

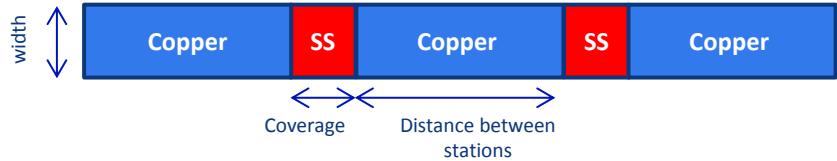
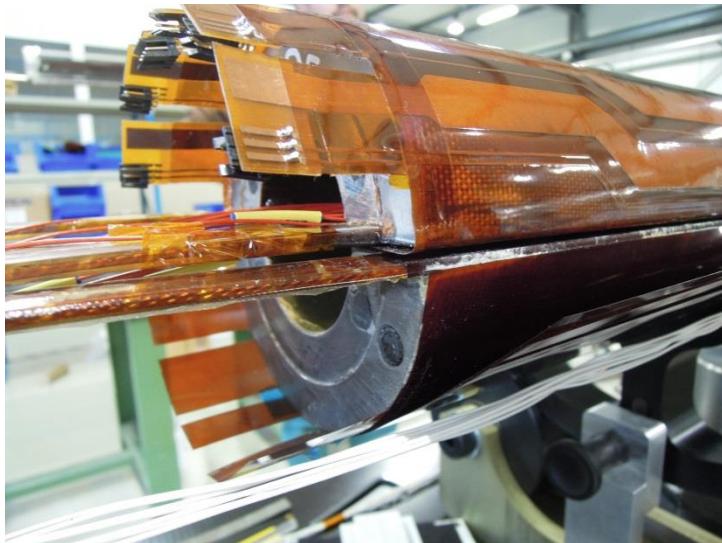
Susana Izquierdo Bermudez. 27-01-2015

# **MBHSP101: Quench Protection Studies**

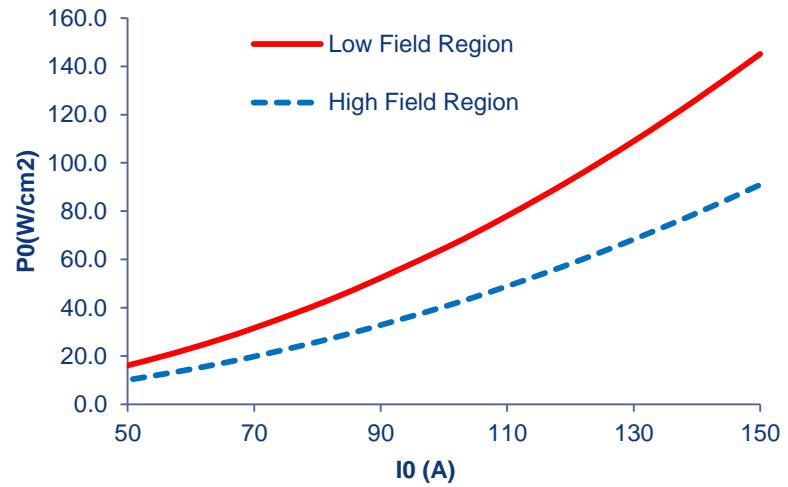


# Heater design

- Heaters are only present in the **outer layer**.
- Heaters are copper plated to reduce the overall strip resistance (max. voltage across the heaters +450 V).
- Width of the heaters and distance between heater stations has been optimized to quench the coil in an uniform way.
- 4 heater circuits per aperture for redundancy (could be increased up to 8 per aperture).

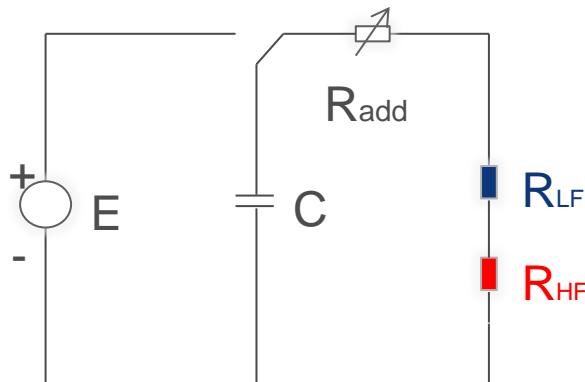


	Low field heater strip	High field heater strip
Coverage (mm)  (Stainless steel part)	50	
Distance Between Stations (mm)  (Copper plating)	90	130
Width (mm)	19	24
Stainless steel thickness (mm)	0.025	
Copper plating thickness (mm)	0.005	

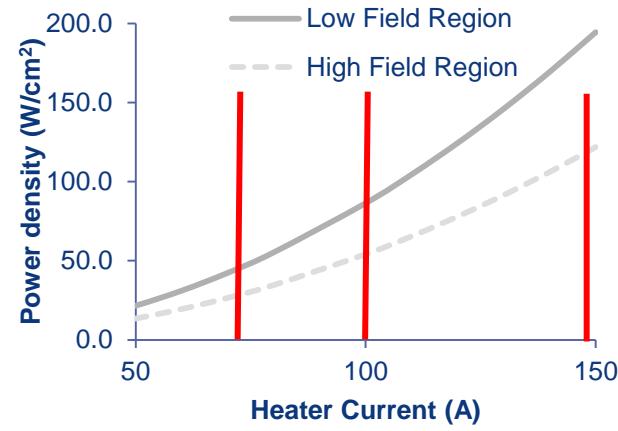
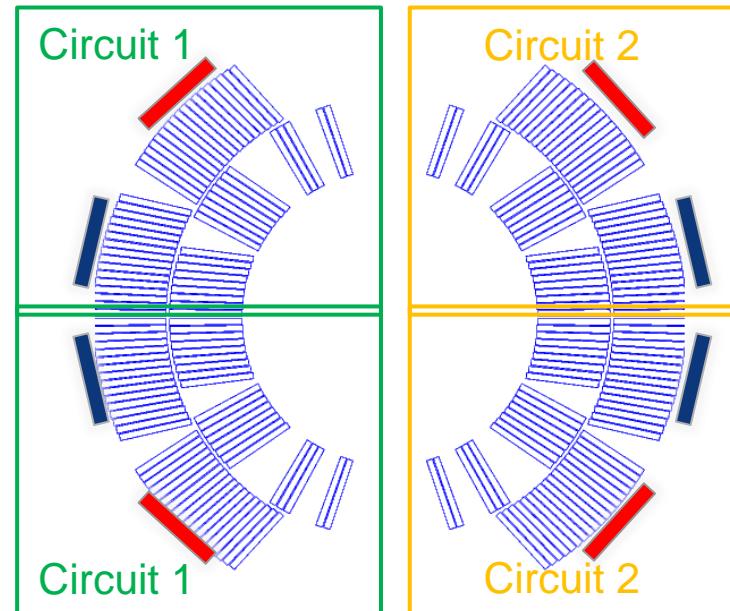


# QH test set up in SM18

- “Standard” LHC Quench Heater Power Supply:  $V = \pm 450$  V,  $C=7.05$  mF
- Maximum current = 150 A
- Voltage is fixed to a total of 900 V, additional resistance in series with the circuit is setting the current
- Three different current levels in the heaters were explored: 80 A, 100 A and 150 A.



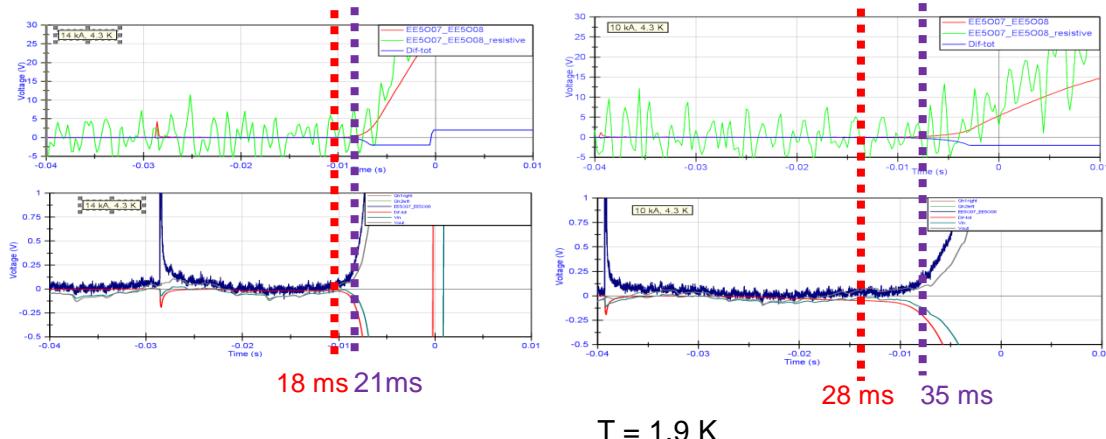
I [A]	P <sub>LF</sub> [W/cm <sup>2</sup> ]	P <sub>HF</sub> [W/cm <sup>2</sup> ]	P <sub>ave</sub> [W/cm <sup>2</sup> ]	RC (ms)
80	41.3	25.9	34	80
100	64.5	40.4	52	64
150	145.1	91.0	118	42



