Smart Sensors for Advanced Combustion

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- Motivation
- Sensor strategy
- Sensor for IC-engine research*
- Sensor for gas-turbine exhaust*
- Sensor for T in coal-fired power plant
- Real-time T for combustion control*
- Opportunities

*see student poster

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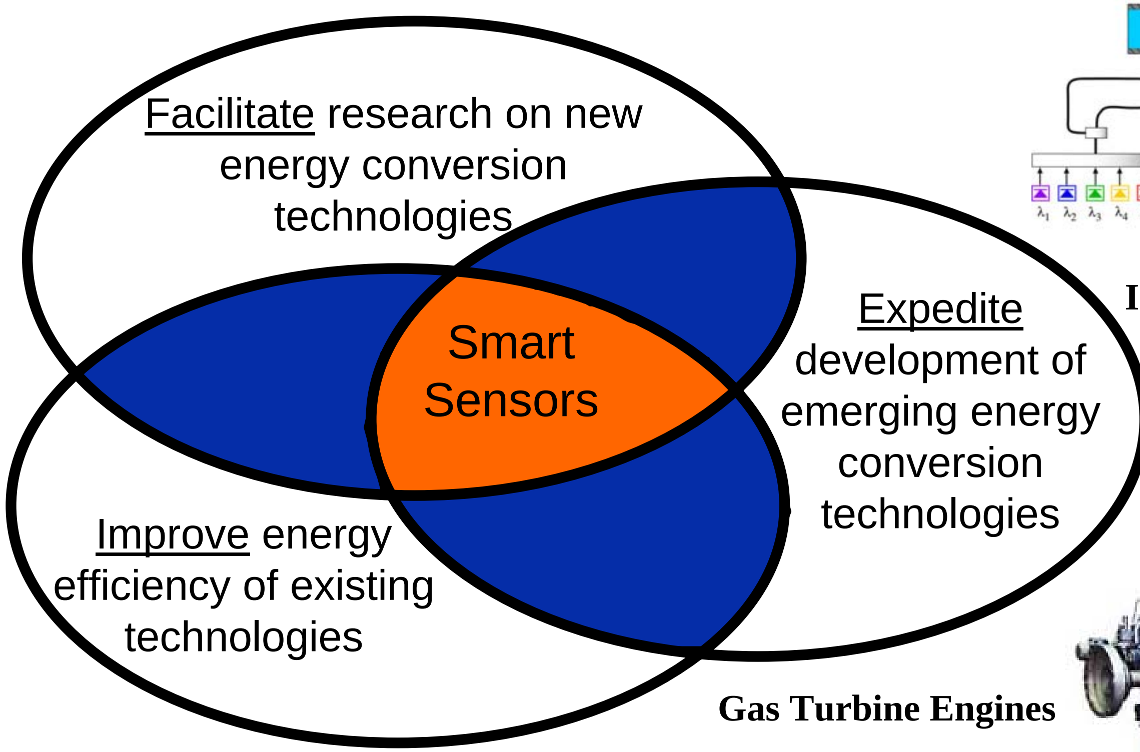
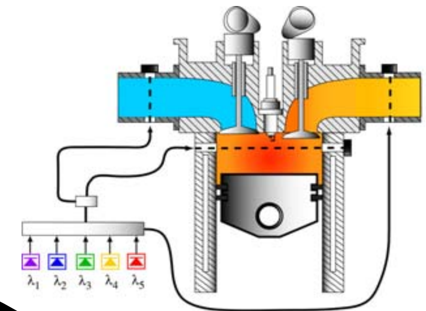
Why Research on Smart Sensors?

- Stanford has pioneered laser-based sensing for combustion systems
- Smart sensors can reduce greenhouse gases in multiple ways

Real-Time Control

Coal-Fired Power Plants





Internal Combustion Engines

Gas Turbine Engines

- Research plan: GCEP-designed smart sensors w/collaborations for practical demonstrations

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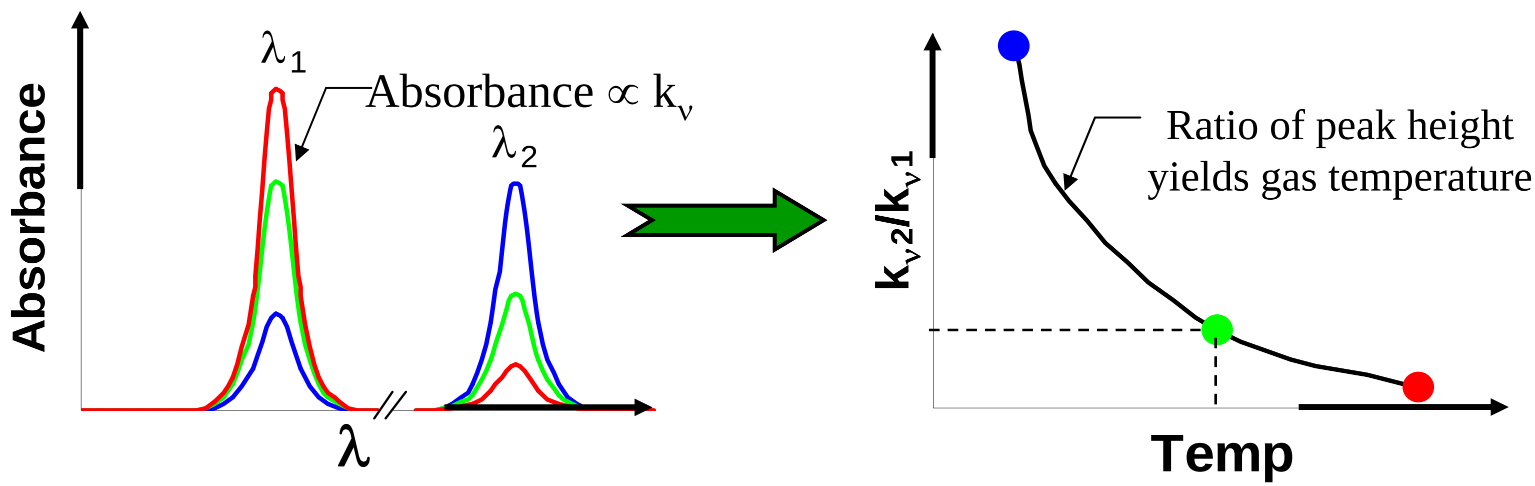
Sensor Strategy: Tunable Diode Laser (TDL) Absorption for Temperature and Gas Composition

Sensing Principle:

- Absorption of laser light by molecular transitions in combustion gases
  - Beer's law: Transmission = $I/I_o = \exp(-k_\nu L)$
  - Absorption coefficient k_ν = f(temperature, pressure, gas composition)
- Ratio of absorbance on two molecular transitions yields gas temperature



- Measurement of absorbance with temperature yields mole fraction
- Use of additional lasers can yield more species (wavelength-multiplexing)

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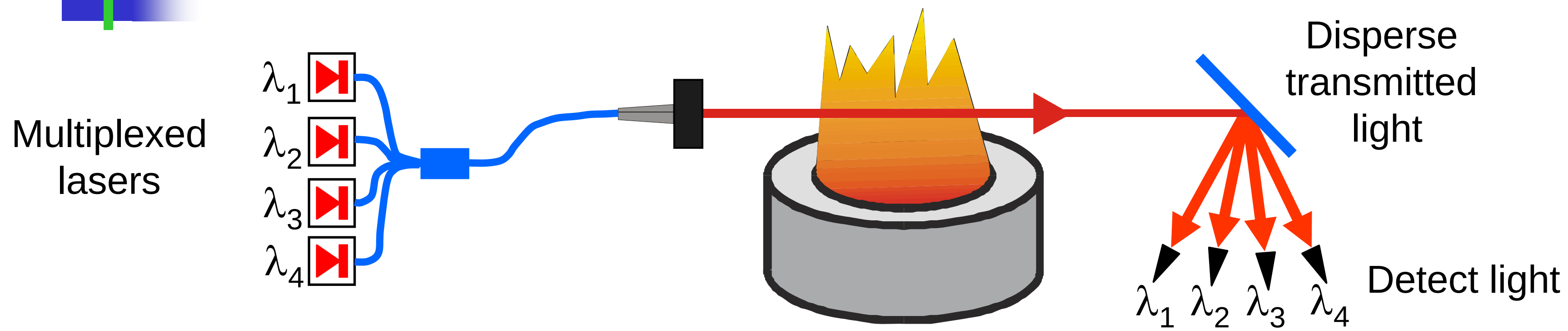
Wavelength-Multiplexing to Extend Sensing Strategy



