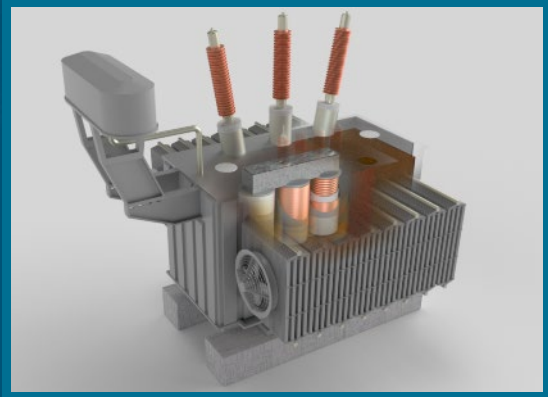
Developing Nuclear Magnetic Resonance Sensor (NMRSense) for Real-Time Monitoring of Transformer Health

DOE OE TRAC Peer Review, September 2026









PRESENTED BY

Todd Monson, Sandia National Labs, tmonson@sandia.gov

Presentation ID#: 1.3

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Harvard University: Yi-Qiao Song

Hitachi Energy: Alan Sbravati, Luiz Cheim, Lukasz Nowotko (PM)

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Project Overview
NMRSense

Project Description:

This program has two technical goals: 1) demonstrate a prototype compact (micro) NMRSense system including a 1 T Halbach magnet array; 2) demonstrate an interpretation algorithm of NMR data to assess transformer condition. Real time monitoring of transformer oil will optimize and stabilize the grid by improving the reliability and performance of power transformers.

Period of Performance:

10/1/2024 – 9/30/2026 (2 Years)

Technology Area: Advanced Transformers

Alignment: Optimize

Prime:

Sandia National Laboratories

Funding Profile & Cost Share:

Federal Funding $1.6M

Hitachi Cost Share $400k

Total $2M

Sandia Labs: $750k

Harvard University: $850k

Problem Statement

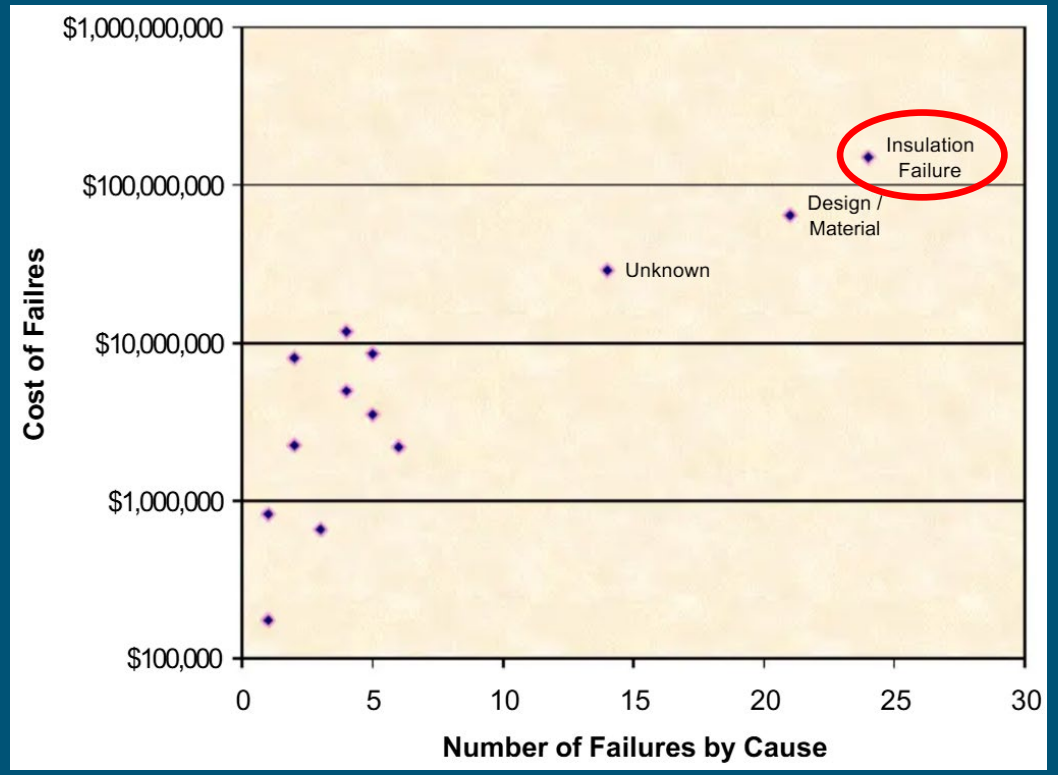
The U.S. grid is full of aging transformer fleets that have exceeded or are soon to exceed their design lifetime.

Most of the by-products of aging and insulation degradation are detectable through chemical analysis.

Developing real-time monitoring capability of transformer oil health is an urgent need of our current and future grid.

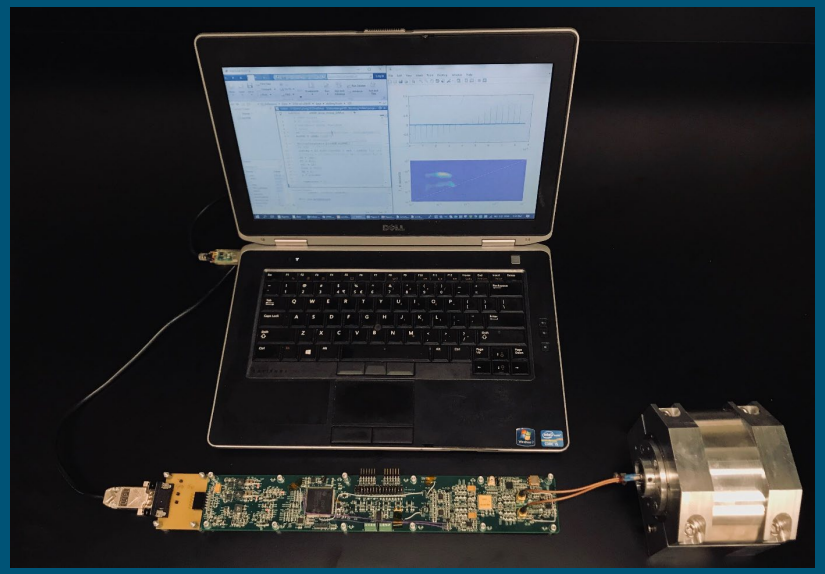
NMRSense will help grid operators reduce failures, avoid transformer damage (possibly catastrophic), extend transformer lifetime, and lower the overall cost of grid operation.

Frequency vs. severity of transformer failures from 1997 - 2001



W. H. Bartley, "Analysis of Transformer Failures," 36th Annual Conference of the International Association of Engineering Insurers, Stockholm, Sweden, 2003.

Technical Approach / Innovation



µNMR at the start of the NMRSense program

Innovation

- No technology for in situ monitoring of transformer oil currently exits
- µNMR is the smallest NMR sensor ever to date

Technical Approach

- Compact (micro) NMR sensor Development
  - Electronics; probe; magnet(s) (Halbach array), shimming; shielding; flowline filter
  - Transformer environments and conditions
  - Component miniaturization
- Application Development
  - NMR experiments + conventional data on transformer oil samples
  - NMR data processing pipeline
- Product Development
  - System miniaturization, prototype sensor
  - Interpretation algorithm
  - Test the NMR sensor in the transformer environment/factory

