Evaluating EM Shielding Fabrics as an option for RF shields at 21.1T

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Introduction

The 21.1 T ultra-high field magnet at the National High Magnetic Field Laboratory (NHMFL) is the world's most powerful MRI system and enables high-resolution preclinical imaging. Effective radiofrequency (RF) shielding is essential for minimizing electromagnetic interference and suppressing eddy currents induced by rapid gradient switching. Without proper shielding, these currents can couple with RF circuitry, degrading coil efficiency, reducing signal-to-noise ratio (SNR), and introducing imaging artifacts that compromise image quality. RF shields currently rely on an electroplating process that cost $600 per unit, while also generating hazardous waste.

To improve sustainability while maintaining shielding performance, this project investigates alternative shield fabrication methods that replace electroplating with copper-clad laminate and conductive woven shielding fabric. Multiple conductive joining materials were evaluated across copper laminate designs, including silver epoxy, gold leaf, solder, no sealant, and slotted configurations. The silver epoxy prototype demonstrated the strongest performance and therefore serves as the reference design for comparison with the woven shield fabric prototype. Designs were evaluated on bench using a Vector Network Analyzer (VNA) and in the 21.1T magnet. On bench, The reflection coefficient (S11) was measured to determine coil efficiency, quality factor (Q), and tuning range, while the transmission coefficient (S21) was analyzed to assess signal coupling. In-magnet performance was characterized using an Echo Planar Imaging (EPI) sequence, which involves rapid gradient switching. Shield effectiveness was determined by its ability to minimize ghosting artifacts, reduce the reference power required for data acquisition, and enable high-resolution imaging.

Shield Construction & Environmental Impacts

The construction methods of the three different RF shields that were built for this project and their environmental impact is described below.

Electroplated Shields

Copper was electroplated onto a G-10/FR4 cylindrical former through an electrochemical deposition process containing an electroless copper (Cu) seed layer (RePliForm, Maryland). The shield consists of base copper and semi-bright copper (SB Cu) resulting in a thickness of 0.0005–0.001 in. The copper flange was machined as a single piece with G-10 cylindrical former to facilitate electroplating.

Although a non-magnetic copper layer is being electroplated onto the G-10 former, toxic chemicals nickel (Ni), chromium (Cr), zinc (Zn), and cadmium (Cd) pollute the electroplated waste-water, producing hazardous sludge, air pollution, increased carbon and energy emissions, and increased resource consumption. Electroplating operations in the U.S. generate 1.3 million tons of wastewater annually, and treatment produces 6.78–38 kg CO_2-equivalent emissions per 1000 m³ (1, 2).

Copper-Clad Laminate Shields

Copper-clad laminate (DuPont Pyralux AC352500R, 25 µm polyimide with 35 µm copper) was wrapped around a G-10 cylindrical former and bonded using Stycast 1266A/B epoxy cured at 65 °C for 2 hours. A single-sided copper-plated flange was glued to the cylindrical former, and electrical continuity between the laminate and flange was joined using 8300D silver epoxy (MG Chemicals, Ontario). as shown in **Figure 1**.

Laminate fabrication primarily generates volatile organic compound (VOC) emissions during resin curing and solvent evaporation. However, this approach eliminates electroplating baths, reduces hazardous wastewater generation, and only produces 2.6 kg/m of CO_2 emissions to manufacture (3).

Conductive Woven Shield Fabric

Conductive shielding fabric Shieldex Bergen, Nylon 6.6 fibers silver-plated with conductive polyurethane) was wrapped around a G-10 cylindrical former. Seams were joined using 3M silver conductive tape, and the flange was glued to the former using silver epoxy to maintain electrical continuity as shown in **Figure 2.**

Environmental impacts arise from silver extraction and processing energy. Since the shield is formed through mechanical wrapping rather than metal deposition, this method eliminates electroplating wastewater and reduces overall environmental footprint.

