CALIBRATION OF MAGNETIC FIELD PROBES AT RELEVANT MAGNITUDES[*]

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Abstract

Difficulty driving large currents through an inductive load at high frequency typically results in field magnitudes of a few microTesla or less. The calibration factor is then necessarily assumed linear, even though the magnetic field of the primary experiment is several orders of magnitude larger than the field magnitude used to calibrate the probe. In this work calibration factors of two differential configuration magnetic field probes are presented as functions of frequency and field magnitude. Calibration factors are determined experimentally using a 80.4 mm radius Helmholtz coil in two separate configurations. A conventional low-magnitude calibration using a network analyzer with field magnitude of 158 nT yielded calibration factors of 15,107±233 and 4,899±180 T/V-s at 457 kHz for the surface mounted inductor and hand-wound probe, respectively. A relevant-magnitude calibration using a pulsed-power setup with field magnitude of 43.5 to 83.0 mT yielded calibration factors of 14,541±41.8 and 4,484±15.8 T/V-s at 457 kHz for the surface mounted inductor and hand-wound probe, respectively. The uncertainty reported is one standard deviation of the repeated calibration measurement. Low-magnitude calibration always resulted in a larger calibration factor, with a maximum difference of 18.5%. Comparison of the pulsed-power Helmholtz coil current waveform with the magnetic field waveform measured with the magnetic probes showed differences of 1.4% and 0.7% in the waveform extrema at 457 kHz for the surface mounted inductor and hand-wound probe, respectively.

I. INTRODUCTION

Magnetic field (B-dot) probes are commonly used in PIP devices to measure time-varying magnetic fields.[1-9] PIP devices typically fall into one of two categories: nuclear fusion and spacecraft propulsion. Fusion devices such as the Z-Machine at Sandia[10] and Field Reversed Configuration Heating Experiment (FRCHX)[11] use several MJ of energy per pulse to produce magnetic fields on the order of Teslas and even as large as 250 T[11] for magnetically-confined fusion. Propulsion systems operate at lower energy, using as little as tens of joules up to a few kJ of stored energy per pulse[12] to produce magnetic fields on the order of tenths of a Tesla.

In its simplest form, a B-dot probe consists of a segment of wire formed into a closed geometric shape, typically a circle. Per Faraday's law, when placed in the presence of a time-varying magnetic field, a voltage is induced in the loop of wire proportional to the time-varying magnetic field. A brief overview of the B-dot probe theory is provided in Ref. 13. The two calibration methods accepted by the Institute of Electrical and Electronics Engineers (IEEE) for calibration of B-dot probes are the Helmholtz coil and Transverse Electromagnetic (TEM) cell.[14] Helmholtz coils are commonly used due to their ease of construction and large area of field uniformity.[15] Additionally, Helmholtz coils can often accommodate larger field magnitudes than TEM cells[14].

Calibration of B-dot probes presents a few challenges. The first challenge is the dependence of the probe sensitivity on frequency. Because the probe head is an inductor, the probe output voltage will attenuate when driven at higher frequencies as a result of increased probe reactance. Messer et al. provide a more complete analysis of B-dot probe sensitivity and incorporate effects of transmission lines on probe response.[16] An additional challenge arises when using a Helmholtz coil as a calibration source. The inductance of the coil windings preclude driving large currents at frequencies of interest for pulsed inductive plasma. Often, calibration of a B-dot probe is performed at relevant frequencies but not relevant field magnitudes. Probes are therefore calibrated in lower magnitude fields and the calibration factor assumed constant for a given frequency.[14] Field magnitudes on the order of 10 μT are used to calibrate probes intended to measure field magnitudes of tens of milliTesla or greater. In Ref. 16, the primary experiment is expected to generate fields of 18 mT at 59 kHz. However, calibration is accomplished with a field

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[*] Work supported in part by AFOSR under contract number DOA-8910

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978-1-4673-5168-3/13/$31.00 ©2013 European Union

magnitude three orders of magnitude less than the intended field magnitude. Similarly, Ref. 17 performs probe calibrations in a Helmholtz coil with a maximum field magnitude of 60 μT. An experimental field magnitude is not explicitly given, however, the author cites plasma experiments such as fusion studies and inductively coupled plasmas as the common applications which have fields often greater than 10 mT as previously stated.

