U.S. DEPARTMENT OF ENERGY
Fossil Energy and Carbon Management

FECM's Optical Sensor Research

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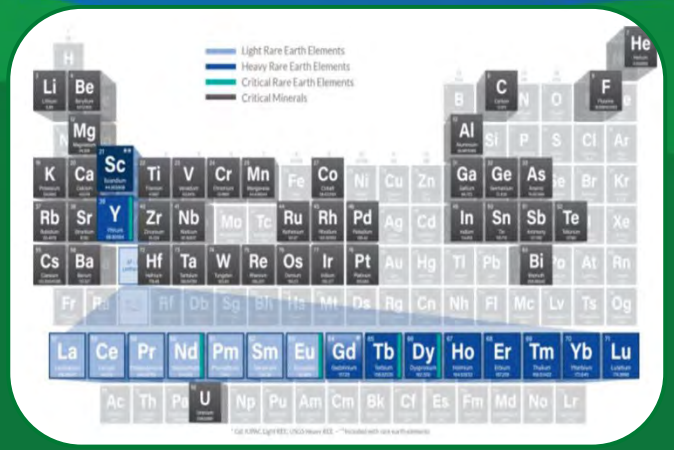
March 3, 2023





FE to FECM – A New Mission

- Focusing on mid-TRL technologies for decarbonization
- Traditionally focused on increasing efficiency and extracting maximum value from stationary fossil energy sources.
- New climate goals for the power sector:
  - 50% emissions reduction by 2030
  - 100% clean electricity by 2035
  - Net-zero carbon emissions by 2050
- Office of Fossil Energy and Carbon Management (FECM)’s new focus:
  - Mitigation of environmental impacts from resource recovery and use
  - Management of carbon dioxide emissions, including legacy emissions

Hydrogen with Carbon Management Mission

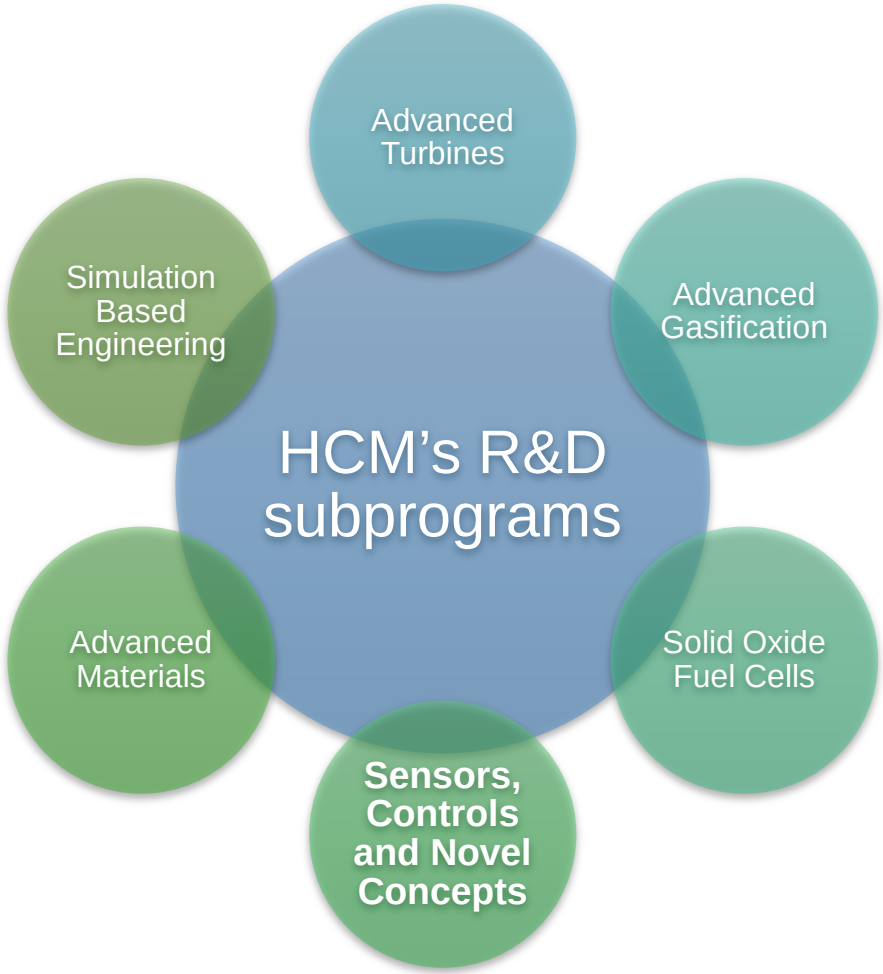
Hydrogen with Carbon Management (HCM) division integrates carbon capture and storage (CCS) capabilities with carbon neutral or net-negative carbon emissions technologies and improved fuel conversion efficiency.

Focus is on improving efficiency, increasing plant availability, and achieving ultra-low emissions of traditional pollutants. Much of HCM's research is targeted at improving overall system efficiency, reducing capital and operating costs, and enabling affordable carbon capture.

Clean hydrogen is defined as 4 kg CO_2e/kg H_2 at the point of production.

Functional R&D Responsibilities Include:

- Clean hydrogen production in bulk quantities through gasification and Reversible Solid Oxide Fuel Cells (R-SOFCs)
- Industrial power production using hydrogen in turbines and SOFCs
- Small, modular gasification systems to accelerate construction and reduce installed costs
- Enabling technologies such as Advanced Materials, **Sensors and Controls** and Simulation Based Engineering



FECM's Sensors & Controls Program

Goal: <u>ENABLE, OPTIMIZE and PROTECT</u> Evolving Generation Technologies

Enable…

- Real-time measurement in extremely harsh environments using novel technologies
- Operations-based predictive maintenance to maximize life and availability
- Increased flexibility (cycling, ramping) to respond to rapidly changing load demand and bolster grid stability
- Widespread use of new, clean generation technologies (H_2, SOFCs, etc.)

