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# SM18 Vertical Cryostat D2 short model Test Procedure:

## MCRD (D2) short model Dipole Model for High luminosity



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# Introduction

This document summarises the successive steps implemented while performing cryogenics tests of prototype magnet in the “SM18 Vertical Test Station” at CERN. The document is divided in three main parts:

1. The first part, from paragraph 1 and 2, describes the procedures to check the *electrical integrity* (instrumentation potentials continuity, connections and insulation) of the magnet on the stand, on the insert and inside the cryostat. A document presenting the various measurements made on the magnet during its assembly should be part of the “Magnet Traveler Documentation” providing by the magnet responsible.

2. The second part, paragraph 3, presents the setup for cold powering test including the *quench detection system* and the *magnet protection scheme*.

3. The third part gives the technical details of the tested magnet, paragraph 4, and the test plan, paragraph 5 to 9, including the *quench performance tests*, the *specific R&D tests* and the *magnetic measurement*.

A separated document is dedicated to the Magnetic Measurement system and the Test Plan Procedure for the magnet field quality assessment (paragraph 7).

The procedures described in this document are used for the test of the “INFN two-in-one aperture NbTi Dipole Short Model”. The main goals of the cold powering tests are grouped in 4 main parts:

- Mechanical structure performances
- Quench performance assessment
- Field quality measurement
- Quench protection study

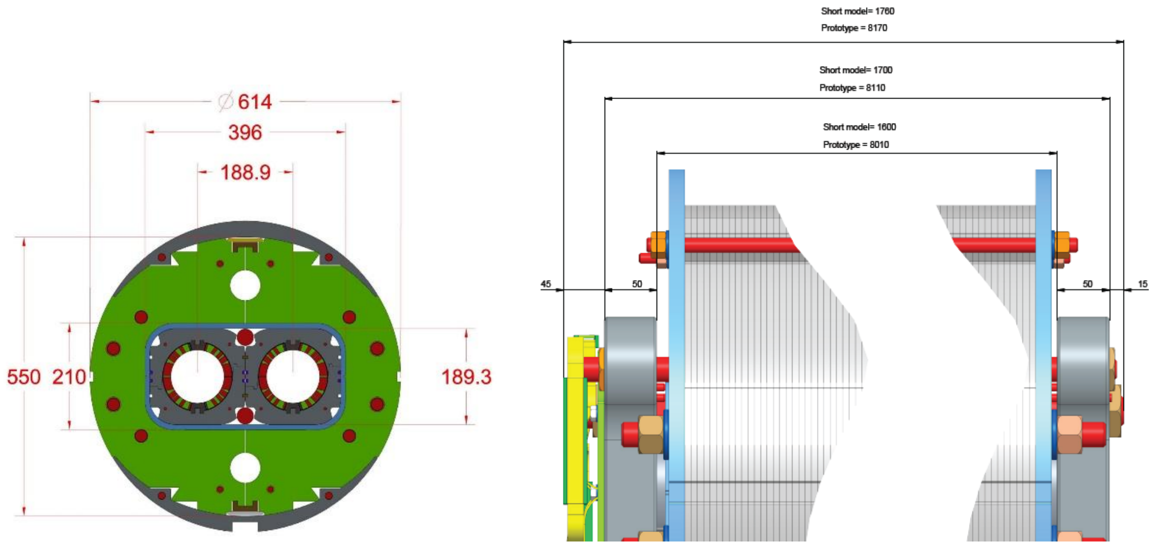



**Figure 1 : Transverse cross section and longitudinal view of the D2 short model**

| Parameters | Unit | Value |
|---|---|---|
| Bore field | T | 4.5 |
| Peak field | T | 5.25 |
| Current | kA | 12.250 |
| Temperature | K | 1.9 |
| Load line margin | (%) | 35 |
| Overall current density | A/mm$^2$ | 443 |
| Stored energy per unit length | MJ | 0.28 |
| Differential inductance per unit length | mH | 3.5 |
| Magnetic length magnet/short model | m | 7.78 / 1.39 |
| Superconductor | | Nb-Ti |
| Strand diameter | mm | 0.825 |
| Cu/No Cu | | 1.95 |
| RRR | | >150 |
| Superconductor current density at 10 T, 1.9 K | A/mm$^2$ | 2100 |
| Number of strands per cable | | 36 |
| Cable bare width | mm | 15.1 |
| Cable bare mid thickness | mm | 1.480 |
| Keystone angle | degrees | 0.90 |
| Insulation thickness per side radial | mm | 0.160 |
| Insulation thickness per side azimuthal | mm | 0.145 |
| Multipole variation due to iron saturation | Units in $10^{-4}$ | < 10 |
| Weight of short model magnet | Kg | 4100 |

**Table 1 : Main features of D2 dipole magnet**

# OUTLINE

# 1. Magnet System Checkout at Room Temperature

This part introduces the series of tests to be performed on the D2 short model magnet as it arrives to the SM18 test facility. It consists in:

1. electrical connections checkout
2. test of the insulation integrity
3. magnet inductance measurement

## 1.1 Magnet on the Stand

### 1.1.1 Magnet electrical connections: first checkout

In order to detect any fault in the wiring of the magnet, the following preliminary tests are performed.

a. ***First magnet wiring checkout***

This step consists in:

- ✓ Numbering and labeling the required channels for the magnet instrumentation signals related to:
  - Voltage taps ( Vtaps)
  - Strain Gauges (SG)
  - Temperature Sensors (TS)
  - Protection Heaters (PH)
  - Magnetic Measurement Shaft (MMS)

- ✓ Connecting every connector to its dedicated magnet instrumentation test read-out.

*(To be verified the compatibility of connectors is used on the specific D2 Short model magnet, as if different from test station there need to be foreseen an adaptation to CERN test station cables).*

b. ***Continuity test***

In order to check if no Vtaps are lost and that the Vtaps are connected in the right order, a continuity test is performed. The method is as following:

- ✓ Power the magnet with low current: the maximum current depends on the cable copper ratio with typically (to be always confirmed by the magnet designer):
  - $I_{mag}$ = ~ 1-10 A

- ✓ Check that the successive potentials along the magnet cables are continuous.
- ✓ Check the warm resistance $R_i$ of cable segments $i$ as compared with expected value $R_i^{ex}$:
  - Measured $R_i = V_i / I_{mag}$ [Ω]
  - $R_i^{ex} = \rho_{cu}.l_i / S_{Cu}$ [Ω]

- ✓ Verify that the values are coherent with the measurements performed previously during the magnet assembly.

c. ***Protection Heater resistance measurement***

- ✓ Check the resistances $R_{PH}$ of each PH with voltmeter at the connectors and compare with expected values:
  - Measured $R_{PH}$ [Ω]
  - $R_{PH}^{ex} = \rho_{PH} . l_{PH} / S_{PH}$ [Ω]

- ✓ Verify that the values are coherent with the measurements performed previously during the magnet assembly.

d. ***Channels connection and chassis preparation***

The "POTential AIMant" (POTAIM) chassis (specific to CERN equipment, developed in-house) is the rack containing the POTAIM cards to which the VTaps are connected via the Burndy connectors. The POTAIM cards provide for analogic signals going to the acquisition system "PCI eXtensions for Instrumentation" (PXI) for signal record and for logic signals (trigger) going to the *Safety Matrix* that contains INTEROUT cards for specific devices control (magnet protection) after POTAIM card's trigger.
The present configuration of the chassis is such that a maximum of 160 channels can be recorded at High Frequency (HF), with an acquisition ranging from 10 to 200 kHz, a resolution of 0.3 mV and a precision of 0.3 mV. The Low Frequency (LF) acquisition allows record 360 channels with one point recorded every second.

To configure the POTAIM cards, the following steps have to be done:

- ✓ Determine the voltage signals that trigger the magnet protection. Typically, these *main voltage signals* are connected to the *safety cards* to form the *Safety Matrix* and are related to:
  - the current leads direct voltages, $V_{lead1}$,$V_{lead2}$
  - the splices direct voltages, $V_{splice-i}$ with $i$ the splice number
  - the direct total magnet voltage, $V_{sum-t}$
  - the direct coil voltages, $V_{sum-j}$ , with $j$ the coil number
  - the coil differential voltages, $V_{diff-k}$ , with $k$ an integer

- ✓ Determine the voltage signals $V_i$ that probe the superconducting cable segments $i$. These signals are connected to the *monitoring cards*.

- ✓ Design and organize the POTAIM cards chassis according to the number of required channels separating the *safety* from the *monitoring* signals.

- ✓ Connect the POTAIM cards to the PXI for signal recording.

- ✓ Connect the POTAIM cards to the Safety Matrix for magnet protection trigger.

At this stage, a clear documentation containing all information regarding the position of the Vtaps is required. For any missing Vtap at this stage, it is necessary to define if it will be simply not used or replaced with an existing one. Any missing Vtaps to be replaced for the security matrix will be submitted for decision to the magnet designer, or magnet responsible.

