TEST OF LARGE MAGNETS

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European Organization for Nuclear Research

(CERN TE-MSC-TF)

EASISchool 3 *5th October 2020*

EASITrain

THE MANDATE OF THE TESTING TEAM

To QUALIFY

magnets and cold powering equipment in real conditions

To PROVIDE FEED BACK

for superconducting cable and magnet design

OPERATE

in **SAFE** condition the test stands

MAINTAIN, DEVELOP, BUILD

test stands

THE CONTENT OF MAY LECTURE

The life of a magnet in the test stand

Magnet test is = Training ?

… and before going ahead with the test program I will recall some essential concepts used for testing as:

- superconductivity : critical parameters
- practical superconductors and their main characteristics
- quench

coming back to the testing we will than go trough (quasi) in chronological order of the test steps

Electrical Integrity checks

Connection to the installations

Cooling of large magnet

Measurements of RRR, Strain and Temperature Thresholds and triggers for protection

at this stage I will switch back to concepts as

- hot spot temperature, Miits,
- minimum propagation zone
- quench propagation velocity
- quench detection
- energy extraction and stored energy
- magnet protection

to explain the way we choose the thresholds before going back to the main subject of

Measurements (protection efficiency, splices, performance indicators and special measurements, recall Paschen’s law)

finally I will complete this lecture with a

Description of a test stand taking as an example a recent test stand built at CERN

THE LIFE OF A MAGNET ON THE TEST BENCH

- *Electrical integrity test*
- *Electrical and hydraulical interconnections (magnet to test bench)*
- *Cooling*
- *Electrical integrity test*
- *Cold Powering Tests*
- *check of protection*
- *check of acquisition*
- *check of extraction (if any)*
- *powering **(=training**)*
- *Warming*
- *Electrical integrity test*

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EDMS Doc No.
2330821

TEST PROGRAM -

COLD POWERING TESTS FOR THE MBHA SERIES MAGNET IN SM18

MAGNET NAME :
HCLMBHA001-CR000001
MBHA-001
SECOND TEST CAMPAIGN

February 2020

Prepared by:	*Checked by:*	*Approved by:*
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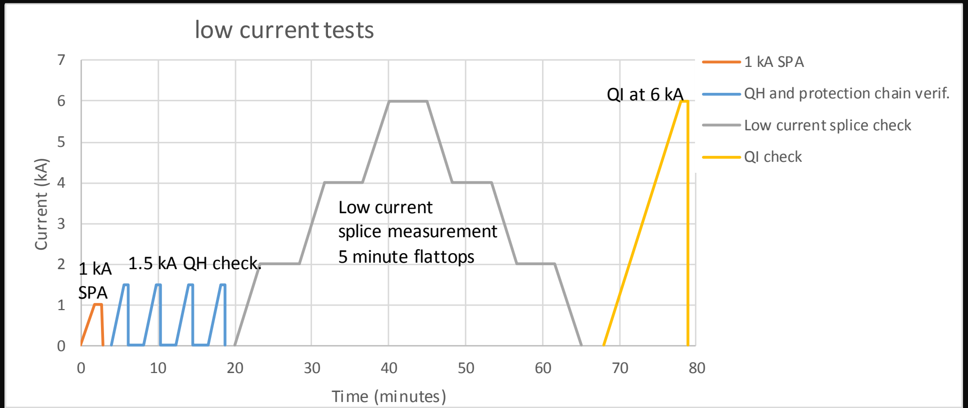
Table of Contents

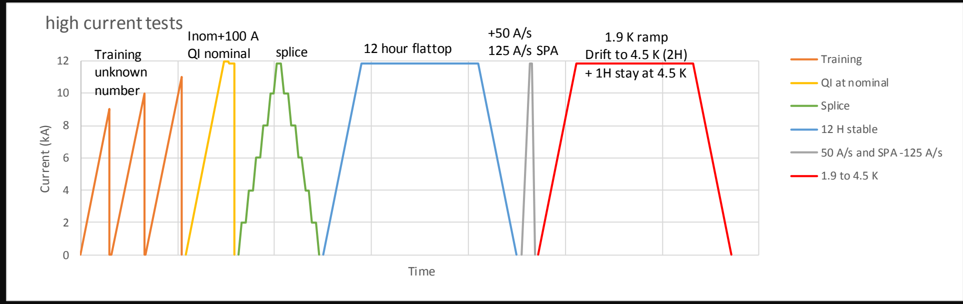
Version

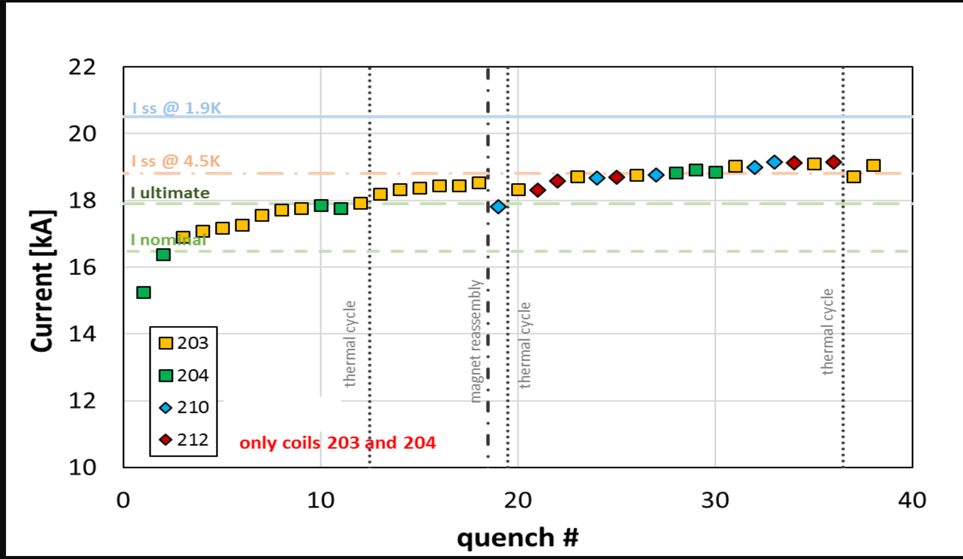
Rev. No.	*Who*	*Date*	*Pages*	*Description of Changes*
0	G. Willering, G. Ninet	21-02-2020	All	Creation

MAGNET TEST = TRAINING ?

The final goal of the powering test is to qualify. In the case of the superconducting magnets we used to consider that testing is to make the TRINING of the magnet



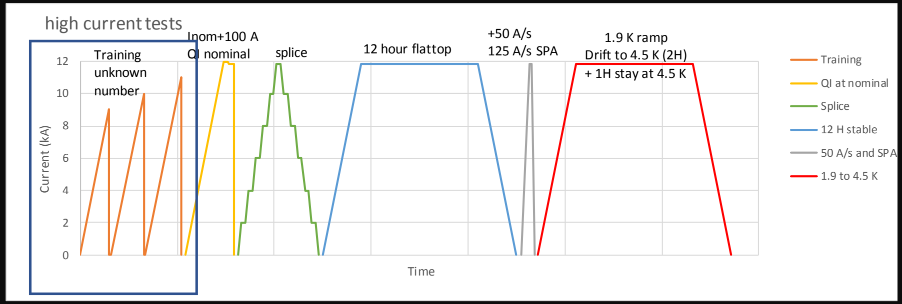




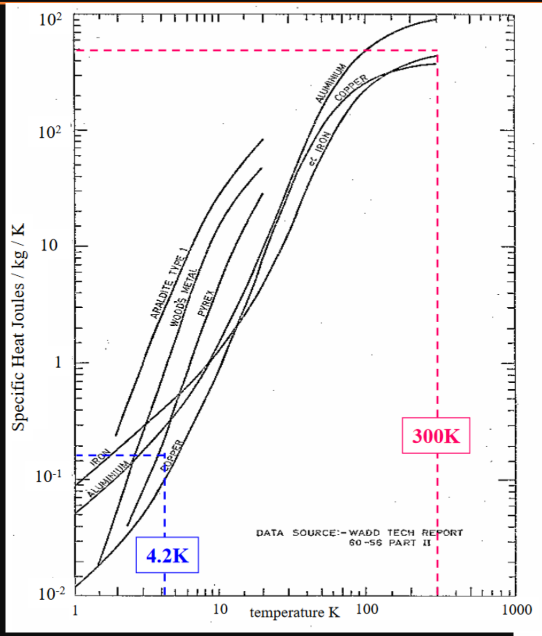
Courtesy of G. Willering/ F. Mangiarotti

TRAINING

- When the current of a magnet is ramped up for the first time, it usually "quenches" at less than the short sample limit .
- At the next trial usually it does better.
- This sequence of events is called : training



Courtesy of G. Willering/ F. Mangiarotti



Ex. conductor motion

work done per unit length of conductor if it is pus[hed a] distance δz

$$W = F.\delta z = B.I.\delta z$$

frictional heating per unit volume

$$Q = B.J.\delta z$$

typical numbers for NbTi:

$B = 5T \quad J_{eng} = 5 \times 10^8 \ A.m^{-2}$

so if $\delta = 10 \ \mu m$

then $Q = 2.5 \times 10^4 \ J.m^{-3}$

Starting from 4.2K $\theta_{final} = 7.5K$

- the specific heat of all substances falls with temperature
- at 4.2K, it is ***~2,000 times*** less than at room temperature
- a given release of energy within the winding thus produce a temperature rise 2,000 times greater than at room temperature
- the smallest energy release can therefore produce catastrophic effects

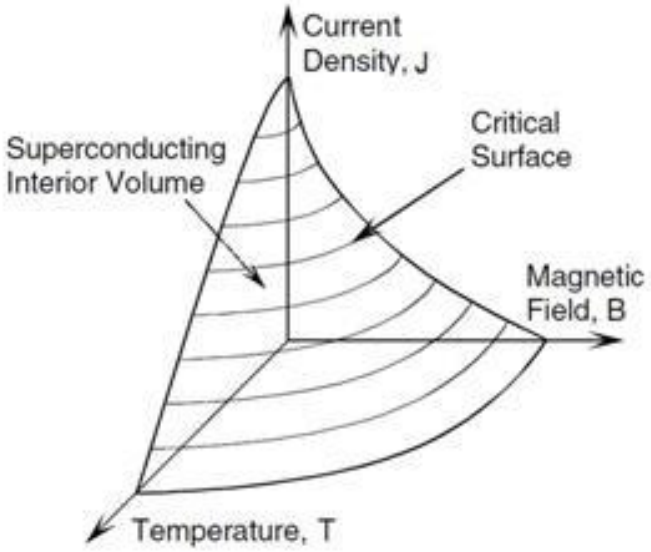
M. N. Wilson

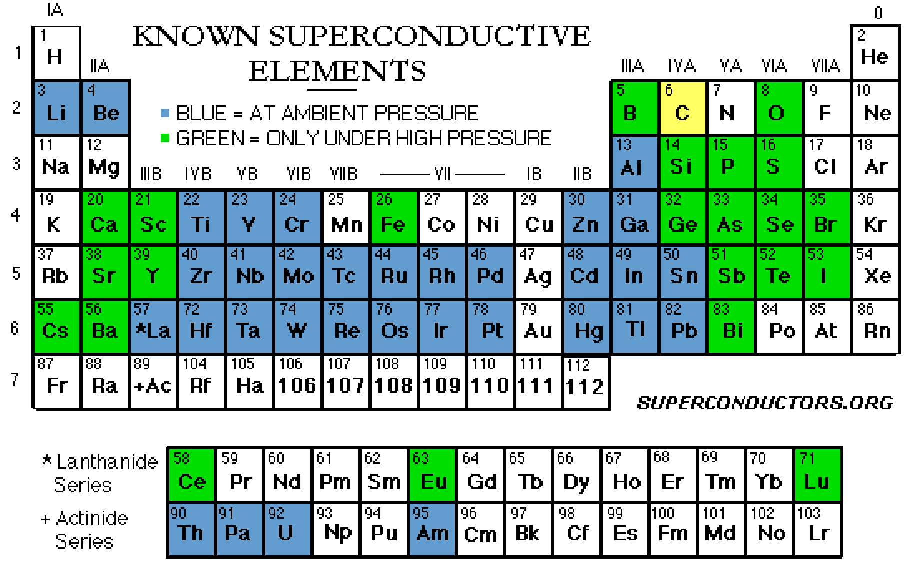
CRITICAL SURFACE

Superconductivity

UNDER CONDITIONS

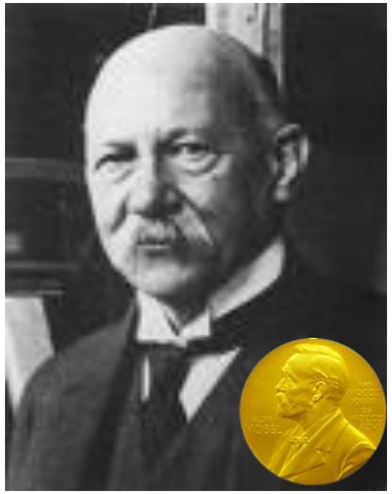
Superconductivity *exists* in a 3-dimensional space given by magnetic field, current density and temperature called critical surface





CRITICAL TEMPERATURE

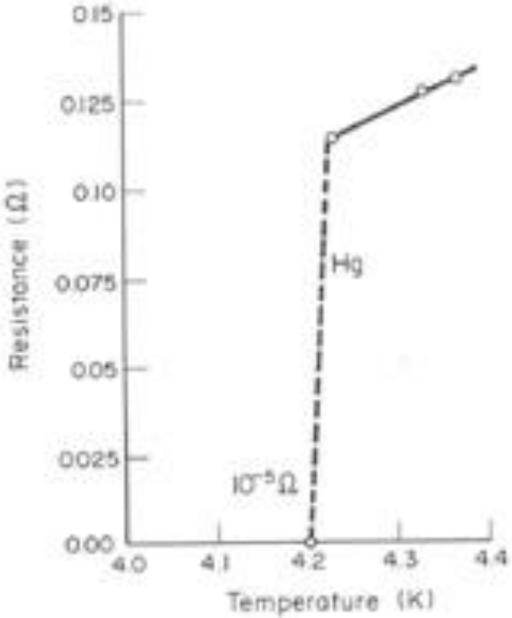
- In 1911, Kamerlingh Onnes discovers the superconductivity of mercury
  - His team was investigating properties (resistivity, specific heat) of materials at low temperature
  - This discovery has been made possible thanks to his efforts to liquefying Helium, a major technological advancement needed for the discovery
  - Nobel prize 1913 “for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium »
- Phenomenology
  - Below 4.2 K, mercury has a non measurable electric resistance – not very small, but zero !
  - 4.2 K is called the critical temperature: below it the material is superconductor



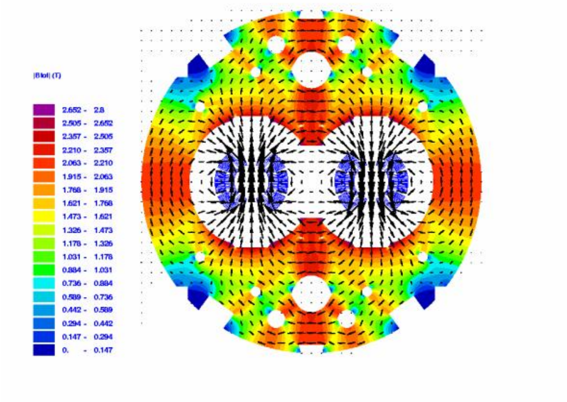
Heinke Kamerlingh Onnes

(18 July 1853 – 4 February 1928)

Nobel prize 1913

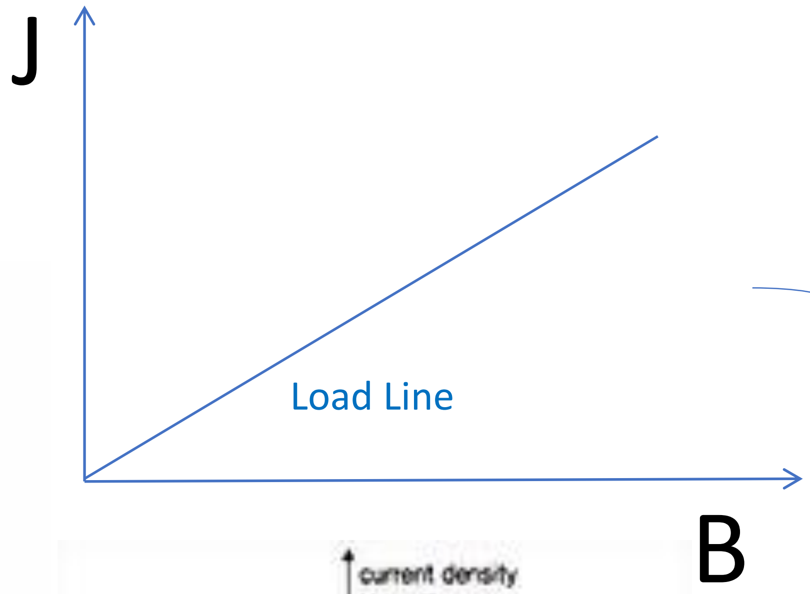


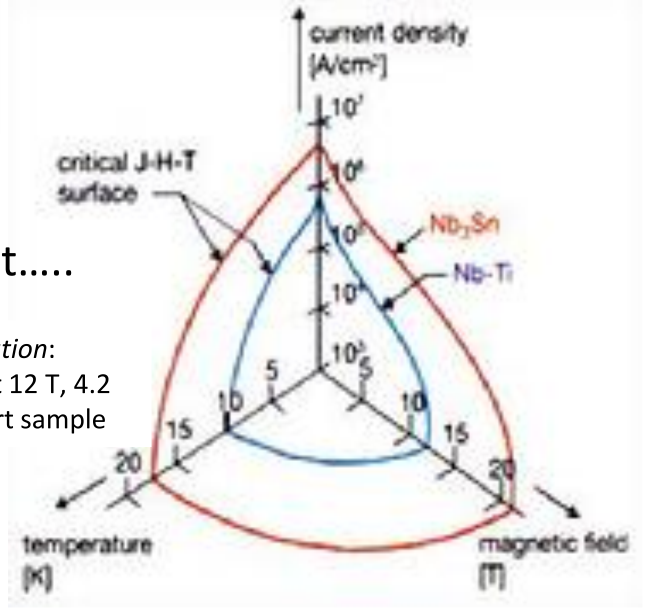
CRITICAL FIELD

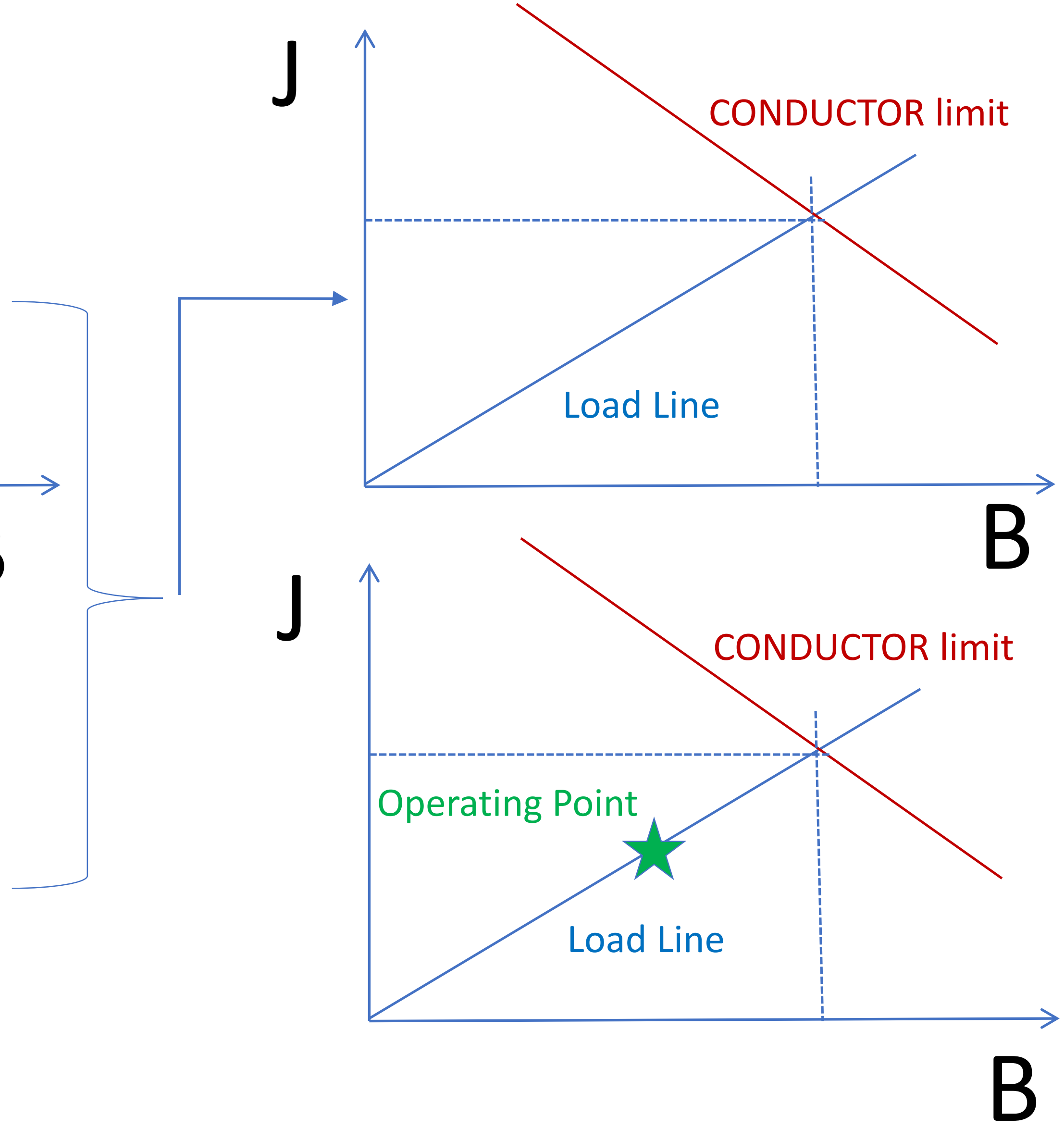


When we design a magnet…..