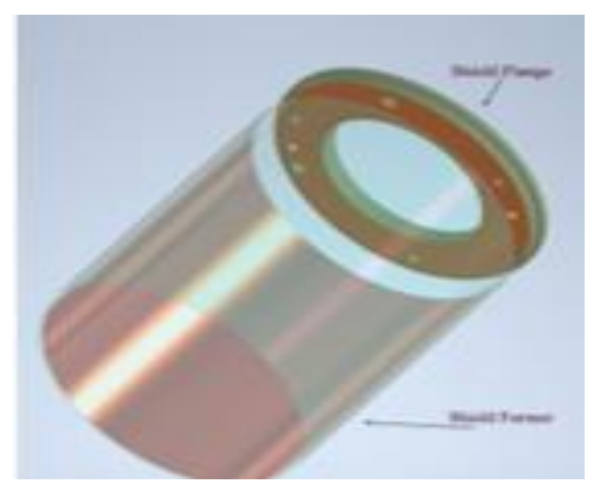

FIGURE 1: Computer-Aided-Design Model of copper laminated shield former and shield flange assembly

FIGURE 2: G10 shield prototypes electroplated, silver epoxy, and EM conductive fabric, pictured to the right of 1H/19F 33m testing RF coil

Method 1: Bench VNA

FIGURE 3: VNA pick-up loop configuration used for normalization

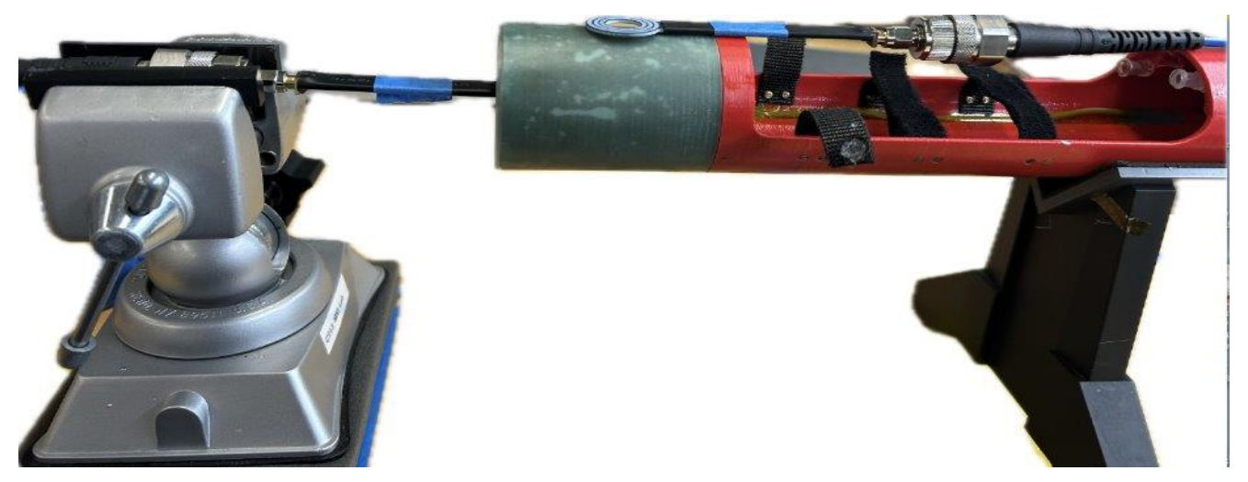

FIGURE 4: Pick-up loops connected to VNA with shield inserted. Port 1 (bottom) is positioned at the center of the B1 field, while Port 2 (top) simulates eddy current interactions.

A 1H–19F 33mm dual-tuned volume birdcage coil (RF 900MHz) and a *Copper Mountain Technologies (CMT808U)* Vector Network Analyzer (VNA) were used to evaluate the following parameters:

- Tuning Range:
  The VNA sweep from 800 MHz–1 GHz determined tuning ranges for each shield configuration, showing how shield geometry affected tuning stability and bandwidth **(Section 1)**
- S11 (Reflection Coefficient):
  The VNA measured S11 to assess the quality factor Q (-3dB) using impedance matching, with variations in return loss indicating matching performance across shield prototypes **(Figure 5).**
- S21 (Transmission Coefficient):
  The VNA measured S21 to assess signal coupling. Pick-up loops were normalized over an 800 MHz–1 GHz span **(Figure 3)**, with one loop at the coil center (B1), simulating the sample, and another above the shield representing external interference **(Figure 4)**. Effectiveness was quantified in dB attenuation, showing how well each shield prevented coupling between the loops.

