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Using Ferromagnetic Material to Extend and Shield the Magnetic Field of a Coil

by W Casey Uhlig

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

This report proposes to extend the magnetic field generated by a coil along its axial direction while simultaneously shielding (or reducing) the field in the lateral direction by the application of ferromagnetic cladding on the coil. Calculations were performed for an infinitely long wire with a 2.5- × 5.0-cm rectangular cross section carrying 607,000 A as well as a magnetically saturated 2.5- × 5.0-cm rectangular piece of iron with a length much greater than the cross-sectional dimensions. These fields were combined as a baseline representative value. Two-dimensional calculations were then performed for a single-turn coil with a 20-cm diameter, metal cladding of varying permeability of μ_o, 10 μ_o, and 50 μ_o, and cross sections identical to the previous infinite wire and iron calculations. The field at the coil edge along the axial direction was extended up to 10%, while the field outside the coil in the radial direction was reduced by an order of magnitude, particularly within close proximity of the cladding.

15. SUBJECT TERMS

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1. Introduction and Initial Field Calculations

Extending a magnetic field in space or shielding nearby structures from the field of a coil can be extremely useful for pulsed power applications. This report investigates this in a very simple geometry to better understand the extent to which the magnetic field may be extended, specifically the field generated by a coil along its axial direction, particularly at the edges of the coil, while simultaneously shielding (or reducing) the field in the lateral direction by the application of ferromagnetic cladding on the coil.

Calculations were performed for an infinitely rectangular long wire clad on one side with a rectangular piece of iron (Fe) with a length much greater than the cross-sectional dimensions. Both had cross sections of 2.5 × 5.0 cm. The fields were determined along the line extending from the wire/cladding junction upward (y-direction), as shown by the dotted line in Fig. 1.

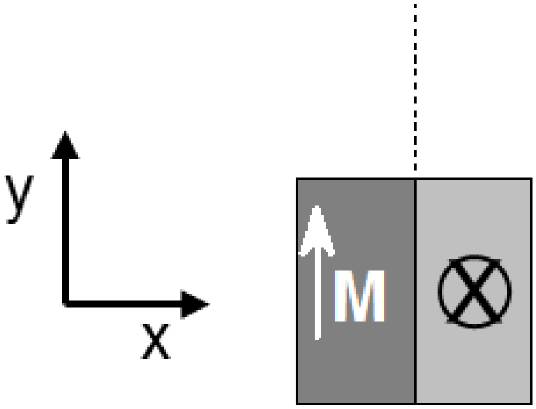

Fig. 1 Cross-sectional configuration for calculation including fully saturated magnetized Fe (dark gray) and current carrying rectangular wire (light gray)

Fe has a saturation field on the order of 1.8 Tesla (T). The field from the saturated magnetic block with uniform magnetization in the y-direction was calculated using a surface current in a rectangular loop integrated over the thickness of the block. A current of 607,000 A in the wire was chosen to produce fields on the same order as the saturated Fe. The current was applied into the page, and a clockwise field around the wire was produced (Fig. 1).

Figure 2 shows the y-component of the field resulting from the magnet, the coil, and the combination of the two. The x-component of the magnetic field produced by the coil is also shown for comparison. The combination of the two fields shows that the field can be extended by the cladding. At a distance of 7.5 cm from the center of the magnet/wire combination, the field in the y-direction goes from 0.31 to 0.57 T, nearly doubling. However, if the total field is considered,

$$B_{mag} = (B_x^2 + B_y^2)^{1/2} \ , \tag{1}$$

the field is increased from 1.25 to 1.34 T, or about 7% (ignoring B_x of the Fe).

