



# Research Proposal

**Optimization of an NV-Diamond CW-ODMR Magnetometer for Sentinel Lymph  
Node Detection**

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# 1 Introduction

NV diamonds has shown great promise in the field of sensing and navigation due to their high sensitivity to small changes in magnetic fields. Its incorporation into magnetometers is favorable due to its functionality at room temperature and ability to be made into a small size. One crystal structure consists of a vacancy and the replacement of a carbon atom with a nitrogen atom. From these defects, the vacancy holds two electrons and magnetic fields alters the spin states of the pair. By shining a beam of green light into the NV diamond, the intensity of the resulting red beam of light can be measured to determine the magnetic field. This project turns last year’s breadboard NV-diamond magnetometer [1] into a soldered, characterized instrument, then tests whether it can locate a magnetic tracer in a lymph-node phantom. It is scoped for about 3 hours of work per week.

When cancer spreads, it usually travels first through lymphatic vessels to the nearest lymph nodes, called sentinel nodes. Surgeons find these nodes by injecting a tracer near the tumor and following where it collects. The standard tracer is radioactive. A magnetic alternative, iron-oxide nanoparticles located with a handheld magnetometer, has been shown non-inferior to the radioactive method in breast cancer [2, 3]. A cheap, sensitive magnetometer therefore has a concrete use. Last year’s device recorded dips in its fluorescence spectrum but was too noisy to extract a field value, and its sensitivity was never measured [1]. Phase 1 of this project fixes this. Phase 2 applies the improved device to a phantom.

## Intellectual Merit

The project will expand upon quantum sensing by creating a robust model using inexpensive materials. The construction of such a system utilizes quantum principles such as electron spin and the Zeeman effect to conduct high precision measurements of magnetic fields. The magnetometer that we seek to create will become more compact and professional to allow for further variations to the design to occur in the future for other applications. Moreover, the project produces a measured noise budget for a low-cost LED-based NV magnetometer where noise sources dominate, and how far the device sits above its own fundamental limit. It then benchmarks the device on a sentinel-node phantom using the same metrics as clinical probe studies [3], so results compare directly with commercial probes.

## Broader Impact

A soldered, enclosed, documented device gives future QLab groups a working platform instead of a breadboard to reverse-engineer. The phantom study tests whether low-cost quantum sensors are a plausible route to radiation-free sentinel node detection. It makes no clinical claims. Magnetometers of this type would have many other uses such as imaging for biomedical practices or surface analysis and GPS-free navigation which could be extrapolated from our base model but is beyond the scope of this project.

# 2 Background and Prior Work

## How the sensor reads a magnetic field

An NV-diamond contains a point defect by replacing a carbon atom for a nitrogen atom, and a vacancy containing two electrons. The NV center can have several charge states. The neutral NV<sup>0</sup> consists of the nitrogen atom having 5 valence electrons, 3 are covalently bonded to neighboring

carbon atoms and the other 2 are located in the vacancy. In its negatively charged form ( $\text{NV}^-$ ), its lowest-energy state has three sub-levels, labeled  $m_s = 0, \pm 1$ . At zero field, the  $m_s = \pm 1$  levels sit about  $D = 2.87$  GHz above  $m_s = 0$ .

Green light shone into the diamond drives a cycle that makes these levels distinguishable. From  $m_s = 0$ , the center returns by emitting red light. From  $m_s = \pm 1$ , it often takes a detour that emits no light and lands back in  $m_s = 0$ . So continuous green light pumps centers into  $m_s = 0$ , and  $\pm 1$  centers glow less.

Microwaves at the right frequency move centers from 0 into  $\pm 1$ , so red fluorescence dips. A magnetic field component  $B_{\parallel}$  along the NV axis moves the two dips to

$$f_{\pm} = D \pm \gamma B_{\parallel}, \quad \gamma \approx 28 \text{ kHz}/\mu\text{T}. \quad (1)$$

The splitting between dips,  $2\gamma B_{\parallel}$ , is the field measurement. Diamond has four possible NV axis directions, so a general field produces up to eight dips. At modest fields the dips are near-symmetric about 2.87 GHz, which is a useful sanity check.

