Advanced optical sensor for monitoring and control of multiple gas and turbine-blade properties

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SCIES Project 03 - 01 - SR105

DOE COOPERATIVE AGREEMENT DE-FC26-02NT41431

Tom George, Program Manager, DOE/NETL

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Project awarded 7/1/2003, 36 month duration

$418,961 total contract value ($418,961 DOE)

Project Objective

- ◆ Develop fiber-optic sensors that can be readily attached to "research-grade" gas turbine engine test facilities
- ◆ Contribute to maturation of "production-grade" sensor designs

Gas Turbine Needs Met

- ◆ Researchers provided with a tool that enables more rapid evaluation of new engine designs

will lead to reduced engineering time

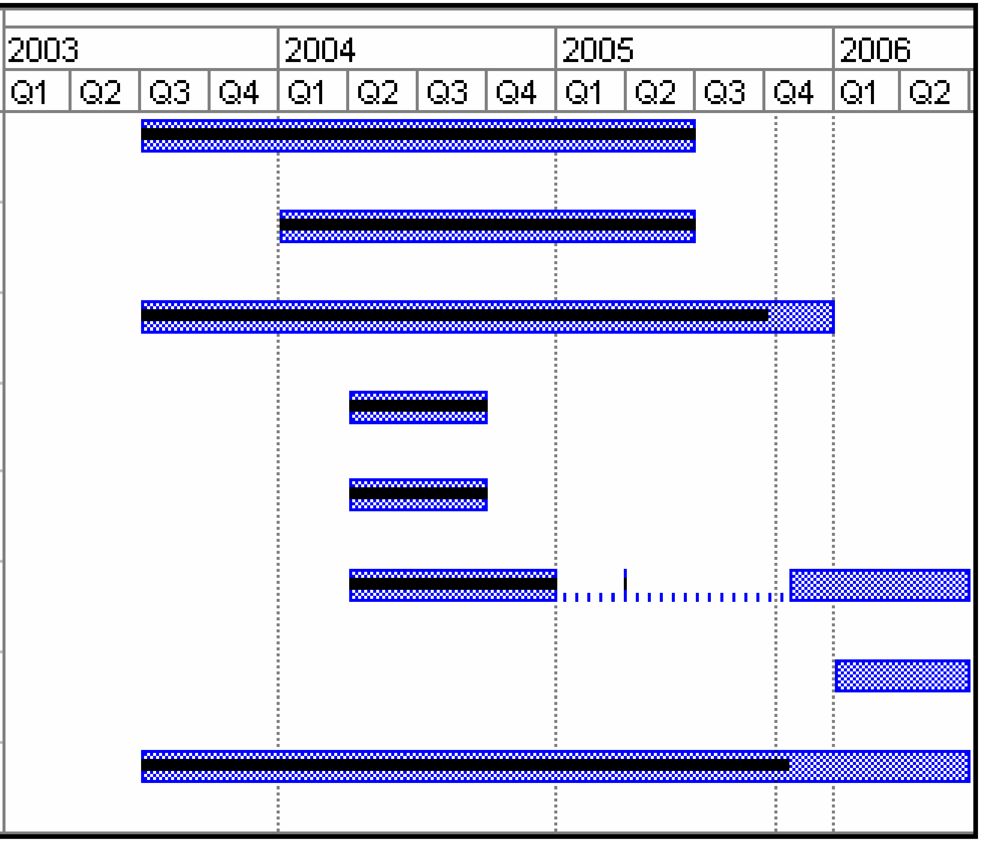
- ◆ Useful information becomes available, ultimately in production engines. For example, the ability to monitor or control the temperature distribution of gases entering the turbine

will lead to…

- increased efficiency
- reduced emissions

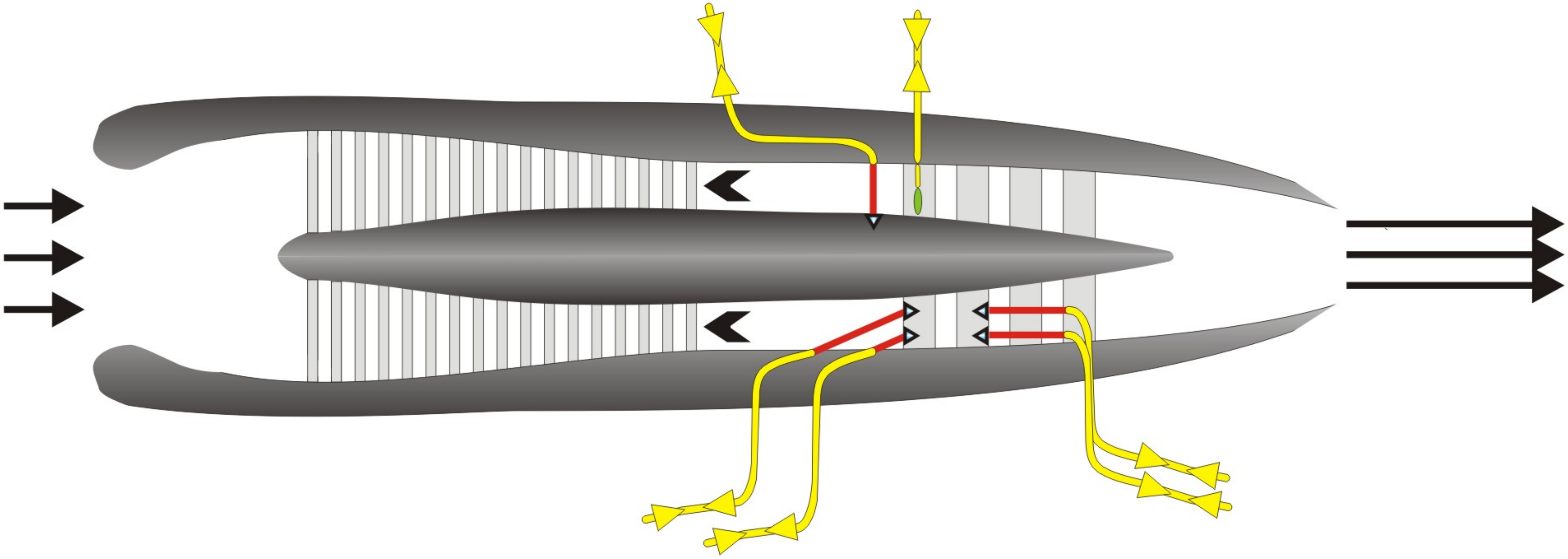
Schedule

ID	Task Name
1	**Adapt wavelength-agile source for application in gas turbine engine**
2	**Refine strategies for routing optical signals in turbine environments**
3	**Refine strategies for embedding fiber optics in moving components**
4	**Demonstrate gas measurements in representative laboratory tests**
5	**Demonstrate moving-component measurements in laboratory**
6	**Measure gas and turbine-blade properties in large-scale test facilities**
7	**Attempt to use sensors for online optimization or control of engine parameters**
8	**Poll gas turbine experts; assess needs / grow synergies**



- Nearly on track with original, aggressive schedule

Approach: Routing Fibers in Gas Turbine Engines



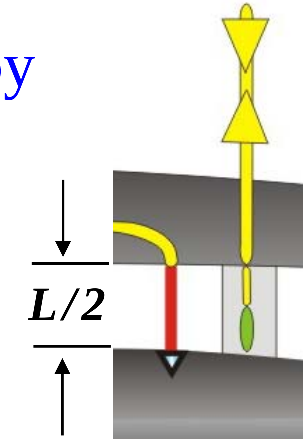
- Multiple gas, turbine-blade properties can be obtained with a single light source
- Each measurement requires a dual-clad fiber connection
- Open question: best option for the retroreflective surface?

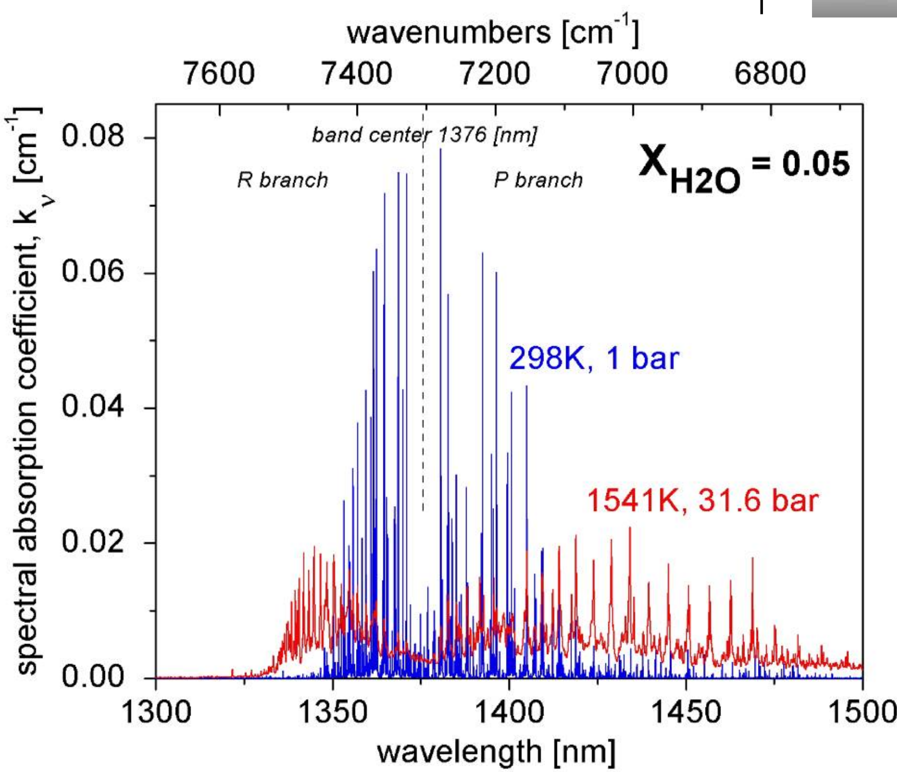
Approach: Inference of Gas, Solid Properties

absorption spectroscopy

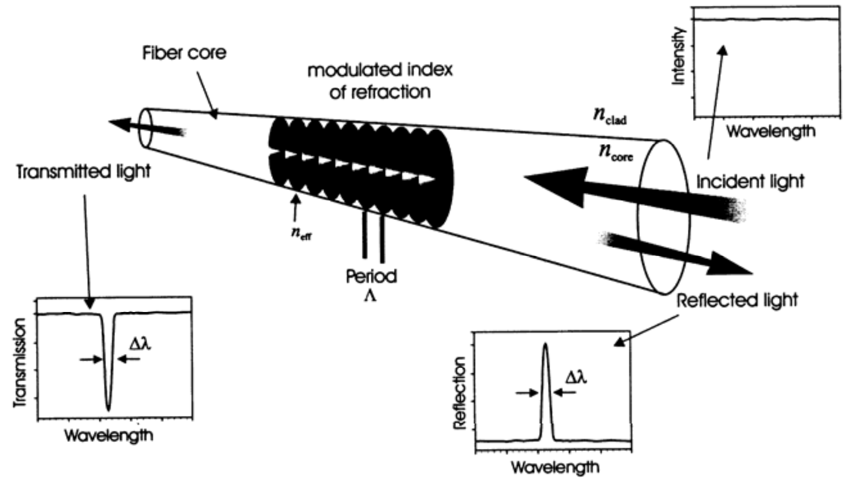
Beer's law:

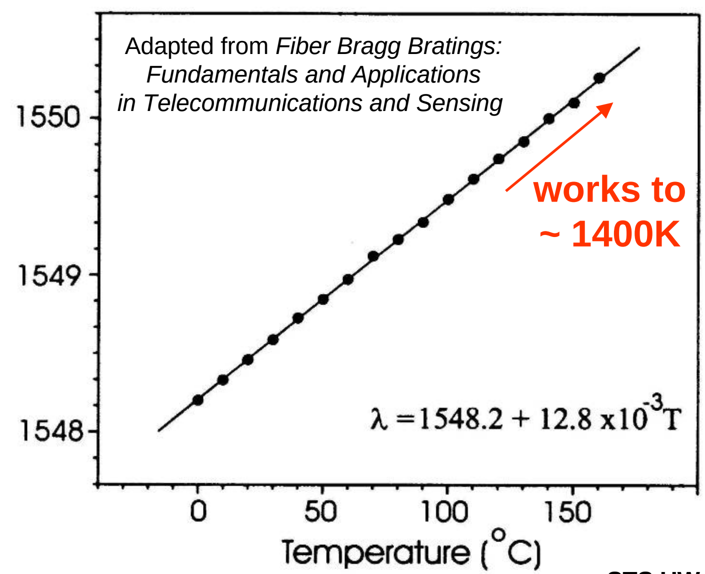
$$T_\nu \equiv \frac{I}{I_o} = \exp(-k_\nu \cdot L)$$



