# Cummins/ORNL-FEERC CRADA: $NO_x$ Control & Measurement Technology for Heavy-Duty Diesel Engines

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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# Overview

## Timeline

- Start: FY1998
- Major Revisions: 2001, 03, 06, 10
- Current term: 2010-'12 revision
- Current end date: Sept. 2012
- ~47% Complete

## Budget

- 1:1 DOE:Cummins cost share
- DOE Funding:
  - FY2009: $400k
  - FY2010: $400k + $250k (Aug. 2010)
  - FY2011: $450k + $400k
    Catalyst + Combustion

## Barriers

- *Engine combustion*
  - Combustion uniformity
- *Emissions controls*
  - Catalyst fundamentals, design, control & diagnostics, (*& efficiency*)
- *Engine controls*
  - Variability & diagnostics
  - Fast PM & species diagnostics
- *Durability*
  - Fuel dilution of oil, (*& efficiency*)

## Partners

- **ORNL & Cummins Inc.**
- Chalmers Univ. of Technology
- Inst. Chemical Tech., Prague
- Informal coordination with CLEERS

# Objectives

**Self-Diagnosing SmartCatalyst (new focus in current term):**

- Enable closed-loop, on-board control & OBD of catalyst systems
  - Understanding the intra-SCR static and dynamic performance distributions & relationships
  - Developing diagnostic tools that measure those performance parameters

Improve catalyst design, control & diagnosis (OBD) for enhanced ***efficiency, durability & emissions control***

**Combustion Uniformity:**

- Reduce cylinder-to-cylinder & cycle-to-cycle combustion variations
  - Understanding the origins of intake & combustion fluctuations

Enable improved ***efficiency, control and emissions***

- Apply Fuel-in-Oil diagnostic to advanced engine technologies

Enable improved ***durability, efficiency and emissions***

Lower development ***cost*** & shorten development ***time***

# Milestones

**2010 Milestone:**

- ✓ Characterize SCR-catalyst performance distribution under select operating conditions
- ✓ Demonstrate high-speed (sufficient for cylinder-resolved) measurement of 0-10% $CO_2$

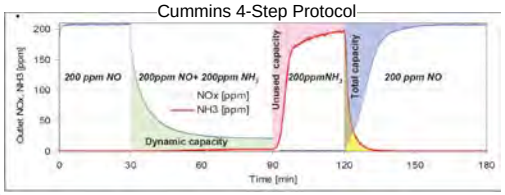
**2011 Milestones (on target for Sept. 2011 completion):**

- Dynamic analysis of SCR-catalyst performance
  - E.g., $NH_3$ capacity distributions & transient response
  - Assess & refine analysis techniques
- Measurement of intake-EGR-charge distribution on engine
  - Build on knowledge from fast exhaust measurements
  - Proof-of-principle and refinement in early 2011
  - Follow-on applications for studying non-uniformity origins and mitigation strategies

# Approach *for addressing SCR Control Challenges*

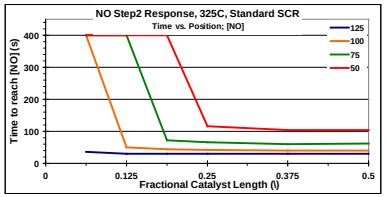
## Catalyst Understanding

**Evaluate static & dynamic catalyst nature**




**Understand chemical & spatiotemporal relationships**

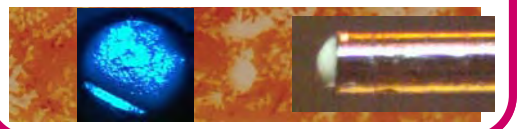
**Identify Control Parameters**




**Improve models & designs**

## Diagnostic Tools

**Develop lab diagnostics (T, species, Z, etc)**



**Prioritize high-potential diagnostics**

**Bench & engine evaluation**

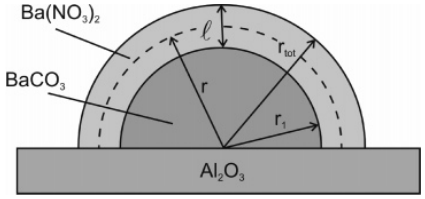
**Understanding + Diagnostics for Real-Time Catalyst Control**

