# Probe for the measurement of magnetic fields with sub-nanosecond resolution

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A double coil differential magnetic probe has been specifically devised for the measurement of magnetic fields with high temporal and spatial resolution. Having a response time of $<1$ nsec, a sensitivity of 0.3 V nsec $G^{-1}$, and high discrimination ($>300$) to all other types of background interference, it is well suited to the analysis of magnetic fields associated with plasmas produced by ultrashort laser pulses.

## I. INTRODUCTION

The measurement of pulse magnetic fields has always been one of the principal methods of plasma diagnosis.[1] The techniques developed have usually been devised to measure either magnetic fields which are used to externally contain the plasma, or magnetic fields which are induced within the plasma. These plasmas are generally large in spatial extent, are reasonably homogeneous, and typically have times of interest in the $10^{-7}$–$10^{-2}$ sec range. In recent times, however, one of the simpler methods of pulsed magnetic field measurement, the use of single coil magnetic probes, has been applied to the analysis of magnetic fields spontaneously generated in plasmas created by pulsed high intensity laser radiation.[2–5] Such plasmas differ significantly from those previously studied in that (i) they are of much smaller spatial extent, (ii) they are inhomogeneous in character, and possess much higher plasma densities, and (iii) they have much shorter formation times, typically in the $10^{-12}$–$10^{-8}$ sec range.

In the present paper, we wish to describe a magnetic probe specifically devised for the analysis of laser plasmas. This is basically a double coil differential probe, of small physical dimensions, providing reasonable spatial resolution. In addition, differential signal retrieval provides high discrimination against various sources of noise, an important experimental factor when it is considered that laser plasmas at present are created by neodymium or high pressure gas laser systems, operating in the 15–500 kV range. In the present case, the magnetic probe developed was to be utilized in an investigation of the spontaneous magnetic field (SMF) generated in plasmas produced from solid targets by single high power, 1 nsec duration, $CO_2$ laser pulses.[6] This particular laser system incorporates large aperture, uv-preionized gas discharge amplifiers, which, unshielded, are also very effective generators of high frequency electrical interference. For this reason, the demands made on noise discrimination criteria were particularly severe. Finally, the probe devised possesses ultrafast temporal resolution, intrinsically $<1$ nsec, thus providing the possibility for the analysis of the SMF within the interaction time of the laser beam with the plasma.

## II. DESIGN CONSIDERATIONS OF ULTRAFAST MAGNETIC PROBES

Many of the characteristics of a coil magnetic probe are interrelated. Thus it is not possible to improve its characteristics in one respect without affecting its performance in other ways. This can be illustrated by defining the important response characteristics of a simple coil probe, and discussion of the optimization of the various parameters involved.

The temporal response of an $n$-turn coil having a loop radius $r$ (cm) is expressed as

$$\tau = L/R_0 = Fn^2r/R_0, \tag{1}$$

where $L$ is the inductance of the coil, $R_0$ is the load resistance, and $F$ is a constant depending on the ratio of the coil length $l$ to its radius $r$ (for $r/l=2$, $F=0.029$).

The sensitivity of the probe can be defined by

$$V = 10n(\pi r^2)dB/dt \tag{2}$$

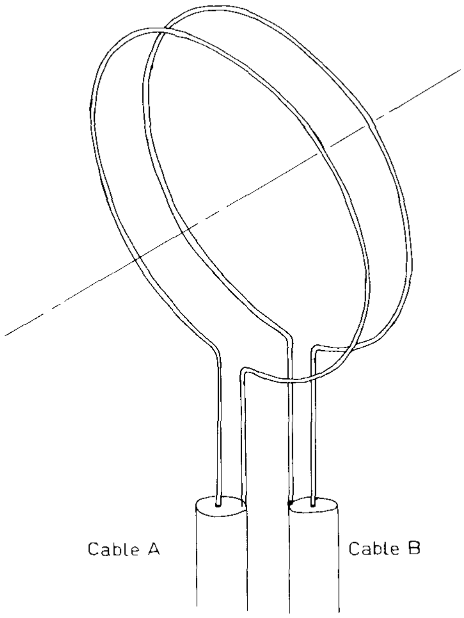
where $V$ is the coil voltage before integration and $dB/dt$ is the rate of field change in units of G/nsec.

It is clear from Eq. (2) that the sensitivity of the probe can be improved by increasing the radius $r$ or the number of turns $n$ of the coil. However, this is achieved only at the expense of the temporal resolution of the probe ($\tau$) and its spatial resolution, defined by the coil radius $r$. It should be noted, too, that the temporal resolution is more critically dependent on the value of $n$ than is the improvement in sensitivity. As can be seen from Eq. (1) it is also profitable to increase the value of the load resistance $R_0$ to obtain maximum temporal resolution. However, this is limited experimentally to fairly low values by the input impedance of available high bandwidth pulse amplifiers and oscilloscopes (typically 50 Ω). Moreover, the amplitude of recorded electrical noise is directly proportional to the value of $R_0$.