### 1.1.2 High Voltage test: insulation integrity checkout

In order to detect any insulation weakness in the magnet, the *High Voltage Test* (HV test) is performed as follows:

- ✓ Disconnect the magnet from all resistance sources.
- ✓ Use the "Megger HV rack" test bench for the HV test.
- ✓ Set the maximum potential to be applied, $U_{MAX}$ [kV] and application time $\Delta t_{HV}$ [min], according to the design criteria.
- ✓ Apply the potential difference between:
    - Magnet Structure & Ground
    - Magnet Structure & Coils
    - Magnet Structure & Protection Heater
    - Coils & Ground
    - Coil & End-shoes
    - Coil & Protection Heater
    - Protection Heater & Ground
- ✓ Measure the various resistances that should stay in the GΩ order of magnitude for the specified time delay.
- ✓ Record the leak currents that should all remain in the nA order of magnitude.

### 1.1.3 Magnet inductance measurement

The magnet inductance can be measured at room temperature using AC current powering and *Transfer Function* (TF) analysis. The procedure is the following:

- ✓ Connect the magnet leads to the "POWERTEK frequency response analyzer".
- ✓ Setup the analyzer and power the magnet with AC current
- ✓ Use the software to determine the TF via the analysis of the *gain* and *phase*.
- ✓ Record the total magnet inductance $L_{mag}$ [mH] as measured by the analyzer and compare with expectation.
- ✓ Check for noise in the signals that would be signs of short cut between coil turns.

*(In order to judge the measurements, it is necessary to have the estimated inductance of the magnet before and after iron saturation. This value has to be given by the magnet designer.)*

## 1.2 Magnet on the Insert

This part introduces the series of tests to be performed on the magnet after it has been mounted on its insert with installed magnetic shaft within the magnet bore. The tests consist in a new checkout of the proper reading of the electrical signals, of a new test of the insulation integrity and a checkout of the magnetic shaft functioning.

### 1.2.1 Magnet electrical connections: potentials at the connecting boxes

a. ***Magnet wiring to the Connecting Boxes***

- ✓ Connect the “Bundy type”, “3M type” connectors to the “Connecting Boxes” placed on the insert.
- ✓ Check the connections and potential reading at the connecting boxes for:
  - Voltage taps
  - Strain Gauges
  - Temperature Sensors
  - Protection Heaters
  - Magnetic Shaft
  - Level sensor
  - Pressure sensor
  - He bath Heater (for magnet warm-up)

b. ***Continuity Test***

- ✓ Perform a new continuity test.
- ✓ Check that the successive potentials are continuous.
- ✓ Check the warm resistance of the cable segments and compare with expectation.

c. ***Protection Heater resistance measurement***

- ✓ Check the PH resistances measured at the connecting box with multimeter and compared with expected values:
  - Measured $R_{PH}$ [Ω]
  - $R_{PH}^{ex} = \rho_{PH} \cdot l_{PH} / S_{PH}$ [Ω]

*(The characteristics of the PHs have to be presented by the magnet designer. It is needed the schematic of the connections, the dimensions and the geometry as well as all measurements done during the fabrications that shows the complete follow up of the electrical integrity of the heaters).*

### 1.2.2 Current leads connection to magnet cable ends

- ✓ Insert the magnet cable ends inside the “Socket Clamp Boxes” and tighten the connections with the NbTi leads to carefully realize the joint.
- ✓ Add extra voltage taps to monitor the connections, named $V_{leads}$ [V] that allow the measurement of the splice resistance of this connection
- ✓ Check with magnet designer the eventual necessity of reinforcement of the leads electrically (with SC cables, with Cu stabilizer) or mechanically.

### 1.2.3 HV test

Perform new HV test as follows:

- ✓ Pay attention to disconnect the magnet from all resistance sources.
- ✓ Perform a new HV test using the “Megger HV rack” at $U_{MAX}$ [kV]:

  - Magnet Structure & Ground

- Magnet Structure & Coils
- Magnet Structure & Protection Heater
- Coils & Ground
- Coil & End-shoes
- Coil & Protection Heater
- Protection Heater & Ground

✓ Measure the various resistances that should stay in the GΩ order of magnitude for the specified time delay.
✓ Record the leak currents that should all remain in the nA order of magnitude.

### 1.2.4 Magnetic measurement using shaft

✓ Insert, fix and connect the "Magnetic Measurement Shaft".
✓ Control the mechanical behavior of the shaft, check for vibration, misalignment.
✓ Perform magnetic measurement at room temperature.

## 1.3 Magnet in the cryostat

This part introduces the series of tests to be performed on the magnet as installed inside the cryostat. It consists in a new checkout of the reading of the electrical signals via the chassis POTAIM by the Data Acquisition System, of a new test of the integrity of the insulations and a checkout of the magnetic shaft functioning.

### 1.3.1 Check of the potentials at the POTAIM Chassis

✓ Connect the cables with the Fischer connectors to the Connecting Boxes and the Burndy connectors to the POTAIM chassis
✓ Check the reading of the magnet potentials at the POTAIM chassis:
  - Voltage taps (Vtaps)
  - Strain Gauges (SG)
  - Temperature Sensors (TS)
  - Protection Heaters (PH)
  - Spot heater (SH)
  - Capacitor pressure transducer (CPT) - when available
  - Magnetic Measurement Shaft (MMS)

✓ Set the proper *gain* of the monitoring and safety cards.
✓ Perform a new continuity test.

### 1.3.2 Check of the DAQ and storage

✓ Verify the proper gain settings of the DAQ.
✓ Confirm readiness of the database for the signals from the POTAIM chassis.
✓ Check that data are recorded in the proper format, extension and file while manually trigger one of the safety card.

*(Pay attention to the fact that in the CERN installations the gain are set up manually and there is no direct record of it via the DAQ. Once the test has been performed and magnet has been*

*tested and disconnected there is no way to check the correctness of the "gain "of the different channels.)*

### 1.3.3 HV test

Perform a new HV test as follows:

- ✓ Pay attention to disconnect the magnet from all resistance sources.
- ✓ Perform a new HV test using the "Megger HV rack" at $U_{MAX}$ [kV]:
    - Magnet Structure & Ground
    - Magnet Structure & Coils
    - Magnet Structure & Protection Heater
    - Coils & Ground
    - Coil & End-shoes
    - Coil & Protection Heater
    - Protection Heater & Ground

- ✓ Measure the various resistances that should stay in the GΩ order of magnitude for the specified time delay.
- ✓ Record the leak currents that should all remain in the nA order of magnitude.

### 1.3.4 Magnetic measurement using the shaft

- ✓ Insert and install the magnetic measurement shaft in the magnet bore.
- ✓ Control the mechanical behavior of the shaft, check for vibration, misalignment.
- ✓ Perform magnetic measurement at room temperature.

# 2. Cooling of the Magnet

The cool-down of the magnet can get started if all previous tests have been successfully done. To be remarked that insulation problems can eventually be solved by adapting acceptance values or by changing connections if there is no problem between the magnet and ground. Any change of the specified values for insulation should be approved by the magnet designer and the responsible of the test in common agreement.

Different steps should then be follows:

- ✓ Define and control the maximum allowable temperature gradient $\Delta T_{max}$[K] that should be defined by the magnet designer (Typically $Nb_3Sn$ magnets are very sensitive to the speed of the cooling)
- ✓ Monitor the cooldown process temperature from Room Temperature to 4.4 K or 1.9 K.
- ✓ Check the cryostat inner pressure all along the cooldown: the pressure should not exceed 3 bars absolute.
- ✓ For the *RRR* measurement during cooldown, power the magnet with low current with maximum current depending on the cable copper ratio (typically $I_{mag}$ = ~ 1-10 A). The value of the current should be given by the magnet designer.
- ✓ Set the "*RRR* rack measurement" with the signals of interest to be monitored during the cooldown.
- ✓ Check the CryoDAQ and start the cooldown in agreement with the cryogenics team.

During the cooling:

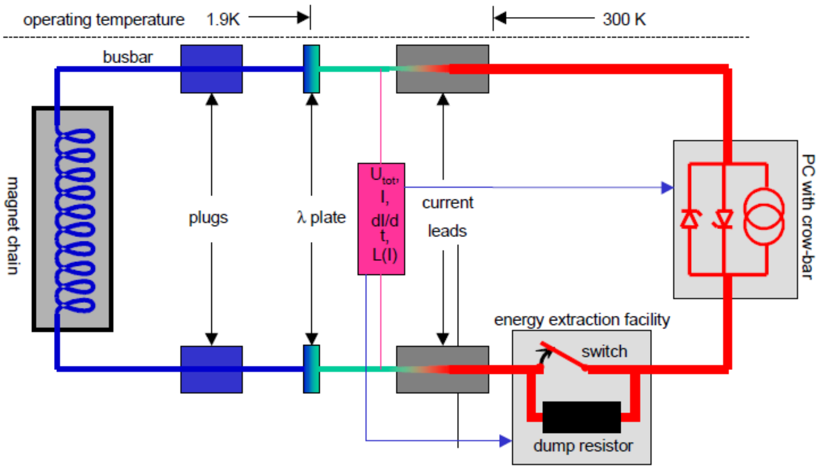
✓ Record and follow the temperature, the CPT and the strain gauge measurements and assess the stress in the various magnet components. Generate the Excel file summarizing stress in:
  - Magnet Structure ( shell) (azimuthal and axial stress)
  - Coil Pole (azimuthal and axial stress)
  - Magnet Structure (Road) (azimuthal and axial stress)
  - Any other gauge signals that are present in magnet

After the cooling:

✓ Determine the *RRR* and the transition temperature $T_c$ [K] of the superconducting cable taking into account NbTi, $Nb_3Sn$ splices.

