THE MAGNETIC DIAGNOSTIC SET FOR ITER*

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Abstract. This paper presents the multiple set of requirements for the ITER magnetic diagnostic systems and the current status of the various R&D activities performed by the EU partners.

Keywords: ITER, magnetic diagnostic system

Introduction

Efficient commissioning and successful operation of ITER require an extensive and reliable set of magnetic diagnostics. According to international agreement, the magnetic diagnostic set is to be provided to ITER as a EURATOM contribution via in-kind procurement through Fusion for Energy (the European Domestic Agency for ITER). These systems need to satisfy multiple requirements: safety and machine protection, real-time plasma control, measurement and stabilization of magneto-hydrodynamic (MHD) modes, post-pulse equilibrium reconstruction, physics diagnostics functions. The proposed magnetic diagnostic systems include measurements of fields, fluxes, plasma current and diamagnetic flux made inside and outside the vacuum vessel. A set of Safety Important Component (SIC) plasma current measurements has recently been considered to complete this set although no final decision has been made. This system is a standard for all operating tokamaks and the spread of knowledge is very abundant [1]. However, there are specific challenges related to developing such diagnostic systems to provide all the required functions for ITER: gamma, neutron, radiation and thermal effects on the in-vessel sensors and cabling, long-pulse integration and drift compensation for the ex-vessel data acquisition electronics, and long-term, access-free reliability for maintenance. Additional non-inductive steady state diagnostics are being studied to meet the challenges associated with the long pulse operation for inductive sensors.

This paper is an extended version of the proceedings of the SOFE 2009 Conference [2]: in this work the present design of the ITER magnetic diagnostic system is summarized and the R&D work underway to meet some of the challenges indicated above is also outlined. This paper is organized as follows. In Section1 we briefly review the current measurement requirements for the magnetic diagnostic set in ITER. Section2 gives an overview of the challenges to these systems which are novel and specific to ITER. In Section3 we review the currently proposed implementation for the magnetic diagnostic systems in ITER. In Section4 we briefly review the risk analysis for this diagnostic system so as to show the complexity of the work in hand. To understand how such complexity is tackled, and using the high-frequency magnetic sensors as a practical example, we then also include in Section4 a more "project management" oriented overview of the currently foreseen planning activities, which are intended at dealing with and mitigating the risks associated to the complexity of the ITER environment. Finally, in Section5 we present a summary and draw some conclusions towards future activities.

1) Measurement Requirements for the Magnetic Diagnostic Systems in ITER.

The detailed requirements for the magnetic sensors needed to meet the purposes of this diagnostic system in ITER are well established [3], and are briefly summarized in Table1 together with the main risks that could prevent achieving the intended goals. These requirements cover measurement capabilities, diagnostic functionalities and safety, and are overviewed in the next sub-sections.

1a) Measure magnetic flux and field around the plasma to reconstruct the magnetic equilibrium.

As in all current tokamaks, values of local magnetic fields and fluxes will be mainly derived in ITER from inductive sensors, measuring $d\Phi_B/dt$, where Φ_B is the total magnetic flux enclosed by a wire loop. Although the time derivative (d/dt) can in itself yield useful information on the currents flowing in the passive structures which surround the measurement device, the signals have to be integrated to be used for equilibrium reconstruction (in real-time for protection and control, post-pulse for more physics oriented data analysis). These flux and field measurements are made inside and outside the vacuum vessel. Figure1 shows some examples of these sensors, as currently being prototyped. As ITER has two 60mm-thick diffusive walls, the measurements made outside the vessel need careful analysis and modeling of the currents flowing in the walls, as the resulting phase delay creates difficulties in stabilizing the naturally unstable n=0 vertical and n=1 tilt modes. Similarly, the detailed magnetic field structure in the divertor region, which is affected by the presence of the divertor coils, must be known accurately to determine precisely the location of the separatrix and the strike points. To this end, specific inductive magnetic sensors are foreseen for installation around the divertor region. These sensors, whose assembly layout is shown in fig2, are subject to strong radiation fluxes, thermal gradients and electric field changes, particularly during a disruption, and would require active cooling to keep the temperature excursion within the nominal $\Delta T=10°C$ range, which in turns imposes very severe constraints on their design and assembly within the divertor cassette [4]. Together with measuring the magnetic fields and fluxes in the poloidal plane, the variation in the toroidal flux also provides a direct estimate of the toroidal field and information on the plasma stored energy. To this end, the diamagnetic flux loop is currently intended to have a sampling rate of at least 10kHz in order to cope with the fast variations caused by Edge Localized Modes, and it is designed with a 2-turns layout (for in-situ compensation of geometrical effects) located in three different machine sectors (for redundancy and assessment and direct compensation of 3D effects due to the vessel walls): this design is however difficult to implement due to lack of space. In addition to the conventional Mirnov-type and flux-loop sensors, for which a schematic system layout is shown in fig3, other techniques are also being considered for application to the ITER long-pulse operation. As two specific examples, R&D studies are being performed on ex-vessel 2D Hall probes and neural networks [5]. Inductive sensors made with wound wire or a sintered stack of ceramic layers with printed metallic lines (Low Temperature Co-fired Ceramic: LTCC) are also being investigated for in-vessel installation [6]. These applications correspond to the axis-symmetric (2D) model of the tokamak plasma, but the same magnetic diagnostic set has to provide the non-axis-symmetric (3D) field distribution. This is intended to be used as a correction for the error field resulting from constructional imprecision and from the presence of non-axis-symmetric magnetic structures, such as the ferritic inserts used to reduce the toroidal field ripple and the Test Blanket Modules (TBMs).

1b) Measure the total plasma current.

This data has been historically provided by a Rogowski coil measuring the contour integral of the magnetic field, yielding the current passing through the enclosed surface. When placed around the vacuum vessel, this loop signal includes the contribution of the currents flowing in the wall, and the measurement is affected by precise knowledge of these currents. Whereas older tokamaks installed specific Rogowski coils to measure such a loop-integrated current, poloidal field measurements are now currently used to create a "*virtual*" Rogowski coil by a weighted sum of the individual signals, which is also the present ITER plan. The magnetic system on the TCV tokamak is a standard example of this approach [7, 8]. Nonetheless, conventional Rogowski coils are being developed to sit inside the TF coil casings at liquid Helium temperature, and a schematic of this system is shown in fig4a. Furthermore, a fiber-optic Faraday rotation measurement device [9] is under development, resulting from a collaboration between SCKCEN and CEA-Cadarache, with an overview of its layout shown in fig4b: the main advantage of this system is that it does not require integration. The first measurements have been recently carried out on Tore Supra and are very promising.

1c) Measure the currents flowing between the plasma and the vacuum vessel walls (halo currents).

The main interest of the halo current measurement studies resides in machine protection. Halos are generally non-axis-symmetric and localized phenomena, as they depend on the specific metallic structures attached to the vessel wall, and can generate significant and fast varying forces when crossed with the tokamak's equilibrium magnetic fields. Hence, a large number of sensors need to be deployed, using different technologies, such as conventional Rogowski coils and current shunts, so as to maximize the quality of the data being gathered. Moreover, it can be shown [10] that a plasma deformation with eigenmode numbers (m,n) produces halo currents whose fundamental components are (2m,2n) (and many higher harmonics). Therefore, according to sampling theory, at least (4m+1,4n+1) sensors are required in order to "recognize" the fundamental component of the halo current distribution. Therefore, the currently proposed number and layout of sensors in ITER gives correct information on plasma deformations with periodicity not higher than (m/n=2/2), and partial information up to (m/n=4/4). Conventional Rogowski coils to fit around the blanket modules are being designed on the basis of the sensors which are currently operational on JET [11], and an overview of the layout of this system is shown in fig5. In addition to Rogowski coils, which are usable only during transient (disruptive) events, current shunts are under consideration for the measurement of steady-state currents from the plasma into the divertor plates. The use of shunts to estimate the current flowing in the purely poloidal divertor cassettes is under consideration due to demonstrated usefulness of an estimate of the localized current deposition at the wall on ASDEX Upgrade [12]. The main issues for installation on ITER of halo current measurement devices are, first, the feasibility of such system, as the number of sensors for the blanket modules implies a very large amount of additional wiring (as >360 Rogowski only equip about 1/3 of all blanket modules), and, second, specifically for the divertor shunts, whether the additional constraints that can be put on the equilibrium reconstruction provided by a single lumped poloidal current measurement in the divertor cassette justifies such a complex addition to this already very challenging system.

