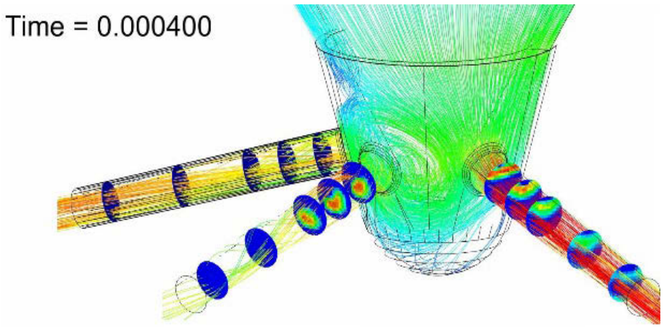
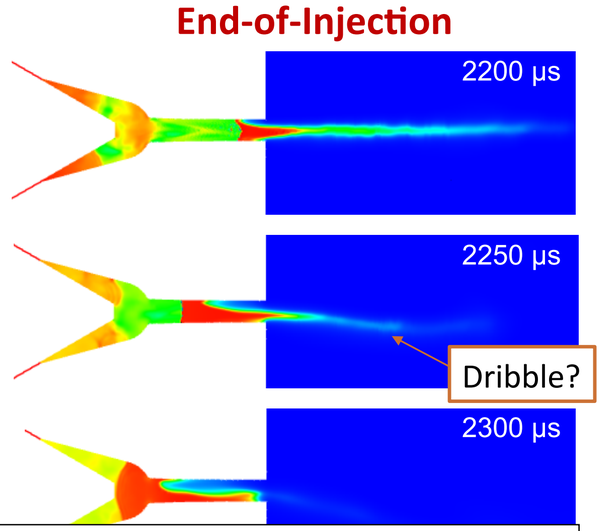
Advanced Nozzle Flow and Spray Modeling

- Able to predict effects of needle wobble
- Able to predict hole-to-hole variations

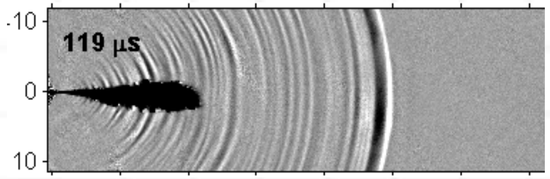


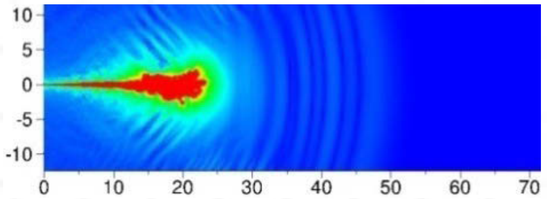


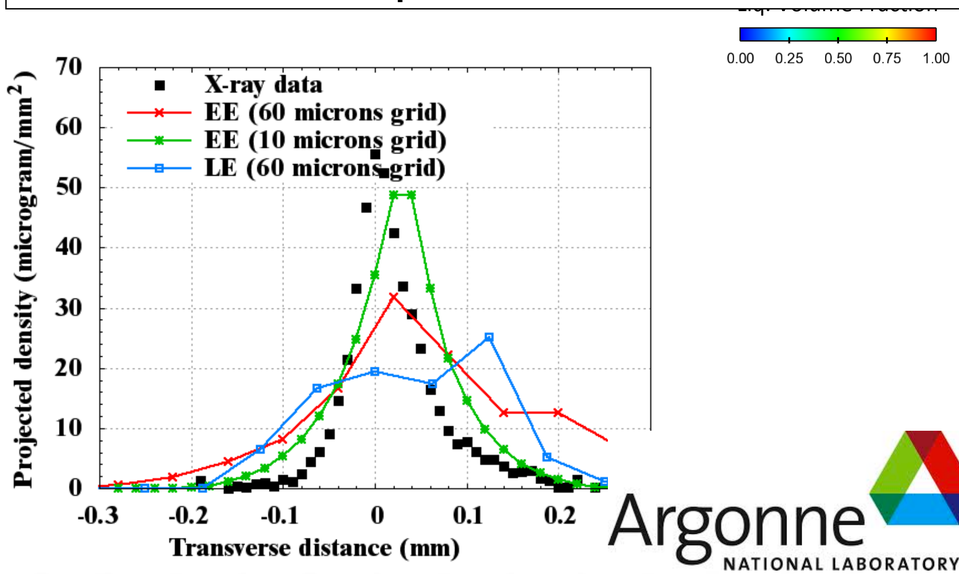
- Start of injection simulations show gas injection before liquid
- End of injection simulations show dribble and ingested gas in the sac

3-4 weeks on 100 processors, ~20 million cells

- Improved near nozzle comparisons with x-ray data
- Spray jet shock wave generation







