WE START WITH YES.

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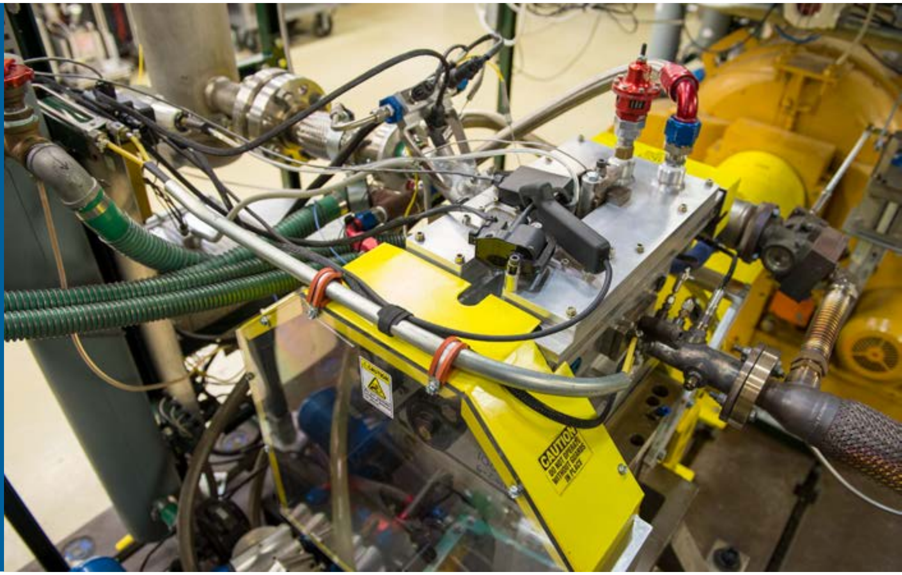
EFFICIENCY-OPTIMIZED DUAL FUEL ENGINE WITH IN-CYLINDER GASOLINE/CNG BLENDING



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Project ID: FT046

DOE Sponsor: Kevin Stork

June 9, 2016

ACKNOWLEDGEMENT OF FEDERAL SUPPORT AND DISCLAIMER

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OVERVIEW

Timeline

- Project start: October 2014
- Project end: March 2017
- Percent complete: 50%

Budget

- Total project funding
  - DOE: $1M
  - 20% in-kind cost share
- Funding in FY15: $512k
- Funding in FY16: $320k
- Funding in FY17: $168k

Partners

- FCA US LLC
- Ford Motor Company

Barriers

- Limited NG infrastructure and refueling station availability currently presents one of the main barriers to large-scale introduction of CNG in light-duty (LD) applications.
- Existing data and models for engine efficiency, emissions, and performance based on fuel properties and fuel-enabled engine designs or operating strategies are inadequate.

RELEVANCE

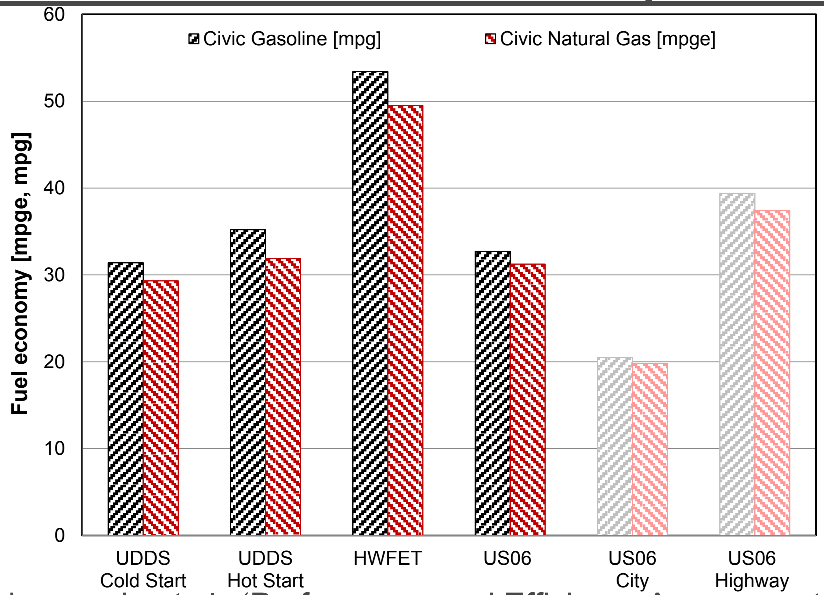
- DOE ARPA-e MOVE is working towards aggressive goals for natural gas at-home-refueling and on-board storage
- Today's NG vehicles have lower fuel economy (FE) compared to gasoline counterparts despite the higher knock resistance of natural gas
- Bi-fuel vehicles use natural gas until depleted and then switch to gasoline thereby leaving overall fuel consumption reduction potential untapped

ARPA-e MOVE program goals*

Component	Current	Needed
At-home refueling	$4,000	$ 500
On-board storage	$3,500	$1,500
Balance of system	$3,500	$1,000
Installation	$1,500	$1,000
Total	$12,500	$4,000

*ARPA-e MOVE program overview. 2012.

Gasoline/NG Vehicle FE Comparison *



*Anderson, J., et al., 'Performance and Efficiency Assessment of a Production CNG Vehicle Compared to Its Gasoline Counterpart,' SAE Paper 2014-01-2694, 2014, doi:10.4271/2014-01-2694.

PROJECT OBJECTIVES

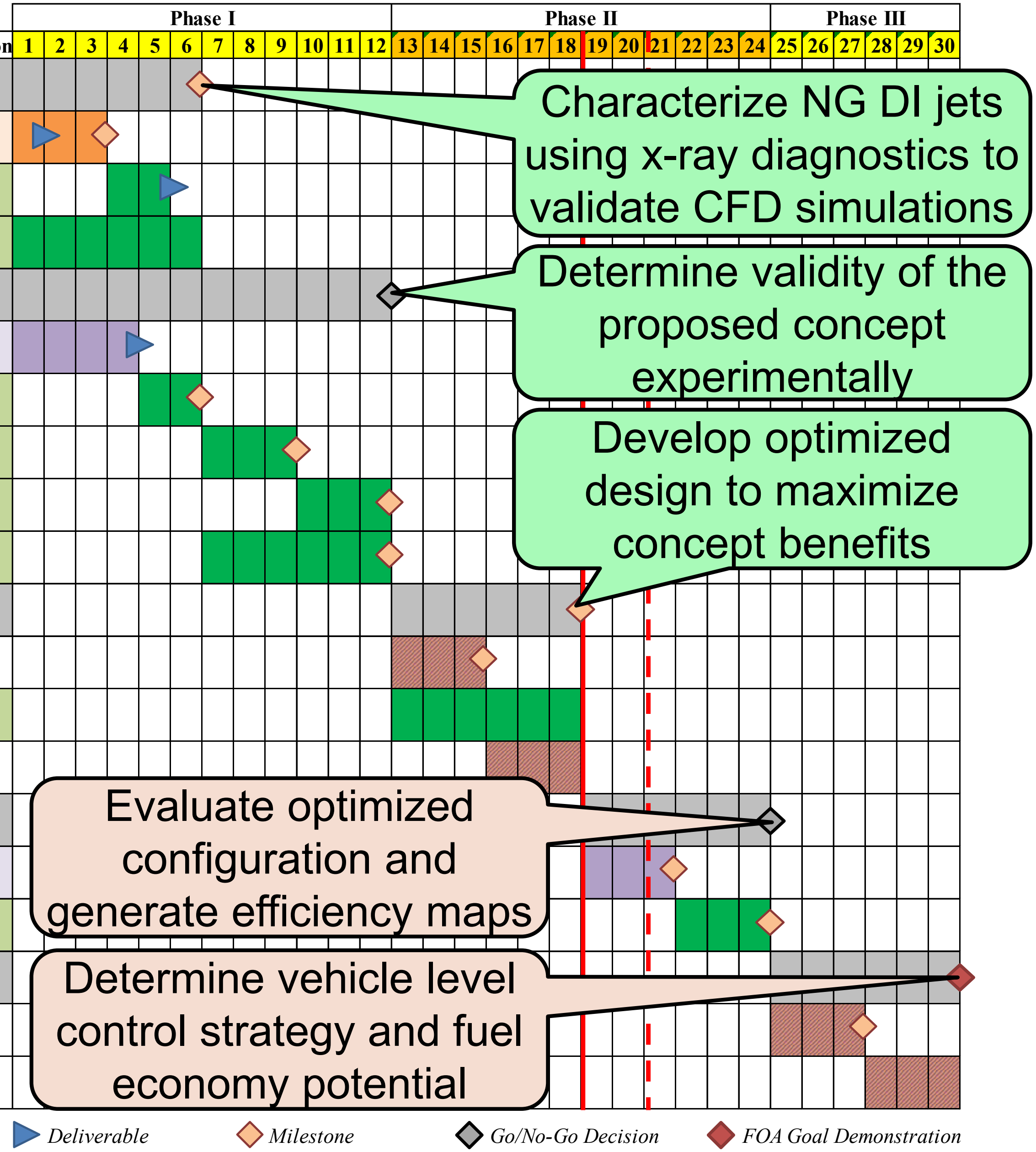
- **What?**
  - Demonstrate the benefits of natural gas direct injection and targeted in-cylinder gasoline/CNG blending on engine efficiency and performance
  - Develop vehicle level blending strategies to maximize attainable fuel economy benefits adhering to limited on-board NG supply constraints
- **Why?**
  - Reduce petroleum consumption of light-duty spark-ignition engine vehicles by at least 50%
- **How?**
  - Petroleum displacement
  - Relative engine efficiency improvement in excess of 10%
  - Retrofitability requirements
  - Anticipated payback period of less than 36 months
  - 10% improvement in power density over the PFI baseline

