MQXF Quench Protection Analysis

HiLumi workshop – KEK, Tsukuba

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High Luminosity LHC

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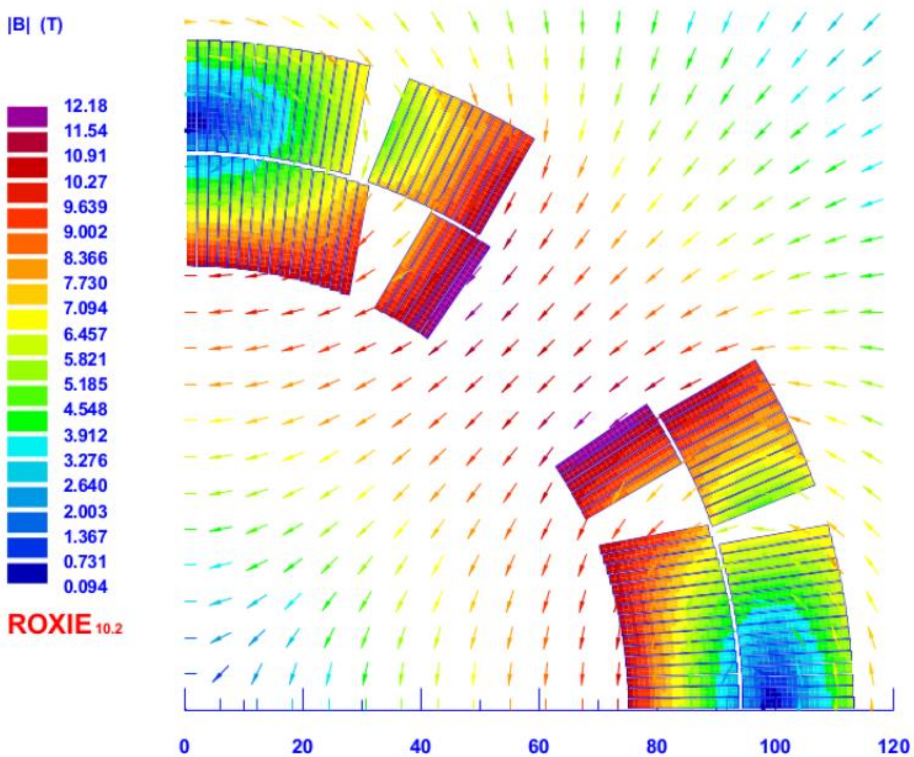
0.1 Introduction



Aperture diameter	150 mm
Gradient	140 T/m
Maximum length	2 x 4 m
Nominal current	17500 A
Magnetic stored energy (2 x 4m)	12 MJ
Inductance	8.3 mH/m
Conductor peak field	12.2 T
Operating temperature	1.9 K
Strand diameter	0.850 mm
Bare cable width	16.638 mm
Bare cable thin/thick edge thickness	1.462/1.673 mm
Insulation thickness	0.150 mm
Strand Number	40
Copper/non-copper ratio	1.2
Copper RRR	≥ 100

Critical parameters make the protection study **very challenging**

Contents:

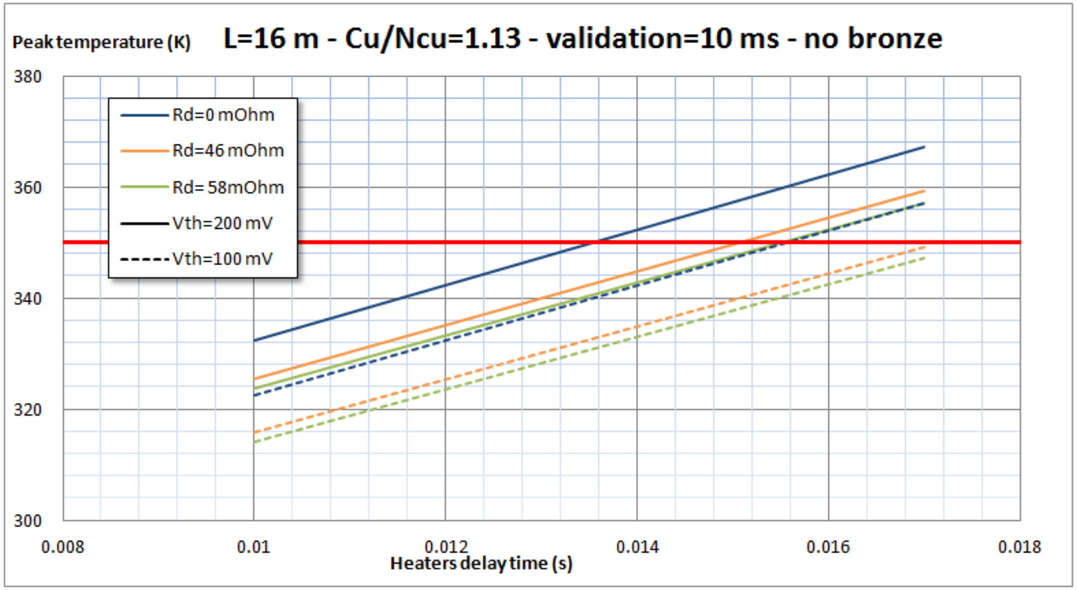
1. MQXF standard **conservative** protection study

