EP Test Standards: Fabrication , Calibration, Usage of Magnetic Flux Probes with Application to Electric Propulsion Testing

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Abstract

   A draft of the EP testing standards recommended practices for magnetic flux diagnostics has been completed and will be presented. This starndard includes recommended design and implementation standards for magnetic flux loops and Rogoswki coils for bulk and external measurement of magnetic flux parameters. A review of magnetic flux probe theory, circuit discriptions, and typical application practices will be described. Additionally, construction techniques from common implementations and commerical applications will be detailed in full.

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I.   Introduction

This draft document provides recommended methods for the general use of magnetic flux probes for electric propulsion measurement applications. The standard includes terminology and a basic theoretical description of probe operation. The standard also recommends guidelines for probe fabrication and calibration. Use of this document will facilitate the exchange of information among users and other interested parties by providing standard methods for magnetic flux probe fabrication, calibration, usage, and data analysis and reporting. This document does not discuss inductive magnetic field probes (sometimes referred to as B-dot probes) Magnetic field probes theory of operation, design, fabrication, and usage guidelines are discussed in a separate standard. The primary difference between a magnetic field diagnostic and magnetic flux is the spatial, temporal, and signal resolutions as well as the physical measurement quantities. Flux probes measure the entire magnetic flux contained within a volume and are used to take measurements of the gross magnetic behavior, as opposed to point B-dot probes. Also, the probes typically are dominated by high voltage insulation and capacitive coupling concerns compared with B-dot inductance and small signal issues.

This document is specifically written to give recommended practices addressing issues associated with the design and usage of magnetic flux probes in EP devices. Pulsed EP applications for which flux and Rogowski probes are typically employed have discharge periods ranging from the order of 1-10 μs to a few ms and pulsed current magnitude ranging from 100-100,000s Amps. These probes have been used with theta pinch devices, field reverse configuration (FRC), magnetoplasmadynamic (MPD), and pulsed plasma (PPT) thrusters.

II.   Excluded Flux Array

A. The Flux Loop

Magnetic flux loops are one of the simplest diagnostics to build and implement and a simple insulated wire loop. Shown in Figure 1 is a typical application of a flux loop or voltage loop. In this application an azimuthal coil current induces an azimuthal current in the plasma. By measuring the flux and magnetic field inside of the magnetic field coil, the total remaining flux trapped within the coil can be measured. In each of the flux probes, the key is the flux integration area. For the voltage loop or flux loop the typical area is the entire thruster geometry. For a Rogowski coil, the flux integration area is a toroidal geometry around the current-carrying conductor. For the vacuum case, the result is simply the magnetic flux due to the magnetic coil, which from the integral form of Faraday's Law is:

$$\Phi_{B} = \iint_{s} B \cdot dS \tag{1}$$

Or for the typical, single turn flux loop the voltage is given by:

$$V_{coil} = -\frac{d\Phi}{dt} = -\pi r^{2}\frac{dB}{dt} \tag{2}$$

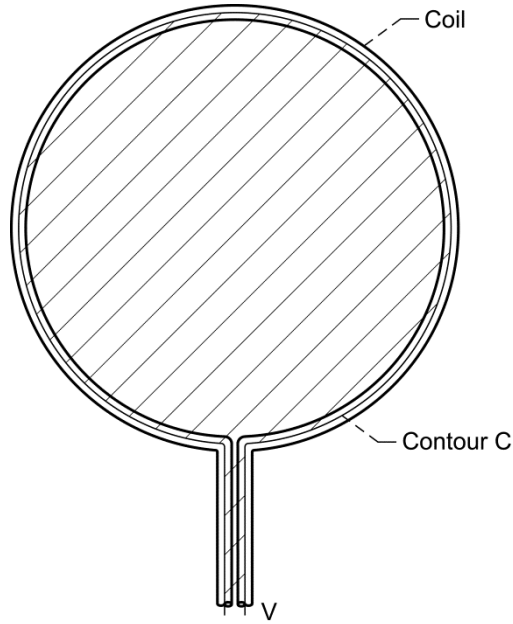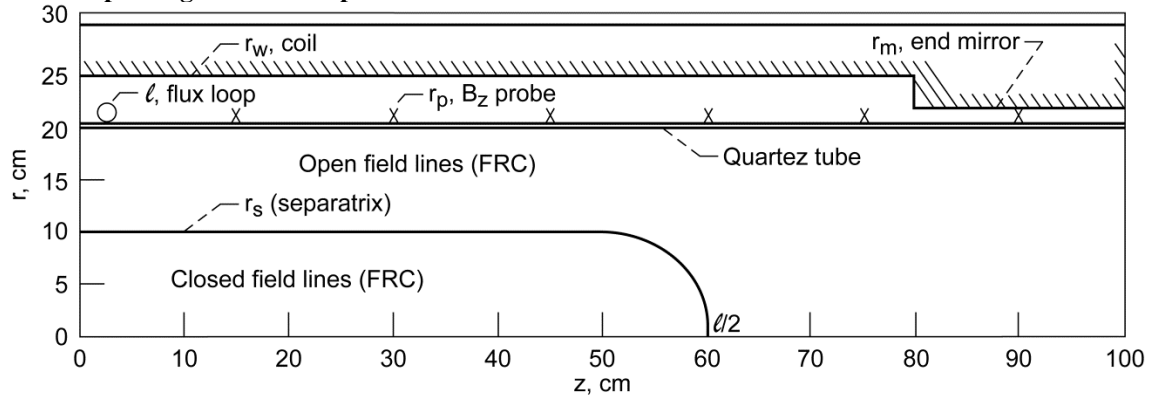**Figure 1. Simple magnetic flux loop**

