Progress in the Construction of the 43 T Hybrid Magnet at LNCMI-Grenoble (Equipex LaSUP)

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MT25

25th International Conference on Magnet Technology

RAI - Amsterdam
August 27 - September 1, 2017

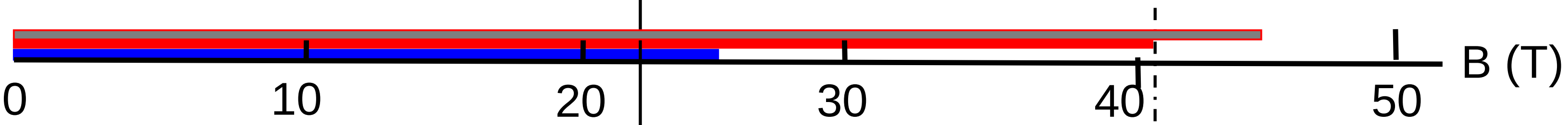
August 28th, 2017

Outline

- Introduction & context
- The Grenoble hybrid magnet
  - Overview
  - Main issues
- Focus on the superconducting outsert magnet
  - The Rutherford cable on conduit conductor (RCOCC)
  - Magnet control & protection systems
  - Coil design & manufacturing
  - Cryostat and supporting structure
  - Cryogenics
- Summary

How to generate high static magnetic fields today?

Commercial laboratory equipment ← → **Specialized facilities**



Superconducting magnets

B_{max} = 23,8 T, 52 mm dia. (Bruker) close to LTS limitation

B_{max} = 24.6 T, 52 mm dia. (Sendai) LTS/HTS(Bi-2223)

B_{max} = 26.4 T, 35 mm dia. (SuNAM) HTS(YBCO)

A breakthrough can be expected with HTS in the coming decade, but still a lot of R&D ahead…

Copper-based & water-cooled resistive magnets
24-32 MW

B_{max} = 38.52 T
32 mm dia.(CHMFL)

B_{max} = 41.4 T
32 mm dia.(NHMFL)

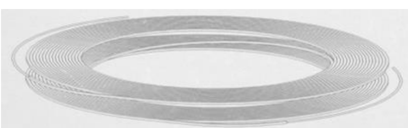
Mostly power & cooling limitations, which can be overcome

Hybrid magnet
superconducting outsert
+ resistive insert

B_{max} = 45.2 T (NHMFL)

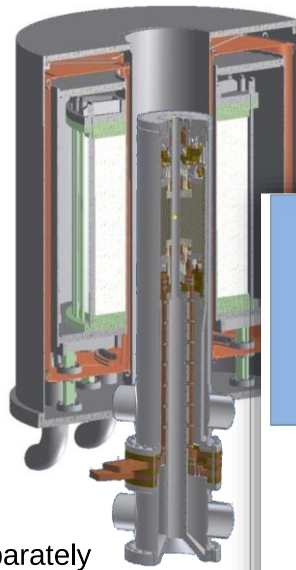
Low Field Magnets *High Field Magnets* *Very High Field Magnets*

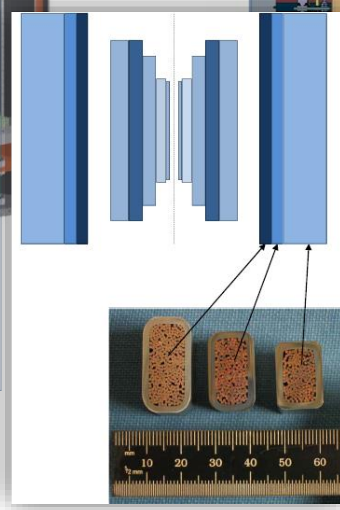
New Hybrid Magnets Worldwide

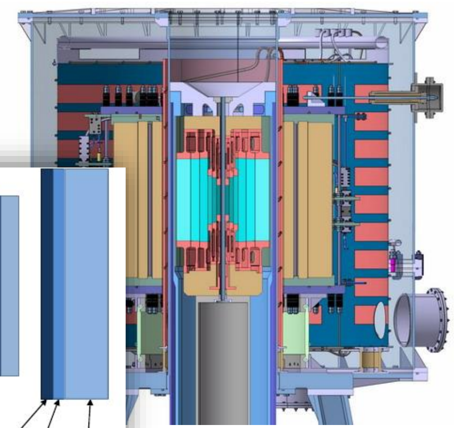


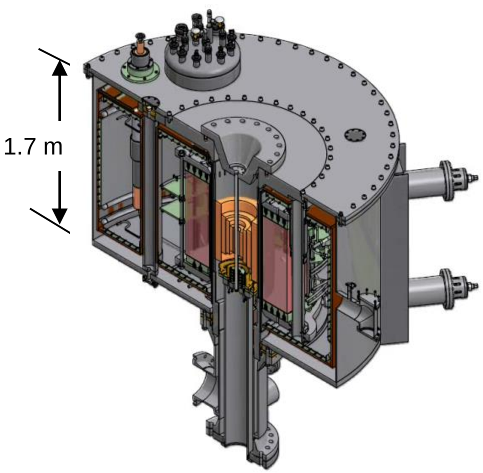
37 DP vacuum impregnated separately

13 x 18 mm^2









Cooling by forced flow supercritical He
~ 11g/s @ 5 bars

Grenoble, France	Nijmegen, Netherlands	Hefei, China	Tallahassee, FL
8.5 (9) + 34.5 (36+) = 43 (45+) T	12 + 33 = 45 T	10 (11) + 30 (33) = 40 (44) T	13 + 23 = 36 T, ppm homogeneity
34 (32-30 ?) mm, 24 (30) MW	32 mm, 24 MW	32 mm, 25.4 MW	40 mm, 14 MW
RCOCC Nb-Ti, 1.8 K	CICC Nb-Sn, 4.2 K	CICC Nb-Sn, 4.2 K	CICC Nb-Sn, 4.2 K
7.1 kA, 1100/1826 mm dia.	20 kA, 720/1286 mm dia.	13.4 kA, 680/1650 mm dia.	20 kA series connected
2018	2018	**40 T Nov. 13, 2016**	**36 T Nov. 8, 2016**

The Grenoble Hybrid Magnet

PROJET LaSUP
Equipex

MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE
COMMISSARIAT GÉNÉRAL À L'INVESTISSEMENT

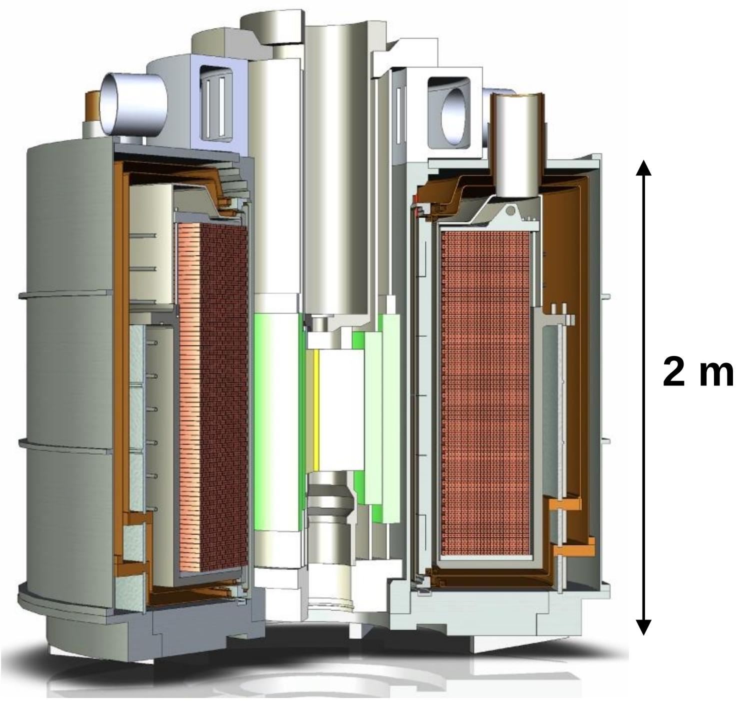
Modular Plateform for the production of High Magnetic Field

- 43 T / 34 mm hybrid magnet 24 MW
  - ► 8.5 + 9 + 25.5 T **/** sc. + poly-Bitter + poly-helix
- 38 T / 34 mm hybrid magnet 12 MW
  - ► Energy saving !
- 27 T / 170 mm hybrid magnet 18 MW
- 17 T / 375 mm hybrid magnet 12 MW
- 8.5 T / 800 mm sc. magnet alone

High Flux Magnets

Under Study

- Upgrade phase of resistive inserts with 9 T produced by the superconducting outsert
  43 T / 34 mm ⟶ 45+ T / 34 mm
- Modular field gradient platform for levitation
- 60 T / 300 ms pulsed field



Hydraulics : 300 l/s
Total stored Energy : 108 MJ ~ 23 kg de TNT

55 t in total incl. 22 t @ 1.8 K

P. Pugnat *et al.*, *IEEE Trans. Appl. Supercond.* **26**, 4302405 (2016)

Resistive Inserts

Specificity of LNCMI

Combination of Bitter & Polyhelix coils

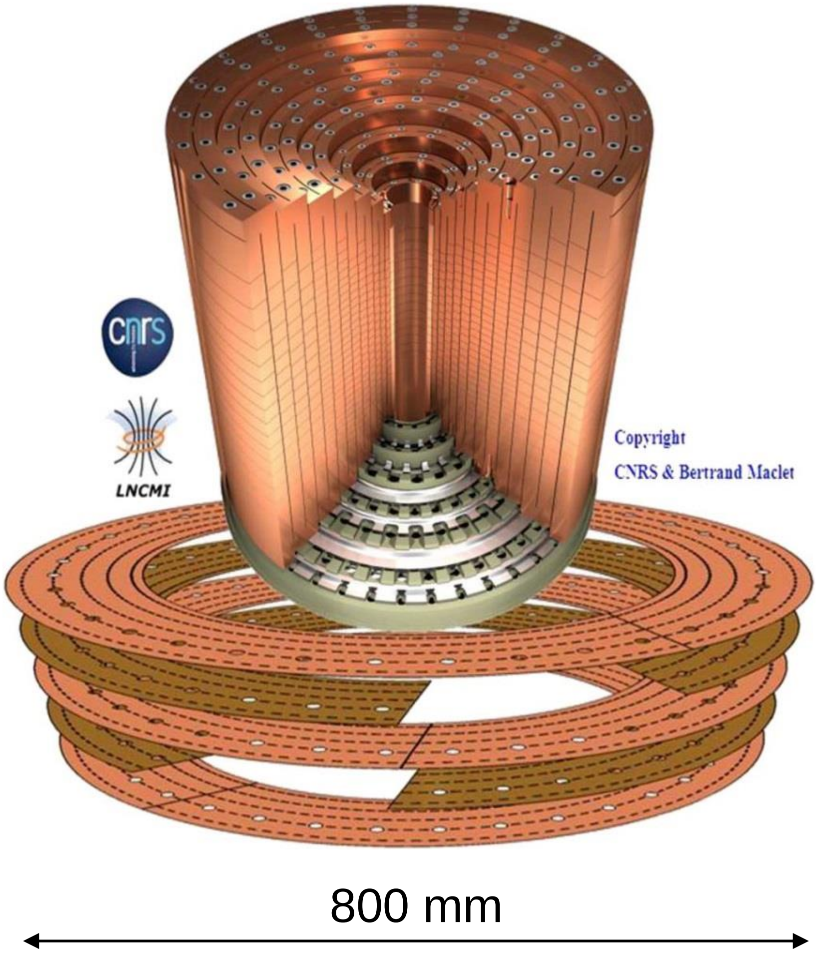
- *Today: 36.5 T in 34 mm dia.*
- *Target hybrid: 34.5 T in 34 mm dia.* in 8.5 T background field

► A challenge *also* for the resistive inserts

For the Hybrid

- Poly-*Bitter coils* already developped and tested : 9 T (9.2 T max) with $\Phi = 800$ mm disks and 12 MW
- *Poly-helix coils* : 25.5 T with 12 MW (under developments, production planned for 2018)

Today, **12 + 12 MW** inserts powered and cooled independently



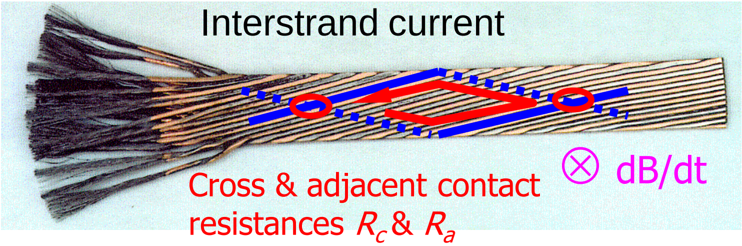
F. Debray

Main Issue for Hybrid Magnets

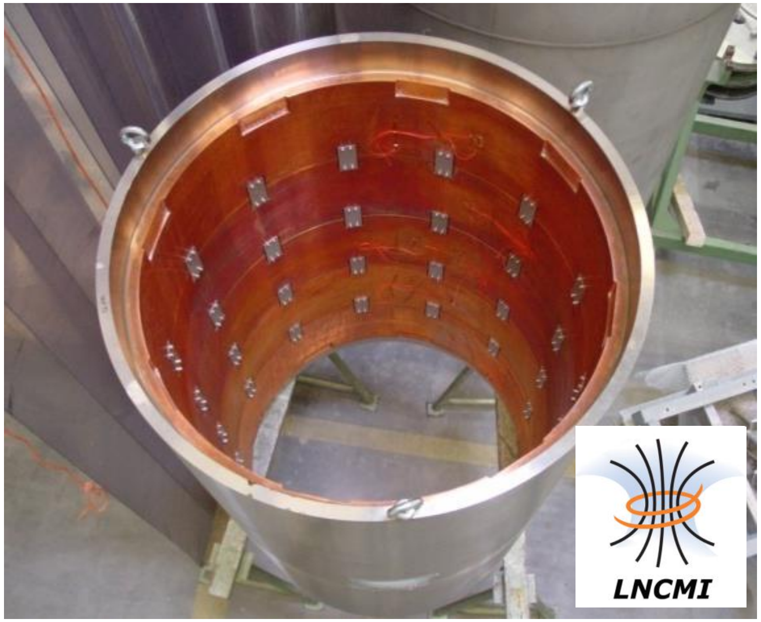
The interactions between resistive and superconducting coils