## What limits sensitivity

Sensitivity  $\eta$  is the smallest field change detectable in one second of averaging, in units of  $\text{T}/\sqrt{\text{Hz}}$ . At the fundamental (shot-noise) limit it scales as

$$\eta \propto \frac{\Delta\nu}{\gamma C \sqrt{R}}, \quad (2)$$

where  $\Delta\nu$  is the dip width,  $C$  its depth (contrast), and  $R$  the rate of detected red photons. Narrower and deeper dips and more collected light all help. Real devices sit above this limit because of LED brightness fluctuations, electronic noise, stray lab fields, and temperature drift of  $D$ .

Lock-in detection addresses most of these. The microwave drive is switched or shifted at a fixed rate, and only the part of the photodiode signal that varies at that rate is kept. Slow drifts and 60 Hz mains pickup fall outside that window and are rejected.

## Prior magnetometers

| Device                     | Light source   | Sensitivity                                                                      |
|----------------------------|----------------|----------------------------------------------------------------------------------|
| Krumins et al. [4]         | 0.5 W laser    | 2.3 nT/ $\sqrt{\text{Hz}}$ measured; 585 pT/ $\sqrt{\text{Hz}}$ shot-noise limit |
| Williams et al. [5]        | High-power LED | $\sim 1 \mu\text{T}/\sqrt{\text{Hz}}$                                            |
| Last year's QLab build [1] | LED            | Not measured                                                                     |

The 585 pT/ $\sqrt{\text{Hz}}$  figure is a limit for that laser system, not a target an LED build can beat. The realistic reference for this project is the  $\sim 1 \mu\text{T}/\sqrt{\text{Hz}}$  LED device [5]. Our design follows the low-cost component choices of Bülau et al. [6].

## Magnetic sentinel node detection

Clinical magnetic probes are benchmarked on phantoms. Nieuwenhuis et al. [3] milled wells into a non-magnetic Delrin block. A  $5 \mu\text{L}$  well of the clinical tracer Magtrace ( $140 \mu\text{g}$  iron) represented one lymph node. The commercial Sentimag probe detected it out to 10 mm, a nonlinear probe to

12 mm, and a gamma probe past 120 mm. Detection meant exceeding the background mean by one standard deviation.

Superparamagnetic iron-oxide particles show essentially no net field until an applied field magnetizes them. Sekino et al. [7] used a permanent magnet with a Hall sensor. Kuwahata et al. [8] built an NV-based probe for this task, magnetizing particles with an alternating coil field of several hundred microtesla and reading out with lock-in detection.

**Project Need / Research Gap.** Last year’s reported dips (2.81 and 2.845 GHz) both lie below 2.87 GHz and are not symmetric about it [1]. Whether they were NV resonances is therefore unresolved, and no sensitivity was measured. Separately, we have not found an LED-based, low-cost NV sensor benchmarked on a standard sentinel-node phantom; the one NV study we found [8] used a fiber-coupled laboratory probe.

### 3 Research Goals

#### Goal 1— Rebuild the Magnetometer and Validate Its Spectrum

**Question / Objective:** Rebuild last year’s device as a soldered, enclosed unit and establish that it records genuine NV resonances.

**Approach:** Move the circuit off the breadboard, mount the diamond on the resonator with optical cement, and record repeated microwave sweeps. Apply known fields from a calibrated coil pair and track how the dips move.

**Measurement / Output:** Sweep data with fitted dip centers, widths, and depths; a plot of dip splitting against applied field.

**Success Criterion:** Three repeated sweeps give dip centers that agree within one dip width, the dips pair up symmetrically about  $\sim 2.87$  GHz, and their splitting grows linearly with coil current.

#### Goal 2— Measure and Reduce the Noise Floor

**Question / Objective:** Measure the device’s sensitivity in  $\text{nT}/\sqrt{\text{Hz}}$ , identify which noise sources dominate, and reduce them.

**Approach:** Record the output at a fixed operating point, compute its noise spectrum, and convert to field units using the measured dip slope. Add one improvement at a time—averaging, lock-in detection, LED-noise subtraction, shielding—and re-measure after each.

**Measurement / Output:** A noise budget listing each source’s contribution, the sensitivity before and after each change, and the calculated shot-noise limit for comparison.

**Success Criterion:** Sensitivity is reported with a stated uncertainty, each change’s effect is quantified, and the final device reaches  $\sim 1 \mu\text{T}/\sqrt{\text{Hz}}$ , matching the published LED design [5].