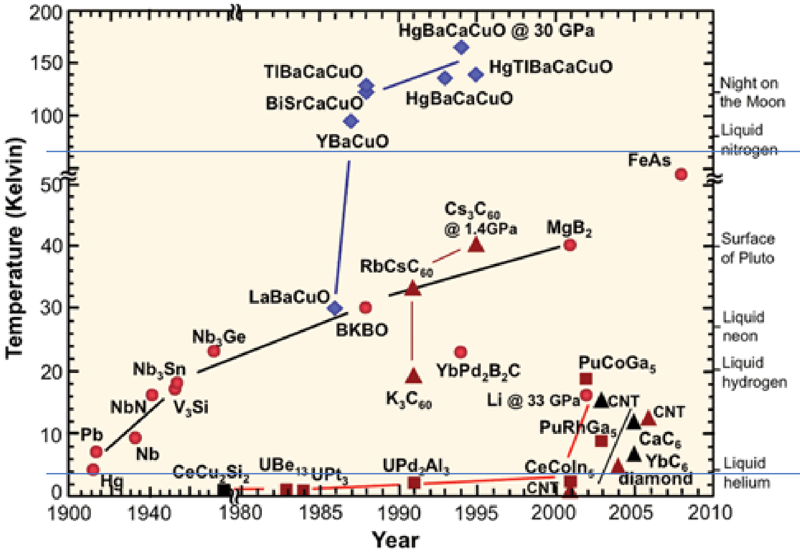
Ex. of a specification:
~2500 A/mm^2 at 12 T, 4.2 K, with 15 T short sample







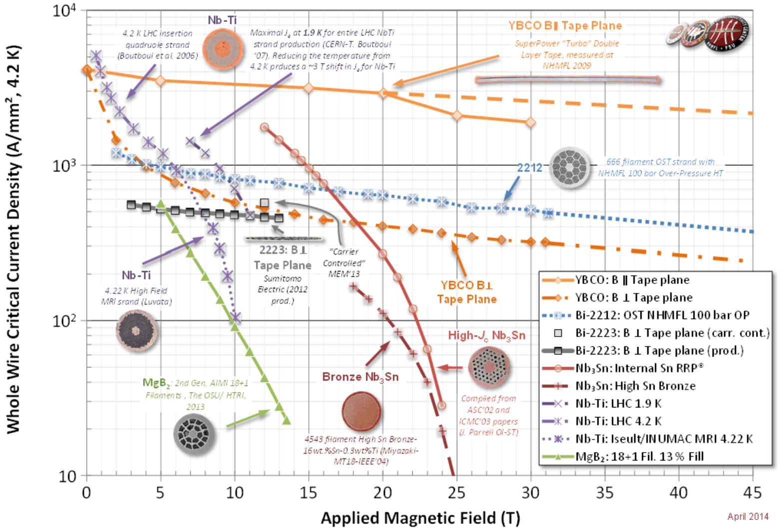
High TEMPERATURE or High FIELD superconductors



77 K LN_2

Practical coolants ?

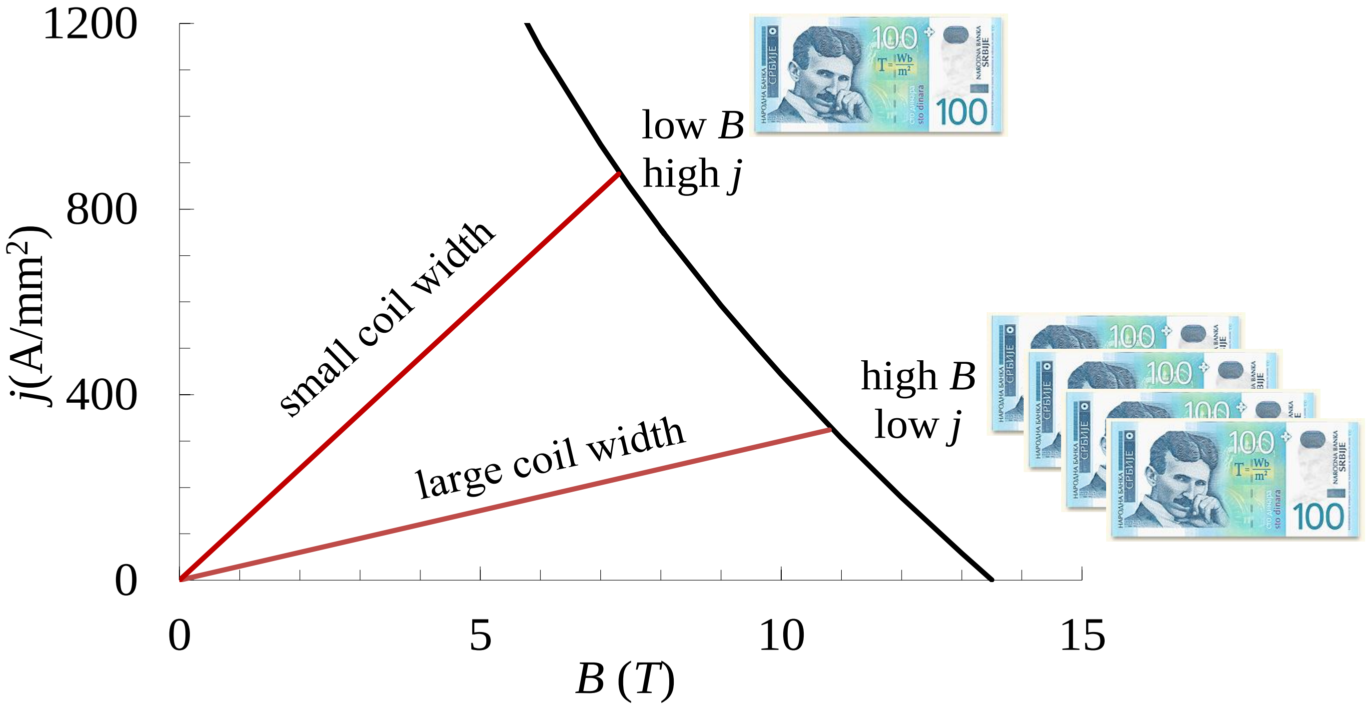
4.2 K LHe



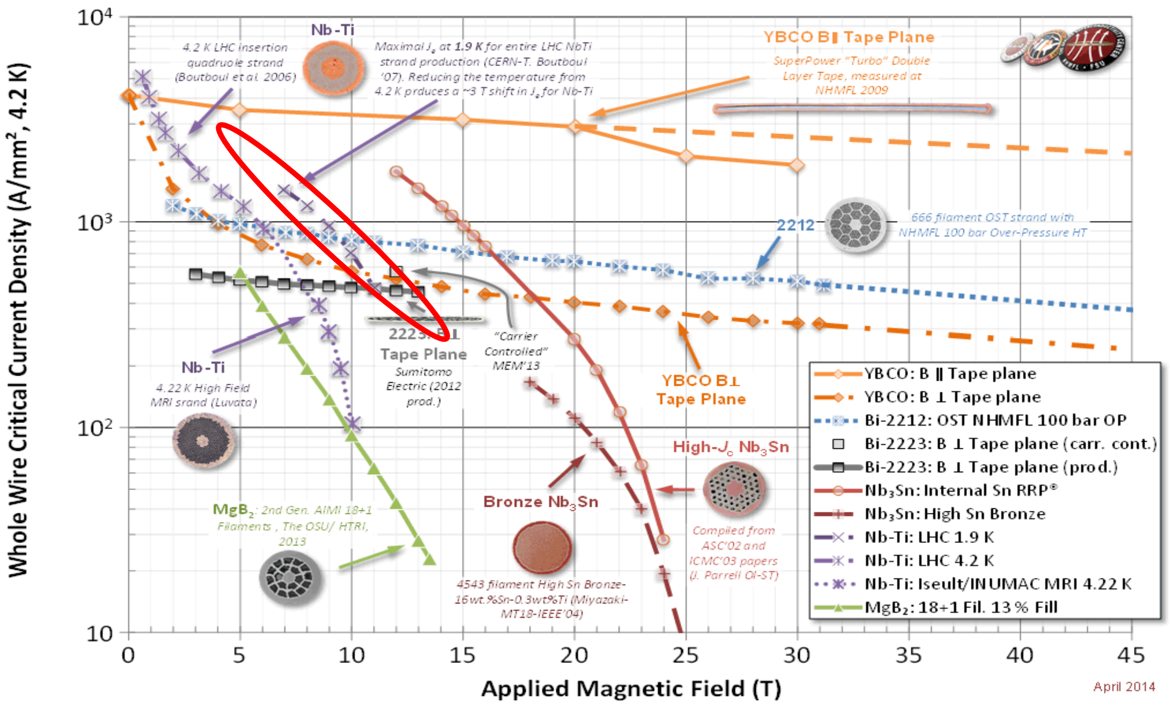
In fact, in addition to their superior properties at relatively higher temperatures, HTS materials also come along with significantly expanded magnetic field capabilities.

CRITICAL CURRENT DENSITY

the short sample field versus the coil width has an implacable law, that make the last teslas are very expensive



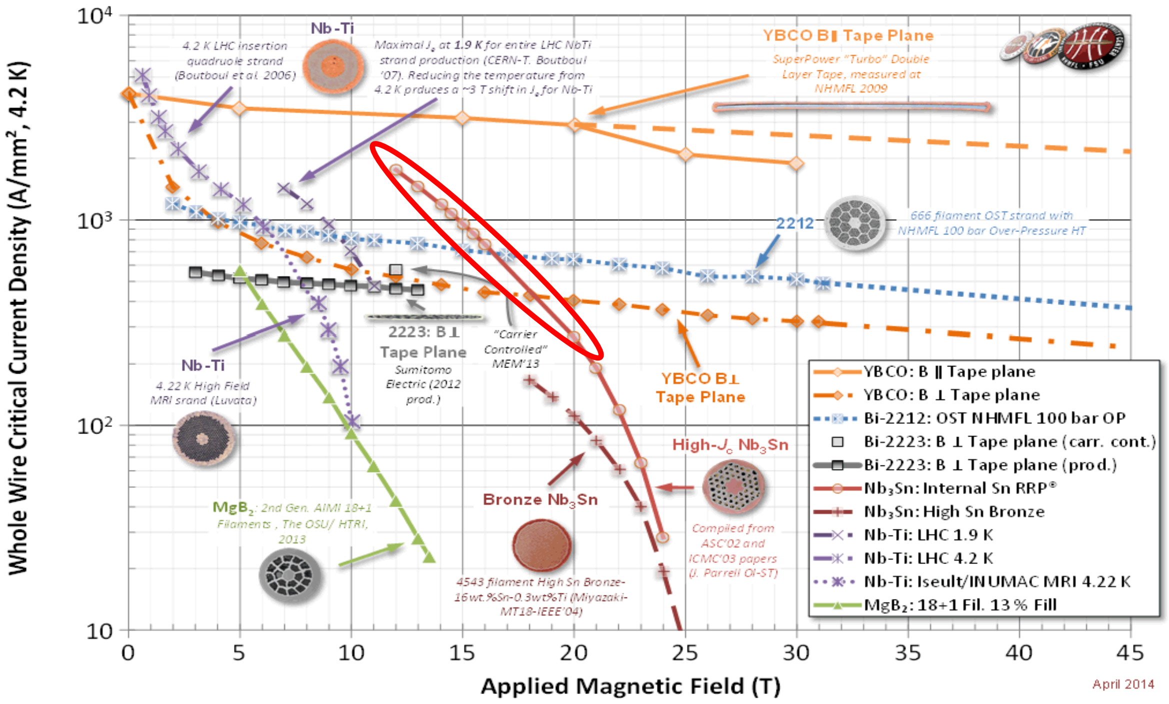
PRACTICAL SUPERCONDUCTORS @ 4.2 K



Critical current density in the superconductor versus field for different materials at 4.2 K [P. J. Lee, et al]
https://nationalmaglab.org/images/magnet_development/asc/plots/JeChart041614-1022x741-pal.png

- Nb-Ti is the workhorse of superconductivity
  - Discovered in 1962
  - Critical temperature of 10 K, critical field of 15 T
  - All superconducting magnets for accelerators are made with Nb-Ti
  - LHC pushed this technology to its limit with 8 T magnets

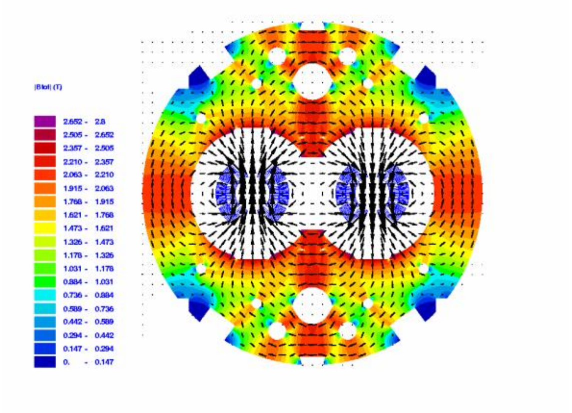
PRACTICAL SUPERCONDUCTORS @ 4.2 K



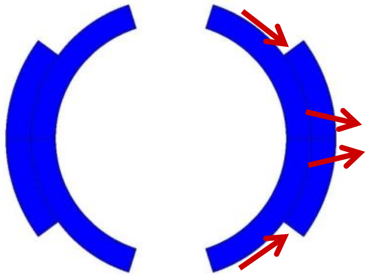
Critical current density in the superconductor versus field for different materials at 4.2 K [P. J. Lee, et al]
https://nationalmaglab.org/images/magnet_development/asc/plots/JeChart041614-1022x741-pal.png

- Nb_3Sn allows doubling the Nb-Ti performance
  - Discovered in 1954, before Nb-Ti
  - Critical temperature of 18 K, critical field of 30 T
  - It is (unfortunately also) strain dependent
  - Must be formed reacting it at 650 C for several days with tight tolerances on temperature
    - After formation it is very brittle so coil has to be impregnated

CRITICAL STRAIN



In the presence of a magnetic field *B*, a conductor element carrying current density *j* (A/mm^2) is subjected to a force density *f* [N/m^3]

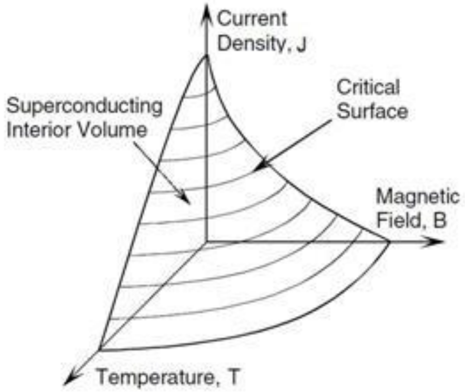


$$\vec{f} = \vec{j} \times \vec{B}$$

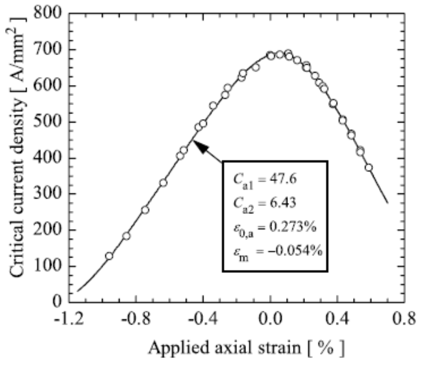
Ex. LHC dipole :
F_x = 340 t per meter

The e.m. force acting on a coil is a body force, i.e. a force that acts on all the portions of the coil (like the gravitational force) – compressing the midplane and pushing the coils outward

So now we have to care ALSO about the mechanics!!
And the strain sensitivity

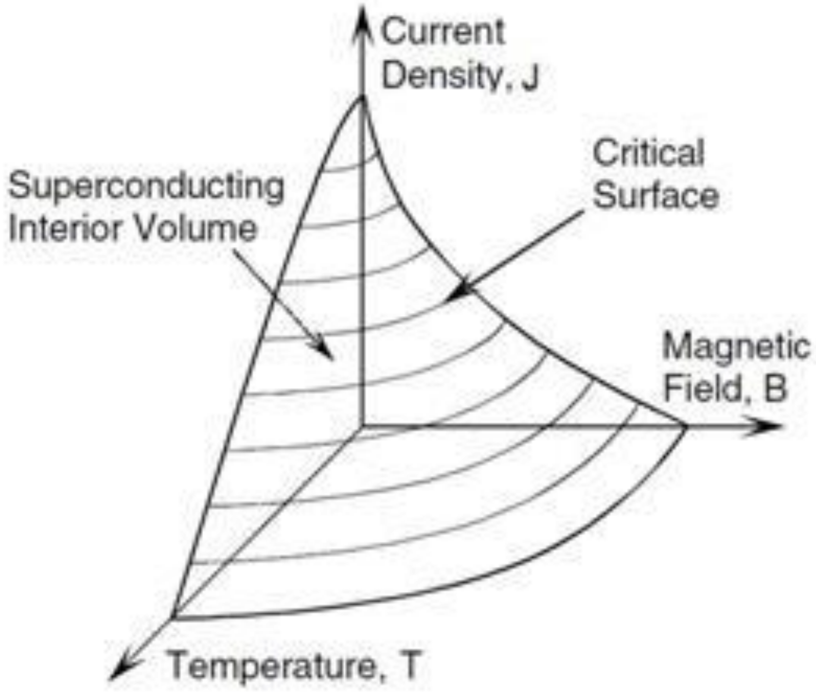


A. Godeke et all 2006



AND WHAT IF WE LOOSE ANY OF THE CRITICAL CONDITIONS?

