# FOS IN CRYOMAGNETS

## POTENTIALS AND CHALLENGES

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TE-MSCTF

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# The mandate of the TE-MSC group

- Design, construction and measurements of superconducting and normal conducting Magnets for the CERN accelerator complex.

- Design and construction of cryostats for magnets, Sc-RF cryomodules and other accelerator equipment.

- Support to operation of the accelerators for magnets, current leads, operation of the magnet and cryostat facilities.

- Development of associated technologies, namely superconductors, insulation and polymers, superconducting electrical devices and magnetic measurements for present and future accelerators

# Organization chart of TE-MSC

| | | |
|---|---|---|
| L. | ROSSI | Group Leader |
| L. | BOTTURA | Deputy |
| F. | BERTINELLI | 3-4 repair and consolidation |

Secretariat : R. DECREUSE-MICHAUD
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# The mandate of the TE-MSC-TF section

- Performance tests of SC magnets, analysis of the tests and measurements data.
- Organization of testing with public and accessible data base.
- Organize analysis of data in collaboration with other sections and groups, with feed back to design, production and machine operation.
- Managing SM18 facility and merging of Block-4 equipment in SM18.

# Why cryomagnets are important for us?

*The LHC is a circular accelerator equipped with **superconducting magnets.** The operation temperature is **1.9 K**.*

- How we arrive to this need?
  - The main ingredients of a circular accelerator are the :

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

- **RF cavities** to accelerate with electrical filed the particles
- ***Bending magnets*** to keep the particles on a circular trajectory
- *Focusing magnets* to reduce the transverse size of the particle beams
- Corrector magnets to correct the filed errors of the bending and focusing magnets

# Superconductors for accelerators?

The energy of an accelerator

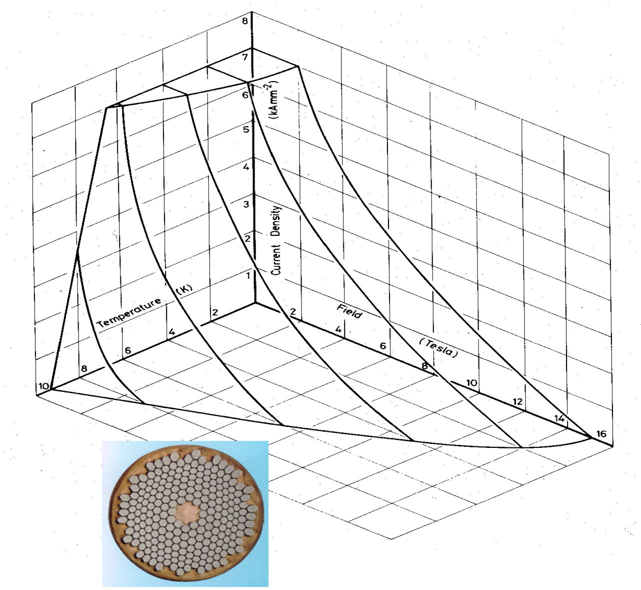
$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

To improve it, there are two ways:

improve $\rho$ (the radius of the tunnel hosting the accelerator ) or improve B (dipolar field of the bending magnets)

LHC with **B = 2 T** magnets would be 100 Km long ( **larger $\rho$** ), and it would not fit between the lake and the Jura mountains

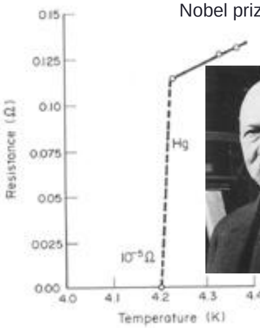
LHC with **B = 8 T** magnets would fit in the existing LEP tunnel ( **constant $\rho$)**




USE **Superconductors** !