This work evaluates the assumption that B-dot probe sensitivity remains constant over large ranges of field magnitude relevant to PIP devices. Construction of the B-dot probes is presented followed by the experimental setups. Results from the two methods of calibration are presented. The assumption of constant probe calibration factor is analyzed and final conclusions presented.

II. PROBE CONSTRUCTION

Special care must be observed in the construction of B-dot probes because of the large field magnitudes encountered in PIP devices. In particular, the capacitive coupling due to fluctuations in electrostatic potentials can produce significant probe voltages that obscure the desired inductive signal and produce significant measurement error. One solution to this challenge is to use a B-dot probe in a differential configuration. Differential probes use two identical B-dot probes to remove the electrostatic coupling. This is possible because inductive pickup (differential mode) is dependent on the orientation of the probe in the magnetic field and capacitive pickup (common mode) remains unchanged with probe orientation. By using two identical probes with one oriented 180º relative to the second, subtracting the resulting signals removes the capacitive pickup and doubles the inductive pickup. The work by Franck et al. analyzes the electrostatic rejection of the most common differential probe configurations.[17] Work done by Carrobi et al. suggests that a center-tapped configuration yields an order of magnitude reduction in capacitive pickup relative to a simply wound magnetic probe.[18]

Two probe variations were constructed for the purposes of this study. The first is a common differential B-dot probe configuration and consists of two sets of ten turns of 32 AWG magnet wire wrapped around a 4.88 mm diameter dowel rod. This gives a nA (turns-area) constant of 205 x 10^{-6} turns-m^2. The probe calibration factor from Faraday's law is defined as the inverse of the nA constant giving a theoretical probe calibration factor of 9,770 T/V-s into 50 Ω. Each probe head has approximately 177 mm of twisted leads that are then connected to twelve centimeters of RG-58/U coaxial cable and terminated with SMA connectors.

The second probe design uses two Coilcraft 1008CS-102XFLB surface mounted inductors (SMIs). The inductors have a rated machine tolerance of 1% with an inductance of 963 nH and a self resonant frequency of 290 MHz. The manufacture provided nA constant of 154 x 10^{-6} turns-m^2 gives a calibration factor of 12,987 T/V-s into 50 Ω. The SMIs are soldered to a custom printed circuit board with two 22.8 cm leads constructed of 3.73 mm diameter semi-rigid coaxial cable and terminated with SMA connectors. Shielding of inductive probes has been well studied[19-21] and has been shown to reduce the electrostatic noise on the probe. For additional shielding, the probe is wrapped in a single layer of copper tape. Solder is used to secure the copper tape to the probe and electrically connect the shield to the ground conductor of the semi-rigid coaxial cables. A gap is added to the shield structure on the back of the probe head. This balances and thus cancels currents generated by the electrostatic noise on the probe shield.

III. EXPERIMENTAL SETUP

Two experimental setups are used in this work. First, a network analyzer is used to provide a typical low magnitude frequency domain calibration. This is the most commonly employed calibration setup and typically produces fields on the order of tens of microTesla. The second method uses a pulsed-power RLC discharge at high voltage at select frequencies to provide relevant field magnitudes over the range of relevant frequencies.

The same Helmholtz coil is used for both calibrations. Each side of the Helmholtz coil used in testing is constructed of a one turn aluminum ring with a cross-section of 6.0 mm x 6.4 mm. Measured from the center of the ring cross-sections, the diameter of the Helmholtz coil is 160.8 mm and the distance between the rings is 80.7 mm.

A large non-conductive slug is placed in the center of the Helmholtz coil to ensure probe placement remains consistent within the Helmholtz field. The machined probe holder ensures that the probe area is perpendicular to the center axis of the probe holder. The larger slug then ensures that the probe holder is axially aligned at the center of the Helmholtz field.

A. Low Magnitude Calibration

For this test, an Agilent Technologies E5071C network analyzer was used to perform frequency domain measurements from 100 – 1,000 kHz. Sweeps were conducted with a 30 Hz filter and results averaged over two tests. The output power was set at the maximum 10 dBm. Calibration of the network analyzer was performed prior to testing using a Hewlett Packard 85033D 3.5 mm calibration kit. The network analyzer produced a driving current of approximately 28.3 mA into the Helmholtz coil resulting in a field magnitude of 158.2 nT.

