Thermo-Mechanical Instrumentation of the ITER Magnets' Structures

A. Poncet, F. Rodriguez-Mateos, S. Brun, A. Foussat, R. Gallix, J. Knaster, F. Simon

Abstract—**The ITER superconducting magnet structures (Toroidal Field coils (TF), Central Solenoid (CS), Poloidal Field coils (PF), Correction Coils (CC) and Feeders), representing a total weight of approximately 10 000 tons, are submitted to gravitational and seismic forces, stresses induced by constrained thermal contractions during cool-down from 300 K to 4.5 K, and large Lorentz forces in the superconducting coils. Although not classified as Safety Important Class (SIC) components, the sensors (stress, displacements, thermometers) used to monitor the thermo-mechanical behaviour of the structures are important diagnostic means to assess the designs, give support to operation and survey possible fatigue effects over the 20 years lifetime of the tokamak. Environmental operating conditions are unique and severe. Sensors and their wiring have to operate under cryostat vacuum ($<10^{-4}$ Pa total gas pressure), under magnetic inductions of several Tesla, at low temperature (4.5 K), in presence of a neutron fluence in the order of 10^{22}n/m^2 and a maximum associated gamma dose of 10MGy over a period of 20 years. In addition, the fast and slow cycling of very large currents in the superconducting magnets and plasma generate large eddy currents, thus heat loads and electro-motive forces (voltages) in the various parts of the structures, and a large electro-magnetic noise. The design philosophy and the choice of sensor technologies, some of which are at the frontier of present technology and as such require development in collaboration with industry, are presented that satisfy objectives and severe working conditions. Specifically, the near to 1 000 measuring points for thermo-mechanical data of the ITER magnet structures will rely for 20% on "classical", copper-wired technologies, and for 80% on specially developed optical fibre-based sensors.**

***Index Terms*—Superconducting magnets- Instrumentation-Optical sensors**

INTRODUCTION

The superconducting magnets of the ITER tokamak (Fig. 1.) are cooled with supercritical helium at 5 K. They operate with electrical currents of up to 68 kA and produce time-controlled varying magnetic fields peaking at 5 T in volumes of several hundred cubic meters, 13 T locally. The large electro-magnetic forces that undergo the magnet structures lead to high stresses and displacements. In addition to the electromagnetic loads the magnets are submitted to thermal contraction stresses and displacements, and seismic events. Furthermore the ITER machine is designed to operate in a cycling mode for 20 years, during which eventual fatigue effects and damage to the structures must be surveyed. Therefore about 1000 measuring points for temperature (5-300 K), very small displacement (< 0.1 mm), long range multi-millimeter displacements, and strains (up to 10'000 micro-strain) are considered necessary to survey and monitor the behavior of the magnet structures throughout the lifetime of the Tokamak. The primary aim is to monitor the behavior of the structure during the life-time of the machine and reveal eventual fatigue effects under cyclic loading. Measurements will be quasi static, with little or no constraint on the acquisition times. The secondary aim of the thermo-mechanical instrumentation is to verify the design under the various loads.

The necessary functional information concerning the thermo-mechanical instrumentation to be installed on the TF, CS, CC and PF coil mechanical structures is given in [1].

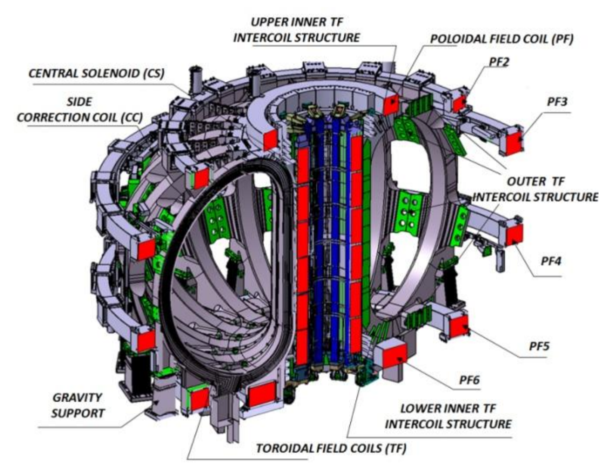

Fig. 1.Overview of the ITER superconducting magnet systems. The feeder lines are not shown.

I. INSTRUMENTATION STRATEGY

Instrumentation sensors will be installed on the magnet structures in locations of highest physical value to be expected from FEM simulations and analysis. The thermo-mechanical instrumentation is purely passive. The values of the structures' strains, displacements and temperatures will be acquired and checked at regular intervals, and no interlocking of the tokamak systems based on signals from sensors is foreseen. Furthermore, redundancy is not a compulsory requirement, as magnets are not part of the Safety Important Class (SIC). Despite this, the physical layout and the technologies retained for the instrumentation are chosen so that some partial redundancy subsists in case of sensor failure:

- Sensors locations respect the magnets' periodic repeatability or symmetry: if a sensor fails on a magnet structure, the generic information is available from other identical sensor in another symmetric location.

