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A Modified Rogowski Coil for Measurements of Hybrid Permanent Magnets

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A Modified Rogowski Coil for Measurements of Hybrid Permanent Magnets

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Abstract

For large permanent magnets, as proposed for the Fermilab Recycler Ring, it may be important to quickly verify that the magnet's strength is correct. This may be important, for example, if a magnet is suspected of having changed due to some sort of accident. The field strength of a pure dipole can be readily measured with a Hall probe, but for indexed dipoles and for quadrupoles a Hall probe will not give very accurate results without precise positioning.

We have investigated a different approach, the use of a modified Rogowski coil to measure the magnetic potential of each pole. As long as magnet geometry is fixed and known, measurement of the magnetic potential at each pole gives a good measurement of field strength even for magnets with large quadrupole components. The construction and use of such a coil and the precision of measurements made with it will be discussed.

1. Introduction

In the approximation that the iron pieces in a hybrid permanent magnet are equipotentials (which will be nearly true for high μ or thick iron) and assuming that the magnet geometry is fixed, the magnetic fields are entirely determined by the geometry and the magnetic potentials of the iron. The fields in the magnet gap are primarily determined by the geometry and relative positioning of the poles and their magnetic potential differences; small motion of magnetic material or of return yokes primarily affects fringe fields and high order multipoles, but not the low order field profile. Hence, for a hybrid permanent magnet with well-defined pole contours and positions, measurement of the magnetic potential of the poles is equivalent to a fundamental-order field measurement.

Offsets in the potentials of the poles with respect to the return yoke potential will generate error multipoles (especially skew). It is important that the poles of a hybrid permanent magnet structure each be at equal (or opposite) potentials to avoid such error multipoles. Measurement of the magnetic potentials of the poles can thus provide more information than just a low order field measurement; it can also provide an indication of low order skew components.

For these reasons, it is desirable to be able to measure the magnetic potentials of the poles in a hybrid permanent magnet, both to measure the magnetic field at initial construction and to verify the field after installation. Through conversations with Klaus Halbach, we decided to investigate the use of a Rogowski Coil for measurement of the magnetic potentials of the magnet poles.

2. Basic Physics

A Rogowski coil is essentially a very tightly wound coil of uniform cross section. The conductor from one end is brought back through the axis of the coil to the other end. The resultant structure can be viewed as a number of single-turn loops wired in series. Each turn sees a flux linkage equal to $\int \vec{B} \bullet d\vec{A}$. The total flux linkage is the sum of the fluxes in each individual turn. For closely and uniformly spaced turns of equal area, this summation may be approximated by an integral:

$$\Phi = An\int \vec{B} \bullet d\vec{l}$$

where A is the cross-sectional area of each winding and n is the coil pitch (turns per unit length). Since the coil is in air, where $B=\mu_0 H$, the flux is thus proportional to the magnetic potential difference ($\int \vec{H} \bullet d\vec{l}$) between the two ends of the coil. Note that the product An is the coil sensitivity, and acts as a calibration constant for magnetic potential measurements.

If the magnet structure is turned off, or the coil is moved so that both ends are at the same magnetic potential, the change in flux (equal to the time integral of the voltage on the coil) is proportional to the initial difference in magnetic potentials at the two ends of the coil. Thus the Rogowski coil may be used to measure the magnetic potential of an arbitrary point in a magnetic circuit.

Such a coil was first proposed by W. Rogowski and W. Steinhaus as a method of measuring magnetic potential in order to find the value of H at various points in a magnetic circuit. [1] Their coil was wound around a long, flat, flexible strip of material, forming a flexible belt-like structure whose ends could easily be moved between various points in a magnetic circuit.

(Today the Rogowski coil is most commonly used in the plasma physics and pulsed power fields as a way of measuring current [2,3]. In this application, a Rogowski coil is bent into a circular loop, forming a torus. This acts as a single-turn pickup coil. The advantage of this toroidal coil over a simple single-turn pickup loop is that the distributed inductance of the coil may be used as part of a passive signal integration circuit, giving a reliable current measurement independent of pulse profile.)

