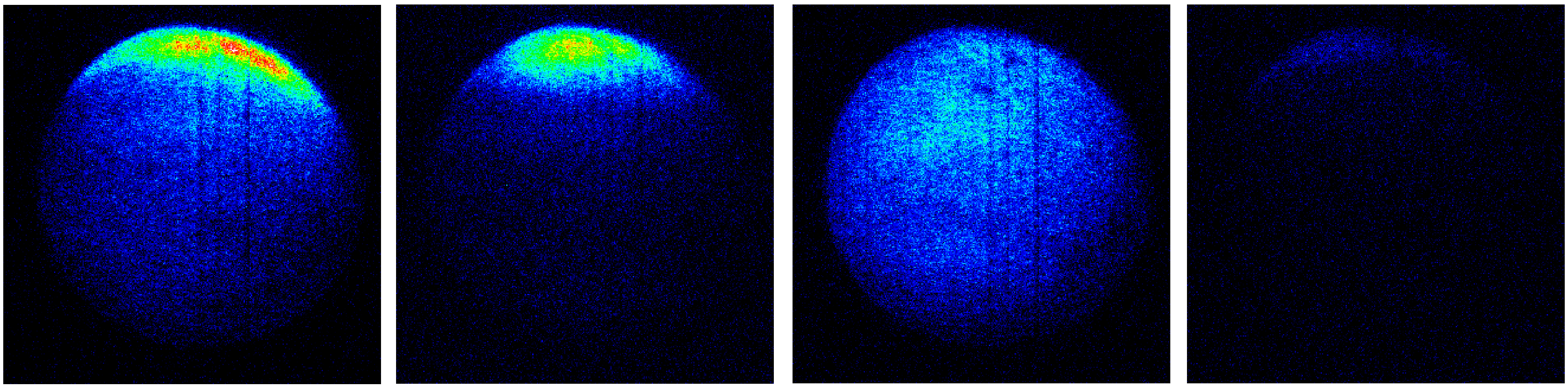
14 deg CA ATDC

0 [scale bar] 500

OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central SOI=80 | **6-hole side SOI=80** | **5-hole side up SOI=80** | **5-hole side down SOI=80**



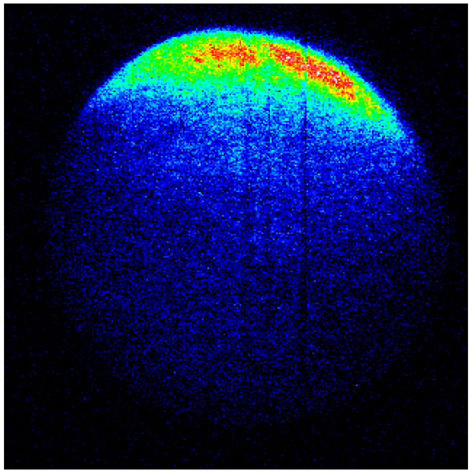
16 deg CA ATDC

0 500

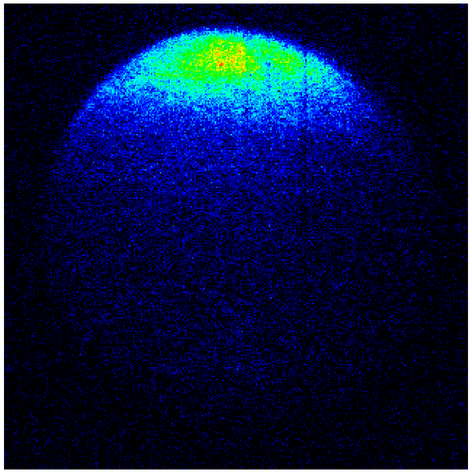
OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

