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THE INSTRUMENTATION OF THE B0 ATLAS MODEL COIL

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Abstract

The ATLAS Barrel Toroid (BT) is a superconducting toroid made of 8 superconducting coils of 25 m length and 5 m width, providing the magnetic field for the muon spectrometer of the ATLAS detector, one of the experiments of the Large Hadron Collider, under construction at CERN.

B0 is a full scale model, one third length of ATLAS barrel toroid eight coils.

The B0 construction was decided to test the technical construction solutions and reproduce the behaviour of the final coils. To fulfil this aim the coil has been equipped with many sensors.

This paper describes the whole sensors/instrumentation system installed on B0.

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1 INTRODUCTION

The Barrel Toroid Magnet (BT) [1] is part of the Magnet System of the ATLAS Detector that will be installed on the large Hadron Collider (LHC). It consists of eight flat superconducting coil of 25 m length and 5 m width, radially assembled around the beam axis and providing the magnetic field required by the muon spectrometer.

The field will extend over a length of about 26 meters with an inner bore of 9 meters and an outer diameter of about 20 meters. These coils being about 5 times larger than any other superconducting coil ever built, the CEA (Saclay), CERN and INFN (Milan) built a working model, called B0. It is similar to one BT coil, both for the design concept and the construction procedure with the same width and the same cross section (4.5 m x 0.25 m, in order to qualify the design, verify the manufacturing procedure and validate the technical solutions) but with a reduced length (9 m). B0 coil installed in the test station at CERN is shown on Fig. 1

FIG. 1 – The B0 model coil in the test station at CERN.

A certain amount of sensors has been installed on B0, in order to have a complete understanding of the behaviour of every component of each part of the magnet.

The sensors installed can be divided into four groups :

1. Temperature sensors
2. Mechanical sensors
3. Electrical sensors
4. Pressure Sensors

Internal sensor, cable, tight connectors and wiring has been shared among the collaboration institutions. External cabling, connectors and infra-structure has been provided by CERN. The electronics for the data acquisition has been provided by the collaboration institutes; CEA provided the acquisition system for the mechanical sensors, CERN the temperature reading system, INFN the acquisition system for the electrical quantities(2). The Magnet Safety System (MSS), devoted to the control of the operation of the magnet and to take the action needed to the safety of the magnet, whenever a dangerous event occurs (a quench, i.e. a transition to the resistive state, an increasing of the operating temperature, a fault of the cooling …) is provided by CERN and CEA.

Sensors choice has been driven by a trade-off between accuracy and cosINFN provided the acquisition system for the electrical quantities(2), CERN and CEA provided the Magnet Safety System (MSS), devoted to the control of the operation of the magnet and to take the action needed to the safety of the magnet, whenever a dangerous event occurs (a quench, i.e. a transition to the resistive state, an increasing of the operating temperature, a fault of the cooling …).

The choice of the sensors has been driven by a trade-off between accuracy and cost; care has been taken in determining the position of the sensors, in order to get high reliability and redundancy in case of fault of some sensors. In addition the symmetry of the system has been taken into account in determining the sensor position, in order to reduce the number of sensors.

2 SENSOR IDENTIFICATION

In order to univocally identify the sensor, a standard naming has been adopted. In this way each sensor is indicated by two/three letters (TE for the temperature sensors, MME for magnetic devices, WE for the strain gages, VE for the voltage taps and so on) and by three numbers, indentifying the localisation in the coil (0 for the cold mass, 1 for the current leads, 8 for the thermal screen, etc.) then an increment number. The identification scheme is shown on Table 1.

The drawing of the coil casing of the B0 magnet is shown on Fig. 2 and 3 and shows the sensor position. Let’s remind again that the drawings of Fig. 2 and 3 show the coil casing only, but not the thermal screen instrumentation.