B. *Relevant Magnitude Calibration*

PIP devices typically have fields greater than 10 mT. To achieve magnetic fields greater than 10 mT at multiple frequencies, multiple capacitor banks were used in combination with two different inductors. Table 1 lists the combination of capacitor and inductor values used and the resulting discharge frequency. Galvanized steel with width of 79.9 mm and a thickness of 1.2 mm was used as transmission line in the experiment. An EG&G GP-41B triggered spark gap was used as the switch in the RLC circuit. A Pearson 1049 current monitor was used to measure the discharge current with a rated accuracy of +1/-0%. The 9.4 μH inductor used to modify discharge frequency was constructed by precisely wrapping ten turns of number twelve AWG magnet wire around a section of 89 mm diameter PVC pipe. To prevent arcing, an air gap between windings was used and the inductor was potted in epoxy to hold the coil shape during testing. Using the method outlined by Lundin[22], the calculated inductance of the Helmholtz coil was 268 nH. Modeling in Spice indicates the parasitic capacitance to be less than one percent of the total circuit capacitance value. The stray inductance of the circuit is approximately 200 nH.

Table 1: Capacitance and inductance values used in generating relevant magnetic fields for calibration of B-dot probe.

Frequency [kHz]		Capacitance	Inductance
Target	Actual	[μF]	[μH]
50	50	1.005	9.40
100	88	7.190	0.00
100	98	0.275	9.40
250	240	1.005	0.00
500	457	0.275	0.00
750	799	0.056	0.00
1000	1089	0.027	0.00

Per IEEE std 1309-2005, the Helmholtz coil must be operated in a volume with a minimum radius of 6.7*r* devoid of conductors which may perturb the field geometry where *r* is the Helmholtz coil radius.[14] For electrical shielding of the high field magnitude tests, the Helmholtz coil was placed in a cylindrical metal enclosure with a radius of 0.91 m and a length of 3 m.

C. *Data Acquisition*

All data in the relevant magnitude calibration were acquired using a PXI-5105 12-bit digitizer. The probes were connected to two 6.1 m RG-400/U cables. The two cables were extended horizontally from the centerline axis of the Helmholtz coil away from the probes. After 0.61 m (as per the 6.7*r* requirement) the cables enter rigid conduit to provide additional shielding as the leads are brought outside of the shielded enclosure. The probe signal transmission lines each enter two Bird 25-A-MFN-10 attenuators connected in series to provide 20 dB total signal attenuation. A 33 cm long section of RG-223/U cable brings the signal to the PXI-5105 digitizer where it is terminated with an external 50 Ω. The Pearson 1049 output signal is treated similarly, however the conduit completely covers the transmission line inside the shielded enclosure as this does not violate the 6.7*r* requirement[14].

IV. RESULTS

This section presents the results of the low magnitude and relevant magnitude calibrations.

A. *Low Magnitude Calibration*

Calibration factors from the low magnitude magnetic field tests using the network analyzer are determined by converting scatter parameters from frequency domain to time domain for direct comparison to relevant magnitude tests. This is accomplished by using the S_{11} parameter to determine the coil inductance and the S_{21} parameter to determine the voltage induced on the B-dot probe on channel 2 by driving the Helmholtz coil on channel 1. The resulting calibration factors are presented in Table 2 at the same frequencies that are used for the relevant magnitude calibrations. Due to hardware limitations, the lowest frequency measurable in the low magnitude is 100 kHz, slightly higher than either the 88 or 98 kHz used in the relevant magnitude calibration. The calibration factors of the A and B halves of the differential probe are averaged together over five tests to give the probe calibration factor shown in Table 2.

Table 2. Results from low magnitude frequency domain Helmholtz calibration.