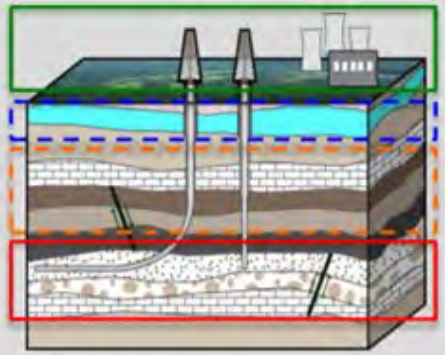
Optimize…

- Plant efficiency and heat rate with advanced control and diagnostic methods
- Sensor capability, placement, size and manufacturability
- Maintenance planning to reduce unplanned outages

Protect…

- Plant equipment and availability by ensuring sensor data, control system, and supply chain security with cutting-edge cyber technology

FECM Sensors & Controls Applications

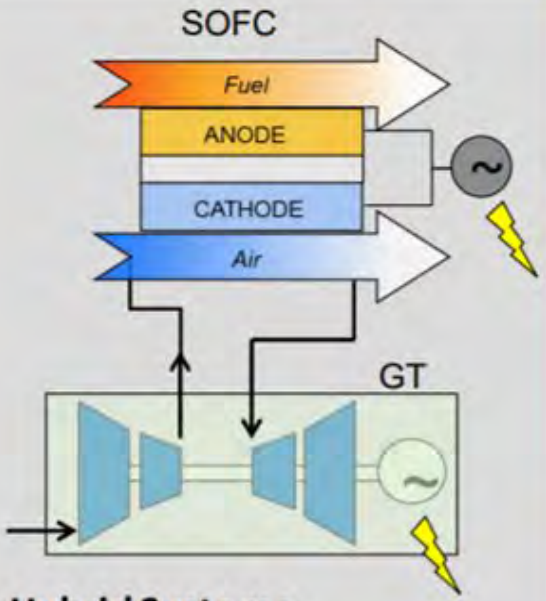


Carbon Storage and Subterranean chemistry

- Assure CO_2 storage stability
- At the Wellhead
- Downhole
- High pressure water or brine

Hydrogen Production and Utilization

- Thermal gasification 1100 - 1500°C
- Microwave fuel reforming
- Chemical Looping
- Hydrogen GT
- SOFC/SOEC
- Ammonia systems



Hybrid Systems

- 800°C in fuel cell
- 1500°C in GT
- Transient controls
- + Storage or polygen

Novel Systems

- Direct Air Capture
- Supercritical CO2 cycles
- FE + storage
- FE + biomass
- FE + plastics

Sensors, Controls & Novel Concepts Technologies

Technologies

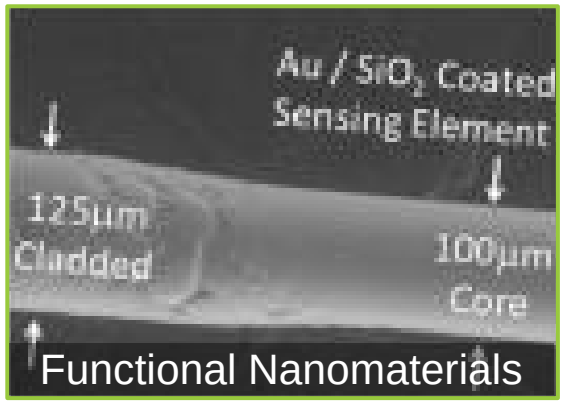
- High-temperatures & harsh environments
- Real-time measurements and diagnostics
- Optical fiber, wireless, embedded
- Materials development, packaging & prototyping
- Testing in relevant environments

- Control strategies for advanced energy systems & hybrids
- PID and MPC controls
- Cyber-physical systems
- Condition-based maintenance
- On-line System Identification
- Critical component failure prediction

- Emerging Technologies
- Cybersecurity (blockchain implementation, visible light communications, etc.)
- Direct Power Extraction
- Quantum Sensing

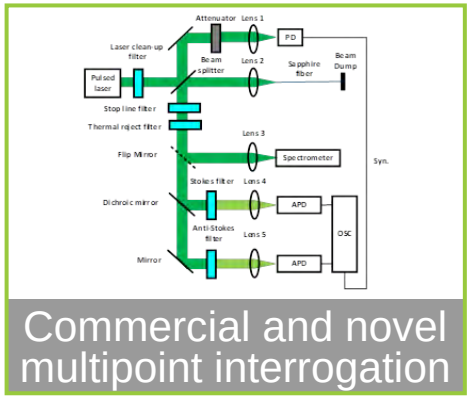
Optical Fiber Sensing for Harsh Environments

- Develop materials and methods for spatially resolved optical fiber-based sensing under harsh conditions (>800°C)
- Develop low-cost functional coating using sputtering and dip coating methods
- Develop economic fabrication process for durable optically clad sapphire fiber and interrogation system