1d) Measure the fast fluctuations in the equilibrium magnetic field driven by MHD instabilities.

MHD activity drives magnetic field fluctuations at frequencies much higher than the plasma skin-depth. Since these instabilities are non-axis-symmetric, many sensors need to be used to reconstruct the spatial and temporal variation of these high-frequency signals in ITER, to provide essential data on the MHD eigenmode structure with toroidal and poloidal mode numbers $|n|\leq30$ and $|m|\leq60$, respectively, and to frequencies at least of the order of 300kHz. In addition to the standard wound inductive sensors of conventional, Mirnov-type design, two other technologies are being considered and are currently being prototyped to perform these high-frequency (HF) magnetic measurements [13-15]: laser-cut non-conventional Mirnov-type pick-up coils and LTCC sensors. Figure6 shows some of these as-built prototypes. The most promising design is the LTCC sensor, as this allows for a significant reduction in the space occupied by the measurement device and removes all difficulties related to the manufacturing of a complex ceramic body and the assembly of a winding pack onto it. The main difficulty with the LTCC technology is related to the metallic ink used to print the circuit onto the green sheets, as current processes mainly use silver and gold, whereas such materials may need to be avoided in ITER due to a perceived risk of transmutation to cadmium and mercury under the expected neutron and radiation fluxes. It is however intuitively expected that, as an alloy is formed when sintering an LTCC sensor, the metallic ink will be sealed in the surrounding ceramic green tape, so that Cd and Hg out-gassing from the LTCC structures would be essentially zero, as any of such atoms should attach to and therefore remain confined within the structural imperfections of the metallic tracks. Similarly, the coil-wiring connections can be sealed by applying a vacuum ceramic paste or glass encapsulation after bonding. A dedicated materials and radiation testing program is currently foreseen to confirm these assumptions.

The number and the spatial distribution of these sensors will also need to be carefully optimized to satisfy the very stringent ITER measurement requirements [13, 16]. Specifically, the currently foreseen layout with ~170 sensors in total does not allow sufficient accuracy in the measurement of instabilities with mode numbers |n|>15 and |m|>20, nor distinction between ballooning and anti-ballooning instabilities. An optimized sensor layout with ~350-400 sensors is being proposed to satisfy the current ITER measurement requirements and allow distinction between ballooning and anti-ballooning modes, at the expenses however of a much larger number of in-vessel services and data acquisition modules and bandwidth that would need to be procured and installed. Two further difficulties for the HF magnetic diagnostic system arise from the fact that such sensors are currently intended to be either "buried" within ad-hoc cutouts in the blanket modules, or in the small gap (of thickness <20mm) between the blanket and the first vessel wall. This not only adds a constraint on the volume available for installation, hence most definitively favoring the LTCC design, but also raises some doubts on the achievable frequency response of these sensors, as the currently unknown electrical properties of the blanket modules may also impact the measurement performance of this diagnostic. Therefore, it is intended to finalize a proposal for the system layout for the HF magnetic diagnostic system, and to continue with detailed prototyping activities, only after the design of the vessel and blanket modules will be completed and their electrical properties can be assessed fully.

1e) Reconstruct the plasma equilibrium.

The ensemble of magnetic measurements recorded at low frequencies (<1kHz) in their derivative and integrated forms, combined with measurements of all the active currents driven by external power supplies, is used to perform a reconstruction of the axis-symmetric equivalent magnetic equilibrium, namely a solution of the tokamak equilibrium equation which would produce a set of signals as close as possible to the measured signals while respecting a regularized solution. This reconstruction will need to be provided both in real-time for engineering protection and control of the plasma discharge, and post-pulse for more detailed, physics-oriented, scientific analysis. Given the many specific difficulties associated with the ITER environment, for instance the effect of 3D passive structures and long-pulse drifts in the electronics, it is planned to perform an optimization between all currently used approaches to this challenge, so as to minimize the risks in such analysis through a diversity of methodologies.

1f) Provide appropriate feedback control error signals.

The plasma equilibrium has two main instabilities that can be stabilized by magnetic feedback control: the n=0 vertical positional instability, which can be attributed to the elongation of the equilibrium by an imposed quadrupole field and the dissipation of induced n=0 image currents in the vacuum vessel and other passive structures, and the n=1 tilting instability, which can similarly be attributed to the dissipation of n=1 image currents in the vacuum vessel. Correcting these instabilities requires prompt action by power supplies: the error signal driving the feedback loop is derived from real-time data produced by the magnetic diagnostic set. Time delays or phase changes in the signals can cause prejudice to the quality of the feedback control. These are likely to occur in ITER due to the large number of complex internal conducting structures, and specific algorithms need to be devised to compensate for such distortions. The remaining part of equilibrium control, which is essentially used to tune the plasma shape, is less demanding in terms of allowable delay but is more demanding in the precision of the integrated signals to meet the error requirements on the reconstruction of the equilibrium. Integration into the real-time CODAC Synchronous Databus Network allows the signals, feedback controllers and power supplies to communicate efficiently between themselves for plasma protection and control.

1g) Provide signals for protection of investment and safety.

The development of the ITER safety case is underway and the need to provide a Safety Important Component (SIC) class measurement of the plasma current is being discussed. This would be the only SIC requirement for the magnetic diagnostic set. Since the magnetic diagnostic is responsible for controlling the high free (internal) magnetic energy of the plasma current itself and the (externally) controlled magnetic energy of the active coil currents, loss of control has serious consequences, such as loss of availability during recovery after a disruption, and a reduction in the total number of disruptions that can be allowed before refurbishment of plasma facing components becomes needed. Hence, it is clear that a significant fraction of the ITER magnetic diagnostic output will be connected to the Plasma Control System, with some data also connected to the Central Interlock System. These decisions clearly impact on the project costs and on the definition of the acceptable risks in terms of the measurement performance, and on the required availability and reliability over the life-time of ITER.

2) Novel and specific ITER challenges.

A number of challenges for implementation of the magnetic diagnostic set in ITER are novel to the tokamak community, as they depend on the harsh environmental conditions of ITER, specifically the long pulse length, the expected neutron, γ and radiation fluxes, fluency and doses, and the need for access-free diagnostic maintenance over the machine life-time. These have been the subject of continuing R&D activities, and are briefly overviewed in the following sub-sections.

2a) Long pulse length.

This challenge to current standard electronic integrators has been adequately addressed over the last few years [17]. Much attention is required, particularly because spurious electro-motive forces (EMFs) due to radiation or thermal effects, as described in more details below, can make this a very critical issue unless a suitable and very reliable mitigation of these unwanted EMFs can be fully implemented and guaranteed.

2b) Radiation and neutron resistance.

Long-term resistance and life-time reliability of the various sensor components to neutrons and radiation is being met by appropriate selection of materials. Numerical simulations of such effects are difficult, as it is already clear from preliminary tests that much of the possible damage to the sensors will be caused by their specific and individual structural properties, and particularly by the presence of defects. Hence these analyses will have to be confirmed by future radiation testing on dedicated facilities on prototypes as close as possible to the as-built sensors and using neutron, γs and radiation spectra as similar as possible to those expected in ITER.

2c) Availability and precision.

The operation of ITER will require a system availability and precision in the output data above those required in current experiments, so as to meet the intended goals within the project lifetime. In particular, the plasma separatrix must be controlled to within a very high precision, relative to the size of the device, of the order of no more than a few mm's compared to a minor radius ~2m, and during very rapid and time-varying intrinsic perturbations to the plasma equilibrium, such as those caused by Edge Localized Modes. This will require specific R&D work to meet the long-term operational requirements, flexible and accurate tools for equilibrium reconstruction and ingenious feedback controllers to tackle the intrinsic perturbations to the plasma equilibrium.

2d) Radiation and neutron induced EMF.