3. Complications

There are a number of factors which can impact the precision of magnetic potential measurement with a Rogowski coil. In order to make high-precision measurements, all significant error contributions should be identified and addressed. These errors can be grouped in three classes: fundamental errors, construction errors, and measurement errors.

3.1 Fundamental Errors

If the potential of a magnet pole is to be measured, it is necessary that one end of the Rogowski coil be placed at the same potential as the pole. In general, the end position of the coil will be poorly defined due to end effects of the winding. Even with a precisely made coil end, this end must be placed very flat against the pole to ensure that the entire end is at the pole potential. Small gaps or angles at the end can introduce large errors and uncertainty in the measurement of potential. The larger the field at the pole, the larger these errors will be.

The uncertainties due to these end effects can be eliminated by forcing the magnetic field to zero at the end of the coil. This can be accomplished by inserting the end of the coil into a recess (slot or hole) on the pole piece rather than flat against its surface. Such a geometry forces the magnetic field lines to enter the coil through its sides instead of through the end, and eliminates end effects.

Similarly, residual fields through the far end of the coil (assumed to be field-free) will cause measurement errors. This can be addressed by use of a steel (or mu-metal) shielding tube which is kept in a fixed position as the magnet is turned off or the coil is withdrawn.

These two features comprise our primary modification to the basic Rogowski coil, and are essential for high precision measurements.

In addition, the discreteness of the wires may produce errors even with a perfectly constructed coil. This is because a discrete summation is being used to approximate an integral. The Rogowski coil may be thought of as performing a spatial sampling and summation of the field distribution. Each winding may be imagined as performing a field sampling with a boxcar integration which extends for one half of the winding spacing on either side of the winding (fig. 1).

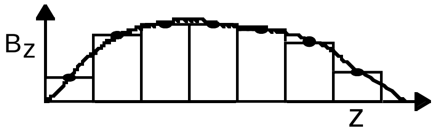

Fig. 1. Illustration of the field sampling performed by each loop of a Rogowski coil, and the summation performed by the entire coil.

Comparing this boxcar integration to the true integral under the curve in fig. 1, there will be an integrated flux error $d\Phi_i$ at each winding which will be a function of the wire spacing and the even axial derivatives of the field:

$$d\Phi_i = \frac{1}{24n^3}\left.\frac{d^2B}{dz^2}\right|_i + \cdots (?)$$

When this is integrated (summed) over the length of the coil, there will be a total flux error $d\Phi$, given by:

$$d\Phi = \frac{1}{24n^3}\left(\left.\frac{dB}{dz}\right|_N - \left.\frac{dB}{dz}\right|_1\right) + \cdots (?)$$

where the subscripts *1* and *N* refer to the first and last winding of the coil. Thus, if the field derivatives go to zero at the ends of the coil (which will be true if the above suggestions are followed to force the fields to zero at the ends of the coil), there should be no error due to this effect.

3.2 Construction Errors

The effects of non-uniform winding pitch and non-uniform coil area were discussed by Rogowski and Steinhaus in their original paper. Again consider the Rogowski coil as performing a spatial sampling and summation of the field distribution. It is assumed that the samples are equally spaced (uniform coil pitch) and of equal gain (uniform coil area). Non-uniform area will produce an error which is proportional to both the variation in area and the field magnitude. Each winding will have a flux error $d\Phi_i$ of

$$d\Phi_i = \Delta A_i B_{z,i}$$

These errors will be summed by the coil. Assuming random, normally distributed errors in coil area, the resultant flux will be in error by approximately:

$$d\Phi_{RMS} = \frac{\sigma_A n}{\sqrt{n l_{char}}} \int \vec{B} \bullet d\vec{l} = \frac{\Phi \sigma_A}{A\sqrt{n l_{char}}}$$

where σ_A is the RMS variation in coil area and l_{char} is the characteristic length over which the magnetic field changes appreciably (and nl_{char} is the number of turns over which the field changes appreciably).