Heinke Kamerlingh Onnes

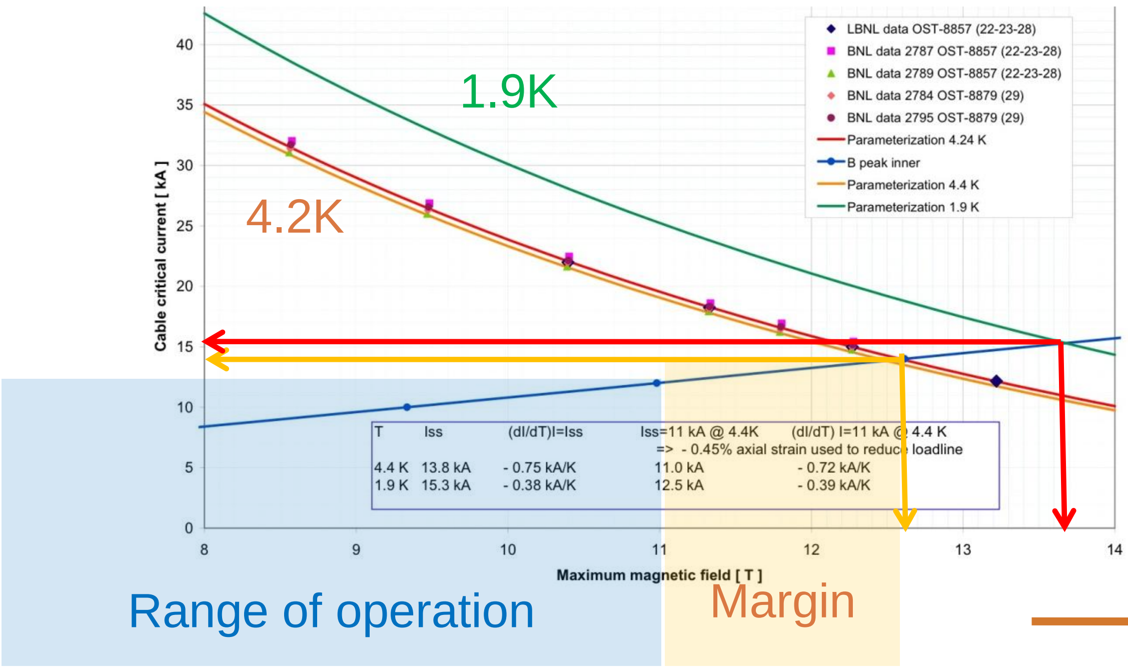
Nobel prize 1913

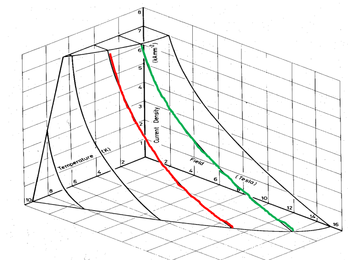



- Industrially producible : NbTi
- Tc : 9.2 K , and up to Bc : 15 T with Jc : 1000 A/ mm$^2$
- How we can cool the magnets?
  - ~~$LN_2$ 77 K~~
  - LHe 4.2 K or Superfluide He : 1.9 K

# Challenges in the operation of Sc magnet

- Having designed the a magnet to attain the highest magnetic filed  with the max current density allowed by the superconductor type, the challenges is to assure in operation the safe condition for the superconductors :the third critical parameter: THE TEMPERATURE (Tc).