In-vessel cables and sensors bombarded by neutron and γ fluxes generate a non-inductive EMF due to energetic electrons produced within the cables and the surrounding structures. This effect appears as an EMF at the integrator input of all in-vessel sensors and leads to a cumulative error in the integrator output baseline [18]. Whereas the neutron-induced effects are well understood, the often dominant effects caused by γs are not believed to be sufficiently reproducible to be compensated on the basis of modeling of the measured rates. The only mitigation other than choice of wire materials is to generate large enough signals in the sensors and reduce them at the front-end electronics. As the level of the radiation-induced EMF signals cannot be estimated precisely given the foreseeable uncertainties in the neutron and radiation flux and the manufacturing tolerances on the in-vessel wires, ex-vessel and steady state sensors have also been included in the baseline system design to provide further mitigation strategies for this source of errors.

2e) Thermally induced EMF.

Cables subject to temperature gradients along their length produce a non-zero thermo-electric EMF due to manufacturing imperfections [19]. In addition to this, nuclear transmutation products can lead to a significant thermally induced EMF at the integrator input during the pulses for in-vessel sensors, causing again a cumulative error in the integrator output baseline [20]. As compensation is currently not foreseen, mitigation of this source of error is only based on thermal gradient reduction in the sensors and cables, on high signal amplitudes and material choice. Specifically, the option of glass-fiber insulated twisted pair cables instead of mineral insulated cables is being considered. The importance of this effect on LTCC sensors is also currently being investigated.

2f) Mechanical distortion during pulses.

Distortion of the in-vessel mechanical support structure for the sensors can occur between different in situ measurements (for instance via photogrammetry surveys), or even during a plasma pulse. These movements can lead to erroneous interpretation of the magnetic signals. The large forces and the thermal cycling are capable of presenting a challenge of mechanical stability on the position and especially on the viewing angle of the sensors with respect to the magnetic field axis, which may in turns lead to an erroneous separation between the 3D components of the measured fields and fluxes.

3) The present magnetic diagnostic set for ITER.

As summarized in Table1, >1700 sensors are foreseen for the magnetic diagnostic set in ITER, compared to ~500 for JET and ~300 for TCV, to name just a couple of currently operating tokamak devices. This large (but actually not-that-large when comparing the size of these machines) number of sensors for the ITER magnetic diagnostic system is driven by several considerations, which are separately highlighted below.

First, non-axis-symmetric n=1 and n=2 modes need to be filtered out for real-time control and post-pulse equilibrium reconstruction by averaging multiple toroidal arrays, leading to an increase in the number of sensors by typically a factor ~2-3. For the same purpose, a large number of poloidal locations are equipped, providing considerable redundancy to combat the risk of statistical failure of individual sensors. Moreover, for non-axis-symmetric mode reconstruction, the resolution of the poloidal and toroidal mode numbers is higher than usual and requires a larger number of probes.

Second, multiple un-evenly spaced arrays of high-frequency sensors are needed to unambiguously resolve the predicted spectrum of MHD fluctuations in order to satisfy the ITER measurement requirements. Furthermore, as the operational experience on current tokamaks indicates that such high-frequency sensors are often more prone than the others to statistical failures, it is foreseen to develop and possibly deploy multiple technologies to perform such measurements so as to reduce the common-mode failure risks via a diversity of methodologies.

Third, diagnosing the halo currents in the blanket modules requires ~1/5 of the magnetic sensors, but only equips ~1/3 of all blanket connections. As halo current measurements are essential for machine protection, the choice of equipping just a subset of in-vessel location is questionable by definition, as one would want to monitor halo currents all over the vessel, and particularly around the most important or "delicate" structures. This, however, implies a very large number of wiring, connectors and in-vessel services, so that an optimum compromise will have to be made.

Fourth, steady-state sensors need to be installed ex-vessel, where the neutron and radiation fluxes are very much attenuated, to mitigate the risks related to radiation and thermally induced EMFs, therefore duplicating in many aspects the in-vessel measurements. This duplication provides some diversity, although the frequency response of the in-vessel and ex-vessel sensors is clearly different due to the double 60mm-thick vessel wall, and will require considerable R&D before installation and detailed commissioning and trouble-shooting during the initial phase of operation to guarantee their use as a long-term fall-back option. To this end, non-inductive sensors and steady-state will also need to be deployed ex-vessel so as to mitigate the risks associated to incorrect understanding of the effect of the walls. These sensors, and especially radiation-resistant Hall probes, represent also a good candidate towards reducing the risks associated to excessive EMF drifts induced by radiation and temperature gradients.

Fifth, external Rogowski coils and Faraday rotation current measurements provide a backup and possibly a SIC class measurement for the plasma current in addition to the currently foreseen use of a "virtual" Rogowski, which is in itself sensitive to 3D effects such as those associated to the ferritic inserts. However, use of these measurements does not constitute functional diversity since these coils do not generate the information required to control the equilibrium or provide stability.

Finally, to satisfy the ITER measurement requirements over the machine life-time, an even larger-than-usual number of sensors need to be installed to provide considerable redundancy and mitigate the risk of statistical failure of individual sensors. It is foreseen that some essential measurements will be performed using different technologies, so as to reduce the risk of common mode sensor failure and provide backup via diversity of instrumentation.

4) Risk analysis and mitigation through R&D activities and planning.

Most magnetic diagnostic systems appear on most tokamaks, but never with the risks associated with ITER operation. As ITER will simply not be able to operate without a functional magnetic diagnostic system, it becomes paramount to review and address the possible risks to achieving such a goal [21]. Direct risks to the mechanical integrity of the ITER device generated by the magnetic diagnostic systems themselves are negligible, since there are no vacuum interfaces (other than out-gassing) and there is no physical danger to ITER from the functionality provided by the sensors. The absence of vacuum interfaces stems from a project decision to separate the sensors from the in-vessel service wiring, allowing the service wiring to be developed independently for thermocouples and bolometers. All risks to the project therefore stem from unavailability or unreliability of the required functionality, which may lead to inadequately precise control of the plasma equilibrium or to the initiation of disruptive events, both of which represent a significant risk to the ITER device. These “residual” risks can be classified in three groups, related to different time points throughout the entire machine life-time:

(1) (not) delivering the measurement requirements for initial plasma operation;

(2) (not) delivering the measurement requirements for first full performance (ignited) plasmas;

(3) (not) delivering the measurement requirements for the last plasma, i.e. at the end of the machine life-time.

A detailed planning analysis has been performed to assess mitigation strategies for these risks, and this has been included in the Project Plan for the development of the ITER magnetic diagnostic, referred to as the MAGDIAG project. The overall Project Plan has been subdivided into individual WBS (Work Breakdown Structure) tasks to facilitate the inter-linking between different activities.

The internal scientific consistency of the full magnetic diagnostic set is still based on the one which has been outlined in the ITER 2001 Design Description Document, later updated in 2004. However, the overall ITER machine design has drifted from a proposed set dating from 1998, with continual revisions of the machine itself and of its goals. Therefore, and as of today, the major outstanding uncertainties in the successful completion of the MAGDIAG project such that it would be meeting all the ITER measurement requirements are considered to be:

1. the technical and scientific risks associated to using the magnetic data to meet the very stringent ITER measurement requirements, especially when considering the novel 3D passive structure effects and the 2D and 3D ferromagnetic effects;
2. the unceasing changes to the ITER project itself, excluding convergence of the work being performed at the level of engineering design, or even conceptual design for some elements.

These uncertainties are reflected in the Project Plan, and the second point also impacts very strongly on the Project Schedule. Each magnetic diagnostic set needs stable measurement requirements and stable engineering drawings, which are not yet fully available for ITER at this time.

The formal ITER measurement requirements for the full magnetic diagnostic set are presented in [3]. Figure7 illustrates the link between meeting these requirements and selecting the subsystems handled under the different WBS tasks in the MAGDIAG project. Figure7 immediately underlines the interconnected nature of the magnetic diagnostic systems. The figure already illustrates that:

- there are few requirements which are met by one single component system, i.e. the loop voltage;
- there is no single component system which satisfies one single requirement;
- there are intermediate usages which require system information outside the MAGDIAG scope, i.e. PF coil currents;

- there are multiple WBS packages which satisfy a single purpose, although being used to meet multiple requirements;
- there is no explicit requirement to reconstruct the equilibrium (as only the separatrix gaps are explicitly required);
- there is no explicit requirement to provide control signals (but implicit in the measurement of the vertical position);
- there is no explicit requirement to provide signals to calibrate an electromagnetic model (which therefore might be performed with reduced reliability requirements and hence reduced cost);
- there is no plan for measuring the induced and magnetization currents.

