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## Cryogenic instrumentation for ITER magnets

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# Cryogenic instrumentation for ITER magnets

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**Abstract.** Accurate measurements of the helium flowrate and of the temperature of the ITER magnets is of fundamental importance to make sure that the magnets operate under well controlled and reliable conditions, and to allow suitable helium flow distribution in the magnets through the helium piping. Therefore, the temperature and flow rate measurements shall be reliable and accurate. In this paper, we present the thermometric chains as well as the venturi flow meters installed in the ITER magnets and their helium piping.

The presented thermometric block design is based on the design developed by CERN for the LHC, which has been further optimized via thermal simulations carried out by CEA. The electronic part of the thermometric chain was entirely developed by the CEA and will be presented in detail: it is based on a lock-in measurement and small signal amplification, and also provides a web interface and software to an industrial PLC. This measuring device provides a reliable, accurate, electromagnetically immune, and fast (up to 100 Hz bandwidth) system for resistive temperature sensors between a few ohms to 100 k $\Omega$ .

The flowmeters (venturi type) which make up part of the helium mass flow measurement chain have been completely designed, and manufacturing is on-going. The behaviour of the helium gas has been studied in detailed thanks to ANSYS CFX software in order to obtain the same differential pressure for all types of flowmeters. Measurement uncertainties have been estimated and the influence of input parameters has been studied. Mechanical calculations have been performed to guarantee the mechanical strength of the venturis required for pressure equipment operating in nuclear environment. In order to complete the helium mass flow measurement chain, different technologies of absolute and differential pressure sensors have been tested in an applied magnetic field to identify equipment compatible with the ITER environment.

## 1. Introduction

CEA-SBT has been contracted to supply ~2300 thermometric chains and 277 venturi tube flowmeters (since December 2013 and June 2014 respectively) to the Magnet Division of the ITER Organization. This instrumentation will be used to operate the superconducting magnets of the ITER tokamak. Safe operation of large superconducting magnets in the range of 4 K requires a precise and reliable measurement of the temperature and the flow rate of the coolant.

In a first section (section 2), we describe the thermometric blocks for the ITER magnets and the development made by CEA-SBT to fulfil the ITER requirements. The CERN based thermometric block design and attachment method onto the helium pipes is presented as well as simulation and experimental results. The fully SBT developed electronic part of the measurement chain, which allows conditioning of the thermometer's electrical signal to the ITER CODAC (Control, Data Access and Communication) system will be described. The ongoing industrial production of the different components will then be presented.



Section 3 describes the flowmeters which will equip the ITER magnets. The sizing of the flow meters with regards to the technical specifications is presented as well as fluid modelling and mechanical calculation, and section 4 concludes the present work.

## 2. Thermometric chains for ITER magnets

The complete cryogenic thermometric chain for the ITER superconducting magnets is described in [1].

### 2.1. Specification of the thermometric chain

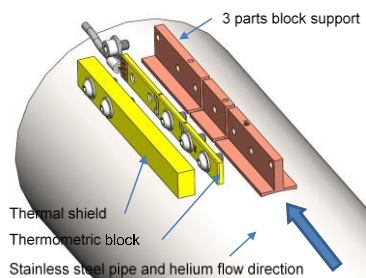
In this section we explain the specifications of the cryogenic measuring chains for magnet structures, coils and helium pipes, and for the thermal shield of the feeders. For monitoring the operating margin of the magnets, the most accurate thermometric block should provide the following accuracy, with a 50 mK resolution below 100K:

- ± 0.1 K from 4.2 K to 10 K,
- ± 0.3 K between 10 K and 80 K,
- ± 0.5 K above 80 K.

Moreover, severe environmental conditions, in terms of magnetic field, vacuum, radiation and EMC are to be considered. A radiation level of 5 MGy integrated over 20 years has to be taken into account, and a limited sensitivity to the applied magnetic field should be guaranteed. The whole thermometric chain should withstand the multiple cryogenic cool down and warm-ups of the ITER magnets as well as the 61000-4-4 level 4, criterion A standards for the EMC specification.

