A Low-Power FPGA-Based Time-Domain NMR Relaxometry System for Field Deployment

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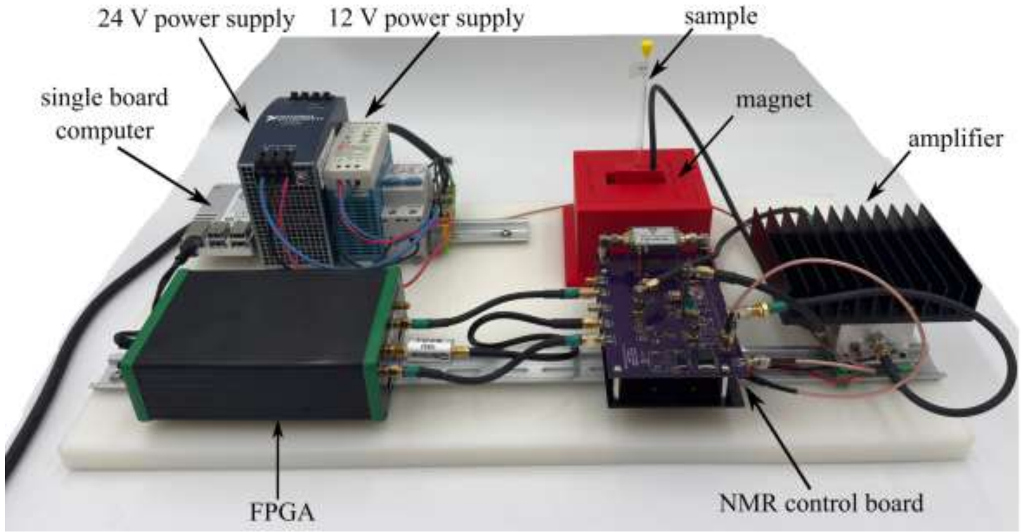
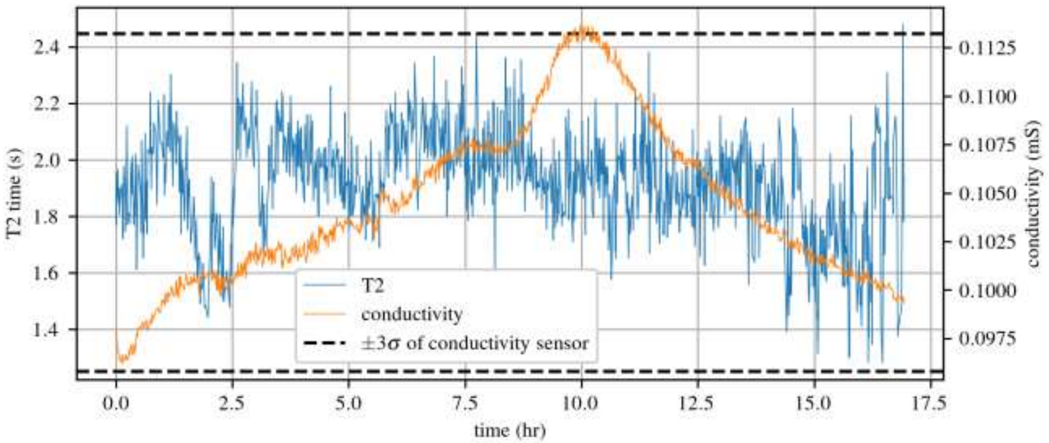
Outline

- Proposed NMR-based Water Quality Monitoring System
- Open-source NMR Hardware
- Use Case: Wildfire Ash
- Field Deployment of In Situ NMR system
- FPGA-Based Time-Domain NMR Relaxometry