Outline: Technical Innovation / Results

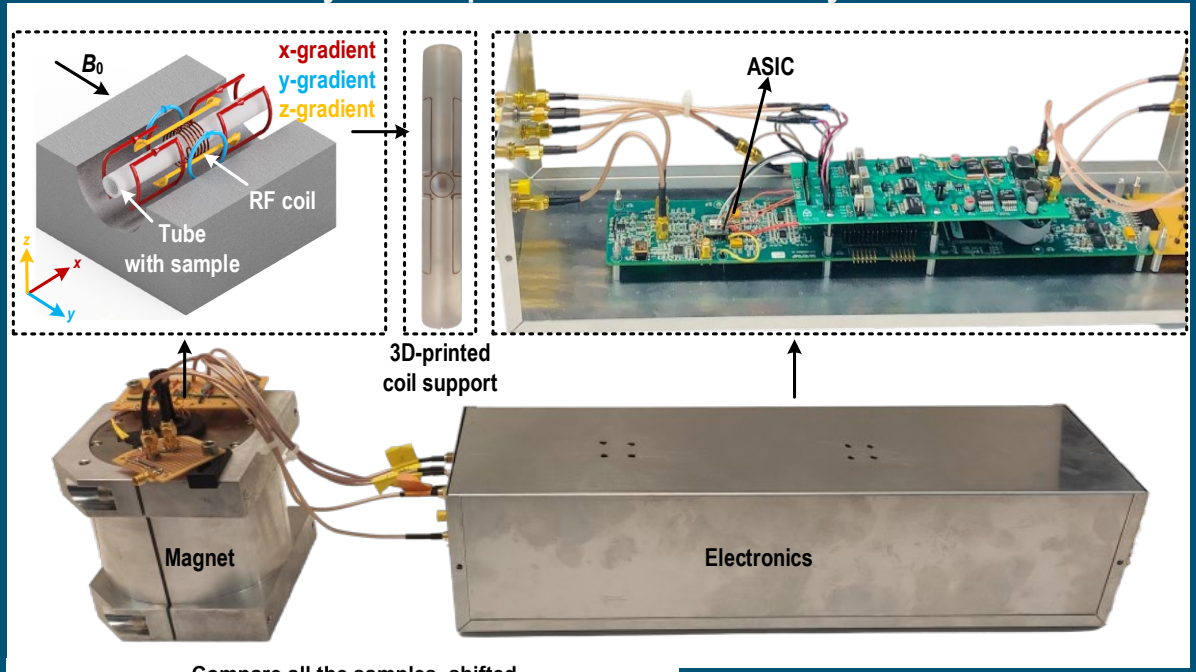
- µNMR system development @ Harvard University
- Precision permanent magnet manufacturing @ Sandia Labs
- Transformer oil NMR characterization @ Sandia Labs

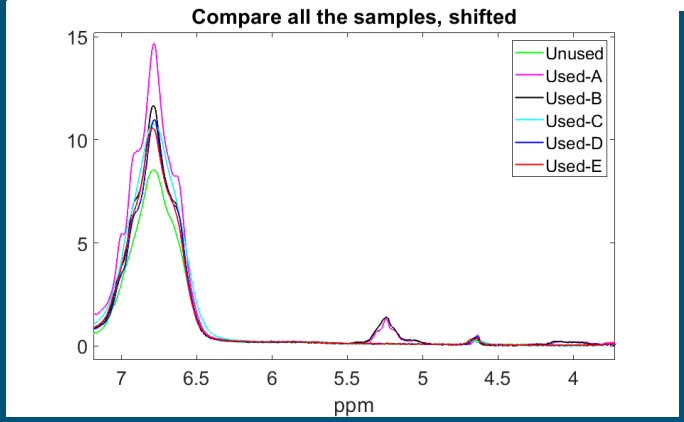


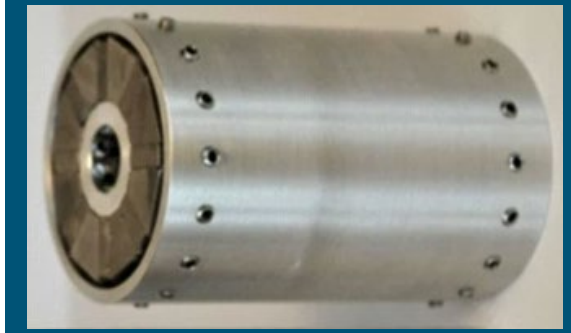
W. H. Bartley, “Analysis of Transformer Failures,” 36th Annual Conference of the International Association of Engineering Insurers, Stockholm, Sweden, 2003.

µNMR System Development
System overview / Halbach magnet array / Shimming

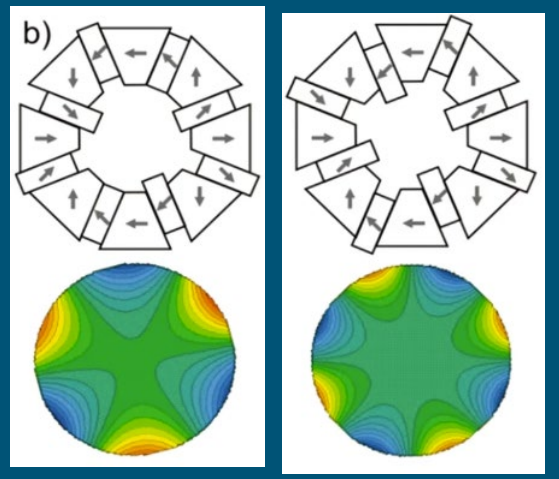
Initial laboratory set-up at the University