- Cu re-inforced stainless steel shield at 30 K to reduce dB/dt in case of trips of resistive inserts 2.3 T/s → 0.5 T/s

- Further reduction of AC Losses & stability of the superconducting conductor / trips of resistive inserts
  - . Hard-draw Cu-$Ag_{0.05\%}$ stabilizer (RRR ≤ 70)
  - . R_c > 100 $\mu\Omega \Rightarrow$ SS core, $R_a \approx$ 0.3-0.6 $\mu\Omega$
  - . $\phi_{filaments} \leq 15$ μm with $l_p = 15$ mm



- EMC : SNR for quench detection & spurious signals coming from insert trips



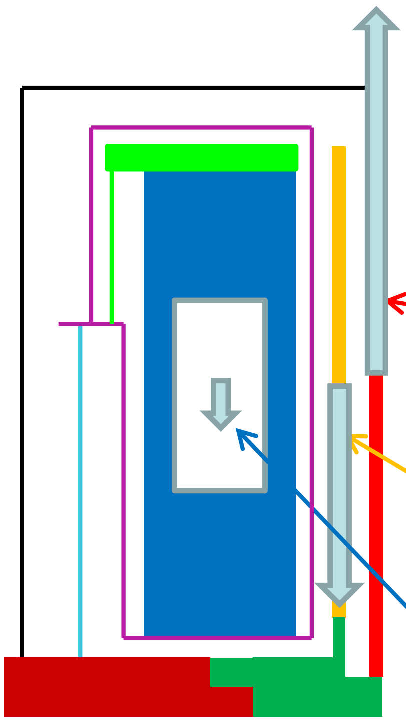
- Transitory forces during the burnout or short-circuit of ½-Bitter inserts
  - ▸ Worst case scenario:

    $F_{z,max} \approx$ 5.1 MN bore tube/base plate

    $F_{z,max} \approx$ 4.5 MN on the Cu-shield/base plate

    $\Rightarrow$ Severe constraints on supporting structures

Magnetic Forces just after a short-circuit of 1/2-Bitter Magnets, *i.e.* the worst case (G. Aubert, Ph. Fazilleau and Ch. Trophime)

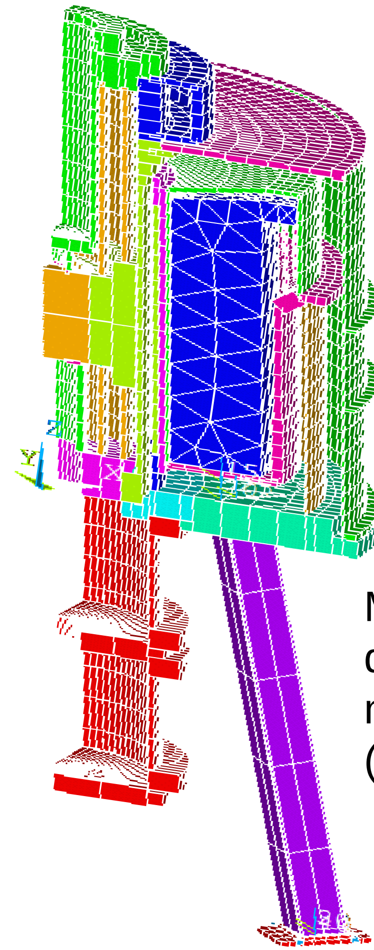


Modelling from L,R electrical circuits

Maximum axial forces on the bore tube : 5.2 MN at t_0

Maximum axial forces on the eddy-current shield : 3.72 MN at $t_0 + 0.1$ s

Maximum axial forces on the SC coil : 0.5 MN



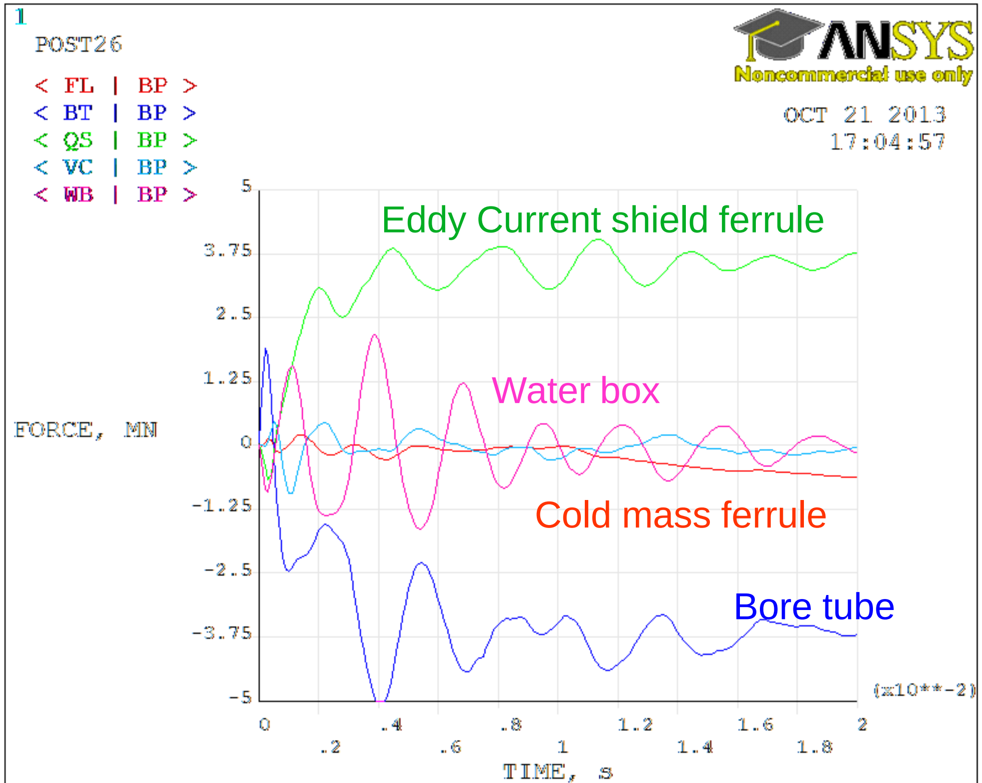
Mesching for dynamical modelling (P. Manil)

Hyp. 1/ Configuration 8.5 T / 24 MW

2/ Instantaneous effect (**overly conservative,** *cf.* H.-J. Schneider-Muntau *Thu-Mo-Or33*)

3/ Lateral forces depend on the part centring. Their maxima are estimated to 10 tons.

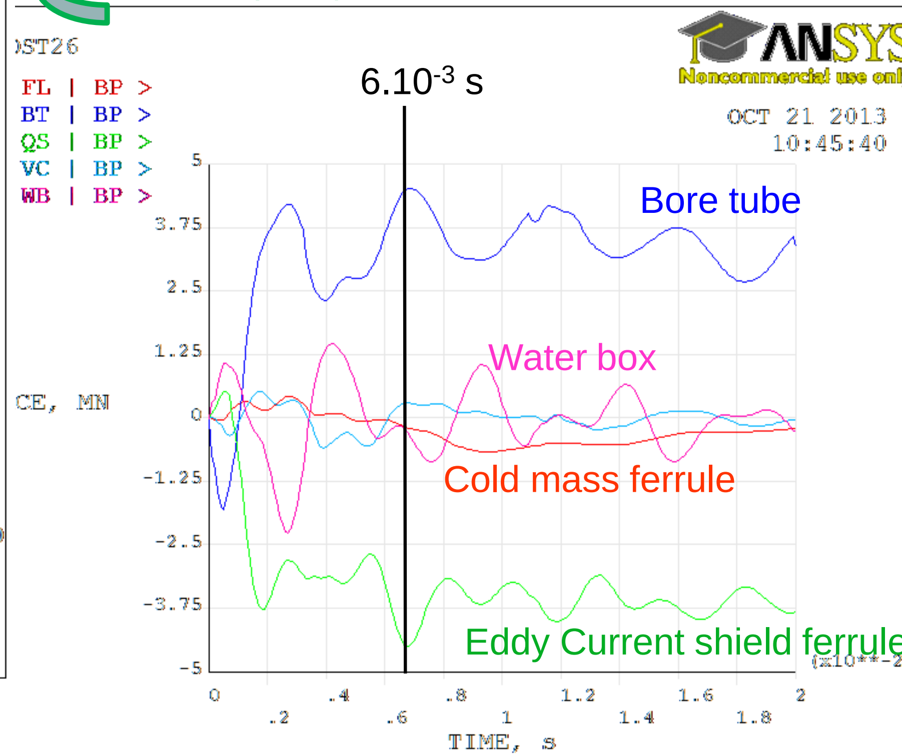
Dynamical Analysis (P. Manil)



Z-forces vs time at the interface (case « up »)

Extreme force at - 5.1 MN (bore tube to base plate)

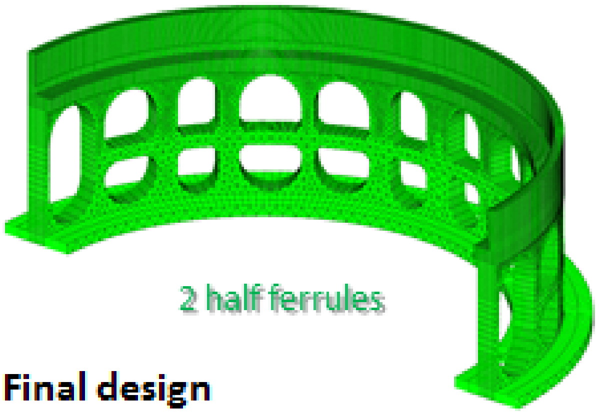
Extreme force - 4,5 MN (eddy-current shield to base plate)



Z-forces vs time at the interface (case « down »)

P. Manil *et al.*, *IEEE Trans. on Appl. Supercond.* **24,** 4300306 (2014)

Support ferrule of the eddy-current shield



Final design

Courtesy R. Berthier CEA/IRFU

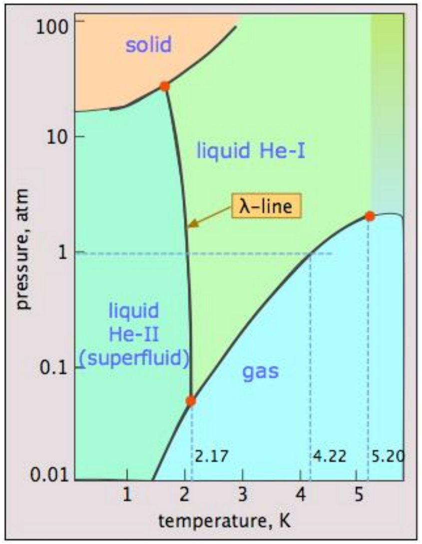
CEA Patent

Part / Load direction	MAX. VON MISES / TRESCA STRESS	Yield strength @ 30 K	allowable stress @ 30 K	Exceptional conditions @ 30 K
		Re	0.67 x Re	1.3 x 0.67 x Re
Supporting ferrule TA6V		920 MPa	613 MPa	797 MPa
Compression	313 MPa			
Traction	601 MPa			
ECS outer cylinder 316LN		880 MPa	587 MPa	763 MPa
Traction	677 MPa			

ECS supporting ferrule LOADING		
Forces	Upwards	4.5 MN (dynamical)
	Downwards	4.05 MN (dynamical)
	Horizontally	0.1 MN (magnetic centring)
Thermal conductivity	77 K	406 W
	30 K	37.2 W