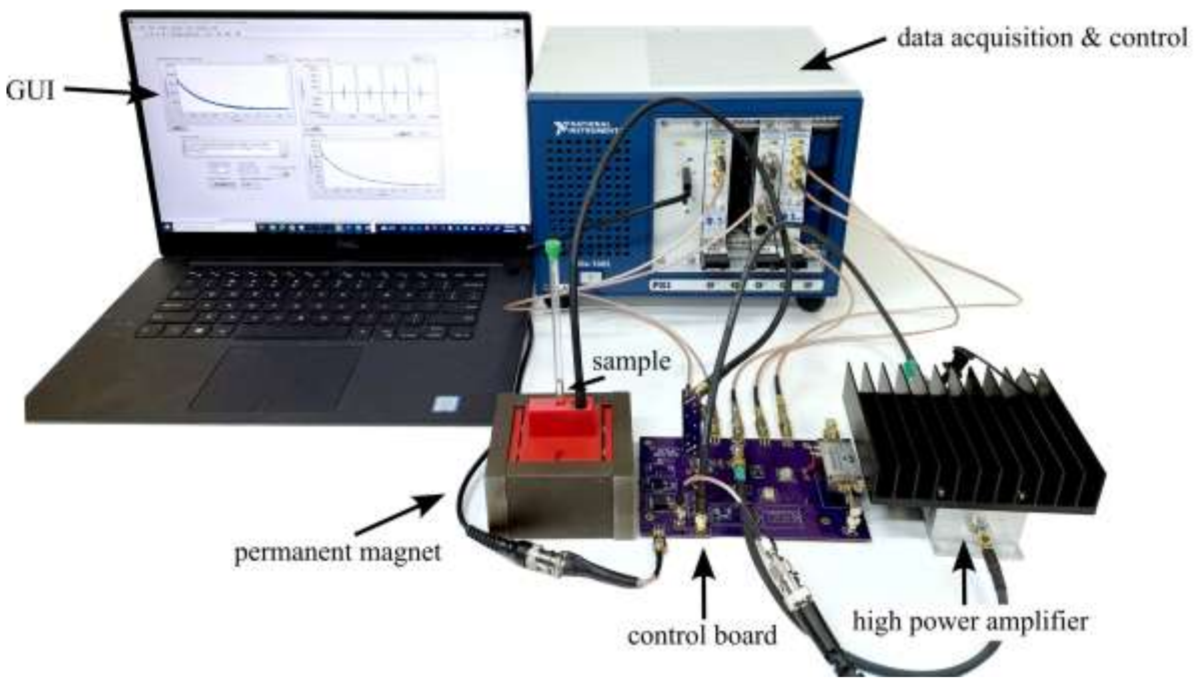


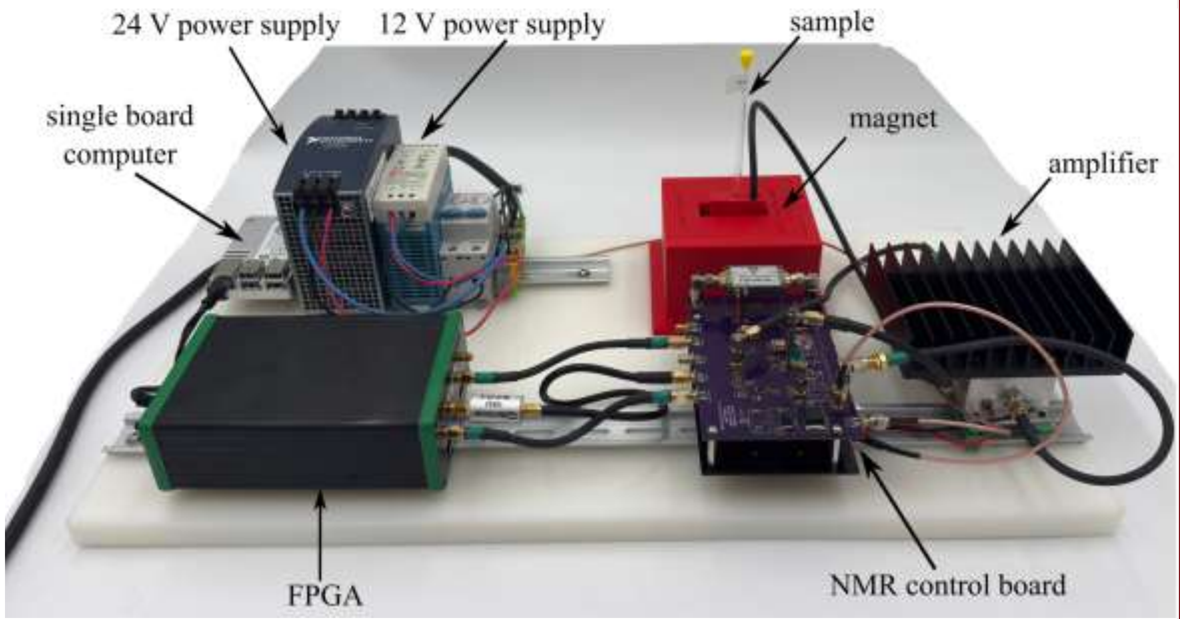


Proposed NMR-based Water Quality Monitoring System

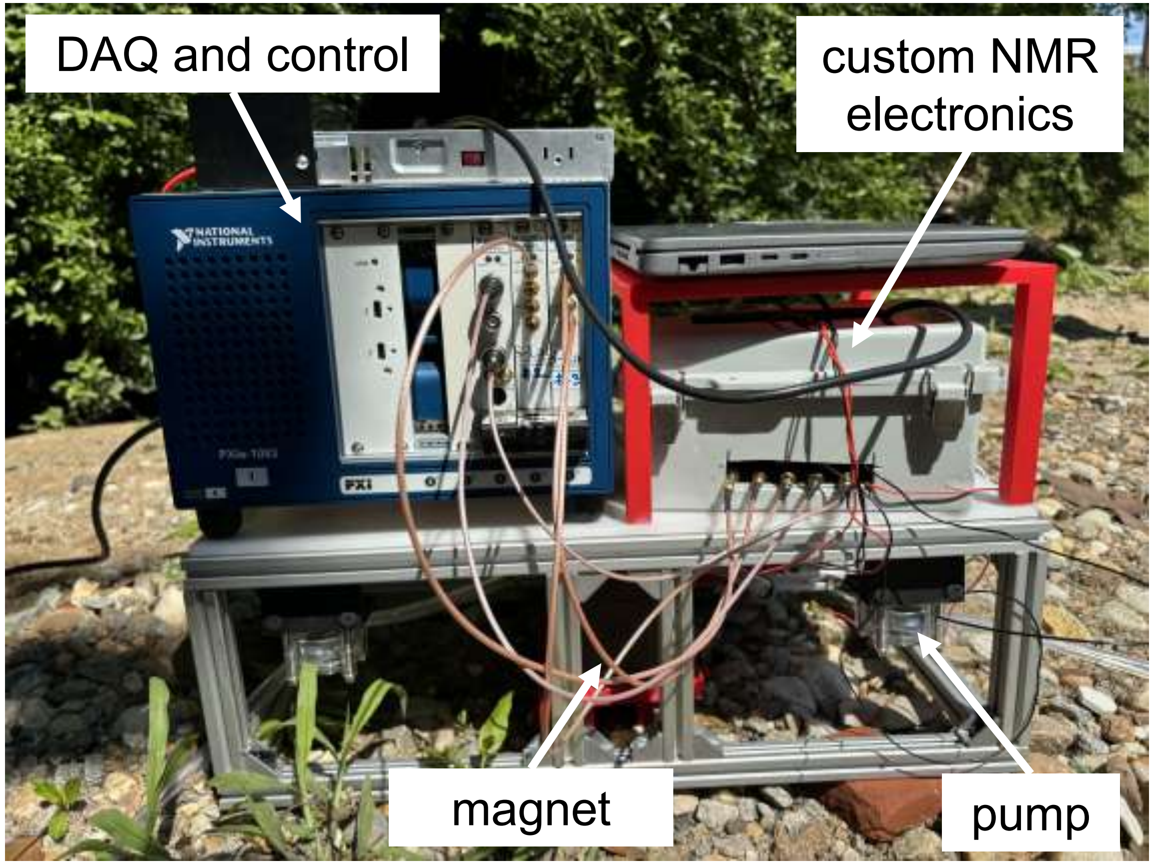
ARTS-Lab Desktop NMR System

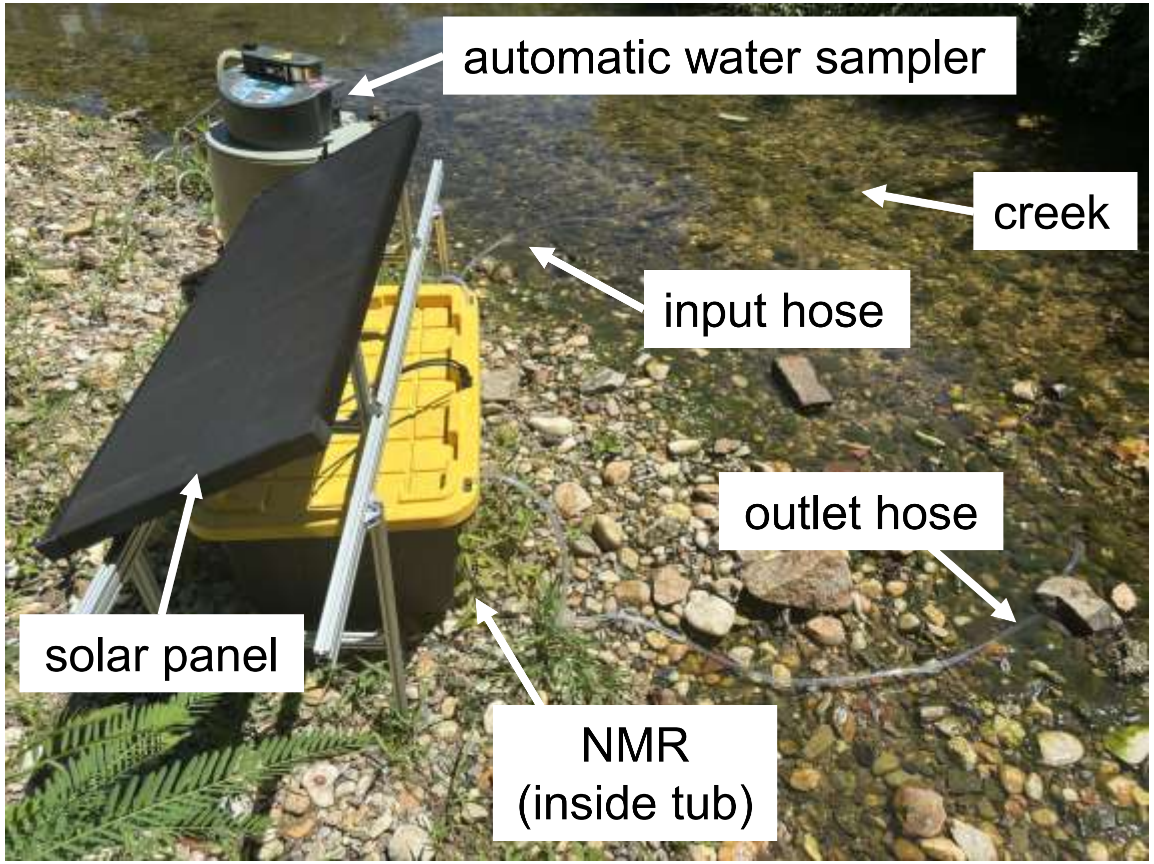
- All electronics (barring two amplifiers) housed on a single PCB
- Goal is to move from PXI-based systems to a custom FPGA-based soluton





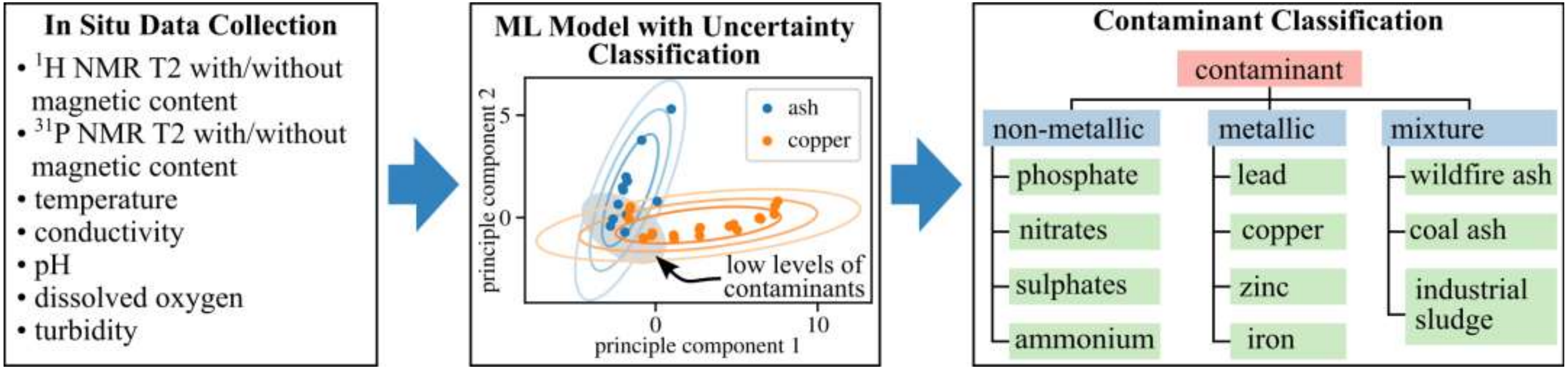
Flow-through NMR





Future Goal: Distinguish Contaminants

- Provide data for multiple contaminants
- Incorporate an ML model with a physics-based understanding of magnetic behavior
- Identify and quantify different contaminants using ML based on T2, water quality, and time series data



Open-source NMR Hardware

Our NMR Development Path

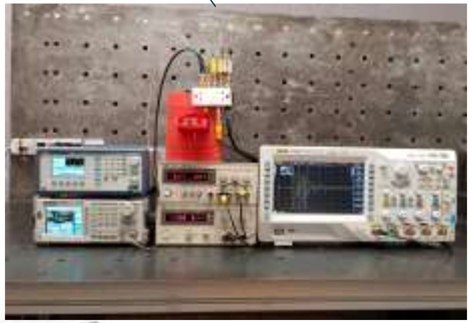
Open-source Design

	2019	2020	2021	2022	2023	2024	2025	2026
Funding	Downey/San Hee		Army	USC	NSF CA			

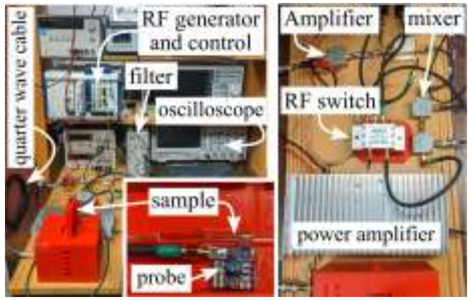
Hardware

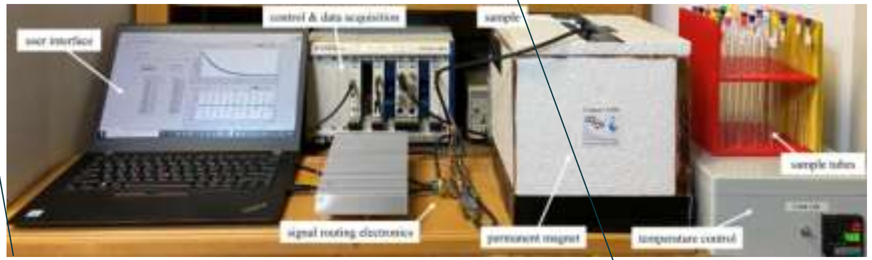
Collogue asks if it can be done?

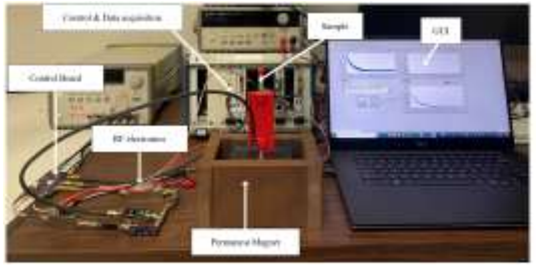
Tracking down specialized hardware, magnets cost 10-20k

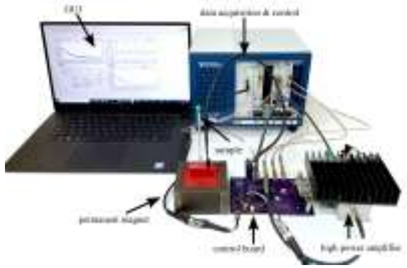


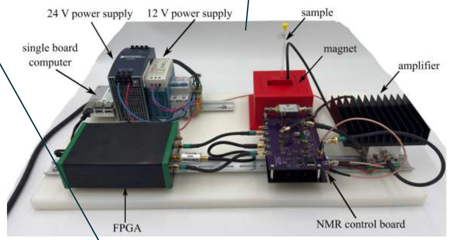
Coil magnet design





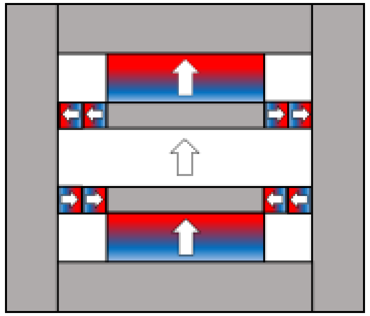




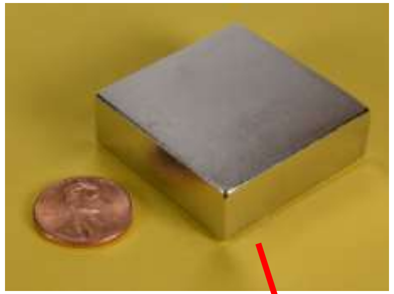


Permanent Magnet Array

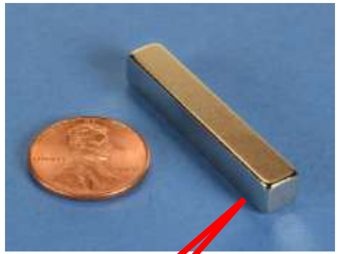
- **0.565 T** strength at 23ºC
  - -800 ppm/K gradient
- Larmor (operating) frequency:
  - $f_{Larmor} = \gamma B = \left(42.58 \frac{MHz}{T}\right)(0.565\ T) \approx$ $\mathbf{24\ MHz}$
- 150 ppm homogeneity
- 4.4 lbs

