Sensing and Instrumentation for Nuclear Applications

Industrial perspectives on advanced sensors

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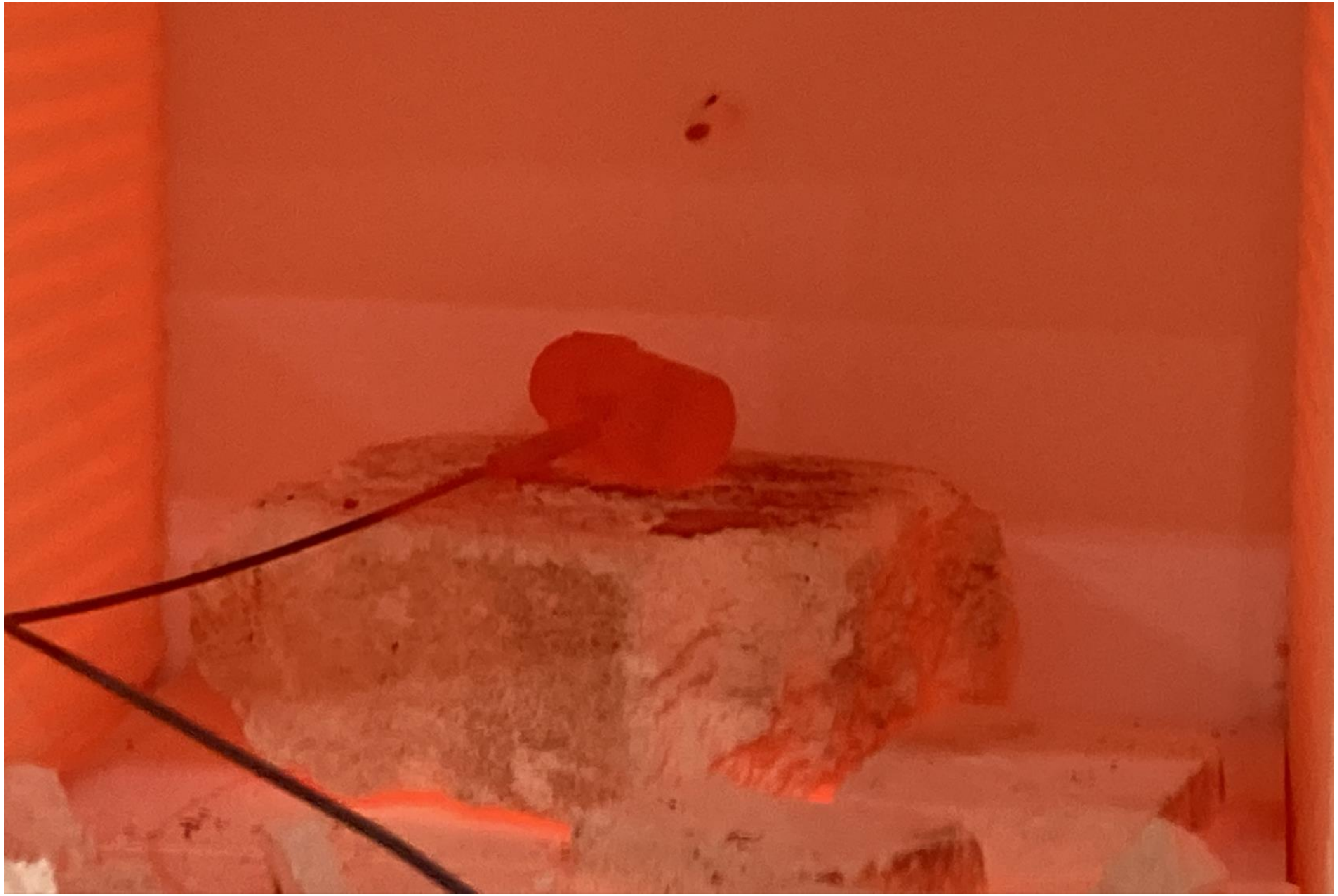
Sensor Technologies have Matured for Many Applications—*BUT*…



Evolving needs mean new sensor environments and better intel through more data

Plant Modernization; Trending more Data, Specificity, and Quality

Diagnostics & Maintenance

Process, Operation

Structural Integrity, Monitoring, Twinning

Safety, Reliability, Economy

Broad measurement, general interpretation:

E.g. Pressure, Temperature, Flow etc
>> inform plant output and control room settings

More mature technology, smaller development gaps, larger support community

Specific measurement, complex interpretation:

E.g. Wall thickness, Creep, Runtime Events etc.
>> Planning, maintenance, justification

More innovative technology, larger development gaps, smaller support community

Sensor Advancements are Important but not Trivial

- Many industries share similar sensing requirements
  - Harsh environments
  - Enhanced reliability and longevity
  - Power reduction and flexible data transmission
  - Measurement types
- Sensor development can take time and bring surprises!