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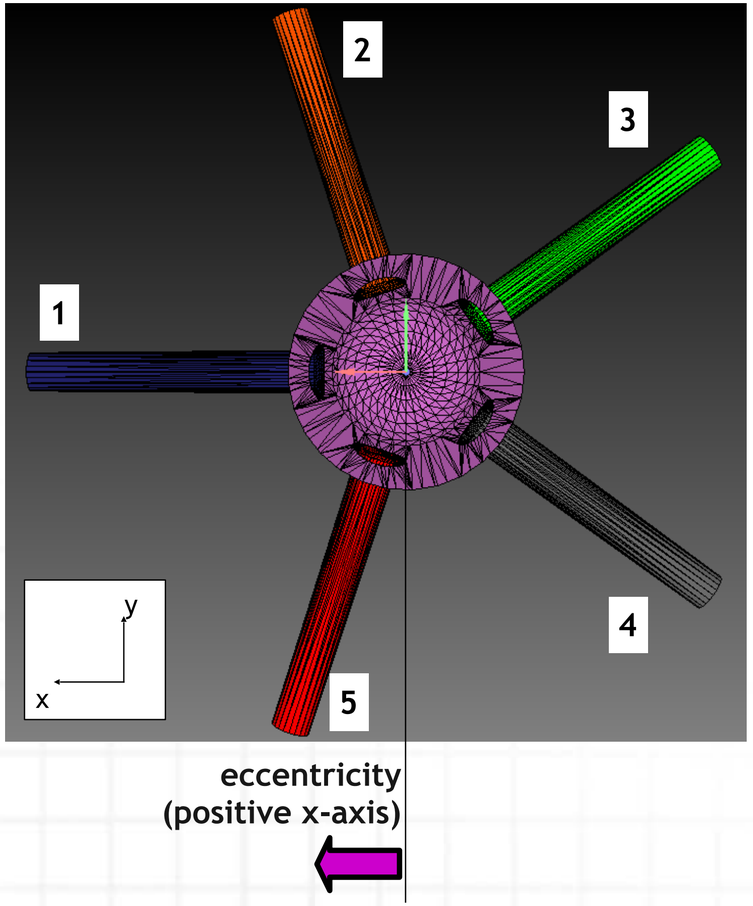
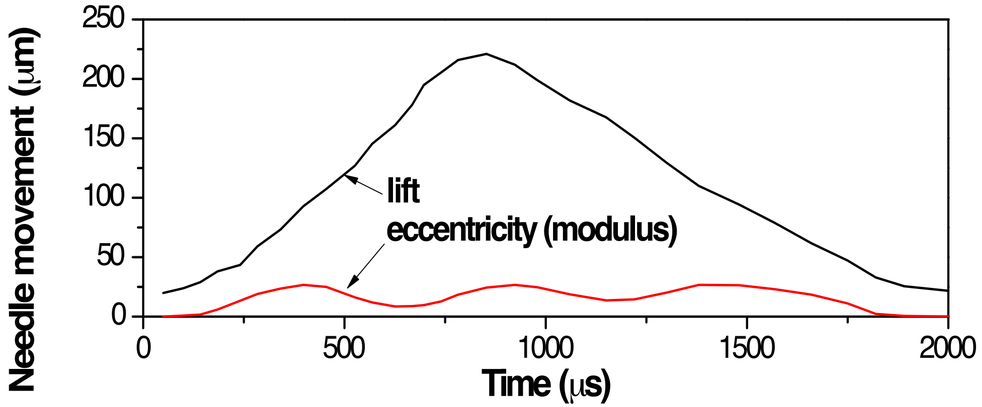
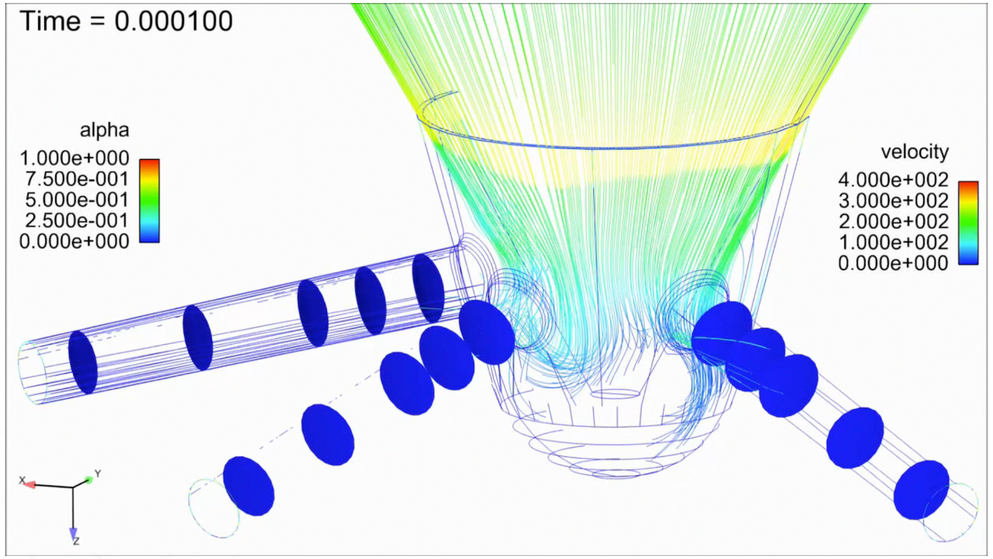
Advanced Nozzle Flow Modeling

- Effect of Needle Side Motion on Hole-to-Hole Mass Flow Variation







*Battistoni et al., SAE 2014

Collaboration with Argonne and Cummins

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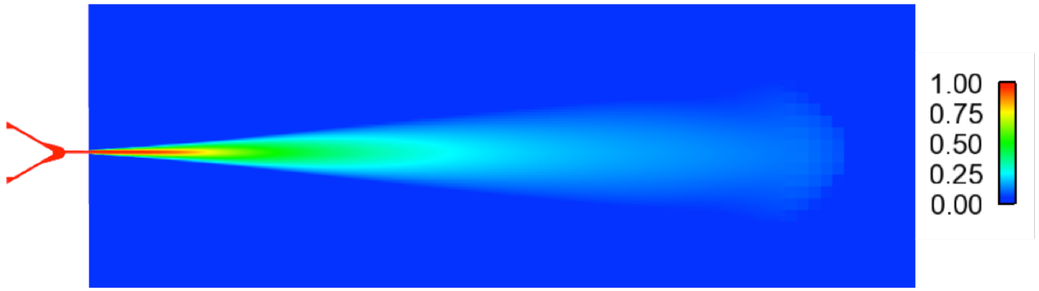
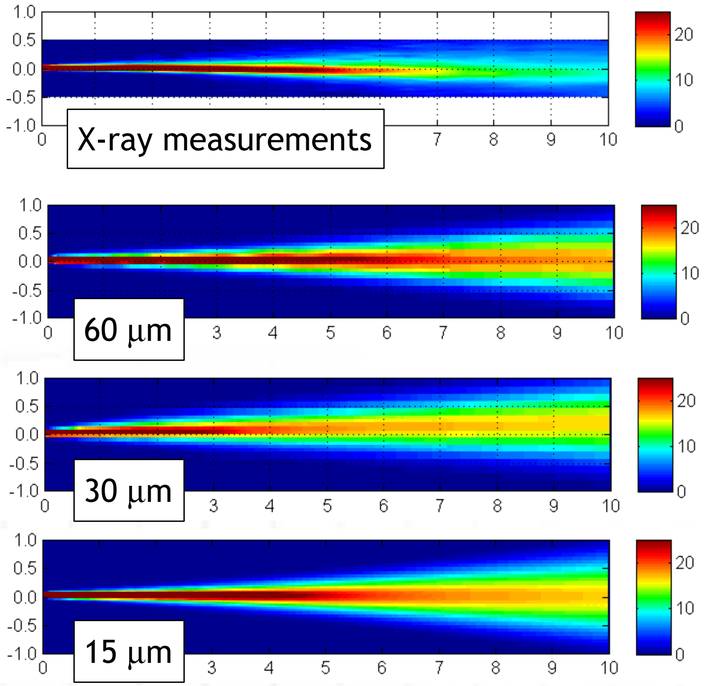
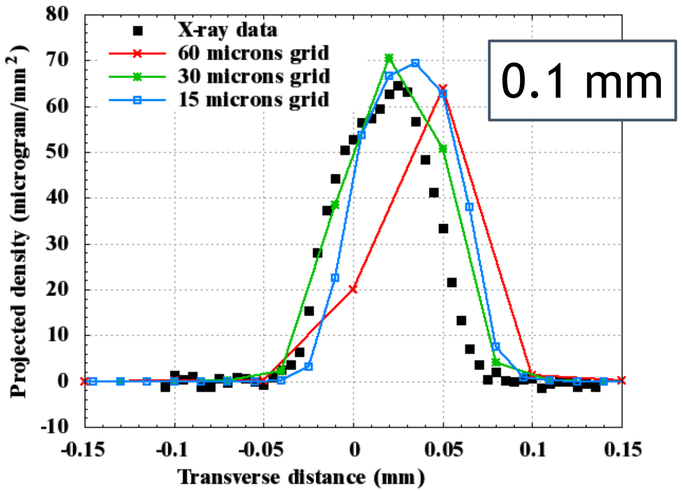
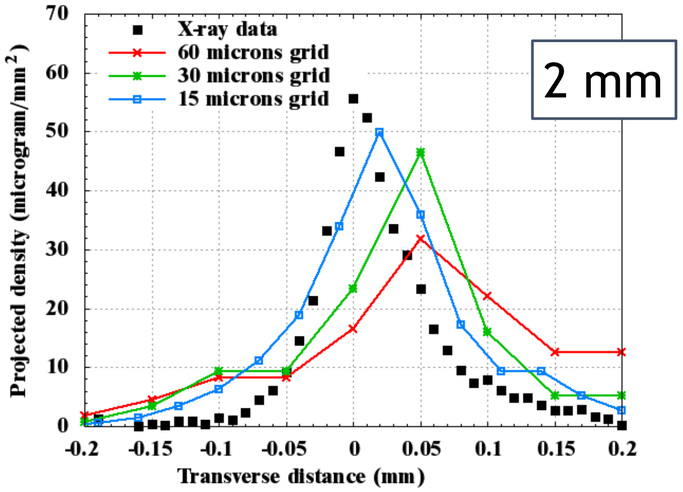
Advanced Spray Modeling