# Quench Heater Delay

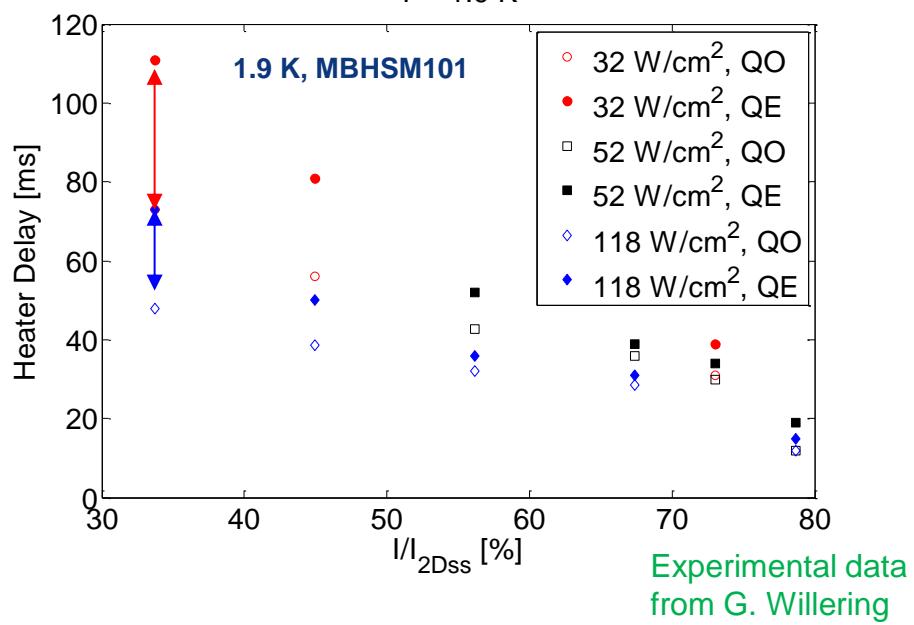
2 times to look at:

- **Quench heater onset (QO):**  
start of the quench
- **Quench heater efficient (QE):**  
time where slope of the resistive voltage cross the “time” axis



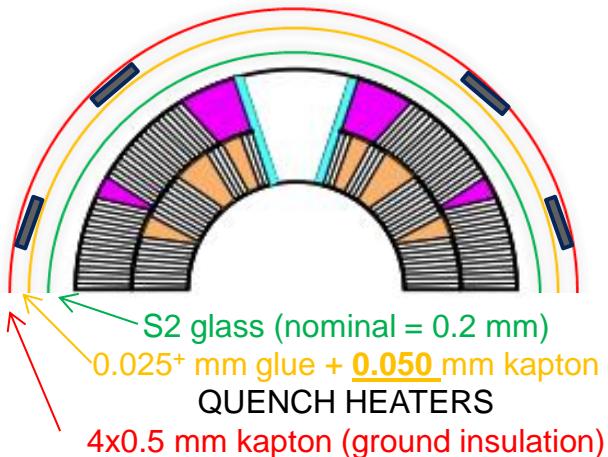
Remarks:

- At high current, the difference between **QO-QE** is very small, but at lower current there is an important offset to keep into account.
- The difference between quench onset and quench efficient increases for low heater power density.



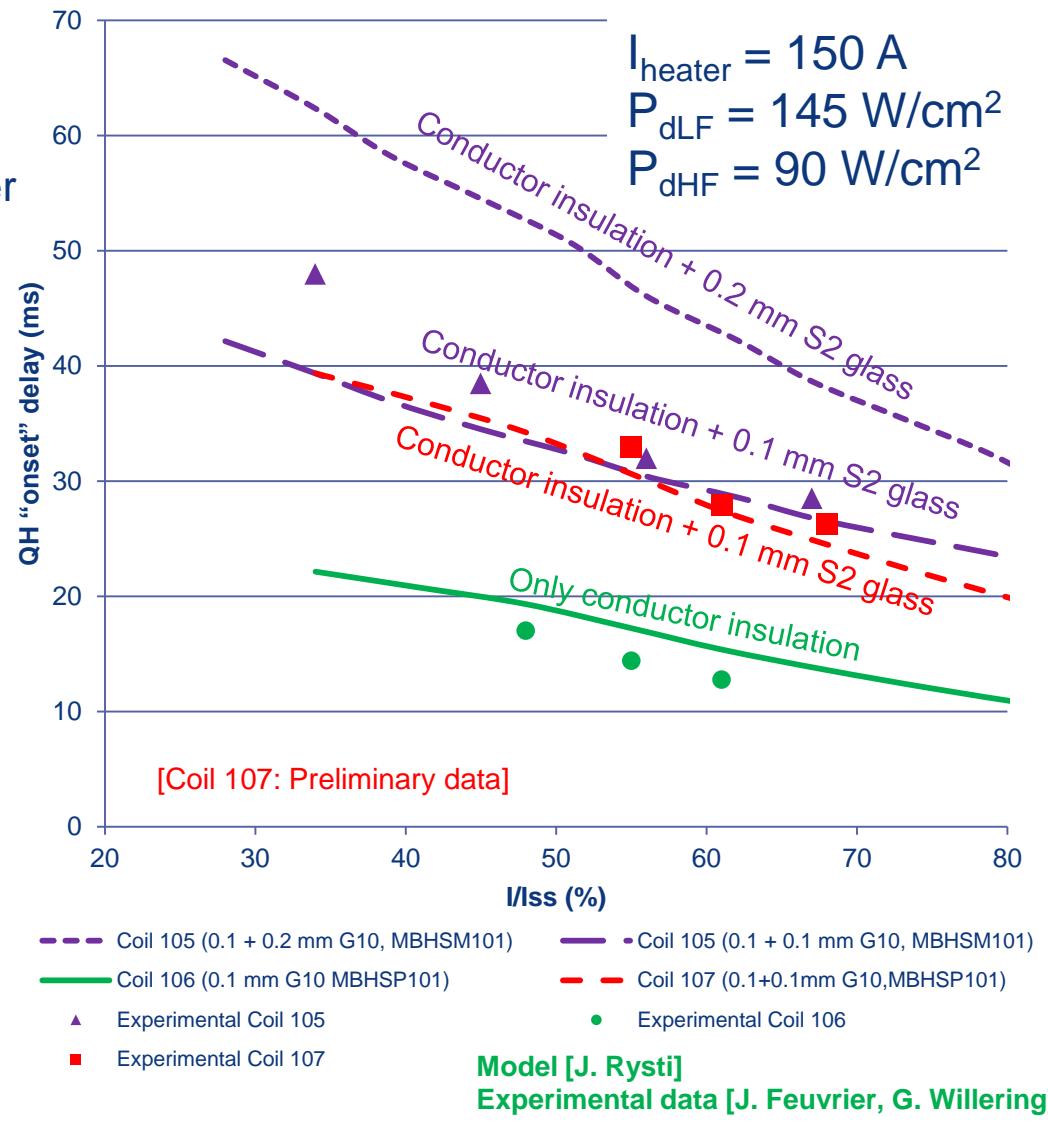
# Heater delay – Insulation thickness

- Heaters are glued on top of the coil after impregnation
- The amount of insulation between heater and coil is the critical parameter



Thickness S2 glass between heater and coil	
Coil 105	0.2 mm
Coil 106	0.0 mm
Coil 107	0.1 mm

Minimizing the S2 glass between heater and coil, expected heaters delays in nominal operation conditions ~ 12 ms



# Comparison to FNAL 11T dipoles

## FNAL MBHSM% insulation between heater and coil:

- 0.125 mm of glass on the outer, impregnated with the coil
- 0.076 mm of kapton between heater and coil

