Design of the ITER High-Frequency Magnetic Diagnostic Coils

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Abstract

This paper is an overview of work carried out on the design of the ITER high-frequency magnetic diagnostic coil (HF sensor). In the first part, the ITER requirements for the HF sensor are presented. In the second part, the ITER reference design of the HF sensor has been assessed and showed some potential weaknesses, which led us to the conclusion that alternative designs could usefully be examined. Several options have been explored, and are presented in the third part: (a) direct laser cutting a metallic tube, (b) stacking of plane windings manufactured from a tungsten plate by electrical discharge machining, (c) coil using the conventional spring manufacture. In the fourth part, sensors using the low temperature co-fired ceramic technology (LTCC) are presented: (d) monolithic 1D magnetic flux sensors based on LTCC technology, (e) monolithic 3D magnetic flux sensors based on the same LTCC technology. The solution which showed the best results is the monolithic 3D magnetic flux sensor based on LTCC.

Keywords:
ITER, high-frequency, coil, in-vessel, LTCC, sensor

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1. Introduction

The HF sensor has to provide essential measurements of magnetohydrodynamic (MHD) modes inside the vessel. The ITER Project Requirements [1] and a thorough review of the latter [2] impose the measurements of oscillating fields $|\delta B_{MEAS}/B_{POL}| \sim 10^{-4}$ up to 2 MHz to resolve toroidal (n) and poloidal (m) mode numbers up to $|n| = 30$ and $|m| = 60$.

When considering those requirements, the estimated length (>50 m) and the electrical specifications for the signal cables and the data acquisition modules, it is clear that the HF sensor must have a self resonance frequency ≥5 MHz and an effective area ≥500 cm^2.

In the harsh ITER in-vessel environment, the HF sensor must resist different types of loads for the ITER lifetime: repeated thermal loads (nuclear heating peak on the inner shell surface at the cross point of blanket modules = $0.5 \cdot 5.5 = 2.75$ W/cm^3 [3]), time integrated neutral wall loading of 0.3 MWa/m^2 [3] and electromagnetic (EM) loads. The materials used for the HF sensor must have good vacuum properties (no outgassing).

Finally, the physical space allowed for the HF sensor on the vessel wall is rather small as it is foreseen to place the HF sensor behind the blanket modules. Hence, the external dimensions of the HF sensor is critical. While minimizing the overall size of the HF sensor, reducing the sensor thickness to less than 7 mm allows placing it almost anywhere under the blanket modules without any special cutouts on them, with quite large length and width (max. 100 x 100 mm).

Summarizing, the HF sensor should have the following properties:

- Self resonance frequency ≥5 MHz
- Effective area ≥500 cm^2
- Resist repeated nuclear thermal loads peak (2.75 W/cm^3)
- Resist total neutron fluence (0.3 MWa/m^2)
- Resist repeated EM loads
- Materials with good vacuum properties (no outgassing)
- Operate during the ITER lifetime
- Small dimensions if possible (ease of siting)

2. The ITER reference design

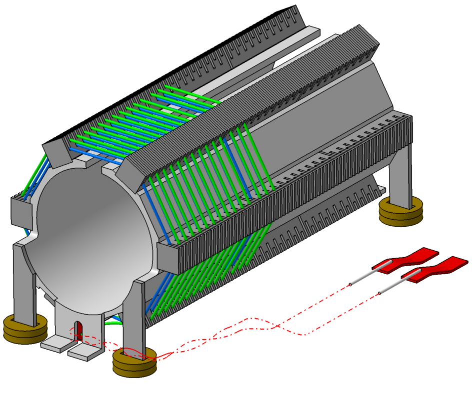

Figure 1: ITER current design without thermal shield and back plate.

The current reference design of the HF sensor [4], is a coil made with 33 turns each on 2 separate layers, wound over ceramic spacers acting as insulating formers and centered on a hollow slotted stainless steel body. The entire HF sensor is fixed

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on a back plate for the fixation on the ITER in-vessel wall and a heat shield is added (fig. 1). Its effective area is of 670 cm^2 for external dimensions of ~ 80 x 40 x 40 mm (128 cm^3, without the back plate and the heat shield).

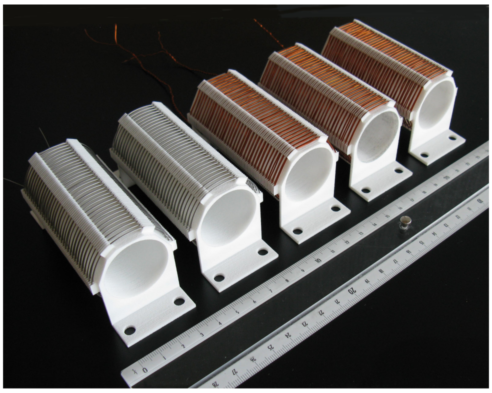

Figure 2: Mock-ups for assessing the reference design.