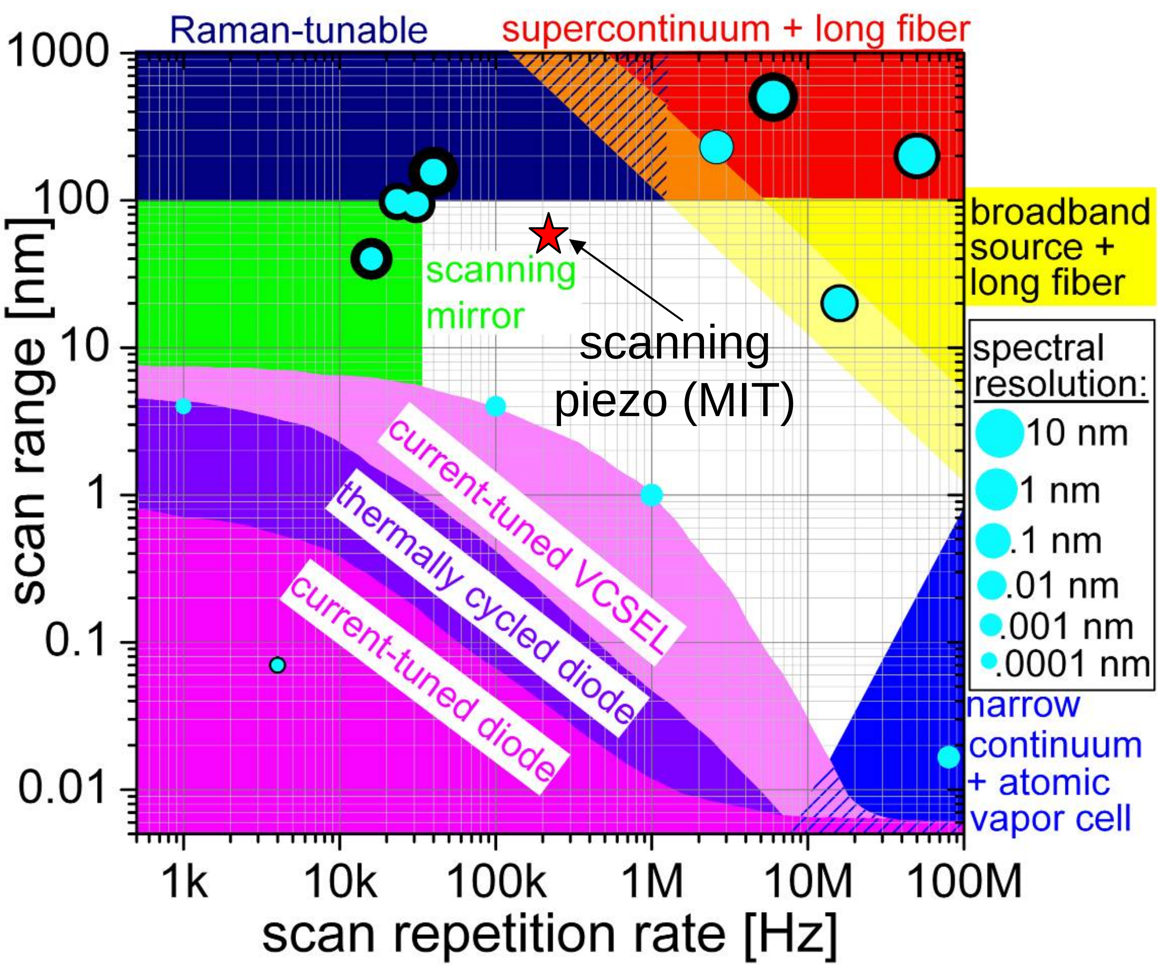


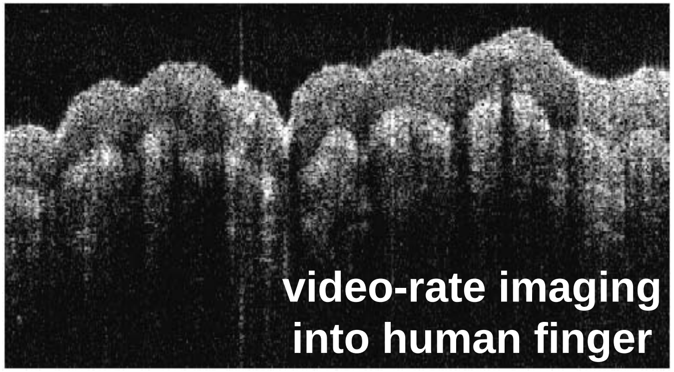
fiber Bragg grating thermometry

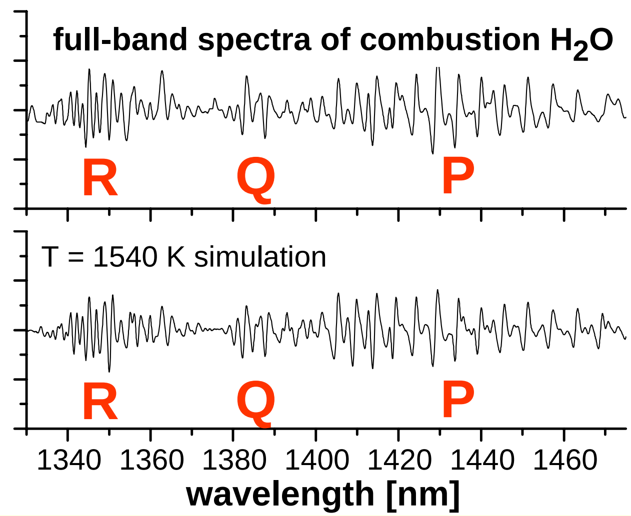




Approach: Wavelength-Agile Sensing

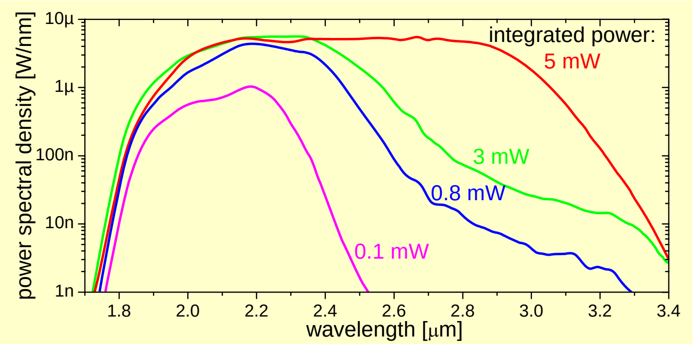




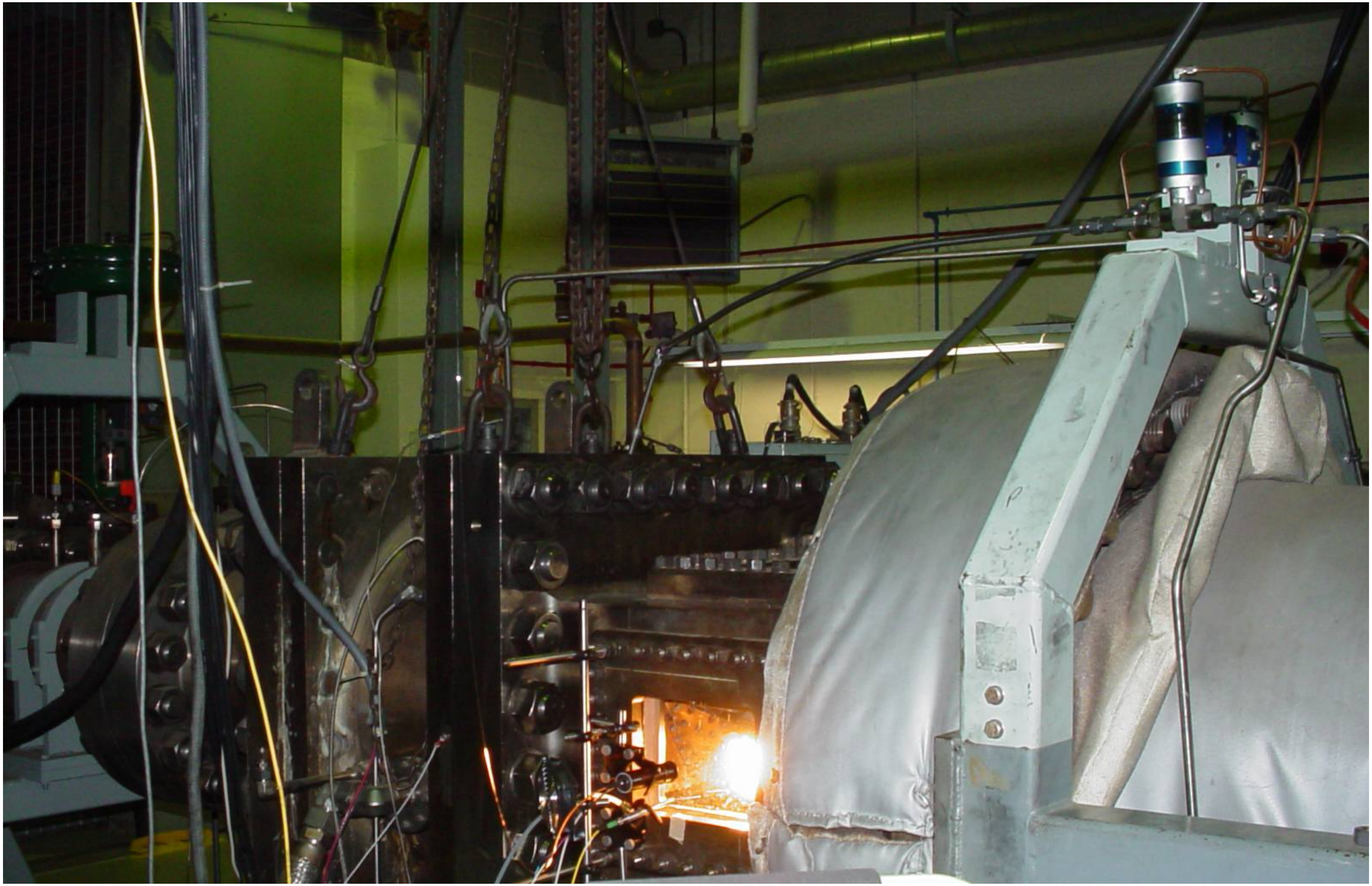


- Many laser systems developed; resulting sensors allow continuous spectral monitoring in dynamic environments

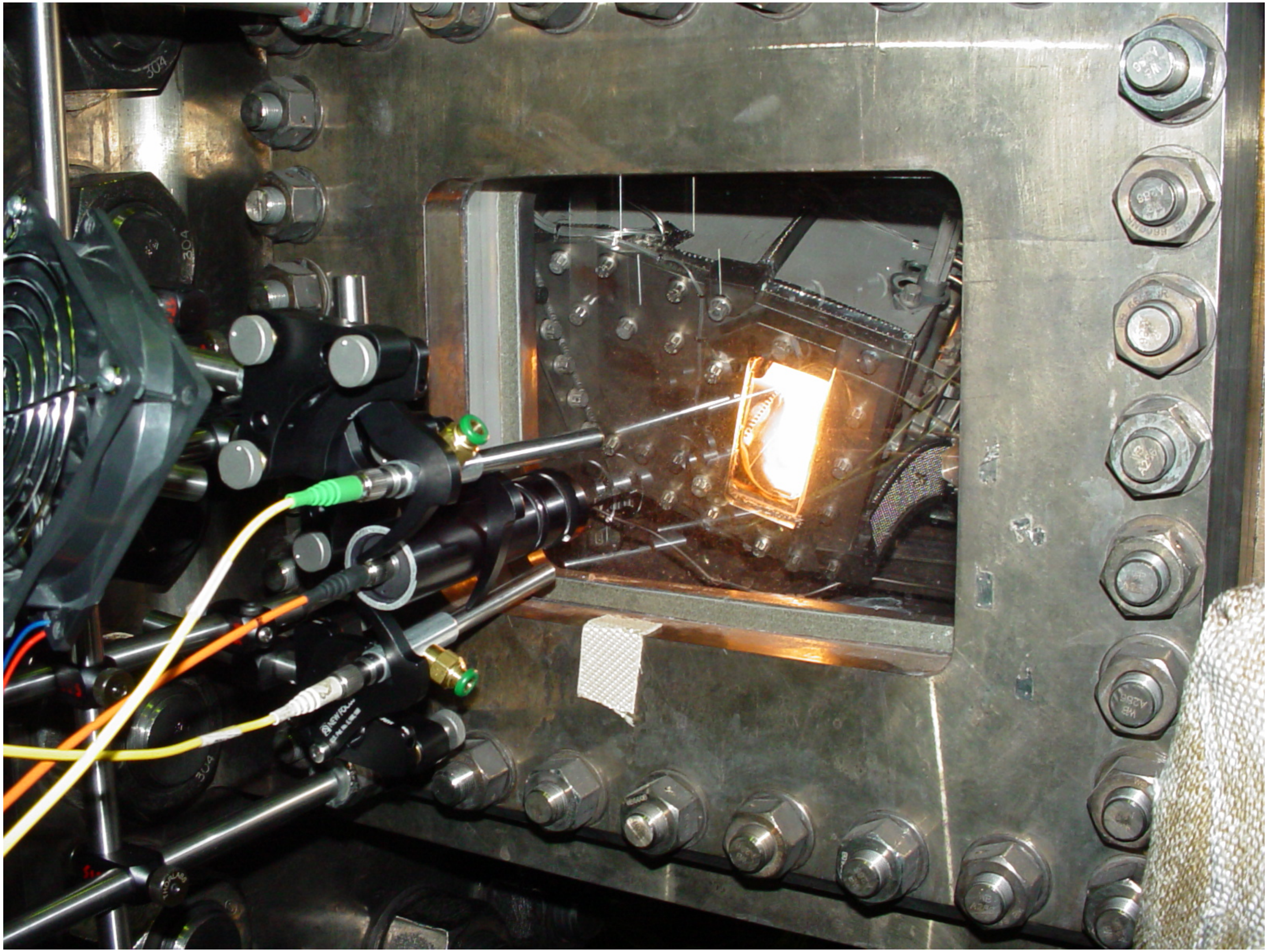
source 5000 x brighter than 3000K blackbody