# 3. Setup for Cold Magnet Testing

Once the magnet is cold (4.2 K or 1.9 K), a last series of tests should be performed to check again the reading and recording of the electrical signals. A new HV test is necessary at cold in liquid. For the magnet protection, the *PH powering system* should be setup with a separated RC circuit. The *dump resistor* used to extract the energy out of the magnet should be set at its nominal value. The *magnet protection scheme* is here defined before connecting the magnet to the main Power Supply.
The protection scheme at different stage of the test has to be discussed between the magnet responsible and the test responsible and commonly agreed on it.




*Schematic view of a LHC circuit including a global quench detector (measurement of* $U_{tot}$ *and* I*). The protection elements for the magnets (parallel diode or resistor, quench heaters) are not included*

## 3.1 Checkout of the electrical connections

✓ Check if no signal has been lost during cooling of the magnet.
✓ Set the *offset* of each voltage taps signal on the POTAIM chassis.
✓ Set the *balance* of each differential signals on the POTAIM chassis.

- ✓ Verify the cold resistance values of the PH circuits and compare with expectation

## 3.2 Protection Heater resistance measurement

- ✓ Check the resistances at cold of each PH with voltmeter at the connectors and compare with expected values:
    - Measured $R_{PH}$ [Ω]
    - $R_{PH}^{ex} = \rho_{PH} \cdot l_{PH} / S_{PH}$ [Ω]

- ✓ Verify that the values are coherent with the measurements performed previously during the magnet assembly.

## 3.3 HV test

Perform the cold HV test as follows:

- ✓ Stop current leads heating and disconnect from power supply.
- ✓ Stop He flow through the leads.
- ✓ Disconnect the magnet from all resistance sources.
- ✓ Disconnect all signals to the POTAIM chassis.
- ✓ Warn cryogenics team about the coming HV test.
- ✓ Disconnect all temperature sensors.
- ✓ Perform HV test.
- ✓ Measure the various resistances that should stay in the GΩ order of magnitude for the specified time delay.
- ✓ Record the leak currents that should all remain in the nA order of magnitude.

## 3.4 Quench detection and magnet protection scheme

When a quench is detected by the Safety Cards of the POTAIM chassis, the Safety Matrix triggers the current extraction and the magnet protection scheme.

### 3.4.1 Quench detection criteria

Quenches are detected by the *Main Voltage Signals* according to defined *threshold* $\Delta V$ [mV] and *validation time* $\Delta t$ [ms].

- ✓ For each triggering card, set:
    - $\Delta V_{lead\text{-}1,2}$ [mV], $\Delta t_{lead}$ [ms]
    - $\Delta V_{splice\text{-}i}$ [mV], $\Delta t_{splice\text{-}i}$ [ms]
    - $\Delta V_{sum\text{-}t}$ [mV], $\Delta t_{vsum\text{-}t}$ [ms]
    - $\Delta V_{sum\text{-}j}$ [mV], $\Delta t_{vsum\text{-}j}$ [ms]
    - $\Delta V_{diff\text{-}k}$ [mV], $\Delta t_{diff\text{-}k}$ [ms]

- ✓ These quench detection criteria can be chosen according to expected quench propagation velocity $V_q$ [m.s$^{-1}$] or after provoked quench at low current and voltage signal checkout together with the magnet responsible.

### 3.4.2 Magnet protection scheme and delays

The *Safety Matrix* is controlling the steps of the *magnet protection scheme* after quench detection.

✓ The *magnet protection scheme* is made of three parts:

1. "Power converter OFF and DAQ ON"
2. "Thyristors and Mechanical Switches OFF for current extraction in the Dump Resistor"
3. "Protection Heater firing ON"

✓ These events can be delayed with respect to the quench detection (attained threshold) and to each other with the following *delays*:

1. $\tau_1$ [ms].
2. $\tau_2$ [ms].
3. $\tau_3$ [ms].

✓ Control of the *Safety Matrix* by triggering each POTAIM card separately in order to verify the response of each associated device.

## 3.5 Setup of the dump resistor

After quench detection, the current is extracted out of the magnet through the so-called *Dump Resistor* (DR). In the SM18 vertical test station at CERN, it consists of four stainless steel bars of 40 mΩ units. The resistor value can then be tuned in order to extract more or less energy by combining them is series and in parallel connection.

✓ Determine the value of the dump resistance $R_{dump}$ [mΩ] according to the HV test result @ cold and check that:

- $R_{dump} < U_{MAX} / I_{mag}$

✓ Define the time constant $\tau_{mag}$ [ms] of the current decay as function of $R_{dump}$ and the magnet inductance $L_{mag}$ as:

- $\tau_{mag} = L_{mag} / R_{dump}$ [ms]

✓ Check the expected *Miits* [MA$^2$.s] and compare to the design limit. When a delay $\tau$ is used, it reads:

- $Miits = \int_o^{+\infty} I_{mag}(t)^2\,dt = I_0^{\,2} \cdot \tau + \int_\tau^{+\infty} I_{mag}(t)^2\,dt$

✓ Setup the DR to the desired value setting the individual elements in a circuit in series and/or parallel connection.

## 3.6 Setup of the protection heaters powering system

The *PH powering system* is to be defined according to the geometry of the stripes, their material properties and the power needed to trigger quench into a given cable. This system is basically made of a voltage supplier to charge capacitors that then discharge their current into the PH. The discharge is trigger by the Safety Matrix. The PH setup is described hereafter:

- ✓ Define the maximum power $P_{PH}$ [W.cm$^{-2}$] to be injected in the Protection Heaters according the PH design.
- ✓ Define the needed decay time constant $\tau_{PH}$ [ms] according the PH design.
- ✓ Define the capacitor $C$ [mF] value to respect the decay time constant with $\tau_{PH} = R_{PH}.C$.
- ✓ Determine the maximum current $I_{PH}$ [A] to be put in the PH.
- ✓ Define the electrical circuit (number of PH, connected in parallel or in series with weakly insulated PH replaced by extra resistor of equivalent resistance).
- ✓ Determine the maximum needed voltage $E$ [V] to be delivered by the power PH supply.
- ✓ Wire the PH power circuit with PH current monitoring.

- ✓ Check the PH system firing without current in the magnet.
- ✓ Verify that the PH voltage and current traces follow exponential decay law.
- ✓ Record the $V_{PH}(t)$ and $I_{PH}(t)$ traces for each circuit as reference signals for further check.

## 3.7 Magnet connection to the main Power Supply

- ✓ Check that all other test stations are disconnected and isolated from the on-going experiment before connecting the main Power Supply (PS).
- ✓ Plug and connected the “PS Connecting Carriage” to the Current Leads.

## 3.8 Setup of the Programmable Logic Controller

The “Programmable Logic Controller” (PLC) integrates electrical and non-electrical signals in order to give or not the possibility to power a magnet. Before allowing powering, the PLC checks if:

- the cryogenics is OK
- the mechanical switches are OFF
- the thyristors are OFF
- the PH are charged
- the safety matrix cards are reading OK
- the LF/HF acquisition system is armed
- the record file configuration and extension are OK

The cryogenics is giving an “OK” to the PLC if the magnet and the current leads are on their cold side covered at the right level by the liquid
If everything is OK then the PLC allows starting the magnet powering test.

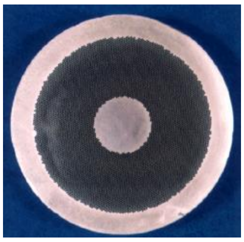
# 4. Main Parameters of the Tested D2 Magnet

In this paragraph, the input data related to the "**INFN double-Aperture MBRD D2 Dipole Short model Model**" are listed. For this model magnet, the main parameters for the magnet test experiment are also introduced.

## 4.1 Magnet components

### 4.1.1 Cable and strand

The LHC Rutherford cable for the outer layer of the main dipole magnets, quadrupole magnets and busbars: 36 strands, width 15.1 mm, $J_c$*(1.9 K, 9 tesla)* ≥ *12900 A,* A=*19.2442 mm²,* strand twist pitch $L^s_p \approx 10.5$ cm. A short longitudinal section is shown on the left; the trapezoidal cross-section on the right. see Fig. 1. a).

a) 

b) 

**Fig. 1 : a) Transverse cross-section of NbTi LHC outer MB layer type strand used in the D2 dipole, d =0.825 mm, dfil ≈6 µm, RRR> 100, 1.9≤ rcu/sc ≤ 2.0, Nfil ≈6400.**

**b) Longitudinal (bottom) and transverse cross-section (top) of the 36-strand cable [LHC ref].**

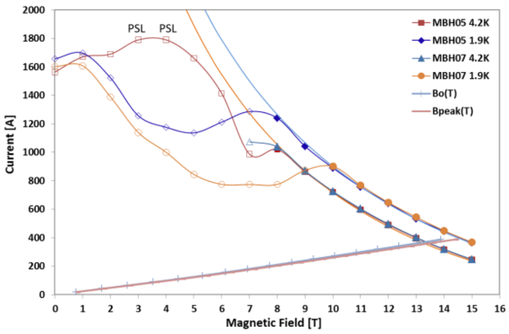
### 4.1.2 Cable

The superconducting cable is composed of $N_s$ = 40 strands with a transposition pitch of $L_p$ = 111 mm, see Fig. 1. b). After reaction, the bare cable width and thickness are respectively $w_c$ = 14.48 mm and $h_c$ = 1.32 mm with a packing factor of PF = 84.8 %. The cable is insulated with one layer of $h_i$ = 0.1 mm epoxy-impregnated E-glass wrap. The insulated and impregnated cable transverse cross-section surface is 22.4 mm$^2$. The cable features a stainless-steel core for the suppression of inter-strand coupling. The average cable *RRR* , see Fig. 2 a) and the transition temperature are expected to be:

- $60 < RRR < 120$
- $T_c$ = 18 K

The critical current has been also measured; see Fig. 2 b).

