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An impedance analyzer has been used in the characterization of a magnetic induction probe (B-dot probe) for use in plasma. The role of the impedance analyzer was to determine the frequency response of a B-dot probe up to 100 MHz. The probe was specifically designed to take measurements in RF plasma driven at 13.56 MHz. Probe sensitivity and calibration are considered based on the impedance values obtained when a B-dot probe is swept over a wide frequency range. Effects such as unbalanced loads based on transmission line inductances and termination impedance are shown to be limiting factors on the probes useful frequency range.

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Magnetic Field Probes for use in Radio Frequency Plasma
(Preprint)

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An impedance analyzer has been used in the characterization of a magnetic induction probe (B-dot probe) for use in plasma. The role of the impedance analyzer was to determine the frequency response of a B-dot probe up to 100 MHz. The probe was specifically designed to take measurements in RF plasma driven at 13.56 MHz. Probe sensitivity and calibration are considered based on the impedance values obtained when a B-dot probe is swept over a wide frequency range. Effects such as unbalanced loads based on transmission line inductances and termination impedance are shown to be limiting factors on the probes useful frequency range.

Magnetic Induction Probes

Magnetic induction probes have been used as a diagnostic to measure plasma and other transiently induced fields since the 1960's [1] [2] [3]. When sized appropriately with respect to the measuring area, a spatial distribution of internal fields can be measured without much disturbance to the plasma or media of interest. However, when designing a probe for use in a high frequency environment the probe's calibration, sensitivity, and frequency response must all be considered. This is especially true since a probe's behavior is not only dependent upon its physical geometry (coil size, etc) but also by non-ideal factors such as cable lengths, cable types, capacitive pickup due to plasma or other sources, and impedance matching of the probe to an oscilloscope or other measuring device. More thorough qualitative considerations on probe characteristics are given in Refs 1-3. In this paper, each of these will be addressed and quantified specifically for B-dot probes that were designed to take measurements on a 13.56 MHz RF cylindrical plasma.

Theory

Inductive probes in the most general sense consist of a loop of wire which when subject to a time varying magnetic flux obey Faraday's Law

$$V_i = -\frac{d\Phi_B}{dt} \tag{1}$$

where V_i is the induced voltage in the wire and Φ_B is the magnetic flux through the loop or coil. We consider the coil's cross sectional area small enough that the flux and magnetic field do not vary over the cross sectional area and obtain

$$V_i = -A_{eff}\frac{dB}{dt} \tag{2}$$

where B is the component of the field that lies along the axis of the coil and A_{eff} is the effective area over which the magnetic flux is measured. A_{eff} can be described by

$$A_{eff} = nA \tag{3}$$

where n is the number of turns in the sensing coil and A is the cross sectional area of each turn. Substituting for A_{eff} yields,

$$V_i = -nA\frac{dB}{dt} \tag{4}$$

However, this will most likely not be the voltage present at the measuring instrument (oscilloscope) due to many non-ideal factors that cause signal attenuation through impedance mismatch. A thorough analysis and theory on the non-ideal characteristics of B-dot probes is given in Refs 3-4. This article will help to quantify the non-ideal behavior of B-dot probes by using an impedance analyzer.

To obtain a large voltage, it is desirable to have a coil with a large cross-sectional area and many turns. However, if the area of the coil is large, the probe can disturb the plasma and measurements become spatially limited. A large number of turns in the sensing coil with a large radius will cause the inductance to rise. This is seen by looking at the inductance of a single layer solenoidal coil[1]

$$L = \frac{r^2 N^2 \pi}{l}\left(1 - \frac{8w}{3\pi} + \frac{w^2}{2} - \frac{w^4}{4} + \frac{5w^6}{16} - \frac{35w^8}{64} + ...\right) \quad where \quad w = r/l \tag{5}$$

Clearly, as the radius of the coil increases, so does the inductance. Consequently, when the inductance L rises, the cutoff frequency f_{co} of the coil decreases according to [4]

$$f_{co} = \frac{Z_0}{2\pi L} \tag{6}$$

Therefore, a compromise must be found that provides an adequate induced voltage (probe sensitivity; large n & A), while maintaining good spatial resolution (small A), and an adequate frequency response (small L → small n & A).

Considering a time varying field $B(t) = B\sin(\omega t)$, equation (4) for the resulting magnitude of the magnetic field, as measured by the probe, becomes

$$|B| = \frac{V_i}{nA\omega} \tag{7}$$

Therefore, in order to characterize a magnetic induction probe for use at a specific frequency f, we must determine the product nA. This is also known as the calibration factor.

Calibration

Previous work has shown that there are typically three ways in which this is accomplished [1-3]:

1) direct geometrical inspection of the coil dimensions (count n, measure A)

2) measuring the output voltage when the coil is put in a known pulsed field

3) comparison of the probe output with that of a coil of known dimensions, i.e, a Helmholtz coil and calculate what B should be generated compared with what B is measured.

More recently, characterization of magnetic induction probes have also utilized network analyzers in conjunction with one of the above methods to gain a more detailed measurement of the probes behavior [4][5]. However, there exist limitations to all three methods regardless of the instrumentation used.

