Design and Construction of a High-Q Resonator for MRI at Ultralow Magnetic Field Strengths

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Motivation

Magnetic Resonance Imaging and Spectroscopy are generally performed at high magnetic field strengths (> 1 Tesla), leading to an enhancement of nuclear spin polarization and an increase in the NMR signal strength. Unfortunately, these strong magnetic fields require superconducting magnets that necessitate cryogenic cooling, resulting in substantial instrumentation and maintenance costs.
Alternatively, homogeneous low magnetic fields can be produced by electromagnets. These electromagnets are more affordable and portable than superconducting magnets, offering a cost-effective solution for MR instrumentation. Despite their cost-effectiveness and portability, low-field MRI systems encounter the challenge of lower signal-to-noise ratio (SNR) compared to their high-field counterparts. This decrease in SNR can negatively impact imaging quality and diagnostic accuracy.
The scope of this work was to construct and characterize a high-quality resonator that significantly enhances MR detection sensitivity at ultralow magnetic field strengths and enables the acquisition of high-quality images and spectra at low field strengths.

Methods

In a magnetic resonance experiment the signal from nuclear spins is detected by using a coil, which is a resonant circuit that typically consists of one or more loops of wire or other conductive material, wound around the sample to create a magnetic field and to efficiently transmit and receive radio-frequency signals. Variable capacitors and sometimes inductors are added to tune the circuit to the Larmor frequency, the frequency at which the nuclear spins precess, and to minimize signal reflection.
The sensitivity of the coil is determined by the quality factor (Q), defined as the ratio of the energy stored in the coil's inductive and capacitive elements versus the the energy dissipated during every cycle.In practical terms, the Q of a coil can be increased by reducing the resistance and increasing the inductance of the circuit. We increased the Q factor by connecting to the coil that wraps around the sample (primary coil), a secondary coil that has a very high inductance (L) and a low resistance(R) [1]. In our case (Figure 1), the secondary coil consists of a low resistance wire (Litz Wire) wounded around a toroidal ferrite. The secondary coil is provided with a center tapping, which enables the use of an instrumentation amplifier for efficient common mode rejection. Before assembling the coil, I simulated the performance of the circuit by using LtSpice (Figure 2). Comsol multiphysics simulations (Figure 3) were also performed to assess the advantage of enclosing the secondary coil in a mu-metal case.