Sensor advancements will require teamwork and industry commitment

EPRI

Sensors for Emerging Applications, & Applications for Emerging Sensors

	Measurand	Application Examples
I&C	Temperature	Core exit, in-core distribution, general I&C, safety, component history, event analysis
I&C	Pressure	General I&C, safety, component history, event analysis
I&C	Flow	General I&C, safety, regulatory
I&C	Chemistry	System health, maintenance strategy, event analysis, monitoring, operations adjustment, leak detection, asset protection, coolant health, adverse condition detection
I&C	Neutron monitoring	Safety, fuel integrity & security, tritium production monitoring
I&C	Fluid level monitoring	Coolant levels, confirmatory sensing
O&D	Leak detection	Fission gas, coolant vapor or liquid
O&D	Operations support instrumentation	Information to maintenance operations (e.g. under-sodium viewing)
NDE	Structural integrity	Component health, damage detection & assessment, digital twin, operations feedback, vibrations, run/repair decision making

Considerations

Changing parameters:
- High-temperature & radiation
- Compact RX sizes
- Advanced materials
- Different species/measurands to accommodate

Sensor strategy considerations:
- Updated tolerance requirements
- Redundant measurements
- Indirect measurements may be required

Sensor viability considerations:
- Size
- Peripheral requirements
  - power, data transmission
- Sensor maintenance
- Installation access
- Mounting and coupling
- Reliability and qualification
- Cost and standardization

Sensor Lifetime considerations:
- Sensor lifetime at high temperature
- Sensor lifetime in radiation environment
- Sensor lifetime in compound environment
- Sensor fidelity versus lifetime, drift
- Caustic Environments

Up to 200 °C (available now) | 350 °C for online monitoring (some technology) | 350 °C to 800+ °C (limited technology)

Autonomous, Permanently Mounted/Embedded Sensors…

Yesterday's UT: Manual deployment

- Volumetric Examination (NDE) >>Run/Repair decision aid

Tomorrow's UT: Control room integration

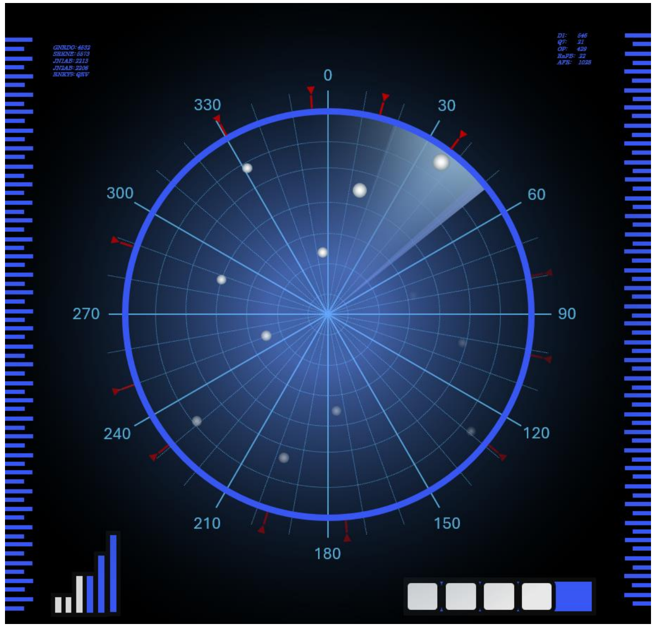
- Volumetric Examination (NDE)
- Flow sensing
- Temperature sensing
- Fluid Level detection
- Viscosity sensing

Other NDE sensors may also be useful for online data collection.

Exploring an Emerging Class of Sensor Technology

Quantum sensing has been used extensively in other areas since the 1970’s, but ***recent developments*** position these sensors for new fields including Energy Supply

- On a rapid maturation pathway
- Large community exists and many connections already established
- Growing commitments from governments and industries for technology development (a.k.a. the quantum race)
  - Funding opportunities are expected in 2026 and beyond



- At EPRI:
  - Completed early scouting to understand impact and value of quantum sensor technology
  - Begun road mapping the use cases for technology application
  - Formed a programmatic approach to advance the Next Generation Sensor work

Quantum sensors appear ripe for industrial development

Quantum Sensors ≠ Quantum Computers

Quantum sensors are *independent* of quantum computers

- They are ready *before* and *without* quantum computers
- They may be integrable with quantum computers later

Examples of Existing Quantum Sensor Applications

Medicine

Assess brain and heart activity via magnetic fields from neural and cardiac currents

Optically Pumped Magnetometers & SQUIDS

Navigation

Navigate submarines and aircraft without GPS by tracking phase shifts in cooled atoms' matter waves

Atom Interferometers

Telecom & Finance

Support GPS sync, telecom, and finance by measuring light frequency absorbed during electron energy transitions

Atomic Clocks

Mineral & Oil Exploration

Conduct mineral deposits and oil exploration by measuring tiny variations in gravitational fields

Cold Atom Interferometry

Climate Change

Track ice-loss, sea level rise, and tectonic shifts by measuring the Earth's gravitational field from orbit