- Wavelength-multiplexed, diode-laser sensors for simultaneous, *in situ* measurement of multiple quantities
  - T, H_2O, CO, CO_2 demonstrated at Stanford
  - Potentially NO, UHC's, fuel
- Fiber-optic technology enables *multiple measurement locations*
  - Fiber optics allows remote location of sensors
  - Fiber switches allow multiple measurements paths for one sensor
- Multiplexed absorption concept pioneered at Stanford

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Smart Sensor Research at Stanford University

Opportunity:

- New smart sensors offer the potential for reduced GHG emissions
  - Enabling new innovative energy conversion concepts
  - Expediting development of emerging energy-conversion concepts
  - Improving efficiency and pollutant emissions from existing technologies

Strategy:

- Develop non-intrusive sensors using NIR absorption and fiber technology
- Test sensor concepts with collaborations that enable access to practical engine environments, examples:
  - IC-engines, gas turbines, coal combustors, and new burner concepts

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Diode-Laser Sensors for IC-Engine Applications

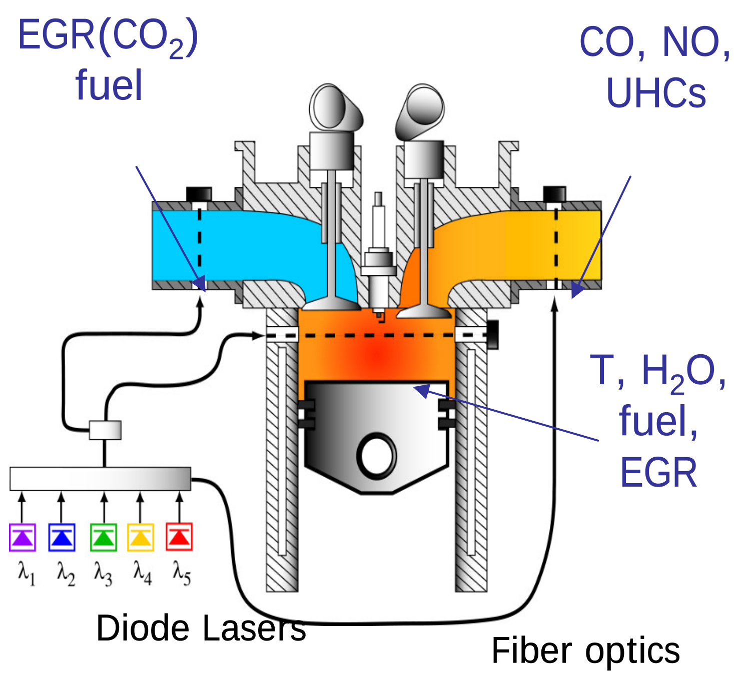
Motivation: Reduce emissions from a major source of GHG

Challenges:

- IC-engines have limited optical access and time-varying T and P with soot and droplet scattering
- Rapid time resolution is crucial

Strategy:

- Develop novel sensors tailored for IC-engine research



Examples:

- HCCI
  - Ignition controlled by chemical kinetics (not spark or fuel injection)
  - Careful control of temperature and fuel/air mixture composition needed
- Hydrogen fueled IC-engines

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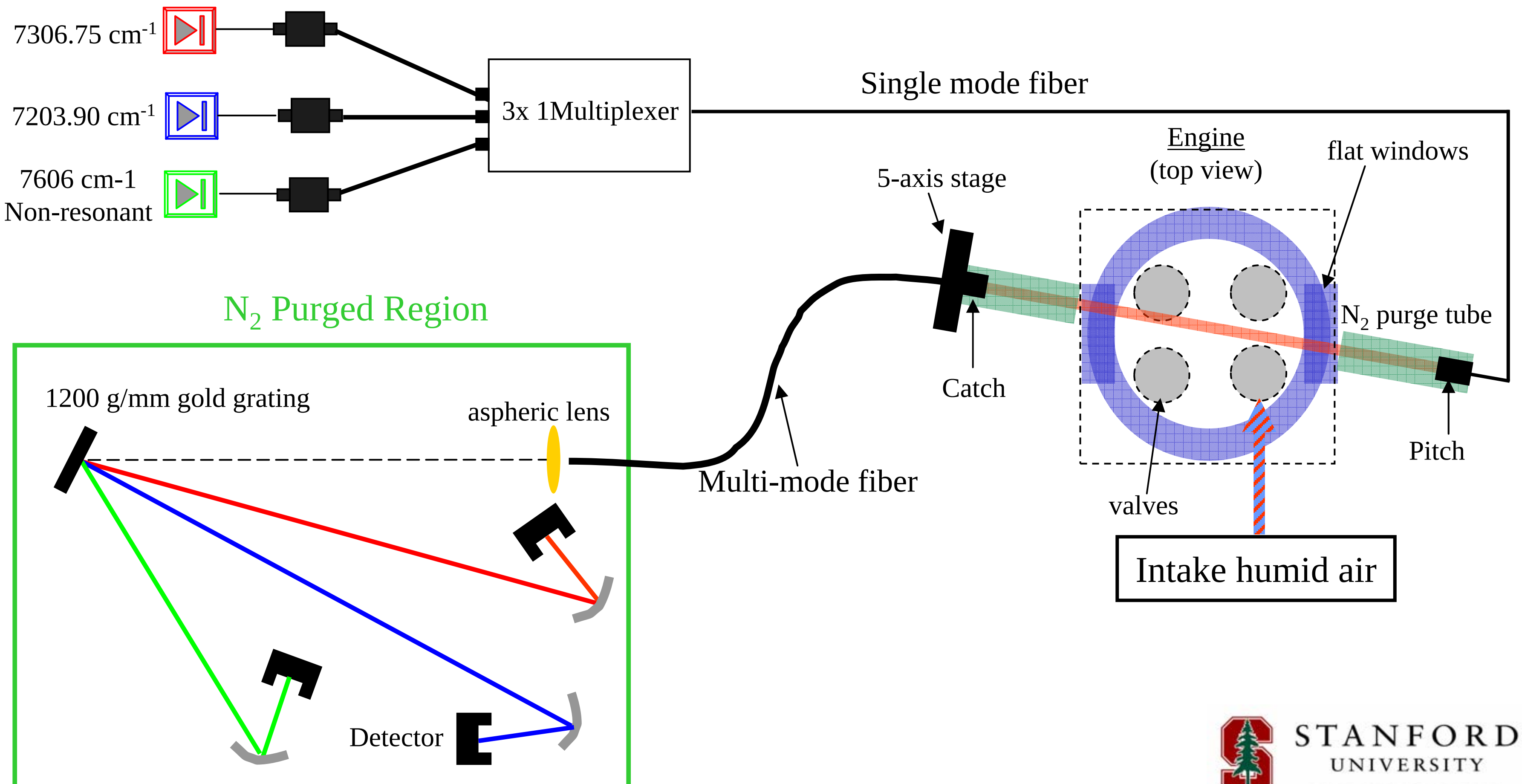
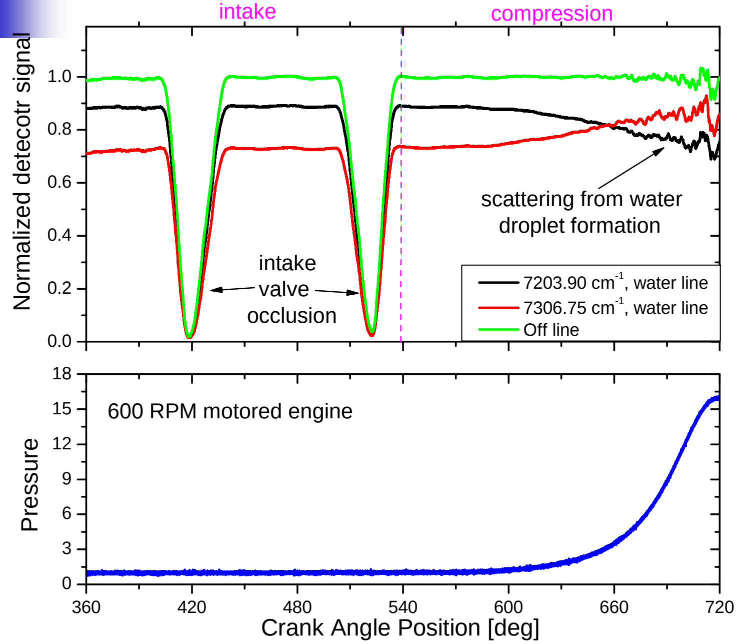
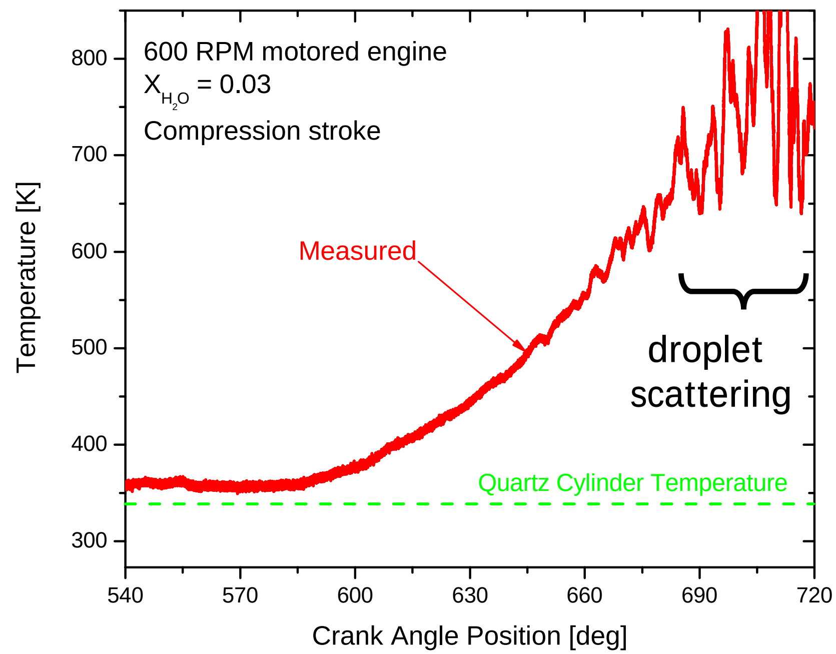
Initial Sensor Design for In-cylinder T