Figure 2. MHD simulation of a diamagnetic plasma, flux loop, magnetic field coil in a typical application

B. Excluded Flux Array

Figure 2 shows a typical application. This analysis is applicable for both cylindrical and conical theta pinch, pulsed inductive and field-reversed thrusters. An excluded flux array measures the magnetic flux that is trapped within a diamagnetic, current-carrying plasma. This is a measurement of stored inductive energy as well as plasma pressure. As shown in the figure, this requires a magnetic field probe (described in detail in Section 4) as well as a magnetic flux loop. In vacuum, a magnetic field coil produces a magnetic flux that is simply,

$$\Phi = BA \tag{5}$$

However, in the presence of a diamagnetic plasma, and thus a significant plasma pressure, the effective magnetic flux can be both cancelled as well as pushed outside of the boundaries of the magnetic field coil. In the most ideal case, a magnetic coil is also a flux conserving boundary. In practice, high energy and high pressure plasma will cause significant flux compression and leakage through a magnetic field coil boundary, upwards of 50%. By measuring the magnetic flux and magnetic field with and without a diamagnetic plasma, the excluded flux radius (or location of the edge of the excluding object) can be directly measured as in equation 6 [3].

$$r_s = r_l \left(1 - \frac{\Phi_p}{\Phi_v} \frac{B_v}{B_p} \right)^{1/2} \tag{6}$$

It has been postulated [3] that the knowledge of a single flux and multiple axial magnetic field probe data is sufficient for complete knowledge of plasma diamagnetic behavior, however, in practice this must be avoided. Non-ideal characteristics such as multiple coils, turns, or non-ideal plasma behavior can lead to complicated and non-accurate estimates of end-of-coil plasma and magnetic parameters. The excluded flux array diagnostic is important for plasma with significant magnetic pressure and diamagnetic current.

C. Circuit analysis

In practice, a magnetic flux loop has large output signals such that active amplifiers and active integration is not typically utilized. Therefore, simple passive integration is shown in Figure 3. Importantly, while not required, this guide recommends splitting the integration into two components if coil and thus probe voltages are greater than typical feedthrough voltages (1 kV). Detailed analyses of these passive integrating circuits are shown elsewhere, but the complete formula is shown in Eq 3 [1,2]. This takes into account reactive and resistive circuit components throughout the entire system. V_p, R_p, and L_p are the probe components, while R_{inst}, R, and C are the digitizer resistance, total circuit and integrator Resistances and Capacitance, respectively. Also, it is important to add cable capacitance (on the order of 100 pF/m for coaxial cable) for the complete circuit response. R is the sum of R_p, R_1, and R_2. C is the sum of C_1, C_0, and C_2.

$$\Phi = \left(RCV_P + L_p C \frac{dV_P}{dt} + \frac{R + R_{inst}}{R_{inst}} \int V_P dt \right) \qquad (3)$$
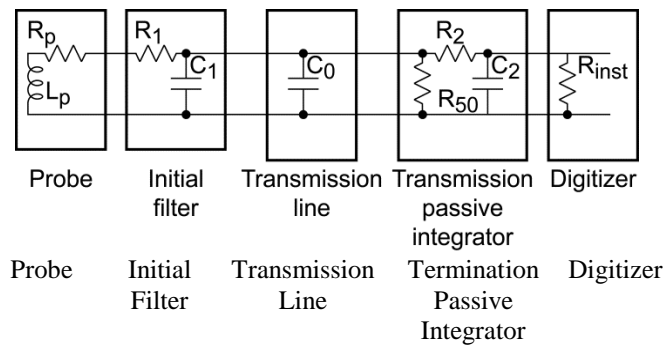

Figure 3. Circuit diagram of typical application.