2. Inter-Filament-Coupling-Currents (IFCC) effects on the **differential inductance**

3. MQXF protection study considering **dynamic effects**

MQXF standard conservative protection study

1.1 MQXF conservative study



<u>Hot spot temperature</u> very close to the upper limit of **350 K**[1]

- Protection heaters only on the **outer layer**

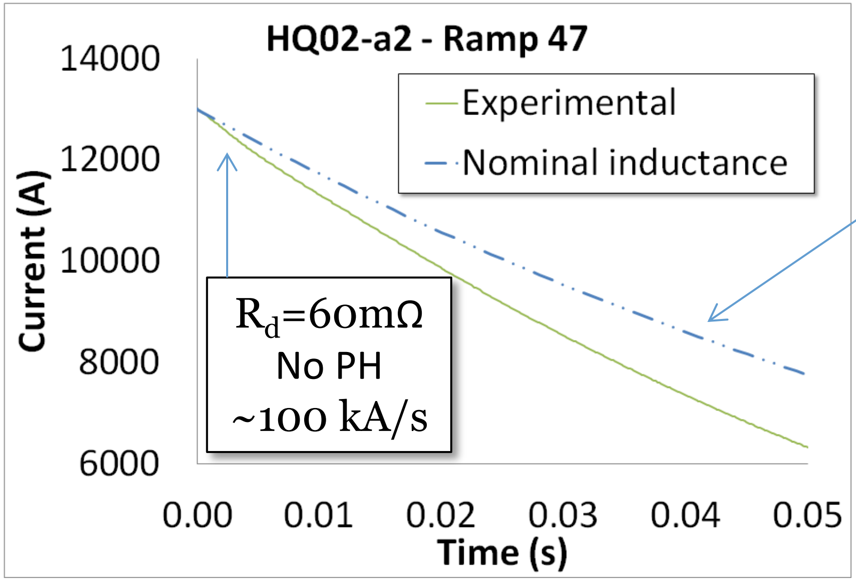
Protection improvements:

- Designing protection heaters on the inner layer[2]
- Improving the protection simulation using **less pessimistic assumptions**

[1] G. Manfreda et al., "*Quench Protection Study of the Nb_3Sn Low-β Quadrupole for the LHC Luminosity Upgrade*" *IEEE Trans. on Appl. Supercond.*, vol. 24, no.3, June 2014.
[2] M. Marchevsky, "*Design optimization and testing of the protection heaters for the LARP high-field Nb3Sn quadrupoles*", presented at ASC2014.

Inter-Filament-Coupling-Currents (IFCC) effects on the differential inductance

2.1 Inductance reduction for high dI/dt



HQ simulation using the nominal inductance, experimentally measured at low dI/dt (<50 A/s)[1]

- ➢ There is an evident **disagreement,** starting from the **very beginning**

- ➢ Similar behavior has been **experimentally observed** in various HQ and LQ decays
- ➢ It is not due to quench back, because of its suddenness
- ➢ It has **benefic effects** on the protection, therefore its **simulation in MQXF** could be very useful
- ➢ The explanation has been investigated as an electromagnetic coupling with **Inter-Filament-Coupling-Currents (IFCC)** in the strand, due to **high dI/dt,** which causes a considerable **inductance reduction**

[1] H. Bajas et al., *"Cold Test Results of the LARP HQ Nb3Sn quadrupole magnet at 1.9 K"*. Presented at the Applied Superconductivity Conference, Portland, Oregon, USA, 2012.

