THE MAGNETIC DIAGNOSTIC SET FOR ITER

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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

I. INTRODUCTION

Efficient commissioning and successful operation of ITER require an extensive and reliable set of magnetic diagnostics. 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 diagnostics include measurements of fields, fluxes, plasma current and diamagnetic flux made inside and outside the vacuum vessel. This system is a standard for all operating tokamaks and the spread of knowledge is large [1]. However, there are specific challenges related to developing such diagnostics to provide all the required functions for ITER: gamma, neutron, radiation and thermal effects on the sensors and cabling, long-pulse integration and drift compensation for the ex-vessel electronics, and long-term access-free reliability for maintenance. The present design of the ITER magnetic diagnostic system is summarized and the R&D work underway to meet some of these challenges is also outlined.

II. ITER MEASUREMENT REQUIREMENTS FOR MAGNETICS

The detailed requirements for the magnetic sensors needed to meet the multiple purposes of this diagnostic system in ITER are well established [2, 3], as presented in Table1. These cover measurement capabilities, diagnostic functionalities and safety issues, and are summarized in the following sub-sections.

A. Measure the magnetic fluxes and fields around the plasma for reconstruction of the magnetic equilibrium.

As in all current tokamaks, values of local magnetic fields and fluxes will be 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 (real-time for protection/control, post-pulse for data analysis). These flux and field measurements are made inside and outside the vacuum vessel. 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. Together with measuring the magnetic fields and fluxes in the poloidal plane, the variation in the toroidal flux also provides information on the plasma stored energy and a direct estimate of the toroidal field. Furthermore, the same magnetic diagnostic set has to provide the non-axis-symmetric field distribution, 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.

TABLE I. 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.

Measurement	Number	Rationale & Risks
in-vessel inductive probes: equilibrium reconstruction, real-time control	150 $B_{tangential}$	current standard method long-term failure, drifts, 3D effects (walls), noise
	72 B_{normal}	
	6 $B_{toroidal}$	
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 (walls), noise
in-vessel probes in the divertor region	36 $B_{tangential}$	current standard method long-term failure, drift, 3D effects (divertor), noise
	36 B_{normal}	
	1 $B_{toroidal}$	
in-vessel sensors for high-frequency MHD	>300 $B_{poloidal}$	current standard method long-term failure, frequency calibration, manufacturing, layout optimization, drifts, noise, 3D effects (passive structures, image currents)
	>100 B_{normal}	
in-vessel flux loops for low-frequency MHD	72 saddle loops	
diamagnetic flux for stored energy	24 loops	current standard method calibration, compensation for passive structures, drift, failure, 3D effects, noise
Rogowski coils for halo current measurement	360 blanket	current standard method long-term failure, , noise
	60 divertor	
ex-vessel inductive probes: equilibrium reconstruction (and real-time control?)	180 $B_{tangential}$	current standard method long-term failure, drifts, 3D effects (walls), noise
	180 B_{normal}	
ex-vessel steady-state sensors for reconstruction and real-time control	60 $B_{tangential}$	new technology long-term failure, 3D effects (walls), noise
	60 B_{normal}	
ex-vessel flux loops for equilibrium reconstruction	5 full loops	current standard method long-term failure, drifts, 3D effects (walls), noise
Rogowski coils inside TF coil casing	9 coils fitted	current method, new location long-term failure, drifts, direct pick-up from TF
ex-vessel sensors using Faraday rotation method	4 sensors in 3 sectors	new method, new location long-term failure, noise

In addition to the conventional Mirnov-type and flux-loop sensors, other techniques are being considered for application to the ITER long-pulse operation. As two specific examples, R&D studies are being performed on steady-state Hall probes and on sensors made on a sintered stack of ceramic layers with printed metallic lines (low temperature co-fired ceramic: LTCC technology), for low- and high-frequency application. Figure1 shows some examples of these sensors, as currently prototyped.

B. 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. Thus, when placed outside the vacuum vessel, this loop signal includes the current flowing in the wall, and the measurement is affected by precise knowledge of these currents. Older tokamaks installed specific Rogowski coils to measure the loop-integrated current. Poloidal field measurements are now currently used to create a *virtual Rogowski* coil by a weighted sum of the individual data, which is also the present ITER plan. Nonetheless, conventional Rogowski coils are being developed to sit inside the TF coil casings at liquid Helium temperature and a fiber-optic Faraday rotation measurement device is under development, resulting from a collaboration between SCKCEN and CEA-Cadarache. The first measurements have been recently carried out on Tore Supra and are promising, as they do not need integration [4].

