Fibre Optic Sensors for the Thermo-Mechanical Instrumentation of the ITER Magnets

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ABSTRACT

ITER will be the world's largest experimental facility to demonstrate the scientific and technical feasibility of fusion power. Fusion is the process which powers the sun and the stars. When light atomic nuclei fuse together to form heavier ones, a large amount of energy is released. Fusion research aims at developing a prototype fusion power plant that is safe and reliable, environmentally responsible and economically viable, with abundant and widespread fuel resources.

ITER is based on the "Tokamak" concept, in which the fusion fuel is contained in a doughnut-shaped vessel. The fuel— a mixture of deuterium and tritium, two isotopes of hydrogen—is heated to temperatures in excess of 100 million degrees, forming a hot gas "plasma". The plasma is kept away from the walls by a strong magnetic field produced by superconducting coils surrounding the vessel and an electrical current driven in the plasma.

The ITER superconducting coils and 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. The (strain, displacement, temperature) sensors used to monitor the thermo-mechanical behaviour of the structures have to operate under unique and very severe conditions (cryogenic temperatures, large magnetic fields, vacuum, high radiation doses and electro-magnetic noise). The near 1000 measuring points for thermo-mechanical data of the ITER magnet structures will rely for 80% on industry-developed optical, fibre-based sensors. These include sensors using the following technologies: Fabry-Perot, Fibre Bragg Grating, Distributed Raman Scattering and Laser Distance Meter.

ITER requires thermo-mechanical diagnostic sensors that do not exist for its specifically harsh environment, and a consistent development effort had to be undertaken by industry in collaboration with research institutes. The sensors design philosophy, arguments for the choice of specific optical sensor technologies, and significant results of the qualification programs of prototypes are presented in this paper.

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1 INTRODUCTION

The growing demand of energy from new sources has led the ITER consortium to develop new apparatus to demonstrate the scientific and technical feasibility of fusion power.

The ITER Tokamak, Figure 1, is composed of superconducting magnets cooled with supercritical helium at a temperature of 4.5 K. The superconducting magnets typically operate with electrical currents of up to 68 kA and can produce time-controlled, varying magnetic fields with peaks at 5 T in volumes of several hundred cubic meters. The huge ElectroMagnetic, (EM) forces that are applied to the Tokamak structure will lead to displacement and high stresses. Besides the EM forces the Tokamak structure will have to withstand the thermal-contraction displacement and stresses; potentially the structure should also withstand seismic events. Moreover the ITER Tokamak is designed to operate in cycling mode over a lifespan of 20 years, over which the effects of the fatigue and damage have to be monitored. A network of approximately 1000 monitoring locations for temperature, between 5 and 300 K, very small displacement, < 0.1 mm, large displacements in the order of several tens of millimetres, and strain, up to 10000 micro-strain, will be developed and installed with the aim to survey and monitor the behaviour of the structures over its whole lifetime in order to reveal potential fatigue effects under cycling loading. Measurement will be carried out in quasi-static regime, with little or no constraint on the acquisition time. The second aim of the monitoring network is to verify the Tokamak design under the various loads. The functional specification for the thermo-mechanical instrumentation to be installed on the TF, CS, CC and PF coil mechanical structures is given in [1, 2].

Within this necessity to design a monitoring network, Fibre Optic sensors, based both on Fabry Perot interferometry, FP, and on Fibre Bragg Grating technology, FBG, have been designed to meet and fulfil the project requirements in terms of sensitivity and measurement accuracy.

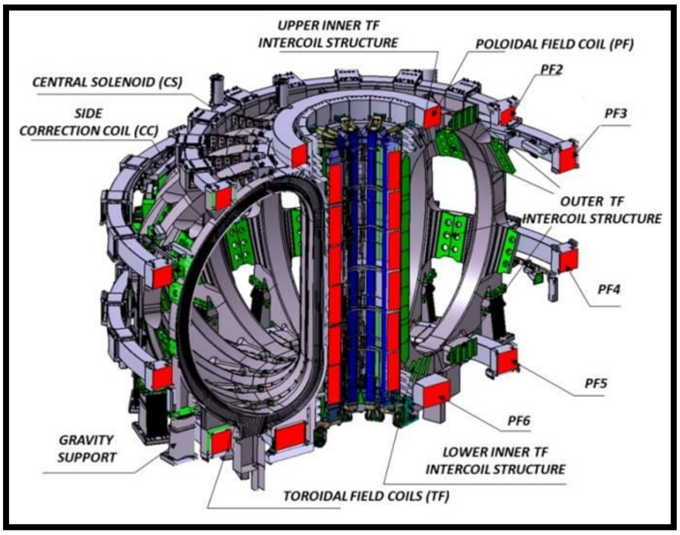

Figure 1. Overview of the ITER superconducting magnet system (feeder lines are not shown)

2 INSTRUMENTATION STRATEGY

The Fibre Optic sensors will be installed on the Tokamak's magnet structure at the locations where simulations and analyses predict the highest physical values. The structural parameters, temperature, strain and displacement will be acquired and checked at regular intervals; no interlocking of the Tokamak systems based on Fibre Optic sensor signals is foreseen. Although redundancy is not a compulsory requirement, since the magnets are not Safety Important Components (SIC), the final physical layout and technologies retained for instrumentation were chosen with the aim to keep a certain level of partial redundancy in case of sensor failure. The locations of Fibre Optic sensors respect the periodic repeatability or symmetry of the magnets: in case the sensor of a magnet structure fails, the generic information will still be retrievable from an identical sensor at a symmetric location. Fibre Optic sensors represent 80% of all measuring points, for a total number of approximately 800 sensors. The main reason their choice is the fact they rely on optical technologies, which have the advantage of being totally immune to electromagnetic interference.