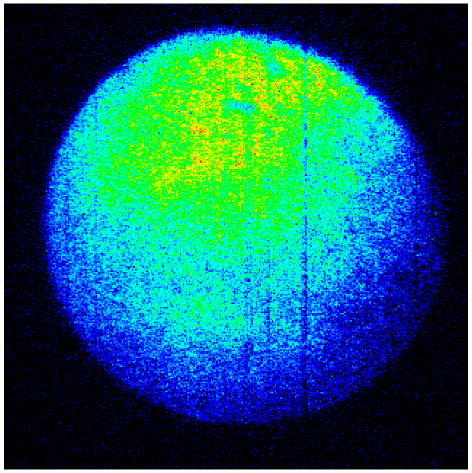
6-hole central
SOI=80



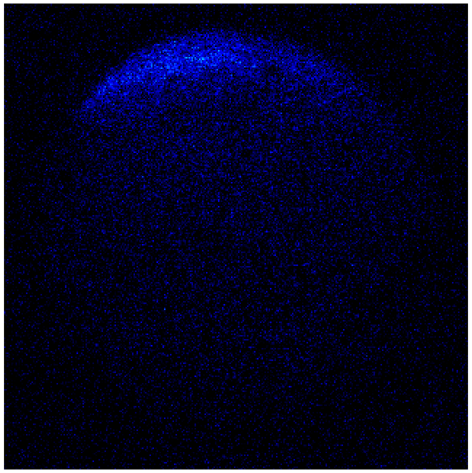
6-hole side
SOI=80



5-hole side up
SOI=80



5-hole side down
SOI=80



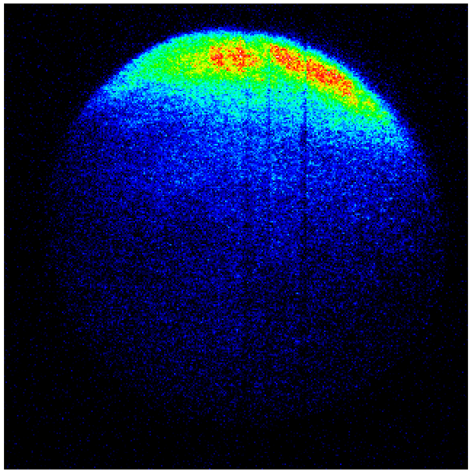
18 deg CA ATDC

0 500

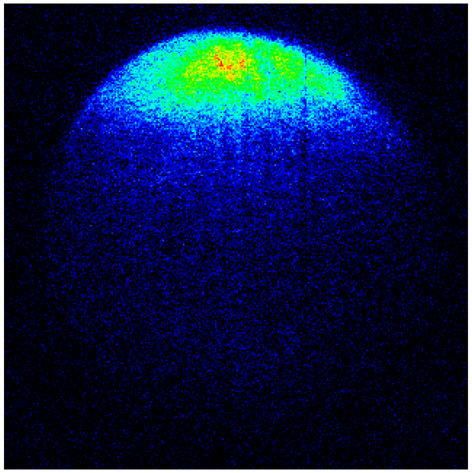
OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

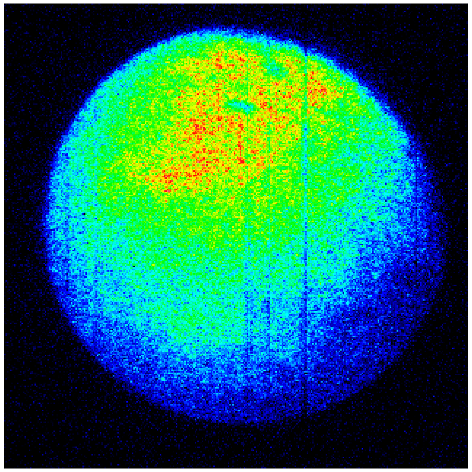
6-hole central
SOI=80



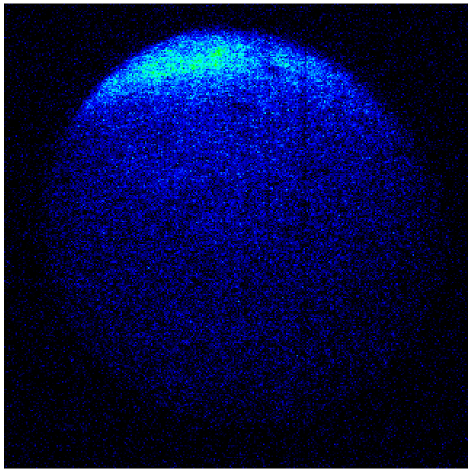
6-hole side
SOI=80



5-hole side up
SOI=80



5-hole side down
SOI=80



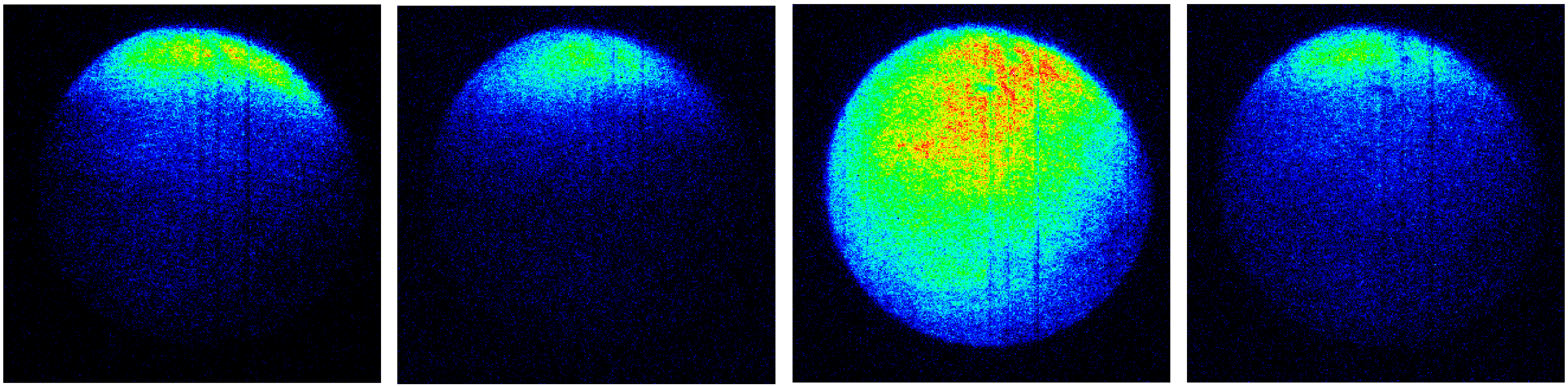
20 deg CA ATDC

0 500

OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central SOI=80	6-hole side SOI=80	5-hole side up SOI=80	5-hole side down SOI=80