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- Sensors are selected among already well proven technologies given the environmental conditions (about 20% overall) such as resistive and capacitive units, together with new emerging techniques essentially relying on optical methods (about 80% of all measuring points), these having the advantage of being totally immune to electro-magnetic interference (e.m.i.).

Table 1 gives the number and types of sensors for each magnet family.

TABLE 1 Magnet System sensors

Magnet System	Measuring points	Strain gages	Displacement sensors	Temperature sensors
TFC	216	27	135	54
CS	202	81	44	77
CC	276	144	36	96
PF	30		24	6
Feeders	118		60	58
Total	842	252	299	291

II. ENVIRONMENTAL CONDITIONS

The ITER magnets thermo-mechanical instrumentation (sensors and wires), mechanically fixed, welded or glued on stainless steel structures, has to be compatible with the main cryostat vacuum (10^{-6} mbar). It is kept at cryogenic temperature (4 K) in operation but has to be resistant and active during thermal transients between 300 K and 4 K (50 cycles over ITER's lifetime). It should be insensitive to varying magnetic fields respectively of 5 T and 10 T/s, and it has to sustain high instantaneous gamma and neutron fluxes (a maximum of $10^{22}sec^{-1}m^{-2}$). The instrumentation system must still be operational up to an integrated dose rate of 10 MGray over its 20 years lifetime. Although not quantified yet, the environmental electro-magnetic (e.m.) noise around the instrumentation is expected to be very high; the sensor design has to take this e.m.immunity into account.

III. SENSORS AND TECHNOLOGIES

A. Displacement sensors

Small displacement sensors monitor relative shears and gaps between mating surfaces of the intercoil structures (Fig. 1) of rather small amplitudes (< 0.1 to 3 mm). Precisions of the order of ~10% of the measured value should be adequate. About 20 % of these measuring needs are covered by capacitive displacement sensors, tailor-made to fit in the available space and designed to deliver both shear and normal displacements of mating surfaces. Fabry-Perot (FP) or Fiber Bragg Grating (FBG) optical sensors of high precision (< 0.1 mm) and low range (e.g. less than 3 mm) monitoring only the shear between mating surfaces will be used for the remaining 80%.

The ITER magnet structures are subjected to large displacements during thermal transients (up to 80 mm) and under the action of Lorentz forces (up to 50 mm). Among the many direct and indirect ways to measure large displacements (several millimeters to centimeters) with the panoply of classical sensors, inductive sensors (LVDT) have to be ruled out because of the varying magnetic environment. Resistive potentiometer-based sensors exist on the market which can operate under the planned environmental conditions with the required precision and strokes fulfilling the specifications.
The remaining 80% will use optical sensors of various designs and physical principles, appropriate to their applicability (e.g. Laser-based Distance Meters (LDM) for long-based measurements and FP or FBG displacement sensors for local small and large displacements).

B. Strain gages

Strain gauges and glues usable in the environment described exist. For all identified measuring points simple uni-axial gauges are sufficient given that the principal directions are known and that the gravity loadings should be straight forwardly assessed. Four radiation-hard gages placed at 90 degrees along the principal directions, forming the four branches of a Wheatstone bridge, will compensate for thermal and magneto-resistive effects. As for resistive potentiometers, e.m.i. will be minimized with the use of 3 twisted pair wires and frequency modulation of the signal. The gages will be pre-assembled on a stainless steel plate that will be spot-welded on the structure. Resistive gages will cover 20% of the needs.

The remaining 80% will be covered by optical sensors based on FBG (Fiber Bragg Grating). This technology is today very mature, for instance massively used on civil engineering constructions, where its capacity to accept several gages on a single optical fiber is a great advantage. In the case of ITER, some successful applications in similar environmental conditions support the choice, if optical fibers and gratings can be shown to resist the radiation. As reported below, there is firm hope that this is the case today.

C. Temperature sensors

The temperature monitoring of the magnet structures has to cover the range 300 K down to 4 K. The required absolute precision on the measurement can be around 5% of the measured value. Cernox™ sensors from Lakeshore Ltd will be used from 4 to 300 K with the required precision over the whole range. They have a low magneto resistance, and are the best choice for applications with magnetic fields up to 30 T (for temperatures greater than 2 K). Cernox™ is resistant to ionizing radiation, and is available in robust mounting packages and probes. Cernox™ thermometers will cover 20% of the needs.