### Goal 3— Detect a Magnetic Tracer in a Lymph-Node Phantom

**Question / Objective:** Determine how far from the sensor a node-sized amount of iron-oxide tracer can be detected.

**Approach:** Fill wells in a non-magnetic phantom with a known iron-oxide dose, magnetize it with an applied field, and step it away from the sensor in 1 mm increments. Use the detection threshold of Nieuwenhuis et al. [3].

**Measurement / Output:** Signal-versus-distance curves for at least two tracer amounts, each measured in triplicate, and a maximum detection distance.

**Success Criterion:** A 140  $\mu\text{g}$ -iron sample (one clinical node dose [3]) is detected above threshold at a measured distance, and the signal-versus-distance curve is compared quantitatively with the dipole model of Eq. (4).

## 4 Proposed Methods and Research Design

The plan keeps last year’s core components—green LED, ADF4351 microwave synthesizer, resonator, red filter, photodiode with transimpedance amplifier, and Raspberry Pi control [1]—and changes how they are assembled, calibrated, and read out. Details below are a starting plan and will change as preliminary measurements require.

### Rebuild (Goal 1)

The circuit moves from breadboard to a soldered perfboard or simple PCB inside an enclosure, so wiring and diamond position stop changing between runs. The diamond is fixed to the resonator with optical cement, leaving the light path clear. A second photodiode samples the LED directly, so LED brightness fluctuations can later be subtracted from the signal.

Known test fields come from a hand-wound Helmholtz coil pair: two coaxial loops of radius  $R$ , spaced  $R$  apart, with  $N$  turns each and current  $I$ . Its central field is

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 N I}{R}, \quad (3)$$

cross-checked with an inexpensive Hall-effect sensor. Each sweep is fit with one Lorentzian per dip, giving center, width, and depth.

### Noise floor (Goal 2)

The microwave frequency is parked on the steepest side of one dip, and the photodiode output is recorded for several minutes. The noise spectrum of that record, divided by the dip’s slope (signal per  $\mu\text{T}$ ), gives sensitivity in  $\mu\text{T}/\sqrt{\text{Hz}}$ . Repeating with microwaves off and with the LED off separates light-related noise from electronic noise. Improvements are then added one at a time so each effect is measurable:

1. averaging many sweeps (many-shot measurement);
2. lock-in detection in software, toggling the microwaves on/off or between two frequencies at a rate away from 60 Hz harmonics;
3. subtracting the reference-photodiode signal to cancel LED fluctuations;
4. physical fixes suggested by the noise budget: shielding cables, moving nearby electronics, stabilizing temperature.

### Phantom study (Goal 3)

The phantom is a non-magnetic block (3D-printed PLA or machined plastic) with wells, modeled on the openly published Delrin design of Nieuwenhuis et al. [3]. The tracer is a commercial iron-oxide nanoparticle suspension or ferrofluid of known iron concentration, diluted so one  $5\mu\text{L}$  well holds  $140\mu\text{g}$  iron, the clinical node dose [3].

The tracer is magnetized either by a permanent magnet [7] or by an alternating coil field read out with lock-in detection [8]; preliminary tests decide which. The magnetizing field also reaches the sensor, so every reading is paired with a reading of an empty well at the same position and subtracted. The sample is stepped away from the sensor in 1 mm increments on a manual stage, three times per distance.

### Feasibility estimate

A magnetized sample acts as a small magnet of moment  $m$ . On its axis, at distance  $r$ , its field is

$$B(r) = \frac{\mu_0 m}{2\pi r^3}. \quad (4)$$

The largest possible  $m$  comes from treating  $140\mu\text{g}$  iron as  $\sim 194\mu\text{g}$  of fully magnetized magnetite ( $92\text{ A m}^2/\text{kg}$ ), giving  $m \approx 1.8 \times 10^{-5}\text{ A m}^2$ . The resulting field is at most  $\sim 3.6\mu\text{T}$  at 1 cm,  $\sim 0.45\mu\text{T}$  at 2 cm, and  $\sim 0.13\mu\text{T}$  at 3 cm. Real particles are far from fully magnetized in a millitesla-scale field, so the true signal could be one to two orders of magnitude lower. Detecting a node dose at  $\sim 1\text{ cm}$ , the range clinical probes reach [3], will likely need sensitivity beyond the  $\sim 1\mu\text{T}/\sqrt{\text{Hz}}$  benchmark, long averaging, or a strong magnetizing field. This is why Goal 2 precedes Goal 3; its measured sensitivity turns this bound into a real prediction.

