# TDL syngas sensor for *in situ* monitoring of CO, $CH_4$, $CO_2$, & $H_2O$ in an engineering-scale high-pressure coal gasifier

**Ronald K. Hanson, Ritobrata Sur, Kai Sun, Jay B. Jeffries**
High Temperature Gasdynamics Laboratory, Stanford University

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Gasifier in Wilsonville, Alabama USA

- Vision for gasifier sensing
- Absorption sensor fundamentals
- NCCC gasifier facility
- Stanford optics design
- Results for CO, $CH_4$, $CO_2$, & $H_2O$
- Summary and further work

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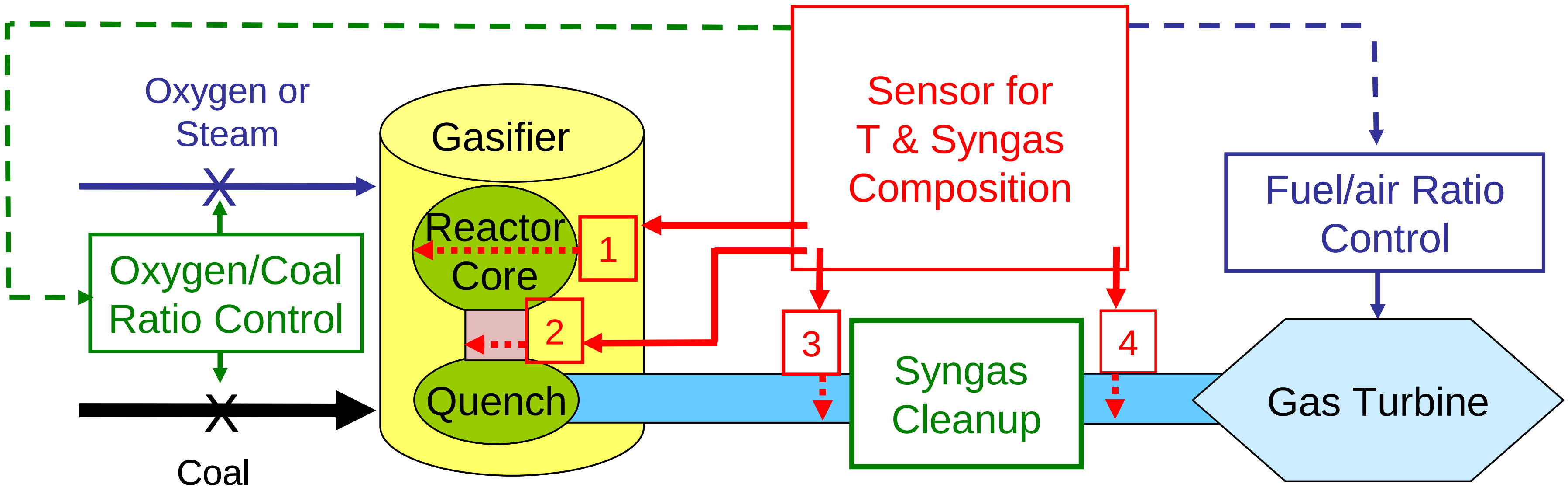
# Stanford's Vision for TDL Sensing in IGCC



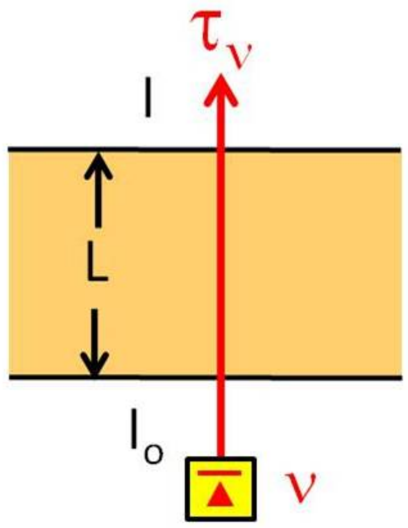

**Vision:** Sensor for control signals to optimize gasifier output and gas turbine input

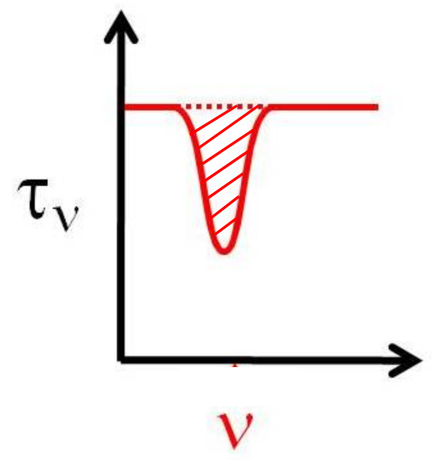
- 1st generation laser absorption sensor for CO, $CO_2$, $CH_4$, and $H_2O$
  - Stanford sensor tested in a pilot-scale (1 T/day coal) gasifier (U Utah 2009-2012)
- 2nd generation CO, $CO_2$, $CH_4$, and $H_2O$ sensor developed
  - Tested in an engineering-scale (30,000 lb/hr syngas) gasifier at NCCC (December 2012 & March 2014)