For example, with direct geometrical inspection, accurate measurement when the probe is nominally small can become difficult. Method (2) requires having a known field near the frequency of interest which is often difficult. Method (3) has been found to be the preferred method of calibration amongst many authors [1-3, 5], however, careful attention must be used when this method is considered.

Most often a Helmholtz coil is utilized due to the uniform field at the center. This field is given by

$$B_z = \left(\frac{\mu_0 N I}{a} \right) \left(\frac{8}{5^{3/2}} \right)$$ (8)

where a is the coil radius and is equal to the coil separation distance, N is the number of turns in each coil and I is the current in the coils. Immediately, we see that geometrical inspection is used in determining the number of turns and the radius of the calibrating Helmholtz coil. Additionally, we must accurately know the current in the calibration

circuitry as well as the frequency response of the Helmholtz coil based upon its capacitance and inductance. As an example, utilizing a low inductance resistor to measure the current through a Helmholtz coil, we find deviations for the ideal impedance response resulting in a 3 dB point of 66.5 MHz for a 120 Ω resistor with < 0.1 μH at 100 kHz as shown in Figure 1.(noted at 100 kHz because the resistive/inductive values will vary at higher frequencies due to factors such as skin depth).

Additionally, attention must be paid to the connection wires the Helmholtz coil (as well as in the case of the magnetic induction probe). For example, the current source for the Helmholtz coil will most likely have some connection lead wires both prior to the Helmholtz windings as well as exiting from the Helmholtz windings. Also, if the current through the calibrating coil is measured as the current through a low inductance resistor, the connection wires that sense the resistor current will have some inherent inductance to them and likewise a cutoff frequency which will dictate the frequency to which a Helmholtz coil can be utilized; the limitation either being the resistor itself, or the cutoff frequency due to the coils inductance. For example, coaxial (BNC) cable is typically rated for 50 Ω use to a few GHz; however, if the load is not 50 Ω, or breakouts are used, the useful frequency range drastically changes. If alligator clip coax breakouts are used to either measure the resistor current or the connectors for the Helmholtz source current, then the useful frequency range of these breakouts is limited to ~ 10 MHz as shown in Figure 2 (note: this measurement not made with impedance analyzer to illustrate limitation of connection wires). This resistor has a similar inductance to that of the 120 Ω resistor previously used; however, when the frequency response is measured with a

function generator and oscilloscope, we find that the frequency is limited by the inductance in the connection wires. Therefore, great care must be taken when utilizing Method (3) as a method of calibration because errors in the calibration circuitry and setup can easily perpetuate into the magnetic probe's circuitry.

Because of the limitations of each of the calibration methods described above it is this author's preference that when using coils that have been prefabricated such as utilizing a surface mount inductor as the sensing coil, that the manufacturers geometrical specifications for the number of turns and area based on the bobbin size the coil was wound on be used.

Capacitive Pickup

A common use of magnetic field probes is measuring the transient fields present in laboratory plasma discharge. Due to the nature of this environment, there are two sources from which a probe will measure pickup. These are inductive (which is due to the magnetic flux lines which pass through the sensing coil) and capacitive pickup which is due to a potential difference between the plasma discharge and coil. These differences are illustrated in Figure 3.

For the purpose of measuring the magnetic field B, the only signal of interest is that induced in the sensing coil. To remove unwanted capacitive pickup, we consider putting two separate sensing coils next to each other but geometrically orientated 180 degrees with respect to the other. The two signals are then combined through a Center-Tapped

Transformer (CTT) such that the capacitive voltage signal is subtracted out when the leads from the two probes are connected to opposite ends of the CTT. The two probe orientation is shown in Figure 4.

The CTT used with these probes is a MiniCircuits T16-6T+ which has a flat frequency response to 75 MHz. Additionally, it is an unbalanced to 50 Ω balanced load transformer with an impedance ratio of 16 [6]. To further reduce unwanted noise and pickup, a differential voltage probe is used. The differential voltage probe used in this setup is the Tektronix P6246 which has a 400 MHz bandwidth, < 1 pF input capacitance, 200 kΩ input resistance, and a 60 dB common mode rejection ratio (cmrr); the B-dot probe/CTT/differential voltage probe schematic is shown in Figure 5.

Probe Characterization

Selection

With knowledge of the leads from the magnetic induction probe lowering the overall frequency response, it was desirable to design a coil with significantly lower inductance such that when the connection wires to the coil are made, allowance for use at 13.56 MHz (desired operating frequency) is accomplished. With this in mind and the desire for good probe sensitivity, a surface mount inductor was selected. This also allowed miniaturization of the sensing coil while providing a larger number of turns for a small cross sectional area.

The inductor selected was a Vishay Dale high frequency surface mount inductor, P/N IMC1008ERR39J. This surface mount inductor has 20 turns wound on a rectangular bobbin measuring [0.83 mm X 1.29 mm]. Physically, the inductor is [2.5 mm X 2.0 mm X 1.6 mm] with a ceramic core, and solder-able end connector plates. The specified inductance is 390 nH with a self-resonant frequency of 530 MHz [7].

