AFRL-RD-PS-
TP-2022-0013

AFRL-RD-PS-
TP-2022-0013

DESIGN, FABRICATION, AND INSTALLATION OF SHIELDED ROGOWSKI COILS

Jerald Parker, et al.

10 June 2022

Technical Paper

AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

NOTICE AND SIGNATURE PAGE

AFRL-RD-PS-TP-2022-0013 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//James Schrock//

JAMES SCHROCK, DR-III
Senior Electronics Engineer, AFRL/RDHP

//Stephen Langdon//

STEPHEN LANGDON, DR-III
Branch Chief, AFRL/RDHP

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10-06-2022

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*
11 JAN 2022 - 11 MAR 2022

4. TITLE AND SUBTITLE
Design, Fabrication, and Installation of Shielded Rogowski Coils

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jerald Parker, James Schrock, Bud Denny, Susan Heidger

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER D0EW

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Leidos
2109 Air Park Rd SE
Albuquerque, NM 87108

Air Force Research Laboratory
High Power Microwave Division
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RD-PS-TP-2022-0013

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
**Air Force Research Laboratory
High Power Microwave Division
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RDHP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION A. Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Public Affairs release approval #AFRL-2022-3193

14. ABSTRACT
Pulsed power current diagnostics are an engineering challenge because of the high rate of change of current and extreme peak current amplitudes inherent to many pulsed power apparatuses. The situation is further complicated by the high degree of ambient fields and complex geometries of compact pulsed power systems. This paper provides a detailed guide for the design, fabrication, and installation of Rogowski coils as implemented at AFRL's Directed Energy Directorate, High Power Electromagnetics Division. Practical designs, shielding techniques, rise time considerations, and signal processing methods are presented.

15. SUBJECT TERMS
ROGOWSKI COILS, PULSED POWER

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			JAMES SCHROCK
Unclassified	Unclassified	Unclassified	SAR	15	**19b. TELEPHONE NUMBER *(include area code)***

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

TABLE OF CONTENTS

LIST OF FIGURES

1.0 Introduction

The Rogowski coil is an easily implemented diagnostic for measuring the time rate of change of current in a pulsed power apparatus. In addition to the simplicity of construction, its principal advantage is that it can be employed in almost any geometry, as long as the sensing coil makes a complete path that encloses the current being measured. This document begins by providing a brief explanation of how the Rogowski coil works. The fundamental physics is followed by descriptions of how to design, build, and install a shielded Rogowski coil. This article concludes with a short discussion of signal processing strategies.

2.0 Rogowski Coil Principles of Operation

Rogowski coil operation is based on Ampere's circuital law which states that the line integral of the vector, H, around any closed path is equal to the current passing through the surface bounded by that path. Note that this is a very general statement which places no restrictions on the length or shape of the path. Mathematically, Ampere's law can be written as

$$I = \oint \bar{H} \cdot d\bar{l} \qquad (1)$$

where the Dot product of *H* and *dl* results in integrating the component of *H* parallel to the line element *dl*. Experimentally, this integral can be approximated by a summation of the form

$$I \cong \sum_{1}^{n} H_k^p \ \partial l_k \qquad (2)$$

where H_k^p is the measured component of *H* parallel to the path element δl at the point *k* and the summation is over all the measurement points. Unfortunately, this relationship isn't particularly helpful as there is no simple experimental way to measure H. However, differentiating Eqn. 2 with respect to time gives a more useful relationship

$$\dot{I} \cong \sum_{1}^{n} \frac{\dot{B}}{\mu_o} \ \partial l \qquad (3)$$

where the k indices have be dropped for clarity and free space is assumed so that $B = \mu_o H$. Eqn. 3 is useful because there is a simple experimental way to measure B-dot as shown in Fig. 1.

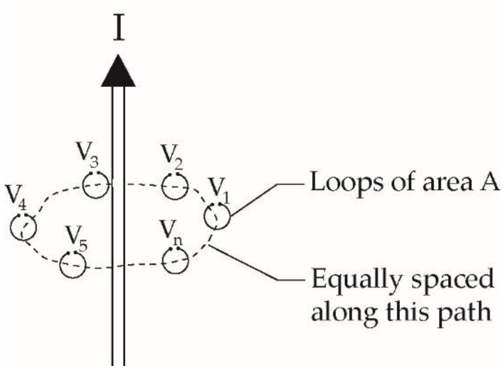

Figure 1: B-dot measurement diagram 1. B-dot can be measured at equally spaced points from the voltage on the terminals of small, equal-area loops.