*Absorption sensing: How does it work?*

# Absorption Fundamentals:  Species

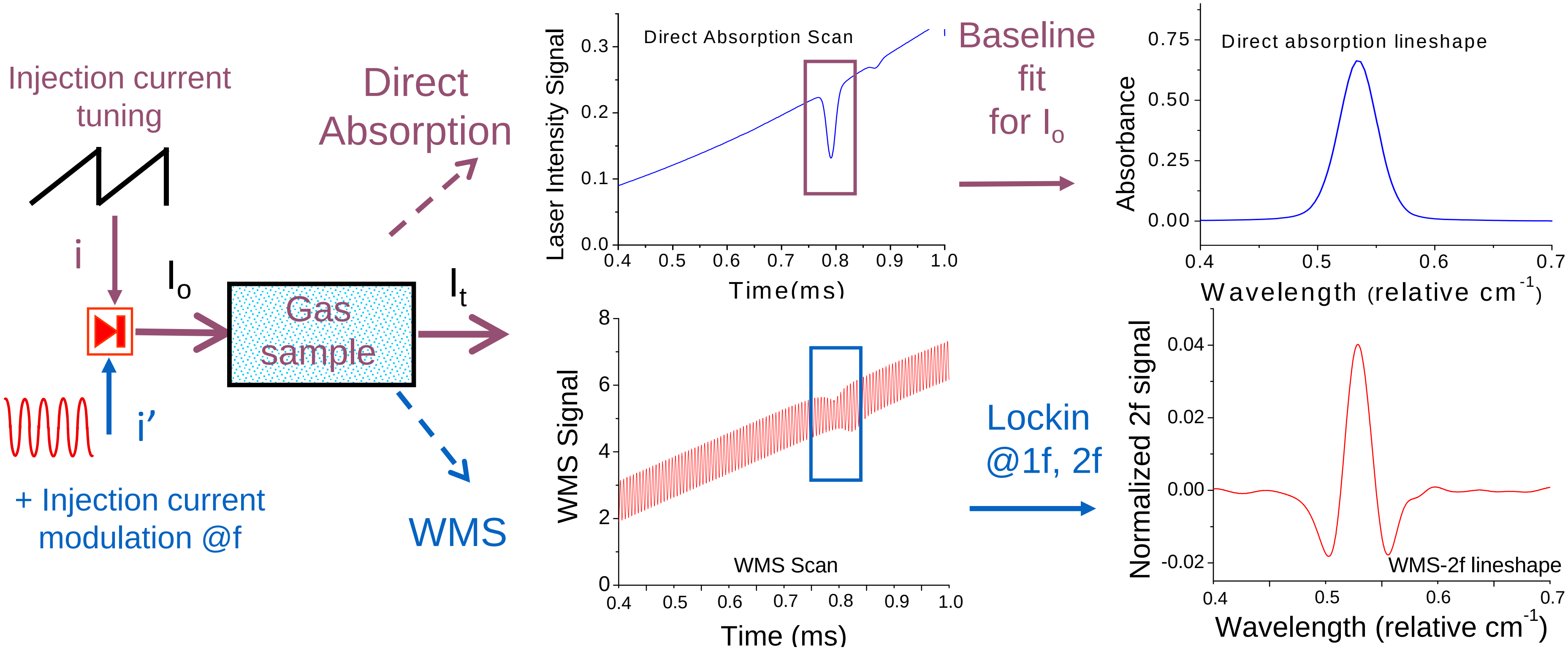
*Absorption of monochromatic light*




- Scanned-wavelength *line-of-sight* direct absorption
  - Beer-Lambert relation $\tau_\nu \equiv \frac{I_t}{I_o} = \exp(-k_\nu \cdot L)$
  - Spectral absorption coefficient $k_\nu = S(T) \cdot \Phi(T, P, \chi_i) \cdot \chi_i \cdot P$
  - Wavelength-scanning yields $\chi$ $\int_\nu k_\nu L \cdot d\nu = \underbrace{S(T) \cdot \chi_i \cdot P \cdot L}_{\text{Integrated absorbance}}$

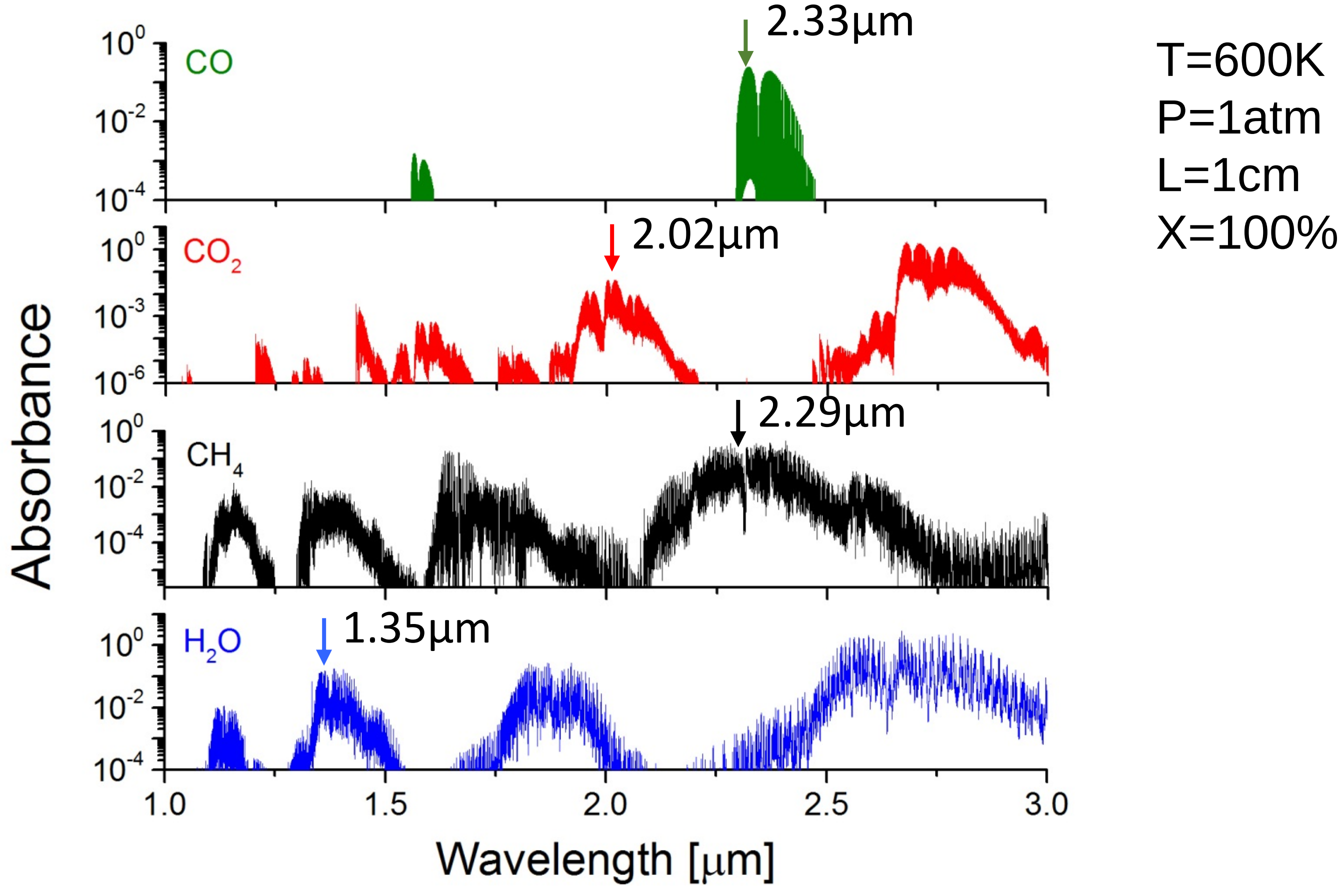
## Two Absorption Sensor Strategies:
## Direct Absorption (DA) & Wavelength Modulation Spectroscopy (WMS)




- Direct absorption: Simple, if absorption is strong and isolated
- WMS: More sensitive especially for small signals (near zero baseline)
  - WMS with TDLs improves noise rejection
  - *Normalized WMS, e.g. 2f/1f* cancels scattering losses!

