Magnetic Diagnostics for Future Tokamaks*

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ABSTRACT

Magnetic diagnostics are critical for future tokamaks such as the International Thermonuclear Experimental Reactor (ITER). Existing tokamaks use inductive coils and loops as magnetic sensors. The sensors are located outside the plasma boundary but within the plasma's external magnetic fields. The electrical signals from these sensors are integrated over time to determine the plasma shape and are used for plasma control.

Present magnetic diagnostics are designed for plasmas lasting seconds to tens of seconds. In their present form, the inductive magnetic sensors and integrators are not suitable for future tokamaks with their long duration plasmas lasting for 1000 s or more. Namely, magnetic diagnostics for future tokamaks require: (1) sensors that will not overheat due to plasma radiation heating, (2) sensor materials that can survive the neutron fluence, (3) sensors designed for the remote handling requirements, and (4) integrators that have a 1000 s measurement capability. This paper presents a high frequency inductive magnetic sensor being developed for ITER.

I. INTRODUCTION

Future tokamaks, such as the International Thermonuclear Experimental Reactor (ITER), require magnetic diagnostics for the control and operation of the tokamak and for understanding plasma behavior. These diagnostics measure the plasma position, equilibrium shape, loop voltage, plasma current, diamagnetism, and other transient electromagnetic phenomena.

Present magnetic diagnostics are designed for short pulse tokamaks with plasmas lasting seconds to tens of seconds. Inductive coils and loops are used for magnetic sensors. The sensors are located outside the plasma boundary but within the plasma's external magnetic fields. A changing magnetic field strength in the coil or loop induces an emf. The electro motive force (emf) signal from the sensor is integrated over time using specialized electronics to determine the desired plasma property.

In their present form, the inductive magnetic sensors and integrators are not suitable for future long pulse tokamaks with plasmas lasting for 1000 s or more. Namely, magnetic diagnostics for future tokamaks require: (1) sensors that will not overheat due to plasma radiation heating, (2) sensor materials that can survive the neutron fluence, (3) sensors designed for the remote handling requirements, and (4) integrators that have a 1000 s measurement capability. The basic approach used here for the development of magnetic sensors for future tokamaks is to use standard methods which have been proven in operation on existing short pulse tokamaks [1–5]. Mineral insulated coax cable (MI cable) formed into coils and loops is a proven magnetic sensor design for the short pulse tokamak environment. Building on this experience, a magnetic sensor design concept suitable for future tokamaks like ITER has been completed

A description of the 1000 s integrator being developed for ITER can be found in Ref. [6].

II. MAGNETIC SENSOR DEVELOPMENT

The high frequency magnetic sensor (hfms) is the most problematic of the many magnetic sensor types because of its required proximity to the plasma. The development work on the hfms can be subsequently applied to the other less problematic sensors. The hfms requires a near line of sight view to the plasma. Installing sensors behind a conducting shield, structure, or vessel wall for protection results in a degradation in the frequency response due to eddy currents in the conductor shield. Sensors installed behind the shield module on ITER for example would have a frequency response of less than 10 kHz. The line of sight condition does have the deleterious effect of exposing the sensor to plasma heat flux, to increased volumetric nuclear heating and to increased neutron fluence.

While the expected frequency of MHD activity in ITER is less than 10 kHz, there is interest in being able to detect Toroidicity-induced Alfvén Eigenmodes (TAE). For ITER, a typical TAE mode frequency is around 80 kHz. A high frequency magnetic sensor having a frequency response of more than twice this frequency and having a –3 db point above 160 kHz is adequate for ITER.

A suitable high frequency magnetic sensor concept for ITER (Fig. 1) is a coil (25 mm diameter x 400 mm length) made from MI cable wound over an alumina ceramic mandrel. An active cooling coil interlaced with the MI cable coil prevents overheating. The sensor attaches to the ITER vacuum vessel (Fig. 2) centered along a 20 mm wide slot between plasma facing shield modules. This attachment location is available on the inboard and outboard walls of ITER and provides the sensor with a direct view of the plasma.

MI cable with its protective coax construction is chosen as opposed to bare copper wire to improve survivability and reliability. The MI cable has other advantages in that it does