### 2.2. Thermometric block presentation

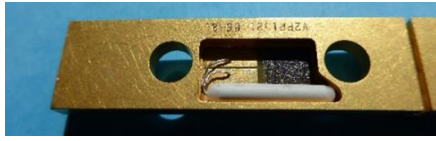
The procurement of the ITER magnets is a world-wide endeavor, with a very large number of sensors to be installed by many different users in different countries. In order to obtain accurate measurements from these sensors, the technology should employ robust and reliable techniques and be to industrial standards. As more than 2000 sensors are concerned in this work, the selected principle of temperature measurement for ITER is similar to that adopted by CERN for the LHC [2]. In this principle, the temperature is measured on the vacuum side, which avoids a cryogen-to-vacuum feedthrough. However, a careful thermal anchoring of the sensor is mandatory in order to measure the temperature of the coolant. For the thermometric block, the choice made for the thermal anchoring in the LHC has a considerable interest as it uses Printed Circuit Board (PCB) techniques, which are easily industrialized.



**Figure 1.** Main components of the temperature measuring system

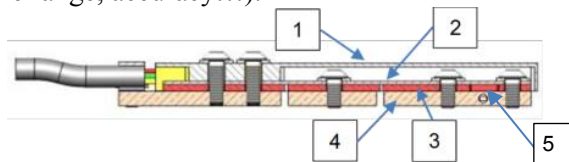
**Figure 1** and **Figure 3**. Assembly of the thermometric block's main components show the principle and the main components of the measuring system. It consists of:

- A support made of three copper blocks, which is vacuum brazed on the steel cooling pipe,
- The thermometric block itself is a double sided PCB attached via a pre-preg on a triple copper heat sink; each heat sink is thermally insulated from the other. The sensor is inserted in a cavity (**Figure 2**) in the third heat sink and is connected to the electrical lines of the PCB, which ensures a good thermalization of the sensor.
- A thermal shield is attached to the first heat sink to shield the sensor from thermal radiation. Heat short cuts between the shield and the sensitive part of the thermometric block have been removed from CERN design.



**Figure 2.** Resistive sensor inserted into thermometric block cavity before epoxy encapsulation

Different types of sensors are inserted in the cavity (cf. **Figure 2**), depending on the specifications (temperature range, accuracy...).

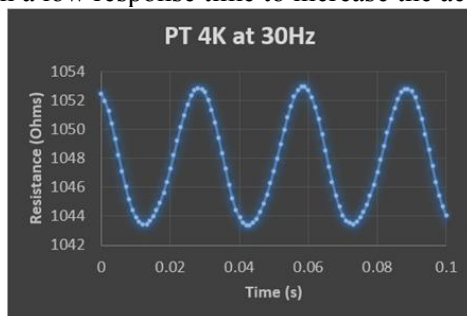


- 1: thermal shield,
- 2: Wires/Sensors PCB links,
- 3: Copper sole heat sink,
- 4: Copper block support,
- 5: Sensor cavity.

**Figure 3.** Assembly of the thermometric block's main components

### 2.3. Electronic board

Five years ago, SBT embarked on a major upgrade of its first generation (1995) of electronic boards dedicated to the measurement of resistive temperature sensors. This CABTR (Central d'Acquisition Basse Température Rapide) board provides a synchronous detection measurement principle, which allows a noise reduction and eliminates thermal electromotive force (EMF) errors. It reaches an electronic accuracy of 0.01% of the resistance which gives 0.3 mK at 4.2 K (with a CX1050 sensor). The dissipated power in the sensor is divided by a factor of 9 which leads to less than 2.5 nW for a sensor of 1000  $\Omega$  resistance. The maximum bandwidth is extended to 100 Hz, allowing the measurement of much faster signals (Cf. **Figure 4**); however, bandwidth can be reduced for systems with a low response time to increase the accuracy.



