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Design of a High Resolution Probe Head for Electromagnetic Turbulence Investigations in W7-X

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***Abstract*—A insertable probe head called High Resolution Probe (HRP) has been developed at Consorzio RFX in the framework of the EUROfusion S1 work program and in collaboration with IPP Greifswald, to study the electrostatic and electromagnetic features of turbulence in the edge region of Wendelstein 7-X using the Multi-Purpose Manipulator (MPM). The paper reports the design development of the HRP diagnostic head, from the choice of the sensors to the engineering design. The assumptions and evaluations supporting the main design choices, together with the R&D tests carried out to check the most critical parts, are described in detail.**

***Index Terms*—insertable probe, electromagnetic fluctuations, stellarator, W7-X**

I. INTRODUCTION

WENDELSTEIN 7-X (W7-X) is a large, superconducting stellarator with modular coils and an optimized magnetic field [1][2].

A multi-purpose manipulator (MPM) system has been developed and installed on the W7-X vessel to investigate the edge plasmas of the stellarator [3][4]. It is a flexible tool for integration of a variety of different diagnostics as e. g. electrical probes, probing magnetic coils, material collection, or material exposition probes, and gas injection [5][6]. The system is designed as user facility for many diagnostics, which can be mounted on a unique interface without affecting the W7-X vacuum. The manipulator system, located in the equatorial plane, transports the inserted diagnostic probe to the edge of the inner vacuum vessel. From there the probe can be moved over a maximum distance of 350 mm to different positions inside the plasma with a maximum acceleration and deceleration of 30 m s^{-2}.

In the framework of the EUROfusion S1 work program for the preparation and exploitation of W7-X campaigns, an insertable probe head called HRP (High Resolution Probe) was developed by Consorzio RFX in collaboration with IPP Greifswald, to investigate the electrostatic and electromagnetic features of turbulence in the edge region of W7-X using the MPM.

This paper reports the design development of the HRP head, from the choice of the sensors to the engineering design. The assumptions and evaluations supporting the main design choices, together with the R&D tests carried out to check the most critical parts, are described in detail.

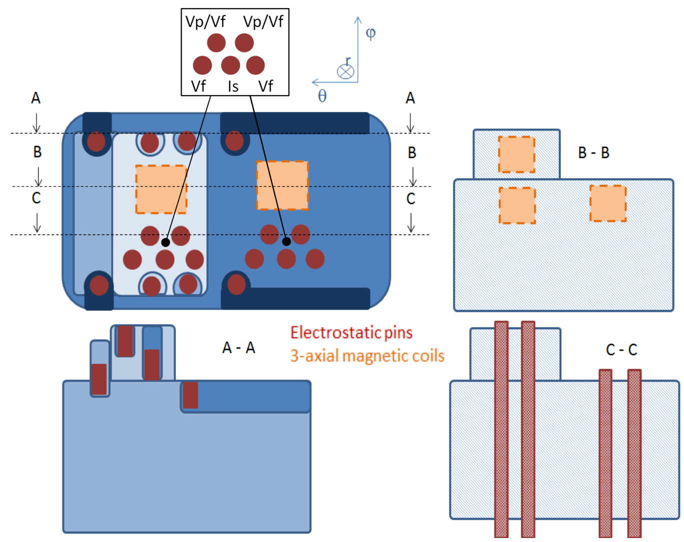

Fig. 1. Conceptual design of the High Resolution Probe Head

II. CONCEPTUAL DESIGN

The principal aim of the HRP head is to provide information on parallel current density associated to L-mode filamentary turbulent structures as well as on ELMy structures in H-mode [7][8][9]. Furthermore the possibility to measure the time evolution of radial profiles of flow was considered as a further interesting part of the study, given the strong interplay expected between the turbulent fluctuation and the average flows.

The conceptual probe head layout is shown in Fig. 1. The front side view is shown on the top-left of the figure. The electrostatic pins are shown in dark red, while the magnetic coils are represented by the orange squares. The probe head case is represented by the blue structure. As a matter of comparison the magnetic 3-axial coil occupies a volume of approximately 1 cm^3. The probe head is conceived according to the reference frame shown in Fig. 1, with the average magnetic field at the long edge along the toroidal direction, φ. The probe head case structure follows the concept of a "castellated shape", in order to have electrostatic pin measurements in different radial positions, with a limited shadow effect due to the flux tube related to the probe head structure itself.