MILESTONES AND DECISION POINTS

Month/Year	Description	Status
Dec 2014	NG DI Hardware available for integration on research engine	Completed
March 2015	Injector gas jet characteristics validated against X-ray data	Completed
June 2015	Baseline maps established with neat fuels	Completed
Sept 2015	Baseline maps established in blended operation	Completed
Sept 2015	Predictive engine simulation validated against experimental data	Completed
Sept 2015	***Successful demonstration of potential of blended approach***	***Completed***
Dec 2015	Design criteria and development targets quantified	Completed
March 2016	Hardware freeze for optimized combustion system design	Completed
June 2016	Optimized hardware available for implementation	
Sept 2016	Performance established with optimized configuration	
Sept 2016	***Efficiency improvement of optimized system demonstrated***	
Dec 2016	Vehicle level control strategy identified	
March 2017	***Demonstrate FOA Project Goals***	

APPROACH

Task	Title	Partner	Duration
1	**Characterization of NG DI injector**		**6**
1.1	Procure/provide NG DI hardware	Chrysler	3
1.2	Characterize CNG jets using Argonne's X-ray diagnostics	Argonne	2
1.3	Perform 3D-CFD simulations to validate gaseous jet characteristics	Argonne	6
2	**Evaluation of experimental baseline and concept potential**		**12**
2.1	Design/modify cylinder head to accommodate NG DI hardware	Ford	4
2.2	Implement NG DI hardware on single-cylinder engine	Argonne	2
2.3	Develop baseline engine maps (gasoline, CNG)	Argonne	3
2.4	Develop baseline engine maps (blended operation)	Argonne	3
2.5	Simulate mixture formation and combustion process	Argonne	6
3	**Virtual combustion system optimization**		**6**
3.1	Determine evaluation criteria/development targets	All	3
3.2	Perform simulations to determine optimized engine configuration	Argonne	6
3.3	Evaluate design options/feasibility	All	3
4	**Experimental validation of optimized combustion system**		**6**
4.1	Design/build optimized engine hardware	Ford	3
4.2	Perform engine tests on optimized hardware	Argonne	3
5	**Vehicle level analysis and cost assessment**		**6**
5.1	Develop vehicle level strategy/estimate vehicle level potential	All	3
5.2	Perform cost analysis	All	3



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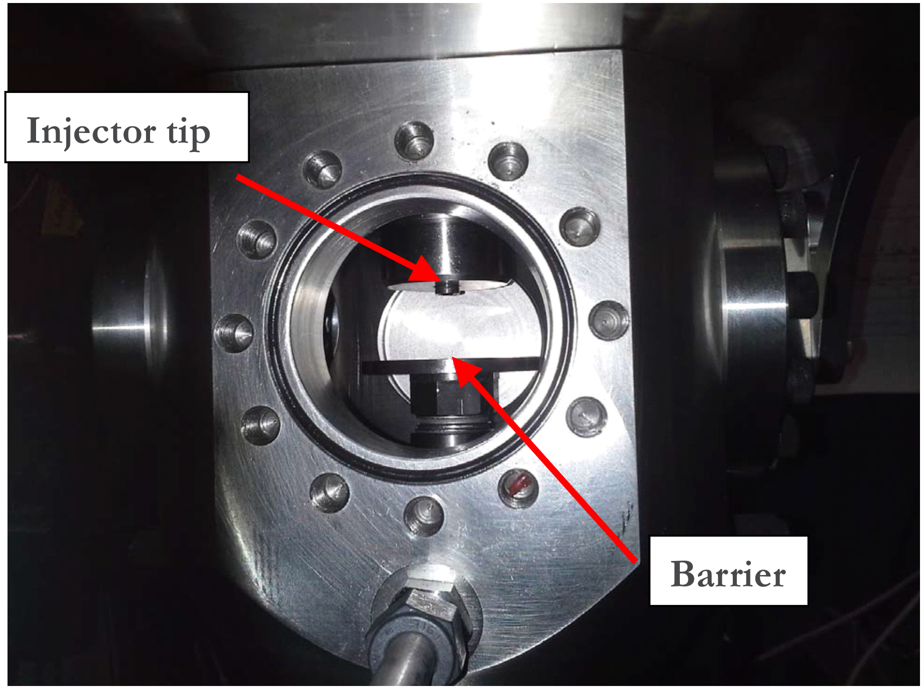
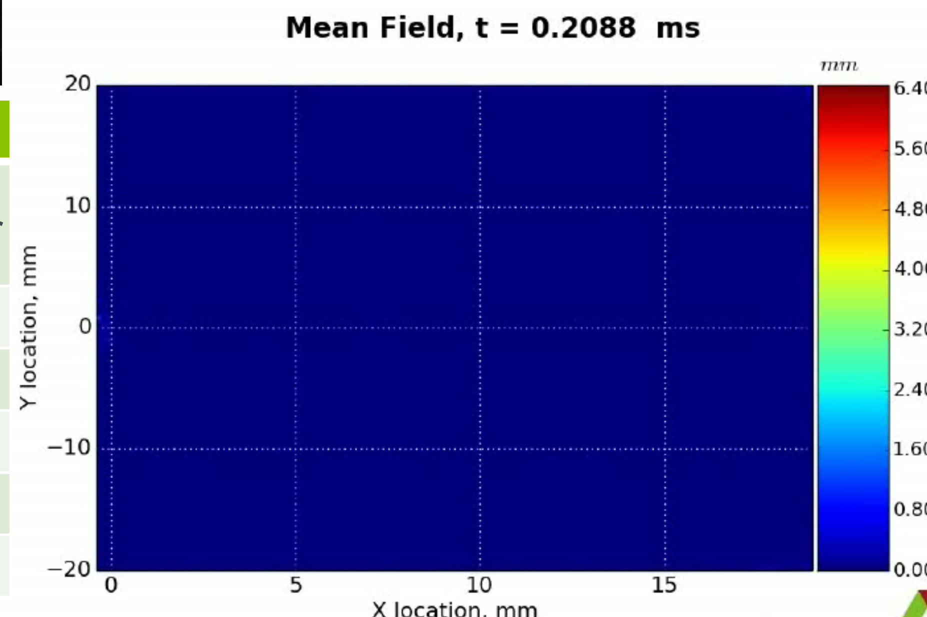
X-RAY INJECTOR GAS JET MEASUREMENTS



- Outward opening NG injector
- Pressure ratios typical for engine operation (injector rated at 16 bar)
- Evaluate cases with wall interaction (engine experiments include central and side NG injector location)

	Pressure, bar			
Condition	Injection Argon	Ambient Nitrogen	Energizing time [ms]	Barrier
1	10	1	2	No
2	15	1	2	No
3	10	2	2	No
1-B	10	1	2	Yes
2-B	15	1	2	Yes



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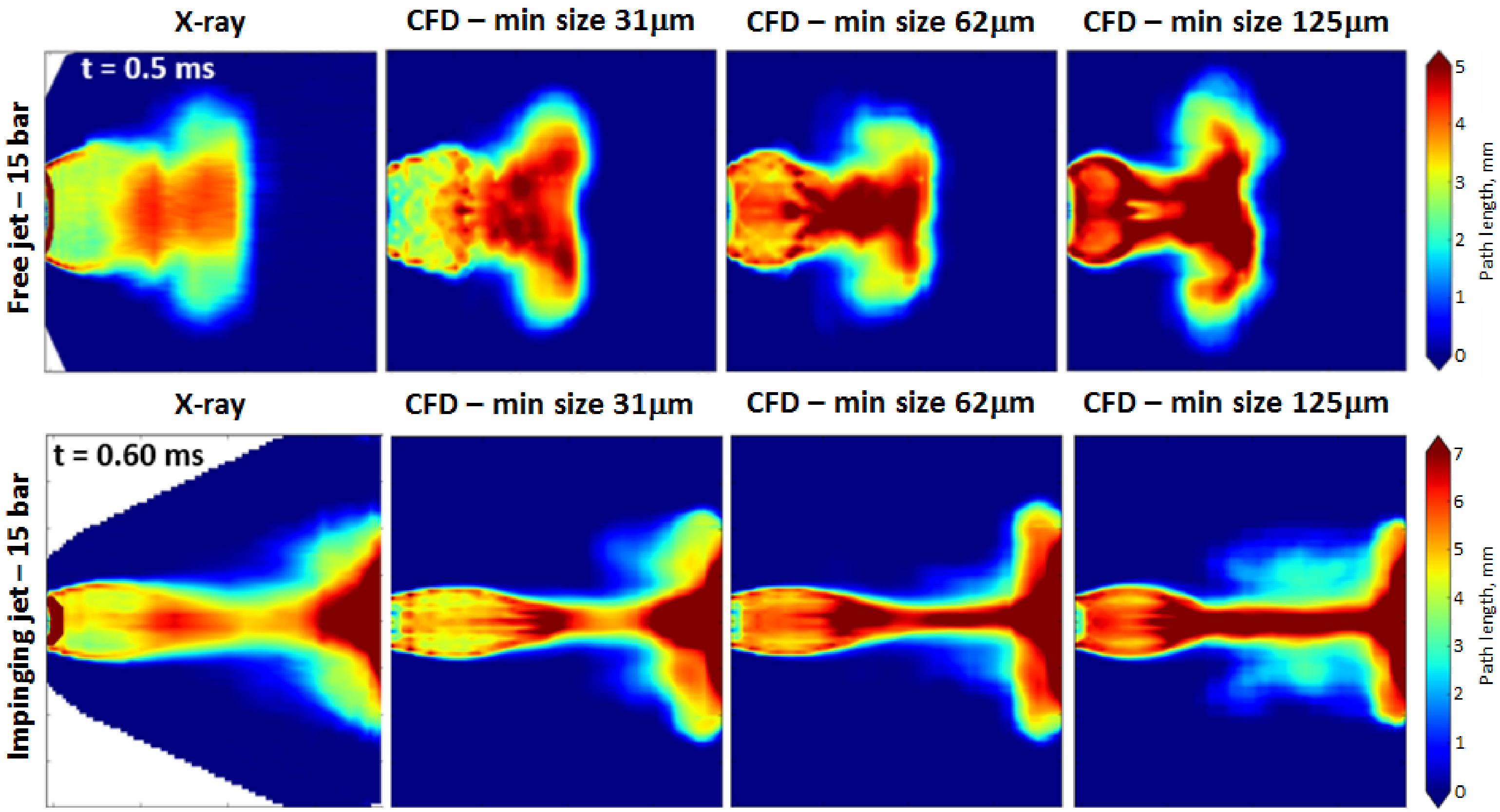
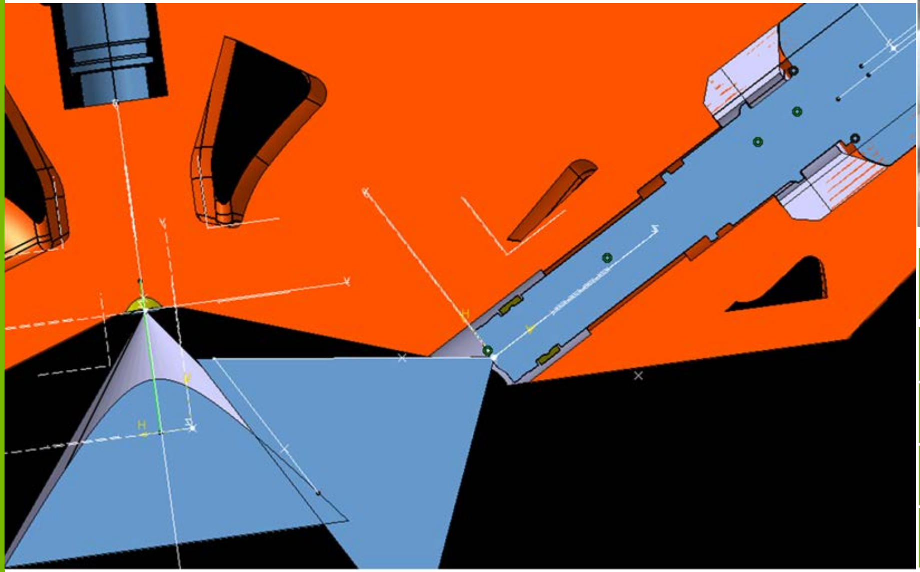
INJECTOR GAS JET SIMULATION VALIDATION