Projected mass density





ECN Spray A

*Xue et al., SAE 2014

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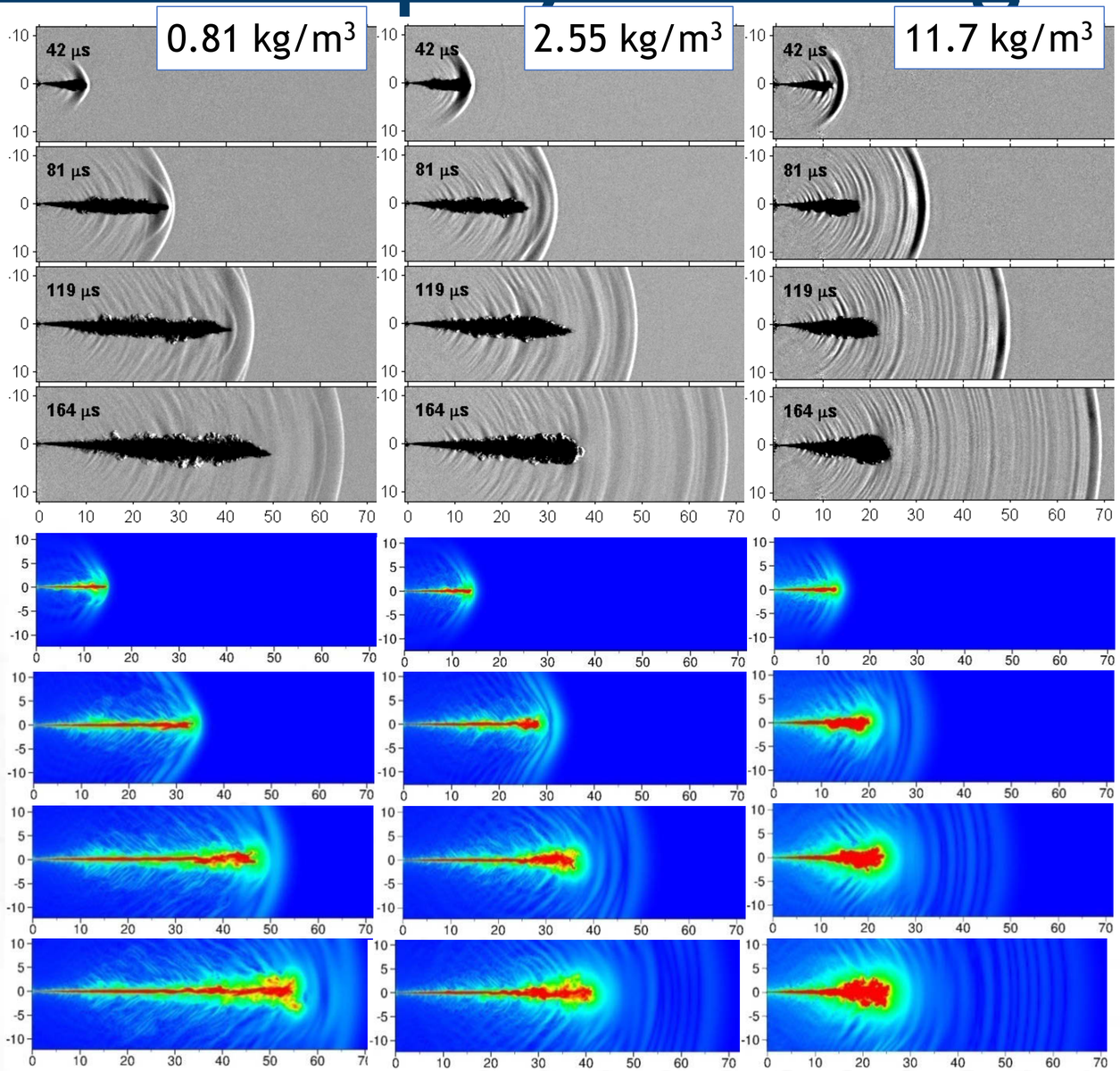
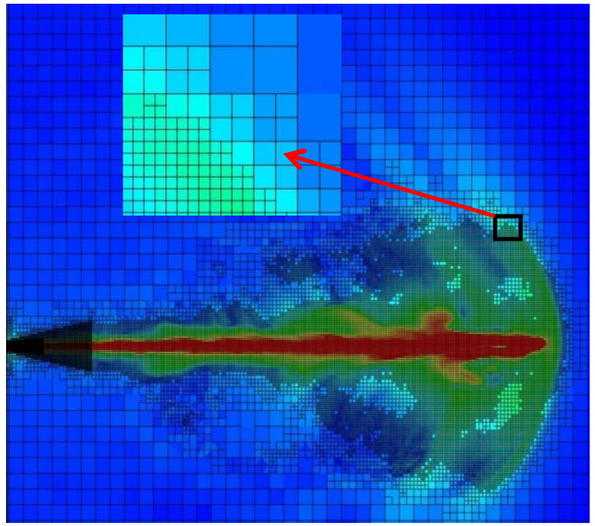
Advanced Spray Modeling



- Eulerian-Eulerian coupled with VOF
- Compressible liquid and gas
- Dynamic structure LES
- AMR