One of the principal questions associated with the design of a magnetic probe is that of the practical signal-to-noise ratio. This is especially important in the case of their application to laser plasma studies. These plasmas are effective sources of high energy radiation, which can induce electrical signals in unprotected probes by x-ray or uv

(a)




(b)

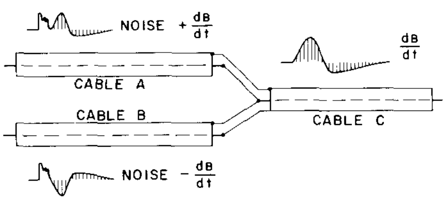



FIG. 1. (a) Schematic configuration of double coil differential magnetic probe. (b) Differential cable scheme for noise elimination.

photoelectric effects, or by secondary electron emission. In addition electrical noise emanating from the high voltage generators associated with the high power lasers used in these studies can be a particular source of interference.

Standard methods of noise elimination[1] are not ideally suited to the present situation. Shielded or jacketed probes and differential amplifiers are not conducive to the measurement of ultrafast magnetic field variations. The use of ferrite core differential transformers[2] with unprotected probes is more applicable, but still limits the probe risetime to several nanoseconds. For instance, with a six turn primary winding on a small ferrite core the probe risetime was $\sim 5$ nsec, and the differential fall time was $\sim 10^{-7}$ sec.

## III. CHARACTERISTICS OF DOUBLE COIL DIFFERENTIAL MAGNETIC PROBE

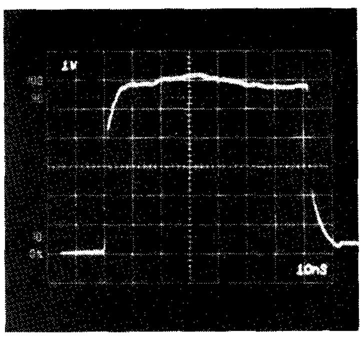
With the previously mentioned considerations in mind, a magnetic probe suitable for the analysis of magnetic fields in small, high density, rapidly changing plasma conditions was developed. In particular, the double coil differential probe developed excludes all signals which are identically received by each coil. It therefore not only has a high discrimination against electrical noise from external generators, but also discriminates well against electrical signals induced by photoelectric and secondary emission effects created by radiation emanating from the laser plasma.

This probe, which is shown schematically in Fig. 1(a), consists of two identical single turn coils, of loop diameter 1–2 mm, and wire thickness $\sim 50\ \mu$, the induced signal in each coil thus being of similar amplitude and proportional to $dB/dt$. The two coils are situated in close proximity, oriented antiparallel to one another, and connected to two 50 Ω cables [A and B of Fig. 1(b)]. After some distance, typically 6–8 m, the two cables A and B are connected by means of a simple, soldered joint, such that the central lead of cable A is connected to the screen of cable B, and vice versa. These two points of contact are then soldered to the central wire and screen of a third 50 Ω cable C, which transmits the resulting signal to a sensitive, 500 MHz bandwidth oscilloscope (Tektronix 7904). Thus equal and opposite polarity signals of the magnetic field propagating along cables A and B, respectively, are preferentially transmitted by the third cable C, while signals of equal polarity, such as "electrical pickup" or electronically-induced noise from the magnetic coils, are selectively cancelled.

A 72 nsec long rectangular electrical pulse having a risetime of 250 psec was used to determine the transmission characteristics of this differential probe system. Since the system is mismatched at the junction of cables A, B, and C, it was necessary to check the transmission linearity. Figure 2(a) shows the output signal of cable C when the above pulse was applied to the input of cable A. As can be seen, the risetime of the transmitted pulse is maintained and the oscillation on the pulse is $<3\%$.

In order to check this system for noise discrimination, two identical signals were transmitted along cables A and B at the same time, and the resulting difference signal transmitted by cable C displayed on a 500 MHz bandwidth oscilloscope [Fig. 2(b)]. Comparing the results shown in Fig. 2(a) and (b), it can be seen that the effective equal pulse discrimination of the system is better than 300:1. It should be noted that in such a system the cables A and B must have exactly the same wave resistance, and this may best be ensured by cutting them from the same roll. Also, for optimum reduction of gigahertz noise levels, the lengths of the two cables should be the same to within $\sim 1$ mm.

