Refinement and application of a generic CFD toolkit covering the heat flows in combined solid-liquid systems to investigate thermal quench limits of superconducting magnets

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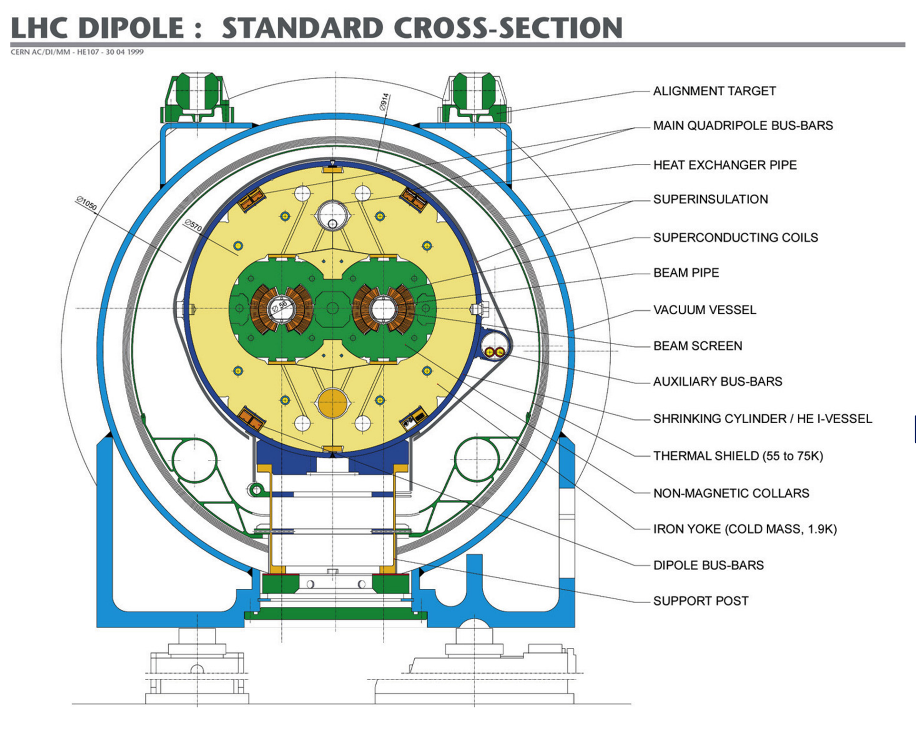
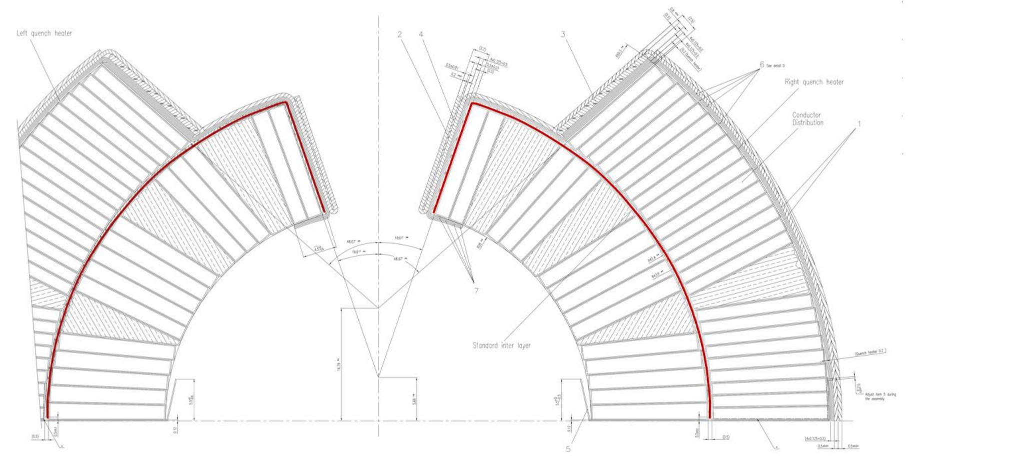
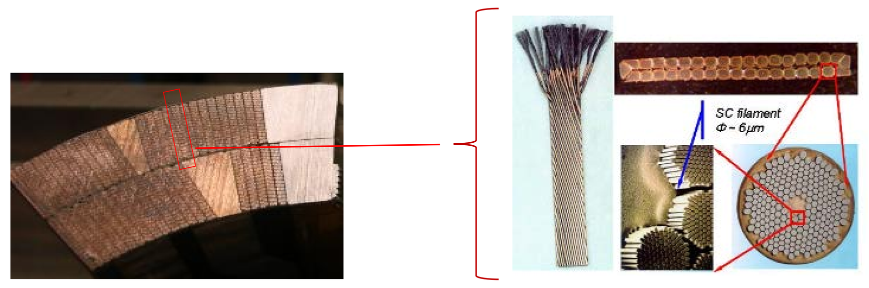
LHC Main Dipole Magnet