All loaded measurements, were performed using a tissue-equivalent phantom designed to effectively simulate the dielectric properties of rat brain.

Shield Model	Q-factor Unloaded	Q-factor Loaded	S21 Transmission Coefficient (dB)	Tuning Range (MHz)	S11 Reflection Coefficient @ 900 MHz (dB)
Electroplated	74.42	137.12	-20.15	825 - 921	-29.48
EM Fabric	64.28	67.53	-35.55	827.78- 930	-25.8
Silver Epoxy	77.24	112.42	-22.25	809 - 921	-24.89

Section 1: VNA evaluation of each shield prototype, showing Q factor, S-parameters, and tuning range measurements

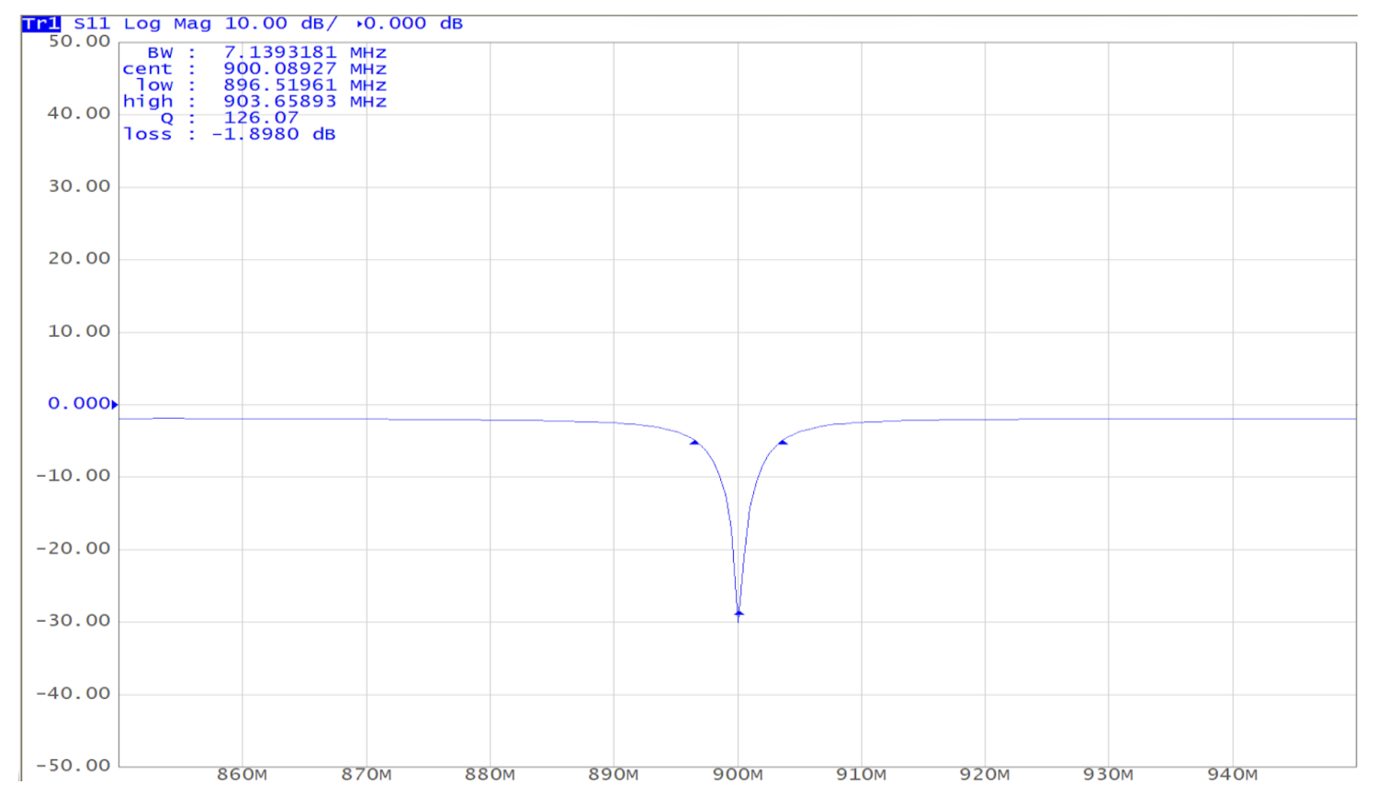

FIGURE 5: S11 reflection coefficient of the electroplated reference model, showing a return loss at 29.48 dB and a tuning range of 825–925 MHz