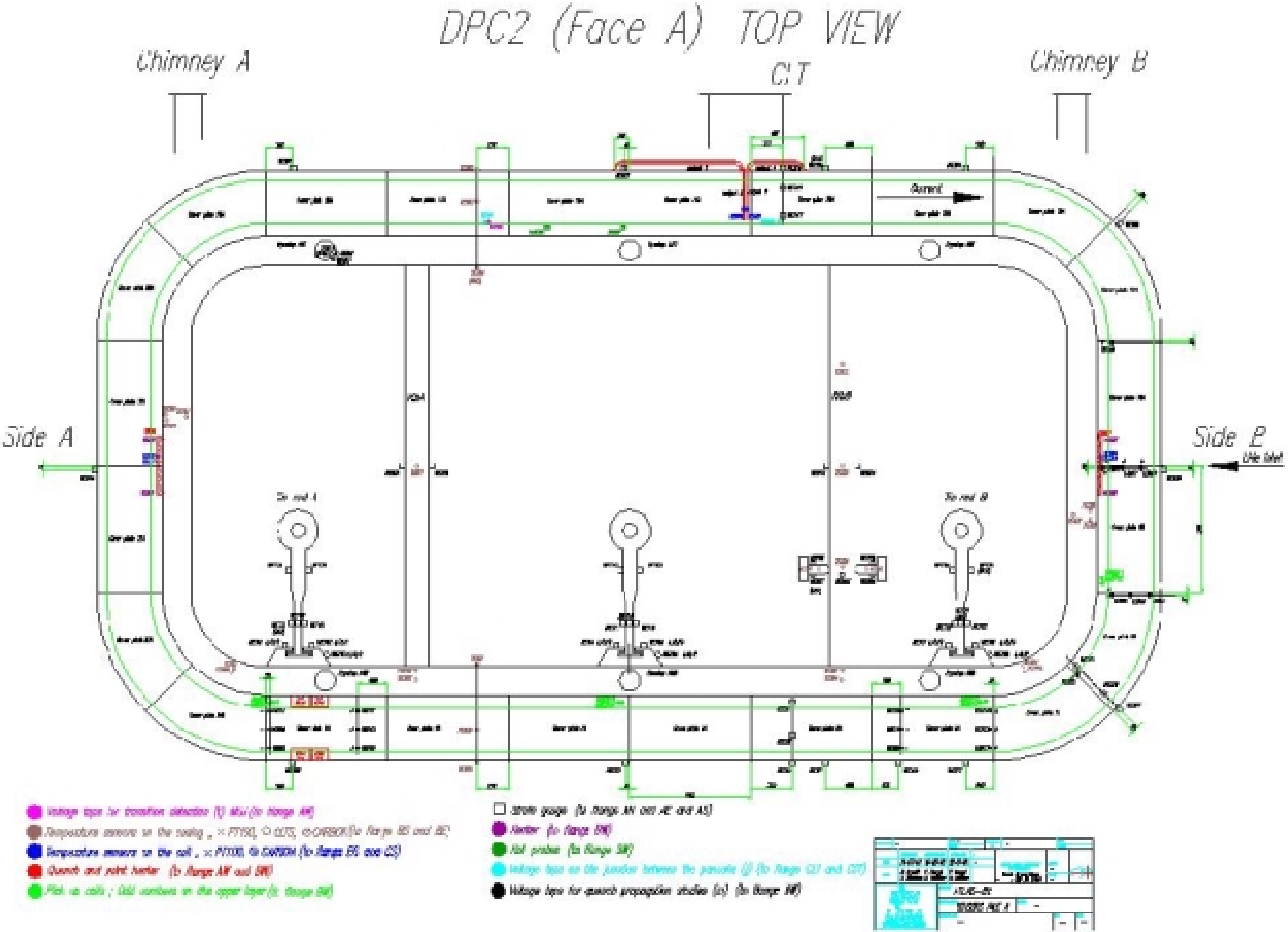


FIG. 2 – Scheme of the sensor positions on the face A of the B0 coil casing.

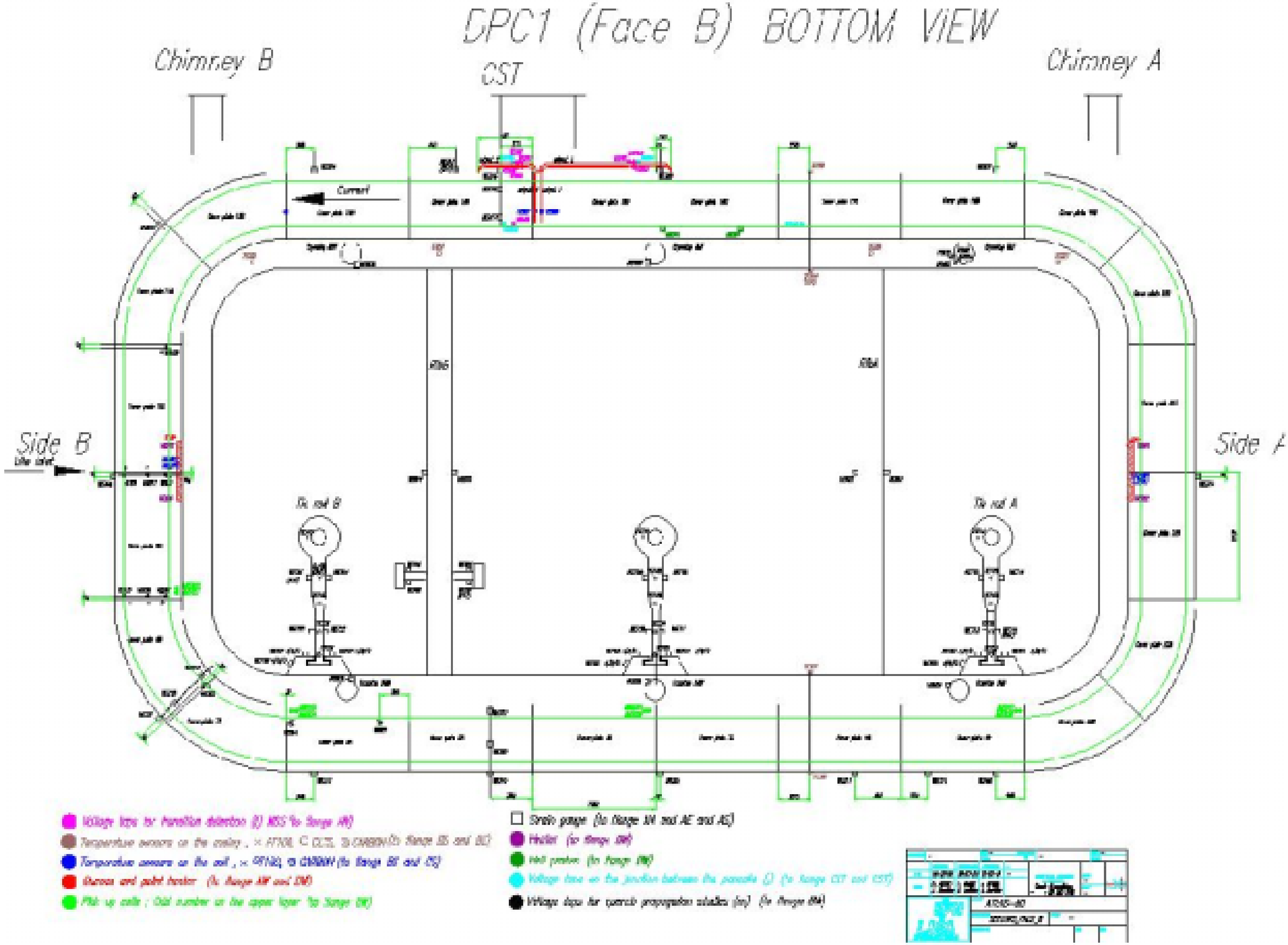


FIG. 3 – Scheme of the sensor positions on the face B of the B0 coil casing.