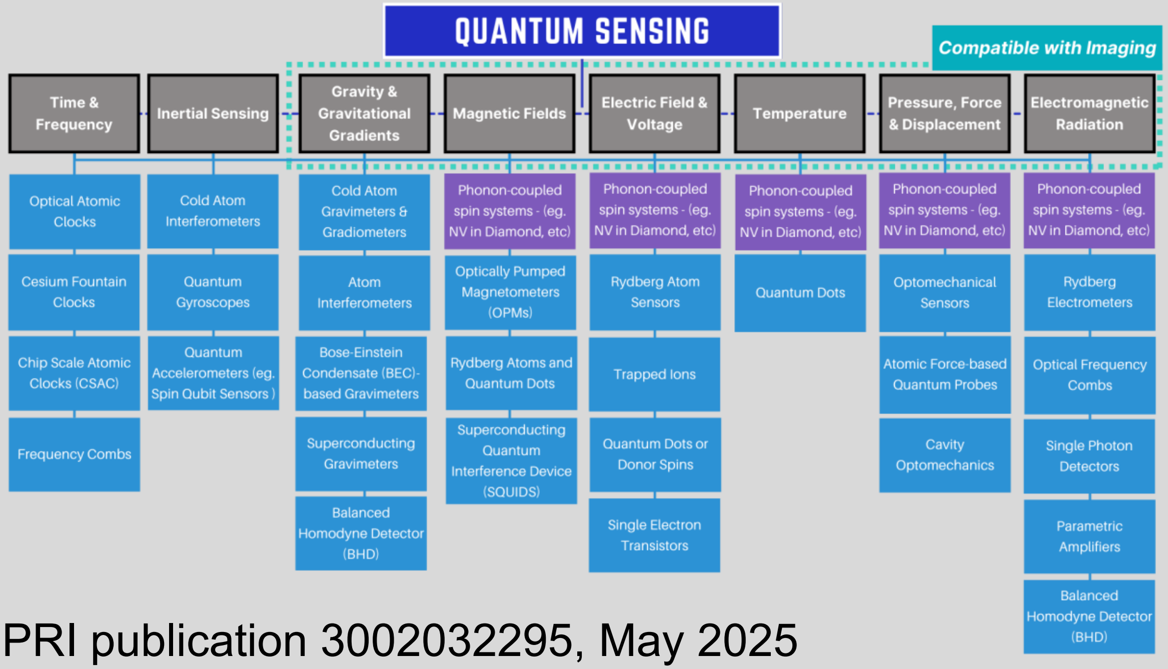
Cold Atom Interferometry

Exploration Indicates Many Potential Applications

- Practical quantum sensors have excellent performance for useful measurements and other properties
  - Timing/frequency—clocks
  - Magnetic fields—current
  - ***Drift-free and self-calibration***
  - ***Multi-measurand***
  - Electric fields—voltage
  - Electromagnetic
  - Optical interferometers
  - Inertia—gravity, acceleration, mass

- Some important potential applications as identified include:
  - Electrical component monitoring
    - Generators, transformers, large motors
  - Drift-free thermometry, self-calibration for instrumentation and control
  - Nondestructive Evaluation
  - Chip breakdown analysis for inverters
  - Monitoring and early warning of biofouling and clogging hazards
  - Battery health
  - Welding arc cloud analysis

Quantum Sensing Measurands and Sensor Types



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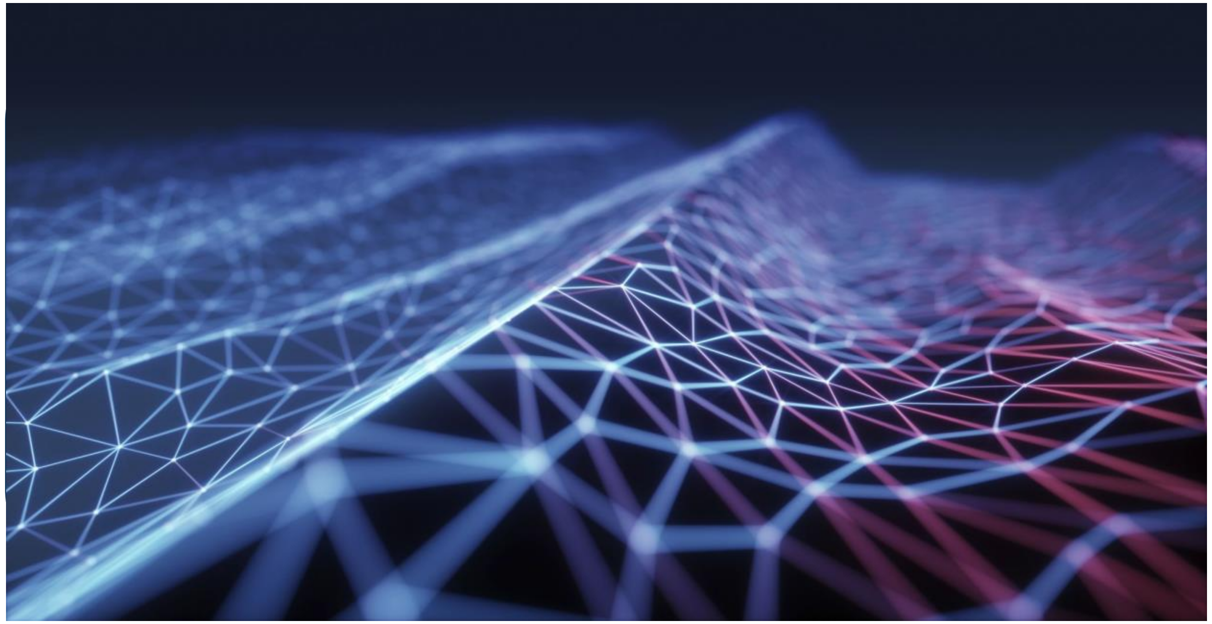
This document is jointly authored by EPRI, EDF, CEA, the U.S. DOE, and NIST. The document presents a primer of quantum sensor technology in the context of energy supply applications and is a foundation for mutual education for sensor developers, end users in energy supply, and users in related industries.

EPRI's Approach to Next Generation Sensors

- Motivation
  - Next generation sensors (e.g., quantum technologies) that overcome the limitations of classical sensors (e.g., ***drift***, ***multiple measurands*** ability) have great promise for energy applications, but there are significant gaps in understanding limitations in harsh environments, packaging, and innovative applications
- Objectives
  - ***Build a community of practice focused on advanced sensors for energy supply applications***
  - Provide guidance, tools, and testing protocols to sensor developers interested in energy applications
  - Training/tech-transfer of utility workforce on next gen sensors
  - ***Demonstrations and field trials of high impact case studies in nuclear, generation, and other energy applications***
- Impact
  - Enabling earlier fault detection, higher data fidelity, and ***safer, more efficient operations across harsh and inaccessible environments***.
  - EPRI collaborative leadership to accelerate new sensor technology deployment.