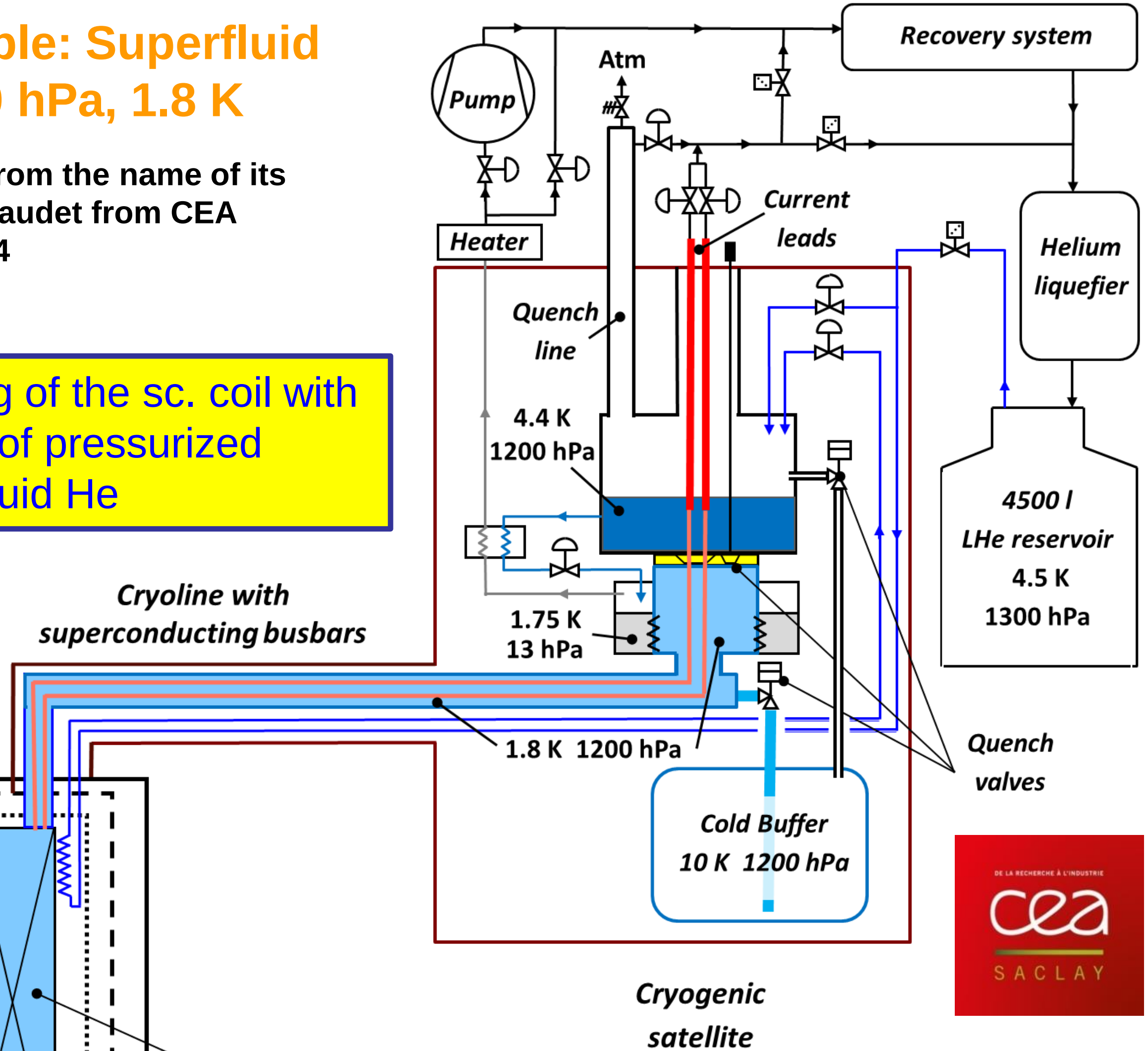
RESISTANCE TO BUCKLING	Load multipliyng factor		Maximum stress
	Elastical Euler buckling	Plastic field collapsing	
Non-buckling criteria	> 20	> 7	$< \frac{Re}{2} = 460$ MPa
Calculation results	24,5	8.3	345 MPa

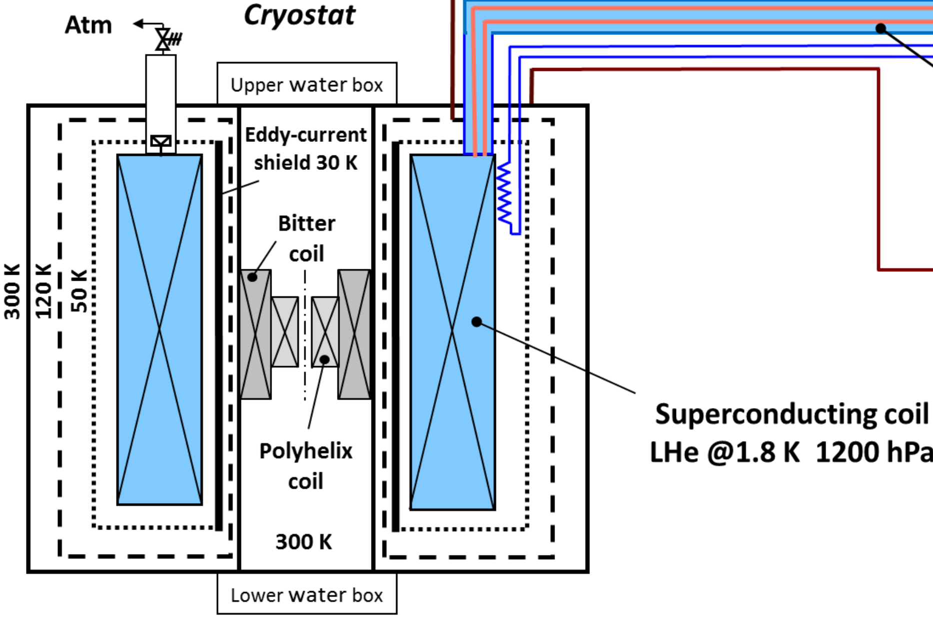
The cryogenic system principle: Superfluid pressurized LHe bath at 1200 hPa, 1.8 K



Claudet bath from the name of its inventor, G. Claudet from CEA Grenoble, 1974

Cooling of the sc. coil with 1100 l of pressurized superfluid He

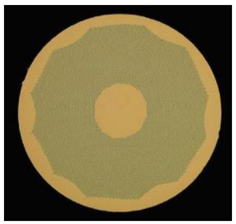


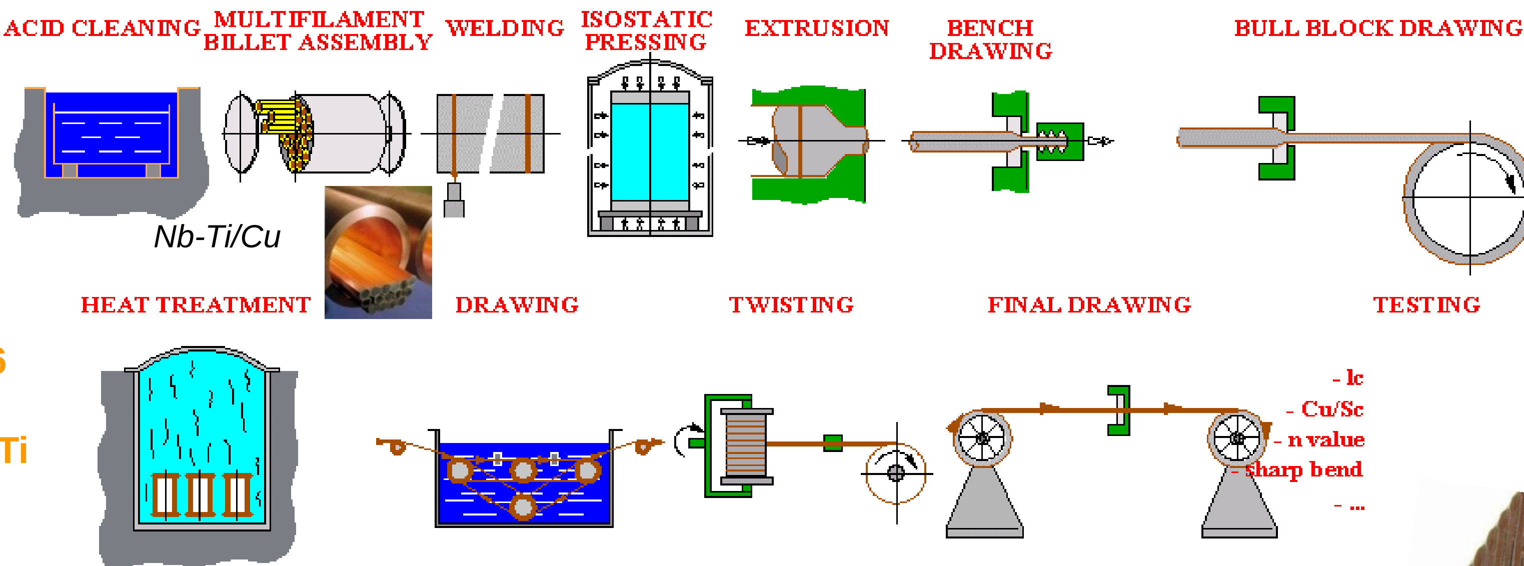


L. Ronayette, B. Hervieu, *et al.* Proceedings of the 12th International Institute of Refrigeration Conference (Cryogenics 2012) pp. 65-72

Production of the Rutherford cable

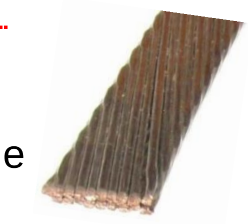
Assembly & transformation of a multifilamentary billet, not less than 75 steps…





1 strand Ø 1.6 mm 6264 filaments Nb-Ti Ø 14 µm

Cabling of the 19 strands with a SS core & thourough control with a cable measuring machine

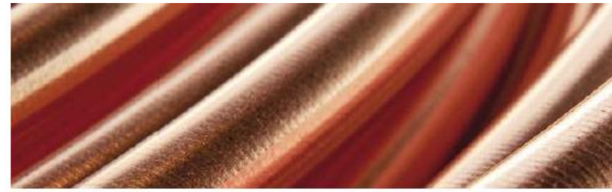


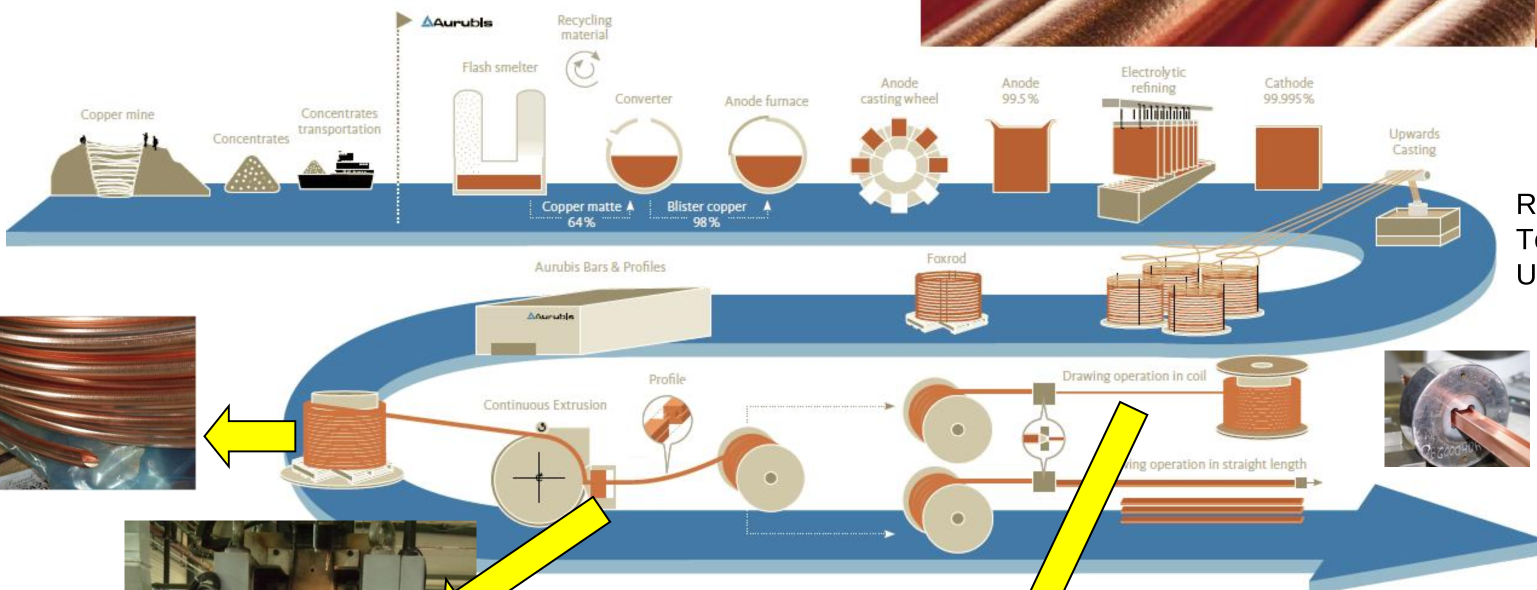
13 km
3,5 tons
produced & delivered
end 2012

Production of the Cu-Ag Hollow profile

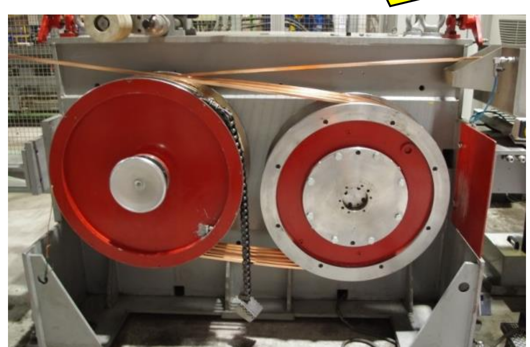
Aurubis

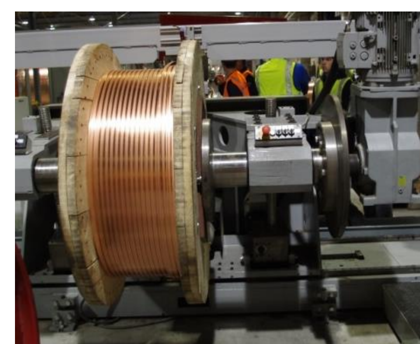
The Process at Aurubis for transforming
copper concentrate into semi-finished copper products