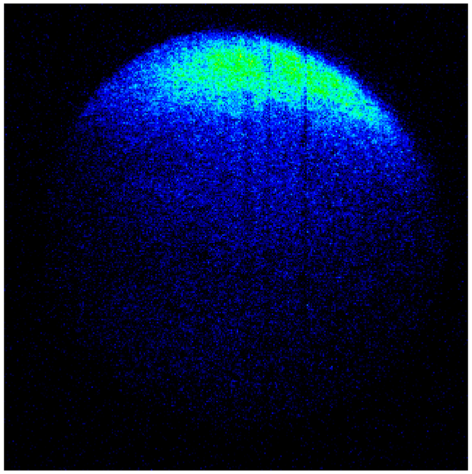
22 deg CA ATDC

0 [   ] 500

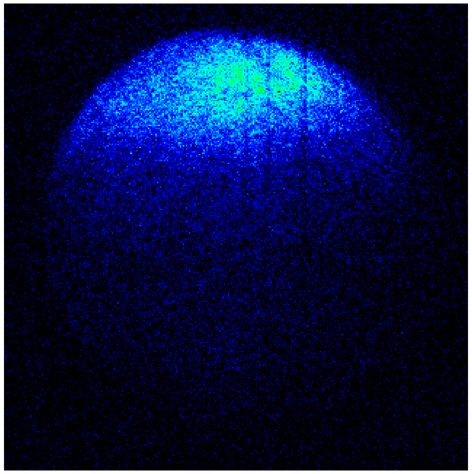
OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

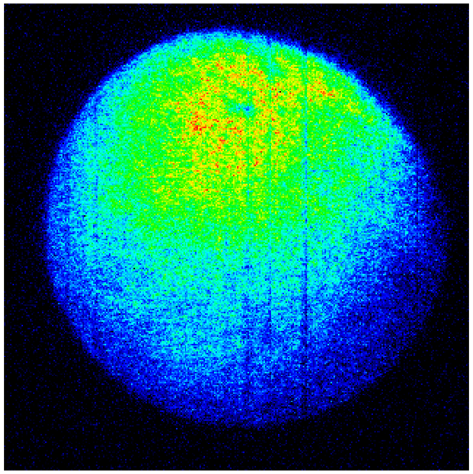
6-hole central
SOI=80



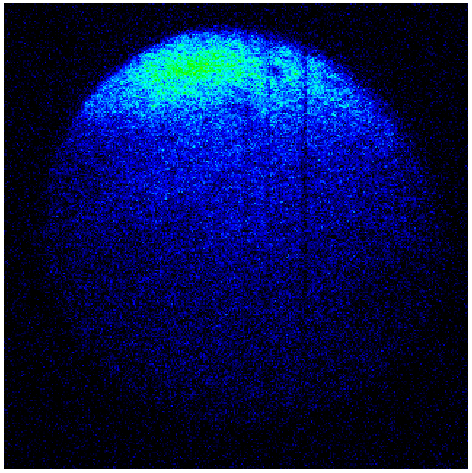
6-hole side
SOI=80



5-hole side up
SOI=80



5-hole side down
SOI=80



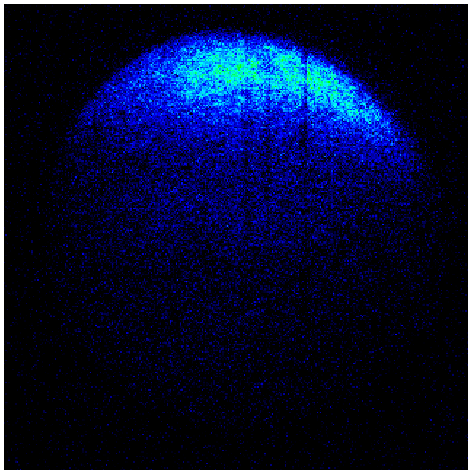
24 deg CA ATDC

0 500

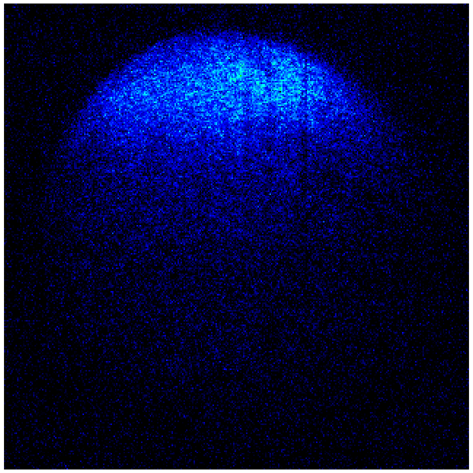
OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