Gas Turbine Burner Test Facility at WPAFB

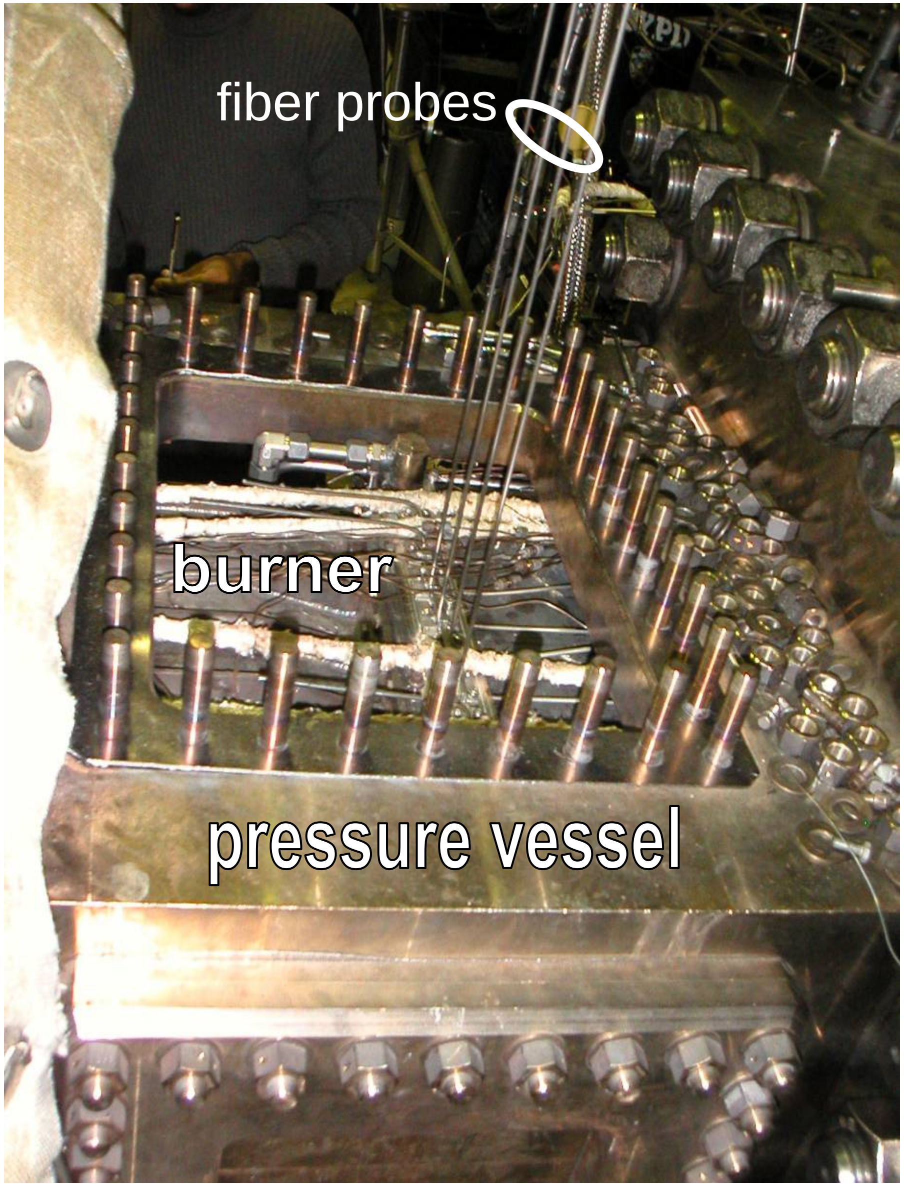


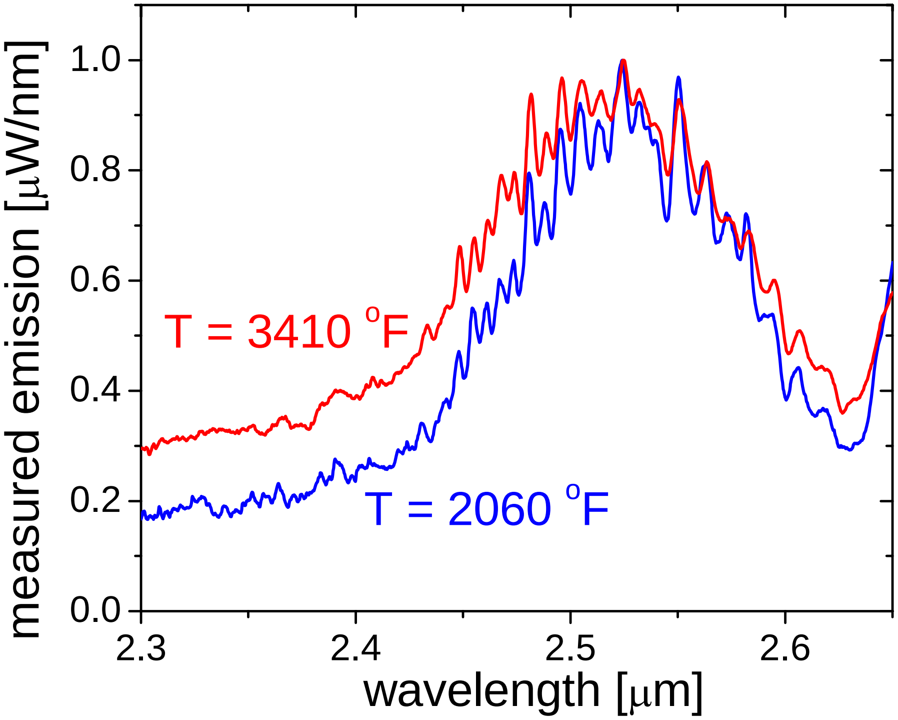
Dual-Clad Fiber Installed at WPAFB (using window)



- Each fiber represents a different sensor

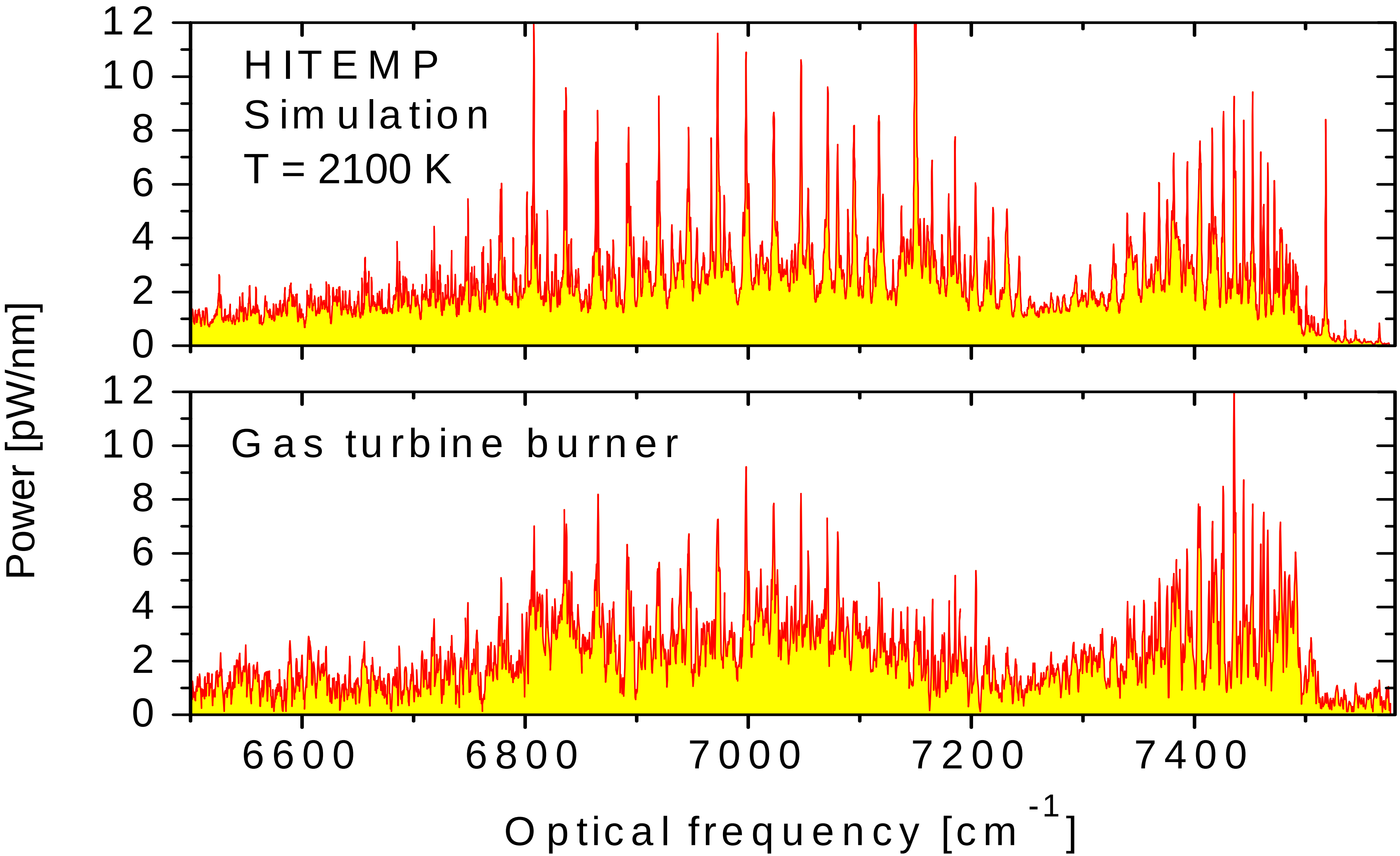
Ruggedized Installation at WPAFB (no window)





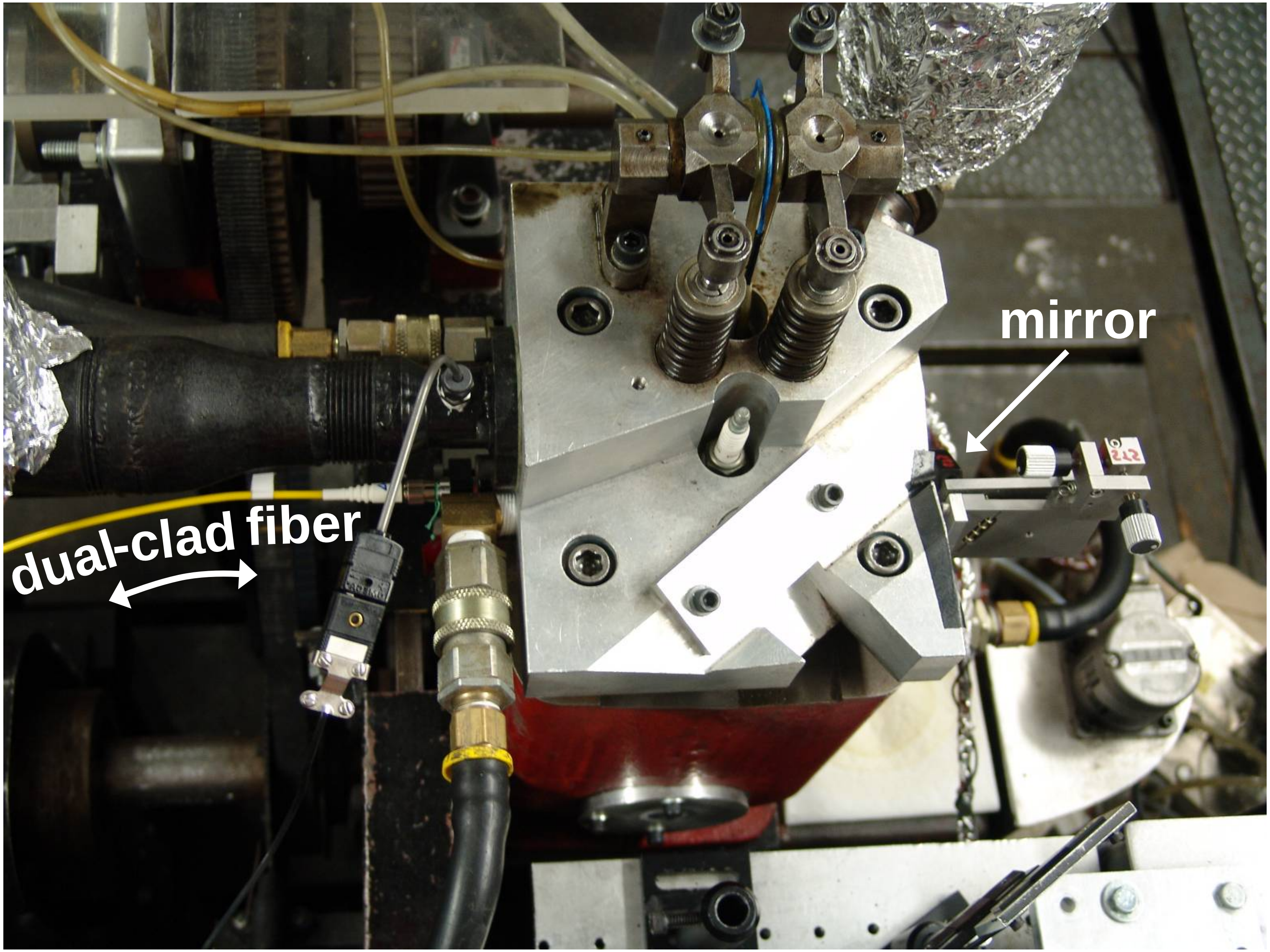
- Gas temperatures inferred from optical measurements

Measurements Reveal Need for Improved Databases



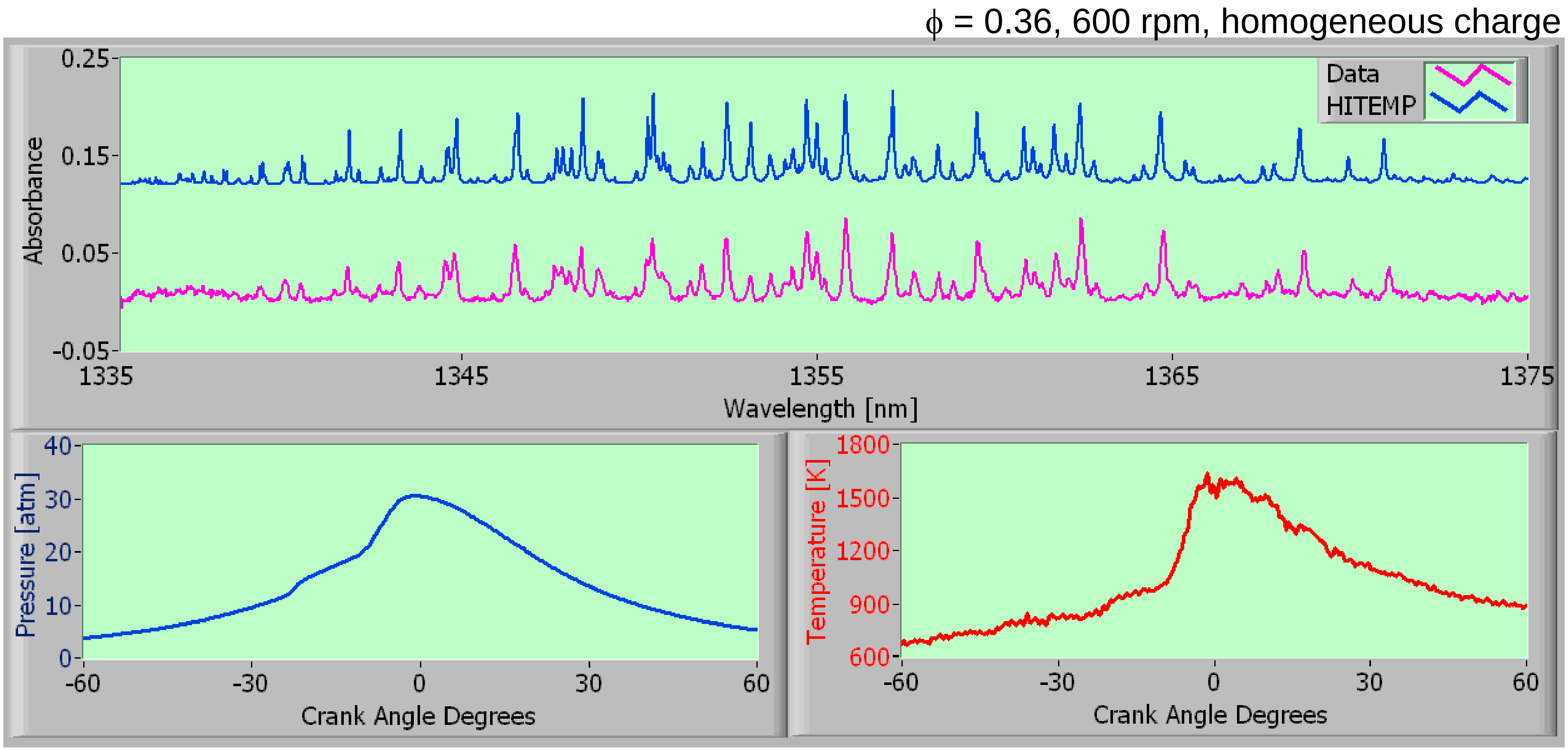
- Numerous discrepancies are apparent between measured and simulated spectra