- Wavelength-multiplexed laser-based sensor (2 colors for H_2O and 1 color off-resonance)
- Perform measurements in an optical research engine to prove sensing concept



Proof-of-Principle Tests @ University of Michigan





- Initial measurement campaign shows promising results
  - Demonstrated feasibility of TDL sensing in IC engines
  - Noise near TDC produced by excess loading of water vapor to intake air
- Potential for significant improvements w/2nd generation sensor design: e.g. line selection to optimize T sensitivity at high P, improved optical engineering to suppress vibration noise,…
- Sensor can be tailored to investigate various engine operation modes and cycles
  - e.g. HCCI, Compression Ignition, Spark Ignition, High-EGR, Supercharged, …

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Tests Planned for 2nd Generation T Sensor in Optical Research Engines @ Sandia National Laboratory

Dual-Engine HCCI Lab
PI: John Dec

Automotive HCCI Lab
PI: Richard Steeper

- Two state-of-the-art optical engine facilities for sensor validation and test
- Utilize TDL-based T and X_{H2O} sensor to investigate HCCI engine operation
- Sensor goal: Facilitate development of HCCI engines to reduce GHG emissions

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Opportunities for Future IC Engine Measurements

- Extend T and P sensing ranges to monitor fired-engine operation
- Investigate other species (CO, CO_2, fuel, UHCs, NO)
- Measure non-uniformities in engine using new TDL concepts
- Utilize advanced TDL schemes for improved SNR (e.g. WMS)
- Monitor at multiple locations: intake, exhaust, in-cylinder
- Extend to Diesel engines

Impact: Unique TDL sensors will facilitate development and control of new concept IC-engines

For details see student poster (Mattison)

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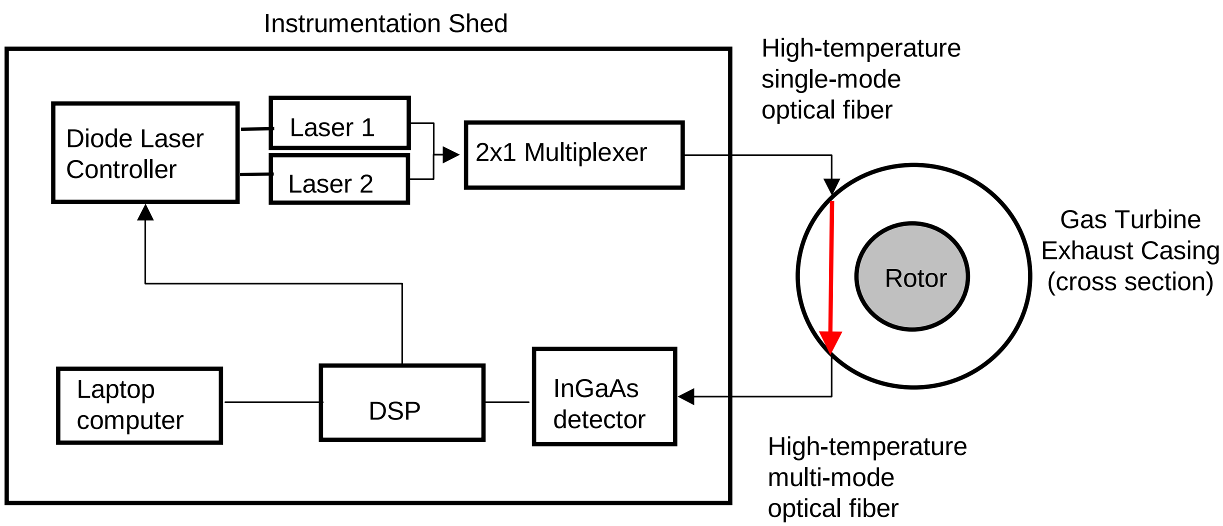
Gas Temperature Sensor for Stationary Gas Turbine Exhaust

Motivation:

- Innovative *in situ* exhaust sensors could provide engine health data needed to minimize environmental impact
  - Optimizing maintenance schedule for planned load management
  - Optimizing burners for minimal pollutants and GHG emissions

Research Plan:

- Two-color T sensor designed and tested at SU
- Demonstrated in exhaust of a 20MW power generator (collaboration with GE Research Center):



- Readily extended to multiple paths (tomography)

For details see student poster (Liu)

Gas Temperature Sensor for Coal-Fired Power Plants

Motivation:

- *In situ* sensors can improve combustion efficiency
  - Efficiency increase of 1% reduces GHG by 1% and saves $1M/year in fuel (coal) costs for a 600 MW boiler
  - Path-integrated sensing allows optimization of over-fire-air addition
- Sensors can optimize maintenance
  - Identify burner malfunction from temperature profile

Challenges:

- Long path, nearly opaque, vibration and thermal movement

Strategy:

- Sensors developed at Stanford tested in coal combustors in Colorado and TVA with collaboration with Zolo Technologies:
  - Provides fiber technology to enable practical implementation
  - Provides access to power plants to test measurement concepts