Superconductivity is DESTROYED when loosing any of the critical conditions: temperature, current density, magnetic field



$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2$$

This is the result of a quench in the pre series magnet during its qualification test

L. Bottura Wamsdo

This is the result of a chain of events triggered by a quench in an LHC bus-bar

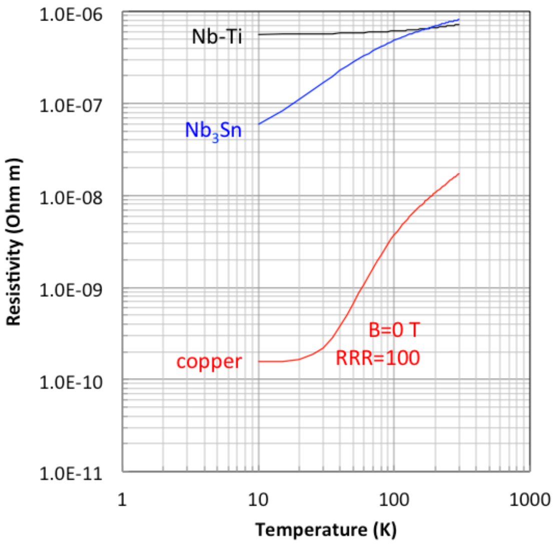
QUENCH

The QUENCH is the result of a resistive transition in a superconducting magnet, leading to appearance of voltage, temperature increase, thermal forces, and cryogen expulsion.

We STABILISE Superconductors with a good conductor as ex. Cu

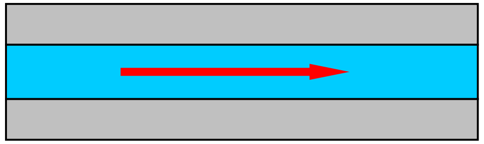
good superconductors are *bad* normal conductors

Typically, the normal state resistivity of LTS materials is two to four orders of magnitude higher than the typical resistivity of good stabilizer materials



Superconducting stage

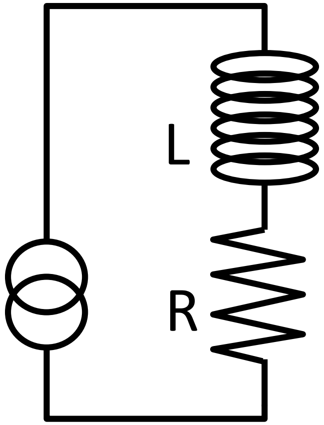
$T < T_{cs}$



R= cons= 0

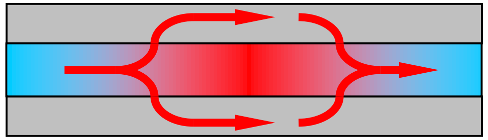
$$L\frac{dI}{dt} = 0$$

Ex of a magnet



Normal conducting stage

$T > T_c$



R= variable = f(Iop, B, RRR, T)

$$RI + L\frac{dI}{dt} = 0 \qquad RI^2$$

L. Bottura Wamsdo

ELECTRICAL INTEGRITY CHECKS: 1

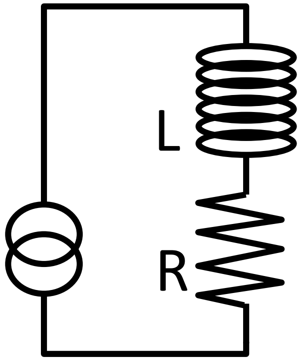
High Voltage withstand level should be compliant with the specifications

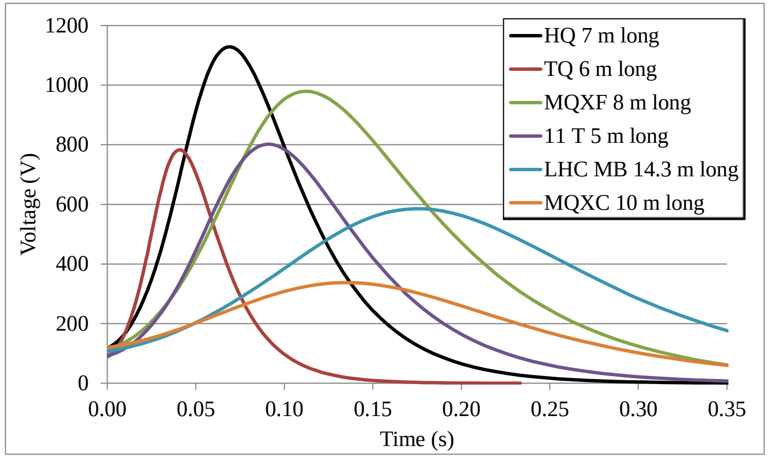
During the quench one has

a. a resistive voltage prop to I (where the magnet is quenched)

b. an inductive voltage prop to dI/dt (everywhere)

$$RI + L\frac{dI}{dt} = 0$$





Courtesy E. Todesco/ H. Felice

ELECTRICAL INTEGRITY CHECKS: 2

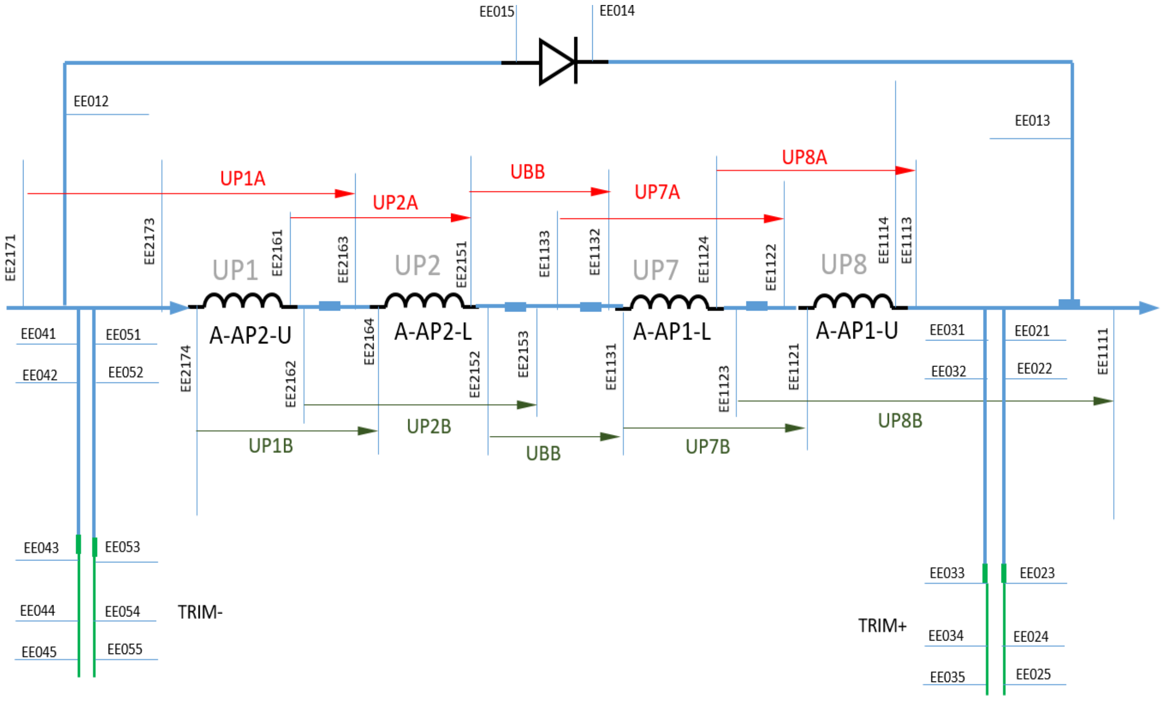
Instrumentation should allow at least to produce the trigger signal for protection but ideally to give the maximum information on the performance

Typical instrumentation is :

voltage taps (monitor transitions)

temperature sensors (monitor cooling)

strain gauges (monitor effect of forces)



Courtesy R. Denz

CONNECTION OF THE MAGNET TO THE TEST STAND

It is a non negligible and precise work!

Do not forget that cryogenic test are long processes (cool down and warm up are long and therefor no room for mistakes!

… also to be retained that here you have to deal with vacuum and low temperature and high current

Instrumentation is going thought several intermediate connections but they still need to bring the signals CLEAN out from the cryostat to communicate with the magnet

COOLING OF LARGE MAGNETS TAKES TIME!

Heat transfer from test stand to magnet

$$\mathbf{Q_{cryo}} = \dot{\mathbf{m}}\ \mathbf{Cp}\ (\boldsymbol{T_{gas\ out}} - \boldsymbol{T_{gas\ in}})$$

Convective heat transfer of Ghe to magnet

$$Q_{conv} = A_{tr}.h.(T_{surf} - T_{gas}) = Q_{cryo}$$

Courtesy Y. Leclerc

Range 300-80 K

Exchanged heat $Q_{cryo} \approx 10$ kW @ 60g.s^{-1} & $(T_{out}-T_{in})$=30K

Energy stored in 10 tons CM ≈ 800 MJ

Cooling time aprox 24 h

Range 80 to 4.5 K

Energy stored in 10 tons CM ≈ 50 MJ

$Q_{cryo} \approx 1.3$ kW in average ≡ 4.3 g/s LHe

Cooling time ≈ 12 h

Once confined to low-temperature physics laboratories, superfluid HeII has become a technical coolant for advanced superconducting devices, to the point that it is now implemented in industrial-size cryogenic systems, routinely operated with high reliability.

There are two classes of reason that call for the use of superfluid helium as a coolant for superconducting devices namely,

a. the lower temperature of operation, and
b. the enhanced heat transfer properties

The chapter of cryogenics is far too complex, nice to keep it in few slides! This subject merits and other lecture!

RRR and RESISTIVITY

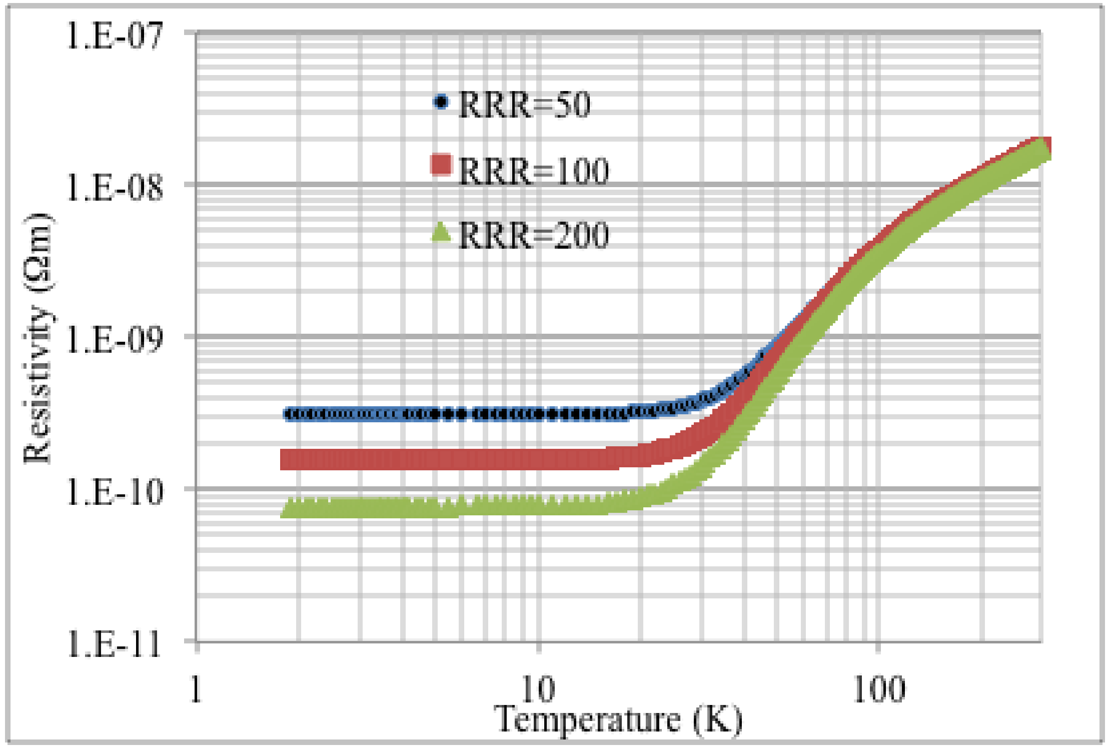
Recall hot spot temperature:

$$\gamma(T_{\max}) \equiv \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)}\, dT$$

Copper resistivity is the physical quantity with the most complex dependence

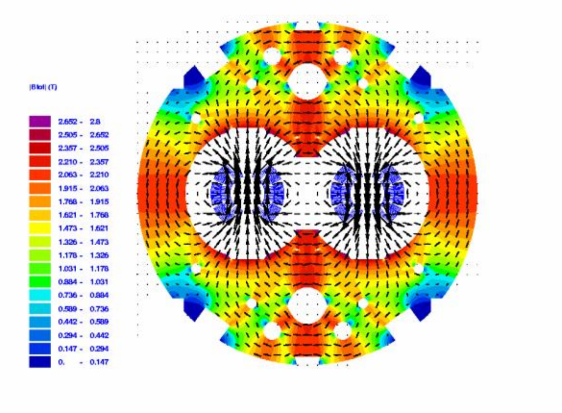
- At low temperatures, the value is dominated by the presence of impurities (measured by the so called RRR, residual resistivity ratio)

Courtesy E. Todesco



This is a measurement you do during cooling, but even better during warming up of the magnet. It gives an idea of a possible degradation if the value is very different from the expected one and allows to estimate the Tmax.

CRITICAL STRAIN



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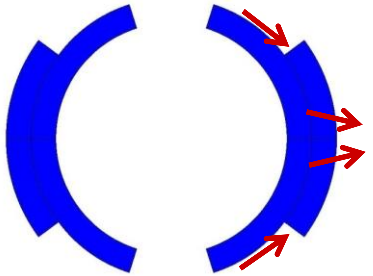

$$\vec{f} = \vec{j} \times \vec{B}$$

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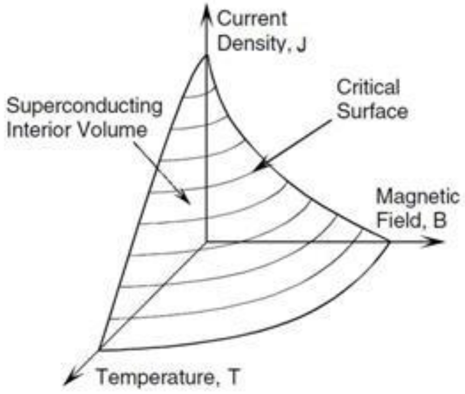
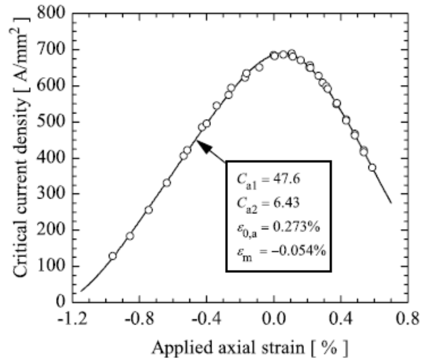


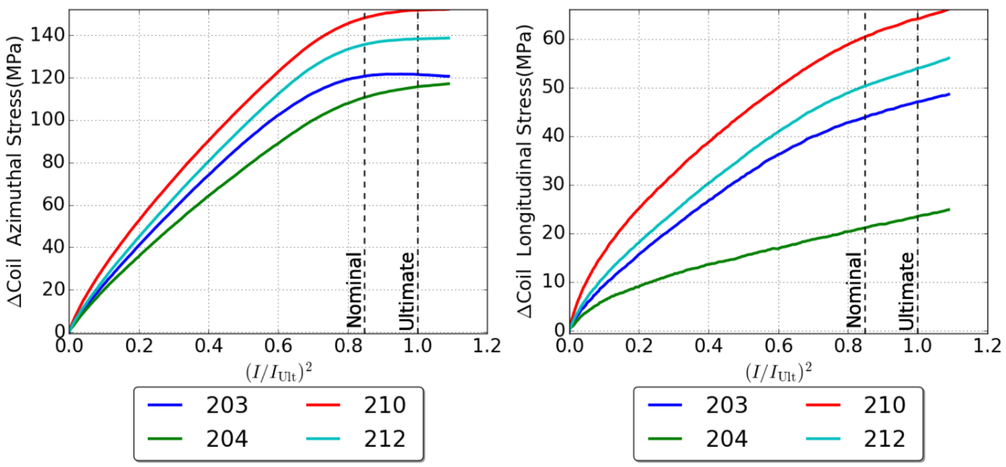
A. Godeke et all 2006



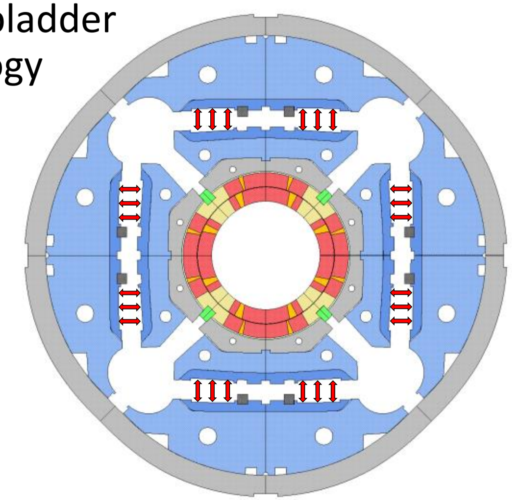
STRAIN MEASUREMENTS

- The prestress paradigm is that coil should never be in tension but always pre-compressed (as reinforced concrete)
- The initial reasons for this paradigm were field quality concerns
- Later, it was believed that the detachment provokes training – and this is what many of us think still today

See presentation of Susana Izquierdo



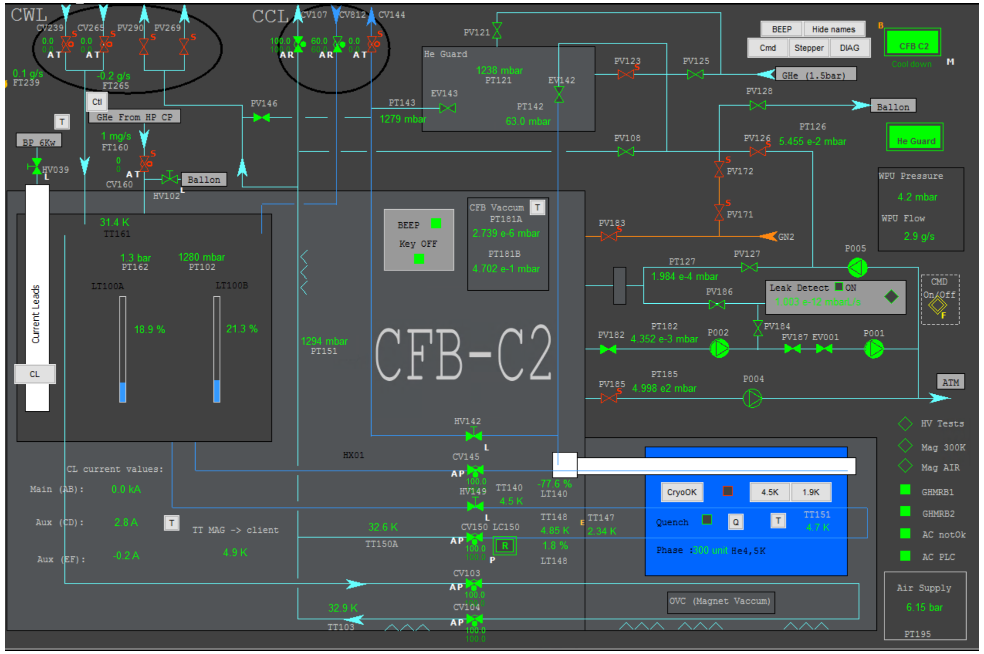
Ex. Aluminum shell, bladder and key technology