The manufacture of HF sensor mock-ups based on the ITER reference design (fig. 2) has confirmed the good electrical properties of this design (resonance frequency of around 6 MHz and DC effective area of around 670 cm^2). According to our Ansys EM load analysis, the maximum Von Mises stress is within the range of 20-50 MPa in the tungsten wire, which is not critical for the sensor. Difficulties regarding the winding process and the routing of the tungsten wire (straightening effect of the stiff tungsten wire during the winding process) have been encountered. The simulated thermo-mechanical behavior of the mechanically preloaded coil assembly is likely to lead to fatigue failure by cyclic differential thermal expansion, with load conditions given in [3]. Different improved variants of such coils have been built with alternative types of guiding grooves and materials for the wire. However, the proposed tungsten wire appeared to be too brittle. In conclusion, our test results have demonstrated that the reference design for the HF sensor could usefully be improved.

3. Exploratory designs

The goal is to explore different ways to manufacture a coil that avoids the potential weaknesses of the reference design, yet respects the ITER requirements.

3.1. Laser-cut prototype

The idea of the laser-cut prototype is to have a tungsten winding pack made of one single part, which has several important advantages. There is no winding operation since the winding is directly machined in the raw tungsten tube. Hence there is no preload in the wire, which implies that no tension is present in the winding when mounting the sensor. The material of the body can be alumina (Al_2O_3), which has a thermal expansion coefficient close to tungsten ($4.5{\cdot}10^{-6}K^{-1}$ for tungsten and $5.0{\cdot}10^{-6}K^{-1}$ for alumina), this could reduce the stresses in the sensor caused by the repeated thermal expansion. Moreover, the laser-cutting manufacturing process is cheap, with a very good capacity for mass production and a good reproducibility. Finally, the alumina body is not complicated to manufacture, since it is a simple cylindrical part. A ceramic coating paste must be used for the insulation.

A prototype of this alternative design has been produced by laser-cutting a winding pack from a stainless steel tube. It has been built mainly to assess the process of laser cutting tubes. As no nuclear or thermal tests will be performed on this prototype, the coil body has been manufactured in Polymethyl Methacrylate (PMMA) (fig. 3).

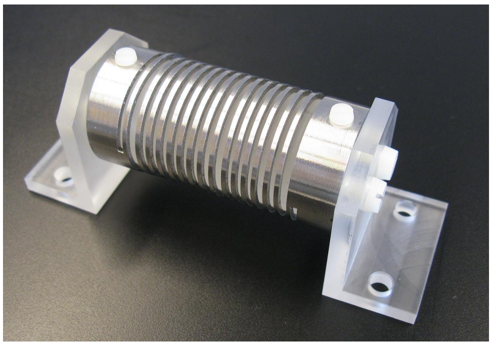

Figure 3: Laser-cut prototype.

In conclusion, this solution showed two main disadvantages. The main one is the difficulty to add a second layer of metallic winding to increase the effective area. The second is the size of the coil, which is as large as the conventional Mirnov-type pick-up coil. For those reasons, this solution has been abandoned.

3.2. Stacking of plane windings

The idea of this alternative solution is to stack tungsten plane windings with sandwiched alumina sheets insulators. First, a manufacturing test has been done to assess the machining behavior of tungsten plates. The manufacturing process which showed the best results is electric-discharge machining (fig. 4).

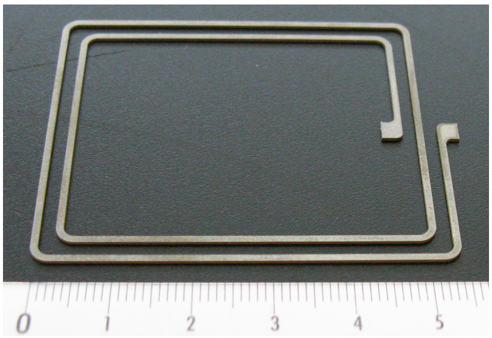

Figure 4: Tungsten plane winding manufactured by electric-discharge machining, thickness 0.5 mm.

The advantage of this alternative solution is the possibility to have very thin tungsten planes for the windings and very thin alumina insulator sheets, which result in a very thin final sensor. Furthermore, the tungsten winding planes are not preloaded because there is no winding operation, and the differential thermal expansion will generate only slight tension in the sensor when repeated thermal loads will occur, since the difference of the thermal expansion coefficient between tungsten and alumina is low.