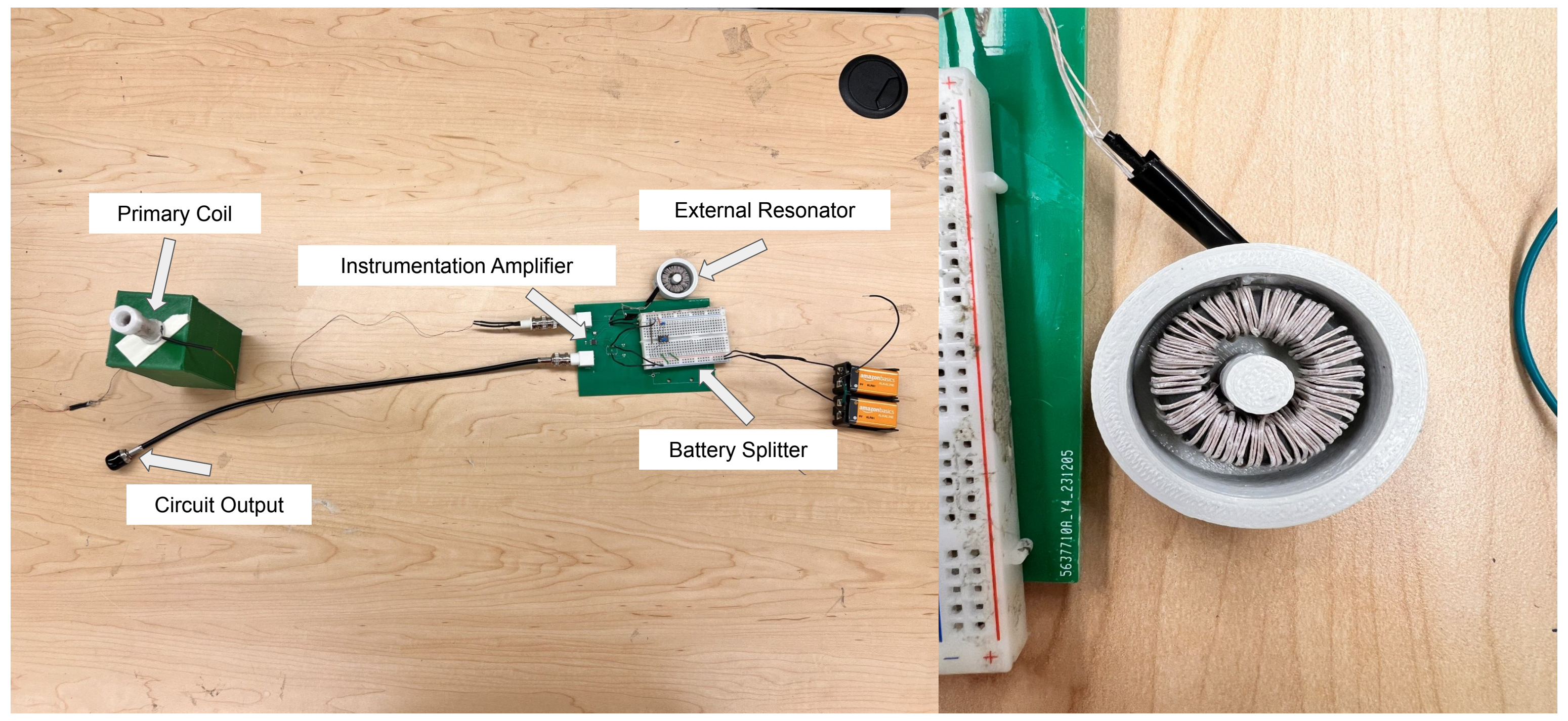


Figure 1: On the left is the setup of the circuit with all the elements labeled. A description of what each component is along with their values can be found in figure 2. On the right is a close up image of the secondary inductor with 69 turns around the core.