Temperature sensors based on optical fibers such as FP or FBG and Raman scattering of light are potentially of great interest in the present application: immunity to e.m.i., possibility to measure a large number of strain and temperature spots on a single fiber. However these technologies have not yet been proven to be able to reliably cover the low temperature range (< 50 K). This will suffice for temperature monitoring of most of the structures if

measurements are assured down to 10 K, thus covering 70-80% of the needs. For the remaining, Cernox™ sensors will be used instead.
Table 2 summarizes the sensor technologies that will be used, together with the required full measurement ranges and precisions.

TABLE 2 Summary of sensors technologies

Physical value	Capa-citive (triaxial)	Resistive (freq. modul. twisted pairs)	Optical FP or FBG displa-cement	Optical FP or FBG strain/temp	Optical LDM	Raman optical fibre
Small displacement	<3 mm <0.5%		20-40 mm < 0.5%			
Large displacement		80 mm 1 %	80 mm <0.5 %			
Long-base displacement					20 m <0.01%	
Strain		0.01 10^{-5}		0.01 10^{-5}		
Temperature		4-300 K 5%		20-300 K 5%		80-300K 5%

D. *Radiation resistant optical fibers and gratings*

As already said above, small sub-millimeter and long range centimeter displacements, strain and temperature measurements can be made by optical means. However these technologies rely on the existence of radiation resistant optical fibers and gratings.
Table 3 shows the types of fibers and associated wavelength required for the optical instrumentation:

TABLE 3 Optical fibers and type of light

Parameter	Number of sensors	Sensor technology	Optical fiber length (m)	Type of Fiber	Light
Small & large displacement strain & Temp.	250 250	FP FBG	12500 12500	MM	Visible 1550-1590 nm
Long-base displacement	5-20		1000	SM	Red
Raman Temperature	10		500	SM	1550 nm

Radiation resistant fibers (Multimode-MM- and Single Mode-SM-) exist on the market. Recent experiments conducted for CERN and ITER of MM and SM commercial radiation-hard fibers have shown that they are suitable for the ITER environmental conditions. Fig.2 gives results of RIA (Radiation Induced Absorption) tests as a function of irradiation dose for 3 categories of fibers. It has been verified that at dose rates of up to 5 MGrays (at least) there is no change of RIA trend for the fluorine-doped samples.
Concerning radiation-hard gratings, hydrogen or fluorine doped fibers show low FBG frequency shifts with radiation doses.

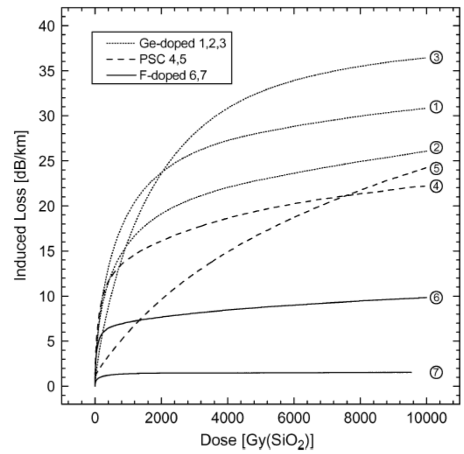

Fig. 2.Induced losses in irradiated (Co 60) commercial radiation-hard fibers as function of dose. Fluorine-doped fibers (curves 6,7) show practically no change in optical transmission.

In addition ITER will use in differential mode an FBG gage for temperature and radiation compensation connected in series with the strain or displacement sensing gage, thus alleviating any residual influence of radiation-induced frequency shift.

IV. Current Status of the Industrial Development

Although all sensors of the relevant technologies as summarized in Table 2 are well developed and can be found in industry, off-the-shelf sensors applicable to the harsh ITER environment do not exist. Therefore ITER IO has placed development contracts with specialized firms in the field of instrumentation, following call for tenders organized in two phases: a) development of prototype sensors adapted to the ITER environment and validation tests in near to real conditions (vacuum, cryogenic temperatures, radiation, sensitivity to e.m.i.), b) after validation of prototypes, final order of the series sensors.
At the time of this conference, phase a) is almost completed for most sensors.

A. *Resistive strain gages and potentiometers*

The corresponding contract has been placed with the firm HBM, Germany [3]. As illustrated in Fig. 3, commercial potentiometers and strain gages have been successfully adapted and vacuum tested down to 4 K and in a magnetic field up to 10 T.

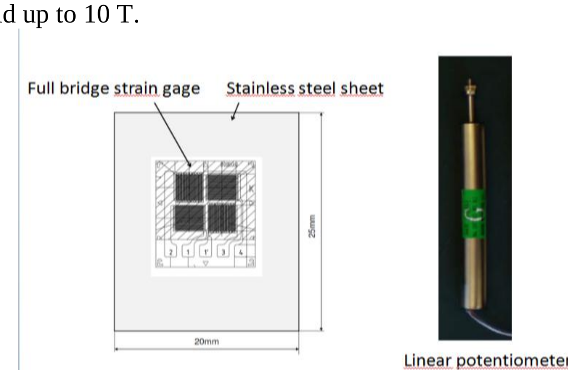

Fig. 3. An HBM full bridge 4 sensors strain gage pre-assembled on a spot-weldable stainless steel sheet (left), and a commercial linear displacement potentiometer adapted to ITER environment (right).