As a specific example of a WBS package, we focus on the HF magnetic sensors (WBS16), and the breakdown of the estimated resource (manpower and cost) requirements for this WBS is shown in Table2. The current system design comprises a large number (200-500) of inductive magnetic sensors which have to be sited inside the vacuum vessel with minimum electromagnetic shielding to provide the required frequency response. The layout of the sensors around the Torus has to be studied for compatibility with allowed space occupancy, added value for mode identification and shielding from the harsh environment. The design of the individual sensors themselves has to cope with maintenance-free operation during the lifetime of the ITER project, even though some of the components are intended to be designed with the possibility of remote maintenance. Therefore, the principal challenges to this diagnostic to meet the ITER measurement requirements [3] are:

- meeting the requirements to identify the small low wavelength perturbations;
- guaranteeing appropriate sensitivity in the presence of massive passive structures;
- guaranteeing the frequency response of the sensors and at the same time meeting the sensitivity requirement;
- meeting the environmental conditions of radiation, thermal and mechanical stresses;
- meeting the high level of reliability compatible with the low maintenance requirement.

As reported in [13-16], technical solutions for the design and construction of the sensors themselves have been explored and adequate solutions are considered to exist, although there is no design fully accepted as of today. Two radically different approaches to the design of the sensors are being examined, namely conventional and non-conventional wired pick-up coils of different designs and LTCC sensors with different spiral winding layouts. Both these approaches require additional R&D before the final choices could be made. Once a sensor design is approved, the appropriate sensor mounting interfaces will have to be developed. Potential designs will also have to be subject to qualification for out-gassing and for thermal, mechanical, thermo-electric, and radiation effects. The main remaining issues that need to be addressed within the Project Planning are therefore related to:

1. the ITER target specifications on mode number identification are considered to be un-reachable with the currently planned number of ~170 sensors;
2. the number and position of the sensors cannot therefore be considered as converged;
3. the mechanical environments of the vessel and blanket modules have not stabilized adequately to advance the individual sensor design and the system layout beyond the design principles.

The principal risks identified for the successful execution of this WBS16 are shown in Table3. These risks have been taken into consideration in developing the Project Plan, but a full analysis has only a very limited scope as these risks are also affected by other developments. Considering now the implementation of future R&D activities for this diagnostic set, it is clear that a diversity of solutions appears to be the most appropriate risk mitigation against unknown risks associated with this one-of-a-kind problem. As of today, and considering the tight ITER scheduling, this involves:

1. developing and assessing *in parallel* different sensor design using different technologies, so that hopefully at least two different technologies can be found to be suitable for installation in ITER ➔ this will reduce the risks associated to "common mode failure" of one type of sensor because of environmental constraints, such as neutron and/or radiation fluxes;
2. developing and assessing optimized strategies for redundancy in the number of sensors so as to reduce the overall procurement and installation costs ➔ this will reduce the risk associated to the "statistical failure" of individual sensors without compromising the budget requirements;
3. developing and assessing *in parallel* different overall system layout (i.e. the in-vessel position of the sensors) in order to meet the intended measurement requirements, so as to be able to cope with possible different constraints and technical specifications that are currently foreseen to be specified at a later date ➔ this will reduce the risk associated to "common mode failure" of the entire diagnostic system because of unknown physical unknowns, i.e. operational scenarios not currently considered in the ITER measurement requirements but that may become utilized at a later date (an example of this is plasmas limited on the high-field side wall).

5) Discussion and conclusions.

The primary use of the ITER magnetic diagnostic system is to estimate the plasma equilibrium for the purposes of feedback control of the plasma current, its position inside the vacuum vessel and the shape of its boundary. To this end, the data from the magnetic sensors are combined in a code which adjusts the measurements to a solution of the Grad-Shafranov equation. ITER imposes severe requirements on the precision with which the measurements can reconstruct the equilibrium, which in turn create very demanding requirements on the accuracy of the individual measurements themselves. Control of the plasma equilibrium is well understood in present day tokamaks, but the

ITER device presents a number of challenges to the precision with which the equilibrium can (and must) be reconstructed.

The first challenge is associated with the long pulses (3000 seconds) and the need to integrate the voltages provided by the sensors, in most cases these being the time derivative of the required values. Development of high quality integrators is essential, and ITER proposes the use of additional “steady state sensors” which do not require such integration. Some of the possible technologies are currently being examined for their reliability in the ITER radiation and thermal environment. The second challenge is associated with the presence of ferro-magnetic material of two classes. First, a periodic set of structures is embedded within the vacuum vessel walls with the purpose of spatially smoothing out the local variations of the toroidal field. The second class sits outside the cryostat and is used to shield components from the tokamak magnetic fields. The ferro-magnetic material has two non-linear effects, modifying the system to be controlled, and modifying the local value of the magnetic field at the sensors. The challenge is to recover an equivalent toroidally symmetric equivalent estimate of the magnetic configuration from the available set of measurements. The third challenge is associated with the dynamical control of the plasma equilibrium. The presence of massive vacuum vessel walls (2x60mm thick), combined with the required fast recovery from disturbances to the plasma equilibrium, requires such a fast actuator response that ex-vessel (safer and easier to use) coils were considered to be marginal. Coils have then been placed inside the vacuum vessel for prompt action. However, they create a local perturbation to the magnetic measurements which must be removed from the measurements themselves before these are used for control, as being currently explored on the TCV tokamak. The fourth challenge is the radiation environment coupled with the lack of access for maintainability of the sensors. This requires a guarantee of functionality in the presence of radiation and a long-term guarantee of availability of the sensors themselves. Although each of these four issues appears solvable, when put together they present an interesting challenge to the implementation of the full diagnostic system.

Acknowledgment

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Figure Captions

Figure1. Four examples of magnetic sensors being currently prototyped for measurements of magnetic fluxes and fields to be used for equilibrium reconstruction.
Figure2. Layout of the divertor cassette: the magnetic sensors are currently intended to be located behind the Inner and Outer Vertical Targets (IVT), under the dome, and under the inner and outer neutral particle reflector (plates that together with the lower ends of the VT form a "V" shape).
Figure3. Schematic layout of the flux loops as currently foreseen for installation on ITER.
Figure4a. Schematic overview of the Rogowski coils to sit inside the toroidal field casing, to be used for the measurement of the plasma current.
Figure4b. Schematic overview of a fiber-optic Faraday rotation measurement device, to be used for the measurement of the plasma current.
Figure5. Schematic overview of the proposed implementation for the Rogowski coils to be used for halo current measurements around the blanket modules.
Figure6. Some examples of the high-frequency sensors being prototyped for ITER; from left to right: one LTCC sensor, one laser-cut non-conventional sensor, and four conventional Mirnov-type coils wound in tungsten and copper (two off, each with different grooving for the ceramic spacers).
Figure7. The link between meeting in full the ITER measurement requirements for the magnetic diagnostic system and selecting the subsystems handled under WBS12-26; ellipses are intermediate treatment of the data generated by sensors on the route to meeting requirements.

Table Captions

Table1. The ITER magnetic diagnostic set: for each technique, the rationale behind its use and the primary risks to achieving the intended measurement performance are summarized.
Table2. Breakdown of assumed resources for the ITER HF magnetic system (WBS16).
Table3. Principal identified risks for the ITER HF magnetic system (WBS16).