## 5 Expected Results and Data Analysis

With no applied field, we expect pairs of dips roughly symmetric about 2.87 GHz, each a few MHz wide, with contrast below the several percent typical of laser systems. Applying coil current should push each pair apart linearly. The slope equals  $2\gamma$  times the cosine of the angle between coil axis and NV axis, so it calibrates the response to fields along the coil axis without knowing the diamond's orientation. This is an expectation based on prior work, not an outcome assumed during analysis.

Noise analysis produces one table: each source, how it was isolated, and its contribution in  $\mu\text{T}/\sqrt{\text{Hz}}$ . The headline number is the ratio of measured sensitivity to the calculated shot-noise limit of Eq. (2); for comparison, the Krumins system sits about  $4\times$  above its limit [4]. The table shows where our gap comes from.

Phantom data are fit to  $B(r) = k/(r + r_0)^3$ , where  $r_0$  is the unknown offset between the stage zero and the sample's center. A good fit confirms the signal comes from the tracer rather than drift. Detection distance, and resolving power between two adjacent wells if time allows, are reported exactly as in [3] for direct comparison.

Uncertainty comes from repeated runs, the coil calibration, and fit residuals. A null result in Goal 3 is still informative if Goal 2 is complete: the noise budget states how much sensitivity a detection would have required.

## 6 Feasibility and Resources

The project is feasible at  $\sim 3$  hours per week because it reuses last year's working components and needs no wet lab, vacuum, or laser. October through May gives roughly 32 weeks, or about 95

hours.

| Phase                                             | Hours (approx.) |
|---------------------------------------------------|-----------------|
| Rebuild, soldering, diamond mounting              | 20              |
| Coil calibration and spectrum validation (Goal 1) | 15              |
| Noise measurement and reduction (Goal 2)          | 25              |
| Phantom construction and measurement (Goal 3)     | 25              |
| Paper and presentation                            | 10              |

Bench time is the bottleneck, so analysis code, fitting scripts, and the phantom design are prepared outside lab hours. Already available: NV diamond, green LED, ADF4351 synthesizer, resonator parts, red filter, photodiode and amplifier, Raspberry Pi, and oscilloscope [1]. Needed: perfboard or a small PCB, enclosure, optical cement, a second photodiode, magnet wire and a current-limited supply for the coils, a Hall-effect sensor, an iron-oxide nanoparticle suspension with a stated iron concentration, a micropipette, a manual translation stage (or a 3D-printed equivalent), and printing filament. If the tracer cannot be purchased with a known iron concentration, its concentration must be measured before Goal 3 results are comparable to [3].

## 7 Safety and Risk Considerations

The hazards are modest and standard for an electronics bench; the only new one is handling nanoparticle suspensions. Soldering will be done with ventilation, eye protection, and a stand for the iron. The high-power green LED can cause glare and discomfort, so no one looks directly into it, and the enclosure blocks direct view during operation. Coils heat up at high current, so they run from current-limited supplies, are checked for temperature, and are switched off before rewiring. Iron-oxide nanoparticle suspensions are handled with gloves and eye protection, spills are contained, and waste is disposed of following the supplier's safety data sheet and school chemical rules. The synthesizer's microwave output is low power; if an amplifier is ever added, it will be enclosed and approved by the supervisor first.

No laser, biological samples, animals, or human subjects are involved. All apparatus changes with new hazards will receive supervisor approval before use.

## 8 Potential Pitfalls and Alternative Strategies

### Goal 1: Rebuild the Magnetometer and Validate Its Spectrum

#### Challenge 1

The rebuilt device still shows no clean, symmetric dips.

**Solution:** Check each stage separately. Confirm microwave power actually reaches the diamond by tuning the resonator and checking its output. Check that the red filter fully blocks green light, since leaked green adds noise and hides the dips. If the signal is still weak, increase LED power or improve light collection before changing anything else.

## Goal 2: Measure and Reduce the Noise Floor

### Challenge 2

One noise source, most likely LED brightness fluctuation or 60 Hz pickup, swamps all others.

