



Design of the ITER High-Frequency Magnetic Diagnostic Coils

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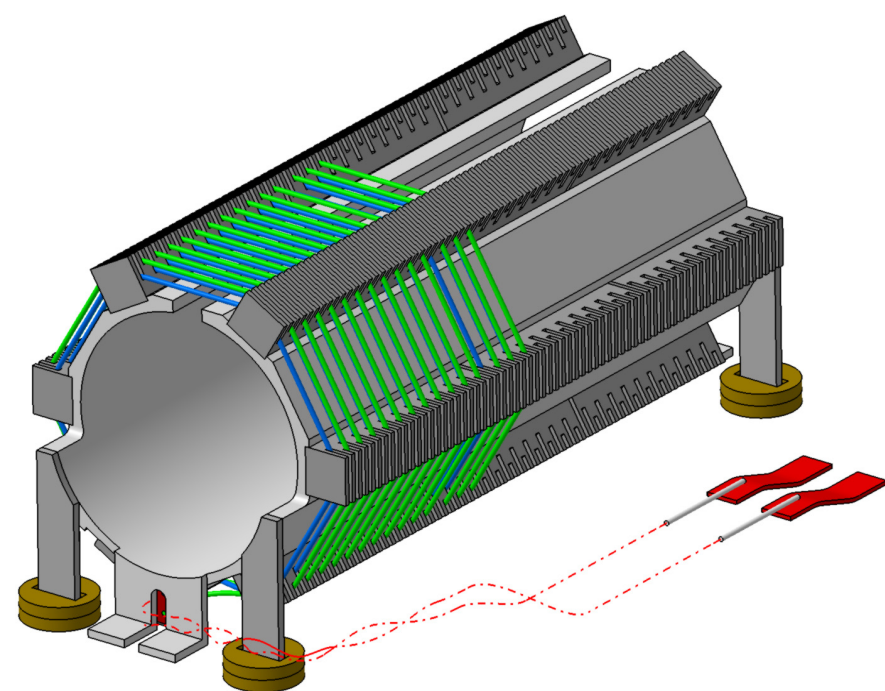
1. Introduction

The ITER High-Frequency Magnetic Diagnostic in-vessel coils (HF sensor) have to provide essential measurements of magnetohydrodynamic (MHD) modes. Summarizing, the HF sensor should have the following properties [1, 2]:

- Self resonance frequency ≥ 5 MHz (measured at sensor contact points)
- Effective area ≥ 500 cm² for each direction measurement (poloidal and toroidal)
- Resist repeated nuclear thermal loads peak (2.75 W/cm³ [3])
- Resist intense neutron flux (14 MeV)
- Resist repeated electromagnetic loads
- Materials with good vacuum properties (no outgassing)
- Operate during the ITER lifetime
- Small dimensions if possible (ease of siting)