In the next paragraphs the Fibre Optic sensors in use are presented together with some test results obtained during their development phase.

3 ENVIRONMENTAL CONDITIONS

The sensors and wires of the mechanical instrumentation of the ITER magnets will be welded or glued on the stainless steel structures; their mechanical fixation has to be fully compatible with the main cryostat vacuum, 10^{-6} mbar. During normal operation, the selected instrumentation will be constantly kept at cryogenic temperature, 4.5 K, but will have to be resistant and active during thermal transient between 300 K and 4.5 K; the predicted number of thermal cycles, during ITER's lifetime, is foreseen to be 100. Sensors and wires will have to be insensitive to constant and varying magnetic fields of 5 T and 10 T/s, respectively, and able to withstand high instantaneous gamma and neutron fluxes, with an expected maximum of 10^{22} $s^{-1}m^{-2}$. Besides these constraints the monitoring instrumentation will have to remain operational at an integrated dose of up to 10 MGy over ITER the 20 years lifetime. Although not quantified yet, the environmental EM noise around the instrumentation is expected to be very high; this aspect is not very relevant for the Fibre Optic sensors that present the advantage of being intrinsically immune at EMI.

4 SENSORS AND TECHNOLOGIES

To design a monitoring network capable of fulfilling the above mentioned technical requirements and at the same time to withstand the demanding environmental conditions, dedicated Fibre Optic sensors were developed. In particular two technologies appeared to be particularly suitable to achieve these monitoring goals:

- Fabry Perot Interferometry;
- Fibre Bragg Grating Technology.

A short presentation of the two technologies is given below [3].

4.1 Fabry –Perot Interferometry - FP

Extrinsic Fabry–Perot interferometers, EFPIs, consist of a capillary silica tube containing two cleaved optical fibres facing each other (Figure 2), leaving an air gap of a few micrometres or tens of micrometres between them. When light is launched into one of the fibres, a back-reflected interference signal is obtained. This is due to the reflection of the incoming light on the glass-to-air and on air-to-glass interfaces. This interference can be demodulated using coherent or low-coherence techniques to reconstruct the changes in the fibre spacing. Since the two fibres are attached to the capillary tube near its two extremities, with a typical spacing of 10 mm, the gap change will correspond to the average strain variation between the two attachment points.

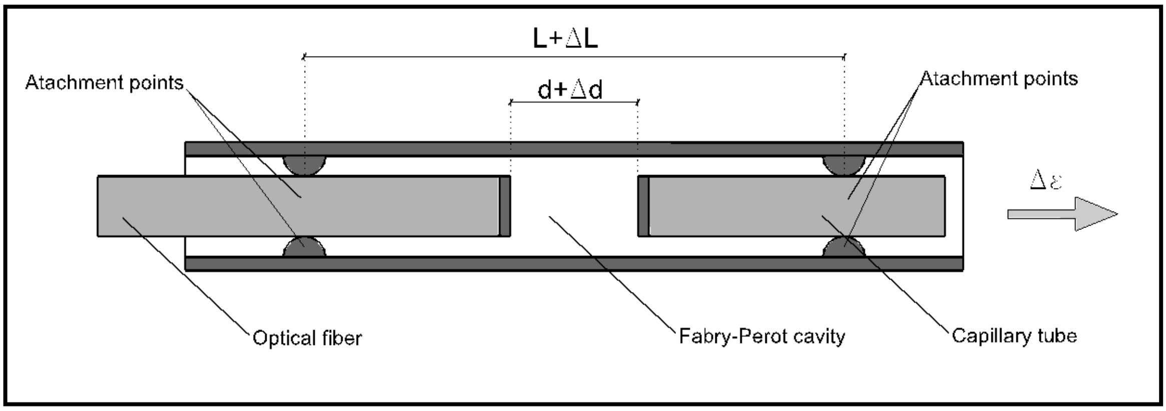

Figure 2: Functional principle of Faby-Perot sensors.

4.2 Fibre Bragg Grating Technology - FBG

Bragg gratings are periodic alterations in the index of refraction of the fibre core that can be produced by adequately exposing the fibre to intense UV light. The gratings produced typically have lengths of the order of 10 mm. If a tuneable light source is injected into the fibre containing the grating, then the wavelength corresponding to the grating pitch will be reflected while all other wavelengths will pass through the grating undisturbed, as depicted in Figure 3.

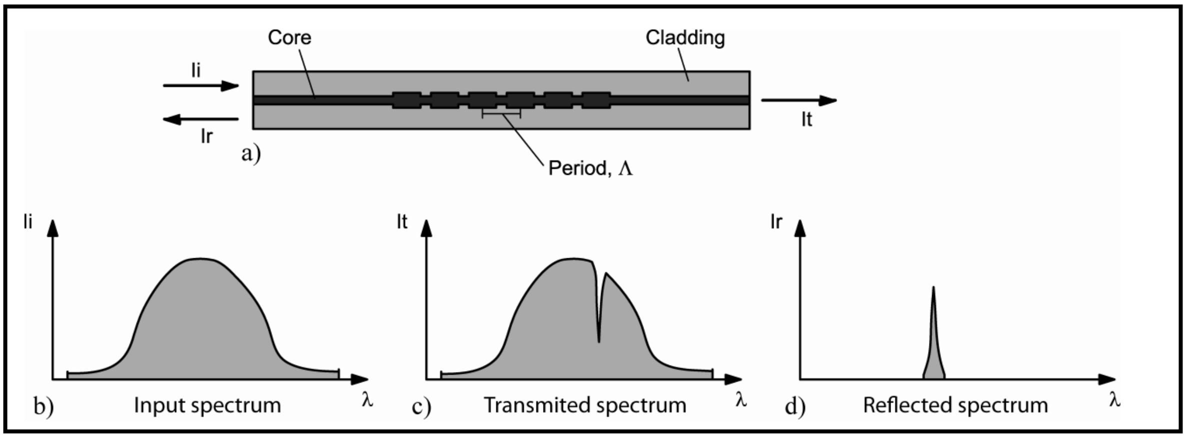

Figure 3. Functional principle of Fibre Bragg Grating sensors.