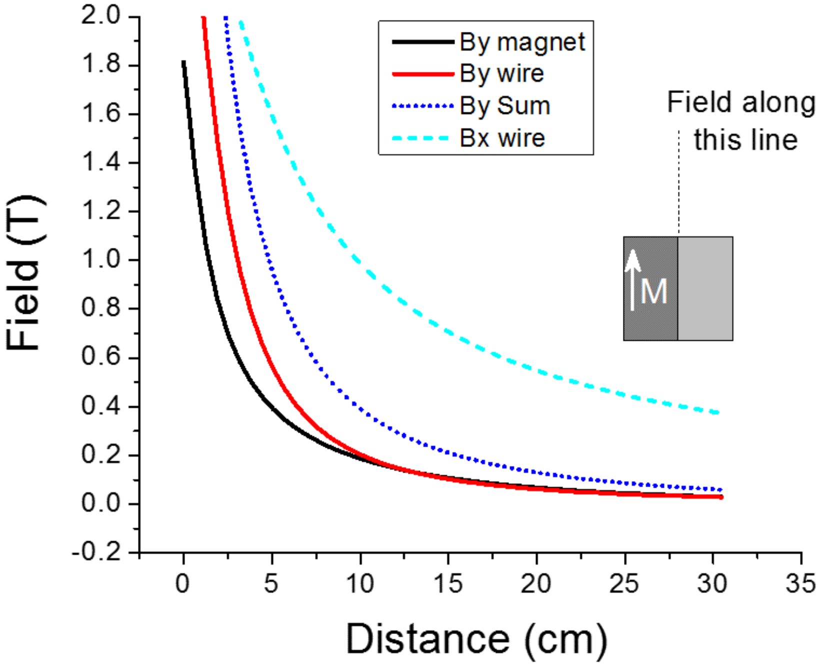

Fig. 2 Field from a rectangular saturated ferromagnetic material and an infinitely long wire with a rectangular cross section

2. Two-Dimensional Calculations

Two-dimensional-axisymmetric analytical calculations* were performed for a 20-cm-diameter single-turn coil with an external metal cladding with varying permeability of μ_o, 10 μ_o, and 50 μ_o, where μ_o is the permeability of free space. Cross sections and applied current were identical to the initial calculation. While Fe has a permeability significantly higher than 50 μ_o (on the order of 1,000 μ_o), the fundamental and most substantial changes to the field occur when initially increasing the permeability and the magnetic flux begins to channel through the ferromagnetic material. Therefore, only calculations at 10 and 50 μ_o were considered for this work. All calculations were performed with a symmetry line along the y = 0 axis. The calculations were carried out to 0.2 s to ensure complete saturation of the fields in the cladding.

The field at the coil edge along the axial direction was extended up to 10%, in good agreement with the calculations in Section 1. The field outside the coil in the radial

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* The 2-D model calculations were performed in conjunction with John Powell, utilizing the code developed in Powell and Zelinkski.[1]

direction was reduced by an order of magnitude, particularly within close proximity of the cladding. Figures 3–5 show the magnitude of the magnetic field for calculations with a permeability of μ_o, 10 μ_o, and 50 μ_o, respectively. The dotted line marks the distance that the 0.6- to 0.8-T contour extends, which is an additional 7.7% from μ_o to 10 μ_o and 10.0% from μ_o to 50 μ_o. Figure 6 shows the magnetic vector potential for the 50-μ_o configuration, while Fig. 7 gives a full 4-quadrant view of the magnetic field.