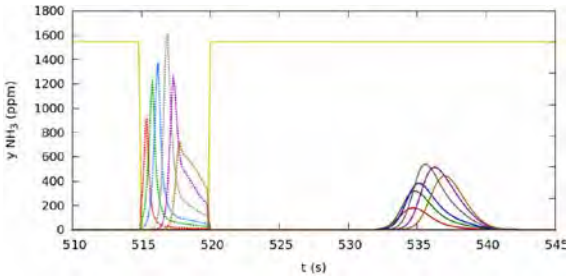
***Improved Fuel Economy, emissions & catalyst durability***

# Technical Progress: ***Self-Diagnosing SmartCatalysts***

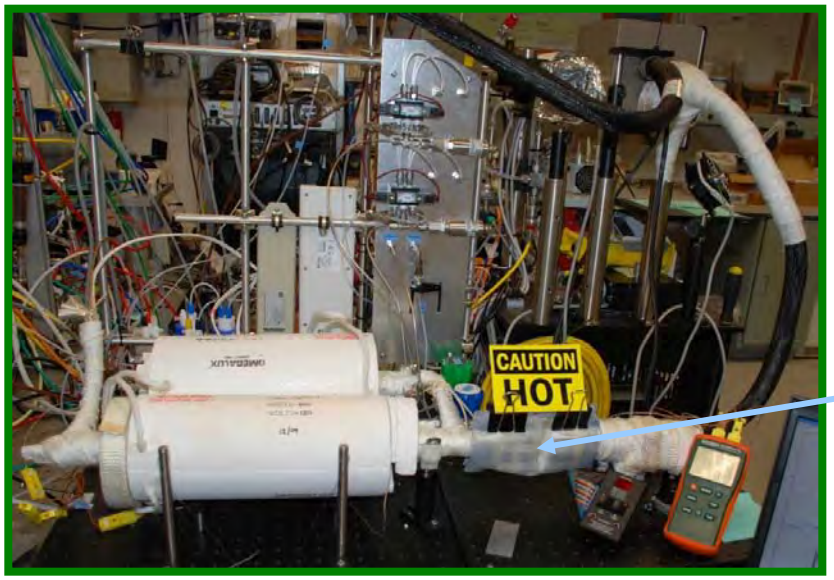
- Distributed SCR Reactions & Ammonia Storage
  - Study static and dynamic reaction/storage distributions
  - Evaluating commercial Fe- & model Cu-zeolite catalysts
    - ***Responsive to 2010 Merit Review feedback***
  - Collaborative with Prof. Louise Olsson, Chalmers
    - Provided model Cu-zeolite catalyst
    - PhD student Xavier Auvray, 6 months at ORNL & ongoing

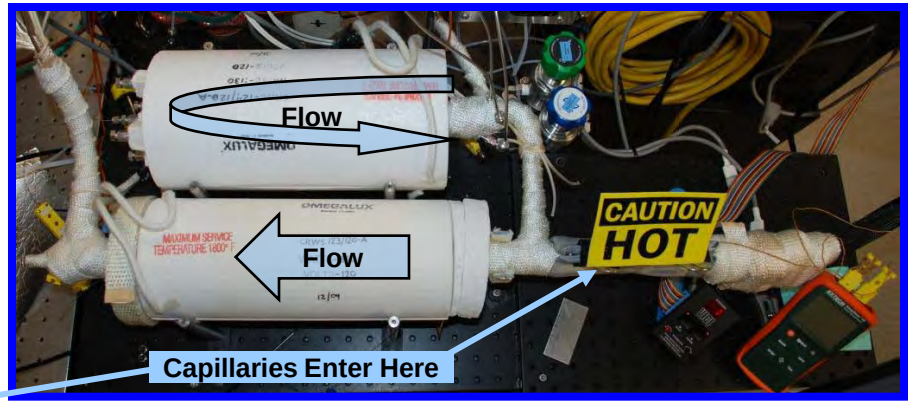

- LNT $NH_3$ & $N_2O$ chemistry
  - Using CRADA data & continuing in CLEERS
  - Collaborative w/ Prof. Olsson, Chalmers
    - MS student Soran Shwan, "Modeling of NOx storage and reduction for emission cleaning from vehicles," August '10 defense
    - Continuing with a new MS student
  - Collaborative w/ Dr. Petr Koci, Prague Inst. Chem. Technology
    - August 2010 at ORNL
    - Ongoing $N_2O$ modeling work
    - Partnering to model & understand SpaciMS sampling details