- $I_{ss}$ (4.2 K, 12 T) = 491 A
- $I_{ss}$ (1.9 K, 12 T) = 643 A

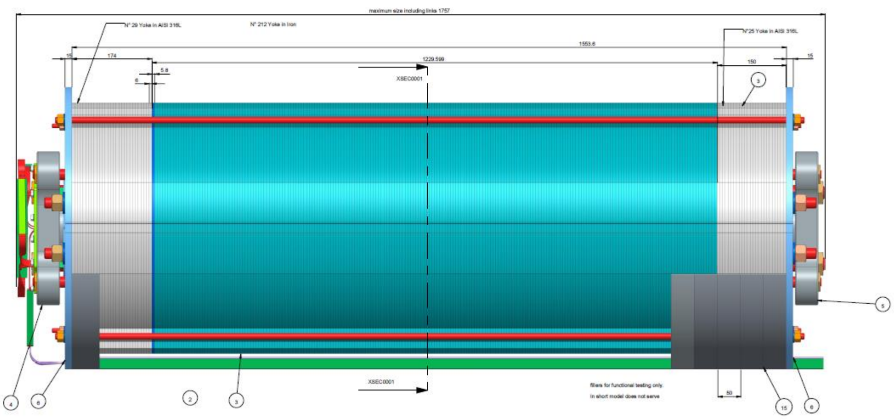



a) b)

**Fig. 2 : a) RRR and b) critical current measurement of the RRP 150/169 strand as extracted from their cables and heat treated with the magnets [Barzi 2012].**

### 4.1.3 Coil

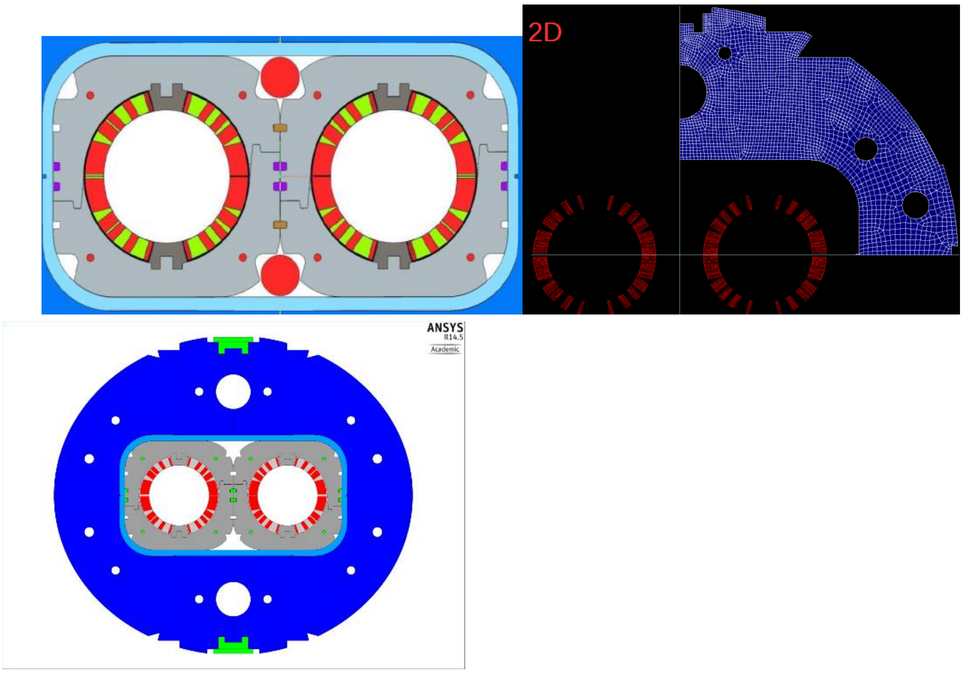
The two coils of the magnet are composed of six blocs with respectively 22 turns in the inner layer and 34 turns in the outer layer, see Fig. 3 a).



### 4.1.4 Magnet

The D2 MBRD dipole short model magnet is $L_M$ = 1.6 m long with an outer diameter of 614 mm and contains two coils made of two layer *cos 2θ* cable. The aperture is $D_M$ = 105 mm wide. The coil pre-stress and support is provided by Stainless steel collar and Aluminium collar, a vertically split iron yoke, aluminium clamps and a 12 mm thick stainless steel skin, see Fig. 3 b). The total weigh of the magnet is M = 1020.5 kg.

a)




b)

**Fig. 3 : a) Transverse cross-section of the D2 dipole coils. The five blocks winding are visible around the 105 mm wide aperture. b) Transverse cross-section of the INFN double aperture D2 dipole magnet [Fabricattore 2016].**

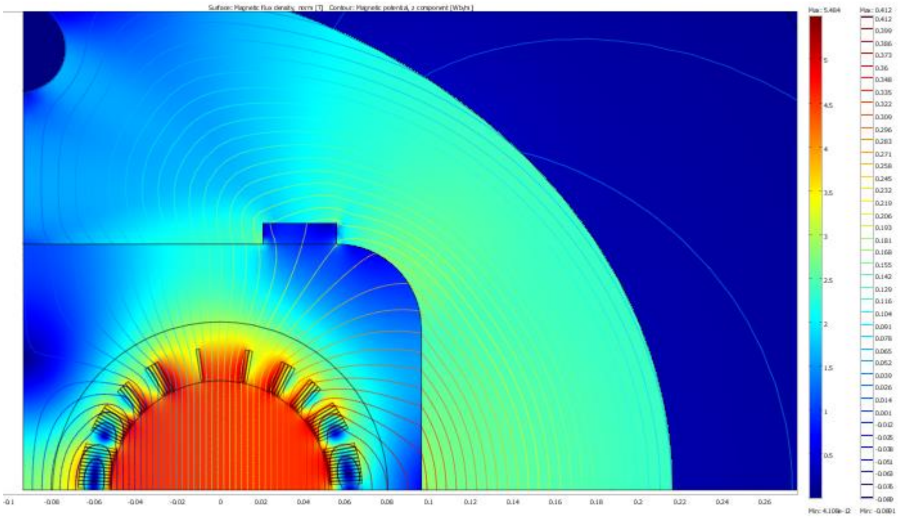


**Fig. 4: Fringe Field @ 1 m midplane 18.6 mT**

## 4.2 Magnet instrumentation

The D2 short model dipole magnet is instrumented with:

- **12 strain gauges** (4-wires resistive) installed on the 6 tie rods, coils and bullets.
- **2 resistive temperature sensors** mounted at top plate, middle of the magnet yoke
- **32 voltage taps** (16 in the coil layer head turns, 16 across the electrical splices), see Fig. 4.

At warm, the maximum current should not exceed $I_{mag}^{max}$ = 10 A.

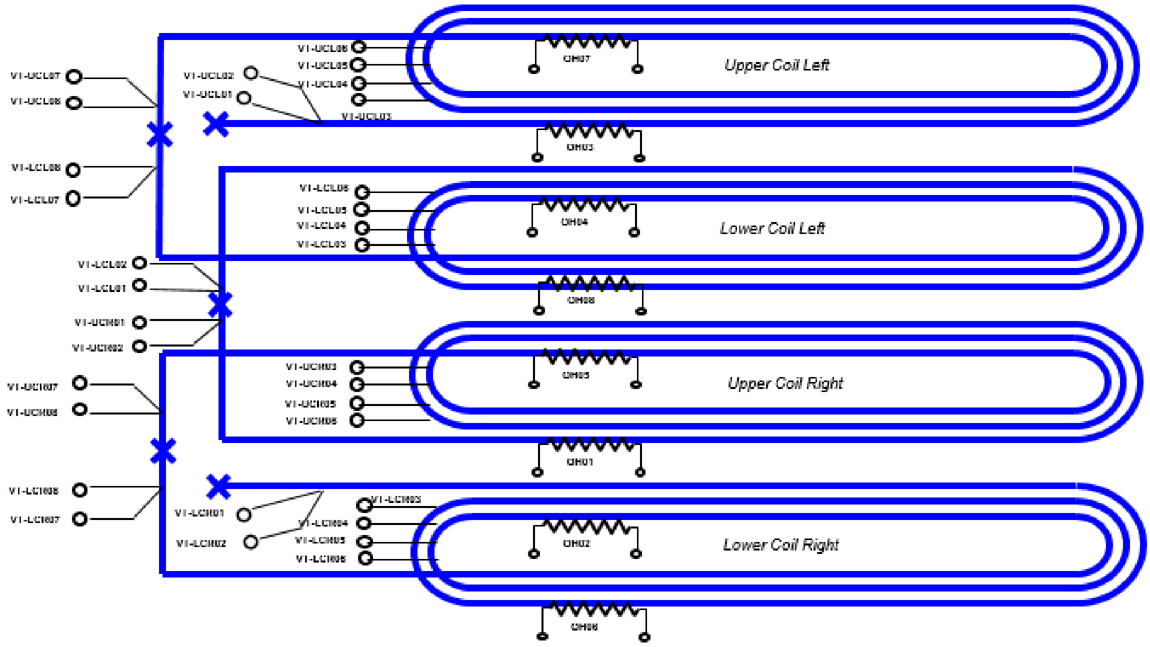



**Fig. 4 : Overview of the voltage tapes position on the single layer of two in one aperture coils.**

## 4.3 Quench detection parameters

For the quench detection thresholds and validation times, the values are chosen according to expected quench propagation velocity [xxx]:

- $V_q$ = ~27 m.s$^{-1}$ @ $I_q$ = 12.25 kA

After t = 10 ms of quench, an estimated voltage $U_q$ is:

- $U_q = (\rho_{Cu}\ V_q\ I_q\ /\ S_{Cu}) * t\ = (7.10^{-10} * 30 * 15000\ /\ 10^{-5}) * 10 = 300$ mV

Based on this consideration, the quench detection criteria are the following:

- $\Delta V_{lead-1,2}$ = 80 mV, $\Delta t_{lead}$ = 500 ms
- $\Delta V_{splice-i}$ = 10 mV, $\Delta t_{splice-i}$ = 10 ms
- $\Delta V_{sum-t}$ = 200 mV, $\Delta t_{vsum-t}$ = 10 ms
- $\Delta V_{sum-j}$ = 200 mV, $\Delta t_{vsum-j}$ = 10 ms
- $\Delta V_{diff-k}$ = 100 mV, $\Delta t_{diff-k}$ = 10 ms

## 4.4 HV test parameters

For the HV test, apply the following potential difference between:

- Shell & Ground, $U_{MAX}$ = 1 kV
- Shell & Coils, $U_{MAX}$ = 1 kV
- Shell & Protection Heater, $U_{MAX}$ = 1 kV
- Coils & Ground, $U_{MAX}$ = 1 kV
- Coil & End-shoes, $U_{MAX}$ = 1 kV
- Coil & Protection Heater, $U_{MAX}$ = 1 kV
- Protection Heater & Ground, $U_{MAX}$ = 1 kV

## 4.5 Magnet test main parameters

### 4.5.1 Short Sample Limit and nominal performances

The Fig. 5 shows the load line of the magnet as well as the measured short sample limits for two temperatures along with their best fit. From this, the cable Short Sample Limits for the two reference temperatures assuming 10% manufacturing degradation are:

- $I_{ss}$ (4.2 K, 11 T) = 13.8 kA
- $I_{ss}$ (1.9 K, 11 T) = 15.4 kA

The nominal operating temperature for the test is:

- $T_{op}$ = 1.9 K

The nominal field at the bore is:

- $B_{nom}$ = 10.9 T

The nominal current is:

- $I_{nom}$ = 11.85 kA

The loadline margin is at $I_{nom}$:

- $M$ = 21 % ($I_{margin}$ = 14.2 kA)

The ultimate field at the bore is:

- $B_{ultim}$ = 12 T

The ultimate current is:

- $I_{ultim}$ = 13.25 kA

The ultimate gradient is:

- $G_{ultim}$ = 199 T/m

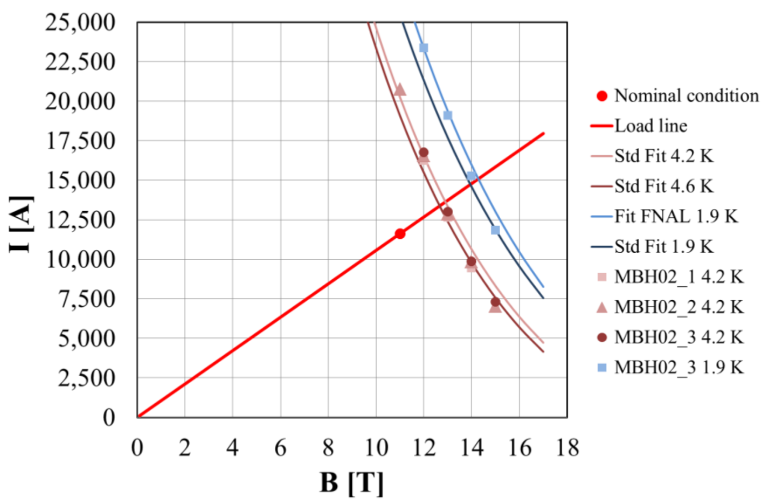



Fig. 5 : FNAL 11 T Dipole Load line and Short Sample limit for the two temperatures.

### 4.5.2 Magnet inductance

The inductance parameters of the 11 T magnet are listed hereafter.

The magnetic length is:

- $l_M$ = 1.39 m

The differential inductance per unit length (at 300 K, 20 Hz) is:

- $dL_M$ = 3.5 mH/m

The differential magnet inductance is:

- $L_{mag}$ =  mH

The expected stored energy is:

- $E_{st}$ = 296 kJ

### 4.5.3 Dump Resistor parameter

The dump resistor is chosen in accordance to the HV test: $R_{dump} < U_{MAX} / I_{ss}$ = 66 mΩ
For the test, the nominal value for the DR was chosen to:

- $R_{dump}$ = 60 mΩ

In order to achieve this value, two 40 mΩ unit will be connected in a parallel circuit (equivalent to 20 mΩ) and then in series with one other unit bringing the total resistance of the circuit to and equivalent of 60 mΩ.
With this value, the current extraction time constant will be:

- $\tau_{mag} = L_{mag} / R_{dump}$ = 65 ms

The expected *Miits* if no time delay is applied between the detection of the quench and the energy extraction is:

- $Miits = 0.5\ \tau_{mag}\ .\ I_{ultim}^{\ 2}$ = 4.7 $MA^2.s$

At 0 T field, 5 Miits corresponds to 50 K whereas it is 75 K at 12 T, see Fig. 6.

The maximum allowable Miits is $Miits^{\ max}$ = 18 $MA^2.s$.

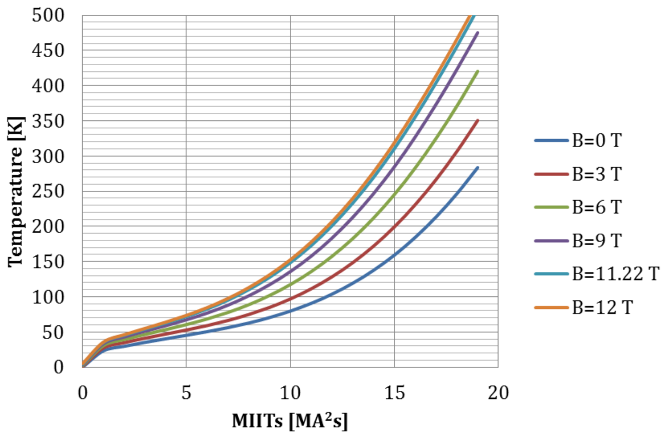



**Fig. 6 : Temperature vs. Miits calculation for the 11 T dipole [xxx].**

## 4.6 Protection Heater nominal parameters

The D2 dipole is equipped with two pairs of Protection Heaters per coil situated on their outer surface. For each coil, these pairs are referred to as H-1 and H-2 and the strips of the pairs are referred to as H1+ (HF) and return H1- (LF), see Fig. 8 a). There is a total of height PH strips in the D2 dipole.
The strips are made of 316 austenitic stainless steel and are electrically insulated from the potted coil by a 125 µm thick Kapton layer.

The heaters for the dipole magnets consist of U shape strips of (0.025 ± 0.002mm thick and either 15.0±0.1mm or wide) bonded in between two layers of polyimide electrical insulation foil (see Fig. 3.14). The latter acts as support and insulates the strips against the coils and the collar structure that is at ground potential
The strips LF and HF are respectively $w_{PH}$ = 15 and 20 mm wide and both are $h_{PH}$ = 0.025 mm thick and $l_{PH}$ = 1130 mm long.

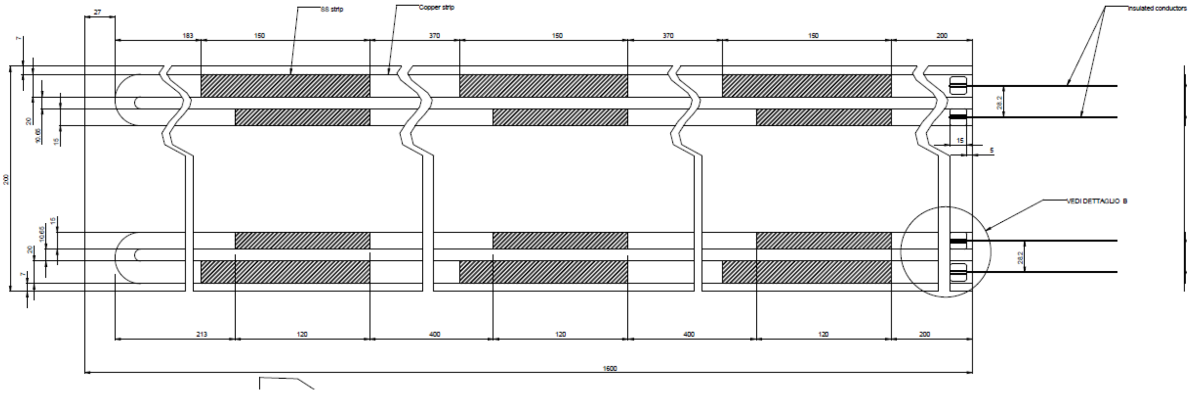



**Fig. 7 : D2 quench heater layout**

One HF and one LF strips of one pair are connected in series, and two pairs from the two coils are connected in parallel to a heater power supply. The expected resistance value of two heaters in series is:

- $R_{PH}^{ex}$ (300 K) = $\rho_{steel}$ (300K)* 2 * $l_{PH}$ / ($w_{PH}$ * $h_{PH}$)
  = 0.78 * $10^{-6}$ * 2*1130 *$10^{-3}$/ (23.5 * $10^{-3}$ * 0.025 * $10^{-3}$)
  $R_{PH}^{ex}$ (300 K) = 3 Ω
- $R_{PH}^{ex}$ (1.9 K) = 2.23 Ω, with $\rho_{steel}$ (1.9 K) =0.58*$10^{-6}$ Ω.m.