***What wavelengths for syngas detection?***

# Gas Species Important to Combustion/Gasification Absorb Light in the Near-Infrared




- Important gasification species can be monitored (e.g., CO, $CO_2$, $CH_4$, $H_2O$)
- Select 2-2.3µm to minimize $H_2O$ interference for CO, $CO_2$, $CH_4$

***What does the facility look like?***

# NCCC Gasifier Large-Scale DoE Demo


Instrumentation shelter

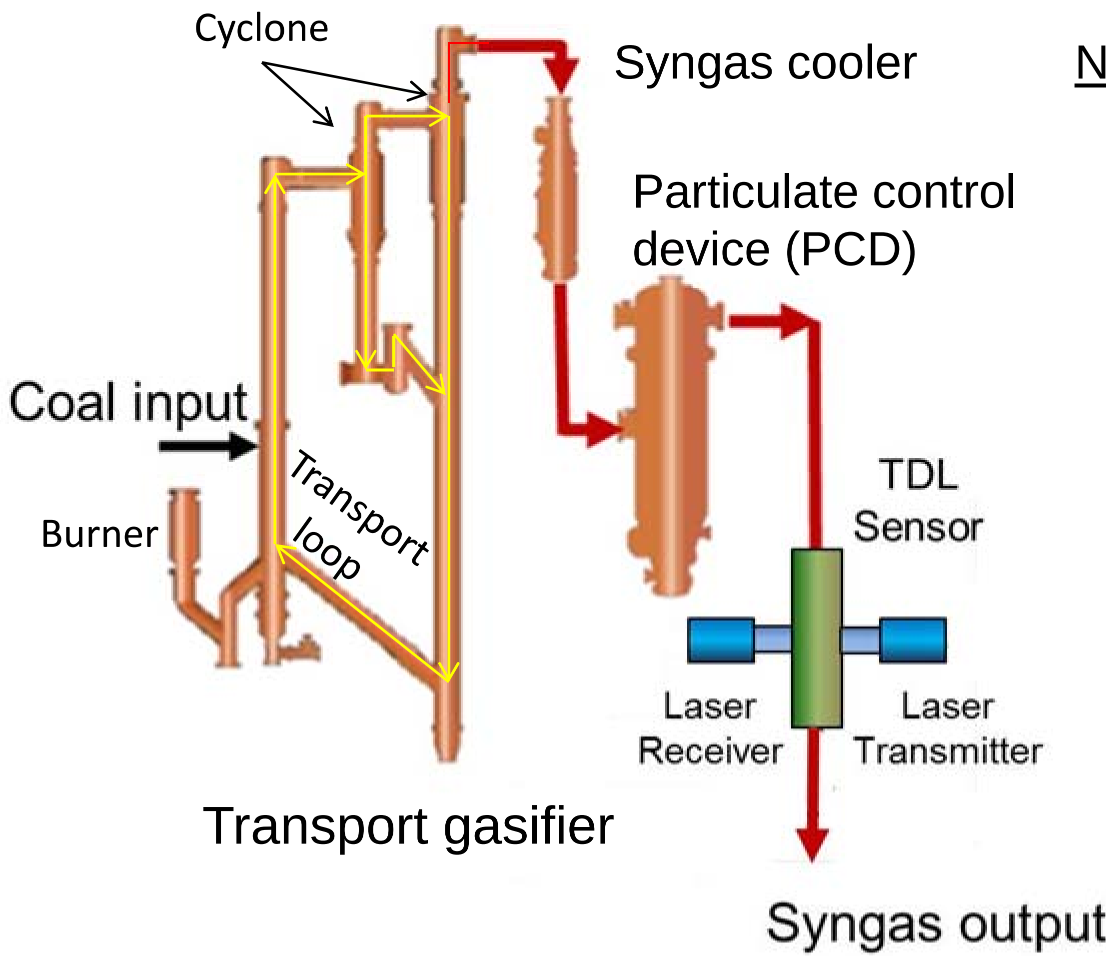
- NCCC transport gasifier based on a circulating fluidized bed concept