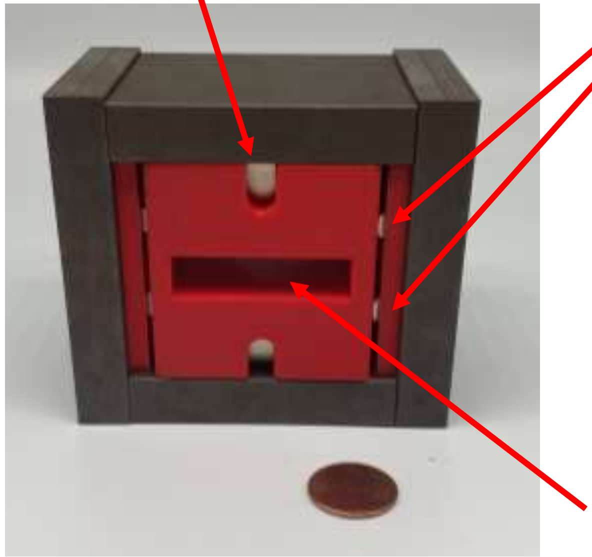


N42 magnet



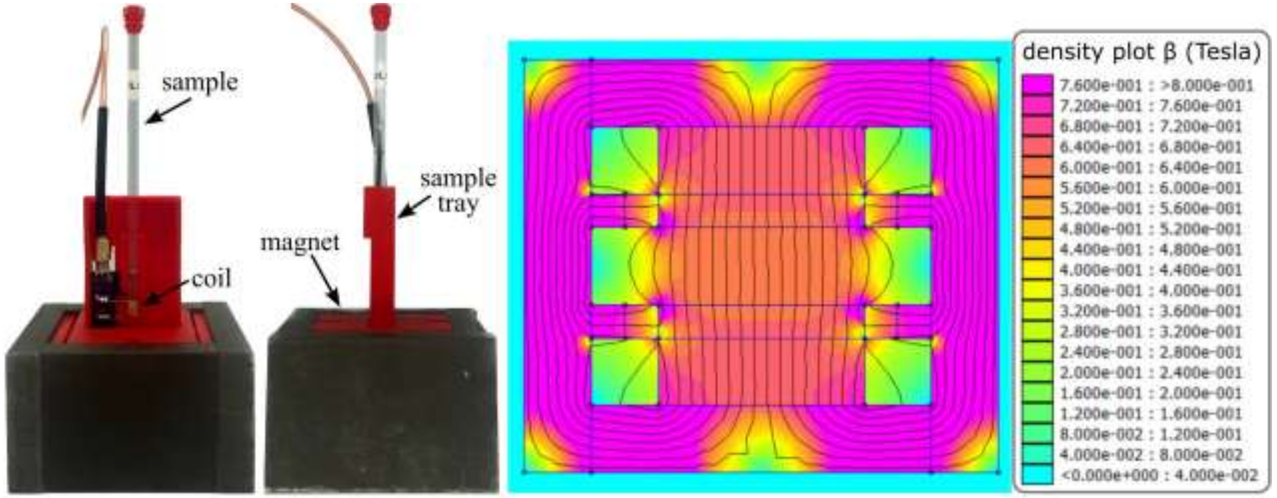
N42 magnet





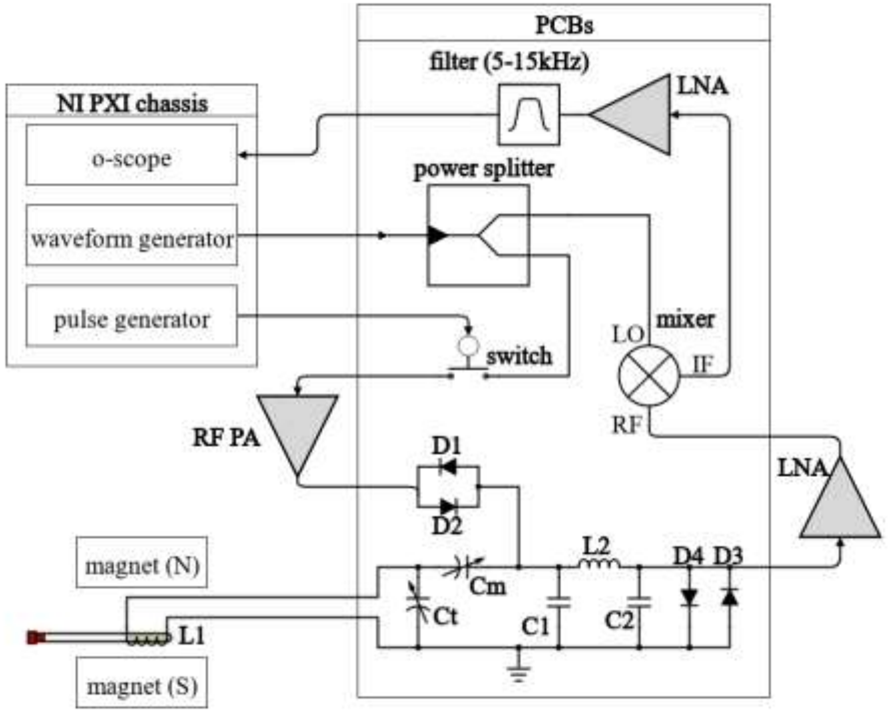
Sample location

Fully assembled



RF Electronics

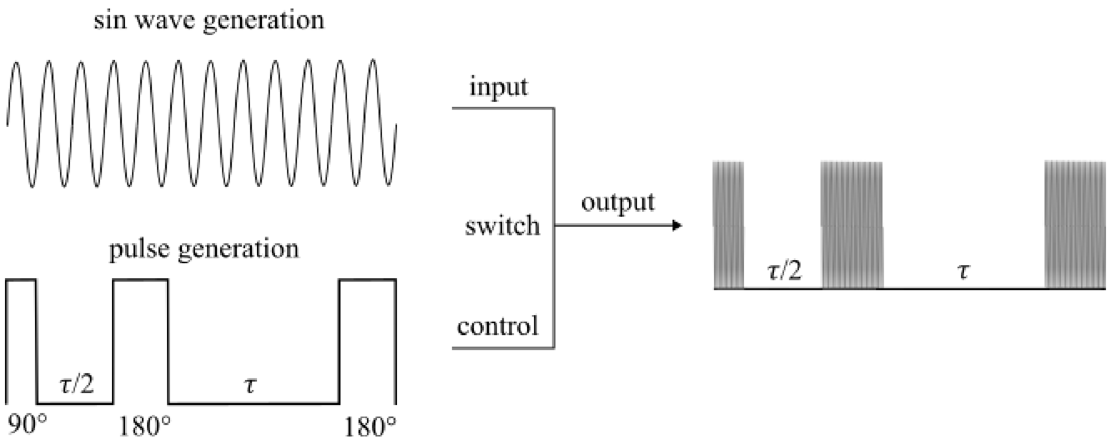
- A single 24 V DC power supply is required
- Impedance of all cables and PCB traces matched to 50 Ω
- Waveform generator → sine wave at Larmor frequency
- Pulse generator → follows CPMG pulse train
- Duplexer (crossed diodes) isolates probe and LNA

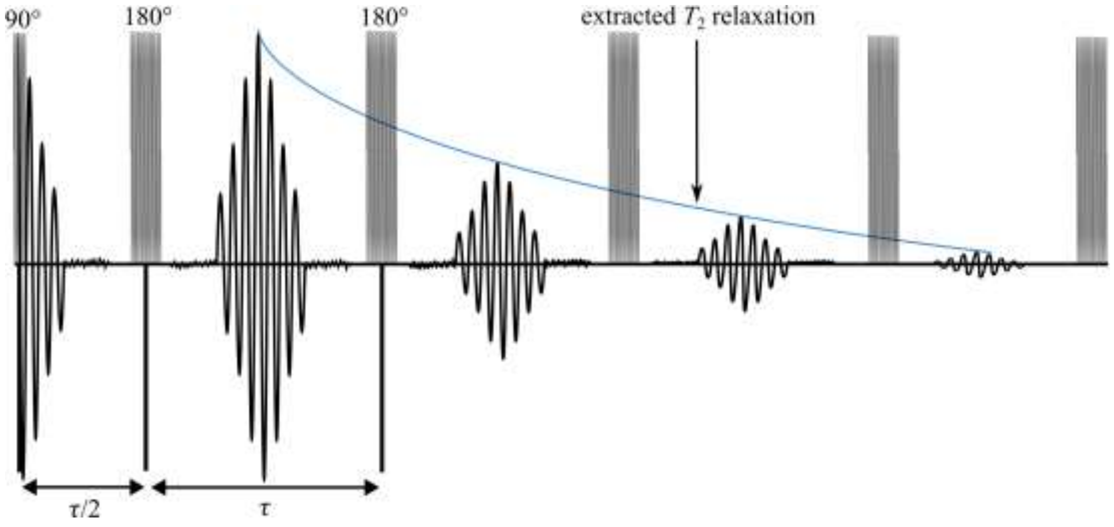


Signal Generation and Control

- NI PXI chassis
  - Arbitrary waveform generator
  - Pulse train generator
  - 16-bit digitizer