$$F = IBL = JSBL = VolJB$$

$$W = Fd = VolJBd$$

$$W = Volc_p \Delta T$$

$$c_{p\,NbTi@4K} = 0.005 J / cm^3 / K$$

$$B = 5T, J = 1000 A/mm^2, d = 1\mu m$$

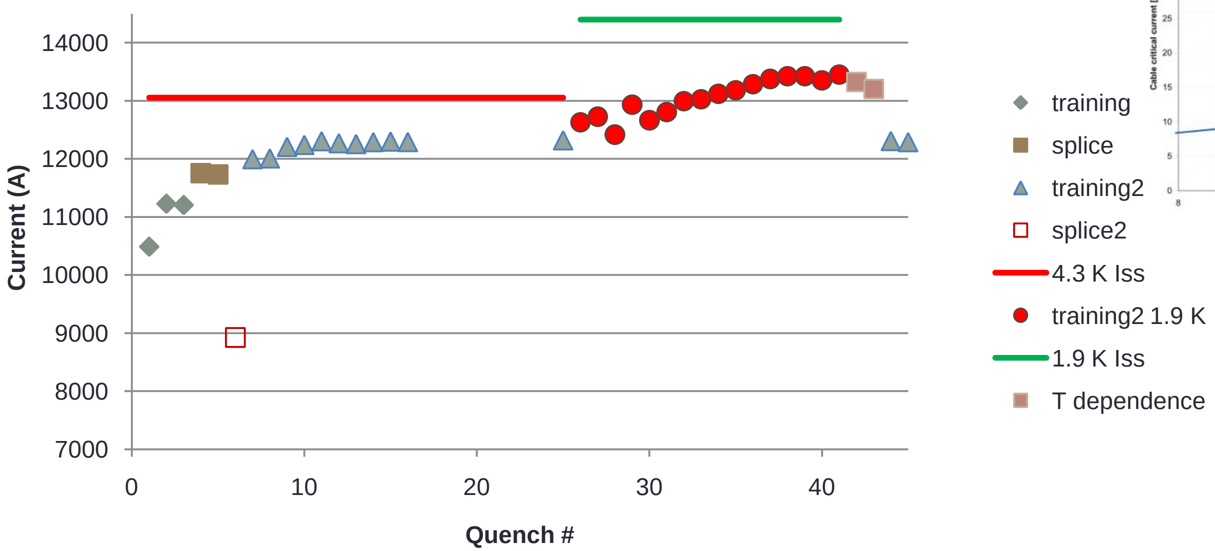
$$JBd = 0.005 J / cm^3$$

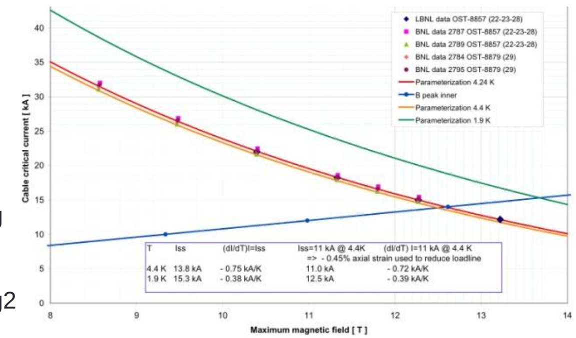
$$\Delta T = 1K$$

**Tc** is assured by the **LHe** ……. while no heating appears for any reason ….. This is not obvious, as we have tones of forces and as a consequence in the non perfect windings of the coils causes **micro movements** which generates **local heating** and a transition from Sc to resistive state. This transition we call in the literature **QUENCH.**

# Performance test of the Sc Magnets

- Electrical integrity tests of the magnets: continuity, insulation to be checked at warm and at cold
- Electrical integrity test of the instrumentation of the magnet to be sure that detection of a quench and protection of the magnet is possible
- **Training of the magnet**: a nr of quenches to accommodate the wires in the coils and to obtain a stabile state of each magnet up to a nominal working condition.

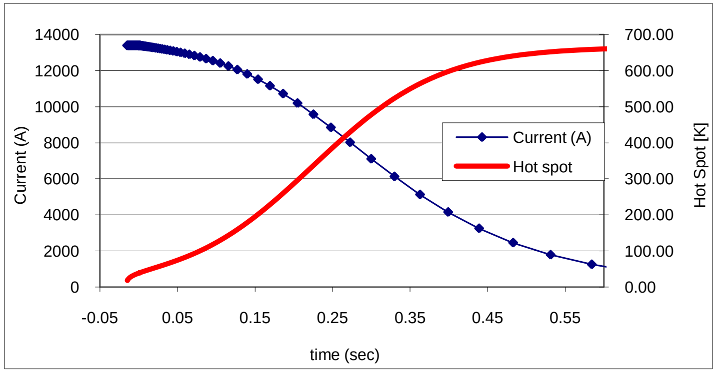


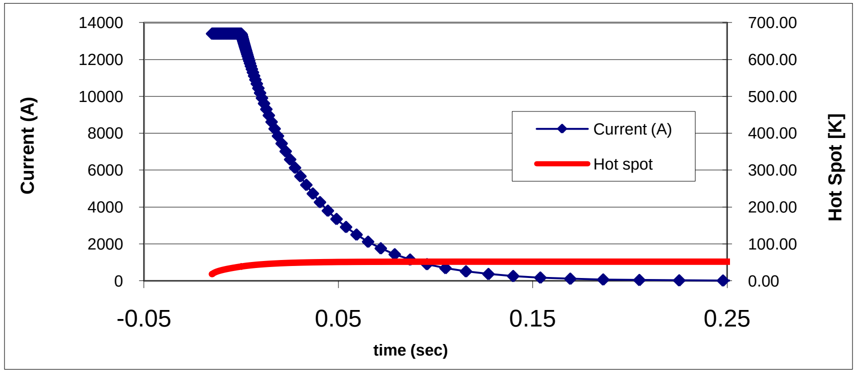




- Magnetic field quality measurements at warm and at cold
- Geometrical axes measurements of the cold bore and all interconnect able elements

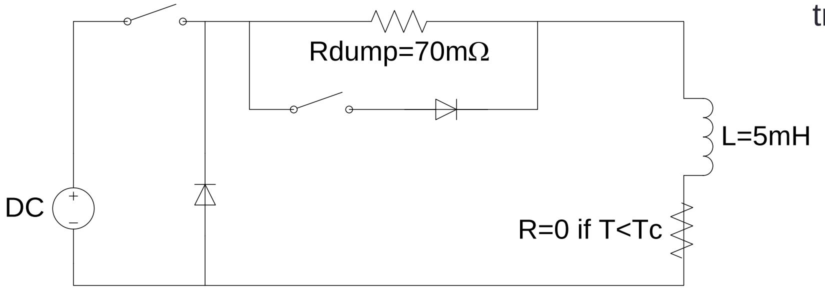
# Quench. Detection. Protection

- The QUENCH is like a chain reaction: when  you generate a heat locally the Sc becomes resistive and while the current is flowing trough it generates Joule heat so the **resistive zone** will propagate.
- If this transition is not DETECTED the coil can burn locally destroying the magnet (objects of 15 m, 27 tones and 300 kCHF, at least 2 mounts of stop of the machine ect… ).



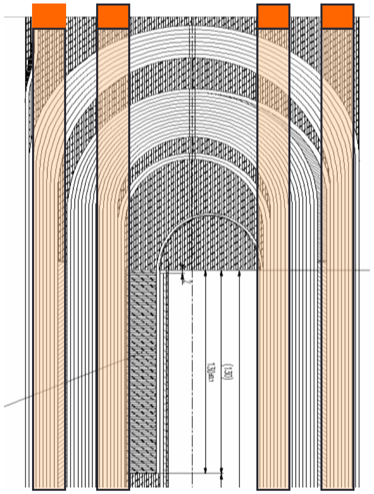




- If this transition is detected the PROTECTION can be applied and transform the quench part of a normal no- accidental operation mode.




