Development of a Ceramic Coaxial Cable Sensor-Based System for Long-Term Down Hole CO2 Sequestration Monitoring

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Title

Robust Ceramic Coaxial Cable Down-Hole Sensors for Long-Term In Situ Monitoring of Geologic CO2 Injection and Storage

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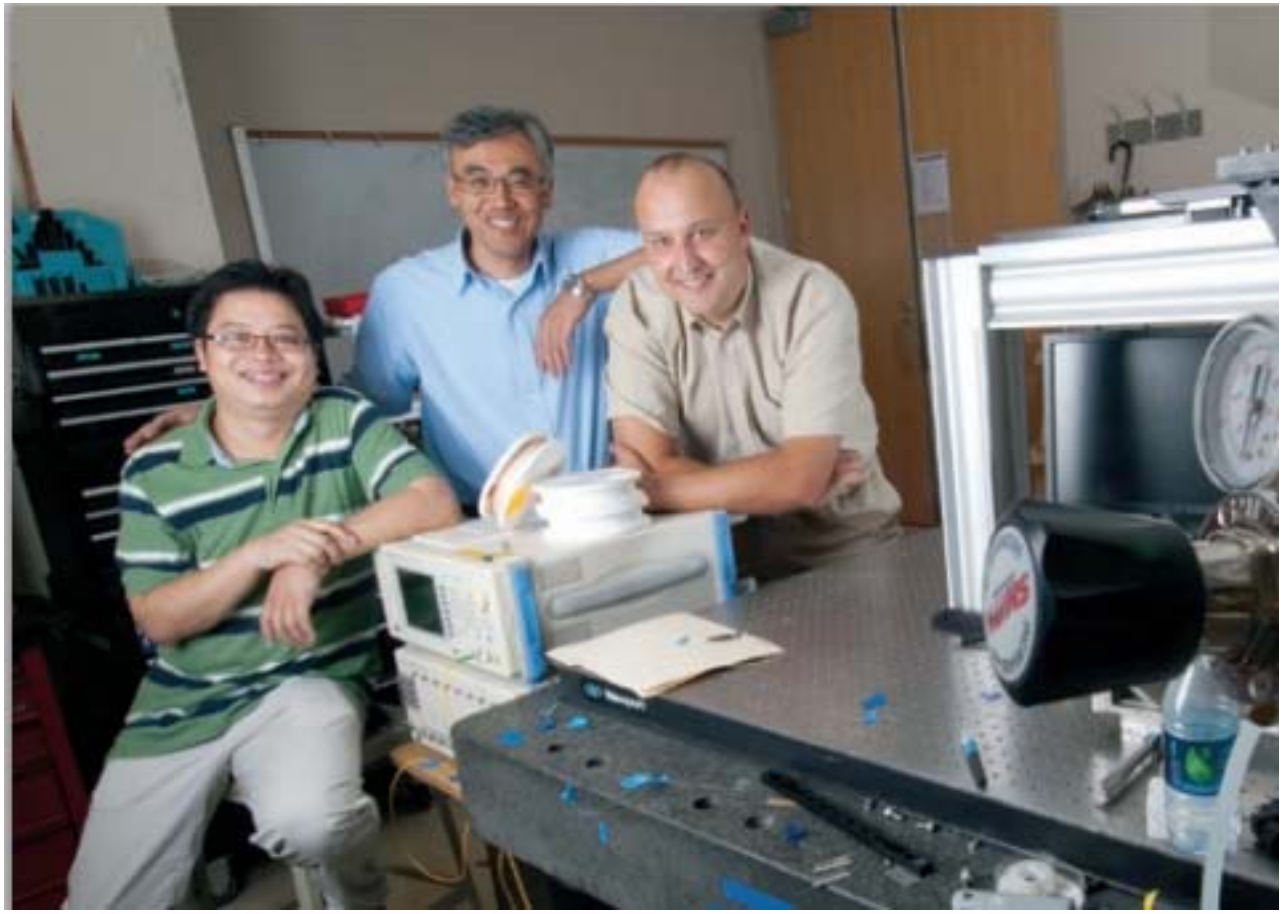
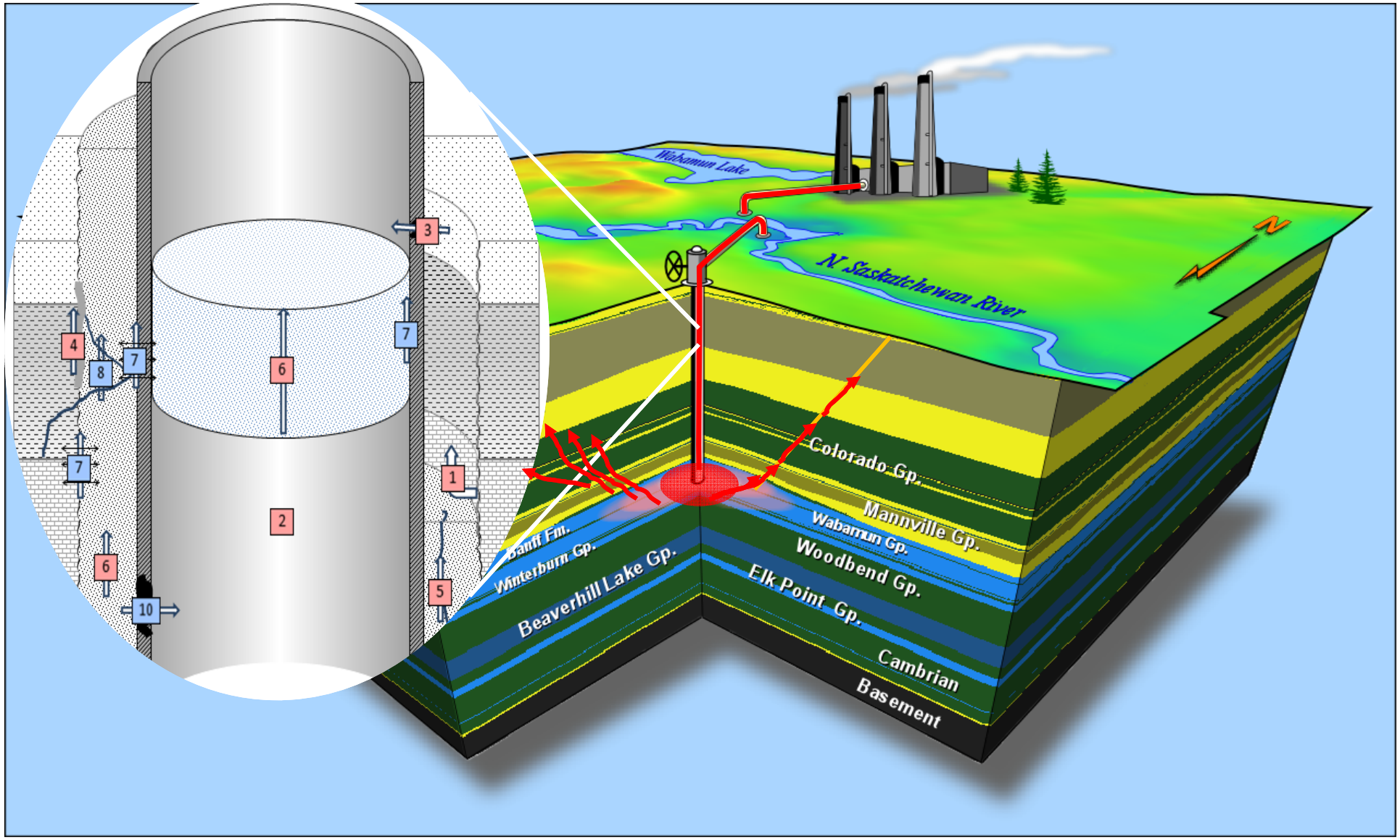


Outline

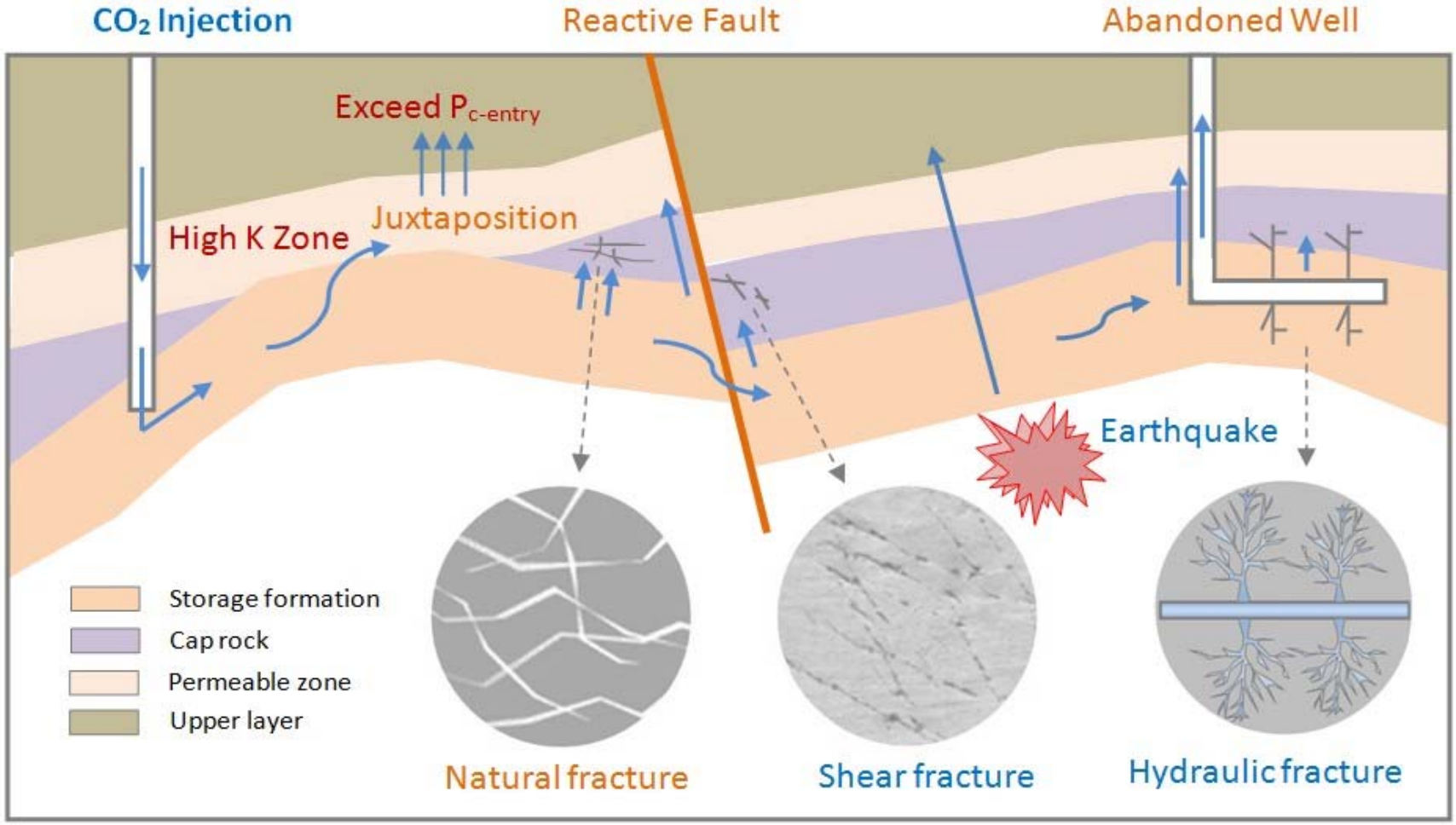
- Long term CO2 injection integrity monitoring – problem statement
- Main objective to demonstrate and develop a novel, robust, down hole sensing technology for in-situ monitoring
  - by developing strain, temperature,
  - and pressure sensors
  - as a distributed sensor system
  - that can integrate the sensor data with models.