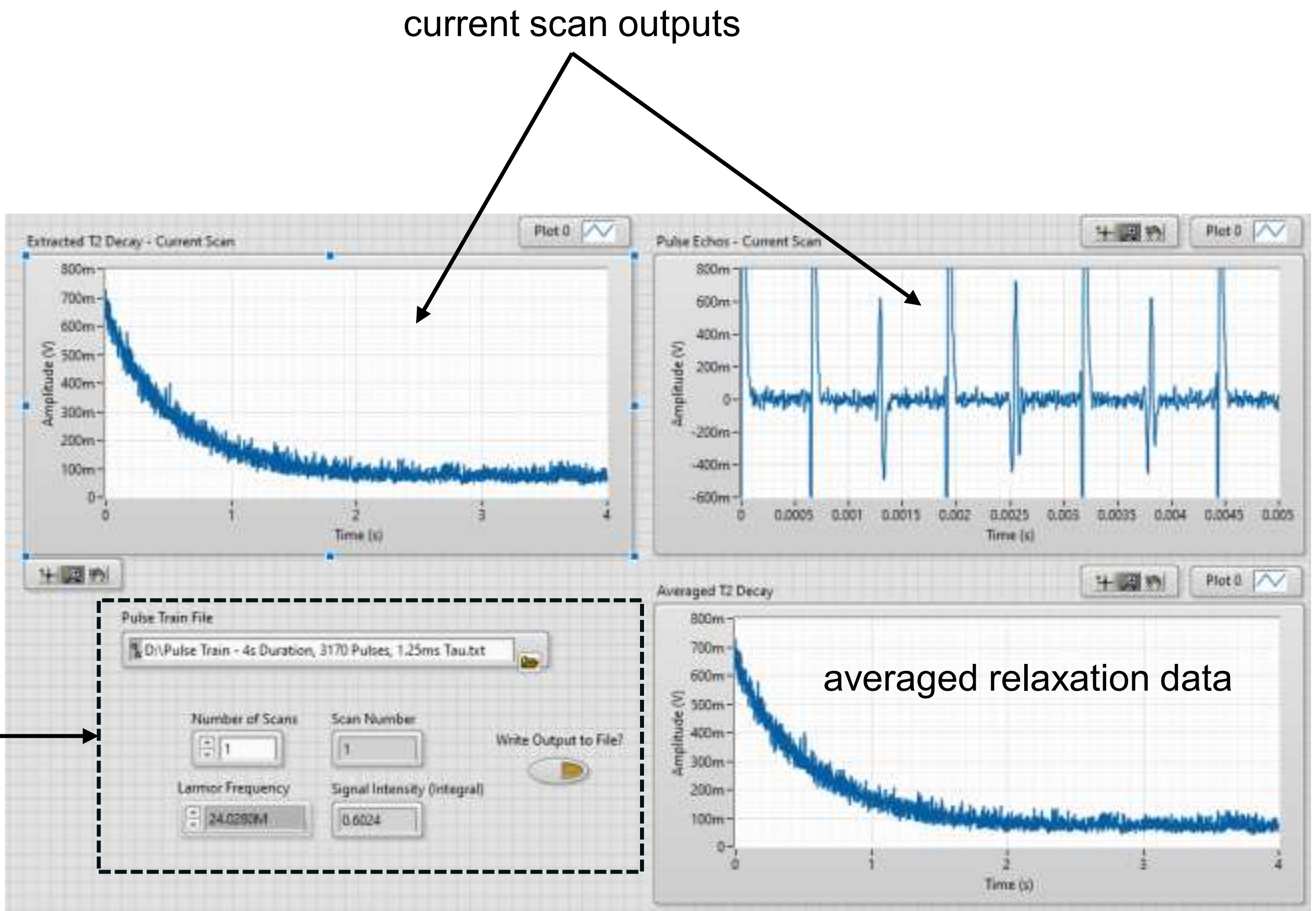
- Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence
  - $90°$ pulse duration is 7 μs
  - $\tau = 1.25$ ms





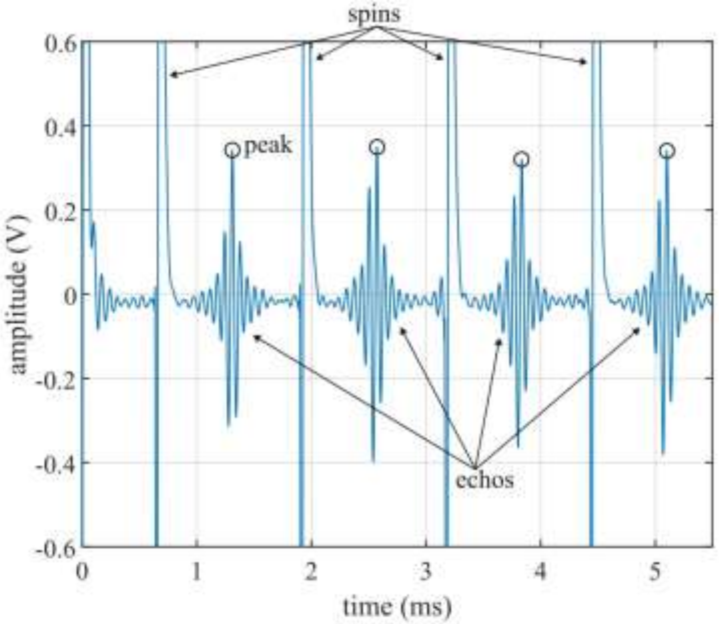
Data Acquisition

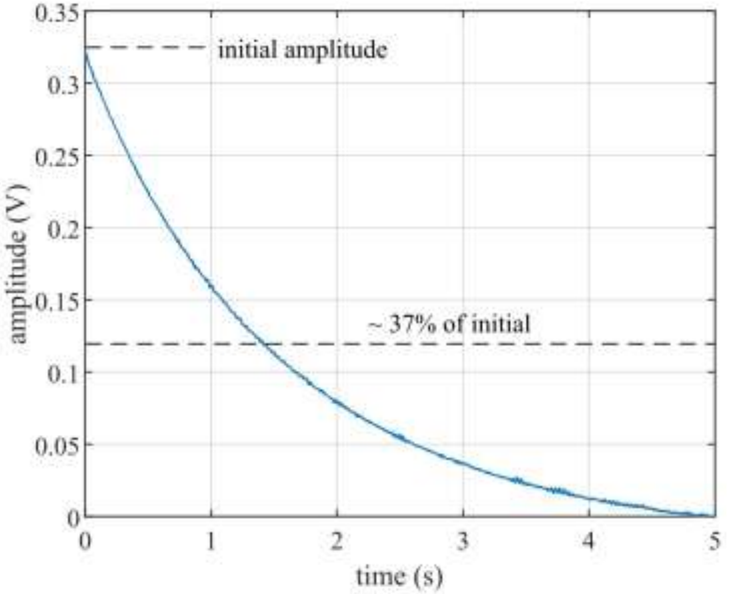
- LabVIEW GUI serves as the front end
- Each test comprises 5 scans (averages)
- Time for T_2 curve acquisition < 10 seconds
- Thermocouple used for frequency calibration



TD-NMR Signals and MP Content

- T_2 relaxation modeled as $M_{\mathrm{xy}}(t) = M_0 \exp(-t/T_2)$
- Relaxation rate is the reciprocal of relaxation time (i.e., $R_2 = 1/T_2$)
- Linear relationship between R_2 and MP concentration well established

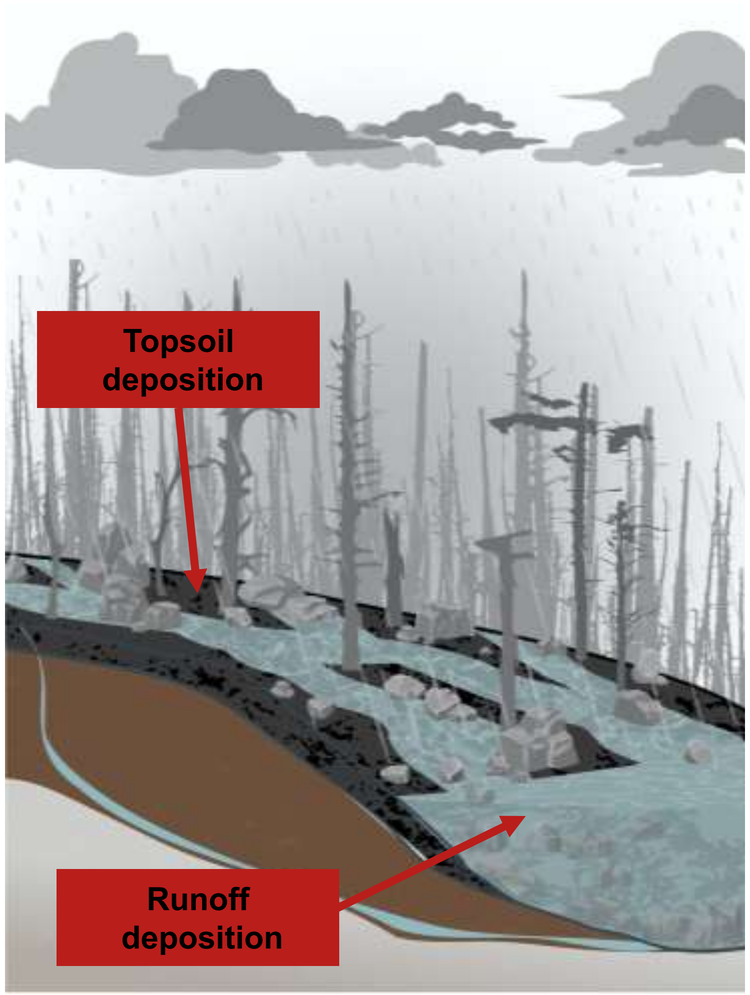




Use Case: Wildfire Ash

Why Monitor Magnetic Contents of Wildfire Ash?

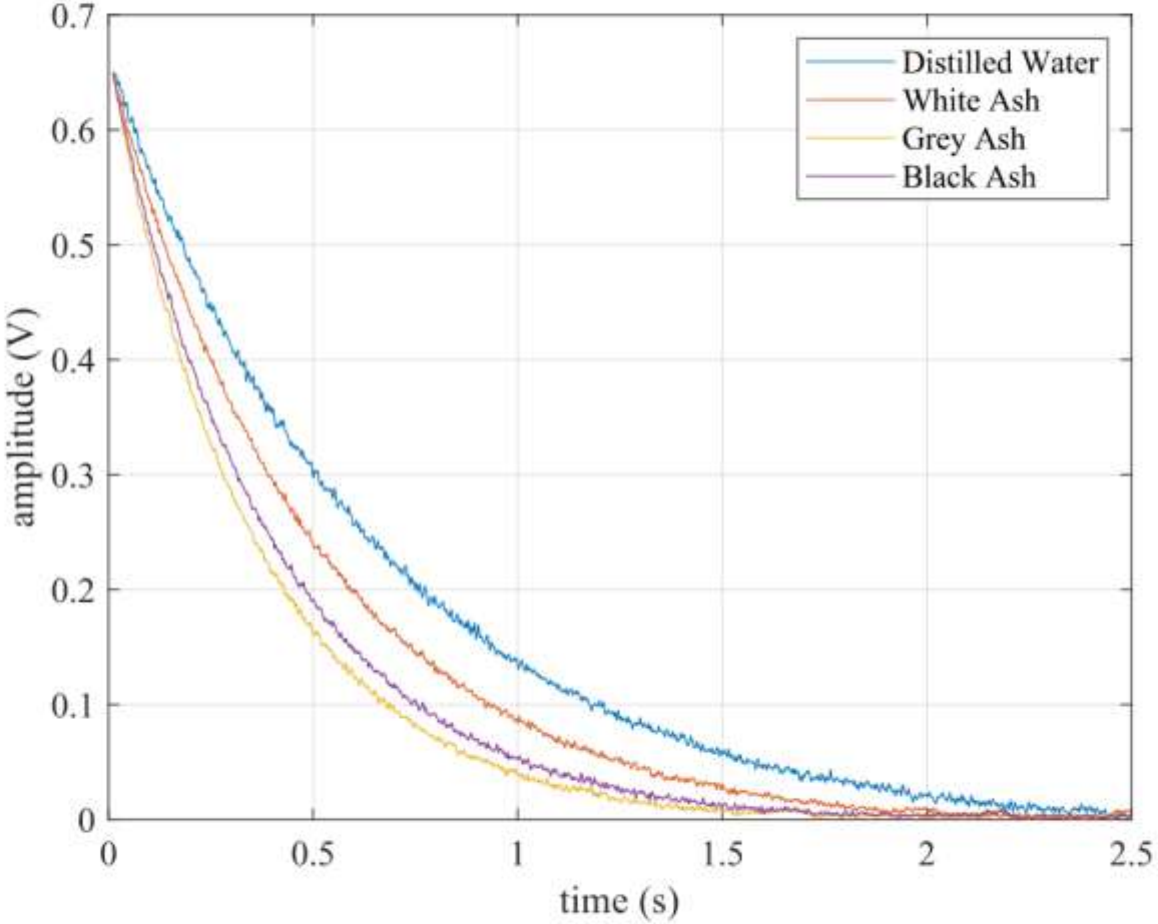
- Effects on topsoil
  - Ash deposits enhance magnetic content in soil
  - Magnetic properties are closely related to climate & rainfall
- Deposition through runoff water
  - Nearby bodies of water accumulate magnetic content
  - Nanoscale magnetite is linked to brain disease
- Understand fire severity and the reaches of magnetic deposition



USGS, "How wildfires threaten U.S. water supplies," Water Data Labs, 06-Nov-2020. [Online]. Available: https://labs.waterdata.usgs.gov/visualizations/fire-hydro/index.html#/. [Accessed: 28-Oct-2022].