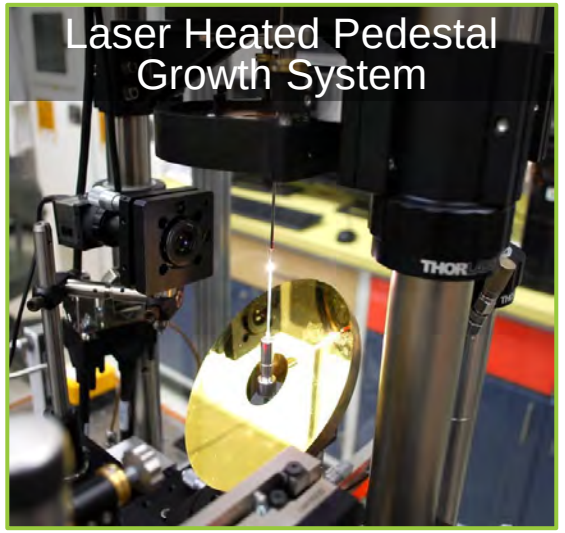


Functional Nanomaterials

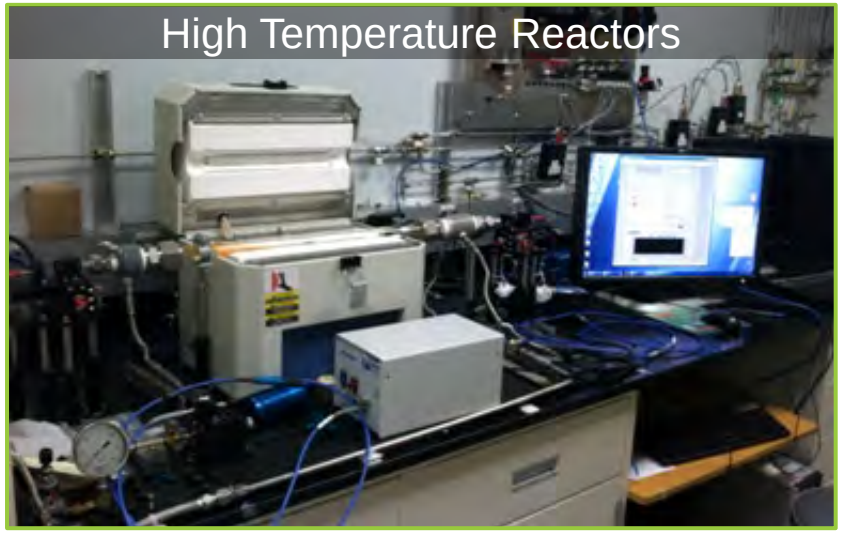

Fossil energy relevant gases



Commercial and novel multipoint interrogation



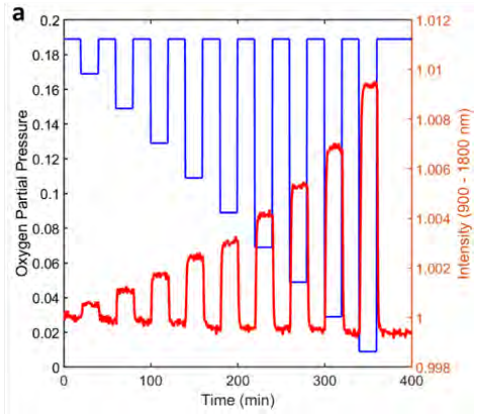
Laser Heated Pedestal Growth System

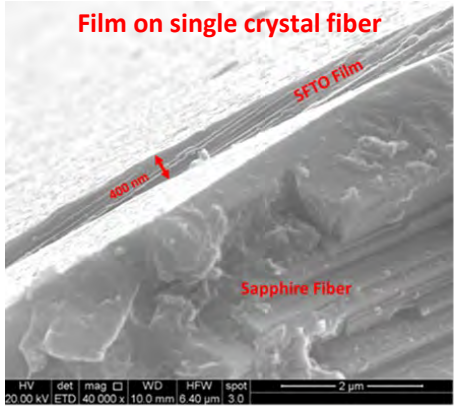

High Temperature Reactors

Optical Fiber Sensing for Harsh Environments (Cont.)

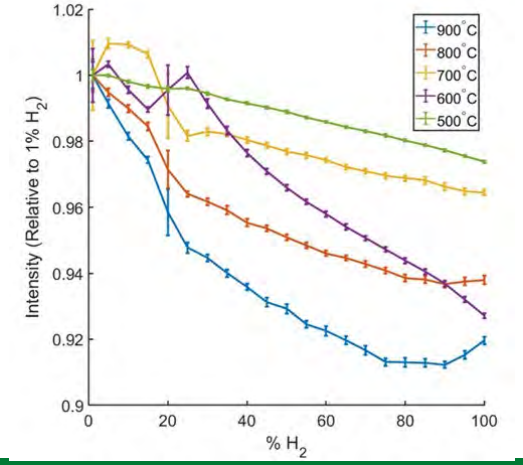
- Completed testing of $La_{0.30}Sr_{0.70}TiO_3$ sensing layer on single crystal sapphire fiber
  - 1-100% H_2 at 500-900 °C under ambient pressure
  - Cross-sensitivity to CO_2, CH_4, and CO
- Completed two draft manuscripts describing demonstration of single crystal fiber sensors for gas sensing at high temperature (500-1000 °C)
- Upcoming work: improve selectivity and stability through protective overcoat, field testing

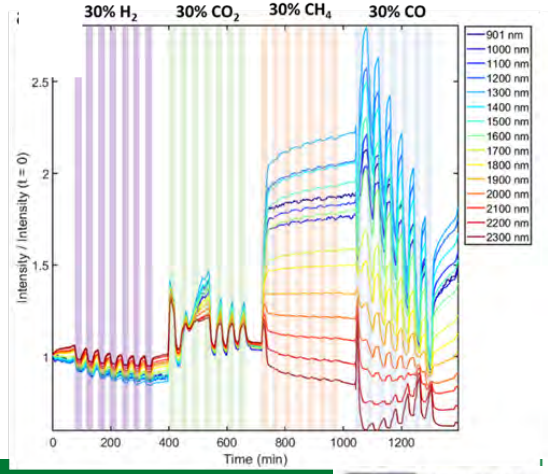
Oxygen Sensing w/ STFO film at 800 °C





Hydrogen Sensing w/ LSTO film at 500-900 °C





Optical Fiber Distributed Temperature Measurement

- Test distributed temperature measurement with optical fiber
- Apply optical fiber temperature measurements in NETL microwave reactor facility (ReACT)
- Design and construct higher spatial resolution temperature measurement unit

