Argonne
NATIONAL LABORATORY

... for a brighter future

H_2 Internal Combustion Engine Research

*Towards 45% efficiency and Tier2-Bin5 emissions**

Project ID: ACE_09_Wallner

Thomas Wallner

Argonne National Laboratory

2009 DOE Merit Review

Washington, D.C.

May 19th 2009

DOE-Sponsor: Gurpreet Singh

*** This presentation does not contain any proprietary, confidential, or otherwise restricted information**

U.S. Department of Energy

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by The University of Chicago

Overview

Timeline

- Project start: 2005
- Project end: Ongoing project

Barriers

- Understand and optimize hydrogen direct injection engine operation
- Evaluate in-cylinder emissions reduction techniques
- Improve injector design

Budget

- Funding in FY08: 400k$
- Funding in FY09: 500k$
- Funding for FY10: 840k$ request

Partners

- Collaborators: Ford, Sandia
- Potential partner: BMW
- Injector supplier: Westport

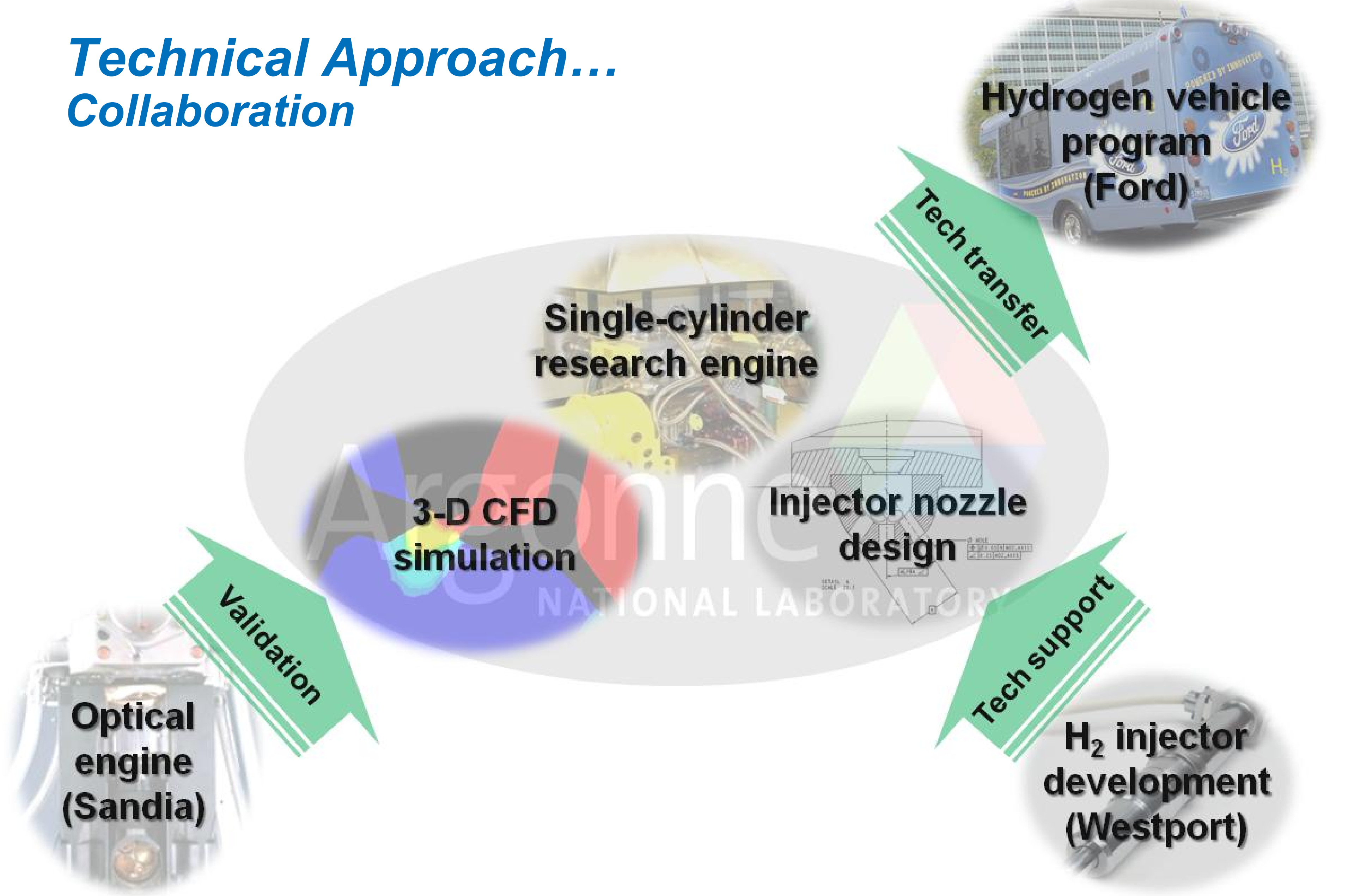
Objectives

- Overcome the trade-off between engine efficiency and NOx emissions in hydrogen direct injection (DI) operation
- Evaluate the NOx emissions reduction potential of in-cylinder measures (e.g. water injection, EGR) in hydrogen DI operation
- Assess the impact of injector nozzle geometry and injector orientation and design optimized configurations
- Investigate the potential of multiple injection strategies