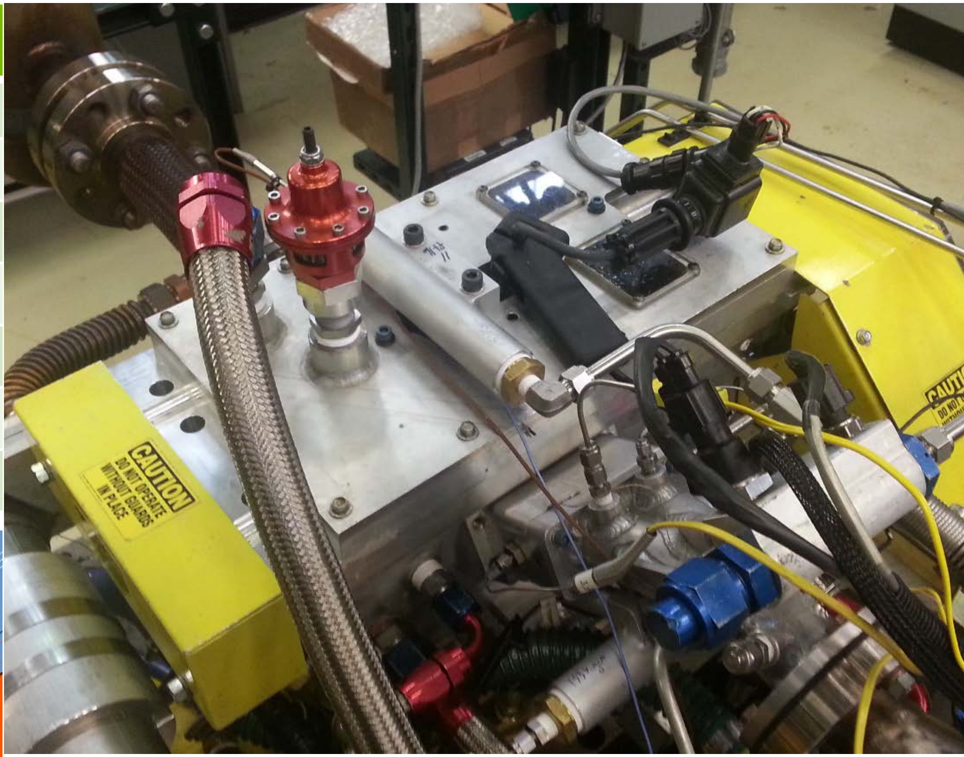
- Successfully validated CFD simulations against X-ray data for free jets as well as impinging jets at several pressure ratios
- Developed best practice (grid resolution, boundary conditions) to achieve good agreement while limiting computational time
- Current minimum mesh size in engine simulations is 125μm



EXPERIMENTAL SETUP

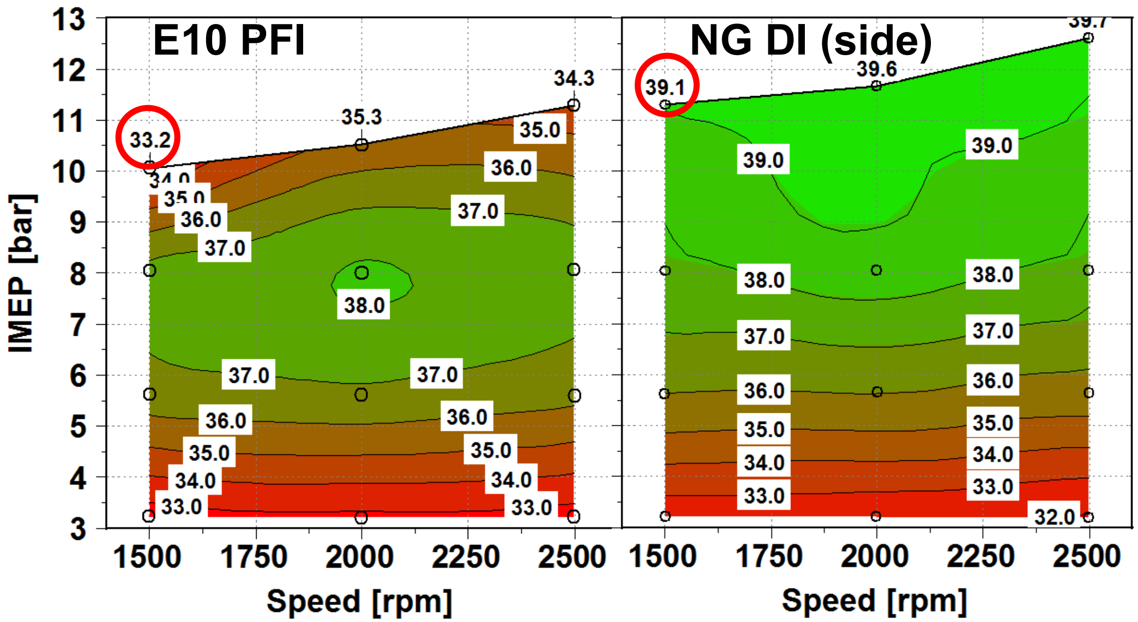
Single-cylinder research engine		
Displacement	L	0.6264
Stroke	mm	100.6
Bore	mm	89.04
Compression ratio	-	10.5:1
Valve configuration	-	4, 40° Pent Roof
Spark plug	-	NGK, 0.7 mm gap
Tumble ratio	-	0.6



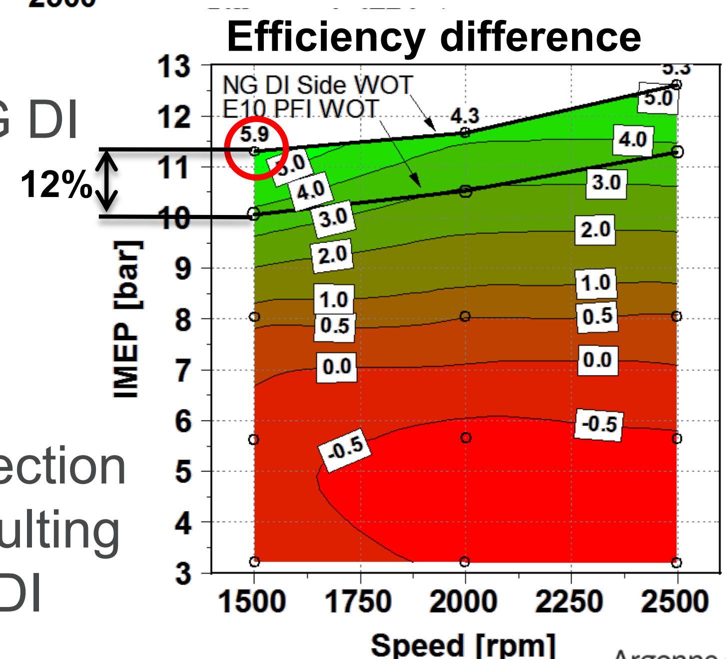


Experimental matrix		
Engine speed	rpm	1500, 2000, 2500
IMEP (net)	bar	3.2, 5.6, 8.0, WOT
SOI DI	°CA BTDC	Sweep, 120-360
SOI PFI	°CA BTDC	Sweep, 150-630

