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A NEW DC MAGNETIC SENSOR

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ABSTRACT

A new concept is proposed to measure a dc magnetic induction vector **B** whose magnitude is sufficiently large to saturate a small ferro- or ferrimagnetic sphere and align its magnetization vector **M** parallel to **B**. The direction of **M** is measured by modulating **B** locally at a convenient ac frequency by one or more small exciter coils near the sphere and using separate detector coils to measure components of the modulated induction due to the ac perturbed orientation of **M**. Equations are derived to relate the perturbed quantities to the original induction **B**. Several combinations of exciter and detector coils are possible, especially if distinct frequencies are used for each direction component. All three vector components of **B** can be calculated from the raw data. Because the proposed sensor has neither moving parts nor semiconductor components, it should be suitable for measurements in ionizing radiation environments, such as long pulse or steady state magnetically confined fusion power reactors.

I. INTRODUCTION

Real-time control of current-carrying toroidal magnetic plasma confinement devices, typified by the tokamak, requires accurate knowledge of the magnetic induction field **B** at many points near the surface of the plasma. The data are also required for post-discharge computational reconstruction and analysis of the magnetic configuration, for example by the EFIT code.[1] The most commonly used technique to measure magnetic induction in magnetic fusion devices at present is active electronic integration of the dB/dt signal from an inductive pickup loop. The conventional technique might be extended by modern electronics and error correcting techniques[2] to the > 1000 s pulse length of next generation tokamaks, such as KSTAR[3] and ITER.[4] However, integration in time eventually suffers from accumulated error, and it will have to be replaced by magnetic sensors capable of measuring steady-state signals. Future fusion power reactors, for example, will have to operate continuously for $> 10^7$ s. Hall effect magnetic sensors measure steady fields, but when they are based on semiconductor materials, they are damaged by the strong ionizing radiation field near a fusion plasma. Sensors based on moving loops can also measure dc magnetic inductions, but it is difficult to design such systems with the necessary reliability in a tokamak environment.

A new magnetic sensor concept is presented to measure a steady-state magnetic induction vector **B** whose magnitude is sufficiently large to saturate a ferro- or ferrimagnetic material. The sensor consists of a small sphere of saturable material with two or three mutually orthogonal inductive detector coils wound on or close to the sphere (see Fig. 1). Also near the sphere are one or more exciter coils driven with low frequency alternating current (ac), which apply a small, spatially uniform, perturbing induction $\tilde{\mathbf{B}}_{\mathrm{exc}}$. The detector coils respond to both $\tilde{\mathbf{B}}_{\mathrm{exc}}$ and the perturbed induction dependent on the ac perturbed orientation of **M**. After subtraction of the driving $\tilde{\mathbf{B}}_{\mathrm{exc}}$ contribution, the signal from the perturbed magnetization $\tilde{\mathbf{M}}$ remains. Then, it will be shown below that the static vector **B** can be calculated from the signals from a suitable set of exciter and detector coils. The technique works because **M** is not linearly proportional to **B**. Rather, **M** is saturated in magnitude, while parallel to **B** as illustrated in Fig. 2.

Many combinations of exciter and detector coils are possible, especially if distinct frequencies are used for each direction component. It is possible to calculate all three vector components of **B**. Because the proposed magnetic sensor has neither moving parts nor semiconductor components, it should be suitable for measurements in ionizing radiation environments, such as long pulse or steady state magnetically confined fusion power reactors, as long as the saturable material remains ferromagnetic. Operation of the sensor is insensitive to the exact value of its saturated magnetization.