**Figure 4.** 30 Hz Pulse Tube temperature oscillations as measured by a CABTR



**Figure 5.** 5 CABTR boards integrated in 19" crate (40 available channels)

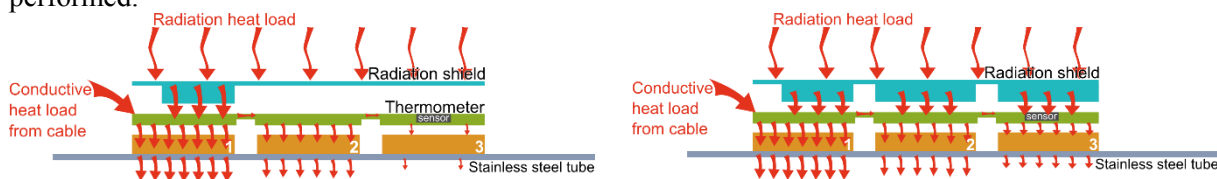
Each board has 8 dedicated channels sampled at 2 kHz. Sensors are excited by a modulated signal whose frequency is adjustable. All channels are controlled by a FPGA (Field Programmable Gate Array) to minimize the cost and to guarantee high performance for the treatment of 32000 samples each second. The FPGA automatically selects the appropriate range and type of excitation according to the value of the resistance for each channel. The CABTR includes a standard calibration curve for PT100 sensors and offers the possibility to upload a file based on the Lakeshore format. For other sensor types, CABTR allows the upload possibility via a web interface and dedicated software. The eight temperature signals are available for a PLC (Programmable Logical Controller) through an Ethernet fieldbus (Modbus TCP and Profinet IO) or can be stored in a file of 60 seconds of data with a time slice of 1ms (for 8 channels). The final measurement accuracy for a CX1050 sensor at 4K, for example, can be of the order of a few milli-Kelvin, and even better if the bandwidth is reduced. An external device can be plugged into the CABTR to perform a self-diagnostic or calibration and so to detect a malfunction. The CABTR has been used to measure fast varying signals, such as the variation of the temperature of the cold finger of a high frequency pulse tube (**Figure 4**).

For ITER purpose, the high frequency capabilities of the CABTR are not necessary. However, its capabilities in terms of minimization of sensor self-heating, accuracy, resolution and communication

with the PLC are of considerable interest. A few adaptations of the CABTR are necessary for ITER requirements, the most important are the following: as the measuring chain includes a long cable (350 m), capacitive effects become important, therefore the selected frequency of the excitation signal is strongly decreased with respect to the standard one. Moreover, ITER needs a large number of boards, so the CABTRs are included in large (19 inches) crates as in **Figure 5**.

2.4. Simulation and experimental results

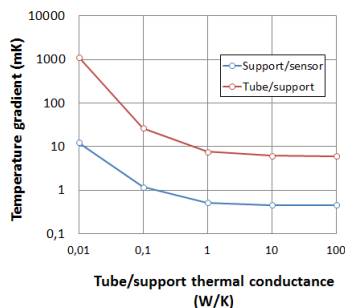
A complete thermal study has been performed to verify the thermometer block performance against ITER requirements: the thermometer should not show a temperature gradient higher than 50 mK between helium coolant and block support, and 50 mK between the block support and the sensor including the electronic measurement error. A Finite Element model, taking into account both parasitic heat loads from the measuring wires and the radiation load from the 80 K environment, has been performed.



**Figure 6.** Thermal flow modeling for CEA and CERN thermometric block.

The expected thermal behavior is shown in

**Figure 6**, where the number and sizes of the arrows represent the intensity of the loads. Copper block 1 intercepts the main part of the load (conductive heat load from the cable and radiation load) except for the parasitic thermal conduction of the PCB. The second block allows a further thermal intercept so that the heat flow at the sensor level is minimal. As the thermal load is reduced, this ensures a low thermal gradient between the sensor and the liquid helium temperature. This was supported by the Finite Element calculations, and experimentally confirmed as a temperature gradient of 15 mK between sensor and helium at 4.2K was measured. This temperature gradient is mainly located in the wall of the steel pipe (1 mm wall thickness as requested by ITER for calculation). Nominal values for the thermal contact conductance are set at 1 W/K for both.

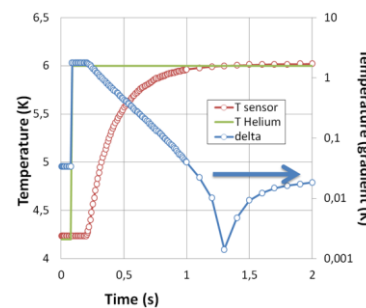


**Figure 7.** Temperature gradients as a function of the tube/support thermal conductance

A sensitivity study regarding thermal contact conductances has also been performed.