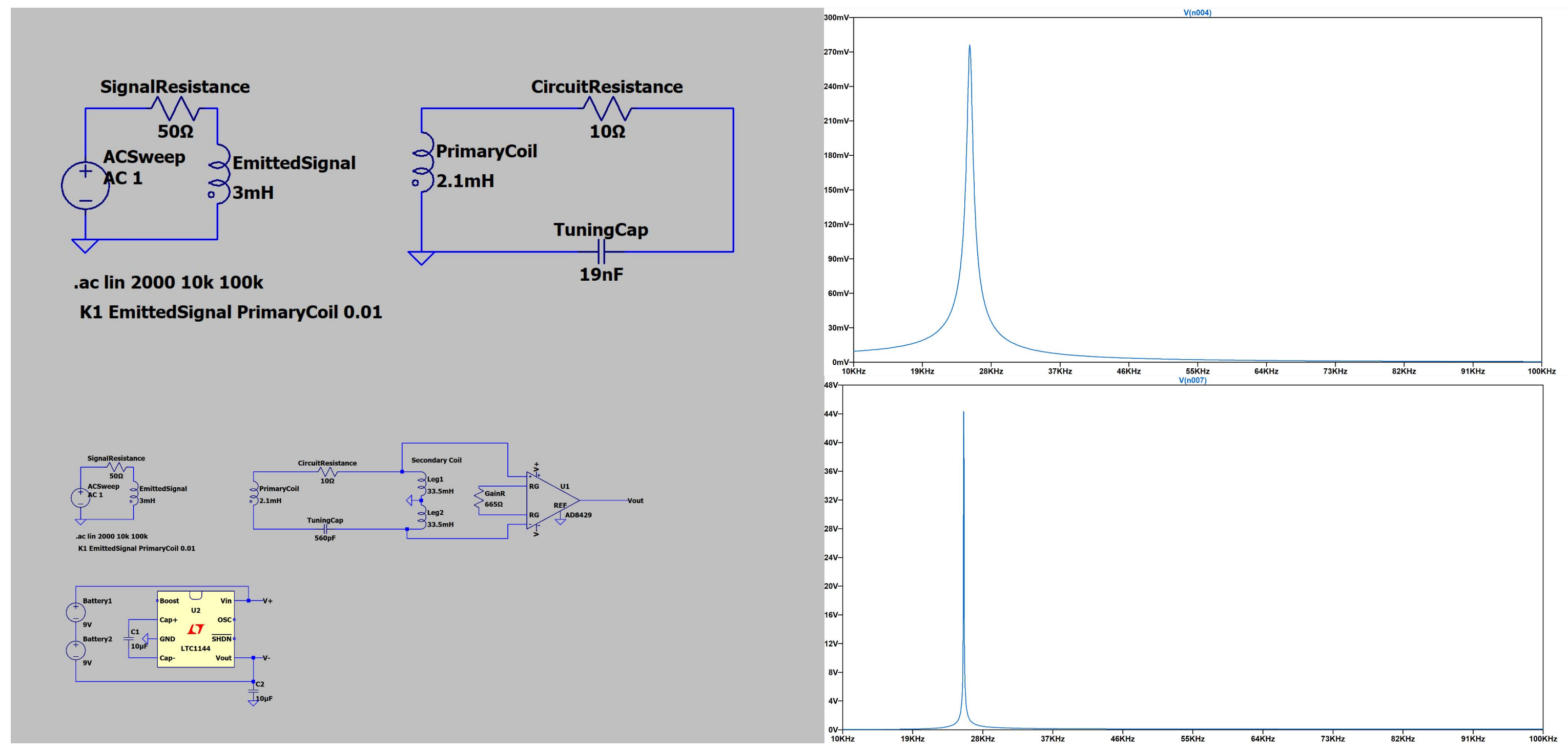


Figure 2: The top row contains the simulated circuit without the external inductor and the simulation results that would result from a frequency sweep of the circuit. The bottom row contains the same information for the circuit with the external inductor. The resonant frequency for the graph on the top row is 25200 Hz with a bandwidth of 800 Hz giving a quality of about 31.5, while the bottom graph has a peak at 25500 Hz with a bandwidth of 45 Hz giving a quality factor of 566.7