B. Capacitive bi-directional sensors

This contract has been placed with the firm Fogale, France [4].Bi-directional sensors use a tri-axial technology, whereby a dual receiver electrode, polarized at a frequency-modulated excitation level, is contained in a guard at the same potential, itself shielded by a ground potential shield (Fig. 4).

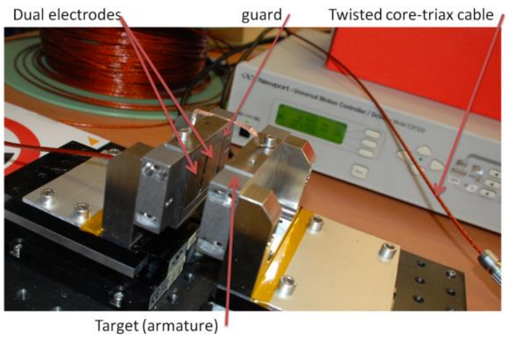

Fig. 4.Fogale-Nanotech bi-directional displacement capacitive sensor.

C. Optical sensors

A contract has been placed with the firm SMARTEC, Switzerland [5]. Fig. 5 below depicts an LDM sensor that will be used to acquire the length of the CS magnet (~15 m), a dual FBG strain gage and a large range FP displacement sensor. As for other technologies, the prototype development phase (phase 1) for optical sensors has been successfully completed, and all sensors tested at 80 K meet the ITER specification.

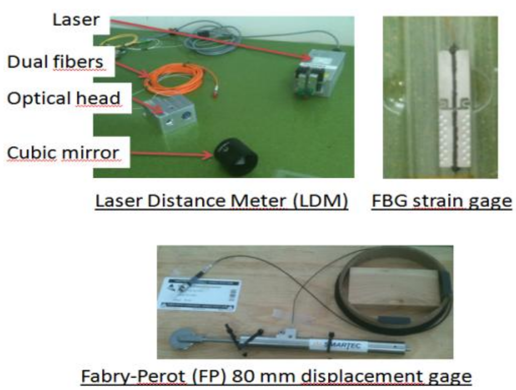

Fig. 5. A SMARTEC LDM long range (20 m) displacement gage (top left), a dual FBG strain gage assembled on a spot-weldable stainless steel sheet; it uses a temperature and radiation compensation FBG gage (top right).A large displacement FP displacement gage (bottom).

V. Wiring Feedthroughs and Data Acquisition

The wiring of the various sensors will respect a number of principles:

- Twisted pairs (shielded and grounded) to reduce e-m noise. The wires will be introduced in long ducts; they must therefore be mechanically resistant
- Polyimide wire insulation (or other radiation resistant, halogen-free material)
- Flexible annealed copper conductors of minimal cross-section (but adapted to the required sensor currents
- Polyimide coated optical fibers encapsulated in a PEEK sheath

Feeder ducts (e.g. one per pair of TF coils) will connect the cryostat to a feedthrough box located at the most outward extremity of the ducts; these feeders provide the routing of the utilities (current, cryogens, instrumentation, etc.) from the outside galleries of the tokamak to the magnets, through the cryostat wall and outer shielding.

Two of the feeders, solely dedicated to instrumentation, will be used to route the thermo-mechanical instrumentation wires from the structures. The vacuum tight feedthroughs for the instrumentation wires will be installed on the cryostat feed through box. There will be 2 sets of feedthroughs, one per feeder box dedicated to instrumentation, each containing between 500 and 1200 insulated pins onto which instrumentation wires will be soldered.

One central measuring unit per type of sensors, interfaced with the machine control computers, will monitor the instrumentation signals, which will be delivered in engineering units. This central unit will optionally be linked to satellite units (one per feeder) in order to reduce the amount of cabling. Signals of individual sensors could be multiplexed by groups on amplifiers located in these units; simultaneity of data acquisition from the sensors is not required.

The central measuring units will be interfaced via Profinet to standardized PLCs (Programmable Logic Controllers), themselves connected to a PSH (Plant System Host) computer via the CODAC (Control and Data ACquisition) networks of ITER.

VI. Acknowledgments

The recent developments in the domain of radiation-hard fibres realised by CERN and collaborating institutes have been a fundamental advantage at the start of this work. Authors express their highest gratitude to D. Ricci and T. Wijnands from CERN.

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