At each of the *n* measurement points a small wire loop of area A is placed and the loop is oriented with its normal vector parallel to the path. In the presence of a time varying magnetic field a voltage V_k is developed on the terminals of each loop. Then Eqn. 3 can be rewritten as

$$\dot{I} \cong \frac{\partial l}{\mu_o A} \sum_{1}^{n} V_k \tag{4}$$

Two important assumptions were made in going from Eqn. 3 to Eqn. 4. First, that all of the loops have the same area A and, second, that the loops are equally spaced along the path. This allowed δl and A to be moved outside the summation.

The next simplification is to perform the summation in Eqn. 4 experimentally as shown in Fig. 2. All of the loops are now connected in series and the resulting terminal voltage *V(t)* is the desired measurement of *I*-dot.

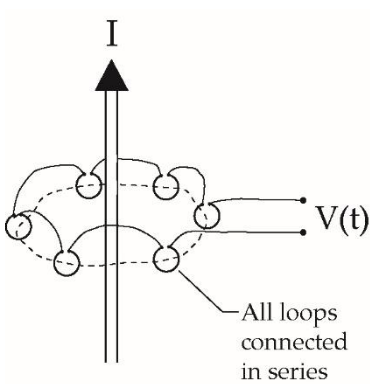

Figure 2: B-dot measurement diagram 2. Summation of the loop voltages can be achieved by connecting the loops in series.

At this point we almost, but don't quite, have a Rogowski coil. Examining Fig. 2 one sees that in addition to all of the small measurement coils the entire conductor makes one large loop in space. If there should happen to be a time-dependent B field passing through this large loop, a false signal will be added to the desired measurement. The final step, as shown in Fig. 3, is to thread the output conductor back through the center of the measurement coils. This extra loop cancels out false signals, and completes the basic Rogowski coil.

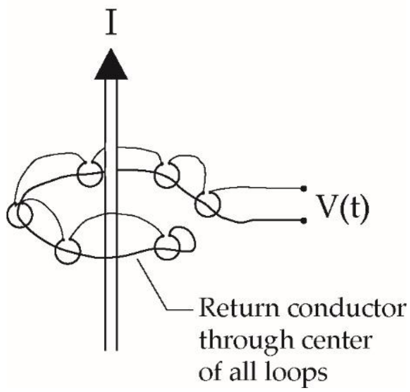

Figure 3: B-dot measurement diagram 3. Passing the output conductor back along the center of the coils prevents the Rogowski from generating false signals from external B fields passing axially through the large loop.

3.0 Basic Rogowski Coil Design, Fabrication, Installation, and Shielding

3.1 Rogowski Coil Design

The need for a return conductor passing through the measurement coils has led to the almost universal use of coaxial cable for the fabrication of Rogowski coils. Stripping off the outer jacket and the shield braid from a length of coaxial cable provides a pristine uniform diameter polyethylene cylinder to wind the coil on and a cable center conductor for the return conductor. The formula for calculating the Rogowski response is basically Eqn. 4 which can be rewritten in a more useful form as

$$V(t) = M\,\dot{I} = \frac{\mu_o\,\pi\,r_e^2}{p}\,\dot{I} \qquad (5)$$

where M is the mutual inductance between the current source and Rogowski, r_e is the effective radius of the coil winding and *p* is the pitch of the winding, i.e., the distance between turns.

Two convenient forms of the relation for M are as follows:

$$M = \frac{(2\,\pi\,r_e)^2}{p}\,x\,10^{-7} \qquad \text{M[H], r[m]. p[m]} \qquad (6)$$

$$M = 0.10\,\frac{(2\,\pi\,r_e)^2}{p} \qquad \text{M[nH], r[mm]. p[mm]} \qquad (7)$$

The design procedure is as follows:

1. Estimate the maximum I-dot that will be measured and the amplitude of the desired electrical signal. Dividing the desired signal voltage by I-dot gives the required M for the Rogowski.

2. Select a coax cable type and a size of magnet wire with which to wind the Rogowski.
3. Measure the diameter of the coax cable insulation and the diameter of the wire. Then the effective radius R_e = (coax diameter + wire diameter)/2. (For example, winding #26 AWG wire on RG223 coax results in R_e = 1.64 mm)
4. Using the formula for M, calculate the required winding pitch, p.