(a)



(b)

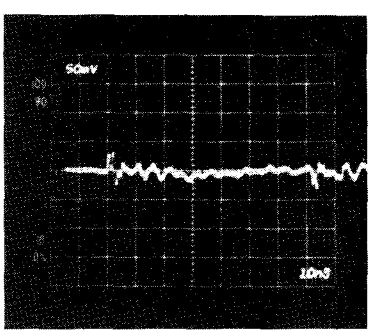


FIG. 2. High frequency properties of differential system. (a) Output signal of system with rectangular pulse applied to input of cable A. Vertical sensitivity—1 V/div; horizontal scale—10 nsec/div. (b) Differential output signal with two similar rectangular pulses applied to cables A and B. Vertical sensitivity—50 mV/div; horizontal scale—10 nsec/div.

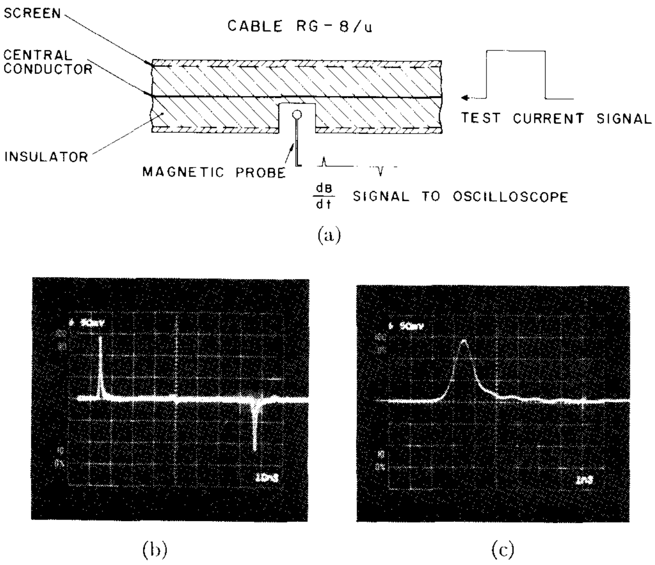



FIG. 3. Calibration and temporal resolution of the magnetic probe. (a) Experimental arrangement for calibration. (b) Response of magnetic probe to rectangular magnetic field pulse (10 nsec/div). (c) Similar pulse to (b) on an expanded time scale (1 nsec/div).

Calibration and measurement of the temporal resolution of the probe was made using the well-known Biot–Savart effect. For this, a rectangular voltage pulse, of amplitude up to 50 V, and risetime 250 psec, from a pulse generator propagated along a length of RG-8/U 50 Ω coaxial cable. There was created, consequently, a pulsed magnetic field between the inner conductor and the outside sheath. At an arbitrary point along the cable's length, a small opening was made in the outside sheath and the polyethylene insulation, in order that the magnetic probe could be introduced in close proximity to the inner conductor, Fig. 3(a). The incision in the cable was small enough so as to preserve the pulse characteristics. Thus a knowledge of the distance of the probe [Fig. 3(b) and (c)], and the measured signal gave an indication of its temporal resolution [Fig. 3(c)]. From this figure, it can be seen that the risetime of the magnetic field signal (proportional to $dB/dt$) is limited by the available bandwidth of the detection system to $\sim 700$ psec (that of a Tektronix 7904 oscilloscope and a 7A19 500 MHz amplifier).

The sensitivity of the probe depends on the value of $r$, the radius of each coil and for $r=1$ mm was found to be 0.3 V nsec $G^{-1}$. Thus with the amplifier and oscilloscope used, which has millivolt sensitivity, it is possible to measure values of $dB/dt$ as low as $10^{-2}$ G $nsec^{-1}$ using such probes.

Although this type of probe can thus be used for the measurement of ultrashort pulses of $dB/dt$, it should be noted that there is a limit to the duration of $dB/dt$ which can be analyzed. This arises because of the unterminated junction between cables A, B, and C, which results in the undesirable propagation of pulse reflections. However, cable lengths of 15 m for cables A and B can be safely used before serious degradation of the pulse risetime occurs, thus permitting values of $dB/dt$ to be recorded for times of $10^{-7}$ sec without interference from reflections.

Thus, the development of this probe permits the measurement of transient magnetic fields with sub-nanosecond resolution. Further improvements in the bandwidth of pulse amplifiers and oscilloscopes would permit increases in the temporal resolution of perhaps a factor of 2 or 3. However, for greater temporal resolution, resort must be made to optical methods of magnetic field measurement. Methods depending on the measurement of Zeeman splitting of emitted x-ray or vuv radiation,[7] or of the Faraday rotation of probing laser radiation,[8] have already been discussed. The use of these techniques in conjunction with ultrafast image converter cameras would provide temporal resolution of SMFs in the picosecond range. Probes of the type described in this paper have been utilized in a study of the magnetic fields spontaneously generated by plasmas produced by 1 nsec duration $CO_2$ laser pulses of high intensity focused onto $CH_2$ and Al targets. The results of this investigation will be reported in a subsequent publication.[9]

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