In Fig. 1 this concept is evidenced by the different blue

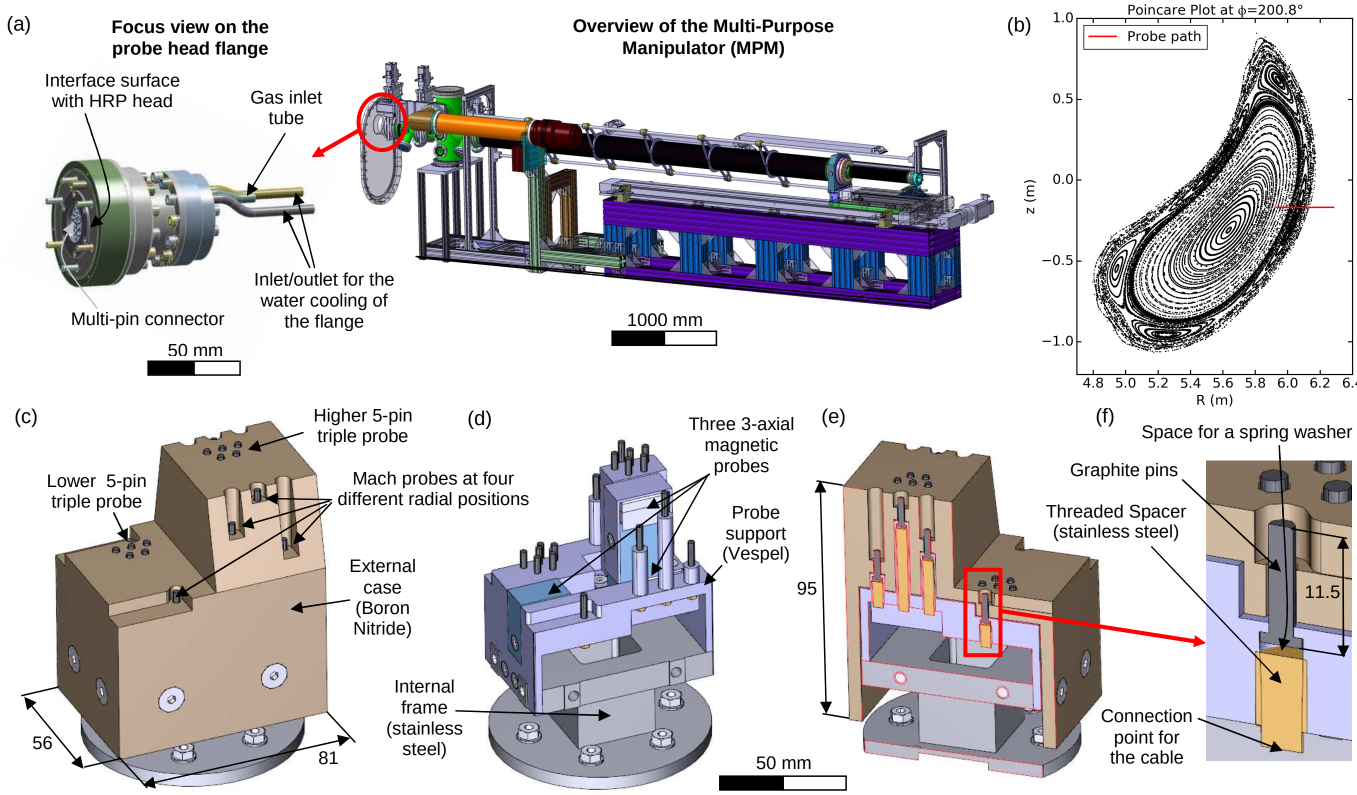

Fig. 2. Engineering design of the High Resolution Probe: (a) multi-purpose manipulator (MPM), with focus view on the interface for mounting the probe head; (b) measurement position of the MPM in the W7-X experiment; (c) overall view of the HRP head, with the external case; (d) overall view of the HRP head, without the external case; (e) section view showing the connections of the pin probes; (f) detail view of a pin probe.

shades, that in the front side view refers to poloidal-toroidal planes, placed from inner radial position (lighter blue) to relatively outer radial position (darker blue). As seen in the front side view, two groups of 5-pins are distinguishable and placed at two different radial positions. These groups are conceived to provide the possibility to realize the 5-pin balanced triple probe configuration [10] as indicated in the upper box of Fig. 1, where the ion saturation current, I_s, the floating potential, V_f, the positively biased potential V_p, are indicated. The method allows measurements of electron temperature, T_e, poloidal electric field, electron density, n_e, virtually in the same location, so that also the measurement of the electrostatic particle flux can also be estimated. On the other side different combination of floating potential measurements allow the estimate of $E \times B$ flow.