This is all straightforward, except when it isn't. What if the required pitch is really long or really short?

A long winding pitch is generally not acceptable because it does not sample the B field often enough to make the summation in Eqn. 2 an accurate approximation of the integral in Eqn. 1. It is generally desirable to have at least 10 turns on the Rogowski coil and even more if the B field has a complex shape, e.g., the field around non-circular conductors. So what is the solution? First, try increasing the acceptable signal voltage. A signal voltage up to 500 V is practical as it can be attenuated with commercial attenuators. Voltages above 500 V may damage attenuators or integrators.

A second option is to use a coax cable with a smaller diameter. Since pitch decrease as the square of the cable diameter this could be very effective. BUT DON'T DO IT. Essentially all of the small diameter coax, e.g., RG174, have a STEEL wire core. The flux in this steel core affects the Rogowski coil output and can produce large anomalous signals when the steel saturates. If a smaller diameter is needed, use copper hook-up wire with thick insulation or put some small heat shrink tubing on a piece of copper wire.

What if the calculated winding pitch is very small? There is nothing intrinsically wrong with this, but it is very tiresome winding 100+, uniformly spaced turns on a Rogowski coil. The obvious option in this case is to accept a smaller signal. With modern oscilloscopes a signal amplitude of 100 mV is generally acceptable. However, if the environment is electrically noisy or if you intend to passively integrate the signal, larger voltages will be needed.

An alternative in this case is to use a larger diameter coaxial cable. Or, if the winding pitch only needs to be increased by a factor of 2 or so, apply one or more layers of heat shrink tubing over the selected coax cable to increase its diameter.

3.2 Rogowski Coil Fabrication

Start by determining the length required for the Rogowski coil. If the coil is not mounted in a fixture, then the length can be chosen arbitrarily. If the Rogowski is required to fit in a groove, for example, in a shield enclosure, then the length must be calculated carefully so that the resulting coil forms an accurate closed loop when installed.

Next, remove the cable jacket and the shield braid as shown in Fig. 4. Trim approximately 3 mm of the polyethylene insulation off the end to expose the center conductor.

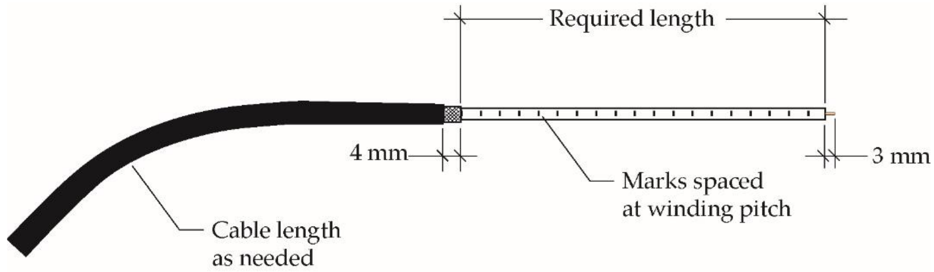

Figure 4: Preparations for making a Rogowski coil from a coaxial cable.

Lay the stripped cable out straight on a bench; use some tape at the ends if necessary. Using a reasonably accurate ruler make marks on the polyethylene insulation at intervals of one winding pitch. Start at the edge of the exposed shield braid and work to the free end. It is best to use a fine point Sharpie for marking, however an ordinary ball point pen will suffice if care is exercised during winding not to rub off the marks.

Prepare the wire that will be used to wind the Rogowski coil by removing the insulation for a length of about 1.5”. Clamp the un-stripped portion of the cable in a small bench vise. The stripped portion should extend out horizontally with the marks on the insulation facing up. Wrap the cleaned end of the winding wire a few times around the exposed shield braid and solder in place. The wire should leave the shield braid aligned with the marks. Wind the wire in a uniform spiral around the cable insulation so that each turn passes over a mark.

When the winding nears the end of the cable it is necessary to stop and prepare the wire for its final connection. The recommended procedure is to stop winding about one turn from the end and clamp the cable and winding wire in a bench vise so that the wire cannot unwind. Then cut the wire about ¾” longer than needed to complete the winding. Strip the insulation off the last 1” of the wire. Then carefully complete the final winding turn and wrap the bare wire 2 or 3 times around the exposed center conductor. Solder the connection and carefully trim off any excess wire and center conductor. Termination of the winding can be accomplished without the bench vise if one is particularly dexterous.