From [Zlobin 2012], the resistance of two heaters in series with $l_{PH}$ = 2106 mm were measured at $R_{PH}^{measured}$ (1.9 K) = 4.23 Ω at 1.9 K, and the parallel-connected heater circuit, including wire and connection resistances was measured at $R_{PHC}^{measured}$ (1.9 K) = 2.59 Ω. We conclude that wiring amounts to 0.48 Ω. The heater circuit's resistance corresponding to Fig. 8 for $l_{PH}$ = 1130 mm is expected to be:

- $R_{PHC}^{ex}$ (1.9 K) = (2.23*2.23) / (2*2.23) + 0.48 = 1.6 Ω

The power $P_{PH}$ dissipated by the PH to the cable with the time constant $\tau_{PH}$ of the PH current discharge should be variable within the ranges of:

- $P_{PH}$ = 25-100 W/cm$^2$
- $\tau_{PH}$ = 25-100 ms

In order to assure these characteristics with the circuit in Fig. 8 b) and the measured $R_{PHC}$, using available capacitor $C$ of 14 mF, it is desirable to add a rheostat in series in the PH circuit that can be adapted in order to get the good time constant. As an example for, $\tau_{PH}$ = 75 ms, the extra resistance value should be:

- $R_{rh} = \tau_{PH} * C - R_{PH} = (75*10^{-3}) / (14*10^{-3}) - 1.6 = 3.8\ \Omega$

The available voltage supply with a maximum delivered voltage $E$ = 800 V can be used. The maximum achievable current in the circuit $I_{PHC}$ is then:

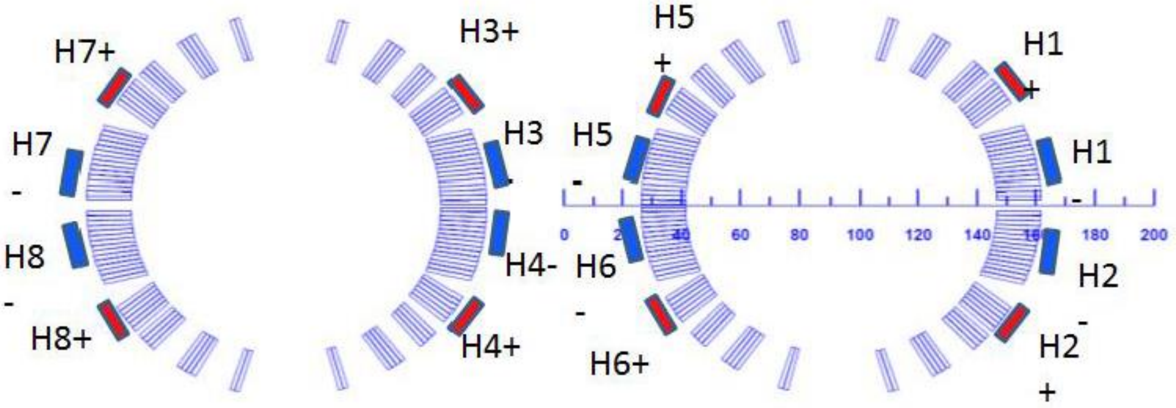
- $$I_{PHC} = \frac{E}{R_c(1.9K)} = \frac{800}{3.8+1.6} = 148\ \mathrm{A}$$

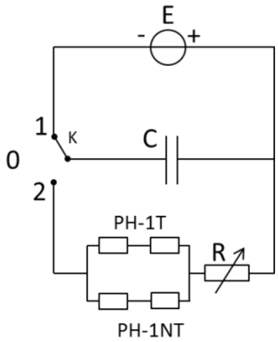
Then the generated power density within the PH is:

- $$P_{PH} = \frac{R_{PH} \cdot (I_{PHC}/2)^2}{l_{PH}\, w_{PH}} = \frac{2.23 \cdot (148/2)^2}{2*1.13*23.5*10^{-3}} = 23\ \mathrm{W/cm}^2$$

It should be noted that the copper wires can carry limited current.

a)




b)

**Fig. 8 : a) Overview of the 8 pairs of PH U shaped strips situated on the outer surface of both apertures coils (H1-H8). b) Equivalent electric scheme for PH powering with parallel two stripe PH.**

## 4.7 Cooling parameters

For the cooldown and warm-up, the maximum value of the thermal gradient between the top and the bottom of the magnet should not exceed:

- $\Delta T_{max}$ = 150K

# 5. Preliminary Cold Tests

The cold test starts with powering the magnet at low currents. Manually triggered quenches and energy extraction help to adjust the detection thresholds if flux jumps are detected. The analysis of the voltage signals at increasing quench currents help deciding whether the experiment can be carried on. As part of the preliminary tests, the splice resistances are measured.

## 5.1 Quench analysis procedure

To analyse a quench with enough details, the steps to follow are listed hereafter:

✓ Check and record:
- the quench current $I_q$ [kA]
- the *Miits* [$MA^2.s$]
- the stored energy $E_{st}$ [kJ]
- the dissipated energy $E_d$ [kJ].

✓ Check voltage profiles using the HF AQA:
- Check for saturated signals that are not supposed to be so, if needed correct their gains in hardware and configuration.
- Check for noise through recorded signals.
- If noise issue, this should be discussed with project engineers before adjusting any threshold.
- Check the current lead voltage rise and adjust lead cooling He flow accordingly.
- Verify that $V_{sum-t}$ corresponds to $I_{mag} . R_{dump}$ during the current extraction.
- Verify that the sum of the $V_{sum-i}$ equals $V_{sum-t}$
- Check the system time constant $\tau_{mag}$ looking at the current decay profile.

✓ Determine where quench initiated:
- Splice, current lead, coil, layer, side, layer jump, multiturns, coil head, pole turn, high field straight part.
- Observe the presence of precursor if any, before quench.
- Determine if multi-quenches are measured out the Vtaps signals.
- Measure the quench velocity $V_q$ [$m.s^{-1}$] with time of flight method if propagation can be followed.
- Assess the quench velocity using *dv/dt* [$V.s^{-1}$] on the quench segment

$$V_q = (dv/dt * S_{Cu}) / (I_q * \rho_{Cu})$$

✓ Check if all the *thresholds* and *validation times* allows a controlled value of the *Miits*. Adapt if needed.

## 5.2 Provoked extractions at low current

The first magnet powering and current extraction are performed at low current. The procedure is as follows:

- ✓ Record the flux jump for the main signals during the ramp.
- ✓ Set the three delays of the protection scheme to zero:
  - $\tau_1 = \tau_2 = \tau_3 = 0$ [ms]
- ✓ Power the magnet using:
  - $RR$ = 50 A/s
- ✓ Provoke the current extraction by firing all heaters at increasing current with:
  - $I_{mag}$ = 1 kA, 2 kA, 4 kA, 6 kA
  - 
- ✓ For each quench, follow the *quench analysis procedure*.
- ✓ Decide if the test can be carried on.

  Length of the test: **4 quenches**, **1 day.**

  **(This time is driven by the cooling capacity of the system after a quench.)**

## 5.3 Splice resistances measurement

For the splice resistance measurement, the procedure is as follows:

- ✓ Connect the splices' potentials to the PXI system for acquisition.
- ✓ Program current cycles in the Power Supply controller by setting stair-step profile with ramp rate of 50 $A.s^{-1}$ and 300 ms plateau at 1 kA, 2 kA, 3kA, 4kA, 5kA, see Fig. 9.
- ✓ Use the PXI to monitor the splice resistance.
- ✓ Perform the test and run the 'Spice Analysis Software'
- ✓ Check that the splice resistance are all below 1 nΩ.

- ✓ Length of the test: **1/2 day.**

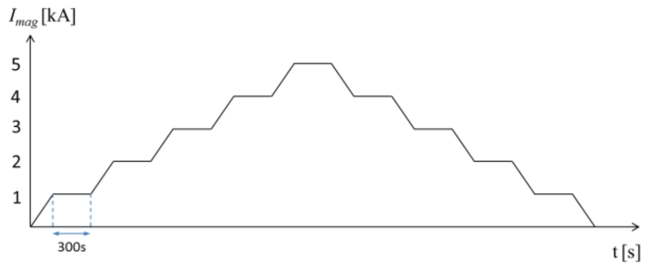



**Fig. 9 : Current profile for splice resistance measurement.**

# 6. Standard quench performance assessment

If the low current preliminary tests have been successful then the training of the magnet can be started. All the quenches done in this part of the test are performed at $T_{op}$. During all this part of the test, the three delays of the protection scheme are set to zero ($\tau_1 = \tau_2 = \tau_3 = 0$ [ms]). If the *Miits* are safe and quench propagation could be measured with longer delay then these are adapted accordingly.