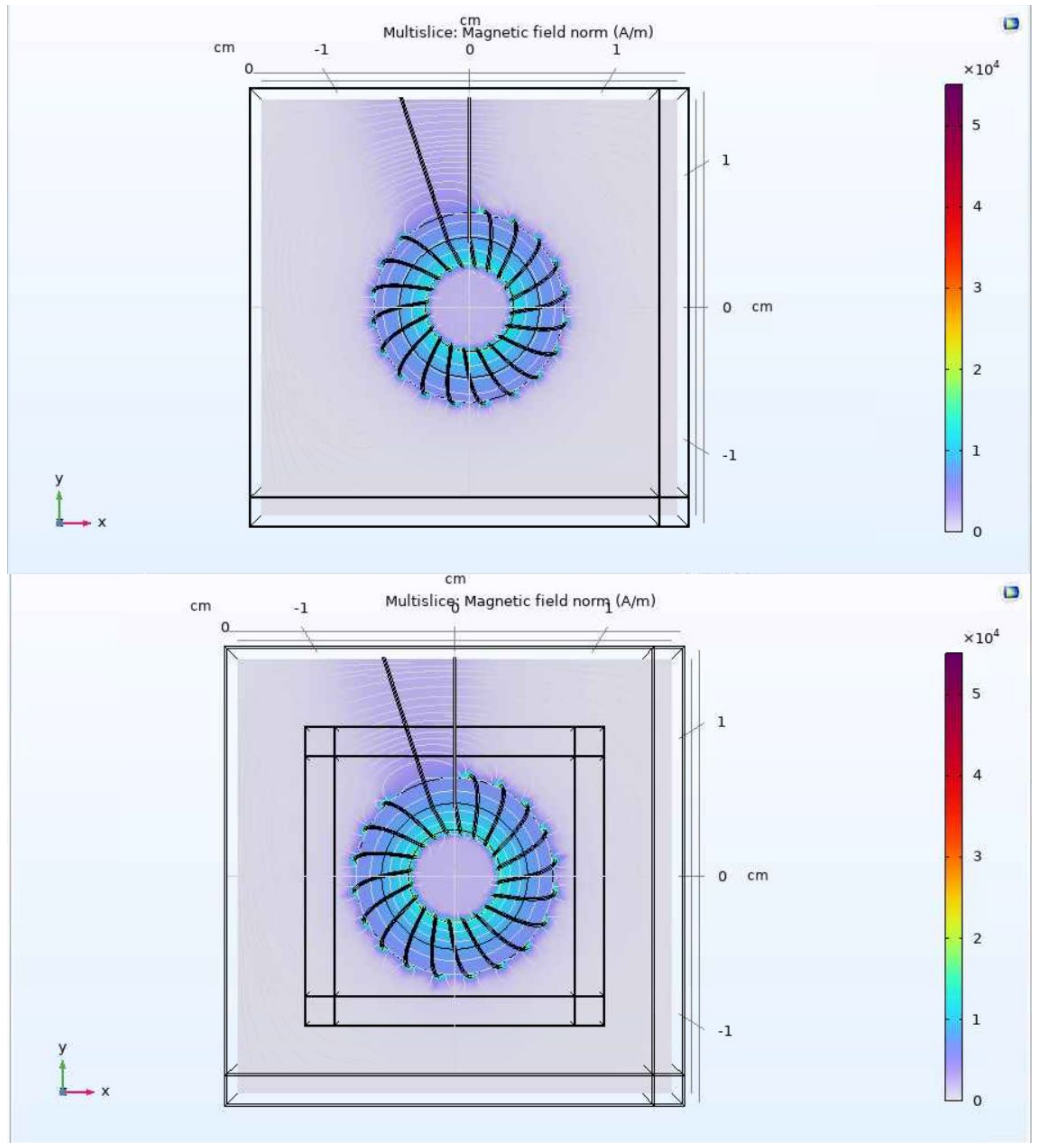


Figure 3: The above two plots show the magnetic field norm evaluated across the xy-plane. The plot on the top shows the inductor modeled without the mu metal shield, while the bottom image shows the magnetic field norm with a mu metal shield.

Results

The LtSpice simulation predicted an 18-fold enhancement of the coil Q factor when the secondary coil was added to the setup. Measurements of the primary and secondary coil inductor performed by using an LC-meter gave a value of 2.1mH and 67mH, respectively. Experimental measurement of the quality factor by using a sniffer coil, showed a quality factor gives 21 for the circuit without the external resonator and 128 for the circuit with the external resonator (figure 4).