Frequency Response

The most important consideration when utilizing a magnetic induction probe is identifying the resonant frequency of the entire measuring circuit. This is based upon many factors beyond just the coil inductance and the parasitic capacitance between successive turns of wire as shown in Figure 6. They include effects such as transmission line lengths, the types of cable used, and the termination impedance. Toward quantifying these effects on the probe's frequency response an impedance analyzer was used.

The impedance analyzer used in this work is the Agilent 4294A Precision Impedance Analyzer. The analyzer can be swept over any specified frequency range from 40 Hz - 110 MHz with a user-defined number of points from 2 - 801 between the frequency intervals. Sweeps can be specified to be linear or logarithmic and typically take < 1 s [8]. The 16047E test fixture was utilized with the 4294A unit. This fixture is attached to the front of the unit and allowed for easy test and measurement of cables and axial leaded components, such as those utilized in this work. All tests were conducted with a 500 mV sinusoidal signal. The analyzer simultaneously displays the impedance magnitude Z and the phase delay θ. While it has the ability to display a variety of other parameters such as

resistance, inductance, and capacitance (both series and parallel values) as a function of frequency, the one of primary interest in probe design is the magnitude of the impedance at the frequency under investigation.

The frequency response of the probe was investigated and found to heavily rely on two things; 1) the length of cable from the inductor coils to the CTT and 2) the type of cabling used; in this case either a twisted shielded pair or coaxial. The length of cable from the 50 Ω balanced side of the CTT to the oscilloscope differential voltage probe was found have a negligible effect on the overall frequency response in comparison to the cable length on the unbalanced side of the CTT ; this is the result of the CTT being a 50 Ω balanced load in conjunction with the transmission line to the differential voltage probe. The relationship between frequency response and transmission line length for a twisted shielded pair of wires and coaxial wire was tested using a single sensing coil. The results are shown in Figure 7.

For the same length transmission line, both cables exhibit nearly identical resonance frequencies. However, at the resonant frequency, the coaxial cable has an impedance value that is five times smaller than the twisted shielded pair. Though for the intent of this probe, the frequency of interest is 13.56 MHz, so that if the transmission line length is kept to less than 1 meter, the type of cable chosen should not have much effect on the passing signal. However, it is prudent to note that probes used in environments such as plasma discharge will be subject to harmonic signals as well as the fundamental.

Therefore, depending upon the application, higher or lower impedance at frequencies larger than the fundamental may be desirable.

In this work, the twisted shielded pair of cable was chosen specifically for the aforementioned reason. Since 13.56 MHz was the desired frequency of study, higher order harmonics are simply viewed as spurious signals. Additionally, the twisted shielded pair of cable was used on the primary winding side of the CTT so that when connected to the differential voltage probe, a differential measurement could take place between two lines not directly connected with an instrument ground.

The line length affect on the twisted shielded pair from the probe to the CTT was then investigated (with the CTT now inserted in-line whereas the CTT was not present previously). These results are shown in Figure 8 and clearly illustrate that shorter line lengths yield a higher resonant frequency and allow the probe to have a wider operating regime.

Discussion

The final probe characteristics were selected based upon some experimental and laboratory limitations.

First of all, the 2-probe combination (180 degree spatial orientation) was measured to be approximately 5.0 mm in length and 2.5 mm in height. The probe was sized specifically to be this dimension so that spatial B profiles could be resolved when probing a 5 cm OD

cylindrical plasma. This ensures that the physical disturbance to the plasma is an order of magnitude smaller than the discharge. The probe is shown in Figure 9.

Second, the size of the CTT was significantly larger than the probe and if they were placed close together (so as to increase the circuit resonant frequency), the probe/CTT combination would become large and disturb the magnetic environment under investigation. As such, the probe-to-CTT length selected was 0.67 meters with a resonant frequency of 27.54 MHz. For the investigation of 13.56 MHz, this resulted in an impedance of approximately 10 Ω's. The calibration factor nA, based off manufacturer specifications was 21.27 mm^2.

The method of using an impedance analyzer eliminates many of the previous difficulties in magnetic induction probe design. Previously, discrete data points would be taken over a large frequency range rather than swept over range of interest. This allows distinct features in the probe/circuit to be readily identified. It is not only a more time efficient method of probe characterization but also allows the user to measure the entire circuit as a function of frequency. One can easily see the effect transmission line length has as well as cable type on the circuit resonance.

Attaching a 1 meter cable to a 390 nH inductor with a self resonant frequency of 530 MHz, quickly drops the circuit resonance to ~ 17 MHz, more than an order of magnitude. The only way to circumvent this problem is to move a balanced-unbalanced CTT closer to the inductor (probe). However, for the 13.56 MHz design point in this work, we were

fortuitous that transmission line lengths did not cause significant concern. Though, this work does approach the limitation of small physical size (small A), with good signal strength (nA), design for frequencies much higher may prove difficult.

Although, if higher frequency operation is desired, one technique recently investigated has been that of frequency mixing where a high signal frequency is mixed with a local oscillator (LO) resulting in a more manageable intermediate frequency (IF)[9]. This method proved unnecessary for the work done here, though a comparison between the two methods is probably warranted.

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