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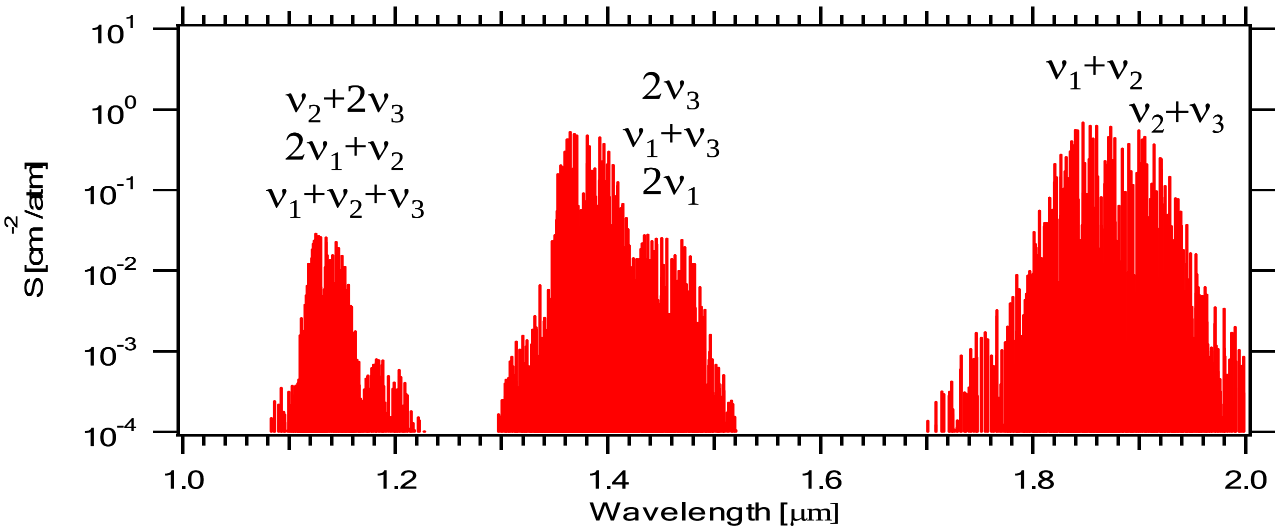
T Sensor Design via H_2O Absorption

- T sensor based on water vapor absorption
- H_2O absorption is strong in combustion gases
  - 4-12% H_2O present in combustion products (depends on coal H_2O content)
  - Nearly 500,000 lines in HITRAN between 1 and 2 μm



- Use Stanford design rules to choose multiple water lines for optimal sensor performance in the harsh environment of the coal combustor
- Exploit 1250-1650 nm region with available telecommunications lasers and optical fiber technology

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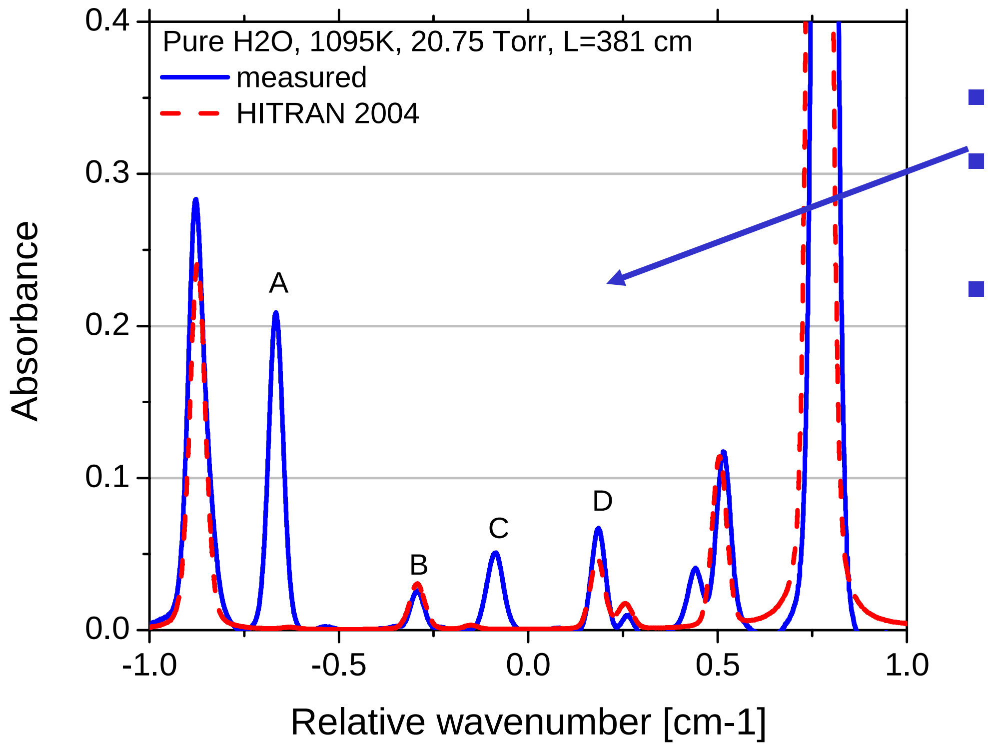
T Sensor Design: H_2O Line Selection

- Coal combustor has long path lengths (10-20 m) and poor transmission
  - Therefore need weak lines (database is not accurate or complete)
- Strategy: Choose 9 suitable lines, scanned by 3 diode lasers
- Need to determine spectroscopic parameters in lab to enable measurements

Example of need for accurate spectroscopic data



- Comparison of HITRAN and SU data
- Lines selected for sensor (A-D)
- Note: A, C missing from HITRAN

- Accurate diode laser sensing of temperature requires laboratory measurements of fundamental spectroscopic data

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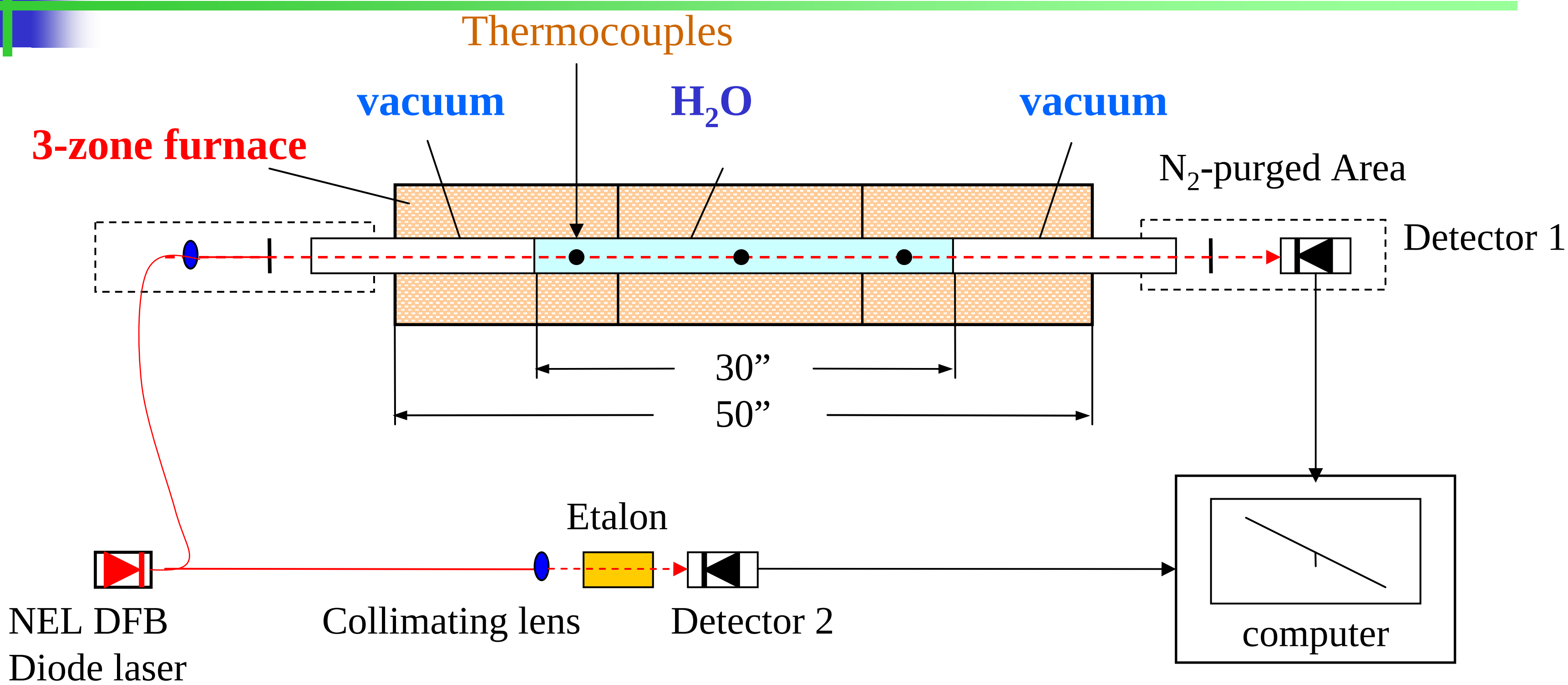
Laboratory Experiments for Quantitative Spectral Data