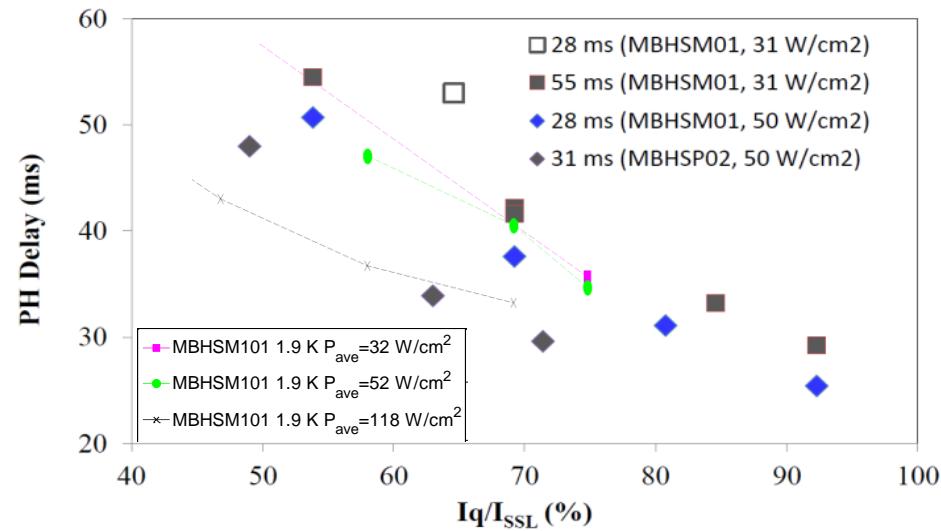
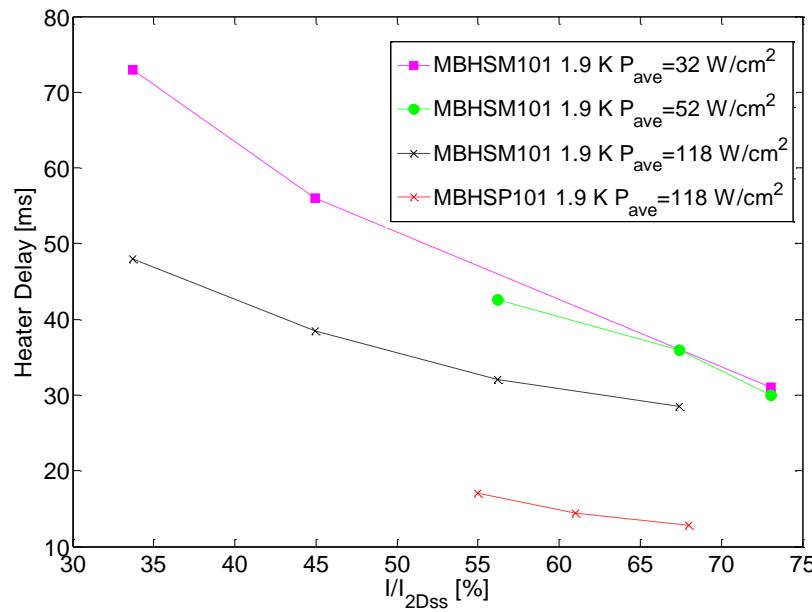
## CERN MBHSM101 insulation between heater and coil:

- 0.200-0.250 mm of glass on the outer, impregnated with the coil
- 0.050 mm of kapton between heater and coil + about 0.025 mm glue

## CERN MBHSP101 insulation between heater and coil:

- Coil 106: no glass on the outer during impregnation
- 0.050 mm of kapton between heater and coil + about 0.025 mm glue

Comparable delays  
Shorter delays

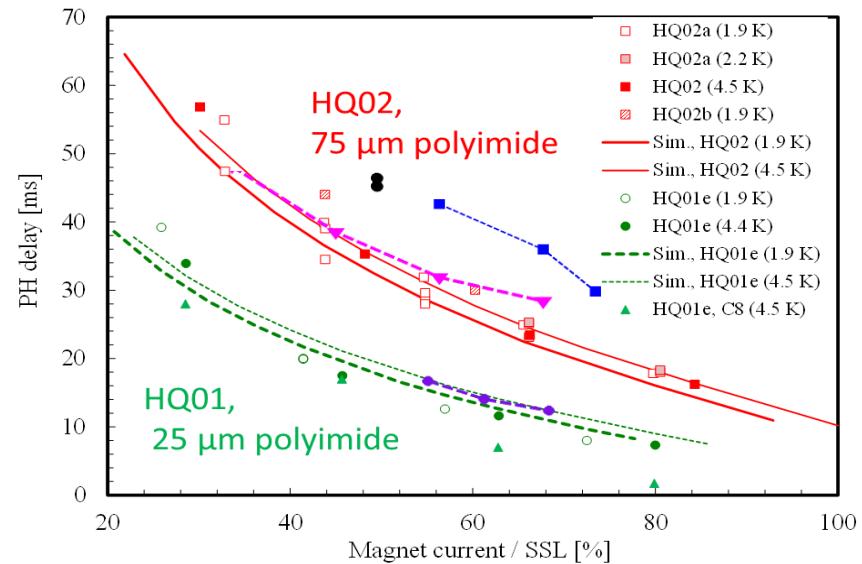
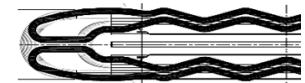


# Comparison to HQ

- Significant longer delays in MBHSM101 than in HQ for the same quench heater power density ( $\sim 50 \text{ W/cm}^2$ ).
- MBHSP101 (coil 106, no additional S2 glass between conductor and trace), heater delays are comparable to HQ, although there is no data for direct comparison (same heater power density).

HQ data from  
<https://indico.cern.ch/event/311824/>  
Slides from Tiina Slami

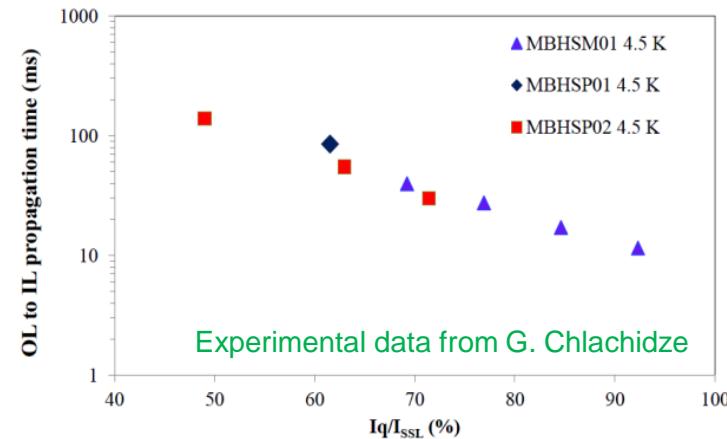
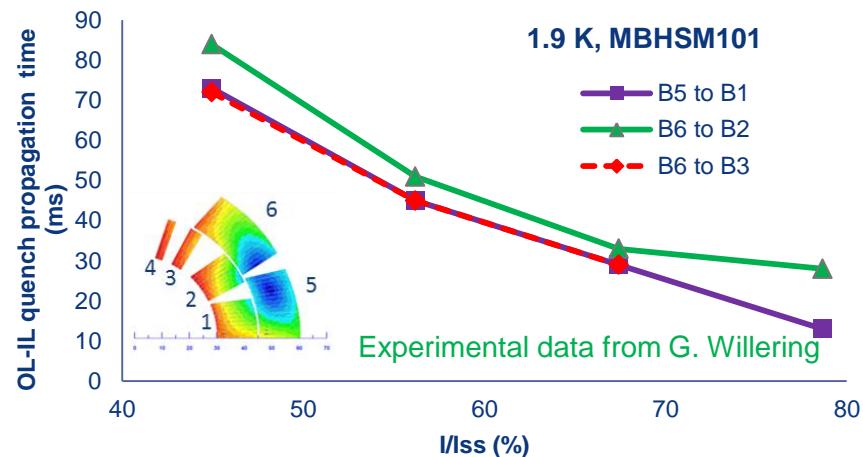
PH peak power = 50-55 W/cm<sup>2</sup>,  
 $\tau = 40-45 \text{ ms}$



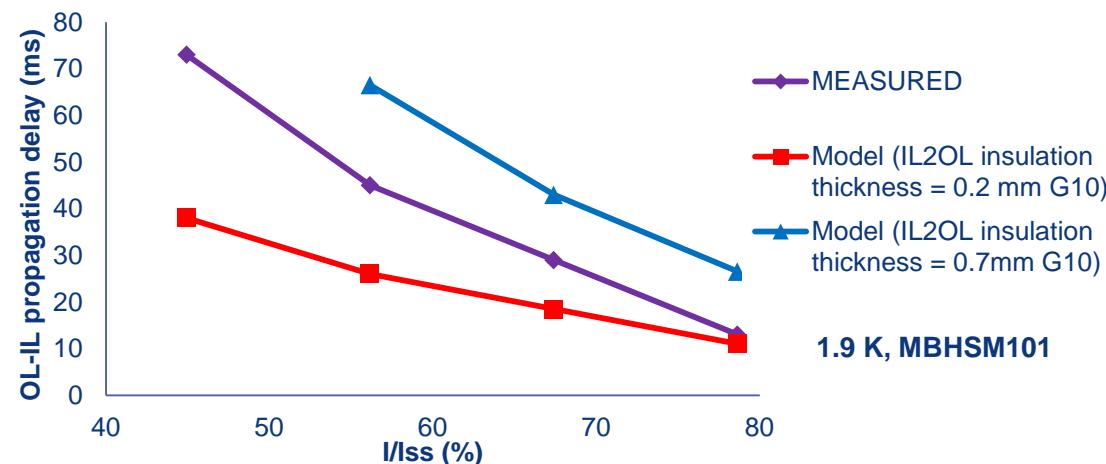
- MBHSM101 4.3 K  $P_{\text{ave}} = 52 \text{ W/cm}^2$
- MBHSM101 1.9 K  $P_{\text{ave}} = 52 \text{ W/cm}^2$
- ▼- MBHSM101 1.9 K  $P_{\text{ave}} = 118 \text{ W/cm}^2$
- MBHSP101 1.9 K  $P_{\text{ave}} = 118 \text{ W/cm}^2$

# Quench propagation within the coil

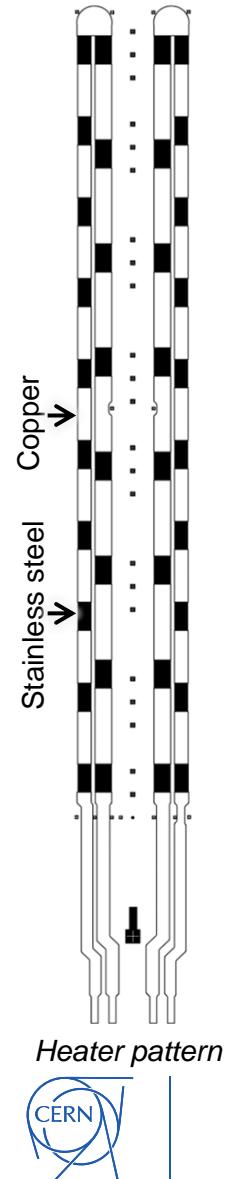
- Measurements at FNAL and CERN show quench propagation from outer to inner layer in the order of 15 ms for 80 % Iss.