CO_2 Sequestration monitoring



Source: Wabamun CO_2 sequestration project - WASP

Potential leakage pathways of CO_2



Matrix
- Capillary entry pressure
- Seal permeability
- Pressure seals
- High permeability zones

Structural
- Flow on faults
- Flow on fractures
- Flow between permeable zones due to juxtapositions

Geomechanics
- Hydraulic fracturing
- Creation of shear fractures
- Earth quake release

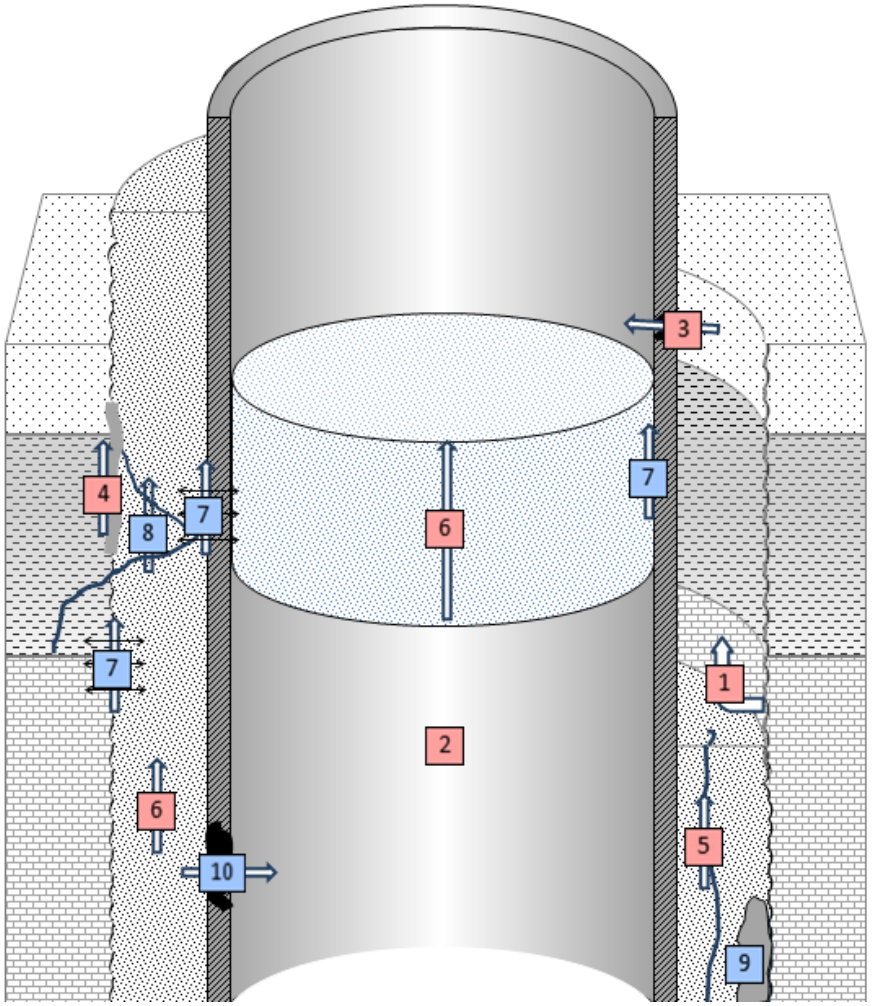
Wellbore Leakage

PRIMARY

1. Incomplete annular cementing job, doesn't reach seal layer
2. Lack of cement plug or permanent packer
3. Failure of the casing by burst or collapse
4. Poor bonding caused by mudcake
5. Channeling in the cement
6. Primary permeability in cement sheath or cement plug

SECONDARY

7. De-bonding due to tensile stress on casing-cement-formation boundaries
8. Fractures in cement and formation
9. Chemical dissolution and carbonation of cement
10. Wear or corrosion of the casing



Long term CO_2 injection integrity monitoring – problem statement

- **Background:**
  - Subsurface geologic formations offer a potential location for long-term storage of CO2.
  - Achieve the goal to account for 99% of the injected CO2 requires advanced monitoring technology to optimize the injection processes and forecast the fate of the injected CO2
- **Status:**
  - Due to the complexity, no single data type is sufficient by itself; different monitoring and characterization approaches are deemed to be necessary.
  - In situ down-hole monitoring of state parameters (e.g., pressure, temperature, etc.) provides critical and direct data points to validate the models, optimize the injection scheme, detect leakage and track the plume.
  - Current down-hole sensors are insufficient to meet the reliability and cost requirements.

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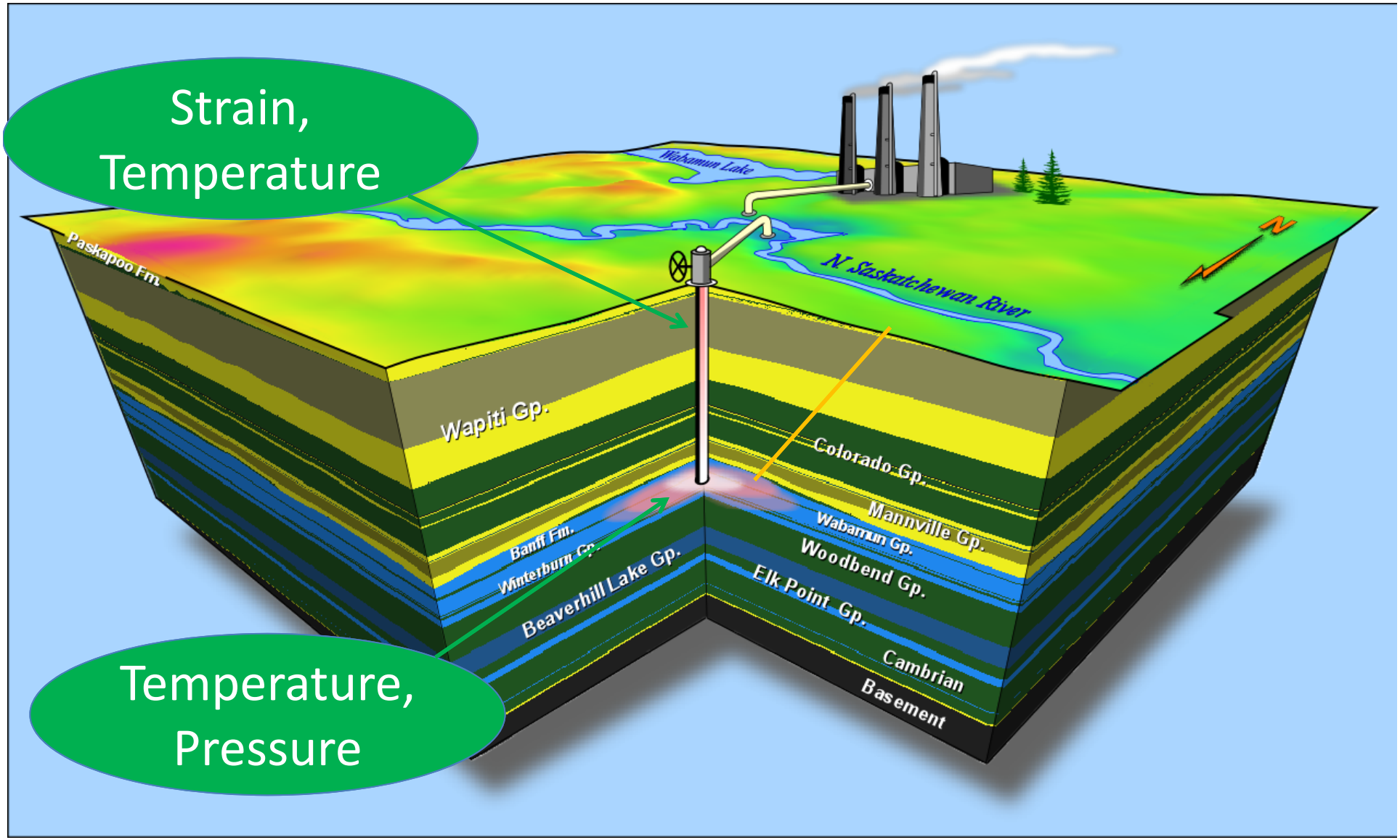
The goal is to develop a monitoring system combined for the wellbore and the reservoir



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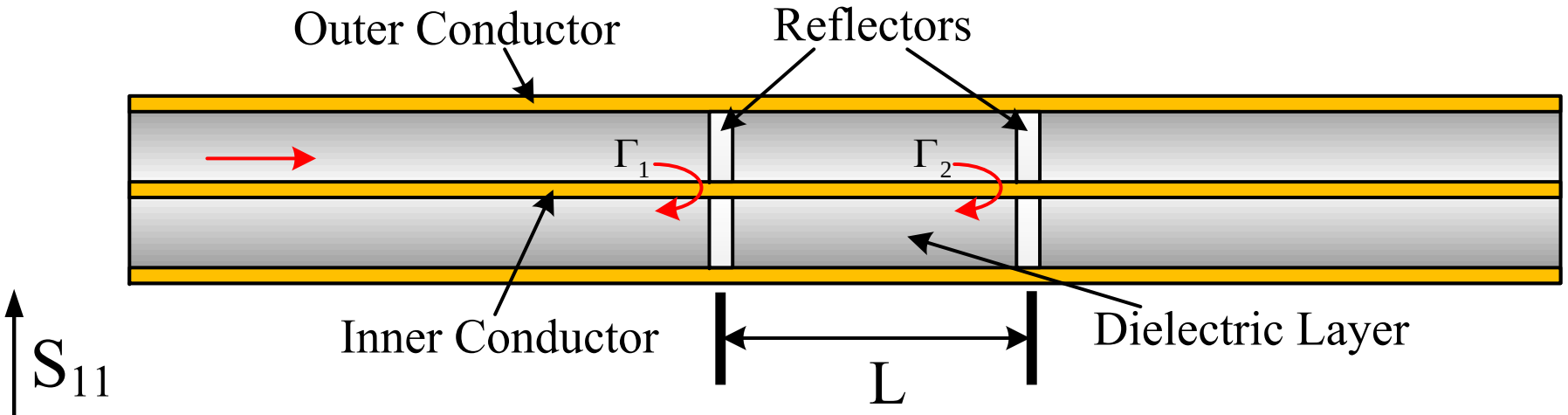
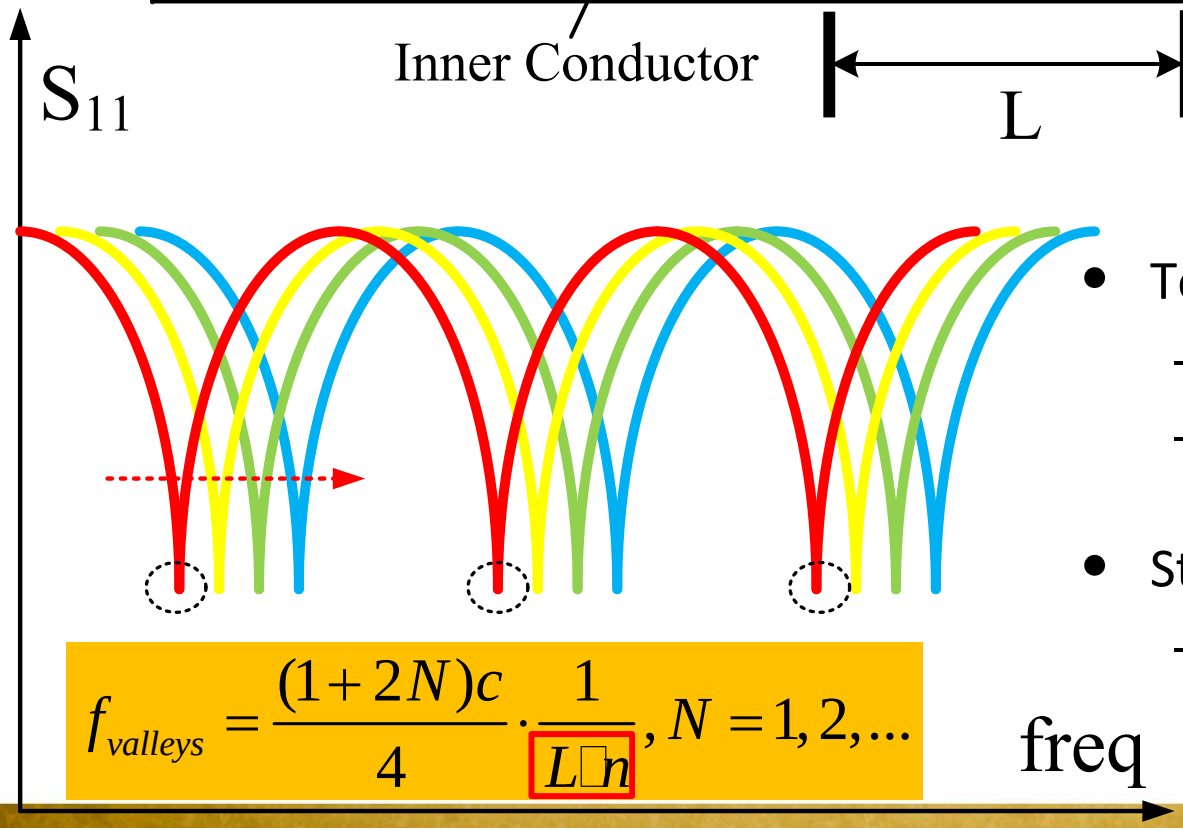
CC-FPI Sensor Principle