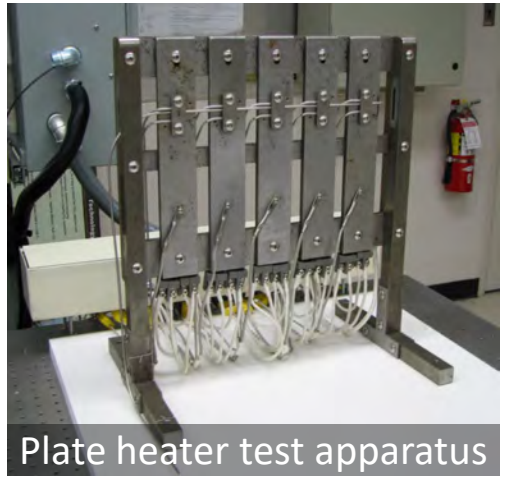
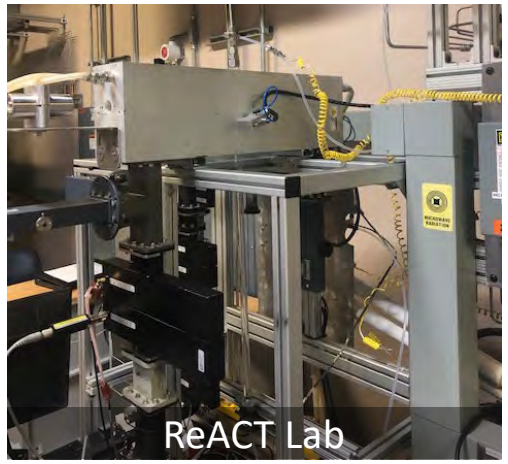
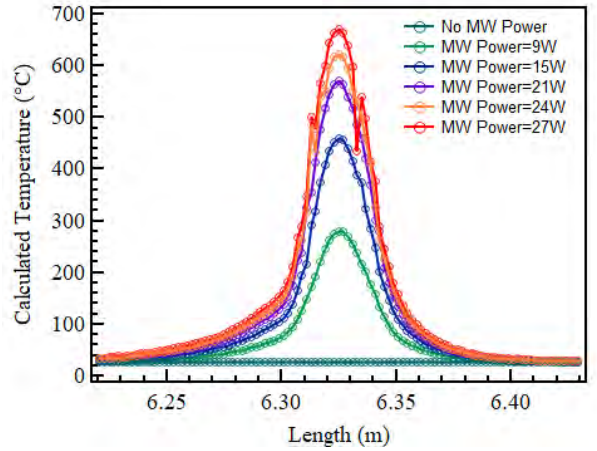
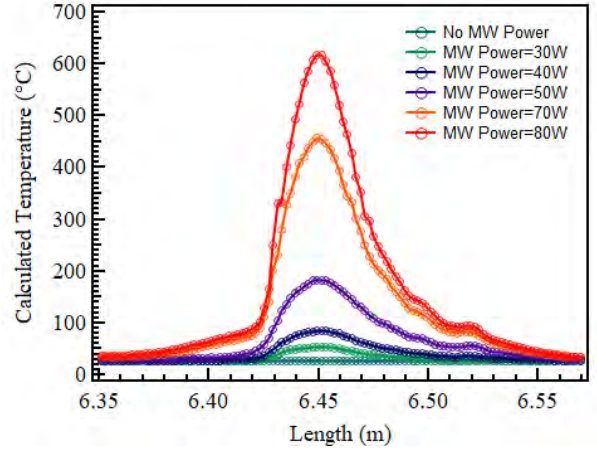


Plate heater test apparatus


ReACT Lab

Initial tests from EY21



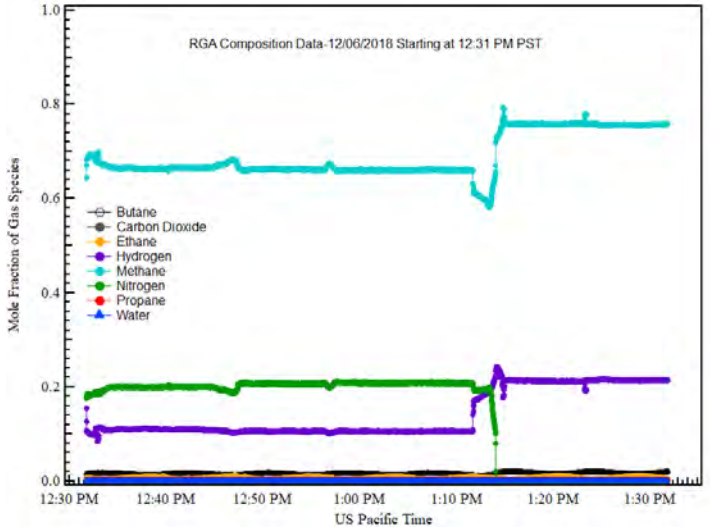


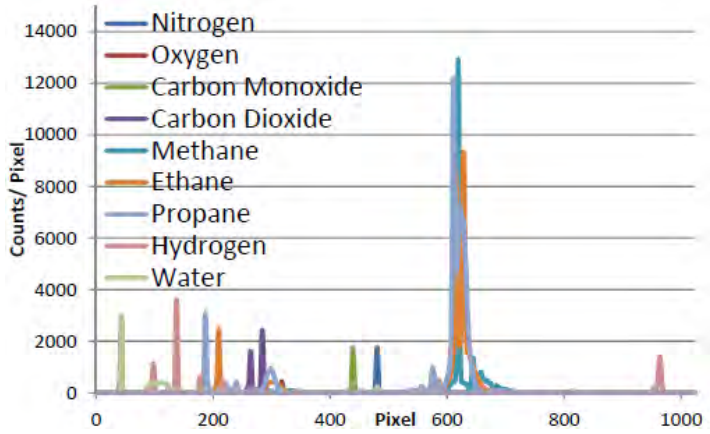
Raman Gas Analyzer (RGA)

- Program and test smaller prototype constructed in EY21 and prepare for field testing
- Identify opportunities for incremental improvements and advance the TRL
- Support field testing and on-site use of the RGA and tech transfer activities