The last fabrication step is to apply a layer of heat shrink (HS) tubing over the coil. Select a HS tubing diameter that will shrink firmly against the winding. For the commonly used RG223 cable a HS diameter of ¼” works well. Cut a length of HS tubing that extends an inch of so over the cable jacket and about 1” past the end of the Rogowski. Start shrinking the tube as the cable end and work toward the free end. At the free end, heat the tubing that extends beyond the Rogowski coil and, before it can cool, compress the excess tubing with a pair of smooth jaw pliers to form a flat tab. This serves the dual purpose of insulating the end of the Rogowski and providing a convenient tab that can be used, along with a couple of small cable ties, to hold the Rogowski in a well-formed loop.

3.3 Installation

The basic instructions for installing a Rogowski coils are: “loop it around the current conductor, line up the ends to close the loop and fix it in place.” However, as always, there are potential issues.

These issues arise if the assumptions made in going from Ampere's law to the Rogowski coil are not valid.

One of those assumptions is that the B field at a point along the path is equal to the average value of B over a loop of area A. This is true if B is uniform and is reasonably accurate if B varies linearly across the area A. However, the field around a conductor falls a 1/R, which is not linear except over short distances. Without going into the mathematical details, the result of this nonlinear dependence is that there will be errors in the calculated Rogowski calibration of order (r/R) where r is the radius of the measuring coil and R is the distance of the coil from the current source.

For a typical Rogowski made with RG223 with r=1.64 mm, the calibration can be off by 5% if the Rogowski loop is less the 64 mm (2.5") in diameter. It is important to understand that this is NOT an issue of errors in the signal. The output voltage will always be proportional to I-dot. The problem is that the calibration constant may not be the calculated value and, furthermore, may change depending on the position of the loop thereby losing one of the advertised advantages of the Rogowski coil.

The second assumption that affects the calibration of Rogowski coils is that the spacing between measurement points (the pitch p) is small enough that the B field measured by the loop, times p, is an accurate approximation to the integral of B along the path. For typical Rogowski measurements around a circular conductor, the B field along the path is nearly constant and pitch is not usually a concern. However, when measurements are made of non-circular conductors there can be an issue. Figure 5 shows a Rogowski coil deployed to measure the current in rectangular busbar. The magnetic field in this geometry is quite non-uniform in the region near the corners.

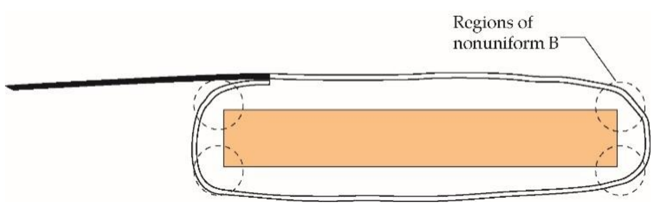

Figure 5: Rogowski coil on rectangular busbar. Regions of non-uniform B can affect the Rogowski response unless care is taken with the design of loop diameter and pitch.

It is difficult to estimate the errors that may occur here because they are geometry dependent. Because the B field varies not only with distance from the corner but also with distance around the corner, both the winding pitch and the winding diameter are important. As a rule of thumb one can use the criterion above, that is, that the diameter of Rogowski winding should be less than 10 % of the distance to the corner and, added to that, that the winding pitch should be comparable to the winding diameter. Because the winding pitch has to be constant along the entire length of the Rogowski, the small pitch needed near the corners often make a true Rogowski impractical is situations like that shown in Fig.5. In that case a Rogowski-like coil can be permanently installed and calibrated in situ. This will give usable measurements with the caveat that the calibration may have some time dependence due to current diffusion into the corners.

4.0 Practical Considerations: Shielding, Termination, Rise time, and Signal Processing

4.1 Shielding

Rogowski coils are very vulnerable to noise induced be external electric fields. A time varying external E field that terminates on the winding will induce a current flow directly into the output cable. To reduce or eliminate this electrical noise it is important to shield the entire Rogowski coil from external fields. The most effective form of shielding is to either place the Rogowski in a flange, Fig.6a, in a slot with a cover, Fig 6b, or to mount the Rogowski in a conducting fixture that can be installed around the current source Fig. 6c.