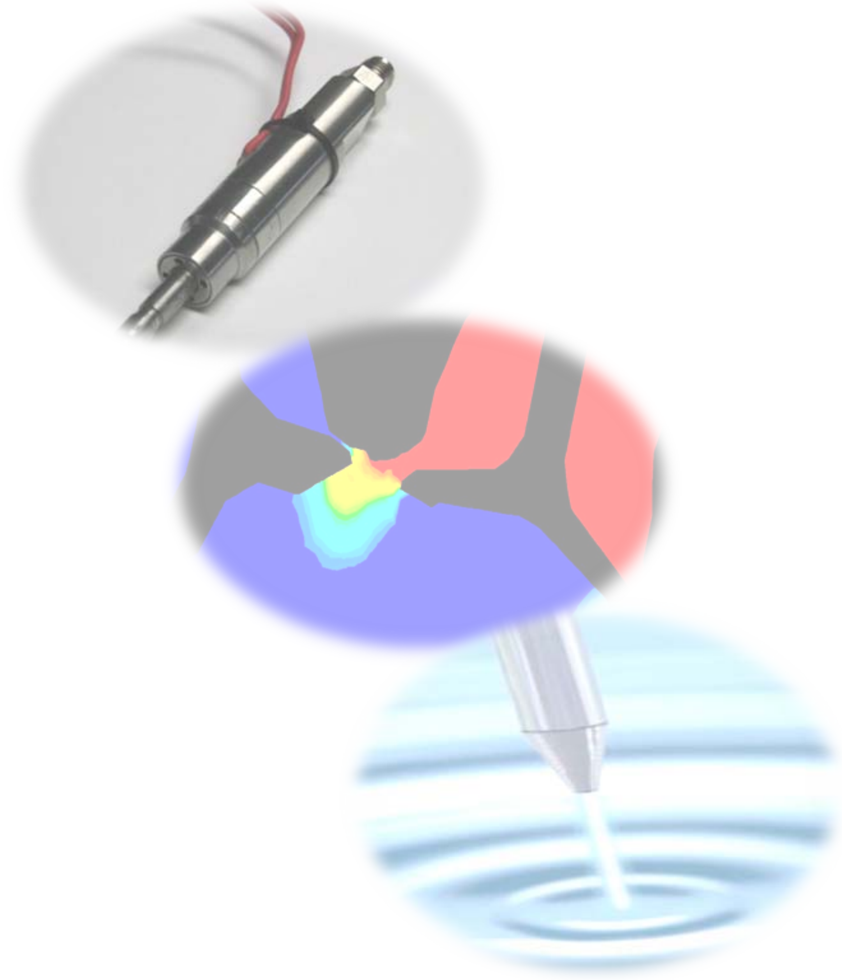
Milestones

- Correlation between OH* intensities from endoscopic measurement and NOx emissions established (**02/2008**)
- Comparative study of central versus side injector location completed (**05/2008**)
- Influence of injector jet direction analyzed for single and multiple injection cases (**07/2008**)
- Water injection demonstrated as an effective technique for NOx emissions reduction (**09/2008**)
- 3-D CFD simulation useable for optimization (**03/2009**)
- Evaluation of NOx emissions reduction potential of exhaust gas recirculation (**expected 05/2009**)
- Implementation of piezo-actuated hydrogen DI injectors (**expected 07/2009**)

Technical Approach…
Collaboration

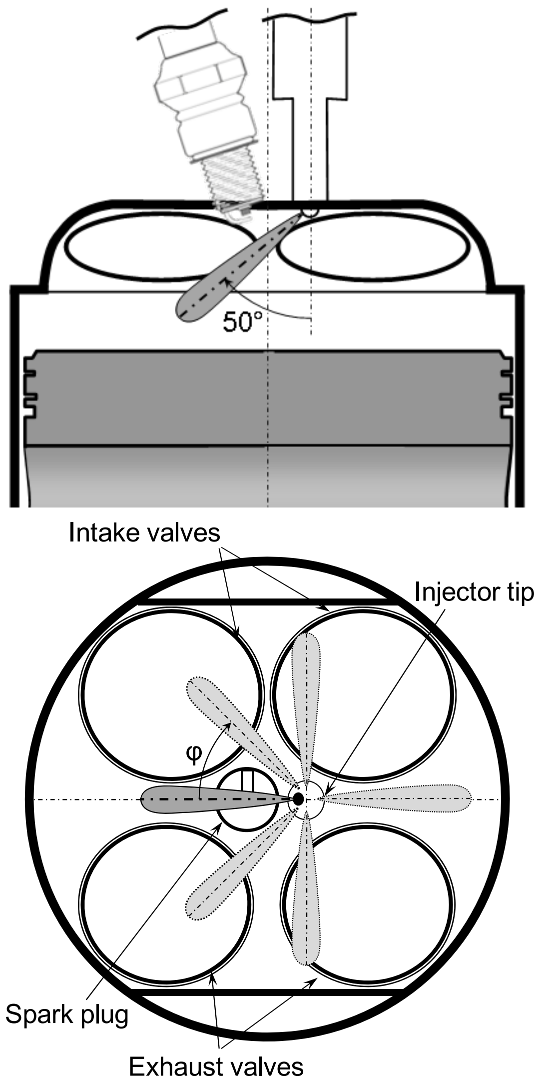


Technical accomplishments/progress/results
Overview



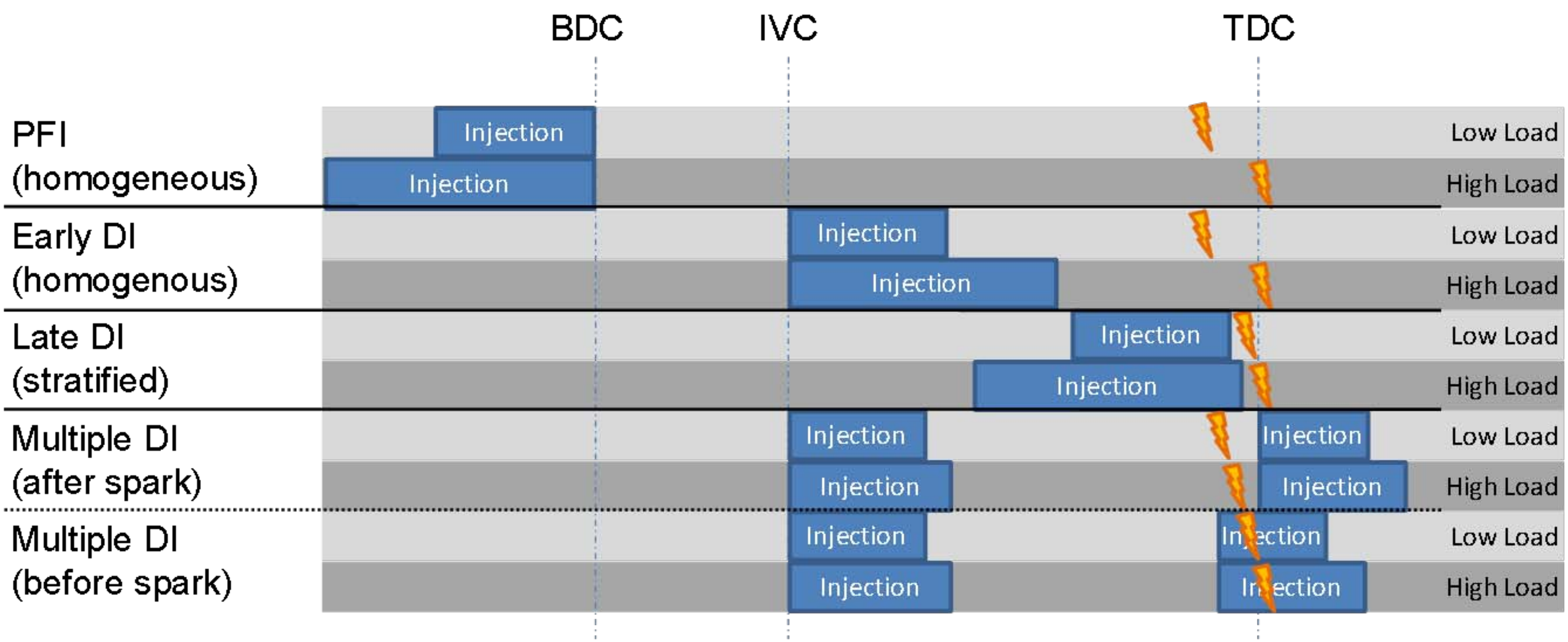
- **Improve injector design**
  - Single-hole nozzle injector tested to evaluate injection direction for single and multi-pulse injection
- **Understand and optimize H_2 DI**
  - 3-D CFD simulation integrated to support data analysis and development of advanced configurations
- **In-cylinder emissions reduction**
  - Water injection study to establish basis for exhaust gas recirculation (EGR) tests completed
  - EGR system for uncooled and cooled testing integrated