In some magnets we have also cold diodes and the so called protection heaters to homogenize the temperature of the coil when a transition has been detected

$$P_W = \frac{R_{heater} I_{heater}^2}{A_{heater}}$$

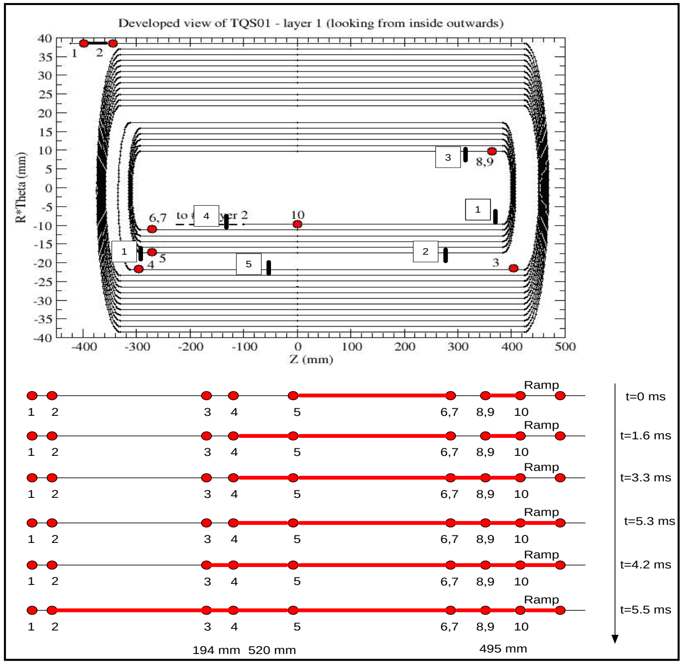


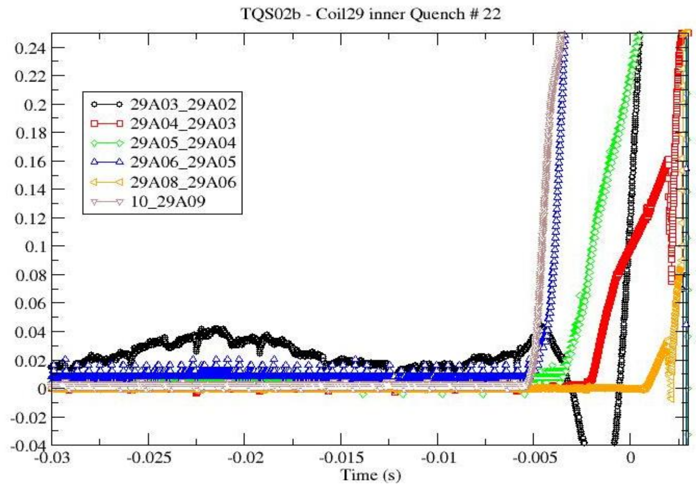
# Detection. Localization for feed back

What do we measure to detect a QUENCH?

**<u>The voltage rise</u>** due to the Joule heating of the transition so **<u>a heat rise</u>**

- The time response of the detection for the protection of the magnet should be in the range of **<u>ms</u>** for the **<u>PROTECTION</u>**



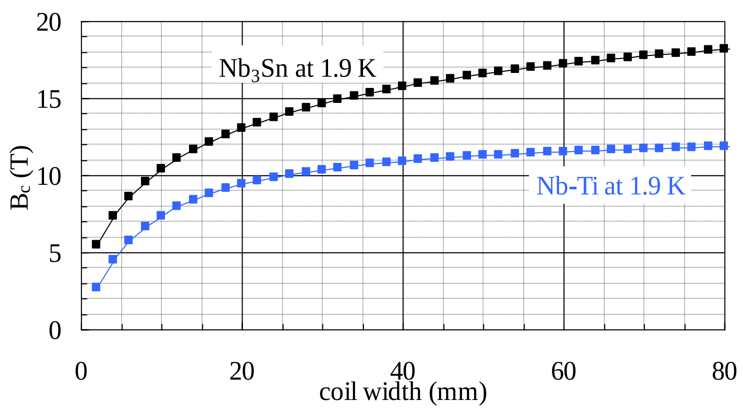



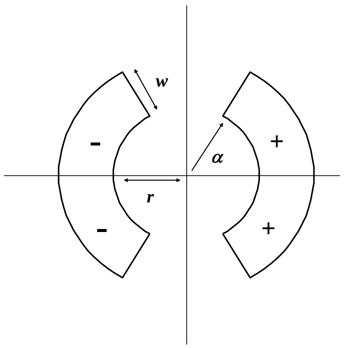

- The so called V taps are used to LOCALISE the quench origin.