Coaxial Cable Fabry-Perot Interferometer (FPI)

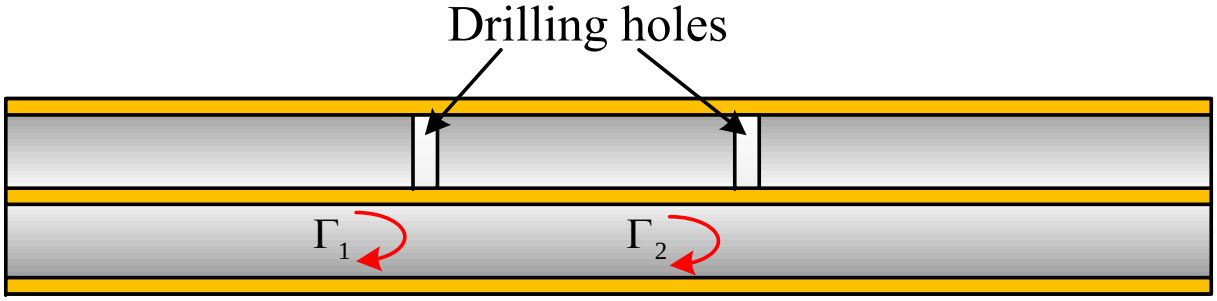


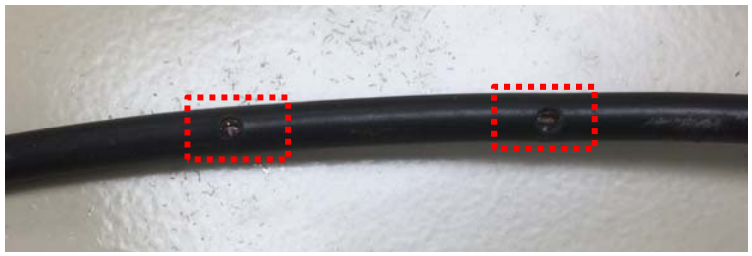


$$f_{valleys} = \frac{(1+2N)c}{4} \cdot \frac{1}{L\square n}, N = 1,2,\ldots$$

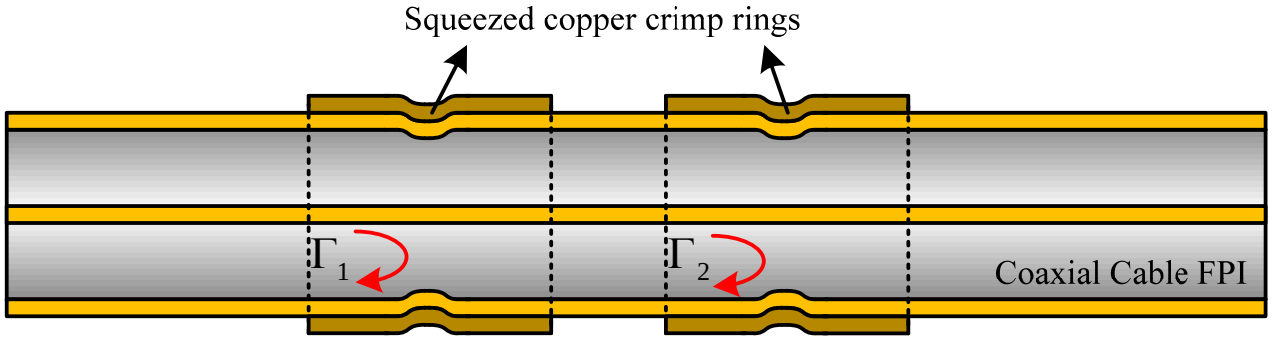
- Temperature sensing
  - Dielectric thermal effect
  - Thermal expansion
- Strain sensing
  - Length elongation

CCFPI Temperature Sensors



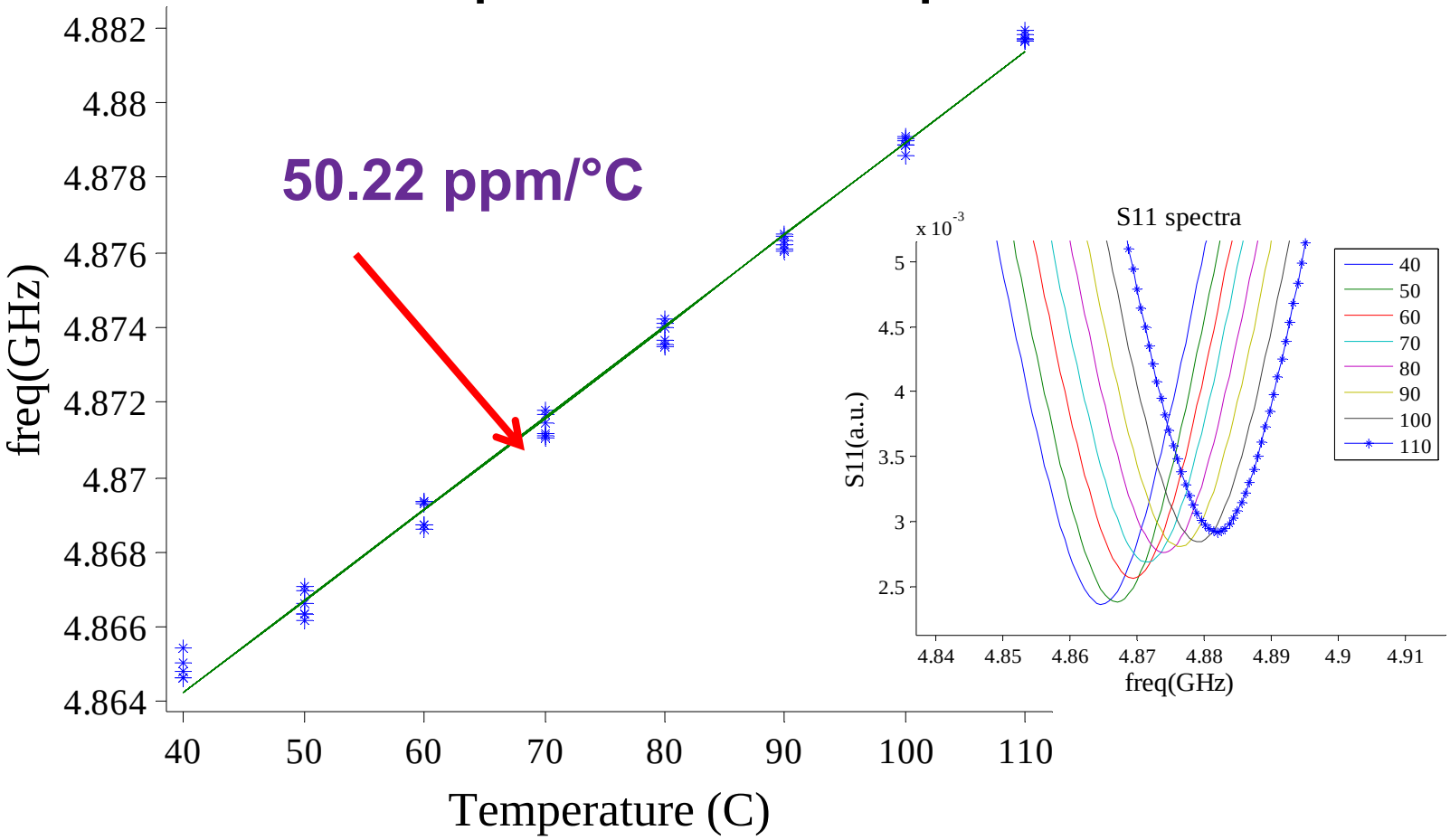


- Half-way holes
  - Unstable structure
  - Package issue



- Crimp ferrule
  - Easy fabrication
  - No further packaging needed

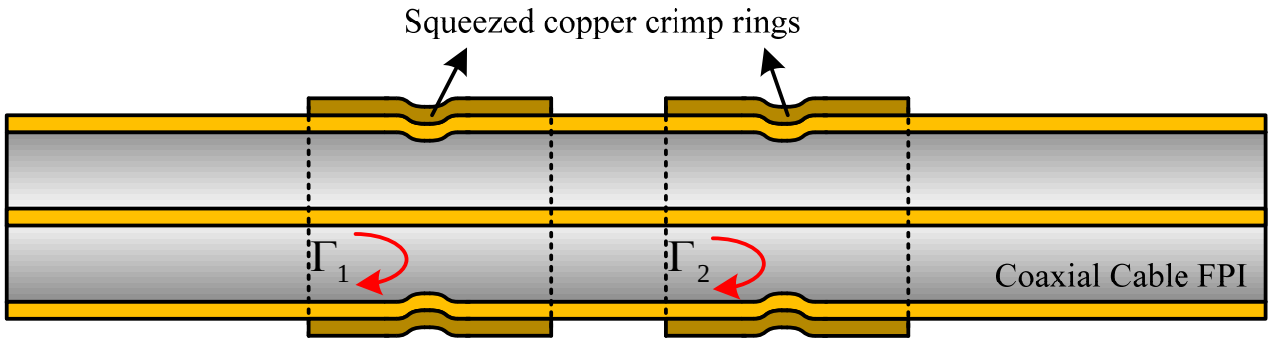
Temperature Response



- Repeatable linear temperature response with high sensitivity

CCFPI Strain Sensors

Strain sensors could be designed in the same method of temperature sensors



Strain sensor

$$\frac{\Delta f_N}{f_N} = \left(\frac{P_{eff}}{2} - 1\right)\Delta\varepsilon - \left(\frac{\alpha_{TCK}}{2} + \alpha_{CTE}\right)\Delta T$$