Method 2: Magnet Evaluation

In-magnet performance was assessed using Echo Planar Imaging (EPI), which features fast gradient switching **(Figure 6)**. Shield effectiveness was determined by its ability to reduce ghosting artifacts, lower the reference power required for data acquisition, and produce high-resolution images. QA SNR sequences were used to assess normalized SNR and B_1 field homogeneity to evaluate signal transmission and field uniformity, as shown in **Section 2**

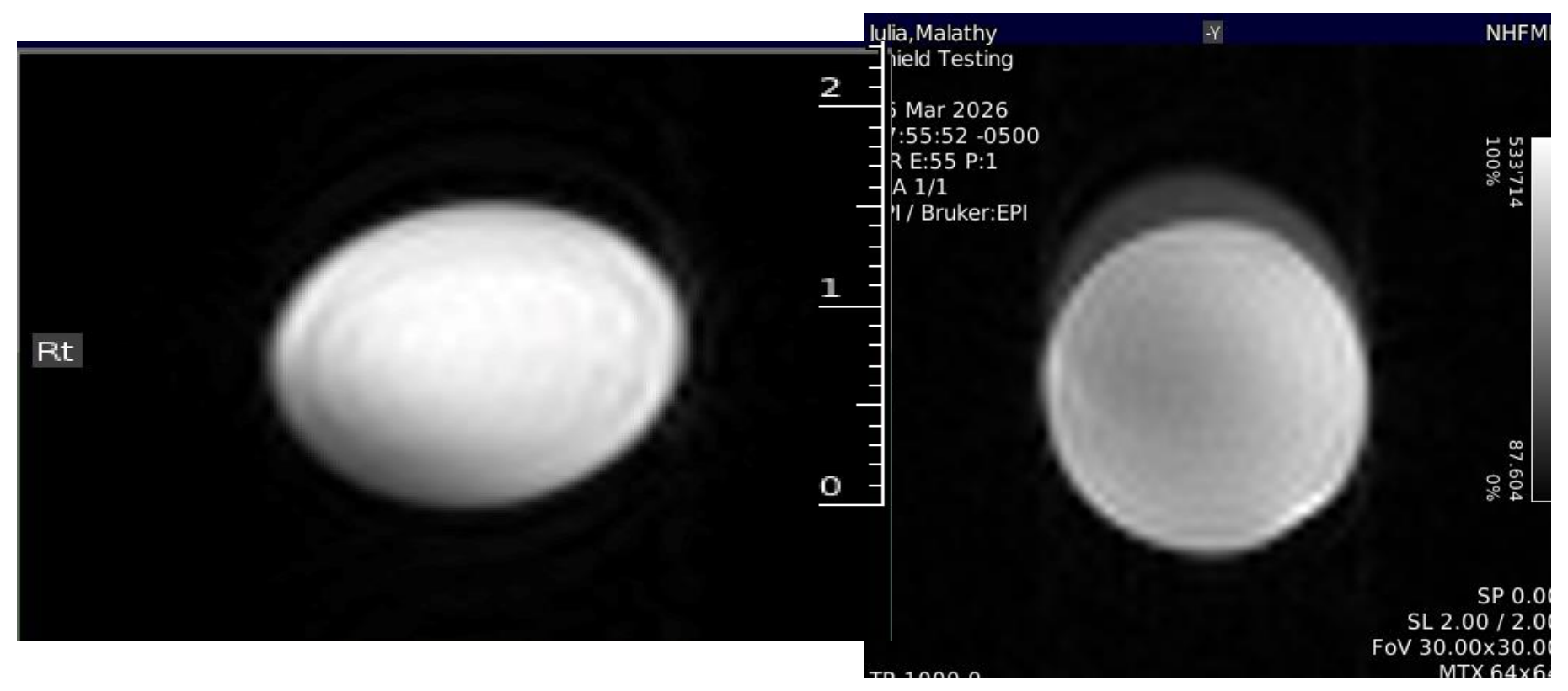

FIGURE 6: Silver epoxy V-D (left) and EM fabric V-D (right) EPI images

Shield Model	Normalized QA SNR (\mm^3)	Reference Power (W)	Echo Time (ms)
Electroplated	1883	0.6078	9.943
EM Fabric	1523	3.91	13.674
Silver Epoxy	1633	0.543	10.877