The selection of passive integrator values should meet criteria in Eq 4. Fundamentally, the integrator should be a balance between voltage drop on the coil and voltage drop within the integrator as. In practice, for a highly integrated flux probe, the response is given by Equation 5.

$$\frac{1}{RC} << \omega << \frac{R}{L_P} \qquad (4)$$

D. Design and Construction

The design of a flux loop is quite straightforward. As it is located outside of the thruster, plasma and plume interaction effects are minimal. Additionally, unlike point inductive magnetic field probes (B-dot), the signals are typically quite large and the capacitive coupling effects are quite small.

The primary concern in the design of a flux loop is voltage isolation and flux vector orientation. Small changes in the orientation relative to the desired center of access will lead to large changes in integrated flux. As alluded to in the probe name, the voltage in a flux loop can be quite high. Typically these loops are used in pulsed electromagnetic thrusters with large voltages and the flux loop will be the same as the voltage on the driving coil. Typically in a thruster implementation this is significantly higher than the voltage rating for traditional diagnostic feeds as well as can lead to significant isolation concerns within the confines of a thruster body. Typically the probe area, and thus the probe resolution, is set by thruster geometry and typically multi-turn

implementation is impractical and unnecessary due to these large signals. In realistic thruster implementations of a flux loop two primary construction rules must be followed: high voltage insulation and integration.

- First, the high voltage nature of the probe means that insulation of the entire diamagnetic loop is critical. Typically, a flux loop is constructed simply and with high precision by simply removing the outer shield from a coax cable. An RG-178 cable stripped of its coax braid yields a high voltage hold-off and extremely consistent probe geometry.In some representative applications, voltages up to 40 kilovolts have been successfully sustained using simply RG-58 cable. In addition, high voltage Teflon or Tef-Zel insulation tubing can be added for additional voltage isolation. The most critical concern with flux loops is the voltage isolation at the probe termination and exit from the coil geometry. This is typically the location of the maximum differential voltage as well as the maximum electric field and the most likely location for an arc or diagnostic failure. Therefore, the recommendation of this guide is to use an RG-178 or other miniature high voltage coax cable and leave the insulation in place until outside of the thruster body. Flux loops are typically twisted for similar reasons given in the magnetic field probe guide and remain twisted until reaching the passive integration components. Because signals are large and electrostatic noise is minimal, cable selection is not critical, though similar to magnetic field probes in Section 4, twisted pair or double-shielded coaxial cable (RG-223) is recommended. Miniature flux loops can be constructed with small gauge magnetic wire and high insulation Teflon.
- The second concern is the integration of this high voltage signal. The recommendation of this guide is to provide in-chamber and near-thruster passive integration. Using high voltage RC passive integration, the probe signal can be reduced to manageable voltages as well as integrating any collected noise. Typical recommendations are to reduce voltages to approximately 100 volts inside the chamber to allow proper termination and feed throughs while still maximizing signal to noise ratio. Circuit description is shown in Figure 3. This guide's authors recommend always using C0G/NP0 capacitors to guarantee low internal capacitor losses and resonances as well as thermal stability. This guide's authors recommend always using film and non-inductive resistors for filters and integrators. An example high voltage filter would use AVX 1 nF 1kV capacitor 1812AA102JAT1A and Ohmite 1kOhm 4 kV resistor SM108021001JE. An example low voltage filter would use AVX 1 nF, 100 V capacitor 12061A102FAT2A and Vishay-Dale 0.5 kOhm CRCW2512499RFKEG.

Additionally, for high temperature applications, magnet wire with mica insulation can be used above 300 degrees Celsius for probes that are directly integrated into the thruster body.

E. Analysis

Analysis on a properly constructed, passive diamagnetic excluded flux array is quite simple. Essentially, the signal is collected in a high speed data acquisition system and digitized. Details of specific data acquisition rate versus accuracy have been detailed elsewhere., however a typical practical rule of thumb is that the data acquisition is required to be 10X the highest frequency signal component of interest. It is then filtered, zeroed, and divided. Typically, analysis concerns involve electrostatic and inductive noise pickup on the low-voltage magnetic field probe signal.