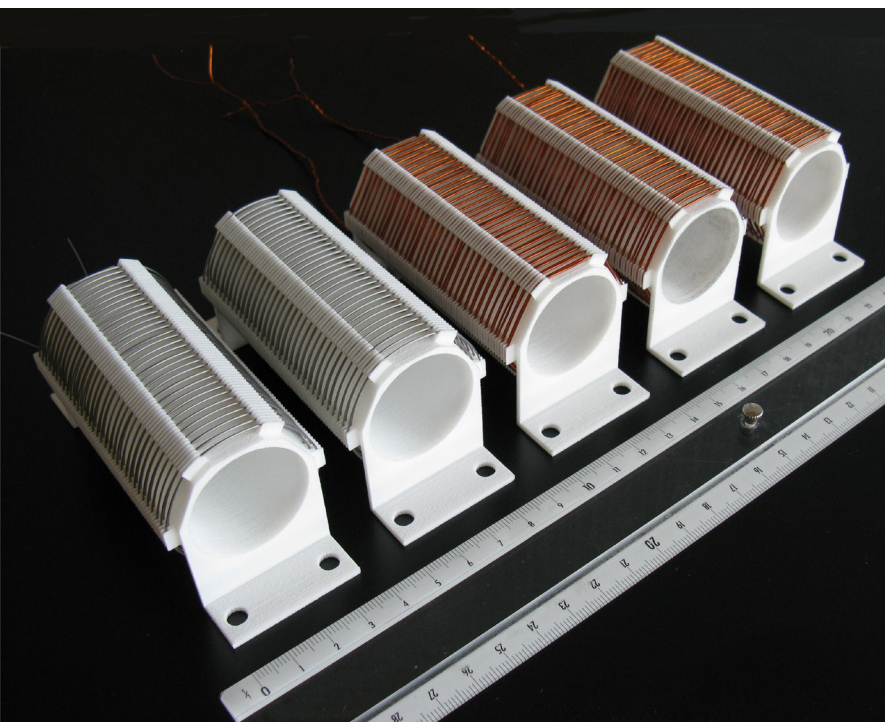
2. ITER reference design

- Coil made with the wire wound over spacers acting as insulating formers and centered on a hollow slotted body [4]
- The entire sensor is fixed on a back plate and a heat shield is added
- Wire material: tungsten
- Body material: stainless steel
- Spacers material: alumina
- Number of turns: 33
- Number of layers: 2
- Calculated effective area: ~ 677 cm²
- External dimensions: $\sim 80 \times 40 \times 40$ mm (128 cm³)



Mock-ups based on the ITER reference design

- HF sensor mock-ups based on the ITER reference design
- Assessment of the electrical properties
- Assessment of the winding process of the wire
- Bodies have been manufactured by laser sintering (rapid prototyping)
- Wire material: tungsten or copper
- Body material: polyamide PA12 powder
- Number of turns: 33
- Number of layers: 2
- DC measured effective area: ~ 700 cm²
- Resonance frequency: ≥ 4.5 MHz
- External dimensions: $80 \times 40 \times 40$ mm (128 cm³)



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| <ul style="list-style-type: none"> + • Materials with good thermal properties • Good electrical properties • Conventional way to manufacture coils | <ul style="list-style-type: none"> - • Difficulties regarding the winding process (straightening effect of the stiff tungsten wire) • Risk of fatigue failure due to both cyclic differential thermal expansion and preload generated during the winding process • Requires cut-out in the blanket modules • Low ratio of the effective area related to the volume of the sensor |
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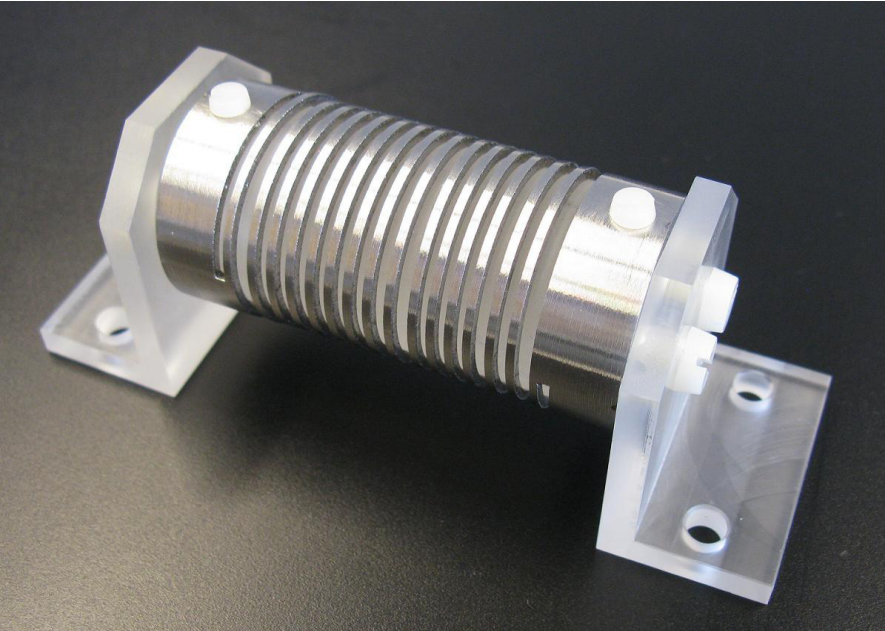
Those results have shown that the reference design for the HF sensor could usefully be improved.