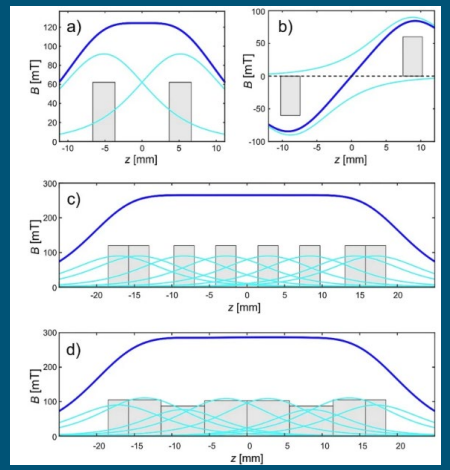




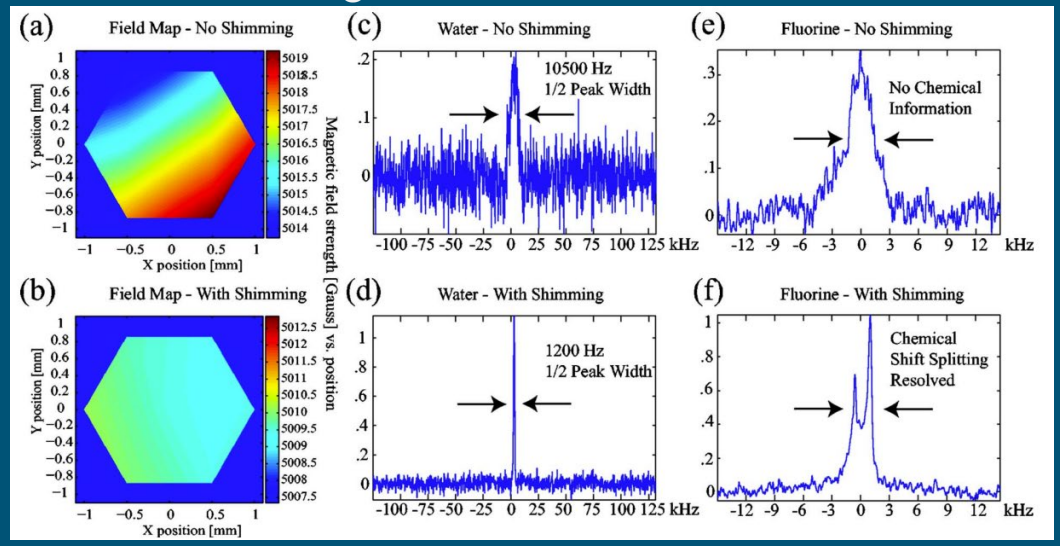
Mechanical Shimming



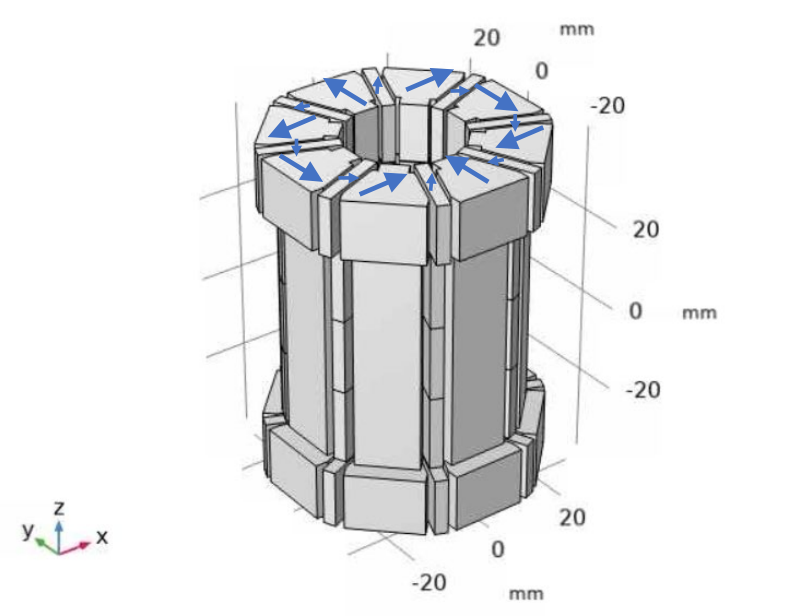
Array of magnets



Active Shimming

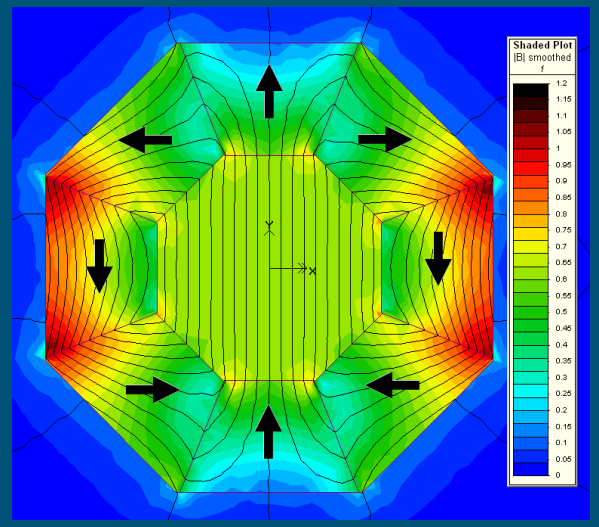


μNMR System Development
Halbach magnet array



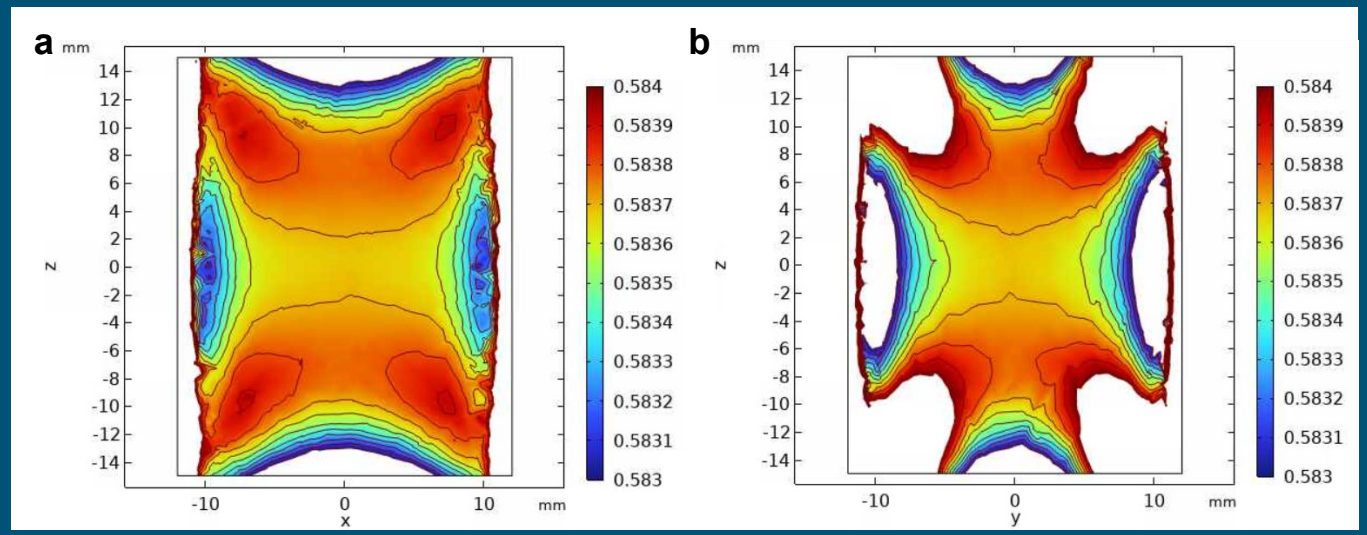
Finite Element Analysis (FEA) model of the Halbach magnet array. The center position is (0,0,0). Blue arrows indicate the easy axis orientation of the magnet groups. The magnetic field in the inner space is along the y-axis.

- **A highly uniform magnetic field is essential for NMR applications**
- Harvard designed a Halbach magnet array capable of generating a highly homogeneous magnetic field
  - Harvard works with a vendor to acquire the Halbach array
- Real-world implementations of the array are subject to manufacturing imperfections at the array and individual magnet level

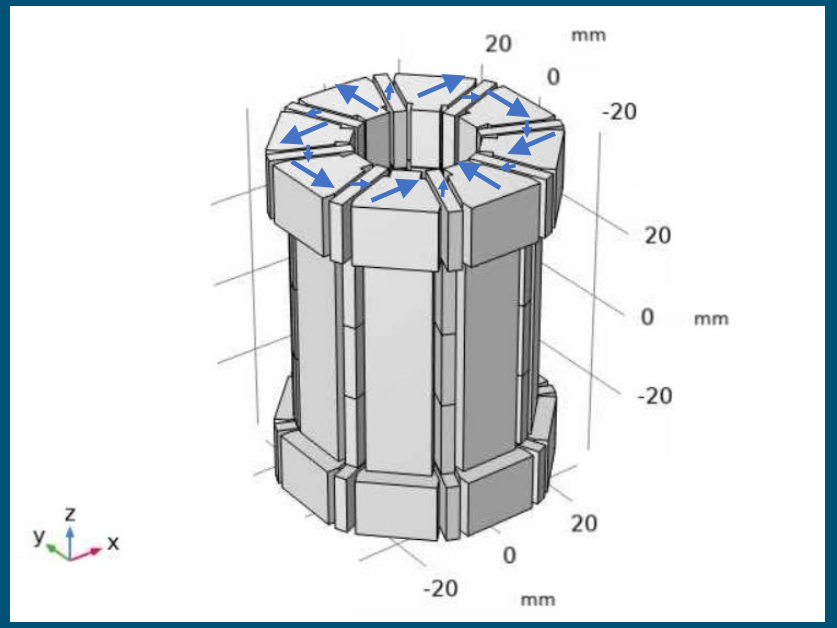


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μNMR System Development
COMSOL (FEA) modeling of Halbach magnet array



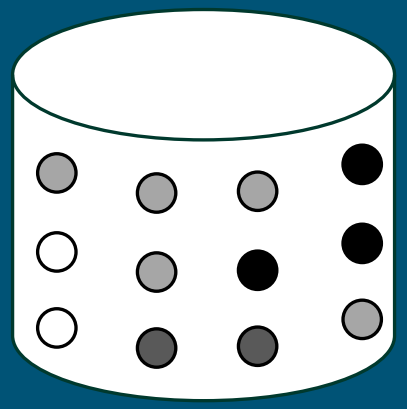
Distribution of the magnetic field strength in (a) xz- and (b) yz-planes. Regions with a magnetic field strength of 0.583 to 0.584 T (10 G) are colored. The step of the contour lines is 10^{-4} T (1 G).