- Status:

  Builds off complete 'scouting' activities in 2025 on quantum sensing
  - *3002032295 Program on Technology Innovation: Review of Quantum Technology for Practical Sensing Applications in Energy Supply: Landscape Overview and Forecasting Future Opportunities*
  - *3002032297 Technology Innovation: Technology Review of Quantum Sensors for Potential Applications in Energy Supply.*

Expansion of existing sensing capabilities for enhanced data analytics and diagnostics

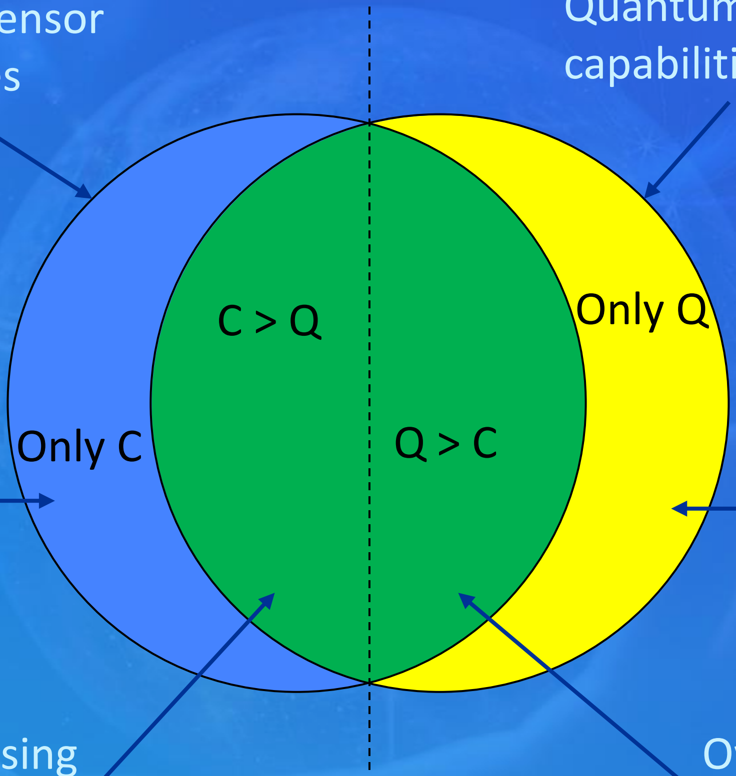
Sensor Technology Development Map

Classical sensing has substantially matured but may never accommodate all valuable sensing applications

Classical sensor capabilities

Quantum sensor capabilities

Early exploration looks at where quantum sensing can enable new applications and where it can improve current applications



Applications where quantum sensing cannot be used

Applications where classical sensing cannot be used

Overlap where classical sensing has ultimate advantage

Overlap where quantum sensing has ultimate advantage

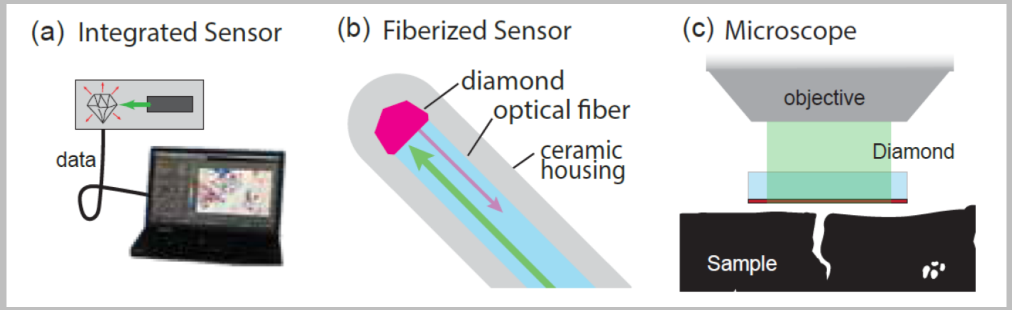
EPRI Demonstration Unit

EPRI has sourced a laboratory prototype NV-diamond-based quantum sensor

- Thermometer / magnetometer
- Feasibility testing of sensor
- Feasibility testing of magnetics-based methodology
- Supporting follow-on R&D

Parameter	Blue Box	Upcoming	Future
Data	Scalar	Vector 3-d	Vector 3-d
AC drive	No	No	Yes
Sample Rate	50 Hz	20 kHz	Limit → GHz
Probe size	20mm	2.5mm	<2.5 mm
Magnetic Sensitivity	$\mu T/\sqrt{Hz}$	$10\ nT/\sqrt{Hz}$	$1\ nT/\sqrt{Hz}$

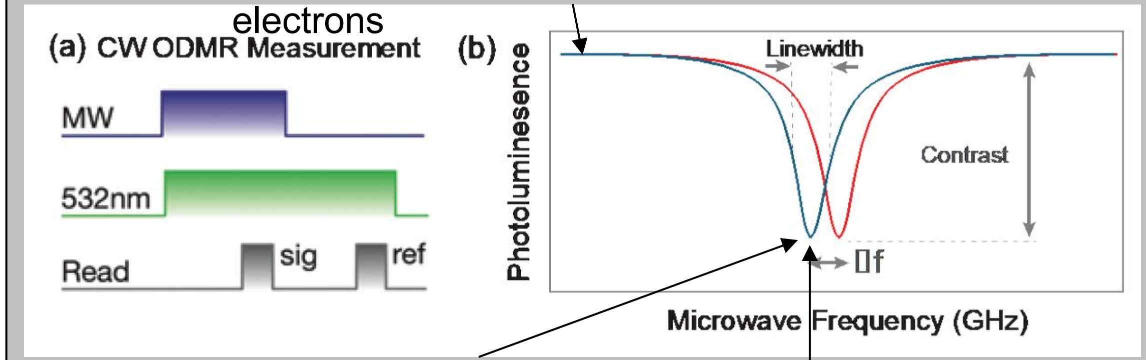
Quantum Principles of NV Sensor Interrogation