Sensor development and refinement in piston engines



◆ Several such engines are readily available to our labs

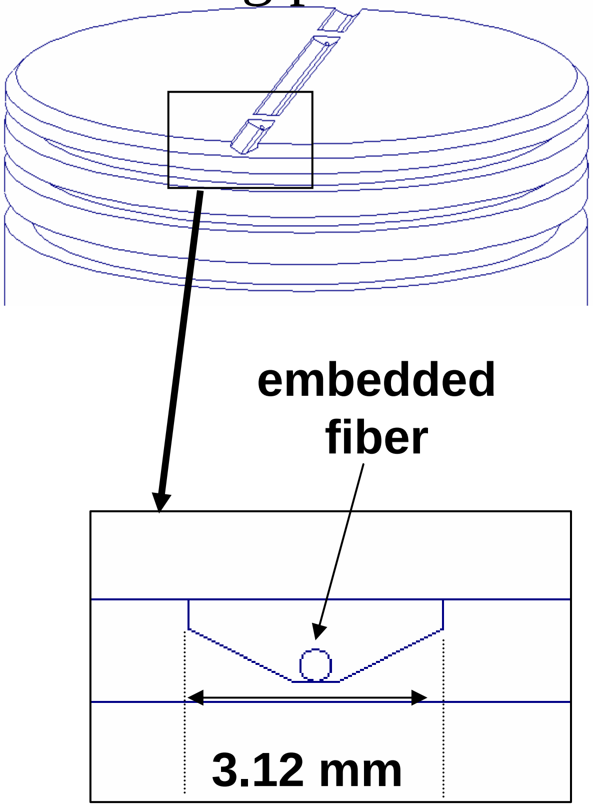
Sensor Refinement in Piston Engine: Results

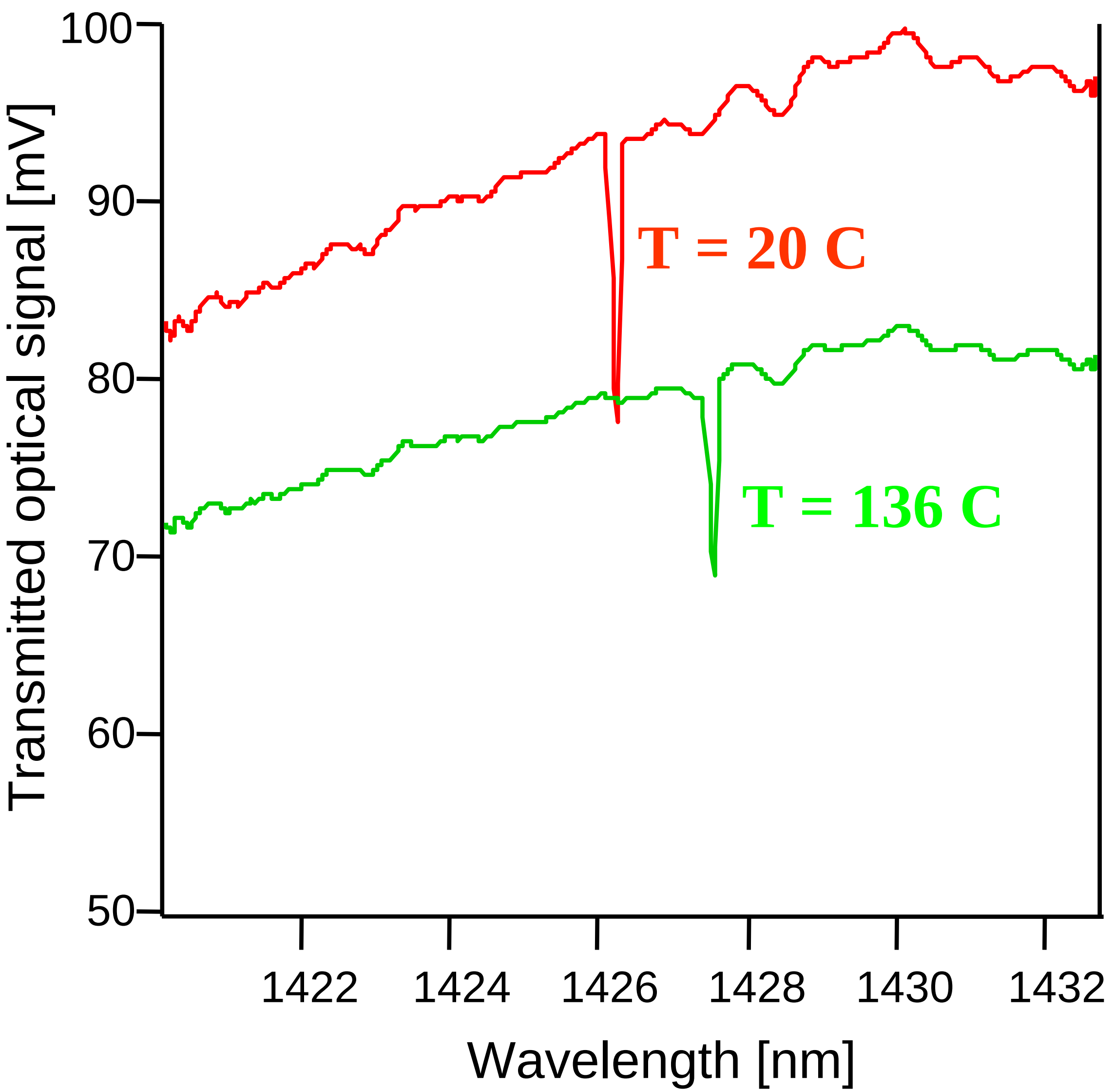


- Spectrum every 0.25 crank angle degrees = 69 μs
- Merits: spectral database; optical thermocouple for ~ uniform flows
- Precision directly visible in data ~ 2%, *expected* absolute accuracy 2%
- Now collaborating with industrial partners to develop sensor costing ~ 1k

Monitoring Temperatures of Moving Components

periodic optical coupling into a moving piston:

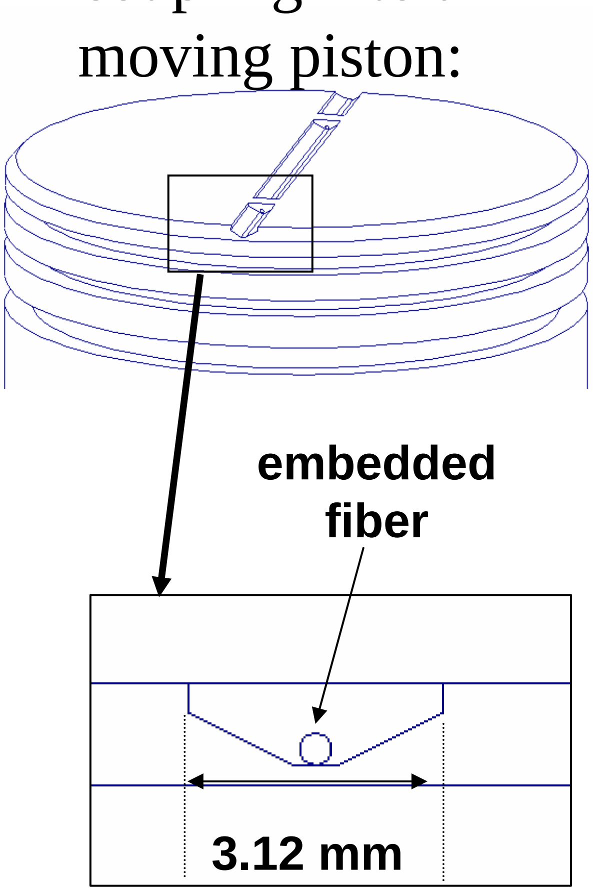


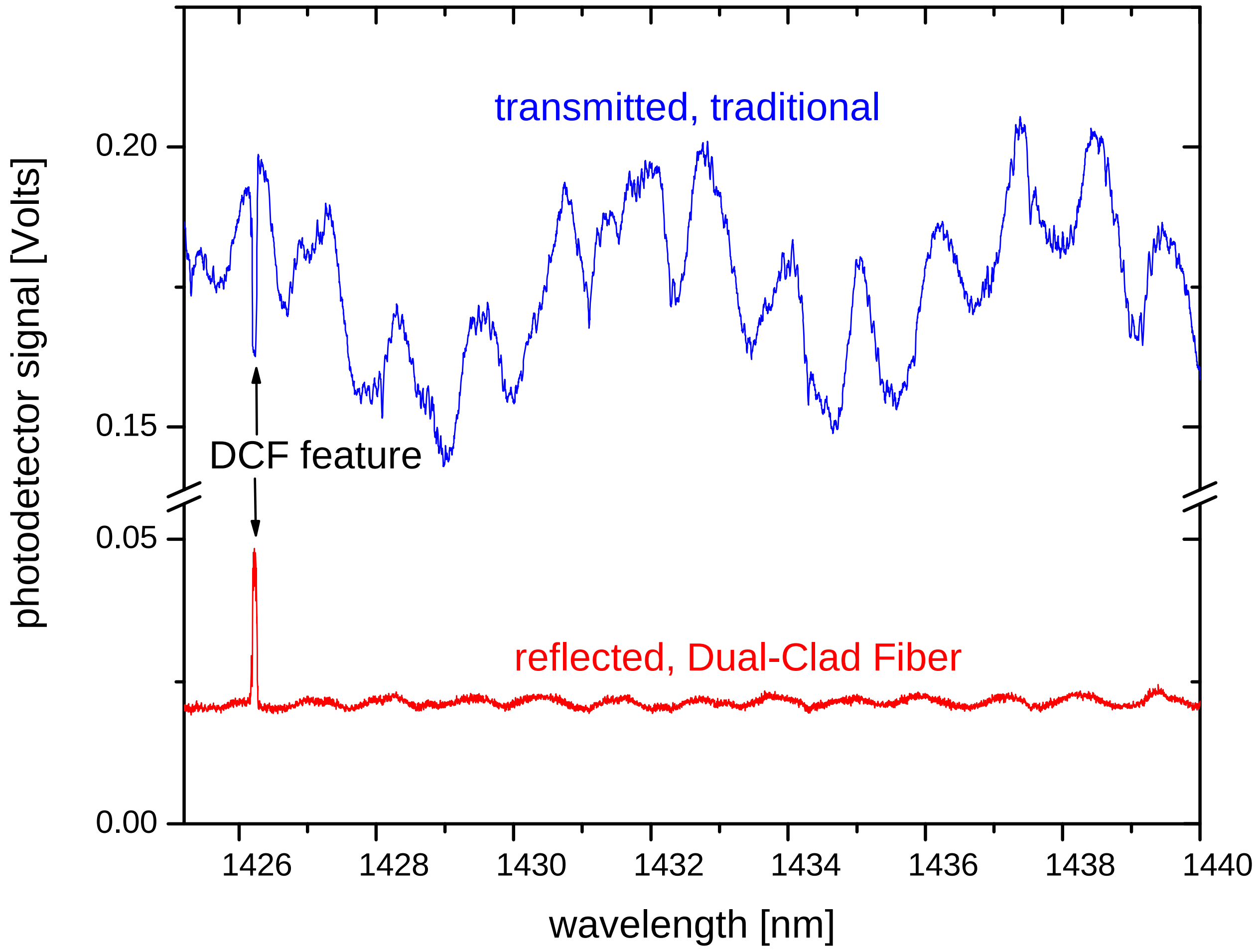


- Bragg gratings suitable for turbine blades (up to 1400 K = 2060 F)

Dual-clad fiber can improve FBG-based strategies

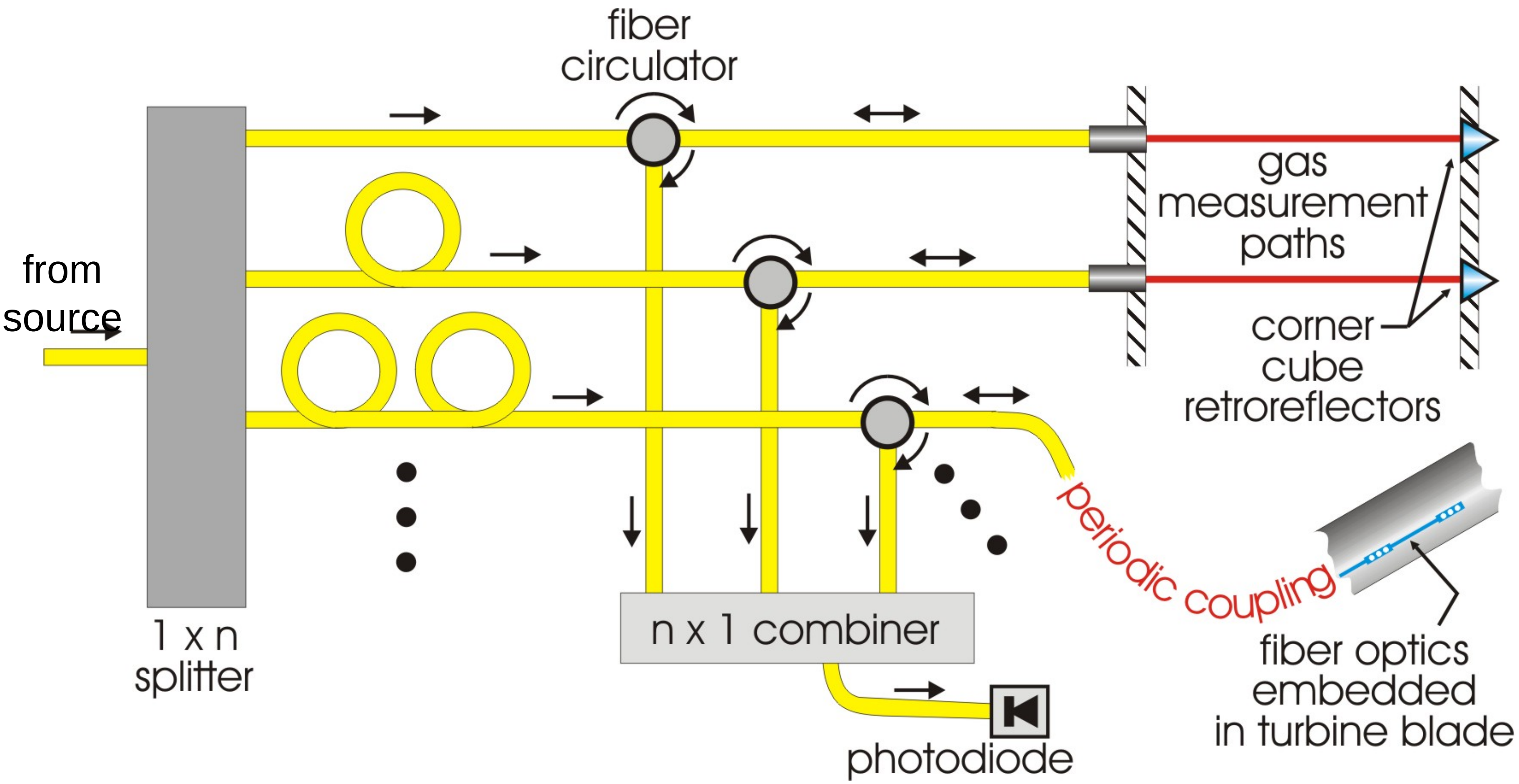
periodic optical coupling into a moving piston:





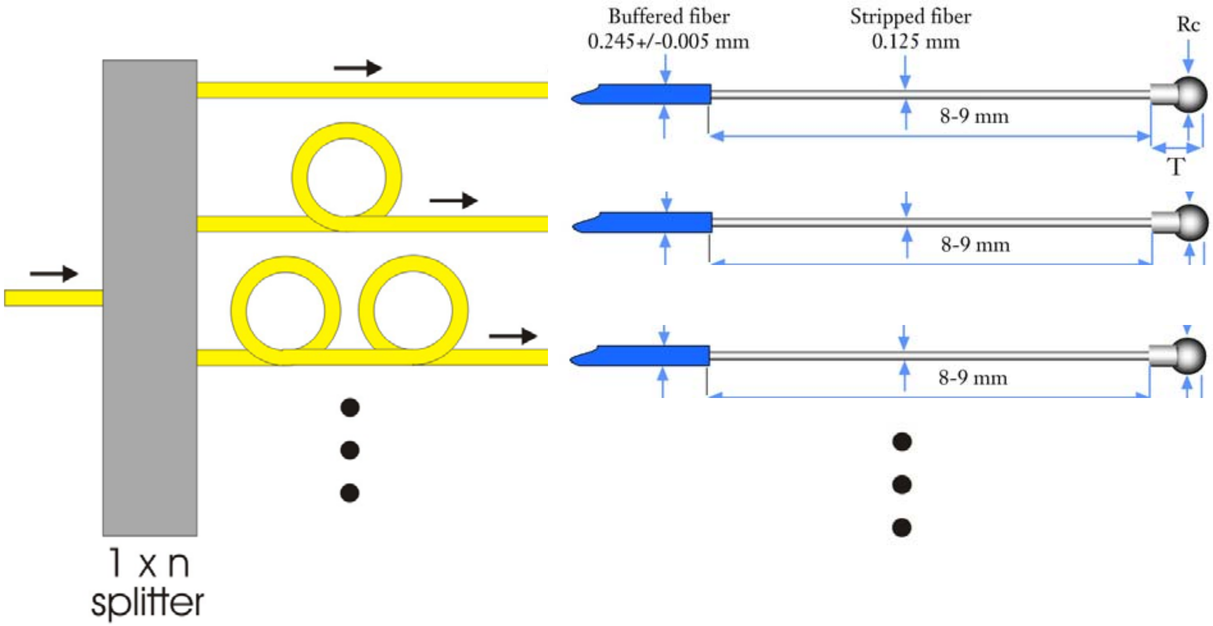
- Now pursuing large mode area fiber Bragg gratings to further improve signal-to-noise ratio

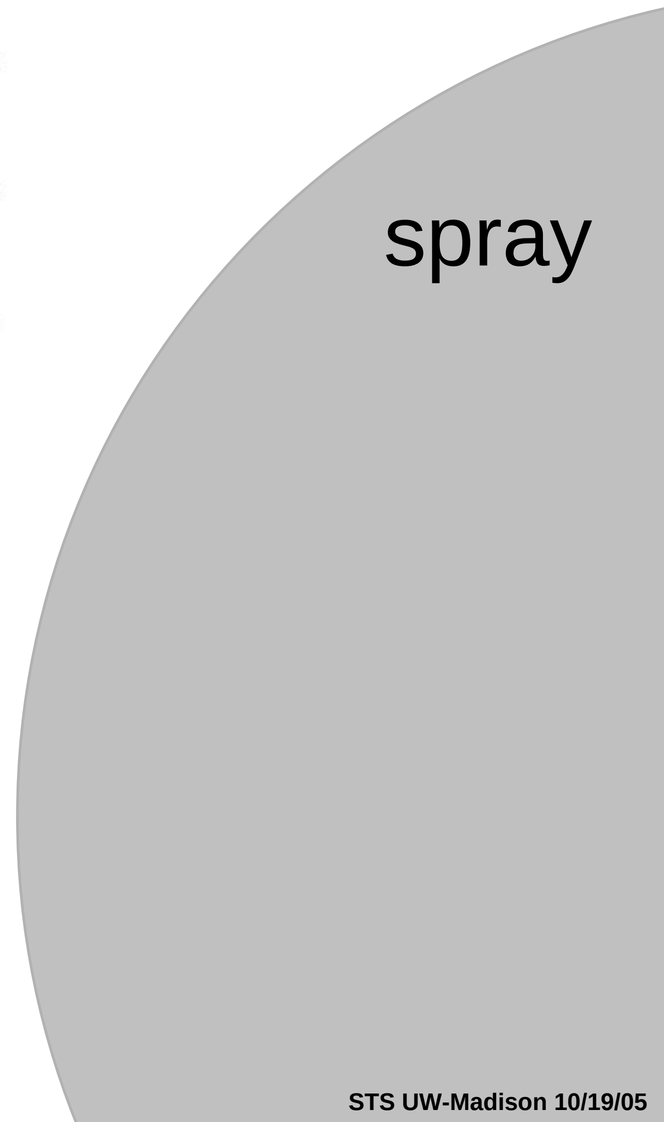
Distributing the Wavelength-Agile Light



- ◆ Each wavelength scan is distributed to many locations using a time-of-flight multiplexing approach
- ◆ Each measurement station requires only a single fiber connection

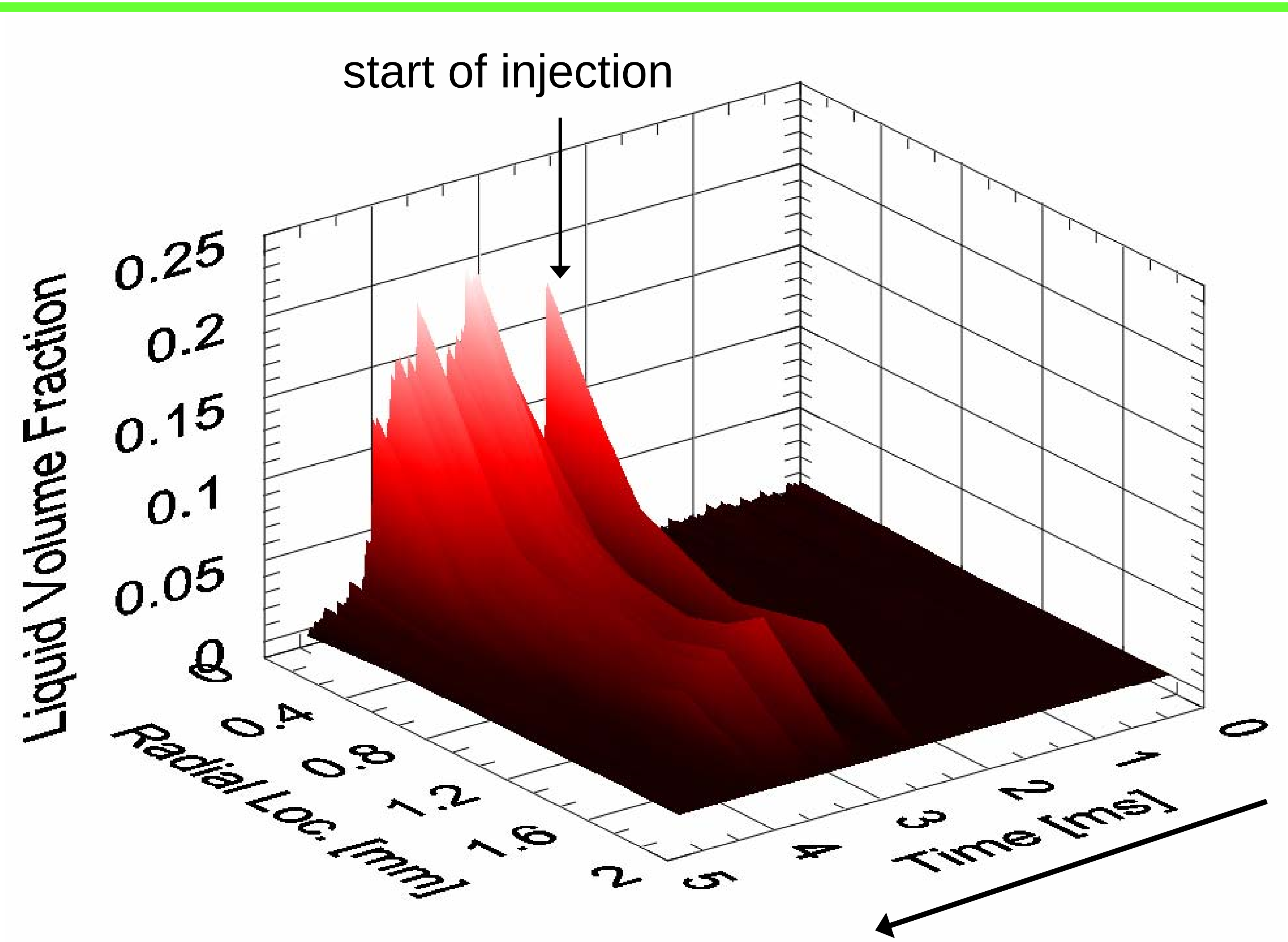
Multi-line-of-sight absorption spectroscopy: application to continuous spray measurements





- Approach: use axis-symmetric reconstruction to determine fuel volume fraction as *f* (radius)

Multi-line-of-sight spray results



- Quantitative volume fraction axis allows detailed, fundamental analyses

Accomplishments / Summary

We have developed:

- Numerous wavelength-agile sources useful for rapid spectral acquisition → gas T, embedded fiber T, …

- An approach based on dual-clad fiber for single-port optical measurements, demonstrated in WPAFB burner test rig

- An "optical thermocouple" appropriate for gas temperature measurements at essentially arbitrary conditions

Next Steps

◆ Publish online database of H_2O spectra at combustion conditions (recorded in controlled facilities: piston engines and possibly shock tubes)

◆ Continue testing optical sensors in off-site gas turbine laboratories: WPAFB planned for mid-November 2005, other testing opportunities always welcome. Is there a control opportunity that makes sense?

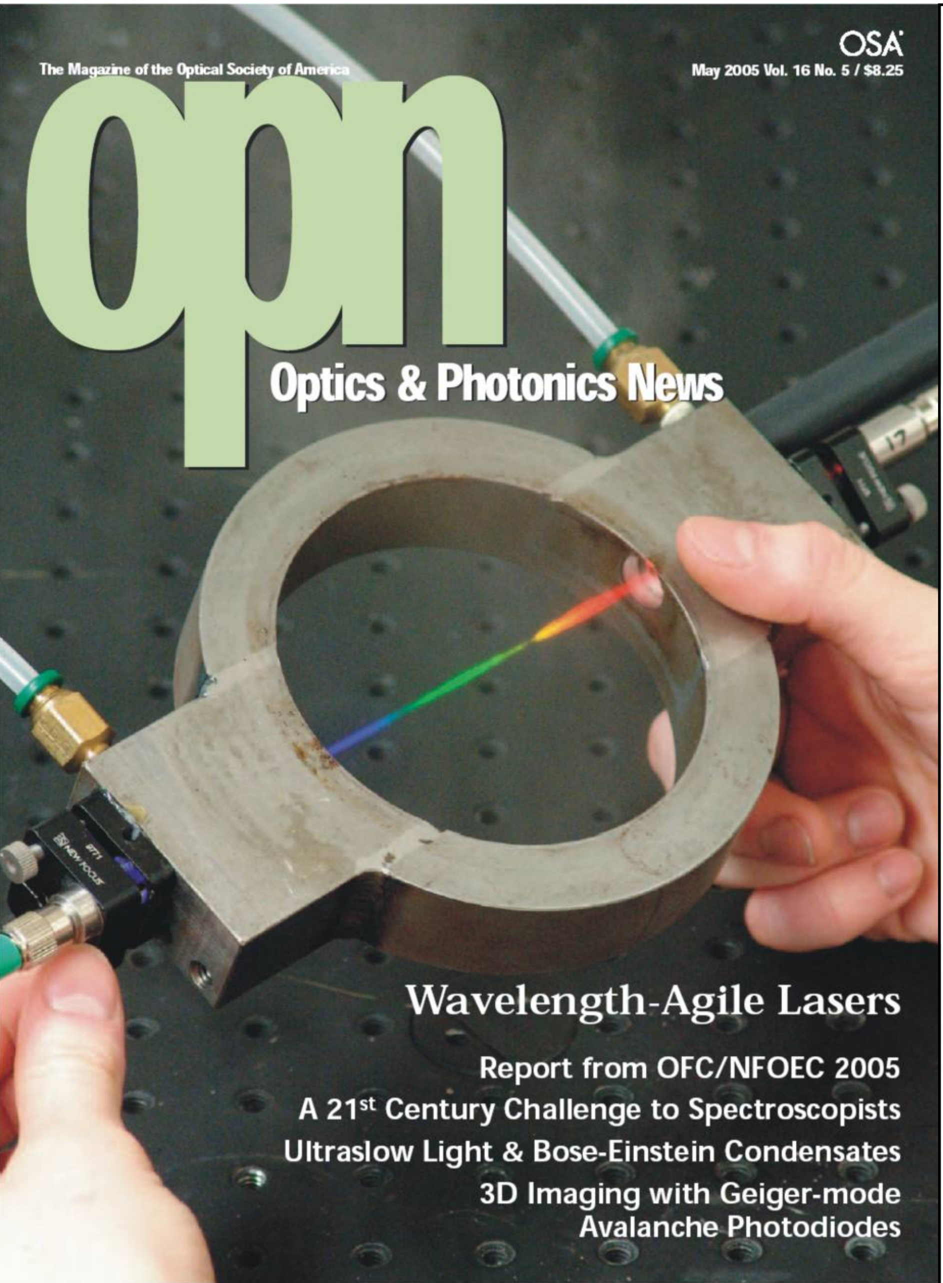
Acknowledgements

massachusetts institute of technology

NUFERN
Driven To Light.

Thermo
ELECTRON CORPORATION

QUESTIONS?



WAVELENGTH-AGILE LASERS

rate of roughly 16 kHz (near point 8 on Fig. 2).

It is helpful to characterize wavelength-agile lasers as shown in Fig. 2 because varying degrees of wavelength-agility are needed for different applications. In short, broad scanning ranges (specifically, a large ratio of scan range to spectral resolution) provide high information depth, and fast repetition rates provide a high information rate. In sensing applications, large depths generally increase the quantity and accuracy of the sensed parameters. Large rates are useful for monitoring high-speed events such as detonations (see Ref. 4), and usually offer increased accuracy because extraneous noise can be essentially frozen in time. Further, large rates generally improve assessment of accuracy by building up measurement statistics while the specimen is "frozen."

These benefits come with a cost. Sensors based on the most agile lasers in Fig. 2 (upper right) often require high-speed (about 20 Gs/s) oscilloscopes and high-speed, small-area (less than roughly 1 mm^2) photoreceivers. These components tend to be expensive and "noisy." In addition, high speed measurements often reveal optical beating that would be negligible in a similar but lower speed experiment.