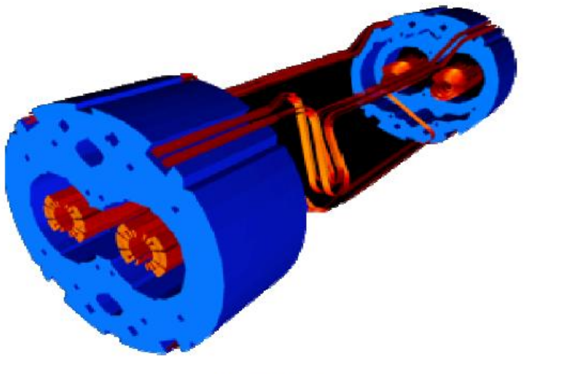
- More V taps we have better we can localize it, but more and more wires are needed.

# New generation Sc magnets for LHC

Field versus coil thickness for Nb-Ti and $Nb_3Sn$ at 1.9 K

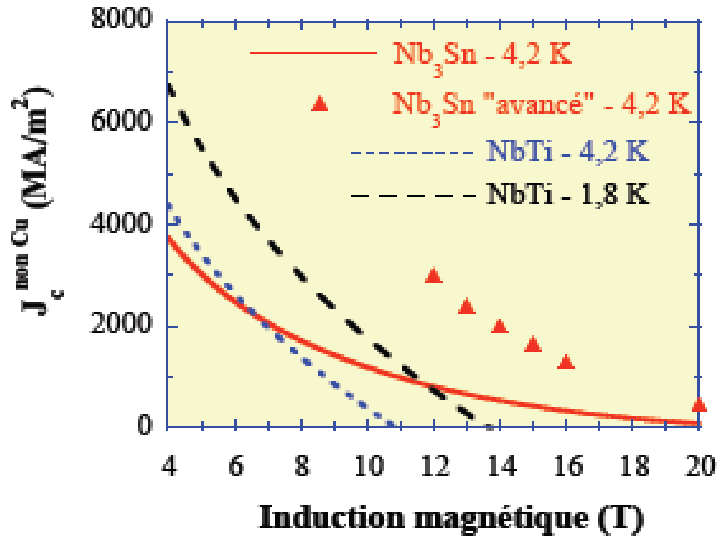


Courtesy of B. Auchmann

Courtesy of E. Todesco

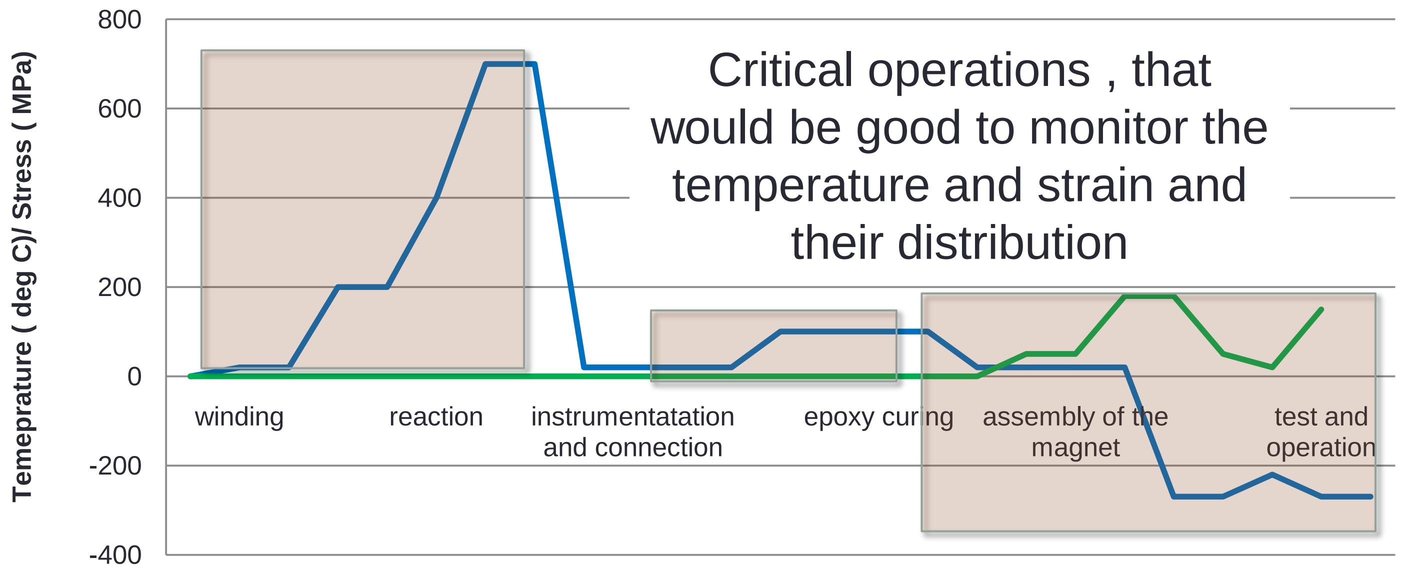



| | $T_c$ (0T) | $T_c$ (11T) | $\mu_0 H_{c2}$ (1,8 K) | $\mu_0 H_{c2}$ (4,2 K) |
|---|---|---|---|---|
| NbTi | 9,5 K | 4,2 K | 14 T | 11 T |
| $Nb_3Sn$ | 18 K | 10,4 K | 25,5 T | 23,2 T |

