Designing Low-cost Resistive Coils for Improving Field Homogeneity In Single-sided NMR Systems

Shinjer Li, Samuel J. Rubin, Tyler Meldrum

William & Mary, Department of Chemistry, Williamsburg, VA

Introduction

Magnetic field shimming plays a crucial role in enhancing the performance of nuclear magnetic resonance (NMR) systems. Achieving a homogenous magnetic field distribution is crucial for accurate and sensitive measurements. We present an inexpensive approach for reducing field inhomogeneity within permanent magnets in single-sided NMR using a robot-assisted measurement technique and open-source optimization algorithms. Initially, a robot moved in uniform increments across the sample region with a 3-D Hall sensor to obtain spatially resolved magnetic field measurements. Utilizing this data, we employed a reverse engineering approach to determine the correction field required for achieving field homogeneity. Subsequently, an open-source coil generator was used to determine the optimal coil configuration for our desired correction field. This coil was then cut out of adhesive-backed copper foil and positioned around the sample area. Experimental results suggest that these low-cost coils may improve field homogeneity, leading to improved resolution and sensitivity in our single-sided NMR system.

Measuring Magnetic Fields

1. MagVector^{TM} MV2 Magnometer

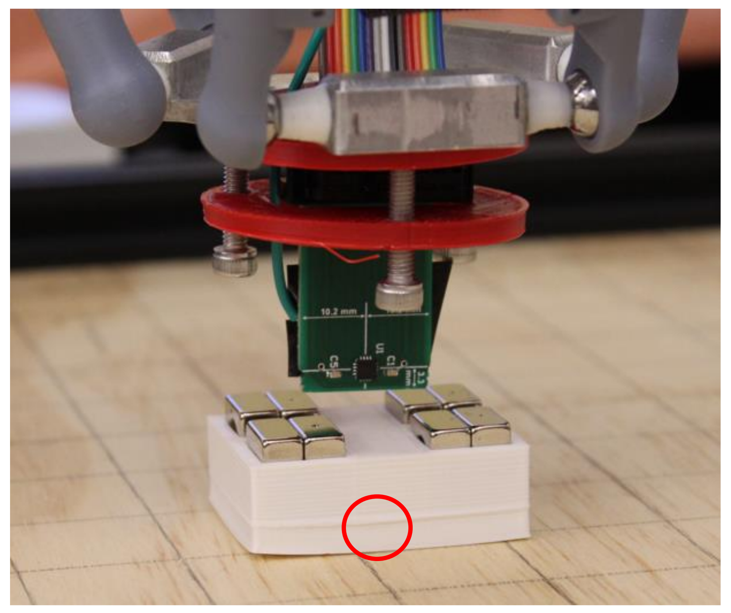

Figure 1. The Hall sensor is the small black square near the end of the PCB, which is mounted to the DeltaX2 robot.

We utilized the embedded 3-Axis Hall Magnometer to measure our magnet's magnetic field in the X, Y, Z direction with the optional parameter of temperature. The Hall sensor has sensitivity settings of 100 mT, 300 mT, 1T, which were each calibrated separately using a known magnetic field created by Helmholtz coils. The sensor averages 100 measurements per scan and every scan requires ~2.5 seconds.