Single-hole nozzle design
Simple configuration with great flexibility



- **Motivation to test single hole nozzle**
  - Easy to machine
  - No jet-to-jet interaction
  - Useable in central and side injector location
  - Basic understanding of jet penetration
- **Tests performed (central injection)**
  - Single injection with variation of
    - Start of Injection (SOI)
    - Injection Angle
  - Multiple injection with variation of
    - Injection Angle
    - Fuel split between injections

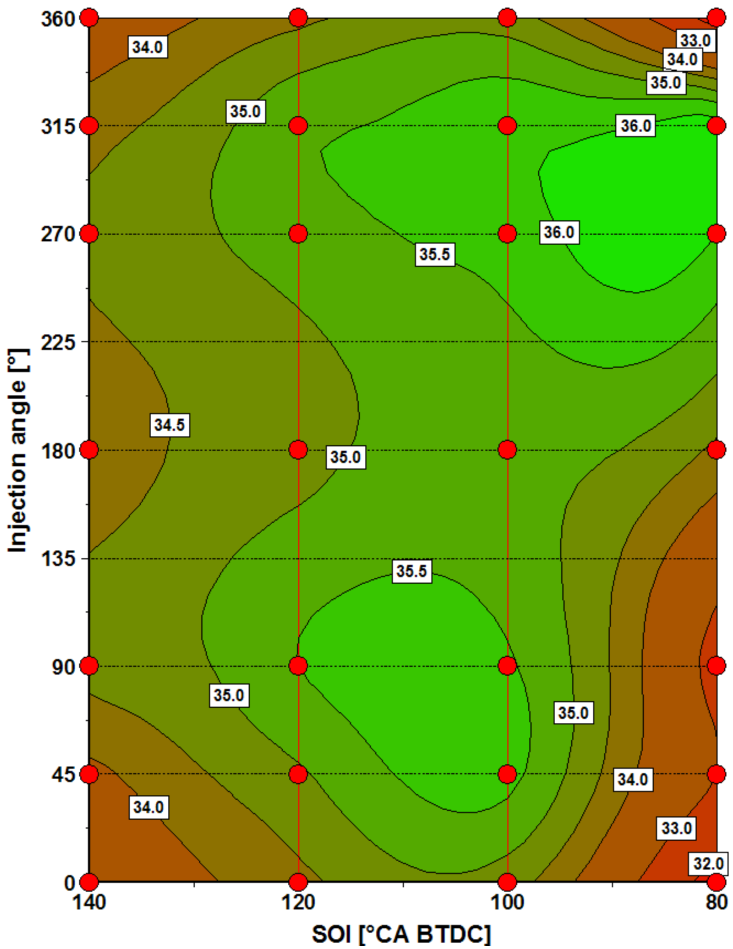
Multiple injection strategies
Overview of injection strategies



- PFI used as early baseline
- Early DI – low emissions at low load
- Late DI – reduced emissions at high load
- Multiple injection – reduced emissions and peak pressure at high load

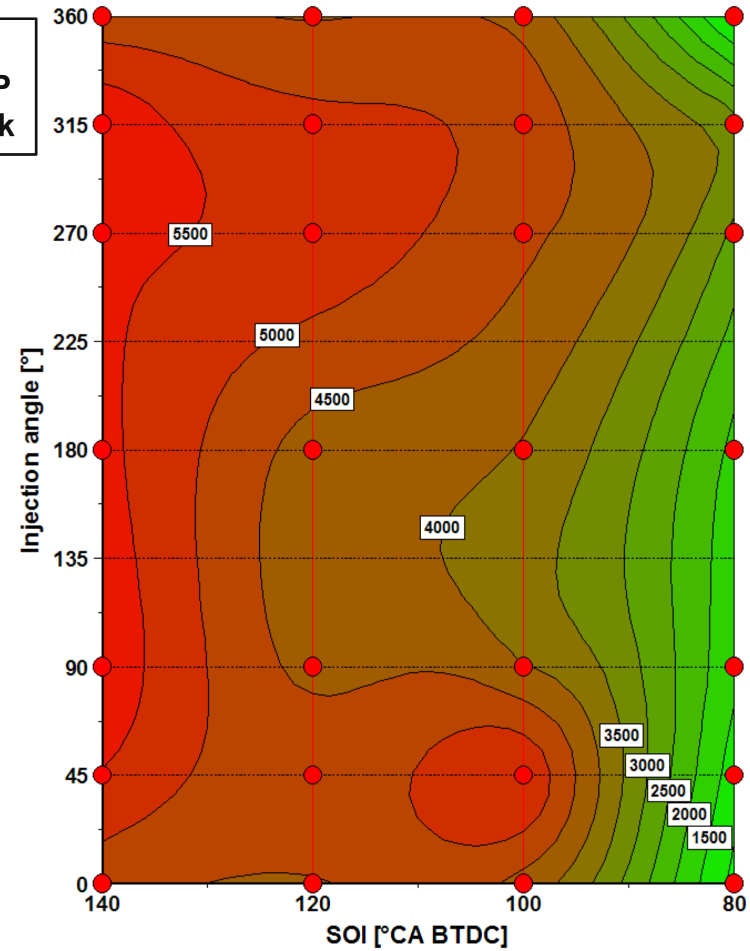
Single injection at high engine load
4% efficiency change with angle – Late SOI reduces NOx

Indicated thermal efficiency [%]