## 6.1 First training quench

For the first training quench:

- ✓ Set the target current to $I_{ss}$ [kA] in the Power Supply controller.
- ✓ Set the acceleration at 25 A.s$^{-2}$
- ✓ Set the ramp rate at $RR$ = 50 A.s$^{-1}$ until 6 kA then at $RR$ = 10 or 20 A.s$^{-1}$ to target current or to quench.

- ✓ **If**, no quench, **then** take the champagne from the fridge and follow the "Organize drink Procedure".
- ✓ **Else**, follow the *quench analysis procedure*
- ✓ **End**, decide if the training can be carried on.

## 6.2 Magnet training

For the magnet training test, the procedure is as follows:

- ✓ Perform training quenches.
- ✓ Wait 25 minutes after the $T_{op}$ recovery for the magnet temperature to be uniform.
- ✓ Follow the *quench analysis procedure* for each quench.
- ✓ Check if $I_q$ increases and quantify any performance improvement/degradation.
- ✓ Plot the training curve with $I_q$ as function of the quench number.

- ✓ To decide about the training ends, follows:
  - **If**, $I_q$ does not exceed $I_{nom}$ after ***20 quenches***
  - **Then**, the training is stopped:
    - New definition of $I_{nom}$ equal to 90% of the maximum quench current that is used for the magnetic measurement.
    - $I_{nom}^{new} = 0.9\, I_q^{max}$
  - **Else if**, $I_q$ reaches $I_{nom}$ before ***15 quenches*** and is maintained (plateau) or exceeded for ***5 quenches*** in a row**.**
  - **Then**, the training of the magnet is a success and the training is stopped.
  - **Else if**, $I_q$ keeps increasing after ***20 quenches*** without visible plateau
  - **Then**, the training is paused and will be resumed later.
  - **End**, defined the maximum training quench current: $I_q^{max}$ [A].

- ✓ The training of the magnet is planned for **20 quenches**, i.e. **2 weeks** of uninterrupted test.
- ✓ If time constrain allows it, the training is carried on after thermal cycle.

*(We should define what we mean by plateau. What is the value between two consecutive "plateau like "quench that we may tolerate.)*

## 6.3 Ramp rate study

The effect of the ramp rate on the quench performance is studied powering the magnet at different rates. The current discharges from nominal current are studied as well.

### 6.3.1 Ramp Up

✓ Ramp up the current at different rates up to quench, from high to low values:
   - *RR* = 500, 300, 200, 100, 80, 50, 20, 10, 5 $A.s^{-1}$.

### 6.3.2 Ramp down

✓ Ramp up the current to $I_{nom}$ at referenced ramp rates.
✓ Hold the current for 5 minutes for the dynamic effect of the ramp to decay.
✓ Ramp down the current from low to high values of RR to quench (if any) or to zero current :
   - *RR* = 5, 10, 20, 50, 100, 200, 300, 500 $A.s^{-1}$.

✓ Conclude on the ramp rate domain where no quench is provoked plotting $I_q = f\,(RR)$.

✓ This test requires around 15 quenches, i.e. 1 week of test.
✓

## 6.4 Holding of the current at nominal current

In order to insure that long run magnetic measurements are possible:

✓ Ramp up the current to $I_{nom}$ at nominal *RR*.
✓ Hold the current for two hours.
✓ If no quench is detected, magnetic measurements are performed.

# 7. Standard magnetic measurement

See the document referred to as: “SM18 Magnetic Measurement Procedure”

# 8. Specific tests

In order to gain a better understanding of the tested magnet behaviour, a series of tests is proposed, for which some can be done during the magnetic measurement campaign.

## 8.1 Inductance measurement

The *inductances* of the coils are measured using the "Low Frequency Acquisition system" (LF AQA). The voltages across each coils and across the whole magnet are monitored during a current ramp up and ramp down cycle. The procedure is as following:

- ✓ Connect $V_{sum\text{-}t}$ , $V_{sum\text{-}j}$ to the LF AQA for record.

- ✓ Ramp the current up to $I_{nom}$ using $RR$ = 20 A.s$^{-1}$ then ramp down to zero at the same ramp rate.
- ✓ Perform three cycles to check the reproducibility.
- ✓ Check the magnet and coils inductance and compare with expectation from model:
  - $L_{sum\text{-}j} = V_{sum\text{-}j} / (dI_{mag}/dt)$.

The inductance measurement can also be done during the magnetic measurement.

## 8.2 AC loss measurement

The *AC losses* of the coils are measured performing current cycle up to different maximum and minimum current using different ramp rates. The energy dissipated into the bath due to AC loss along the cycle is computed based on electrical signals by dedicated software. The procedure is as follows:

- ✓ Connect the signals $V_{sum\text{-}t}$ , $V_{sum\text{-}j}$ to the LF AQA for record.
- ✓ Perform current pre-cycle with:
  - $RR$ = 50 A.s$^{-1}$.
  - $I_{mag} = I_{nom}$
  - Use 300 s plateau between each cycles
  - Maintain $I_{nom}$ for 100 s plateau.
- ✓ Use the following ramp rates for the following current cycles:
  - $RR$ = 200, 100, 75, 50, 20, 10, 5 A.s$^{-1}$.

- ✓ Perform the same test using current from 1 kA to 20 % of $I_{nom}$ in order to separate magnetization effect from inter/intra-strand resistive effect out of the AC losses.

- ✓ Determine the total loss $E_T$ [J] and the loss per coils $E_i$ [J] from the 'AC loss analysis software' and compare to expectation [Verweij 1995], [Ang 1998], [Roxie].

The AC measurement can also be done during the magnetic measurement.

## 8.3 Protection Heater study

This PH study is composed of 2 parts:

1. Study of the PH efficiency in terms of delay as function of the magnet powering current
2. Study of the heater efficiency in terms of delay in function of the deposited energy in the coils trough the heaters

All of the Protection Heater study is performed at $T_{op}$. All the proposed tests assume the insulation integrity of the PH. In case of insulation failure, the study should be adapted. The proposed test campaign is divided in two runs for both coils:

- Run 1: tests of the first coil PH.
- Run 2: test of the second coil PH.

If one coil is investigated, it leads to a total of **2x5 = 10 quenches** to perform with eventual check quenches, **1 weeks**.

### 8.3.1 Measurement of the delay between PH firing and induced quench

✓ The delay of the PH is measured as function of the quench current with PH firing at:

- $I_{mag} = 0.2\ I_{nom}$, $0.4\ I_{nom}$, $0.6\ I_{nom}$, $0.8\ I_{nom}$, $1.0\ I_{nom}$

✓ Perform this test for both sides of the two coils.
✓ Checkout of the voltage signal to detect any issues.
✓ Measure the delay $\tau_{PH}$ [ms] between PH firing and first resistive voltage rise and plot:

- $\tau_{PH} = f\,(I_{mag} / I_{ss})$

### 8.3.2 Dependence of the delay on the PH power

✓ The delay of the PH is measured as function of the PH power with PH firing at:

- $I_{mag} = 0.8\ I_{nom}$
- $P_{PH} = 0.4\ P_{PH}^{nom}$, $0.6\ P_{PH}^{nom}$, $0.8\ P_{PH}^{nom}$, $1.2\ \mathrm{P_{PH}}^{\mathrm{nom}}$

✓ Checkout of the voltage signal to detect any issues.
✓ Measured the delay $\tau_{PH}$ [ms] and plot:

- $\tau_{PH} = f\,(P_{PH})$

✓ The dependence of the delay with the PH RC circuit can also be studied, adapting either C or R.

## 8.4 Temperature dependence study

The dependence of the quench current on the operational temperature is investigated as follows:

✓ Performed 8 training quenches at:

- $T_{op}$ = 1.8, 2.0, 2.2, 2.6, 3.2, 4.0, 4.2, 4.4 [K]
- Plot $I_q = f\,(T_{op})$ and compare with $I_c\,(\varepsilon, T, B)$ law.

✓ Length of the test: **8 quenches**, **3 days.**

## 8.5 Spot heater study and beam loss simulation

This test will be not performed as there is no instrumentation in the 11T dipole for this specific test.

## 8.6 Quench back measurement

The question of eddy currents inducing quenches, when the current is rapidly discharged is addressed. For this experiment, the magnet current is discharged from different values in the dump resistor by opening the switch of the circuit without firing the PHs. The procedure is as follows:

- ✓ Ramp the current with nominal *RR* to the following magnet current:
  - $I_{mag} = 0.2\ I_{nom}, 0.4\ I_{nom}, 0.6\ I_{nom}, 0.8\ I_{nom}, 1.0\ I_{nom}$
- ✓ Hold the current for 5 minutes for the dynamic effect of the ramp to decay.
- ✓ Trigger the current extraction without firing the Protection Heater.
- ✓ Compute the increase of the coils resistance $R_j$ [mΩ] during the magnet current decay using the following equivalent relations:
  - $R_j(t) = -L_j\,(I_{mag})\dfrac{d}{dt}\left(\ln\left[\dfrac{I_{mag}(t)}{I_q}\right]\right) - R_{dump}$
  - $R_j(t) = \dfrac{1}{I_{mag}(t)}\left(V_j(t) - L_j(I_{mag})\dfrac{d}{dt}I_{mag}(t)\right)$
- ✓ Compare the two methods.
- ✓ Conclude in the occurrence of quench back according to the rise of the coils resistances.