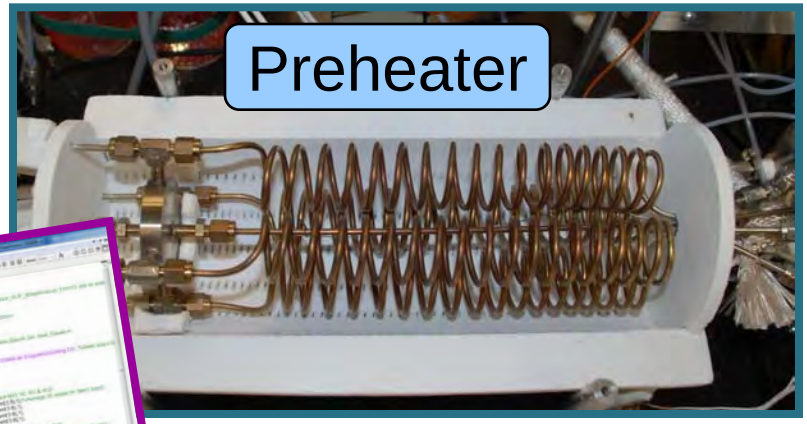


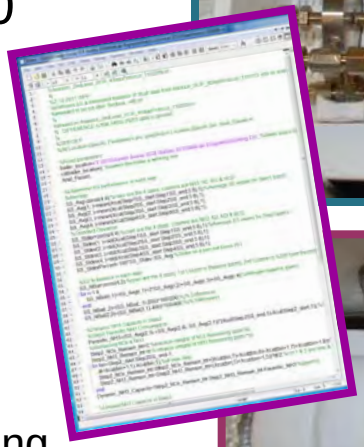



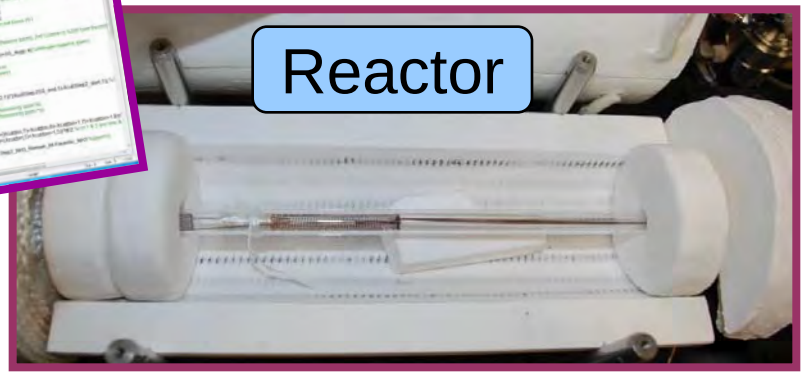
# Technical Progress: ***Intra-SCR Measurements & Analysis***