	Calibration Factor [T/V-s]	
Frequency [kHz]	SMI	Hand-Wound
100	16975 ±1838	4984 ±51.0
240	15529 ±8.00	4955 ±195
457	15107 ±233	4899 ±180
799	15691 ±244	4978 ±142
1000	15945 ±23.0	5003 ±178

B. *Relevant Magnitude Calibration*

The goal of field magnitudes greater than 10 mT is achieved for all tests except the 1,089 kHz test at 13 kV. This case had a field of only 8.7 mT. The magnitude of the magnetic field is calculated using the Helmholtz equation using the filtered current measured from the Pearson current monitor. The pulsed power circuit was discharged at voltages from 13 to 23 kV to provide a range of relevant field magnitudes for calibration of the B-dot probes. Table 3 provides the minimum and maximum peak magnetic field for different frequencies tested. Minimum corresponds with the peak magnetic field for the lowest voltage tested, while maximum corresponds with the highest voltage tested. Using the peak magnetic field values given in Table 3 and the corresponding peak of the integrated B-dot signal, a calibration factor can be calculated. The calibration values for a given discharge frequency are averaged over the voltage range at which they are tested. The resulting calibration values are shown in Table 4.

Table 3: Magnetic fields produced during relevant magnitude testing.

Frequency [kHz]	Field Magnitude [mT]	
	Minimum	Maximum
50	21.5	35.5
88	245	354
98	10.8	18.3
240	84.8	131
457	43.5	83.0
799	14.4	25.3
1089	8.7	16.4

Table 4: Results from relevant magnitude time domain Helmholtz calibration.

	Calibration Factor [T/V-s]	
Frequency [kHz]	SMI	Hand-Wound
51	14532 ±80.0	4529 ±38.1
88	14566 ±11.2	4482 ±4.63
98	14374 ±219	4429 ±238
240	14364 ±61.3	4447 ±13.9
457	14541 ±41.8	4484 ±15.8
799	14394 ±102	4425 ±99.0
1089	13733 ±1862	4222 ±132

V. ANALYSIS

Low magnitude calibration results in larger calibration factors than relevant magnitude calibration. The percent difference between relevant magnitude and low magnitude calibration factors is shown in Table 5 (low magnitude minus relevant magnitude divided by relevant magnitude). The 100 kHz low magnitude calibration factor is used for both the 88 and 98 kHz relevant magnitude comparison, and the 1000 kHz low magnitude calibration factor is used for the 1,089 kHz relevant magnitude comparison. The average percent difference over all frequencies tested is 12.0% and 12.6% for the SMI and hand-wound probes, respectively. The maximum and minimum percent difference for the SMI probe is 18.1% and 3.9%, respectively, while for the hand-wound it is 18.5% and 9.2%, respectively.

Table 5. Percent difference of relevant magnitude and low magnitude calibration factors for SMI and hand-wound probes.

	Calibration Factor [T/V-s]	
Frequency [kHz]	SMI	Hand-Wound
88	16.5 ±12.7	11.2 ±1.25
98	18.1 ±14.8	12.5 ±7.61
240	8.11 ±0.52	11.4 ±4.74
457	3.89 ±1.90	9.26 ±4.41
799	9.01 ±2.50	12.5 ±5.87
1089	16.1 ±18.4	18.5 ±8.18
Avg.	12.0 ±8.50	12.6 ±5.34

The uncertainty in the calibration factors is compared for low-magnitude and relevant-magnitude calibrations. One standard deviation of the repeated calibration tests is reported as the probe uncertainty. The standard deviation of probe calibration factors for low magnitude calibration is 699 T/V-s and 40 T/V-s for the SMI and hand-wound probes, respectively. These standard deviations are 4.4% and 0.8% of the average probe calibration factors, respectively. The standard deviation of probe calibration factors for relevant magnitude calibration is 289 T/V-s and 99 T/V-s for the SMI and hand-wound probes, respectively. These standard deviations are 2.0% and 2.2% of the average probe calibration factors, respectively. The relatively large uncertainty of the SMI probe during low magnitude calibration can be explained by its lower turns-area product compared to the hand-wound and thus lower output voltage for a given field strength. This decreases the signal-to-noise ratio (SNR) resulting in increased uncertainty in the measurement, especially at low frequencies where the probe output voltage is a minimum. The relevant magnitude calibration resulted in similar uncertainty for both probes (about 2%). This may be indicative of the repeatability of the pulsed-power discharge rather than the random error uncertainty of the probes.