- ✓ Perform the test firing the Protection Heater simultaneously with the current extraction at:
  - $I_{mag} = I_{nom}$

- ✓ The length of the test: **5 quenches, 2 days**

## 8.7 Pause during ramp up

In order to observe dynamic effects during the current ramp, some pause can be done during the ramp.

- ✓ The procedure is as follows:
  - Ramp the current at 50 A/s to $I_{mag}$ = 50% $I_{max}$
  - Pause the ramp for 10 min.
  - Change the ramp rate from 50 A/s to 20 A/s
  - Ramp the current to $I_{mag}$ = 90% $I_{max}$
  - Pause the ramp for 10 min.
  - Change the ramp rate from 20 A/s to 5 A/s.
  - Ramp the current to quench

- ✓ Observe if the quench current increases showing the AC loss effect in term of cable Joules heating.
- ✓ Perform 5 other quenches and observe if $I_q$ improves with respect to the training curve with the reference powering procedure.

✓ Length of the test: **5 quenches**, **2 days.**

## 8.8 Increasing Miits test

### 8.8.1 Current extraction delay

For this test, the delay $\tau_2$ between quench detection and current extraction in the dump is gradually increased aiming at determining if dump resistor is needed *in fine*. The procedure is as follows:

✓ Ramp the current at nominal rate to quench.
✓ Trigger the current extraction with the following delays:
- $\tau_1$ = 5, 10, 15, 20 ms
- $\tau_2$ = 0 ms
- $\tau_3$ = 0 ms

✓ Check the *Miits* that should remain below 18 $MA^2$.s.

✓ The length of the test: **4 quenches, 2 days.**

### 8.8.2 Protection Heater firing delay

For this test, both $\tau_2$ and $\tau_3$ are gradually increased aiming at determining if the Protection Heaters are needed *in fine* considering the importance of quench back effect. The procedure is as follows:

✓ Ramp the current at nominal rate to $I_{nom}$.
✓ Trigger the Protection Heater firing with the following delays:
- $\tau_1$ = 0 ms
- $\tau_2$ = 2□=s
- $\tau_3$ = 5, 10, 15, 20 ms

✓ Check the *Miits* that should remain below 18 $MA^2$.s.

✓ The length of the test: **4 quenches, 2 days**.

# 9. Thermal cycle

Perform the magnet warmup and cooldown.
Estimated length: **1x2 weeks**.

# 10. Re-Training

Resume the magnet training for 10 more quenches.
Estimated length: **10 quenches, 1 week**.

# 11. Warm-up

- ✓ Perform the magnet warm-up.
- ✓ Perform electrical integrity test and insulation before the magnet is leaving the cryostat, the insert and the Sm18 test station. Record the measured values.

# 12. Summary of the test plan length

1. Low current Provoked Quenches: 4 quenches, 1 day.
2. Splice resistance measurement: 1/2 day.
3. Magnet training: 20 quenches, 2 weeks.
4. Ramp Rate Dependence: 15 quenches, 1 week.
5. Magnetic measurement test campaign, 3 weeks
6. Pause during ramp: 5 quenches, 2 days
7. Protection Heater Study: 10 quenches, 1 week.
8. Temperature Dependence: 8 quenches, 3 days.
9. Quench back: 5 quenches, 2 days
10. Current extraction delay: 4 quenches, 2 days.
11. Protection Heater firing delay: 4 quenches, 2 days.
12. Thermal cycle: 2 weeks.
13. Training resumption: 10 quenches, 1 week.

**This estimate brings us to: 2 week of preparation and 9 weeks of test.**

# Variables

The variables used in the document are listed hereafter:

| | | |
|---|---|---|
| $B$ | [T] | Magnetic field |
| $B_{nom}$ | [T] | Nominal magnetic field |
| $B_{ultim}$ | [T] | Ultimate field at the bore |
| $C$ | [mF] | Capacitance |
| $D_f$ | [µm] | Filament diameter |
| $D_M$ | [mm] | Magnet aperture |
| $D_s$ | [mm] | Strand diameter |
| $\Delta T_{max}$ | [K] | Maximum thermal gradient |
| $\Delta V_{xxx}$ | [V] | Voltage threshold for quench detection |
| $\Delta t_{HV}$ | [min] | HV application time |
| $\Delta t$ | [ms] | Quench detection validation time |
| $E$ | [V] | Protection Heater Power Supply voltage |
| $\varepsilon$ | [-] | Strain |
| $E_{st}$ | [kJ] | Magnet stored energy |
| $G_{ultim}$ | [T/m] | Ultimate gradient |
| $h_c$ | [mm] | Cable thickness |
| $h_i$ | [mm] | Insulation thickness |
| $h_{PH}$ | [mm] | Protection Heater thickness |
| $I_{margin}$ | [A] | Nominal current with margin |
| $I_{mag}$ | [A] | Magnet current |
| $I_{mag}^{max}$ | [A] | Maximum current at warm |
| $I_{nom}$ | [A] | Nominal current |
| $I_q$ | [kA] | Quench current |
| $I_{PH}$ | [A] | Protection Heater current |
| $I_{ss}$ | [A] | Short Sample Limit |
| $I_{ultim}$ | [A] | Ultimate current |
| $L_{mag}$ | [mH] | Magnet Inductance |
| $l_M$ | [m] | Magnetic length |
| $l_{PH}$ | [m] | Protection Heater length |
| $l_i$ | [m] | the length of the cable segment *i* |
| $L_M$ | [m] | Magnet length |
| $L_p$ | [mm] | Cable transposition twist pitch |
| $M$ | [%] | Current margin |
| $m_M$ | [kg] | Magnet weight |
| *Miits* | $[MA^2.s]$ | Miits |

| | | |
|---|---|---|
| $N_s$ | [-] | Number of strands of the cable |
| $P_{PH}$ | [W.cm$^{-2}$] | Protection Heater power |
| $p_f$ | [mm] | Twist pitch of the filament of the strand |
| $PF$ | [%] | Cable packing factor |
| $\rho_{Cu}$ | [Ω.m] | Copper resistivity |
| $\rho_{PH}$ | [Ω.m] | PH material resistivity |
| $\rho_{ss}$ | [Ω.m] | Stainless steel resistivity |
| $R_{dump}$ | [Ω] | dump resistor resistance |
| $R_j$ | [Ω] | Resistance of quenches coil *j* |
| $R_j^{ex}$ | [Ω] | Expected resistance of quenches coil *j* |
| $R_i^{ex}$ | [Ω] | Expected resistance of the cable segment *i* |
| $R_i$ | [Ω] | Resistance of the cable segment *i* |
| $R_{PH}$ | [Ω] | Protection Heater resistance |
| $R_{PH}^{ex}$ | [Ω] | Expected Protection Heater resistance |
| $RR$ | [A.s$^{-1}$] | Ramp Rate |
| $RRR$ | [-] | Cable RRR |
| $S_{Cu}$ | [m$^2$] | Cable cross-section copper surface |
| $S_{PH}$ | [m$^2$] | Protection Heater cross-section surface |
| $t$ | [s] | Time |
| $T_c$ | [K] | Superconducting transition temperature |
| $\Delta t_{xxx}$ | [ms] | Validation time for quench detection |
| $T$ | [K] | Temperature |
| $T_{op}$ | [K] | Operating temperature |
| $\tau_{PH}$ | [ms] | Protection Heater current discharge time constant |
| $\tau_{mag}$ | [ms] | Magnet current discharge time constant |
| $\tau_1$ | [ms] | Delay between quench detection and main Power Supply cut off |
| $\tau_2$ | [ms] | Delay between quench detection and current extraction |
| $\tau_3$ | [ms] | Delay between quench detection and Protection Heater firing |
| $U_q$ | [V] | Voltage rise during quench |
| $U_{MAX}$ | [kV] | HV test maximum voltage |
| $V_i$ | [V] | Voltage along the cable segment *i* |
| $V_{lead}$ | [V] | current leads direct voltage |
| $V_{splice\text{-}i}$ | [V] | direct voltage of the splice *i* |
| $V_{sum\text{-}t}$ | [V] | direct total magnet voltage |
| $V_{sum\text{-}j}$ | [V] | direct voltage of the coil *j* |
| $V_{diff\text{-}k}$ | [V] | coil derivative voltage with *k* an integer |
| $V_{PH}$ | [V] | Voltage signal across the Protection Heaters |

| | | |
|---|---|---|
| $V_q$ | [m.s$^{-1}$] | Quench propagation velocity |
| $w_c$ | [mm] | Cable width |
| $w_{PH}$ | [mm] | Protection Heater width |

# D2 Short model cable type 2

| | |
|---|---|
| **Strand diameter after coating** | 0.825 ± 0.003 mm |
| **Nominal filament diameter** | 6 μm |
| **Copper to superconductor volume ratio** | 1.90 |
| **Filament twist pitch after cabling** | 15 mm ± 1.5 mm |
| **Filament twist direction** | clockwise |

the critical current at a temperature of 4.22 K is 387 A at 6 T for cable 2.

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