In addition the probe head is equipped with four couples of pins arranged in order to provide four Mach probes placed at different radial positions, and with three 3-axial magnetic probes. The latter ones are arranged to form an L-shaped configuration lying on the cross-field plane (radial-poloidal in the Fig. 1). The concept allows for a direct estimate of the parallel current density fluctuation from the Ampere's law.

This method represents a simplified 2D version of the one adopted in the Cluster mission for the measurement of currents in the magnetosphere [11] and was applied for the first time in a fusion experiment in RFX-mod. In this case with a probe head combining both magnetic and electrostatic pins dubbed U-probe [7]. By using the analogous diagnostic concept the estimate of the current density associated to turbulent filaments was estimate and compared in different experiments including RFX-mod in Reversed Field Pinch as well as in tokamak configuration, in Torpex device, in the stellarator TJ-II [12] and also in COMPASS tokamak [13], where a direct estimate of current density inside ELMs was provided [14].

Summarizing the proposed sensors to be installed on the HRP head are the following:

- two 5-pin triple probes at two radial positions, providing measurements of n_e, T_e, E_θ , v_r, Γ_{es}/E_r, $v_{E\times B}$;
- four Mach probes at four different radial positions;
- three 3-axial magnetic probes on (r,θ) plane.

III. Engineering Design

The guideline for the design of the various components of the HRP head has been the combination of the maximum reliability with a manufacturing and assembly processes maintained as easy as possible. To do this, the manufacturing feasibility of the various components has been considered since the beginning of the design phase, by a close interaction among the drawing office and the mechanical workshop of Consorzio RFX. During all the design phases, the mechanical and thermal robustness of the head has been taken in great consideration, by foreseeing a sufficient thickness for the most critical parts. On this regard, the most critical component is the external ceramic case, that has been designed with a minimum thickness of 5 mm.

The MPM, shown in Fig. 2a, features a mounting flange made of stainless steel with 6 fixing bolts, a multi-pin connector and a gas feeding connection [3]. The measurement point of the MPM in the W7-X experiment is shown in Fig. 2b.

The structure of the HRP head was designed to be interfaced with the fixing bolts and the multi-pin connectors of the MPM. It basically consists of an internal frame, made of stainless steel, supporting an external case (shown in Fig. 2c), and a set of probes (electrostatic pins and magnetic sensors) supported by a vespel structure (shown in Fig. 2d). The volume of the HRP head has been minimized in order to perform the measurements in a volume as limited as possible.

The electrostatic pins are inserted from below and then blocked with a stainless steel threaded spacer, as shown in the section views of Fig. 2e and Fig. 2f. A good electrical contact between the pin and the threaded spacer is provided by a spring washer located between the two parts. For an easier manufacturing, the length of the graphite pins has been minimized to 8.5 mm for the 5-pin triple probes and to 11.5 mm for the Mach probes. The support system is designed to be compatible also with the large accelerations, up to 30 m s^{-2}, foreseen during the operations of the HRP head.

The parts facing the plasma are the electrostatic pins and the external case. The main proposed materials are graphite for the electrostatic pins and Boron Nitride (BN) [15] for the external case. While the graphite can be accepted as plasma facing material without specific tests, the possibility to use the Boron Nitride for the plasma facing external case was examined in detail. In fact, the heating system of W7-X experiment is based on Electron Cyclotron Resonant Heating (ECRH) working at a frequency of 140 GHz. In order to minimize possible spurious effects that may be caused by conducting materials on the 3-axial magnetic sensors measurements, a careful choice of the plasma facing material and in particular for the external case must be made. Among the available BN on the market, the Combat BN AX05 was selected as the most suitable material, as it is transparent to microwave energy and it provides high resistivity and dielectric strength with a low loss tangent and dielectric constant.