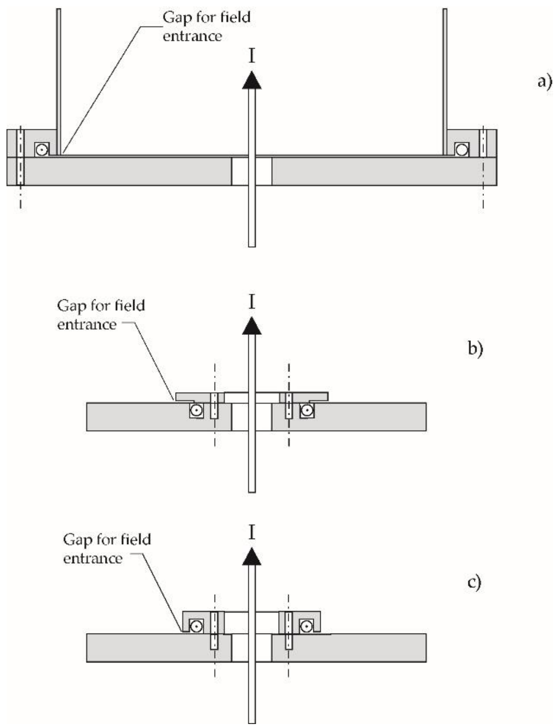

Figure 6: Rogowski coil shielding techniques: a) in a mounting flange, b) recessed in a plate with a cover, c) in a separate holder. In all cases, care must be taken to provide an azimuthal opening for the B field to reach the Rogowski c

In either case, there must be an open, azimuthal slot that allows the B field to enter into the region containing the Rogowski coil. The slot can be very thin and long to exclude electric fields. A gap of even 0.005” is sufficient if provisions are made to prevent it from shorting. Typically a gap of 0.020” is adequate if its depth is 0.1” or more.

Of the three configurations shown in Fig. 6 the two shown in 6a and 6b are preferable because the Rogowski output cable can pass out through the flange into a field-free region. With the configuration 6c, the output cable is exposed to fields within the apparatus. In this case it is important to use a double shielded cable such as RG223 to minimize noise pickup by the output cable.

If there is no practical means to install the Rogowski coil inside a shield, the Rogowski can be wrapped in copper foil with the foil connected to the cable shield. This still requires an azimuthal opening for the B field, usually in the form of some electrical tape insulating the region where the foil wrap overlaps. With a foil shielded Rogowski, the output cable should be grounded securely to the apparatus ground, e.g., passing through a BNC bulkhead fitting, before being connected to a recording instrument. Electric fields can induce large currents in the foil shield that should not be allowed to enter the recording instrument ground.

4.2 Termination

cThe Rogowski coil is effectively a short circuit at one end of the output cable. If the other end of the cable is connected to a high impedance oscilloscope input, the cable will support long-lasting reflections that corrupt the signal.

The general practice is to deal with this by,

1. Connecting to a 50 Ω scope input. However, the maximum voltage allowable may be limited by the oscilloscope settings.
2. Install a 50 Ωterminator on the cable and connect to a standard 1 MΩ input. This is generally preferable.
3. Using a commercial passive integrator with a 50 Ωinput resistance.

As an alternative, it is possible to internally terminate the Rogowski as shown in Fig.7. In this case the output cable can be directly connected to a 1 MΩ input without risking cable reflections. There is a downside to internal termination. If the output cable is inadvertently connected to a 50 Ω input, the response of the Rogowski is cut in half. This is the same behavior exhibited by Pearson current transformers which are internally terminate.

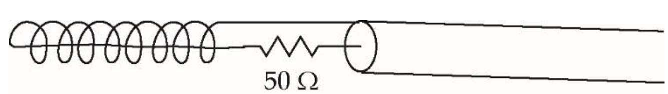

Figure 7: Rogowski coil termination diagram. A Rogowski coil can be internally terminated for use with a high impedance scope input. However, if used with a 50 Ω input, the signal will be reduced by ½.

4.3 Risetime

There are two effects which limit the rise time achievable with a Rogowski coil; internal inductance and transit time. The effect of internal inductance is easily understood. Referring to Fig. 8, the Rogowski coil can be represented as an inductor L_R in series with a 50 Ω resistor and coupled to the current to be measured by a mutual inductance M. The rise time of the output signal is limited to L_R/50 Ω.