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

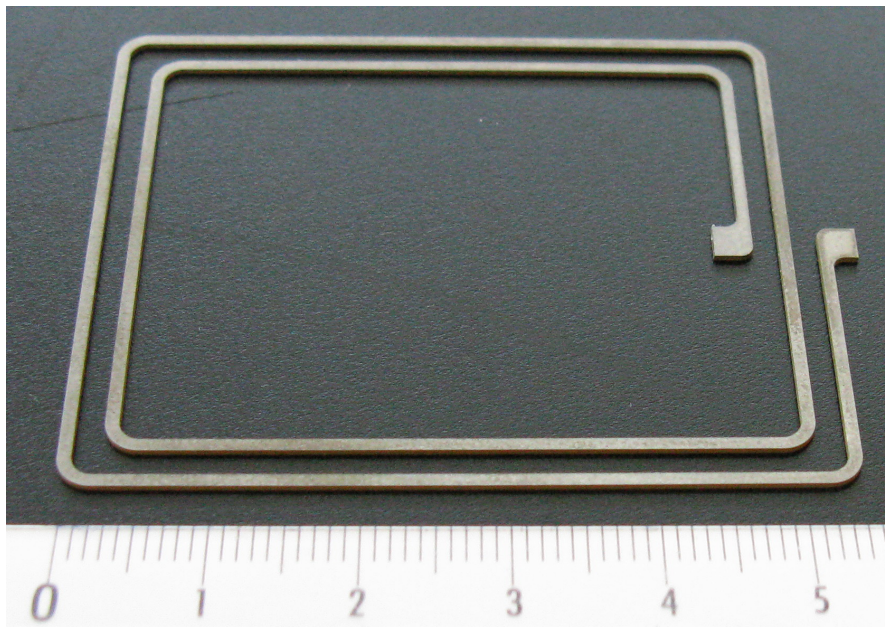
- Tungsten winding pack made of one single part by laser cutting a tube fixed and coated with a ceramic paste on an alumina body
- Prototyped only for assessing the laser cutting of tubes (stainless steel tube)
- External dimensions: $80 \times 40 \times 40$ mm (128 cm³)
- Number of turns: 15



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| <ul style="list-style-type: none"> + • Good electrical properties • Materials with good thermal properties • No winding operation • No preload in the wire • Materials with close thermal expansion coefficient • Cheap manufacturing process • Alumina body not complicated to manufacture | <ul style="list-style-type: none"> - • Difficulty to add a second layer of metallic winding • Not very good results with the laser cuted tube • Low ratio of the effective area related to the volume of the sensor |
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3.2 Stacking of plane windings

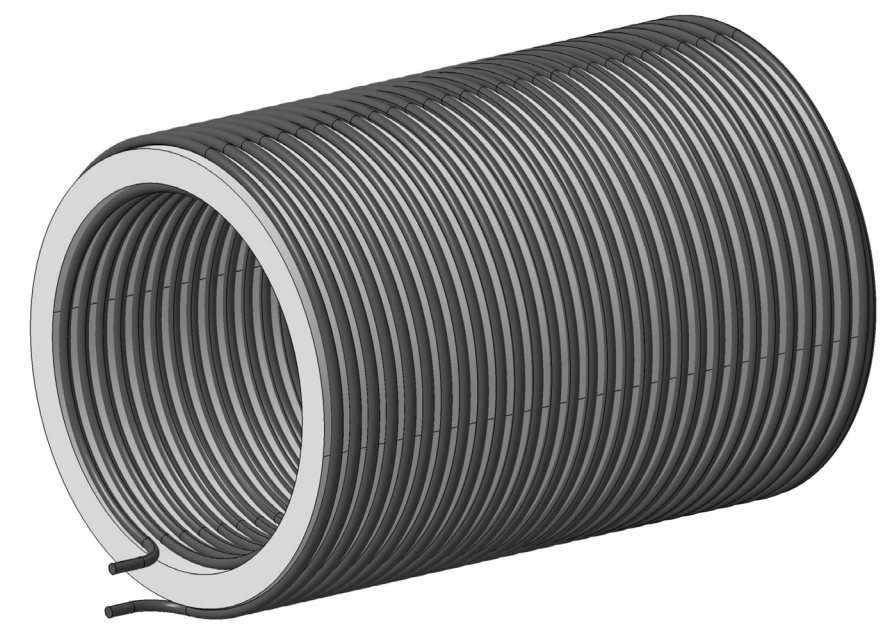
- Tungsten plane windings stacked with sandwiched alumina sheets insulators
- Best manufacturing process for the plane tungsten windings is electro-discharge machining
- The connection of each tungsten winding plane can be made by means of special brazing paste
- Foreseen external dimensions: $100 \times 100 \times 10$ mm (100 cm³)
- Number of turns: 2
- Number of layers: 4
- Effective area: ~ 500 cm²



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| <ul style="list-style-type: none"> + • Possibility to have a final sensor very thin • Materials with good thermal properties • No preload in the tungsten winding • Materials with close thermal expansion coefficient | <ul style="list-style-type: none"> - • Difficulty to fix together the alumina sheets • General difficulty to make the final assembly |
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3.3 Spring winding technology

- Double layer spring manufactured without discontinuity in Alloy 90
- Fixed on an alumina support by plasma spraying a ceramic coating
- Foreseen external dimensions: $100 \times 40 \times 40$ mm (160 cm³)
- Number of turns: 35
- Number of layer: 2
- DC calculated effective area: ~ 700 cm²