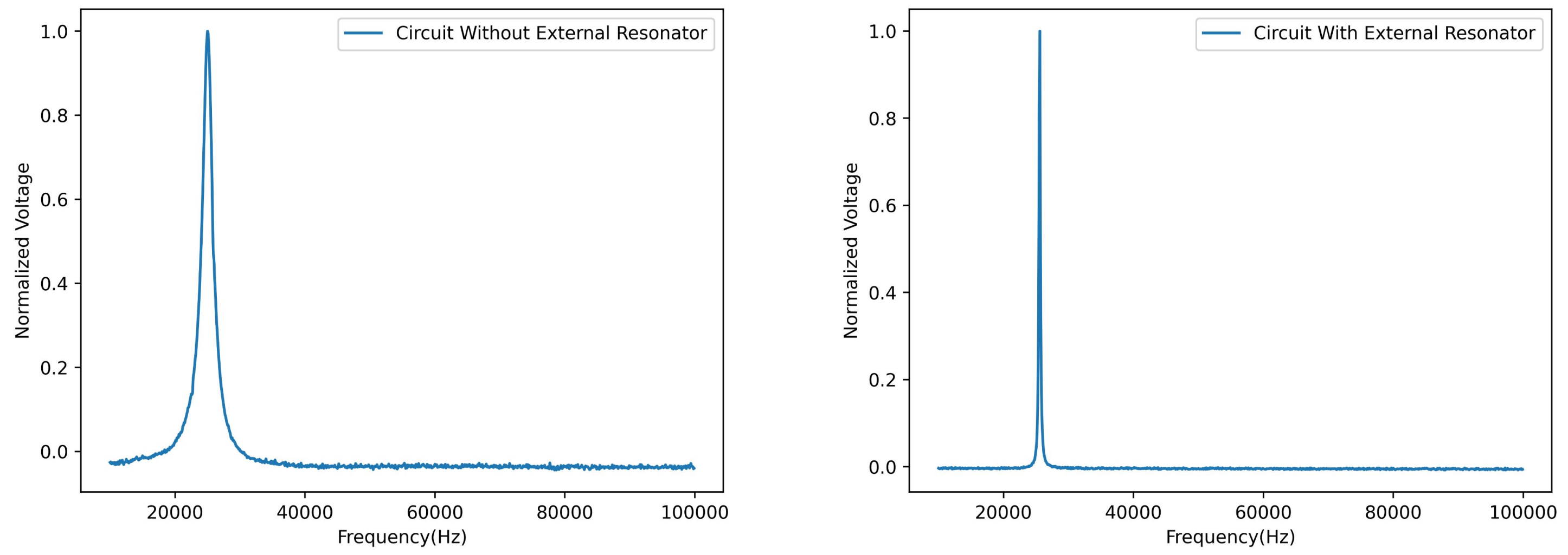
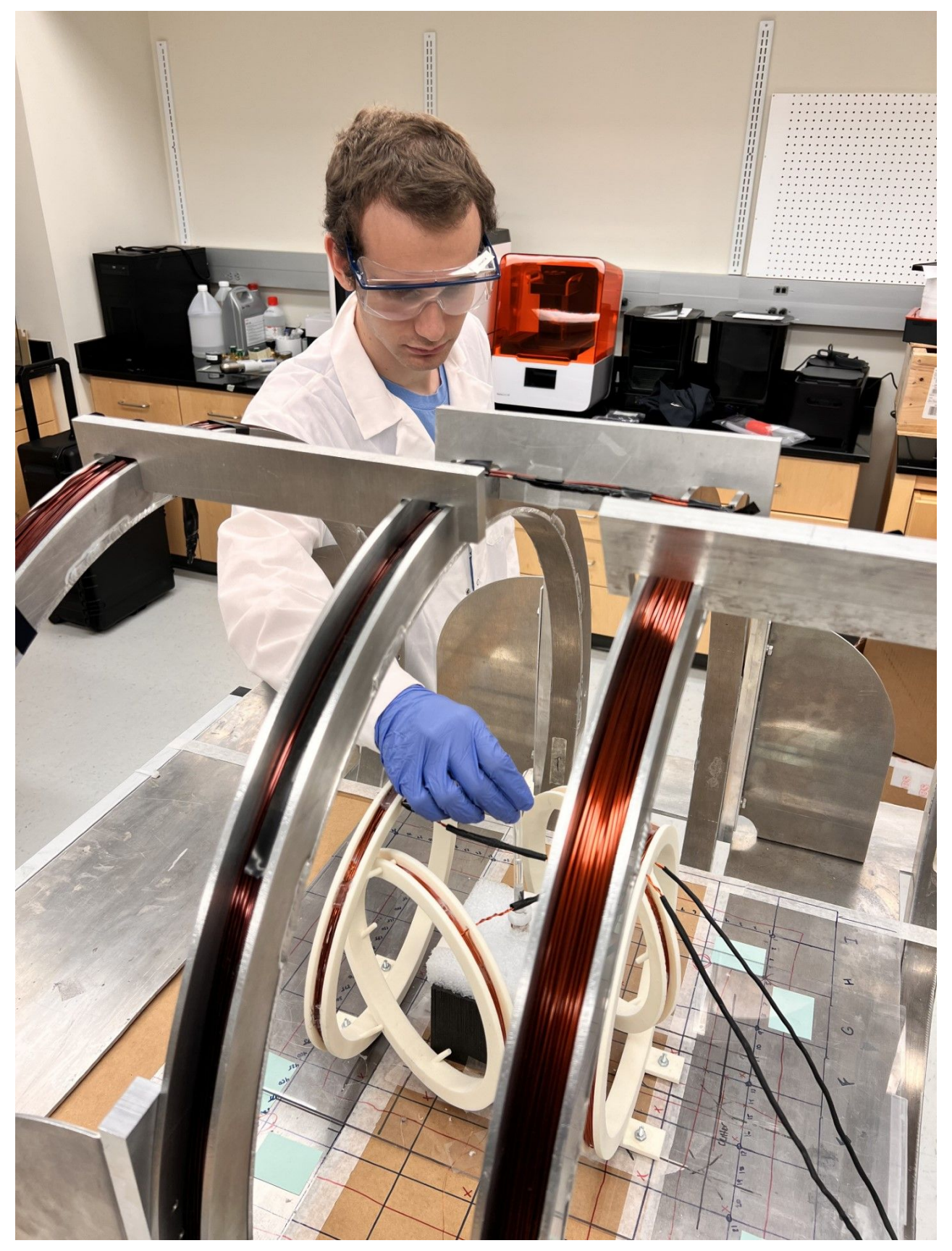


Figure 4: On the left there is a plot of the frequency sweep on just the input coil and on the right is the output of the circuit with the external inductor added.

Conclusion and Future Work

By connecting the primary coil to a high-Q resonator and an instrumentation amplifier, we were able to increase the overall quality factor of our coil by a factor of 6.
A similar increase in signal intensity is expected when this coil will be used for magnetic resonance experiments at ultralow field, something that we plan on testing in the near future.



References

[1] Suefke, M., Liebisch, A., Blümich, B., & Appelt, S. (2015). External high-quality-factor resonator tunes up nuclear magnetic resonance. Nature Physics, 11(9), 767–771. https://doi.org/10.1038/nphys3382