Susana Izquierdo Bermudez, Hugo Bajas, Juho Rysti, Gerard Willering

MBHSP102 – Quench Protection Studies

Outline

- Reminder on some important magnet parameters
  - Conductor parameters
  - Coil parameters
  - Magnet parameters
- Initial quench propagation
- Quench heater performance
- Assessment of AC losses contribution
  - AC loss measurements
  - Magnetic measurements
  - Ramp rate study
  - Energy extraction tests
- Quench integral studies

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Conductor parameters

Here we only present the conductor parameters relevant to quench protection for the two coils assemble in MBHSP102

Details regarding the conductor are available in :

https://indico.cern.ch/event/406942/

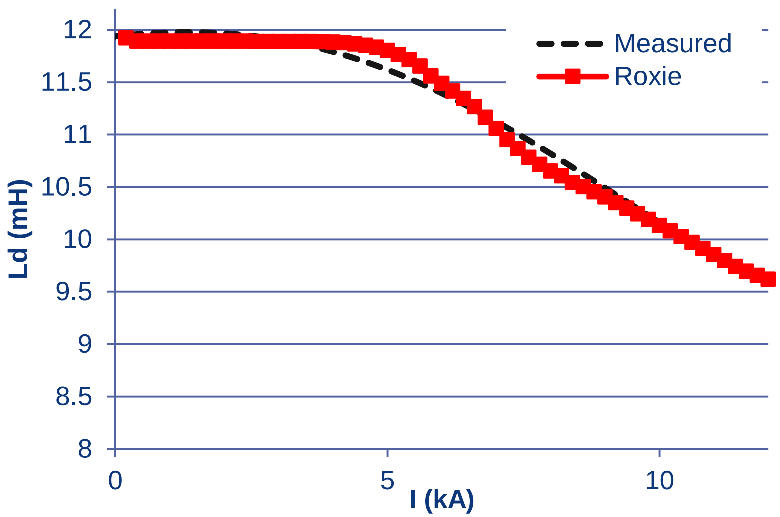
[B. Bordini]

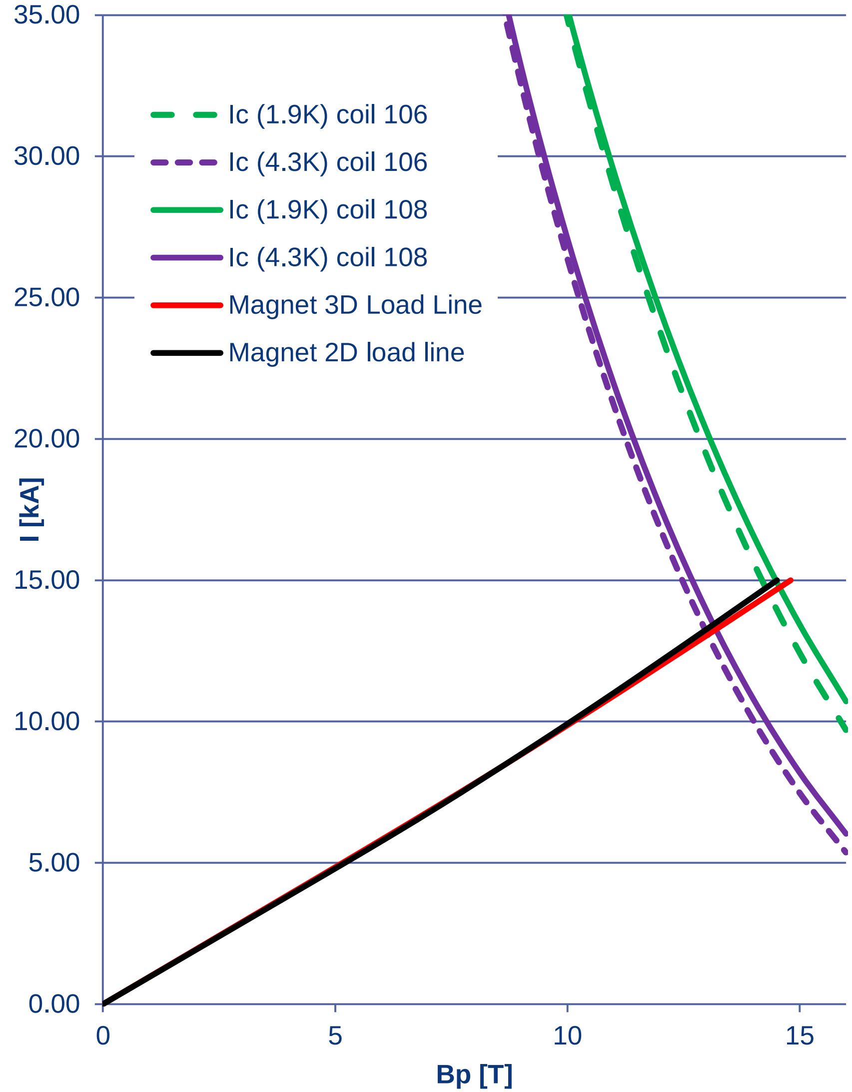
		Nominal	Coil 106	Coil 108
Strand			RRR 108/127 Ta-Dopped	RRP 132/169 Ti Dopped
Cu/nCu	--	1.15+-0.1	1.22	1.22
Cable width	mm	14.7	14.717	14.696
Bare Cable Thickness	mm	1.25	1.2491	1.246
Keystone angle	deg	0.79	0.783	0.787