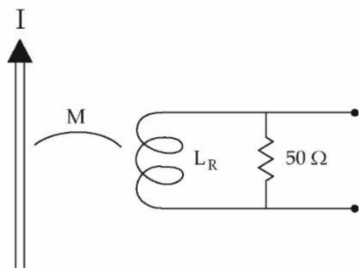

Figure 8: Rogowski coil rise time. The rise time of a Rogowski coil is limited be the self-inductance of the coil, not by the calculated mutual inductance. Long Rogowski coils with many turns have a slower risetime.

The rise time of a Rogowski coil depends on both winding pitch and total length, unlike the responsivity which depends only on winding pitch. In general, Rogowski coils have acceptably fast rise times. For example, a RG223 Rogowski loop that is 3" in diameter with a winding pitch of 5 mm has an inductance of 110 nH and, thus, a risetime of 2.2 ns.

Rise time can become an issue when trying to measure small signals. The signal generated by a Rogowski is proportional to 1/p while the inductance, proportional to N^2, increases as $1/p^2$. Adding turns to increase the signal will rapidly degrade the risetime. A better approach is to increase the diameter of the Rogowski winding. The risetime will still increase, but only linearly with the output signal amplitude and not as the square.

Transit time also effects the risetime of the Rogowski output. When there is an instantaneous rise in the current being measured a voltage step appears simultaneously all along the length of the Rogowski coil. This induced voltage must then propagate along the coil to the output cable. The induced signal propagates in both directions along the coil so one half of the signal travels to the shorted end where it reflects and travels back to the output. As a result the output signal is spread out over two transit times of the Rogowski coil.

Without going into the details of the analysis, the Rogowski coil looks like a transmission line with impedance Z_R. The one-way transit time is approximately L_R/Z_R. Typical RG223 Rogowski coils have $Z_R \sim 170\ \Omega$. The example coil mentioned above with $L_R = 110$ nH has a two-way transit time of ~ 1.3 ns. Combining the 2.2 ns L/R time and the 1.3 ns transit time gives a predicted risetime of 2.55 ns, so transit time is not very important in this case. There are cases where transit time can be important, but that is beyond the scope of this memo.

4.4 Signal Processing

There are two common ways of recording the output of the Rogowski coil: (1) directly to obtain a record of I-dot, or (2) after passive integration to obtain a record of the current. Each method has its advantages and disadvantages.

Direct recording of the I-dot signal is particularly advantageous when working with apparatus or experiments where the behavior is uncertain. For example, measurements of the current in plasma experiments. Unusual behavior is often evident in short transient signal that have negligible effect on the recorded current but are easily seen in the I-dot waveform. The primary disadvantage of recording I-dot is that post-processing of the recorded waveform by numerical integration is required to obtain a current waveform. Another potential disadvantage is that the I-dot signal sometimes has a large dynamic range, making it difficult to accurately record with 8 or 10 bit digitization.

Passively integrating the Rogowski signal has the advantage of providing a quick-look at the current waveform. Often, this is all that is needed, for example, in routine operation or testing. There are two downsides to passive integration. First, the signal amplitude is reduced, particularly for signals that require a long integration time. For the typical integrator circuit shown in Fig. 9; the output voltage is

$$V_I(t) \cong \frac{M}{\tau}\, I(t) \qquad (8)$$

where τ = R_I C_I is the integration time. The ratio of the integrated voltage to the direct output voltage, is displayed in Eqn. 9.

$$\frac{V_I}{V_R} = \frac{I}{\tau\, \dot{I}} \qquad (9)$$

Assume the current pulse, I, has a duration of 100 ns and a rise time of 5 ns. To get a reasonably accurate current waveform, assume a τ value of 500 ns. Eqn. 10 demonstrates the significant reduction in amplitude.

$$\frac{V_I}{V_R} = \frac{5\, ns\ x\ \dot{I}}{500\, ns\ x\ \dot{I}} = \frac{1}{100} \qquad (10)$$

The second downside is that the recorded signal is only approximately equal to the true current because of integrator droop. An accurate expression for the signal voltage can be obtained by solving the circuit equations for the integrator shown in Fig. 9.