BASELINE MAPS WITH NEAT FUELS

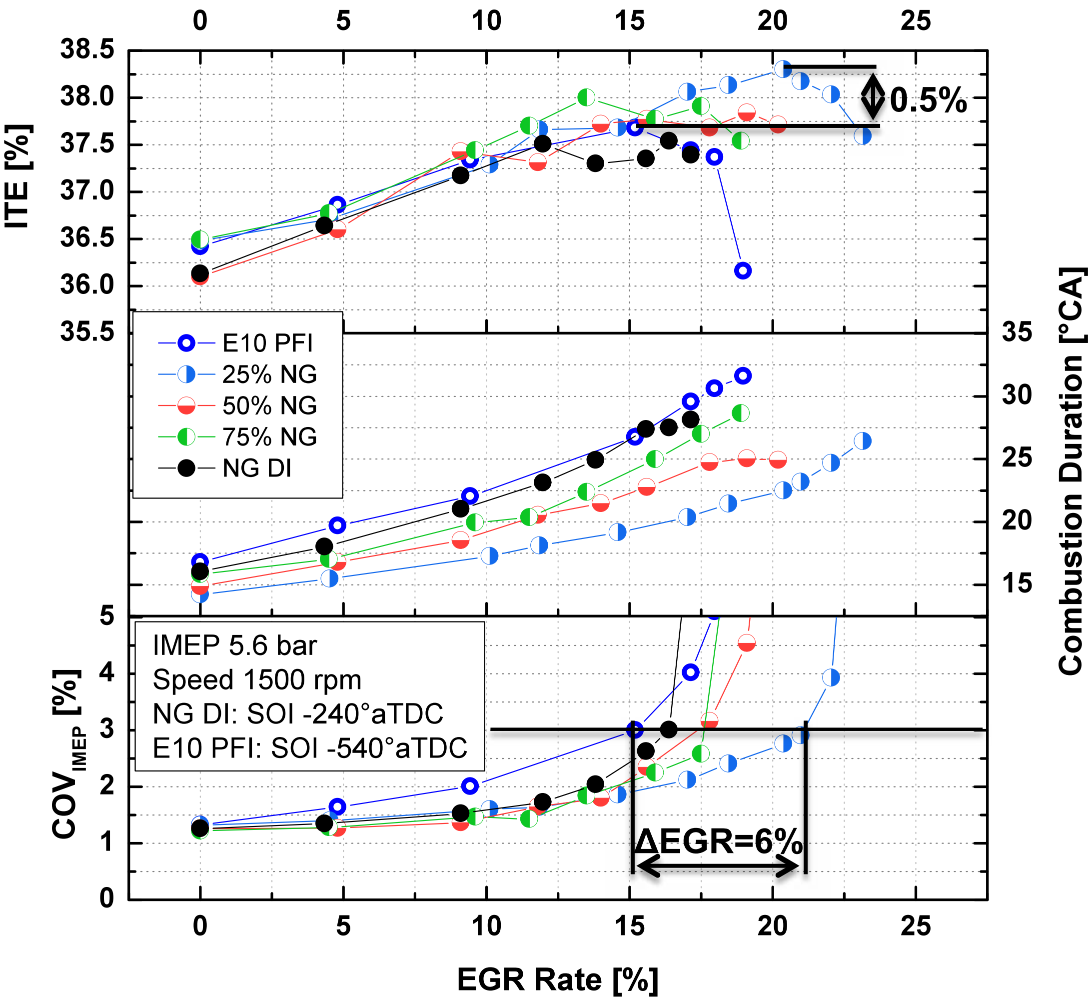


- Retarded ignition starting at 8 bar IMEP reduces ITE for E10 PFI (only 33.2% ITE at WOT and 1500 rpm)
- NG DI shows high ITE (39.1%) at WOT and 1500 rpm due to efficient combustion phasing



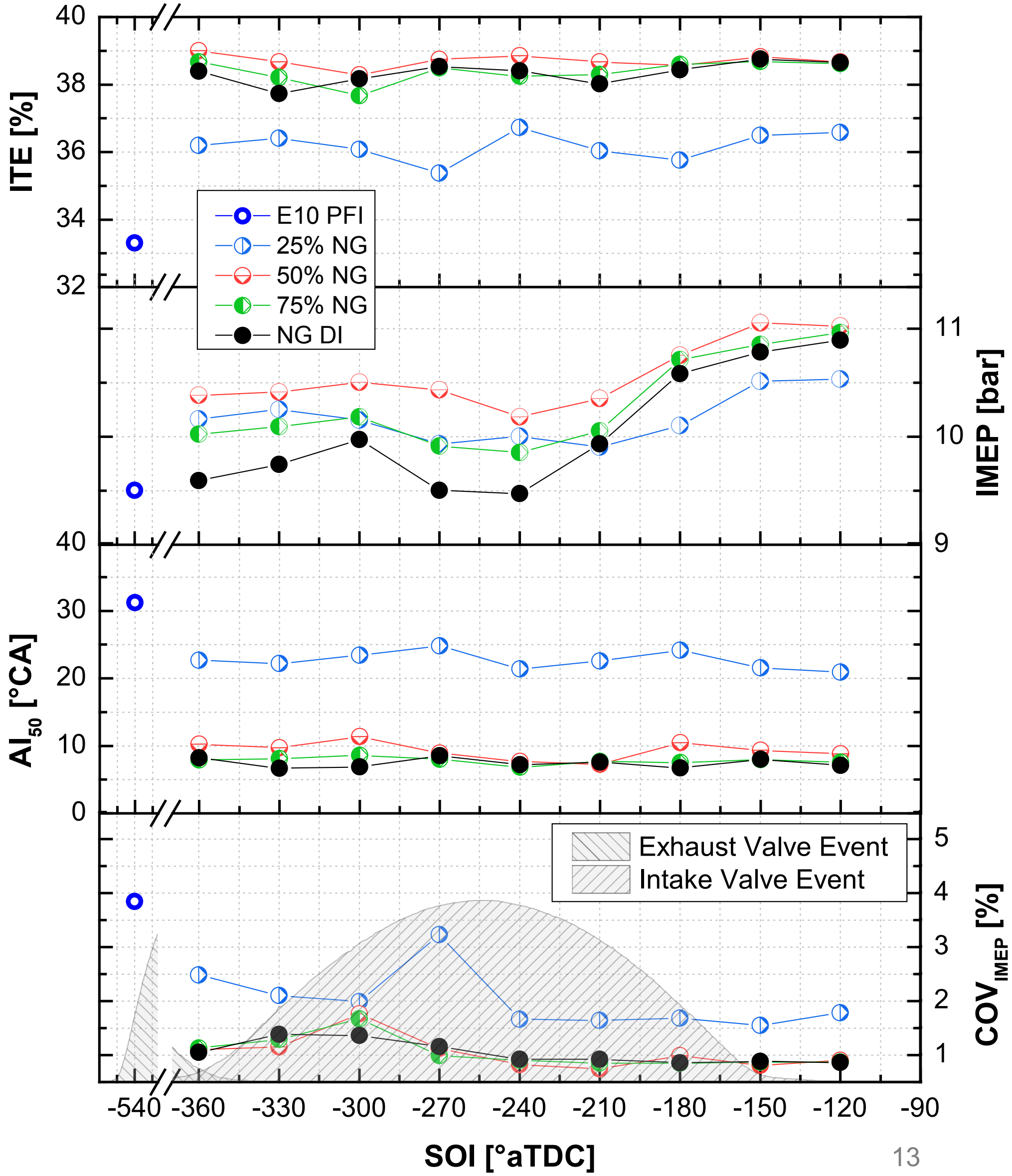
- Highly efficient WOT operation with NG DI compared to E10 PFI results in 18% relative increase in ITE
- Result is beyond project target of 10% higher efficiency for NG DI
- High efficiency operation and direct injection allow increased WOT performance resulting in 1.3 bar (12%) higher IMEP with NG DI compared to E10 PFI

SUCCESSFUL DEMONSTRATION OF POTENTIAL OF BLENDED APPROACH



- Induced turbulence due to direct injection is capable of extending EGR dilution tolerance
- Best performance shown by fueling the engine with 25% NG
  - 25% NG shows 0.5% higher ITE compared to E10 PFI
  - 6% higher EGR dilution tolerance for 25% NG compared to E10 PFI by maintaining 3% COV_{IMEP}