**Goal:**

Laser absorption *in situ* measurements of syngas products composition

***Where is sensor located?***

# TDL Sensor Location and Syngas conditions



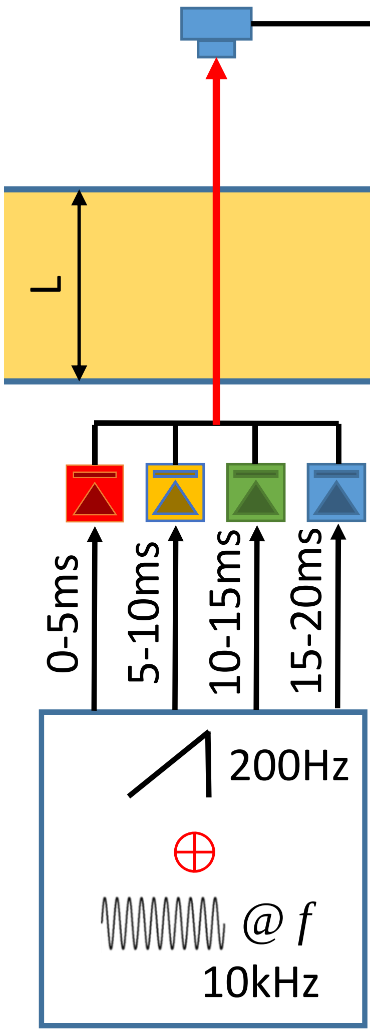

<u>Nominal conditions at TDL sensor</u>

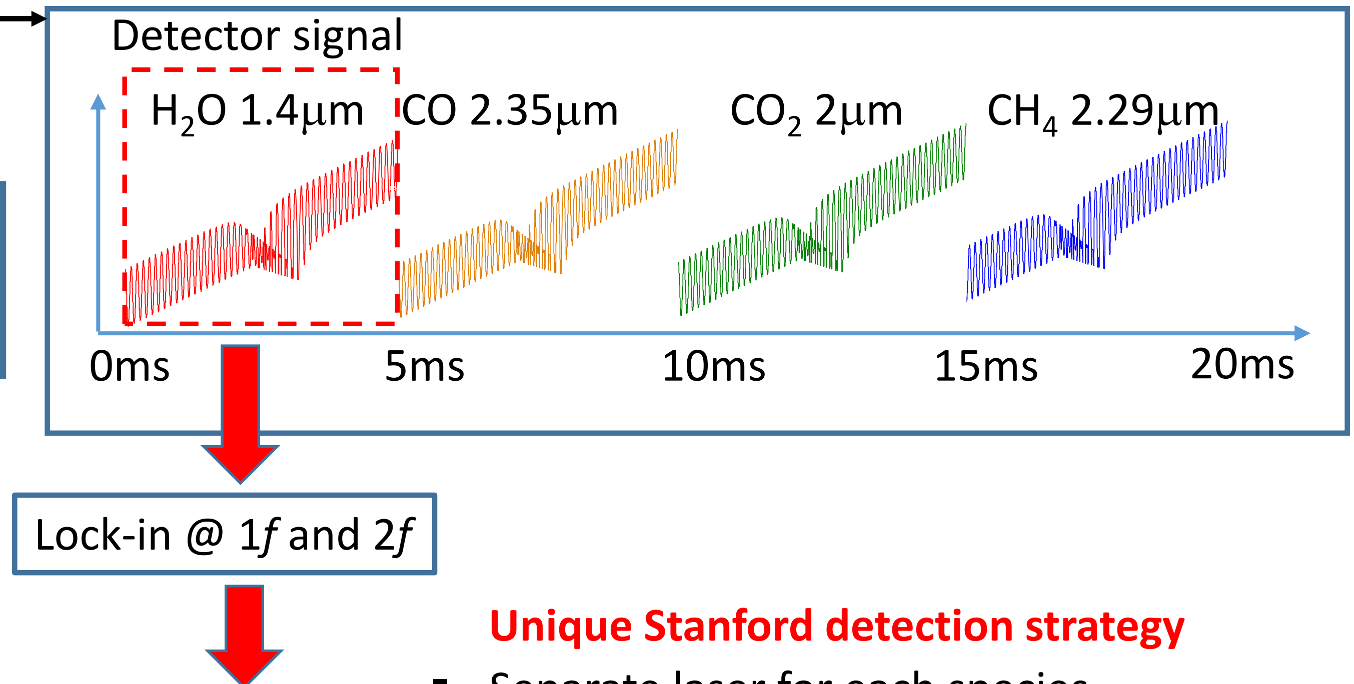
T~600 K
P~220 psig (15 atm)
Gas composition
- $H_2O$ 6-10%
- $CO_2$ 6-10%
- CO ~12%
- $H_2$ ~ 8%
- $CH_4$ ~ 1%
- Minor species <1% (e.g., $NH_3$, $H_2S$, $SO_2$…)
- $N_2$ Balance

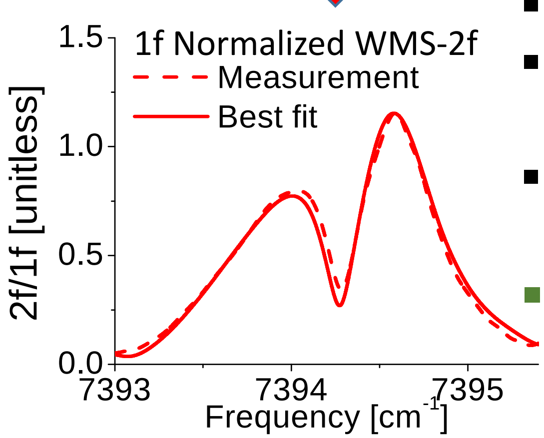
- TDL sensor monitors syngas flow 30m downstream of the PCD
- Flow laden with particulate (< 0.1% transmission) at sensor location