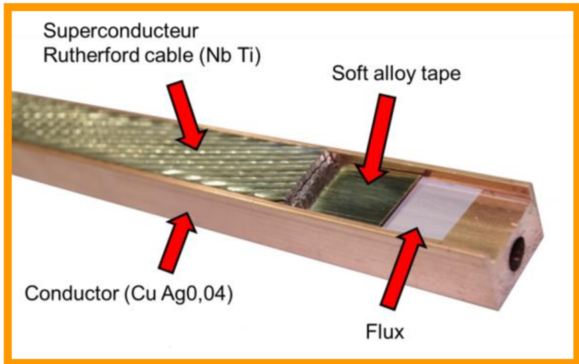


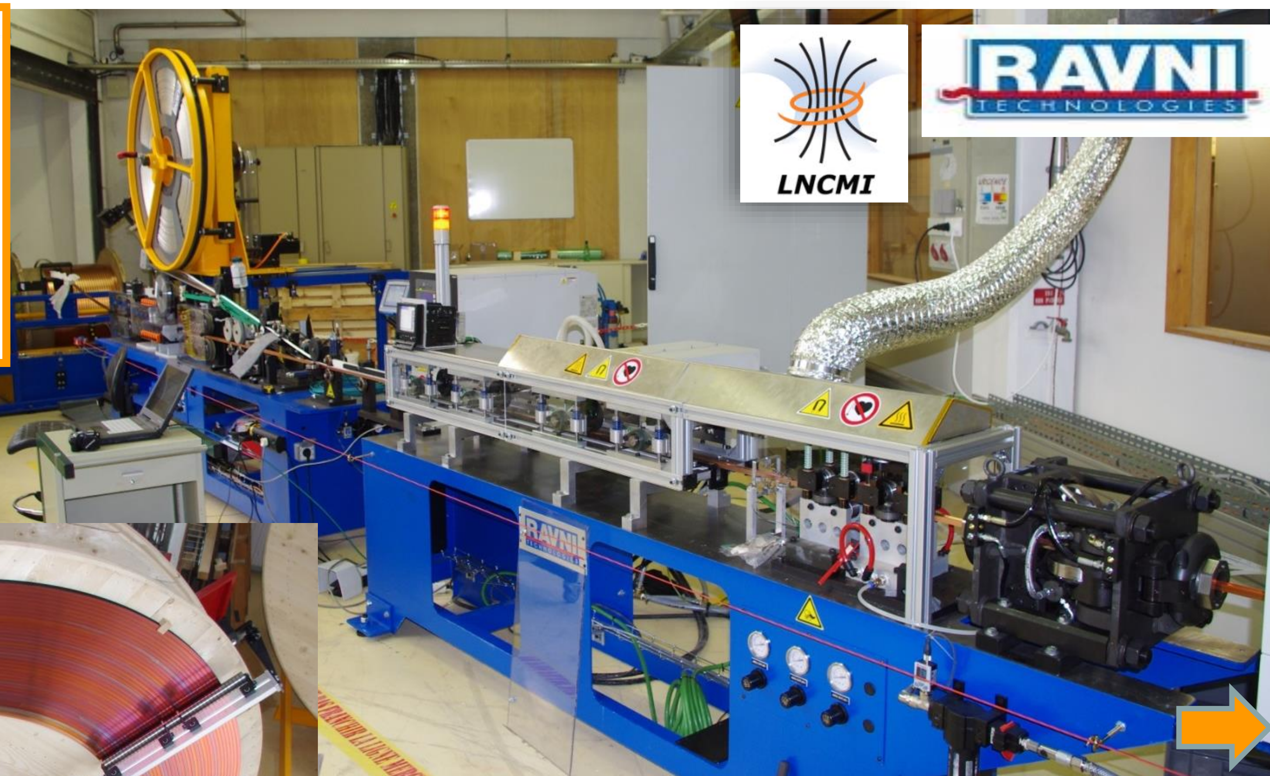
$R_{p0.2}(300\ K) \geq 240$ MPa
Tolerences +/- 0.08 mm
Unit length 325 m



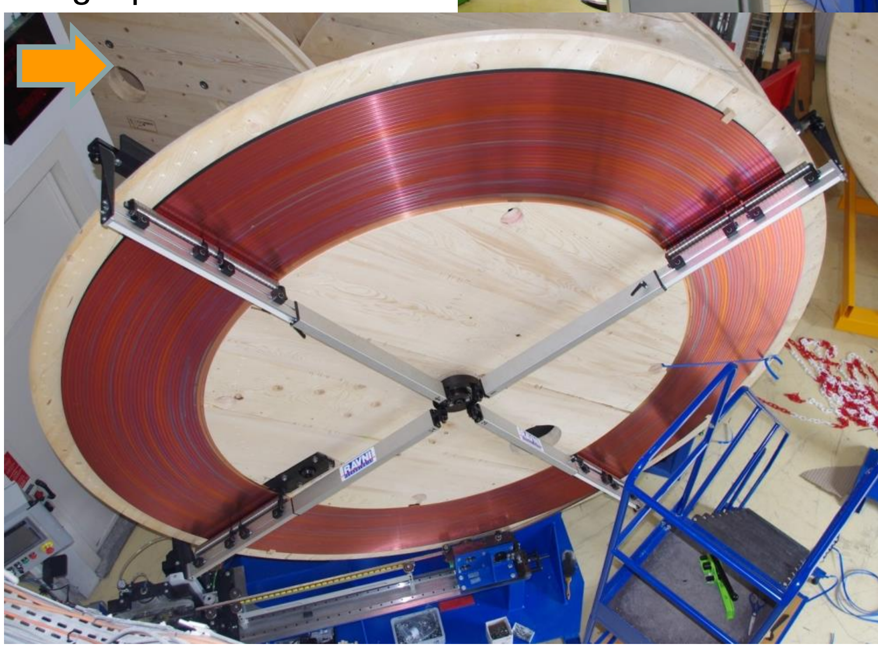


Industrial production line developed, built & installed at LNCMI





Crimping, soft-soldering, calibration & winding in single pancakes

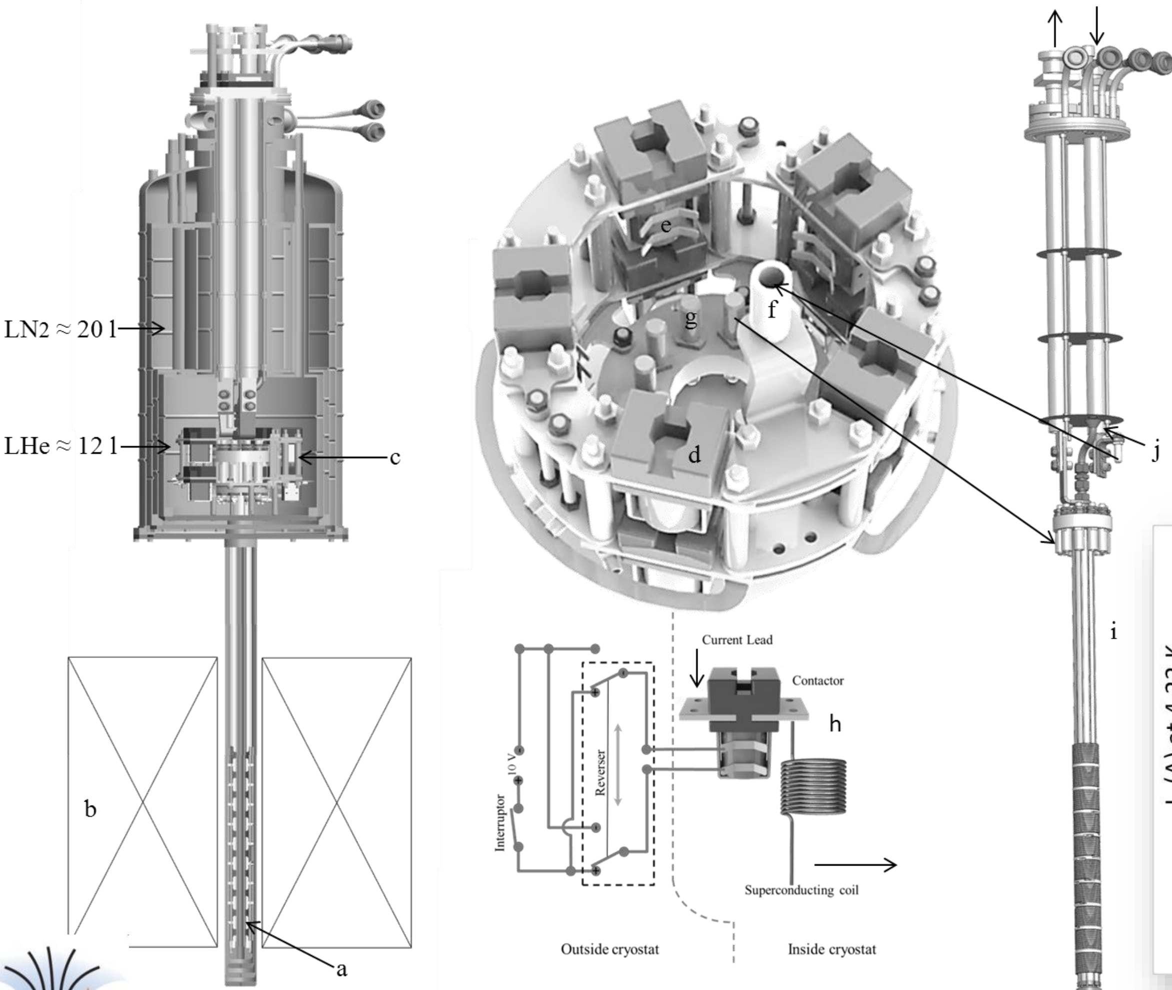


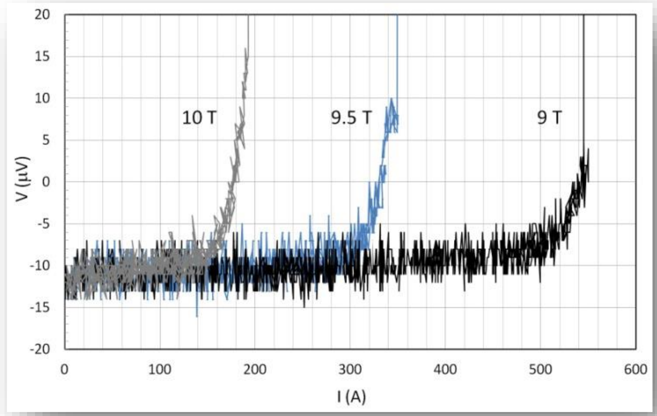
Innovative developments have been achieved based on induction heating to strictly control R_a

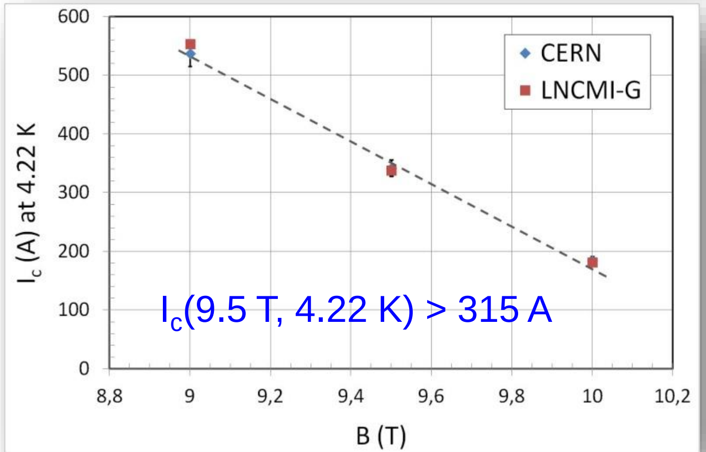
Optimum with $Sn_{61.5}Pb_{37}Sb_{1.5}$ ribbons of 0.11 mm thick & 14 mm width

P. Pugnat, R. Pfister *et al., IEEE Trans. Appl. Supercond.* **26**, 4302405 (2016)

Development of a cryogenic test station for I_c & RRR measurements





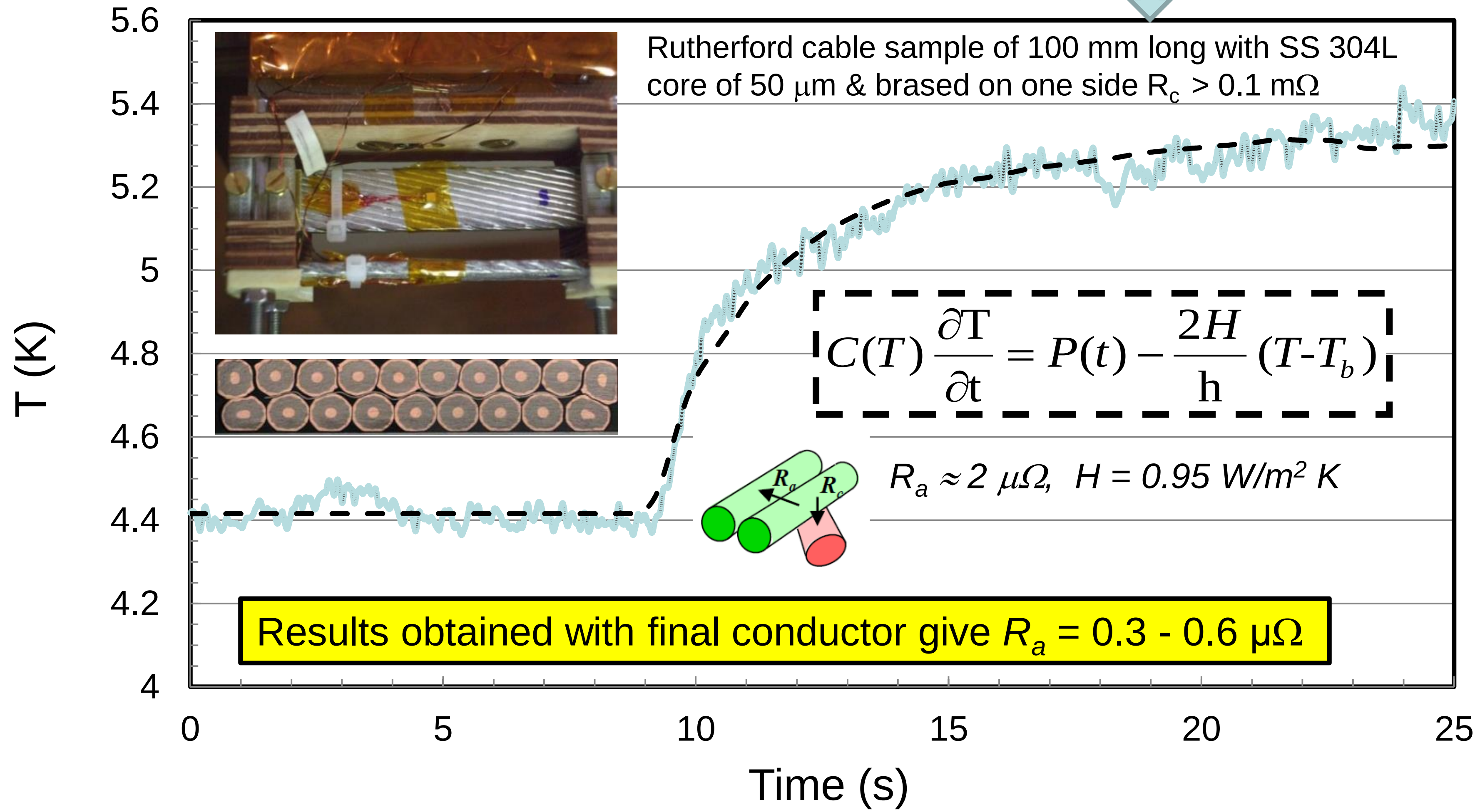


R. Pfister, P. Pugnat et al.,
IEEE Trans. Appl. Super. **22** (2012) 9500504

RCOCC I_c within specification, no degradation measured after thermal cycles simulating the insertion & VPI processes