**Solution:** Reference-photodiode subtraction targets LED noise; choosing a lock-in rate away from 60 Hz harmonics targets pickup. The zero-field splitting  $D$  drifts with temperature, by about  $-74\text{ kHz/K}$ , which mimics a field change. Tracking both dips of a pair cancels this, because temperature moves both the same way while a field moves them apart [4].

## Goal 3: Detect a Magnetic Tracer in a Lymph-Node Phantom

### Challenge 3

The tracer signal is below the noise floor, or the magnetizing field overwhelms the sensor.

**Solution:** Increase the tracer amount (the  $2800\text{ }\mu\text{g}$ -iron injection-site dose in [3] is  $20\times$  larger), reduce distance, or lengthen averaging. For magnetizing-field leakage, position the sensor where that field is weakest and rely on sample-minus-empty-well subtraction. If detection still fails, report the minimum detectable iron mass at each distance, which remains a useful benchmark.

## 9 Research Timeline

### Milestone 1: Mid-October: Formal Proposal and Parts Order

**Task — What will you do?** Finish the literature review, submit this proposal, order missing parts, and start the soldered rebuild.

**Objective — What measurable result should this work produce?** An approved scope, a parts list, and a safety plan.

**Goal — What larger research capability or milestone does this establish?** A reviewable plan for rebuilding and applying the magnetometer.

### Milestone 2: Mid-December: Rebuilt and Validated Device

**Task — What will you do?** Complete the enclosed device, wind and calibrate the coils, and record repeated sweeps under applied fields.

**Objective — What measurable result should this work produce?** Reproducible, symmetric dips whose splitting grows linearly with applied field (Goal 1).

**Goal — What larger research capability or milestone does this establish?** A calibrated instrument whose readings can be trusted before any noise work begins.

### Milestone 3: Late February: Noise Floor Characterized

**Task — What will you do?** Measure baseline sensitivity, then add averaging, lock-in detection, and LED-noise subtraction one at a time. Design and print the phantom in parallel.

**Objective — What measurable result should this work produce?** A noise budget and a measured sensitivity with uncertainty (Goal 2).

**Goal — What larger research capability or milestone does this establish?** A known sensitivity that predicts what the phantom study can detect.

#### Milestone 4: End of May: Phantom Results and Documentation

**Task — What will you do?** Run the phantom distance measurements, analyze them, and prepare the paper and presentation.

**Objective — What measurable result should this work produce?** Signal-versus-distance curves and a detection distance for a node-sized dose (Goal 3), plus build documentation.

**Goal — What larger research capability or milestone does this establish?** A reproducible benchmark and a device future QLab groups can extend.

## 10 Group Responsibilities

### Eshaan Sombhatta — Hardware

Primary responsibilities will be the soldered rebuild, diamond mounting, enclosure, and coil winding and calibration. Supporting responsibilities will include noise-source isolation and phantom stage setup.

### Anderson Hao — Software and Analysis

Primary responsibilities will be sweep control, Lorentzian fitting, noise-spectrum analysis, and software lock-in and averaging. Supporting responsibilities will include uncertainty analysis and figures.

### Brian Ko — Phantom and Application

Primary responsibilities will be phantom design and printing, tracer sourcing and dilution, distance measurements, and comparison with published phantom data. Supporting responsibilities will include literature review and safety documentation.

All students will participate in data collection, interpretation of results, and preparation of the paper and presentation. The division of technical ownership does not remove any student from responsibility for understanding the complete experiment.

## Annotated Bibliography

- [1] E. Cai, H. Han, and I. Park, *Lightweight NV diamond CW-ODMR magnetometer coupled with GPR in a navigation application*, QLab preprint, Thomas Jefferson High School for Science and Technology, 2026.

**What did this work do?** Built an LED-based CW-ODMR magnetometer on a breadboard and recorded fluorescence dips, but the signal was too noisy to extract a field value and no sensitivity was measured.

**Why is it relevant?** This is the device this project rebuilds and the baseline it must improve on.

**How will we use it?** We use its component list and reported spectrum as the starting point for Goal 1.

- [2] M. Douek et al., “Sentinel node biopsy using a magnetic tracer versus standard technique: the SentiMAG multicentre trial”, *Annals of Surgical Oncology* (2014).