Section 2: 21.1 T evaluation of each shield prototype, showing normalized SNR, reference power, and echo time measurements

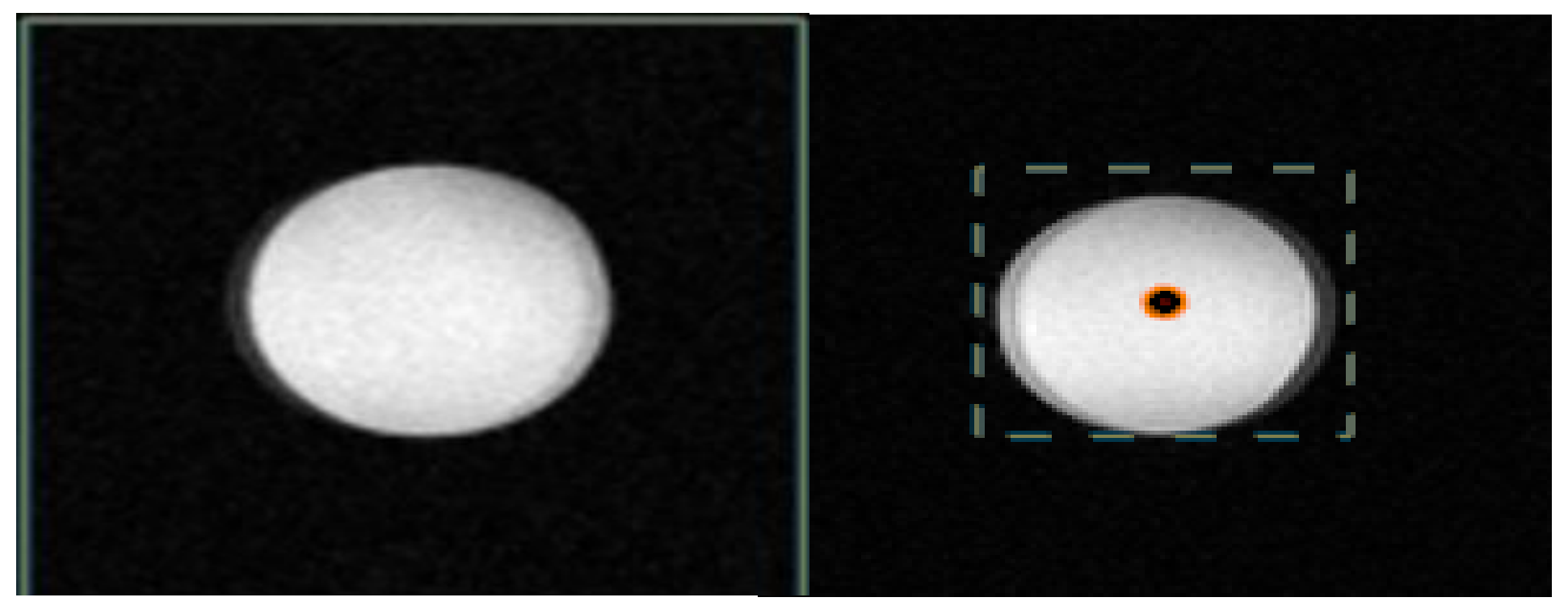

FIGURE 7: QA SNR sequence of silver epoxy (left) and EM fabric (right) run with a TR of 500ms