Non-uniform coil pitch will similarly produce an error signal which is proportional to the axial field gradient and the coil position error. Again assuming that these errors are normally distributed and random, the resultant flux error will be approximately:

$$d\Phi_{RMS} = \frac{\Phi n \sigma_{spacing}}{\sqrt{n l_{char}}}$$

where $\sigma_{spacing}$ is the RMS turn spacing error.

Because of these effects, precision measurements suggest that a coil be relatively rigid rather than flexible, as was the original Rogowski coil.

The position of the return wire as it comes back through the coil is also important. A side view of the coil will look something like fig. 2:

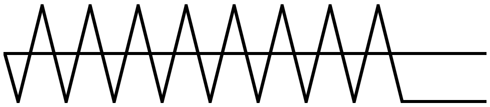

Fig. 2. Side view of coil with return wire running along the axis. Note that for an ideal spiral winding, the effective coil area when viewed transversely is zero.

If the return wire comes exactly down the axis, the projected loop area in the body of the coil is zero. If it is off-axis, there will be a residual loop area looking from the side, and this will generate an error flux of

$$d\Phi = \int x_{offset} B_y dl$$

where x_{offset} is the off-axis position of the return wire, and the coil is assumed to extend in the z-direction. The coil signal will then be rotationally dependent if placed in a non-uniform field. Thus the return wire should be well centered in the coil. (For multi-layer coils, the return wire of each layer should be arranged symmetrically around the center of the coil.)

Note that "slanted" or "angled" coils will also present a non-zero loop area to transverse fields (fig. 3).

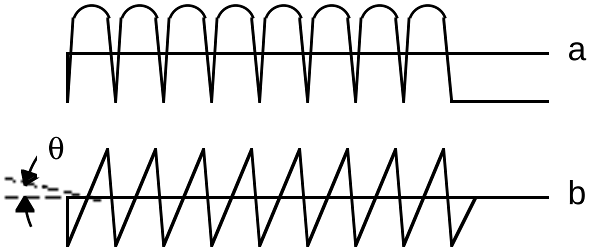

Fig. 3. Side view (a) and top view (b) of coil which is wound on a slant of an angle θ. Note that the effective coil area when viewed from the side is non-zero.

This will generate an error flux which is proportional to the *sin* of the angular error in the coil planes:

$$d\Phi = An\int \sin\theta_{error} B_y dl$$

These effects can be controlled by careful construction of a coil. In addition, errors due to these effects are small if the field to be measured is predominantly axial, which is the case for the proposed use of Rogowski coils for hybrid permanent magnets at Fermilab.

3.3 Measurement Errors

If the flux integrating circuit has a finite impedance, the current flow in the coil may affect the magnetic field distribution. However, this should not affect the integrated flux.

A greater concern is noise in the flux integration circuit. Typical high resolution flux integrating circuits have noise limits set by pre-amplifier noise [4]. White noise and 1/f noise generally have comparable contributions at approximately 1 Hz. Measurements over time scales of a few seconds are typically subject to 10^{-6} to 10^{-7} volt-sec. of noise.

Integrators are also subject to drift and offset. These effects can be minimized by the use of a measurement procedure whereby a background reading is taken both before and after the measurement to isolate the drift and offset and correct for them, assuming the drift to be linear over the short time required for a measurement.