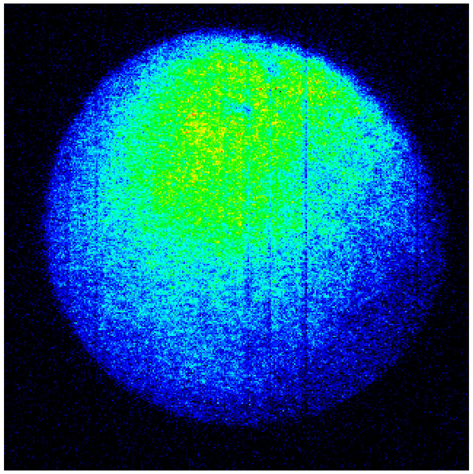
6-hole central
SOI=80



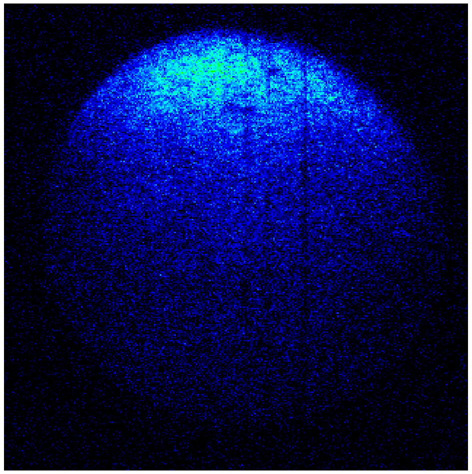
6-hole side
SOI=80



5-hole side up
SOI=80



5-hole side down
SOI=80



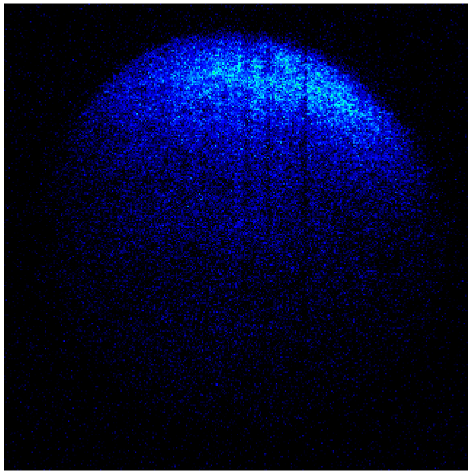
26 deg CA ATDC

0 500

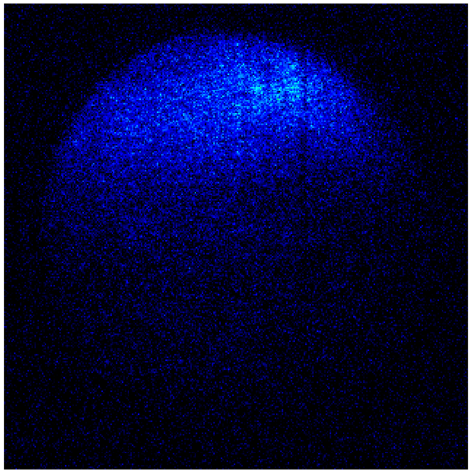
OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