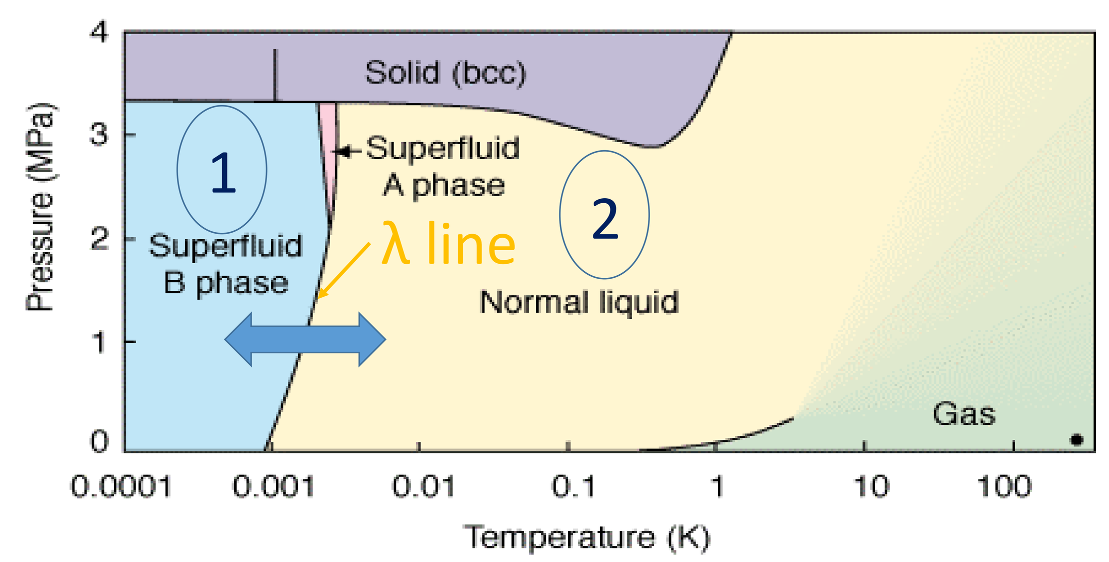




Liquid Helium penetrates the cables through porous insulations



Numerical Tool Development



1

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot \left[\left(\frac{1}{f(T)|\nabla T|^2} \right)^{1/3} \nabla T \right] + q_{vol}$$

$$\frac{1}{f(T,p)} = g(T_\lambda)[t^{5.7}(1-t^{5.7})]^3$$

$$g(T_\lambda) = \frac{\rho^2 s_\lambda^4 T_\lambda^3}{A_\lambda} \qquad t = \frac{T}{T_\lambda}$$