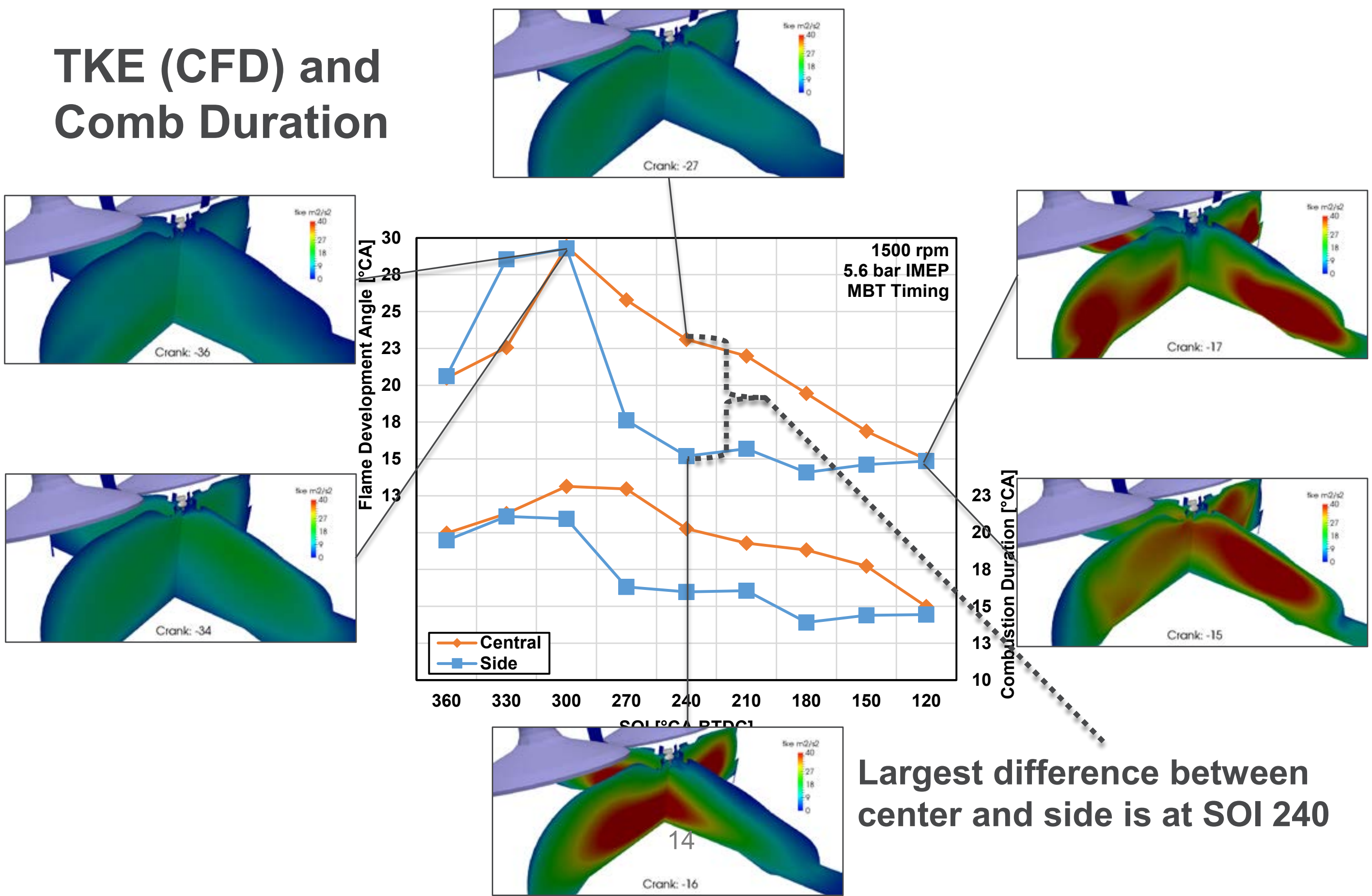
SUCCESSFUL DEMONSTRATION OF POTENTIAL OF BLENDED APPROACH



- E10 and 25% NG require retarded ignition in order to avoid knocking
- No knock mitigating measures when engine is fueled with 50% NG (or more)
- WOT performance can be significantly increased when NG is injected after (or at) IVC
- Highest IMEP (more than 11bar) can be achieved using 50% NG in its current configuration (CR=10.5)

PREDICTIVE ENGINE SIMULATION VALIDATED AGAINST EXPERIMENTAL DATA

- Predicted effect of DI injection timing on mixture homogeneity and efficiency
- Correlated DI location effect on turbulence (TKE) with measured Flame Development Angle (FDA) and Combustion Duration
- Provided insight for the optimization of in-cylinder mixing and turbulence



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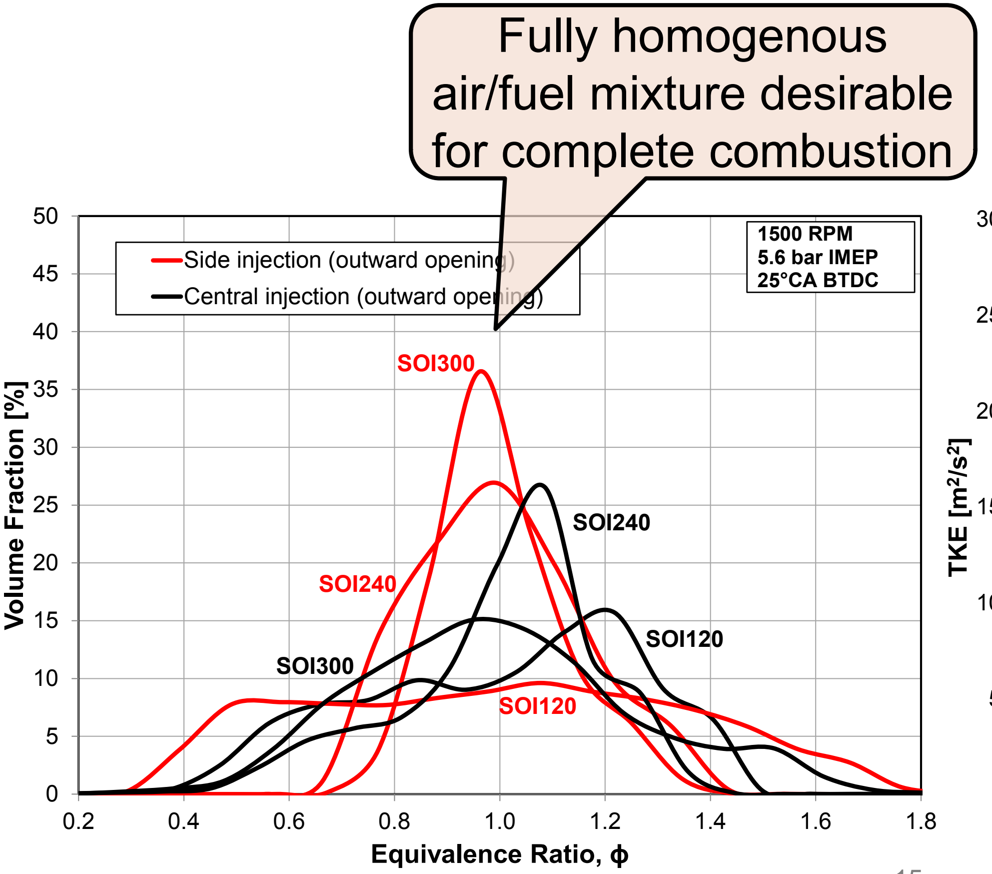
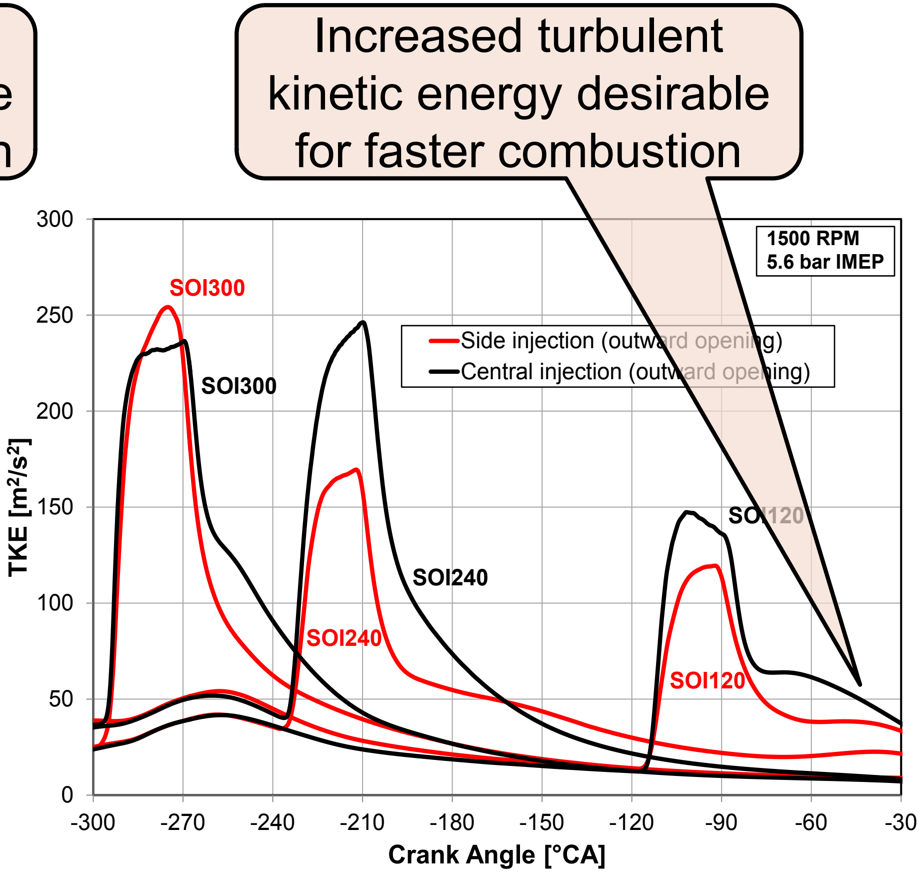
DESIGN CRITERIA AND DEVELOPMENT TARGETS

- Derive quantifiable metrics from 3D-CFD mixture formation simulations
- Trade-off: Maximize mixture homogeneity while maintaining high levels of (injection-induced) charge motion