2.2 IFCC as magnetization currents

- The **differential inductance** can be computed as:

$$L = \int \left\{ \frac{\mu_0 H}{I}\frac{dH}{dI} + \frac{\mu_0 \chi H}{I}\frac{dH}{dI} + \frac{\mu_0 H^2}{I}\frac{d\chi}{dI} \right\} dV$$

Static inductance

Magnetic susceptibility related to IFCC

- Under **exponential** assumptions, the magnetic **susceptibility** related to the IFCC can be computed as:

$$\chi = \frac{2\lambda\tau\left(e^{-\frac{t}{\tau_e}} - e^{-\frac{t}{\tau}}\right)}{\tau e^{-\frac{t}{\tau}} - \tau_e e^{-\frac{t}{\tau_e}} - 2\lambda\tau\left(e^{-\frac{t}{\tau_e}} - e^{-\frac{t}{\tau}}\right)}$$

$\tau = \frac{\mu_0}{2\varrho_e}\left(\frac{p}{2\pi}\right)^2$ is the IFCC decay time constant[1]

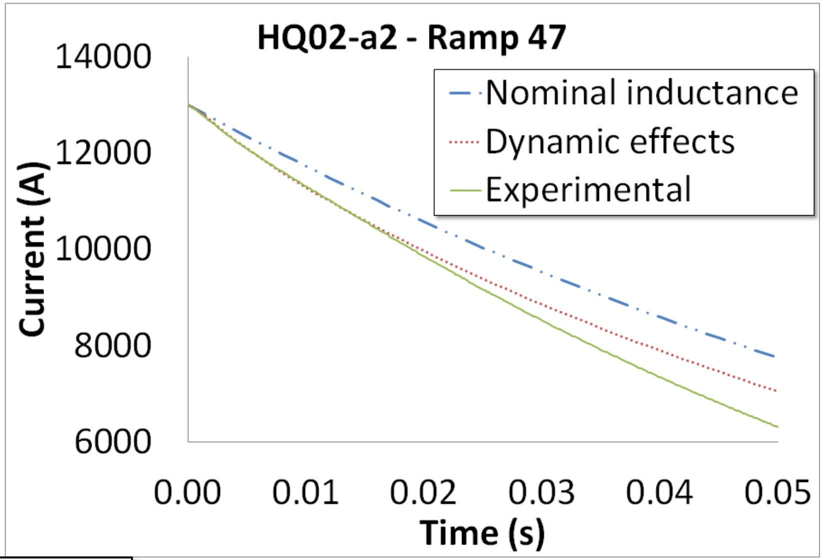
$\tau_e = \frac{L}{R_d}$ is the current decay time constant

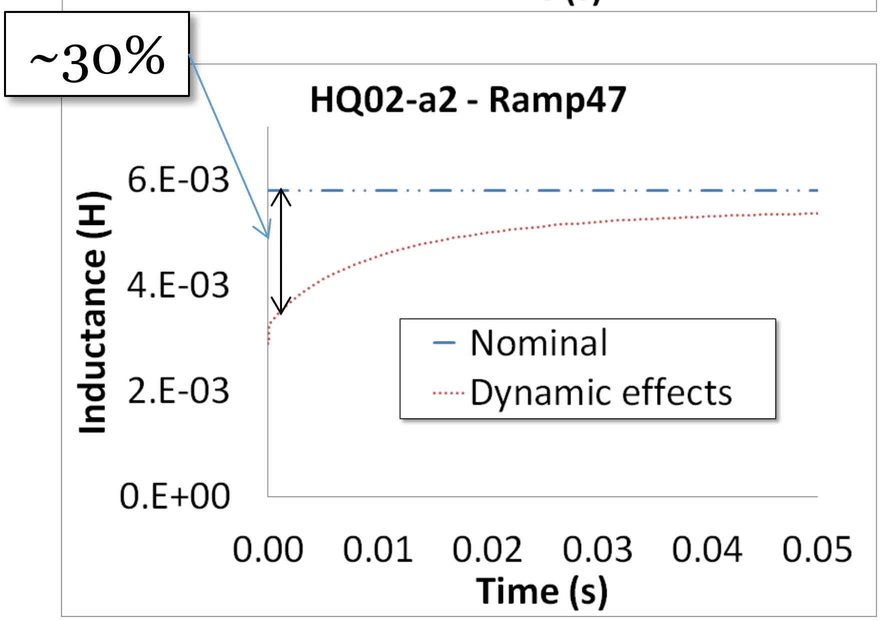
λ takes into account the insulation and the packing in the strand

- This model has been implemented in **QLASA**[2]

[1] M. N. Wilson, "*Superconducting Magnets*", Clarendon Press Oxford, 1983.
[2] L. Rossi and M. Sorbi, "*QLASA: A computer code for quench simulation in adiabatic multicoil superconducting windings*", Nat. Inst. of Nucl. Phys. (INFN), Rome, Italy, Tech. Rep. TC-04-13,2004.