***How do we measure 4 species?***

# Detection Strategy: Time Demultiplexing
# Wavelength Scanned WMS-2f with 1f Normalization



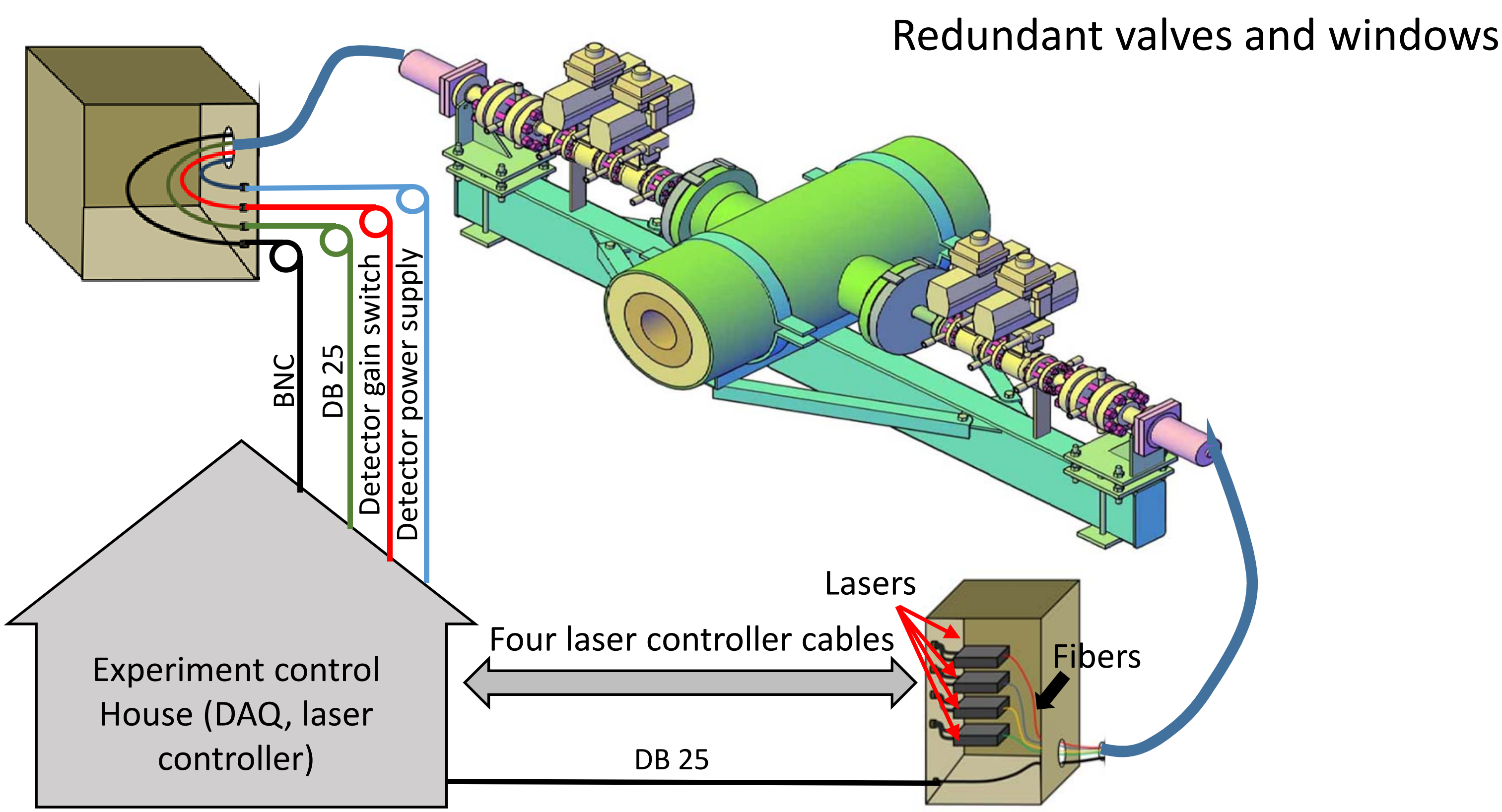




**Unique Stanford detection strategy**

- Separate laser for each species
- Time multiplexing (each laser takes a turn)
  - 4 species in 20ms w/ one detector
- Wavelength scanned 1f-normalized WMS-2f

- **Enables measurements in opaque flows**

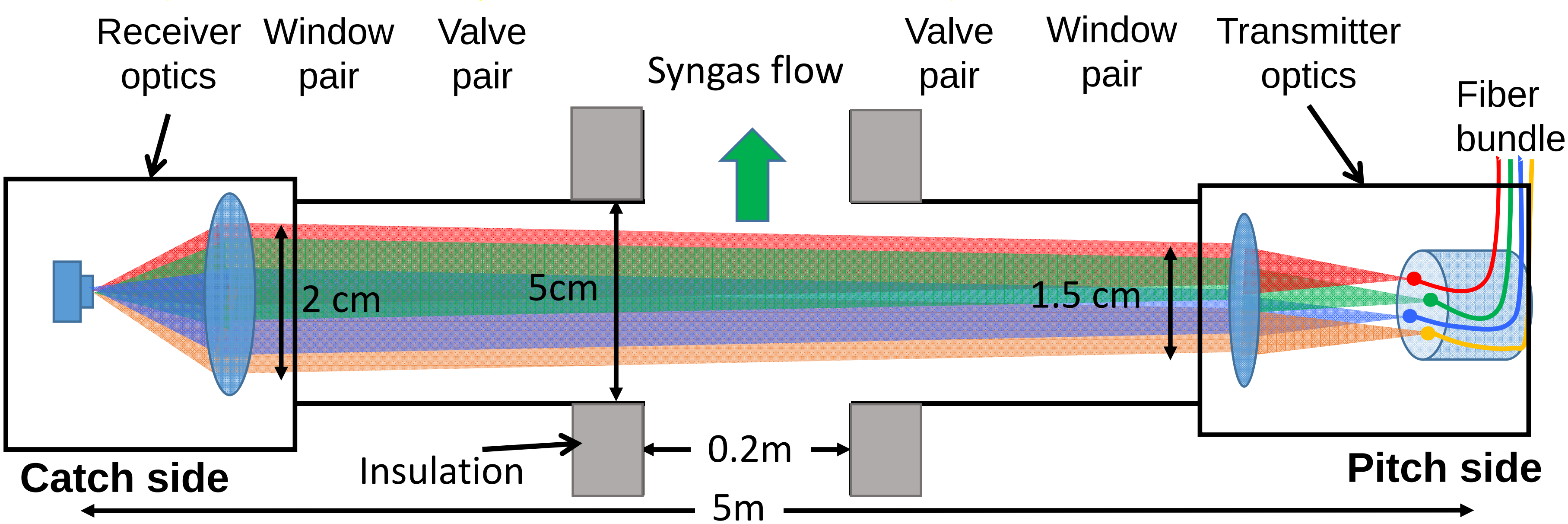
# Connections of Stanford Sensor to NCCC Facility




- Electronics in the control house ~30m to measurement location
- Lasers near measurement location (~ 2m away)
- Sensor operated remotely (alignment, detector gain, laser scanning)