Original Model

2

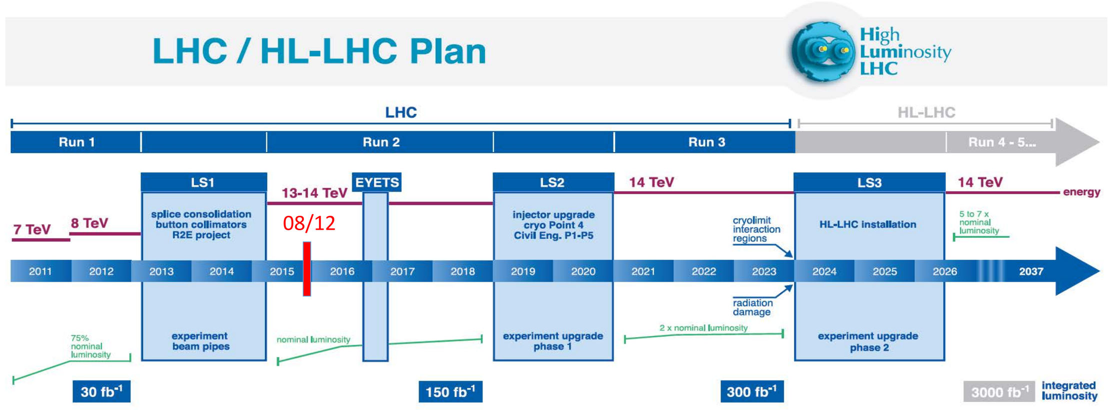
$$X(T) = X_n T^n + X_{n-1} T^{n-1} + \dots + \delta_X$$

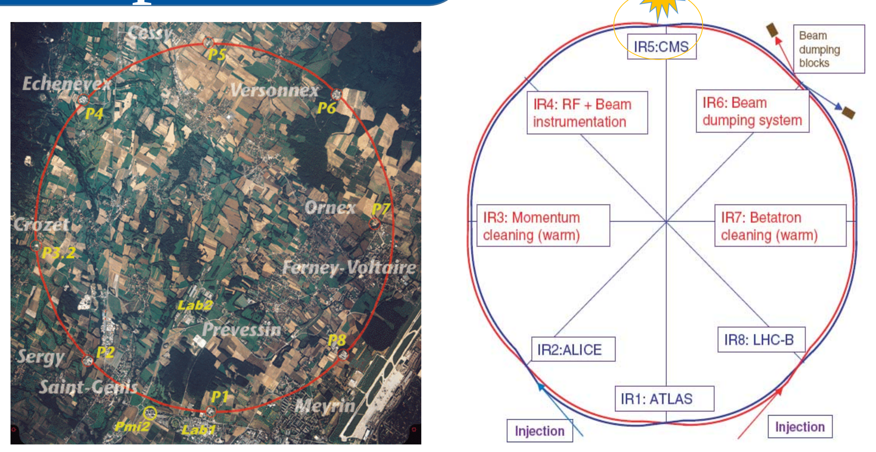
With n the degree of the polynomial and X the zero degree constant.

In the porous elements, we compute the effective thermo-physical properties using the fraction of void ε in the solid where LHe penetrates:

$$X_{solid}(T) = (1-\varepsilon)\, X_{solid} + \varepsilon\, X_{solid}$$

The LHC Quench Test Experiment



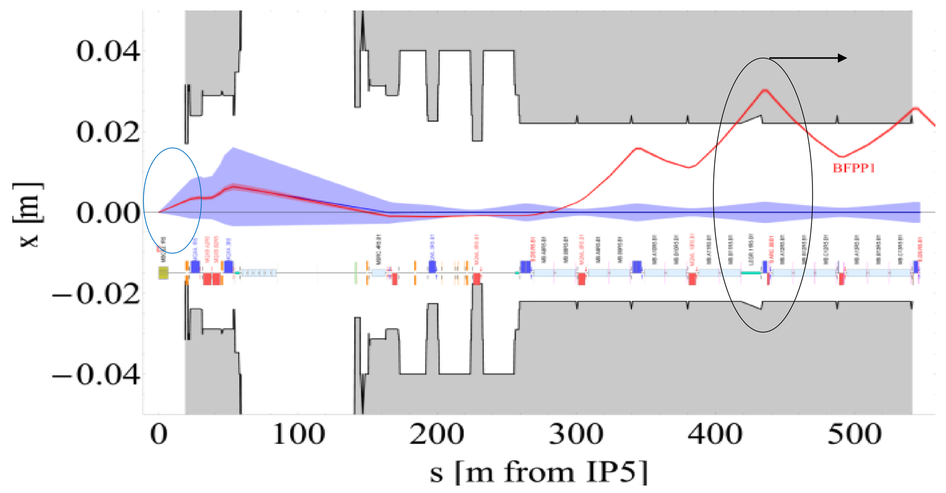


Single BFPP1

$$^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + \boxed{^{208}Pb^{81+}} + e^{+}$$