US Patent 8,674,306, NETL and Pitt

Compact RGA

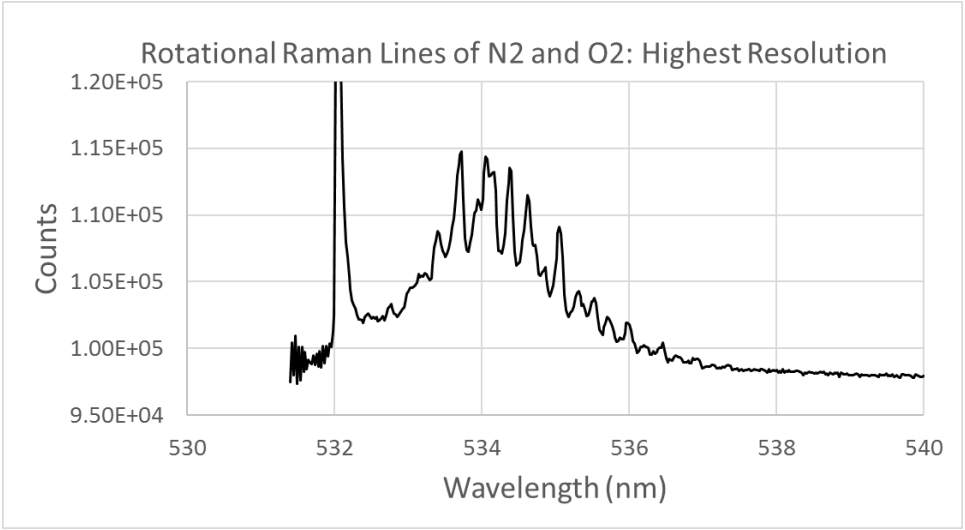


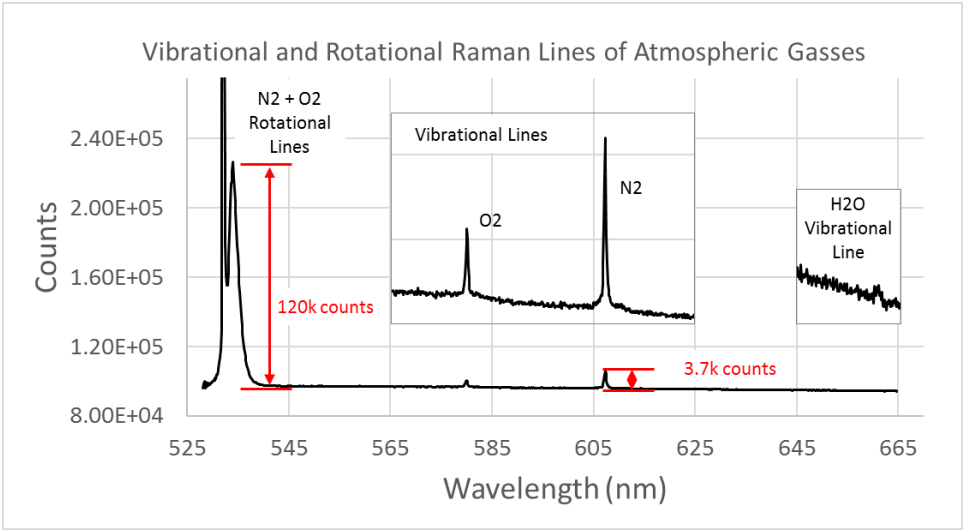


- Applications to **low carbon power generation** (e.g. hydrogen blend turbines)
- Prototype tested in pilot scale laboratory applications
- Fast - 1 second measurement time
- Species concentrations measured to 0.1%
- Optical waveguide technology boosts Raman signal more than 1000X
- No recalibration needed in normal operation
- **EY21: Rack mount design constructed**

Ultrafast Laser Measurements for Harsh Environments

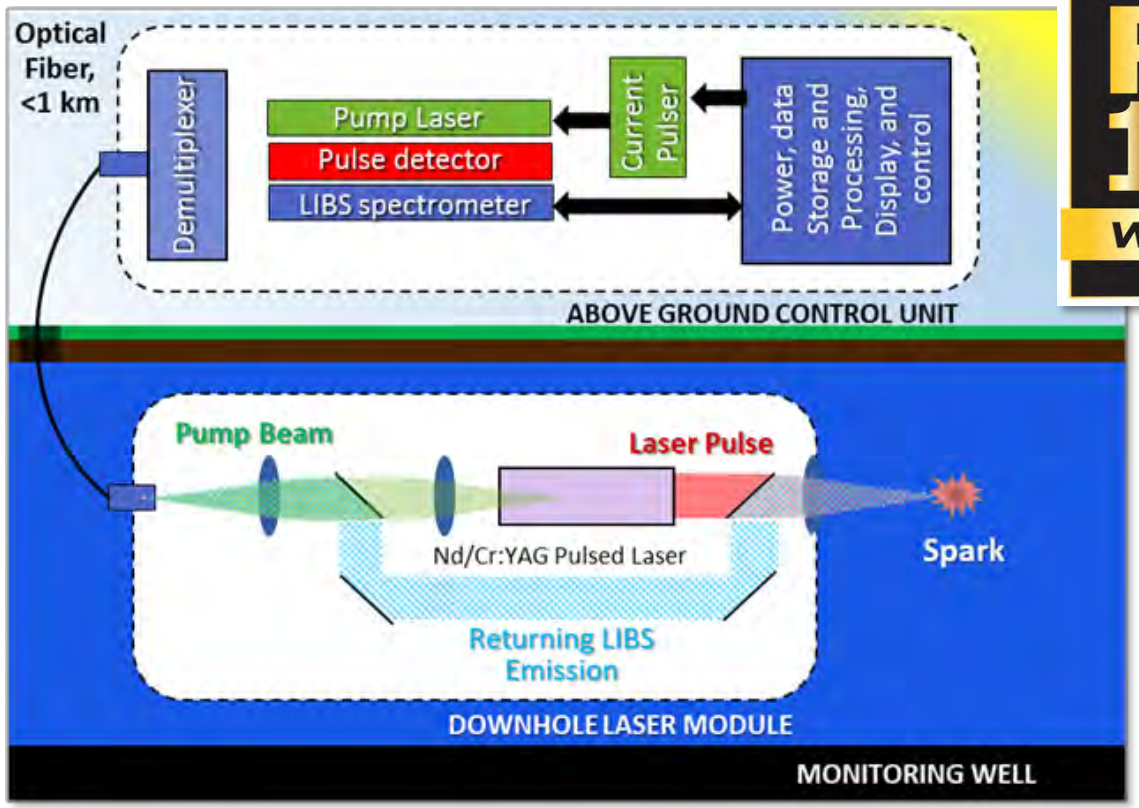
- Proof of concept Raman LIDAR system built
  - Pure vibrational and rotational Raman lines of N_2 and O_2 (rotational lines are ~30x more intense) at room temperature
- Preparations for high temperature testing completed
  - Tube furnace configured to test flue gas components (e.g., N_2, O_2, H_2O, CO_2)
- Custom optical arrangement for improving resolution has been designed and components ordered
- Scheipflug optical arrangement currently under test to improve spatial resolution
- Precise gas mixing apparatus has been engineered and will be constructed soon.