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| <ul style="list-style-type: none"> + • Materials with good thermal properties • Winding easily produced in one operation with conventional spring technology | <ul style="list-style-type: none"> - • Materials with different thermal expansion coefficients • Difficulty to apply ceramic coating inside the sensor • Low ratio of the effective area related to the volume of the sensor |
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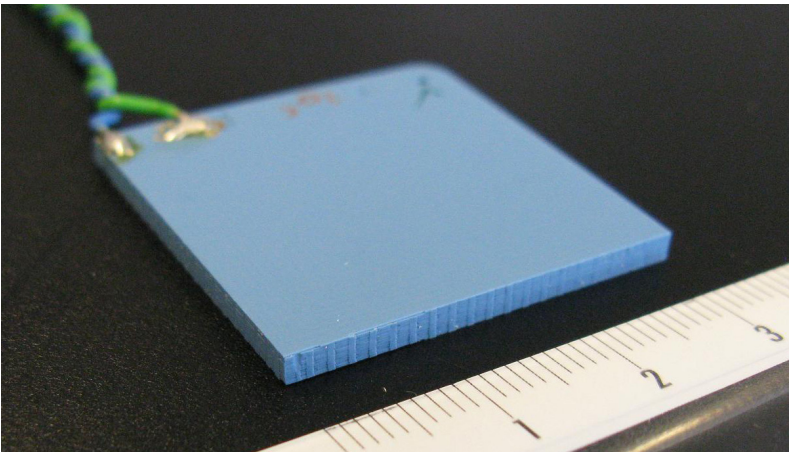
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This work was partly supported by the Swiss National Science Foundation and by the European Communities under Contracts of Association, and was partly performed within the framework of Fusion for Energy.