$$\frac{dV_I(t)}{dt} = \frac{i}{C_I} = \frac{(\, M\dot{I} - V_I(t))}{R_I\, C_I} \qquad (11)$$

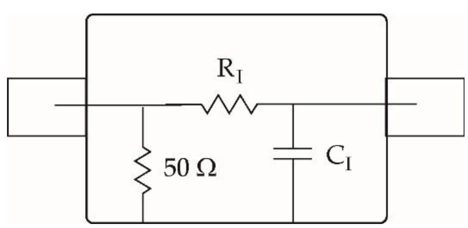

Figure 9: A passive integrator circuit with a resistor RI and a capacitor CI has a signal droop time τ = RI CI. Typically RI >> 50 Ω.

Integrating both sides of this Eqn. 11 with respect to time gives the correct expression for the output voltage from the integrator.

$$V_I(t) = \frac{M}{\tau}\, I(t) - \frac{1}{\tau} \int V_I(T)\, dT \qquad (12)$$

The second term on the RHS of the equation causes the recorded voltage to fall, or droop, below the true current, hence the term "integrator droop." Fortunately, this droop error can be corrected exactly by post processing the recorded waveform. The droop error is equal to the integral of the recorded waveform. Numerically integrating the recorded waveform, dividing by the integration time constant, and adding to the recorded signal gives the true current.

$$V_I(t) + \frac{1}{\tau}\int V_I(T)\,dT \;=\; \frac{M}{\tau}\,I(t) \tag{13}$$

Note that the accuracy of this correction does not depend on the droop being small. If one plans to post-process the integrated waveform, there is no advantage to using a long integration time. Rather, the selected integration time should be as short as practical, i.e., producing an acceptable displayed waveform prior to processing.

The use of short integration time provides a "hybrid" approach to dealing with Rogowski signals that have a large dynamic range. A classic example is recording a fast rising, long duration signal with accurate resolution of both the rise and the flat top. For example, consider a 1 µs pulse with a rise time of 10 ns and a flat top that needs to be measured with 5% accuracy. The peak I-dot signal is ~I/10 ns while the signal from the flat top is ~0.05 I/1000 ns. The dynamic range of this I-dot signal is 2000:1. With a typical 8 bit scope the best available resolution is 256:1 so there is clearly an issue.

This issue can be addressed by passively integrating the signal with a short time constant; for example, a 200 ns integrator can be used. Then the amplitude of the initial spike is reduced by 10 ns/200 ns and the dynamic range reduced from 2000:1 to 100:1, within the capability of an 8-bit recorder. Although the recorded signal will be difficult to impossible to interpret directly, after droop correction it will be a faithful record of the actual current waveform.

An alternative for dealing with large dynamic range signals is to record the signal on multiple channels with a different attenuation on each channel. However, using this technique results in the most sensitive channel being severely overdriven. The overdriven channel may not recover rapidly enough to accurately record details of the small signal that follows.

Finally, an alternative way to obtain a current waveform is known as the "self-integrating" Rogowski. Referring back to the Rogowski circuit shown in Fig. 8, replace the 50 Ω resistor with a very small resistance, for example, 0.1 Ω. Then the rise time in our earlier example would increase from 2.2 ns to 1100 ns. Why would one do this? Because the voltage across the 0.1 Ω resistor is proportional to I, in this case, and not I-dot. In the self-integrating configuration, the current signal is also subject to droop, but with the integration time now being L_R/R. Achieving a long integration time thus means increasing the self-inductance while reducing R as much as practical. This design works and is occasionally used for very fast pulse measurements. An obvious improvement to the self-integrating Rogowski would be the use of a ferromagnetic core to make L_R very large. This works very well, and in fact, results in the well-known Pearson Current Transformer.

5.0 Conclusion

This article provides an overview of the implementation of Rogowski coils by AFRL's Directed Energy Directorate, High Power Electromagnetics Division. Practical designs, shielding techniques, rise time considerations, and signal processing methods are detailed. This articles serves to document effective techniques for shielded measurement of high rate of change currents and extreme peak currents in compact pulsed power apparatuses.

Distribution List

DTIC/OCP 8725 John J. Kingman Rd. Suite 0944 Ft Belvoir, VA 22060-6218	1 cy
AFRL/RVOP Kirtland AFB, NM 87117-5776	1 cy
James Schrock Official Record Copy AFRL/RDHP	1 cy