Since the grating period is strain and temperature dependent, it is possible to measure these two parameters by analysing the intensity of the reflected light as a function of the wavelength. This is typically done using a tuneable laser containing a wavelength filter, such as a Fabry–Perot cavity, or a spectrometer. Resolutions of the order of 1 με and 0.1 °C can be achieved with the best demodulators. If strain and temperature variations are expected simultaneously, then it is necessary to use a free reference grating that measures the temperature alone and use its reading to correct the strain values. The main interest in using Bragg gratings resides in their multiplexing potential. Many gratings can be written in the same fibre at different locations and tuned to reflect at different wavelengths. This allows the measurement of strain at different places along a fibre using a single cable. Typically, 4–16 gratings can be measured on a single fibre line. It has to be noted that, since the gratings have to share the spectrum of the source used to illuminate them, there is a trade-off between the number of gratings and the dynamic range of the measurements.

5 SENSORS AND RESULTS

The main target in developing Fibre Optic sensors based on FP and FBG technology was to meet the technical specifications requested within the ITER projects; the required sensors performances are summarized in Table 1.

Table 1. FO sensors requested performances

Fibre Optic Sensors specification	
Strain sensor	
parameter	**target performance**
strain range [microstrain]	0 to + 10’000 or -10’000 to 0 plus -3’000 for thermal contraction between 300 and 4 K
resolution	-
accuracy and stability	5%
operating temperature [K]	4 – 300
Small displacement sensor	
parameter	**target performance**
displacement range [mm]	0-3
resolution	-
accuracy and stability	10%, 0.1 mm
operating temperature [K]	4 – 300
Large displacement sensor	
parameter	**target performance**
displacement range [mm]	0-80
resolution	-
accuracy and stability	0.5 mm
operating temperature [K]	4 – 300
Temperature sensor	
parameter	**FBG target performance**
temperature range [K]	4 – 300
resolution	-
accuracy and stability	5% 15K @ 300K 0.2K @ 4K

5.1 Strain sensors

Nearly the 80% of the total sensors that will be installed on the ITER’s magnet, approximately 800 sensors, will be based on Fibre Optic technologies. To meet the ITER requirements, Table 1, a set of FP and FBG sensor was developed, Figure 4, and tested at different environmental conditions.

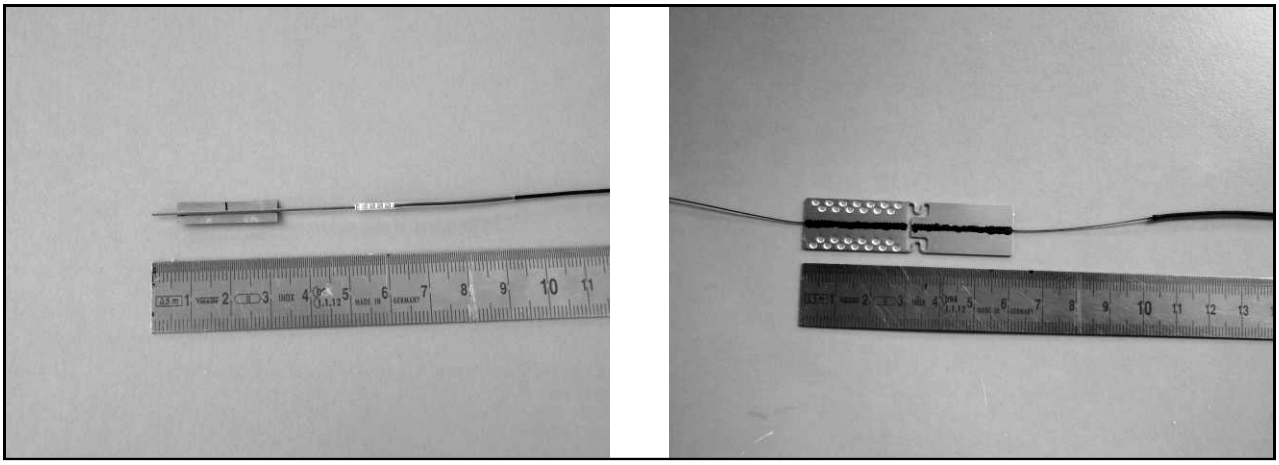

Figure 4. Fibre Optic strain sensors, FP left, FBG right.

After complete characterisation and qualification of the prototype sensors at room temperature (300 K), a second phase included the testing at liquid nitrogen temperature. In order to carry out a proper qualification, a dedicated testing facility was developed; the testing setup is composed of a cantilever beam where the sensors are mounted, installed in a cryostat cooled with liquid nitrogen.

Strain steps were applied with displacements controlled by a computer-controlled displacement table connected to the free end of the testing bar.