Thus, I recommend choosing a laser that is only as agile as needed for a given application, aided by plots like Fig. 2. This figure does not include every possible method of generating wavelength-agile light; as more wavelength-agile lasers emerge, the plot is expected to expand to include new colored regions. For example, the vacant space in the middle of the plot does not represent any fundamental limit and is not expected to persist for the next decade.

Figure 2 highlights wavelength-agile laser systems developed primarily for monitoring combustion processes, such as those used in piston engines (points 7 and 9), pulse detonation engines (point 4) and gas-turbine engines (see Fig. 3). A typical target in such measurements would be to record combustion gas temperature and/or composition once per microsecond. Such measurements

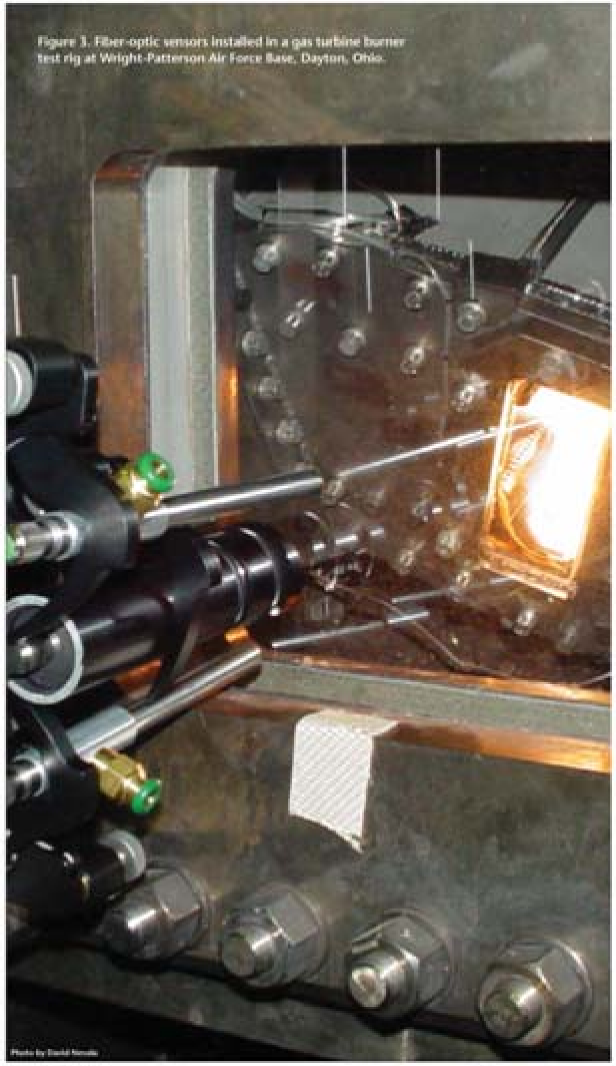
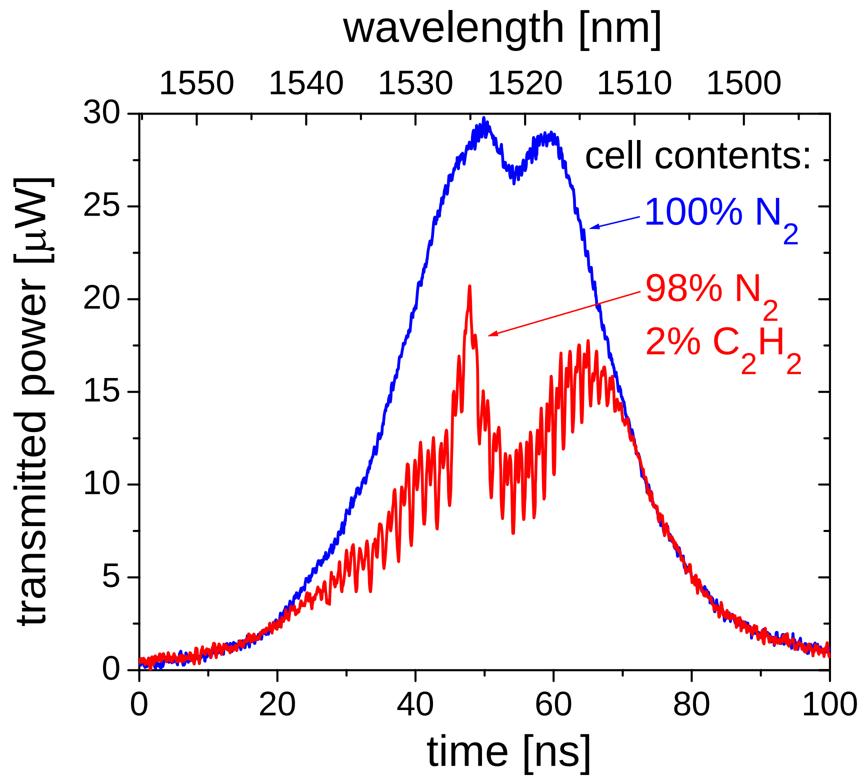
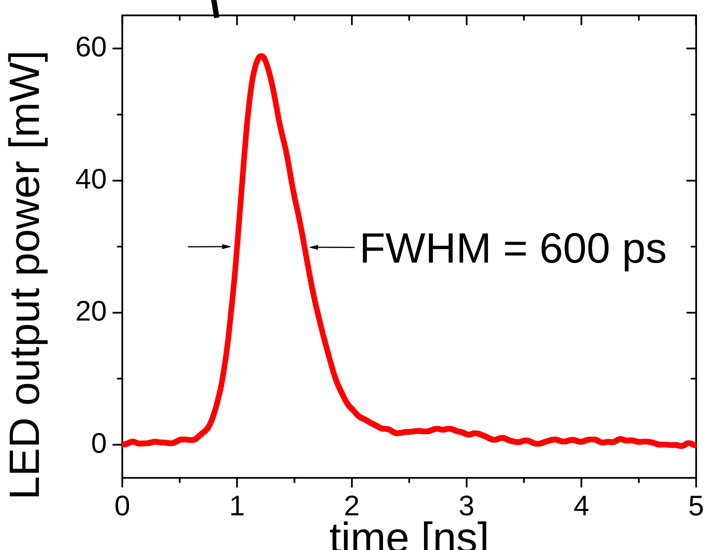
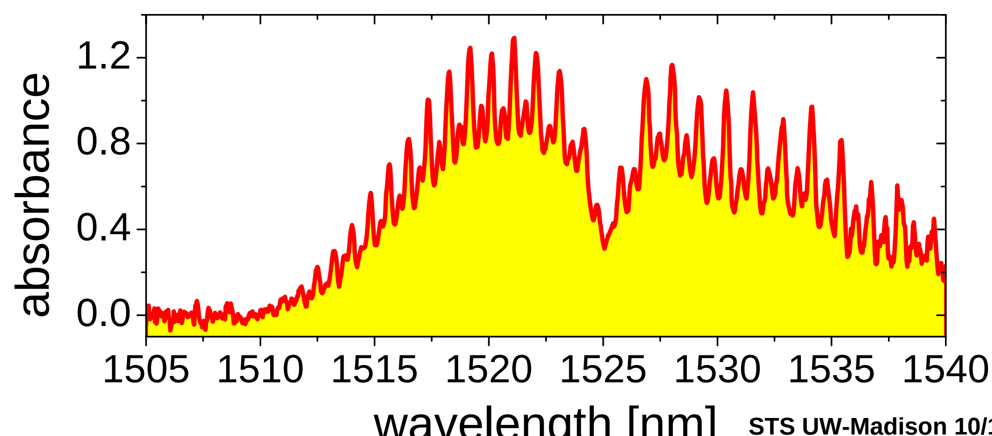


Figure 3. Fiber-optic sensors installed in a gas turbine burner test rig at Wright-Patterson Air Force Base, Dayton, Ohio.

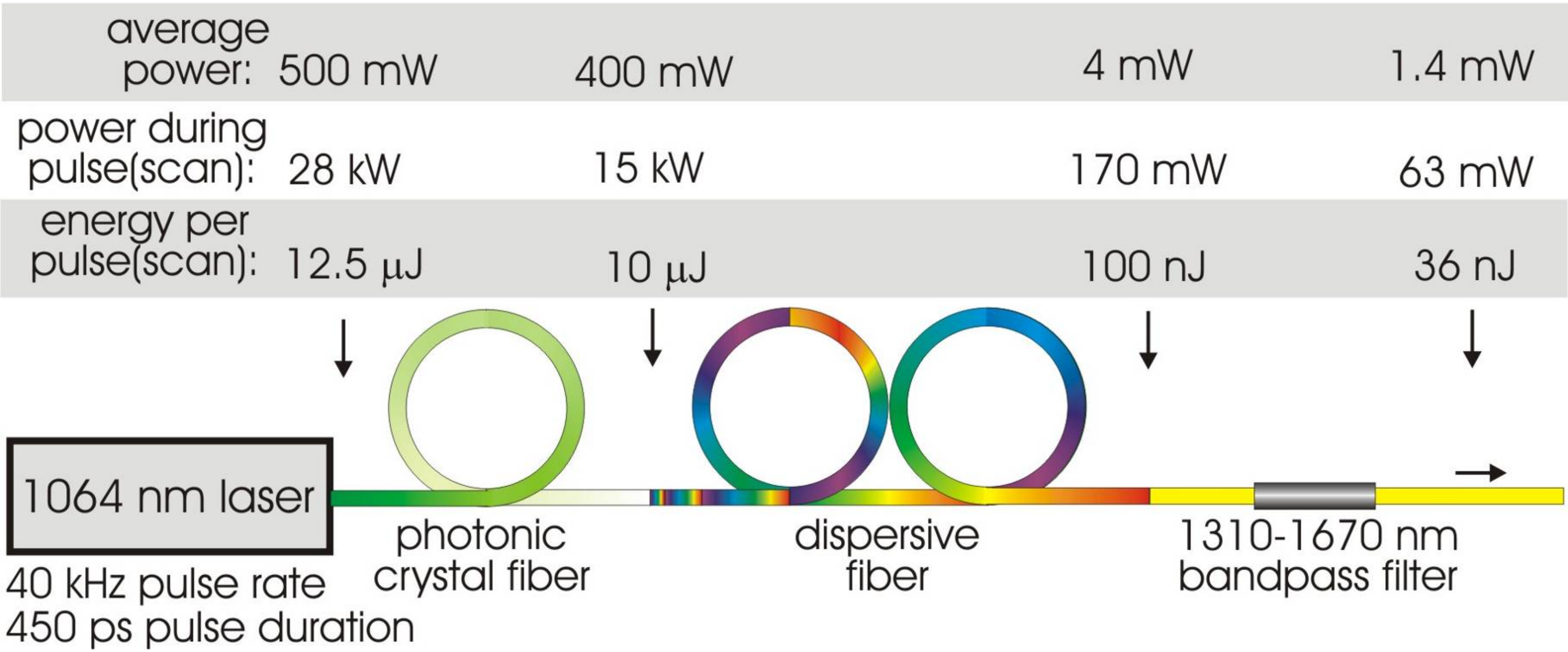
Rugged Wavelength-Agile Source







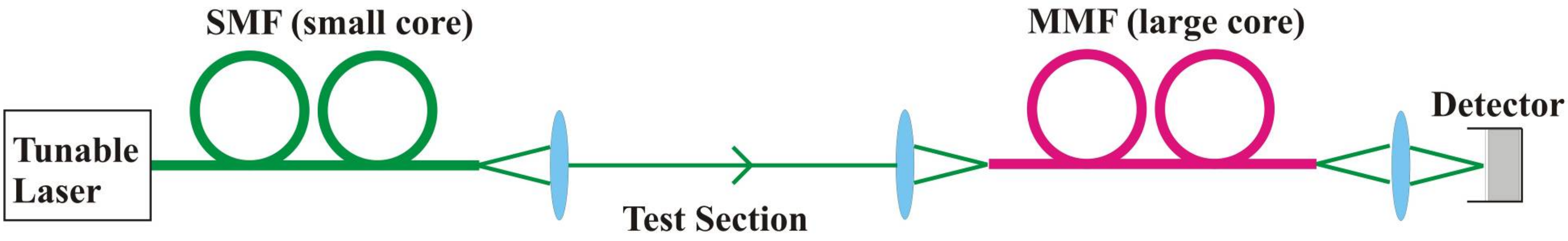
High-Power Wavelength-Agile Light Source



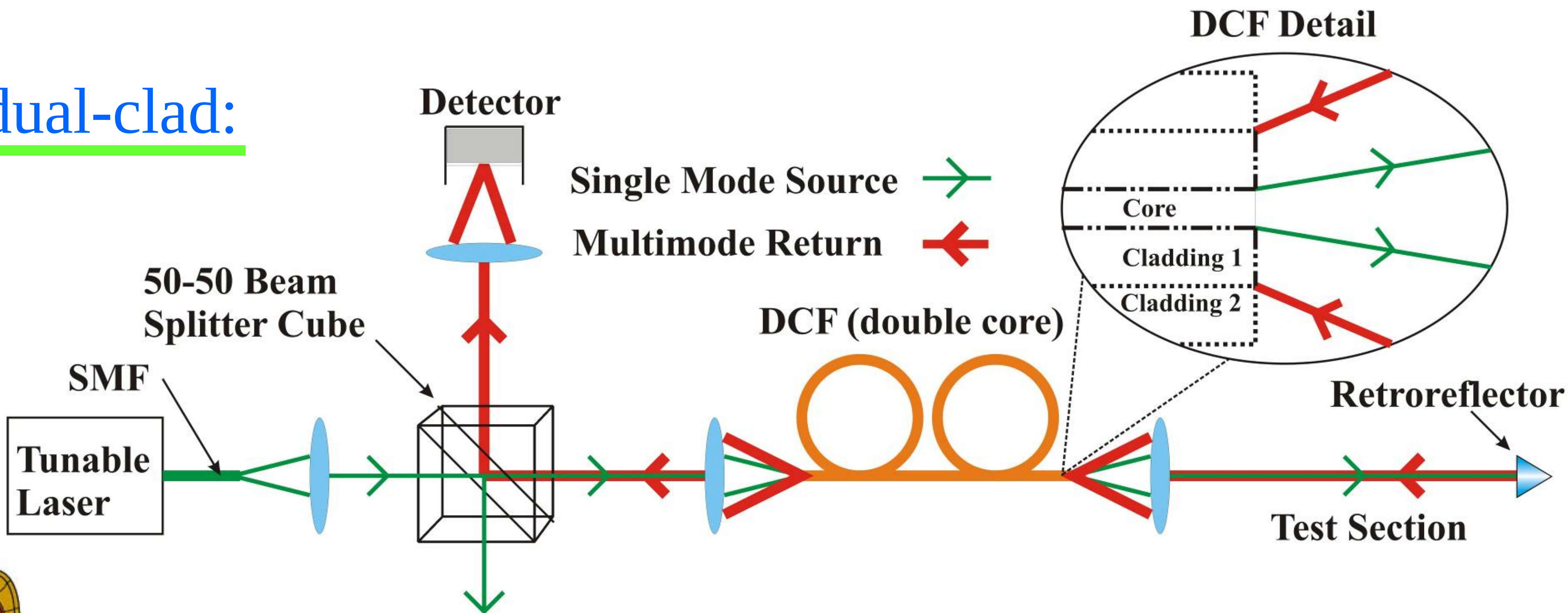
- Based on inexpensive (~10,000 USD) 1064 nm microchip laser
- Output scans from 1670 to 1310 nm in 1 microsecond