Macro-view of sensor hardware:
Sensor tip is constructed as a diamond lattice serviced by a fiber optic to deliver and receive photons

- Fiber optic need not be in contact with diamond

PL from ms=0 electrons

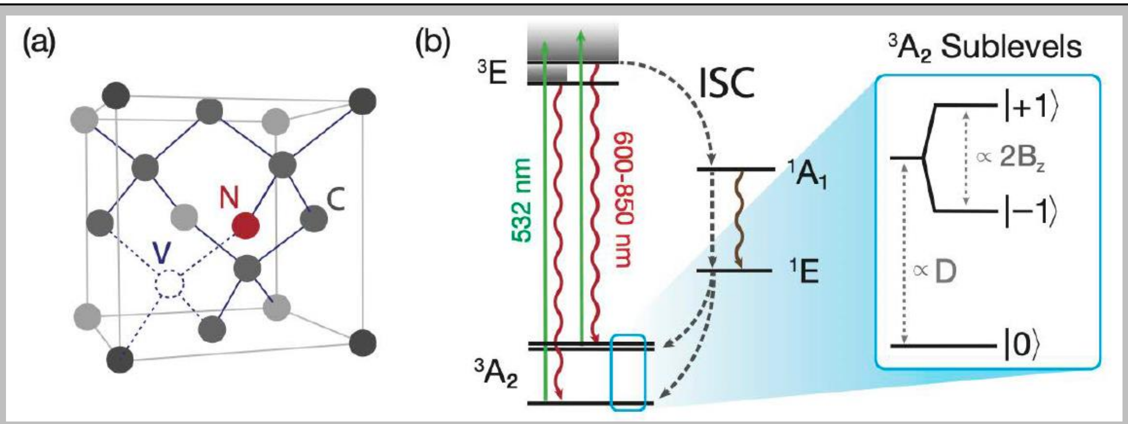


PL from ms=±1 electrons

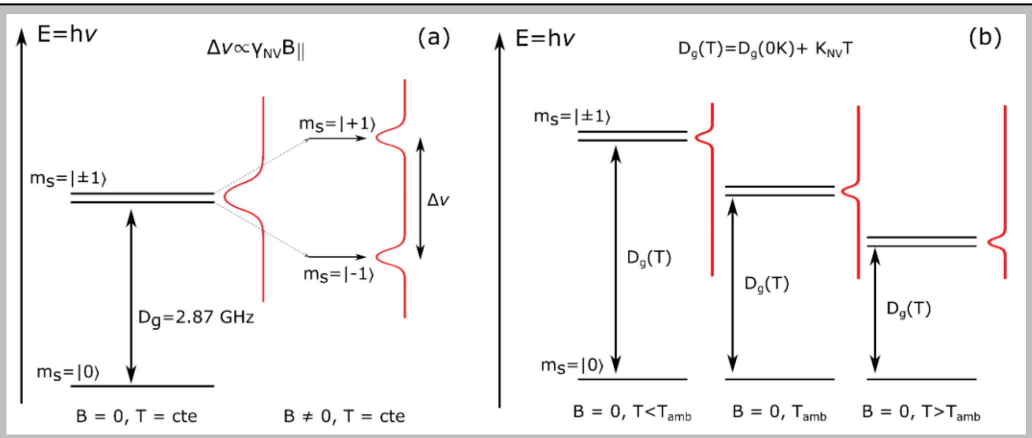
- Resonant microwave frequency needed to move electrons from ms=0 to ms=±1 (observed by lower photoluminescence)

Sensor & deployment (top); underlying material and electron states (bottom)

Measurement principles (top) and quantum properties (bottom)



- NV “defect” has two electrons, which can be in ms = (0, 1, or -1) ground states
- Once elevated, ms=0 electrons emit a red photon ~85% of the time, and ms=±1 electrons emit a red photon ~45% of the time



- Magnetic field modifies resonant frequency needed to move electrons from ms=0 to ms=±1 (Zeeman Effect, higher or lower frequency depending on spin)
- Temperature changes average resonance frequency of electron spin shifts

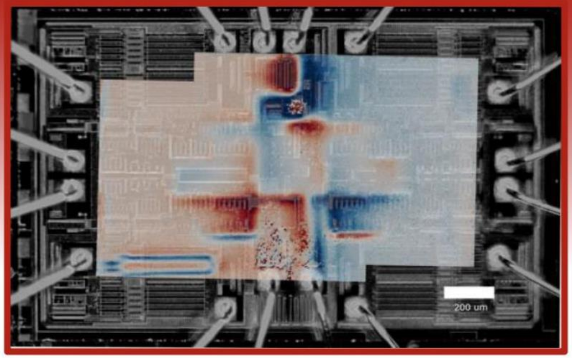
Lab Demonstration of Sensor Capability

Magnetic Microscopy for Semiconductor Metrology

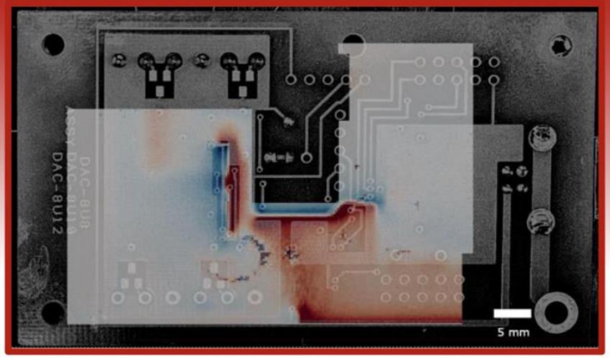
EuQlid

- Pilot projects with strategic partners to study silicon, package, board, and battery metrology needs
- Development of benchtop metrology tools

intel. imec micron HRI Honda Research Institute US SAMSUNG TIE TEXAS INSTITUTE FOR ELECTRONICS HONDA