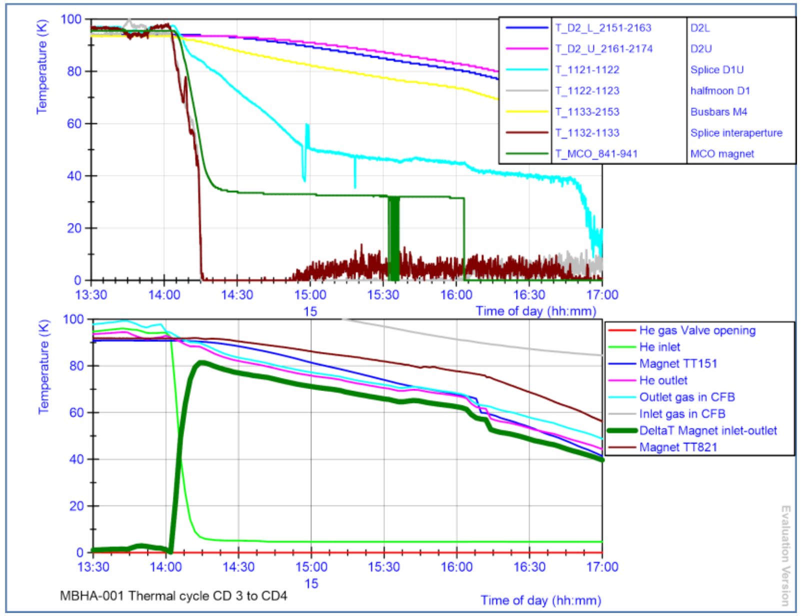


During cool-down increase in coil/shell stress

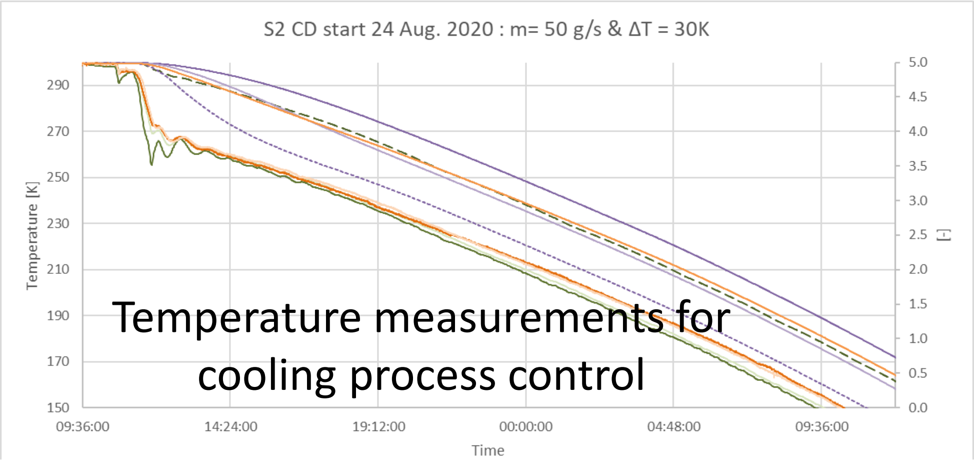
- Capability to control final coil and shell stress

TEMPERATURE MEASUREMENTS





Courtesy G. Willering



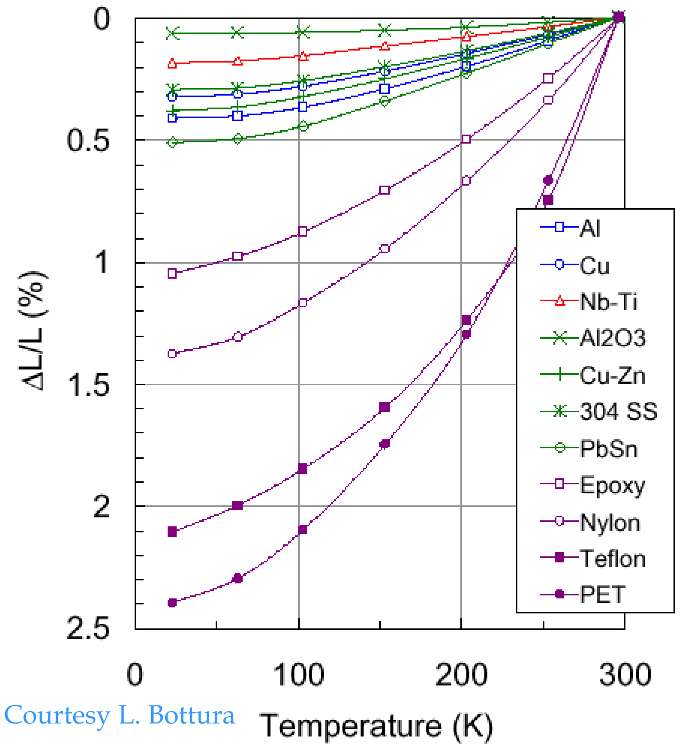
Temperature measurements for cooling process control

In general rule we limit the colling speed to a max thermal gradient in the magnet not exceeding 30 K (on this graph this was up to 80 K!)

Temp gradient of the magnet for stress control

ELECTRICAL INTEGRITY CHECKS AT COLD 1

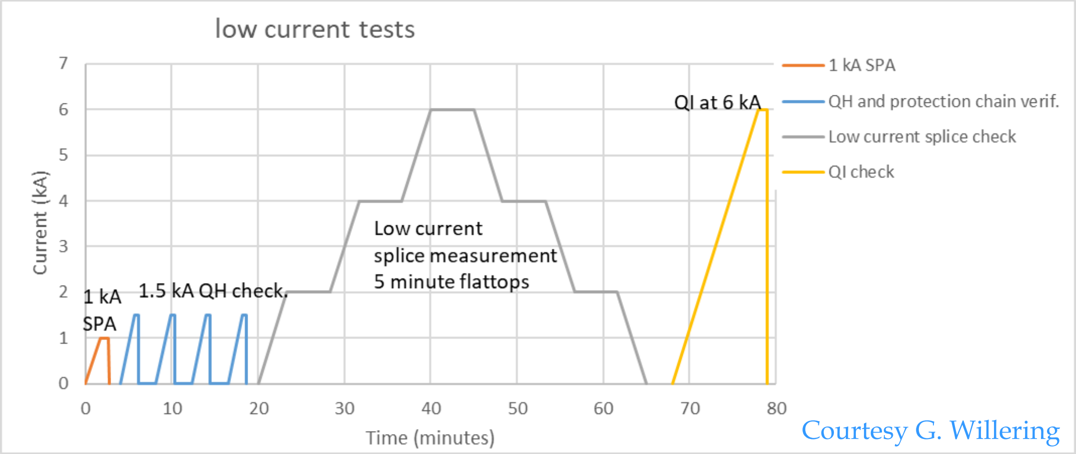
High Voltage withstand level compliant with the specifications (aprox. 3 kV)



Courtesy L. Bottura

Be sure that thermal contraction does not damaged the insulation

Check the good working conditions of the detection, and triggering of protection, extraction



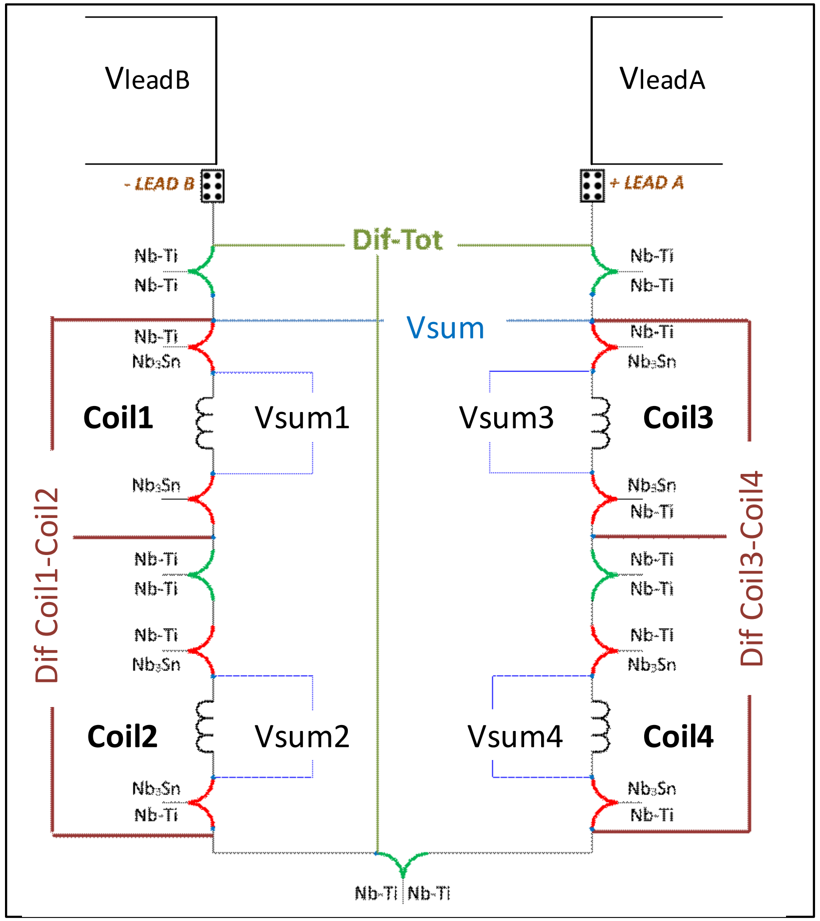
Courtesy G. Willering

Be sure that protection is working and no high resistance connections are present

THRESHOLDS FOR PROTECTION

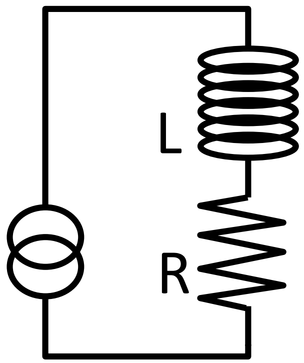
The **SAFETY MATRIX** system is using a redundant way of detection based on several signals. Any of the following signals fails it specified *threshold* values for the given *time windows, the system sends a trigger to* provokes a **FAST POWER ABORT**.

- V Coil1- VCoil2 50-100 mV for 10 ms
- V Coil3- V Coil4 50-100 mV for 10 ms
- Vsum 50-100 mV for 10 ms
- $V_{Splices}$ 8-10 mV for 8 ms
- V_{Leads} 80 mV for 500 ms



..but how we define these schematics and the threshold levels?

COMBINING SIGNALS FOR QUENCH DETECTION



$$RI + L\frac{dI}{dt} = 0$$

- During the ramp, the magnet has an inductive voltage
  - Example of LHC dipole: ramp at 10 A/s, inductance of 100 mH, voltage during ramp is 1 V
- The inductive voltage is removed by subtracting signals from two coils, or from two apertures (if the magnet has two apertures)
  - The assumption is that only one coil is quenching, so that subtracting the two voltages the inductive part is removed and the resistive is left
  - This is not working in the case of quench developing in the two coils at the same time (symmetric quench), where a second level of control is added
- The inductive part can be also removed by software (based on model) to reduce the voltage taps

If the signals are well combined,. and the magnet is superconductor , the acquired volatge signals are all indicating 0 V!

HOT SPOT TEMPERATURE

- the quench starts in a point and propagates with a *quench propagation velocity*

- hot spot temperature: the conductor that has crossed the critical surface (current sharing temperature) and is in normal state is heated by the Joule effect

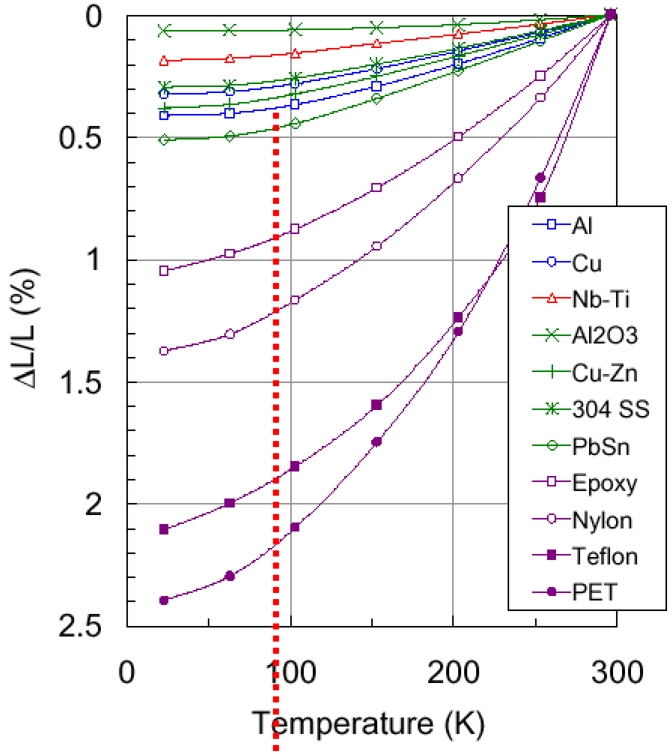
$$\rho j^2(t)dt = C_p(T)dT$$

  - where t is time, T is temperature, ρ is resistivity and C_p is volumetric specific heat

$$\gamma(T_{\max}) \equiv \int_{T_0}^{T_{\max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$

HOT SPOT TEMPERATURE

- hot spot temperature: $$\gamma(T_{max}) \equiv \int_{T_0}^{T_{max}} \frac{C_p(T)}{\rho_{Cu}(T)} dT$$



E. Todesco - Superconducting magnets

T_{max} must be limited to:

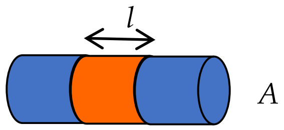
limit thermal stresses (see graph)
avoid material damage (e.g. resins have typical T_{cure} 100…200 °C)

T_{max} < 300 K for well-supported coils (e.g. accelerator magnets)

T_{max} < 100 K for negligible effect

MINIMUM PROPAGATION ZONE

- We now consider a superconductor wire where a length *l* and section *A* is above the critical surface (resistive condition)
  - Local dissipation is $\mathrm{D}q = r\, j^2$
    - ρ: resistivity
    - j: current density
    - q: dissipated heat density due to Joule effect



- Dissipation over the volume is $\Delta Q = Al\rho j^2$
- Heat propagation through the surface *A* is $\Delta Q = \dfrac{2kA(T_c - T_{op})}{l}$

$$l_{mpz} = \frac{1}{j}\sqrt{\frac{2k(T_c - T_{op})}{r}}$$

- T_c: critical temperature
- T_{op}: operational temperature
- k: conducibility (W/m/K)

So above the length l_{mpz} the quench propagates

MINIMUM PROPAGATION ZONE

Let us estimate this length, with j=2000 A/mm^2, ρ=6.5×10^{-7} Ω m, k=0.1 W/(m K), ΔT=2 K

$$l_{mpz} = \sqrt{\frac{2\times 0.1\times 2}{6.5\times 10^{-7}\times 4\times 10^{18}}} = \sqrt{\frac{10^{-12}}{6.5}} = 0.4\ \mu\text{m}$$

This is very small

Embedding the filaments of superconductor in a copper matrix one can increase the minimum propagation zone by several orders of magnitude

Cu resistivity 3×10^{-10} Ω m (2000 less than Nb-Ti)
Cu conductivity 350 W/(m K) (3500 more than Nb-Ti)

The gain is of the order of 3000, so the minimum propagation zone increases from fraction of μm to mm, and the energy from nJ to μJ

QUENCH PROPAGATION VELOCITY

- Typical quench velocities (along the cable) of the order 10 m/s
  - The equation for quench velocity is

$$v_q = \frac{j}{C_p}\sqrt{\frac{k\rho}{\Delta T}}f$$

  - Parametric dependence:
    - proportional to current density in copper
    - Inverse proportional to square root of temperature margin
  - Can also be written as
    - L_0 Lorentz number 2.45×10^{-8} W Ω /K^2

$$v_q \approx \frac{j}{C_p}\sqrt{\frac{L_0 T_s}{T_s - T_{op}}}$$

  - Example
    - j: 400 A/mm^2 = 4×10^8 A/m^2
    - C_p: 5×10^3 J/K/m^3 (considering at 4 K)
    - T_s: 4 K T_{op}:2 K
    - One finds $v_q=4\times10^8 / 5\times10^3 \times \sqrt{(2.5\times10^{-8}\times 4/2)} =$ 18 m/s

QUENCH DETECTION

- How to translate the quench velocity in a resistance growth ?
  - Equation for resistance growth

  - For example, LHC dipole
    - I = 12 000 A
    - A_{Cu}= 15 mm^2 = 15×10^{-6} m^2
    - ρ = 5×10^{-10} Ω m
    - Scaling factor from velocity to voltage increase: 5×10^{-10} / 15×10^{-6} × 12000 = 0.4 V/m
    - Therefore for a 17 m/s quench velocity, the voltage increase of of the order of 7 V/s
    - So for a 100 mV threshold, reached after 15 ms

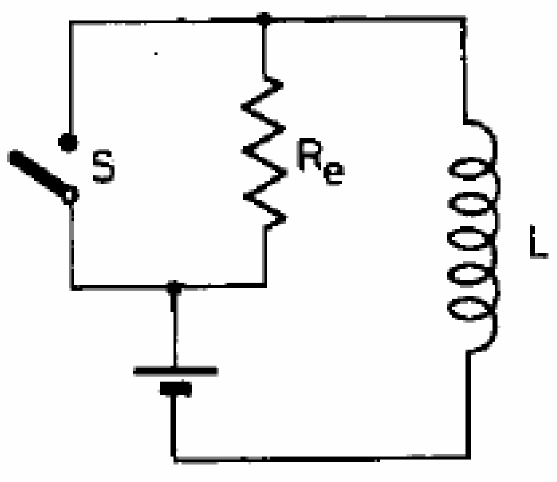
$$\frac{dV}{dt} = \frac{dR}{dt} I = \frac{r_{Cu}}{A_{Cu}} \frac{dl}{dt} I = \frac{r_{Cu}}{A_{Cu}} I v_q$$

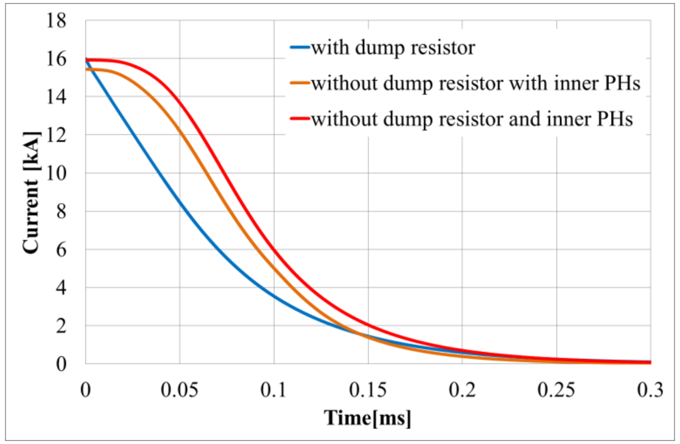
The presence of the Cu fasten the resistance growing allowing the detection of a quench and so the extraction of the energy without damaging the coils.