The connection of each tungsten winding plane can be made by means of a special silver brazing paste (CF 72, special brazing paste for vacuum applications) but no solution has been found to fix together the alumina insulator sheets.

We have not continued this alternative solution because it was additional of the LTCC technology (see section 4 of this paper) but with difficulties for the assembly.

3.3. Spring winding technology

The idea is to have a double layer spring and to fix it on an alumina support by plasma spraying a ceramic coating (fig. 5). The manufacturing of a spring with 2 layers in Alloy 90, diameter 1.5 mm, is possible. The assembly is made with an alumina tube on which the metallic spring is plasma sprayed with a ceramic coating. The difficulty of this alternative solution is to apply ceramic coating at the interior of the tube. The size of the coil has no advantage compared with the reference design.

Figure 5: Double layer spring in Alloy 90, ceramic coated by plasma spray on an alumina tube.

4. Low temperature co-fired ceramic technology

Low temperature co-fired ceramic (LTCC) is a well established technology that has been in use for many years in the microelectronics packaging industry. This technology is based on sintering of multi-layered thick-film sheets (50-400 μm), which are screen-printed with thick-film metallic pastes (fig. 6). The ceramic stack of layers is then laminated at ~ 20 MPa and fired at ~ 900°C.

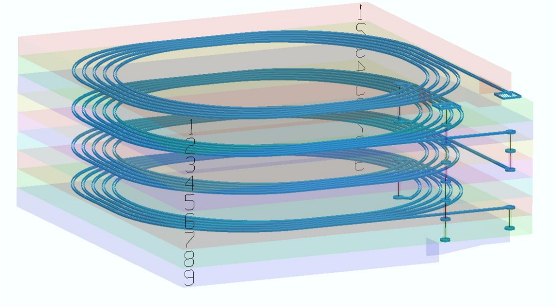

Figure 6: View in 3D of an LTCC electrical circuit.

This technology has already been prototyped and proposed for similar applications [5, 6, 7].

While used for high temperature/vacuum applications in industry, some tests under the expected neutron and radiation flux have to be done in order to assess the compatibility with ITER conditions. Besides that, the LTCC technology has many other advantages. Mass production can easily be done with high reproducibility. There is no handling operation for the winding, therefore there is no tension in the wire and in the ceramic body. All the circuit is integrated into the ceramics, so no mounting operations are needed and no short circuit are possible. As the metallic ink becomes an integral part of the ceramic sensor, there is no risk of metallic track destruction due to the repeated thermal expansion stresses. Another advantage of this technology is the ratio of the effective area related to the volume of the sensor.

4.1. LTCC 1D sensor prototyping

Various prototypes for this magnetic sensor have been produced in-house by varying the number of layers, the number of turns and the separation distance between the ceramic layers, so as to assess the electrical properties of the sensors. The material of the thin layers is alumina (DuPont 951 Green Tape, 165 μm and 254 μm thickness), the material of the screen printed paste is silver (DP 6141 and DP 6145). The external dimensions of the prototypes are 30 x 30 x 0.7 to 2.4 mm. This first set of prototypes has demonstrated that the electrical parameters needed for ITER can be reached with this technology [8].

4.2. LTCC 3D sensor prototyping

In the light of the good results obtained with our first prototypes, we have continued in this direction by developing an LTCC sensor with the electrical properties needed for ITER. As the magnetic fluxes have to be measured for the poloidal and toroidal directions, both directions have been integrated into a single monolithic LTCC sensor. Adding a third direction of measurement (z direction) offers the possibility to obtain more information on the magnetic fluxes and is simple to realize.

This prototype includes 19 LTCC modules for the x direction and 19 LTCC modules for the y direction (fig. 7), connected in series. The x and y LTCC modules are soldered (62Sn-36Pb-2Ag alloy) onto a suitably metallized alumina base plate. Each LTCC module includes 8 layers of 2 turns. The ESL (Electroscience Laboratories, USA) 9635B Ag-Pd metallization on one side of the base plate also includes the metallic tracks that interconnect the LTCC modules. The z direction measurement is performed by 8 conductor turns (ESL 9912A, Ag), directly screen printed on the other side of the base plate (fig. 8). The screen printed metallic tracks for the LTCC modules connections and for the z measurement are protected by a glass layer (ESL G-485-1). In this way, all metallic conductors are protected.