R_a extracted from thermometry in

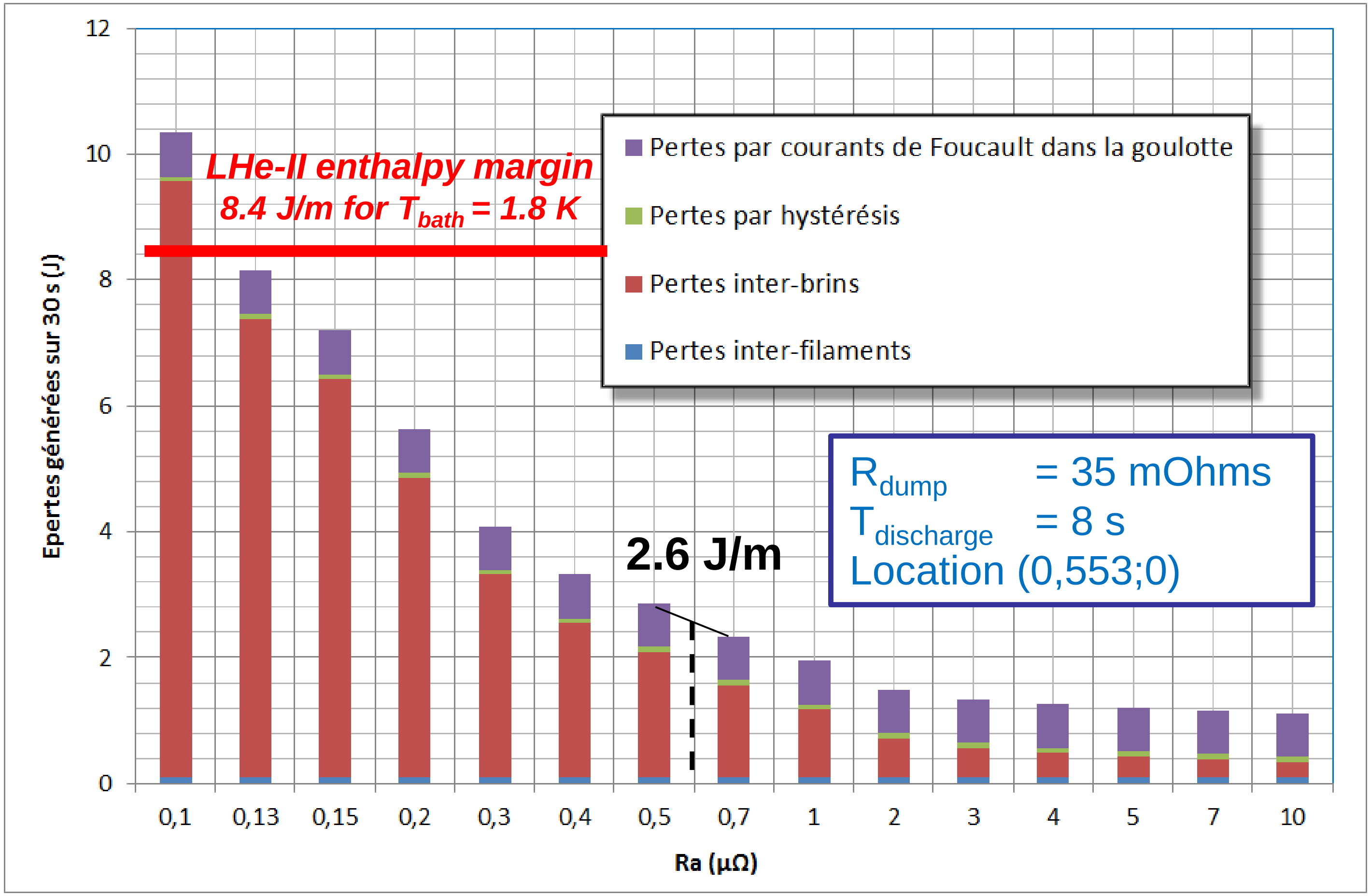
- Liquid He with $B^{-1}dB/dt \sim 0.01\text{-}1$ Hz
- Gaseous He with $dB/dt = 0.187$ T/s



RCOCC Production

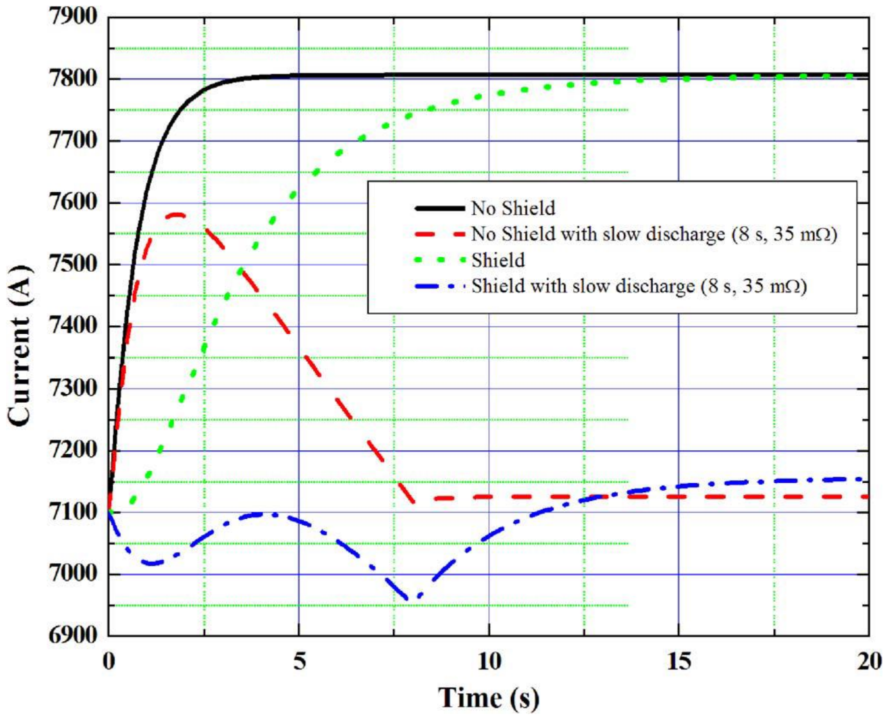
- 37 + 7 full lengths of 265 m RCOCC winded in single pancakes of 2 m internal dia. produced and delivered to Babcock Noell GmbH
  - 1 rejected & used for testing the winding line & VPI process
  - 25 minor non-conformities including 14 concerning the process
- Characteristics of the RCOCC produced
  - Dimensions 12.96 +/- 0.04 mm & 17.92 +/- 0.05 mm
  - Stabilizer Cu-Ag after thermal cycles
    - $\sigma_{p0.2\%}$ at 300 & 4.2 K = 235 & 290 MPa (FEM results : maximum at 203 MPa)
    - RRR < 70
  - Ultimate shear stress 24-37 MPa at room temperature
  - R_a(effective) ≈ 0.3-0.6 μΩ on straight samples
    - Effect on R_a of the curvature at 550 mm radius, 0.3 → 0.5 μΩ, *i.e.* + 67 %

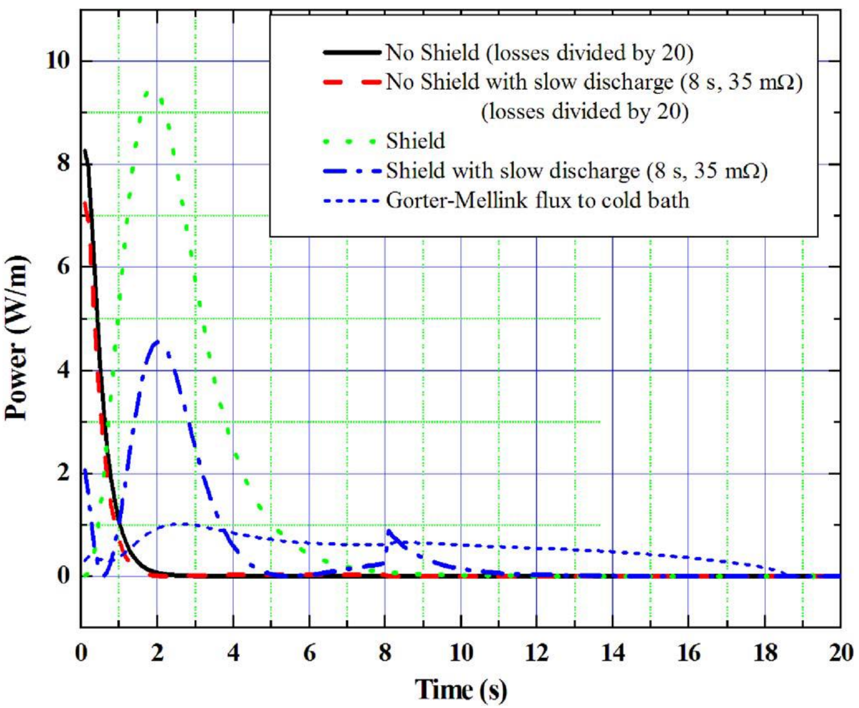
AC losses budget in case of the disruption of resistive magnets versus R_a



To minimize AC losses, the slow discharge is stopped after 8s, which is sufficient to prevent the current increase in the sc

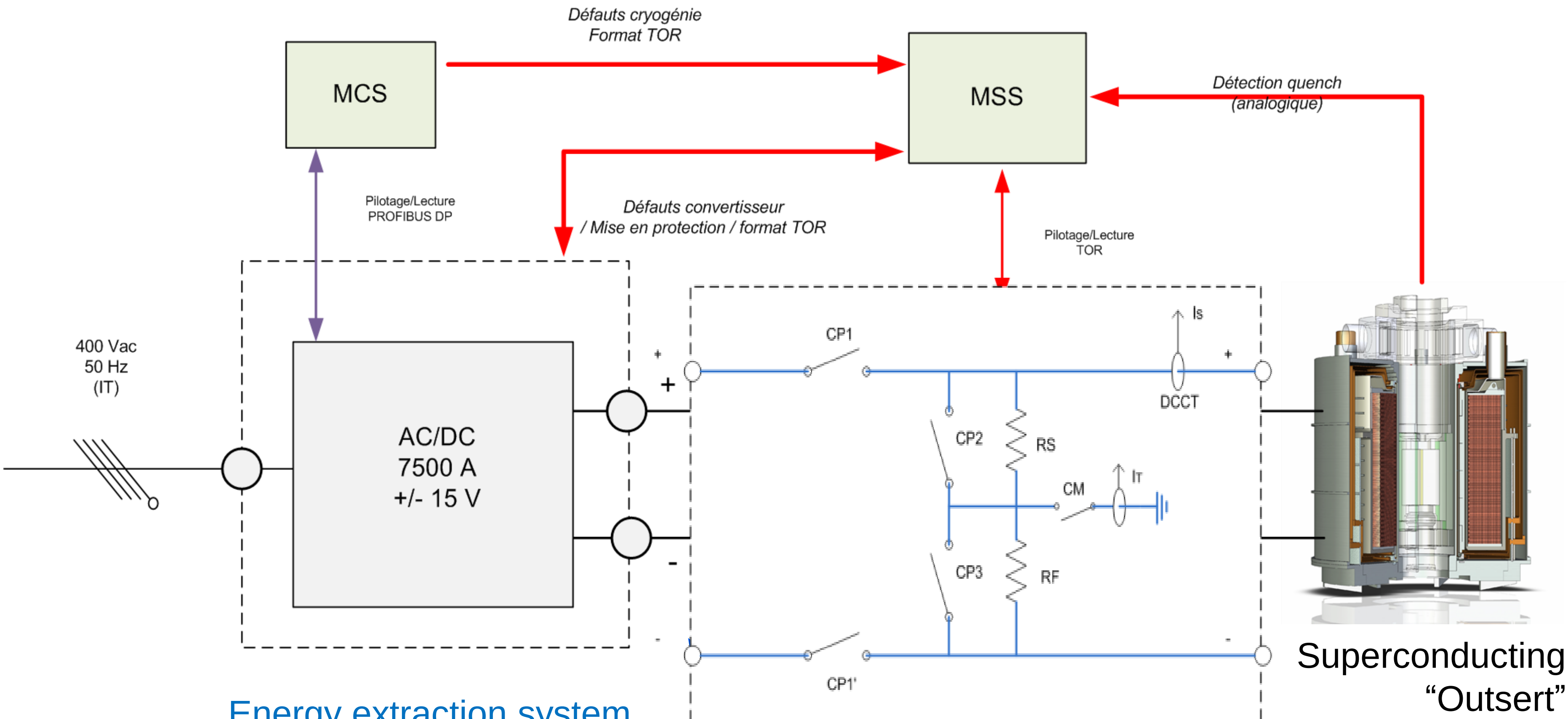
Consequences of an insert trip





P. Fazilleau, G. Aubert, C. Berriaud, B. Hervieu, and P. Pugnat, *IEEE Transactions on Applied Supercond.*26, 4301305 (2016)