4. Low temperature co-fired ceramic technology (LTCC)

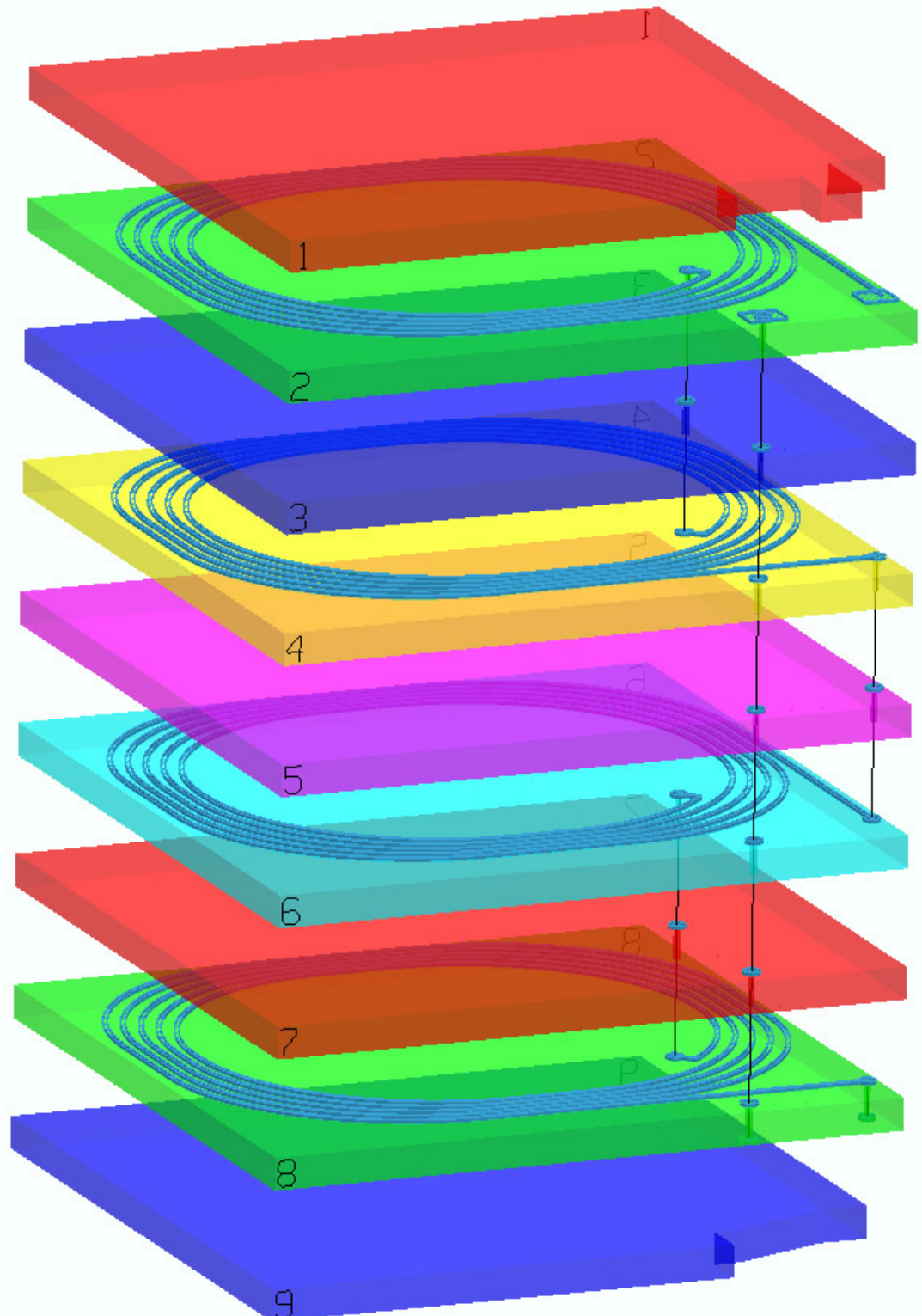
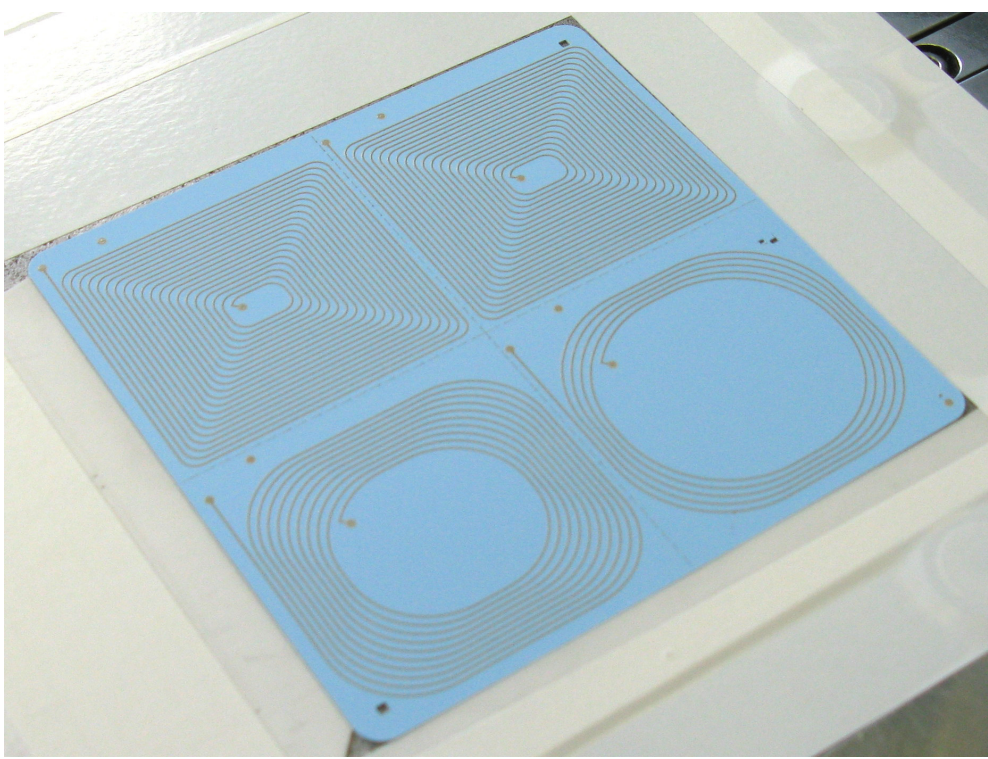
- Well established technology that has been in use for many years in the microelectronics packaging industry
- Technology based on sintering of multi-layered thick alumina film sheets, which are screen printed with thick-film metallic pastes
- Ceramic stack is then laminated at 20 MPa and sintered at 900°C
- Already been proposed for similar applications [5, 6, 7].