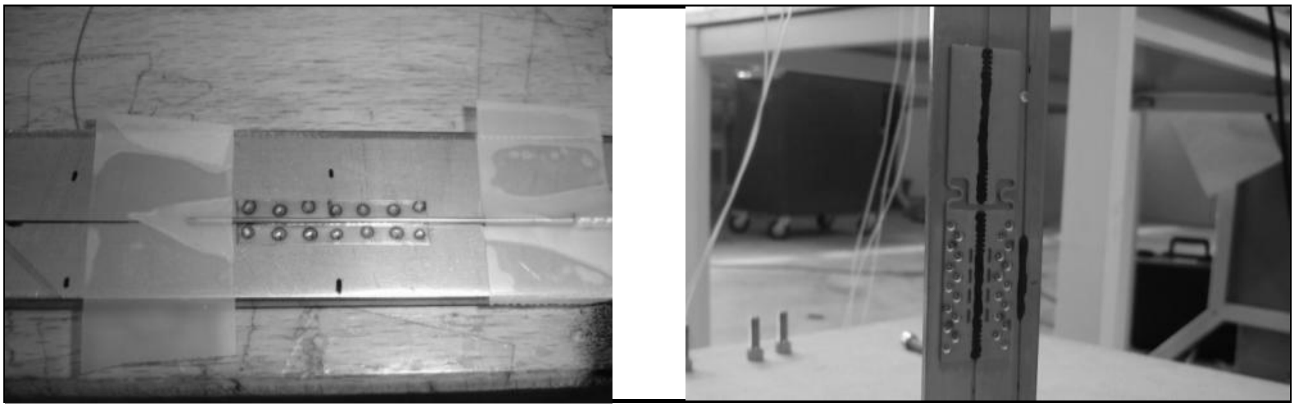

Figure 5. Fibre Optical strain sensors, FP left, FBG right, during testing.

In order to evaluate the strain resolution, strain steps were applied to the sensors spot-welded on the testing bar, using controlled displacements of the free end of the testing cantilever bar. The testing range is ±1000 micro strain. The applied strain is controlled with an external independent strain gage bonded to the bar that measures the relative strain steps. Temperature is controlled with a calibrated temperature probe. Five measurements at each strain step are considered for average and standard deviation calculations. Calibration of the strain sensors is done at room temperature. The results are presented in Figure 6.

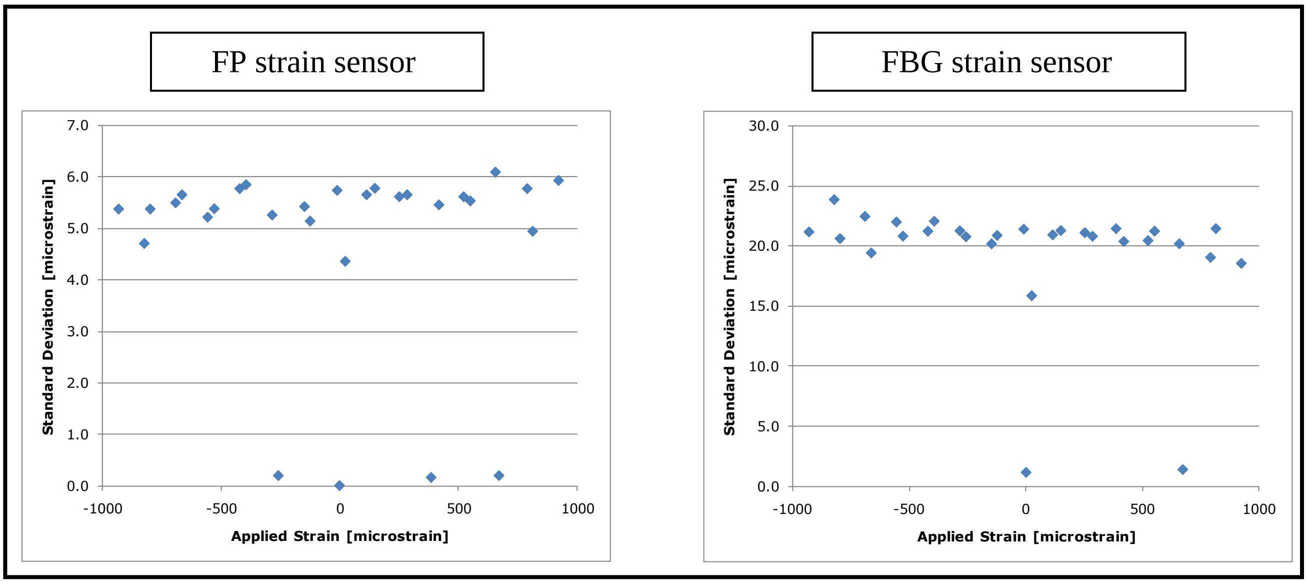

Figure 6. Strain resolution test results at nitrogen temperature.

The tested Fibre Optic strain sensors, both Fabry-Perot Interferometer and Fibre Bragg Grating, presented a strain resolution that made these sensors suitable for use in the ITER monitoring system development:

- Fabry Perot Interferometers: resolution around 6 microstrain.
- Fibre Bragg Grating: resolutions around 2 microstrain at Room temperature increasing to 23 microstrain at low temperatures. The increase on the resolution value at low temperatures is due to the deformation of the spectral response of the FBG sensor at these temperatures. The gluing process, thought to be the origin of the effect, was intensively studied, improved and tested afterwards with good results. The resolution at liquid nitrogen is now expected to be similar to the value obtained at room temperature.

During the testing campaign the measurement accuracy was tested as well. The results are presented in Figure 7.