TABLE 1 – Sensor naming

First wo letters		First number		Second number		Last number	
type	name	localisation	#	sensor	#		#
Magnetic sensors :		Double pancakes and lines	0	Magnetics measurements :			
Pick up coil	MME	Current leads	1	Flux coil	1 for DPC1	Incrementation :	0 to 9
Hall probe	MME	Electrical external parts	2		2 for DPC2		
External hall probe	MME	Coil casing and cover plate	3	Hall probe : internal/external	3/4		
Compensation coil	MME	Cooling pipes	4	Compensation coil	5		
Temperature :		Ribs and fixed point	5	Temperature :			
Carbone	TE	Cryogenic stops	6	Carbone	0 to 1	Incrementation :	0 to 9
CLTS	TE	Tie rod and tie rods roots	7	CLTS	2 to 3		
PT100	TE	Thermal shield	8	PT100	4 to 7		
Thermocouple	TE	Coil external parts and supports	9	Thermocouple	8 to 9		
Voltage tap :	VE			Voltage tap :	0 to 9	Incrementation :	0 to 9
Strain gage :	WE			Strain gage :	0 to 9	Incrementation :	0 to 9
Pressure sensors :	TP			Pressure sensor	0	Incrementation :	0 to 9

First letter		First number		second number		Last letter	
type	name	localisation	#	localisation	#	Coil side	letter
Quench heater	E	Quench heater	0	Double pancake 1	1	Chimney ChA	A
Point heater	E	Point heater	1	Double pancake 2	2	Chimney ChB	B

Examples :

TE121 is the temperature sensor CLTS n°1 placed on the current leads
TE101 is the temperature sensor carbone n°1 placed on the current leads
WE801 is the strain gage n°1 placed on the thermal shields
E01A is the quench heater placed on the double pancake n°1 and connected to the chimney ChA

Lexicon :

- DPC : double pancake
- SC lines : superconducting lines
- Th. shield : thermal shield
- PS : power supply
- Th. Cpl. : thermocouple
- CL : current lead
- CLT : current lead turret
- CST : cryogenic supply turret
- Trigg. : trigger
- Qch. : quench
- Qch. Detect. : Quench detection
- Monit. : monitoring
- Acqui. : acquisition

3 SENSORS INSTALLED

3.1 Temperature Sensors

Temperature sensors installed on B0 are of four type. With the exception of the thermocouples, all the temperature sensors are Resistance Temperature Devices, temperature being determined by the resistance of the sensing material. The description and characteristics of the temperature sensors used are reported in[3].

The sensors installed are:

- Carbon sensors
- Cryogenic Linear Temperature Sensor (CLTS)
- Pt100
- Thermocouple in differential configuration.
- Superconducting Quench Detectors (SQD)

The carbon sensors give the best accuracy for low temperature and are used to check the operating temperature of the coil and of the critical part of the magnet, like the foot of the current leads.

The CLTS, calibrated over the whole operating temperature range, gives a less accurate measurement. They are used only to have a general indication of the thermal behaviour of the magnet.

The low accuracy and the need of a high precision reading system makes the CLTS not very useful for an accurate temperature measurement, conversely the whole range operativity of the CLTS reduces sensors number and wiring and connector cost.

To ease their installation, some temperature sensors have been glued onto an aluminum small plate, together with the electrical connections. In this way the mounting consists of gluing and screwing the plate on the surface.

All other sensors have been glued directly on the magnet, in particular for those glued on fragile aera where screwing is forbidden (for example the sensors on the tie rods). A CLTS mounted on its aluminium plate is shown on Fig. 4.

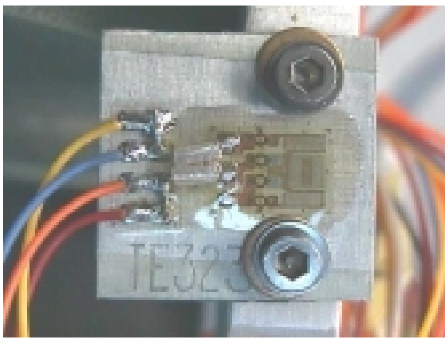


FIG. 4 – A CLTS mounted on the Al plate

Once verified their standard, Pt100 are used in the upper operating temperature range, from 50 K to the room temperature. So most of them are on the thermal screens.

PT and CLTS temperature sensors were calibrated at INFN/LASA[3].

In three spots, thermocouples give direct differential temperature measurement. This differential configuration avoids the propagation of the error of the absolute temperature measurement to the temperature difference.

The SQDs are not an usual temperature sensors, as a matter a fact they do not give an absolute temperature measurements. Actually they are used by the MSS to detect a quench into the electrical superconducting lines between the current lead and the coil. In this way they are used as a binary on/off device.