- Agreement with the model is reasonable, given the uncertainties in the thermal conductivity properties of the material in the interlayer



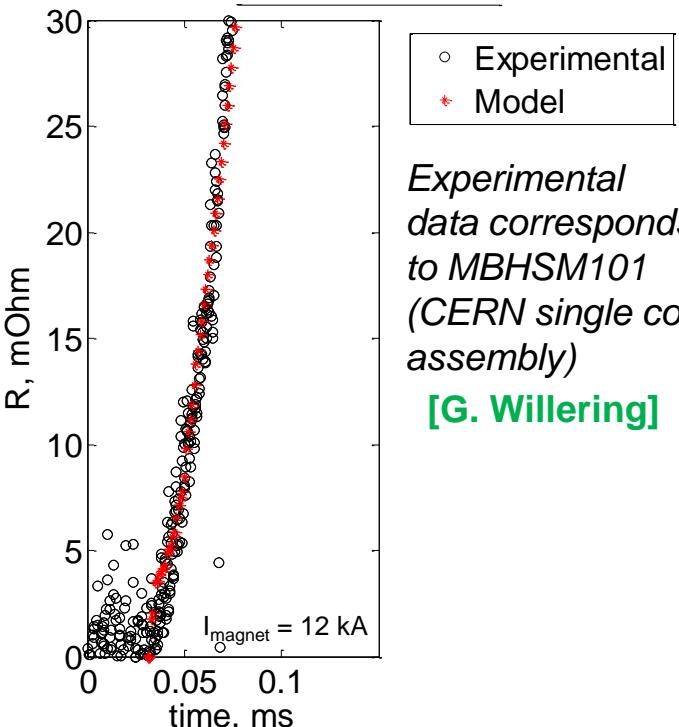
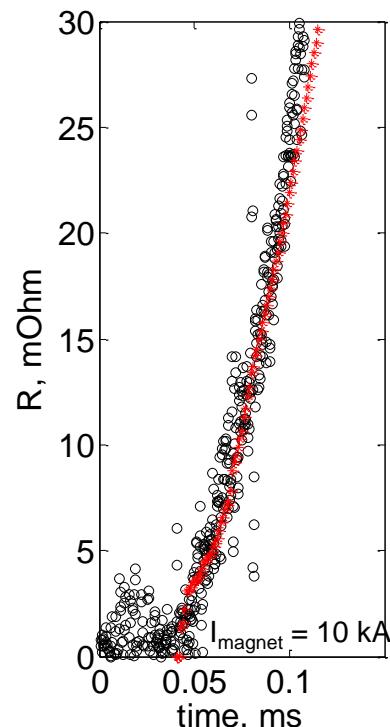
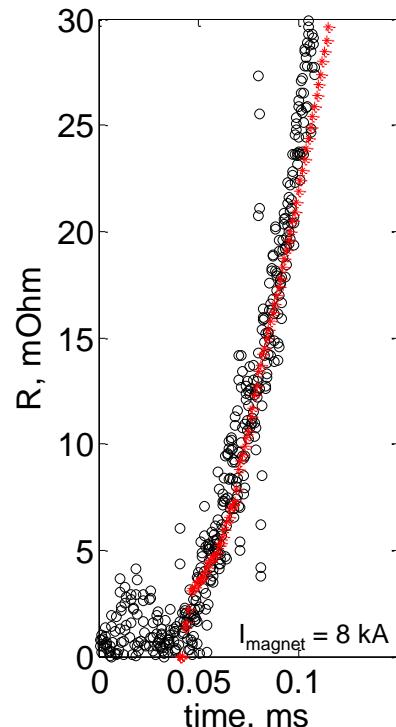
# Coil resistance growth



Quench heaters are covering ~ 1/3 of the magnet in the longitudinal direction, but resistance growth is well reproduced by the model assuming that the entire magnet length is covered my heaters



A decrease of the distance between the heater stations will not significantly improve the quench heater performance.

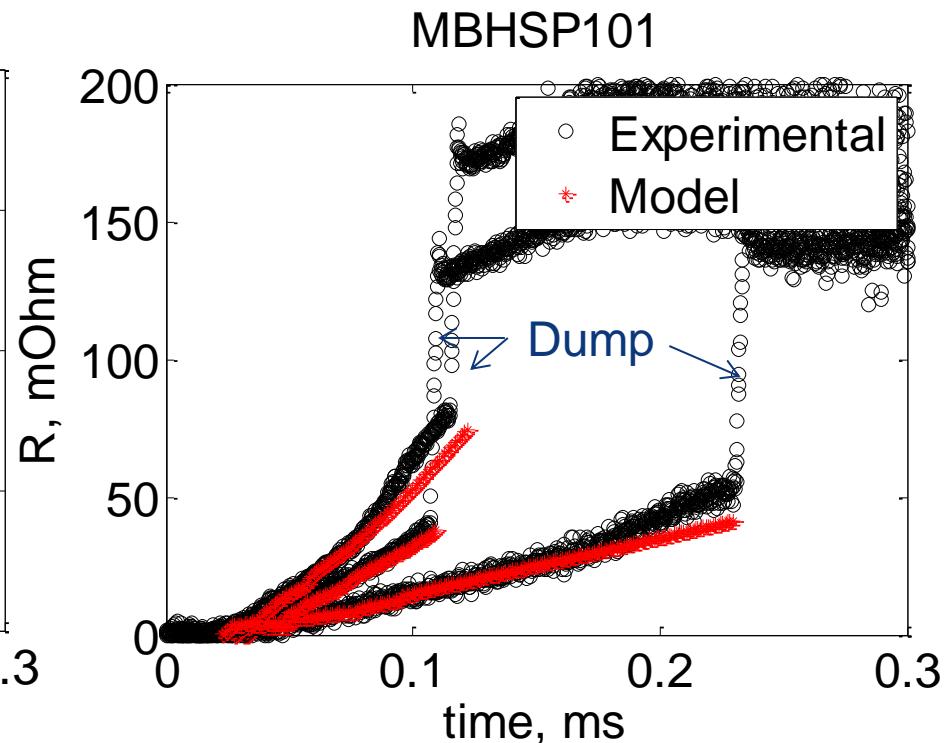
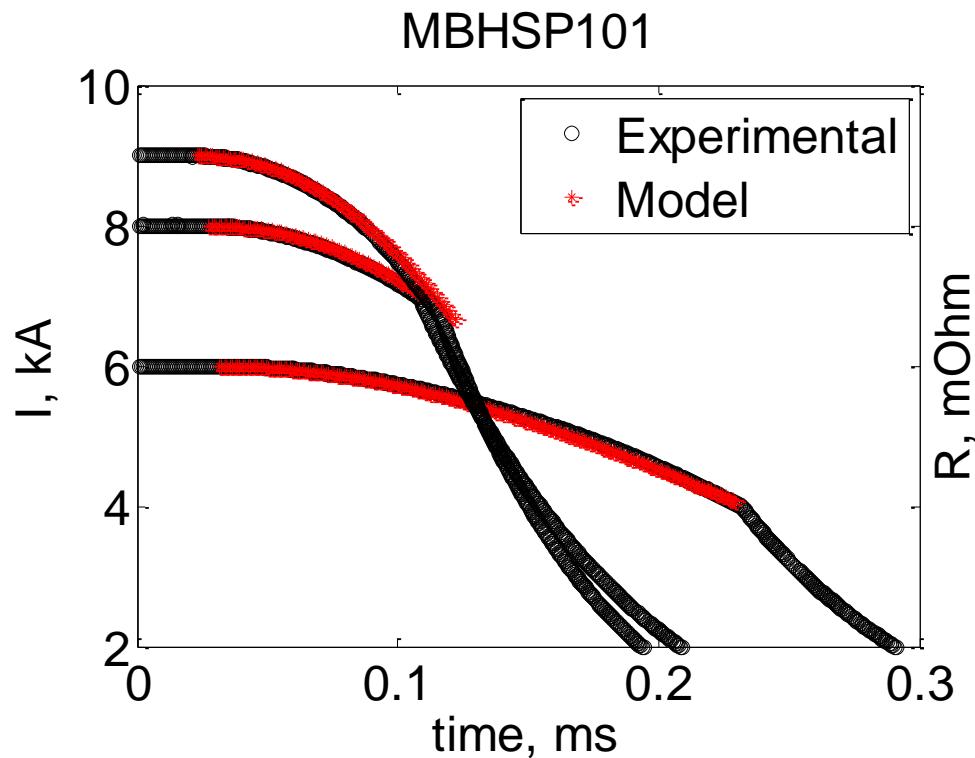