2. Delta X 2 Robot

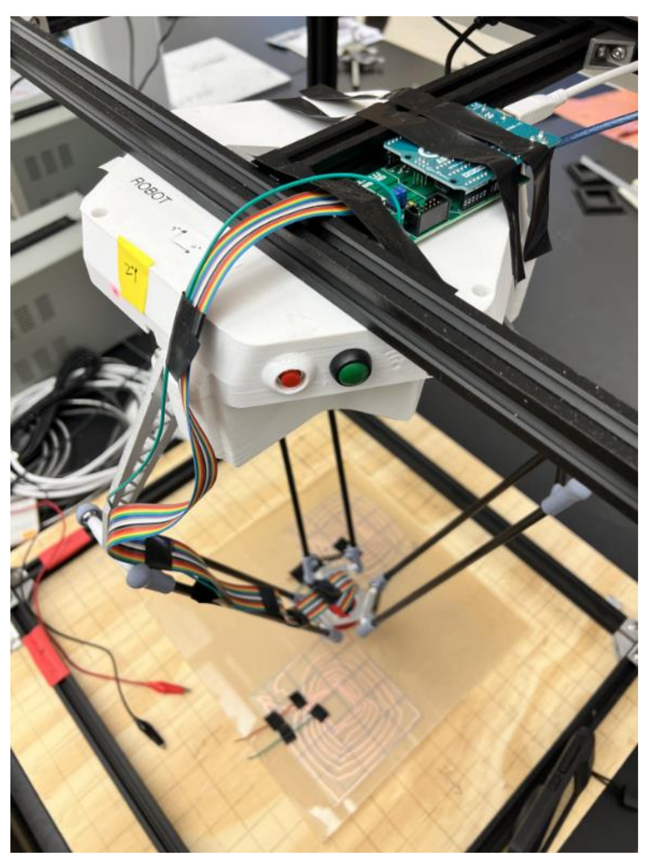

Figure 2. An overhead view of the Delta X 2 robot with the mounted hall senor. The Hall sensor's Arduino component is at the top of the robot and is connected to the sensor through the ribbon cable.

The Hall sensor was mounted onto a robot. This set up allows us to move our sensor across our interested region of space accurately. The combined apparatus will move the hall sensor, and the sensor will then record an average of 100 measurements. The robot has an accuracy of 0.15 mm and has a working space of ~320 mm but this space varies with the height. This combination of robot and sensor allows us to accurately measure the magnetic field of any magnet or magnet array we might be interested in that can fit within the robot's frame.