μNMR System Development
Magnetic field shimming using a button array

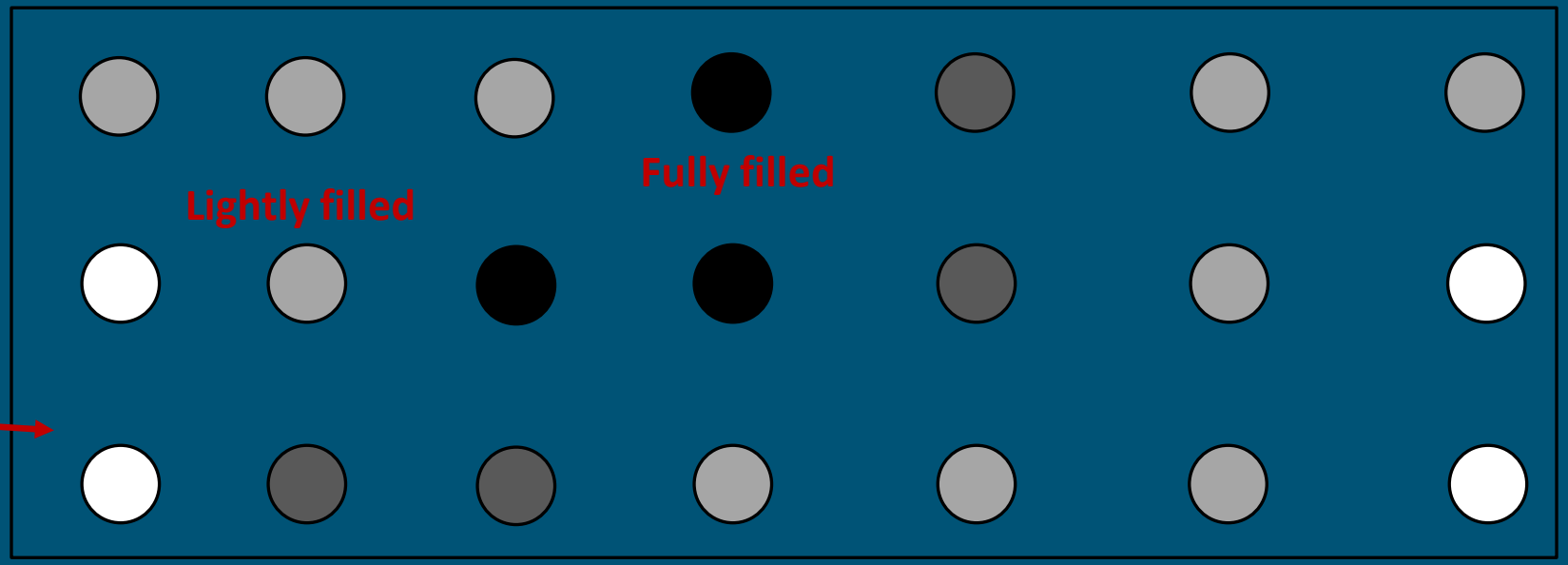
- To produce magnetic shims, Harvard will design a magnetic button array pattern on the surface of a cylinder that is inserted into the Halbach array (NMR cavity).
- Each element of the pattern is a circular space, and according to calculations, the circular gaps will be filled with different amounts of magnetic material to correct the magnetic field.