Experimental data corresponds to MBHSM101 (CERN single coil assembly)

[G. Willering]

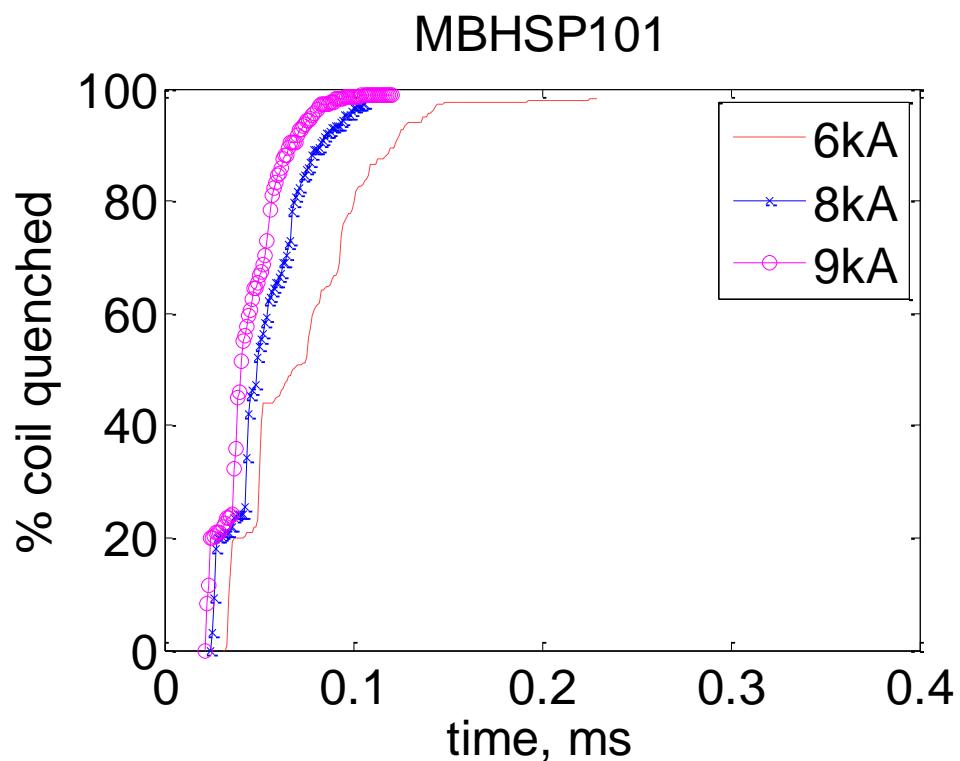
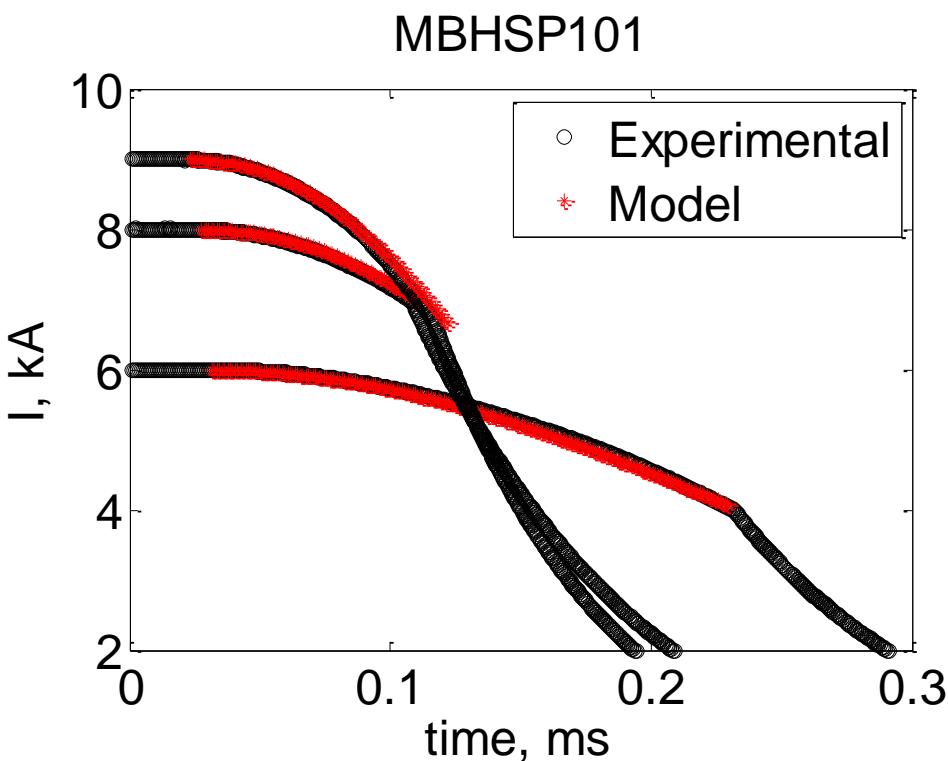
# Coil resistance growth

- Agreement with the model is also reasonably good for MBHSP101
- Refinement of the model required to account for AC-losses and variation of inductance which might explain the difference between experimental and modelled values



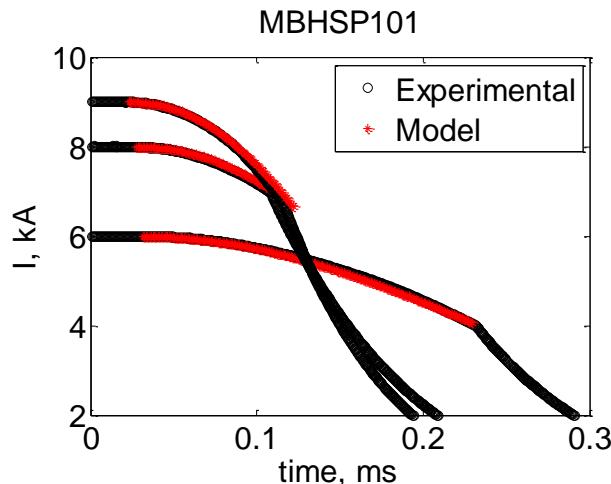
# Coil resistance growth

- According to the model, all the magnet is already quenched before dumping the current through the resistor



# Quench Integral Studies

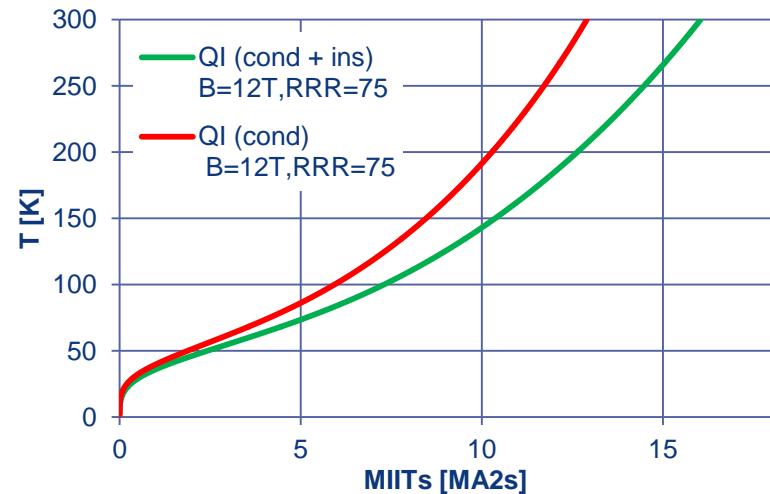
- QH provoked quenches delaying the protection, we were **very conservative!**



I [kA]	MIITs from heaters fired to effective [MA <sup>2</sup> s]	MIITs decay [MA <sup>2</sup> s]	TOTAL MIITs [MA <sup>2</sup> s]
6.0	1.10	6.40	7.5
8.0	1.48	7.02	8.5
9.0	1.68	8.02	9.7
10.0	1.67	8.53	10.2

- Most of the energy was already dissipated due to the coil resistance growth before dumping the current through the resistor  
→ for the **next aperture** we should perform tests without extraction relaying **only** in the quench heaters

I (kA)	MIITs decay measured (QH+Dump) [MA <sup>2</sup> s]	Expected MIITs decay if only QH [MA <sup>2</sup> s]	diff(%)
6.0	6.40	7.23	86
8.0	7.02	8.07	87
9.0	8.02	8.75	92
10.0	8.53	9.2	93