The LTCC 3D sensor external dimensions are 7 x 100 x 100 mm (70 cm^3), allowing its siting behind the blanket modules without any special cutout. The effective area of the x and y directions is ~500 cm^2 and ~600 cm^2 for the

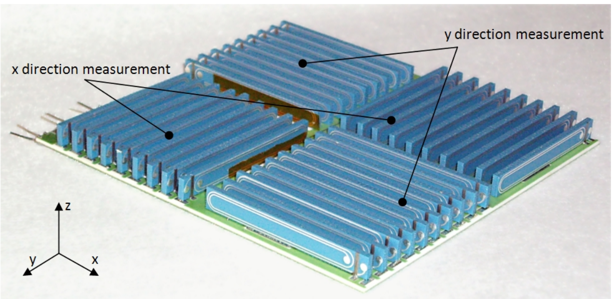

Figure 7: LTCC 3D prototype, top view.

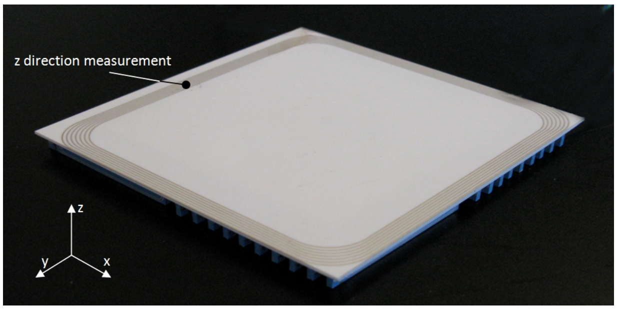

Figure 8: LTCC 3D prototype, bottom view.

z direction. The resonance frequency for the *x* and *y* direction is of ~2.8MHz and of 10 MHz for the *z* direction. The resonance frequency of the *x* and *y* directions can easily be increased by adding a neutral layer between each conductive layer (which contributes to decrease the interlayer capacitance).

4.2.1. Thermal analysis

A simple thermal analysis of the LTCC 3D sensor has been performed. The material considered is alumina, the geometry is a rectangular parallelepiped with dimensions 10 x 100 x 100 mm, the heat load is the neutronic heating, and the cooling load is the conduction between the sensor and the cooled vacuum vessel (VV) wall (design temperature of VV: 200°C, [9]). Different area ratios (area in contact with VV / total area of the sensor) have been considered. Results are given in figure 9.

The temperature increases and reaches a maximum of 235°C after 1000 seconds for the lower contact surface (area ratio 1/4). This temperature is not a problem for LTCC technology. However, the Sn-Pb-Ag solder used for assembling the LTCC modules on the base plate and those which will be used for the connection of the electrical cables have to be adapted to resist to this temperature. Solutions with appropriate materials can be found [10].

5. Conclusion

The manufacture of an HF sensor that meets the ITER requirements is challenging. The exploratory designs have shown potential difficulties to build HF sensors using conventional manufacturing processes. This paper shows that an extremely promising way to obtain an HF sensor, which meets all the requirements, is by using LTCC technology. Our LTCC 3D sensor has demonstrated very encouraging results. The requirements for the HF sensor can all be met using a LTCC 3D sensor (although some tests have to be done under the expected neutron flux). Furthermore, the ratio of effective area related to the volume of the sensor is very interesting with the LTCC technology comparing to conventional sensors. The future work on this task would be to find assembly technologies and signal output cables that withstand the required in-vessel conditions.

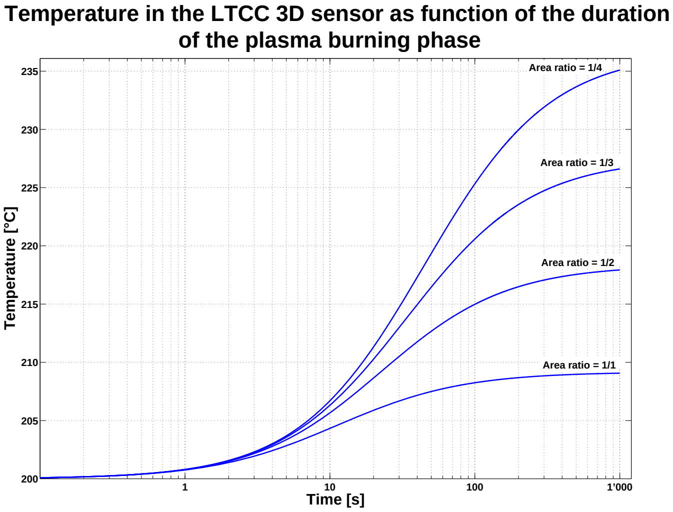

Figure 9: Maximal temperature increase in the LTCC 3D during the plasma burning phase, with different area ratios.

6. References

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