Temperature sensor number and theit location are shown on Table 2.

TABLE 2 – Temperature sensors position and name.

SENSOR	Quantity	Name	Localisation	TOTAL
CARBON	8	TE001 to TE008	DPC1/2	22
	4	TE101 to TE104	Current Lead	
	8	TE301 to TE302	Coil Casing	
	2	TE401 to TE402	Cooling pipe	
CLTS	10	TE321 to TE330	Coil Casing	31
	8	TE421 to TE428	Cooling pipe	
	1	TE021	CST junction	
	4	TE521 to TE524	Rib	
	2	TE621 to TE622	Cryostops	
	6	TE721 to TE726	Tie rods	
Pt100	5	TE041 to TE045	PC1/2	47
	6	TE141 to TE146	Current Lead	
	2	TE541, TE644	Fixed Point	
	2	TE641 to TE642	Cryostop	
	9	TE741 to TE749	Tie rods	
	23	TE841 to TE852 TE854 to TE864	Thermal Screen	
Thermocouples (Differential)	2	TE881 to TE882	Th. screen panels	3
	1	TE883	Tie rod thermaliz.	
SQD	3	TE901 to TE903	Supercond. Lines	3

3.2 Mechanical Sensors

The cable characteristics of the B0 magnet have already been tested in the small B00 magnet, but they have to be tested in the strong stress and force environment of the final magnet. In addition one of the purposes of this model coil is to verify the mechanical behaviour of the magnet and check the technological construction choices (i.e. tie rods and cryostops). To this aim a magnetic mirror has been installed in the B0 test area to reproduce the forces of the other 7 magnet of the full ATLAS magnet configuration. The mirror is done with the old CERN Intersecting Storage Ring magnets. For the importance of the mechanical behaviour many mechanical sensors are installed on B0.

They are of two types:

– Strain gages
– Capacitive transducers (Load Cell)

We used four type of Micro-measurement strain gages :

- SK-15-250AF-350, because of their successfully use in the test of the race-track magnet[(4)] (a 2 m length protoyipe of the B0 coil)
- SK–15-250RA-350, a 45° “rosette” configuration in order to have all the strain component on the tie rod root,
- SK-15-250WT-350, a 90° “rosette” on tie rod for the Poisson compensation method.
- WK-15-250BG-350, additionnal strain gage added after the full integration of the magnet; in order to get more informations about the behviour of the cryostops.

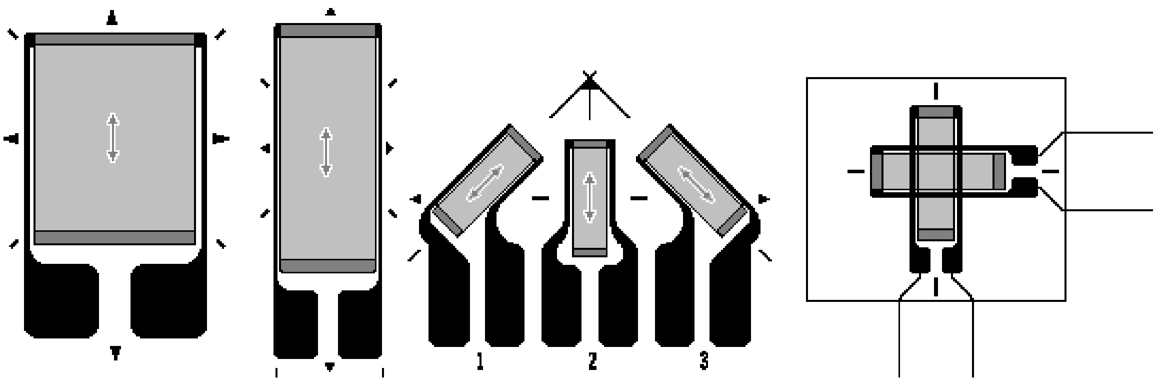
Magnetic and temperature effect compensation is don by connecting the strain gages and their compensation in half-bridge configuration. The Poisson compensation is used for the rosette.

The localisation and number of strain gages is summarized in Table 3.

TABLE 3 – Strain gages position and name.

SENSOR	Quantity	Name	Localisation	TOTAL
SK-15-250AF-350	15	WE301 to WE315	Coil casing	43
	6	WE316 to WE321	Casing cover plates	
	5	WE501 to WE505	Ribs	
	4	WE506 to WE509	Fixed Point	
	4	WE601 to WE604	Cryostop	
	9	WE801 to WE809	Thermal screen	
SK–15-250RA-350	9	WE701A/B/C to WE703A/B/C	Tie rod root A	27
	9	WE704A/B/C to WE706A/B/C	Tie rod root M	
	9	WE707A/B/C to WE709A/B/C	Tie rod root B	
SK–15-250WT-350	5	WE711 to WE715	Tie rod A	15
	5	WE716 to WE720	Tie rod M	
	5	WE721 to WE725	Tie rod B	
WK-15-250BG-350	5	WE605 to WE609	Cryostop	5

The sensing pattern of the four type of strain gages is shown on Fig. 5 (the relative dimensions are not respected).