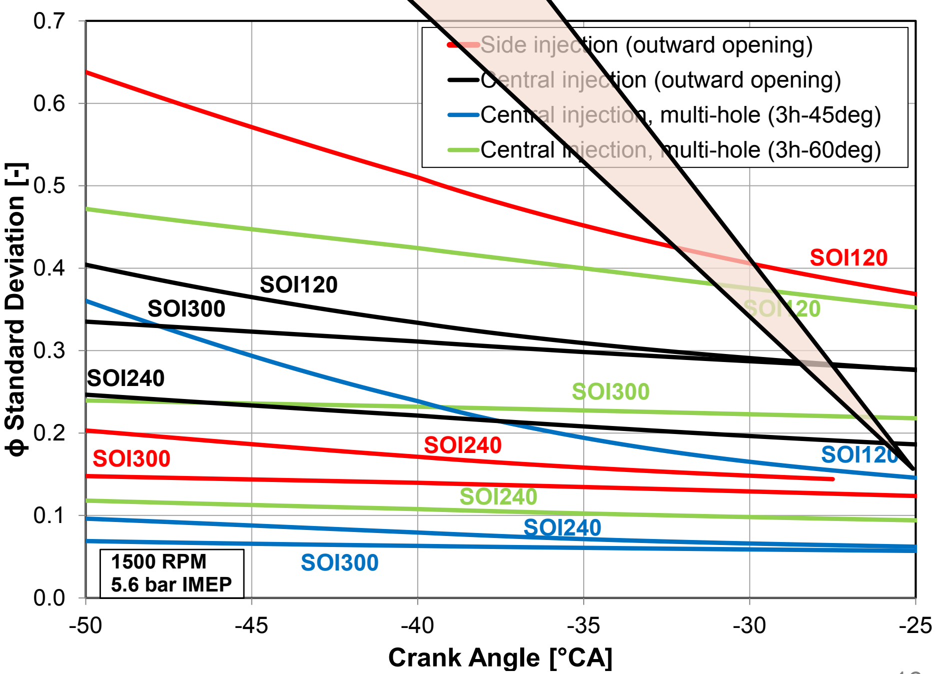


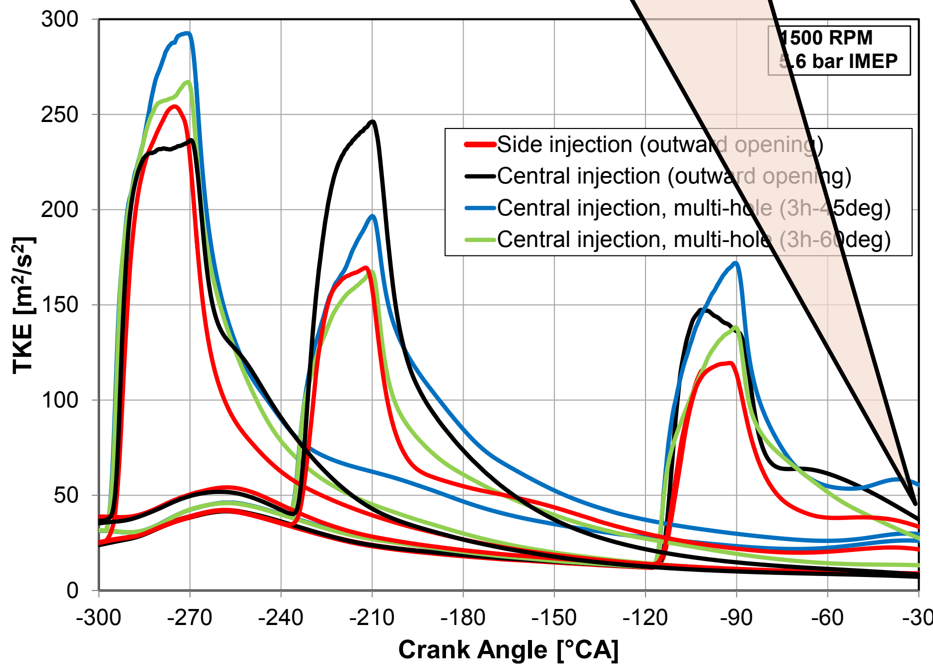
ANALYSIS OF DESIGN PARAMETERS

- Injector design and location
  - Central vs. side, outward opening vs. multi-hole
- Intake design
  - Influence of charge motion
- Compression ratio

Good homogeneity with multi-hole nozzles despite late injection

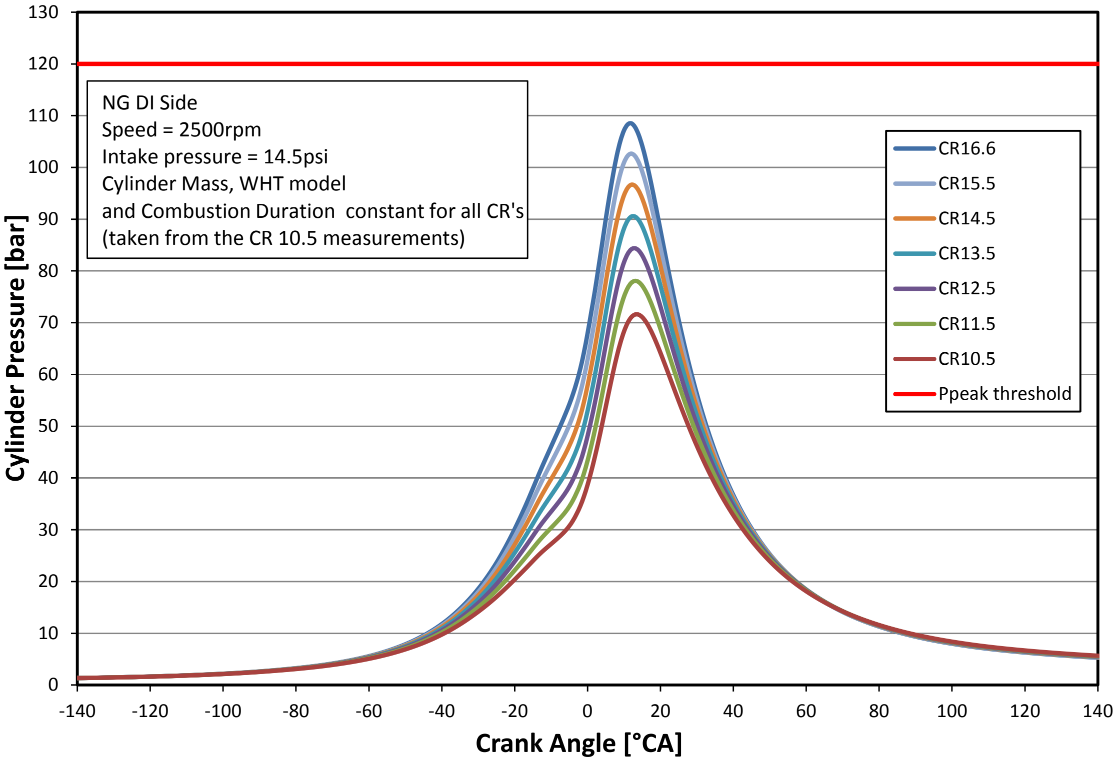
Multi-hole nozzles and late injection increase turbulent kinetic energy

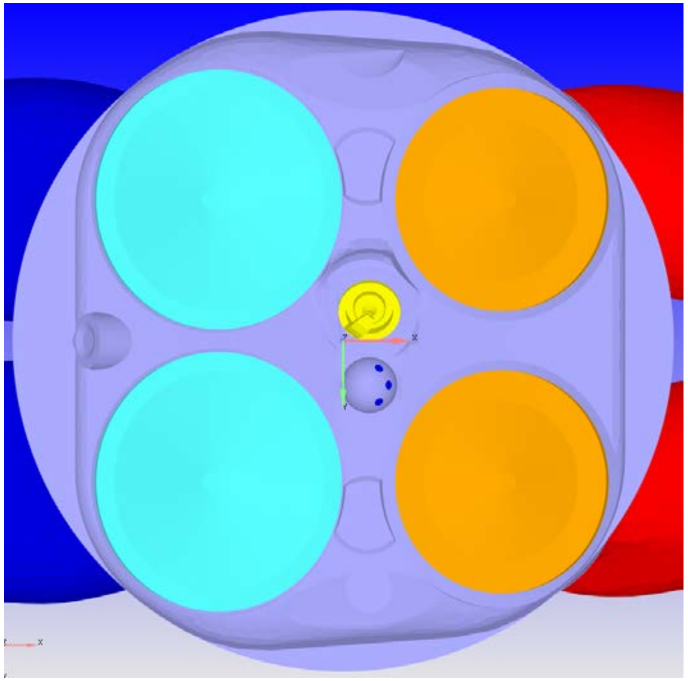




HARDWARE FREEZE FOR OPTIMIZED COMBUSTION SYSTEM DESIGN

- Increase compression ratio from 10.5:1 baseline to 12.5:1 and 14.5:1
- Increase tumble ratio from 0.6 to 1.5 for improved dilution tolerance
- Focus on side NG DI location for outward opening injector
- Evaluate inward opening injector concept in central NG DI location





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RESPONSE TO REVIEWER COMMENTS

- This project is a new start and has not previously been reviewed at an Annual Merit Review

COLLABORATION AND COORDINATION

- **Jointly proposed project in response to FY 2014 Vehicle Technologies Program Wide Funding Opportunity Announcement (DE-FOA-0000991)**

Ford
- Engine hardware
- Technical guidance

FCA FIAT CHRYSLER AUTOMOBILES
- Injection hardware
- Technical guidance

Bi-weekly conference calls
Several in-person meetings
Quarterly progress reports to DOE
Joint publications

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- Engine experiments
- CFD simulations