Nominal parameters			
		Before Reaction	After Reaction
Number of strands	-	40	40
Strand diameter	mm	0.7	0.7
Cu/nCu	-	1.2	1.2
Cable width	mm	14.7	14.847
Bare Cable Thickness	mm	1.25	1.202
Insulation thickness	mm	0.155	0.1
Wire			
Swire	mm^2	0.385	0.385
Swire_sc	mm^2	0.175	0.175
Surfaces			
S_{cable}	mm^2	15.39	15.39
S_{bare}	mm^2	18.38	17.85
S_{cu}	mm^2	**8.40**	**8.40**
S_{sc}	mm^2	7.00	7.00
S_{impreg}	mm^2	2.45	2.45
$S_{insl.}$	mm^2	3.25	3.25
$S_{insl.+imprg.}$	mm^2	5.70	5.70
S_{total}	mm^2	**21.10**	**21.10**
Volum Ratio			
Copper	-	**0.398**	**0.398**
Superconductor	-	**0.332**	**0.332**
insulation & impregnation	-	**0.270**	**0.270**

Coil and magnet parameters

		106	108
Coil Resistance at RT	**mOhm**	423	406
ground wrap outer	**type/mm**	none	Glass 0.1
ground wrap inner	**type/mm**	none	Glass 0.1
Average RRR coil		62	165
Iss	**kA**	14.5	14.75





Measurements: Gerard Willering

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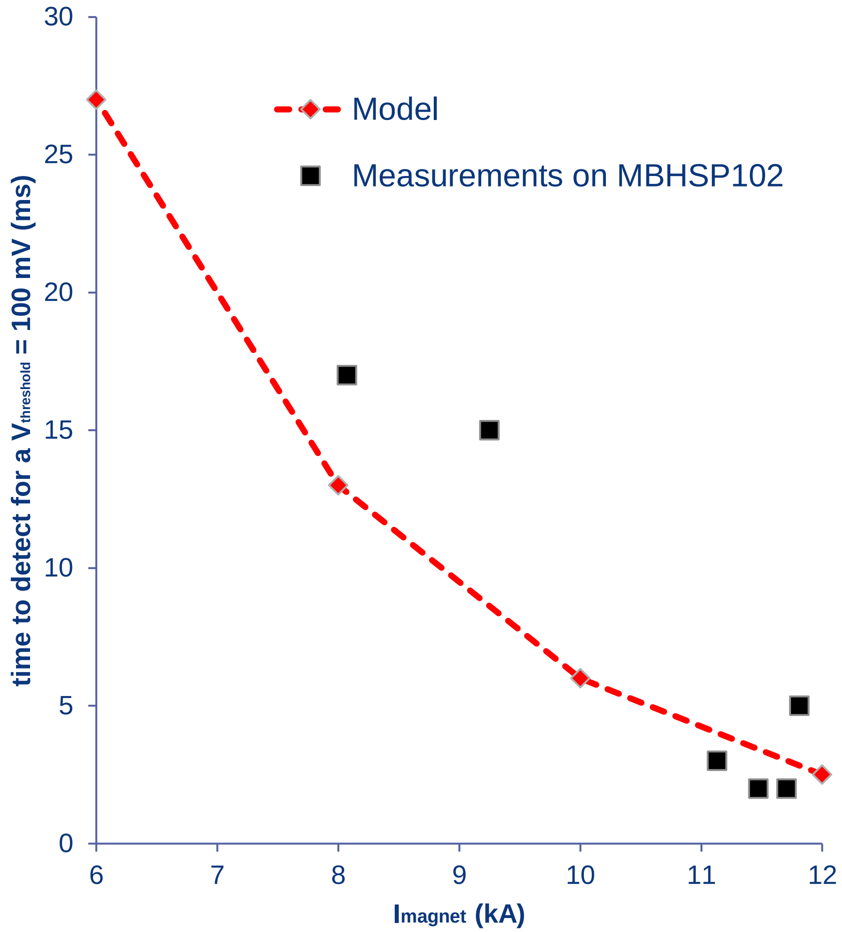
Initial quench propagation

- Time to detect the quench is very close to expected values at high magnet currents.
- At lower current, more discrepancy, but still within reasonable limits.