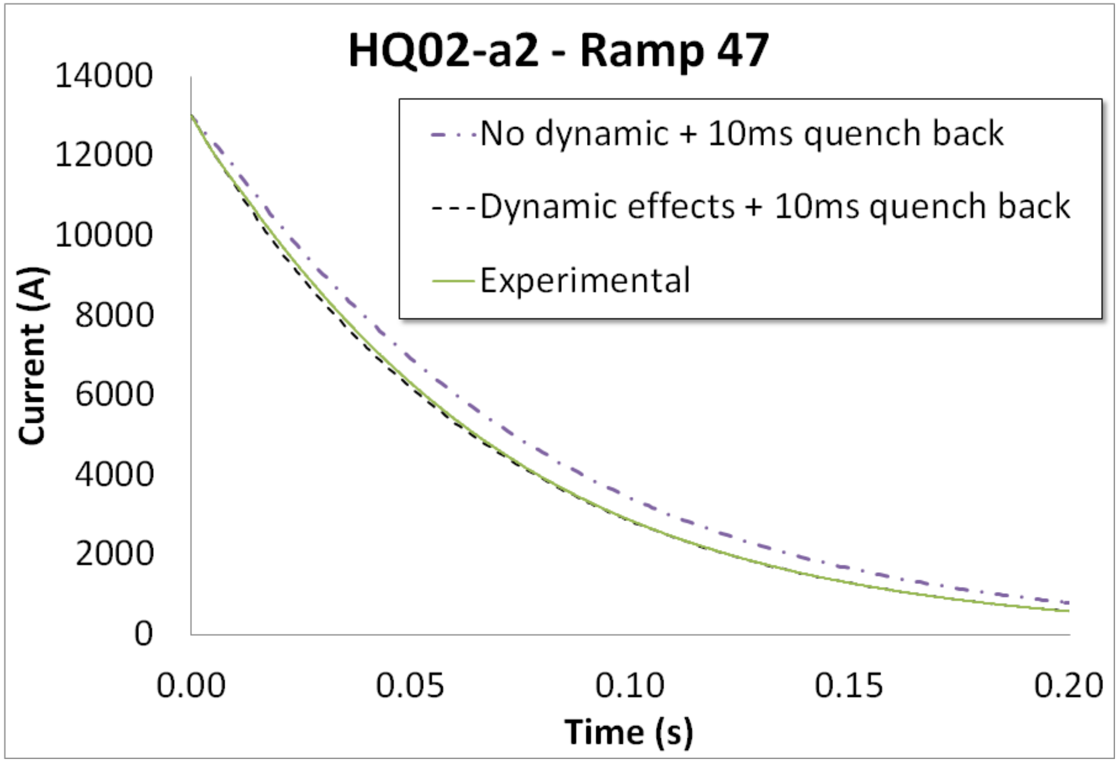
2.3 HQ simulation





- Considering dynamic effects allows to **simulate well** the experimental decay from the very beginning to t=~15 ms
- In this decay, the **MIITs** produced considering dynamic effects are **~20% less** then using nominal inductance
- The disagreement after 15 ms could be due to **quench back**

2.4 IFCC and quench back



Quench back after 10 ms together with **dynamic effects** allow to reproduce the decay **until its end**

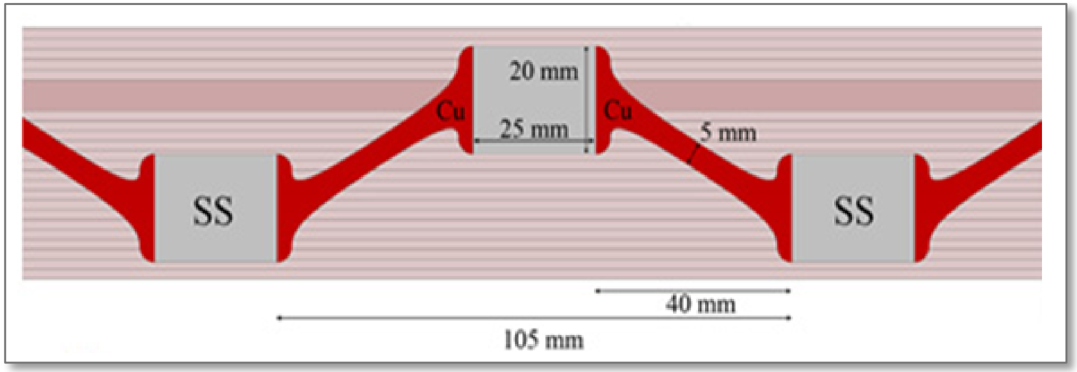
Conclusions:

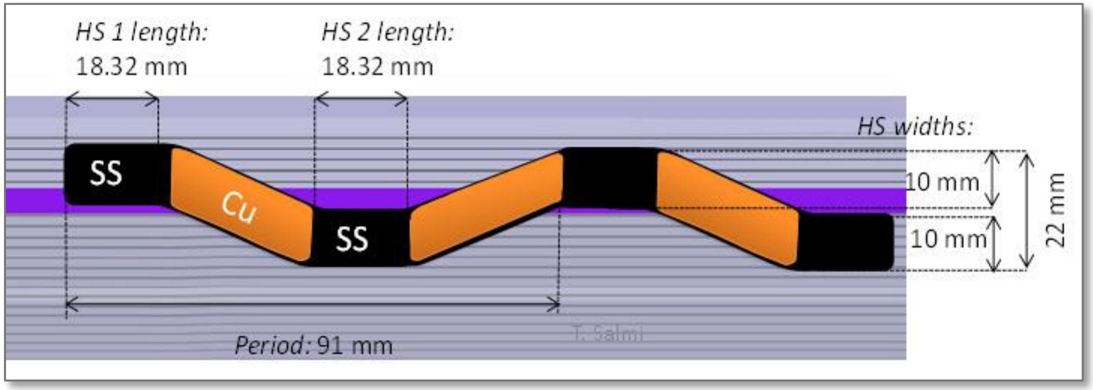
- **Both** quench back and dynamic effects are needed in order to reproduce the decay **until the end**
- Quench back **alone** is not enough
- QLASA cannot predict the **time** of quench back occurring, but it can now predict the **inductance reduction** due to dynamic effects. Improvement of QLASA is under way.

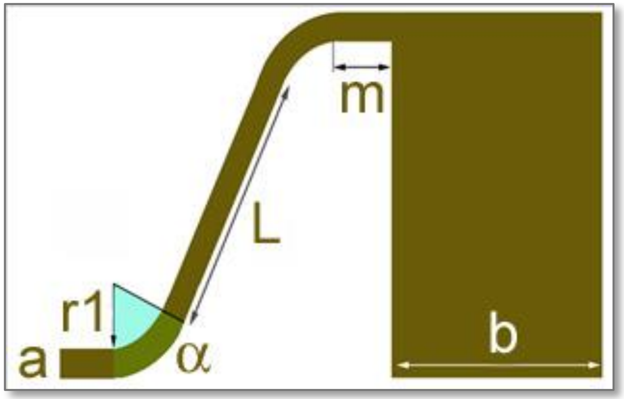
MQXF protection study considering dynamic effects

3.1 MQXF inner-layer quench heaters

In order to **improve** the protection, various quench heaters for the **inner layer** have been designed[1]