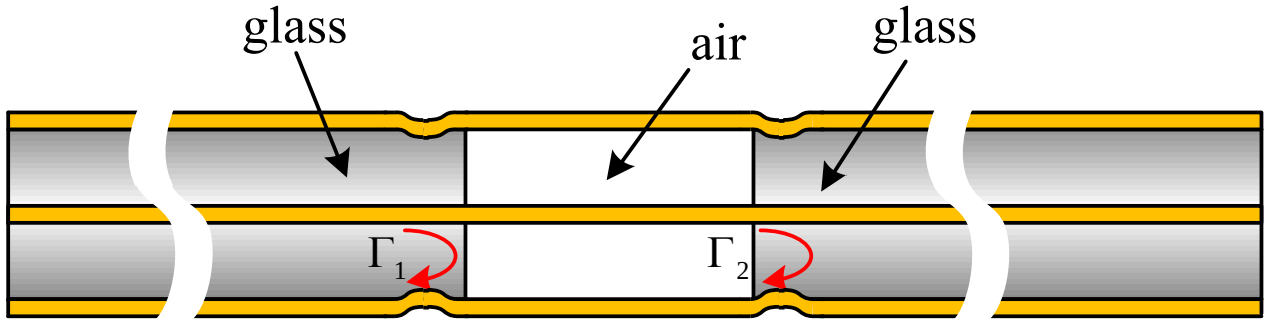
Temperature cross talk

Minimize the T cross talk

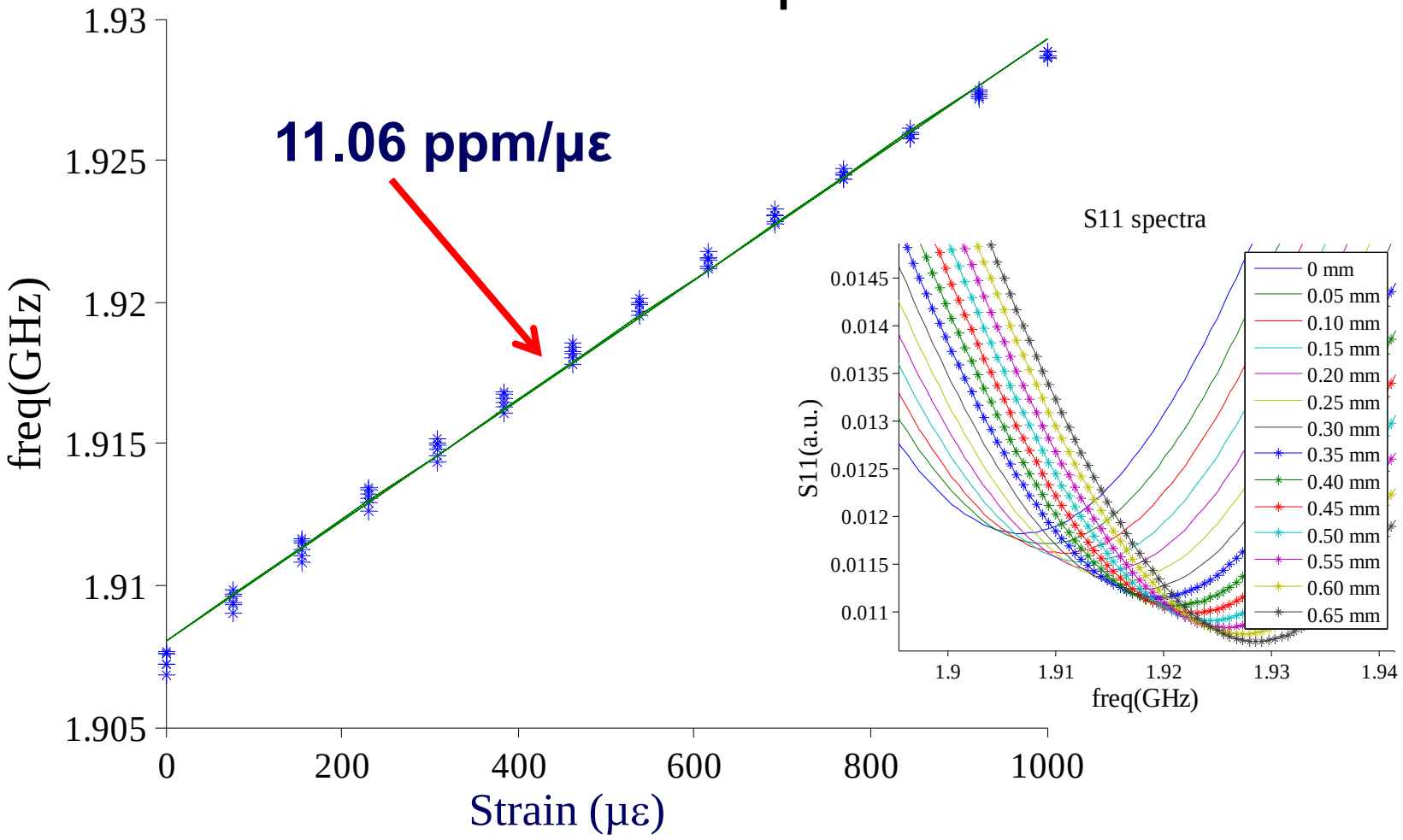
$$\frac{\Delta f_N}{f_N}\Big|_{crosstalk} = -\left(\frac{\alpha_{TCK}}{2} + \alpha_{CTE}\right)\Delta T$$

Use air cavity to minimize T-dependence of dielectric constant

Use glass to minimize thermal expansion

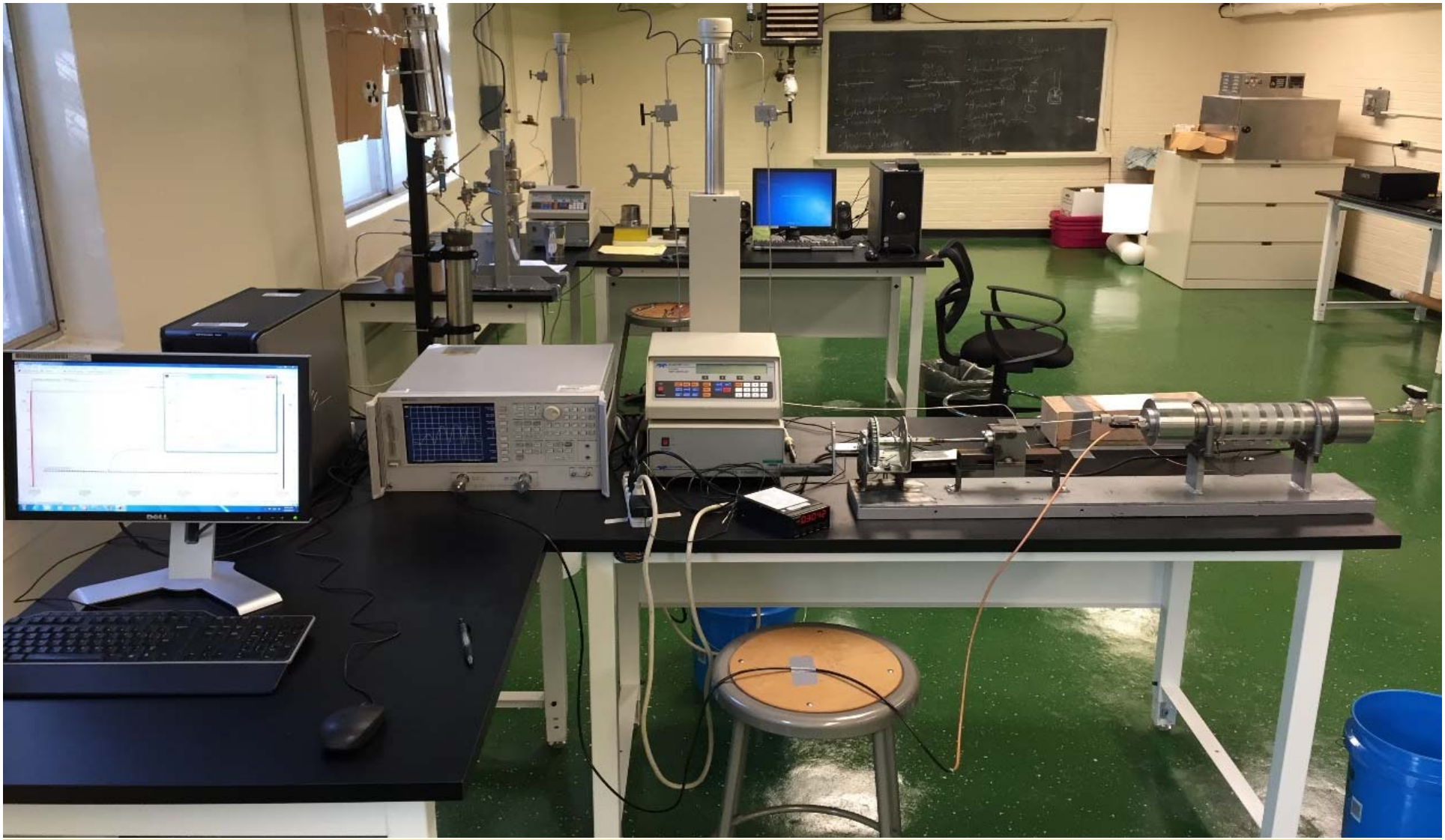


Strain Response

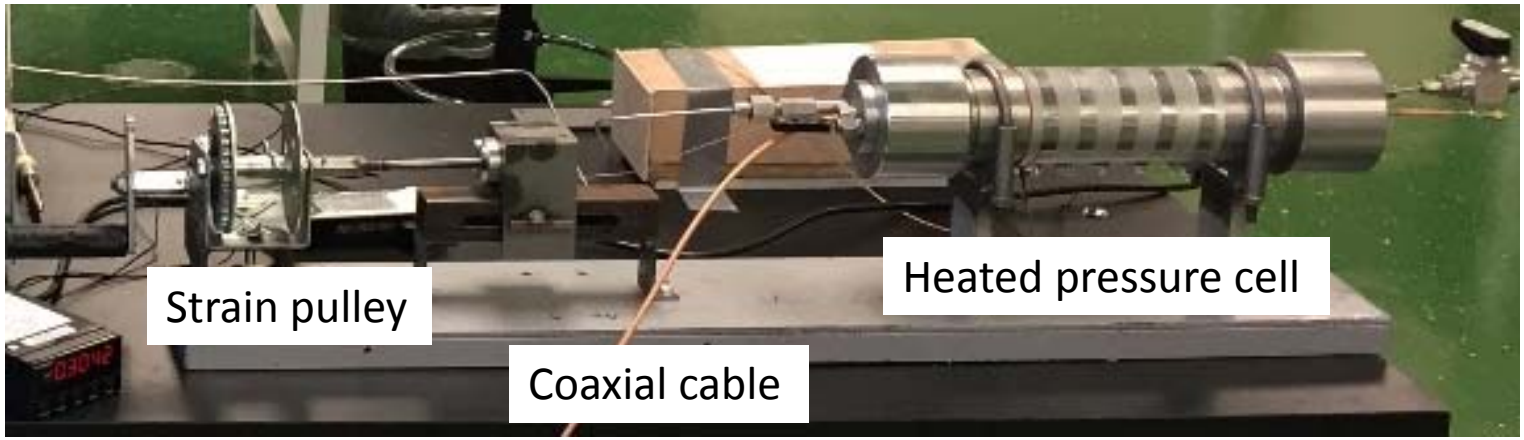


Temperature cross talk is reduced to 20 ppm/°C (or 2με/°C), which is very close to the theoretical minimum of 16.6 ppm/°C (limited by the CTE of copper)

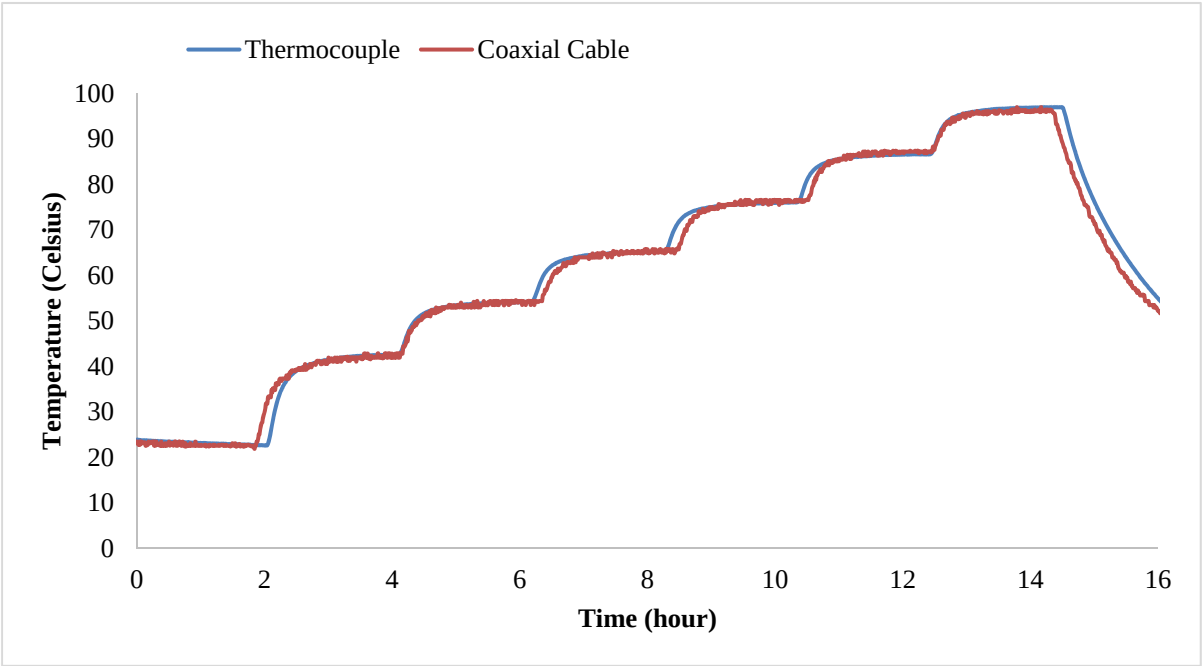
Temperature and strain sensor testing with combined loads