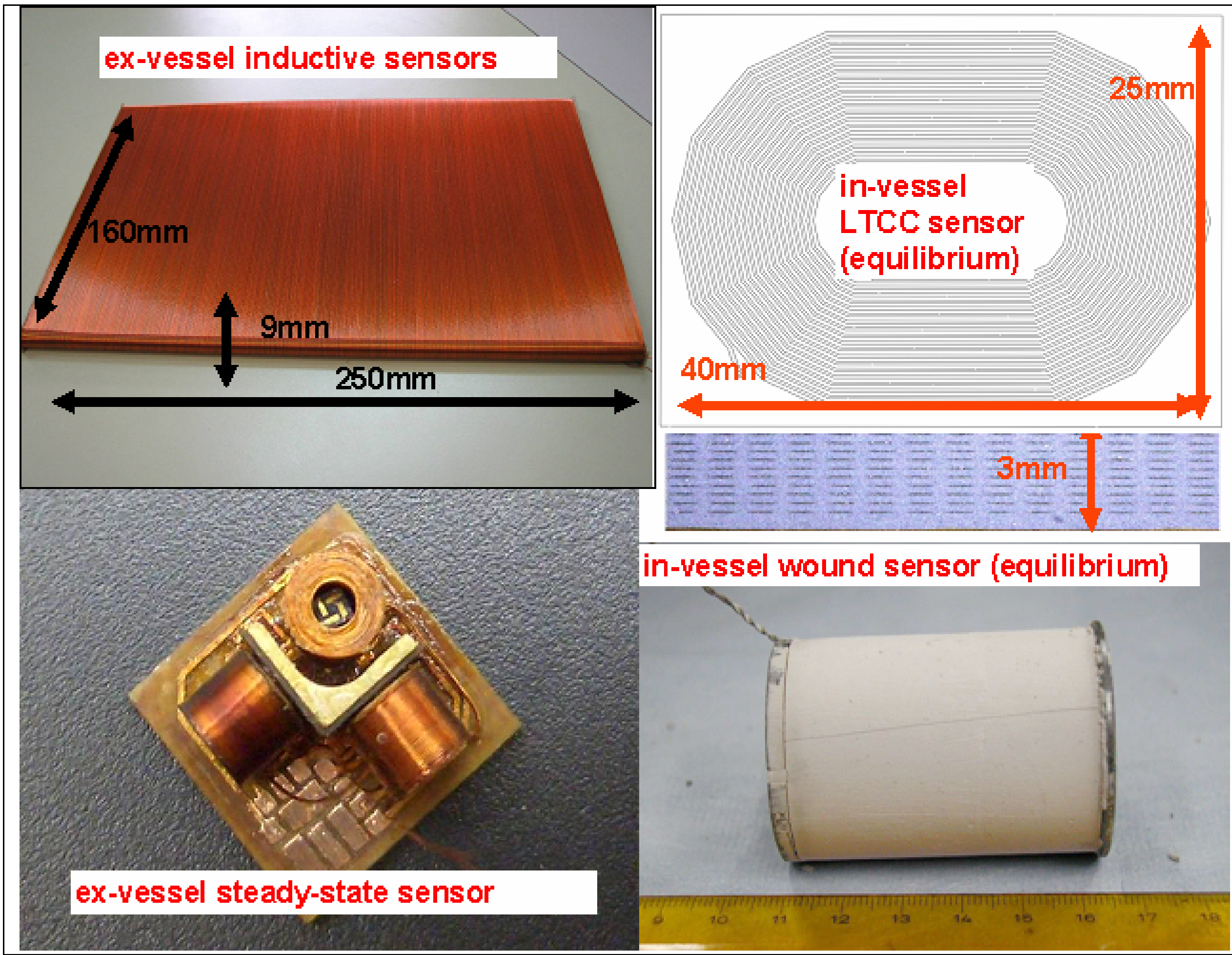
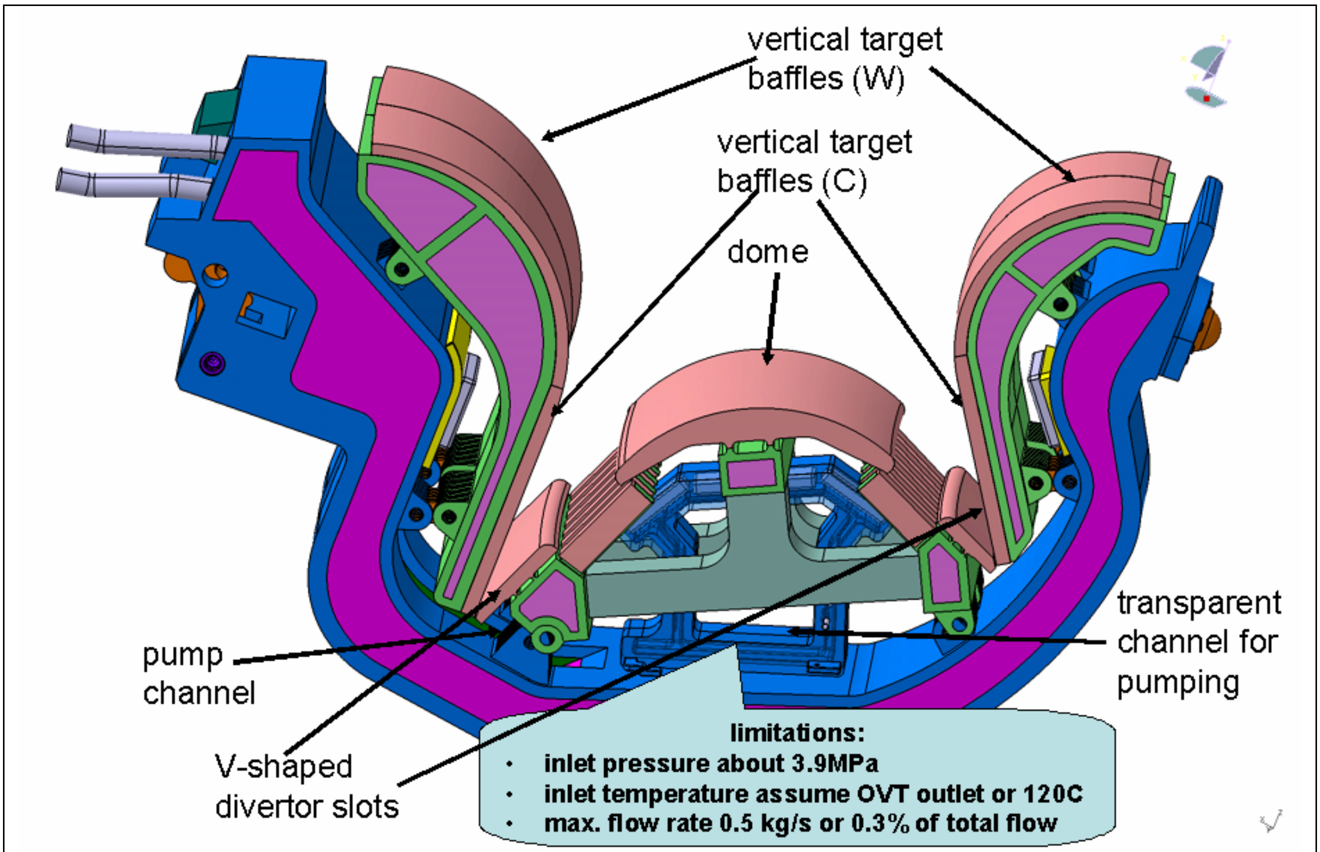


Figure1. Four examples of magnetic sensors being currently prototyped for measurements of magnetic fluxes and fields to be used for equilibrium reconstruction.