IV. Design of a shield for the magnetic sensors

It has to be considered that the experimental campaign in W7-X will be characterized by ECRH heating system with a power of $7MW$ at the frequency $f_{ECRH} = 140GHz$. The discharge lengths will eventually approach 10-20 s. In these conditions the definition of the ECRH stray radiation is $P_{ECRH-stray} = 50kW/m^2$ [16].

The magnetic pick-up coil sensors constitute an important part of the HRP head design and a specific attention is devoted to this issue. It could be considered that the probe head will be installed on the MPM and most of the time the probe head will be located on the "park position", behind the first wall elements, where a reduction of 25% on the radiation power can be expected and a further reduction due to the relative distance of ECRH launchers [16].

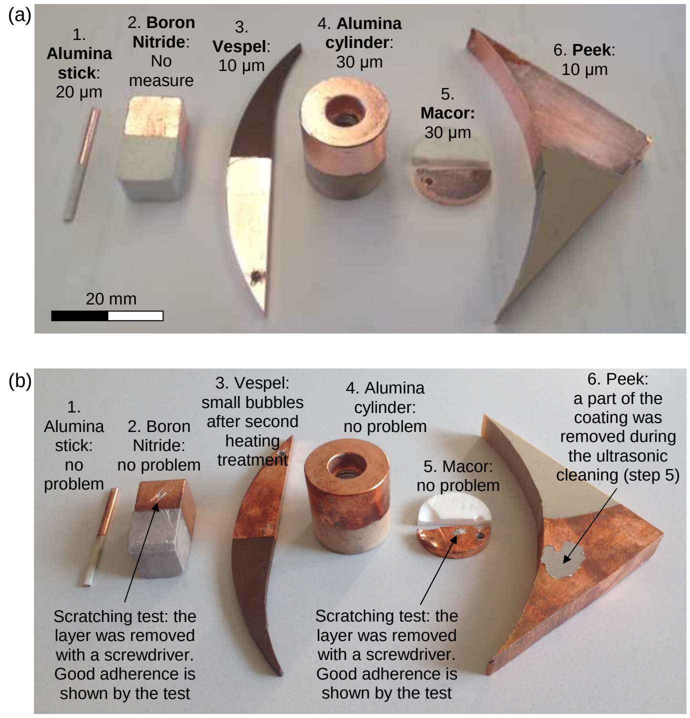

Fig. 3. Thin layer electrodeposition test on different materials: (a) samples after electrodeposition (step 3) with measurement of the electrodeposited copper layer; (b) samples after all tests.

However the value of $P_{ECRH-stray} = 50kW/m^2$ is kept conservatively as a reference for the HRP head design. It is worth mentioning that if on one side the BN insulating probe head case can be considered substantially transparent to the $f = 140GHz$ ECRH stray radiation, on the other side the magnetic sensors needs to be protected from the same radiation. Filtering out the $f = 140GHz$ however has to be achieved without compromising the magnetic fluctuations to be measured by the sensors. It was evaluated that a good compromise for the HRP head turbulence measurements would be to make the magnetic sensor fluctuations available in the range $f_{measure} \leq 1MHz$.

The suitable shield for magnetic sensor therefore should work as a low-pass filter for the magnetic fluctuation to be measured (up to $f_{measure} = 1MHz$), and at the same time should act as effective shield at $f = 140GHz$ to prevent the ECRH stray radiation damage of the sensor itself. According to the theory [17], this shield can be obtained by surrounding the magnetic sensors with a very small metallic layer (5 μm).

V. R&D on Thin Copper Electrodeposition

Consorzio RFX has a long experience on copper electrodeposition [18][19], hence to provide the electromagnetic shield it was chosen to test a thin layer electrodeposition of copper on a non-conductive base material. The base material is required to be electrically insulating, vacuum compatible, providing good adherence for the copper film and having a good resistance to high temperature, at least to 250 $°C$. In fact, when the coating layer absorbs the ECRH radiation, it can heat up and hence also the base material on which it is connected can reach high temperatures.