Magnet Safety System (MSS) & Magnet Control System (MCS)



Superconducting
"Outsert"

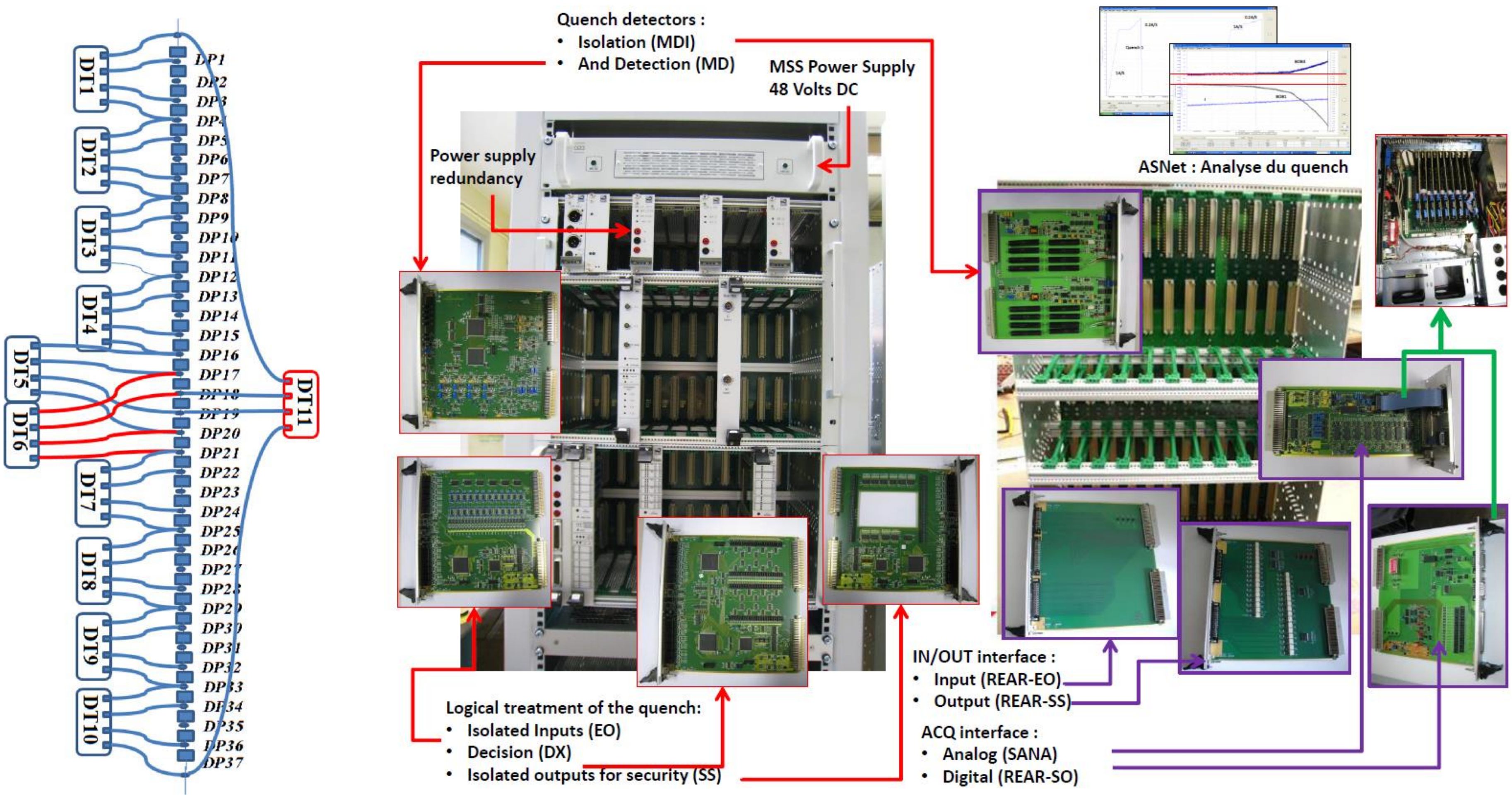
Energy extraction system
with slow (43 s) and fast discharges (86 s)
RS = RF = 35 mΩ, Max. 500 V/ground and 60 K adiab.

I (8.5T/9 T) = 7.1/7.5 kA
Stored Energy = 76/84 MJ
L = 3.03 H

The rules:

- Fast discharge (43 s) to lower MIITs (quench,…)
- Slow discharge (86 s) to limit voltage increase & AC losses (insert trip,…)

Magnet safety system based on voltage compensation method (MSS-I)

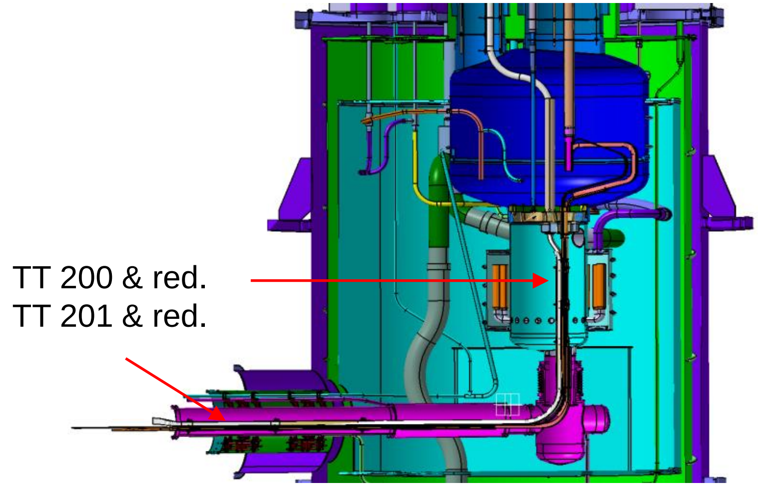


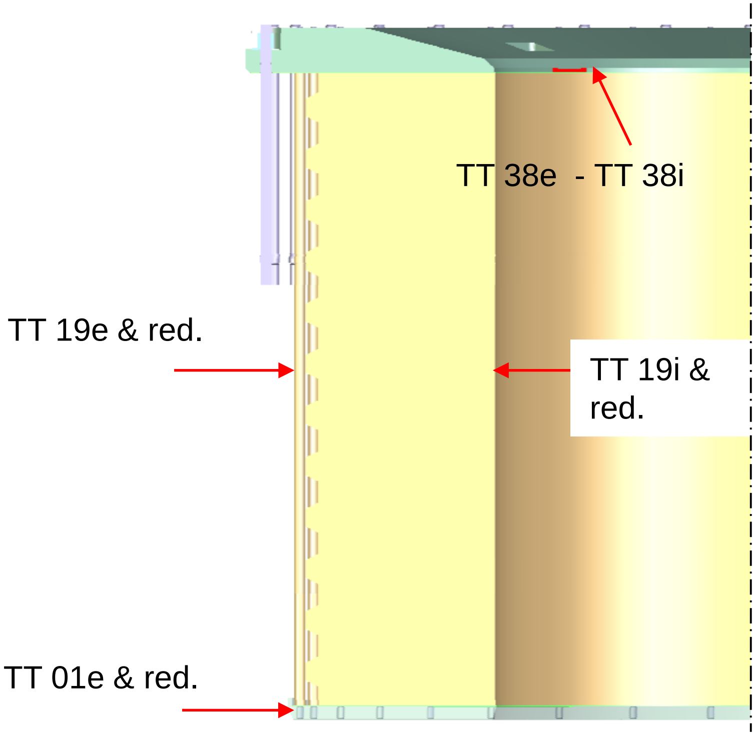
P. Fazilleau

Y. Queinec, F. Molinié

Fully redundant cryogenic magnet safety system (MSS-III)

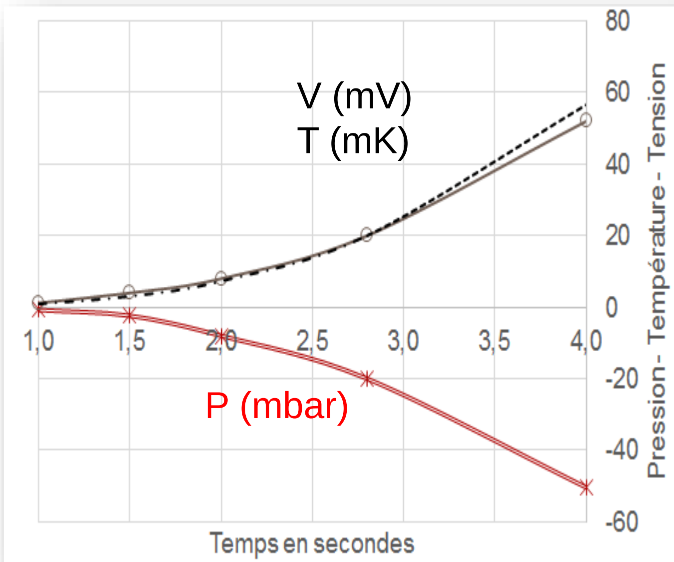
- Use of the 6 cernox temperature sensors on current leads & bus bars near the junctions
  + 3 in the coil to detect any abnormal heating
- Use also the 2 pressure sensors in the satellite
- 4 SQD for bus bars