Preliminary Data Analysis

3. Visualizing Data and Choosing Magnetic Components to Correct

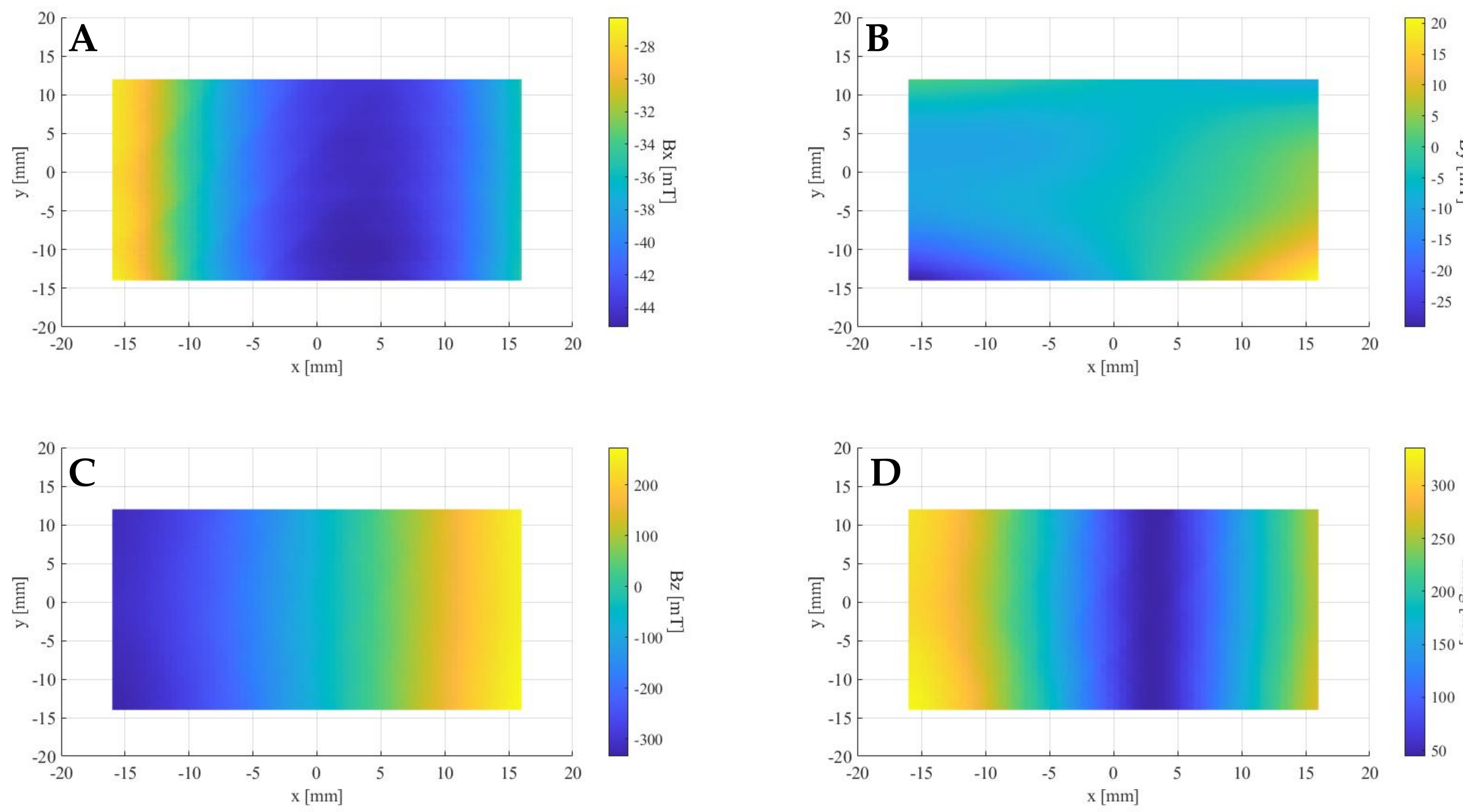

Figure 3. Magnetic field measurements for the PM5 magnet. The graphs are plotted against the x, y position. Fig. A shows Bx, Fig. B shows By, Fig. C shows Bz, and Fig. D shows the magnitude of the magnetic field.