To choose the most suitable base material, six samples with different shapes and materials were compared, as shown in Fig. 3a. The materials tested were Alumina, Boron Nitride, Vespel, Macor and Peek. The main steps of the test were the following:

1) Measurement of the thickness of the sample before the electrodeposition, using a micrometer.
2) Pre-treatment: application of a silver paint on about half of the sample surface.
3) Electrodeposition for 15 minutes with tension of 1 V. All samples were treated together in the same bath.
4) Measurement of the thickness of the sample with the electrodeposited layer, using a micrometer, and evaluation of the electrodeposited layer thickness.
5) Ultrasonic cleaning of the samples in an ethanol bath.
6) Thermal treatment for 1 hour at 120 °C in vacuum (10^{-6} mbar).
7) Drying with nitrogen.
8) Check of the status of the electrodeposited layer.
9) Thermal treatment for 1 hour at 250 °C in vacuum (10^{-6} mbar). Note: the Peek sample has been excluded from this treatment because of the low thermal resistance of the material.
10) Drying with nitrogen.
11) Scratching test with a screwdriver on samples 2 (Boron Nitride) and 5 (Macor).
12) Check of the status of the electrodeposited layer.

The samples after the electrodeposition (step 4) are shown in Fig. 3a, with indication of the measured thickness of the electrodeposited layers. It can be observed that:

- The electrodeposited layer thickness is different in the different samples. In fact, it was found to depend on the shape of the samples and on the porosity of the base material.
- The values of the electrodeposited layer thickness are generally higher than the required values of 5 μm. For this reason, the electrodeposition time has been reduced in the sample manufacturing, described in the following paragraph.
- The coating layer thickness could not be measured for sample 2, because in this case the material increased its dimensions while in the galvanic bath because it absorbed some liquid.

The samples after all the tests are shown in Fig. 3b. It can be observed that:

- Samples 1 (Alumina stick), 2 (Boron Nitride), 4 (Alumina cylinder) and 5 (Macor) had no problem after all the tests;
- Samples 3 (Vespel) showed some small bubbles after the second heating treatment (step 9);
- In samples 6 (Peek), a part of the coating was removed during the ultrasonic cleaning (step 5).

A scratching test was carried out on samples 2 (Boron Nitride) and 5 (Macor). In both cases, the result was the following:

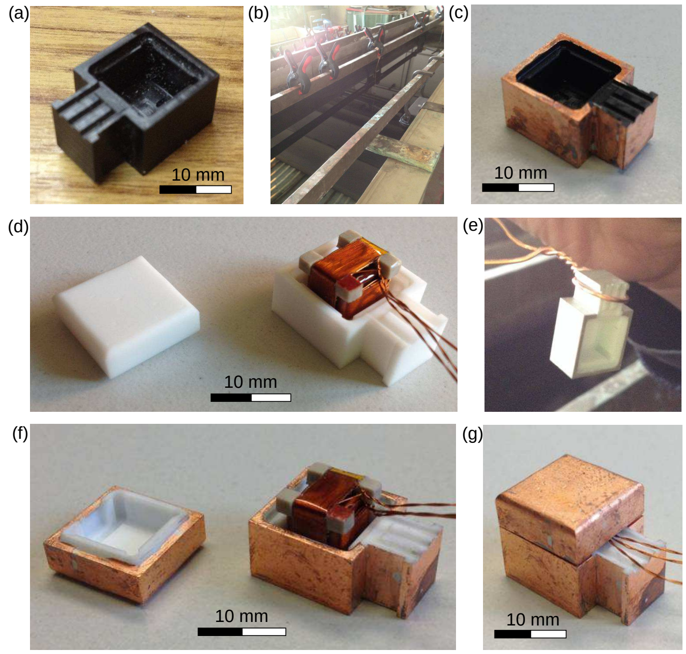

Fig. 4. Manufacturing of a sample of the electrostatic shield: (a) sample 1, made of Delrin, after milling; (b) galvanic bath; (c) sample 1 after coating; (d) sample 2, made of Macor, after milling; (e) sample 2 with silver paint on the surfaces to be coated; (f) sample 2 after coating, open; (g) sample 2 after coating, closed.

- light scratching (with a nail) did not cause any damage to the electrodeposited layer;
- heavy scratching (with a screwdriver) caused some local removal of the electrodeposited layer.

As the electrodeposited layer will be protected by the external case, this result is considered acceptable for the implementation in the HRP diagnostic head.

Summarizing, the tests on thin copper electrodeposition provided the best results for the ceramic materials: Boron Nitride, Alumina and Macor. The latter was selected for the shield support for its mechanical properties, low roughness and for its easier machining.