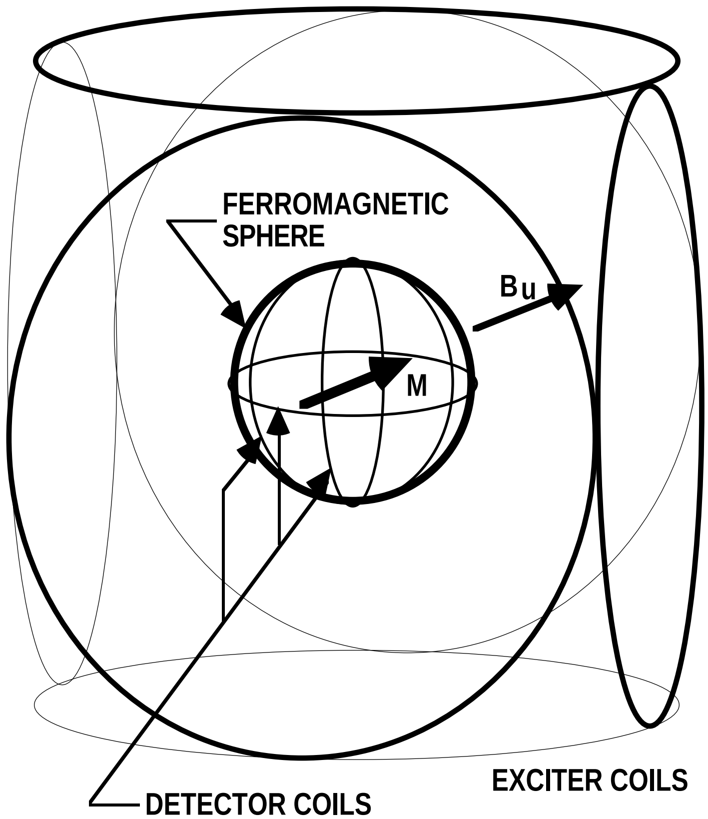

Fig. 1. Magnetic sensor, consisting of ferromagnetic sphere, exciter coils and detector coils. Magnetization $\boldsymbol{M}$ *in the sphere aligns with the external uniform induction field,* $\boldsymbol{B}_u$.

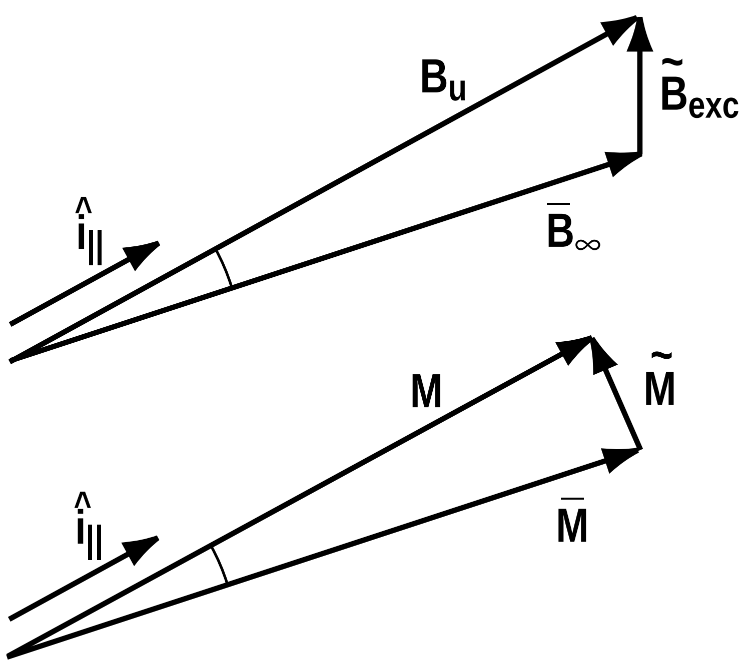

Fig. 2. The instantaneous magnetic field $\boldsymbol{B}_u$ *(top) and magnetization (bottom) vectors. Also shown is the instantaneous unit parallel vector,* $\hat{i}_{||}$.

II. MAGNETIC FIELD RELATIONS

This section derives the magnetic flux measured by a detector coil. To avoid possible confusion, in this section the steady field to be measured, **B**, is written as $\overline{\mathbf{B}}_\infty$. The small, externally applied uniform excitation field is $\tilde{\mathbf{B}}_{\mathrm{exc}}$. An overbar means a steady quantity, and a tilde means an ac quantity. Define the total externally applied uniform field as $\mathbf{B}_{\mathrm{u}} = \overline{\mathbf{B}}_\infty + \tilde{\mathbf{B}}_{\mathrm{exc}}$ (see Fig. 1). The unit vector in the $\mathbf{B}_{\mathrm{u}}$ direction, to first order in $\tilde{\mathbf{B}}_{\mathrm{exc}}$ is