**Figure 7** shows that the performance is severely degraded only for unlikely low contact conductances.

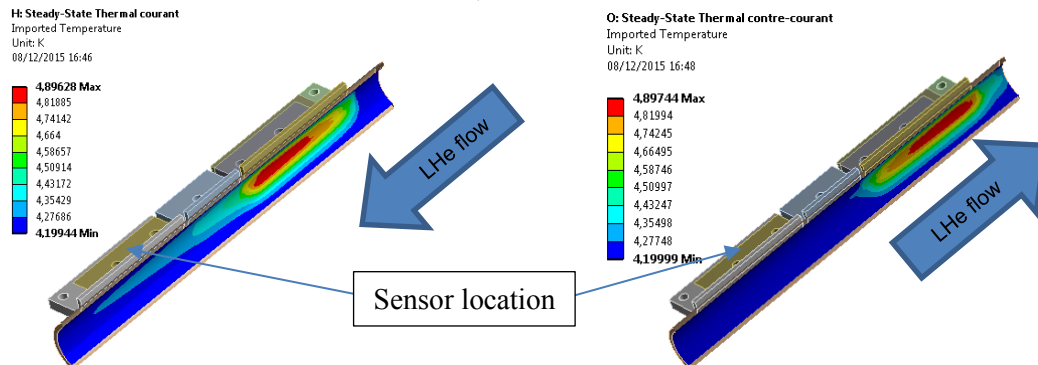
A question arose about the response time of the system to a temperature variation. A transient calculation modeling a temperature step between 4.2 and 6 K shows that the system time constant remains below 1 s (Cf. **Figure 8**).



**Figure 8.** Transient calculation from 4.2 K up to 6 K

Simulation of the effect of the thermometric block mounting orientation with regards to the helium flow direction has been done and is shown on **Figure 9**. The temperature gradient increases by 50 mK

when the thermometric block is mounted along the helium flow (i.e. downstream of the thermal interception of the cable and radiation heat loads).



**Figure 9.** Along (left) and against (right) the flow thermal gradient on DN15 pipe (10g/s)

### 2.5. Industrial production

After one year of validation activities on prototype components of the thermometric chain, the series production of the components has started.

For the CABTR, the production of 210 boards integrated in 42 crates has been undertaken by SEICO (Nantes – France) which should deliver the first pre-series (10 units) in mid-2016.

The cable production is undertaken by AXON Cable&Interconnect (Montmirail – France). The pre-series (2 km) of the 22 kilometres of cable is expected in April 2016.

CRYOFORUM (Triel/Seine – France) will import more than 2000 LAKE SHORE Cryotronics sensors (Westerville – USA) almost equally divided in batches of calibrated and un-calibrated CX1050 CERNOX™ and platinum PT103 type sensors.

The production of 2300 thermometric blocks with the integration of the sensor and the cable is performed by PROTECNO – GTID group (Brest – France). The pre-series (250 units) is expected at the end of March 2016.

All the assembled thermometric blocks will be thermally cycled 5 times at 80 K on a dedicated test bench which is currently being commissioned by CEA Grenoble, and a sample of the production will be tested at 4.2 K to control the quality of the production.

### 3. Venturi tube flowmeters for ITER magnets

Six sizes of venturi tube flowmeters have been designed to measure the full range (Table 1) of helium mass flow rates required for the ITER magnets (**Figure 10** for a typical design and [3] for more details)

**Table 1.** List and characteristics of series of the venturi tubes.

Size	Mass flowrate	Temperature	Pressure	number
DN8	0.1 to 1g/s	Near 300 K	3 to 4 bars	18
DN10	1 to 7g/s	Near 300 K	3 to 4 bars	42
DN15.20	2 to 20g/s	4.2 to 6K	4 to 6 bars	89
DN15.30	3 to 30g/s	4.2 to 6K	4 to 6 bars	28
DN20	13 to 130g/s	4.2 to 6K	4 to 6 bars	40
DN25	40 to 400g/s	4.2 to 6K	4 to 6 bars	60

In addition to the supply, different tests will be performed in order to guarantee the correct operation of the entire acquisition chain; they are described in [3] with the corresponding test benches.

Due to the number of venturis to be supplied, the required measurement accuracy and the specific conditions of use, a dedicated production process has been developed. This comprises the detailed

design of the venturis, the development of specific test benches and the organization of the manufacturing activities. This article describes the approach for the design and a first analysis of the results obtained from the pressure transducers tested in an applied magnetic field.

### 3.1. Sizing of the venturi flowmeters.

The venturi flowmeters for ITER have been designed following the French and European standard NF EN ISO 5167-4 [4] even if this standard is not strictly applicable in our case (as described in [3]). Nevertheless the CEA/SBT experience is that such a design can give good results in cryogenic conditions. A key point is that the flowrate coefficient, which takes into account the fluid compressibility and the pressure losses in the venturi, must be measured in order to achieve high accuracy flowrate measurements.