ADG444 die
[Area = 1.3 mm^2, Resolution = 5 μm, Image time = 5 min]



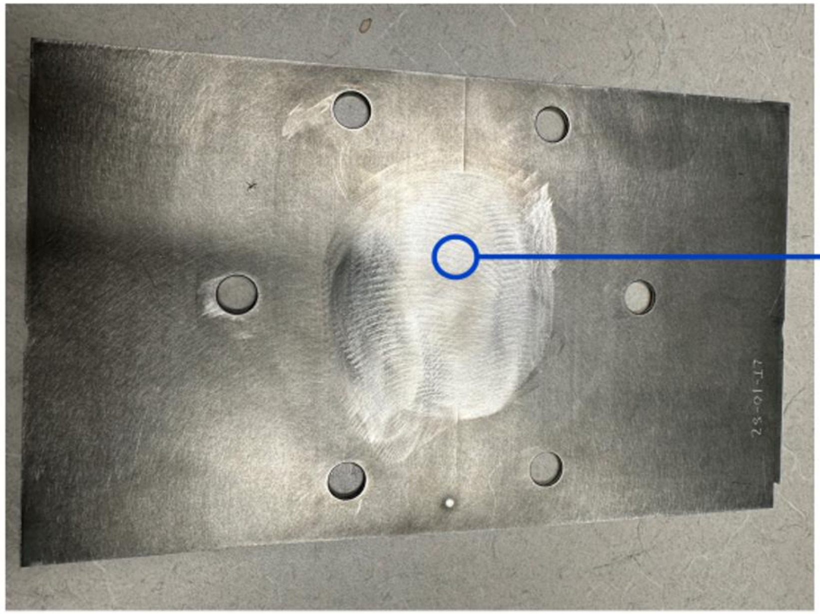
EECI DAC board
[Area = 18.3 cm^2, Resolution = 300 μm, Scan time = 176 min]

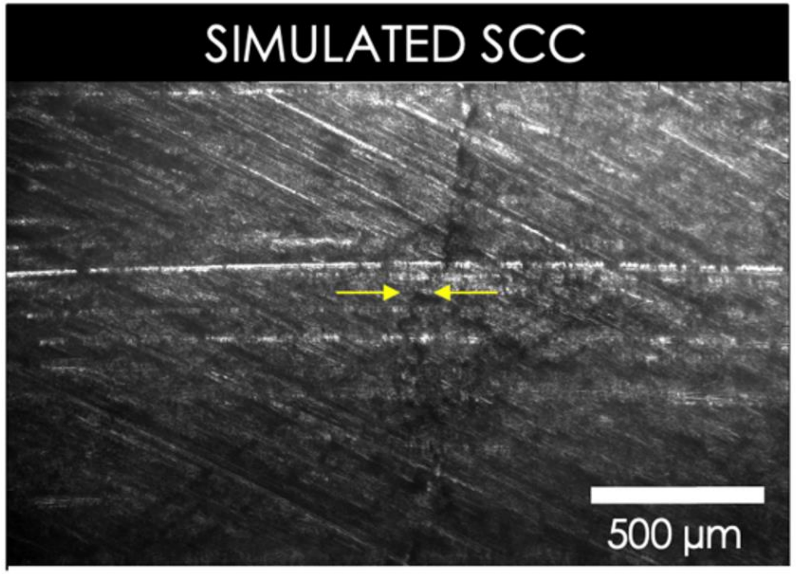
PRT13853 Li-Ion battery
[Area = 5 cm^2, Resolution = 500 μm, Image time = 20 min]

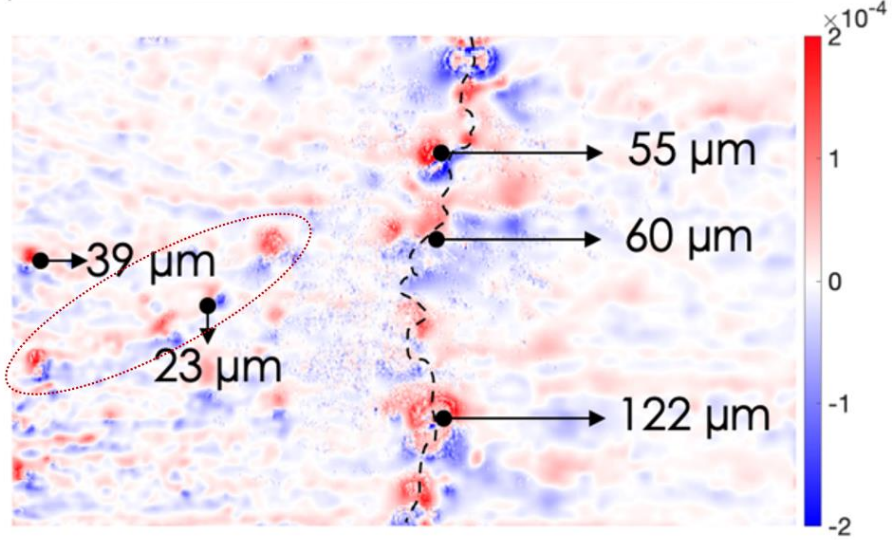
Courtesy of Quantum Catalyzer and EuQlid

Simulated Stress Corrosion Crack (SCC) Detection via QDM

- The QDM is detecting intrinsic magnetic signatures associated with SCC, likely arising from electrochemical activity, residual currents, or deformation-induced magnetic changes
- QDM map unaffected by surface finish
- Other signals (red dashed oval) to the left of the SCC crack may indicate defect feature deeper in the material.