$$\hat{\mathbf{i}}_{\|} = \frac{\mathbf{B_u}}{B_u} \approx \frac{\overline{\mathbf{B}}_\infty}{\overline{B}_\infty} + \frac{\tilde{\mathbf{B}}_{\mathrm{exc}}}{\overline{B}_\infty} - \frac{\overline{\mathbf{B}}_\infty \cdot \tilde{\mathbf{B}}_{\mathrm{exc}}}{\overline{B}_\infty^2} \frac{\overline{\mathbf{B}}_\infty}{\overline{B}_\infty} \ . \tag{1}$$

The italicized variables represent the magnitudes of their vector counterparts. The magnetic induction inside a magnetized sphere is well known and is

$$\mathbf{B}_{\mathrm{int}} = \mathbf{B}_{\mathrm{u}} + (2/3)\mu_0 \mathbf{M} \tag{2}$$

in SI units. The external field is the sum of $\mathbf{B}_{\mathrm{u}}$ and a dipole field of magnitude $(1/3)\mu_0 M$ aligned with it. Assuming that **M** is spatially uniform and parallel to $\mathbf{B}_{\mathrm{u}}$, then

$$\begin{aligned} \mathbf{M} &= M\,\hat{\mathbf{i}}_{\|} = \left(\overline{M} + \tilde{M}\right) \mathbf{B}_{\mathrm{u}} / B_{\mathrm{u}} \\ &\approx \left(\overline{M} + \tilde{M} - \overline{M}\, \frac{\overline{\mathbf{B}}_\infty \cdot \tilde{\mathbf{B}}_{\mathrm{exc}}}{\overline{B}_\infty^2} \right) \frac{\overline{\mathbf{B}}_\infty}{\overline{B}_\infty} + \overline{M}\, \frac{\tilde{\mathbf{B}}_{\mathrm{exc}}}{\overline{B}_\infty} \end{aligned} \tag{3}$$

to first order in $\tilde{\mathbf{B}}_{\mathrm{exc}}$. The possibility of a small residual ac variation of M is retained, even though the sphere is expected to be strongly saturated.

The internal field $\mathbf{B}_{\text{int}}$ follows from Eqs. (2) and (3). Keeping only ac components and considering now $\tilde{\mathbf{B}}_{\text{s}} \equiv \tilde{\mathbf{B}}_{\text{int}} - \tilde{\mathbf{B}}_{\text{exc}}$ as the interesting signal, this is

$$\tilde{\mathbf{B}}_{\text{s}} \approx \frac{2}{3} \mu_0 \overline{M} \left(\frac{\tilde{M}}{\overline{M}} \frac{\overline{\mathbf{B}}_\infty}{\overline{B}_\infty} + \frac{\tilde{\mathbf{B}}_{\text{exc}}}{\overline{B}_\infty} - \frac{\overline{\mathbf{B}}_\infty \cdot \tilde{\mathbf{B}}_{\text{exc}}}{\overline{B}_\infty^2} \frac{\overline{\mathbf{B}}_\infty}{\overline{B}_\infty} \right) . \quad (4)$$

$\tilde{\mathbf{B}}_{\text{int}}$ must be measured by the detector coils. This is done most directly if the detector coils are wound directly on the surface of the sphere and do not pick up any contribution from the external dipole field. Otherwise, additional signal processing is required. Once $\tilde{\mathbf{B}}_{\text{int}}$ is known, $\tilde{\mathbf{B}}_{\text{s}}$ can be calculated, because $\tilde{\mathbf{B}}_{\text{exc}}$ is also known.