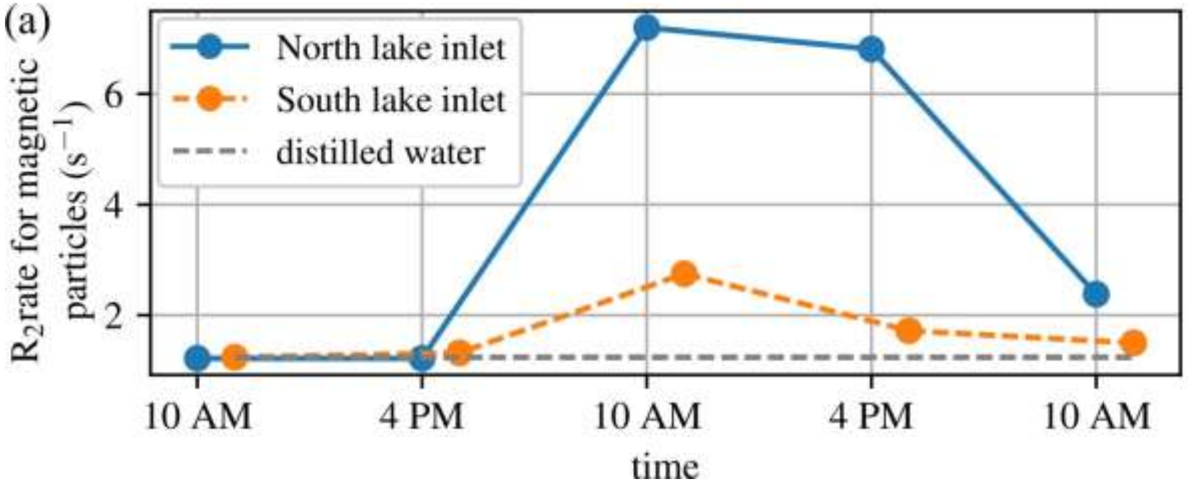
NMR Relaxometry with MPs

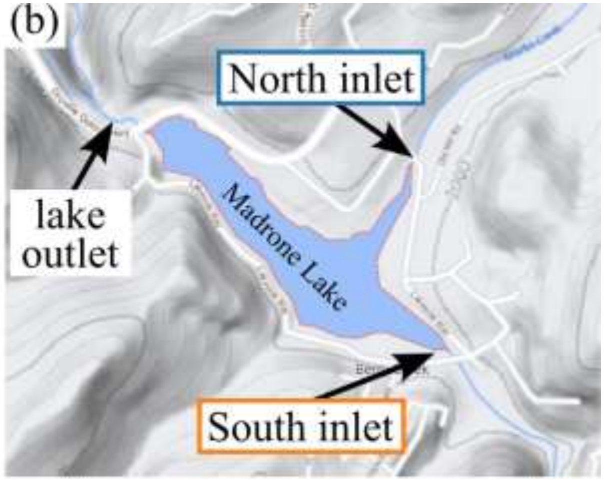
- 10 total ash samples
- 20 mg in 20 mL of water
- Distilled water used as reference
- R_2 extracted via least squares regression
    - $M_{xy} = M_0 \exp(-R_2 t)$



Real-time In Situ Tracking

- Monitoring wildland-urban interface fire ashes and total runoff
- 10 surface water samples collected from two inlets to Lake Madrone that were subjected to runoff following the North Complex Fire in California

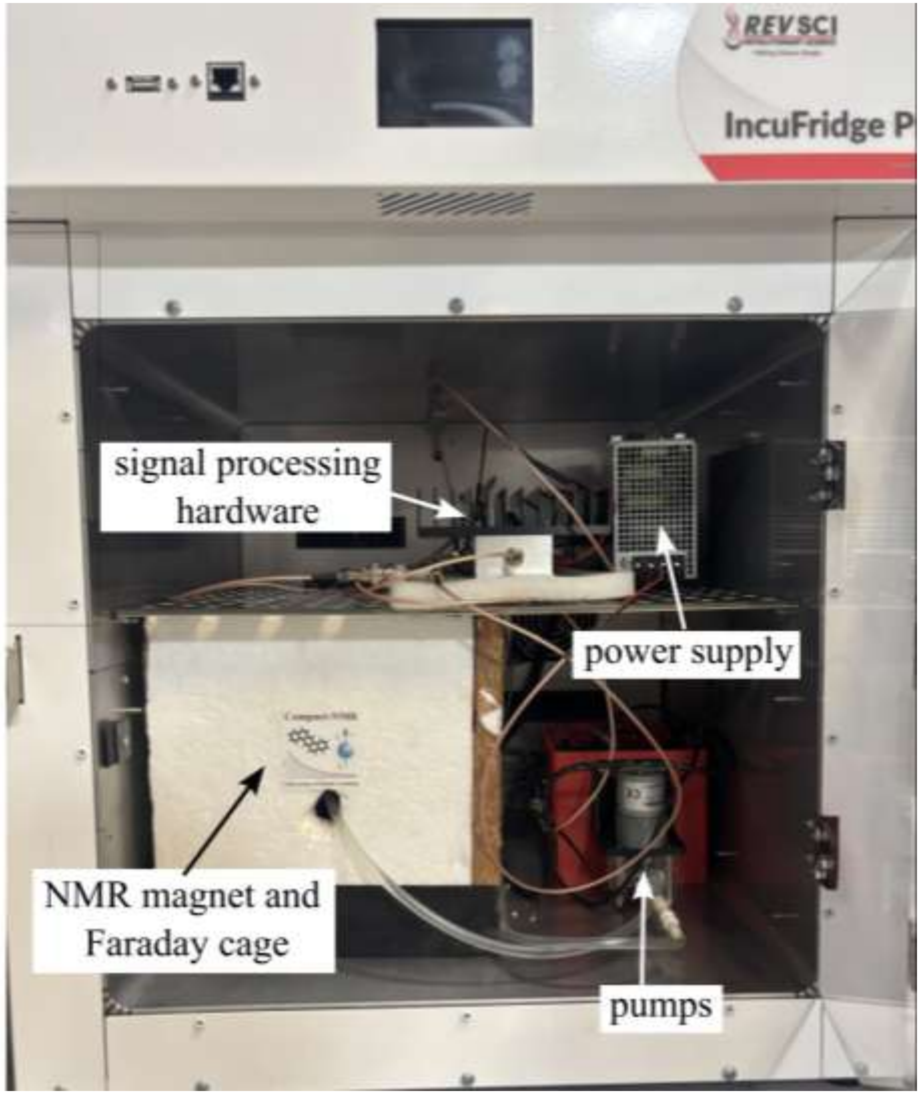




Field Deployment of In Situ NMR system

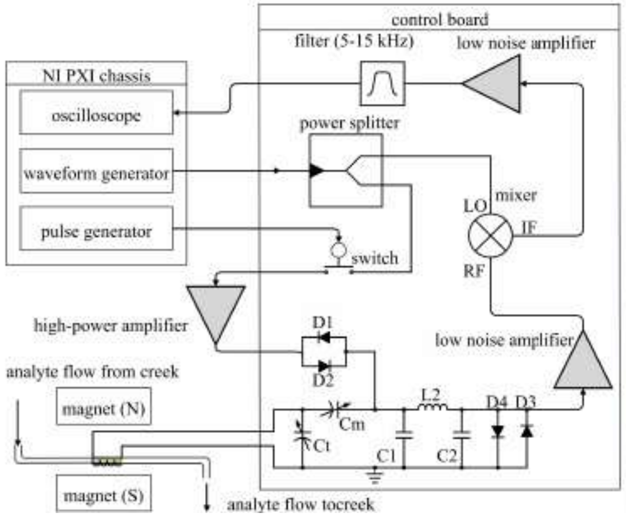
NMR in Environmental Chamber

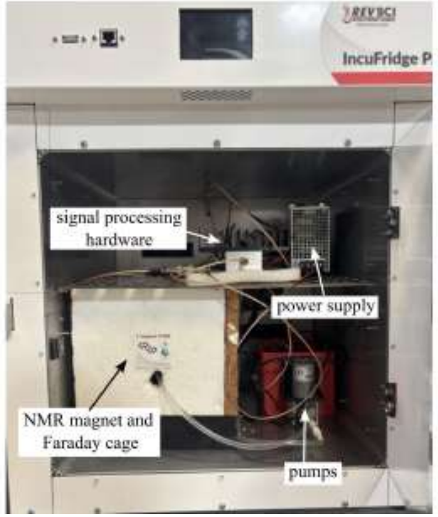
- NMR is placed in an environmental chamber for temperature control.
- Long-term, an environmental chamber would not be easy if the magnet is calibrated over a temperature range.
- Over-sized chamber used for simplicity.