Shimming Cylinder

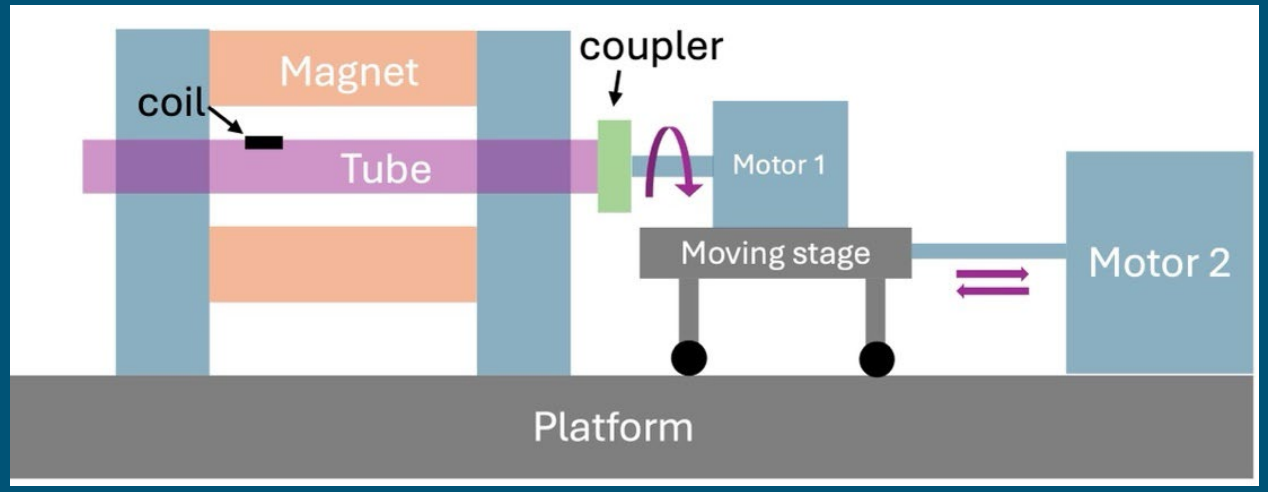


Unwrap

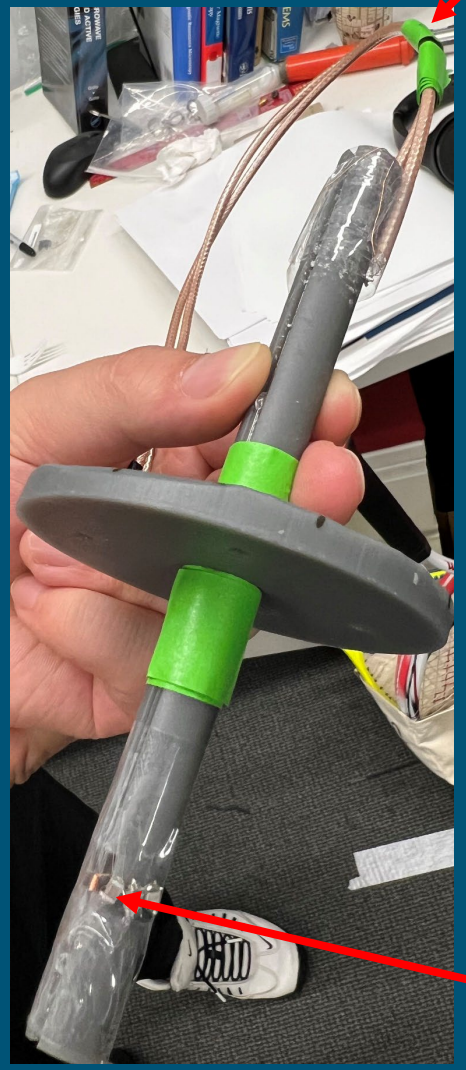
Example button array pattern



μNMR System Development
Field mapping system based on the microNMR



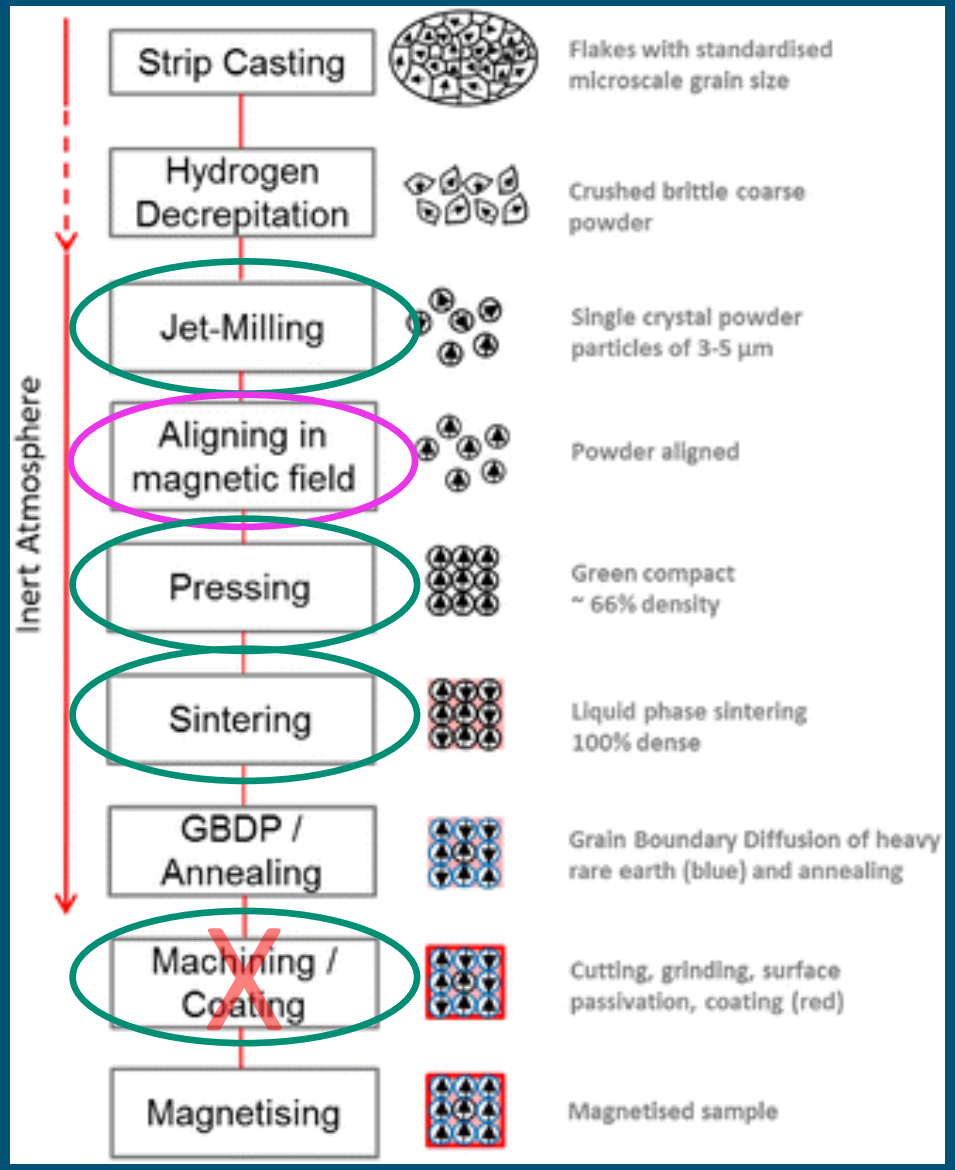
System schematics



Preliminary test of 3D printed probe

- Setup is designed to conduct automated linear and rotational motions so that the coil can measure magnetic fields in both axial and angular directions.
- 3D printing techniques allow us to iterate the design quickly.
- Preliminary data shows we can measure field variations.

Precision Permanent Magnet Manufacturing
Permanent magnet manufacturing today…and opportunities to improve



Magnet Makeover, IEEE Spectrum



Y. Yang, A. Walton, R. Sheridan, K. Güth, R. Gauß, O. Gutfleisch, et al., "REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review," Journal of Sustainable Metallurgy, vol. 3, pp. 122-149, March 01 2017.

Precision Permanent Magnet Manufacturing
Spark Plasma Sintering (SPS)

Fuji Dr. Sinter Lab Jr. SPS-632Lx



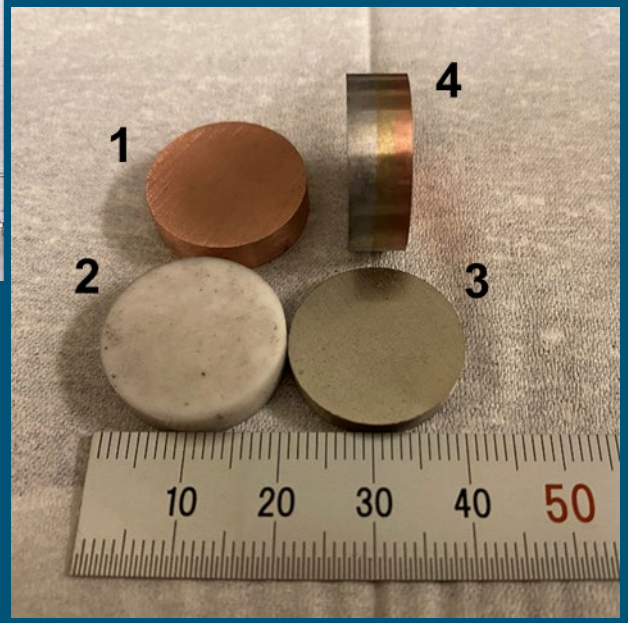
- Max. pressure of 60 kN
- Max. current of 3000 A
- Max. temperature of 2500 °C
- Max. sample diameter of 20 mm
- Max. diameter at 500 MPa = 10 mm



Dr. Sinter SPS-632Lx at SNL

Trial samples fabricated using SPS

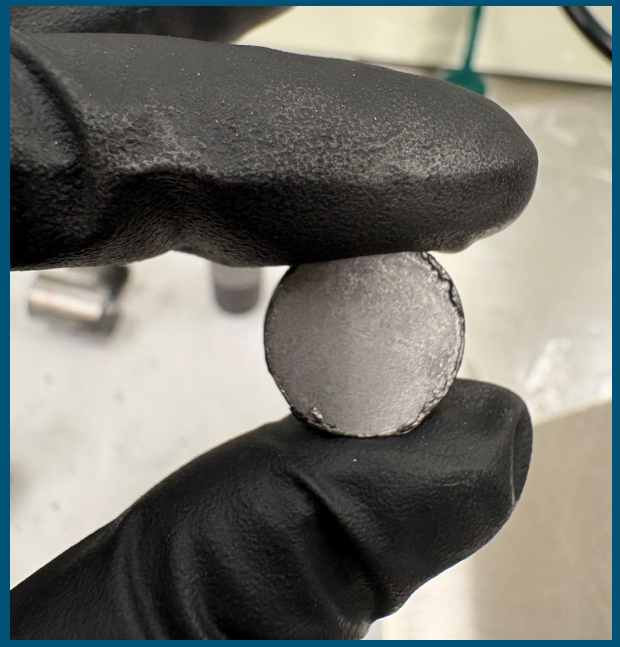
1. Copper (Cu)
2. Alumina (Al_2O_3)
3. Nickel (Ni)
4. Ni/Brass/Cu



Precision Permanent Magnet Manufacturing
Spark Plasma Sintering (SPS)



SPS graphite die glowing red hot at 950 °C



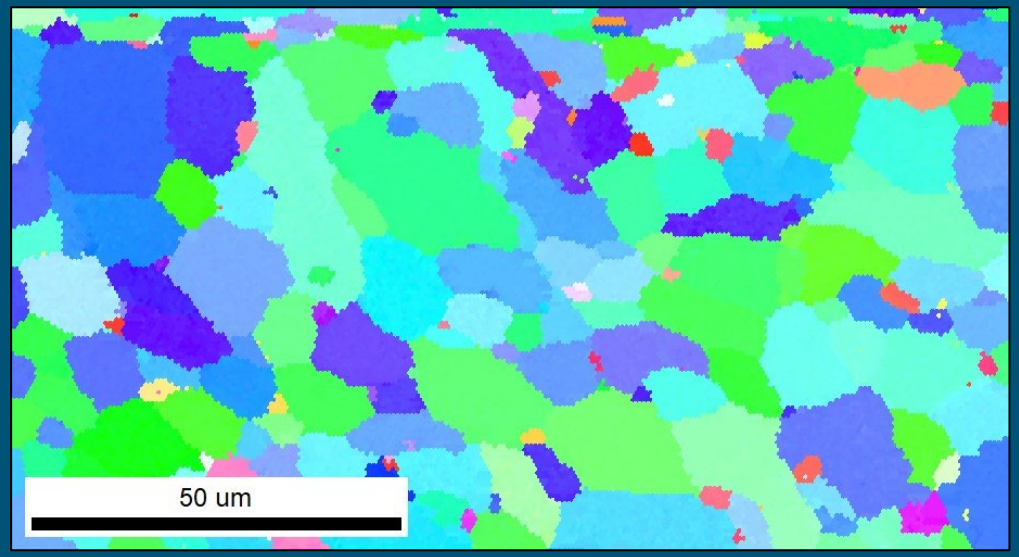
Sintered $SmCo_5$ prior to carbon paper removal