VI. Construction of Two Samples of the Shields for the Magnetic Sensors

Due to the complicated shape, small dimensions and extremely thin thickness of the copper layer, the construction of the magnetic sensor shields is not straightforward. Hence two samples of this critical part have been constructed:

- Sample 1: Delrin (polyoxymethylene) sample of the shield base, shown in Fig. 4a
- Sample 2: Macor sample, featuring a shield base and a shield cover, shown in Fig. 4d.

The design of the shields for the magnetic sensors have been developed in order to obtain a design compatible with the limitations of the state-of-the-art milling tools. Due to the very small size of the pieces, the construction procedure have been first tested on Delrin and then extended to Macor. After the construction, the samples have been prepared for electrodeposition by covering the surfaces to be electrodeposited

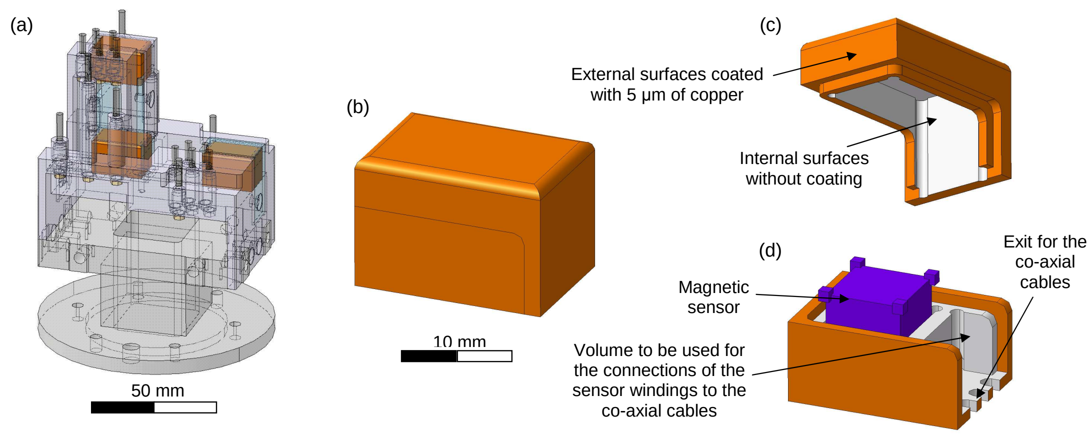

Fig. 5. Design of the electrostatic shields for the magnetic sensors: (a) position of the three magnetic sensors; (b) magnetic sensor shield; (c) cover part; (d) bottom part and magnetic sensor. The parts in orange are coated with a 5 μm layer of copper.

with a silver paint (see Fig. 4e). Then, the pieces have been immersed in a galvanic bath (see Fig. 4b), where an ultra-thin layer of 5 μm have been applied (see Fig. 4c for the Delrin sample and Fig. 4f and 4g for the Macor sample). Following the experience of the previous coating tests, described in the previous paragraph, and of a preliminary test on the Delrin sample, the required thickness of 5 μm was obtained on the Macor sample using an electrodeposition voltage of 0.7 V and a time length in the galvanic bath of 2 minutes.

Sample 2 have been then tested in order to check its effectiveness in shielding the magnetic sensors from the ECRH radiation. The test were successful, hence the manufacturing process was confirmed.

Moreover, during the manufacturing of the samples, there were several discussions on how to optimize various functional and manufacturing aspects of the magnetic sensor shields and as a consequence their design was improved to the one shown in Fig. 5. The main advantages of the updated design are the following:

- the connections of the magnetic sensor to the co-axial cables that will bring out the signals are also shielded;
- the shielding is more uniform, due to the almost cubic shape and to the new position of the holes to let out the cables, that were moved to the edge of the lower surface to avoid the interruption of the shield in a critical zone;
- the manufacturing process is simplified.

VII. Conclusion

The HRP head has been developed to provide information on parallel current density associated to filamentary electromagnetic turbulent structures in the edge region of Weldelstein 7-X experiment. The engineering design of this probe has been developed in order to minimize the volume of the head and maximize its robustness, taking also into account the manufacturing feasibility and the easiness of assembly.

An R&D campaign has been carried out to choose the most suitable material for the shields for the magnetic sensors. Then, the mechanical feasibility of the shield design has been demonstrated by manufacturing two samples representing the main technological issues. The following tests have demonstrated that the shield is effective in filtering the radiations from ECRH. Moreover, the manufacturing of the samples has permitted to improve the design of this critical part.

Acknowledgment

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