4. Prototype

We built a prototype Rogowski coil (fig. 4) to make measurements on hybrid permanent magnets. This was made of two layers of #36 (about 0.005" diameter) magnet wire wound on a 1/4" diameter fiberglass-epoxy rod. Winding density is about 400 turns per inch, and coil sensitivity *An* (see section 2, above) is about 0.50 V-s/T-m. Two shallow, narrow, diametrically opposed, longitudinal grooves were cut in the rod to bring back the return wires.[*]

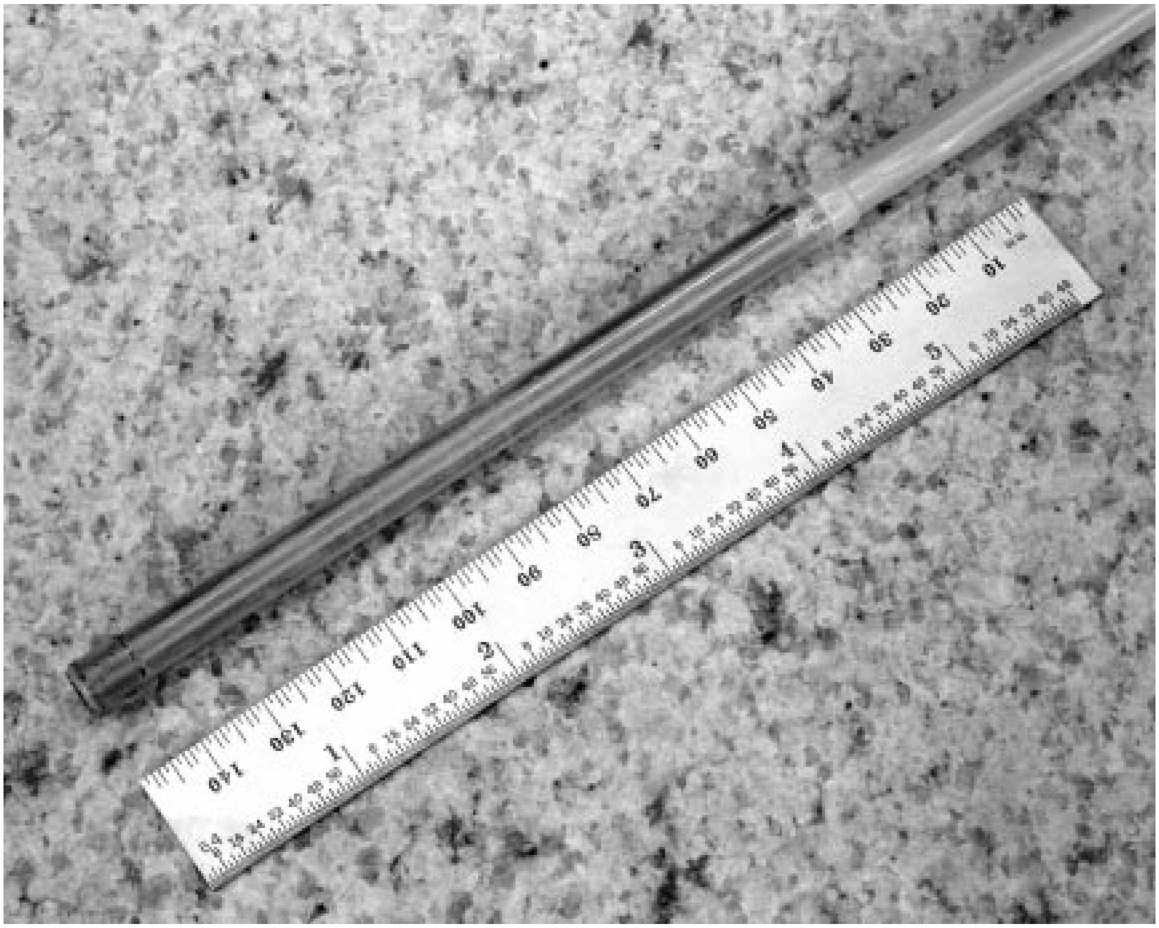

Fig. 4. The prototype Rogowski coil, made of two layers of #36 magnet wire wound on a 1/4" diameter fiberglass-epoxy rod.