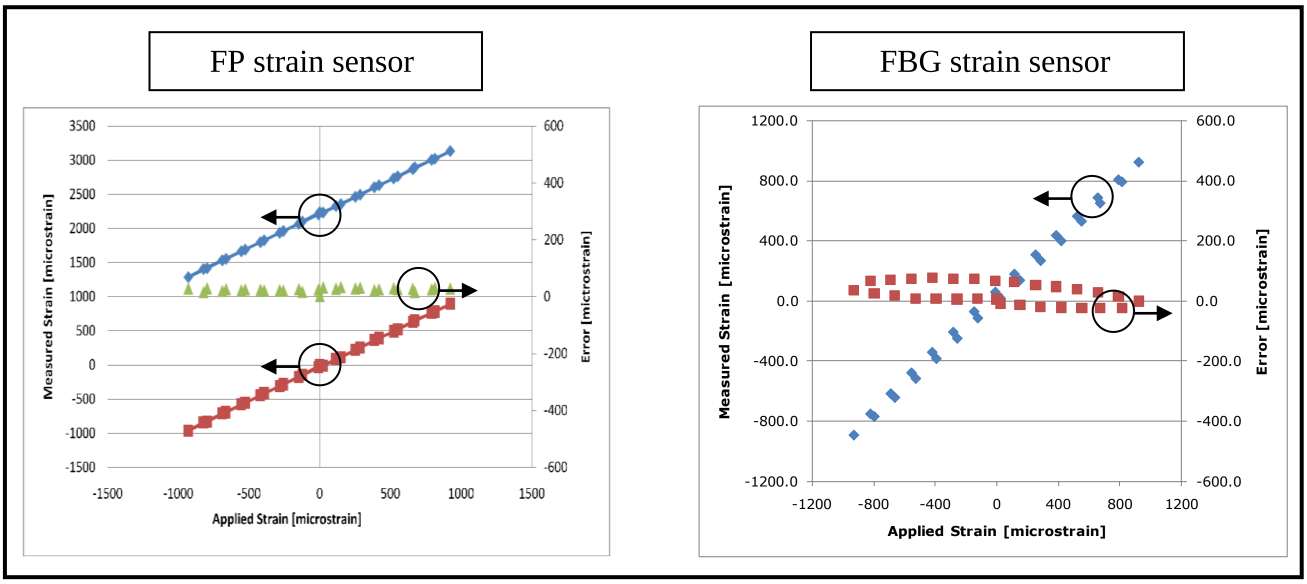

Figure 7. Strain accuracy test results at nitrogen temperature.

The tested Fibre Optic strain sensors, both Fabry-Perot Interferometer and Fibre Bragg Grating, presented a strain accuracy that overcomes the accuracy specified by ITER, in detail:

- Fabry Perot Interferometers: accuracy of the sensor at cryogenic temperature, after the thermal compensation, is below 30 microstrain.
- Fibre Bragg Grating: accuracy of the sensor at cryogenic temperature is 77 microstrain.

The two sensors thermal behaviour is different:

- Fabry Perot Interferometer: this sensor does not compensate for the effect of temperature shift on the sensor response as well as for the thermally induced strain on the support material.
- Fibre Bragg Grating strain sensor: this sensor is auto compensated for temperature effect on the sensors response and on the thermally induced strain on the support material.

It is to be highlighted that the accuracy was limited by hysteresis, probably due to the bending of the cantilever in the plastic range. This limitation is due to the construction of the testing setup. The accuracy evaluation with longitudinal strain applied without bending would yield better results for both sensors.