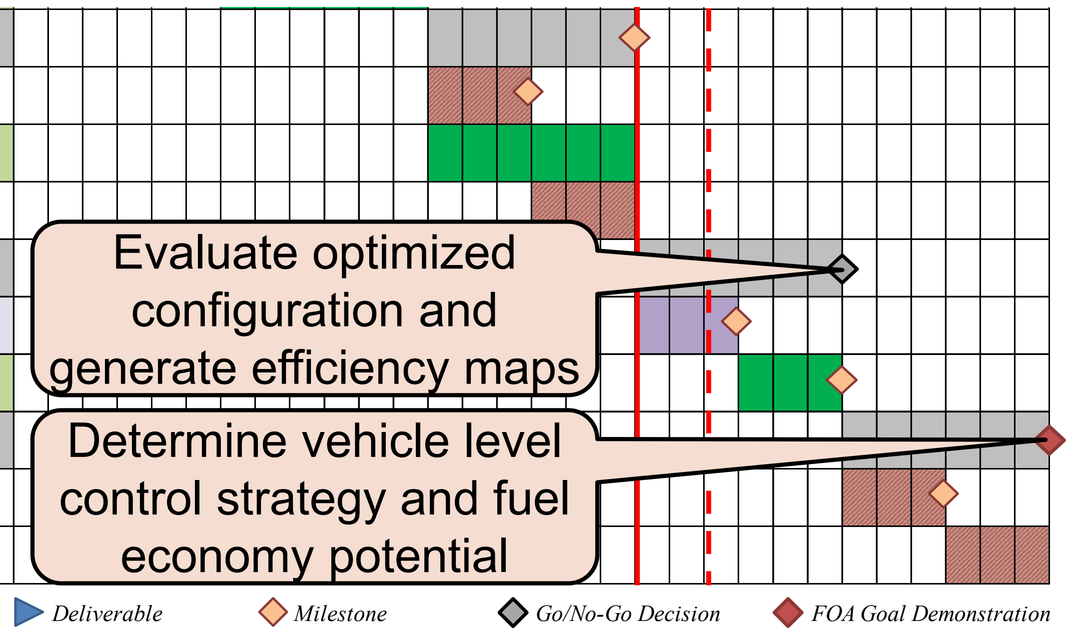
REMAINING CHALLENGES AND BARRIERS

- Identify main operational parameters (injection strategy incl. timing and number of pulses) for optimized engine configuration (compression ratio, in-cylinder flow, injector configuration) that yield maximum benefits
- Derive approach to predict minimum NG level in the fuel blend to avoid knocking combustion as a function of speed, load and compression ratio
- Design, build and evaluate optimized configuration adhering to project and technical boundary conditions
- Translate single-cylinder engine results into vehicle level fuel economy data and establish vehicle level in-cylinder gasoline/CNG blending strategy to maximize fuel economy benefits
- Estimate vehicle level fuel economy gains compared to baseline cases
- Perform cost assessment and payback calculations

PROPOSED FUTURE WORK

- Complete experimental evaluation of in-cylinder blending concept with optimized configuration
- Design vehicle level control strategy targeting maximum overall efficiency while adhering to project goals and limitations

3	**Virtual combustion system optimization**		**6**
3.1	Determine evaluation criteria/development targets	All	3
3.2	Perform simulations to determine optimized engine configuration	Argonne	6
3.3	Evaluate design options/feasibility	All	3
4	**Experimental validation of optimized combustion system**		**6**
4.1	Design/build optimized engine hardware	Ford	3
4.2	Perform engine tests on optimized hardware	Argonne	3
5	**Vehicle level analysis and cost assessment**		**6**
5.1	Develop vehicle level strategy/estimate vehicle level potential	All	3
5.2	Perform cost analysis	All	3



SUMMARY

- Collaborative research project between FCA US LLC, Ford Motor Company and Argonne National Laboratory designed to evaluate an ***Efficiency-Optimized Dual Fuel Engine with In-Cylinder Gasoline/CNG Blending***
- Successfully demonstrated the efficiency and performance potential of the proposed concept and developed tools and a pathway towards assessing an optimized configuration including vehicle level simulations
- Project is on schedule and has a clearly defined path to on-time completion

Project goal	Target	Status	Target met
Power density improvement	10%	13% 10.0 (NG PFI) to 11.3 bar (NG DI) IMEP	Yes
Efficiency improvement	10%	18% 33.2 (E10 PFI) to 39.1% ITE (NG DI)	Yes
Retrofitability	Yes	Engine/system design complete	Yes
Petroleum reduction	50%	Not started (task 5)	TBD
Payback period	36 months	Not started (task 5)	TBD

TECHNICAL BACK-UP SLIDES

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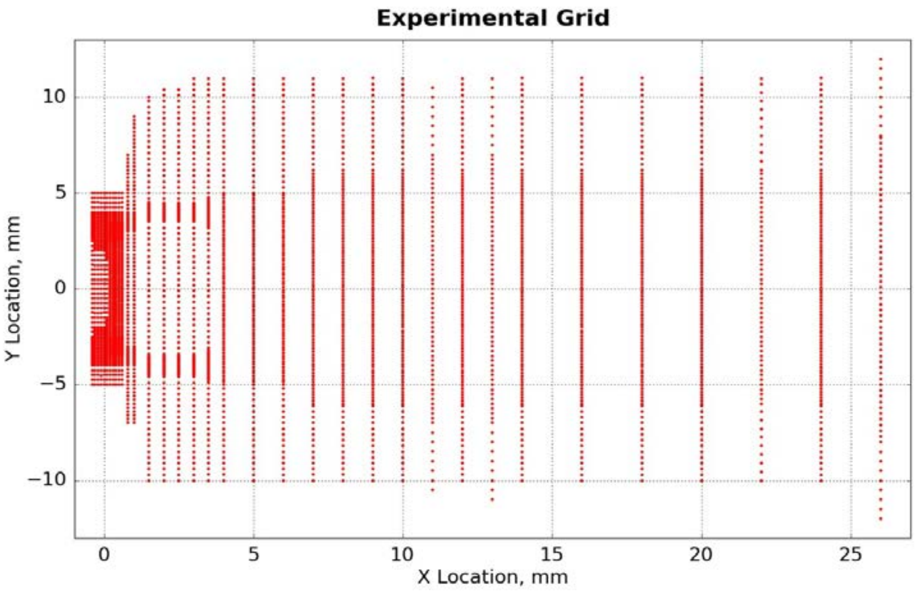
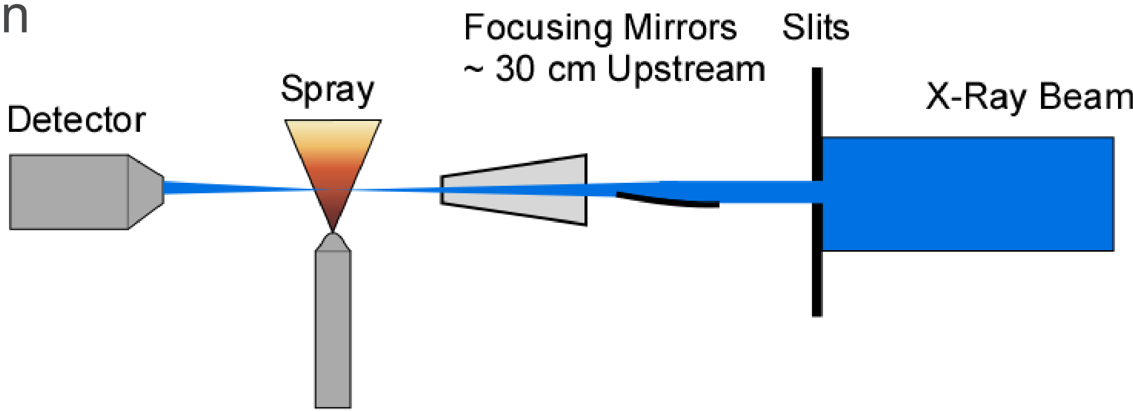
X-RAY MEASUREMENT DETAILS

- Focused beam in raster-scan mode
- Beam size 5 x 6 μm FWHM
- Divergence 3 mrad H x 2 mrad V
- Beam size constant across spray
- Time resolution: 3.68 μs
- Each point an average of 32-256 injection events
- Beer-Lambert law to convert x-ray transmission to mass/area in beam





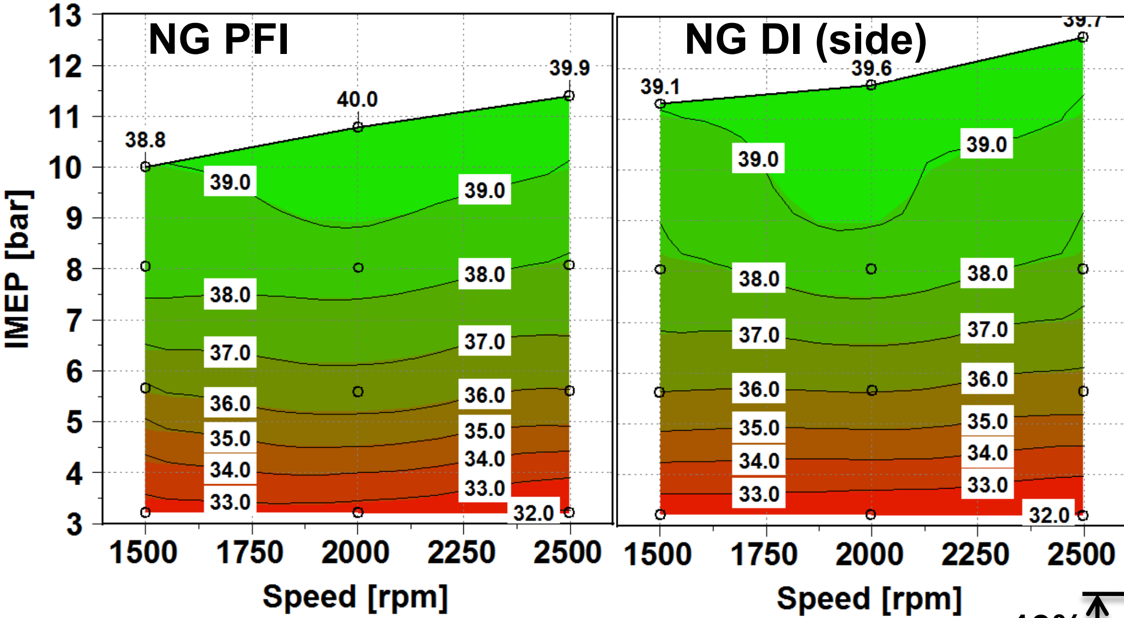
FUEL AND NG DI INJECTOR SPECIFICATIONS

Natural Gas (CNG)		
CH_4, C_2H_6, CO_2, N_2	mol%	94, 3, 2, 1
Methane number	-	90.7
Lower heat value	MJ/kg	46.93
Stoichiometric A/F Ratio	-	16.2