*Quan et al. SAE 2014

Collaboration with Sandia and Argonne

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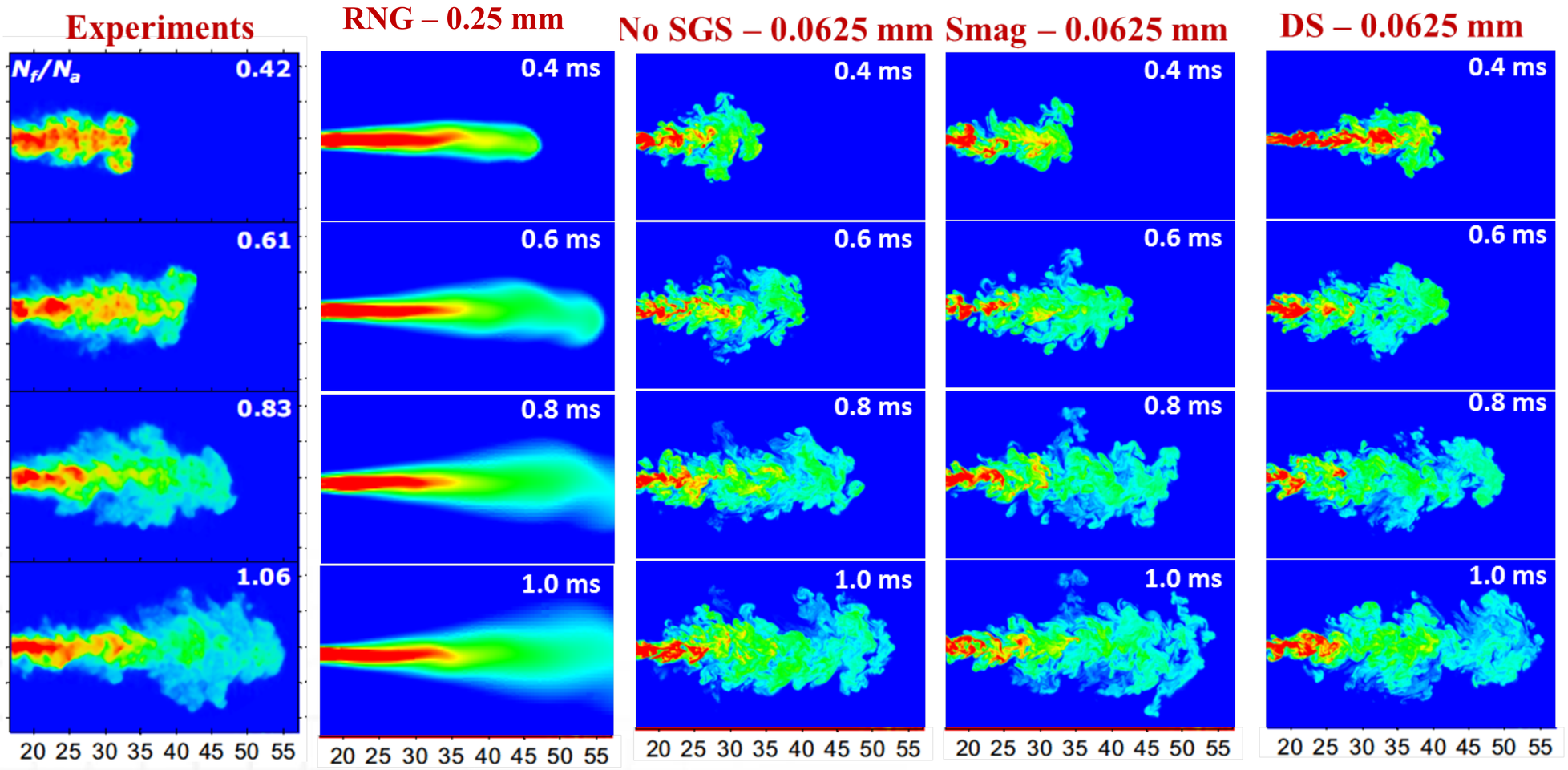
Advanced Turbulence Modeling



The computational cost of grid-convergent LES (@ 0.0625 mm) is about 30-40 times compared to grid-convergent RANS (@ 0.25 mm)

Collaboration with Argonne and Cummins

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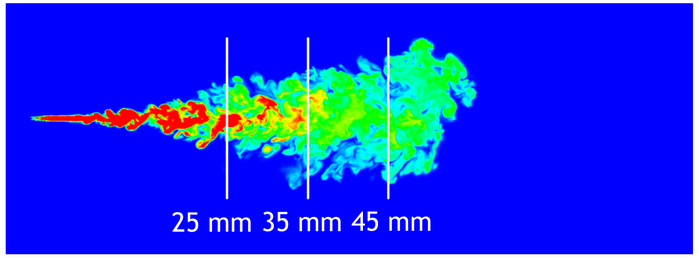
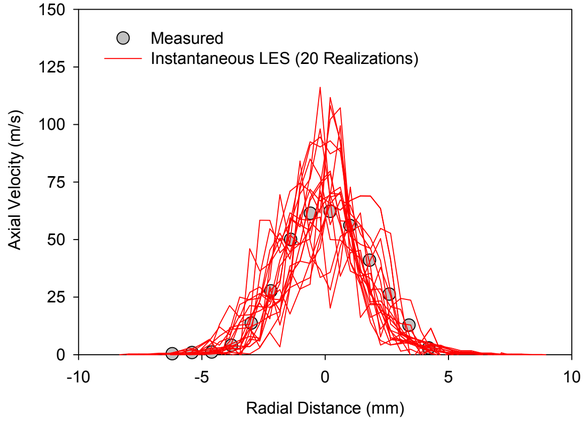
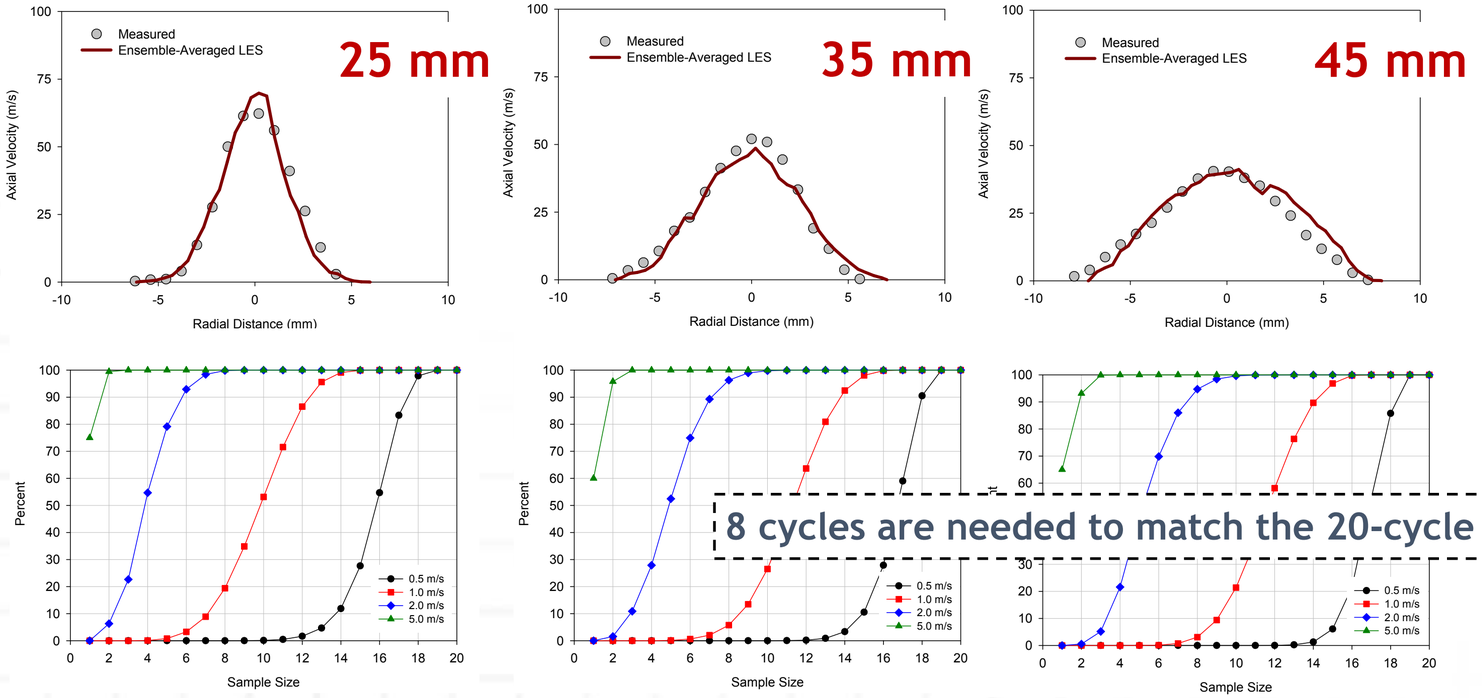
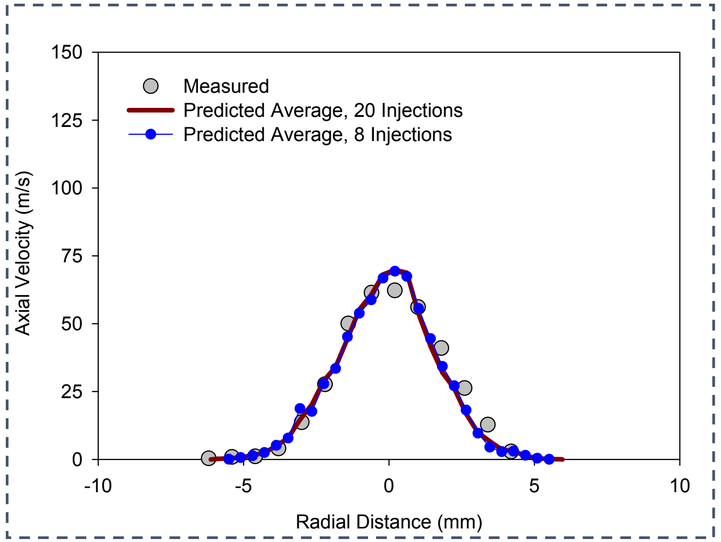
Advanced Turbulence Modeling