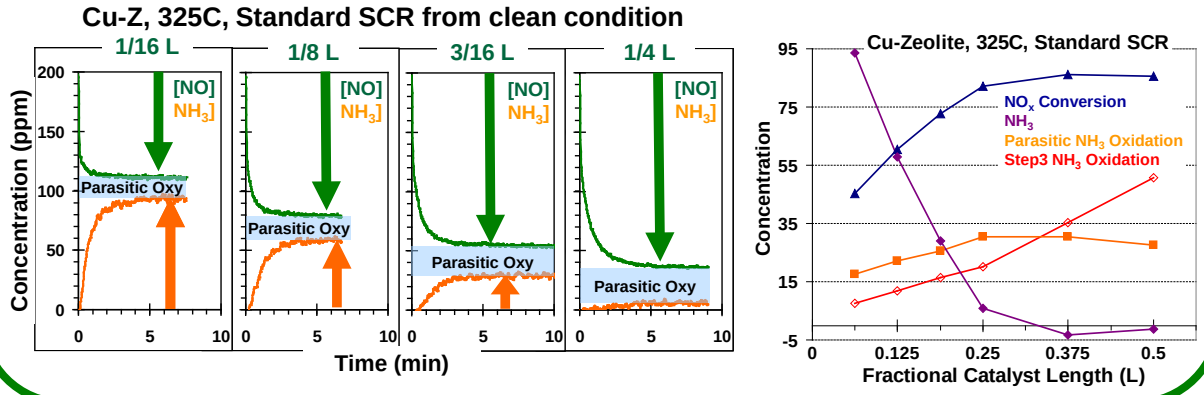



- MicroReactor redesigned mid 2010
  - Improved SpaciMS capillary access
  - Improved temperature control
    - Separate gas preheat before mixing
    - Catalyst T uniformity > 99%
    - Capillaries > 195°C
  - 2x independent gas switching feeds
  - LabView microreactor control & monitoring
- MatLab analysis:
  - Steady state, transient & integrated analysis

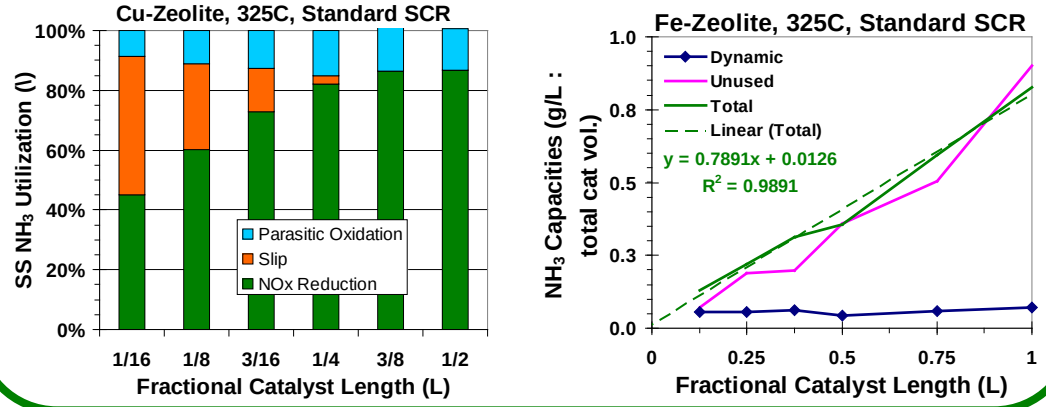
# Technical Progress: ***Intra-SCR Distributed $NH_3$ Functions***

- Protocol measurements:
  - Static & Dynamic reactions
  - $NH_3$ utilizations and capacities
- Focus on Cu-zeolite:
  - 200, 325 & 400°C
  - Standard & Fast SCR reaction
  - Degreened & Aged conditions
- 325°C, Standard SCR
  - ~3 min to reach steady state
  - Active $NH_3$ capacity in front 1/16L
  - SCR distributed over front 1/4L
    - Max in front w/ active $NH_3$
  - Parasitic $NH_3$ oxidation increases through SCR zone to ~15%
    - Apparently proportional to $NH_3$
- 400°C, Standard SCR
  - Parasitic oxidation in very front
  - Greater SCR gradient

## Static & dynamic reaction distributions




## $NH_3$ utilization & capacities




**Understand Basic Physics & Chemistry**

***Real-time catalyst state assessment & control***

# Approach *for Advancing Engine-System Efficiency*

**Develop & apply advanced diagnostics for engine system characterization to enable & support model validation and engines controls for fuel efficient engines**