Sintered $SmCo_5$ after carbon paper removal

Precision Permanent Magnet Manufacturing
Grain structure comparison

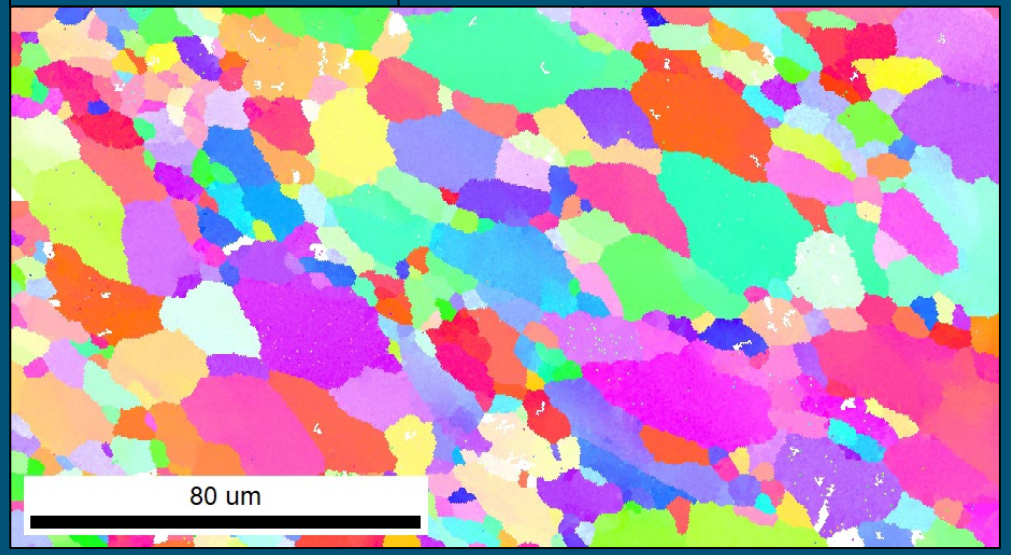
NTS Commercial Magnet Avg Grain Size: 11.45 µm



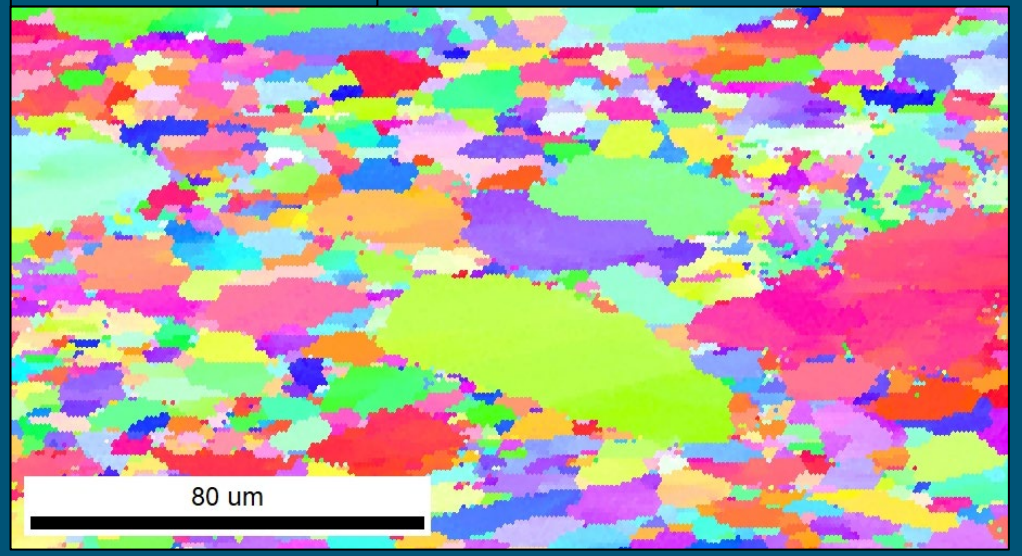
- Commercial magnet was clearly field aligned before solidification
- Higher temperature of 1050 ˚C caused some grain growth but not excessive
- Both SPS samples have very irregular shaped grains but similar in size to the commercial magnet

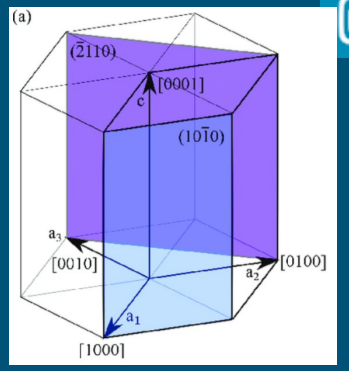
New powder from Ames Lab plus field alignment will increase magnet performance.

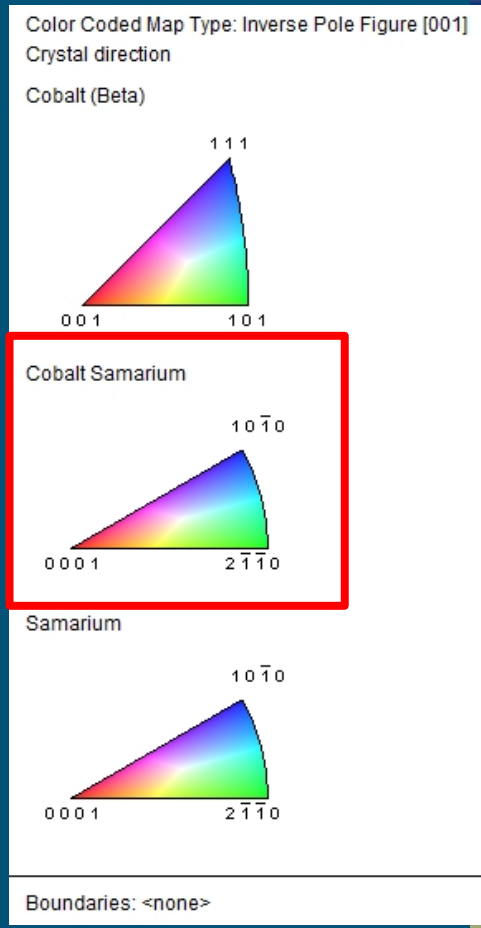
SPS Sample 1050˚ C Avg Grain Size: 13.67 µm



SPS Sample 950˚ C Avg Grain Size: 13.78 µm





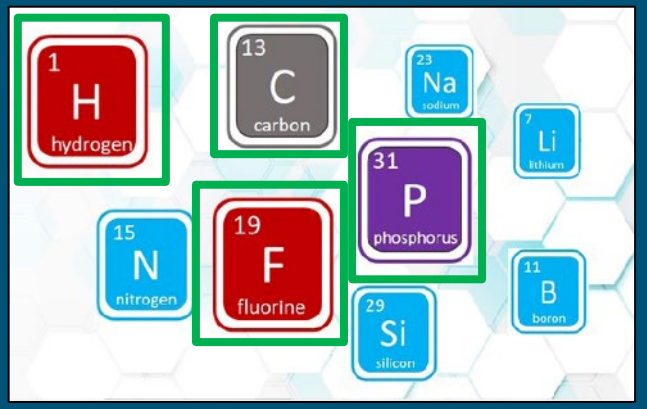


Oil NMR Characterization
Magritek Spinsolve Multi-X 60 MHz NMR



Features of Spinsolve 60 MHz

- ^{1}H frequency: 60 MHz
- ^{1}H and ^{19}F on all systems + X nuclei for dual channel systems
- Resolution:
  - Spinsolve 60 : <0.5 Hz (50%) / <20 Hz (0.55%)
  - Spinsolve 60 Plus: <0.35 Hz (50%) / <10 Hz (0.55%)
  - Spinsolve 60 Ultra: <0.2 Hz (50 %) / <7 Hz (0.55%) / <14 Hz (0.11%)
- Exceptional Sensitivity: 200:1 (Single channel) / 140:1 (Double channel) for 1% Ethyl Benzene
- 3D PFG gradients optimized for gradient-enhanced methods
- Optional PFG gradients for diffusion spectroscopy (>0.5 T/m)
- No cryogens
- Unparalleled stability
- External Hardware Lock with no need for deuterated solvents
- Suitable for on-line reaction monitoring
- Easy to operate
- Compatible with automatic sample changer