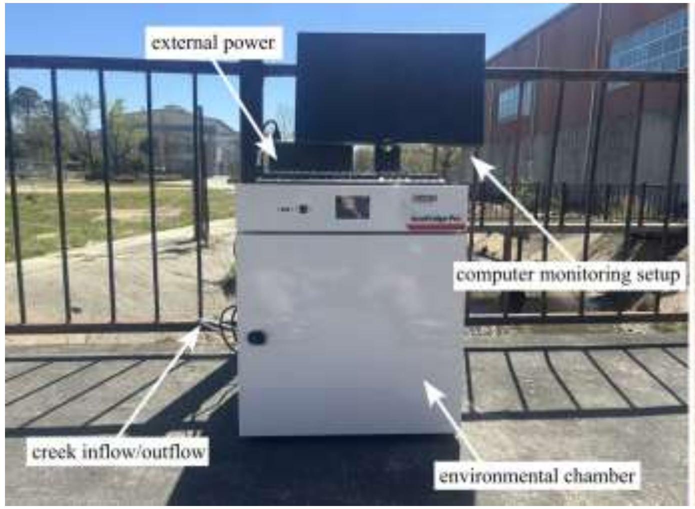


Field Deployed System

- Environmental chamber: enables temperature control for magnet and RF electronics
- Flow-through pumps: enable automatic sample collection
- NI PXI-8821: enables remote data acquisition with LabVIEW software
- Water quality sensor: measures pH, temperature, turbidity, and conductivity

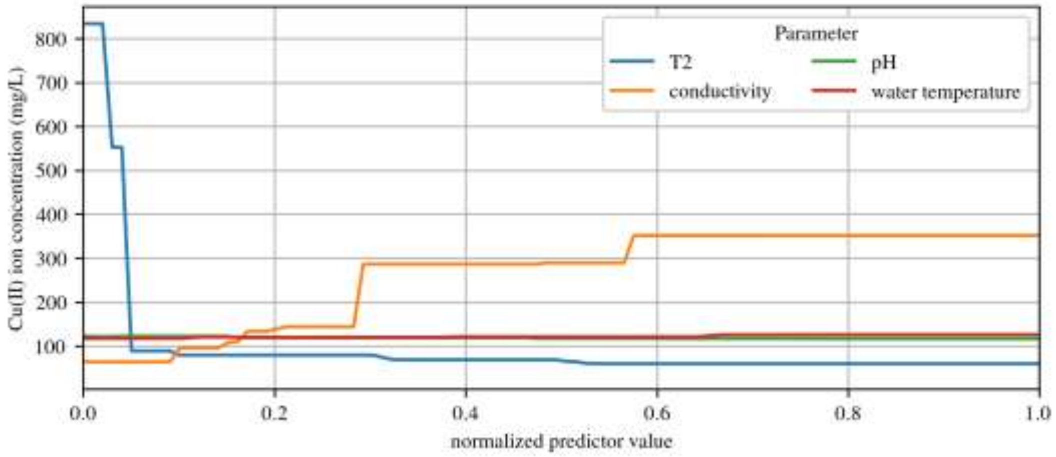


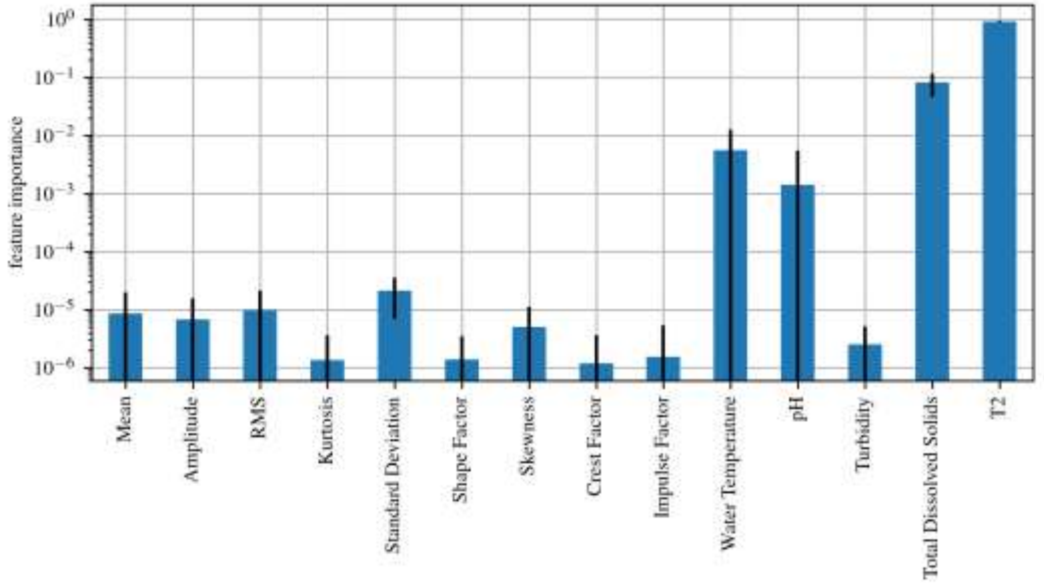




Machine Learning Model

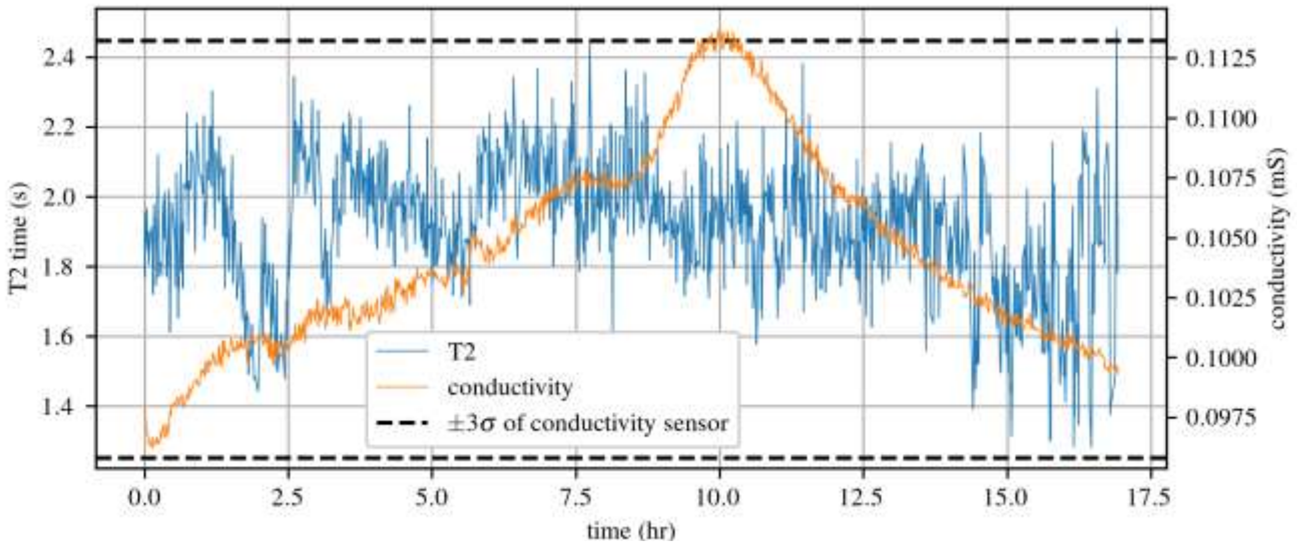
- Partial dependence plot: indicates low T2 and high conductivity cause high Cu(II) concentration and high T2 and low conductivity cause low Cu(II) concentration
- Importance plot: shows that T2 and conductivity are by far the most important
- Together, they indicate the model is thinking correctly

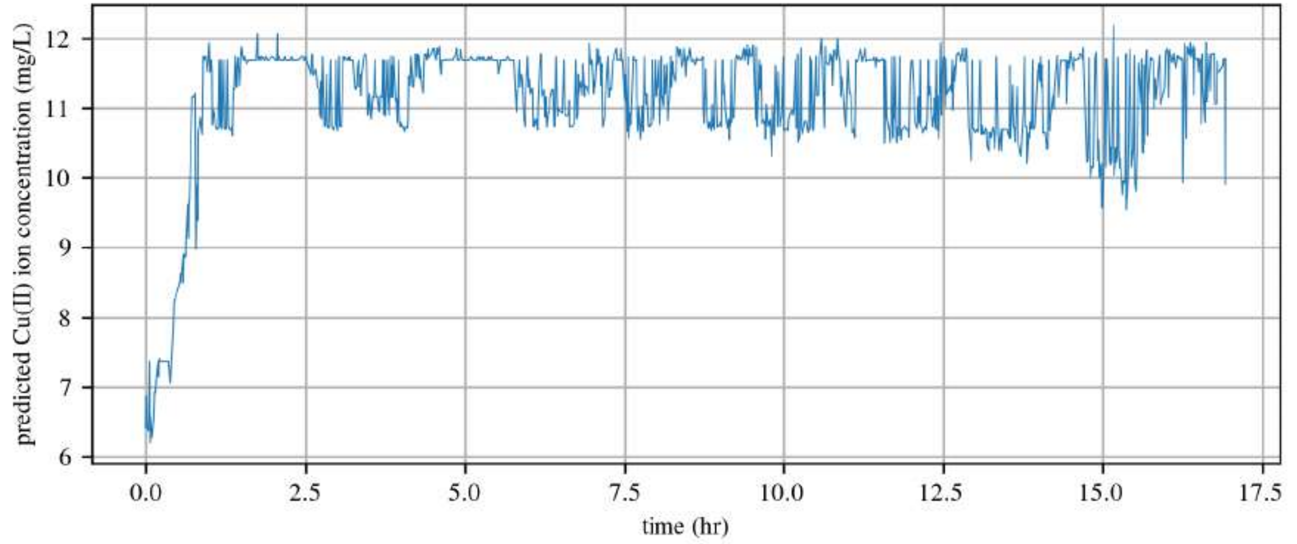




Rocky Branch Creek Data

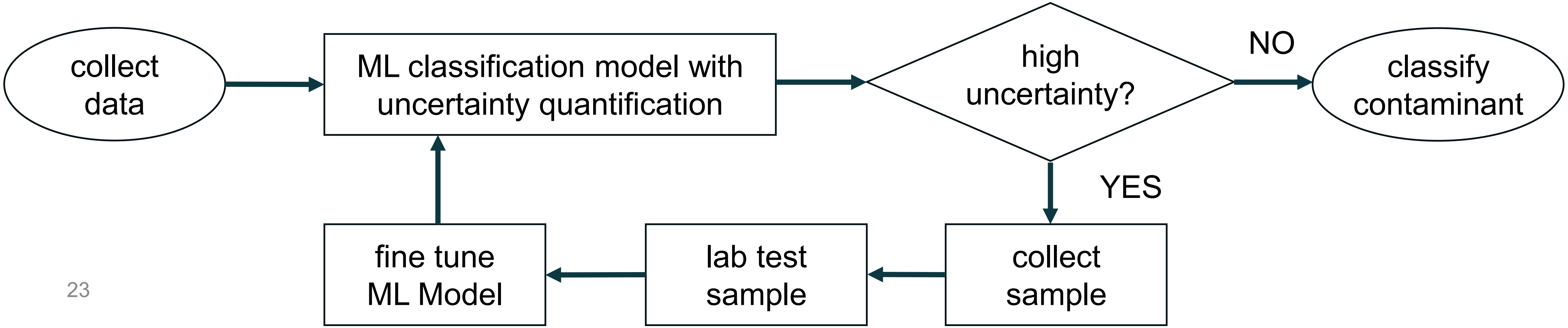
- T2 and conductivity data collected in-situ over 17 hours
- T2 and conductivity (within 3σ) stay the same
- Model predictions agree with the consistency of data collection