Results

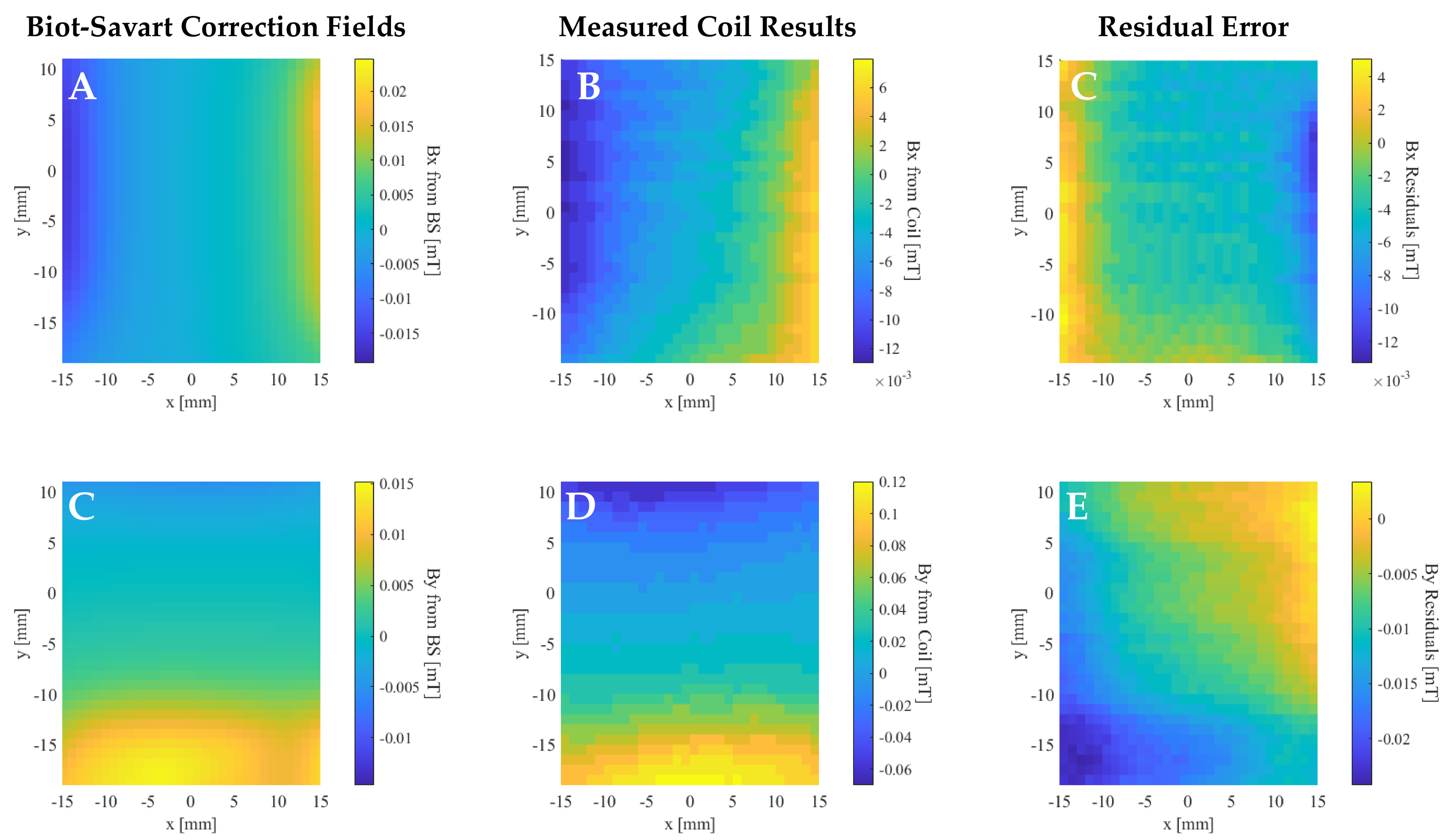

Figure 6. The graphs above are separated into three columns: the correction fields calculated by the Biot-Savart algorithm in Fig 5, our measured coil results using the coils in Fig 6 , and the residual error between theory and experiment. The top row highlights the Bx component while the bottom highlights the By component.

Future Directions/References

After calculating our residual errors, we find that there is good agreement between the fields our coil produces and what we expect to get using the Biot-Savart algorithm. We would then test this on our PM5 and see if there are any spectroscopic improvements. We also hope to send our coil design to a manufacturer to test more robust coils that can handle more current and thus produce a strong magnetic field.

L. Quéval; "BSmag toolbox user manual"; Tech. report, Dept. Elect. Eng., University of Applied Sciences Düsseldorf, Germany, **2015**.
Philipp Amrei et. Al; "CoilGen: Open-source MR Coil layout generator"; *Magnetic Resonance in Medicine* **2022**, 88 (3), 1465-1479.