(a) (b) (c) (d)

FIG. 5 – Gage pattern of the strain gaged installed in B0
(not in scale, see below for the dimensions).
(a) SK-15-250AF-350 (overall dimension 14.5 x 9.1 mm^2)
(b) WK-15-250BG-350 (" " 13.2 x 5.6 mm^2)
(c) SK-15-250RA-350 (" " 19.8 x 23.6 mm^2)
(d) SK 15-250WT-350 (" " 13.0 x 15.2 mm^2)

The 4 additionnal strain gages glued close to the position of the cryostop on the external part of the vacuum vessel (so they are in air and at room temperature), have been added to test the possibility to "remotly" measure of the strain of the cryostop[(5)]. After the first cooldown 4 more strain gages have been glued on the external part of the vacuum vessel (so they are in air and at room temperature), close to the position of the cryostop, in order to "remotely" measure the strain of the cryostop[(5)].

The strain gage SK-15-250-AF-350 and SK-15-250RA-350 are shown on Figs. 6 and 7.

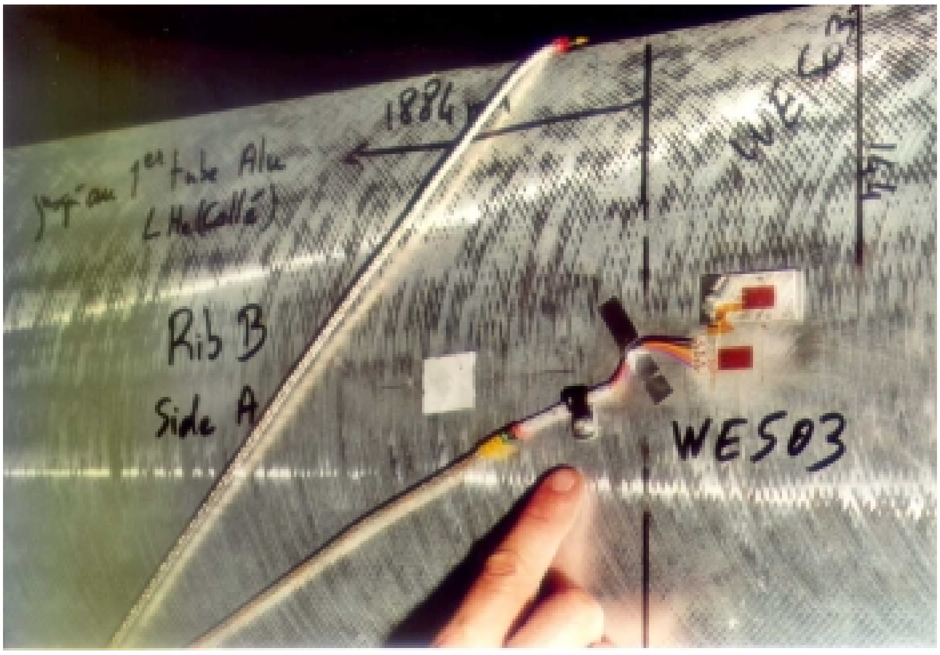


FIG. 6 – Strain gage WE503 (type SK-15-250-AF-350) mounted on a B0 rib. The measuring gage is the lower one, the compensation gage, mounted on the plate is the upper one.

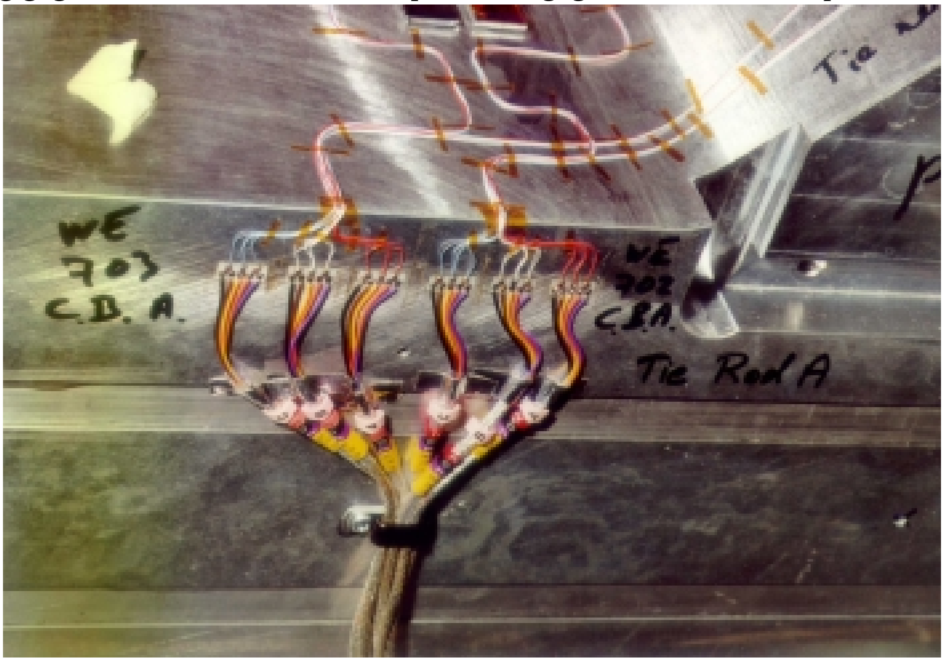


FIG. 7 – Strain gage WE703 of type SK-15-250-RA-350 mounted at the tie rod A root.

The load cells are not installed into B0 but are placed outside the coil, near the magnetic mirror, to measure the magnetic force between the magnet and the mirror.

3.3 Electrical Sensors

All the sensors related to the current in the coil are classified as electrical sensors. So this group includes both electrical and magnetic sensors:

- Voltage taps from any part of the electrical circuit of the coil.
- Pick-up coil.
- Hall probe magnetic field sensors.