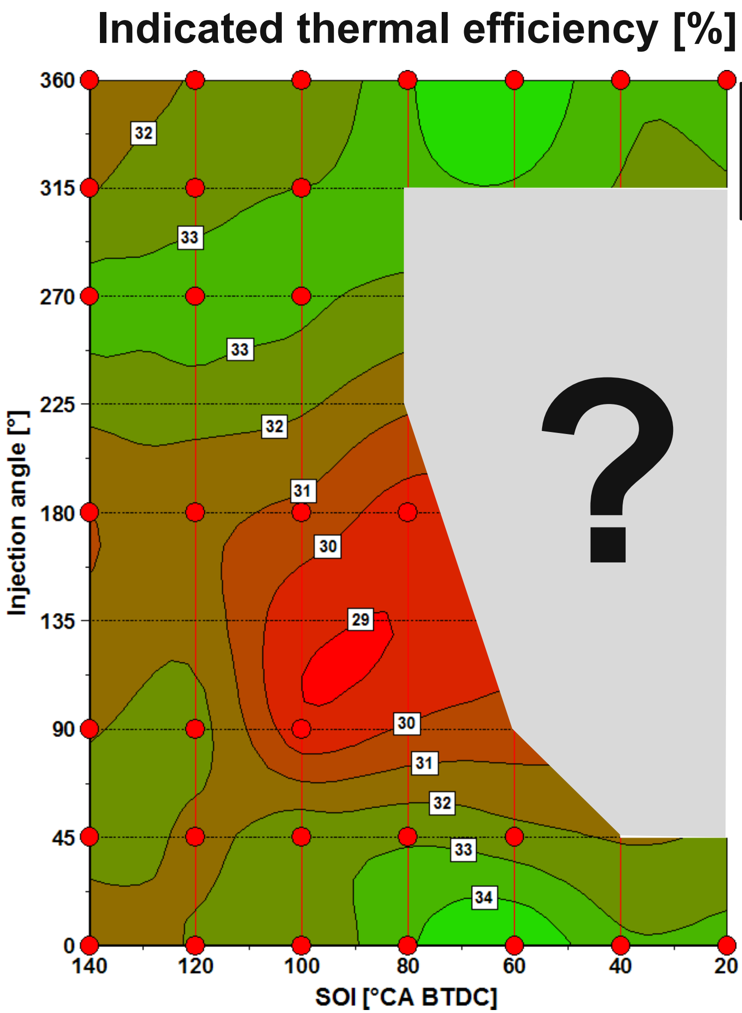


2000 RPM
8 bar IMEP
MBT Spark

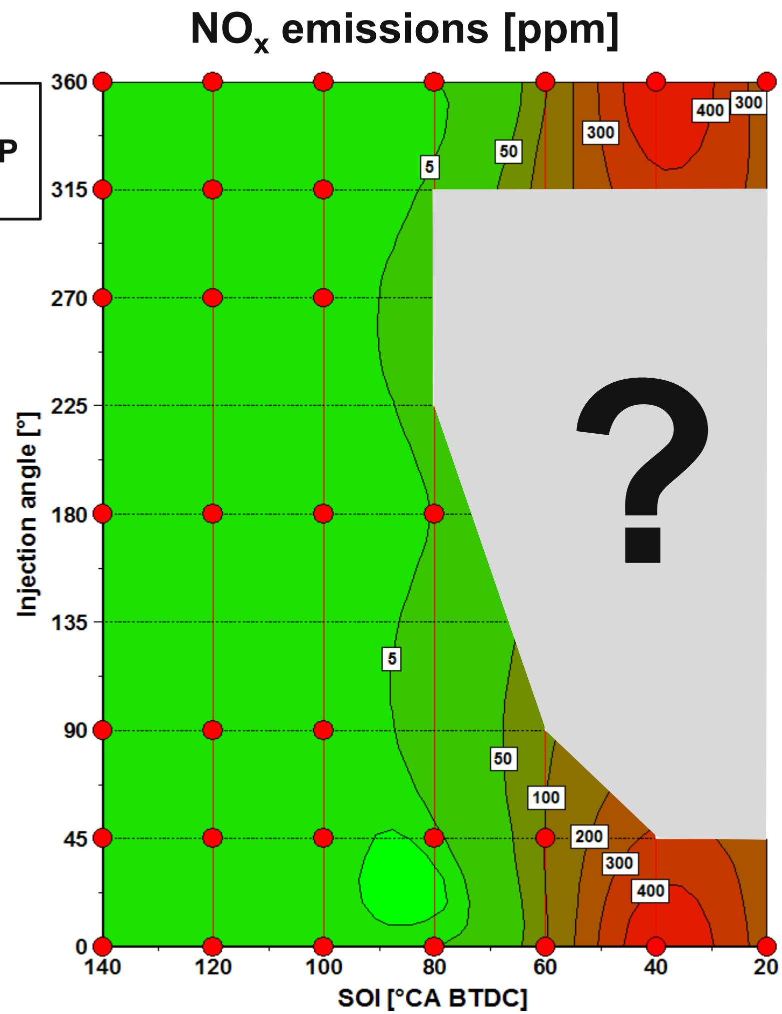
NO_x emissions [ppm]



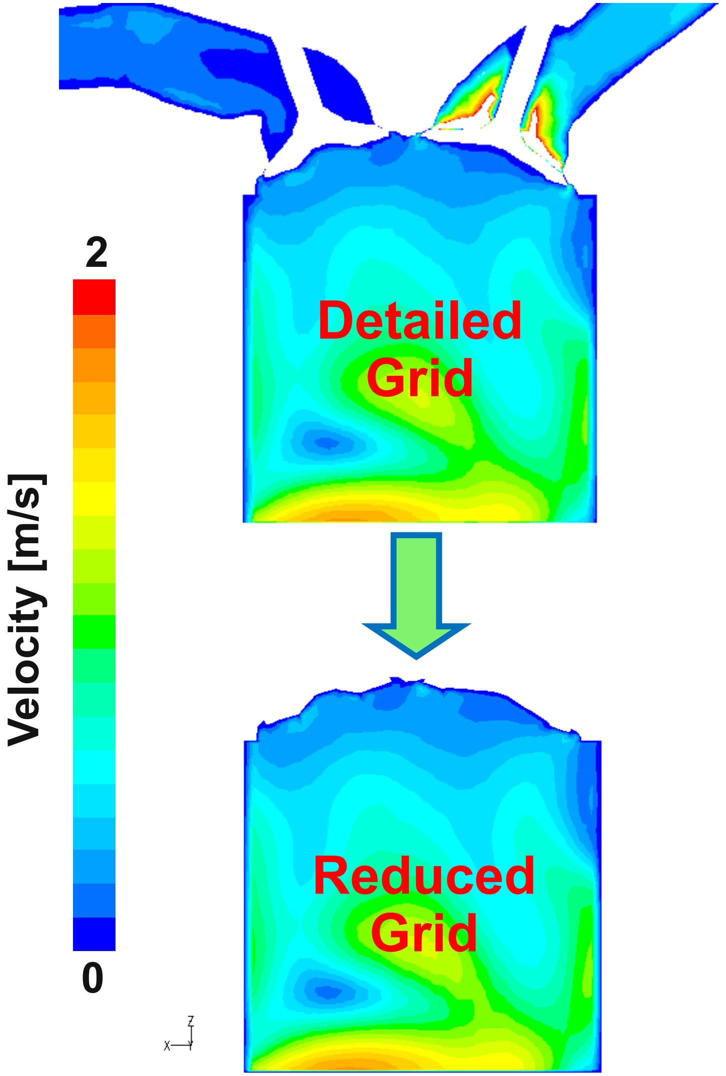
Single injection at low engine load
5% efficiency change with angle – SOI dominant for NOx