III. MAGNETIC SENSOR CONCEPTS

This section shows how one or more components of the distant external magnetic induction, $\overline{\mathbf{B}}_\infty = \mathbf{B} = B_x\hat{\mathbf{i}}_x + B_y\hat{\mathbf{i}}_y + B_z\hat{\mathbf{i}}_z$, can be calculated from measurements of the signal $\tilde{\mathbf{B}}_s$. It is convenient to resolve Eq. (4) into its Cartesian (x,y,z) components:

$$
\begin{aligned}
\frac{\tilde{B}_{s\,x}}{2\mu_0 M/3} &= \frac{\tilde{M}}{M}\frac{B_x}{B} + \frac{\left(B_y^2 + B_z^2\right)\tilde{B}_x - B_x\left(B_y\tilde{B}_y + B_z\tilde{B}_z\right)}{B^3} \\
\frac{\tilde{B}_{s\,y}}{2\mu_0 M/3} &= \frac{\tilde{M}}{M}\frac{B_y}{B} + \frac{\left(B_z^2 + B_x^2\right)\tilde{B}_y - B_y\left(B_z\tilde{B}_z + B_x\tilde{B}_x\right)}{B^3} \\
\frac{\tilde{B}_{s\,z}}{2\mu_0 M/3} &= \frac{\tilde{M}}{M}\frac{B_z}{B} + \frac{\left(B_x^2 + B_y^2\right)\tilde{B}_z - B_z\left(B_x\tilde{B}_x + B_y\tilde{B}_y\right)}{B^3}
\end{aligned}
\qquad (5)
$$

The overbars have been dropped from the steady quantities, and $\tilde{B}_{x,y,z}$ are the known components of $\tilde{\mathbf{B}}_{\mathrm{exc}}$.

Each exciter coil can be driven at a separate frequency, and frequency selective detection can be applied to the detector coil signals. This yields a total of nine signal data, three detector directions for each of three exciter directions. Therefore, several possible combinations of the data can be chosen to calculate the desired components of **B**. If desired, the redundancy can be used to improve measurement reliability and accuracy.

As an example, consider measurement of **B** at the edge of a tokamak plasma. Let the z direction coincide with the local toroidal direction; then x and y are poloidal components. The toroidal field is already known from measurement of the toroidal field coil current, so only the two poloidal field components need to be measured. This is possible with excitation of only the

$\tilde{B}_z$ coil. Let the relative variation of the magnetization, $\tilde{M}/M$, be negligibly small. Then Eq. (5) yields the poloidal components as

$$B_{x,y} = -\frac{B}{2\mu_0 M/3}\frac{B}{B_z}\frac{\tilde{B}_{s\,x,y}}{\tilde{B}_z}\,B \tag{6}$$

with the signal $\tilde{B}_{s\,x,y}$ measured at the $\tilde{B}_z$ exciter coil frequency. Because the $\tilde{B}_{s\,x,y}$ signals are perpendicular to the $\tilde{B}_z$ excitation, their separation from $\tilde{\mathbf{B}}_{\mathrm{int}}$ detected signal is straightforward. Also, the $\tilde{B}_{s\,x,y}$ signal magnitudes are acceptable. The ratio between the detected and exciter induction ac magnitudes is $\tilde{B}_{s\,x,y}\big/\tilde{B}_z = (2\mu_0 M/3B)(B_z/B)\big(B_{x,y}/B\big)$. Since $B_z/B \approx 1$ in a tokamak, the ac signal is proportional to the poloidal/toroidal field ratio and the saturation magnetization M. If the magnetization magnitude M can drift, say due to changing temperature, it can be found from the known toroidal induction and third component of Eq. (5),

$$\frac{2}{3}\mu_0 M = +\frac{B^2}{B_x^2 + B_y^2}\frac{\tilde{B}_{s\,z}}{\tilde{B}_z}\,B\ . \tag{7}$$

All of the above information is obtained by driving a single exciter coil, $\tilde{B}_z$, at a single frequency. However, $\tilde{B}_{s\,z}$ used in the determination of M in Eq. (7) is second order in the poloidal/toroidal field ratio, which is small in tokamaks. Furthermore, measuring this small $\tilde{B}_{s\,z}$ requires subtraction of the much larger $\tilde{B}_z$ from the raw $\tilde{\mathbf{B}}_{\mathrm{int}}$ signal. Therefore, the calculation of M from Eq. (7) might not be sufficiently accurate. The magnetization can be calculated redundantly and with higher accuracy from x and/or y detector coil signals at their separate respective frequencies. From Eq. (5),

$$\frac{2}{3}\mu_0 M = +\frac{B^2}{B_{x,y}^2 + B_z^2}\frac{\tilde{B}_{s\,x,y}}{\tilde{B}_{x,y}} B \ . \tag{8}$$

Similarly, B_x and B_y can be calculated redundantly from the appropriate frequency components in the $\tilde{B}_{s\,z}$ signal if the x and/or y exciter coils are driven.