Measurements: Gerard Willering

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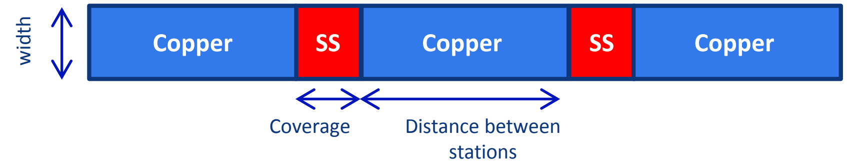
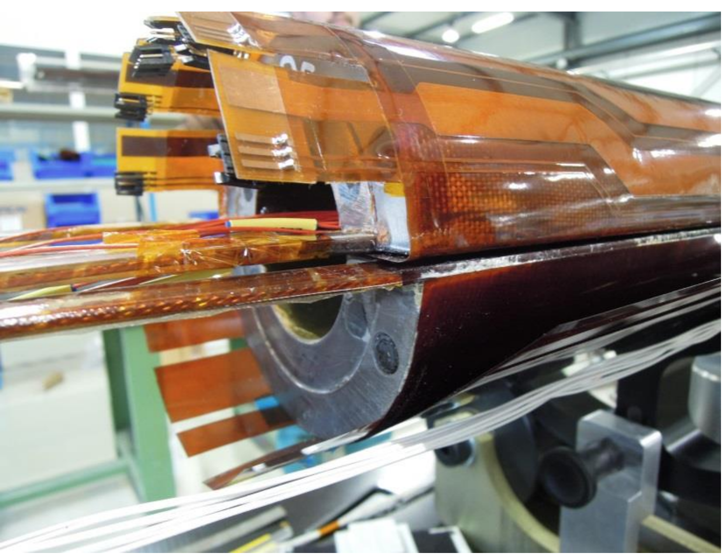
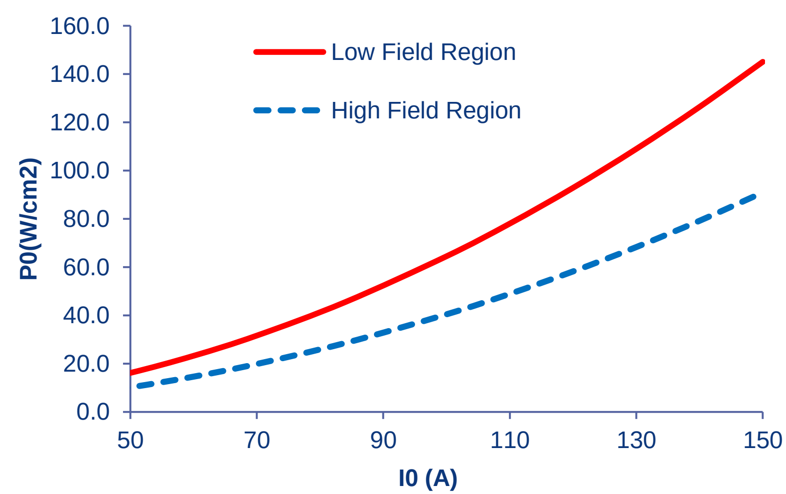
Heater design

- 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).
- Heater to coil insulation
  - 0.0-0.2 mm S2 glass (outer wrap during insulation, different thickness depending on the coil)
  - 0.050 mm of kapton + ~ 0.025 mm glue



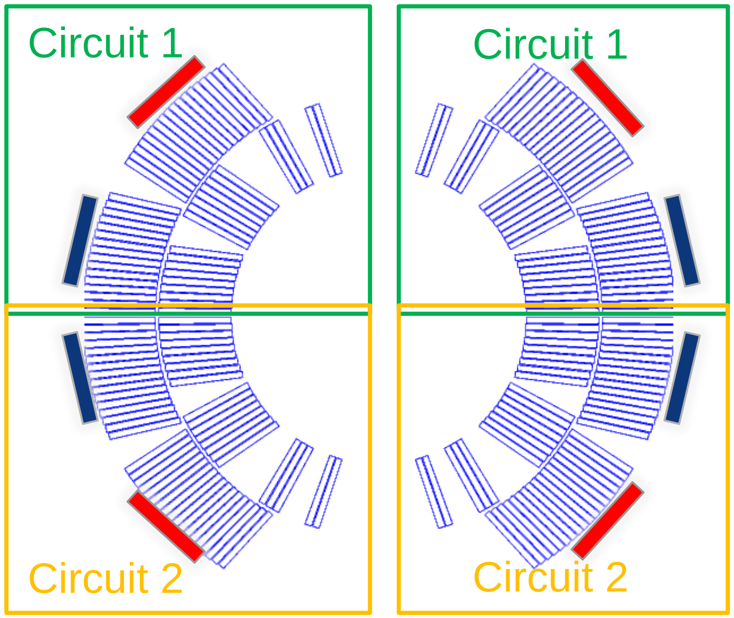
	Low field heater strip	High field heater strip
Coverage (mm) (Stainless steel part)	50	
Distance Between Stations (mm) (Copper plating)	90	130
Width (mm)	19	24
Stainless steel thickness (mm)	0.025	
Copper plating thickness (mm)	0.005	