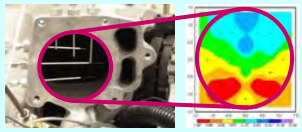

**Cummins Prototype Engine Build Up**

***Model Validation***

***System Studies***

**ORNL Diagnostics Development & Applications to Cummins Engine Systems**

- Fast Air & Exhaust Handling
- Fuel in Oil Measurements
- Exhaust Gas Chemistry



**Cummins Controls Development**

***Clean Fuel-Efficient Engines in the Marketplace***

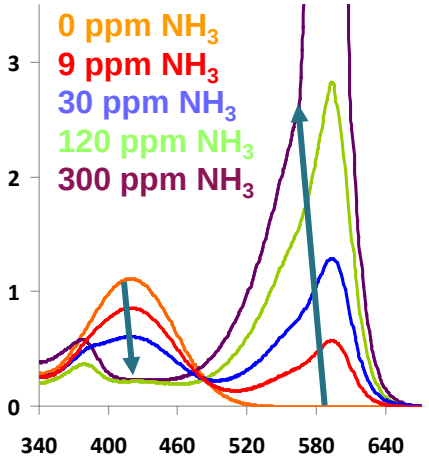
# Technical Progress: ***Combustion Uniformity***

- Developing tools to validate intake EGR-mixing
  - Fast intake $CO_2$ fluctuations measurements
  - Critical to fuel efficiency & emissions
  - Very relevant to high-EGR systems

Enables improved ***engine efficiency & control, and reduced emissions***

- Sensing exhaust species for improved control
  - Combustion uniformity, catalyst control

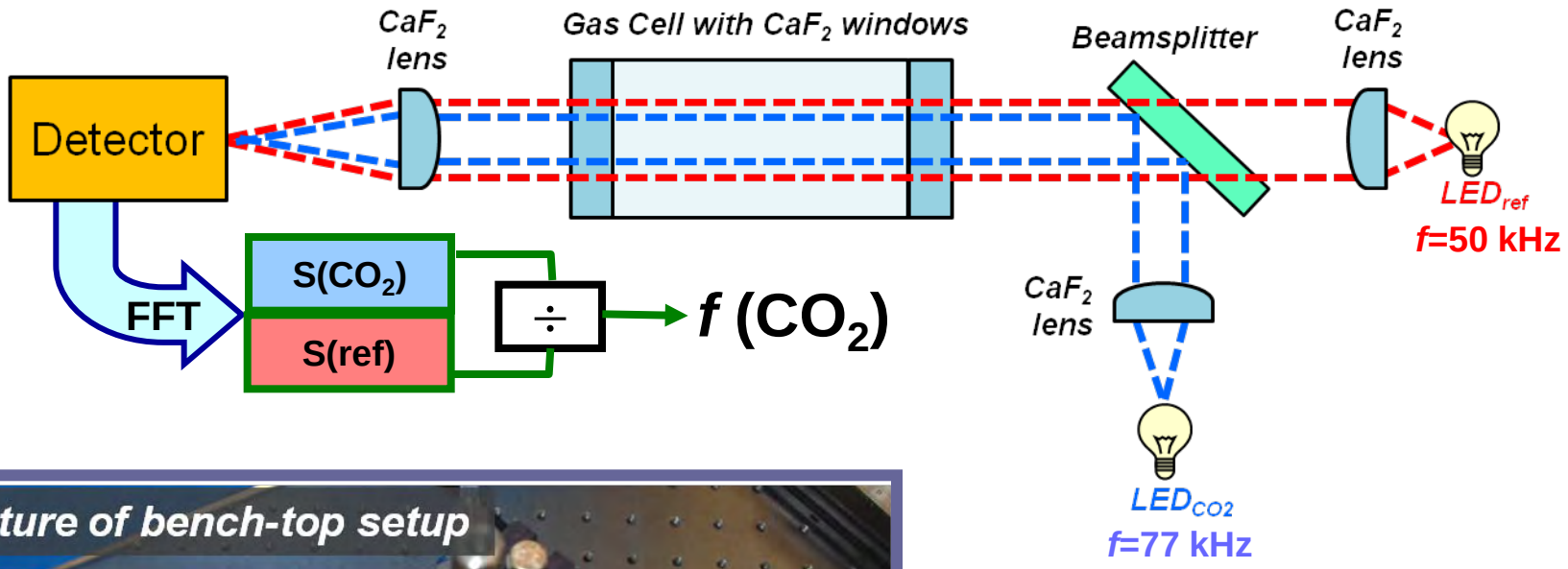
Enables improved ***efficiency & durability***