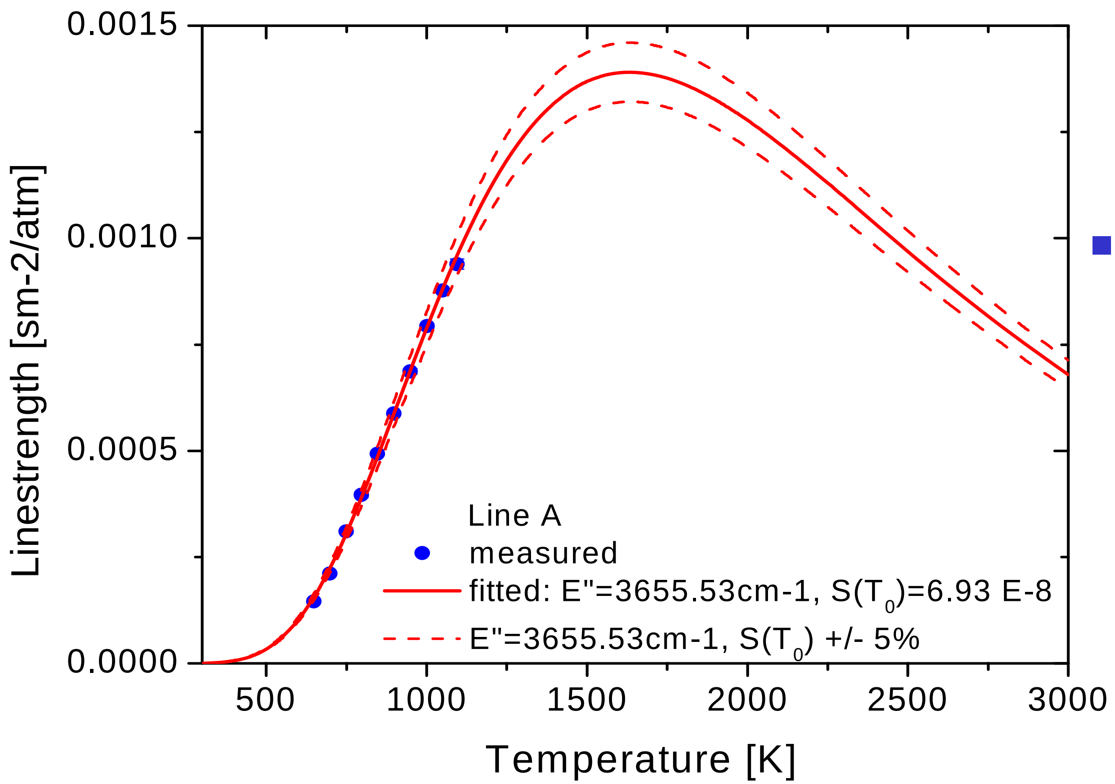


- Measure line strength versus T to verify E” assignment and provide quantitative S(T), line broadening, and line shift data
- Use multi-pass geometry for accurate measurement of weak lines
- Approach yields substantial improvements to current spectral database

Linestrength Measurements: Example for Line A

- Measure absorbance for known H_2O in heated cell for S(T)
- Fit to confirm E" assignment and find $S(T_0)$

$$S(T) = S(T_0)\frac{Q(T_0)}{Q(T)}\exp\left[-\frac{hcE''}{k}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]\times\left[\frac{1-\exp(-hcE''/kT)}{1-\exp(-hcE''/kT_0)}\right]$$



- End result: First determination of line strength for this previously unknown hot line

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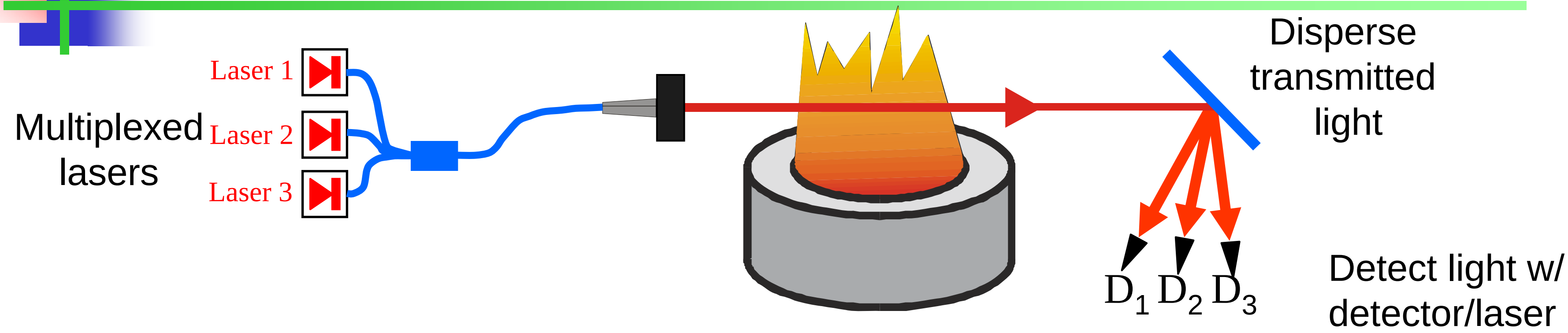
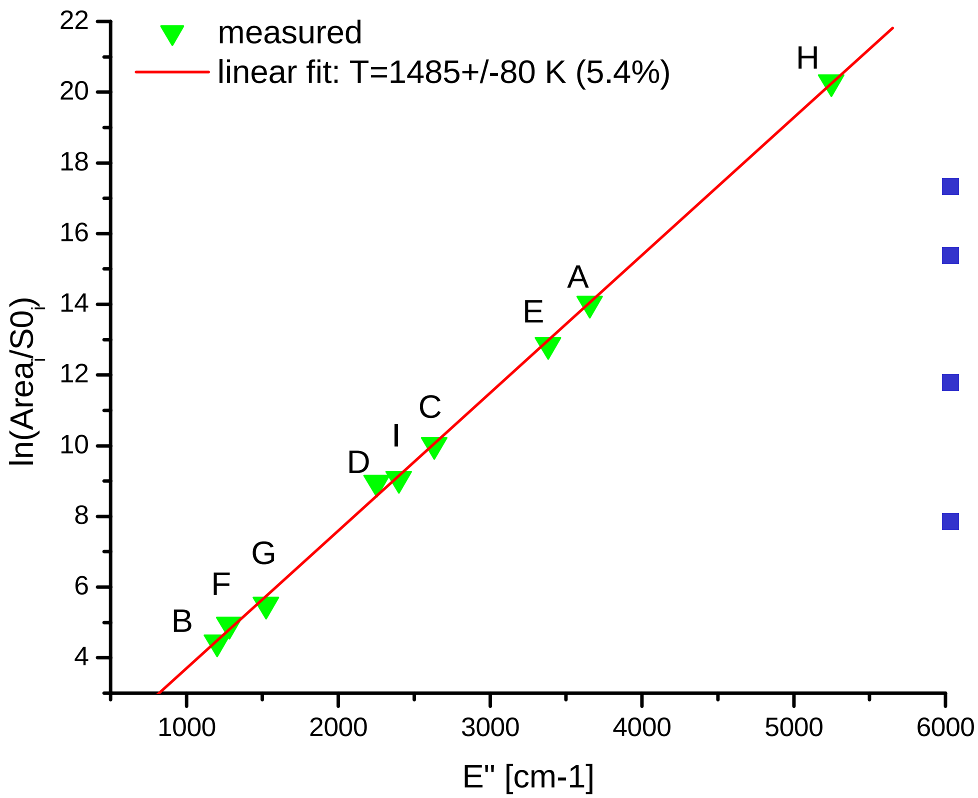
Example Results w/ Nine-Line H_2O T Sensor: 220MW Plant