D.Testa, Figure1



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D.Testa, Figure2

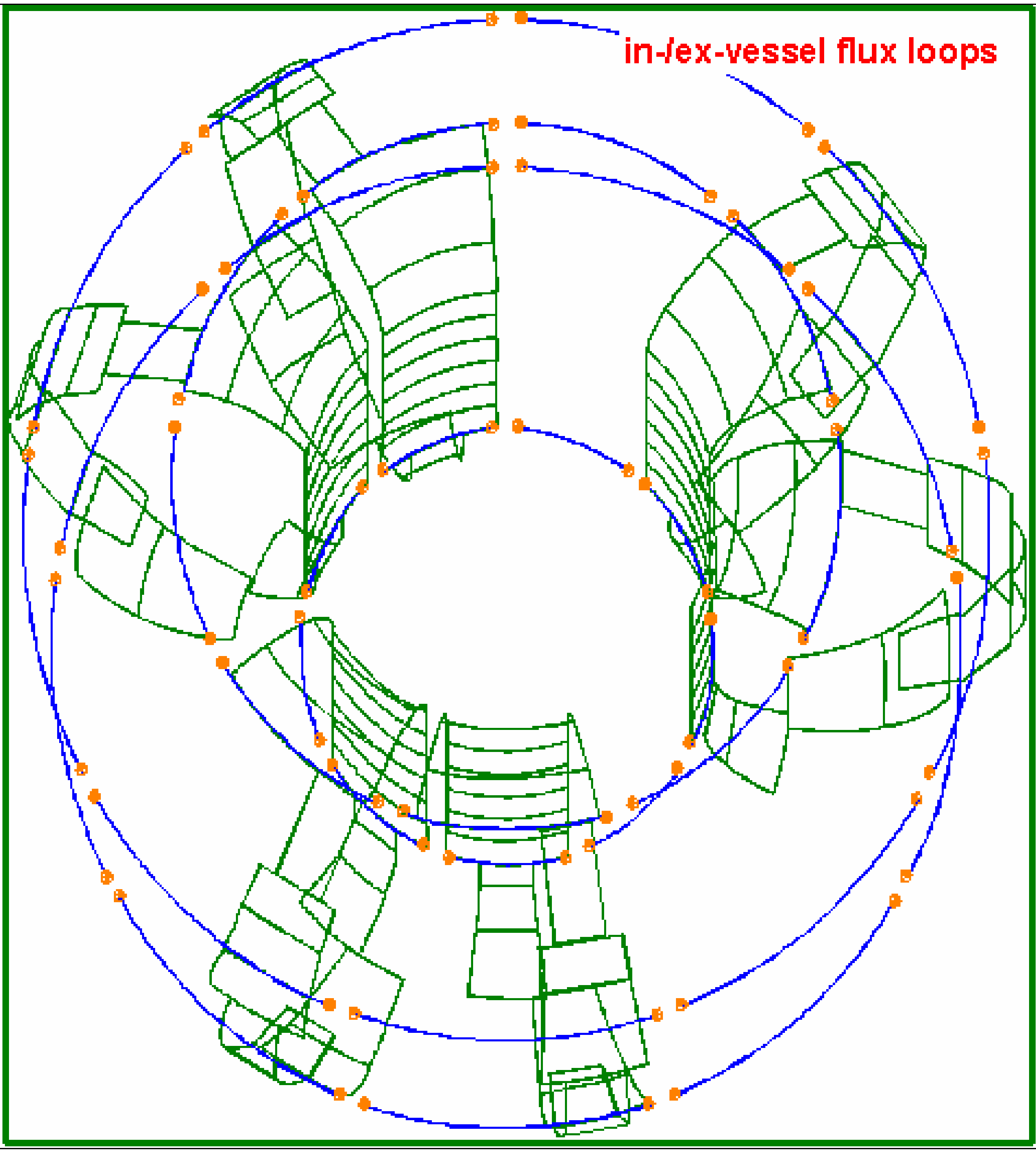

Figure3. Schematic layout of the flux loops as currently foreseen for installation on ITER.

D.Testa, Figure3

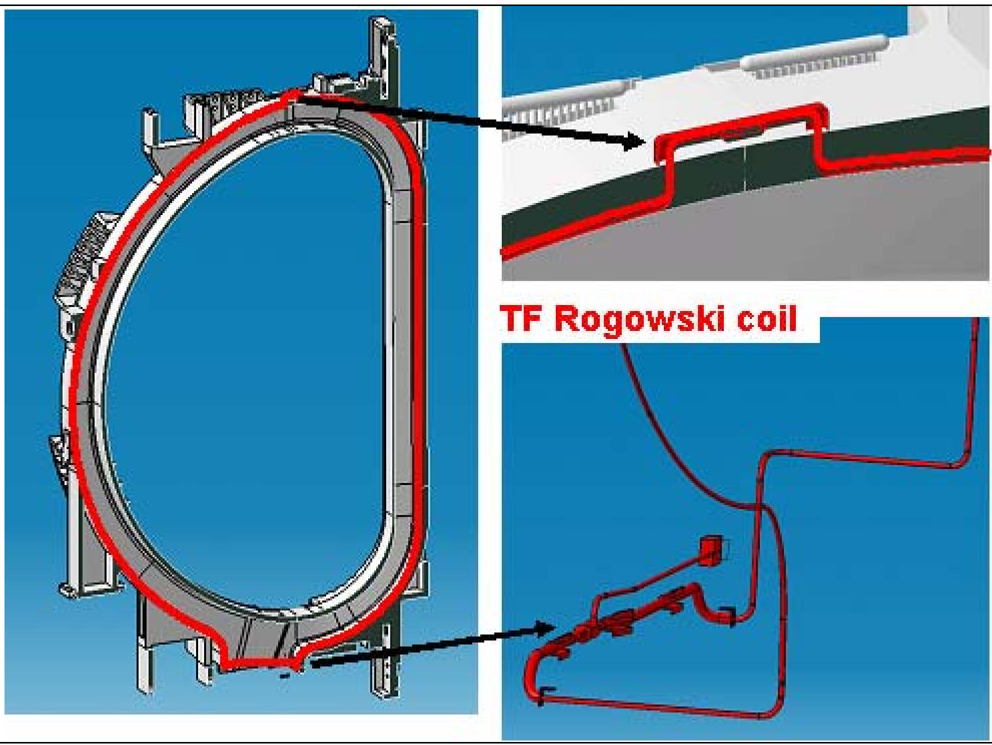

Figure4a. Schematic overview of the Rogowski coils to sit inside the toroidal field casing, to be used for the measurement of the plasma current.

D.Testa, Figure4a

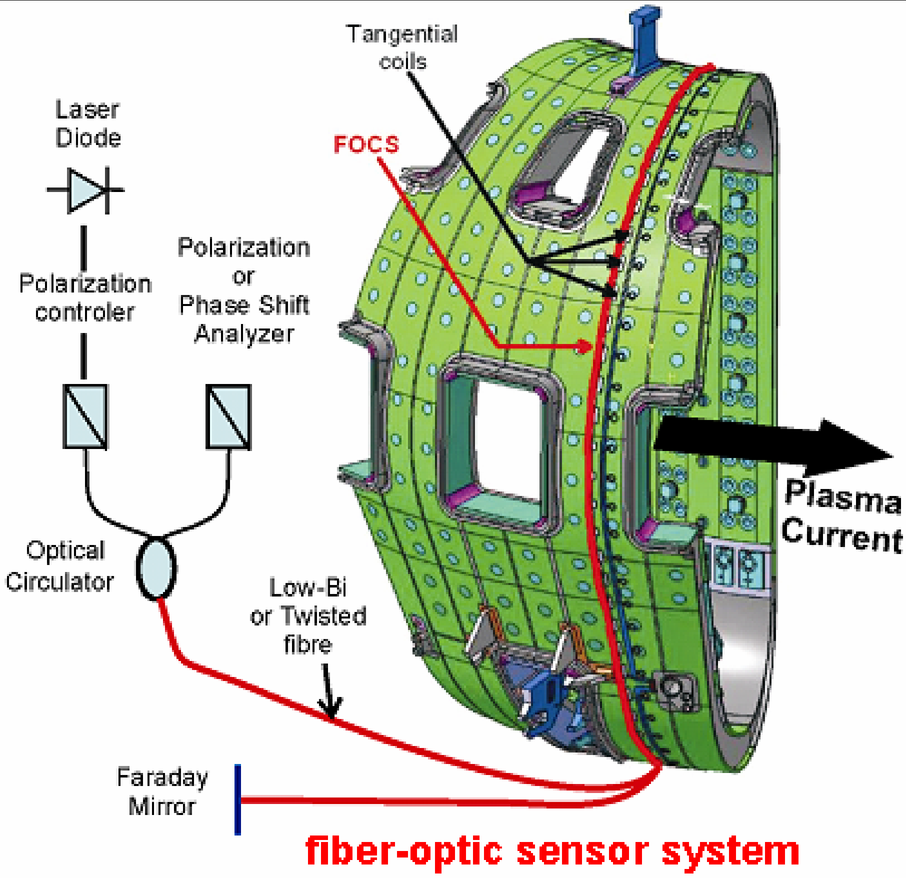

Figure4b. Schematic overview of a fiber-optic Faraday rotation measurement device, to be used for the measurement of the plasma current.