- Each simulation requires 60 hours on 64 cores
- Peak cell count: ~20 million





8 cycles are needed to match the 20-cycle average to within a tolerance of 2 m/s

*Senecal et al. ASME 2013

Collaboration with Argonne and Cummins

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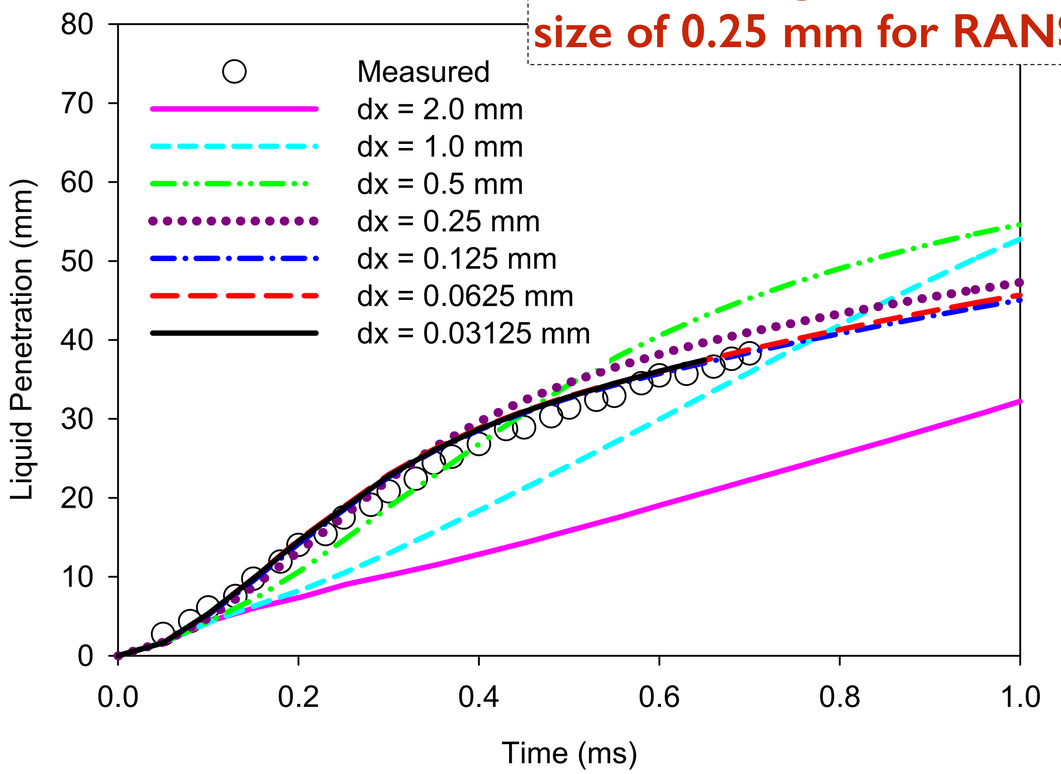
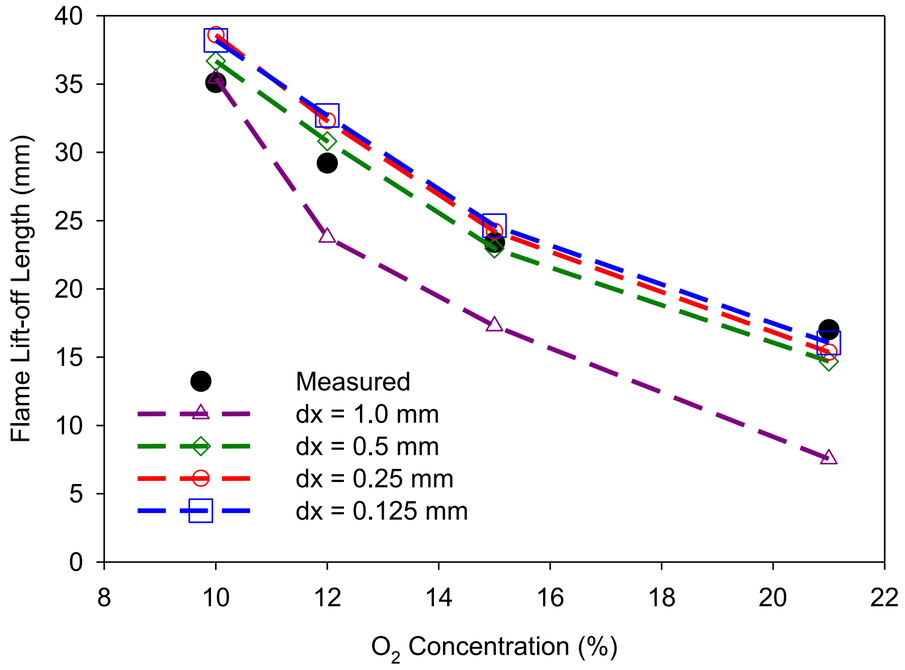
Grid Convergence

Grid-convergent AMR cell size of 0.25 mm for RANS



Up to 4 - 5 cells inside the nozzle diameter at finest resolution



- Great care has been taken to ensure grid convergence in the CONVERGE spray models, such that the results can be analyzed with confidence
- Cell sizes down to 30 microns have been analyzed (AMR)
- Allows for accuracy/run-time tradeoff