The mass flow rate in a venturi can be derived from the Bernoulli relation, adapted for venturi flowmeters (1):

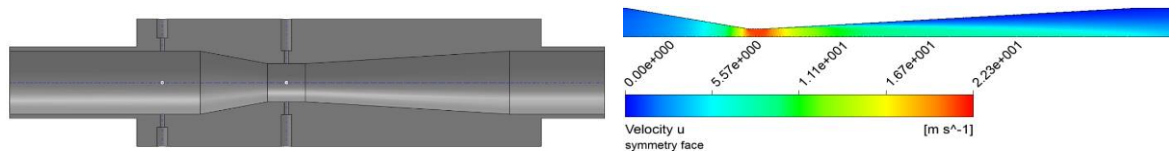
$$m = \alpha \cdot \frac{\pi}{2\sqrt{2}} \cdot (d^{-4} - D^{-4})^{-0.5} \cdot \sqrt{\rho(P_D, T_D) \cdot (P_D - P_d)} \quad (1)$$

where:

m	mass flow rate	D, d	upstream and neck diameters respectively
$\alpha$	flowrate coefficient	$P_D$ and $T_D$	pressure and temperature in the upstream pipe
$\rho$	density of the fluid	$P_d$	pressure at the neck diameter

### 3.2. Fluid modelling

All sizes of venturi flowmeters have been designed to have the same differential pressure ( $\Delta P = P_D - P_d = 200$  mbar) at their maximum flowrate, so as to use only one kind of differential pressure transducer. As mentioned previously, it is important for helium application to measure the flowrate coefficient and especially in the ITER case as the operating conditions are very different between warm and cold flowmeters. In order to estimate this coefficient, before the manufacturing phase, some fluid calculations have been performed with ANSYS CFX. The diameter of the neck of the venturi has then been adapted accordingly. **Figure 10** shows an example of these calculations.



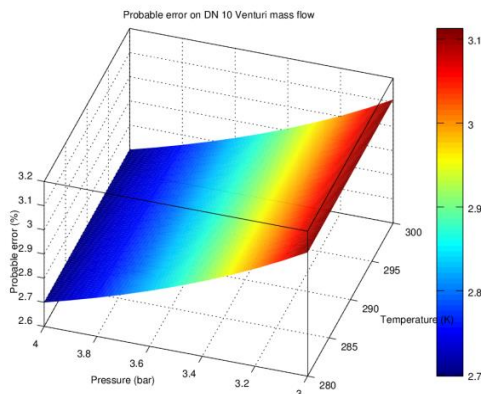
**Figure 10.** Typical design and velocity of helium in a DN 15 flowmeter

For the warm flowmeters, which have a low Reynolds number, a significant difference has been calculated for the flowrate coefficient compared to the value available in the standard. For the cryogenic flowmeters, the values obtained are similar but with an important impact of the roughness of the wall on the pressure drop. The uncertainties on the results are important and these values will be confirmed by measurement of the flowrate coefficient in two dedicated experiments (one at room temperature and the other at cryogenic temperature)

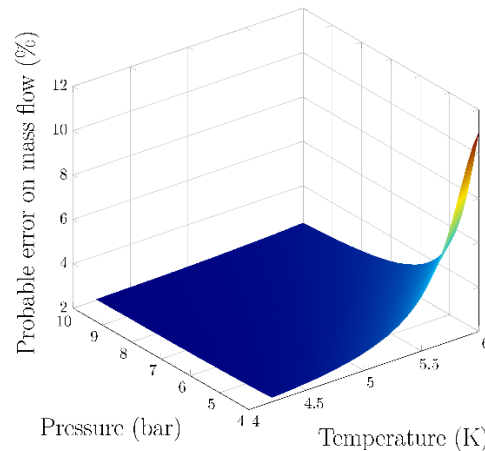
### 3.3. Measurement accuracy

As for all measuring tools, the results obtained include some uncertainties. The uncertainty calculations have been presented in [3]; here we just recall the formula of the quadratic error (2) and the typical uncertainty curves obtained for a warm and a cold flowmeter (**Figure 11** and **Figure 12**).