ENERGY EXTRACTION

The higher the resistance, the faster the current dump, the lower hotspot …

For a fast de-excitation in the case of a quench, a magnet can be equipped with external energy extraction systems with circuit breakers and energy-absorbing dump resistors.
The reaction time of the switch is not zero!!





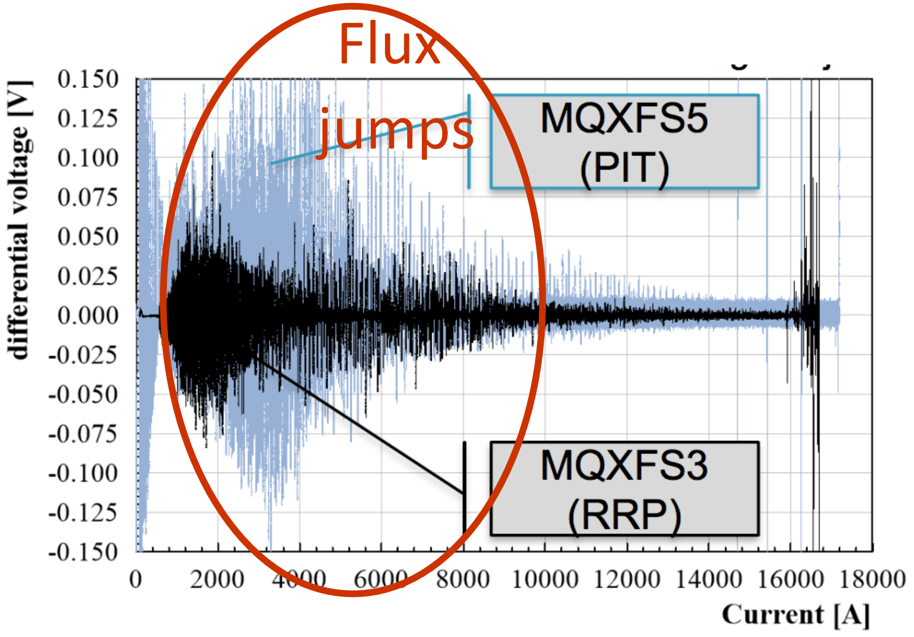
E. Todesco - Superconducting magnets

$$I = I_0 e^{-\frac{t}{t}} \qquad t = \frac{L}{R}$$

…..but adding an external dump resistor creates a voltage at the magnet leads, proportional to the dump resistor. So the resistor size is limited by magnet insulation.
Moreover for a chain of magnets (as in the LHC) or long is not efficient (n x L/R)

NOISES AND FLUX JUMPS

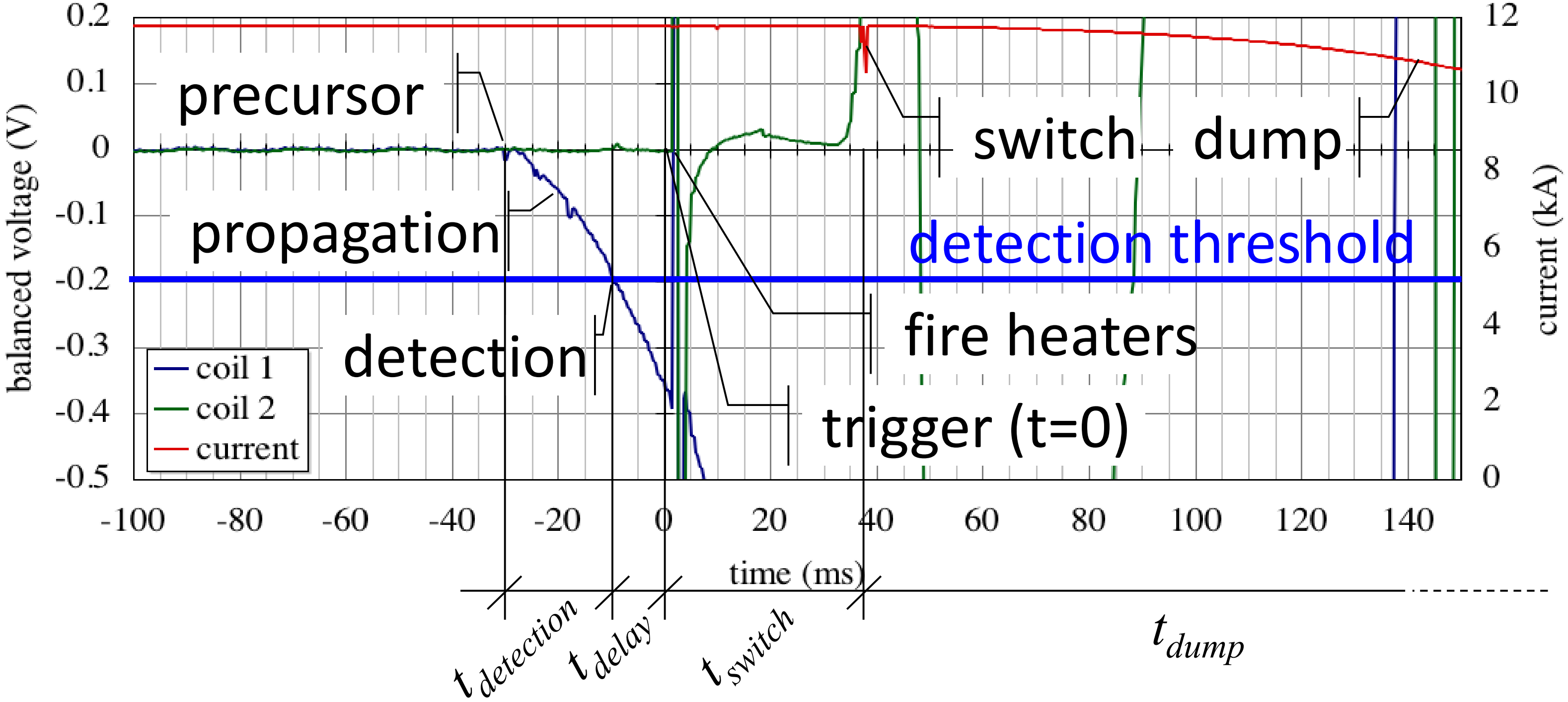
- Flux jumps in Nb_3Sn
  - In magnets based on Nb_3Sn conductor, at low fields flux jump phenomena provoke spikes in voltages
    - These spikes can be much larger than 100 mV, and therefore can be erroneously interpreted as a quench
  - Larger thresholds have to be used at lower current
    - Protection is not put in danger since at lower current there is more margin

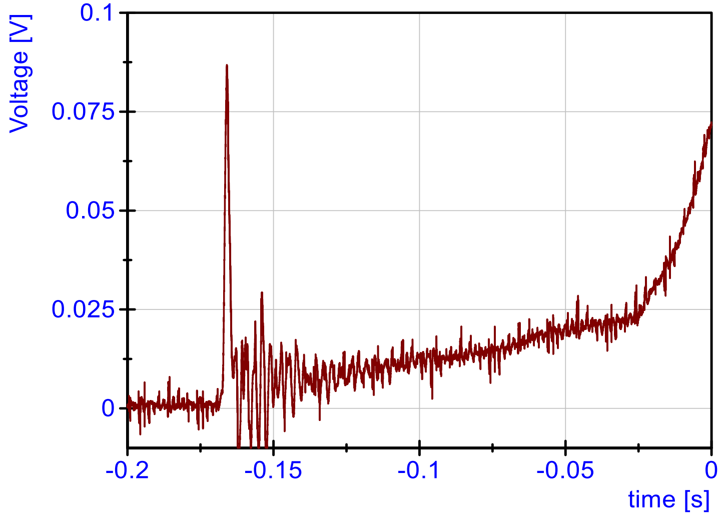


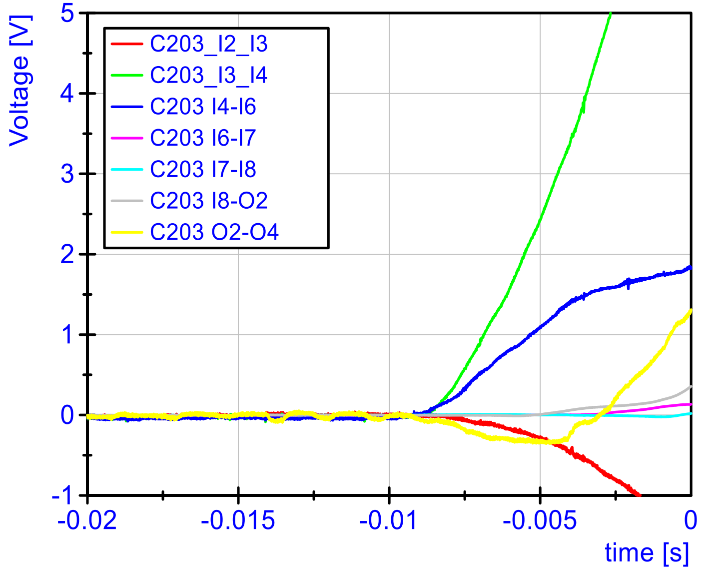
E. Todesco - Superconducting magnets
H. Bajas

..BUT HOW WE DEFINE THE THRESHOLD?

Example of an LHC dipole magnet training quench







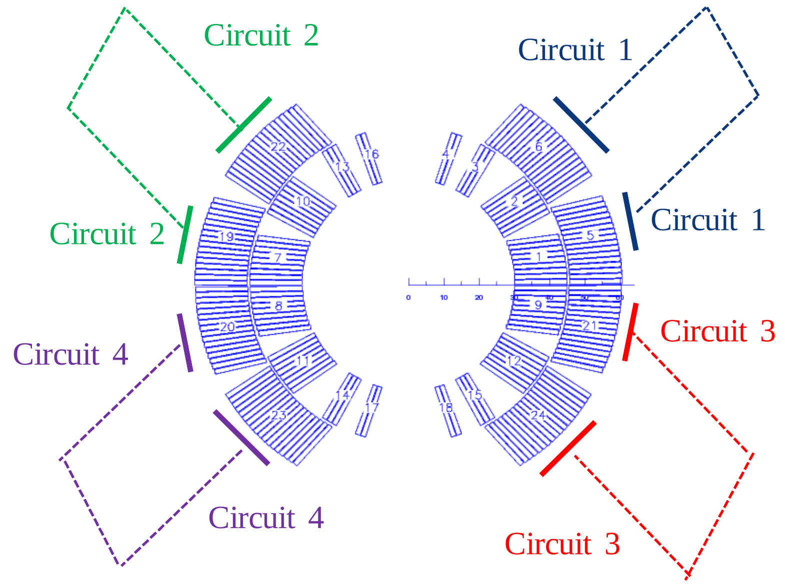
$$t_{quench} \approx t_{detection} + t_{delay} + t_{switch} + f\,t_{dump}$$

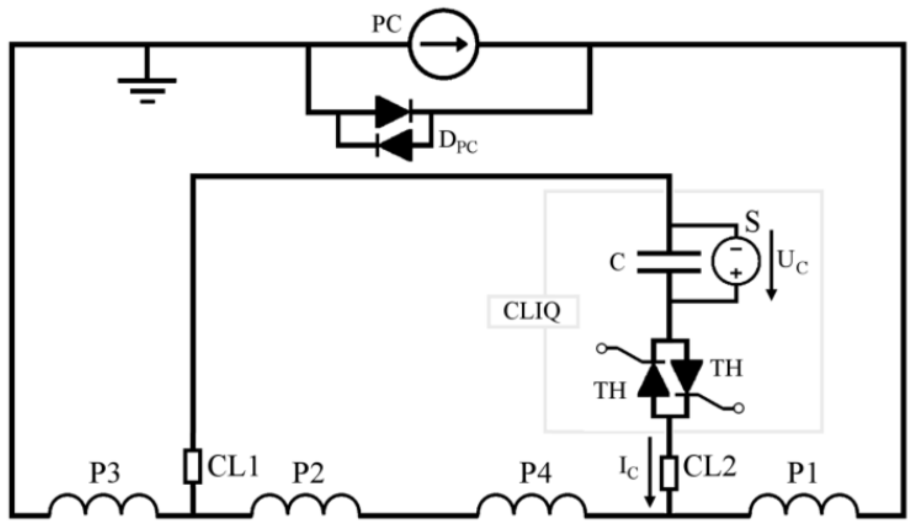
Courtesy L. Bottura Wamsdo

HEAT TO PROTECT

The best way to get rid of the current is to increase the resistance, transforming the ***local transition in a global transition*** to normal conducting state

This corresponds to rapidly heating the whole coil above the critical surface of the superconductor





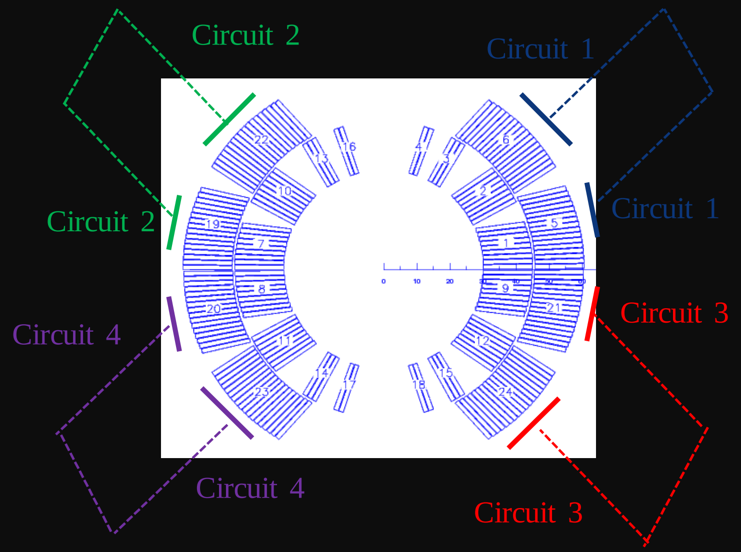
QUENCH HEATERS

Quench heaters are strips of stainless steel where an impulse of current by capacitor discharge is put as soon as the quench is detected.

Strips heat thanks to Joule heating and give heat power to the coil. The reaction time that can be obtained is of the order of 10-50 ms

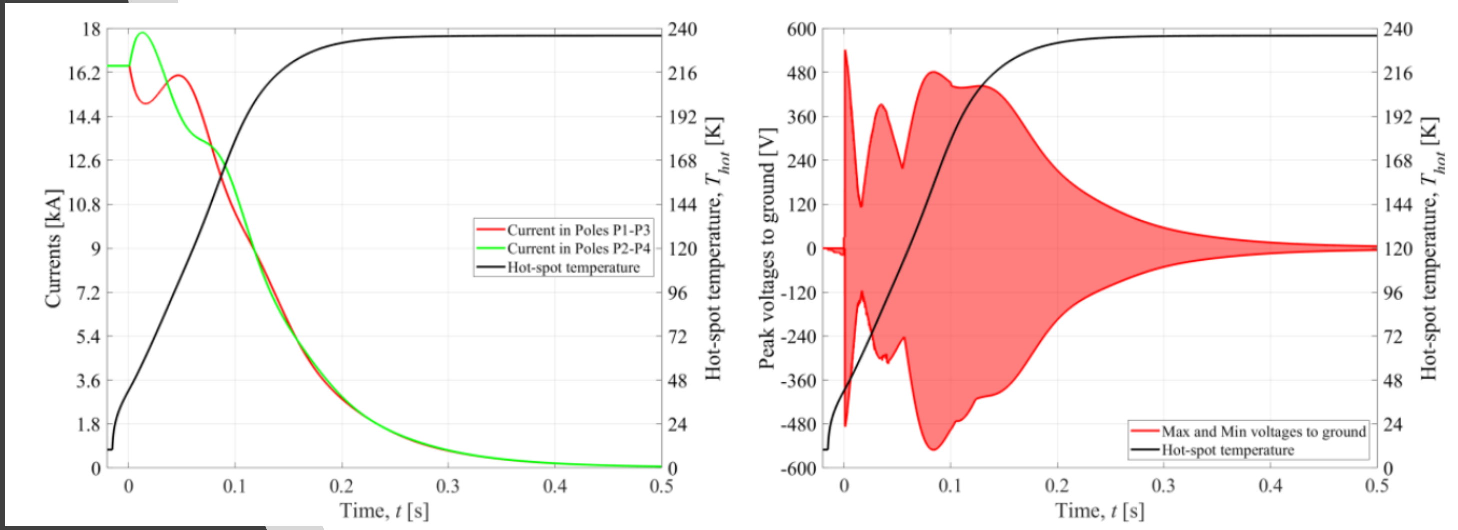
One has to guarantee two conflicting conditions:

- a good electrical insulation between heater and coil
- a good thermal conductivity between heater and coil



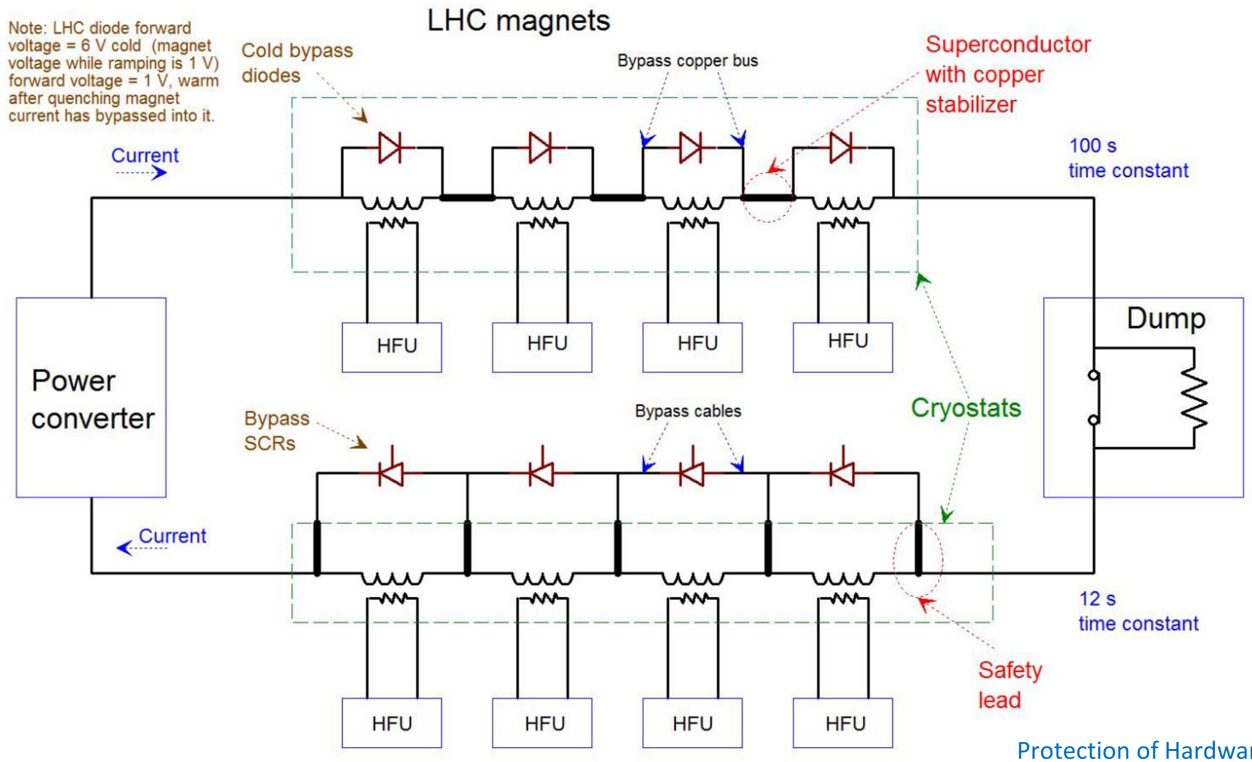
CLIQ

- CLIQ (Coupling Losses Induced Quench)
    - This system is based on injecting in the magnet coils two opposite impulses of current via a capacitor.
    - The mechanism is the heating due to ***interfilament coupling losses*** induced by the variation of the field
- It has been developed at CERN and patented in 2014 (EP13174323.9)



D. Wollmann HL-LHC Technical Design Report

PROTECT WITH BYPASS DIODES



In case of a resistive transition in the superconducting magnet, the turn-on voltage of the diode is exceeded, and ***the current commutates*** from the quenched magnet to the diode during the de-excitation of all magnets in the circuit.