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[*] It is tempting, for an even number of layers, to wind the layers continuously up and down the rod. However, this reverses the winding pitch and tends to cause the windings to become very uneven, destroying the uniformity needed for a high precision measurement. It is preferable to wind each layer with the same pitch, requiring a separate return wire for each layer.

The coil was protected with a layer of heat-shrinkable plastic tubing. A break in one of the layers in one of the last two or three turns necessitated removal of the last 1/2" or so of the tubing to enable repair, which accounts for the break in the tubing near the end.

All of the prototype magnets on which this coil has been tested have been prepared with a 3/8" to 1/2" counterbore in the end of the pole, and a corresponding hole in the end field clamp for insertion of the Rogowski coil (fig. 5).

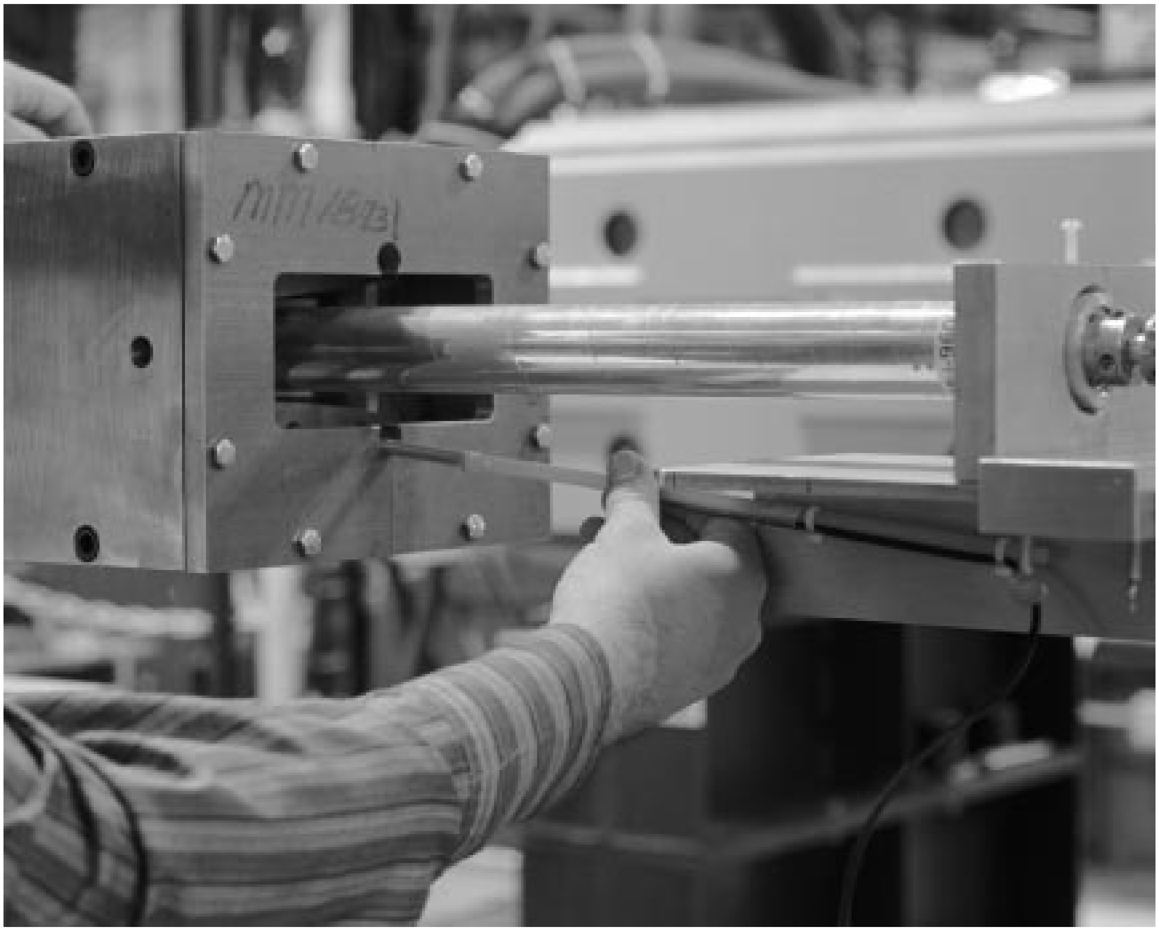

Fig. 5. The Rogowski coil in use. The coil is inserted through a hole in the magnet flux return and into a counterbore in the pole piece. The large cylinder in the magnet bore is a rotating coil field measurement probe. As explained in the text, the large aperture in this magnet allows significant field leakage; the outer end of the Rogowski coil should be magnetically shielded for high-precision measurements.

5. Tests

This coil has been tested on a number of permanent magnet designs, including high-field dipoles, gradient dipoles, and quadrupoles. In these tests, the coil was inserted through the hole in the field clamp at the end of the magnet and into the counterbore in the pole (fig. 5). This was connected to an analog integrator, set to 10mS integration time and carefully adjusted to minimize drift. The integrator was then reset, the probe was withdrawn and its tip placed against the flux return, and the integrator reading was recorded.

As mentioned above, this procedure is subject to errors due to integrator drift. With a carefully zeroed integrator, the drift produced relative errors at about the 10^{-4} level, which was judged adequate for preliminary tests. These errors can be reduced by use of a modified procedure (suggested above) whereby the probe is re-inserted into the counterbore and a final measurement is taken to isolate the drift and correct for it, assuming it to be linear. Preliminary measurements with such a procedure suggest relative error contributions of about 5×10^{-5}.