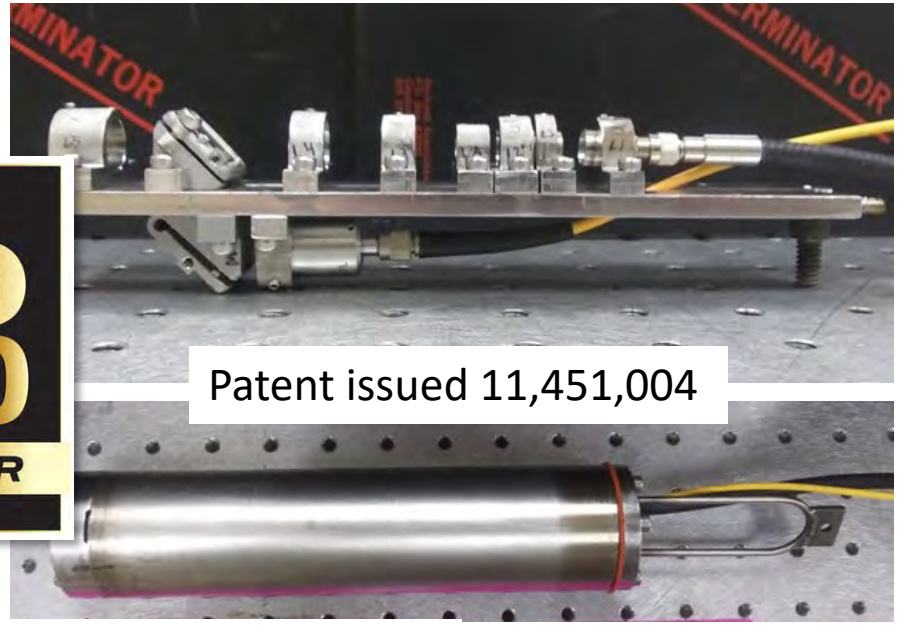


LIBS for Subterranean Sensing

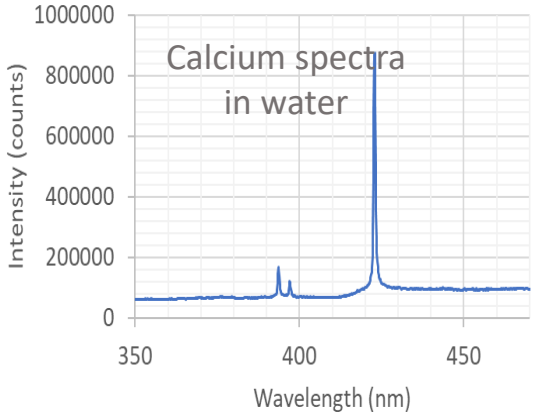
- Development, optimization and testing of a deployable miniaturized LIBS system for subterranean chemical sensing



2019 R&D 100 WINNER

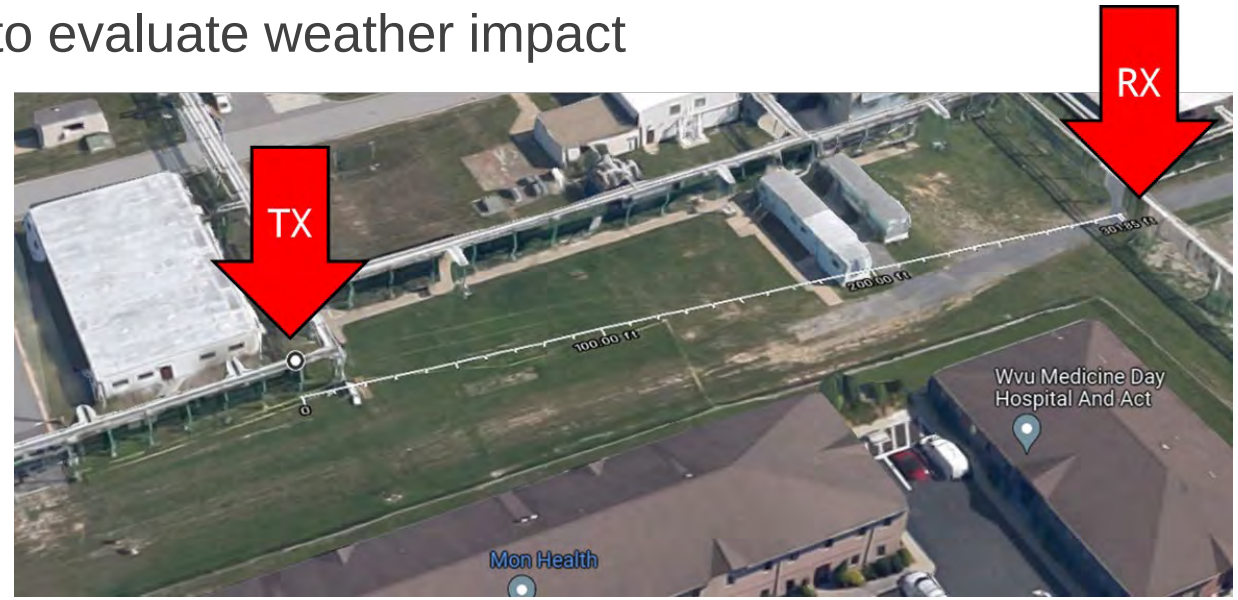


Patent issued 11,451,004



Visible Light Communications (VLC) / Li-Fi and Sensors for Secure, Wireless Alternative

- Develop more secure alternative to RF communication for sensors
- Transmitter and receiver in testing
  - Eye-safe, power LED based system
  - Mounted onto poles separated by 100 yards on NETL site
  - Battery powered with solar recharge
- Data collection to evaluate weather impact



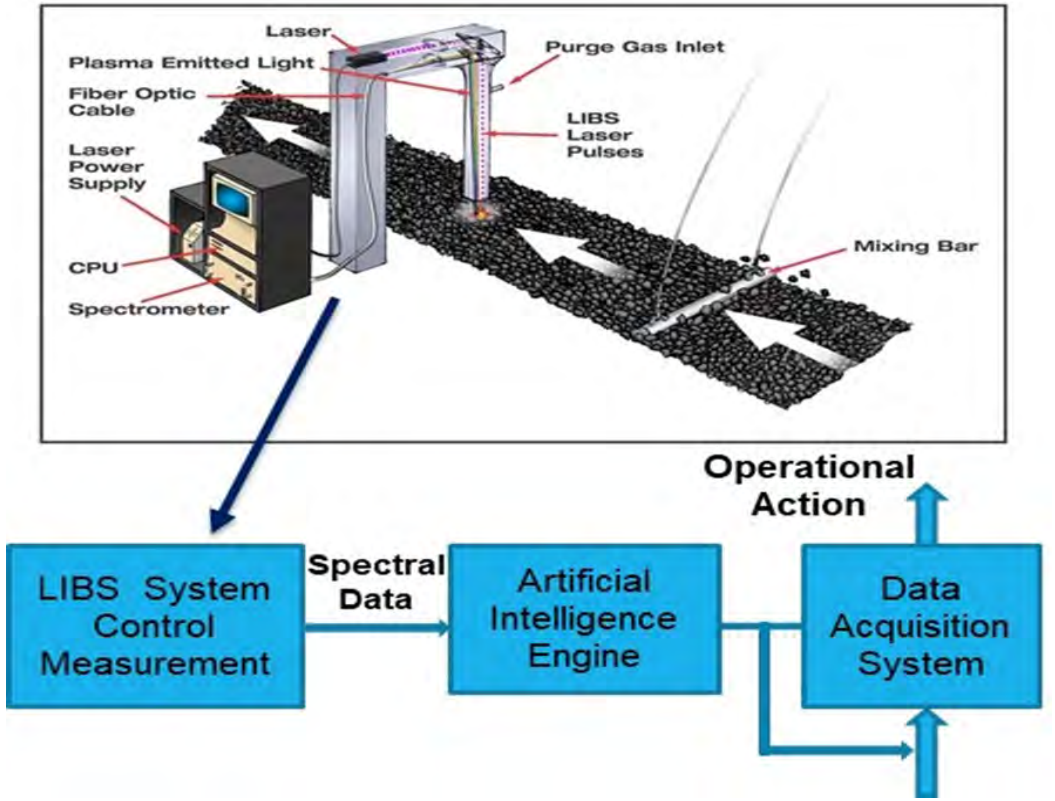
Extramural Project - DE-FE0032177 – Lehigh University