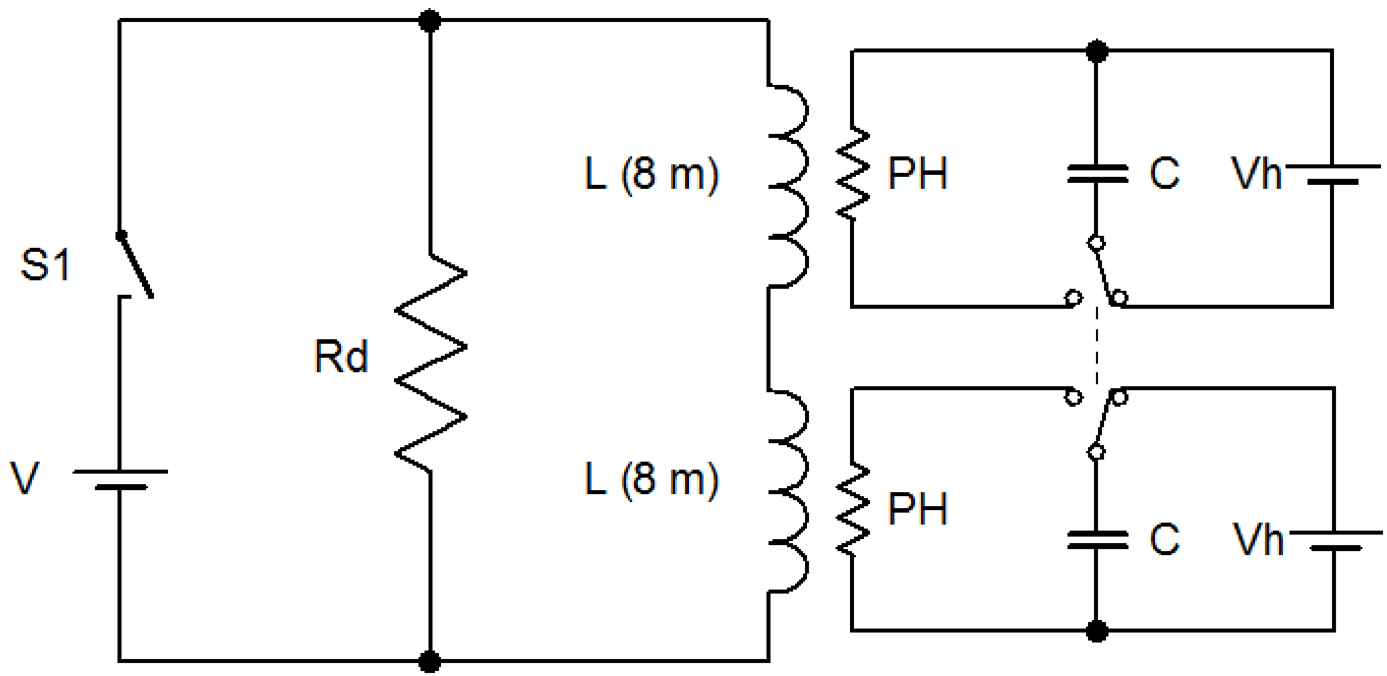


➢ The protection heaters are designed in order to avoid as best as possible the damages coming from **helium bubbles**

[1] M. Marchevsky, "*Design optimization and testing of the protection heaters for the LARP high-field Nb3Sn quadrupoles*", presented at ASC2014.

3.2 MQXF protection scheme

Dumping resistance	48 mΩ
Maximum voltage to ground	800 V
Voltage threshold	100 mV
Validation time	10 ms
Heaters delay time from firing (inner layer) (CoDHA)[1]	12 ms
Heaters delay time from firing (outer layer) (CoDHA)[1]	16 ms



[1] T. Salmi et al., "*A Novel Computer Code for Modeling Quench Protection Heaters in High-Field Nb3Sn Accelerator Magnets*", IEEE Trans. Appl. Supercond. vol 24, no 4, 2014.

3.3 MQXF protection with IL-PH

- Dynamic effects are **not yet** considered in these simulations

No inner layer PH	Inner Layer PH
35.5 MA^2s	32.8 MA^2s
330 K	290 K

- The MQXF hot spot temperature **decreases** of **~40 K** inserting inner layer protection heaters

Open question:
Are these protection heaters reliable for helium bubbles issue?

3.4 MQXF protection considering IFCC

No inner layer PH	No inner layer PH+ IFCC	Inner Layer PH	Inner Layer PH + IFCC
35.5 MA^2s	34.2 MA^2s	32.8 MA^2s	31.3 MA^2s
330 K (365 K)	**306 K** (342 K)	**290 K** (311 K)	**266 K** (288 K)

The numbers between parenthesis are referred to a failure of half of the heaters

- IFCC dynamic effects **decrease** the MQXF hot spot temperature of **~25 K**. The effect is therefore appreciable
- The hot spot temperature is enough **below the designed limit** (350 K) also in the case of no inner-layer protection heaters, considering IFCC dynamic effects (**306 K**). Anyway this case does not ensure protection **redundancy (342 K)**
- Further improvements could come from quench back, which has not been considered (work in progress)

Conclusions:

- Previous standard **conservative** works on the MQXF protection **did not** ensure the magnet **safety**.
- Protection has been **improved** designing protection heaters for the **inner layer**. This improvement gives a margin of additional **40 K** in the hot spot temperature.
- The IL-PH suffer the **helium bubbles** issue.
- An electromagnetic model for the **IFCC** has been developed and **validated** with HQ experimental data in order to compute the **inductance reduction** during fast decays.
- The IFCC model has been applied for the **MQXF** protection study. It gives additional **25 K margin** in hot spot temperature. A further improvement could come from **quench back**.
- Both IFCC dynamic effects and IL-PH ensure the magnet safety and redundancy.
- Another possible solution could be to use **CLIQ** together with outer layer PH. This analysis is under study.