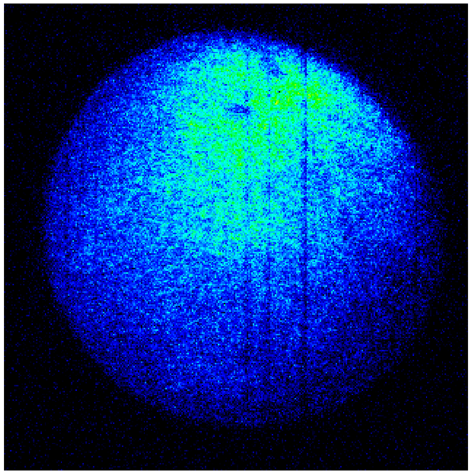
6-hole central
SOI=80



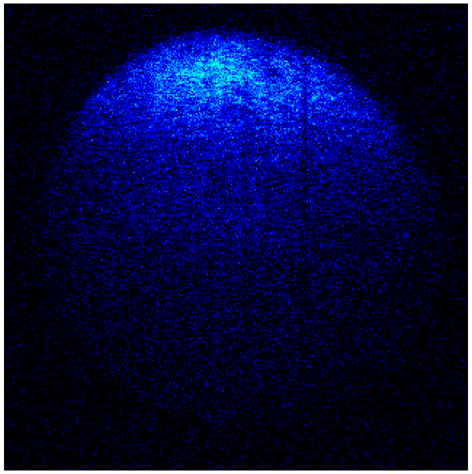
6-hole side
SOI=80



5-hole side up
SOI=80



5-hole side down
SOI=80



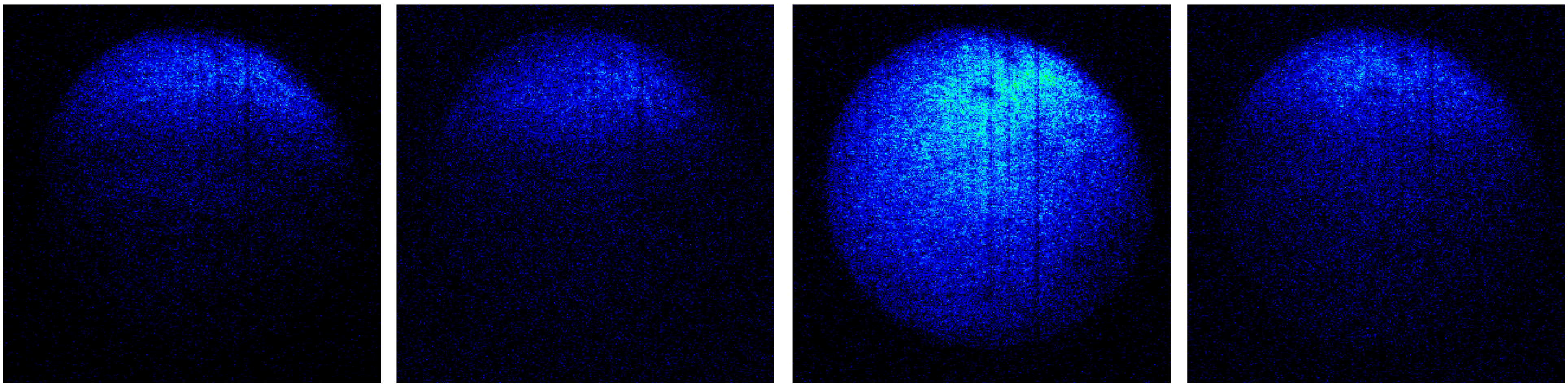
28 deg CA ATDC

0 500

OH* Intensity [a.u.]

Experimental results
Sample images (2000 RPM 8 bar IMEP)

6-hole central SOI=80 | **6-hole side SOI=80** | **5-hole side up SOI=80** | **5-hole side down SOI=80**