D.Testa, Figure4b

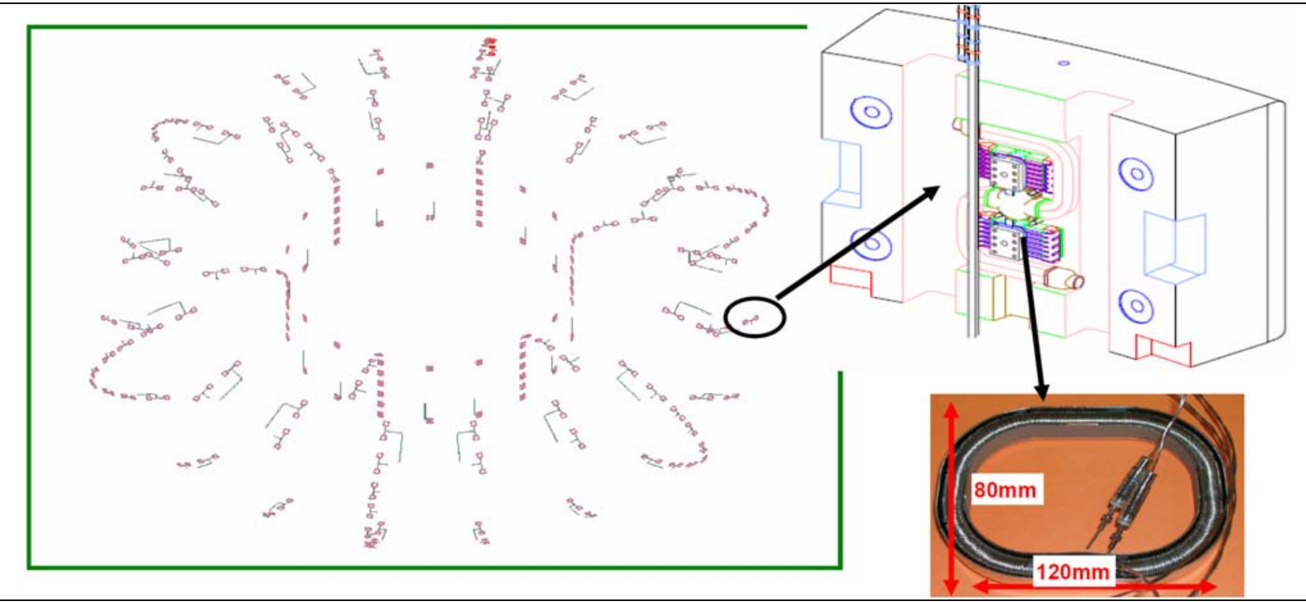

Figure5. Schematic overview of the proposed implementation for the Rogowski coils to be used for halo current measurements around the blanket modules.

D.Testa, Figure5

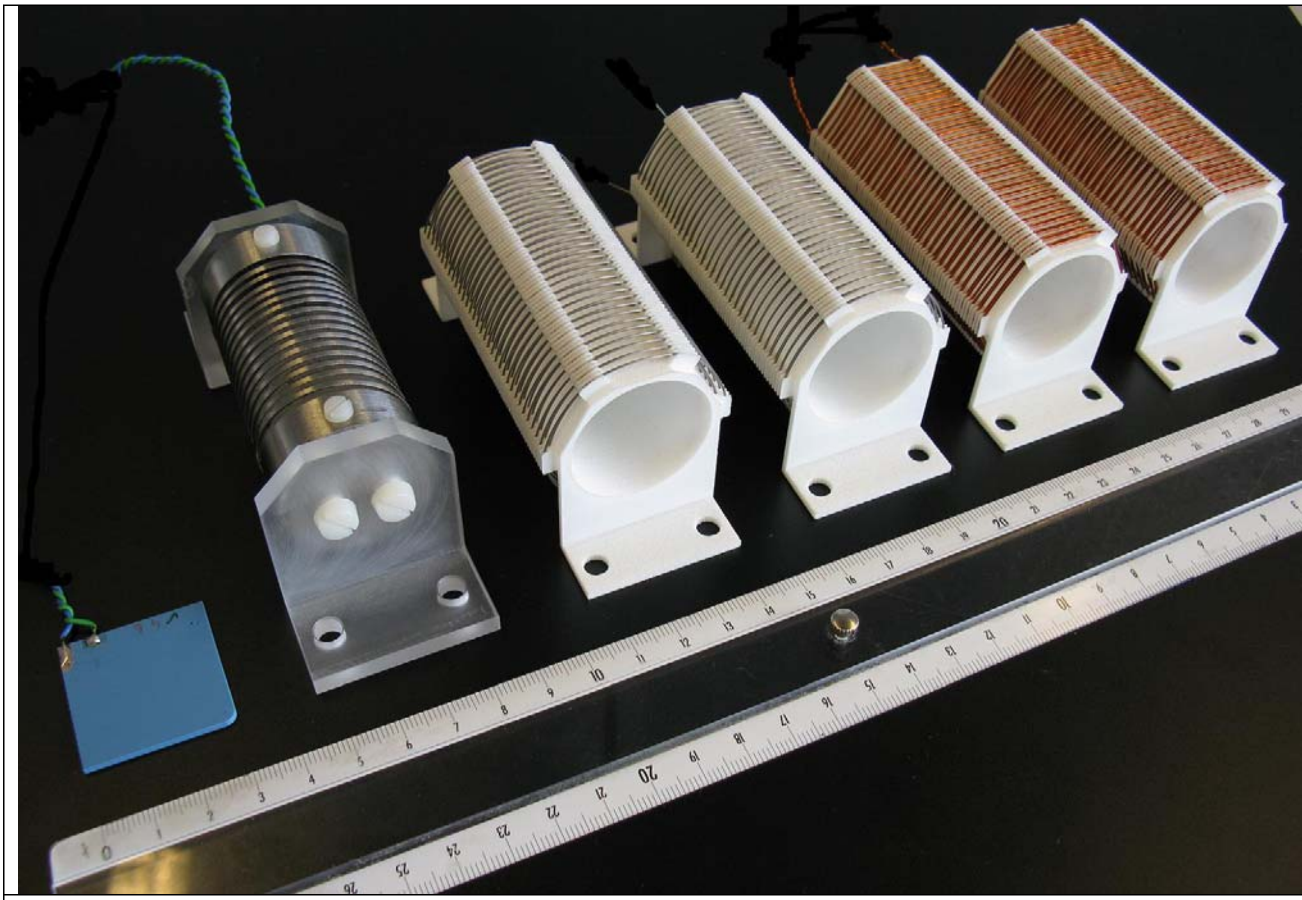

Figure6. Some examples of the high-frequency sensors being prototyped for ITER; from left to right: one LTCC sensor, one laser-cut non-conventional sensor, and four conventional Mirnov-type coils wound in tungsten and copper (two off, each with different grooving for the ceramic spacers).