**What did this work do?** A clinical trial finding magnetic-tracer sentinel node detection non-inferior to the radioactive standard in breast cancer.

**Why is it relevant?** It establishes that magnetic tracer detection is a clinically validated task.

**How will we use it?** We use it to motivate Phase 2.

- [3] E. R. Nieuwenhuis, N. Mir, M. M. Horstman-van de Loosdrecht, A. P. W. Meeuwis, M. G. J. de Bakker, T. W. J. Scheenen, and L. Alic, “Performance of a nonlinear magnetic handheld probe for intraoperative sentinel lymph node detection: a phantom study”, *Annals of Surgical Oncology* **30**, 8735–8742 (2023).

**What did this work do?** Benchmarked two magnetic probes and a gamma probe on a Delrin phantom whose 5  $\mu\text{L}$  wells of Magtrace (140  $\mu\text{g}$  iron) represent lymph nodes.

**Why is it relevant?** It defines the phantom geometry, tracer dose, detection threshold, and metrics used for clinical probes.

**How will we use it?** We copy its phantom design, dose, threshold, and metrics so Goal 3 results compare directly.

- [4] V. Krumins, I. Krastins, O. Rudzitis, R. Lazda, F. Gahbauer, and M. Auzinsh, *Using NV centers in diamond to detect DC to very-low frequency magnetic fields*, 2025.

**What did this work do?** Built a portable laser-based NV magnetometer that reads two resonances at once to cancel temperature drift, measuring 2.3 nT/ $\sqrt{\text{Hz}}$  against a calculated 585 pT/ $\sqrt{\text{Hz}}$  shot-noise limit.

**Why is it relevant?** It shows how a tabletop device reports a noise floor relative to its fundamental limit.

**How will we use it?** We use it as the model for noise-budget reporting and for dual-resonance drift cancellation.

- [5] H. Williams, A. Newman, S. Graham, C. Stephen, and G. Morley, *A portable LED-based diamond magnetometer for outreach and teaching labs*, 2025.

**What did this work do?** Built an NV magnetometer using a high-power green LED instead of a laser, with sensitivity on the order of 1  $\mu\text{T}/\sqrt{\text{Hz}}$ .

**Why is it relevant?** It is the closest published analogue to our LED-based design.

**How will we use it?** We use its sensitivity as the realistic benchmark for Goal 2.

- [6] A. Bülau, D. Walter, and K.-P. Fritz, “Components for an inexpensive CW-ODMR NV-based magnetometer”, *Magnetism* **5**, 18 (2025).

**What did this work do?** Showed that a low-cost CW-ODMR magnetometer is feasible using an LED, a single-stage transimpedance amplifier, and an inexpensive microwave generator.

**Why is it relevant?** It is the design our device descends from.

**How will we use it?** We use it as the component reference for the soldered rebuild.

- [7] M. Sekino, A. Kuwahata, T. Ookubo, M. Shiozawa, K. Ohashi, M. Kaneko, I. Saito, Y. Inoue, H. Ohsaki, H. Takei, and M. Kusakabe, “Handheld magnetic probe with permanent magnet and hall sensor for identifying sentinel lymph nodes in breast cancer patients”, *Scientific Reports* **8**, 1195 (2018).

**What did this work do?** Built a clinical probe that magnetizes tracer with a permanent magnet and senses it with a Hall sensor.

**Why is it relevant?** It shows a simple DC magnetization scheme that works for sentinel node detection.

**How will we use it?** We use it as the model for the DC magnetization option in Goal 3.

- [8] A. Kuwahata, T. Kitaizumi, K. Saichi, T. Sato, R. Igarashi, T. Ohshima, Y. Masuyama, T. Iwasaki, M. Hatano, F. Jelezko, M. Kusakabe, T. Yatsui, and M. Sekino, “Magnetometer with nitrogen-vacancy center in a bulk diamond for detecting magnetic nanoparticles in biomedical applications”, *Scientific Reports* **10**, 2483 (2020).

**What did this work do?** Built a fiber-coupled NV probe that magnetizes nanoparticles with an alternating coil field and reads out with lock-in detection.

**Why is it relevant?** It is the closest prior work applying NV sensing to sentinel node tracers.

**How will we use it?** We use it as the model for the AC magnetization option in Goal 3.