*Senecal et al. ASME 2012

Collaboration with Argonne

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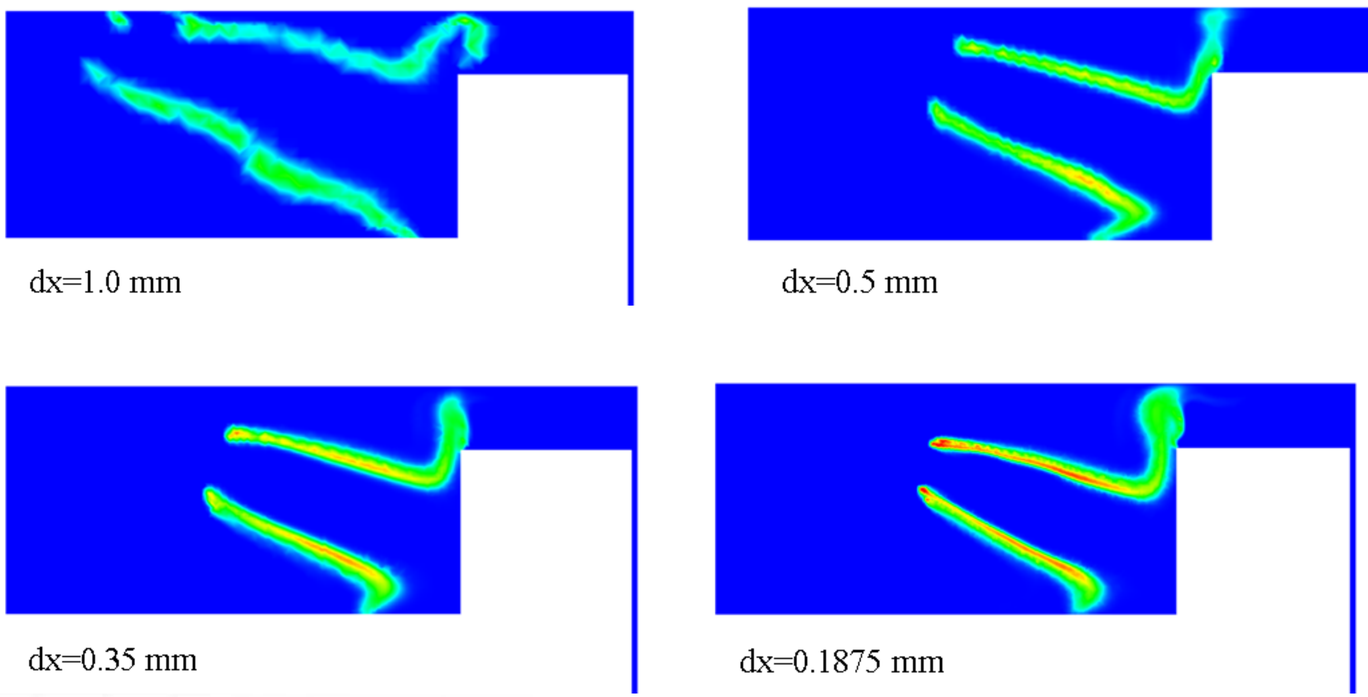
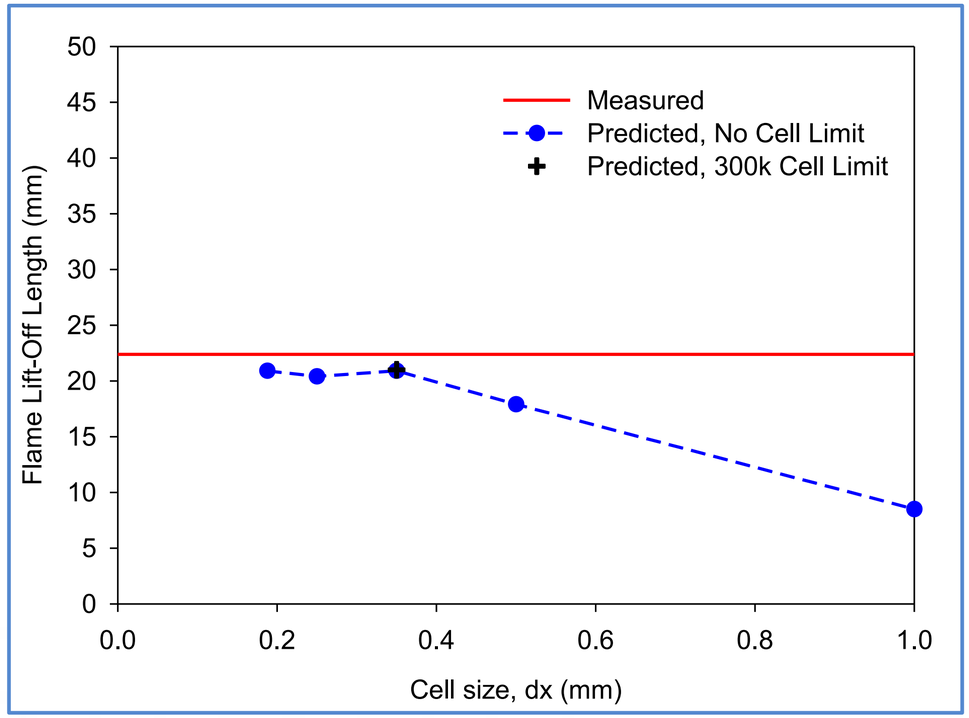
Extending Grid Convergence to Engines