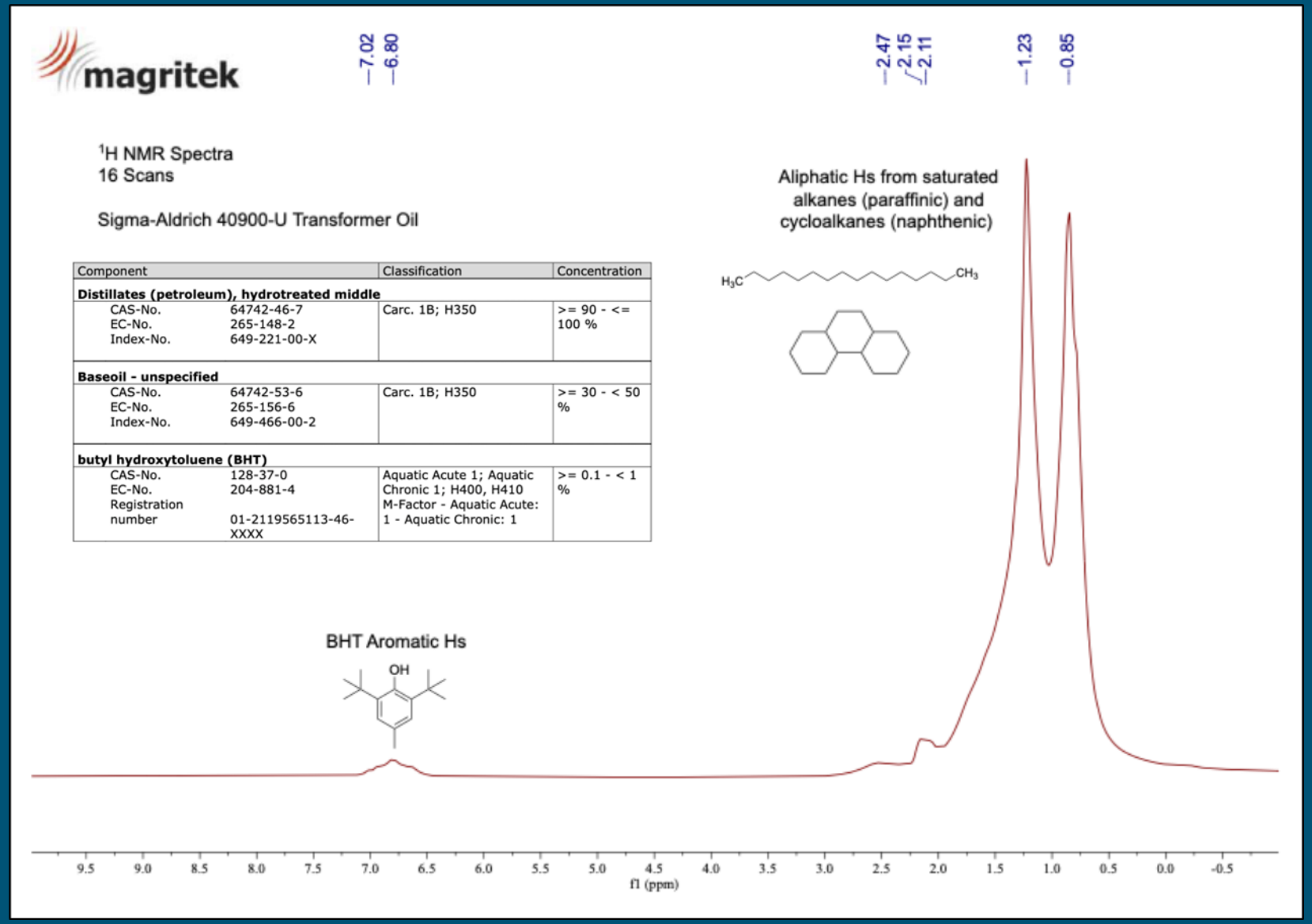
<u>Specific Features</u>

- ^{1}H, ^{13}C, ^{19}F, ^{31}P nuclei
- Autosampler robot
- Quantitative NMR analysis software
- Reaction Monitoring Setup

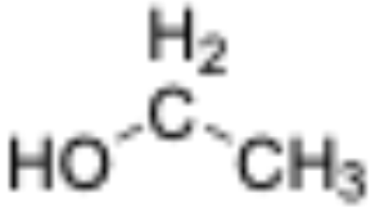
<u>Ties to Harvard Work</u>

- Commercial 60 MHz vs 22 MHz
- Halbach magnet array
- Neat liquid analysis (no deuterated solvent required)
- No cryogens required

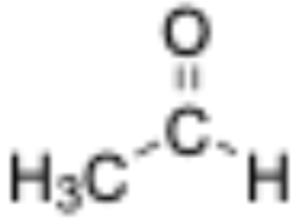
Oil NMR Characterization
^{1}H NMR Spectrum – Sigma Aldrich (SA) 40900-U Oil



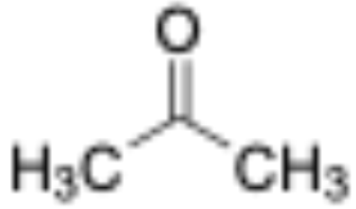
Oil NMR Characterization
Key Organic Contaminants Investigated



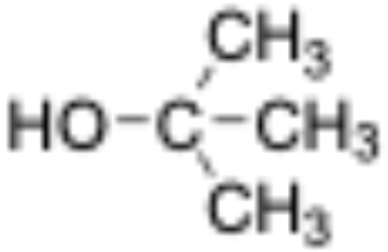
Ethanol



Acetaldehyde

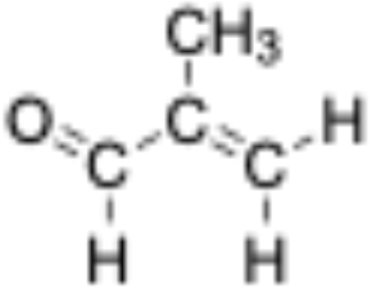


Acetone



2-Methyl-2-Propanol

(t-Butanol)