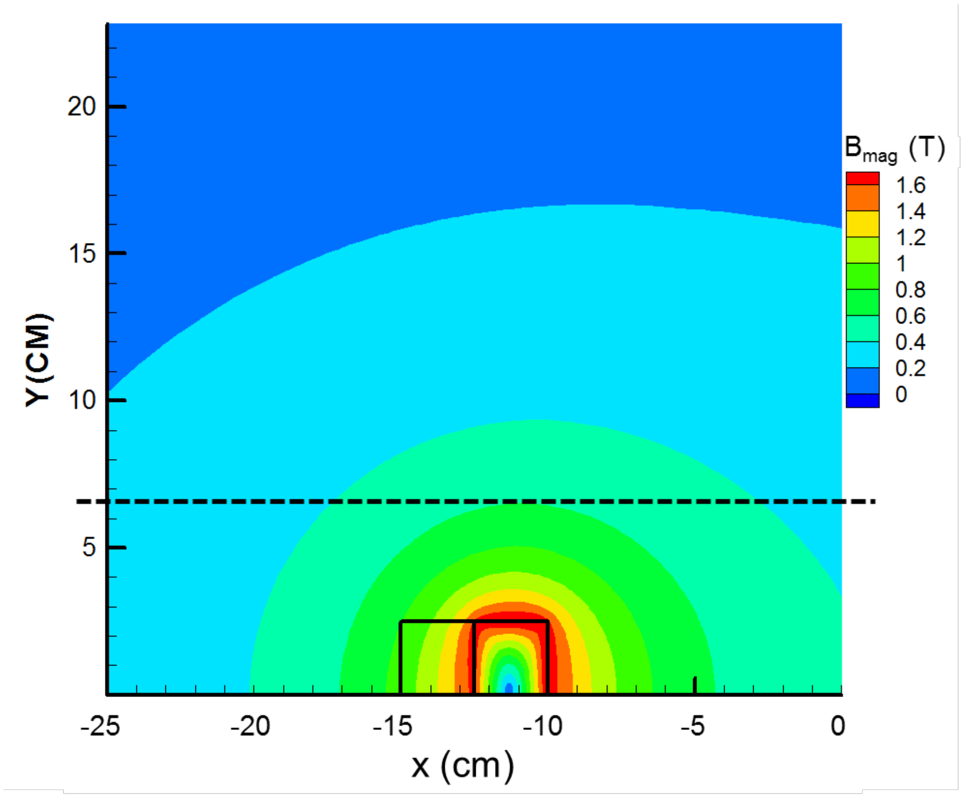

Fig. 3 **Two-dimensional calculation of the field of a single-turn coil (right) with external metal cladding (left) with a permeability of μ_o**

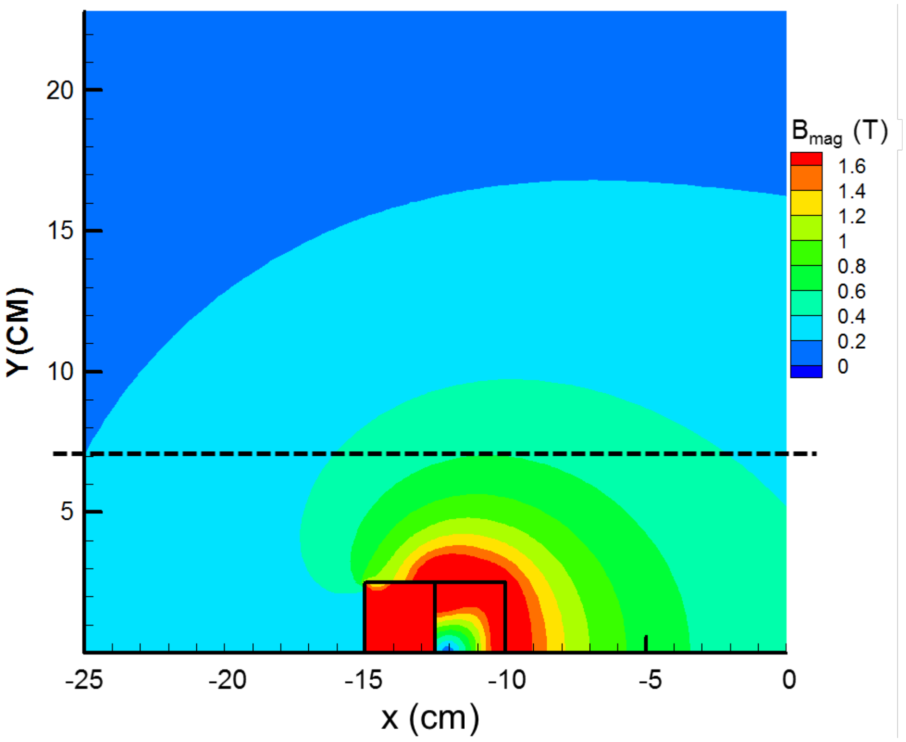

Fig. 4 **Two-dimensional calculation of the field of a single-turn coil (right) with external metal cladding (left) with a permeability of 10 μ_o**