The voltage taps are twisted two by two according to the voltage drop to be measured. Each differential signal is galvanically isolated from the acquisition system in order to interrupt the ground loops and protect the acquisition system from overvoltages during the quench event (2).

Moreover a protection resistor of 4.7 kΩ protects each voltage tap wire from overcurrent due to short to ground. In Table 4 the electrical sensors are listed.

TABLE 4 – Electrical sensors position and name.

SENSOR	Quantity	Name	Localisation	TOTAL
Internal Voltage Taps	20	VE00 to VE020	DPC2	65
	10	VE021to WE030	DPC1	
	6	VE041 to WE046	Junctions	
	9	VE061 to VE069	SPC/DPC quench detection	
	4	VE081 to VE084	Current Lead – Coil line	
	4	VE141 to VE144	Current lead-coil junction	
	2	VE145 to VE146	Current lead 1	
	2	VE147 to VE148	Current lead 2	
	8	VE091 to VE098	Quench Heater Voltage	
External Voltage Taps	2	VE261 to VE262	Dump Resistor Voltage	8
	2	VE263 to VE264	Earth Bridge	
	2	VE265 to VE266	Coil+Current Leads Voltage	
	2	VE267 to VE268	Coil+Current Leads+Busbars	
Pick-up Coils	8	MME011 to MME018	DPC2	16
	8	MME021 to MME028	DPC1	
Hall Probes (int.)	4	MME031 to MME034	Junction	4
Hall Probes (ext.)	2	MME941 to MME942	Magnetic Mirror	2

Three more type of devices are mounted in the coil: quench heaters, point heaters and compensation coils. These devices cannot be considered as sensors, because they do not give a measure of physical quantity, but are anyway essential for the quench detection and the magnet protection. Quench heaters accelerate the transition to the resistive state of the whole coil, once the quench occurs, while point heaters are used to locally induce a transition zone as small as possible, in order to study the quench characteristics.

Compensation coils avoid spurious quench detection triggers, due to inductive signals. As a matter of fact the quench in the coil is detected by separately measuring the voltage of the single pancake and of the double pancakes, the compensation coils allow a measuring of the pure resistive voltage by removing the inductive voltage component.

A voltage tap is shown in Fig. 8. It consists of a stainless steel screw , to be screwed into the cable aluminum, coupled with a hollow brass cylinder, providing the electrical connection to the protection resistor and wire; it is the feedthrough through the casing cover plate.

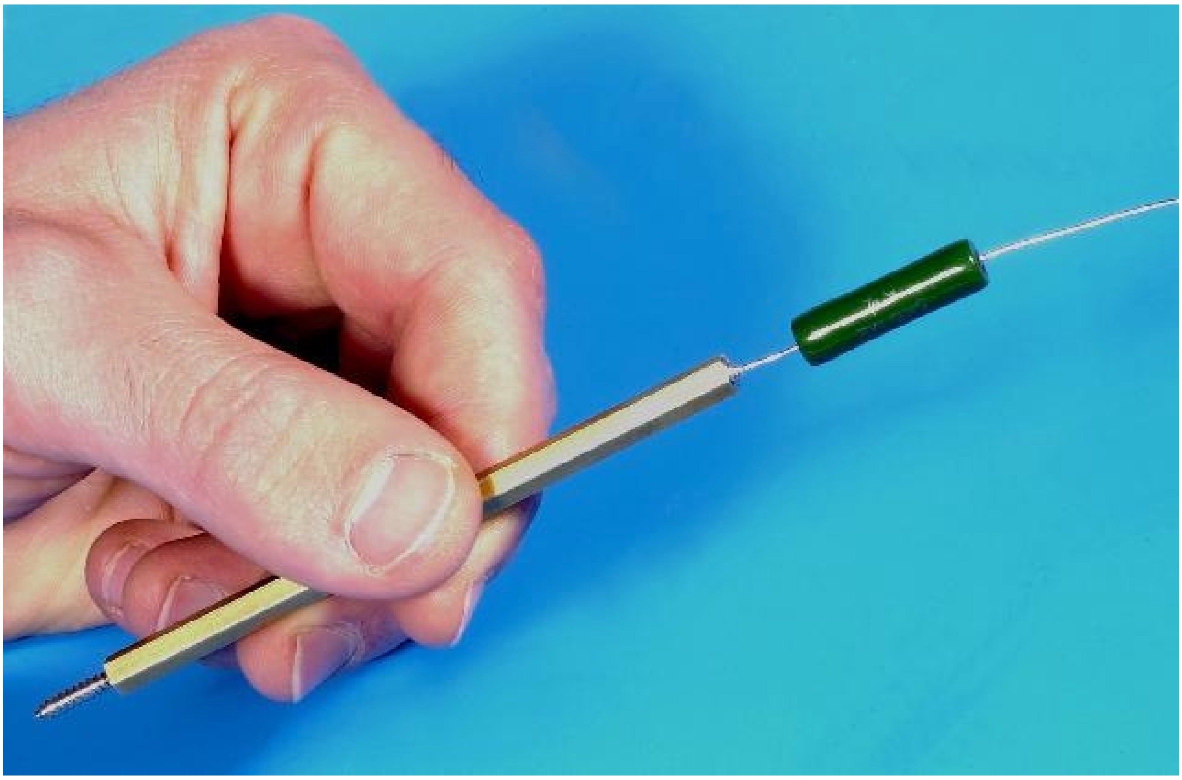


FIG. 8 – A voltage tap.