- Multiplex 3 lasers and scan 9 H_2O lines
- Valmont coal-fired 220MW power-plant in Colorado (dry coal)
- Boltzmann plot fits one temperature (1500K) with X_{H2O} ~ 5.9%
- Sensor confirms uniform T in combustor, i.e. well-balanced burners with proper over-fire-air flow

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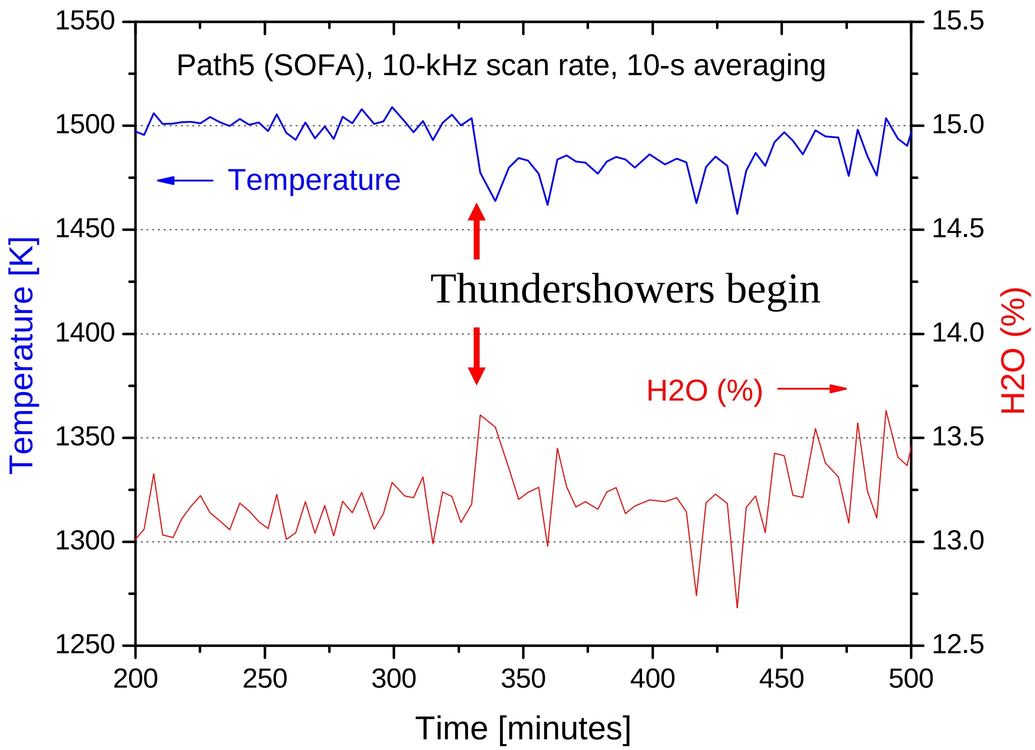
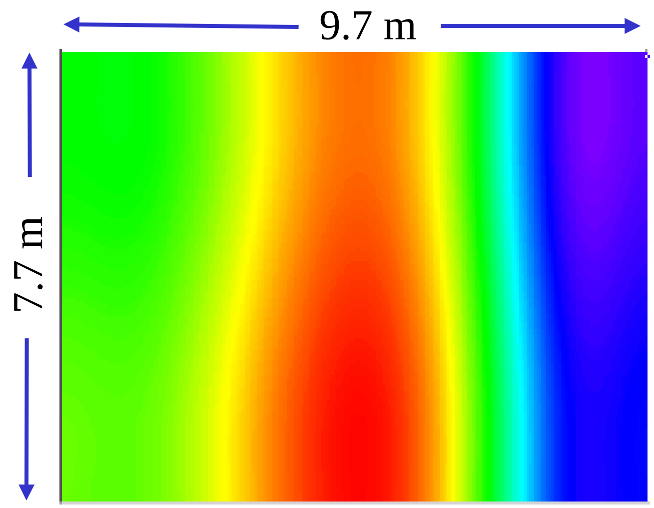
Example Results w/ 2nd Generation Sensor: 280MW Plant (T vs Time w/Multiple Paths)

- TVA: coal-fired power plant
  - 280 MW, tangentially fired
  - Fiber-coupled sensor (multiple locations)
  - Coarse tomography (4X2) of T field





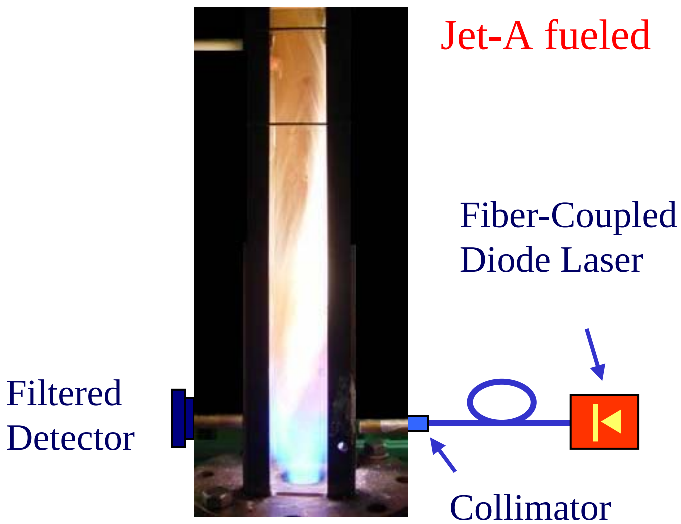
2-D temperature map @ 10m Secondary-over-fire air location (Max: 1528K, Min: 1425K)

- Note sensitivity of sensor to intake air/fuel conditions
- Success achieved has led to a proposal for a permanent sensor installation to improve combustor efficiency and reduce GHG emissions

Demonstrate Use of T Sensor for Combustion Control

<u>Motivation:</u>

- Reducing the fuel-air equivalence ratio can improve combustor emissions and combustion efficiency
- But fuel lean systems are notoriously unstable
- TDL sensors offer the potential for control strategies to <u>extend lean operating limits</u>



<u>Challenges:</u>

- Poor optical access, high noise/vibration, time-varying transmission, and need for high-speed, real-time sensor

<u>Strategy:</u>

- Develop fast, real-time (2kHz) gas temperature measurement for combustion control
  - Novel wavelength modulation design to enable real-time data analysis
- Test Stanford sensors in practical swirl-stabilized burner
  - Triple annular swirl-stabilized burner at Stanford simulates next-generation gas turbine fuel nozzles