Dual-Clad Fiber Enables Single-Port Measurements

standard:

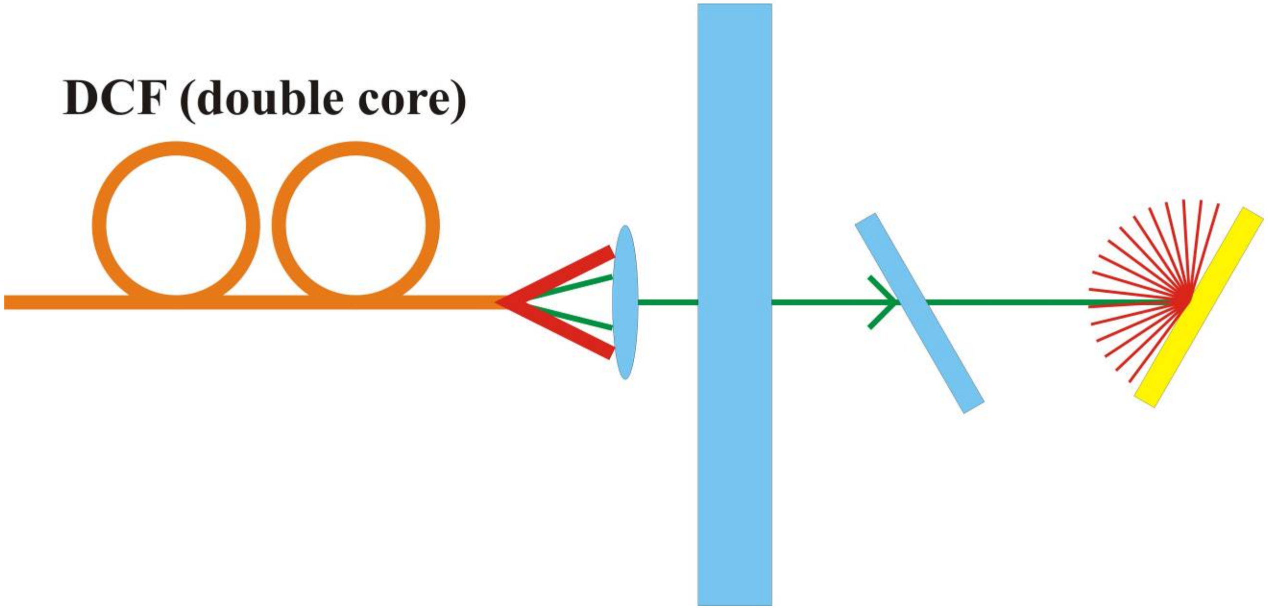


dual-clad:



- Bonus: DCF approach doubles the absorption signal

Dual-Clad Fiber Enables Single-Port Measurements



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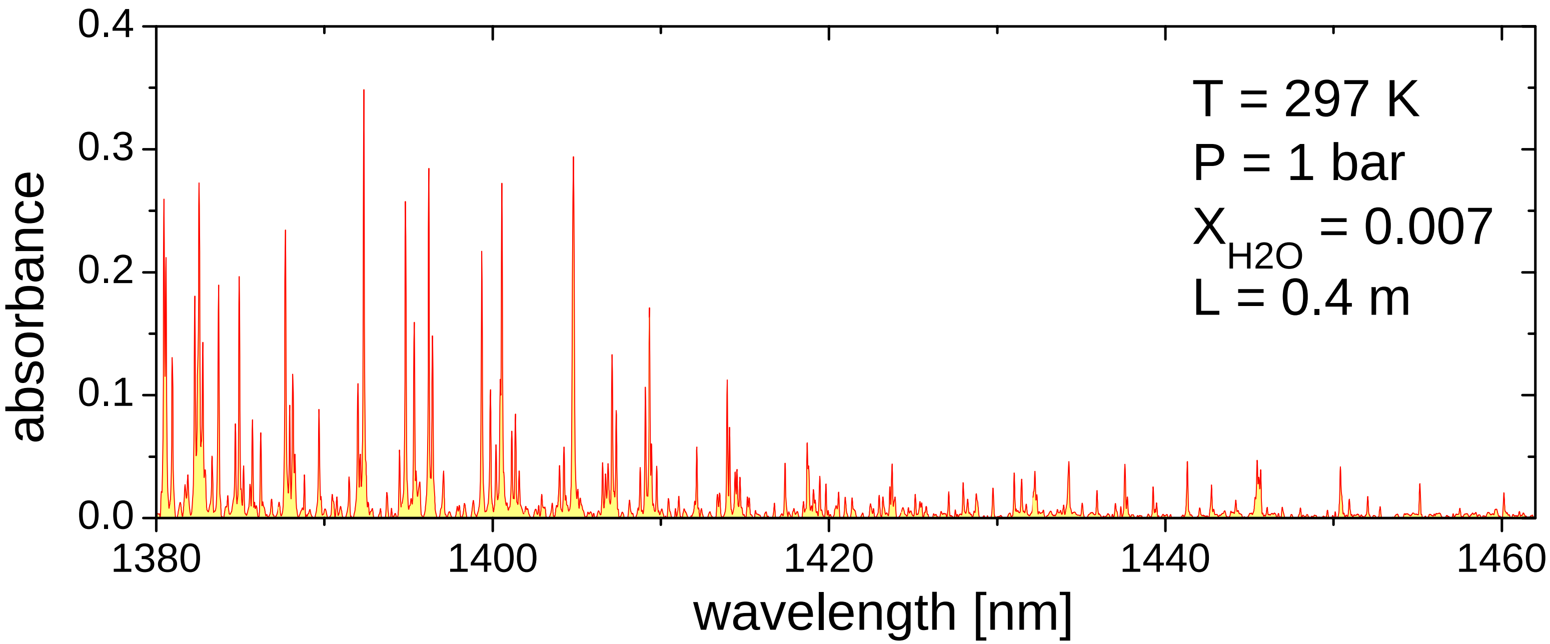
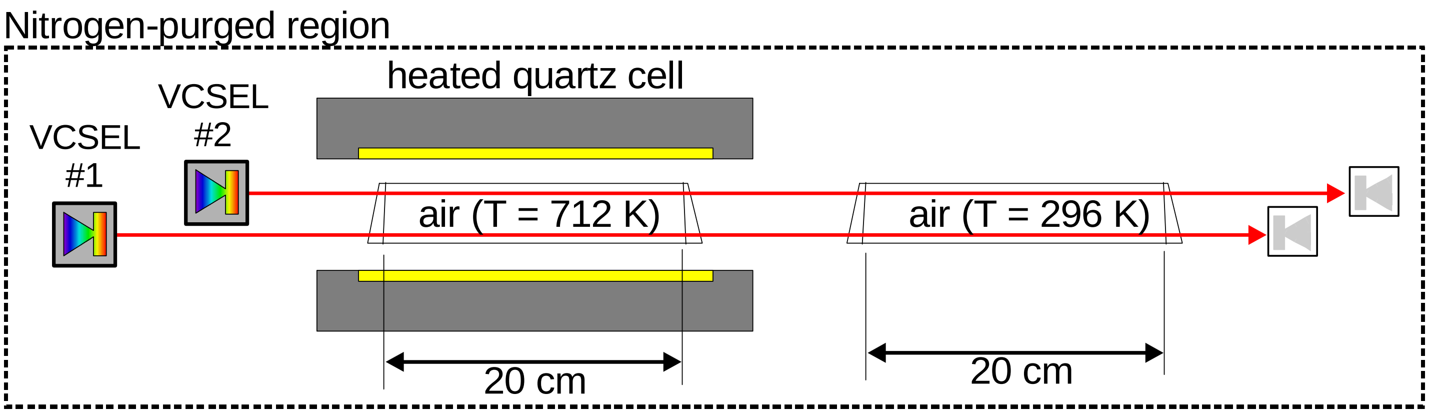
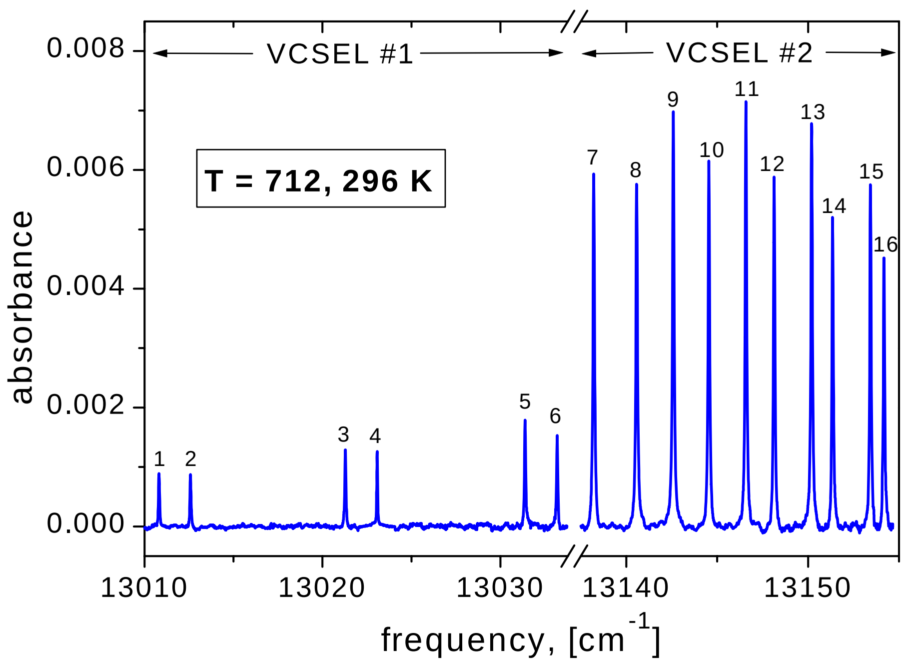
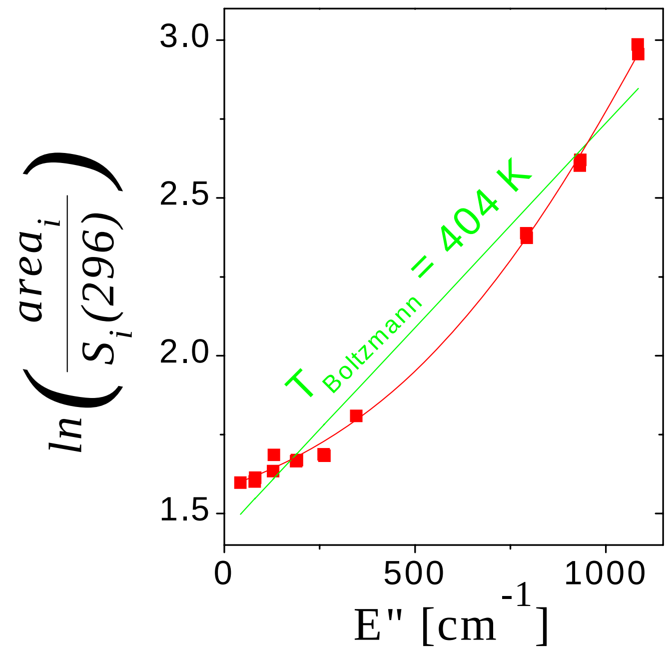
Measured H_2O Absorption Spectrum (Engine Off)



Applying Path-Integrated Sensor to Nonuniform Flows







- Probing multiple absorption lines, O_2 sensor can infer *temperature distribution*
- Useful for characterizing uniformity of combustion reactants

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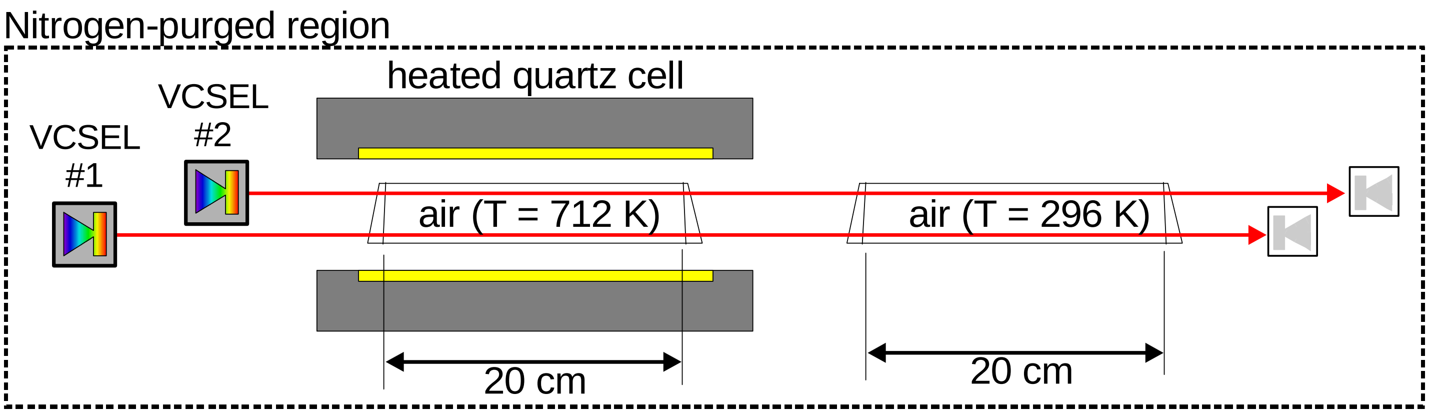