# New generation Sc magnets: $Nb_3Sn$

## Temperature and stress profile from winding to operation

$Nb_3Sn$: Wind and React technique



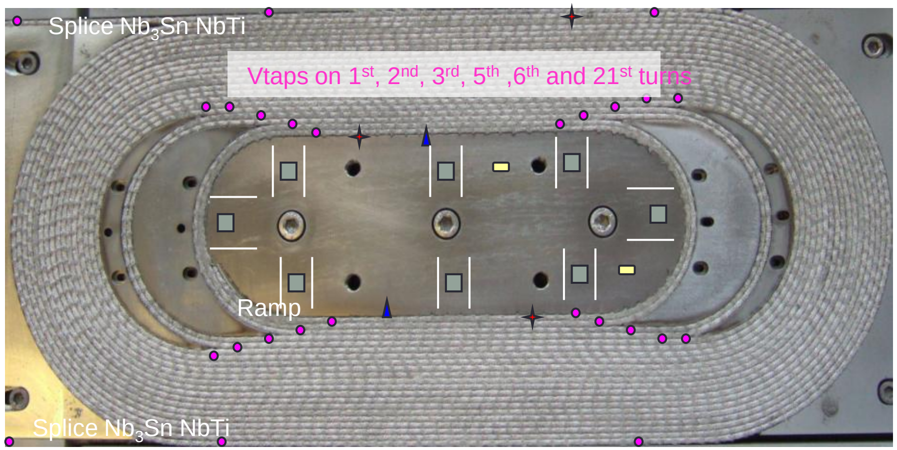

Challenge for all materials to be used for INSTRUMENTATION. It has to be done typically after reaction when the coils are fragile!

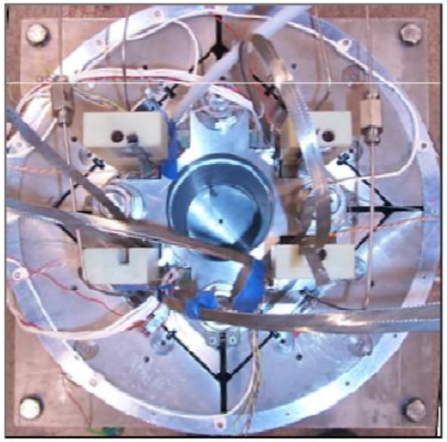
Challenge for Nb3Sn materials that is STRAIN SENSITIVE. A max. of 150-200MPa is allowed at any place in the coil and ant any moment from the assembly and operation.

# New generation Sc magnets: $Nb_3Sn$

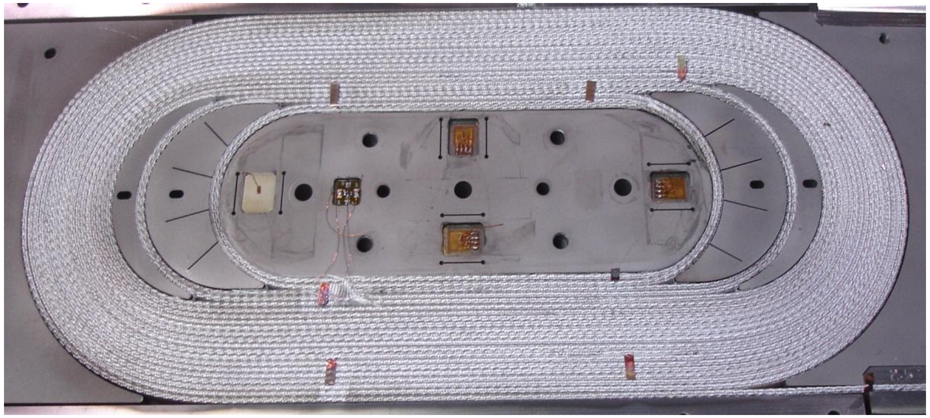
## Instrumentation for R&D

What we would like to have AT LEAST….



What we have at the end to reduce nr of wires and complexity of the operation….