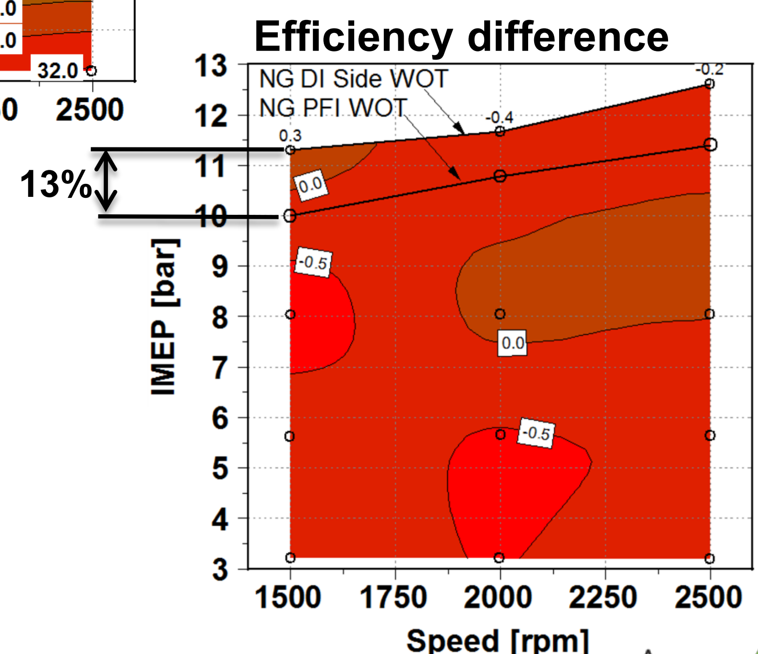
Gasoline (E10)		
C, H, O	wt%	82.08, 14.13, 3.79
AKI (RON+MON)/2	-	87.2
Lower heat value	MJ/kg	42.017
Stoichiometric A/F Ratio	-	14.1

NG DI Injector Concept	Outward Opening	Multi-hole
Status	Hardware tested	Simulation only
Pressure range	6 – 16 bar	
Asymmetry option	No	Yes
Nozzle design changes	No	Yes
Diameter, tip	7.5 mm	
Diameter, maximum	21 mm	

BASELINE MAPS WITH NEAT FUELS (NG PFI VS DI)



- Similar efficiencies for both fueling strategies
- NG DI delivers significantly higher WOT IMEP compared to NG PFI

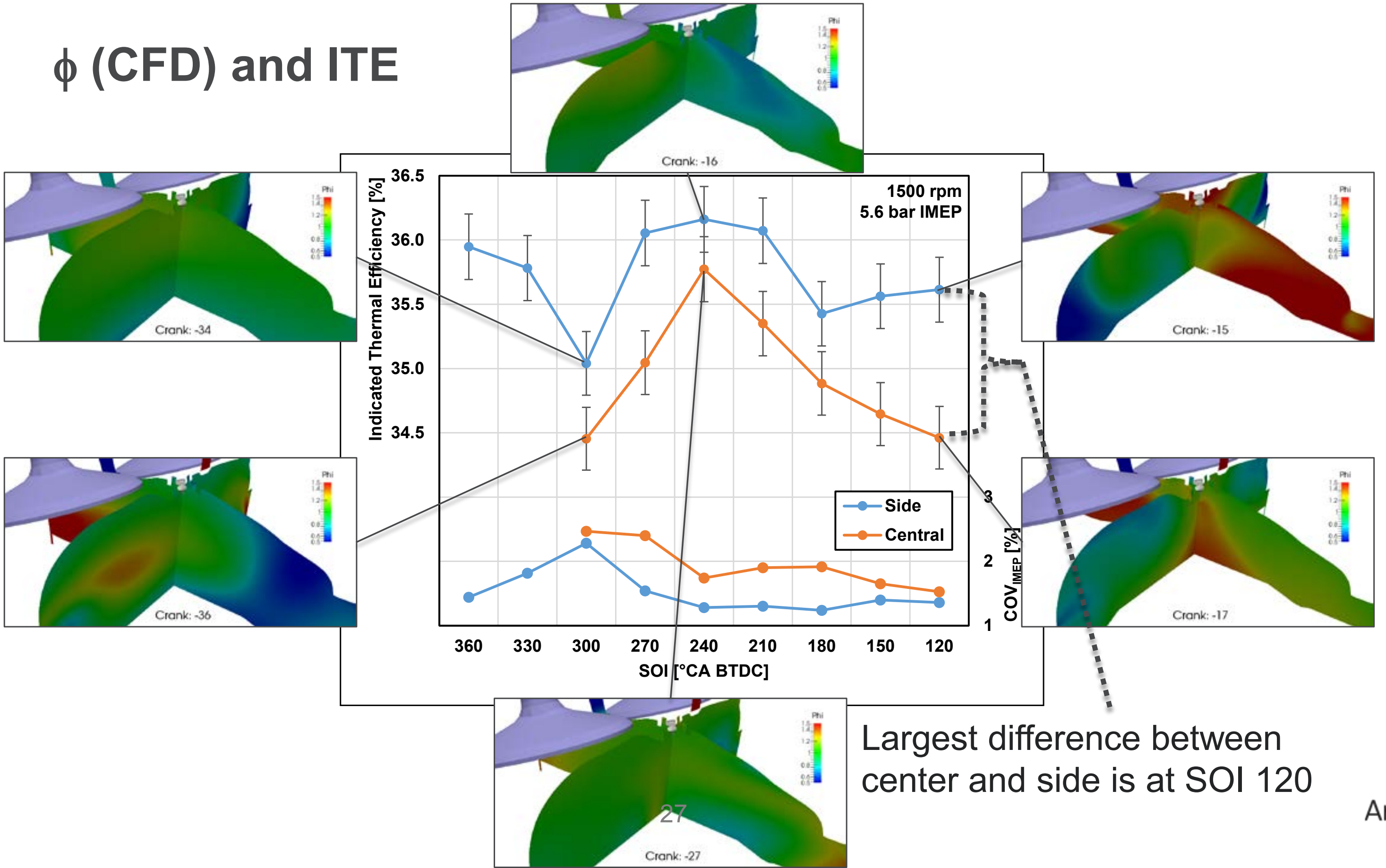


- NG DI achieved an IMEP of 11.3bar at 1500rpm and WOT
- Project target of 10% higher power density for NG DI compared to NG PFI was exceeded

PREDICTIVE ENGINE SIMULATION VALIDATED AGAINST EXPERIMENTAL DATA

- Predicted effect of DI injection timing on mixture homogeneity and efficiency
- Correlated DI location effect on turbulence (TKE) with measured Flame Development Angle (FDA) and Combustion Duration
- Provided insight for the optimization of in-cylinder mixing and turbulence

ϕ (CFD) and ITE



Largest difference between center and side is at SOI 120

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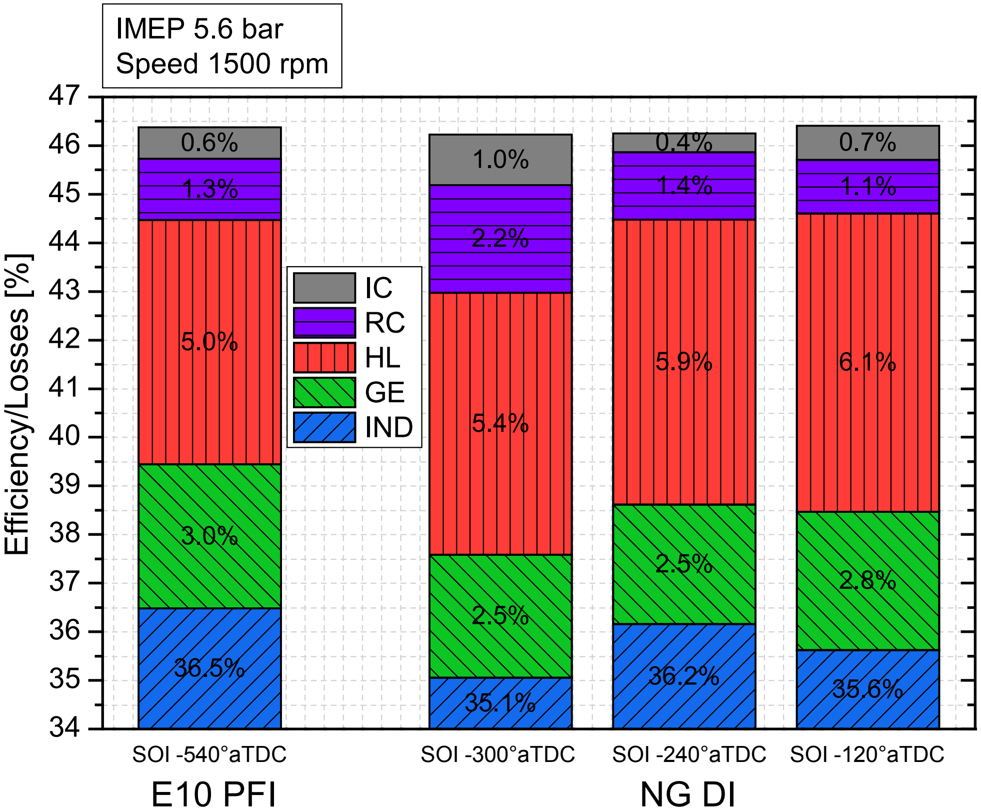
COMPARATIVE EFFICIENCY ANALYSIS



- Theoretical efficiency similar for all conditions (CR, Gamma, Residuals)
- Incomplete Combustion (IC) losses account for unburned fuel species
- Real Combustion (RC) losses include combustion duration and phasing
- Faster flame speeds of gasoline result in benefits compared to early NG DI (SOI -300°aTDC), later DI results in stratification affecting both, IC and RC
- Heat Loss (HL) increase with later NG DI operation due to induced turbulence resulting from the injection event
- Gas Exchange (GE) losses higher for E10 PFI compared to NG DI due to increased throttling requirements stemming from changes in mixture calorific value, charge cooling (E10 PFI vs. NG DI at SOI -120°aTDC) and air displacement with open valve natural gas injection

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