Testing under combined loads



Test of temperature censor under 1000 psi pressure



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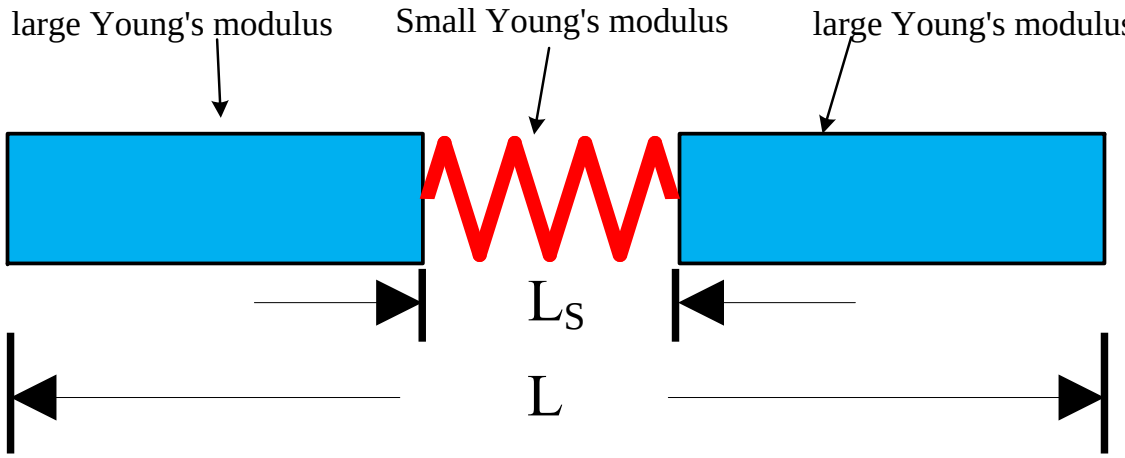
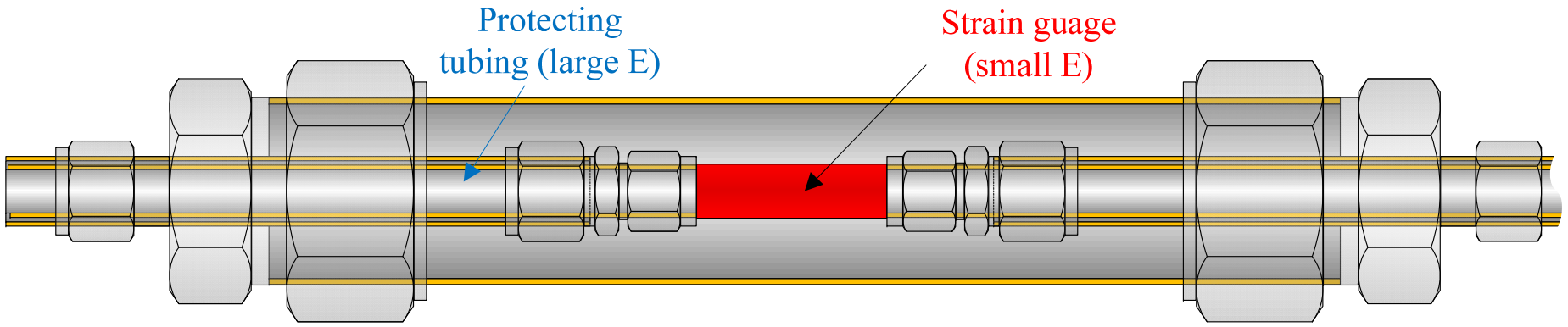
CCFPI Pressure Sensor

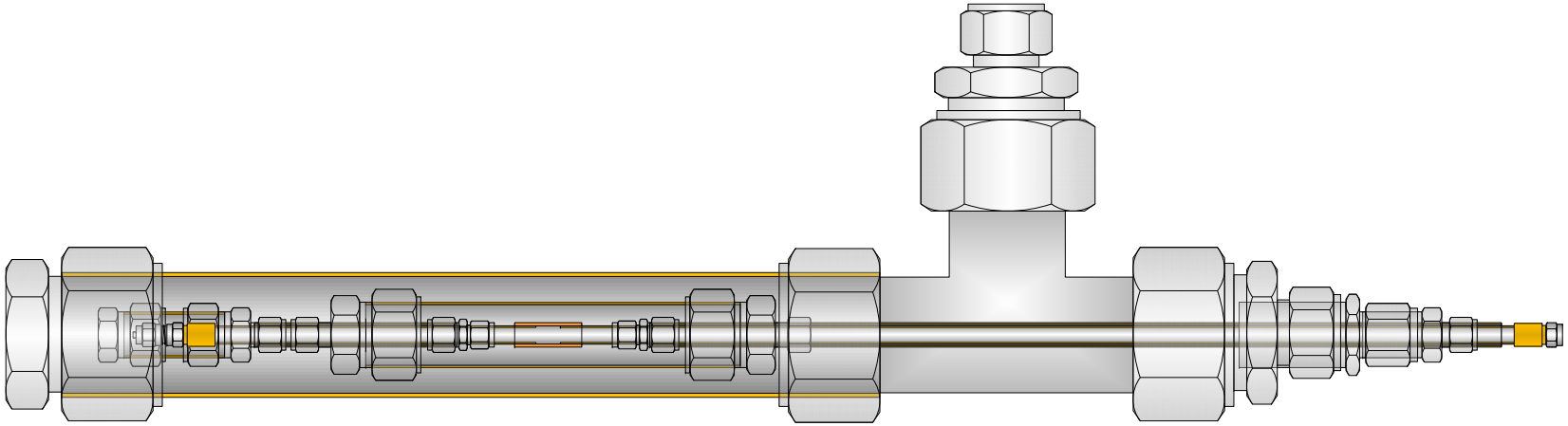


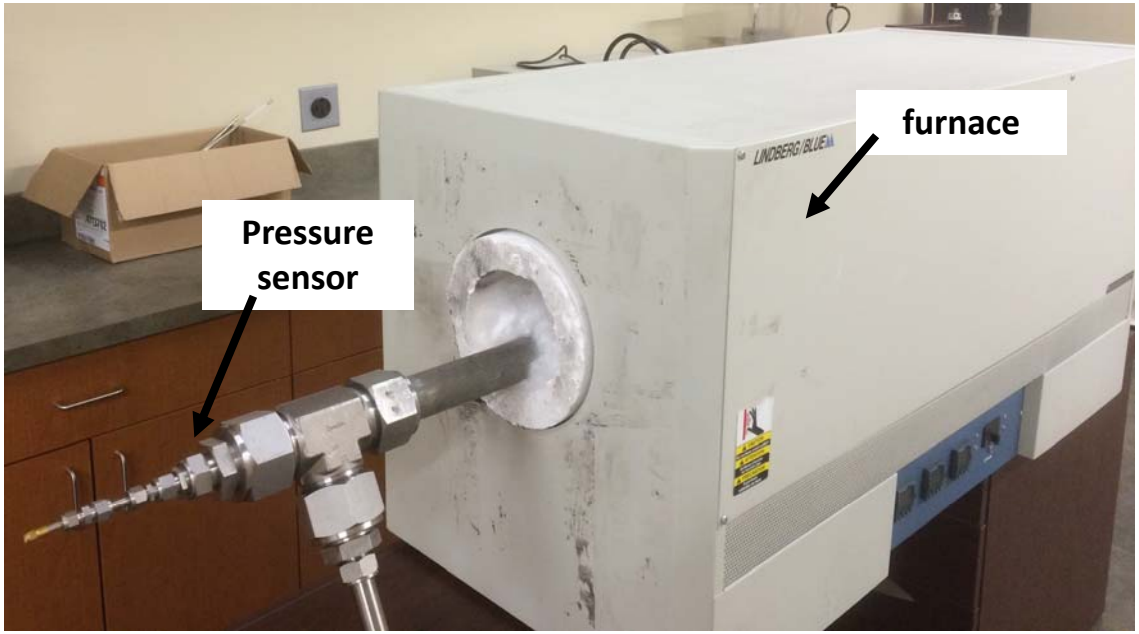
$$A = \frac{L}{L_S}$$

The elongation almost concentrates on the part with a small Young's modulus. The pressure induced strain can be amplified