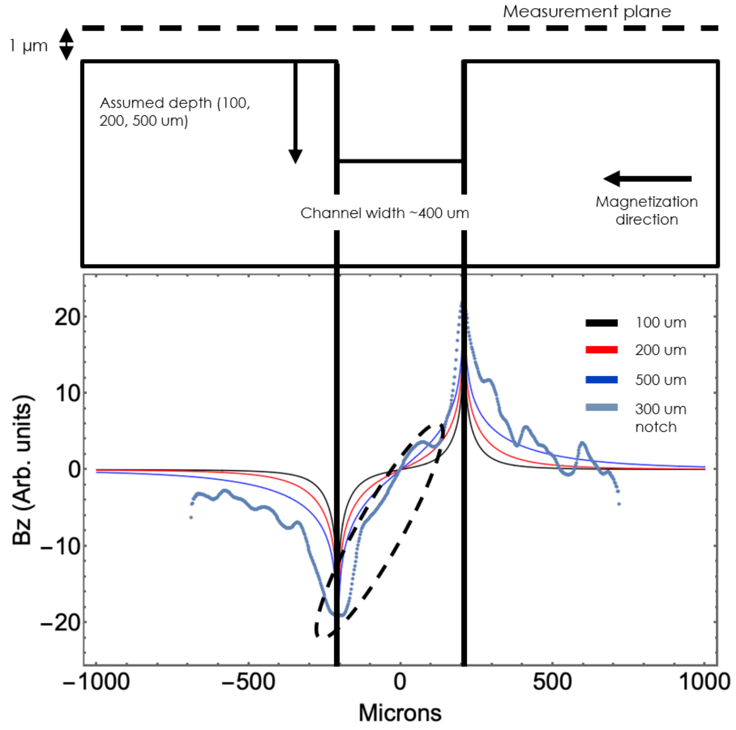




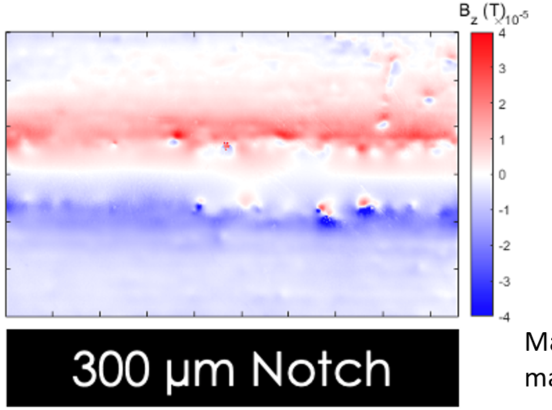
Stainless Steels: Modeling Depth Across a Crack

Magnetic map encompasses depth information of the feature, which can be evaluated in post-processing