Future Work: Fine-tuning ML Model

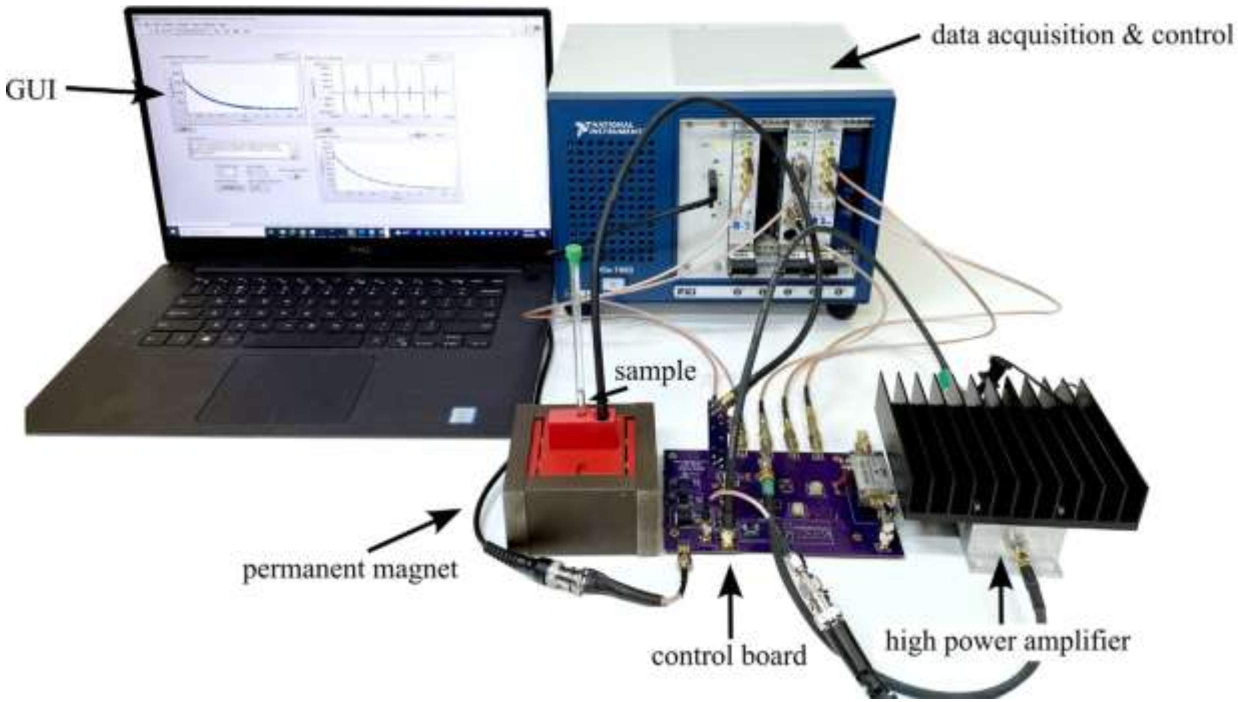
- The flow-through NMR will be deployed with an automatic water sampler and will trigger a sample based on uncertainties in predicted contaminants.
  - Collected samples will be returned to the lab for further assessment.
  - Lab results will be used to fine-tune the model
  - Over time, fewer lab samples will be required as the AI/ML model will more closely track the system.
  - Unknown contaminant events will trigger a sample to be taken, limiting False Negatives.



FPGA-Based Time-Domain NMR Relaxometry

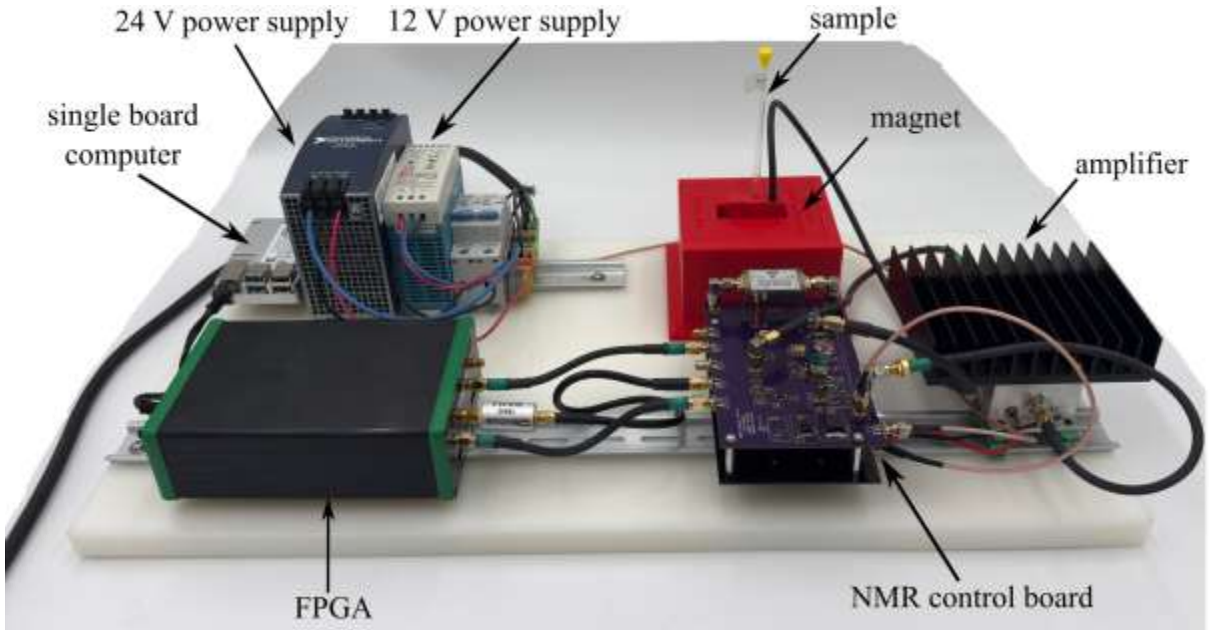
Current NMR System

- The previous NMR system requires a PXI-1062
- Thousands of dollars, more than 100 watts, almost 10 kg.
- Requires a personal computer to use.
- Not field-deployable.



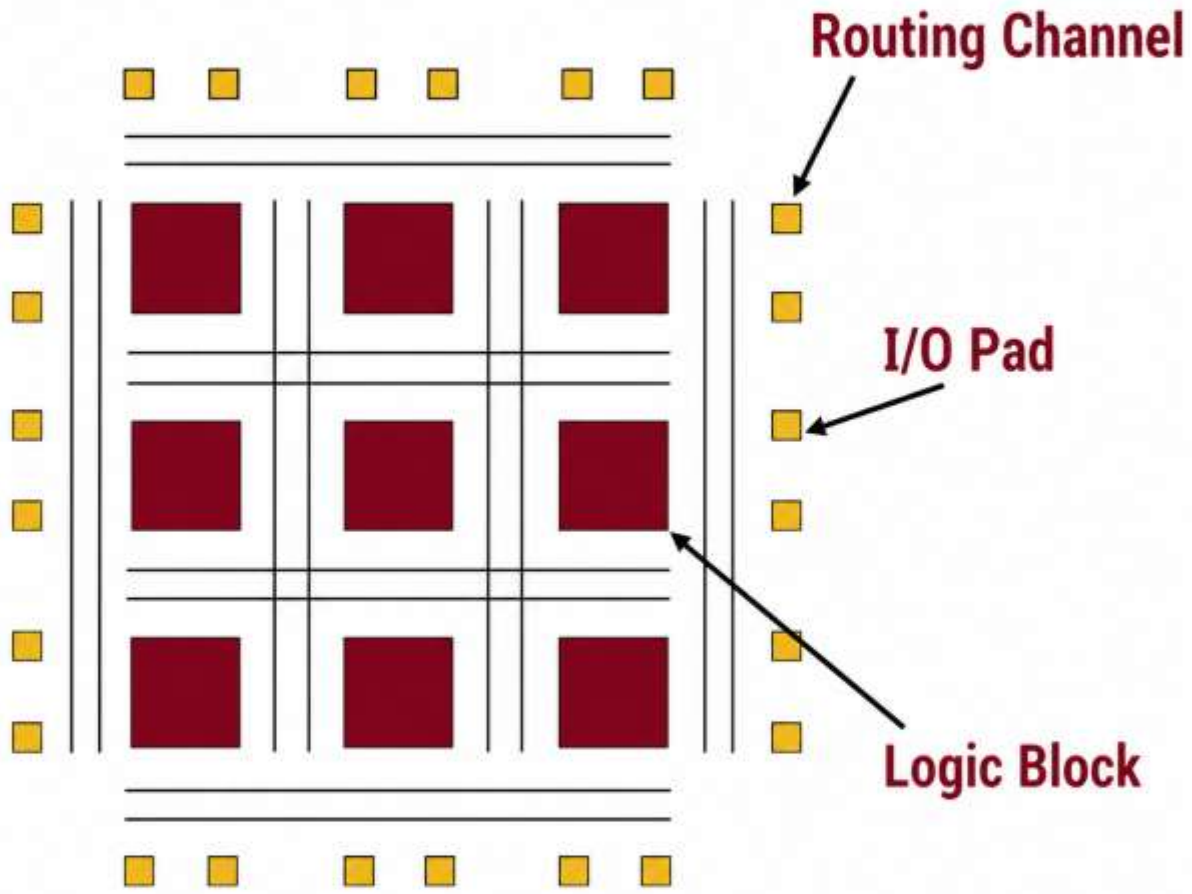
System Integration Overview

- Entire NMR control stack consolidated on a DIN-rail-mounted assembly
- FPGA (Zynq-7020-based Eclypse Z7) replaces:
  - Traditional waveform generators
  - Standalone DAQ systems
  - External timing/control units
- Direct integration of:
  - RF generation (DDS-based Larmor excitation)
  - CPMG pulse sequencing (hardware FSM)
  - High-speed ADC streaming + DMA pipeline



Field Programmable Gate Arrays

- FPGA development boards are configurable hardware platforms
- Fast digital signal processing capabilities
- Difficult to work with
- Low-cost, low-power
- Small