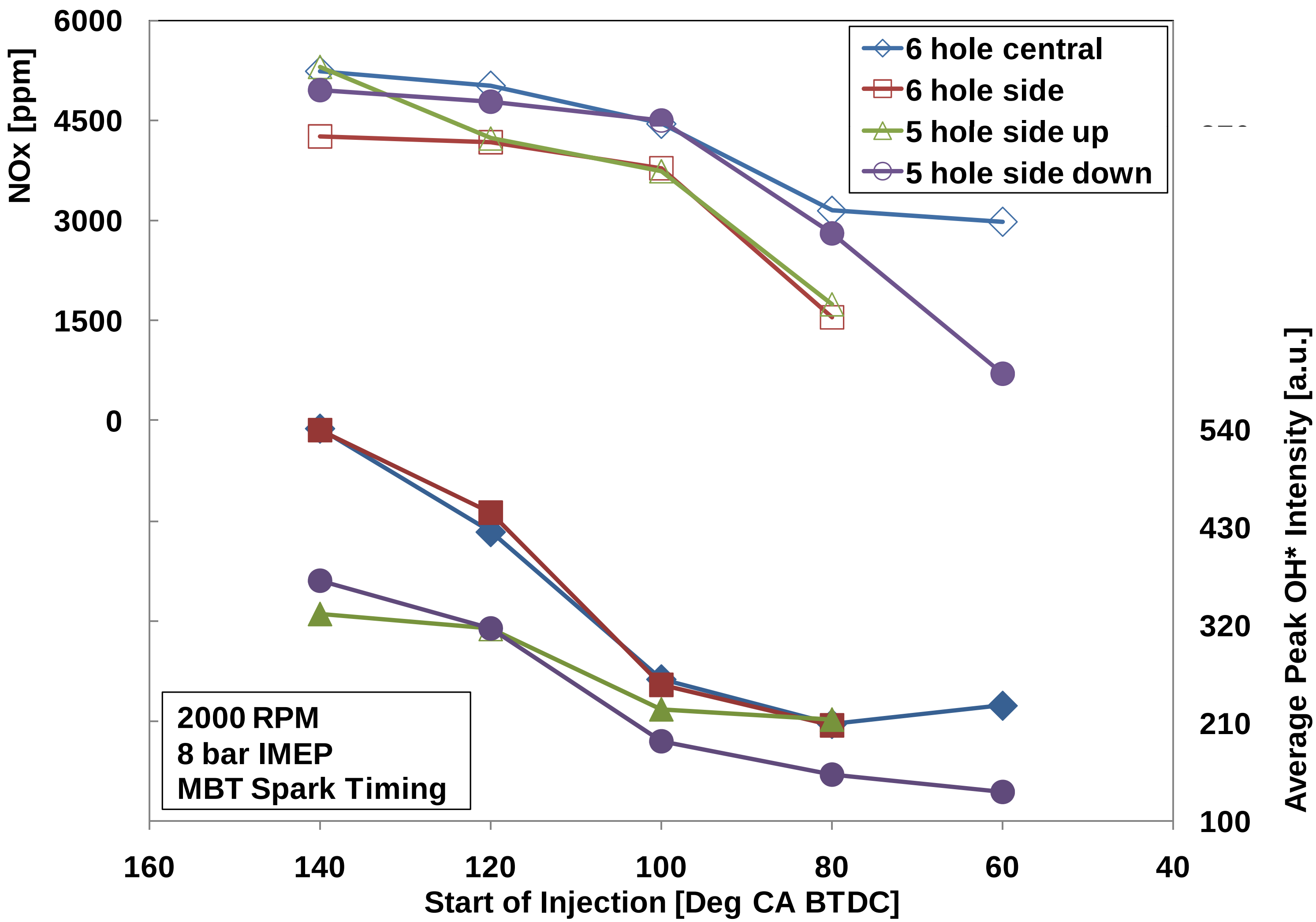


30 deg CA ATDC

0 — 500

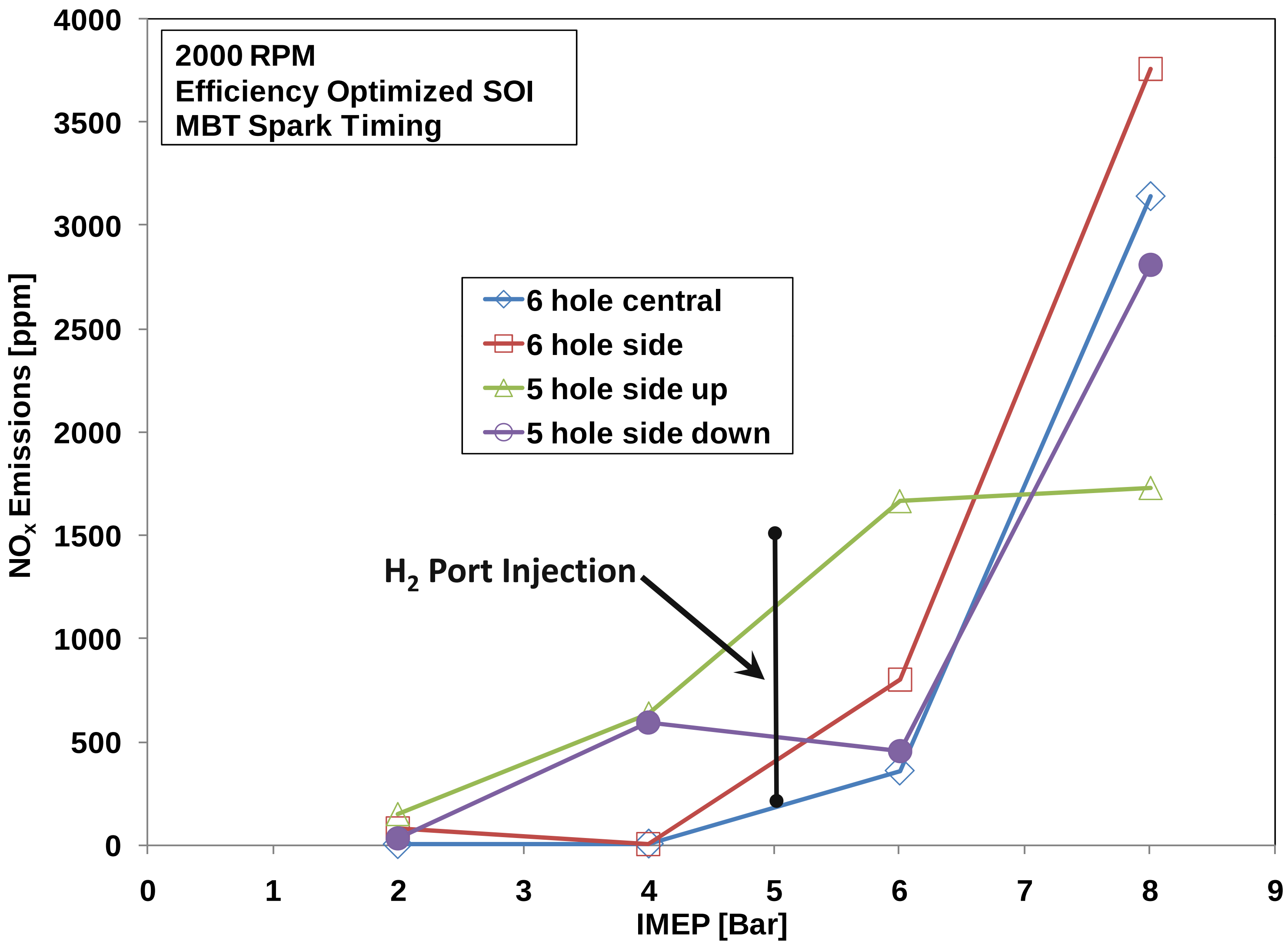
OH* Intensity [a.u.]