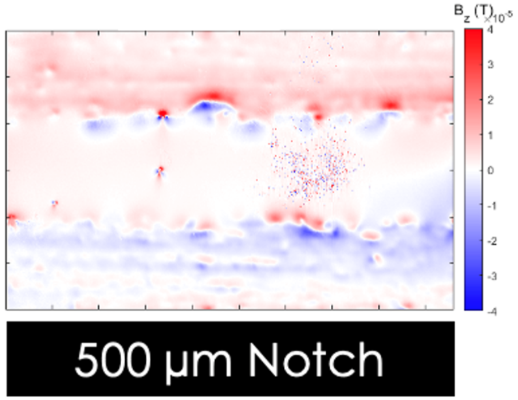
Model



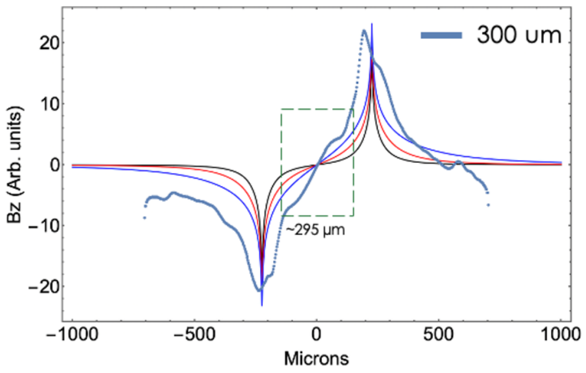
Results on 300 µm notch

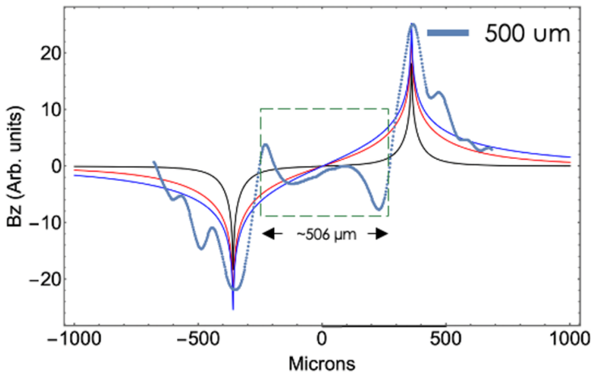


Results on 500 µm notch



Magnetic map





Notch depth evaluation

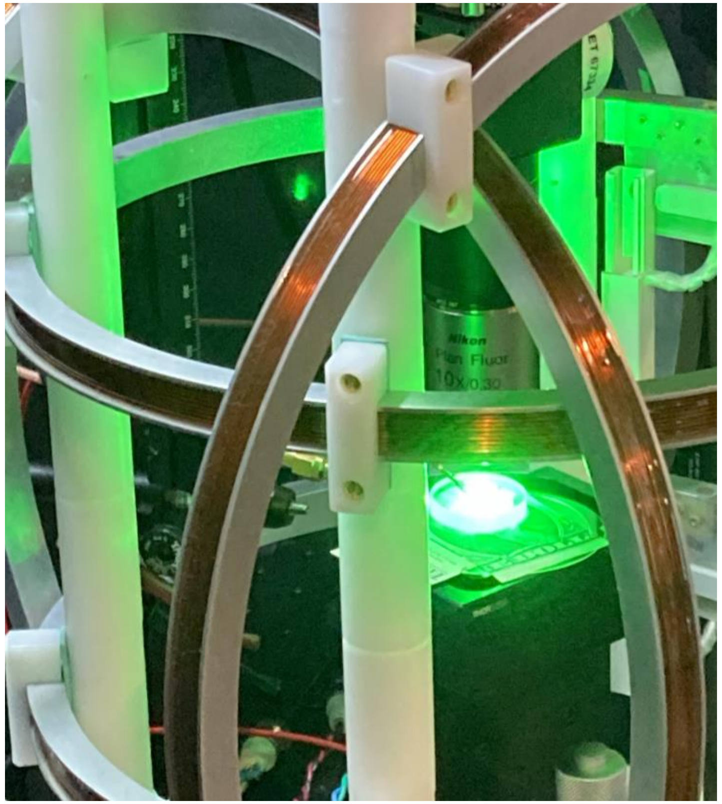
Optical reconstruction (300 µm notch)

Legend

Reference infinite plane depths
- 100 um
- 200 um
- 500 um

2026 Exploration Activities at EPRI

- Selected projects:
  - Quantum lidar:
    - Crack detection and characterization for underwater applications
    - Intake monitoring (e.g. bio clogging, plants, wildlife)
    - Electrical equipment (e.g. transformers and motors)
  - Diamond & diamond-like sensors:
    - Separate effects and synergistic effects studies
      - Magnetic, thermal, pressure, radiation
      - Functionality with/without sensor packaging
  - Applications suitability
    - Eddy current
    - Motor current signature analysis
    - Partial discharge detection (& more)
- Evaluate commercial systems
  - Bring vendors up to speed in energy supply applications
- Sensors test bed for prototype evaluation and demonstration



Additional work scopes of recent initiation: (ongoing or in development):

- Gravity sensors
- Quantum challenges
- FME, iron concentration monitoring

Quantum Sensor Technology Contacts at EPRI

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  - Pr. Technical Leader, Nondestructive Evaluation
  - Quantum sensor applications evaluation
  - Lead for Mission: ***SENSORS***
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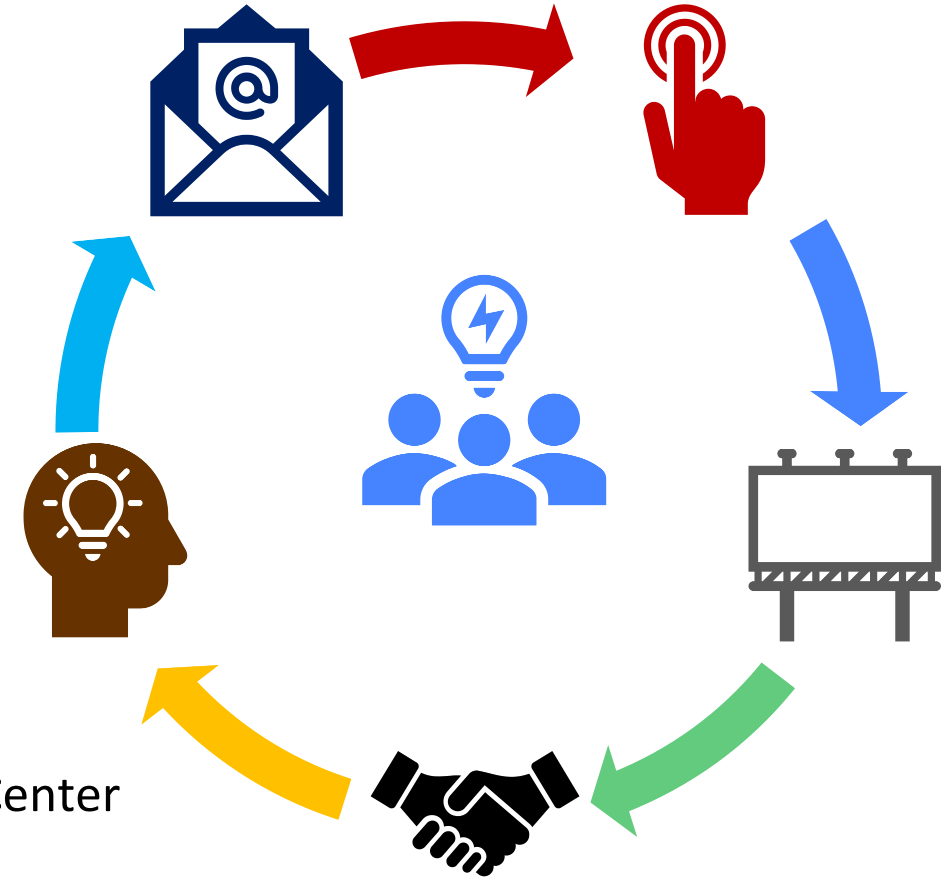
  - Senior Pr. Engineer, Innovation
  - Quantum technology feasibility evaluation



Join the quantum community interest group!

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