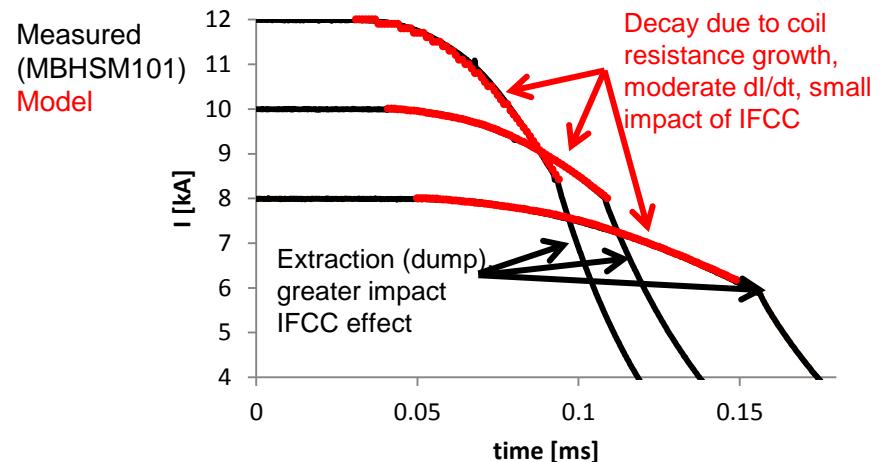
# Quench Back & Dynamic Effects

No specific tests were performed in MBHSP101. Next aperture

- Fast energy extraction tests
- AC loss measurements

Nevertheless, AC losses and reduction of apparent inductance due to the IFCC does not seem to play an dominant role at the expected range of  $di/dt$ : current decay is pretty well reproduced neglecting dynamic effects

For higher  $di/dt$ , this effect can have an important impact on the decay.



Experimental data from [G. Willering]

If present, it will help to spread the magnet stored energy, but as there is not clear evidence of it, it is not being consider for the model

# Remarks/Conclusions

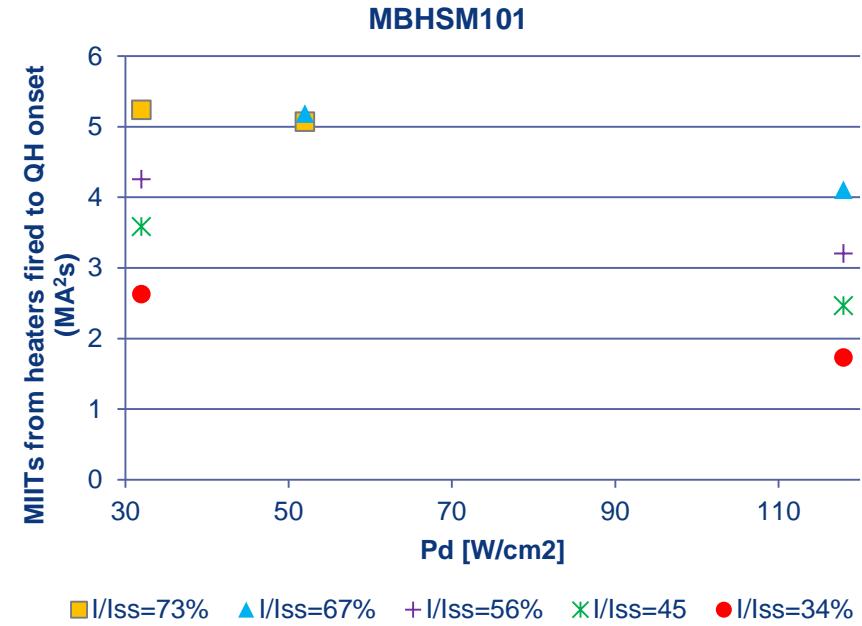
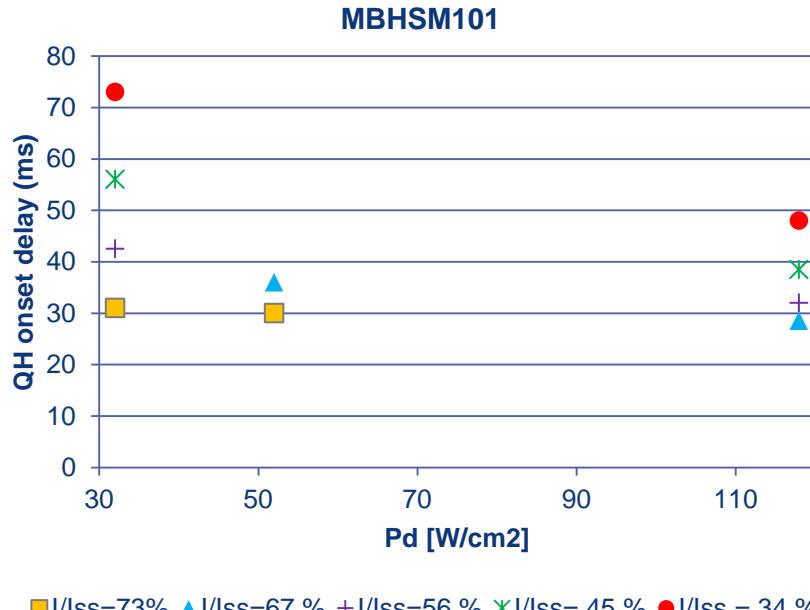
- Efficient heat transfer from quench heaters to coil is a must, so the **insulation thickness** between quench heaters and insulation **should be minimized!**
- High MIITs tests should be done in the next aperture to demonstrate if the magnet can be protected with only the outer layer heaters in redundant configuration.
- EE discharges at different current level and with different values of extraction and AC loss measurements will be also done to further understand the contribution of the dynamic effects.

# Additional slides



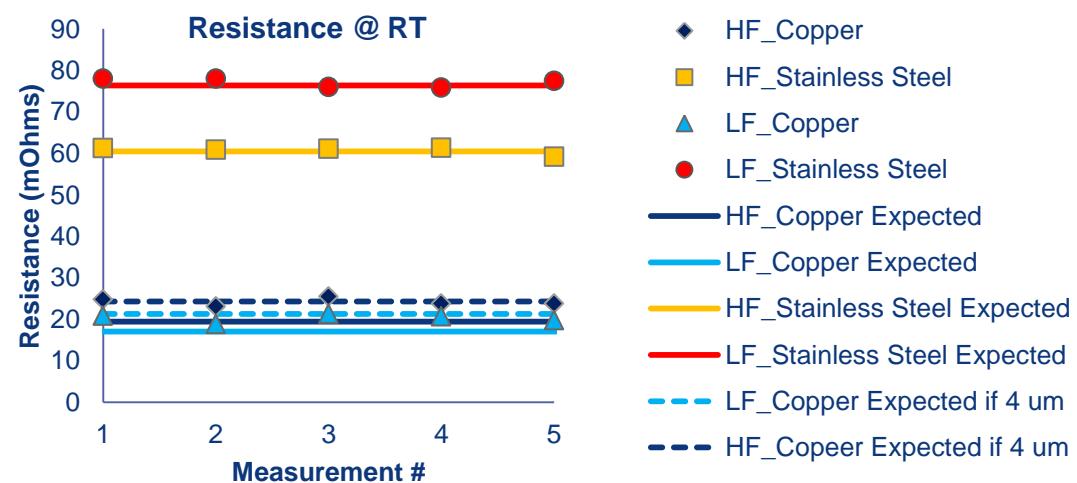
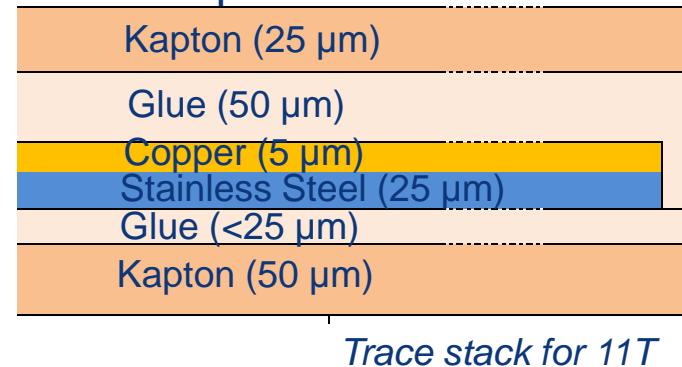
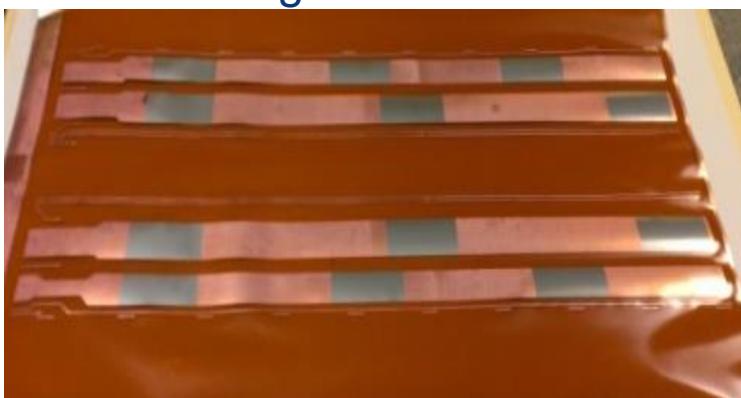
# Heater delay – Heater power density

- The impact of the quench heater power density in the heater delay was studied in the mirror assembly (MBHSM101)
- At low  $I/I_{ss}$  level, the heater power density has a strong impact on the delay. The impact decreases when increasing the current and an increase of heater power density beyond  $120 \text{ W/cm}^2$  will not significantly reduce the heater delay.
- Even if the delays are much longer at low current, the high current region is the critical point.