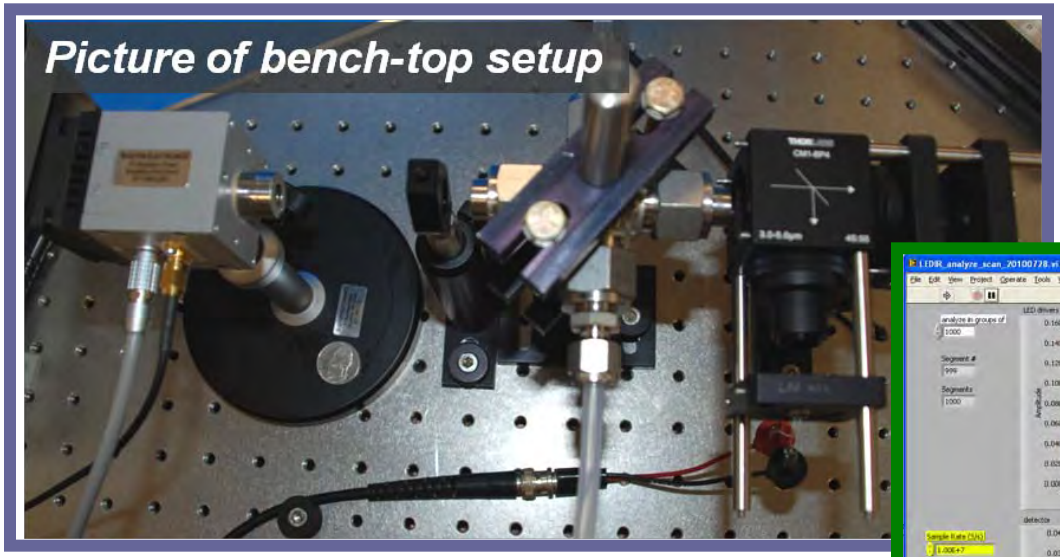


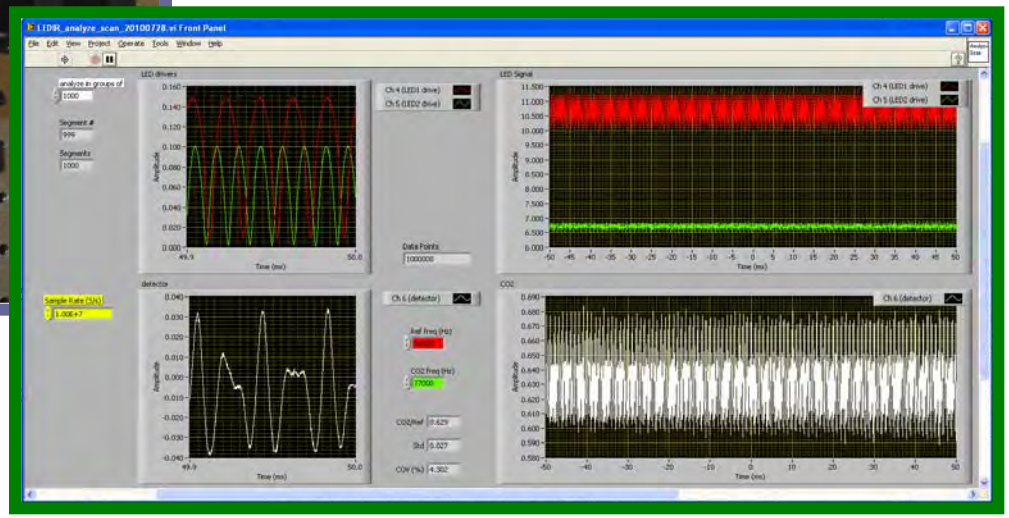

- Applying Fuel-In-Oil diagnostic to advanced engine applications
  - 2011 National FLC Excellence in Technology Transfer Award
    - Da Vinci Emissions Services commercializing DAFIO


Enables improved ***engine calibration, durability, efficiency & emission; and lowers development costs***