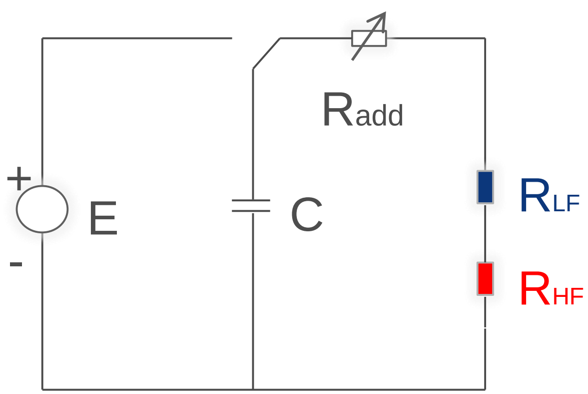




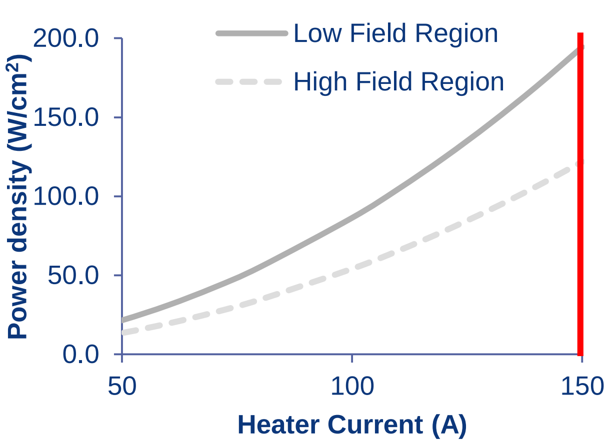
QH test set up in SM18

- "Standard" LHC Quench Heater Power Supply: V = ± 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
- In the previous assemblies, three different current levels in the heaters were explored: 80 A, 100 A and 150 A. For MBHSP102, quench heater tests performed only for I_{qh}= 150 A.





I [A]	PLF [W/cm²]	PHF [W/cm²]	Pave [W/cm²]	RC (ms)
80	41.3	25.9	34	80
100	64.5	40.4	52	64
150	145.1	91.0	118	42

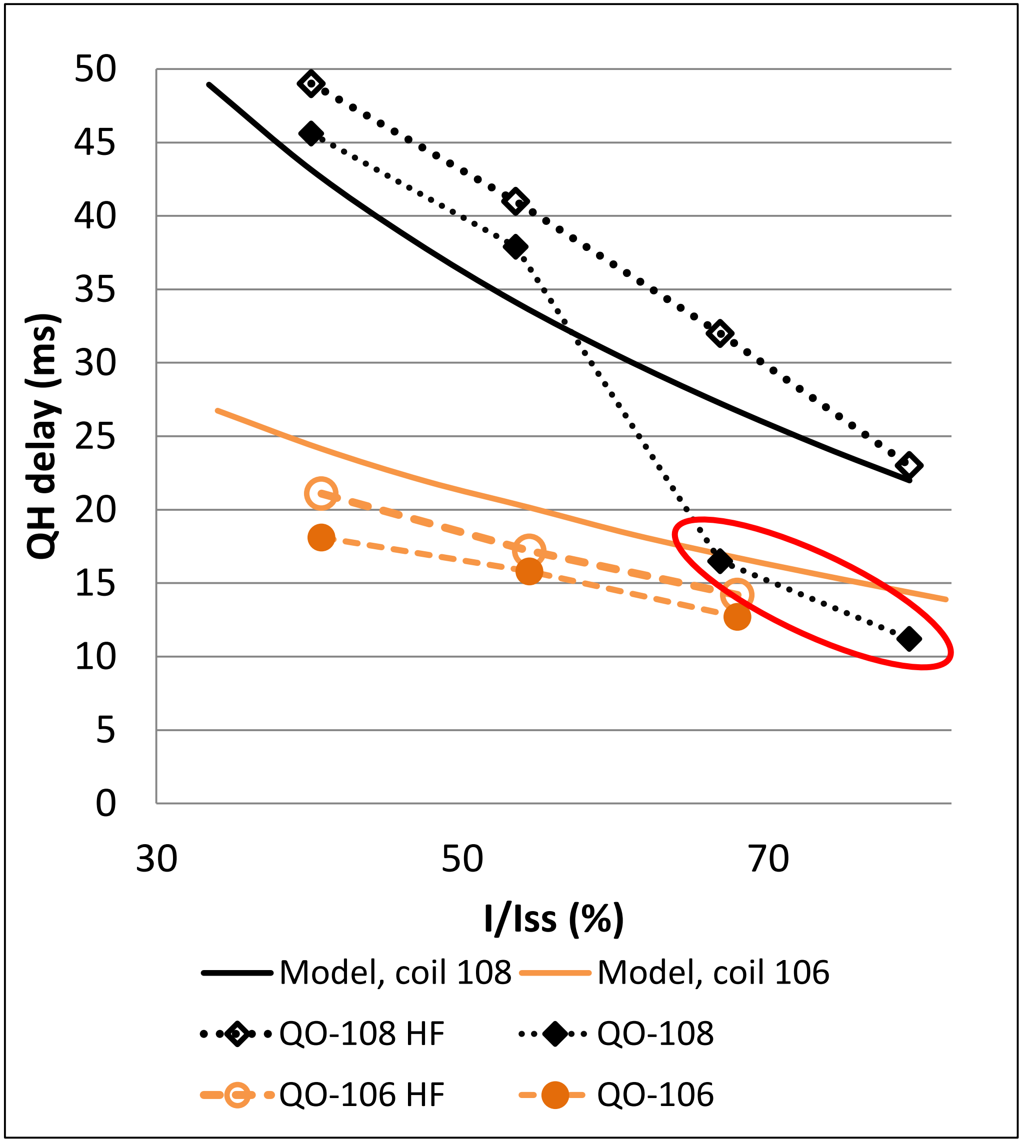


Quench heater study test plan

1. **Tests performed:**
   1. PH delay as a function of the magnet current for a quench heater current = 150 A.
   2. Compare performance of the 106 and 108 heaters.
      1. If from the previous test it is not possible to evaluate QH delay in coil 108, repeat the test from firing only coil 108 heaters
2. **Not performed, to be done in the next aperture if enough time available:**
   1. Check the lowest required power density quenching the magnet at different currents I_{mag} = 2 kA, 4 kA , 6 kA, 10 kA and I_{nom} (11.85 kA). All heaters are fired, gradually increase the heater current.
   2. PH delay as a function of the heater current (I_{qh} = 80A, 100A and 150A) at 6 kA, 10 kA and I_{nom}.
   3. PH delay as a function of the HFU decay time constant at I_{mag}=0.6Inom, 0.8Inom and Inom. (Probably it is not possible)
   4. Reproducibility check for the 106 and 108 heater delay at 6 kA, 10 kA and Inom. I_{qh} = 150A (lower priority, magnet current levels will depend on previous tests)