In Fig. 9 six installed voltage tap, as seen from the coil casing are shown. They are wired with green and blu wires and covered by an insulating sheet (yellow).

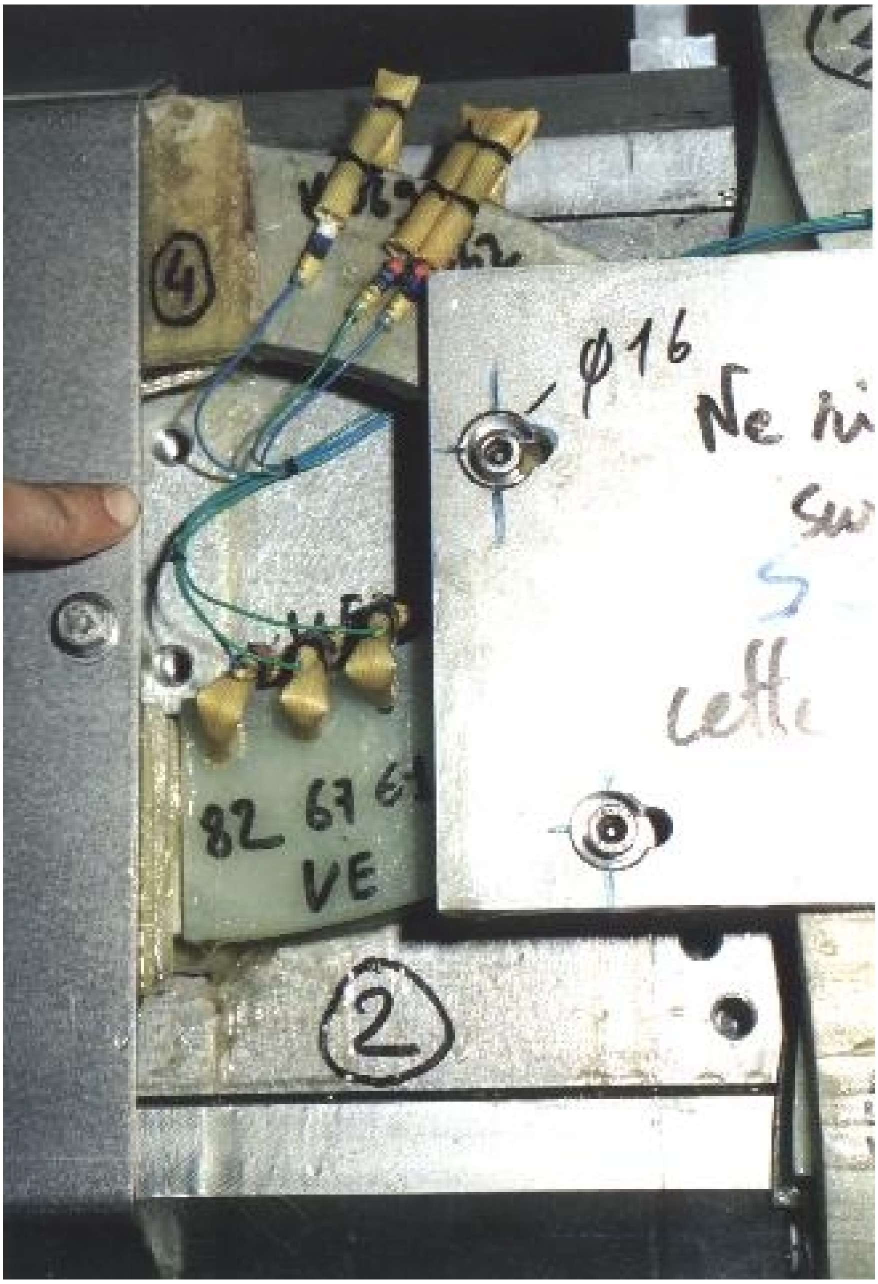


FIG. 9 – Six installed voltage taps seen from the coil casing.
The yellow sheet is an insulating protection.

A pick up coil is shown on Fig. 10. It consists of 4600 turns[(6)] providing an equivalent cross section of about 0.53 m^2. The pick up coils face the conductor and provide a voltage signal proportional to the vertical magnetic field variation, occurring during the cable resistive transition.

FIG. 10 – A pick-up coil

3.4 Pressure Transducers

In order to study the Helium overpressure in the cooling pipe, during a quench, four pressure transducers are installed.

Two of them are placed at the middle of the long arm of the coil and two other at the He inlet.

They run similarly to a ¼ sensor: they are powered and give a voltage signal proportional to the pressure variation.

4 CABLING

The characteristics of B0 internal instrumentation cables are listed below. We only refer to internal wires because they are specifically adopted for the specificity of each sensor type. The external wiring is less crucial because it just groups together similar sensors and lead them to the acquisition, control and safety systems.

Different sensors require different wiring: each voltage tap needs only one wire, while temperature sensors are 4 wire sensors, when compensated strain gages are five wires for an half bridge connection.

The main constraint to be fulfilled by the voltage taps wires is the maximum voltage between wires and between wire and ground. As a matter of fact in the final BT configuration voltages of up to about 1000 V DC can arise in particular situation, so the wires must support a permanent voltage up to 1500 V DC. This situation cannot occur in B0, nevertheless the same final solution is adopted, in order to reproduce the same mechanical and thermal configuration.

For all the other sensors cables, we used the same insulation voltage to get the best mean time before failure.

The other limitation that can generally occurs in the detector magnets is the radiation constraints. As a matter of fact the detector, for its nature, must be placed in a radiation environment and this can lower the performances of an insulating material.