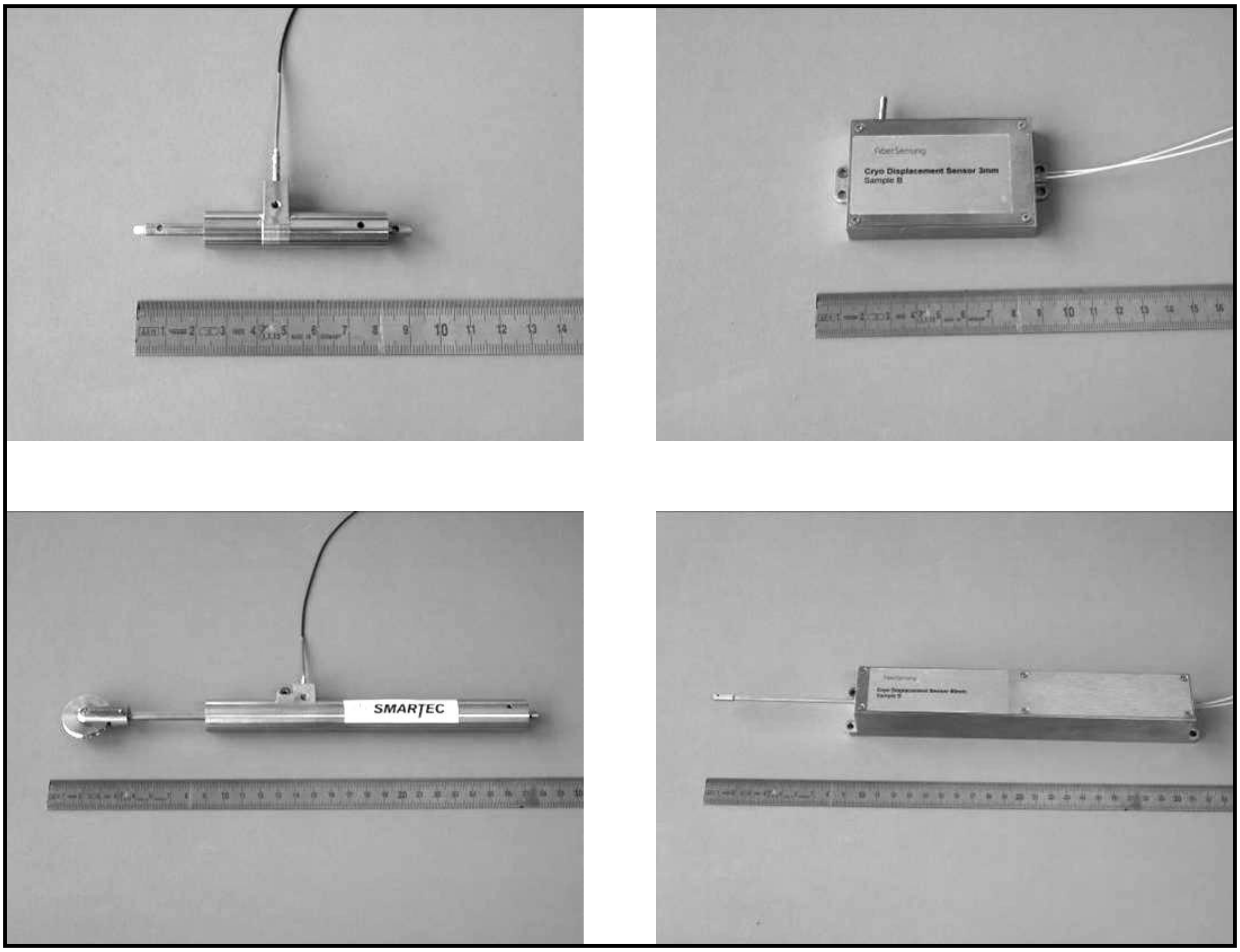

Figure 8. Fibre Optic displacement sensors, FP small displacement top left, FBG small displacement top right, FP large displacement bottom left, FBG large displacement bottom right

5.2 Displacement sensors

Small displacement sensors will have the main aim to monitor the small relative shears and shear gaps between the mating surfaces of the intercoil structures. Besides these small displacements, the ITER structures will have to withstand also large displacements, up to 80 mm during the thermal transient, and up to 50 mm under the action of Lorentz forces.

Nearly 80% of the total displacement sensors that will be installed on the ITER's magnet, approximately 500 sensors, will be based on Fibre Optic technologies. To meet the ITER requirements (Table 1) a set of FP and FBG sensors was developed (Figure 8) and tested at different environmental conditions.

After complete characterisation and qualification of the prototype displacement sensors at room temperature (300 K), a second phase included the testing at liquid nitrogen temperature.. In order to carry out a proper qualification a dedicated testing facility was developed. The cryostat consisted of a vessel where a movement actuating device was located and where the liquid nitrogen was poured. The movement actuator is fixed to the vessel. Outside the vessel, and on the bottom, thermal isolation was applied preventing fast heating of the setup and for user safety.

The sensors, installed on a suitable support that inhibits any movement, are cooled down to the testing temperature. When the temperature is stable, 10 measurements are taken. The calculated standard deviation of the measurement must be below the specified resolution. Displacement steps were applied by adding stainless steel calibrated shims between the sensor displacement bar and a fixed support (Figure 9).

Figure 9. Fibre Optic sensors during the testing campaign.

The tested Fibre Optic displacement sensors, both Fabry-Perot Interferometer and Fibre Bragg Grating, presented a displacement resolution that made these sensors suitable to be used in the ITER monitoring system development:

- small-range FOD, FP, 0-10 mm: within the target resolution of 0.002 mm.
- long-range FOD, FP, 0-40 mm: at room temperature the tested samples present values within the target resolution of 0.002 mm; at cryogenic temperature the tested sensors present values that typically match or slightly exceed the target resolution of 0.002 mm;
- small-range FOD, FBG, -3 mm to +3 mm: : at room temperature the tested samples present values within the target resolution of 0.001 mm; at cryogenic temperature the tested sensors present values that typically match or slightly exceed the target resolution of 0.001 mm. Moreover within an interval of 3 mm, as per ITER requirement, the tested sensor presents a resolution that is within the target of 0.001 mm;

- long-range FOD, FBG, 0-80 mm: The tested samples provide a typical resolution of 0.02mm, higher than the target resolution.

During the testing campaign the measurement accuracy was tested as well. The collected results are presented in Figure 10.