2000 RPM
2.5 bar IMEP
MBT Spark

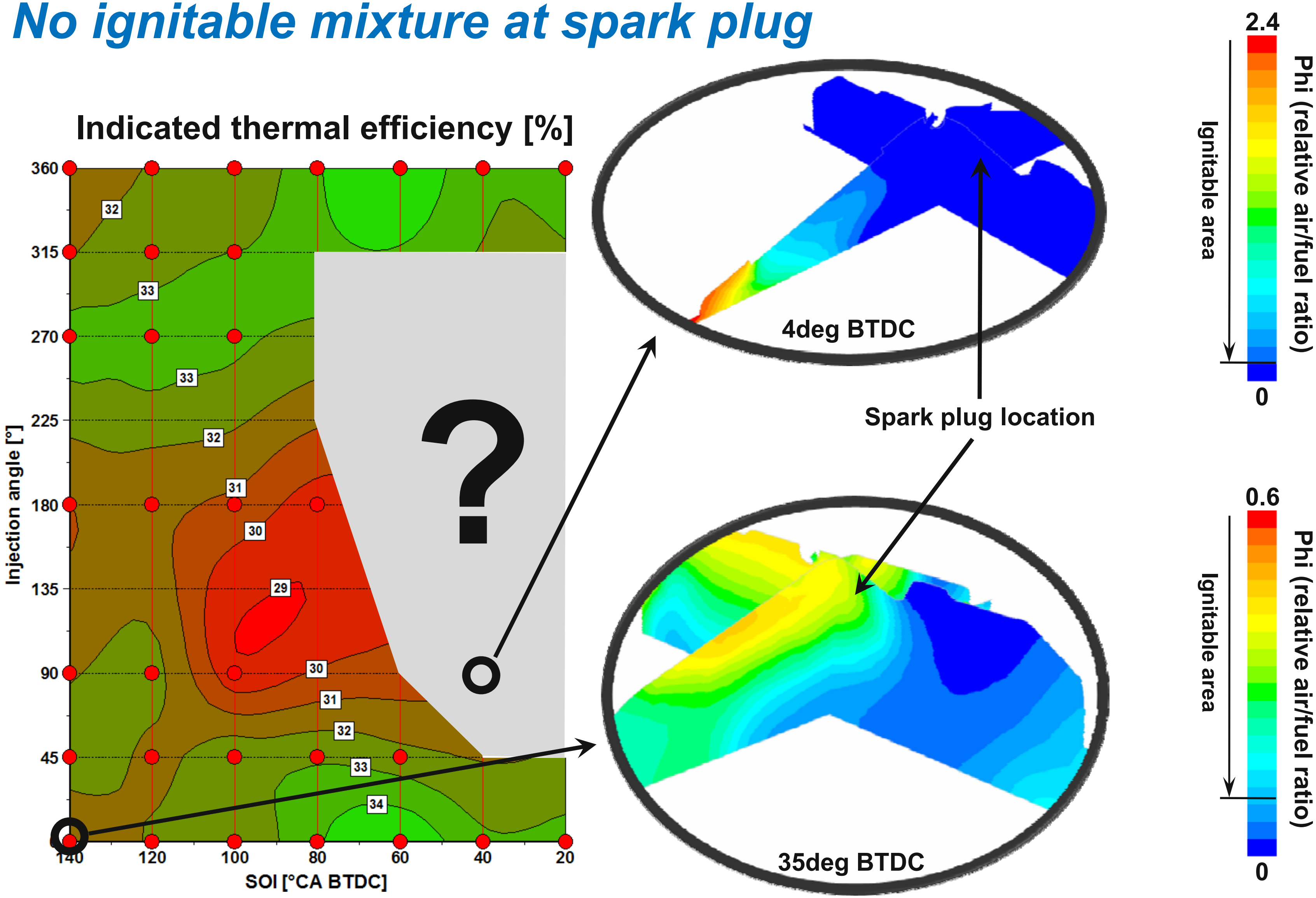


Merge experiment with simulation
3-D CFD results using a commercial code



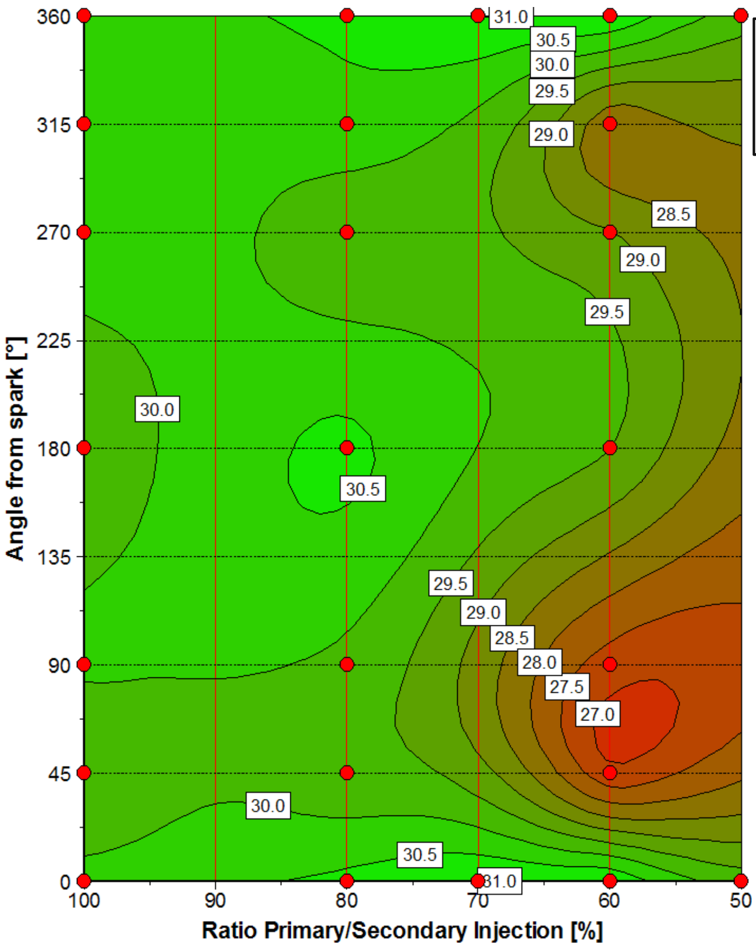
- **Motivation to 3-D CFD simulation**
  - Further insight into the mixture formation process
  - Straightforward validation of 3D-CFD simulation using data from Sandia National Laboratory
  - Support development and optimization of advanced mixture formation concepts
- **Approach**
  - Use detailed grid and experimental data to correctly simulate gas exchange (once for each load point)
  - Switch to reduced grid for compression and injection process
  - Use reduced grid for variation calculations

How does simulation help?
No ignitable mixture at spark plug



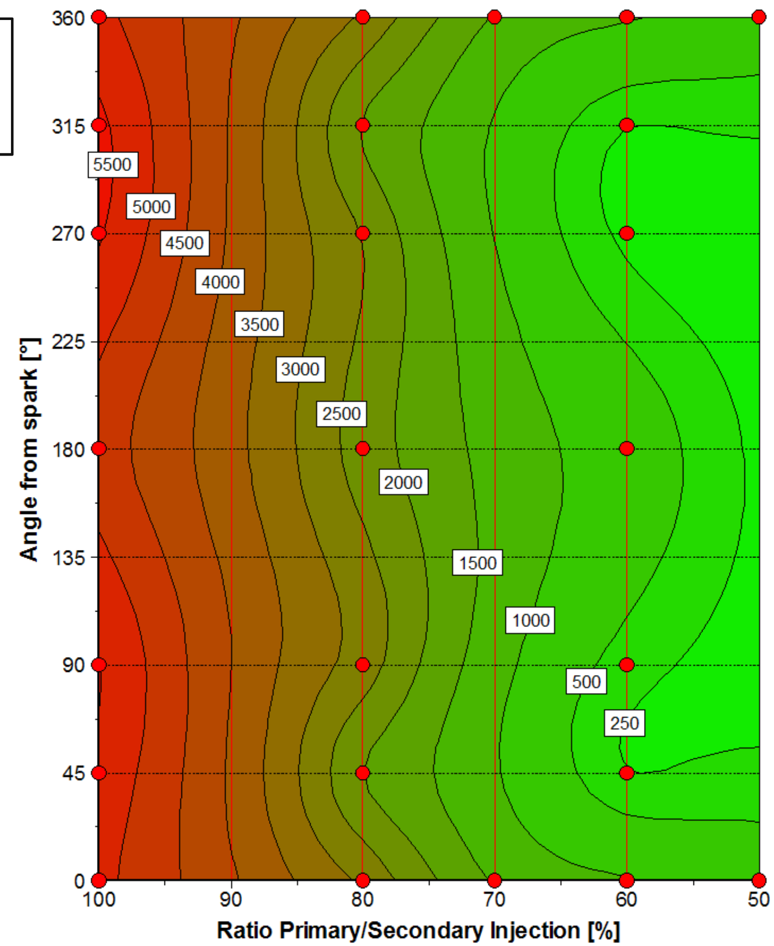
Multiple injection operation
Angle impacts efficiency – Ratio reduces NOx up to 95%