5. LTCC 1D sensor prototyping

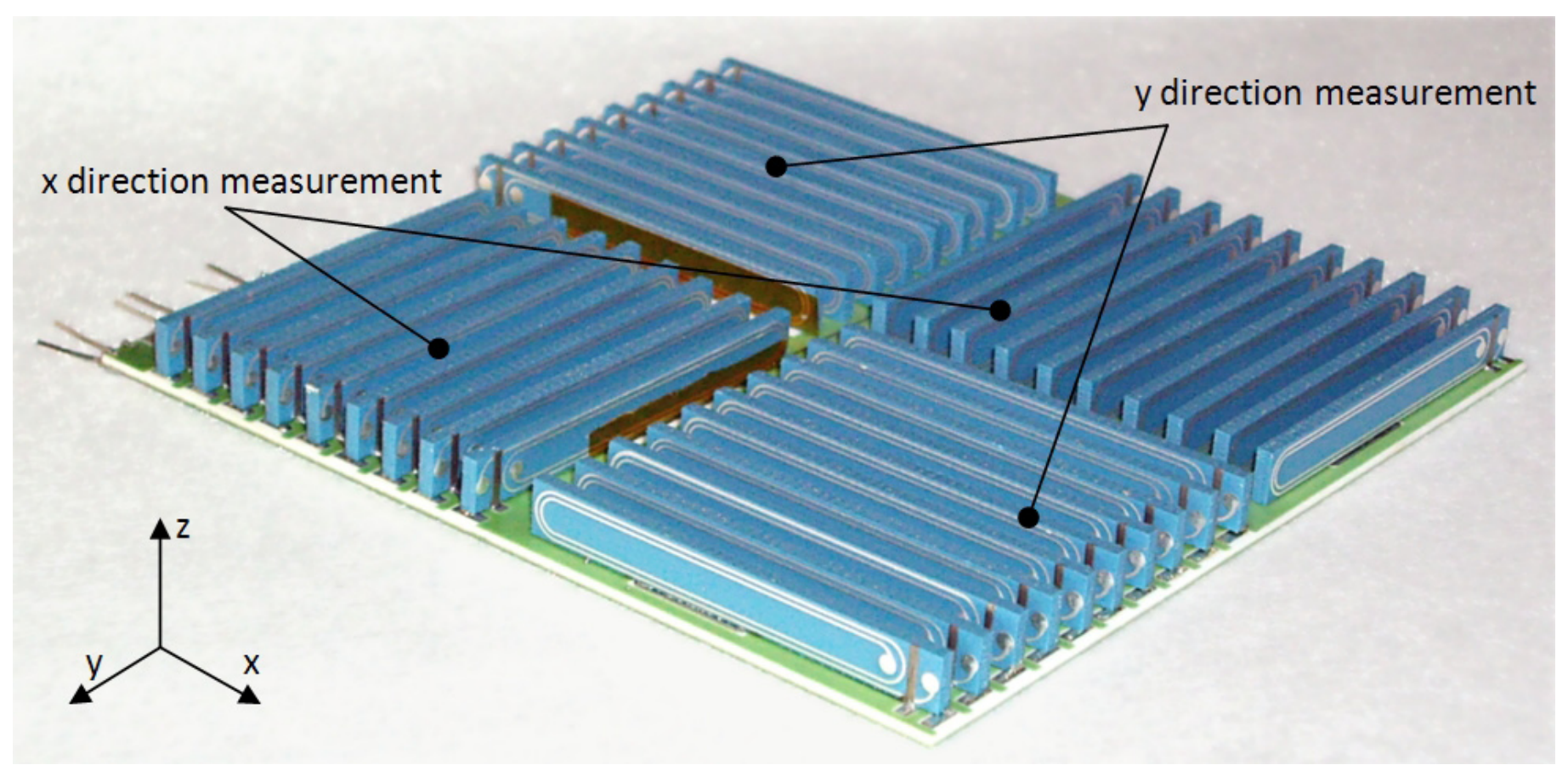
- Various prototypes have been produced in-house by varying the number of layers, the number of turns and the separation distance between the ceramic layers, so as to assess the electrical properties of the sensors
- This first set of prototypes has demonstrated that the electrical parameters needed for ITER can be reached with this technology [8]
- Wire material: silver
- Body material: alumina
- Number of turns: 5, 10 and 20
- Number of layers: 2, 4, 6, 8 and 10
- External dimensions: $30 \times 30 \times 0.7$ to 2.4 mm