Protection of Hardware: Powering Systems (Power Converter, Normal Conducting, and Superconducting Magnets) By B. Flora et all

CHECK OF PROTECTION EFFICENCY

Measurement of the time between heater activation and transition to resistive state of the coil are done typically during the R&D phase.

The quench heater strip is made by stainless steel – ususally 25 mm

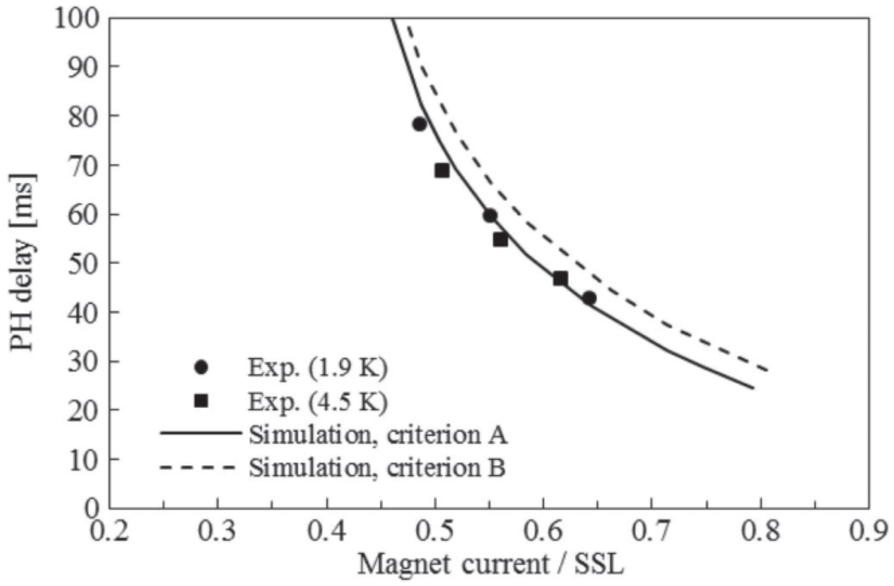
One has to guarantee two conflicting conditions:

a good electrical insulation between heater and coil

a good thermal conductivity between heater and coil

This is achieved with a polyimide strip of 25-75 mm thickness

- The thicker the polyimide, the longer the time to heat the coil
- The thinner the polyimide, the higher the risk of electrical short between heater and coil



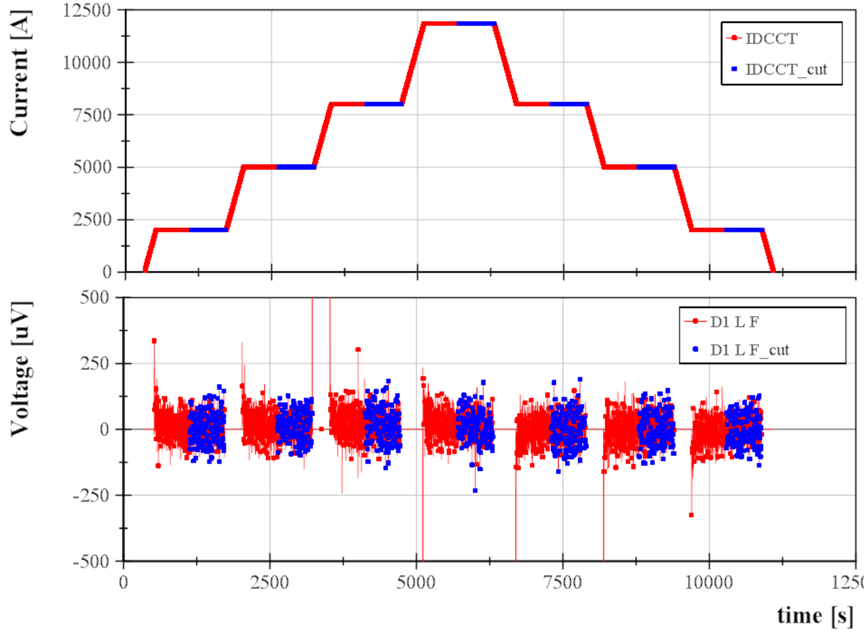
Heaters delay measured vs model in HQ, 25 μm polymide (left) and 11 T 75 μm polyimide (right)

[T. Salmi, et al, IEEE TAS 25 (2015) 4004212]

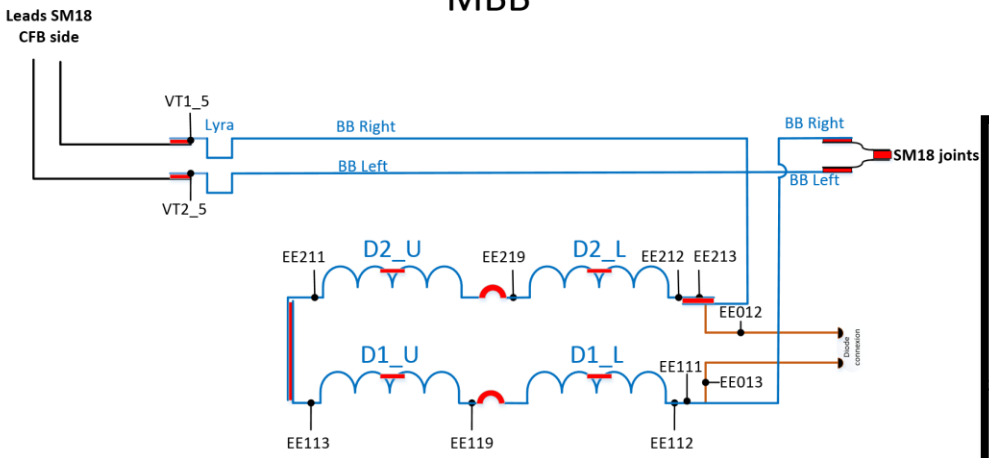
SPLICE MEASUREMENTS

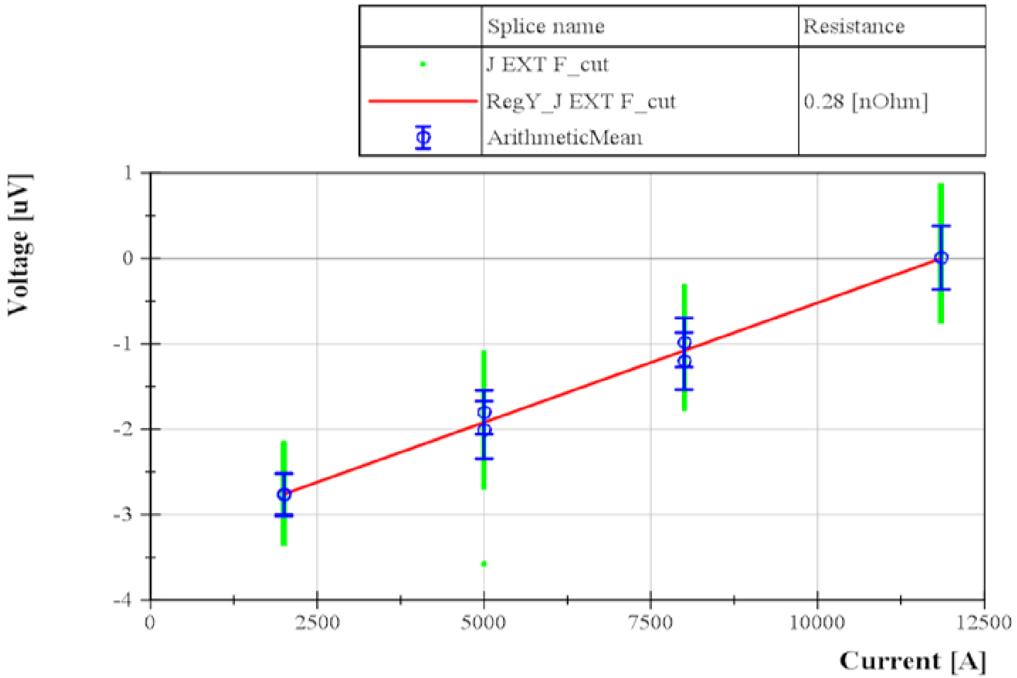
- Current cycle from 50 to 11850A with voltage measurements on plateaus (dI/dt=0)
- Slope of curve is the resistance (get rid off offset)

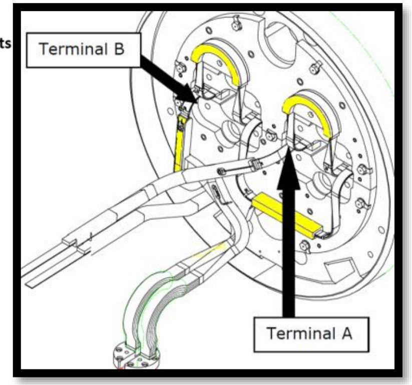
U=RI + LdI/dt



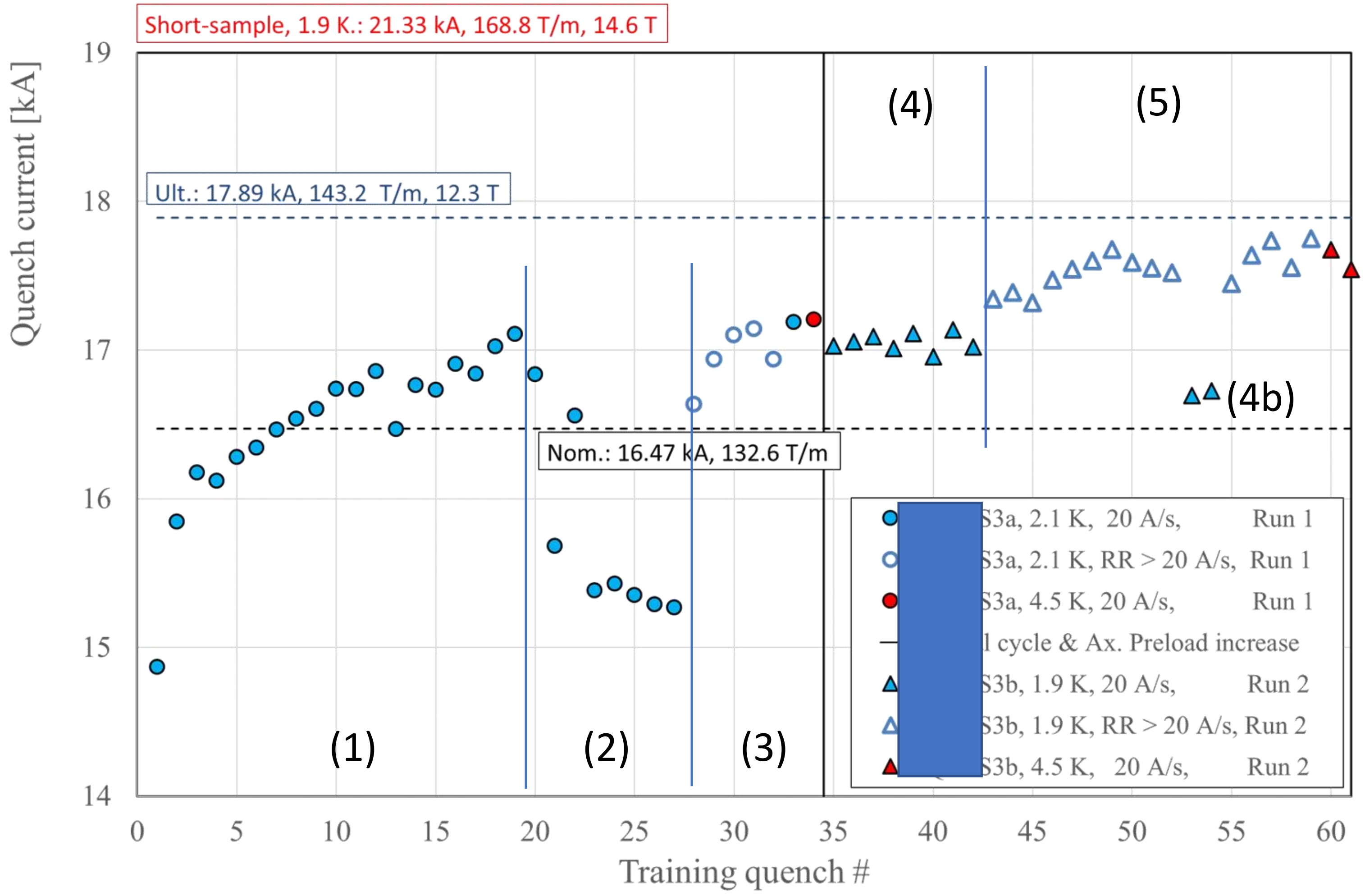
MBB







PERFORMANCE INDICATOR: **TRAINING**, MEMORY



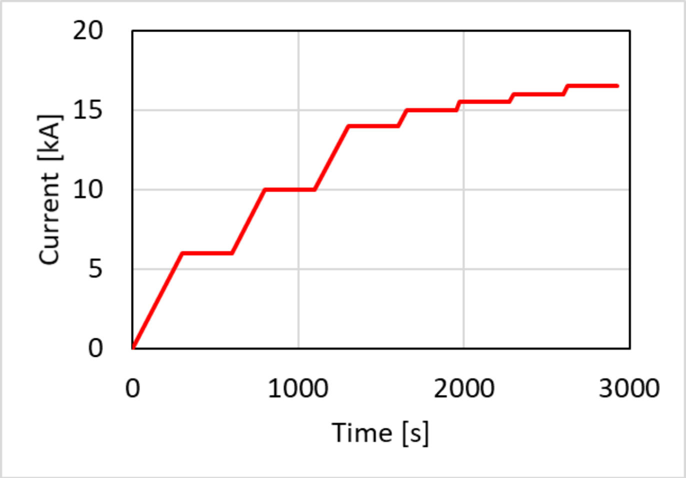
1) S3a training in many different locations, all coils.
2) Detraining in coil 7 I3I4
3) High ramp rate quenches (several locations) allow to overcome c7 I3I4 limitation up to higher level

Axial preload is increased during thermal cycle (S3a→S3b)

4) S3b quenches at nominal ramp rate in c7 I3I4 and c105 I3I4
5) High ramp rate allows higher quench current but does not overcome the limitation (4b)

Courtesy of F. Mangiarotti

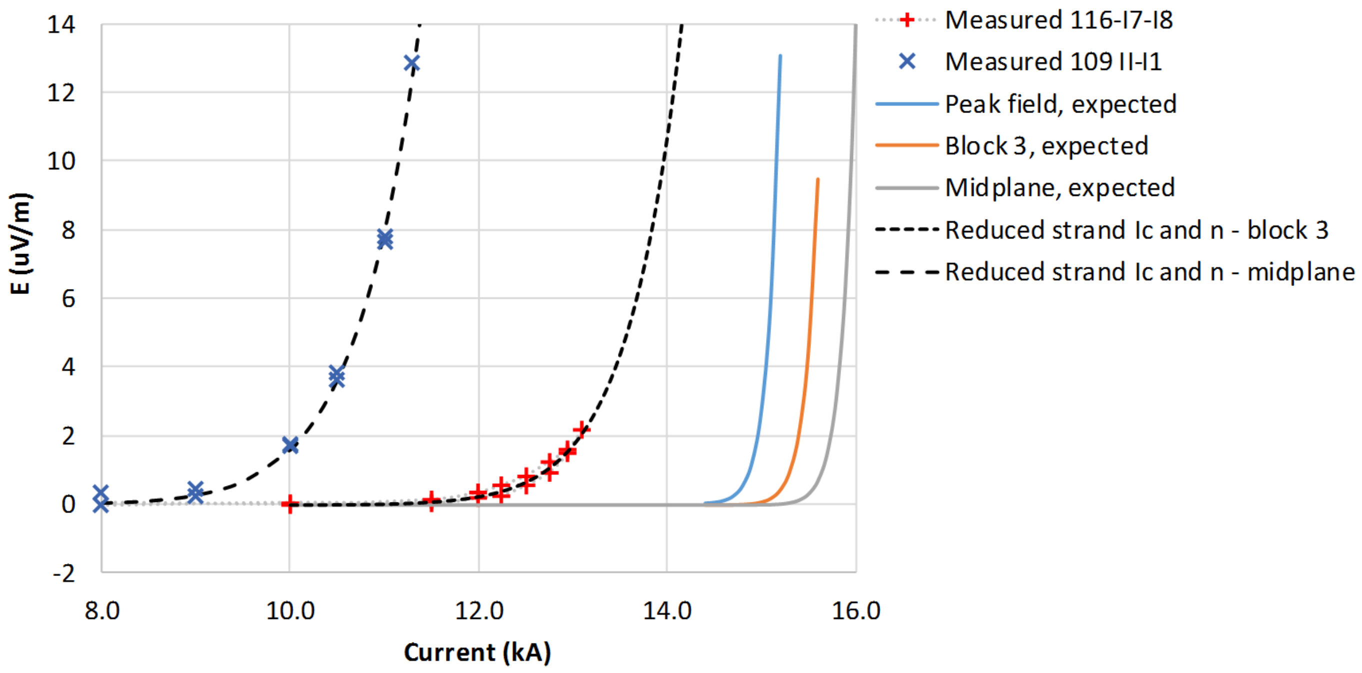
PERFORMANCE INDICATOR: VI measurements



Expected electric field in a degraded conductor.
Simply adding
- a reduction factor (f_{I_c}) for I_c
- a reduction factor (f_n) for n

$$E(I,B) = E_c\left(\frac{I}{f_{I_c}I_c(B)}\right)^{(f_n n(B))}$$

f_{Ic}	0.62 (38 % reduced)	0.26 (74 % reduced)
f_n	0.20 (80 % reduced)	0.12 (88 % reduced)



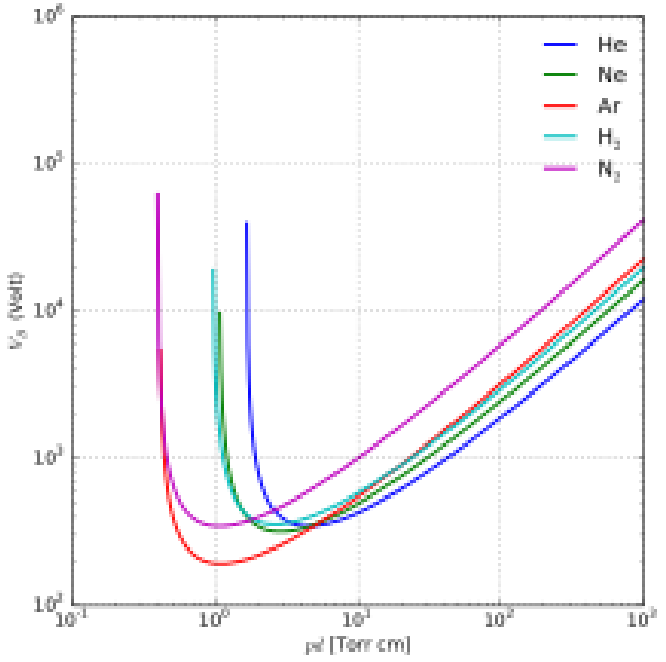
Courtesy of G. Willering

PASCHEN'S LAW

Mean free path of an electron… chain reaction and avalanche breakdown.

$$\mathbf{V_B} = \frac{a \cdot (p \cdot d)}{\ln(p \cdot d) + b}$$

p = pressure
d = distance between the electrode
a & b depend on the media



The critical voltage: minimum of the Paschen's curve

The break voltage:

decreases with the distance between electrodes

decreases with the pressure

decreases with increasing temperature (better at cold)

in air, increasing humidity decreases the breakdown voltage.