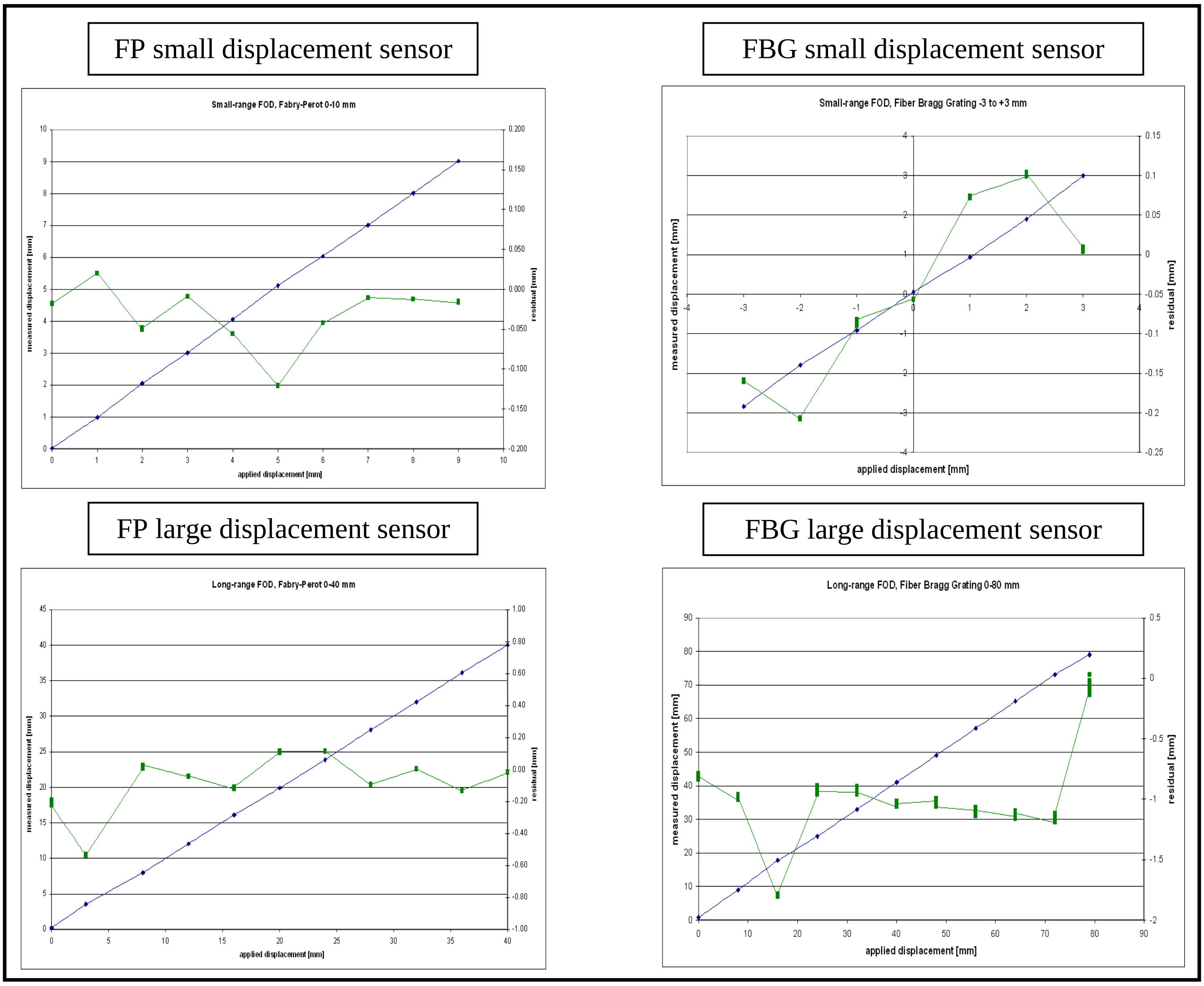

Figure 10. Displacement accuracy test results at nitrogen temperature. Sensor response and error compared to the true value are depicted for each type of sensor

The tested Fibre Optic displacement sensors, both Fabry-Perot Interferometer and Fibre Bragg Grating, presented a displacement accuracy that matches the accuracy specified by ITER:

- small-range FOD, FP, 0-10 mm: within an interval of 3 mm, as per ITER requirement, the tested sensor presents an accuracy that is within the specified 0.1 mm;
- long-range FOD, FP, 0-40 mm: this sensor was tested in a displacement range between 0 and 40 mm. The specified 0-80 mm displacement sensor uses the same design, with the addition of a pulley (cabestan) to double the stroke. This addition does not affect the results. Within the tested range the sensor presents an accuracy that is within the specified 0.5 mm;
- small-range FOD, FBG, -3 mm to +3 mm: within an interval of 3 mm, as per ITER requirement, the tested sensor present an accuracy that is within the specified 0.1 mm;

- long-range FOD, FBG, 0-80 mm: except for 2 steps, corresponding to 2 different applied displacements during the test, the slope of the calculated regression line is constant and matches the ITER specifications. Additionally an offset was observed; this induced offset let the sensor out of the required target for absolute accuracy. This offset can be explained either by a mechanical asymmetry that led to a slightly different behaviour of the two FBGs, or a different thermalization of the 2 FBG within the sensor, that have differently reacted to the cooling down of the whole sensor.

5.3 Temperature sensors

The temperature monitoring of the magnet structures needs to cover the range from 300 K down to 4.5 K. The required absolute precision on the measurement should be of the order of 5% of the measured value. Temperature sensors based on Fibre Optic technologies are of great potential interest in this application because they are immune to EMI.

This led to the development of a set of FP and FBG sensors to meet the ITER requirements (Figure 11).

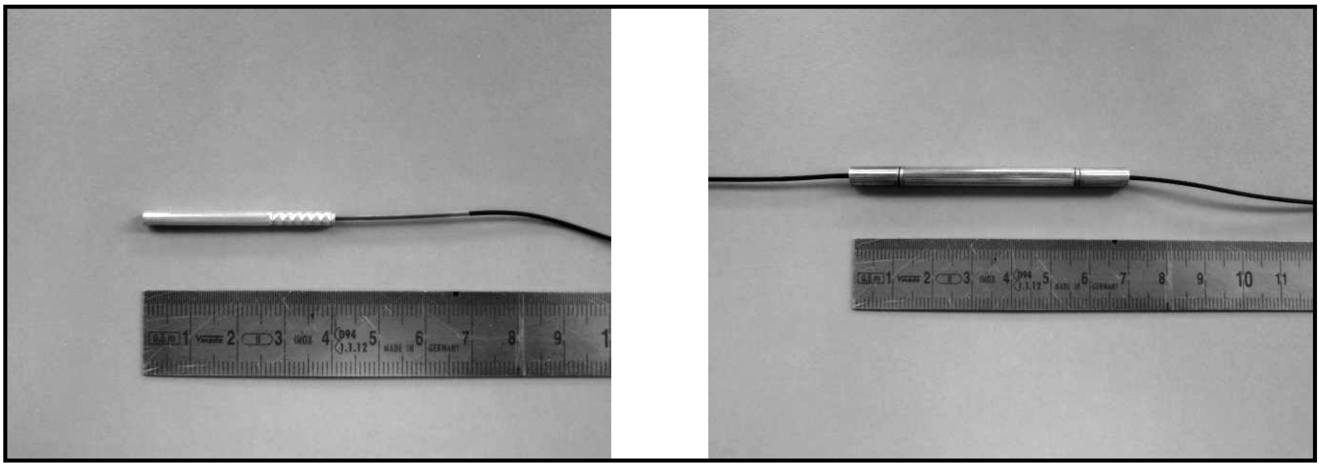

Figure 11. Fibre Optic temperature sensors, FP left, FBG right.