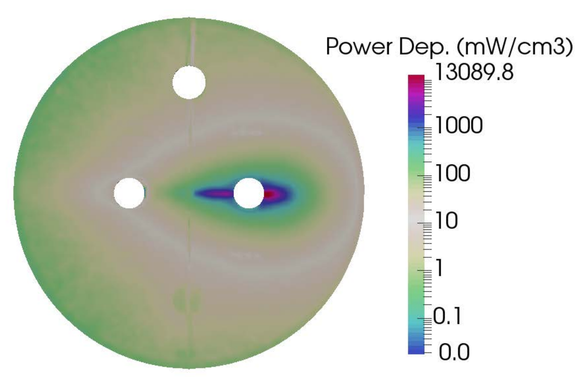
Electromagnetic interactions of Pb nuclei at the LHC :

- ✓ Tiny proportion of bound-free pair production (BFPP).
- ✓ The modified nuclei emerge from the collision point.
- ✓ Impacts on the beam screen downstream.

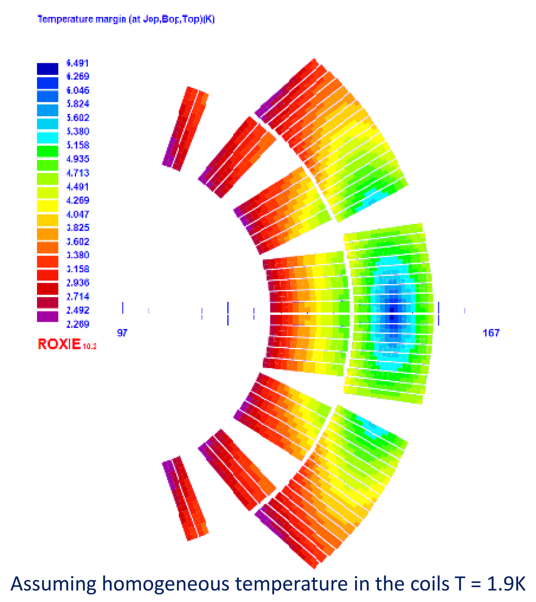


Pre-Processed Input Data

FLUKA



ROXIE

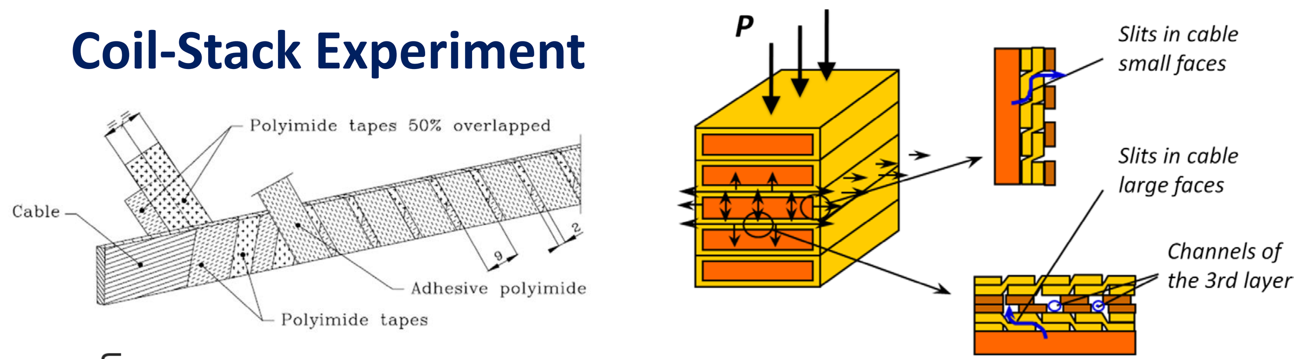


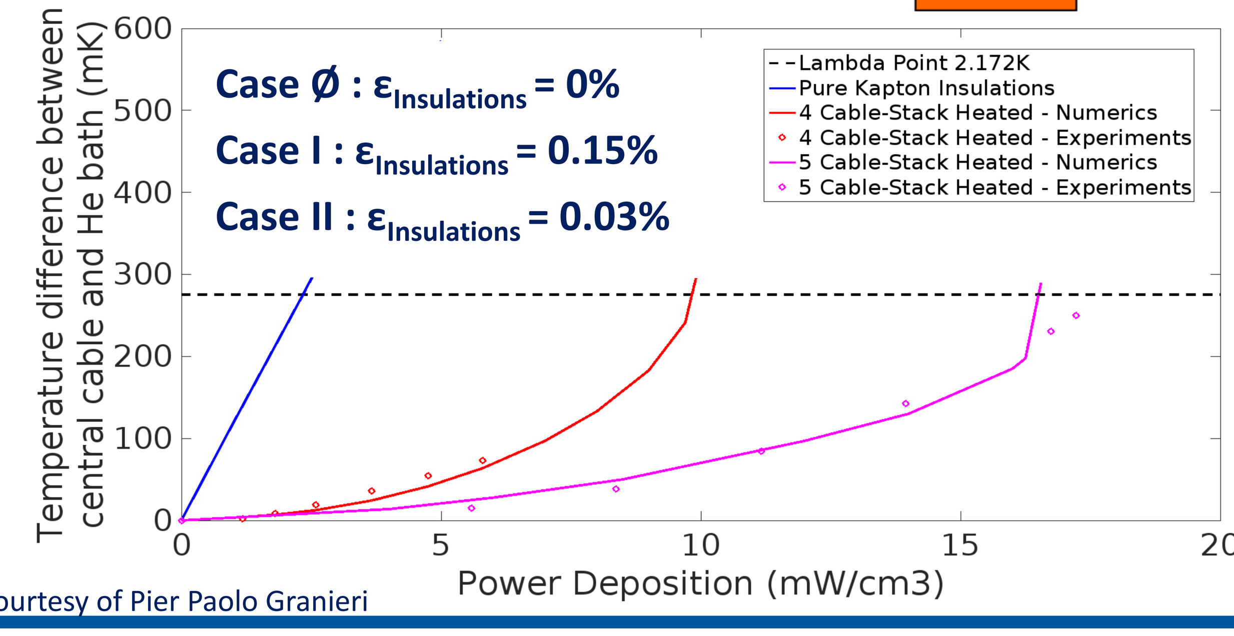
- ✓ FLUKA shower simulations to evaluate the peak power density deposited in the magnet coils during the quench test.
- ✓ ROXIE computes the temperature difference that the coils can undergo before transiting to a resistive state (temperature margin).

Courtesy of Susana Izquierdo Bermudez

Determining The He Volume Fraction

Coil-Stack Experiment



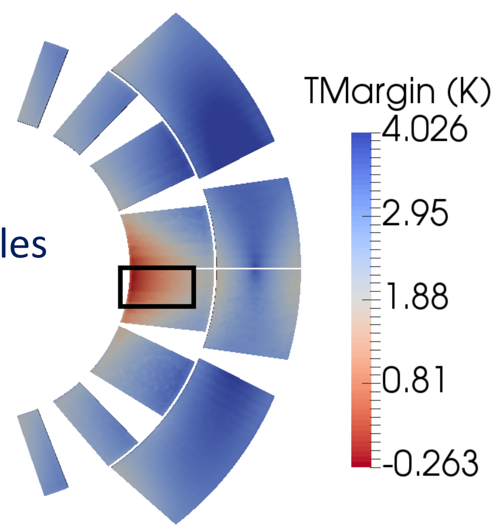


Courtesy of Pier Paolo Granieri

Application To The MB(A) LHC Dipole

The temperature margin in the squared region is < 0.
A quench is expected in that scenario