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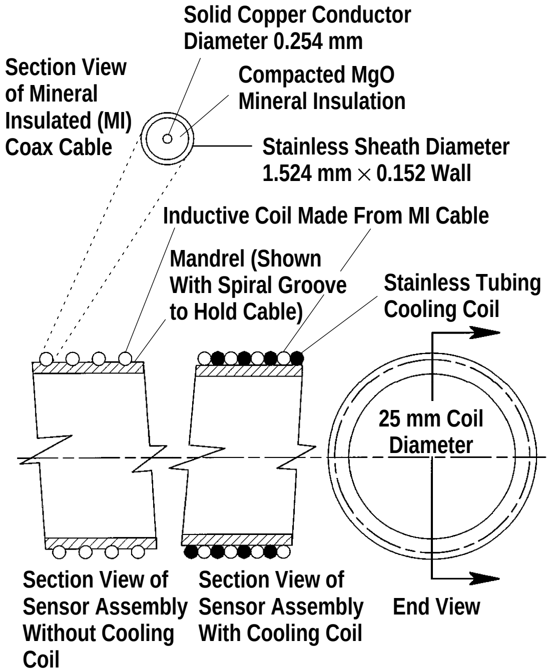

Fig. 1. Concept design for a high frequency inductive coil magnetic sensor shown with and without cooling coil.

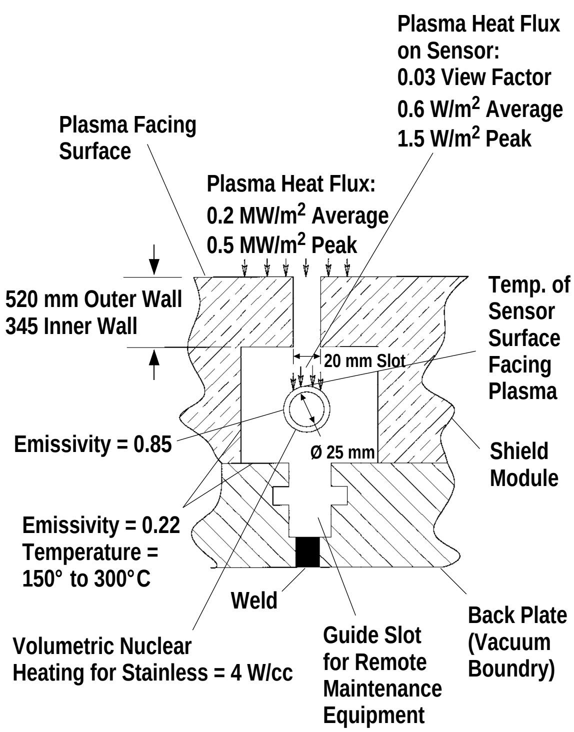

Fig. 2. Schematic of ITER first wall showing location of high frequency inductive coil magnetic sensor (not to scale).

not require ceramic to metal vacuum seals, does not require any in-vessel electrical joints, and provides its own grounded support structure and electrostatic shielding. The cooling coil is made from tubing of similar diameter and wall thickness as the MI cable sheath. The cooling coil and MI cable can be brought through the same vacuum feed through flange using a metal to metal brazed or welded vacuum seal. This makes a simple and robust sensor.

A sensor made from MI cable does not require an in-vessel connector unless the sensor must be remotely handled. Generally, an in-vessel connector adds complication and will probably reduce the reliability of the sensor. Experience in the short pulse tokamak environment has shown that existing off-the-shelf ceramic connector designs are fragile and not suitable for remote handling. Here, a conceptual design for a robust connector for use with MI cable is presented (Fig. 3) for consideration.

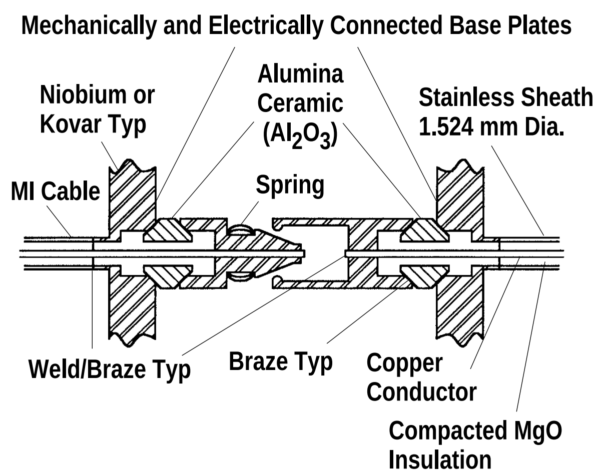

Fig. 3. Connector conceptual design for mineral insulated (MI) coax cable.

The neutron fluence survivability of the materials used to construct the sensor (alumina, stainless, compacted MgO and OHFC copper) is not fully known and requires further study. Other materials can be substituted (e.g., titanium for stainless, SiC for MgO or alumina, etc.) as necessary to improve survivability.