Technical accomplishments
Correlation between NO_x and endoscopic images



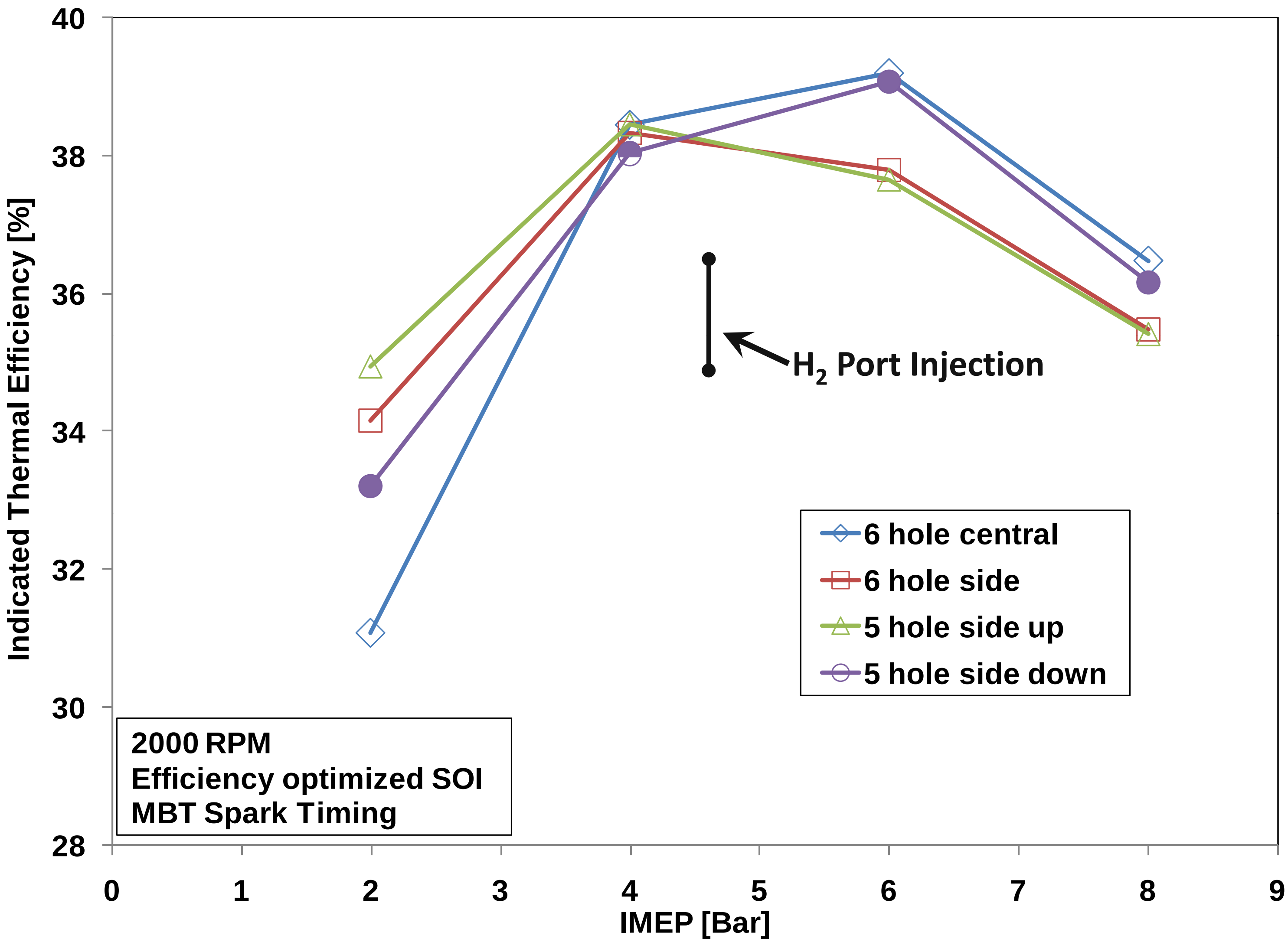
- Average Peak OH* Intensity explanation
- Good correlation