Indicated thermal efficiency [%]

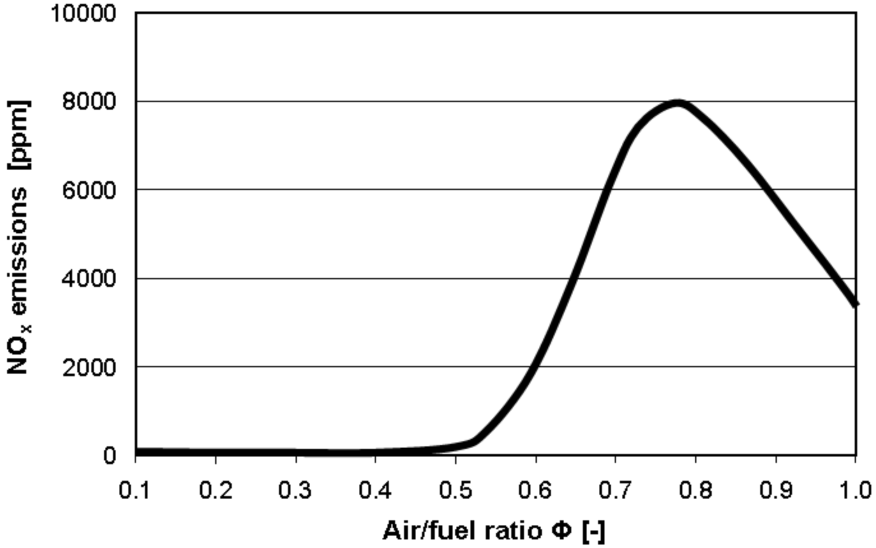


1000 RPM
6 bar IMEP
MBT Spark

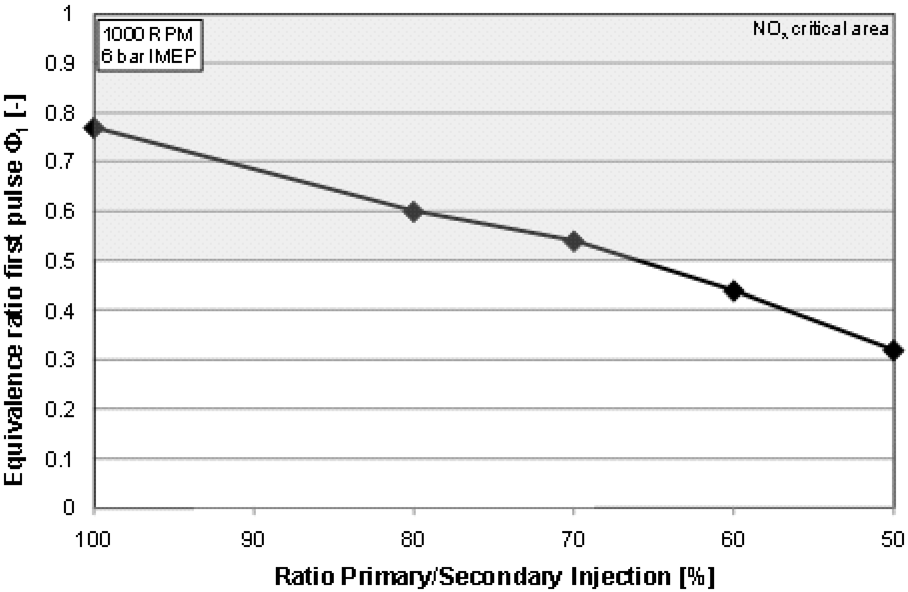
NO_x emissions [ppm]



Multiple injection operation
Hypothesis for NOx emissions reduction

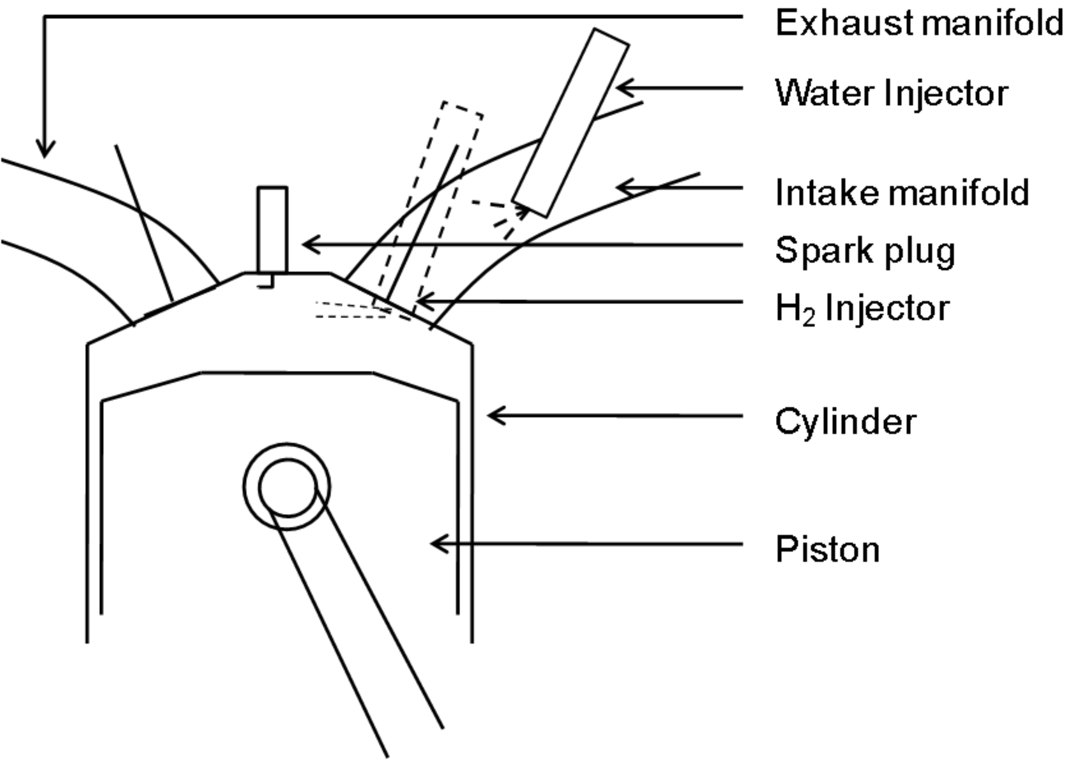


- **Primary injection**
  - Very low NOx emissions if air/fuel ratio of primary pulse is lower than 0.5