***Next: Further details of optical system***

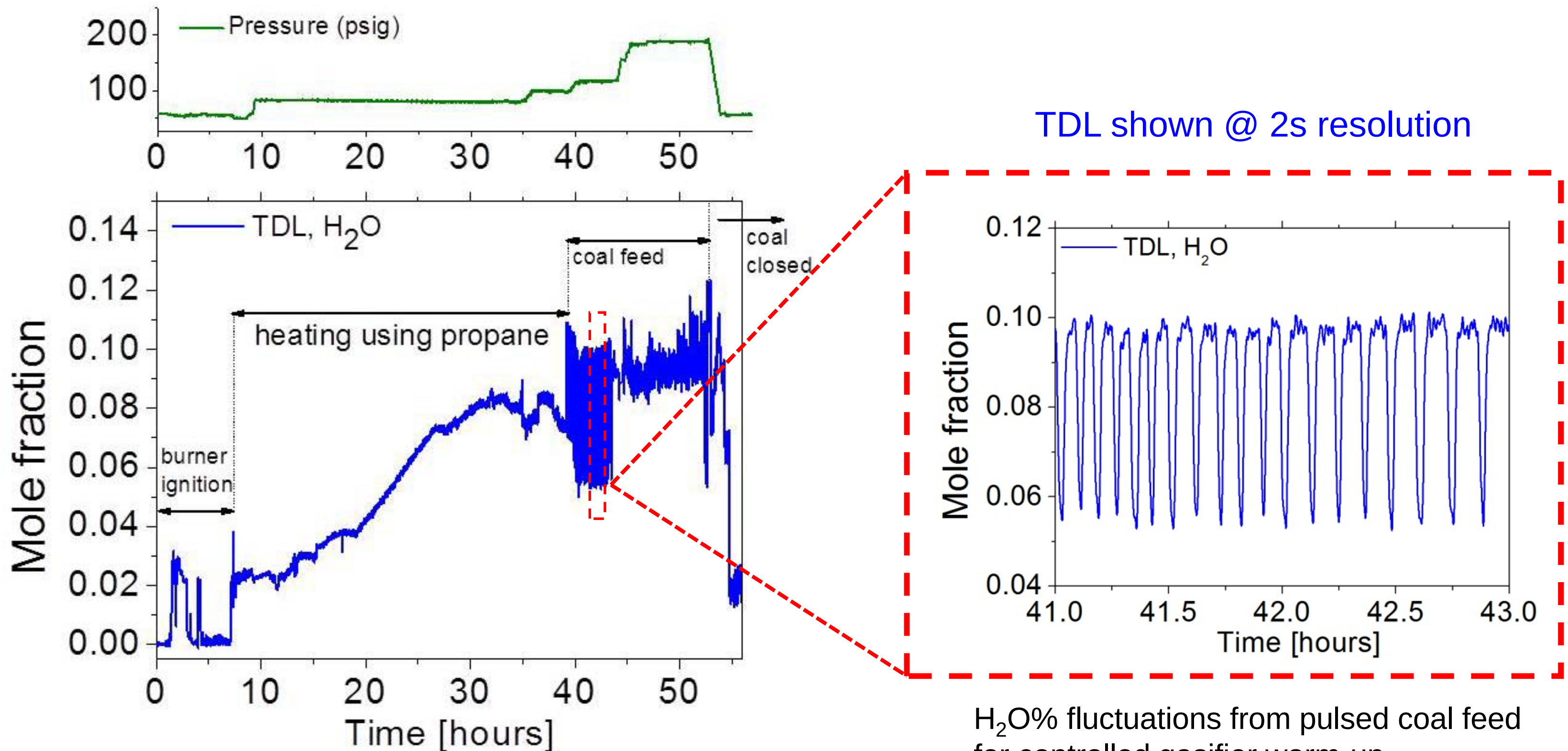
# Optics Design：Multiplex Four Lasers




- Fiber bundle delivers light from four lasers
- Optics combine all beams onto common line-of-sight w/ only one detector
- Large beam size reduces beam steering noise

***Next: Data from gasifier warm-up***

# Time-Resolved $H_2O$ During Gasifier Warm-up

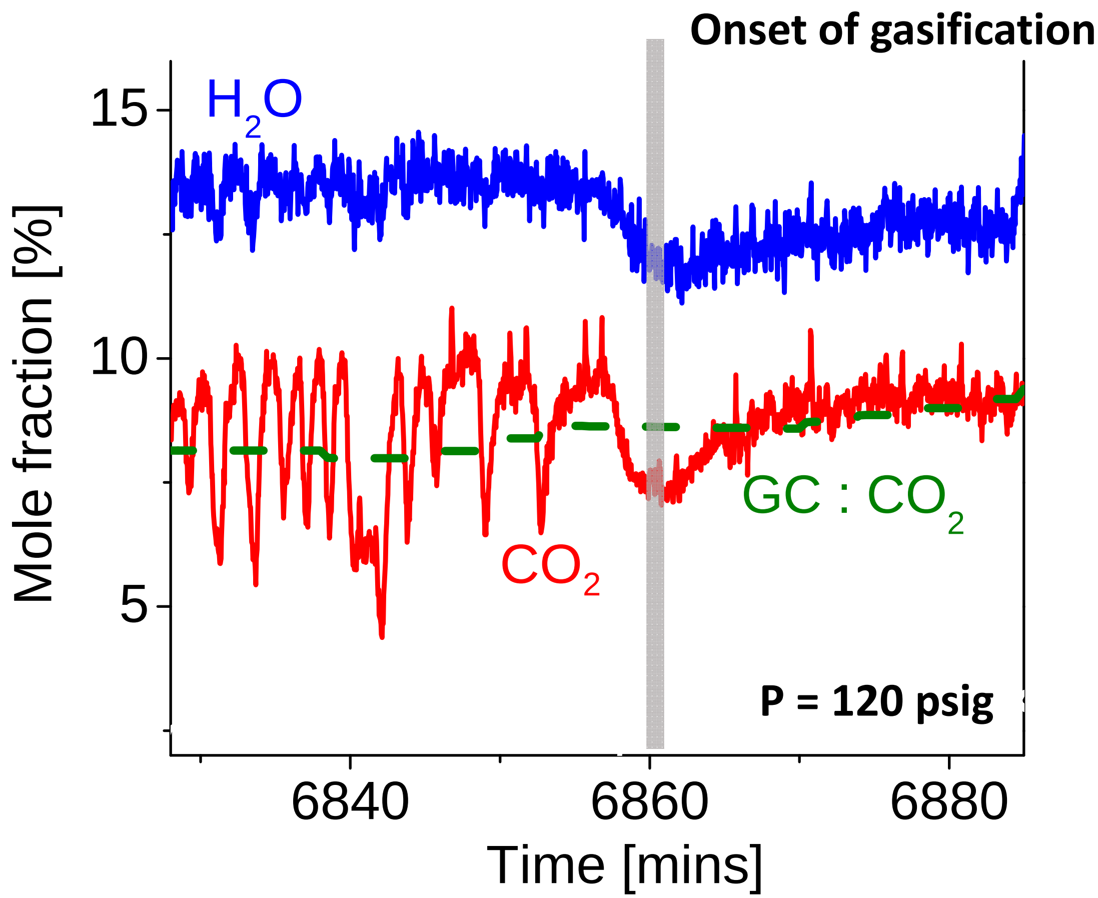



$H_2O$% fluctuations from pulsed coal feed for controlled gasifier warm-up

- *In situ* measurements of syngas moisture content capture transient events
  - Propane used for slow heating of ceramic linear
  - Pulsed coal feeding begins at hour 38
  - Reactor shut down at hour 54 (before transition to stable gasification)