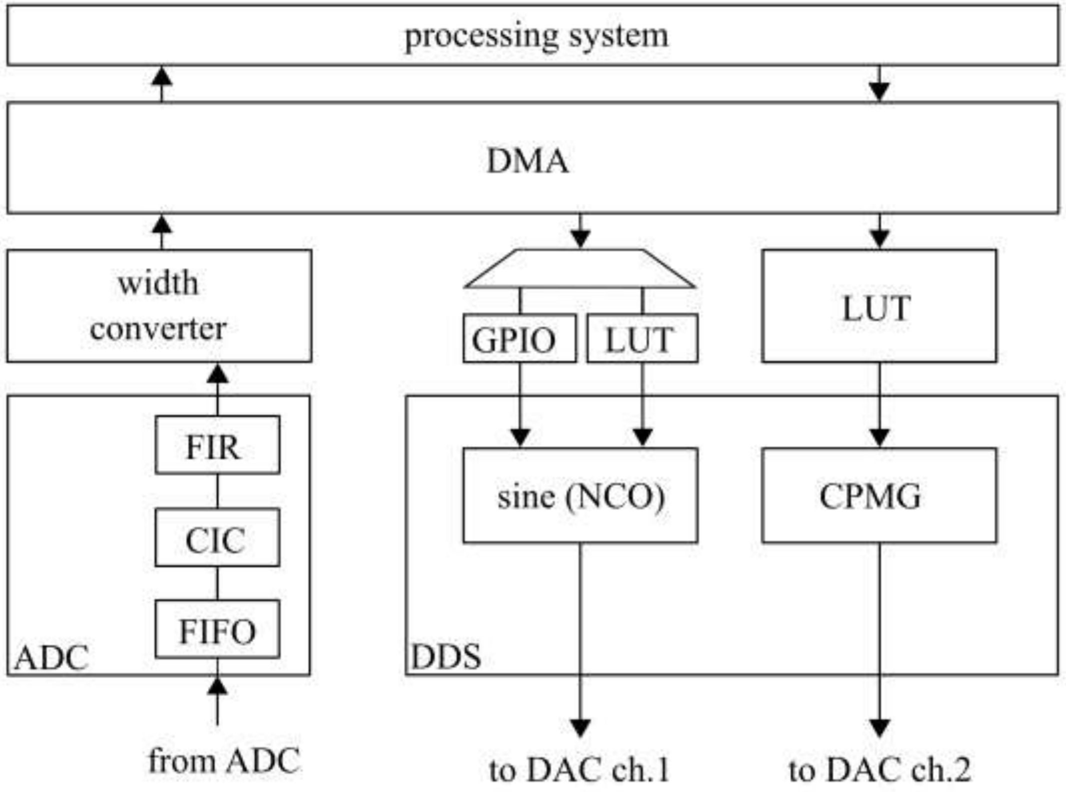


FPGA - Eclypse Z7

- Eclypse Z7 combines FPGA + ARM processor on a single Zynq-7020 SoC
- An embedded Linux image is run on the ARM SoC, which communicates with the FPGA via Direct Memory Access
- SYZYGY-standard ports allow plug-and-play Zmod daughter cards with no custom interfacing
- Zmod DAC 1411 and Zmod Digitizer 1430 snap directly onto the board
- Less power and cost

FPGA System Block Diagram

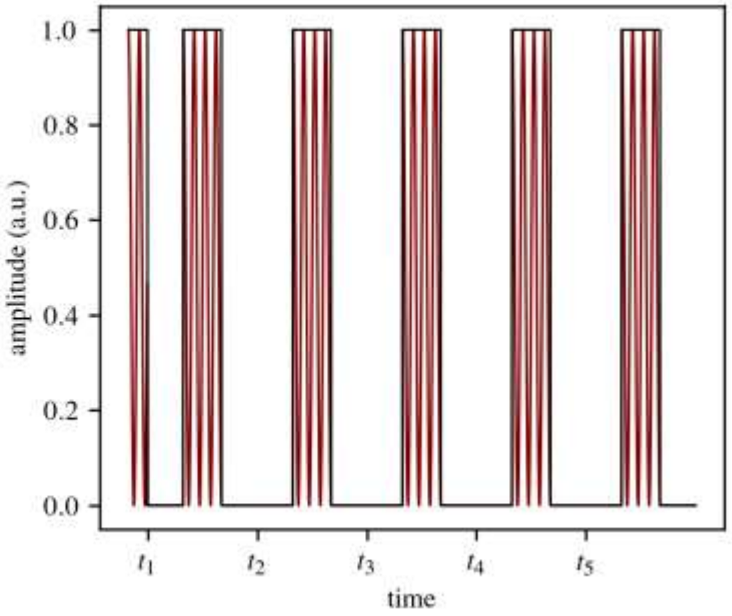
- FPGA handles signal generation, acquisition, and transfer
- DAC → generates RF excitation + gating signals
- ADC → captures NMR response signal
- DMA → streams data to memory efficiently
- ARM processor → configuration and control
- Programmable logic (PL) → parallel DSP operations
- Modular architecture → easy integration with NMR hardware

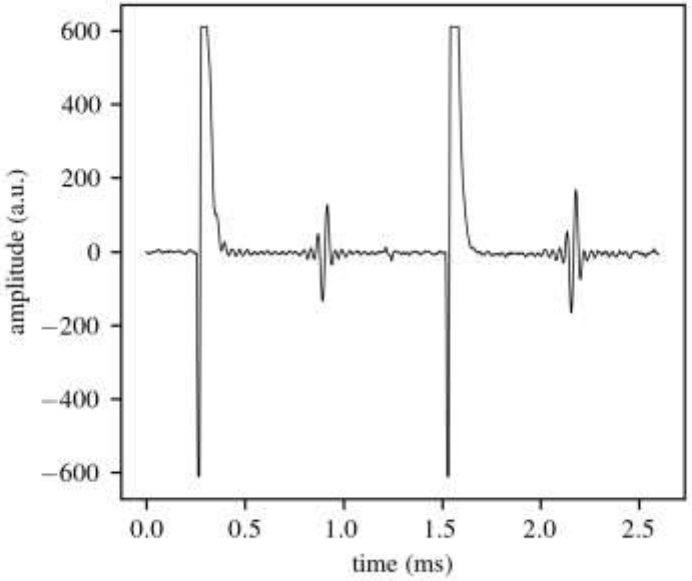


Results

Echo Response by CPMG Signal

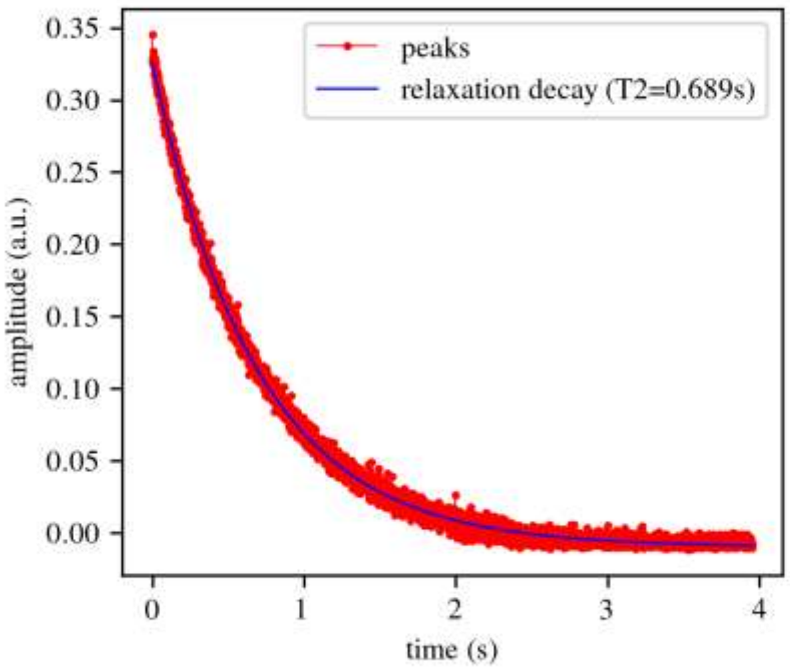
- First two 180° spin echo signals of n-decane captured by FPGA
- Echoes observed at intervals of t = n(2τ)
- Large amplitude spike followed by free induction decay ringdown
- Confirms successful spin refocusing by CPMG sequence

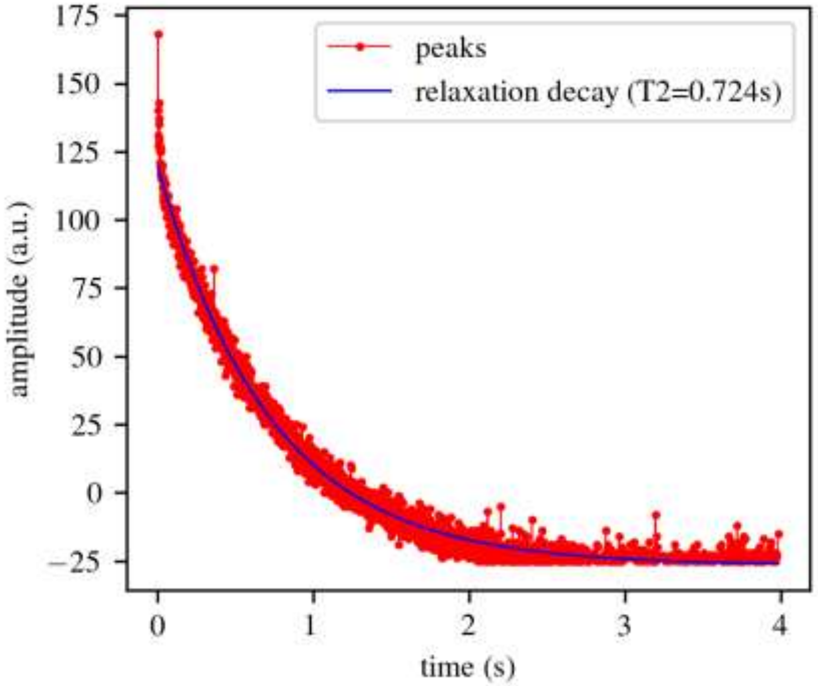




T_2 Relaxation: PXI vs FPGA Comparaison

- Both PXI (on the left) and FPGA (on the left) systems show consistent exponential FID decay.
- Extracted T_2 values are in close agreement across both platforms.
- Overall relaxation behavior is preserved despite hardware simplification.





Cost and Power Efficiency Comparison

- ~95.6% reduction in active power consumption
- ~97.3% reduction in system cost
- Enables battery-powered or field-deployable operation

Platform	NI PXIe-1062Q	Digilent Eclypse Z7
Cost	~$37,000	~$900
Input Voltage Range	120 VAC	9–12 VDC
Input Current	8 A	5 A
Width (mm)	271.4	99
Length (mm)	396.5	160
Weight (kg)	8.8	0.612

Metric	NI PXIe-1062Q	Eclypse Z7
Idle Power (W)	109.0	2.9
Active Power (W)	110.6	4.9

Future Work

- FPGA
  - The FPGA's serial connection is limited to ~900 Kb/s
  - Using Ethernet or another method to increase bandwidth would reduce complexity by eliminating the need for CIC and FIR filters.
- Ease of Use
  - Use of the system in its current state requires a Linux shell
- Packaging
  - Further reduction in size and cost would make this system deployable in even more areas.

Acknowledgement

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Thank You for Your Time

NMR Hardware

https://github.com/ARTS-Laboratory/Paper-2025-Continuous-Water-Quality-Monitoring-using-Field-Deployable-NMR

FPGA Controller

https://github.com/ARTS-Laboratory/signal-processing-instrument-for-NMR

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