F. Calibration

In Magnetic flux loops the output on a magnetic flux loop is simply the applied azimuthal voltage, E_Theta, since these probes are typically used in theta pinch coils. The calibration of the integrating circuit is typically done in-situ in vacuum (no plasma). A low voltage discharge induces an integrated signal on the output of the flux probe and passive integrating circuit. By comparing this to a known coil voltage, calibration constants can be obtained. Also, knowing the average radius of the conductor then yields an area integrated magnetic field. In fact, in practice for theta pinch coils, the flux loop is used to calibrate the local magnetic field probe. In the case of a non-theta pinch system, such as a Rotating Magnetic Field, an externally-calibrated magnetic field probe or magnetic field loop can should be used to calibrate a flux loop.

III.   The Rogowski Coil

A.   Theory of Operation

The Rogowski coil is an excellent robust method for measuring pulsed currents. The major benefits are the ability to non-intrusively measure current. Rogowski coils are used to measure the pulsed feed current and pulsed plasma currents for electromagnetic thrusters. The first complete description of a Rogoswki coil was given by Walter Rogoswki and W. Steinhaus in 1912 [4]. The most common use has been for Pulsed Plasma Thrusters, Pulsed Inductive Thrusters, and Field Reverse Configuration thrusters [5]. This guide describes traditional, robust Rogoswki coil design and implementation. Another useful guide for the power relay industry has been published by IEEE [6].

A Rogowski coil is an N turn coil wound in the poloidal direction on a toroidal coil form having a major radius R and a minor radius a. Figure 4 shows the geometry of a Rogoswki coil. It is important to note that the return connection is strung toroidally back through the poloidal windings so as to avoid having a net toroidal turn. The current, I to be measured passes through the hole in the torus and produces a toroidal magnetic flux. Advanced commercial designs described below may incorporate specific electrostatic shielding, poloidal inner windings, or on-coil integration. A Rogoswki coil can be clamped on to a circuit, can be flexible over a range of geometries, and provide accurate measurements of transient phenomena. Unlike current transformers, and other ferromagnetic-cored devices, Rogowski coils are linear, so there are no effects from saturation and the mutual inductance is independent of the current being measured. However, typically Rogowski coils are very sensitive to capacitive coupling and external interferences..
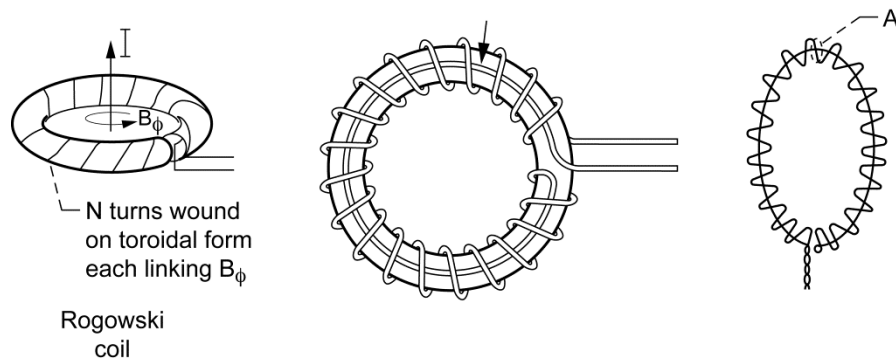

Figure 4. Schematic of a Rogowski coil with N turns.

Figure 5. Photograph of a constructed Rogowski coil.

Figure 6. Photograph of a commercial Rogowski coil. DENT Rocoil.

An integral application of Faraday's law is sufficient to describe a Rogowski coil.

$$\Phi_B = \iint_s B \cdot dS \tag{7}$$

Thus, integrating over a toroidal tube with N turns yields a magnetic flux which is the time integrated voltage response of the coil, V_R

$$\Phi = \mu_0 \pi N I a^2 \int V_R dt \tag{8}$$

From the same analysis, it can be computed that the inductance of a circular cross-section Rogowski coil is given by Equation 4.

$$L = \mu_0 N^2 \left(R - \sqrt{R^2 - a^2} \right) \tag{9}$$

Various alternate inductances and geometries are given in [7].

B. Circuit Considerations

Probe | Transmission line | Passive integrator | Digitizer
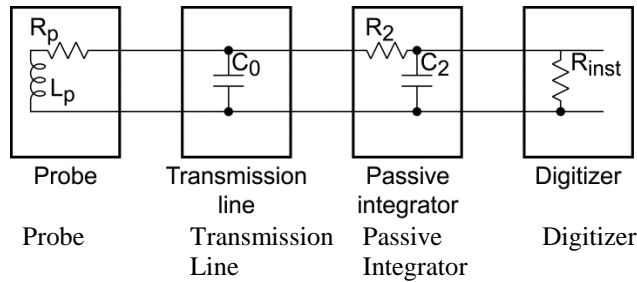Probe | Transmission Line | Passive Integrator | Digitizer

Figure 7. Circuit diagram of typical application.

$$I = \frac{1}{\mu_0 \pi N I a^2} \left(RCV_P + \frac{R_p + R_{inst}}{R_{inst}} \int V_P dt \right) \tag{8}$$

Circuit analysis for a Rogoswki coil is similar to magnetic flux and field probes. In the case of the Rogowski coil, electrostatic pickup will be significant so proper filtering and passive integration is critical. Additionally, as high frequency noise will be higher than a flux loop, the LC term is typically neglected. Also, as resistance is usually higher, termination is usually not required. Selection of R2 and C2 values follows criteria in Eq. 4.