# Tech. Progress: ***Fast Intake $CO_2$ Measurements***

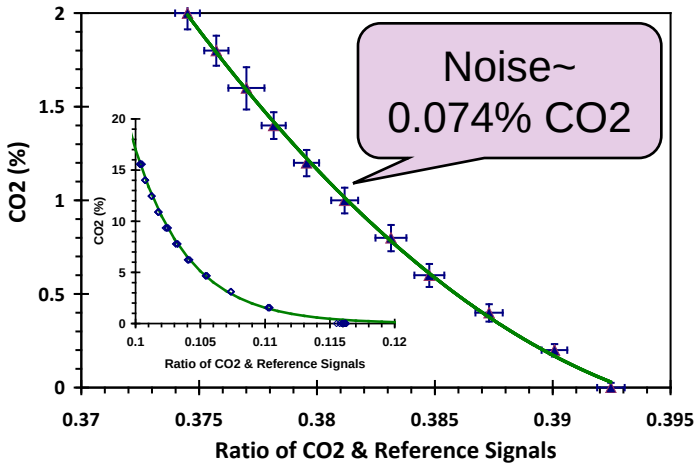


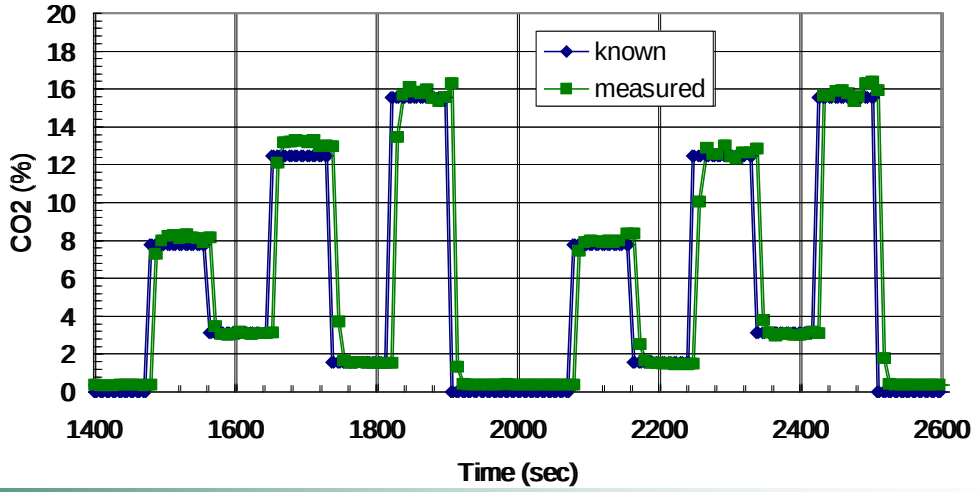



# Tech. Progress: ***Fast Intake $CO_2$ Calibration & Speed***

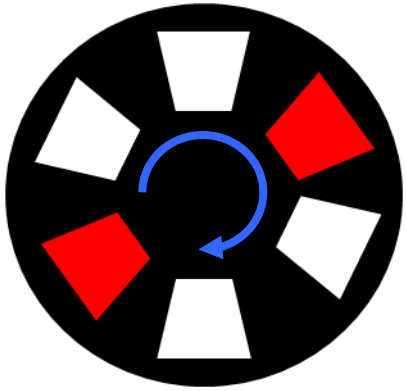
## Calibration

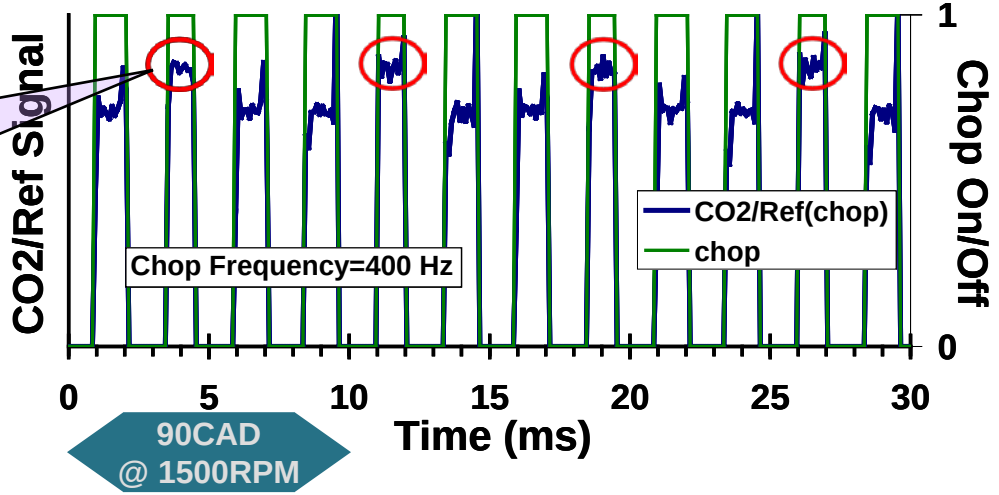



## Speed Demonstration

- 400Hz chopper in IR path
- Plastic over every 3rd window
- Plastic simulates greater [$CO_2$]






**On-Engine Application at Cummins Tech Center April 11-15, 2011**

# Collaborations & Coordination

- Cummins
  - CRADA Partner
- Cummins SuperTruck Program
  - CRADA-developed tools support SuperTruck project
- Prof. Louise Olsson, Chalmers
  - SCR measurements & modeling,(PhD student, Xavier Auvray)
  - LNT modeling $NH_3$ & $N_2O$ chemistry (MS student)
- Dr. Petr Koci, Prague Institue of Chemical Technology
  - LNT modeling $N_2O$ chemistry
  - SpaciMS capillary sampling modeling
- CLEERS
  - LNT $NH_3$ measurements & modeling, SCR measurements
- Dr. Alex Goguet, Queen's University Belfast
  - SpaciMS invasive nature under varying conditions (MS student)
  - Developing Time-of-Flight SpaciMS
- Dr. Kent Froelund, Da Vinci Emissions Services
  - DAFIO licensed for commercial sales

# Future Work

**2011 Work:**

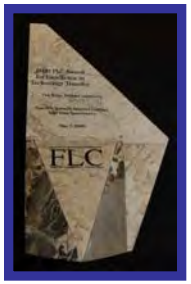
- Other conditions (e.g., SV, $NH_3$:$NO_x$, NO:$NO_2$) to study performance impact
- Mine spatial & temporal species distributions for control relationships
- Fiber-based $NH_3$ and other diagnostics
- Fuel-in-oil applications to advanced engine technologies
- Mid-IR laser for improved intake-$CO_2$ SNR
- SCR, LNT & SpaciMS modeling (joint w/ CLEERS, Chalmers & ICT Prague)