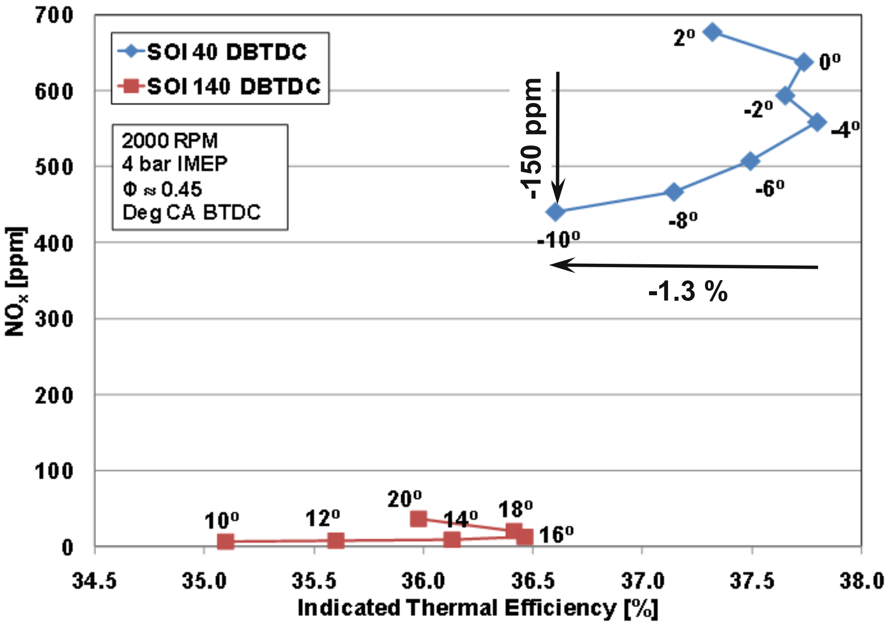
- **Secondary injection**
  - Occurs during combustion
  - Hydrogen burns at stoichiometric air/fuel ratio avoiding NOx critical regime (0.5<Φ<1)

Water injection
Setup and strategy

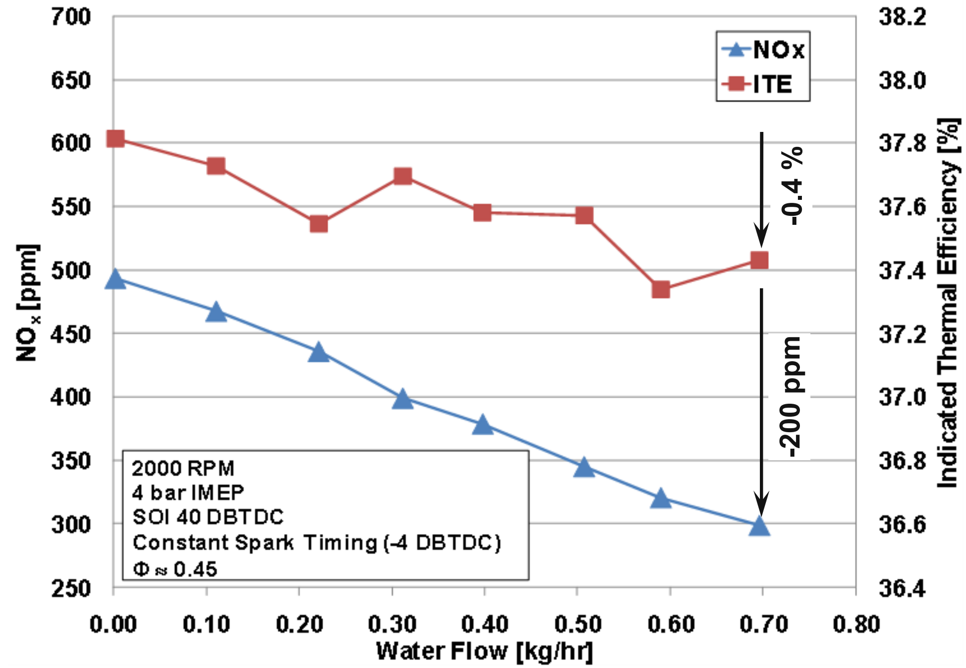


- **Water injection**
  - Use production gasoline injector to accurately control water injection into the intake manifold
  - Coriolis meter used to measure water flow
  - Water injection tested as benchmark for effectiveness of exhaust gas recirculation

Water injection at medium engine load
Comparison of effectiveness with spark retard