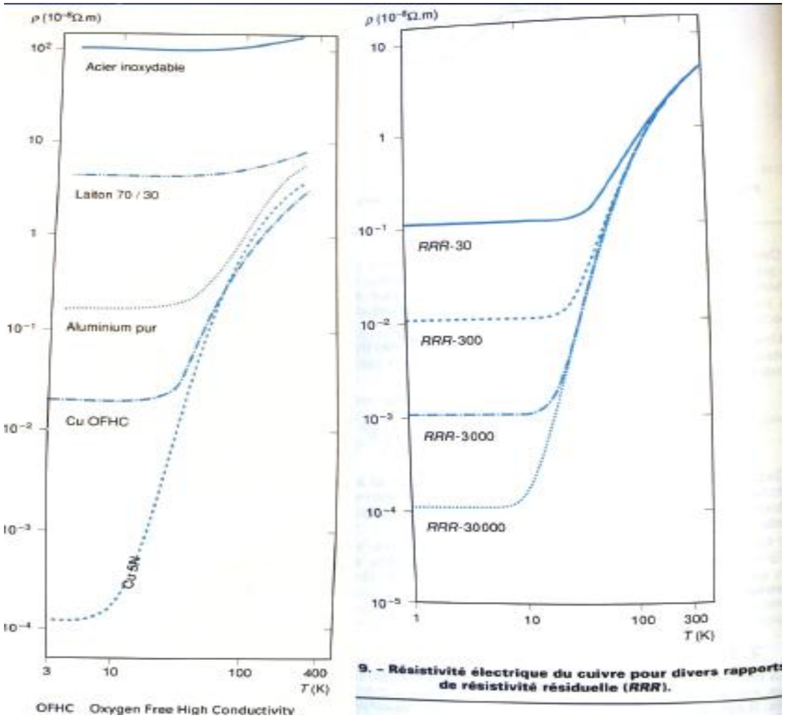
# Thermometry in cryogenics in few lines

- Thermometry based on the first principle of thermodynamics ( so measurement of the pressure of a gaz) $PV = NRT$

- Thermometry based on the variation of the resistance of metals ( platinum, bronze-phosphore, rhodium fer) or non metals( semiconductors: carbon- Allan Bradley, dopped germanium ) with temperature ( so measure of voltage over a resistance) . Due to the fact that there are very few phonos below 3K the resistance is mainly determined by impurities and thus basically independent of temperature. *Often they are not covering the full range of temperature variation or not with the same calibration curve. It present a magneto resistance!*

*( only the carbon is not included).*

$$Z = \frac{R_T - R_{4.2K}}{R_{273.15K} - R_{4.2K}}$$




9. - Résistivité électrique du cuivre pour divers rapports de résistivité résiduelle (RRR).

- Thermometry based on diodes ( voltage measurements with few microA current): l arseniure de gallium, germanium ou silicium) between 1 K-300 K
- Thermometry based on thermocouples (a junction between two different metals that produces a voltage related to a temperature difference): ex. copper constantan.

- Other thermometry based on : paramagnetism ( so measure magnetization), thermometry based noise measurement (so measure Johnson noise) , acoustic thermometry ( so measure the velocity of the sound in gas)
- ect…

# Potentials for the use of fibers x temperature

- To monitor temperature of the coils during reaction, curing , cool down, powering and warm up
- To monitor the temperature rise and make with this technique localization of the hot spot being the origin of a quench
- To measure the temperature of the hot spot from quench origin to detection and feed back for the design
- To measure the temperature of the protection heaters and the coil windings when fired the heaters to check efficiency of the heaters
- To measure the temperature of the bath during cool down, after quench during warm up in any cryostat.

# Potentials for the use of fibers x strain

- To monitor the strain and the strain distribution of the coils and of the magnet structure during assembly, cool down powering and warm up

- To monitor the strain variation during assembly, cool down powering and warm up

| | | TQS02b | | TQS02c | |
|---|---|---|---|---|---|
| | | warm | cold | warm | cold |
| shell (µStrain) | BT1 | 533 | 1200 | 572 | 1292 |
| | BT3 | 612 | 1633 | 737 | 1808 |
| | AT1 | 466 | 1911 | 501 | 2073 |
| | AT3 | 598 | 1609 | 651 | 1720 |
| | **average** | 552 | 1588 | 615 | 1723 |
| | AZ1 | -221 | 777 | -241 | 755 |
| | AZ2 | | | -15 | 1024 |
| | AZ3 | 168 | 1347 | 273 | 1474 |
| | AZ4 | -27 | 1200 | 52 | 1219 |
| | **average** | -27 | 1108 | 17 | 1118 |
| rod(µStrain) | rod1 | 202 | 1198 | 241 | 1566 |
| | rod2 | | | 280 | 1607 |
| | rod3 | 271 | 1231 | 247 | 1607 |
| | rod4 | 288 | 1272 | 249 | 1609 |
| | **average** | 254 | 1234 | 254 | 1597 |

| Equivalent avegare stress (MPa) | | |
|---|---|---|
| **TQS02b** | warm | cold |
| shell azimutha | 35 | 139 |
| shell axial | 9 | 115 |
| rods axial | 14 | 75 |