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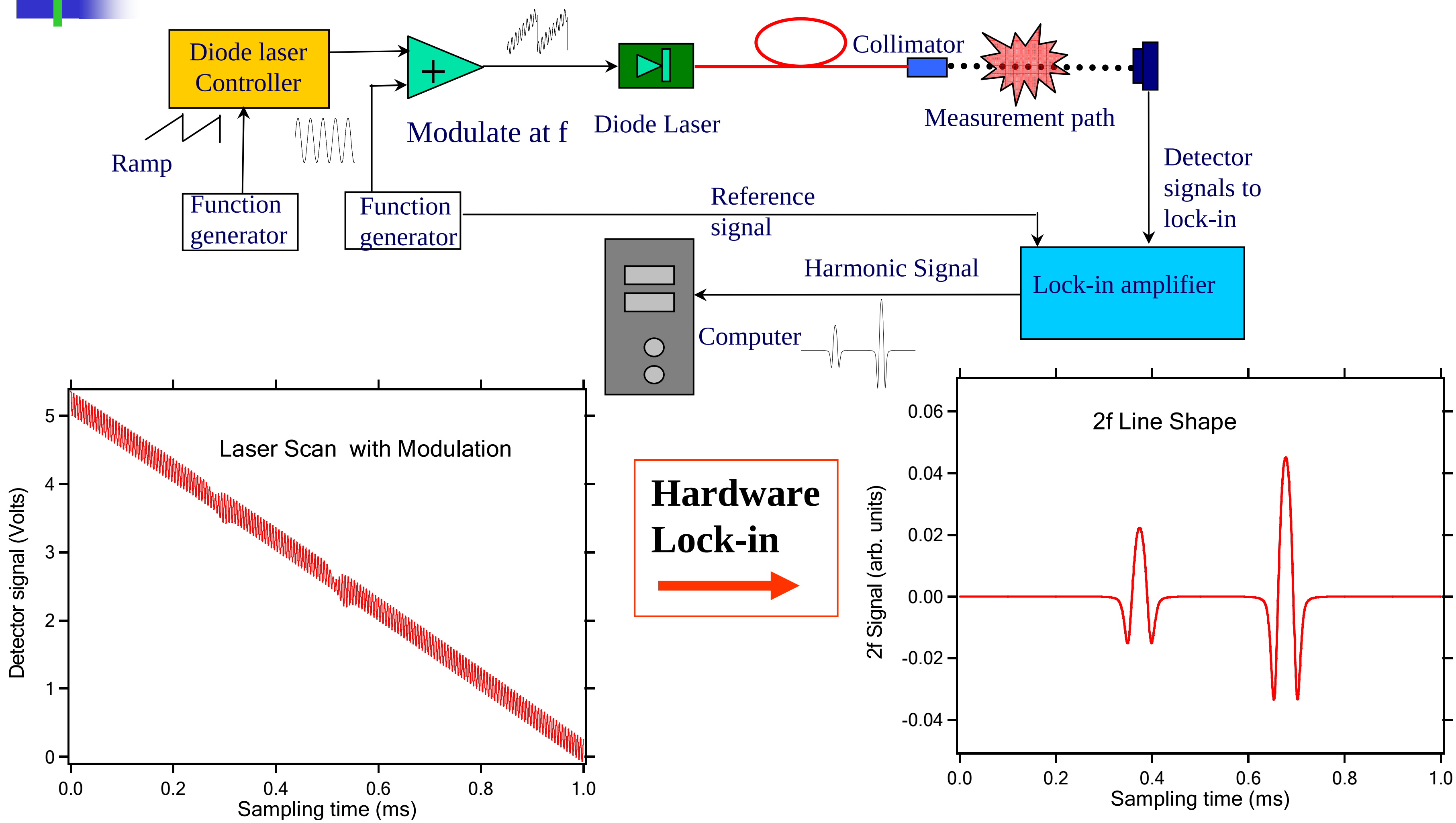
Scanned-Wavelength Modulation with 2f Detection: Facilitates Real-Time T Measurement



- Use of 2f simplifies data analysis ==> *increases measurement bandwidth*
- Development of 2f method for T requires extension of 2f theory

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WMS Sensor for Real-Time T@ 2kHz: Relevant Absorption Theory

- The transmission coefficient can be written in terms of the modulation and expanded in a Fourier series: $\tau(\bar{\nu} + a \cdot \cos(2\pi f t)) = \sum_{k=0}^{\infty} H_k(\bar{\nu}, a)\cos(k 2\pi f t)$
- The interpretation of 2f signals is simplified for weak absorbances ($k_\nu L << 1$) :

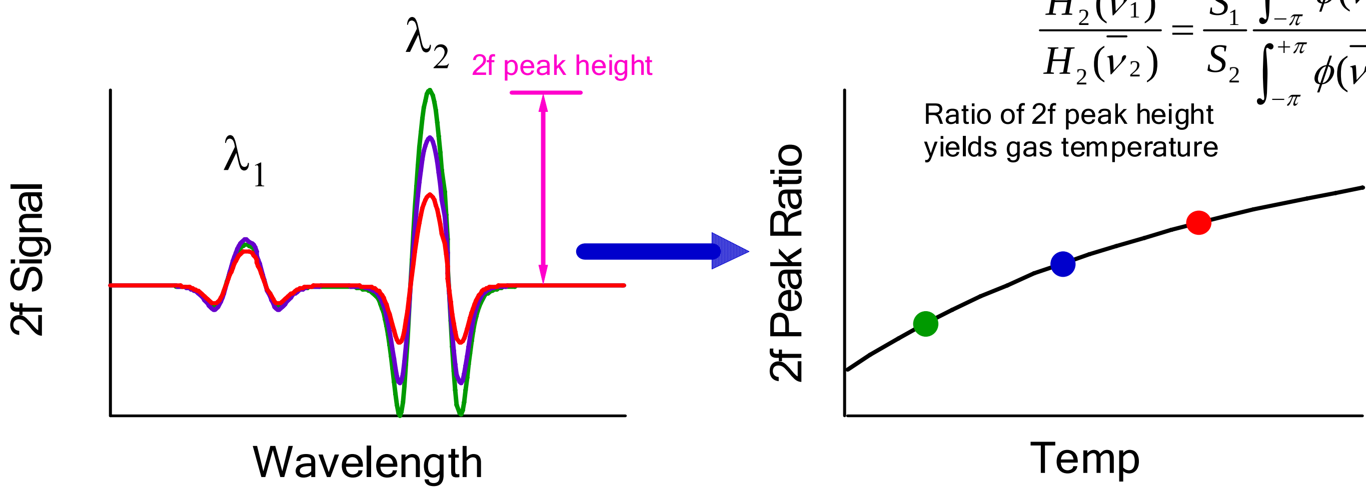
$$\tau = \exp(-k_\nu L) \approx 1 - k_\nu L = 1 - S(T)\phi(P, T, X_{H2O})PX_{H2O}L$$

- The 2f Fourier component simplifies as:

$$H_2(\bar{\nu}, a) = -\frac{S \cdot p_i \cdot L}{\pi}\int_{-\pi}^{+\pi}\phi(\bar{\nu} + a \cdot \cos\theta)\cos 2\theta \cdot d\theta$$

- The ratio of 2f peak heights is used to determine temperature :

$$\frac{H_2(\bar{\nu}_1)}{H_2(\bar{\nu}_2)} = \frac{S_1}{S_2}\frac{\int_{-\pi}^{+\pi}\phi(\bar{\nu}_1 + a \cdot \cos\theta)\cos 2\theta \cdot d\theta}{\int_{-\pi}^{+\pi}\phi(\bar{\nu}_2 + a \cdot \cos\theta)\cos 2\theta \cdot d\theta}$$



- Impact: New 2f T-sensor should have broad impact on energy conversion research and technology