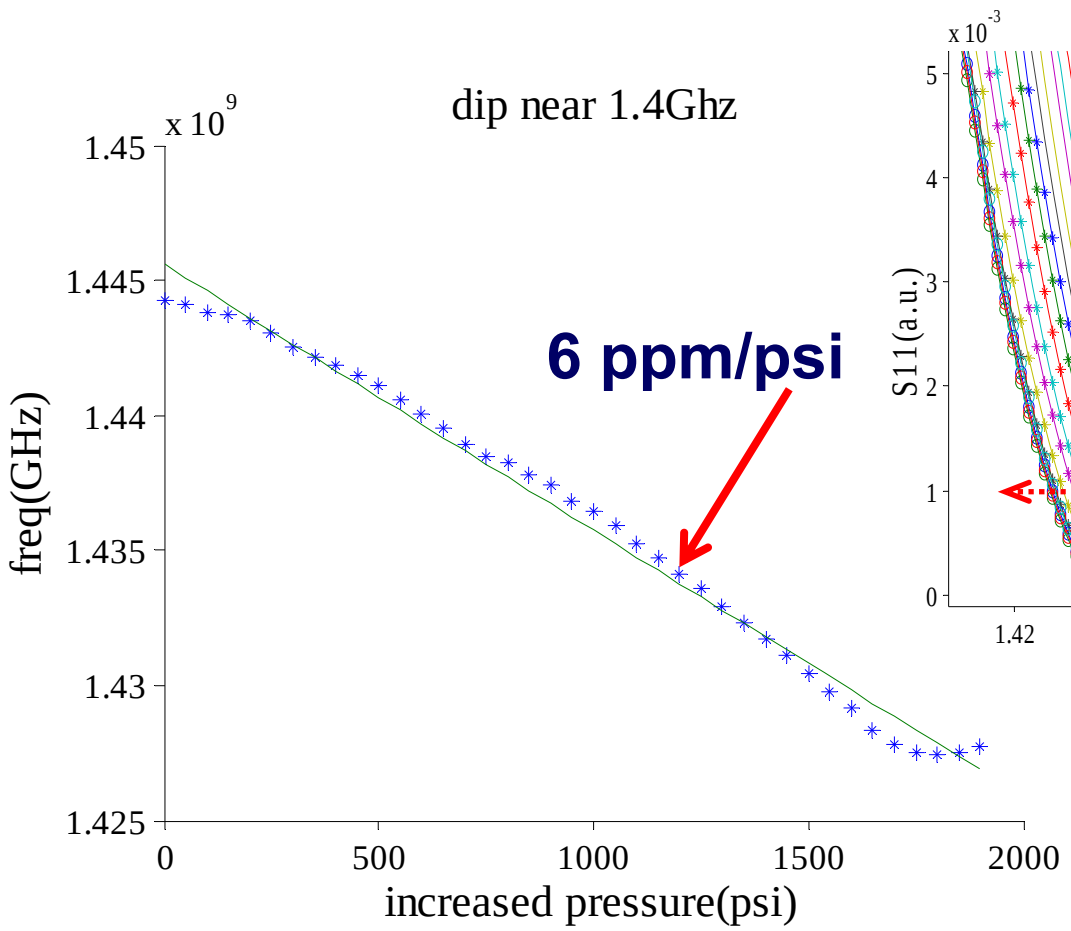


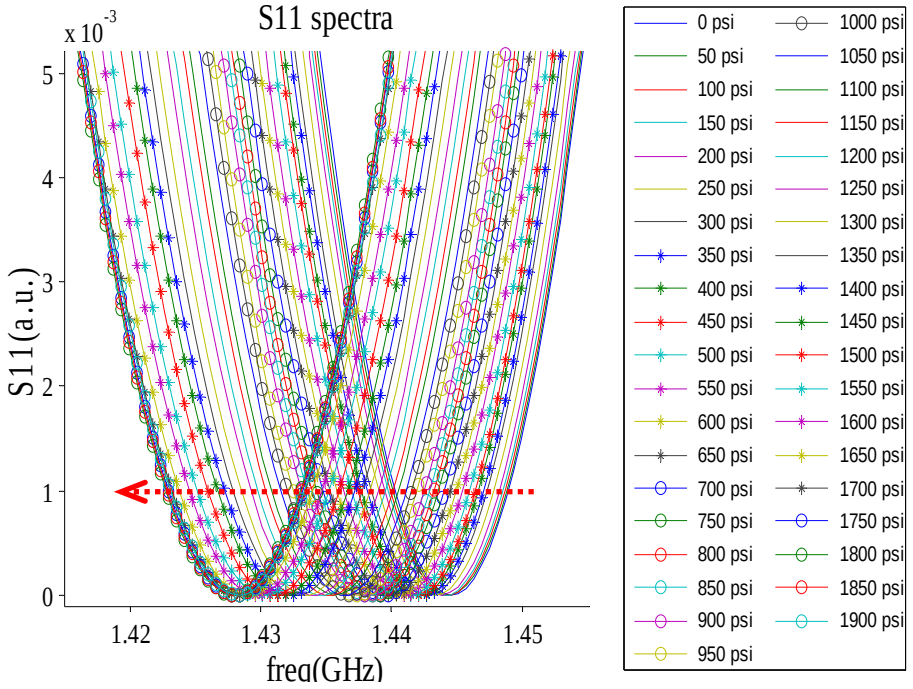
Pressure Test Facility





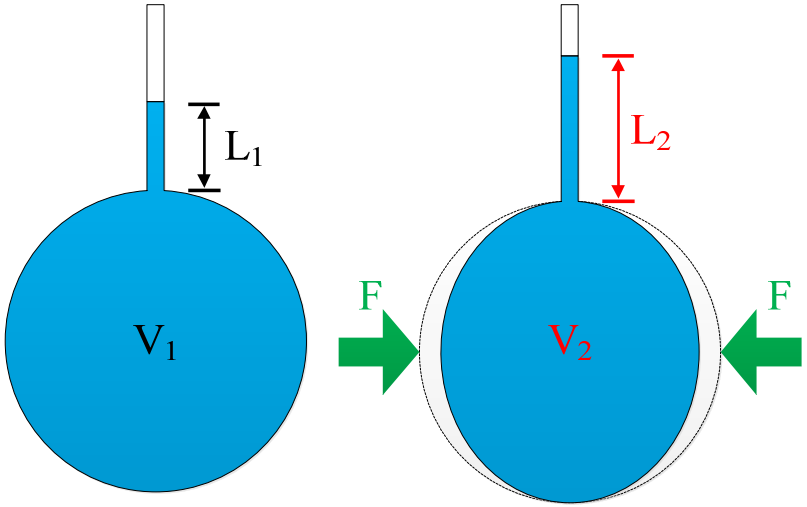
Pressure Response





- Nonlinear responses
- Sensitivity is not high enough
- Temperature cross talk is difficult to compensate

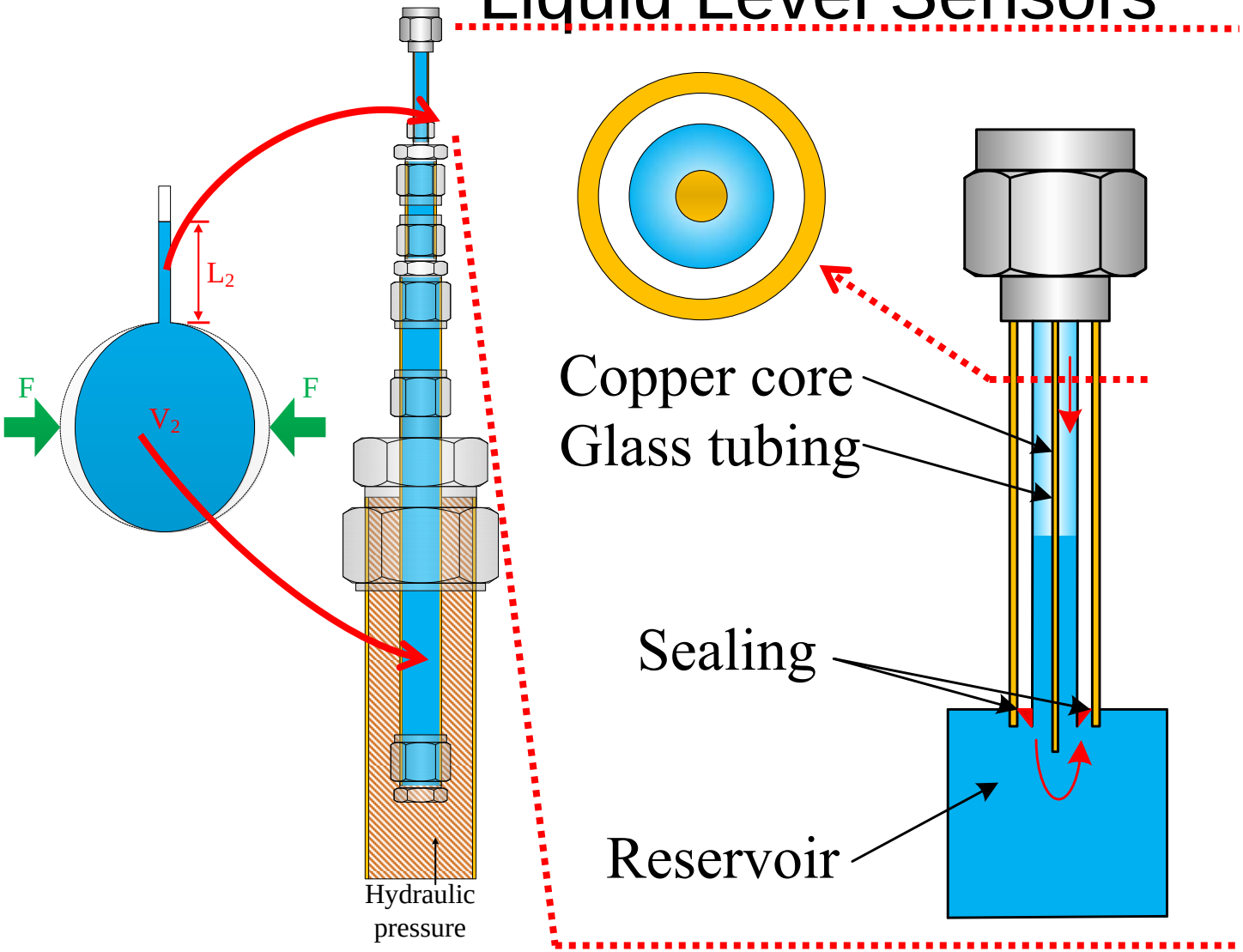
Fluidic Based Pressure Sensors



Amplification by volume effort: Small volume change can be transferred to large liquid level change

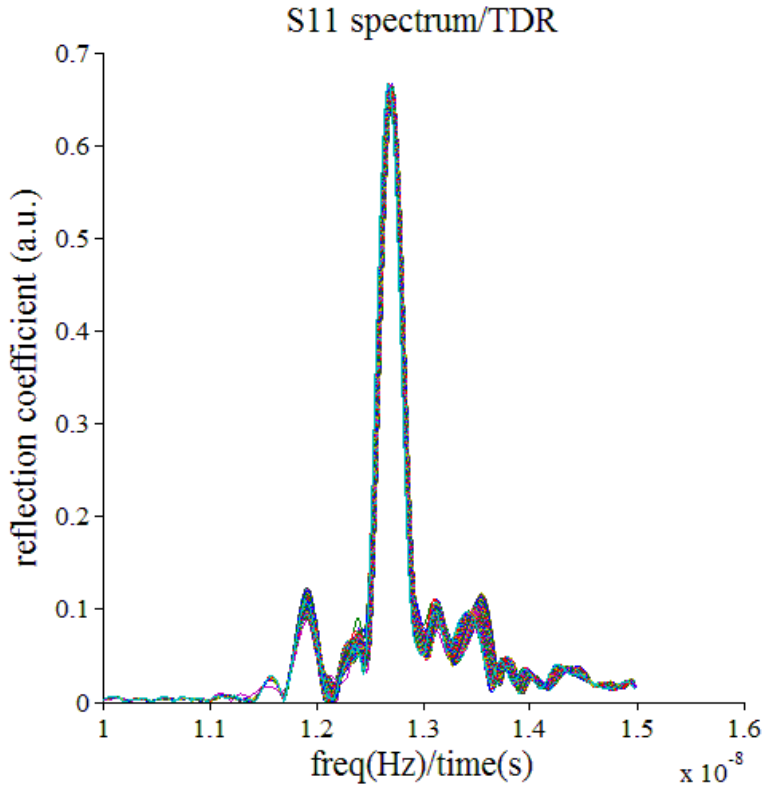
- Linear response
- Sensitivity is high
- Robustness because of the protection reservoir

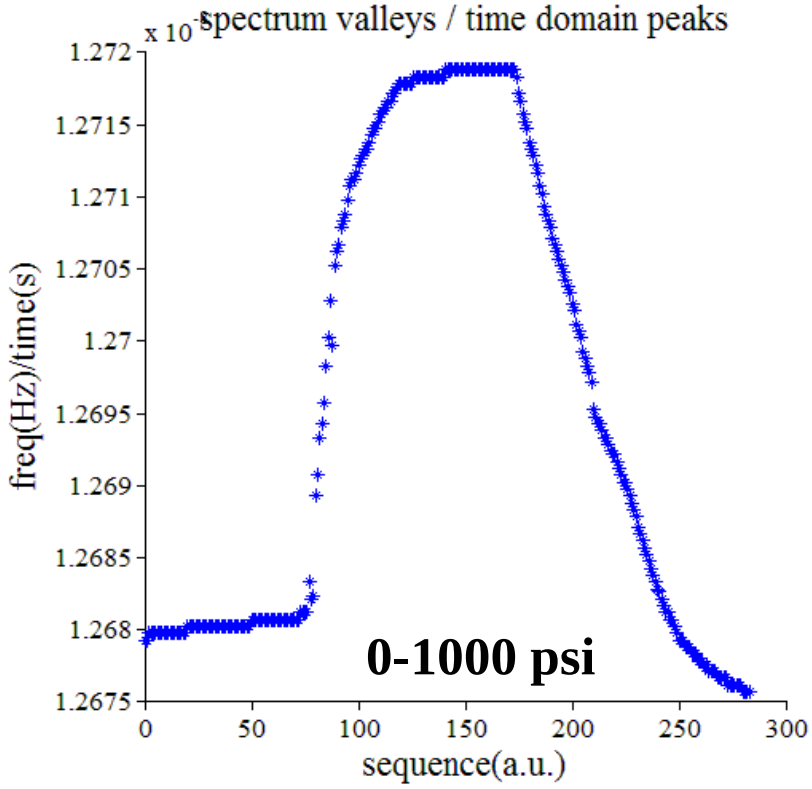
Liquid Level Sensors



Pressure Response

- **The volume effect based amplification significantly improved the sensitivity**