Courtesy of H. Bajas

Table 1.1. Minimum Sparking Constant for various gases

Gas	*(pd)min*	*V_b min volts*
Air	0.55	352
Nitrogen	0.65	240
Hydrogen	1.05	230
SF_6	0.26	507
CO_2	0.57	420
O_2	0.70	450
Neon	4.0	245
Helium	4.0	155

Typical values for A, B and ν for air are $A = 12$, $B = 365$ and $\nu = 0.02$.

ELECTRICAL INTEGRITY CHECKS AFTER THERMAL CYCLE

After a thermal cycle one can not exclude the presence of He gas in the coil which would reduce the breakdown voltage… therefore the final voltage withstand test should consider that and adapt the insulation checks by :

To be noted:
Room temperature GHe is the most critical media.
Pressure helps… temperature does not.
(Hot Spot – Vmax – Pmin ?)

a. reducing the voltage and so the safety margin (and taking the risk to not detect a problem)

b. adapting the conditions: temperature and pressure…

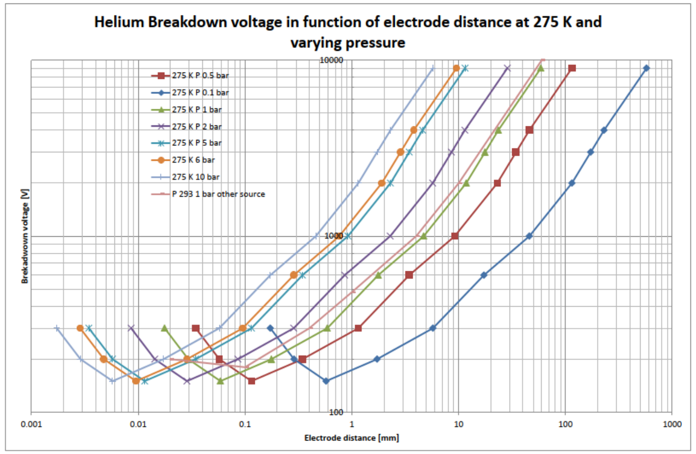


Chart I Helium breakdown voltage vs. electrode distance at 275 K and with varying pressure

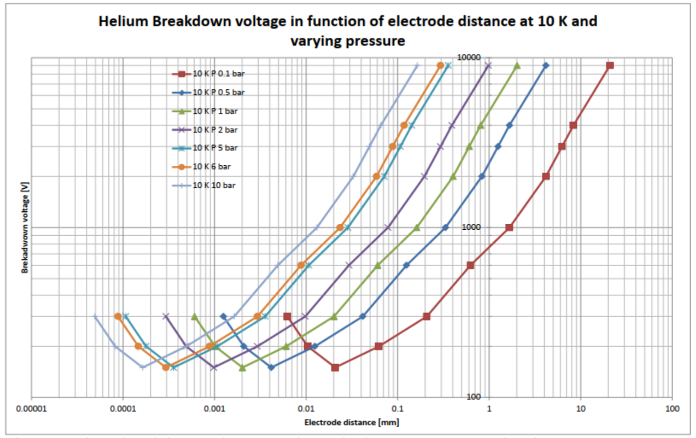
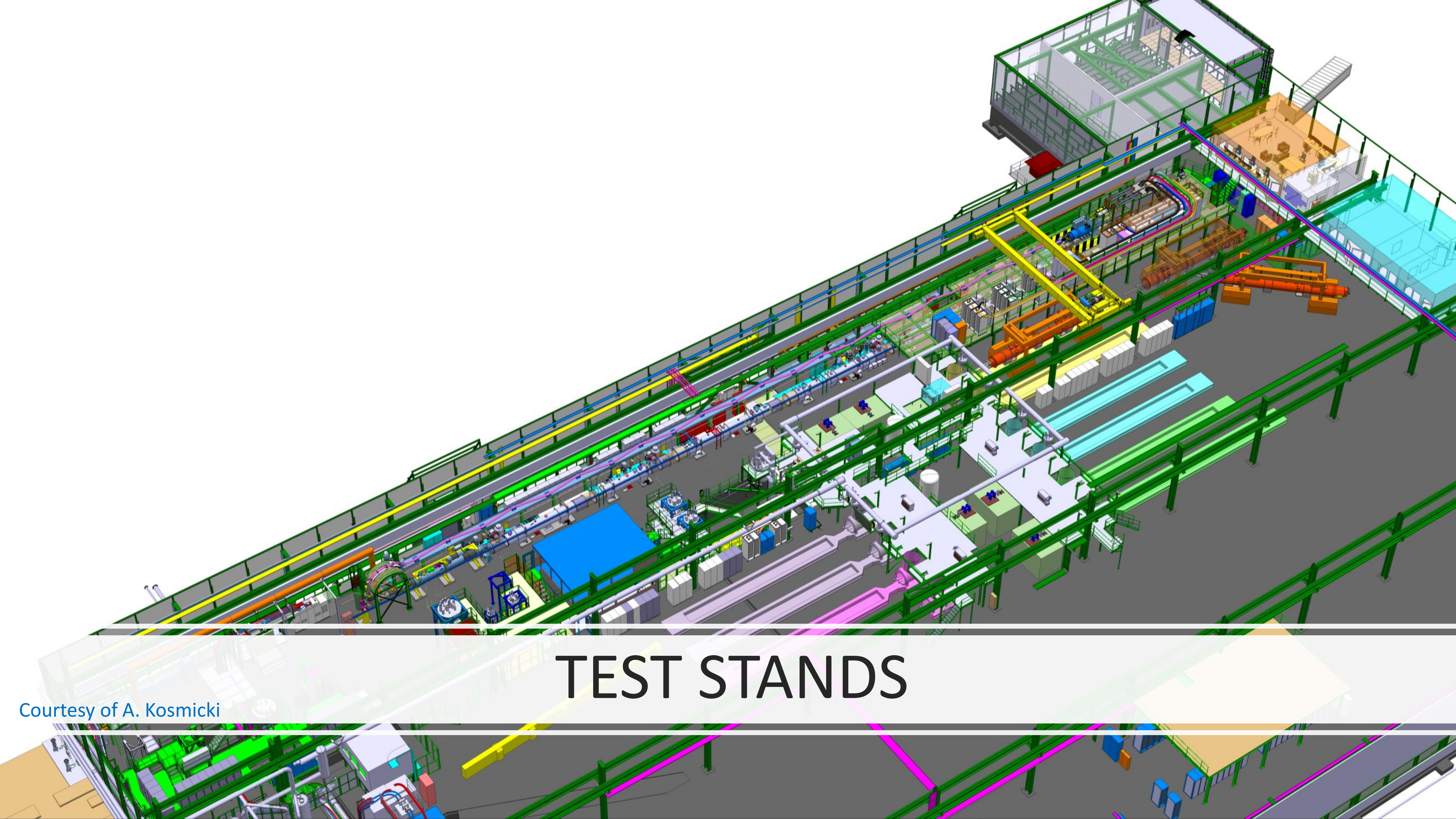


Chart II Helium breakdown voltage vs. electrode distance at 10 K and with varying pressure

Courtesy of P. Fessia



TEST STANDS

Courtesy of A. Kosmicki

TEST STAND MAIN INGERDIENTS

- Test cryostats
- Powering circuits
- Protection elements
- Cooling elements
- Handling tools
- Cryogenic infrastructures
- Data acquisition systems
- Safety interlock systems
- Analysis software…. ect








…..but before all it is an interdisciplinary, enthusiastic team

TEST CRYOSTATS

They can be very versatile and different from each other; the typical image we have about is a vertical cryostat with a He vessel, a vacuum tank and an insert with or without a lambda plate

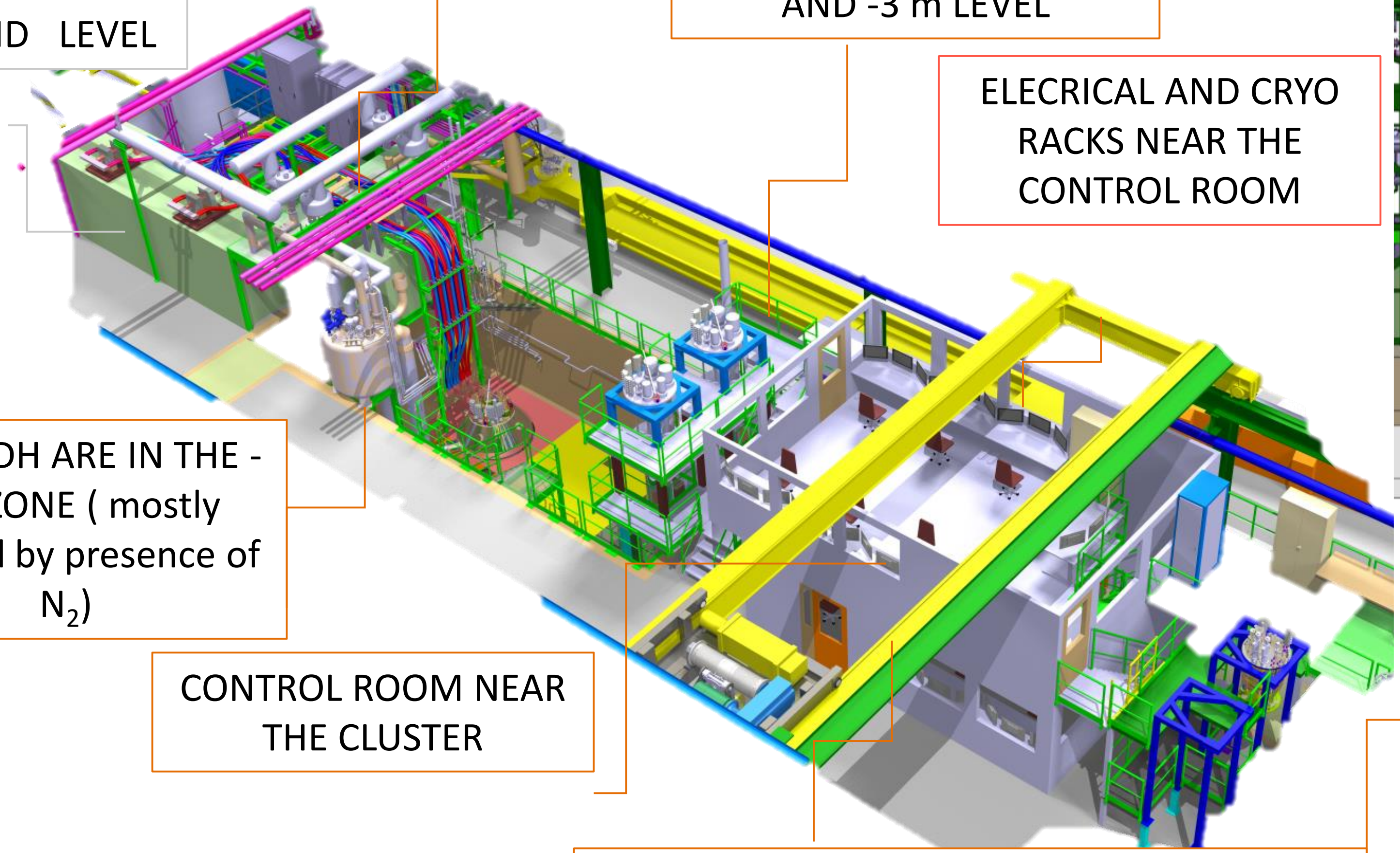
A RECENT INSTALLATION AT CERN: CLUSTER D

POWER CONVERTERS AT GROUND LEVEL

EE and DUMP on the 2 m LEVEL

PREPARATION ZONE AT 0 AND -3 m LEVEL

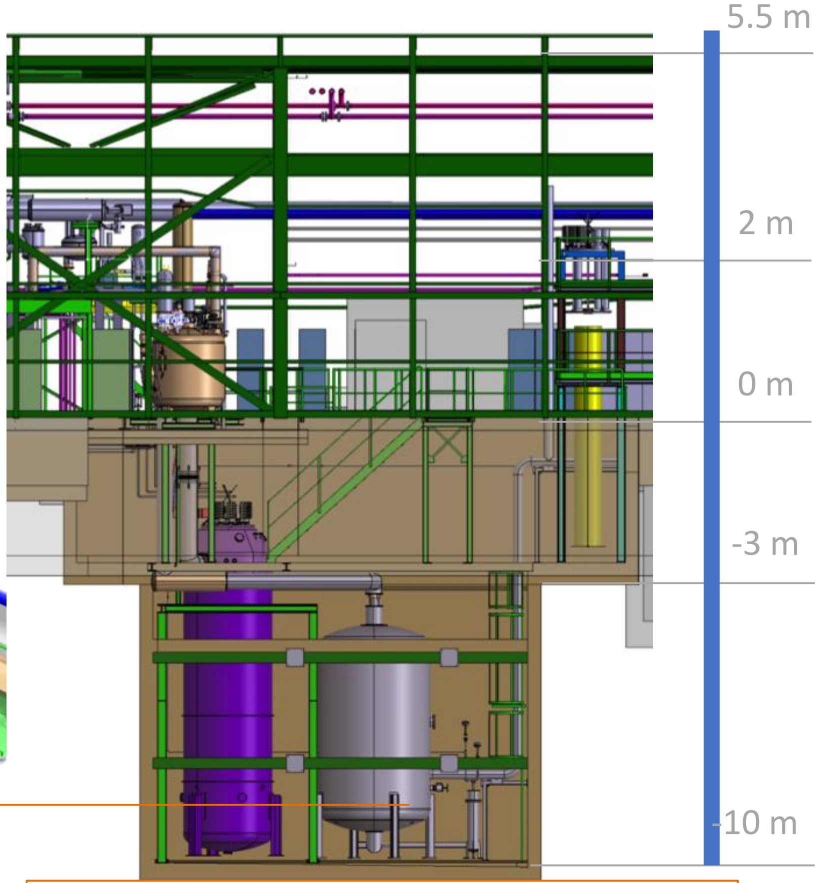
ELECRICAL AND CRYO RACKS NEAR THE CONTROL ROOM



TWO ODH ARE IN THE -3 m ZONE (mostly justified by presence of N_2)