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| <ul style="list-style-type: none"> + • Materials with good thermal properties • Production with high reproducibility • No preload in the wire • No winding operation • No risk during the repeated thermal expansion stresses as the metallic ink becomes an integral part of the ceramic • High ratio of the effective area related to the volume of the sensor | <ul style="list-style-type: none"> - • Connection with transmission cables |
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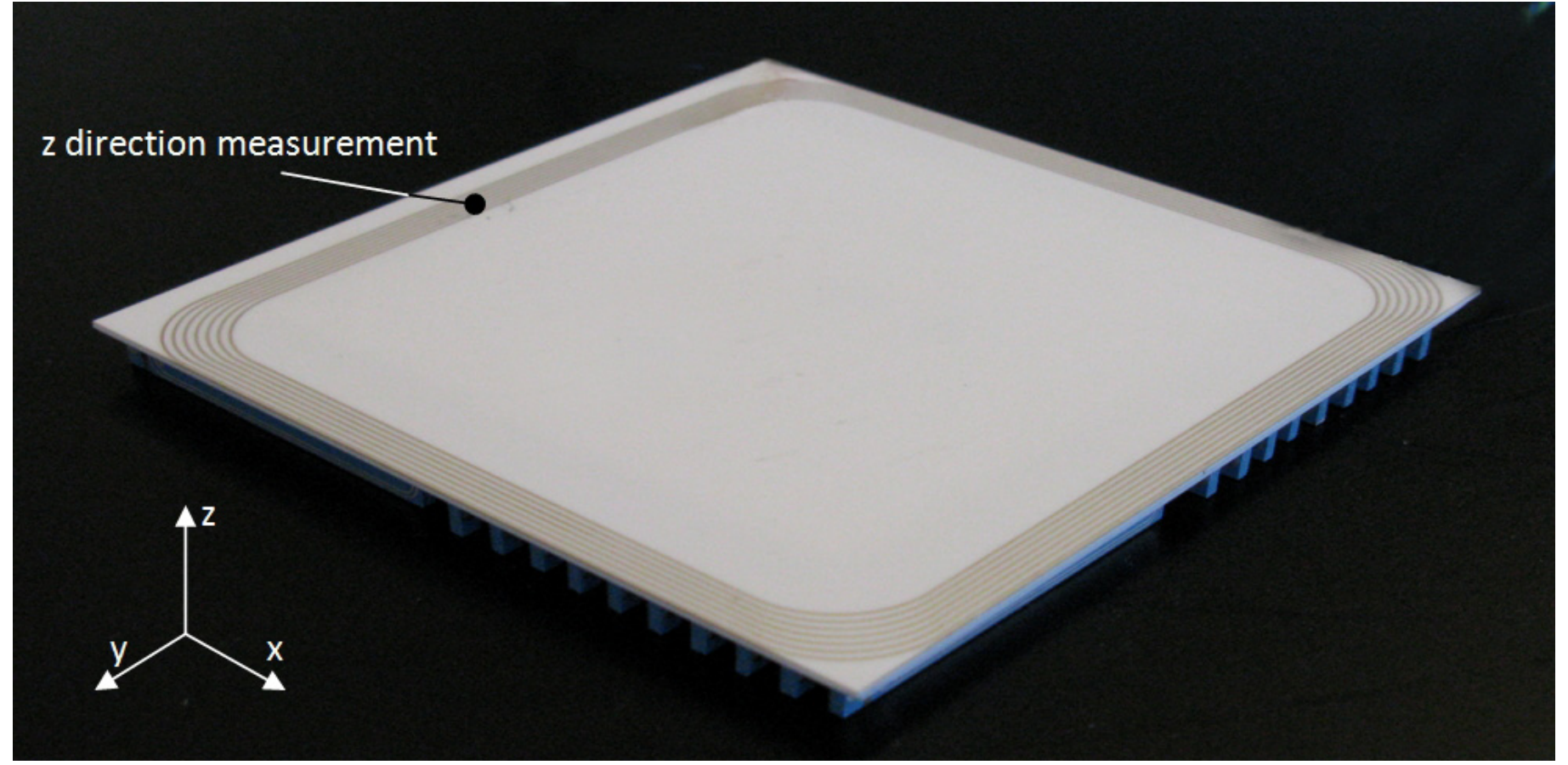


6. LTCC 3D sensor prototyping

- An LTCC with appropriate electrical properties has been produced
- Allows the measurement of fields in three directions (x, y and z)
- Wire material: silver
- Body material: alumina
- Size: $100 \times 100 \times 7$ mm
- Number of turns x and y direction: 2
- Number of layers x and y direction: 19×8
- Number of turns z direction: 8
- Number of layers z direction: 1
- Resonance frequency x and y direction: ~ 2.8 MHz
- Resonance frequency z direction: ~ 10 MHz
- DC measured effective area x and y direction: ~ 500 cm²
- DC measured effective area z direction: ~ 600 cm²