Polytetra-fluore-thylene (PTFE or Teflon®) or polyether-ether-ketone (PEEK) are usally used for cryogenic application. PEEK has an higher resistance to radiation but in ATLAS barrel toroid the radiation level is not so high[7] to endanger the performances of the PTFE. Thus this eases the choice of the PTFE solution.

The wires adopted for B0 are of four types, all from AXON company :

- 2xEE2607 (one twisted pair) for voltage taps,
- EE2807S4 (four wire cable) for temperature sensors, hall probes and pressure sensors,
- EE2807S5 (five wire cable) for compensated strain gages,
- EE1219 (one twisted pair) for quench heater.

The cables used for the internal wiring are shown on Fig 11.

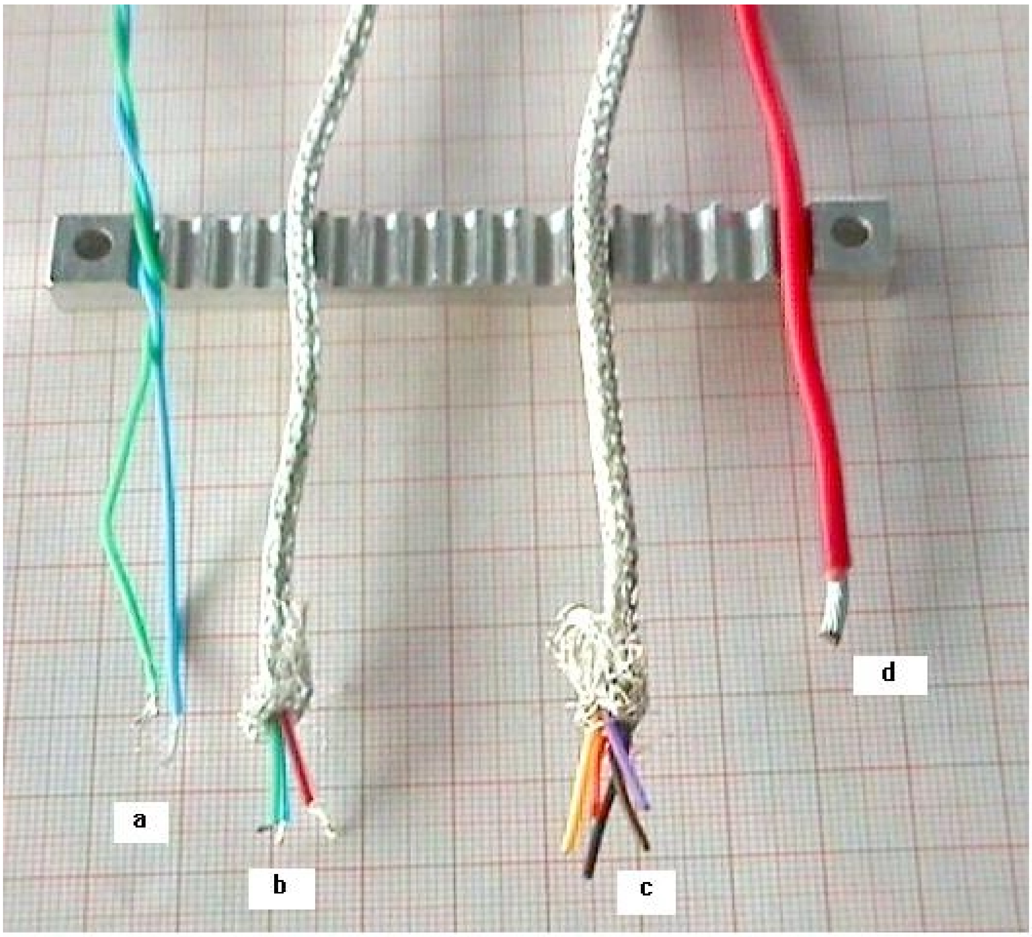


FIG. 11 – TInternal wiring cables.
(a) 2xEE2607; (b) EE2807S4; (c) EE2807S5; (d) EE1219

5 CONNECTORS

The insulation and radiation resistance requirements for the internal wires hold for the connectors too.

Three types of connectors has been used for the different needs. The main subdivision is the system to which is dedicated the sensor, i.e. to the MSS or to the MCS. The diameter of the connector is like a key for an evident indication of the different functions of the associated sensors.

MCS connectors are Fischer 106 size, while the MSS are 104. “A” or “Z” types are used according to the sink or source function of the connected sensors. So the “A” type has pins on the plug and receptacles on the socket and is therefore dedicated to the sensors that do not need to be powered (pick up coils, voltage taps). Conversely the “Z” type having the receptacles on the plug and pins on the socket are used for the powered sensors as temperature sensors and strain gages.

The 106 size connectors are shown on Fig.12.

FIG. 12 – The 106 size connectors used in B0.

6 CONCLUSIONS

All the sensors and equipment described has been installed at Saclay during the so-called “B0 Integration 2”.

Of course during the installation handling some sensors ware damaged, but some spare were disposable.

Unfortunately the pick up coil MME022 and one of the pressure transducers were damaged and replaced: Moreover few strain gage broke during the first powering of the magnet.

Nevertheless the accurate work done to identify the critical points of the magnet, the general good reliability of the whole systems, the redundancy foreseen, even taking into account some symmetries, allowed a successful commissioning and extensive measurement campaign on the B0 coil, validating most of the technical solution for the final BT.

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