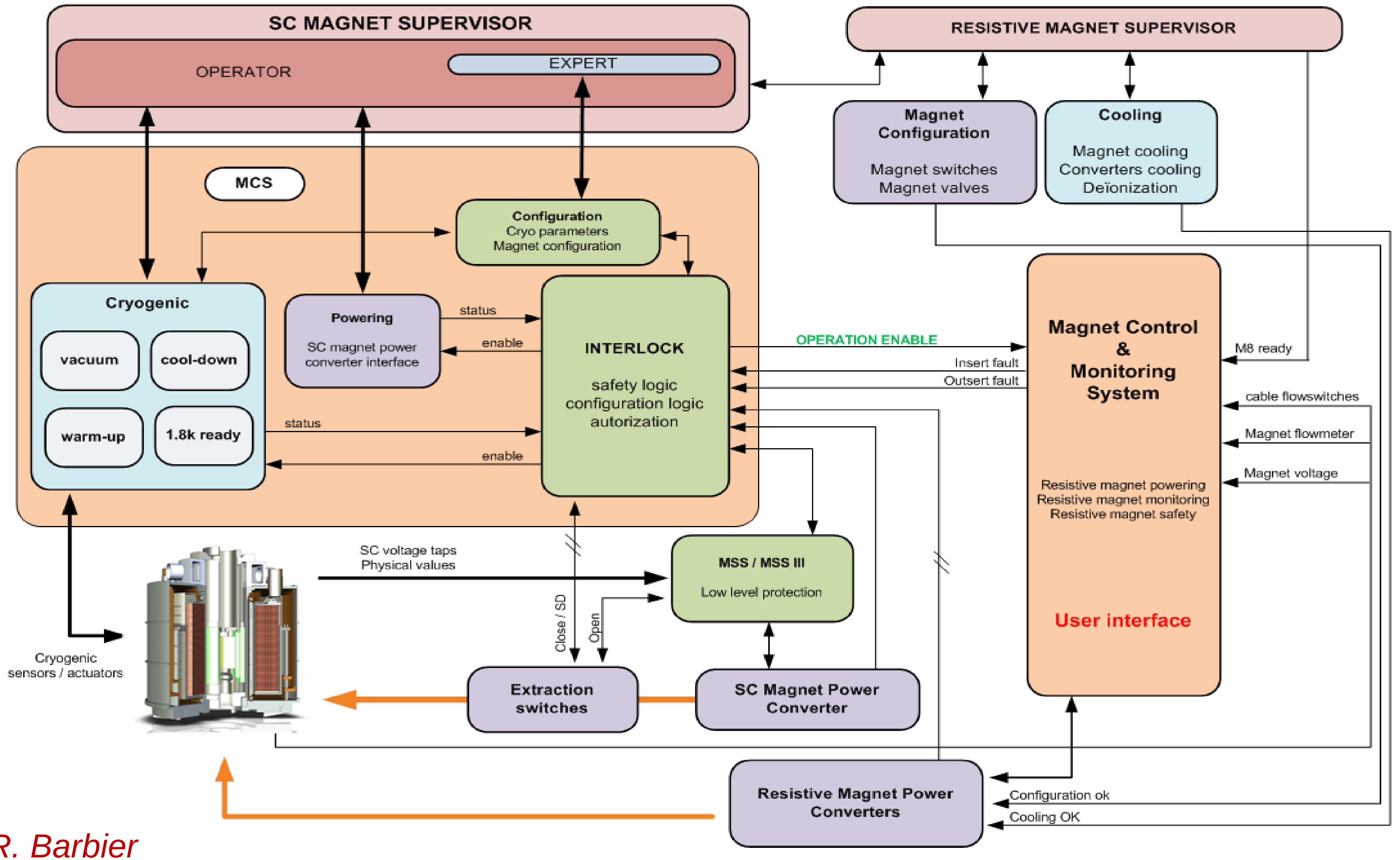
Case of a slow quench

Typical stability of the helium II bath
+/- 2 mK
+/- 5 mbar



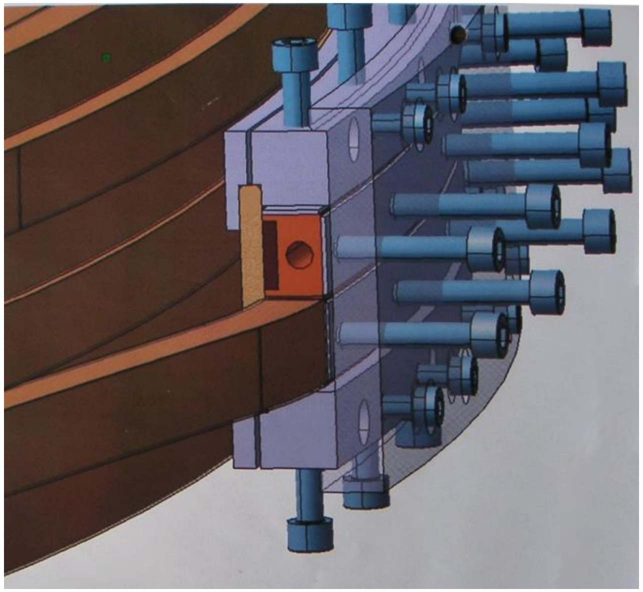
B. Hervieu

Global architecture Overview

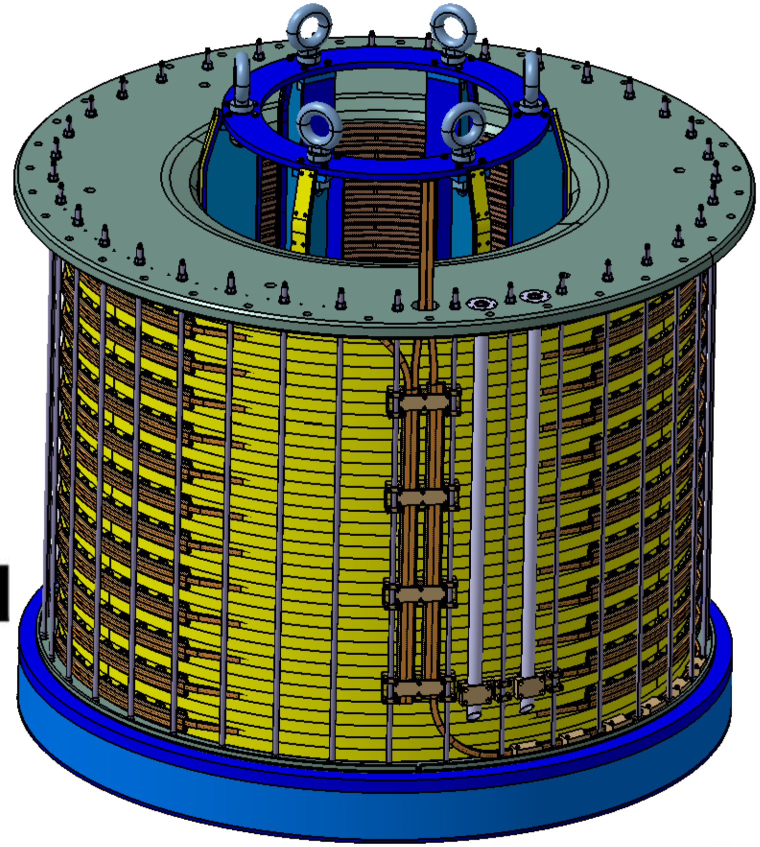


R. Barbier

Coil Winding: Assembly of 37 Double-Pancakes vacuum impregnated separately

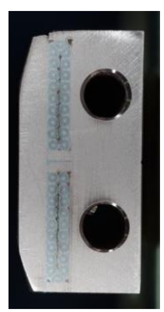


Courtesy
C. Berriaud,
R. Berthier



Specification
700 mm overlap
R (4.2 K, 2 T) < 1 nΩ

Measurements on prototype
R (4.2 K, $B_{self@1\,kA}$) = 0.37 nΩ



Contract signed in January 2016
Delivery in April 2018

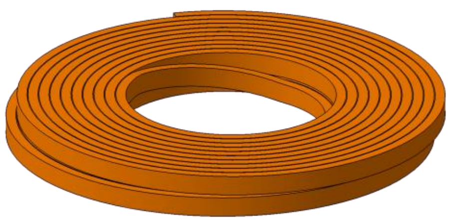
BiLFINGER
Babcock Noell GmbH

Double-pancake winding line

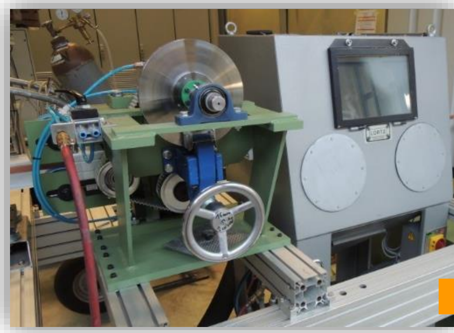
BILFINGER

Babcock Noell GmbH

Dia = 1868 ± 0.5 mm



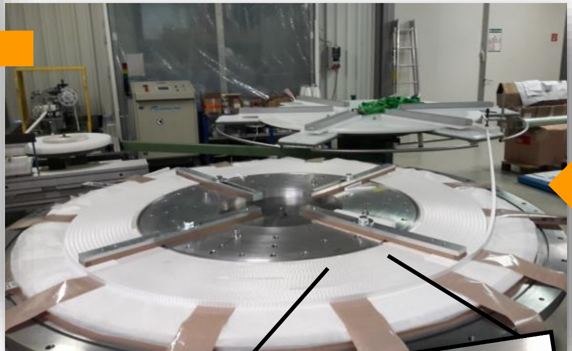
Geometry of the double-pancake (DP)

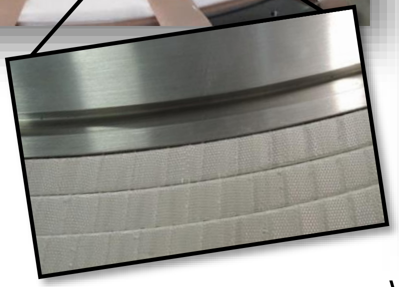


Sandblasting of the conductor followed by the wrapping of the fiberglass conductor insulation in a clean area

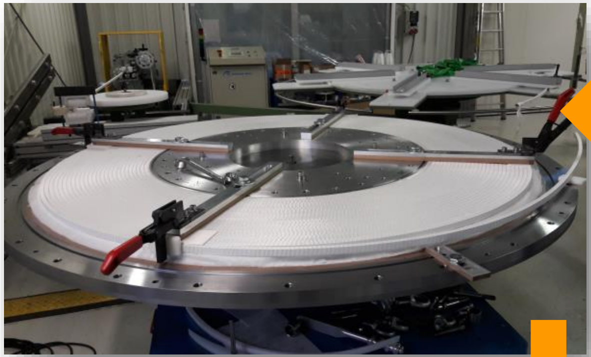
Forming the layer jump at the middle of the DP

Winding the 1st layer after having stored on the upper part the conductor length for the 2nd layer





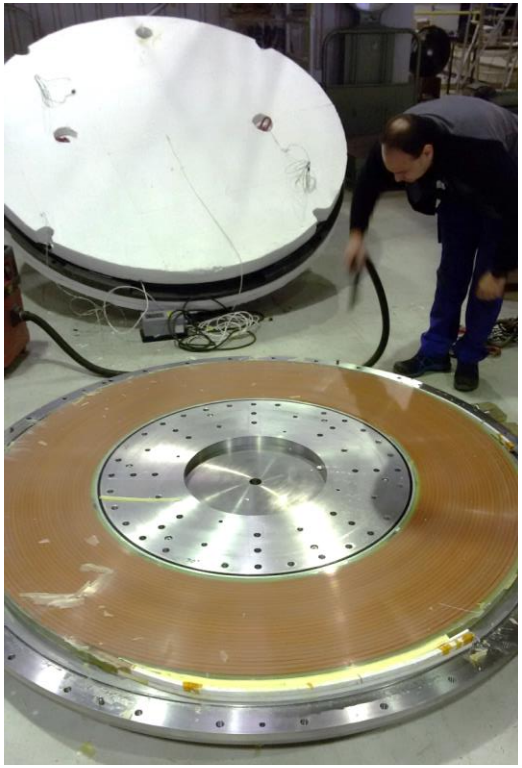
Winding of the 2nd DP layer



Epoxy resin impregnation under vacuum in a mold

Quality of the vacuum pressure impregnation

- First dummy epoxy resin impregnated DP in its mold (heating @ 40 – 65 - 75°C during 3 x 24h)

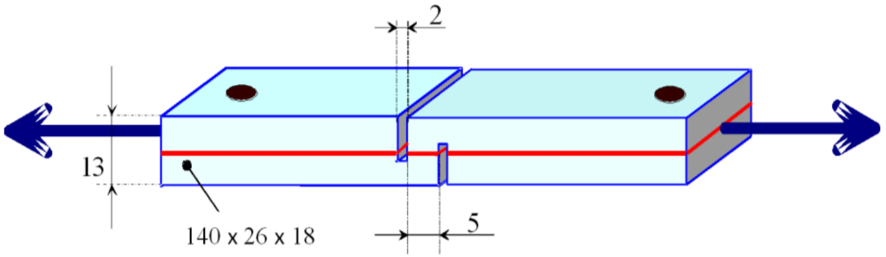


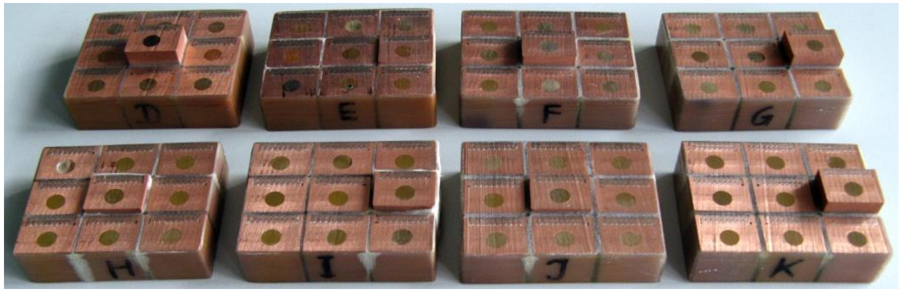
- Second dummy & first qualification DP impregnated successfully this summer with ultimate shear reaching 33.5 MPa

- Specification for the bounding of the electrical insulation after VPI on the Cu-Ag profile, *i.e.* ultimate shear at 36 MPa (*challenging on Cu surface)*

  ⇒ Dedicated investigations:
  - Reinforcement of the sandblasting
  - Coating of the Cu surface with a primer

  Maximum reached at 38 MPa on samples





Hybrid magnet system

sdms
la chaudronnerie blanche ®

Cryostat for the coil

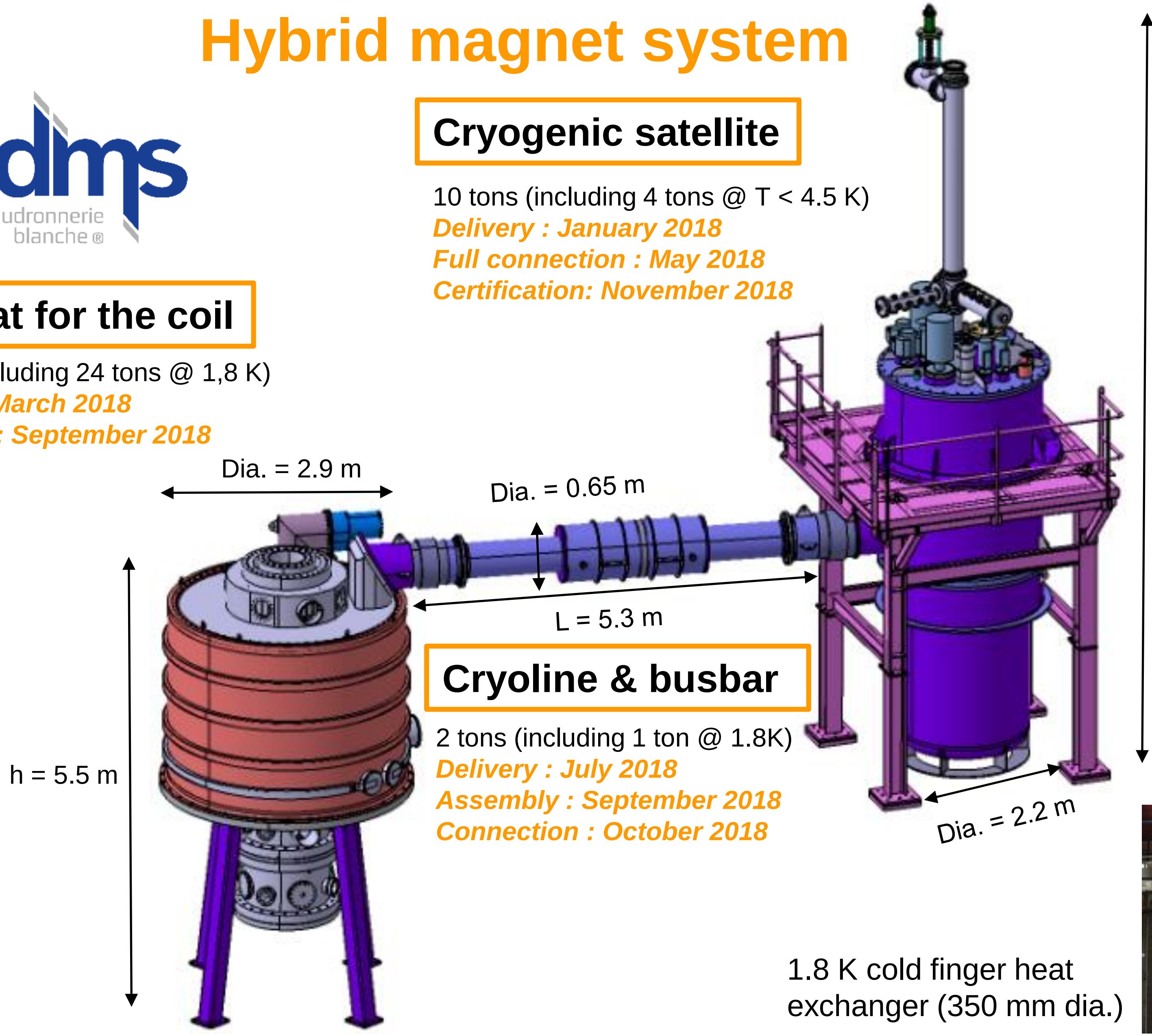
52 tons (including 24 tons @ 1,8 K)
Delivery : March 2018
Assembly : September 2018