Sandia National Laboratories

*Senecal et al. JEGTP 2014

Collaboration with Sandia and Caterpillar

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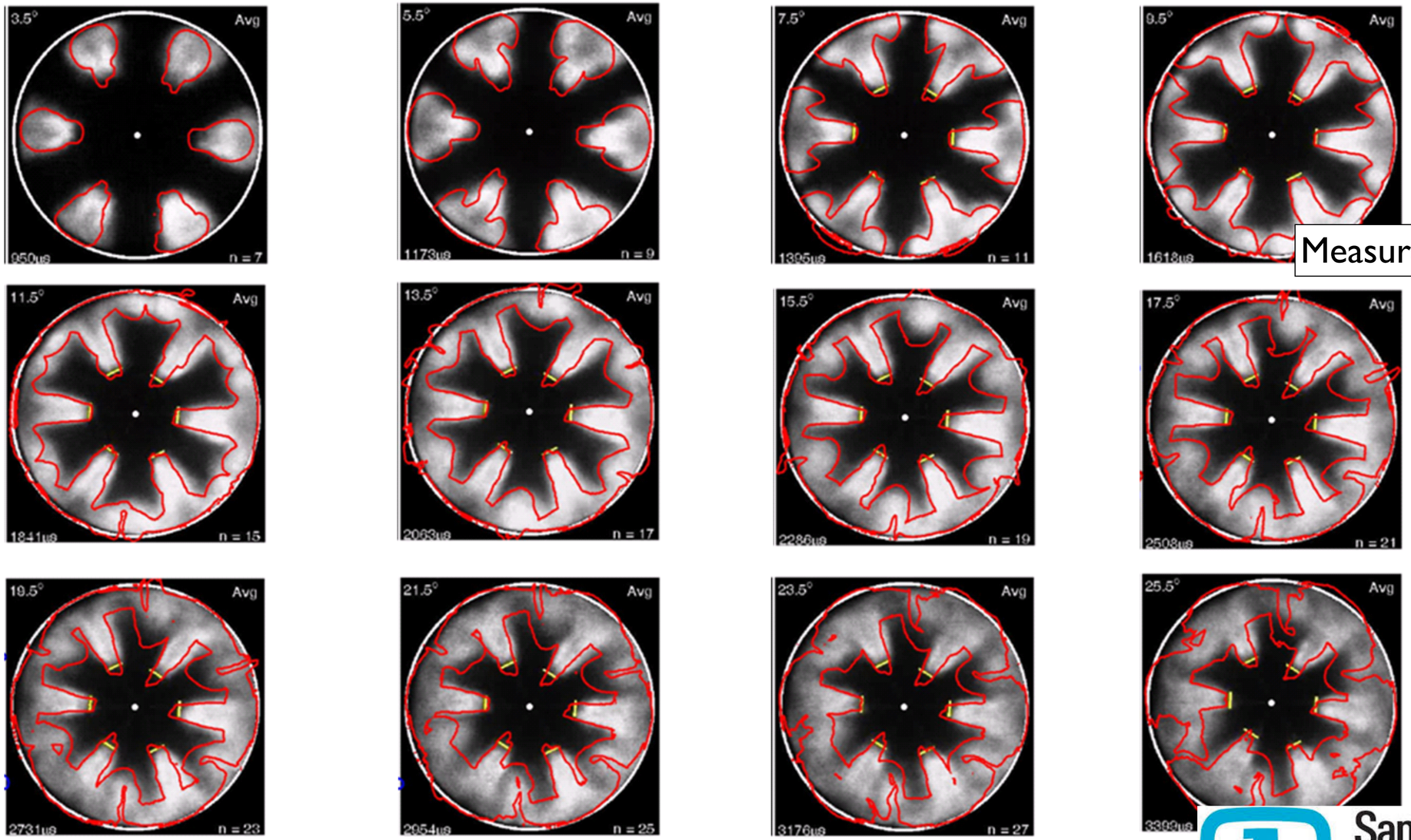
Extending Grid Convergence to Engines



Measured CL of OH*

*Senecal et al. JEGTP 2014

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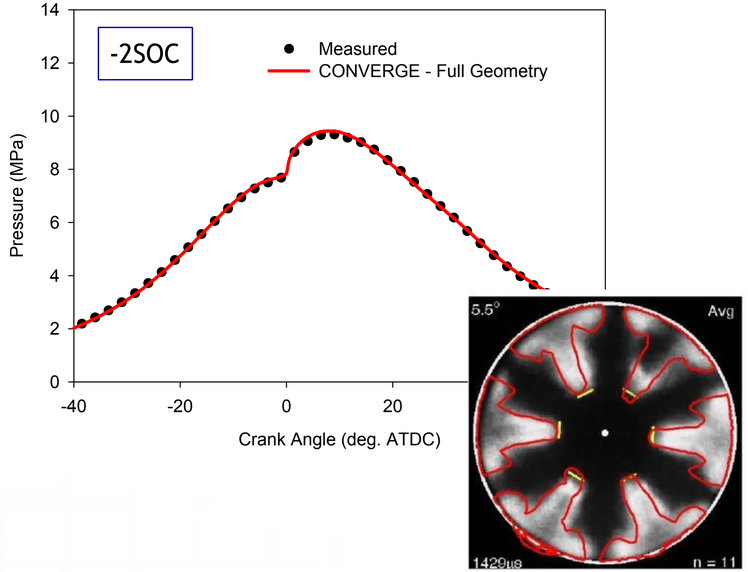
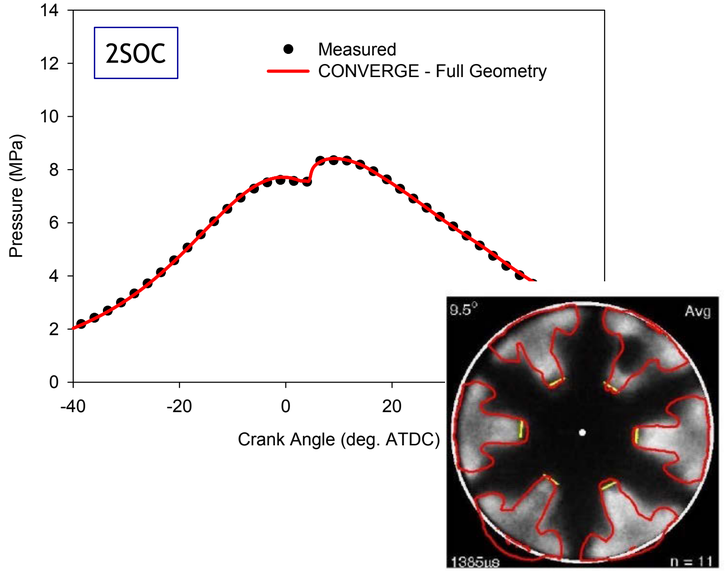
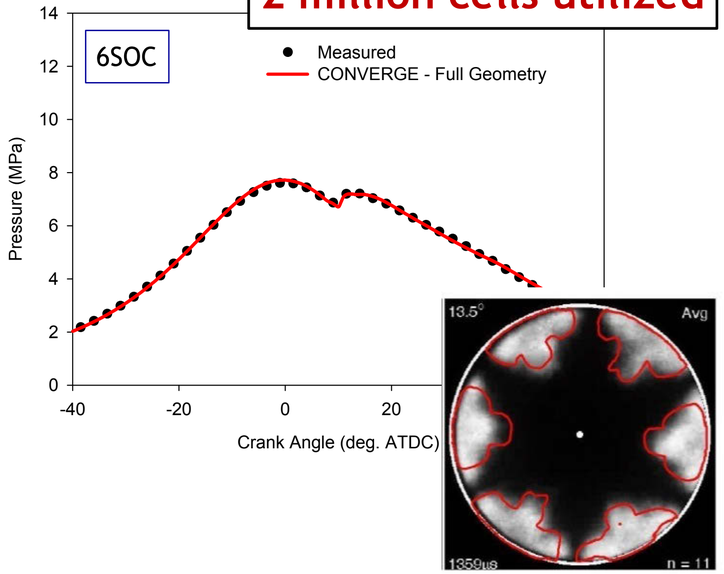
Extending Grid Convergence to Engines

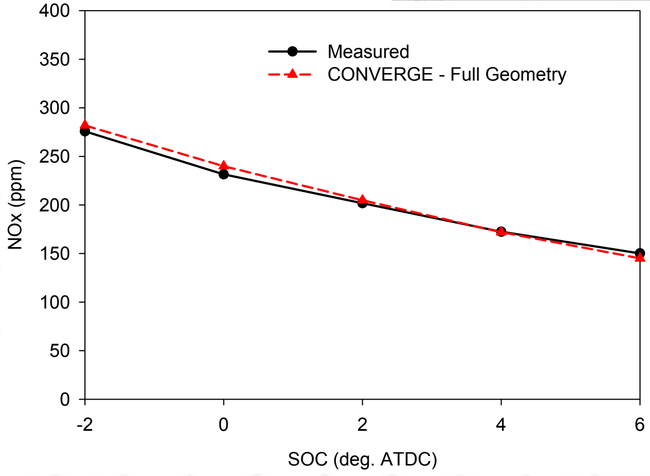
2 million cells utilized







OH* Chemiluminescence vs. OH iso-surface, 7.5 degrees after SOC



The grid-convergent methodology results in excellent agreement with global combustion behavior as well as flame lift-off length and flame location