D.Testa, Figure6

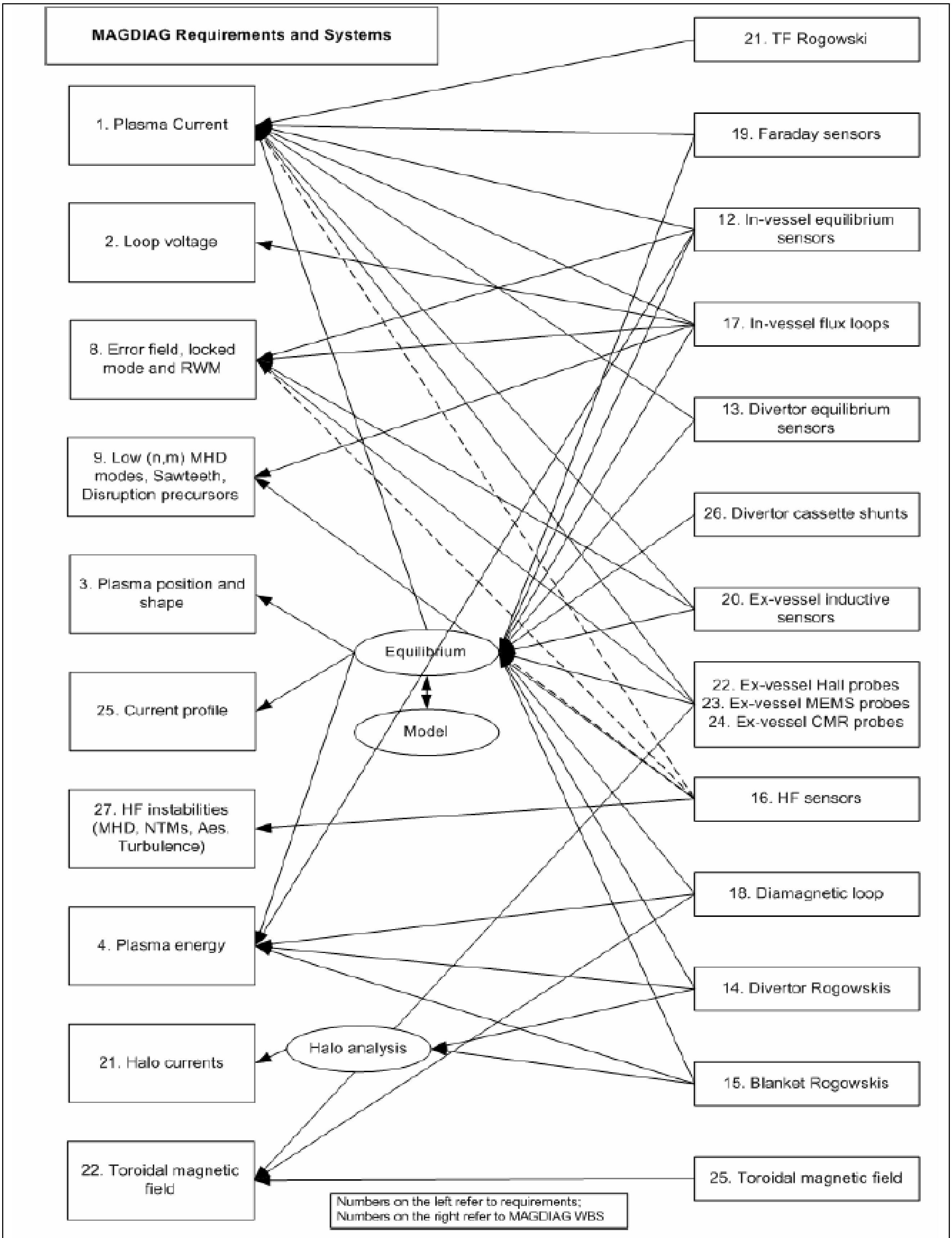

Figure7. The link between meeting in full the ITER measurement requirements for the magnetic diagnostic system and selecting the subsystems handled under WBS12-26; ellipses are intermediate treatment of the data generated by sensors on the route to meeting requirements.

D.Testa, Figure7

measurement type	number of sensor	rationale and main risks
in-vessel inductive probes for equilibrium reconstruction and real-time control	150 x Btangential	current standard method long-term failure, drifts, 3D effects (ferritic inserts, TBM), image currents (walls), noise
	72 x Bnormal	
	6 x Btoroidal	
in-vessel flux loops for equilibrium reconstruction and real-time control	4 full loops in 9 sectors	current standard method long-term failure, drifts, manufacturing, noise
	120 saddle loops	current standard method long-term failure, drift, 3D effects (ferritic inserts, TBM), image currents (walls), noise
in-vessel probes in the divertor region for reconstruction of the strike points and separatrix position	36 x Btangential	current standard method long-term failure, drift, 3D effects (divertor structures and coils), noise
	36 x Bnormal	
	1 x Btoroidal	
in-vessel sensors for high-frequency / high mode number MHD instabilities	>300 x Bpoloidal	current standard method long-term failure, frequency calibration, manufacturing, layout optimization, drifts, noise, 3D effects (passive structures, image currents)
	>100 x Bnormal	
in-vessel flux loops for low-frequency / low mode number MHD instabilities	72 saddle loops	
measurements of diamagnetic flux for stored energy	2-turns diamagnetic flux loop in 3 separate machine sectors 24 saddle loops	current standard method calibration, compensation for passive structures, drift, failure, 3D effects (ferritic inserts, TBM), image currents (walls), noise, ELMs (time resolution)
Rogowski coils for halo current measurements	360 for blanket modules	current standard method long-term failure, 3D effects (ferritic inserts, TBM), image currents (walls), noise
	60 in divertor	
ex-vessel inductive probes for equilibrium reconstruction (and real-time control?)	180 x Btangential	current standard method long-term failure, drifts, 3D effects (ferritic inserts, TBM), image currents, noise
	180 x Bnormal	
ex-vessel steady-state sensors for equilibrium reconstruction (and real-time control?)	60 x Btangential	new technology long-term failure, 3D effects (ferritic inserts, TBM), image currents, noise
	60 x Bnormal	
ex-vessel flux loops for equilibrium reconstruction	5 full loops	3D effects (ferritic inserts, TBM), image currents, noise
Rogowski coils inside TF coil casing to measure plasma current	9 TF coils fitted with these Rogowski sensors	current method, new location long-term failure, drifts, direct pick-up from TF
ex-vessel sensors using Faraday rotation method to measure plasma current	4 sensors in 3 machine sectors	new method, new location long-term failure, noise

Table1. The ITER magnetic diagnostic set: for each technique, the rationale behind its use and the primary risks to achieving the intended measurement performance are summarized.

D.Testa, Table1

WBS element	cost (k€)	effort (man-days)
WBS16.1 - System Management	0	1
WBS16.2 - Development	644	1381
WBS16.2.1 - Review and Plan	0	175
WBS16.2.2 - System Design	7	452
WBS16.2.3 - Component Design	0	150
WBS16.2.4 - Component Prototyping	534	552
WBS16.2.5 - Component Qualification	50	20
WBS16.2.6 - Design Decisions	53	32
WBS16.3 - Engineering Design	27	676
WBS16.3.1 - Mechanical Design	12	499
WBS16.3.2 - Electrical Design	15	177
WBS16.4 - Production	787	583
WBS16.4.1 - Contracting	18	137
WBS16.4.2 - Pre-series	128	117
WBS16.4.3 - Manufacturing	510	40
WBS16.4.5 - Test and Acceptance	131	289
WBS16.5 - Installation	103	225
WBS16.6 - Commissioning	93	907

Table2. Breakdown of assumed resources for the ITER HF magnetic system (WBS16).

D.Testa, Table2

ID	Risk	principal consequences	approach to mitigate or avoid
R.16.0	unknown	loss of identification of mode numbers and/or loss of frequency response	diversity of design and production, safety margin on number of sensors and thorough peer-review
R.16.1	poor grounding rules generating noise on cabling	noise at the low frequency end of the MHD spectrum	careful review of the signal and power cabling close to the tokamak
R.16.2	pick-up from in-vessel active currents not adequately compensated	noise at the low frequency end of the MHD spectrum; potential saturation of the front-end electronics	choice of location and precision of drawings of the active coils
R.16.3	excessive shielding not understood during design	poor calibration of the amplitude and phase at the high frequency end of the MHD spectrum	ensure that all design modifications are validated by MAGDIAG
R.16.4	inadequate number of sensors to meet requirements	uncertainty at the high-n spectrum, confusing physics interpretation	review the existing design
R.16.5	quality of welding of inaccessible components	excessive loss of sensors and consequent loss of (m,n) identification	mockups, tests and strong QA during installation
R.16.6	excessive statistical loss of sensors	loss of (m,n) identification	qualification, diversity of production and design
R.16.7	systematic loss of sensors within the allowed statistical levels (due to halo current effects, disruption forces)	loss of (m,n) identification	identify and reduce common mode failures
R.16.8	degradation of performance following irradiation	loss of (m,n) identification	qualification, diversity of production and design

Table3. Principal identified risks for the ITER HF magnetic system (WBS16).

D.Testa, Table3