C. Resonance

One critical difference between Rogowski coils and other magnetic diagnostics is resonance. As the self-inductance and self-capacitance of a Rogowski coil is typically larger than a magnetic field probe or flux loop, the internal resonance of the coil is relevant. Practically, this is the upper frequency limit for Rogowski and is usually ~ 1-10 MHz. Increases in coil capacitance, and thus a decrease in the useable frequency, are the traditional reasons why electrostatic shielding and poloidally-would return feeds are not used. A typical capacitance for a single-layer Rogowski coil is 50 pF/m of total length [8]. Resonance frequency is given in Equation 9.

$$f_{Resonance} = \frac{1}{2\pi\sqrt{L_p C_p}} \qquad (10)$$

D. Design and Construction

Although the basic design of a Rogowski coil seems to be relatively simple in design, careful and accurate preparation is strongly recommended to obtain the expected performance. First, it is important to ensure the uniformity of the winding (for perfectly uniform winding the output signal does not depend on the path the coil follows around the current-carrying conductor or on the position of the conductor). Also, the positioning of the return loop is important such that both terminals should be at the same end of the coil to simplify arrangement of the connectors. When the coil is wound on a coaxial cable the central conductor can be used as the return path Additionally, probe connections and cabling must be specifically chosen that will minimize irregularities while maintaining insulation in the high voltage thruster environment. Two types of probe designs have been constructed for propulsion and each will be detailed here.

1. Fixed

A fixed Rogoswki coil has been repeatedly used in PPT research [9]. This coil was integrated into the body of a PPT for in-situ current measurements. This fixed Rogowski used a toroidal polycarbonate form with a=0.105" and R=1.02" and 45 turns of 20 AWG wire. A fixed coil has excellent repeatability and can be directly and permanently integrated into the thruster body.

2. Flexible

Figure 6 shows a typical design for a flexible Rogoswki coil that will be used outside of a thruster body, but in a high-voltage environment. This coil is flexible. The center core is RG-233 double shielded coaxial cable that has been stripped for the length of the Rogoswki coil. The poloidal windings are high voltage (5 kV, 20 AWG) stranded core-wire that are tightly wound around the coil. Importantly, they are secured with two layers of adhesive heat shrink for voltage isolation and to maintain strict coil winding spacing. An additional 1" length and cap allow ease of installation and assembly. The coil is 125 turns of 20 AWG wire with a=0.125" and R=1.31". A flexible Rogowski coil can be easily moved, secured, and fit into demanding locations such as high power feed lines.

E. Calibration Example

Calibration of a pulsed current probe is straightforward. Simply using a known current and a pulsed LRC circuit use the Rogowski coil and another known current or voltage probe. Ideally, this is done in-situ and at relevant frequencies to minimize frequency and orientation effects. Rogoswki coils are not sensitive to saturation effects, so for a given frequency they are fully calibrated to all current magnitudes. A suitable and typical calibration circuit, waveform, and diagnostic package are given in Figure 8. In this setup, coil current is known from both measured

Current Transformer current (Pearson coil) as well as coil voltage $\left(V_c = L_c \dfrac{dI}{dt} \right)$.
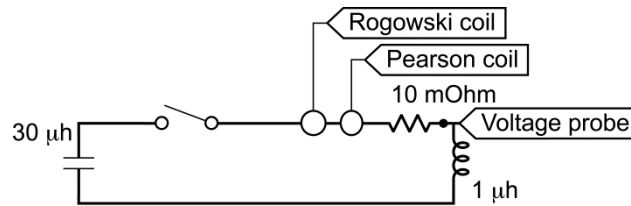
Figure 8. Simple calibration circuit.

F. Advanced Applications

Several useful advancements have occurred in Rogowski coil development. Listed are a few unique applications.

Non-circular coils .... [9]
Low Frequency Rogoswki Coil .... [10]
Electrostatic Shield .... [7]
Poloidal Inner Winding .... [11]
Micro-Scale Rogowski .... [12]
Combined Voltage and Current Monitor .... [13]

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