# Trace manufacturing and characterization

- Resistance measurements at RT and 77 K
  - Stainless steel stations: Measured resistance close to expected values
    - 3% difference at RT
    - 8 % difference at 77K
  - Copper regions: Measured resistance higher than expected value
    - 20% difference at RT
    - 25 % difference at 77K
- High current test
  - No degradation was observed in the bonding
- Temperature cycling at 77 K
  - No degradation



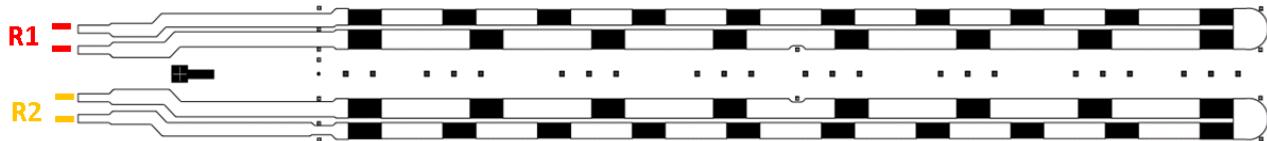
$$\rho_{ss} = 7.3 \cdot 10^{-7} \Omega m, RRR_{ss} = 1.34$$

$$\rho_{ss} = 1.8 \cdot 10^{-8} \Omega m, RRR_{ss} = 30$$

# Trace QA

## Before trace installation

- Resistance measurements at RT

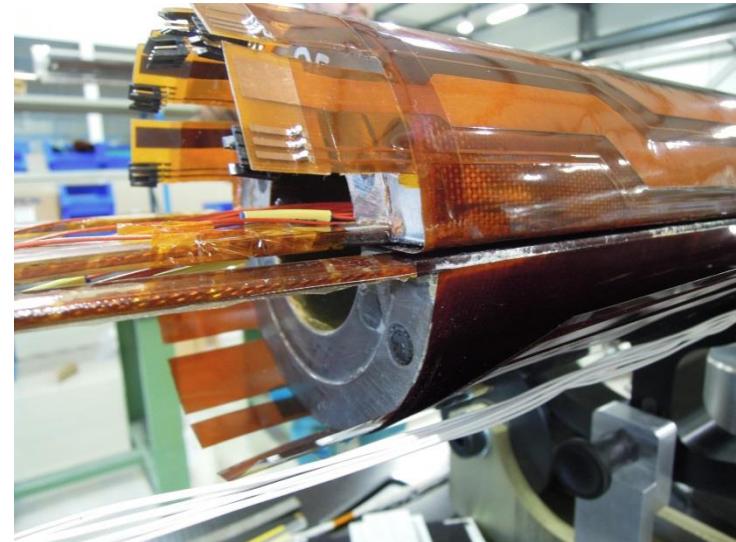


Expected value:  $R1=R2=1.65 \Omega$   
Measured value  $\approx 1.7 \Omega$

- High voltage test to ground under 20-30 MPa pressure (**2kV**).

## After trace installation, every step of the manufacturing process

- Resistance
- QH to ground and QH to coil (1 kV)
- Discharge test (pulse). Low thermal load to the heaters (under adiabatic conditions and assuming constant material properties, peak current defined to limit the temperature increase to 50 K) (only in the manufacturing steps after collaring)

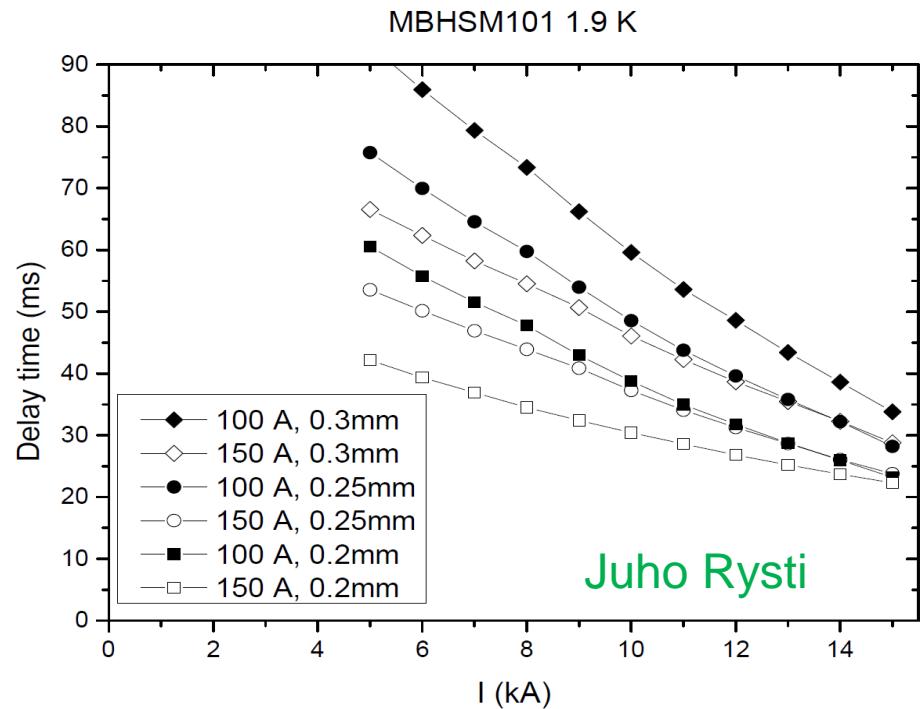
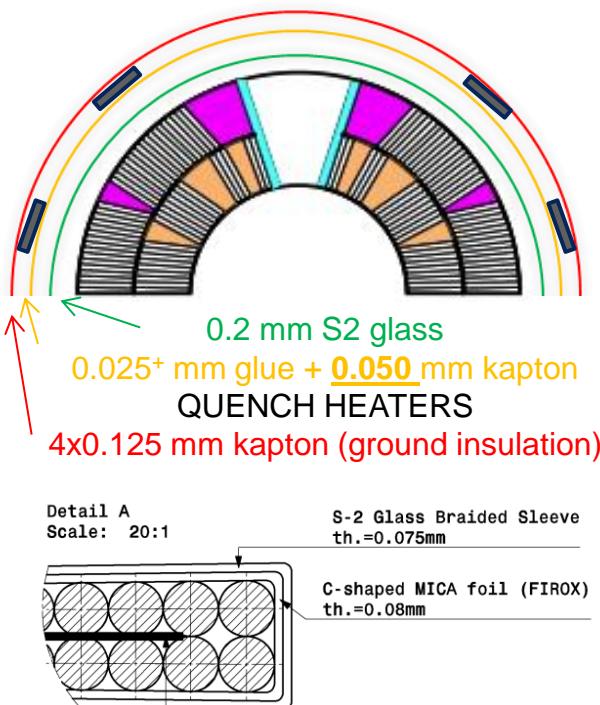