Different prototypes were implemented and different material substrates were tested, with results which do not currently match all ITER specifications, in particular for temperatures below 20 K. It is possible that a refined design, improved calibration and temperature pre-cycling procedures would significantly improve the sensor performance. It is however difficult to foresee that the required accuracy of 0.2K at 4K can be reached.

It is nevertheless likely that the ITER specification can be met if a cross calibration with a classical electrical sensor at 4 K can be made in operation. This would be useful if the electrical sensors are affected by noise or drift due to the presence of strong EM disturbance that do not affect optical fibre sensors. In this case a combined use of electrical and optical sensors would be meaningful.

5.4 Radiation-resistant Optical Fibres and Gratings

As exposed, in the final monitoring design a number of approximately 800 sensors, between strain, displacement and temperature, based on Fibre Optic technologies will equip the ITER magnets structures. The Optical Fibre necessary to develop this monitoring network can be estimated to be approximately 25 km. In order to provide an effective and durable system both sensor and fibre optics shall be developed relying on radiation-resistant optical fibres and gratings.

Nowadays Multi Mode (MM) and Single Mode (SM) fibres exist on the market. Recent measurements conducted on commercial MMF and SMF, carried out for CERN and ITER, have shown that these fibres are suitable for the demanding environmental conditions of the ITER project. In Figure 12 the test results of the Radiation-Induced Absorption, RIA, as a function of the irradiation dose for three categories of fibres are presented. It has been verified that a dose level of up to 5 MGy does not change the RIA trend for fluorine-doped samples [4]. Concerning radiation-hard gratings, hydrogen or fluorine doped fibres show low FBG frequency shifts with the radiation dose. In addition, for temperature and radiation compensation, it was decided to use a FBG sensor, connected in series with the strain or displacement sensors, in order to reduce any residual influence of radiation induced frequency shifts.

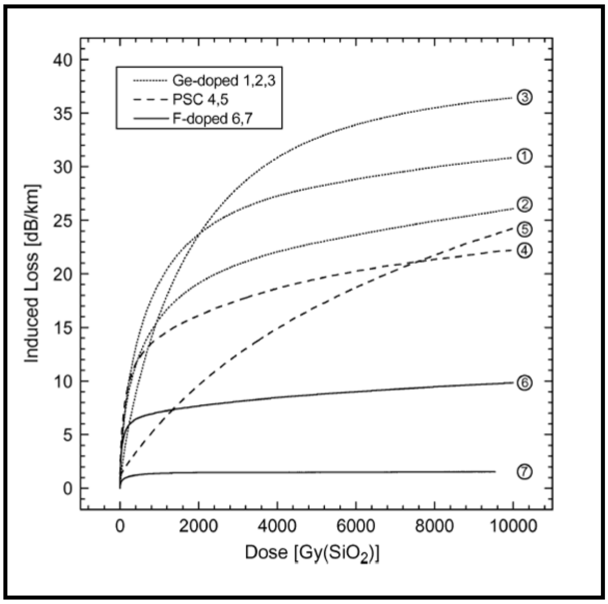

Figure 12. Induced losses in commercial radiation-hard fibres according to the radiation dose (Co-60). Fluorine-doped fibres (curves 6 and 7) show almost no change in optical transmission.

5.5 Data Acquisition

One central measurement unit per sensor typology will be installed and will be used to monitor the instrumentation signals. The central measuring unit will be interfaced via Profinet to standardized Programmable Logic Controllers, PLCs, themselves connected to a Plant System Host, PSH, computer via the Control and Data Acquisition networks of ITER, CODAC.

6 CONCLUSIONS

The sensors design philosophy, arguments for the choice of specific optical sensor technologies, and significant results of the qualification programs of prototypes have been presented in this paper.

The presented results, collected during the design and testing phases, show the suitability of these sensors in the implementation of a monitoring network for the demanding ITER environment.

The next phases, in the sensors development schedule, include full testing at 4.5 K both for strain, small displacement and temperature sensors. Part of these tests has already been carried out at CERN but is not presented in this paper. Besides these mechanical tests, a complete radiation resistant qualification will be carried out.

7 ACKNOWLEDGMENTS

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"The views and opinions expressed herein do not necessarily reflect those of the ITER Organization."

REFERENCES

[1] A. Poncet, F. Rodriguez-Mateos, "Thermo-Mechanical Instrumentation of the TFC, CS, PFC Magnet Structures", Functional Specification; ITER Internal Document, Reference ITER_D_2_LHDXW

[2] A. Poncet, S. Brun, A. Foussat, R. Gallix, J. Knaster, F. Rodriguez-Mateos, F. Simon, "Thermo-Mechanical Instrumentation of the ITER Magnet Structures", 22nd Magnet Technology Conference 2011, Marseille, France

[3] B. Glisic, D. Inaudi, "Fibre Optic Methods for Structural Health Monitoring", John Wiley & Sons Ltd, 2007

[4] T. Wijnands, L.K. De Jonge, J. Kuhnhenn, S.K. Hoeffgen, U. Weinand, "Optical Absorption in Commercial Single Mode Optical Fibers in a High Energy Physivs Radiation Field", *IEEE Transactions on Nuclear Science,* Vol. 55, No. 4, August 2008.