Quench Onset

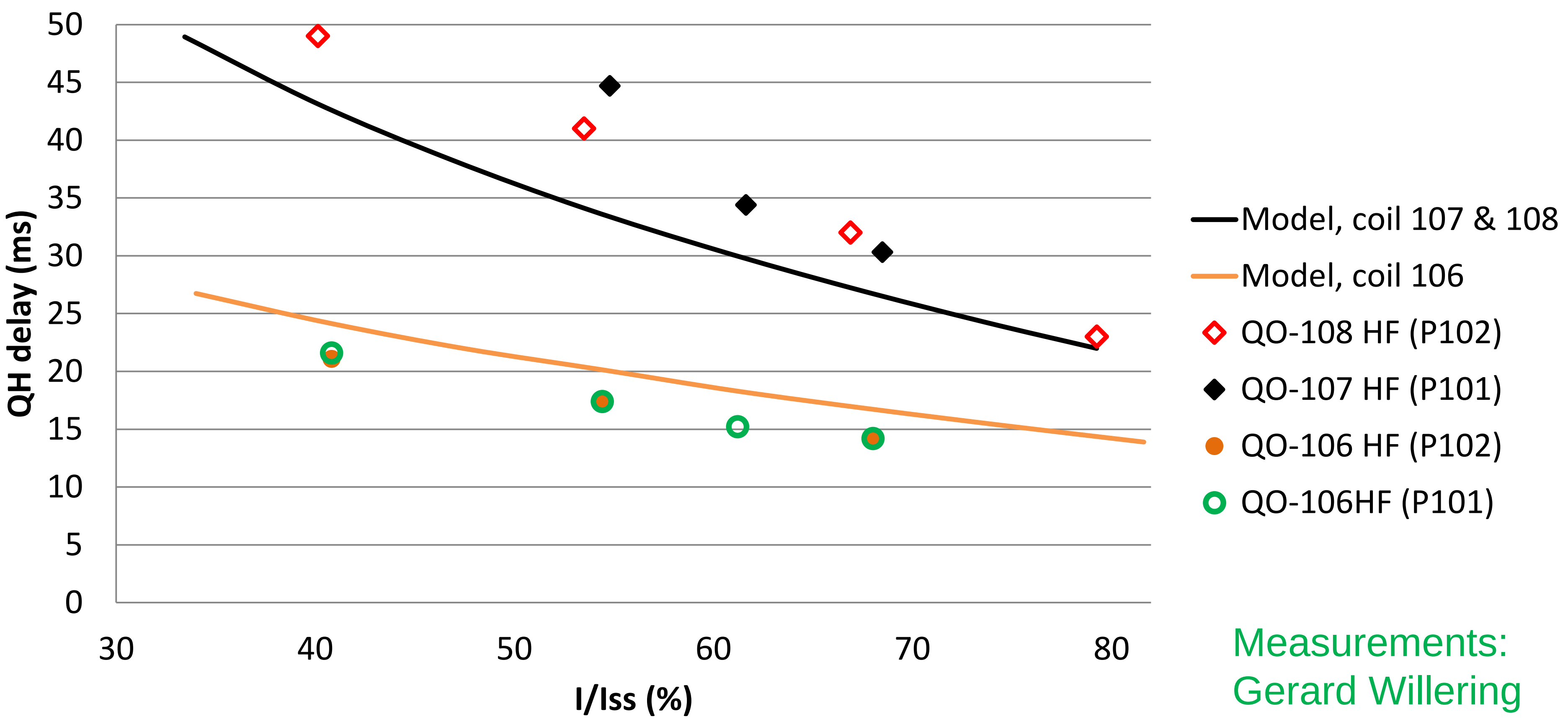
- Good agreement on the quench heater onset under the heaters (QO – HF, as expected, quench starts in the high field region).
- As observed in MBHSM101 (coil105), very fast quench starts in the pole turn (not covered by the heaters) in coil 108 at high current:
  - It has to be linked to the quench heater firing
  - Pole turn and heater are not in thermal contact, so it is difficult to explain this fast quench due to heat propagation from heater to coil