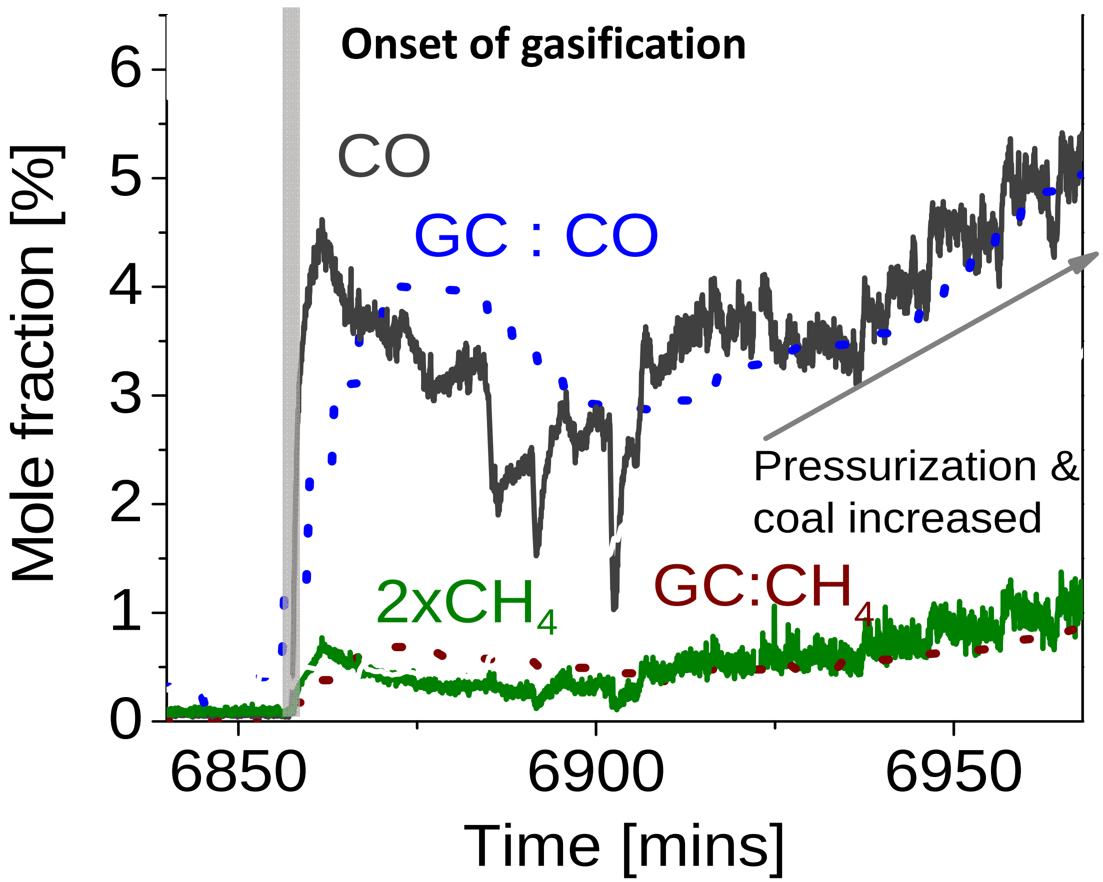
***Next: Transition to gasification***

# $H_2O$ and $CO_2$ During Transition to Gasification




- $CO_2$ fluctuations damped when reactor transitions to gasification
- GC time resolution does not capture transients, only average mole fraction

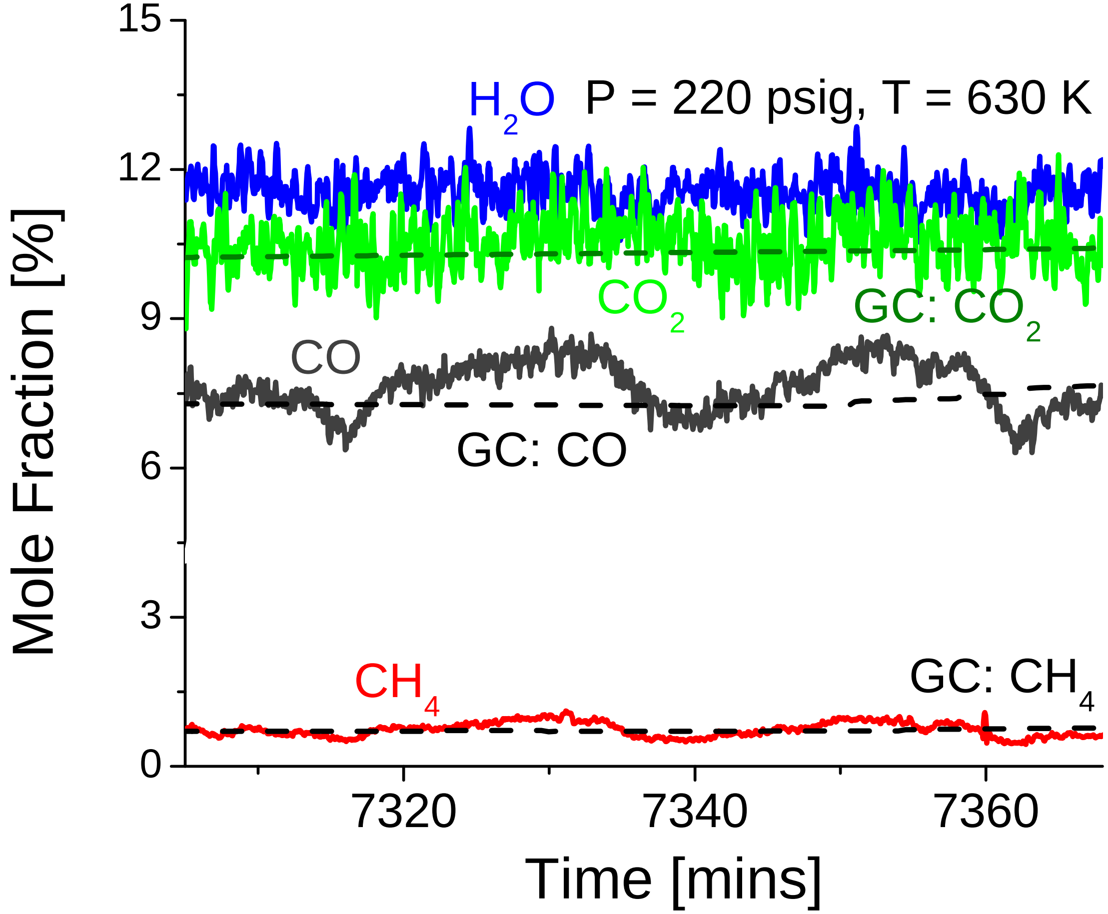
# Sensor Captures Onset of Gasification via CO & $CH_4$




- Rapid jump in CO and $CH_4$ at onset of gasification
- GC data have large time lag (shifted here by 20 minutes for comparison with laser)
- GC data also have poor time resolution (note slow CO response vs laser)