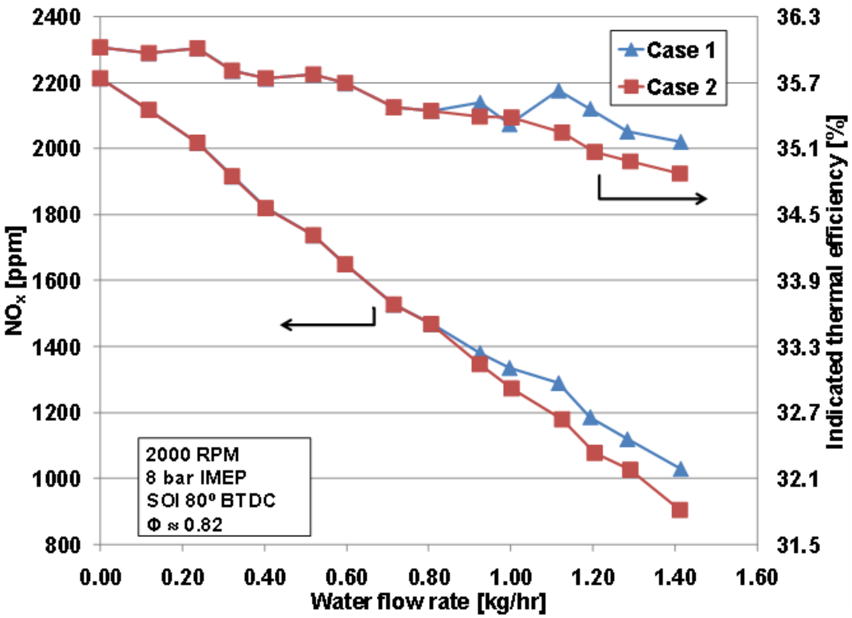


- **Spark retard**
  - 25% NOx emissions reduction with 1.3% efficiency loss

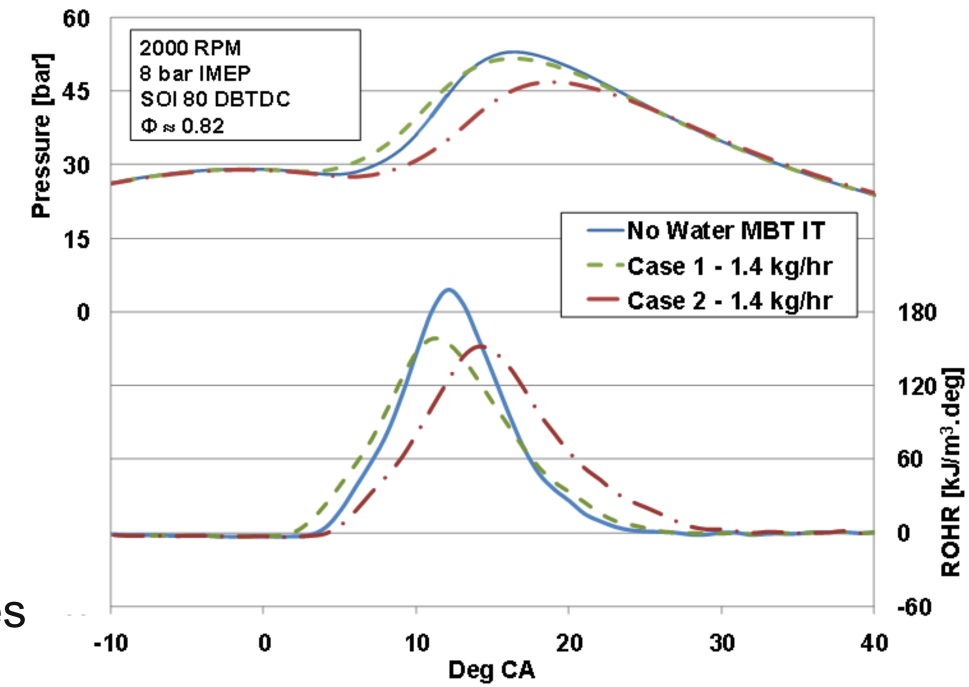


- **Water injection**
  - 40% NOx emissions reduction with 0.4% efficiency loss

Water injection at high engine load
Emissions reduction potential and impact on combustion

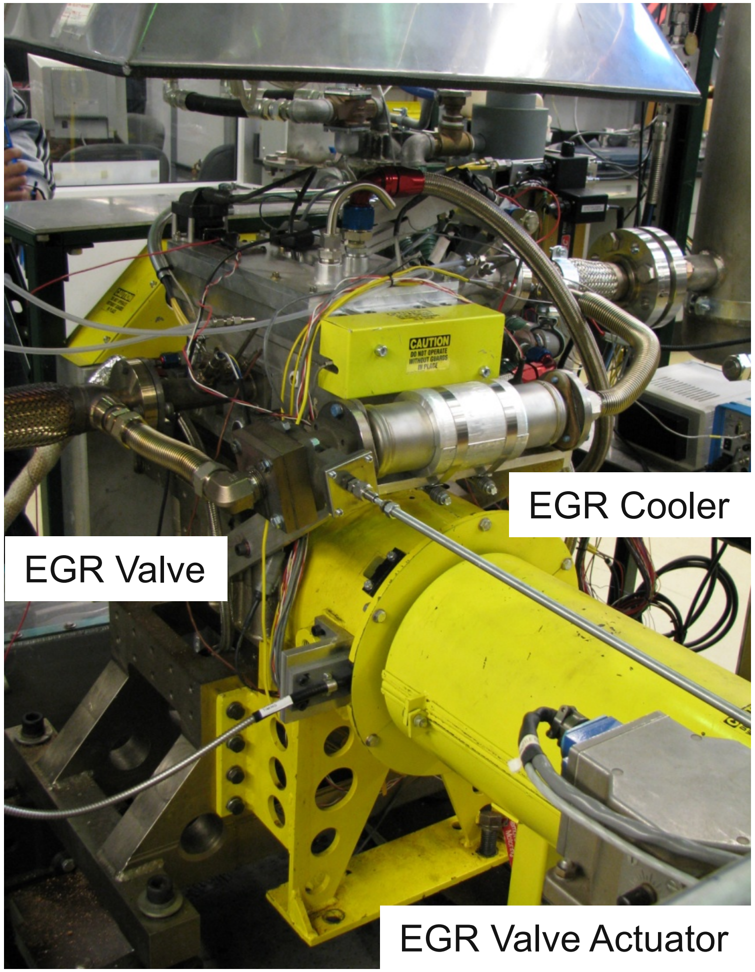


- **Water injection**
  - 55% NOx emissions reduction with 0.8% efficiency loss



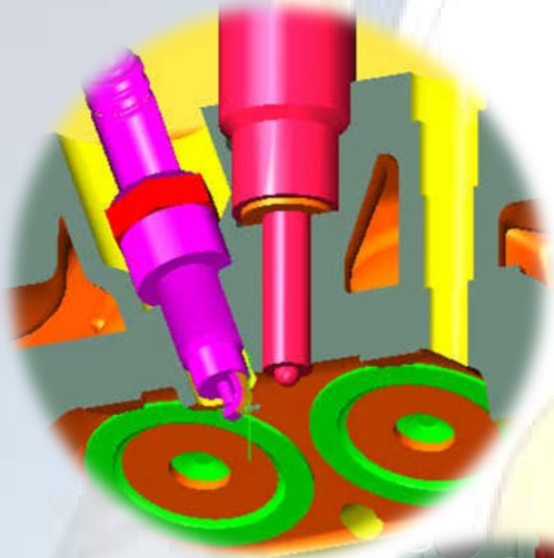
- **Combustion with water injection**
  - Water injection reduces peak heat release rate, therefore temperatures and NOx emissions

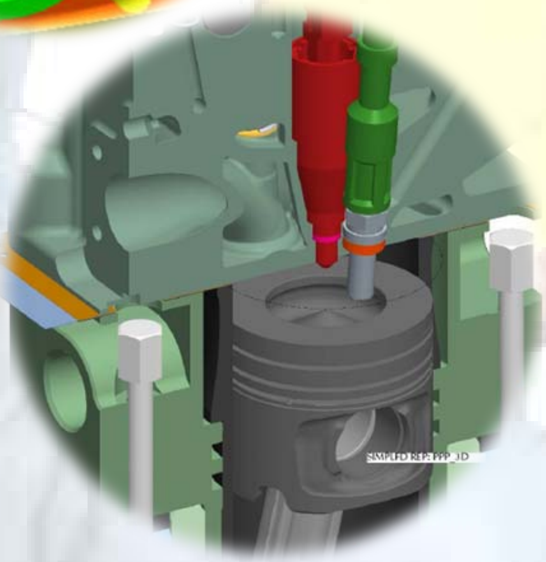
Exhaust gas recirculation
Setup complete and tests in progress



- **Exhaust gas recirculation**
  - Setup using automotive EGR valve
  - Intake and exhaust pressure individually adjustable
  - Integrated automotive EGR cooler
- **Approach**
  - Evaluate EGR rate determination strategies in hydrogen operation
  - Assessment of impact of EGR rates and temperatures on
    - NOx emissions
    - Engine efficiency
    - Combustion stability

Future work





- Complete assessment of exhaust gas recirculation for NOx emissions reduction
- Implement and test piezo-driven hydrogen DI injectors at elevated engine speeds (single and multiple injection)
- Upgrade research engine to optimized bore/stroke ratio
- Expand hydrogen combustion strategy development to a ‘Diesel-style’ combustion chamber with flat cylinder head and piston bowl

Summary

- Engine efficiency and NOx emissions is very sensitive to mixture formation strategy, in particular injector design, location, as well as injection strategy
- 3-D CFD simulation and optical engine work are ideally suited to provide further understanding of hydrogen mixture formation processes
- Multiple injection as well as water injection can significantly reduce NOx emissions at high efficiency levels
- Future work will focus on exhaust gas recirculation, integration of higher flow, piezo activated injectors and assessment of Diesel-style combustion chamber design