A different approach to measurement of **B** in tokamaks is to drive all three exciter coils at a single frequency and regulate their amplitudes in feedback loops so as to null the detector coil signals $\tilde{B}_{s\,x,y}$. Then, according to Eq. (5), the following relations hold:

$$\frac{\tilde{B}_x}{B_x} = \frac{B_z\tilde{B}_z + B_y\tilde{B}_y}{B_z^2 + B_y^2} \ , \qquad \frac{\tilde{B}_y}{B_y} = \frac{B_z\tilde{B}_z + B_x\tilde{B}_x}{B_z^2 + B_x^2} \ . \tag{9}$$

The two equations suffice to determine the two unknown quantities, B_x and B_y. This method depends only on ratios of measured and known quantities, and it is insensitive to the magnitude of M.

IV. SATURABLE MATERIAL

The proposed concept requires that the magnetization vector rotate freely and align with **B**. Fully saturated ferromagnetic materials satisfy this requirement. (The stick-slip Barkhausen effect is a subsaturation phenomenon as magnetic domain walls move. In saturated material there are no domain walls left.) Ferromagnetic metals and ceramic ferrites are candidate materials for the sensor sphere.

Iron and some of its alloys, which have $\mu_0 M$ ~ 2 T well below the Curie temperature, are preferable on the basis of signal amplitude for the high field strength applications typical of hot, magnetically confined plasmas. Ceramic ferrite materials have M on the order of ten times smaller and would give correspondingly smaller $\tilde{B}_s / \tilde{B}_{exc}$ signals (see discussion after Eq. (6). The Curie temperature of Fe, 1043 K, is higher than those of ferrites, which makes the metals more suitable for high temperature environments, such as fusion reactors.

Because metals are good electrical conductors, the allowable ac frequencies are limited by the skin effect, which must be avoided. In strongly saturated metals, $B >> \mu_0 M$, the skin depth is nearly the same as in a nonmagnetic conductor, $\delta = (2\eta/\omega\mu_0)^{1/2}$, where η is the electrical resistivity, $\omega = 2\pi f$ and f is the frequency. For example, for Fe with $\eta \approx 10^{-7}$ Ω/m, the frequency 250 Hz corresponds to δ = 0.01 m. Because $\delta r > 1$ is required for small skin effects, where r is the sphere radius, the ac frequencies are limited to < 100 Hz for a 1 cm radius sphere. Ceramic ferrites, which are insulators, are not subject to the skin effect, and they are compatible with any convenient frequencies.

In a fusion reactor the ferromagnetic material will be bombarded by neutrons. The main damage caused by energetic neutrons is usually atomic displacements. The initial effects in metals are usually similar to work hardening. In the present context this would make the material magnetically "harder." Magnetic hardness restricts domain wall motion, but this is an issue only below saturation. The proposed magnetic sensor, wherein the ferromagnetic material is always strongly saturated, should be relatively unaffected by displacement damage. Only if the displacements become sufficient to destroy the interatomic spin coupling that is responsible for ferromagnetism itself will the sensor fail. This important topic of neutron damage to the ferromagnetic sphere must be investigated more deeply.

IV. DISCUSSION AND CONCLUSIONS

The proposed concept for a magnetic sensor works easily, according to the idealized calculations presented here. More detailed calculations, including error analysis, are needed for specific applications. In a long-pulse or fusion reactor magnetically confined plasma application, an array of the proposed dc sensors would be used to correct conventional, time-integrated magnetic loop sensor signals, which are subject to long term baseline drift. If the ferromagnetic sphere were to degrade prematurely due to neutron damage, then the sphere and its attached detector coils might be designed as an assembly that could be pushed into place deep within the reactor along a tube from the outside.[5] The exciter coils could remain permanently in place in the tokamak or, for the price of a larger diameter access tube, also be part of the replaceable assembly.

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