*Senecal et al. JEGTP 2014

Collaboration with Sandia and Caterpillar

Sandia National Laboratories

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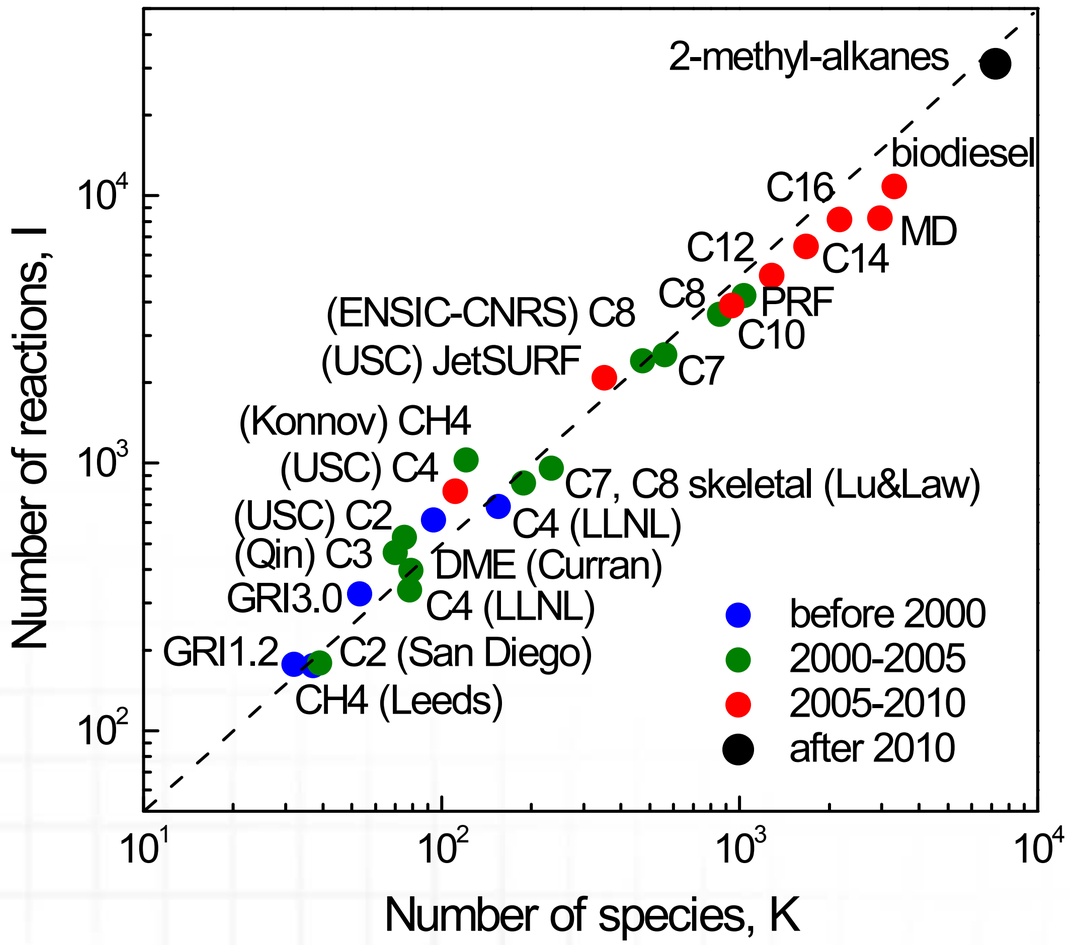
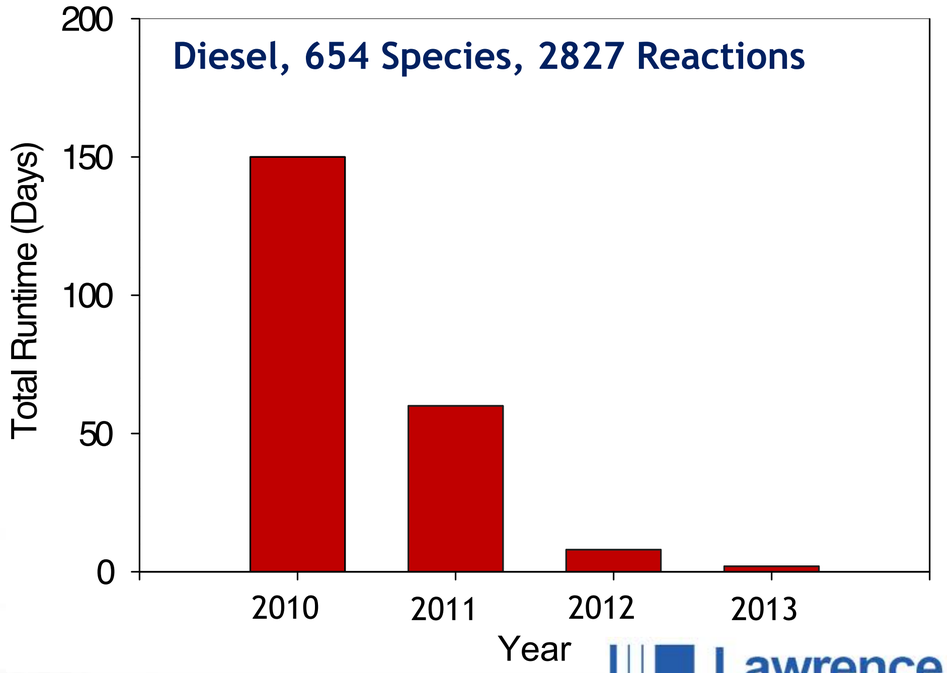
Collaborations with LLNL



654 Species, 2827 Reactions	Total Time (days)
SAGE	150
SAGE-MZ, Direct	60
SAGE-MZ, Iterative	8
SAGE-MZ-DMR, Iterative	2
GPU	???



Mechanisms with up to 1,000 species can now be simulated with CFD

Lawrence Livermore National Laboratory

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Key Findings and Recommendations

RANS Spray Simulations

- 0.25 mm cell sizes provide reasonably grid converged results for non-evaporating, vaporizing, and combusting sprays

LES Spray Simulations

- 0.125 mm or finer resolutions necessary (recommended to use 0.0625 mm)
- Multi-realization averaging is necessary to mimic experimental data (at least 8 realizations need to be averaged)

Eulerian Spray Simulations

- Near nozzle spray features are better predicted by the EE model
- EE simulations require at least 15 micron resolution near the nozzle

Nozzle Flow Simulations

- 10-15 micron resolution is sufficient to capture bulk flow features
- 5 micron or finer may be needed to capture opening and closing transients
- Needle wobble has a large influence on plume-to-plume variations

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Future Directions - Engine CFD in 5 Years in CONVERGE

- Massively parallel simulations, CPUs and GPUs
- Improved chemical mechanisms and emissions models - predictive soot
- LES with grid-converged mesh resolution
- Eulerian spray modeling linked to nozzle flow
- Multiple cycles routinely
- Multiple cylinders routinely
- CHT routinely

High Performance Computing is a significant enabler to helping us achieve these goals.

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