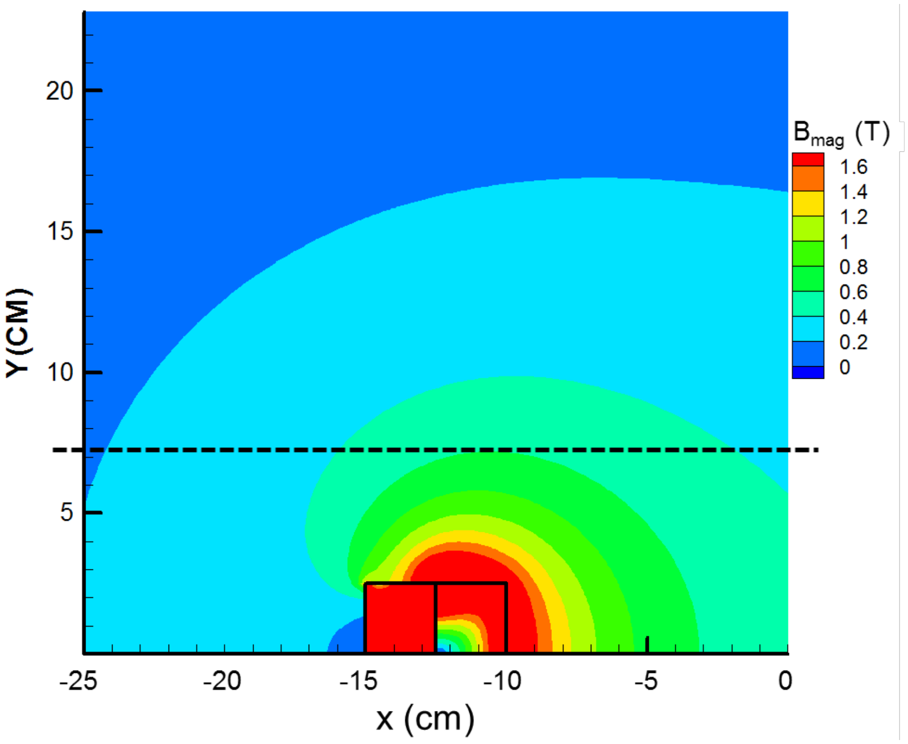

Fig. 5 **Two-dimensional calculation of the field of a single-turn coil (right) with external metal cladding (left) with a permeability of 50 μ_o**

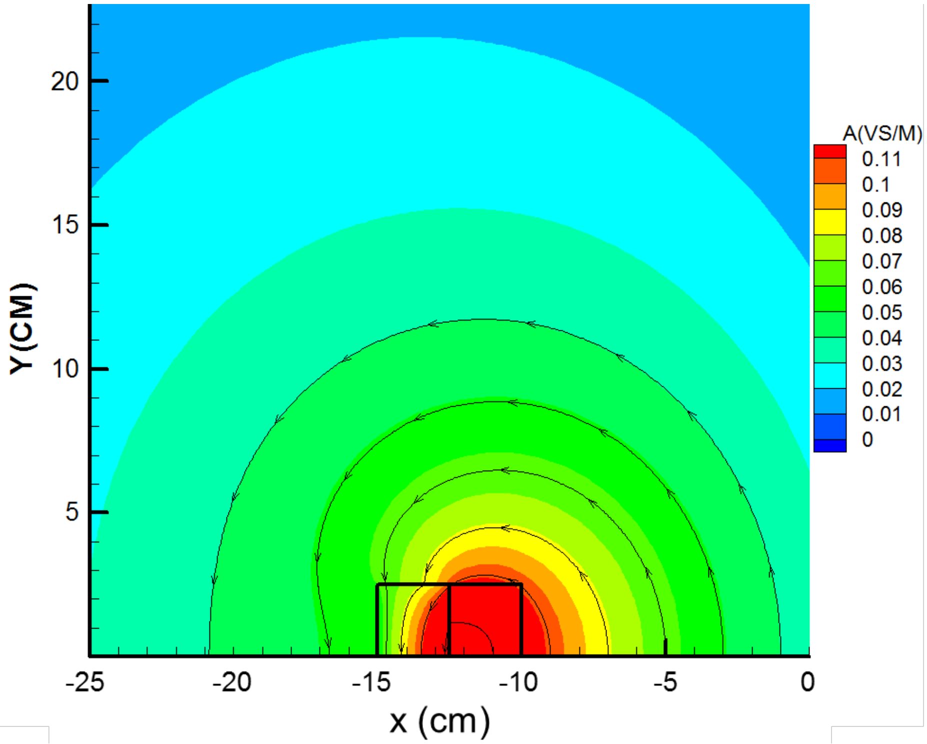

Fig. 6 Two-dimensional calculation showing the magnetic vector potential produced by a single-turn coil (right) with external metal cladding (left) with a permeability of 50 μ_o