LTCC 3D - Top view



LTCC 3D - Bottom view

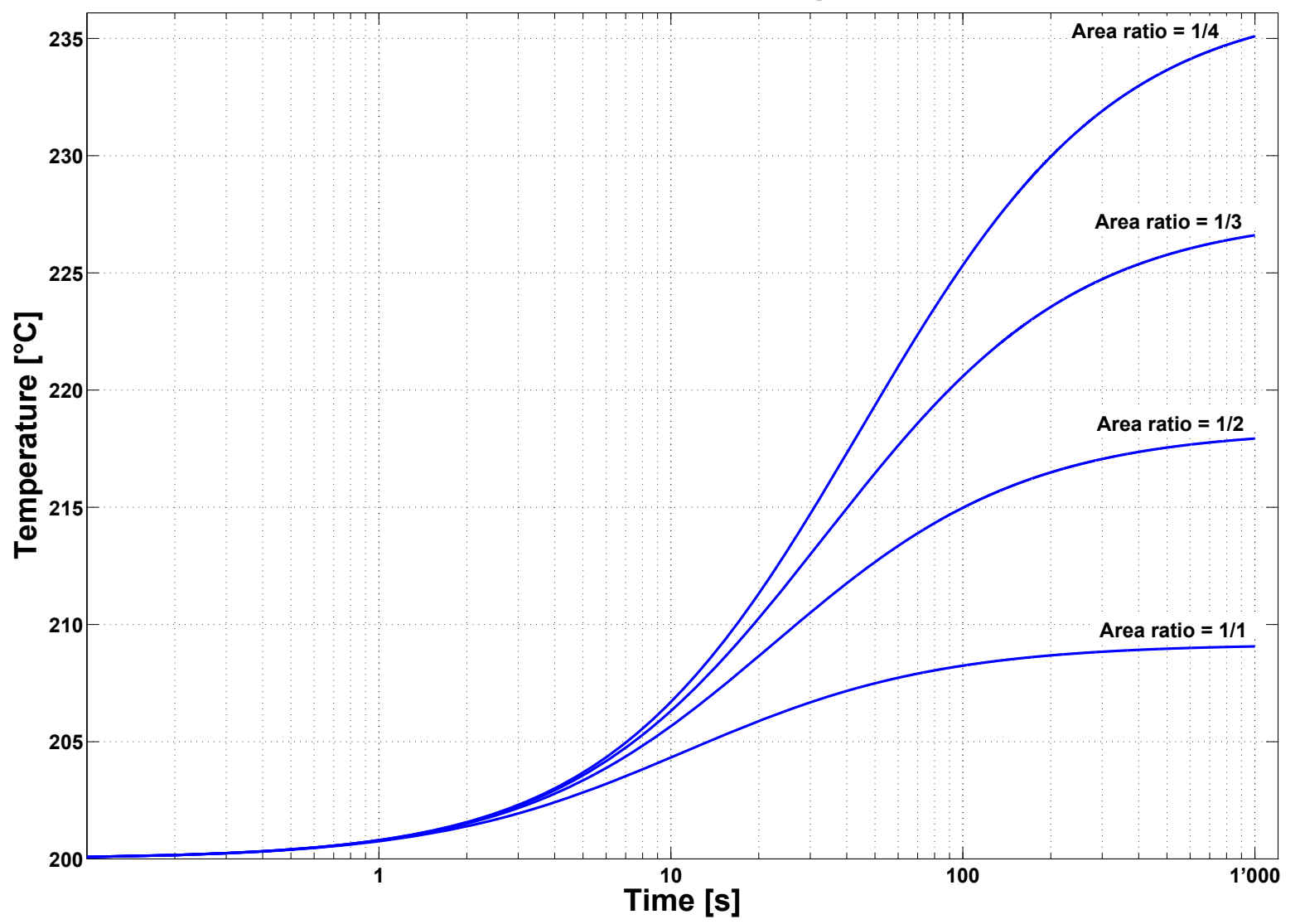
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| <ul style="list-style-type: none"> + • Possibility to measure fields in 3 directions • No cut-outs in blanket modules required • Materials with good thermal properties • No preload in the wire • No winding operation • No risk during the repeated thermal expansion stresses as the metallic conductor becomes an integral part of the ceramic | <ul style="list-style-type: none"> - • Low resonance frequency in the x and y directions, can be corrected by adding a neutral layer between each conductive layer • Soldering paste used for assembling the LTCC modules on the base plate and those for the connection with electrical cables must be adapted to high temperature (solutions with appropriate materials can be found [10]) |
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Thermal analysis of the LTCC 3D prototype

A simple case considered:

- Geometry: parallelepiped
- Dimensions: $100 \times 100 \times 10$ mm
- Material: alumina
- Heat load: neutronic heating (2.75 W/cm³)
- Passive cooling: conduction between the sensor and the actively cooled vacuum vessel (vacuum vessel considered at constant temperature of 200°C [9])
- Different area ratios (area in contact with vacuum vessel/total area of the sensor) have been considered

Temperature in the LTCC 3D sensor as function of the duration of the plasma burning phase



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 soldering paste 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].

7. 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. An extremely promising way to obtain an HF sensor which meets all the requirements has been worked out using LTCC technology. The requirements for the HF sensor can all be met using an LTCC 3D sensor (although some tests remain 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 should be to find interfacing technologies and signal transmission cables that withstand the required in-vessel conditions.