Measurements:
Gerard Willering

Quench onset

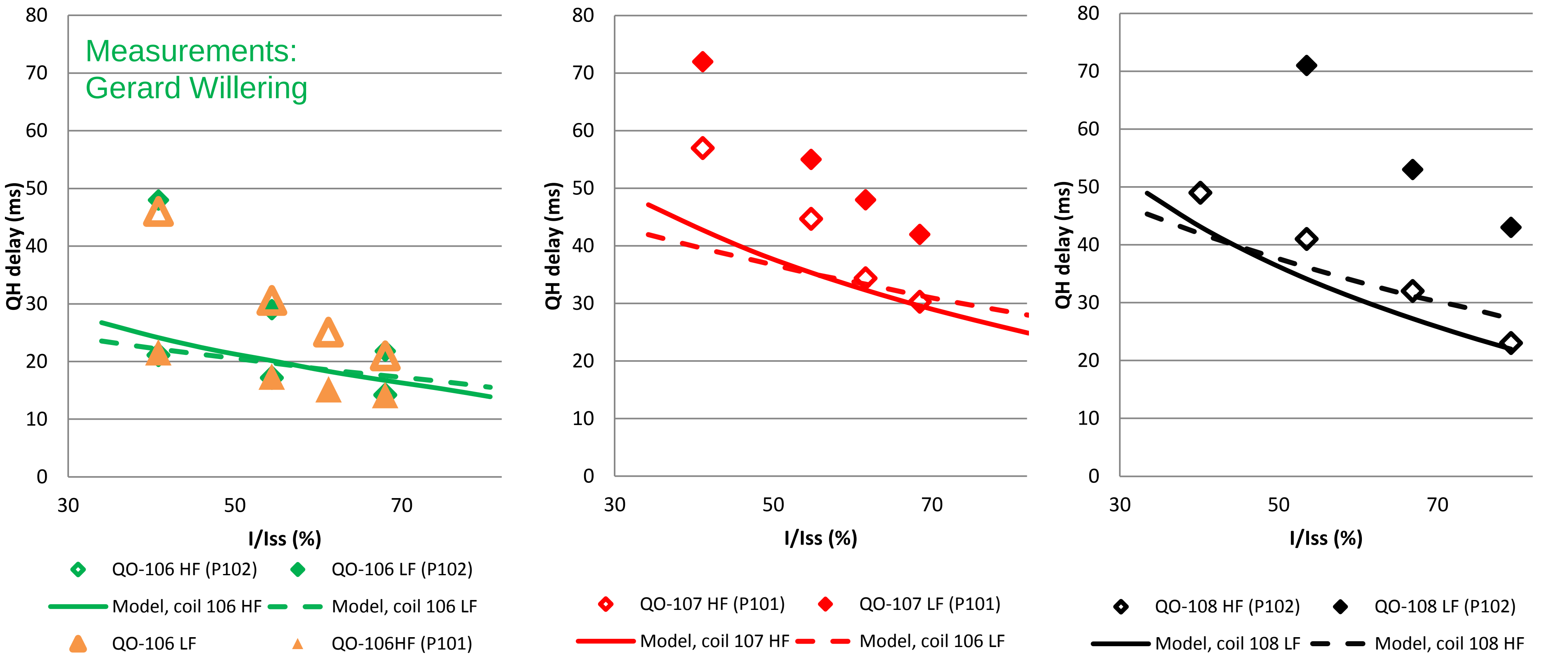
- Quench onset delay is consistent with the measurements in MBHSP101
- Differences in coil to heater insulation:
    - Coil 106: no glass on the outer during impregnation
    - Coil 107 & Coil 108: 0.1 mm S2 glass



Measurements:
Gerard Willering

Quench Heater Efficiency

- The quench heater delay for the low field region is much longer than expected
- The behaviour is reproducible in coil 106
- The discrepancy is stronger for coil 108 than for coil 108 but both coils have the same insulation scheme so in principle the behaviour should be similar.



Quench Heater Efficiency

- Quench heaters of coil 108 are much less efficient that the heater of coil 106.
- In coil 108, the energy dissipated in the inner layer is about the same as the energy dissipated in the outer layer → quench back is present and its contribution is not negligible

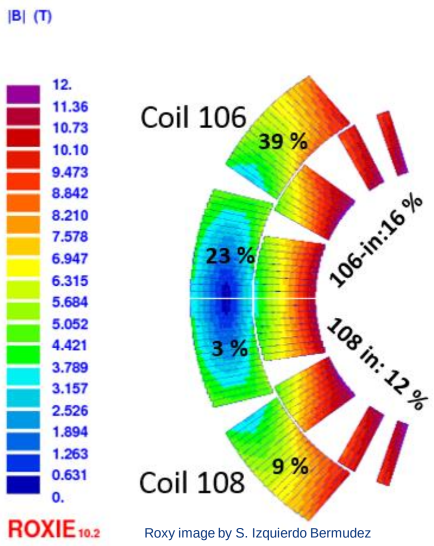
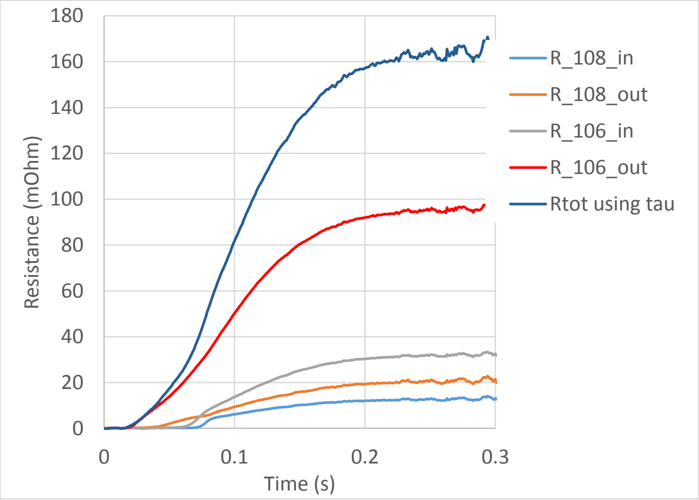
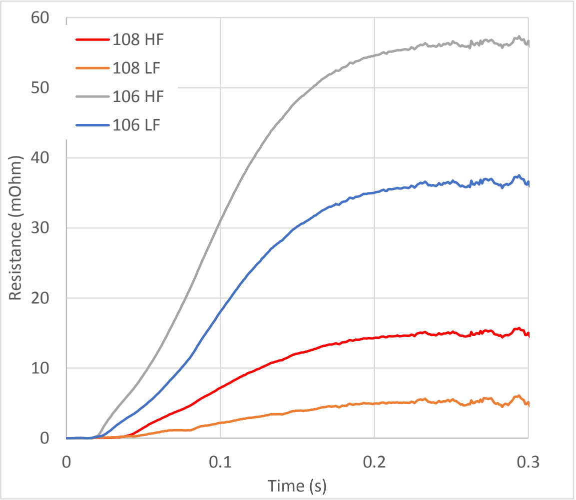