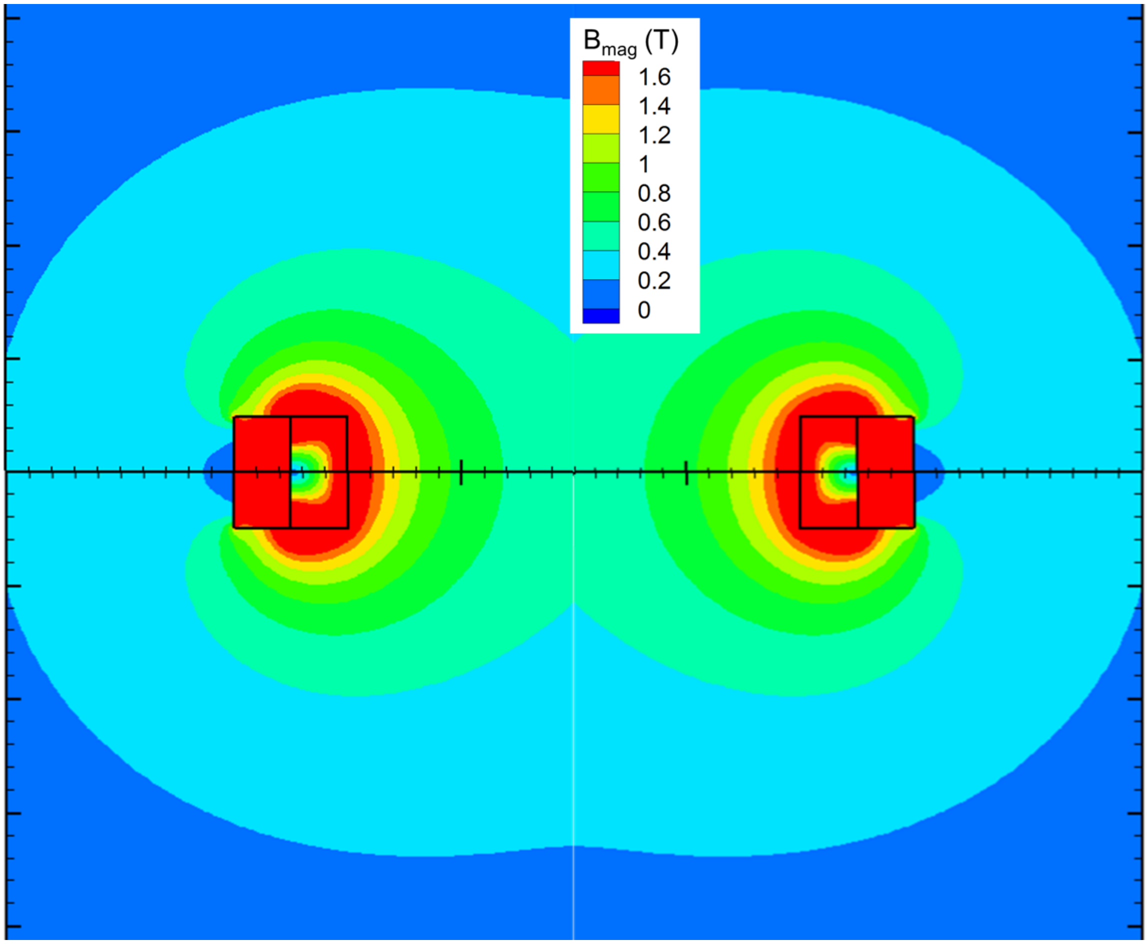

Fig. 7 Full cross-sectional view of the field and coil with external cladding of 50 μ_o

3. Conclusion

Adding soft ferromagnetic cladding with high-saturation magnetization to a coil can extend the field in the vicinity of the coil edge. In addition, the cladding also shields the nearby lateral direction of the coil from the generated magnetic field. This can be very useful for shielding sensitive assets or for reducing the coupling that would occur between neighboring inductive loads.

4. References

1. Powell JD, Zielinski AE. Two-dimensional current diffusion in the rails of a railgun. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2008 Oct. Report No.: ARL-TR-4618.

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