# AC loss

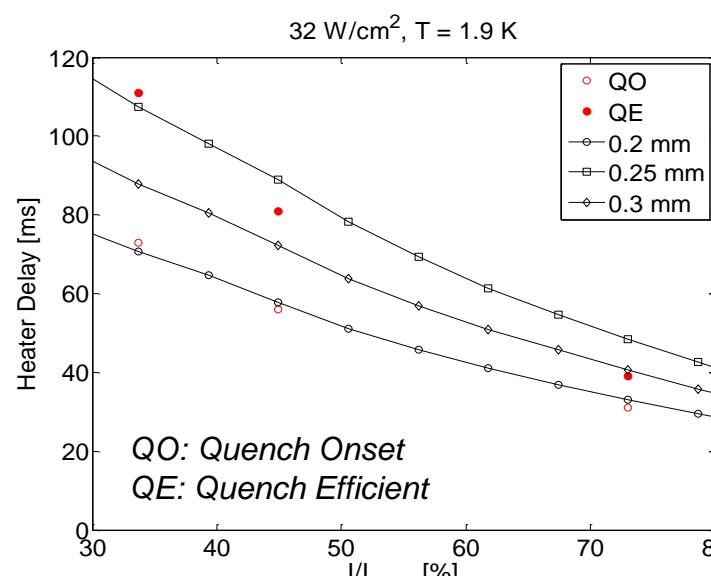
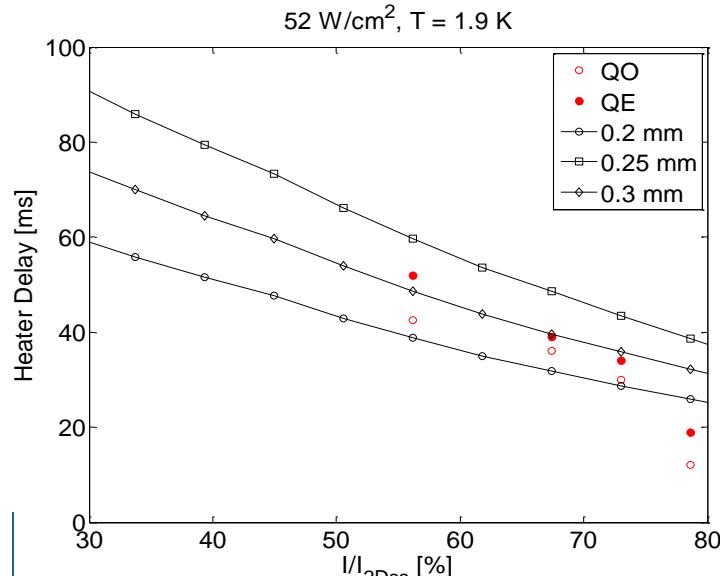
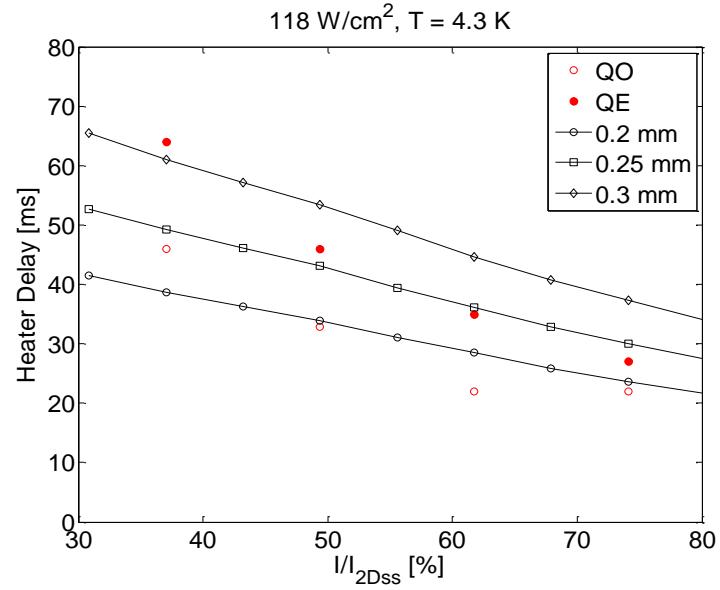
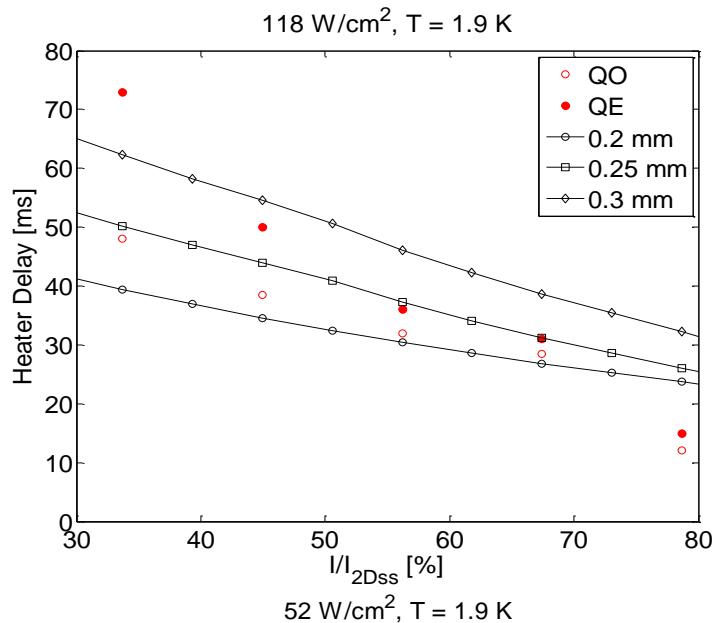
1. EE discharges at different current level and with different values of extraction resistor; manually triggering the EE, without firing QH (quench protection is not disabled, so in the case of a natural quench the magnet is protected by EE).
  - measuring the voltage and current we'll be able to observe the presence of quench back and assess the contribution of IFCC/ISCC dynamic effects
    - $R_{EE} = 10 \text{ mOhm}$ ,  $I_0 = 3, 5 \text{ kA}$
    - $R_{EE} = 20 \text{ mOhm}$ ,  $I_0 = 3, 5, 7 \text{ kA}$
    - $R_{EE} = 40 \text{ mOhm}$ ,  $I_0 = 3, 5, 7, 9 \text{ kA}$
    - $R_{EE} = 60 \text{ mOhm}$ ,  $I_0 = 3, 5, 7, 9, 11 \text{ kA}$
    - $R_{EE} = 120 \text{ mOhm}$ ,  $I_0 = 3, 5, 7, 9, 11 \text{ kA}$
2. AC loss measurements. Trapezoidal cycles between 500 A and 6000 A at different ramp rate  
The first trapezoidal cycle should be performed twice; during the first pre-cycle the AC loss due to magnetization in the superconductor will be different from the others
  - ramp rates: 10, 20, 50, 100, 150 A/s (possible 200 A/s?)
  - Plateau of 30-60 seconds between each ramp.
  - Max current of 6 kA to avoid measuring the iron-saturation effects
  - From this measurements we can try to extrapolate the value of cross-contact resistance

# Comparison to modelled delays

- Model by Juho Rysti using the commercial software COMSOL
- Basis of the model are the same as Tiina's model (<https://indico.cern.ch/event/311824/>)
- Quench heater delays modelled for different thickness of S2 glass between coil and heaters. Nominal should be close to 0.3 mm.



# Comparison to modelled delays



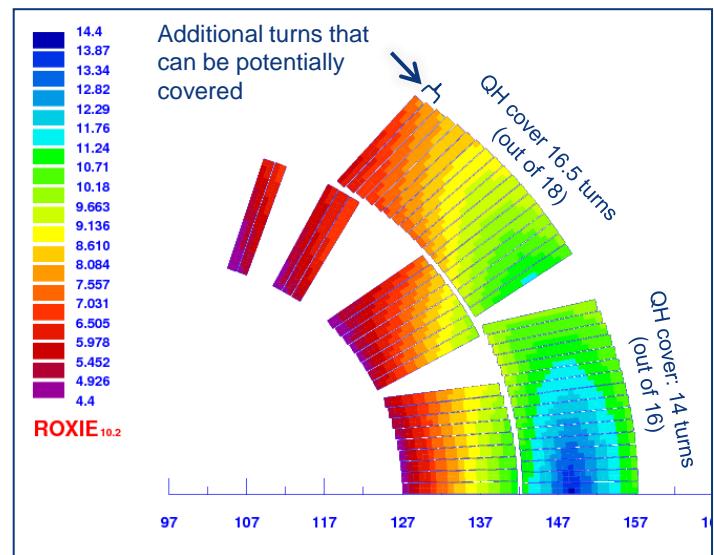
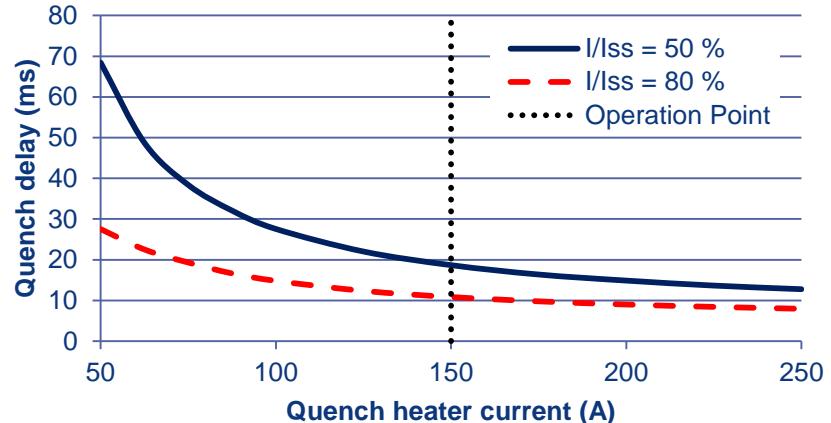
# Can we further optimize the outer layer heaters?

- The dominant parameters is the amount of insulation between heater and coil.
- If the insulation between heater and coil is only the conductor insulation + 50 µm of kapton, further increase of the heater power density is not going to improve the heater performance.
- Quench heaters are already covering most of the conductors in the outer layer. Two additional turns can potentially be covered if some voltage taps are removed, but the overall heater performance will not change significantly.



**Not a lot of room for optimizing the outer layer heaters**

(except further reduction of the insulation thickness between heater and coil)



# Training quench analysis