Generating Coils

4. CoilGen (open-source MR coil generator)

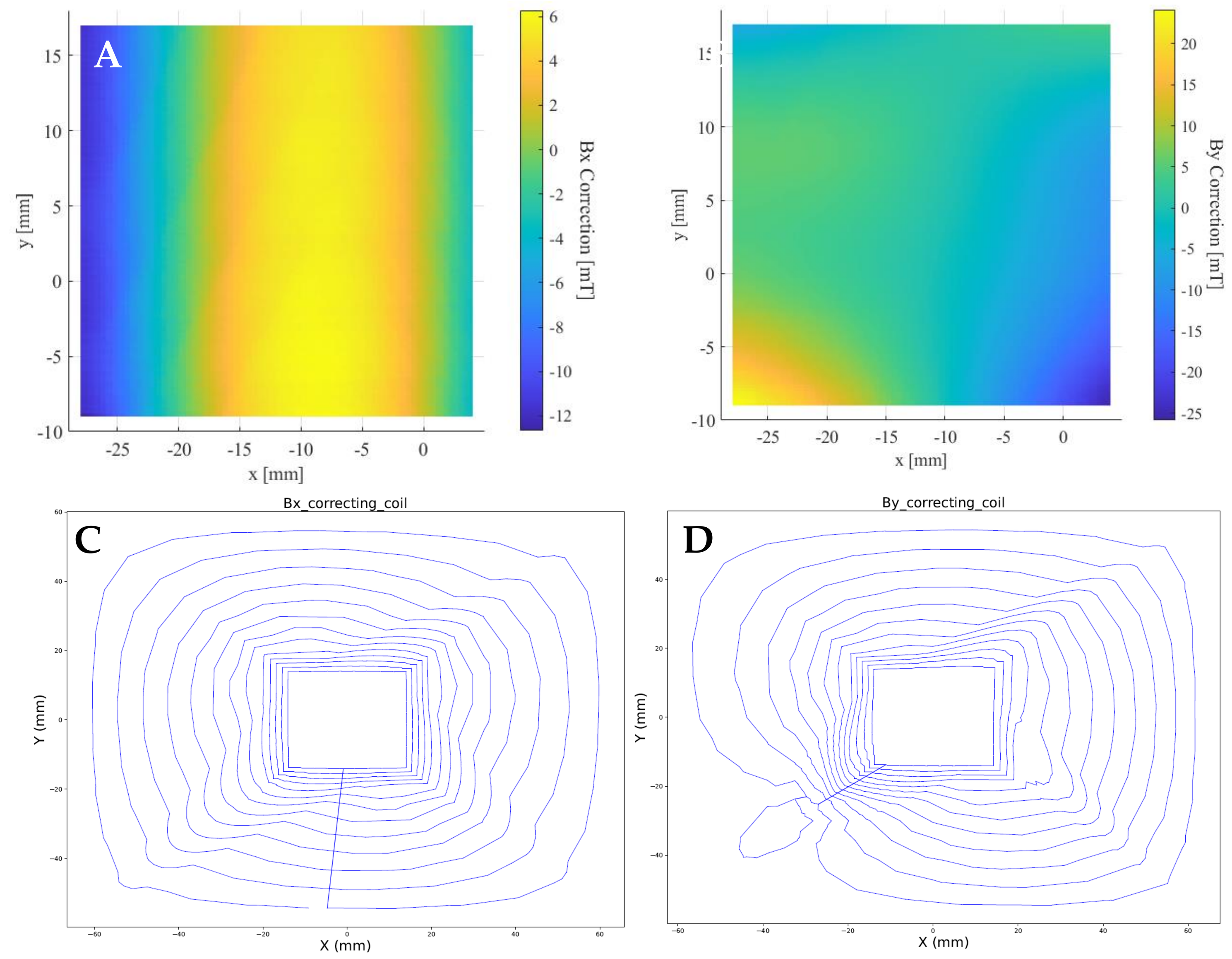

Figure 4. Correction fields for Bx and By, shown in A and B, were calculated using the average magnetic field in Fig 3 A and B. We utilized Coil-Gen, an open-source coil-generating algorithm to create shim coil traces that would correct their respective fields.