The dipoles and quadrupoles which we have measured typically have pole potentials of 20 to 40 gauss-meter, and the prototype Rogowski coil typically produces 1 to 2 mV-sec, resulting in a 0.1 to 0.2 V signal after integration with a 10mS integration time. Based on a sampling of about 20 measurements of pole potentials on quadrupoles, the RMS repeatability of measurement is about 4×10^{-4}, relative to these typical signal levels. It is thought that much of this is due to integrator offset and drift, and that the improved measurement procedure described above will improve this to better than 1×10^{-4}. Increasing the cross-sectional area or the number of turns on the coil to increase the signal strength should also help in reducing these contributions.

Measurements of high-field dipoles, as shown in fig. 5, exhibit poorer measurement repeatability, approximately 1×10^{-3}. This is due to field leakage out of the magnet aperture, which causes residual fields at the end of the Rogowski coil. As mentioned above, it is possible to eliminate this by the use of a steel flux-shielding tube around the Rogowski coil which is firmly held against the flux return as the coil is moved. A hand-held tube did not prove to be stable enough, but it should be possible to design a simple fixture which will hold the tube in a fixed position to allow measurement precisions again approaching 10^{-4}.

6. Conclusions

We have shown that with careful design, assembly, and use, a Rogowski coil is capable of rapid, high-precision measurements of magnetic potential. The repeatability of our prototype Rogowski coil is a few parts in 10^{-4}. Limitations to precision have been identified, and it should be possible to improve this to better than 1×10^{-4} without difficulty.

This should be more than adequate for the Recycler Ring magnets. At this level, the non-uniformity of the potential on the pole (due to the finite μ of the iron) should dominate any measurement errors due to the coil.

For hybrid permanent magnets with fixed geometry, such magnetic potential measurements provide accurate, indirect measurements of magnetic field strength. This is applicable both to uniform field dipoles and to non-uniform field magnets, such as gradient magnets and quadrupoles. A Rogowski coil as described in this paper has already proved to be useful in identifying problems in hybrid permanent magnet construction, such as improperly magnetized permanent magnet material. It is potentially more useful as a diagnostic for hybrid permanent magnets which have been installed in an accelerator, as it allows rapid verification of magnet strength without the need to remove a magnet from the accelerator tunnel or to remove beam tubes from the magnet.

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