The draw back of the MI cable sensor is the reduced frequency response due to the metal shield that forms the outer jacket of the MI cable and to the metal tubing that forms the cooling coil. However, the frequency response of the sensor can be improved as demonstrated on DIII–D [7] by tuning the coil/cable circuit to a resonance by adjusting the inductance of the coil and capacitance of the cable. The solid curve in Fig. 4 is an example of the improvement in the frequency response of the sensor with a tuned resonance over the frequency response of a sensor without a tuned resonance (the dashed curve in Fig. 4 is the frequency response of the sensor only taking into account the attenuation of the field strength due to the metal sheath of the MI cable). The calculated normalized response (Fig. 4 solid curve) of the sensor with a cooling coil (Fig. 1) is greater that 0.5 in the frequency range of 0 Hz to above 200 kHz. The response of the sensor to a B dot signal at the plasma surface of frequency 80 kHz is approximately 2 mG/mV including

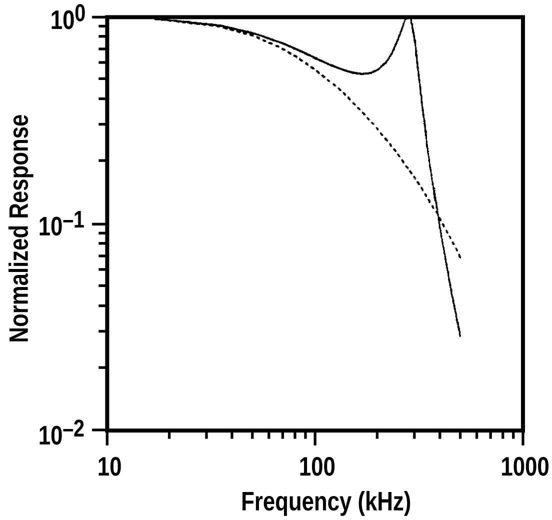

Fig. 4. The dashed curve is the normalized field strength at the sensor. The attenuation of the magnetic field strength is due to shielding by the MI cable metal sheath. The solid curve is the frequency response of the sensor including the shielding by the MI cable metal sheath and a damped resonance involving the inductance of the coil and the capacitance of the cable.

attenuation due to the 20 mm wide by more that 1000 mm long slot.

During plasma operations, the sensor is heated by volumetric nuclear heating and by plasma heat flux. The volumetric nuclear heating is caused by neutron and secondary gamma-ray fluxes. The anticipated volumetric nuclear heating rates at the Fig. 2 location for the sensor materials are 4 W/cc for stainless, 6 W/cc for copper, 4.8 W/cc for MgO and 4.8 W/cc for alumina [8]. These rates are a factor of 4 above the baseline rates (1.9 for the 20 mm wide slot, 1.6 for modeling and 1.4 for nuclear data correction) [9]. The anticipated plasma heat flux at the first wall is 0.2 MW/m^2 average and 0.5 MW/m^2 peak. The view factor from the plasma to the sensor through the 20 mm slot is about 0.03. Therefore, the adjusted plasma heat flux on the surface of the coil that faces the plasma is 0.6 W/cm^2 average and 1.5 W/cm^2 peak.

The absolute upper temperature limit for the sensor is difficult to set. Certainly the primary temperature concern is melting of the copper conductor in the MI cable. Copper melts at 1083°C. Secondary temperature issues include outgassing rates, electrical resistivity and thermal stresses. The design minimizes thermal stresses since the MI cable, cooling coil and mandrel are not welded or brazed together.

The surface temperature has been calculated (Table I) for the sensor with and without the cooling coil using the thermal parameters given in Fig. 2. With the cooling coil the sensor temperature should be acceptable reaching a surface temperature of 450°C under the wort case conditions (Table I Case 6). The worst case conditions consist of volumetric nuclear heating, peak plasma heat flux and 300°C surroundings. The sensor design without a cooling coil is not acceptable since it reaches a temperature of 845°C under the worst case conditions (Table I Case 6).

The thermal analysis is based completely on radiation exchange between the surroundings, mandrel, MI cable and cooling coil. No conduction paths have been included for several reasons. First, contact between the mandrel, MI cable and cooling coil cannot be guaranteed due to thermal movements. Second, when contact does exist it is line contact at low contact pressure providing poor conditions for conduction. Finally, this represents worst case heat transfer and is a conservative approach.

Thermal-hydraulic calculations have been performed to determine the requirements for using water or helium coolant in the cooling coil. The results are presented in Table II. Helium requires a high operating pressure (130 to 150 bar) which translates into a high system cost. However, the cost of recovering from a coolant leak must be considered noting that an in-vessel water leak can cause a lengthy and costly downtime.