5. Compare results with Biot-Savart Law

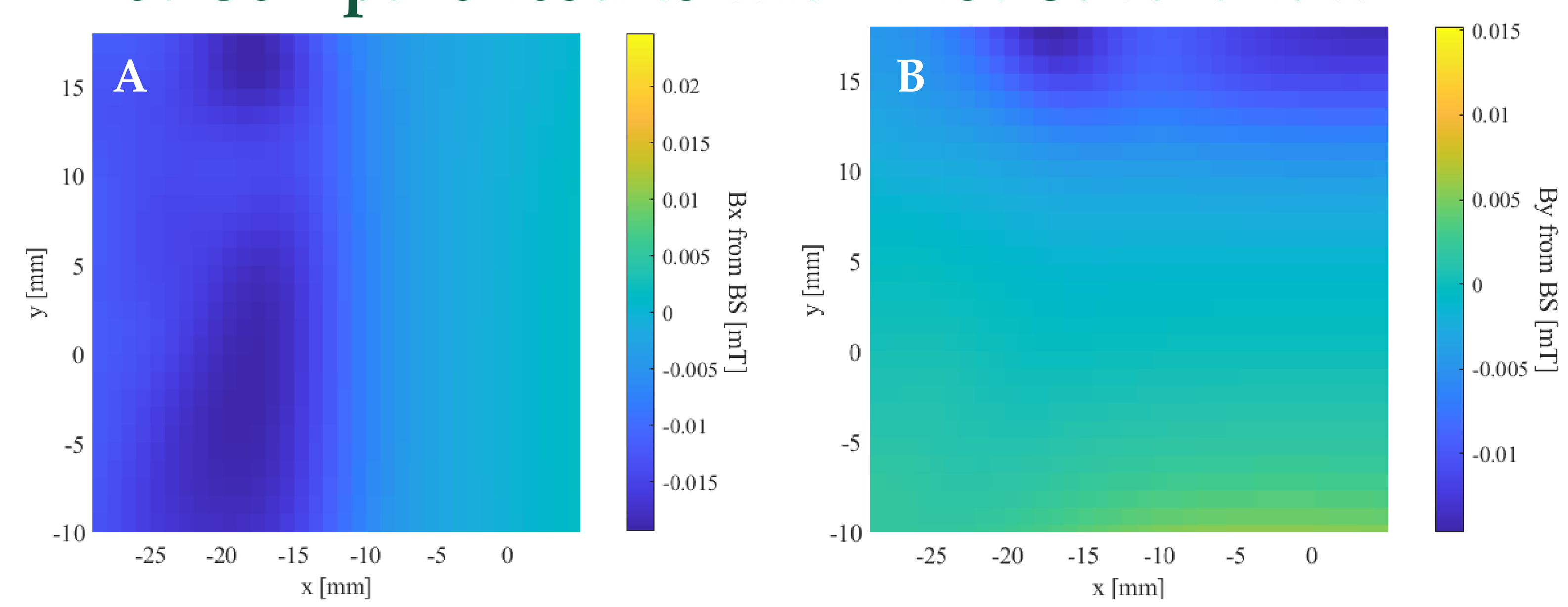

Figure 5. A and B show the magnetic field generated by the coil traces in Figure 3 C and D using a Biot-Savart's algorithm. Fig A shows the magnetic field generated from the x correction coil. Fig B shows the magnetic field generated by the y correction coil.

6. Printing Coils

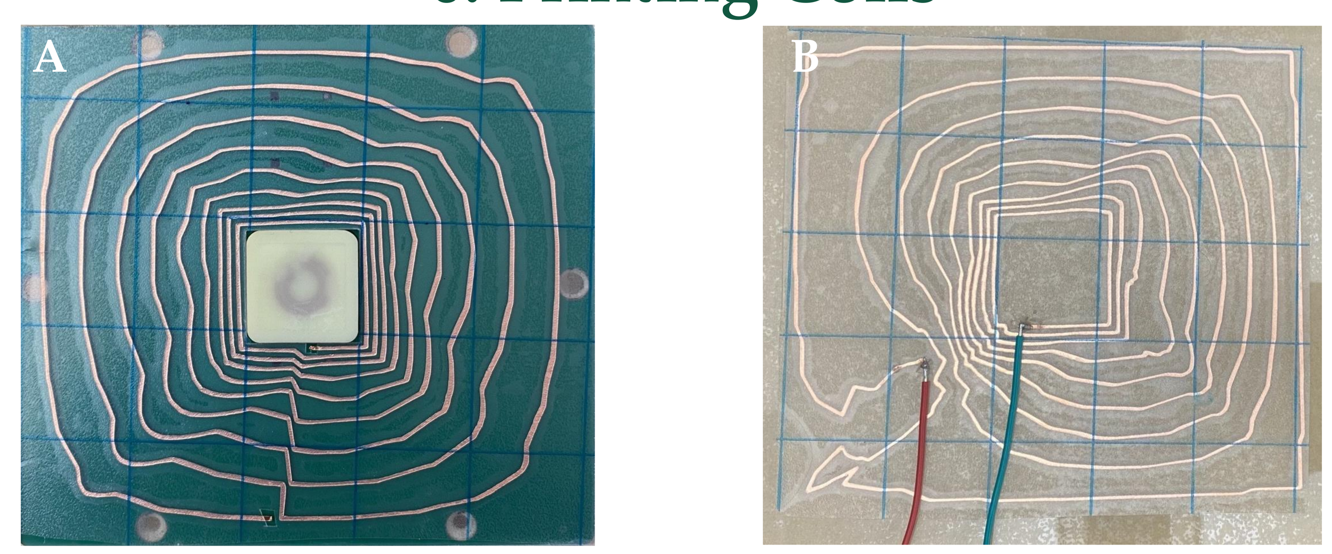

Figure 6. Bx and By correcting coils were cut out using a Silhouette CAMEO 4 vinyl cutter and copper foil tape. Printed coils were placed onto acrylic for testing as seen in B with soldered on wired to drive currents through the wires. Final coils were placed on laser cut acrylic to match the rf coil dimensions of the PM5 as seen in A.