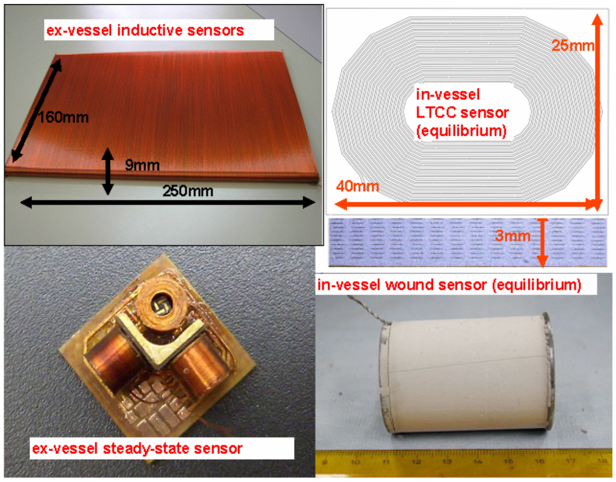

Figure 1. *Four examples of magnetic sensors being currently prototyped.*

C. Measure the currents flowing between the plasma and the vacuum vessel walls – halo current analysis.

The main interest in the *halo currents* 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. The main issue for installation on ITER is feasibility, as the number of sensors implies a very large amount of additional wiring.

D. Measure the fast fluctuations in the equilibrium magnetic field driven by magneto-hydro-dynamic instabilities.

MHD activity drives (non axis-symmetric) magnetic field fluctuations at frequencies much higher than the plasma skin-depth. Hence, 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 $|n|\leq 30$ and $|m|\leq 60$, respectively, up to frequencies above 300kHz. Various technologies are being considered to perform this task [5]: wound inductive sensors of conventional, Mirnov-type design, laser-cut non-conventional Mirnov-type and LTCC sensors; fig2 shows some of these prototypes. The spatial distribution of these sensors will also need to be carefully optimized to satisfy the ITER measurement requirements [5, 6].

E. 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, in real-time and for more detailed post-pulse analysis. Given the many specific difficulties of 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.

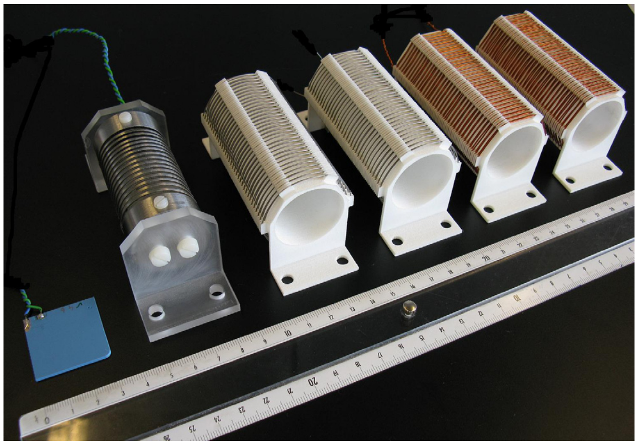

Figure 2. *Some of the high-frequency sensors being prototyped for ITER: LTCC and laser-cut non-conventional sensors, conventional Mirnov-type coils wound in tungsten and copper (two off, each with different grooving).*

F. *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 and the n=1 tilting instability. 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: specific algorithms need to be devised to compensate for such distortions. The remaining part of equilibrium control, 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 *Synchronous Databus Network* allows the signals, feedback controllers and power supplies to communicate efficiently for plasma control.

G. *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 magnetic energy of the plasma current itself and the 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 is 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 the availability and reliability over the life-time of ITER.

III. 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 specific environmental conditions of ITER. These have been the subject of continuing R&D activities.

A. *Long pulse length.*

This challenge to current standard electronic integrators has been adequately addressed over the last few years [7]. Much attention is required, particularly because spurious EMF due to radiation or thermal effect can make this a very critical issue.

B. *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 and will have to be confirmed by future radiation testing on dedicated facilities.

C. *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. 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.

D. *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 [8]. The neutron-induced effects are well understood, but the often dominant effects caused by γ's 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 were also included in the baseline system design to mitigate this source of errors.

E. *Thermally induced EMF.*

Cables subject to temperature gradients along their length produce a non-zero thermo-electric EMF due to manufacturing imperfections [9]. 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 [10].

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 considered.

IV. THE PRESENT MAGNETICS 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. This large number of sensors for the ITER magnetic diagnostic system is driven by several considerations.

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 3. Second, multiple non equi-spaced arrays of sensors are needed to resolve unambiguously the predicted spectrum of MHD fluctuations to satisfy the ITER measurement requirements. 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. Fourth, steady-state and non-inductive sensors must be installed ex-vessel to mitigate the risks related to radiation and thermally induced EMFs, therefore duplicating in many aspects the in-vessel measurements. 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.

V. 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 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.

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