Project Overall Goal

- Assess the feasibility and potential of using Laser Induced Breakdown Spectroscopy (LIBS) linked to Artificial Intelligence-Machine Learning (AI-ML) for real-time and in-situ chemical analysis of waste materials (biomass, waste plastics and legacy coal waste; individually and in blends), of interest to hydrogen production gasifier operators.

Proposed Approach

- Technology will allow **rapid, in-situ characterization** of gasifier feedstock, providing critical characterization data in minutes for continuous confirmation of feedstock specifications and **potential feed-forward process control** of downstream hydrogen production.
- This would represent a **hundred-fold improvement in the feedstock characterization throughput**, over current methods of grab sampling, compositing, and costly laboratory analyses.



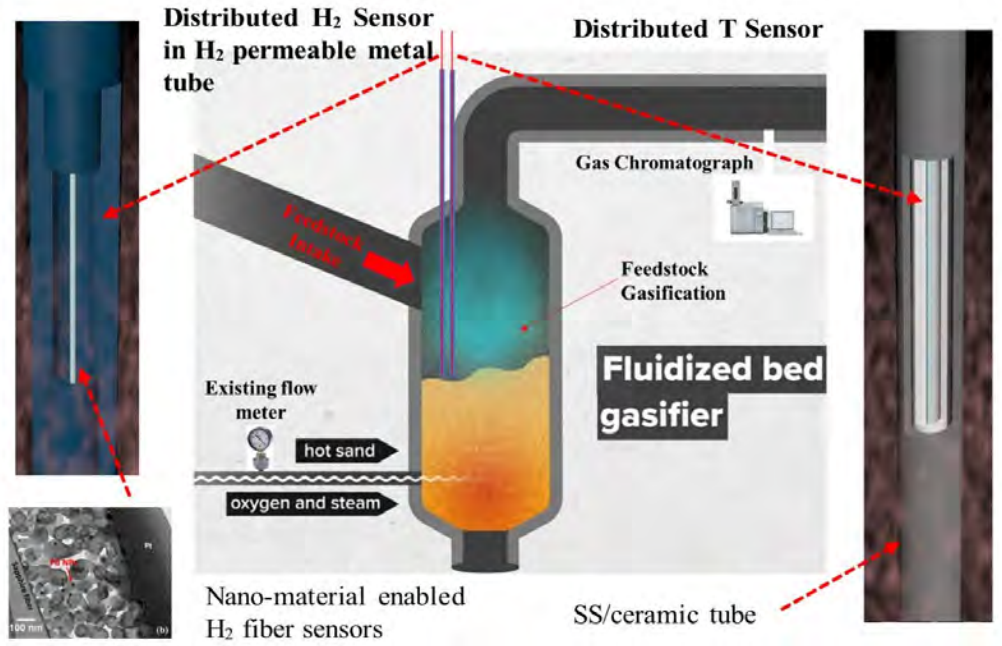
Extramural Project - DE-FE0032210 – U Pittsburgh

Project Overall Goal

- This project seeks to develop distributed fiber sensors to perform real-time temperature and hydrogen concentration measurements to improve hydrogen production and energy efficiency for waste plastics gasification processes. The team will demonstrate a sensor-enabled gasification optimization process and reduce harmful chemical generation.

Proposed Approach

- **Femtosecond laser direct writing** techniques to **fabricate stable and hydrogen-resistant sensing fibers** with strong Rayleigh backscattering profiles for in-situ distributed temperature measurements inside a gasification reactor.
- Develop **distributed fiber** hydrogen sensors for in-situ monitoring of hydrogen production inside a gasification reactor with a **5-cm spatial resolution** during the gasification process.