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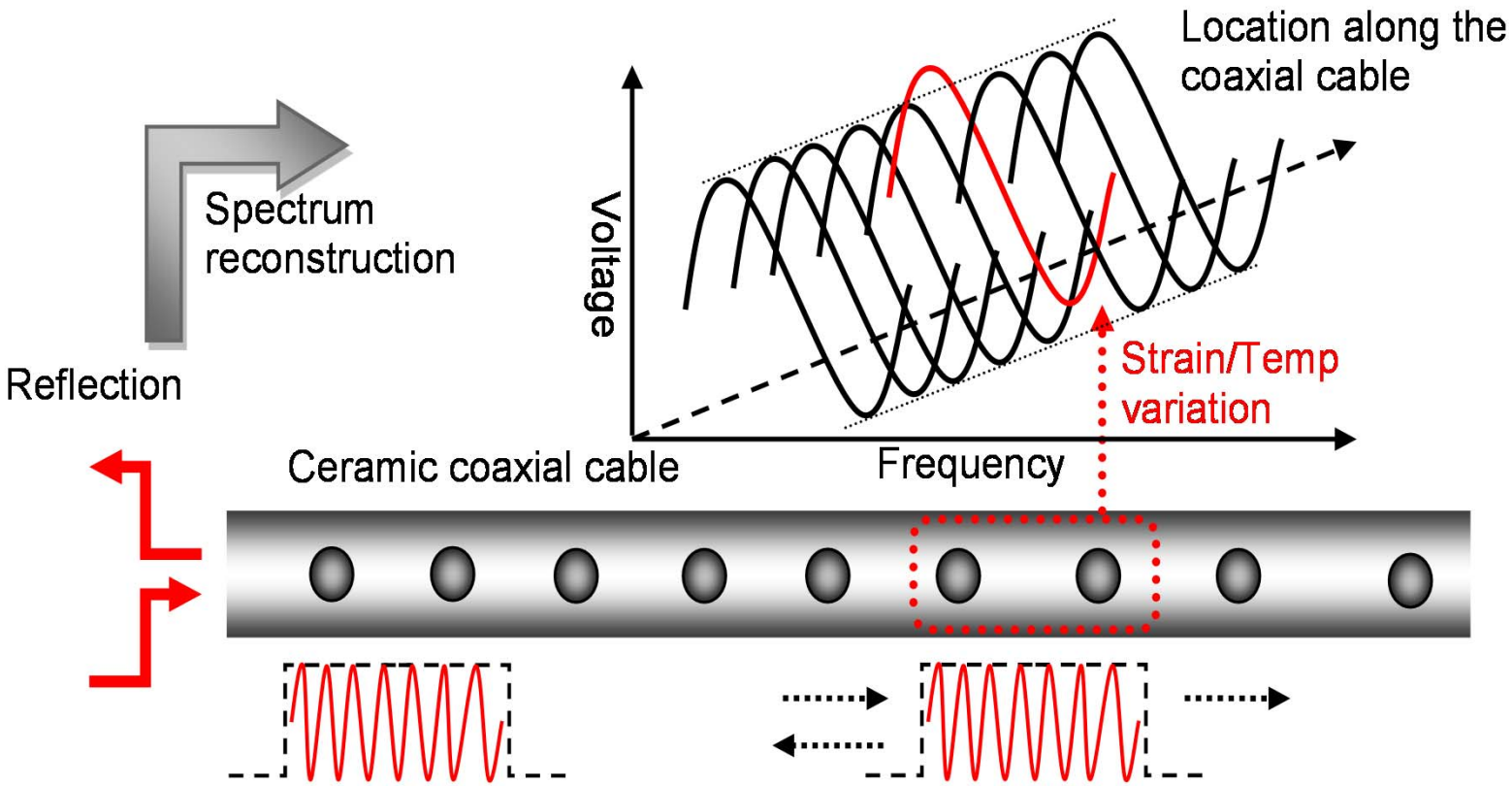
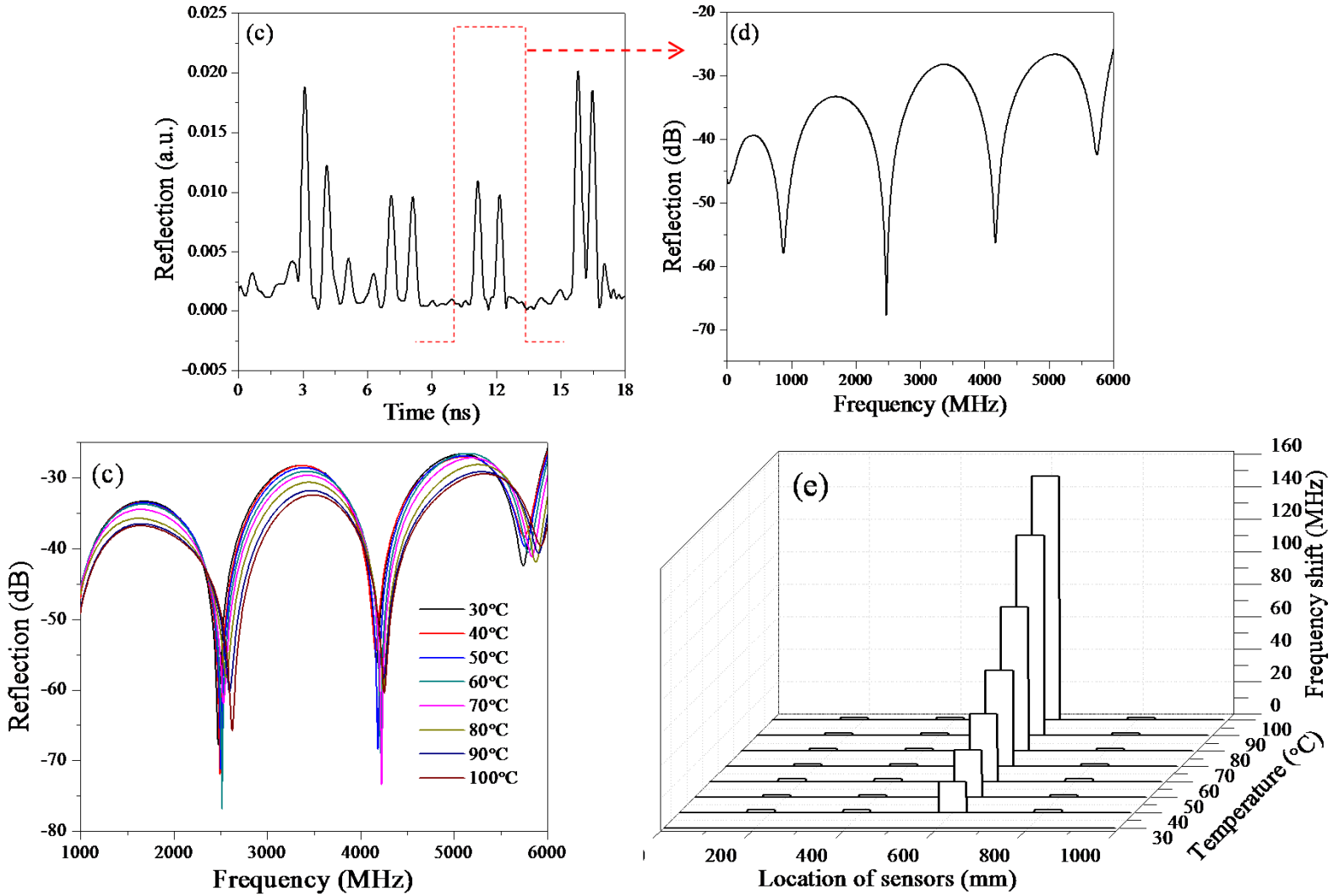
Distributed Coaxial Cable FPI



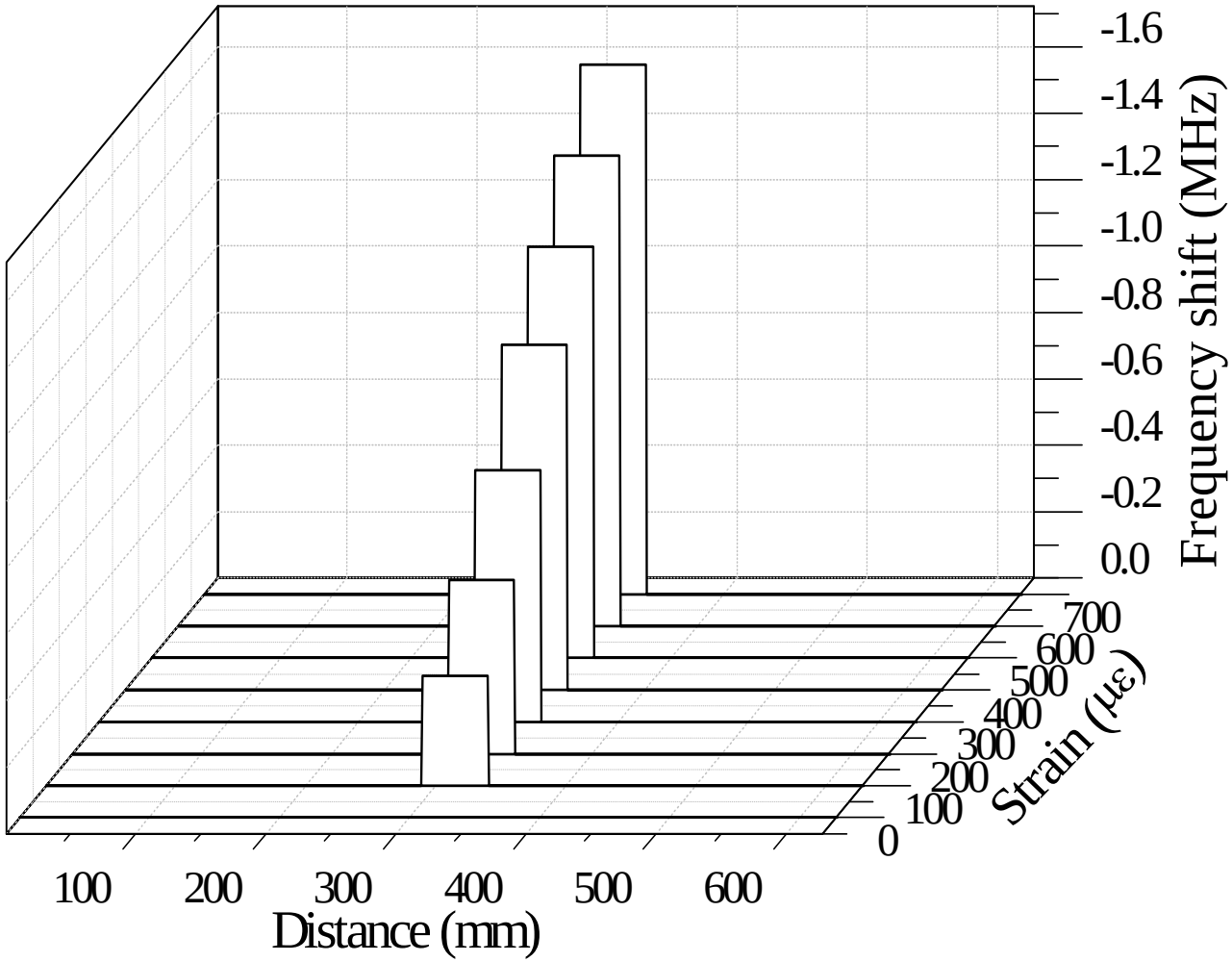
- Microwave can detect both amplitude and phase
- Frequency-Time-Frequency processing can isolate any individual sensor along the cable

Distributed T sensing



- **Successfully measured the temperature variations at the location of 600 – 650 mm.**