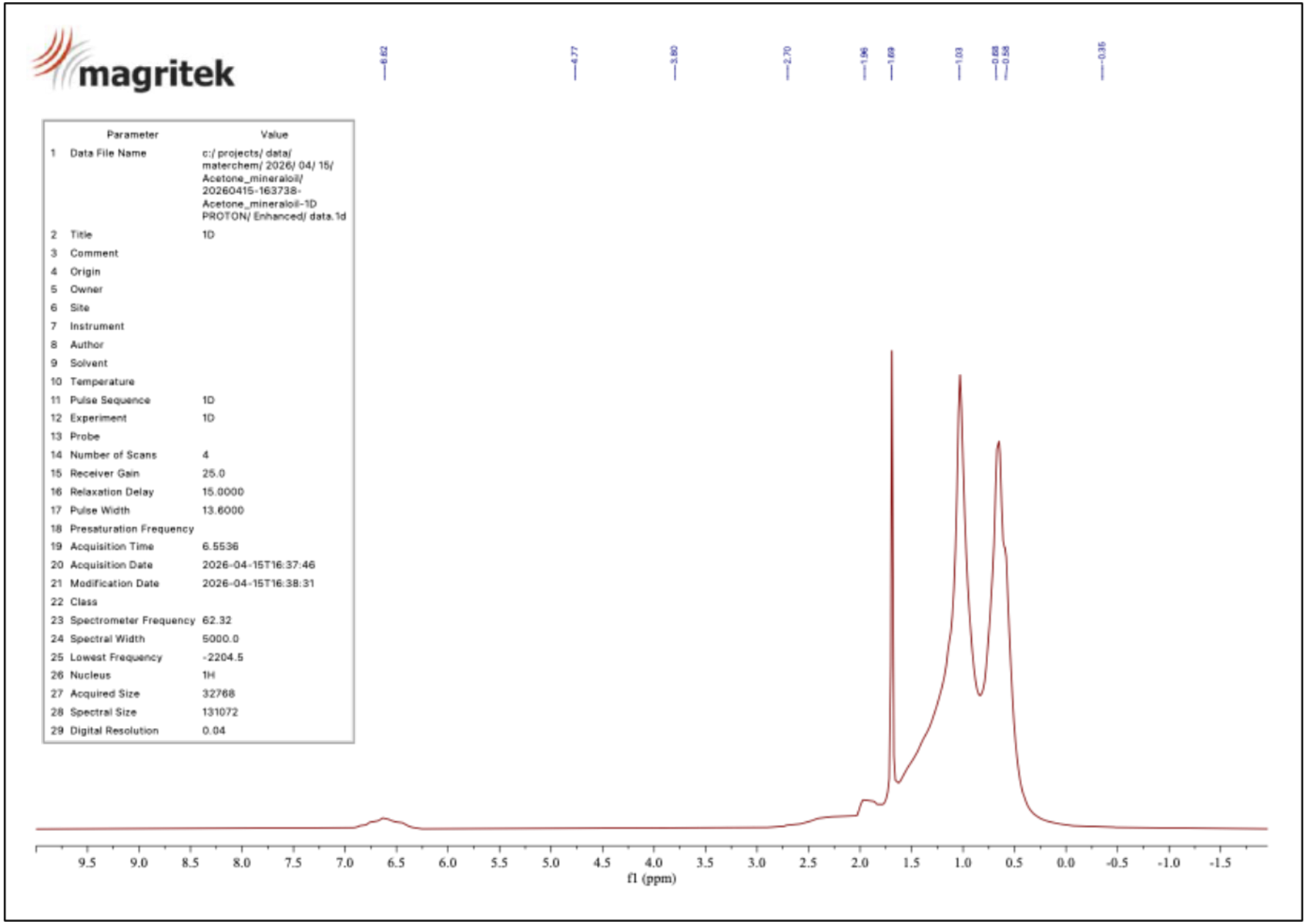


Methacrolein

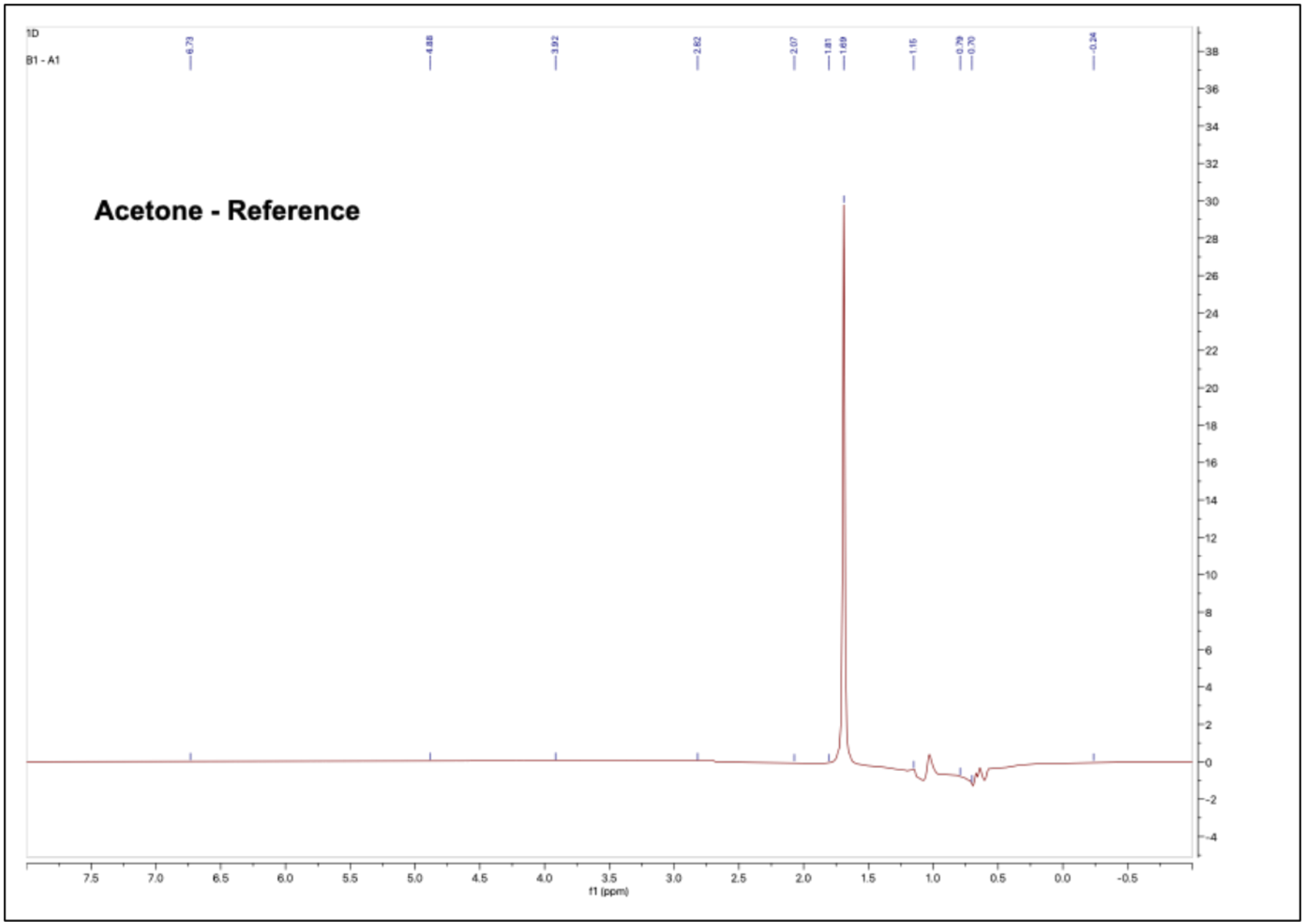
Chemical Spike	^{1}H signature	^{13}C signature
Acetaldehyde	X	
Acetone	X	X
Ethanol	X	X
t-butanol	X	X
Methacrolein	TBD	TBD

* Methacrolein being evaluated on high resolution NMR to confirm peaks

Oil NMR Characterization
Acetone



Oil NMR Characterization
Acetone - Reference



Conclusions / Impact

- µNMR can detect contaminants of interest in aged transformer oil
  - Both proton and carbon NMR can provide useful information
- Improvements in µNMR sensor design and magnetic shimming have improved instrument robustness and sensitivity
- SPS offers improvement for permanent magnet (e.g. $SmCo_5$) consolidation and manufacturing
- Analysis of µNMR data for contaminants of interest can be automated

Impact

- Power transformer failures will be significantly reduced with in situ oil monitoring
- Median transformer lifetime can be extended from 40 to 80 years

Future Directions / Next Steps

- Prototype µNMR will be completed, tested, and demonstrated
- Prototype $SmCo_5$ magnets for a 1 T Halbach array will be manufactured with SPS
- Analysis of dissolved gases with benchtop NMR will be completed
- NMR data analysis will be automated

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE).



U.S. DEPARTMENT of ENERGY