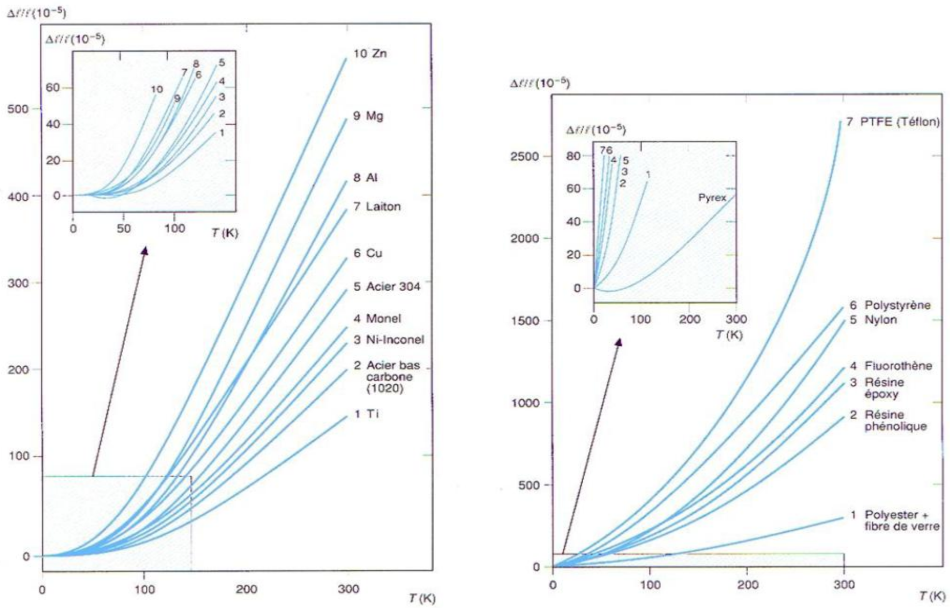
| Equivalent avegare stress (MPa) | | |
|---|---|---|
| **TQS02c** | warm | cold |
| shell azimutha | 40 | 149 |
| shell axial | 13 | 118 |
| rods axial | 14 | 97 |

# Potentials for the use of fibers: any other place ….

- To map the field in the magnet specially in magnets without aperture
- We have a tunnel at 4.2K of 27 km in which the magnets are placed (1232 dipole, 400 quads)
- Sc link is a High TC Superconductor to be cooled with gas of up to 50 K between the tunnel and the surface
- We are developing the shunted interconnects for the LHC consolidation and many studies are done in variable temperature ranges ……
- They are small in diameter, insensitive to magnetic filed effects, , made by insulation material, low heat in-leak into the bath due to low thermal capacity of the fibers, small nr of connectors for many sensors over long lengths…..ect

# Challenges

- **Temperature**
- The extreme values of temperature to be monitored or to survive ( max. 700 degC and min 1.9K). Find good base materials……= with the good α
- The wide range of temperature to be measured
- The question of thermalisation when monitor the temperature of a bulk material ( easier when gas or liquid)




$\Delta\ell/\ell = \frac{\ell(T)-\ell_0}{\ell_0}$

**Strain**

The technique and modus operandi at low temperature including the question of gluing the fibers on the objects to be measure

$$\Delta\lambda_{BT} = \lambda_B(\alpha+\xi)\Delta T$$

α : coefficient of thermal expansion

ξ : thermo-optic coefficient

**Field and Filed quality**

To measure magnetic fields up to 15 T at 1.9K

To measure filed quality

**Make splicing …ect**

**Competitive price!!!!!!of sensors and read out system**

# Lessons learned in using FBG at low T

- WE do not know if FBG survives the 700 deg C?
- We know that FBG can survive the low temperature: up to 50 K there are possibilities to use fibers with coatings that are producible with known technology and gives sufficient amplification of the temperature signal.
- We know that FBG survives the 1.9K but the signal is not sensitive enough to monitor temperature variation below 50 K with known technology
-
- We know that some materials could give the necessary signal amplification below 50K and until 4.2K.
- We have to develop this signal amplificatory technology ( base material + glue and feasibility of coating with the fibers)
- We do not know how to integrate the fibers in the coils: how to fix and to thermalize to the conductor and at which stage of the coil fabrication?
- We know that strain measurements are possible but a correct modus operandi has to be followed ( see report EN MME ).
- We do not know if FBG is better adapted than any other FOS technique to cryo magnet applications
- ( see patent : **Brillouin-based temperature sensing in optical fibres down to 1 K by** A. Fellay, L. Thévenaz, J. Perez Garcia*, M. Facchini, W. Scandale*, P. Robert)

# What are the next steps?

- Set up the measurement procedure
- Get familiar with the read out system
- Qualify the database and make connection with Sm18 database
- Continue to develop analysis tools
- Make statistics at different temperature range
  - up to 700 deg C, LN, LHe and between ( cryo cooler up to 12 K)
- Qualify the “amplifier” materials
- Define calibration method
- Qualify gluing for test
- Check feasibility of coating
- Make trials for sensor integration into a Sc coil or in a Sc cable ……
- 
- Make a comparative study of other FOS techniques in the view of using them in cryomagnets.