Distributed Strain Sensing



- **Successfully measured the strain applied at the location from 300 to 350mm**

Distributed strain sensor demo

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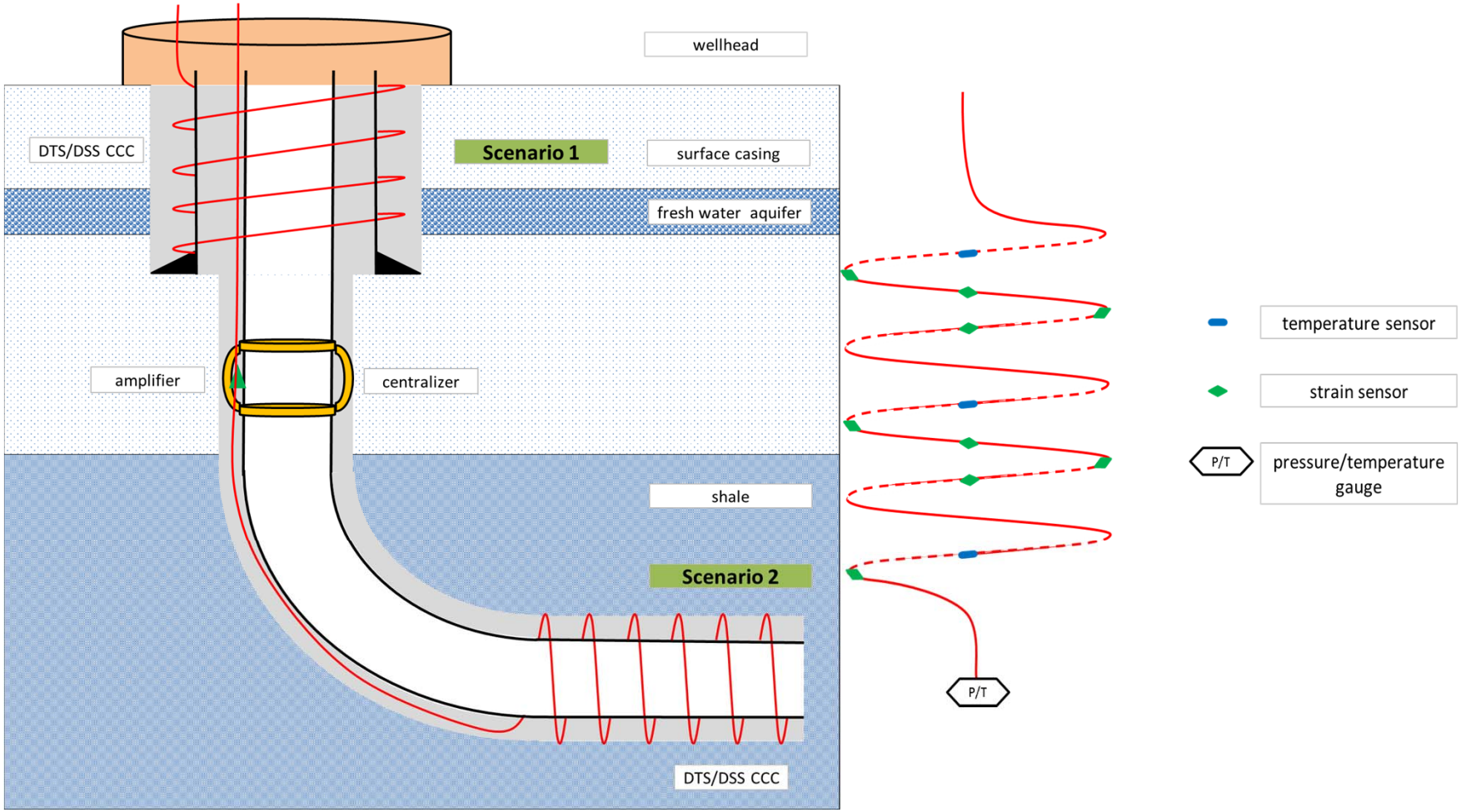
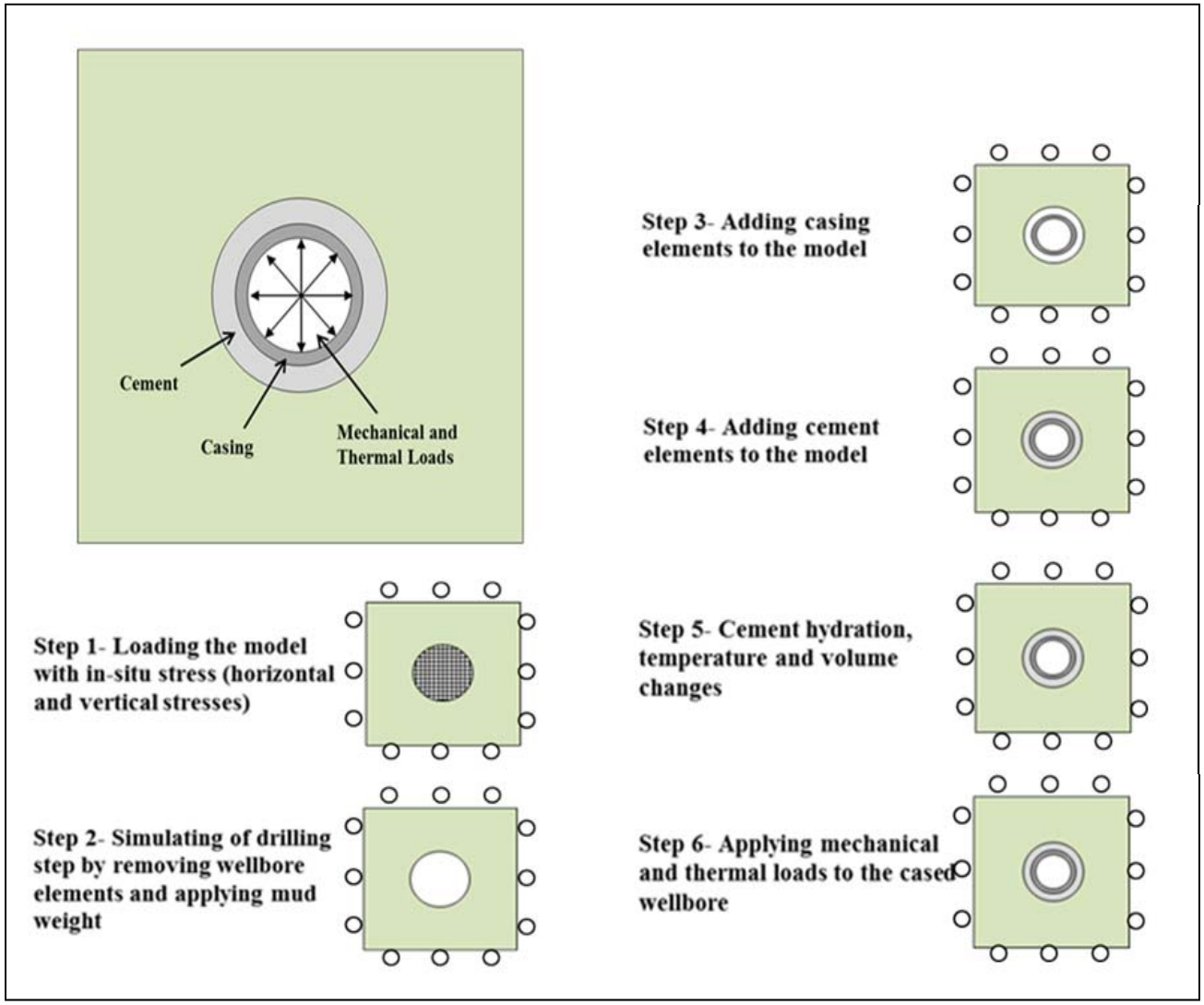
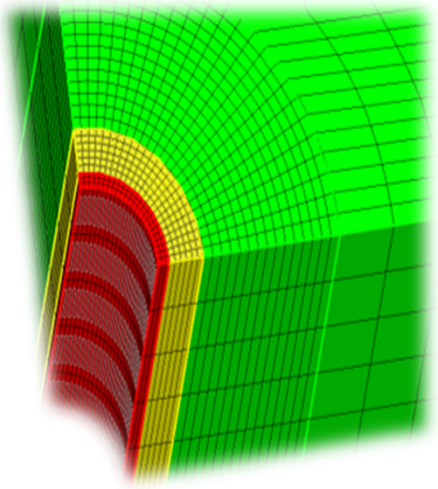
Coaxial cable sensing system deployment

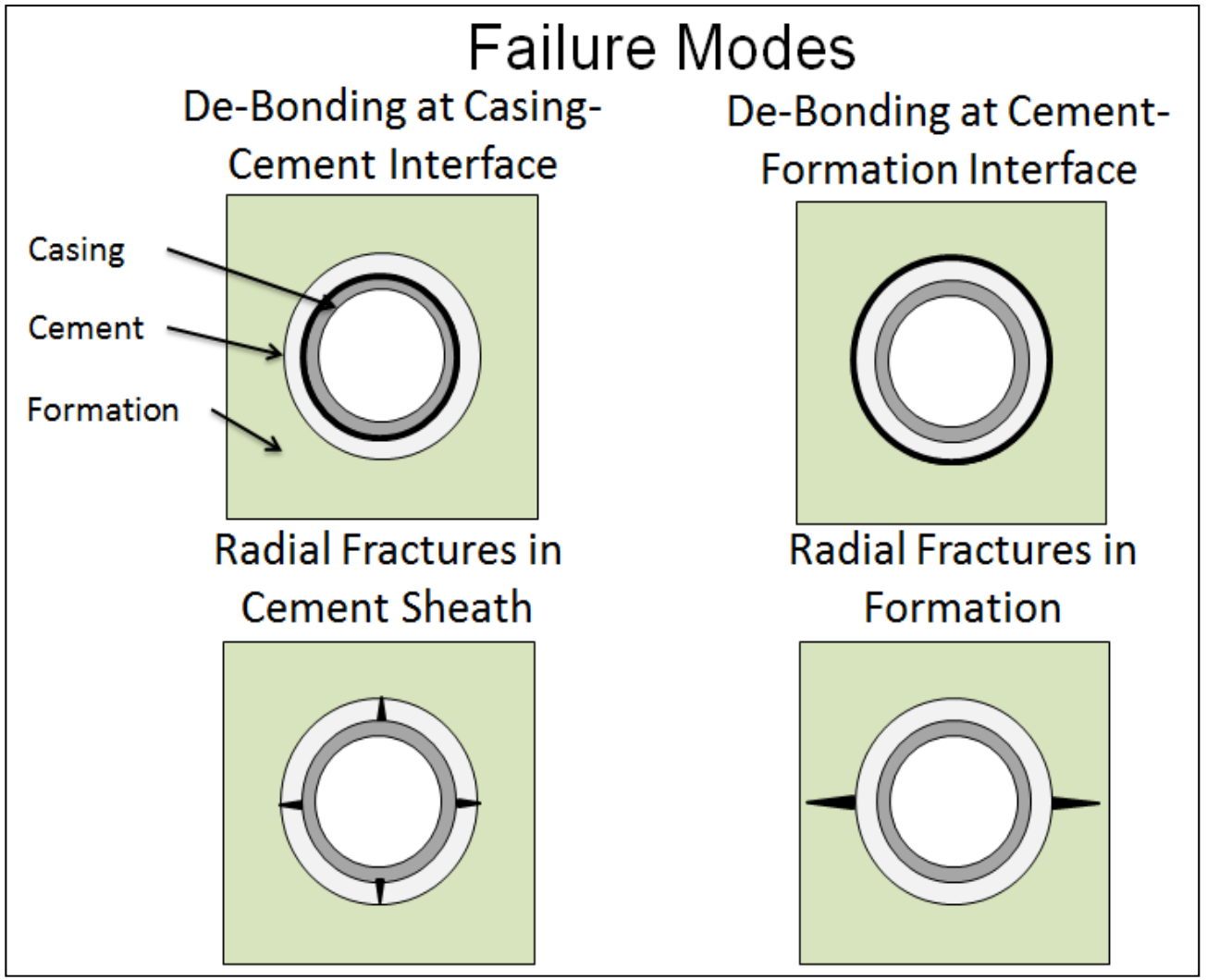


Mechanical wellbore integrity modeling





Failure Modes in the cement sheath



Summary

- Distributed strain and temperature rigid coaxial sensors for down hole conditions have been developed and tested at down-hole conditions
- The pressure sensor is developed and concept is proven during testing
- Distributed sensing concept using coaxial cable is validated
- Final year will focus on proof of concept of the integrated monitoring system