Table I
Sensor Surface Temperature in the Configuration of Fig. 2 for six cases

Case	Temp. of surroundings °C	Plasma heat flux MW/m^2	Surface temp. of sensor without cooling coil °C	Surface temp. of sensor with cooling coil °C
1	150	0	600	315
2	300	0	685	340
3	150	0.2	690	370
4	300	0.2	760	390
5	150	0.5	790	435
6	300	0.5	845	450

Table II
Coolant Requirements For The Sensor in 300°C Surroundings and with Volumetric Nuclear Heating Plus Peak Plasma Heat Flux Applied

	Coolant	
	Water	Helium
Flow Rate	0.076 l/min.	0.00055 kg/s
Inlet Temp.	30°C	20°C
Outlet Temp.	70°C	90°C
Inlet Pressure	8 bar	150 bar
Outlet Pressure	3 bar	130 bar
Coolant Velocity (inlet)	1.5 m/s	30 m/s

III. TESTING

A prototype magnetic sensor made from MI cable has been constructed. Preparation is underway for testing in a nuclear environment its frequency response and its susceptibility to induced emf (Fig. 5). The neutron and gamma nuclear environment can induce a deleterious emf between the copper conductor and stainless metal sheath that form the MI cable. The testing will take place in the HFBR fission reactor at Brookhaven National Lab. The prototype sensor was constructed by winding 1.52 mm diameter MI cable around a 13 mm diameter x 270 mm long alumina mandrel. A second coil of MI cable was wound on top of the first coil creating two separate coils. One coil (exciter coil) is connected to an amplifier for magnetic field generation. The other coil is the sensor coil (pick up coil). The signal from the sensor coil will be measured by the prototype digital integrator testing its 1000 s measurement capability. Size limitations imposed on the prototype sensor by the HFBR reactor make it impractical to include the cooling coil creating the need for a separate testing program to validate cooling coil performance.

Other testing that has been proposed for the MI cable magnetic sensor is neutron fluence testing. The neutron fluence testing consists of inserting a MI cable sensor (and possibly a connector) in a fission reactor for about a month simulating the neutron fluence of future tokamaks to determine if the sensor materials can survive.

IV. SUMMARIZING REMARKS AND CONCLUSIONS

The development of a magnetic field measuring diagnostic for future long pulse tokamaks like ITER is progressing. Analysis has determined that a high frequency magnetic sensor constructed from MI cable and actively cooled with an interlaced cooling coil should be acceptable for ITER. MI cable with its protective coax construction is chosen as opposed to bare copper wire for many reasons such as survivability, reliability, grounded support structure, electrostatic shielding, no ceramic to metal vacuum seals and no in-vessel electrical joints. A prototype sensor has been constructed from MI cable and preparation is underway for testing in a nuclear environmental its frequency response and susceptibility to induced emf. ITER like nuclear environmental conditions will be applied by inserting the prototype sensor into the HFBR fission reactor. The signal from the sensor will be measured by the prototype long pulse integrator verifying its 1000 s measurement capability. Testing results are expected in the fall of 1995. Additional testing has been identified including neutron fluence testing and cooling coil performance testing.

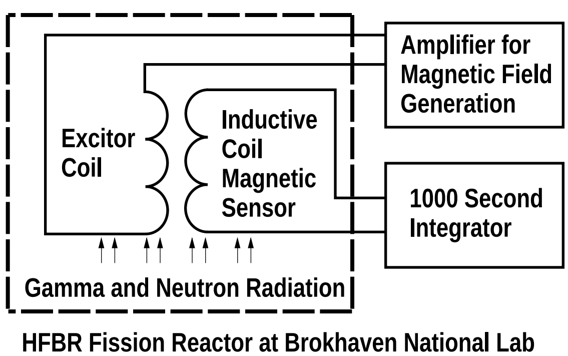

Fig. 5. Simplified schematic for testing in a nuclear environment the response of an inductive coil magnetic sensor made from mineral insulated (MI) cable.

REFERENCES

[1] L.C. Johnson and K.M. Young, “TFTR diagnostics” Course on Diagnostics for Fusion Reactor Conditions, Varenna, Italy, vol. II, pp. 551–580, 1982.

[2] P.E. Stott, “Review of JET diagnostics and results,” JET Report JET-P-87-04.

[3] P.E. Stott, “Electric and magnetic measurements,” Course on Diagnsotics for Fusion Reactor Conditions, Varenna, Italy, vol. II, pp. 403–418.

[4] C. Messick, P.A. Anderson, “Field installed brazed thermocouple feed throughs for high vacuum experiments,” in Proc. 9th Symp. on Fusion Engineering, 1981.

[5] Y. Neyatani, et al., “Development of magnetic sensors in JT-60 upgrade,” in Proc. 14th IEEE/NPSS Symp on Fusion Engineering, p. 1183, 1991.

[6] J.D. Broesch, “A digital long-pulse integrator,” this conference.

[7] E.J. Strait, “Frequency response of metal-clad inductive magnetic field probes,” General Atomcs Report GA-A22049, 1995.

[8] Private communication with W.B. Gauster of the ITER Joint Work Site, Garching, Germany.

[9] Memo from C. Wong of General Atomics, San Diego, CA., and E. Cheng of TSI Research, Inc. San Diego, CA.