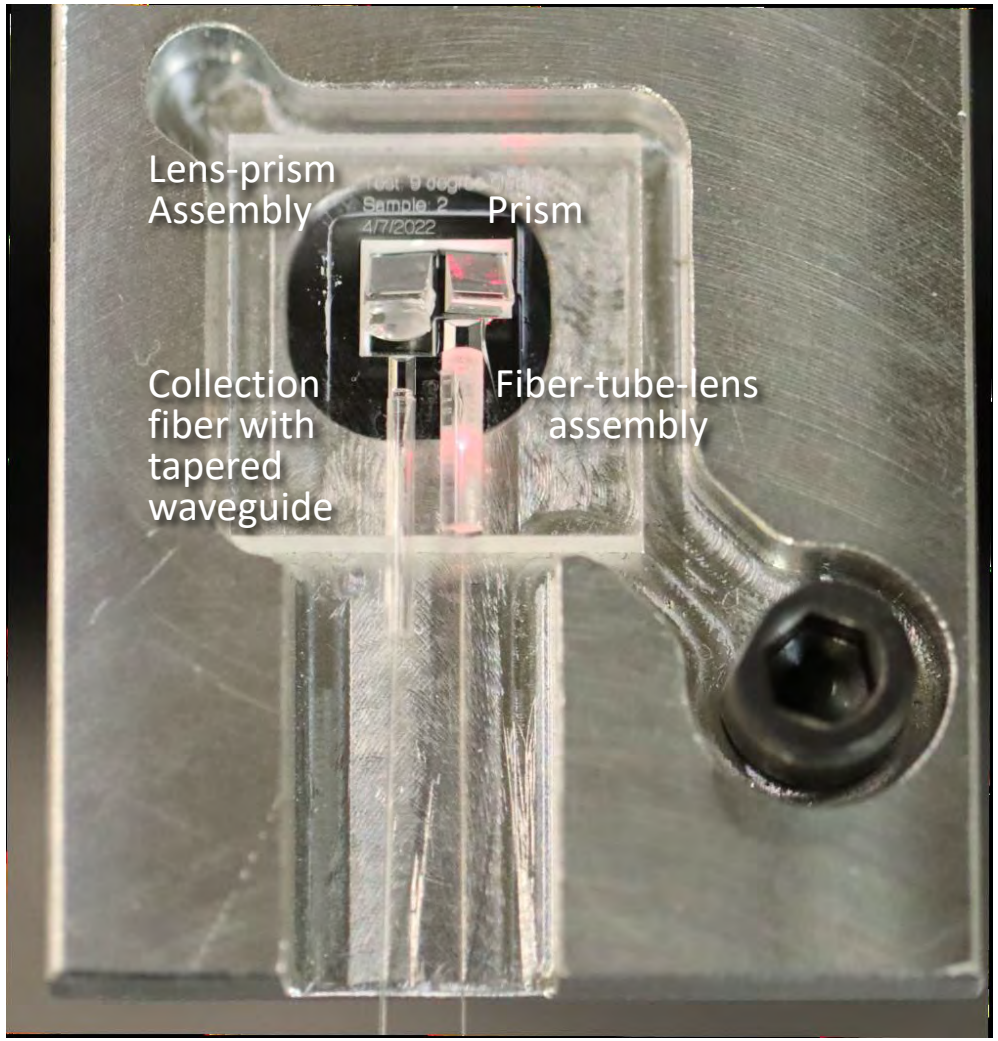
Extramural Project - DE-FE0031826 – Clemson University

Project Overall Goal

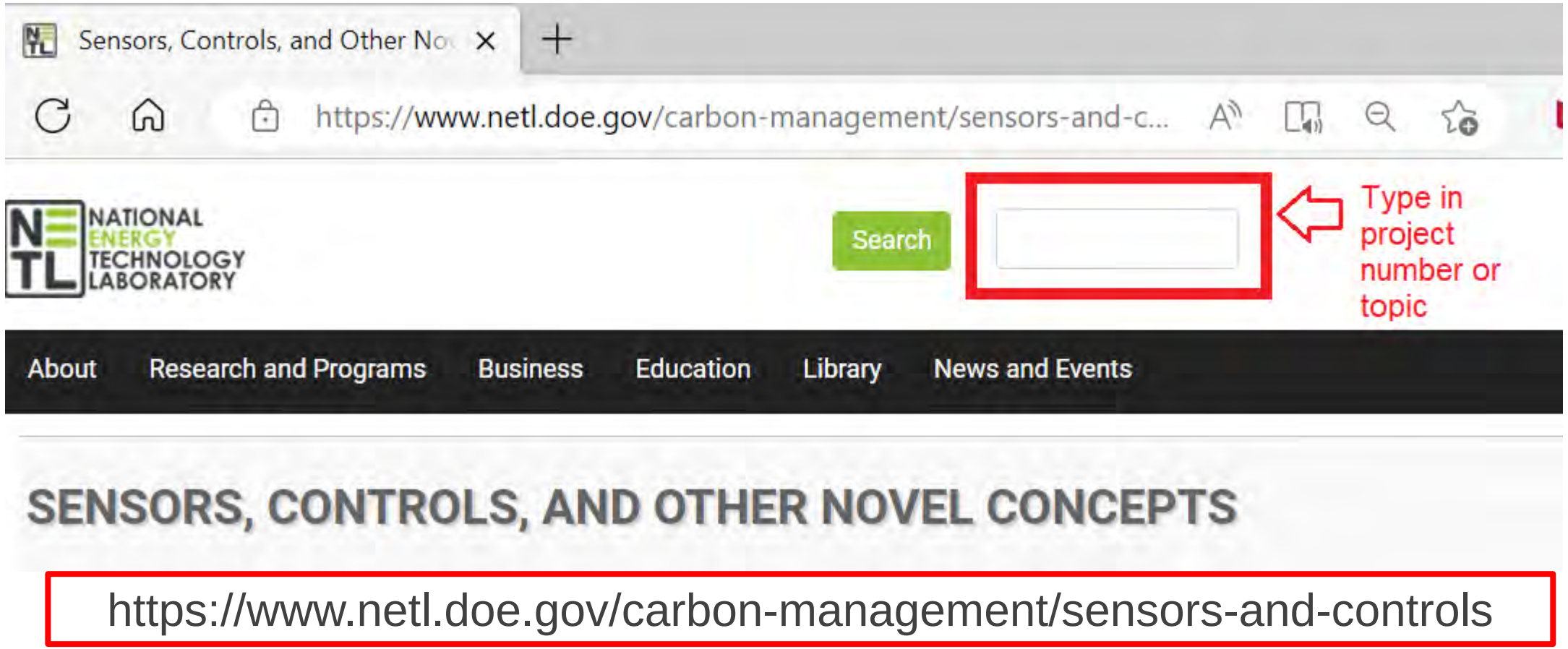
- To design, additively manufacture, and test the circumferentially installed sensor modules for in situ monitoring the temperature, pressure and blade tip timing in turbines.

Proposed Approach

- **Design** optical temperature, pressure, and blade tip timing/clearance sensor modules
- Develop processes to **additively manufacture** the designed optical sensor modules
- **Test and validate** the optical sensor modules **in laboratory** simulated environments
- **Test and evaluate** performance of the optical sensor modules **in an industrial scale test facility**



Learn More about FECM S&C Projects



https://www.netl.doe.gov/carbon-management/sensors-and-controls

Or type “NETL sensors and controls” into a search engine

Summary

- Continuing to make progress on key sensing technologies for FECM applications
  - Economic and robust optical fiber formulations and measurement systems
  - Development of compact prototypes for Raman gas analyzer, LIBS, VLC
  - Ultrafast laser measurement techniques for distributed gas/temp sensing
- Unique control strategies being developed to accelerate technology development and allow for controls improvement in new or existing facilities
- Developing next-generation sensing technologies using quantum sensing and machine learning approach

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Thank You

Energy.gov/fecm

https://www.netl.doe.gov/carbon-management/sensors-and-controls