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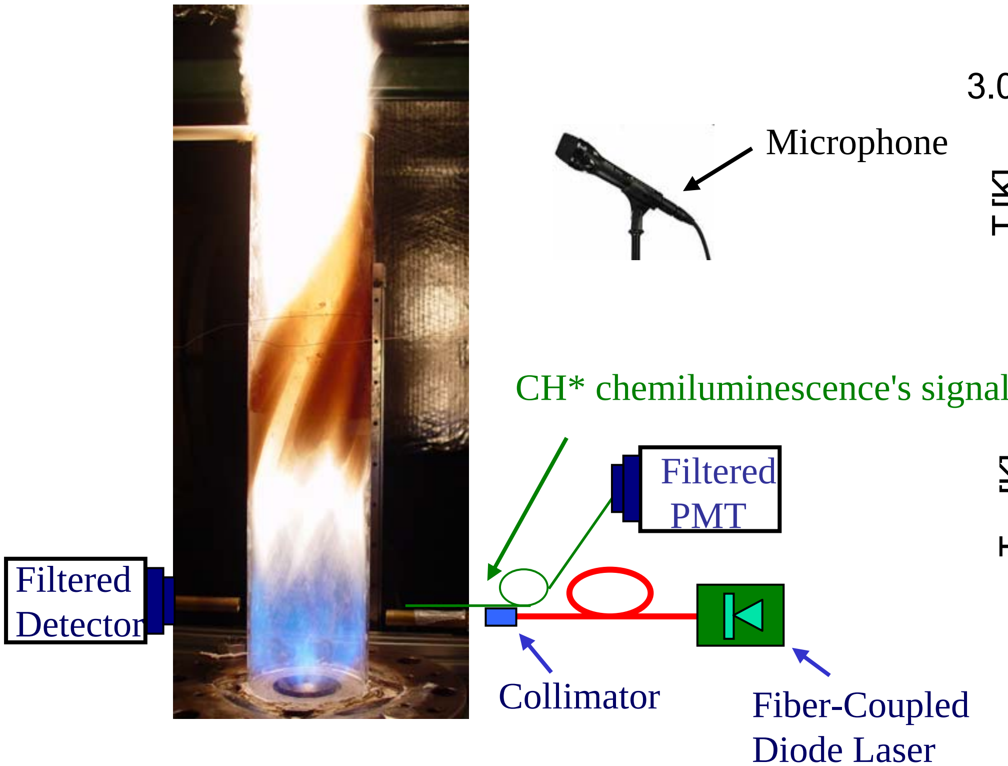
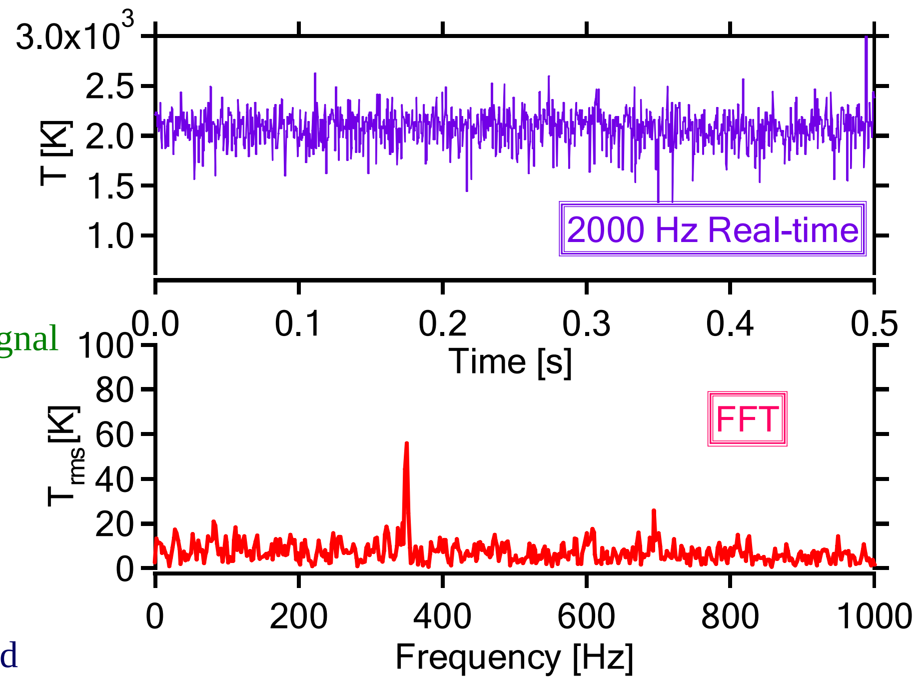
Example Results: Sensor Reveals Thermal Acoustic Instability

• 2kHz real-time T measurement in unstable ethanol/air flame





- First application of TDL sensing in a spray flame
- Quartz duct used to generate natural flame instability
- Power spectrum yields the T_{rms} at the instabilities near 350 and 700 Hz
- Scanned-wavelength 2f sensor shows promise for control applications

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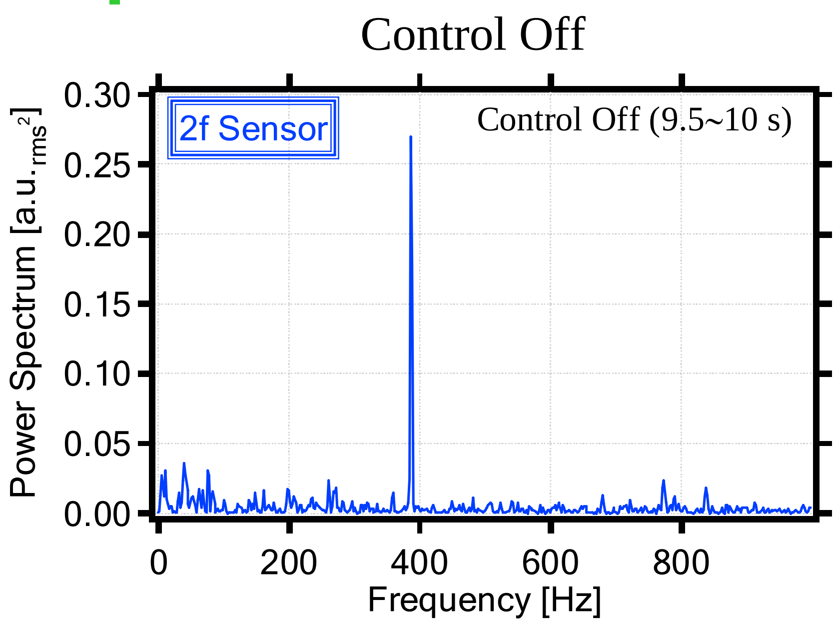
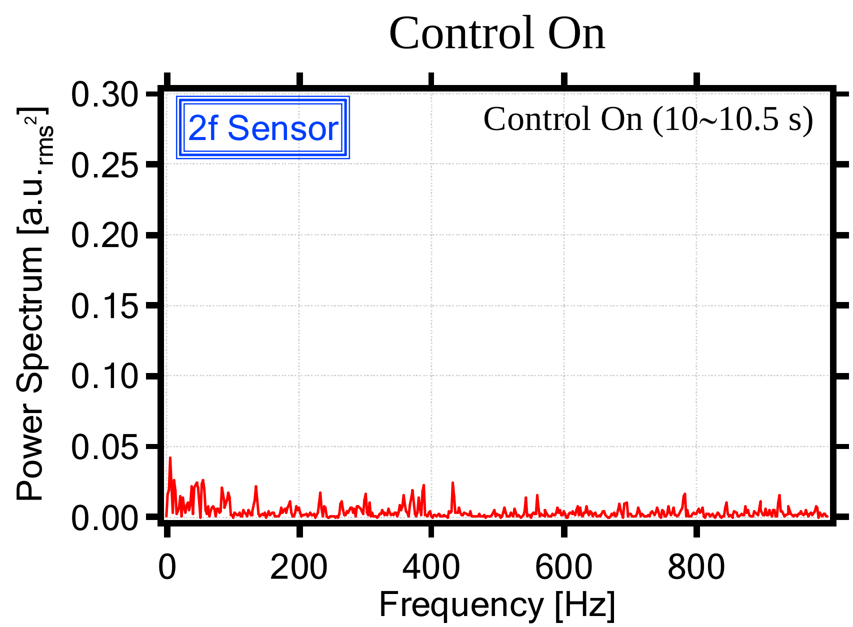
Example Results:
First TDL Sensor Control of Swirl-Stabilized Flame





- First application of TDL sensing to stabilize a spray flame
- Naturally unstable flame from finite length flame duct
- Active control of air flow suppresses instability
- Results suggest that the T sensor has good potential as a localized control variable, and could be combined with species concentration sensor

For details see student poster (Li)

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Summary of Key Accomplishments – Future Opportunities

Key Accomplishments:

- Innovation and design of unique *in-situ* sensors based on fiber-coupled near-infrared diode lasers
- Contributions to the NIR H_2O spectral database
- Sensors demonstrated in practical environment with help from collaborators
- Sensors can reduce GHG emissions in multiple ways:
  - Improve fuel efficiency
  - Facilitate R&D of new energy conversion concepts
  - Reduce combustion-generated pollutants

Future Opportunities:

- Extend sensing concept to mid-infrared for fuels and trace gases
- Develop sensors for applications to other energy conversion schemes;

  e.g. fuel cells
- Continue Stanford's unique role of sensor innovation, engineering, and transfer to practical combustion systems

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