**2012 Work:**

- Inhibitor & Inhibition impact on SCR catalyst reaction and storage distributions
- Correlate control relationships w/ performance parameters
  - Identify strategies for SCR-catalyst control & diagnostics
- Apply diagnostics to understand combustion variations
  - Correlating intake and combustion variations

# Summary

- On path to Self-Diagnosing SCR Catalyst
  - Focusing on Cu-zeolite catalyst ***(cf. 2010 Review feedback)***
  - Intra-SCR static & dynamic performance distributions ***(2010 milestone)***
  - Enhance design, modeling, specification, control & OBD for ***improved efficiency, durability & emissions***
- Studying intake variations impact on combustion uniformity
  - Build on cylinder-resolved exhaust $CO_2$ measurements ***(2009 milestone)***
  - Synergistic with Cummins' SuperTruck program
  - Evaluates engine variations and mitigation strategies for ***improved efficiency, control and emissions***
- CRADA-developed Fuel-In-Oil Diagnostic nationally recognized
  - 2011 National FLC Excellence in Technology Transfer Award
  - Applying to advanced engine technologies
  - Commercially available as DAFIO from Da Vinci Emissions Services
  - Applied at Cummins for ***improved durability, efficiency and emissions***




- CRADA approach consistently yields practical techniques and solutions
  - E.g., EGR mixing, Fuel dilution, Catalyst & Engine control, Models, SpaciMS, OBD
- Future work focuses on:
  - Understanding distributed intra-SCR chemistry & performance for OBD applications
  - Studying engine variations and mitigation strategies
  - Advanced variation diagnostics for catalyst, combustion & engine characterization