Figure: heat deposition distribution.
10 kA, all heaters fired simultaneously, I_{QH} = 150 A.



Resistance growth inner and outer layers.
10 kA, all heaters fired simultaneously, I_{QH} = 150 A.



Resistance growth HF and LF blocks.
10 kA, all heaters fired simultaneously, I_{QH} = 150 A.

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Assessment of AC losses contribution

Different contributions to be taken into account:

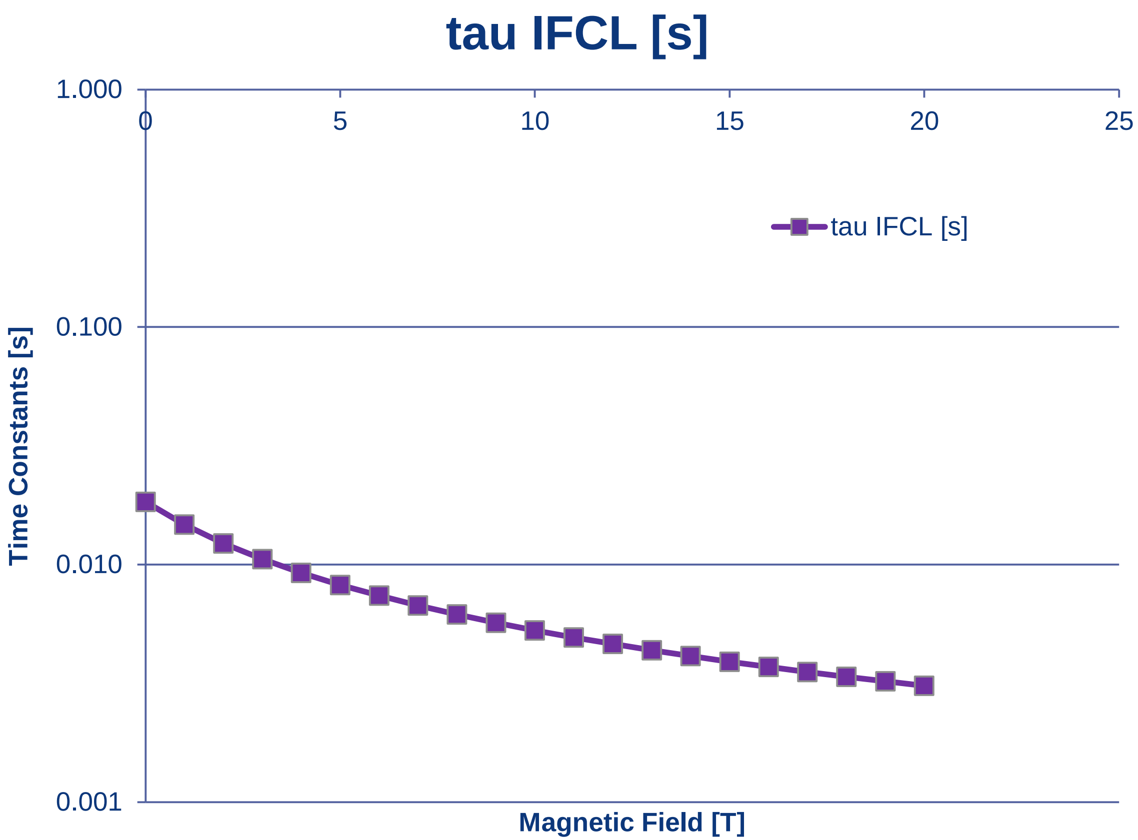
- Superconductor Magnetization Losses
  - Depend on the initial magnetization state and the current level
- Inter-Filament Coupling Losses
  - Depend on the current ramp rate and the current level
- Inter-Strand Coupling Losses
  - Depend on the current ramp rate, but not on the current level
- Losses due to Eddy Current in the Iron Yoke (we neglect them)

A set of tests were done to understand the contribution of the AC loss to quench protection:

- Magnetic measurements
- AC loss measurements
- Ramp rate study
- Energy extraction tests