***Next: Data from "Stable Gasification"***

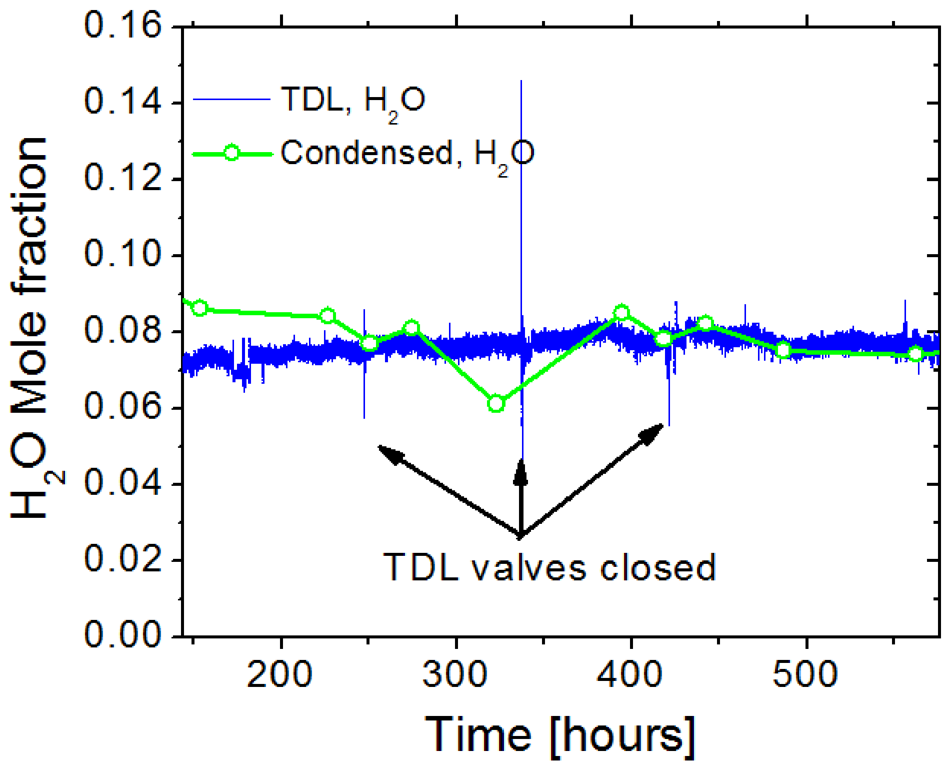
# Four Species Measurements After Gasifier “Stable”




- Laser sensor provides simultaneous CO, $CH_4$, $CO_2$, and $H_2O$
- Correlation of CO with $CH_4$ confirms that fluctuations are real
- GC time resolution does not capture temporal fluctuations

***Next: Long unattended monitoring***

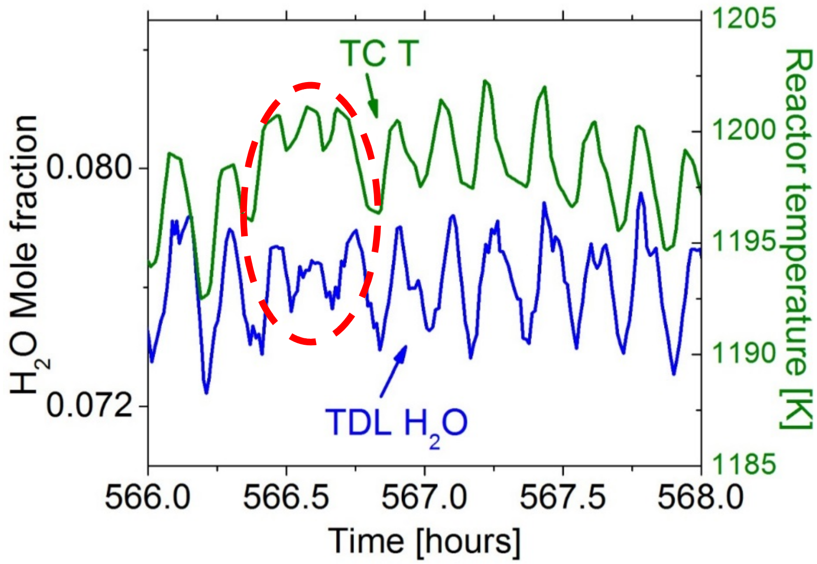
# 18 Days of $H_2O$ Unattended Monitoring

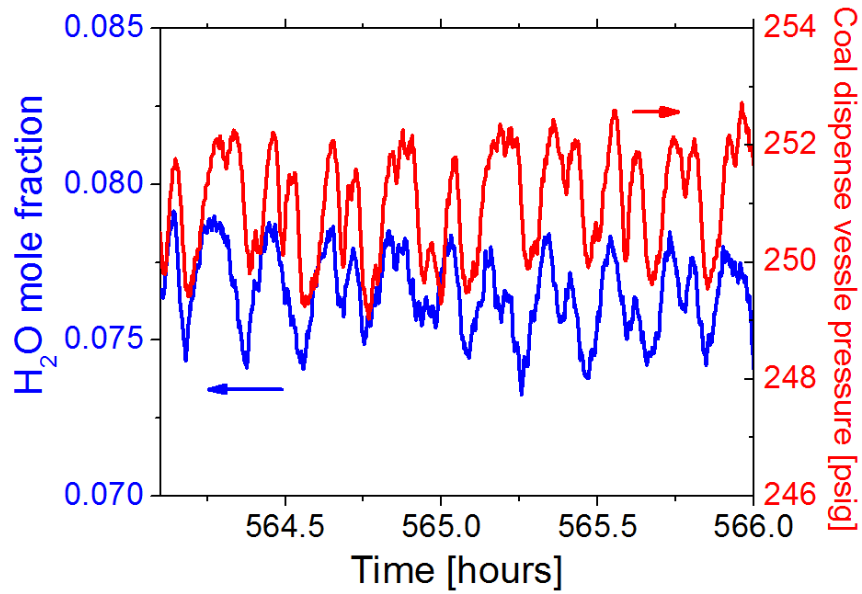



- Continuous, stable measurements for 18 days (terminated by NCCC)
- Periodic liquid $H_2O$ samples taken from syngas agree with laser sensor
- Laser sensor show small fluctuations in the $H_2O$ mole fraction

***Are sensor fluctuations real or noise?***

# $H_2O$ Sensor Captures Fluctuations in Gasifier Reactor




- $H_2O$ fluctuation tracks the reactor thermocouple (note small $\Delta T$)
- $H_2O$ fluctuation tracks the reactor coal feed pulse
- Laser sensor captures small $H_2O$ change ($\Delta$ mole fraction ~ 0.1%)

# Summary

- Laser sensor yields successful measurements in syngas
  - First-ever *in situ* laser absorption in pilot scale gasifier (Utah, 2010)
  - First-ever *in situ* laser absorption at NCCC (2012)
  - Successful in harsh environment, even with large (>99.9%) transmission losses due to scattering & pressure ~15atm
- Demonstrated excellent detection sensitivity at 1-second (1Hz):
  - $H_2O$ : 200ppm - m
  - CO : 200ppm - m
  - $CH_4$ : 300ppm – m
  - $CO_2$ : 800ppm - m
- Unattended operation (>435 hours demonstrated)
- Sensor strategy useful for other applications, especially at elevated pressure and/or dusty gases

# Recommendations for future work

- Add additional species important to specific application, for example
  - $NH_3$, $H_2S$, $SO_2$, ….
- Improve data processing
  - Provide real time readout compatible with facility record
  - Provide web-based monitoring for unattended operation
- Refine optical engineering and repackage in smaller containers

# Acknowledgements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