Low SNR ratio during low magnitude calibration results in a different frequency trend. Table 2 shows that as frequency increases the calibration factor initially decreases, but then increases after 457 kHz. The calibration factor is inversely proportional to the turns-area product of the probe. As frequency increases, the probe impedance increases producing a "virtual" area smaller than the physical area of the probe. This should result in a larger calibration factor as frequency increases. However, for low magnitude calibration the calibration factor trend changes due to low SNR. The SMI and hand-wound probes were designed to produce an output voltage of approximately 5 to 10 V in relevant magnitude fields. Placing these probes in a field five orders of magnitude lower than designed (158 nT vs. 43.5 mT) reduces the probe output voltage by five orders of magnitude. This effect was observed during testing when the output power of the SMI and hand-wound probes at 100 kHz was approximately -90 dBm and -70 dBm, respectively. These power levels are far below the -60 dBm generally regarded as the noise threshold.

In addition to the uncertainty and trends associated with the calibration factors, it is also important to compare and quantify differences between the pulsed power Helmholtz coil current waveform and the magnetic field waveform measured with the magnetic probes. Extrema agreement and decay deviation are defined as metrics for assessing and quantifying the difference between these waveforms associated with relevant magnitude calibration. Theoretically the magnetic field inside the Helmholtz coil is directly proportional to the coil current. Therefore the magnetic field waveform should agree closely with a suitably scaled current waveform. The first three extrema of the current and magnetic field waveforms are compared and the average percent difference as the extrema agreement reported. Additionally, the magnetic field waveform should decay to zero along with the coil current. The decay deviation is defined as the average of the tail regions of the magnetic probe relative to the peak magnetic field measured during a test. The tail region is defined as the last ten percent of the waveform that is within a temporal window of 20 periods based on the discharge frequency of the given test. A large percentage indicates that the waveform did not decay back to zero and retains some signal offset due to integration. A small decay deviation means that the probes fully decayed to the quiescent state.

Results of the extrema agreement and decay deviation analysis are shown in Table 6. The SMI probe had an average extrema agreement and decay deviation of 1.3% and 0.9%, respectively, over all frequencies tested. The hand-wound probe had an average extrema agreement and decay deviation of 1.8% and 1.6%, respectively, over all frequencies tested. In addition to better extrema agreement and decay deviation, the SMI probe had a narrower range of results across the frequencies tested. SMI probe extrema agreement ranged from 0.5% to 2.3%, while the hand-wound probe ranged from 0.5% to 3.4%. SMI probe decay deviation ranged from 0.5% to 1.5%, while the hand-wound probe ranged from 0.5% to 5.4%. This is attributed to the hand-wound probe's greater sensitivity to switching transients. Often transients twice that seen on the SMI probe were present on the hand-wound probe. The presence of these large transients would result in increased integration drift relative to the SMI probe.

VI. CONCLUSIONS

While network analyzers provide a fast method of producing a wide-band calibration of B-dot probes, the relatively low frequency of pulsed-inductive plasma devices can make calibration more challenging. Operating a network analyzer in this low frequency regime of interest results in large uncertainties due to low driving current and slow time-varying fields. Additional complications arise when using B-dot probes designed to provide five to ten volts output in fields of milliTesla or larger and attempting to calibrate in field magnitudes of tens to hundreds of nanoTesla. When operating the same B-dot probe at the same frequencies but with fields on the

Table 6: Analysis of relevant magnitude B-dot calibration. Extrema agreement calculated by comparing peaks and troughs of scaled current and integrated B-dot signals. Decay deviation represents probe drift from zero field magnitude as t→∞ due to signal integration.

Frequency [kHz]	Surface Mount Inductor		Hand-Wound	
	Extrema Agreement [%]	Decay Deviation [%]	Extrema Agreement [%]	Decay Deviation [%]
51	1.9	1.3	2.1	1.7
88	0.5	0.5	0.5	0.5
98	1.1	1.5	3.4	5.4
240	1.2	0.6	0.8	0.6
457	1.4	0.7	0.7	0.6
799	1.0	0.9	1.7	0.9
1089	2.2	1.0	3.0	1.2

order of nanoTesla, the resulting probe output will be proportionally reduced by five or six orders of magnitude. Such small signals make accurate calibrations difficult and produce large uncertainties.

Relevant magnitude calibration requires significantly more design and engineering, especially if calibrations at multiple frequencies are desired. Based on the experiments described here, calibration factor accuracies of 2% can be achieved.

VII. ACKNOWLEDGEMENTS

The author would like to thank AFOSR (award# FA9550-10-1-0204) for funding of this research. Additional thanks to Guanghua Li for assisting in the low magnitude calibration.

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