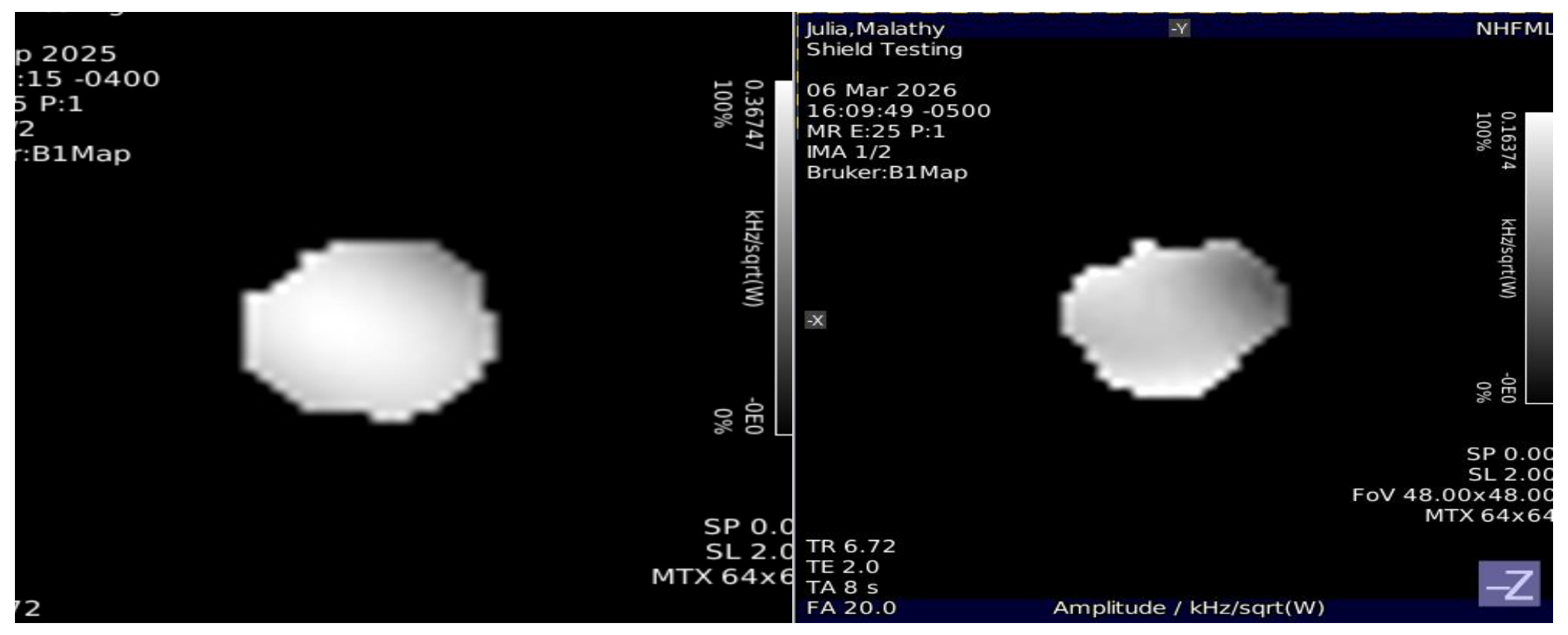

FIGURE 8: B_1 homogeneity map of the silver epoxy (left) and EM fabric (right).

Results show that the RF shield constructed with 3525 copper-clad laminate joined using silver conductive epoxy demonstrated the strongest overall performance, with a tuning range of 809–921 MHz, a loaded Q factor of 77.24/112.42, and strong B1 field uniformity. Bench measurements showed that fabric and silver epoxy shields outperformed the electroplated reference in S21 shielding. In the magnet, the silver epoxy shield achieved the same imaging resolution as the electroplated shield while requiring less RF power (0.543 W) to produce images in both the left–right (L–R) and ventral–dorsal (V–D) directions.

Bench measurements of the woven shielding fabric prototype showed promising S21 transmission performance, but establishing reliable electrical connectivity between the fabric and the RF circuit remains challenging due to grounding limitations. Improved grounding strategies may allow the fabric-based shield to match or potentially outperform the silver epoxy in magnet.

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Future Work

Future work for this research includes exploring S-Bond solder alloys to better establish ground connection in shield fabrics and to improve EM simulation accuracy results in CST Microwave Studio. Collectively, these developments aim to reduce machining time and cost of new RF shield designs.

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