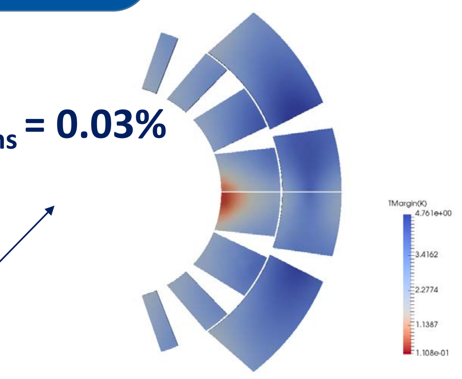
Scenario with impermeable cables



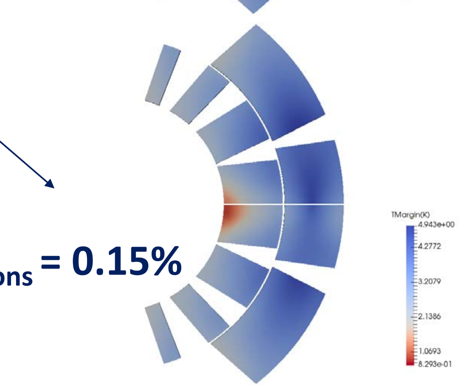
Introduction of Helium in the coils

$\varepsilon_{Insulations} = 0.03\%$

Case II



Case I

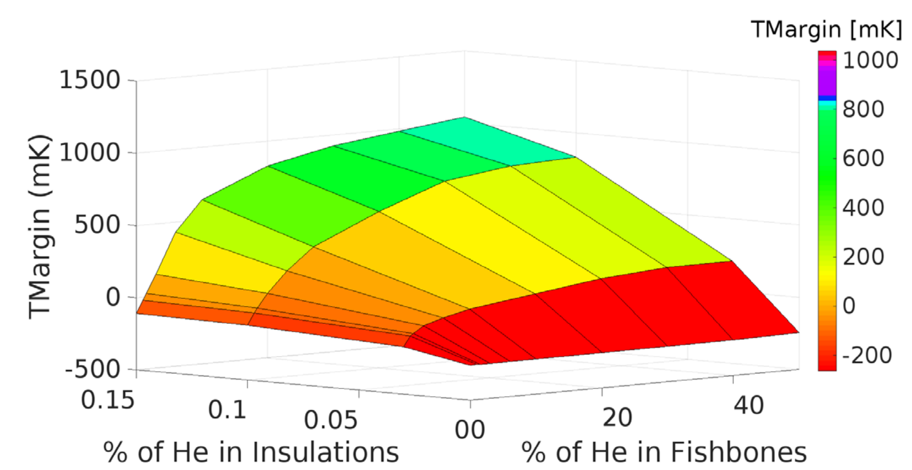


$\varepsilon_{Insulations} = 0.15\%$

The temperature margin is positive (**+110mK**). The coils retain their superconductive properties under the operating conditions.

The increased porosity of the cable insulations allows for a better cooling of the coils : The gain in temperature margin is significant (**+830mK**).

Variation of LHe in Fishbones & Insulations



In Case II, positive temperature margins are achieved for ε = 6% in the interlayers, and this value drops below 2% in Case I. The effects of the fishbones on the cooling are significant for $\varepsilon_{Fishbones} \leq 10\%$, while the insulation parameter dominates for values ≥ 10%.

Power (%)	T_{Margin} (mK)
95	155
100	0
105	-159

Uniform variation of the Energy Deposition in the scenario with 6% of Helium in fishbones & 0.03% in insulations (Case II).

Power (%)	Abs. $T_{Margin}\alpha$ (mK)	Rel. $T_{Margin}\alpha$ (mK)	Abs. $T_{Margin}\beta$ (mK)	Rel. $T_{Margin}\beta$ (mK)
95	431	201	364	154
100	230	0	210	0
105	46	-184	73	-137

Scenarios α and β and II: 6% of helium in fishbones & 0.10% in Kapton (α) And 50% of helium in Fishbones & 0.03% in Kapton (β).

Conclusions

The numerical model we developed provides a quantitative insight into which parameters, in the design of the magnet and the actual setting of the experiment, are significant in the cooling mechanism. Under the present assumption that $2\% \leq \varepsilon_{Fishbones} \leq 6\%$ (values deduced from the quench test), $0.03\% \leq \varepsilon_{Insulations} \leq 0.15\%$, and the observation that the variation in T_{Margin} for each of them individually is comparable to ≈ ±5 % in power deposition, we'd postulate with some reserve that the spread in MQE of the 1232 LHC main dipoles could be 10 %: 11.7 mW/cm3 – 14.3 mW/cm3.