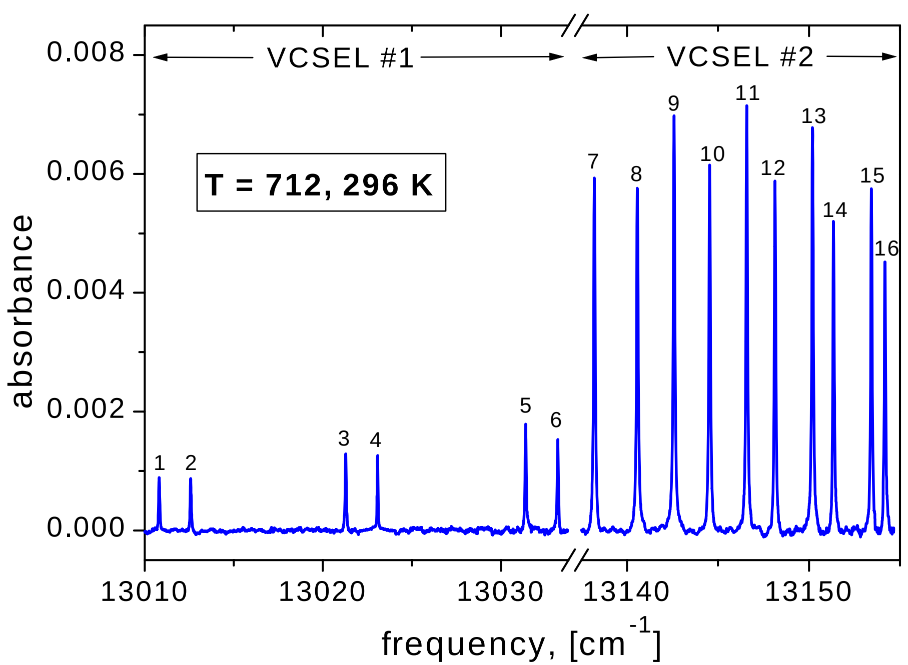

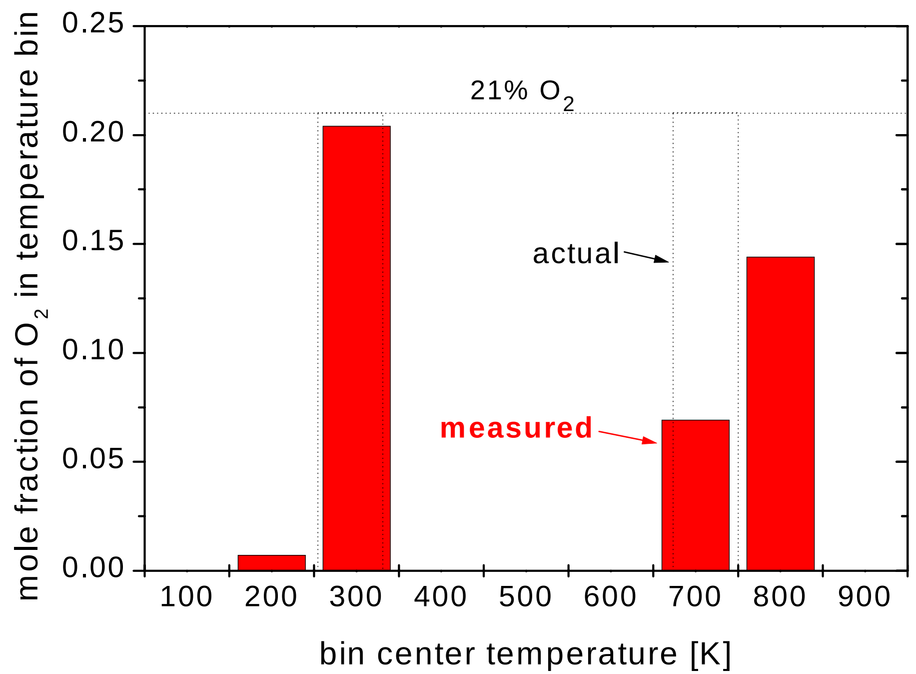

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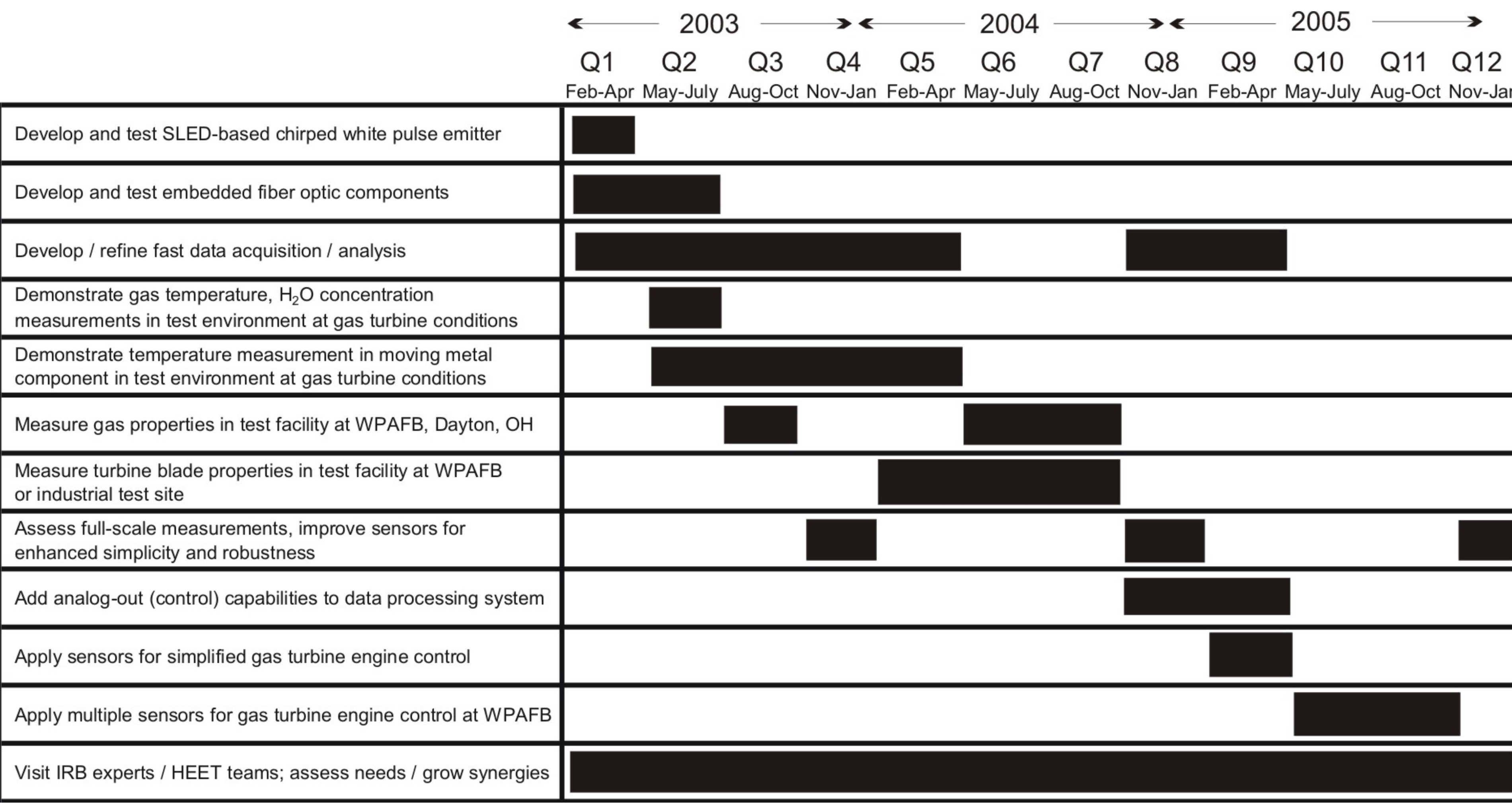
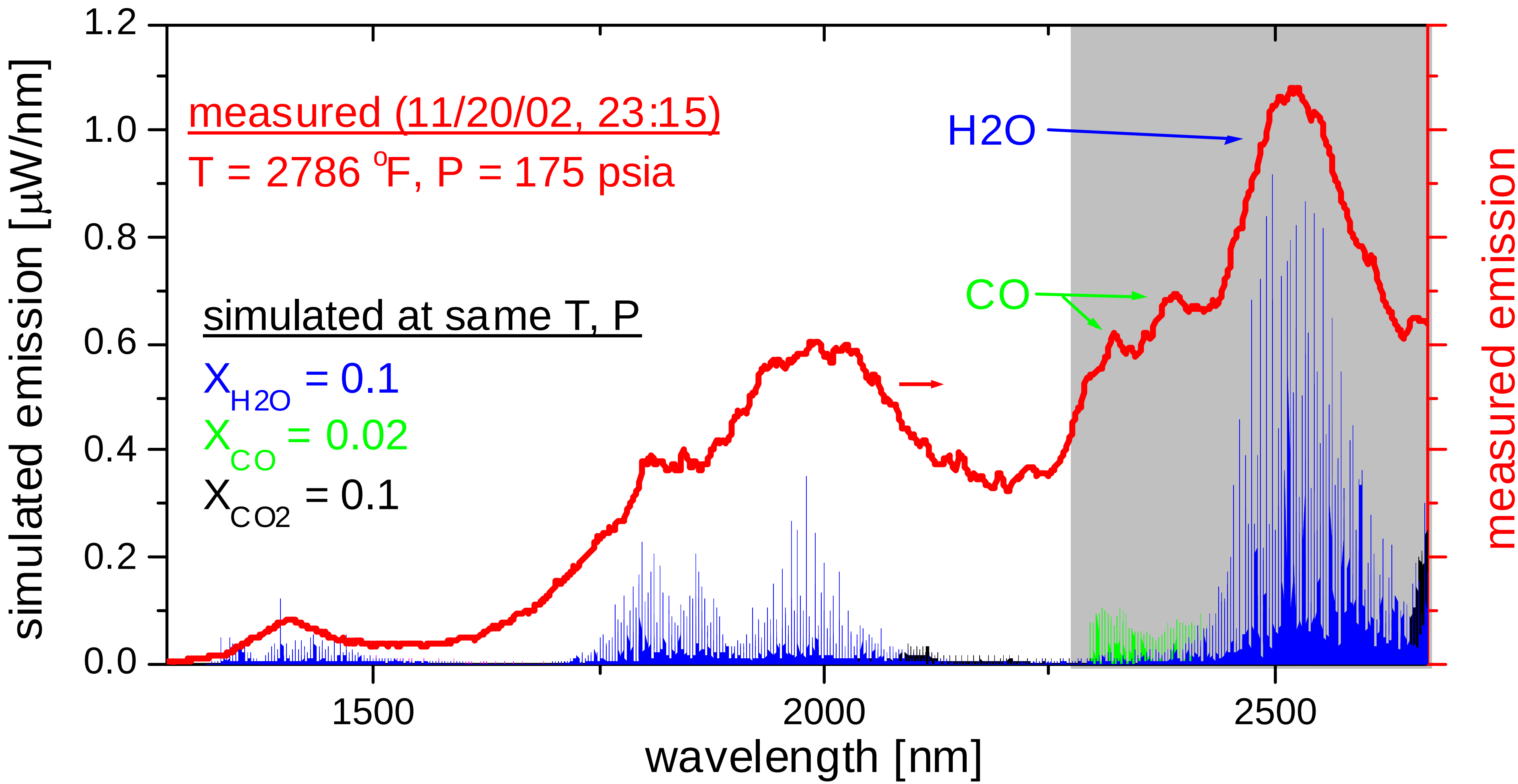
Original Schedule



Project Technical Results to Date

◆ Broadband gas emission spectrum recorded at WPAFB shows potential for measuring properties of multiple species (H_2O, CO, etc):



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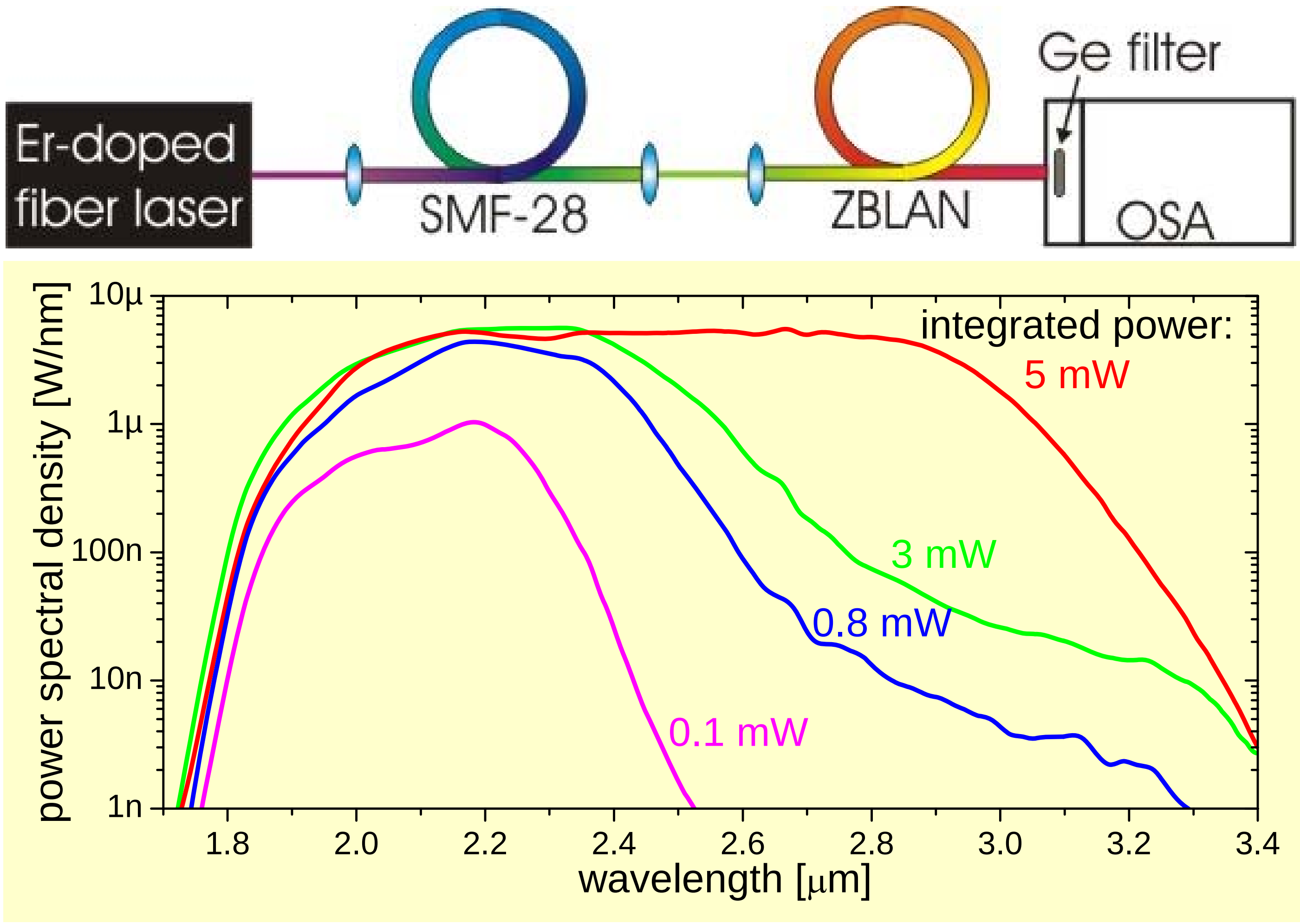

- > 5000 x the spectral radiance of a 3000 K blackbody
- use chirped fiber Bragg grating for dispersion?

The supercontinuum approach