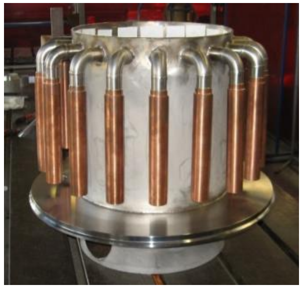
Cryogenic satellite

10 tons (including 4 tons @ T < 4.5 K)
Delivery : January 2018
Full connection : May 2018
Certification: November 2018

Cryoline & busbar

2 tons (including 1 ton @ 1.8K)
Delivery : July 2018
Assembly : September 2018
Connection : October 2018





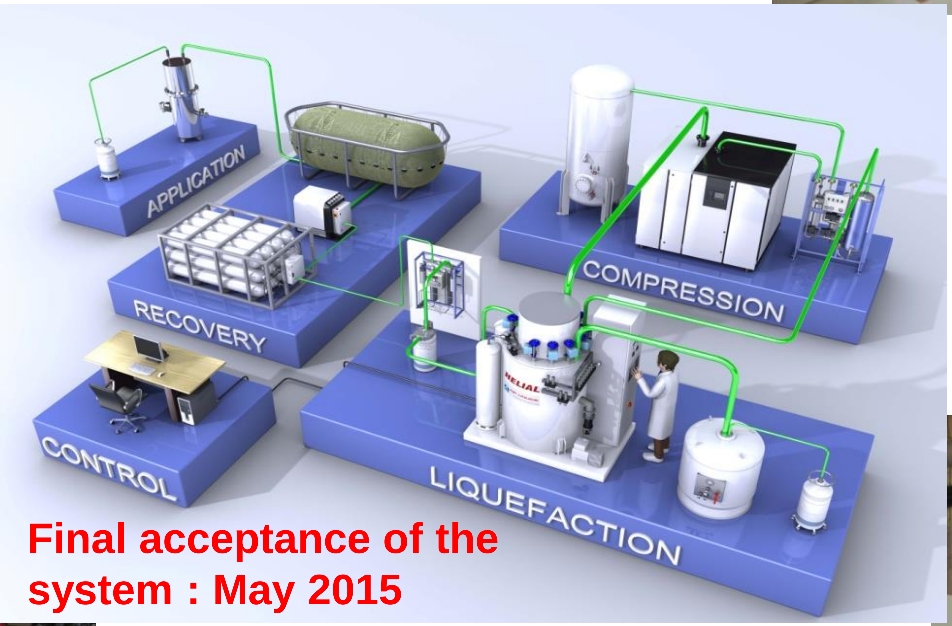
1.8 K cold finger heat exchanger (350 mm dia.)

Helium liquefier

Continuous operation dryer
(< 1 ppm H_2O)

AIR LIQUIDE ADVANCED BUSINESS & TECHNOLOGIES

180 kW He compressor
54 g/s @ 14.5 bar abs
with VFD (25 to 50 Hz)



Final acceptance of the system : May 2015

HELIAL ML coldbox
and the 4500 L Dewar

Oil removal system
(< 1 ppb C_nH_m)

Special ML coldbox
made by AL for LNCMI-G

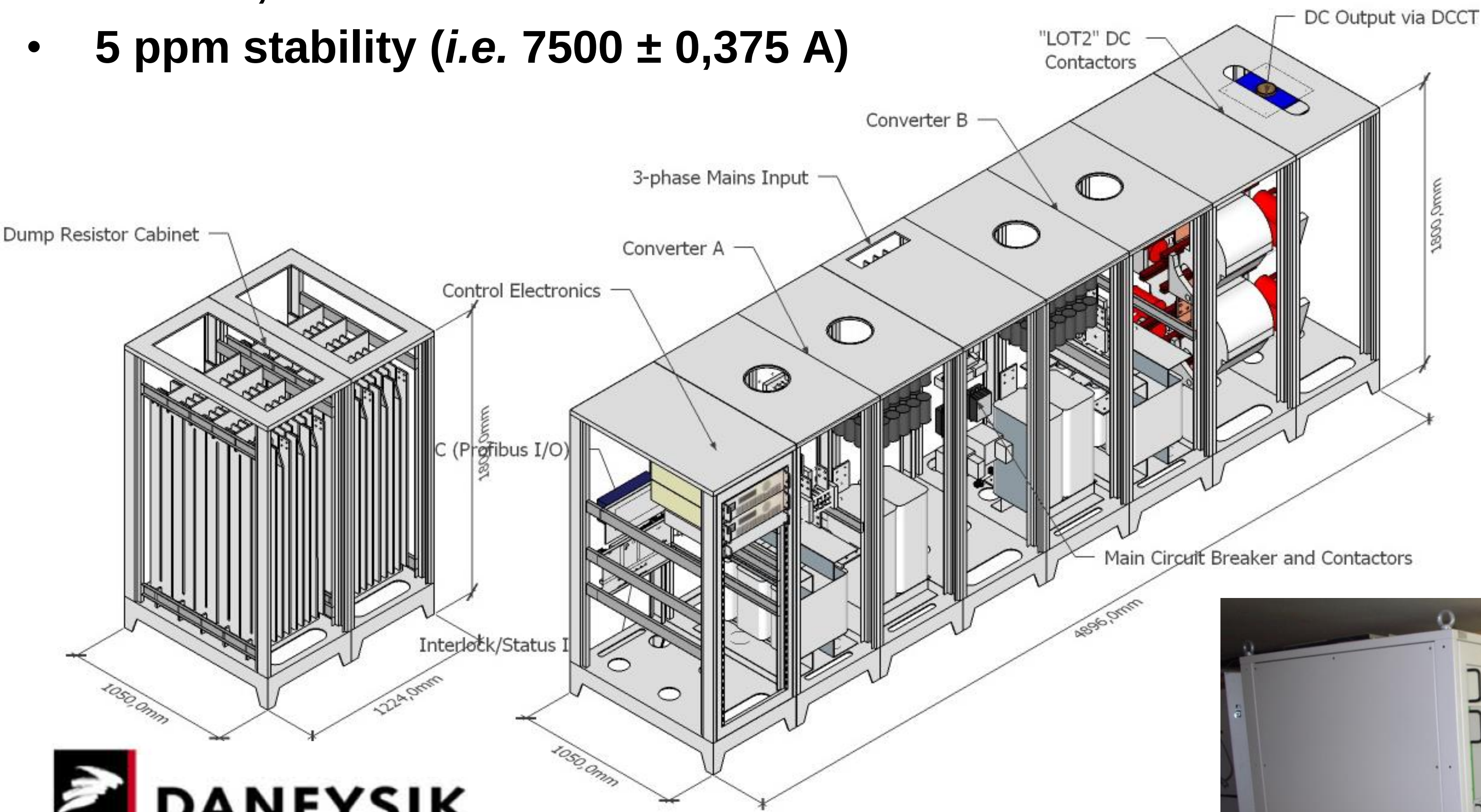
Special 3D turbine (left)
≠ standard 2D turbines (right)

Internal cryogenic purifier
(can purify He to be liquefied
containing up to 2 % air)

L. Ronayette

Power converter for the superconducting coil

- **7500 A , 30 V**
- **5 ppm stability (*i.e.* 7500 ± 0,375 A)**



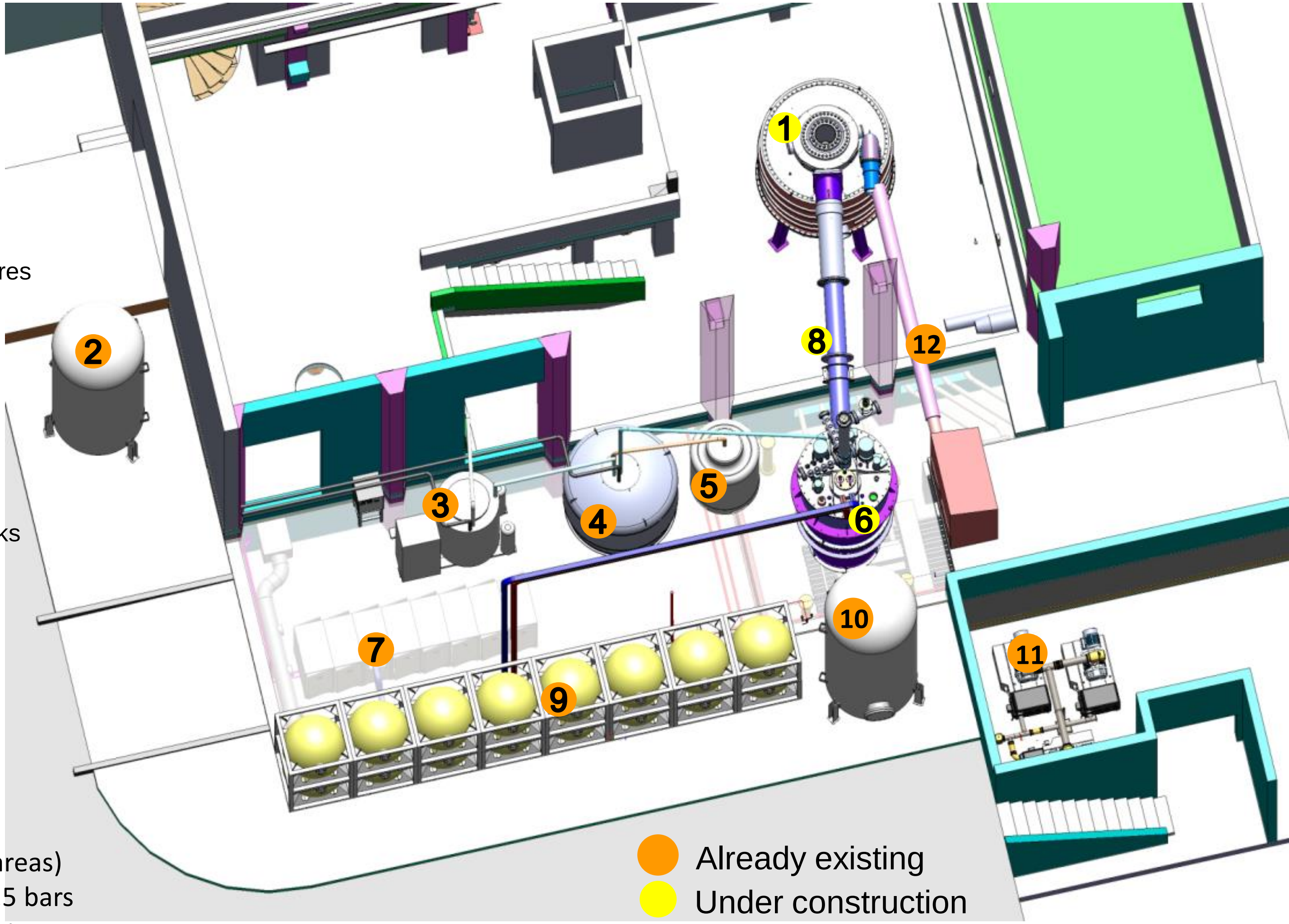
DANFYSIK

Commissioned in August 2016

B. Vincent

Overview of the complete hybrid magnet system

1	Hybrid Magnet 43 T
2	LN_2 tank 27 000 litres.
3	He liquefier coldbox 150 l/h @ 4.5 K , 1.3 bar
4	Main LHe Dewar 4500 litres
5	Secondary LHe Dewar 1700 litres
6	Cryogenic satellite to produce the 1.8 K LHe bath
7	DC power converter 7500 A , 30 V (underground)
8	Cryoline with busbars @ 1,8 K
9	High pressure gaseous He tanks 16 x 1 m^3 @ 200 bars
10	Liquefier pure He buffer tank 15 m^3 à 20 bars
11	Helium pumping system 5000 m^3/h @ 10 mbar, 20 °C
12	Quench line



Not represented (located in other areas)

- Liquefier cycle compressor @ 14.5 bars
- He recovery balloon : 30 m^3 @ Patm
- He recovery compressor @ 200 bars
- 32 x 0.5 m^3 high pressure gaseous He tanks @ 200 bars
- Magnet Safety and Magnet Control Systems

Summary

- The Grenoble hybrid magnet built in collaboration with CEA-Saclay & industrial partners (Air Liquid, Aurubis, Bruker, BNG, Ravni Technologies, SDMS) is well engaged in its construction phase with all major contracts signed.

- **43 T is expected with 24 MW in 2019**

  ► Studies of possible upgrade scenarios at 45+ T is ongoing by optimising poly-Bitter, poly-Helix resistive magnets and upgrading the electrical installation up to 30 MW (phase-1) and 36 MW (phase-2)

  - Mon-Mo-Or2 changed to Thu-Mo-Or33 : "Ultimate Forces of the Grenoble Hybrid Magnet," H. J. Schneider-Muntau, G. Aubert, Y. Eyssa, C. Trophime, B. Vincent, and P. Pugnat

  - Mon-Af-Po1.12: "Upgrade of the Grenoble High Magnetic Field Facility ," R. Barbier, B. Vincent et al.

- Dedicated efforts have been conducted to standardize a robust design for large bore superconducting solenoids and prepare future projects such as a for exemple a 60 T hybrid magnet…

Highlights

Thank You for Your Attention

ligne lncmi light.mp4