$$\frac{dm}{m} = \sqrt{\left(\frac{dm_m}{m_m}\right)^2 + 2 \cdot \left(\frac{2 \cdot d^4}{(D^4 - d^4)} \cdot \frac{dD}{D}\right)^2 + 2 \cdot \left(\frac{2 \cdot D^4}{(D^4 - d^4)} \cdot \frac{dD}{D}\right)^2 + \left(\frac{d(\Delta P_m)}{2 \cdot \Delta P_m}\right)^2 + \left(\frac{d(\Delta P)}{2 \cdot \Delta P}\right)^2 + \left(\frac{1}{2 \cdot \rho_m} \cdot \left(\left(\frac{\partial \rho}{\partial T}\right)_P dT_m + \left(\frac{\partial \rho}{\partial P}\right)_T dP_m\right)\right)^2 + \left(\frac{1}{2 \cdot \rho} \cdot \left(\left(\frac{\partial \rho}{\partial T}\right)_P dT + \left(\frac{\partial \rho}{\partial P}\right)_T dP\right)\right)^2} \quad (2)$$



**Figure 11.** Uncertainties on the DN 10 mass flow rate



**Figure 12.** Uncertainties on the DN 25 mass flow rate

### 3.4. Mechanical calculations

The venturi flowmeters are integrated in the ITER feeder circuits and are considered as pressure equipment. Mechanical calculations are required to fulfil the regulations imposed to guarantee the safe operation of these components. Three load cases have to be considered, and are different depending on the operating temperature (see Table 2 and Table 3):

**Table 2.** Load cases of **warm** flowmeters.

#### N° Load case

- 1 Normal operation: dead weight, connecting pipework, maximum internal pressure
- 2 Fault condition (accidental cooling at 50 K): load case 1 + additional load on pipework
- 3 Fault condition (accidental cooling at 50 K and seismic loads): load case 2 + seismic loads

**Table 3.** Load cases of **cold** flowmeters.

#### N° Load case

- 1 Normal operation: dead weight, connecting pipework, maximum internal pressure
- 2 Fault condition: load case 1 + additional loads on connecting pipework
- 3 Fault condition: load case 2 + seismic loads

The complex geometry of the flowmeters doesn't allow the use of analytical formulae available in standard codes such as the CODAP (French code for pressure equipment). The calculation has been performed by using finite element methods in two steps: after the calculation of the stresses in the flowmeters, a linearization of stresses has been done in areas with high levels of stress to obtain the membrane stress and the membrane + bending stress. It is these values that have been compared to the allowable stress in the CODAP. After some optimization of the geometry, all the required criteria have been fulfilled. Thanks to this validation, the manufacturing of the flowmeters has been launched.

### 3.5. Test of pressure transducers under magnetic field

Absolute and differential pressure transducers will be used to calculate the mass flow rate in the flowmeters. They will be installed in an area with residual magnetic field (up to 100 mT) produced by the superconducting magnets of the ITER machine. In order to identify a suitable pressure transducer technology, eight pressure transducers (four absolute and four differential pressure transducers) have been tested in an applied magnetic field.

Four sensor technologies have been tested: piezo resistive, resistive gauge, capacitive and optical. The results are shown in Table 4.

**Table 4.** Summary of pressure transducer test results in an applied magnetic field

Technology	Behaviour in an applied magnetic field up to 100 mT
Piezo resistive	Very low deviation observed from the differential pressure transducer No influence on the absolute pressure transducer
Resistive gauge	Significant deviation on the absolute pressure transducer and prohibitive error with the differential transducer
Capacitive	Erratic and unpredictable behaviour with the 2 capacitive transducers
Optical	No influence of the magnetic field – with a correct choice of the optical fiber material, these transducers should also be able to operate in a nuclear environment

At the end of the test, the magnetic field was increased up to 3 T for the optical absolute pressure transducers and up to 300 mT for the others. The behavior reported in Table 4 is unchanged at these increased magnetic fields. The magnetic tests performed have validated the behaviour of two technologies for the transducers (Behaviour in nuclear environment to be investigated).

#### 4. Conclusion

Cryogenic thermometric chains, based on a development made by CERN, have been further developed and upgraded by the CEA for use in the ITER magnets. These thermometric chains meet the stringent requirements set by ITER and are produced according to industrial production standards. Production has started, and Quality Assurance controls are in place to guarantee a high quality of production which will continue to the end of 2017.

Based on the CEA-SBT know-how in cryogenic venturi flowmeters, the design of six venturi flowmeter types required to operate the ITER superconducting magnets has been performed. To fulfil the ITER specification, a complete approach has been proposed: analytical design, fluid modelling to estimate the flowrate coefficient, mechanical calculations to respect the pressure equipment regulation and uncertainty estimations in order to use the flowmeters correctly. A test of eight absolute and differential pressure transducers under magnetic field has been done and two types of transducers have been identified which can operate in the ITER environment.

#### Acknowledgment

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

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