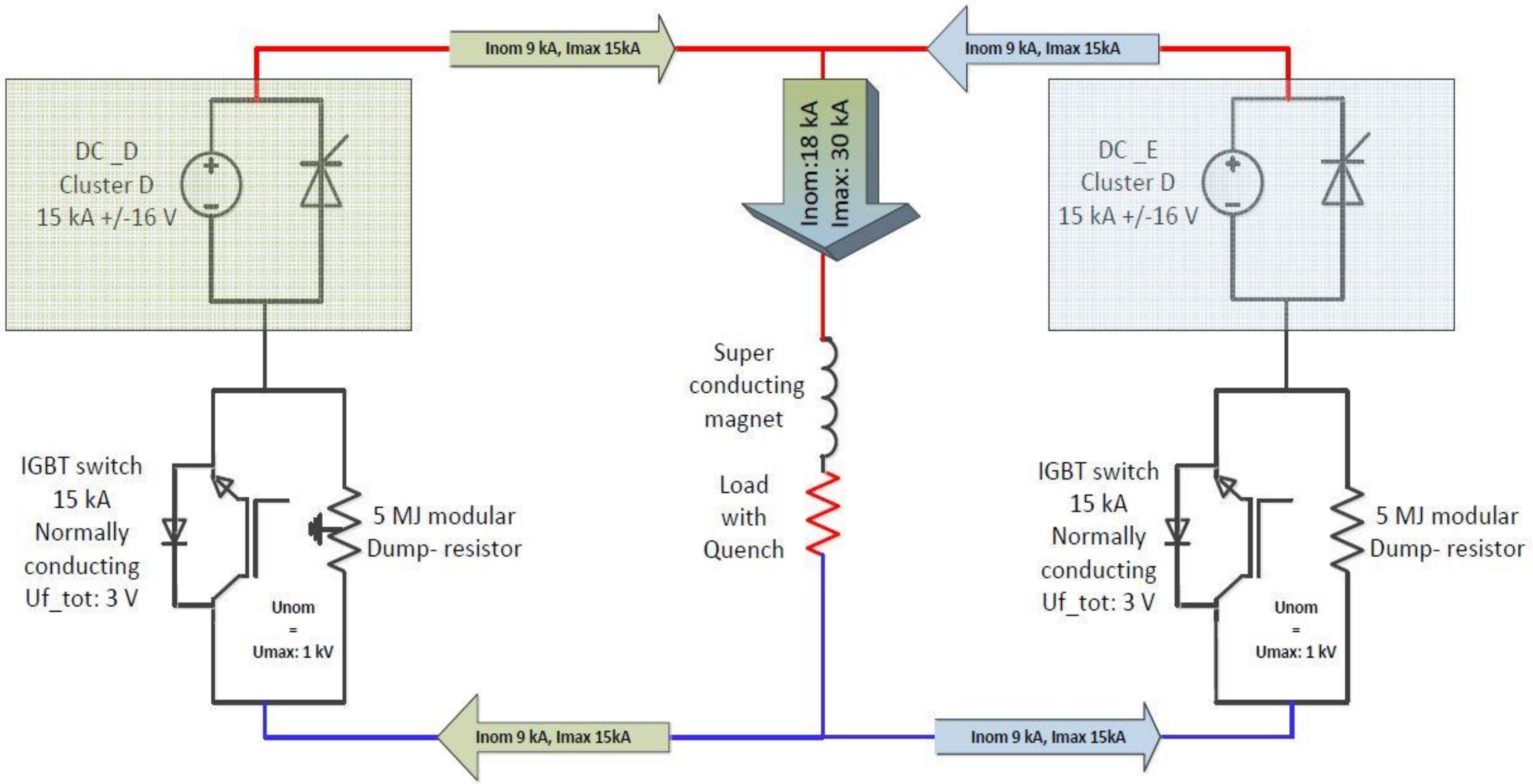
CONTROL ROOM NEAR THE CLUSTER

NEW OVERHEAD CRANE ALLOWS HADLING 25 t AND AT -3 m LEVEL



COLD He RECOVERY BUFFER - 8 m^3 à 5 bar, UNDER THE WORKING AREA IN CONFINED SPACE

CLUSTER D: ELECTRICAL CIRCUIT



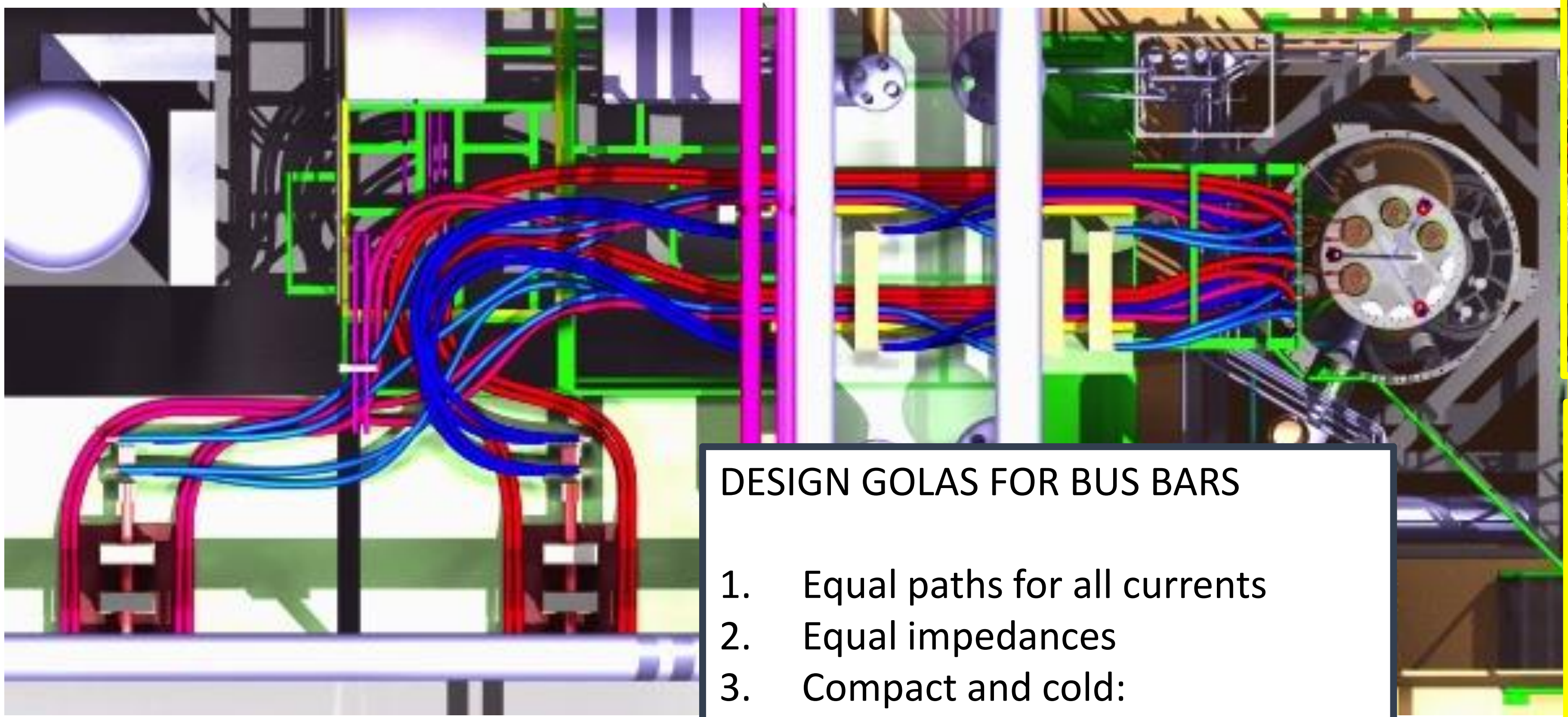
EL CIRCUIT PARAMETERS

Maxi stored energy	10 MJ
Short Sample current	21.5 kA
Magnet inductance mH/m	8. 27
Nominal Ramp Rate	11 – 20 A/s
Max Ramp Rate	200 A/s
Max current	**30 kA**
Max EE voltage	1 kV
Reaction time :	**< 10 ms**

DESIGN DRIVEN BY: cost reduction and operation optimization implying to use two existing 15 kA power converters for the new circuit

THE ENERGY EXTRACTION OF THE CLUSTER D

DESIGN DRIVEN BY : Reaction time **< 10 ms**, which implied the use of **IGBTs**



EQUIPPED WITH A DUMP

DESIGN GOLAS FOR BUS BARS

1. Equal paths for all currents
2. Equal impedances
3. Compact and cold:

(T max 110 °C and 80 °C on junctions)

QUENCH HEATER DISCHARGE SUPPLIES

The Quench Heater Discharge Supplies are the units ***responsible for energizing the quench heaters*** strips installed on the magnet coils in order to dissipate the energy stored in the magnet into its full volume, hence limiting the hot-spot temperature at the location of the original quench and preventing damage to the coil.

Ex. A DQHDS for HL-LHC magnets:

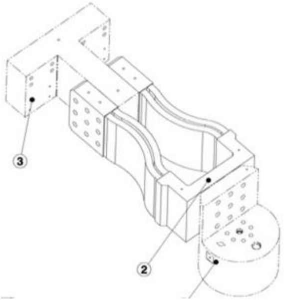
- a bank of capacitors (7 mF/ 1000 V).
- nominal operating voltage of the capacitors will be 450 V and therefore an overall voltage for the capacitor bank of 900 V is expected to
- deliver ~ 3.5 kJ to a single quench heater strip

D. Wollmann HL-LHC Technical Design Report

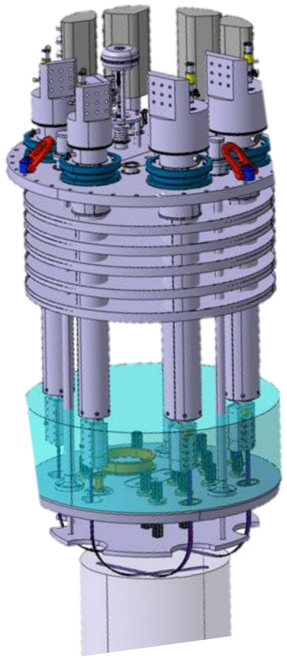
WATER COOLING AND CURRENT LEADS

DESIGN DRIVEN BY Optimization in operation :

- Flexible cables
- Current lead operation homogenized with the rest of the test stand and minimized flow



CONVENTIONAL GAS COOLED Cu LEADS:
length: 1.7 -2.1 m
top flange d:260-280 mm
Connection : SC cable

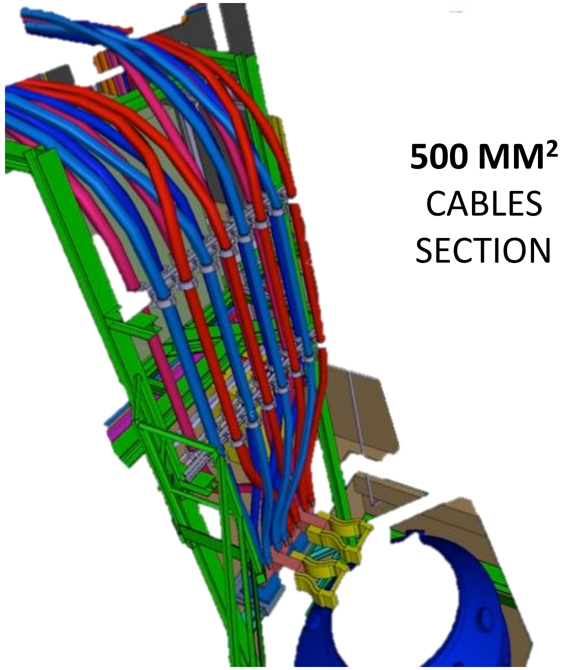


He vapor flow @ 4.2 K:

- 20 kA lead: 0.87 g/s
- 30 kA lead: 1.82 g/s
- 15 kA lead: 0.88 g/s

Water Cooled Cables
SPECIFIED PARAMETERS

Current:
5 kA DC
Max in. temperature: 28°C.
Pressure in operation: 16 bar.
Maximum delta T: 10°C.
Water speed : <2.5 ms^{-1}
Max. temperature : 50°C.
Operating Voltage: 1 kV
(if fault to ground)



500 MM²
CABLES
SECTION

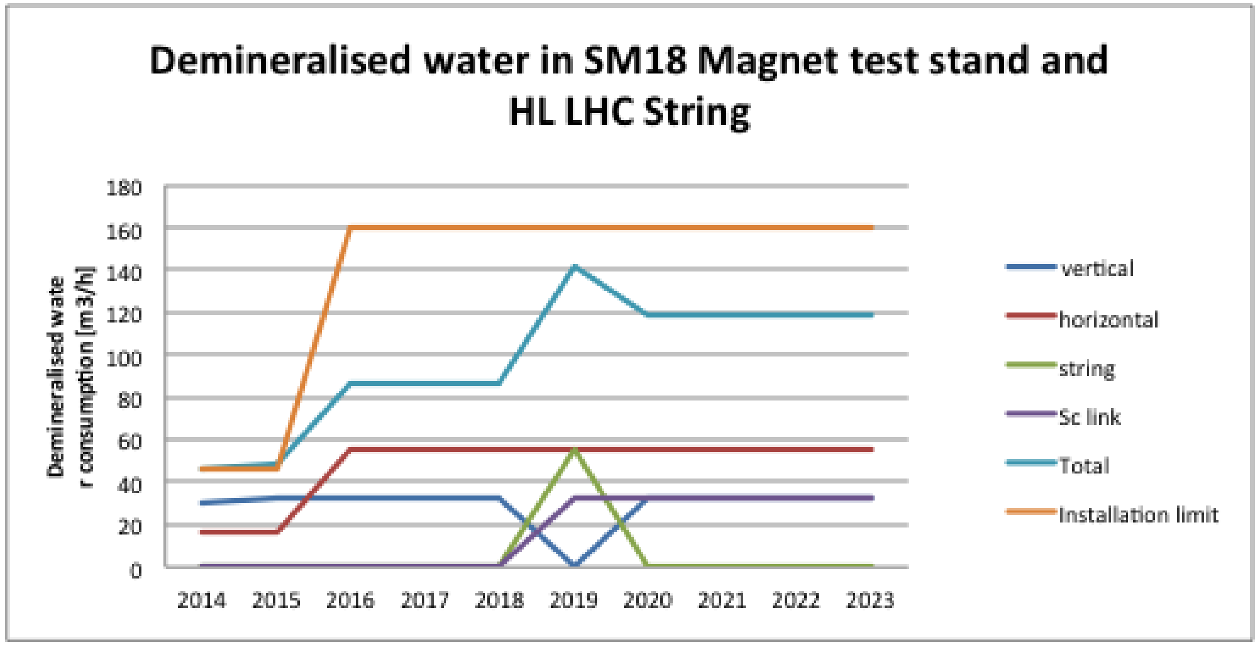
Current Leads
SPECIFIED PARAMETERS

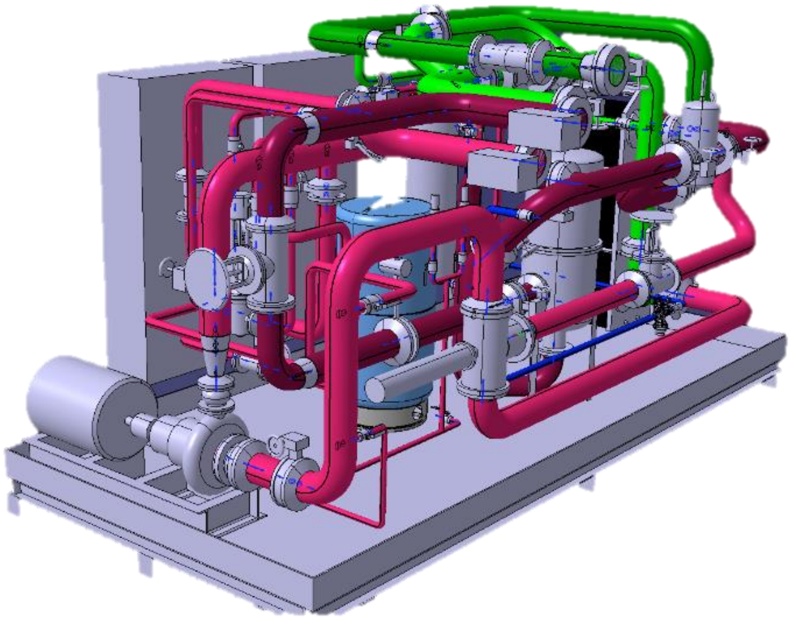
Main circuit: 20 kA/30 kA
Secondary circuit: 15 kA
Design pressure : 5 bara
Max. Voltage to GRD: 3.5 kV

TEST STANDS : DEMINERALIZED WATER

a need estimated to 1.7 MW (142 m^3/h).

….demineralised water station with a thermal capacity of 800 kW limiting the operation to two test stands





CLUSTER D DAQ SYSTEM

LHC Project Do
CERN Div./Group or Supplier
TE/MS
EDMS Docu
1518

High Luminosity LHC

NI PXIe-6358

Simultaneous X Series Data Acquisition

Example of HF system

Zoom/Alternate Images

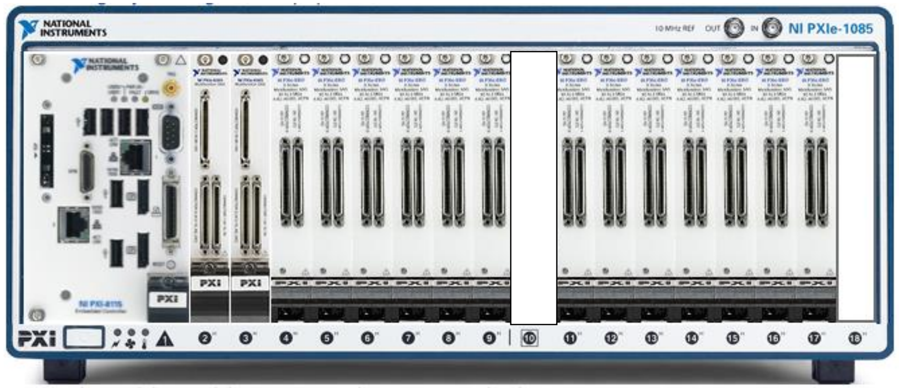
Starting at ~~$ 6,086~~ $ 5,355.68 (view pricing options)

View Data Sheet

- 16 simultaneous analog inputs at 1.25 MS/s/ch with 16-bit resolution; 20 MS/s total AI throughput
- Four analog outputs, 3.33 MS/s, 16-bit resolution, ±10 V
- 48 digital I/O lines (32 hardware-timed up to 10 MHz)
- Four 32-bit counter/timers for PWM, encoder, frequency, event counting, and more
- Analog and digital triggering and advanced timing with NI-STC3 technology
- Support for Windows 7/Vista/XP/2000

DAQ
SPECIFIED PARAMETERS

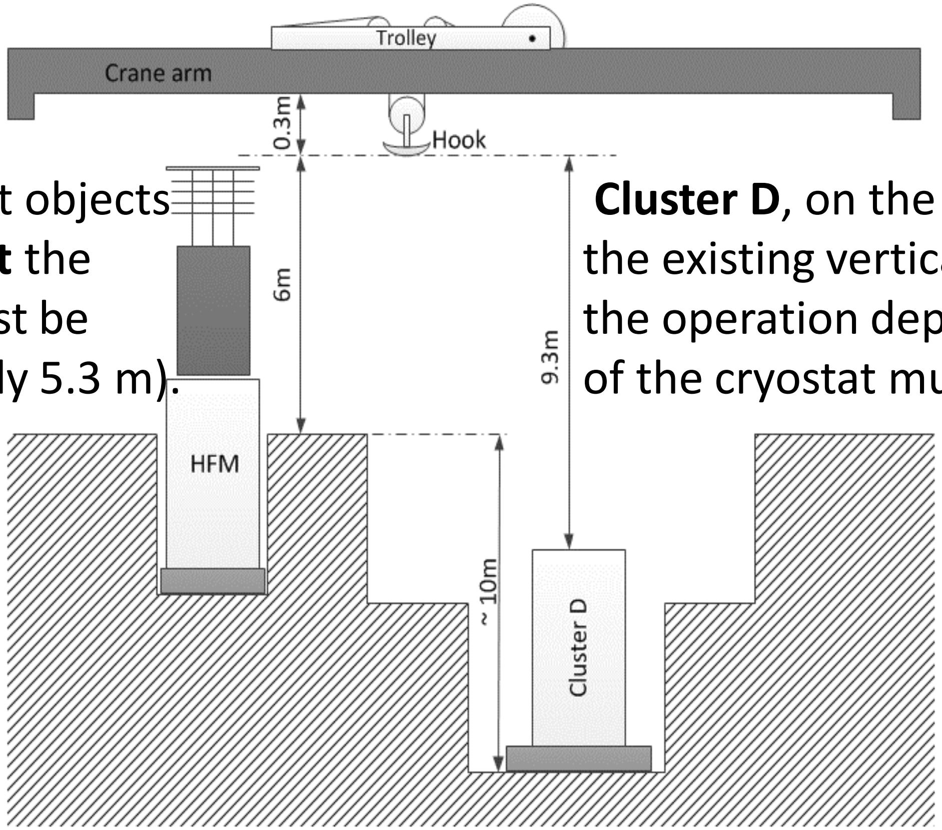
Input channels:	+/- 10 V
Nr of HF channels:	200 differential
HF frequency:	200 kHz
HF,MF,LF resolution:	16 bit resolution
HF,MF,LF accuracy:	1mV
MF frequency:	50 kHz
Nr of LF channels: 144	
LF frequency:	1kHz
Timing:	GMT
synchronization	



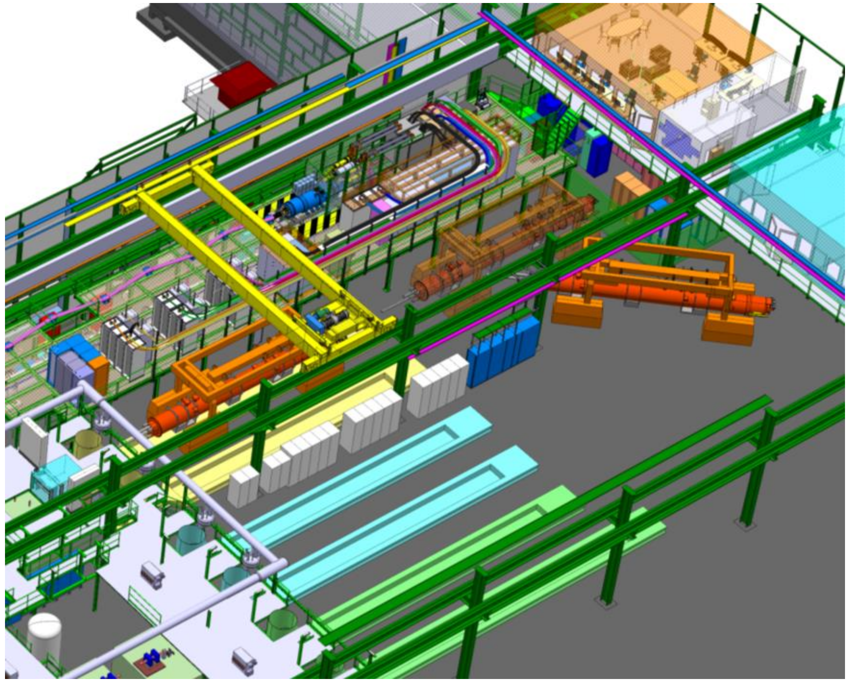
Data Analysis with DIADEM

TEST STAND : HADLING

To enable insertion of test objects into the **HFM cryostat** the operating height, must be increased to **6 m** (presently 5.3 m).



Cluster D, on the other hand, will be deeper than the existing vertical facilities. To handle the inserts the operation depth between the hook and the top of the cryostat must be increased to **9.3 m**.



Heavy and long magnet needs adequate handling systems!

Summary

YOU CAN ONLY MAKE AS WELL AS YOU CAN MEASURE

BY. JOSEPH WITHWORTH