Progress



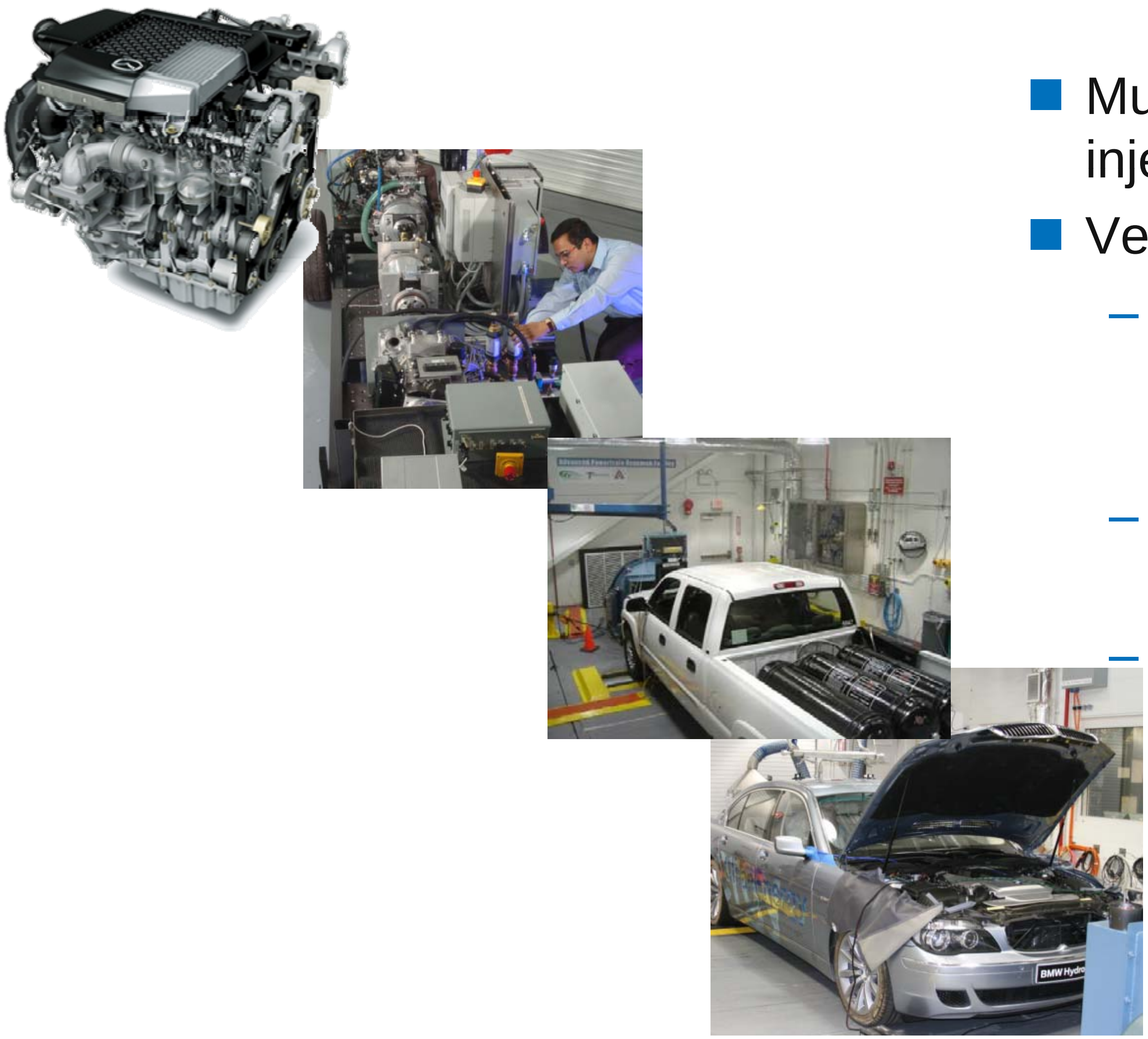
- Emissions levels comparable to port injection
- High loads – NO_x optimization potential

Progress



- Improvement compared to port injection
- Low loads – efficiency optimization potential

Technology Transfer



- Multi-cylinder hydrogen direct-injection engine proposal
- Vehicle level application
  - Mobile Advanced Technology Testbed (MATT) concept studies
  - ETEC Silverado durability testing (NETL)
  - Development of test procedures with BMW Hydrogen 7 vehicles

Activities for Next Fiscal Year

- Evaluate custom designed injector nozzles
- Investigate in-cylinder NO_x reduction measures
  - Water injection
  - Cylinder charge motion (swirl)
- Expand operating regime to higher engine speeds
- Verify H_2-DI findings in a multi-cylinder DI engine (separate proposal for FY08)

Publications

- Recently published
  - Lohse-Busch, H.; Wallner, T. ‘Optimized operating strategy for a supercharged hydrogen powered 4-cylinder engine.’ JSAE/SAE Fuels and Lubricants. 2007.
  - Wallner, T.; Lohse-Busch, H.; Shidore, N. ‘Operating Strategy for a Hydrogen Engine for Improved Drive-Cycle Efficiency and Emissions Behavior.’ World Hydrogen Technology Convention. 2007.
- Upcoming events
  - Wallner, T.; Gurski, S; Lohse-Busch, H.; Duoba, M.; Thiel, W. ‘Challenges in Fuel Efficiency and Emissions Measurements for Hydrogen Vehicles.’ NHA Annual Hydrogen Conference. 2008.
  - Wallner, T.; Nande, A.; Naber, J. ‘Evaluation of Injector Location and Nozzle Design in a Direct-Injection Hydrogen Research Engine.’ SAE International Powertrains, Fuels and Lubricants Meeting. 2008.

Summary

- Hydrogen direct injection engine research seeks to develop a combustion concept with high engine efficiency and virtually zero emissions while maintaining the power density of current gasoline engines
- Main barriers are combustion anomalies with hydrogen port injection as well as trade-offs between NO_x emissions and power density and engine efficiency
- Several nozzle designs for hydrogen direct injection with central and side injector location have been tested
- 2% increase in engine efficiency with hydrogen direct injection compared to port injection without NO_x emissions penalty
- Further work will include evaluation of additional NO_x reductions measures (water injection, swirl etc.), expansion of operating regime and testing of advanced injection concepts with optimized custom nozzles

H_2 Internal Combustion Engine Research*

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