Inter-Filament Coupling Losses

$$Q_{IFCL} = \frac{2\tau_{IFCL}}{\mu_0}\left(\frac{dB}{dt}\right)^2 \qquad \tau_{IFCL} = \frac{\mu_0}{2\rho_{eff}}\left(\frac{p_f}{2\pi}\right)^2$$



IFCL are a function of:

- **Filament twist pitch:**

$$p_w = 14\ mm$$

- **Effective transverse resistivity:**
  - Constant part of the magneto resistive matrix copper (Fil. R_O)
  - Derivative dR/dB of the magneto resistive matrix copper (Fil. dR/D_{b0})

$$\rho_{th} = \rho_0 + \rho_1 B$$
$$\rho_0 = 7.7E-11$$
$$\rho_1 = 4.45E-11$$

Inter-Strand Coupling Losses

$$Q_{ISCL} = \frac{2\tau_{ISCL}}{\mu_0}\left(\frac{dB_\perp}{dt}\right)^2$$

For a cable (from Arjan's Thesis):

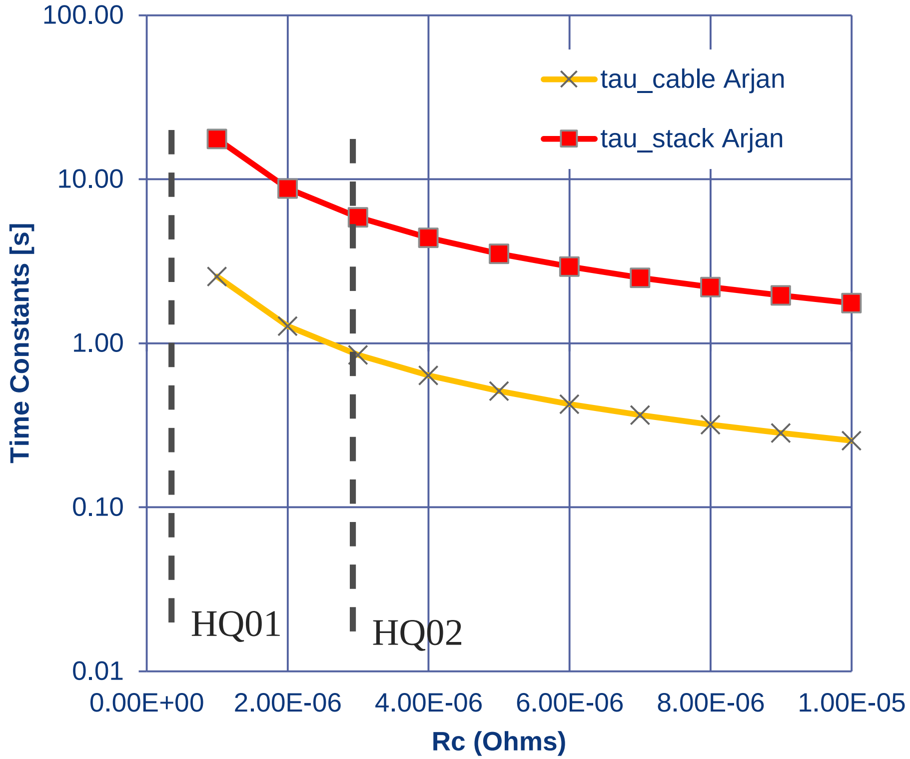
$$\tau_{ISCLc} = \frac{1.6 \cdot 10^{-8} p_s}{R_c}(N_s^2 - 4N_s)$$

For a stack (from Arjan's Thesis):

$$\tau_{ISCLs} = \tau_{ISCLc}\frac{N_s N_c}{4}\frac{1}{\frac{N_s}{4} + (N_c - 1)}$$

In our case:

- Strand transposition pitch p = 100 mm
- Number of strands Ns= 40
- Nc=20



[X. Wang] Multipoles Induced by Inter-Strand Coupling Currents in LARP Nb3Sn Quadrupoles

HQ01: (un-cored cable) Rc ~0.3 μΩ τ ~30-60 s

HQ02: (cored cable) Rc ~ 3 μΩ τ ~3-6 s

Magnetic measurements

- Very small dynamic effects observed.
- Comparing to HQ, R_c should be about 100 times more, this is too much, additional model validation needed!
- Remark! core coverage in HQ/11T is different:
  - HQ02 ~ 60 % core coverage
  - 11T ~ 80 % core coverage

Cable transposition pitch (mm)	Rc (μΩ)	Ra (μΩ)	
100	30	0.3	
5kA	20A/s	50A/s	100A/s
b3	1.39	1.97	2.93
b5	-0.15	-0.42	-0.86
b7	-0.19	-0.20	-0.21

Cable transposition pitch (mm)	Rc (μΩ)	Ra (μΩ)	
100	300	3	
5kA	20A/s	50A/s	100A/s
b3	1.04	1.08	1.16
b5	0.01	-0.01	-0.06
b7	-0.18	-0.18	-0.19

HQ:
- Rc ~ 0.3 μΩ for un-cored cable (HQ01)
- Rc ~ 3 μΩ for cored cable (HQ02)

[X. Wang] Multipoles Induced by Inter-Strand Coupling Currents in LARP Nb3Sn Quadrupoles

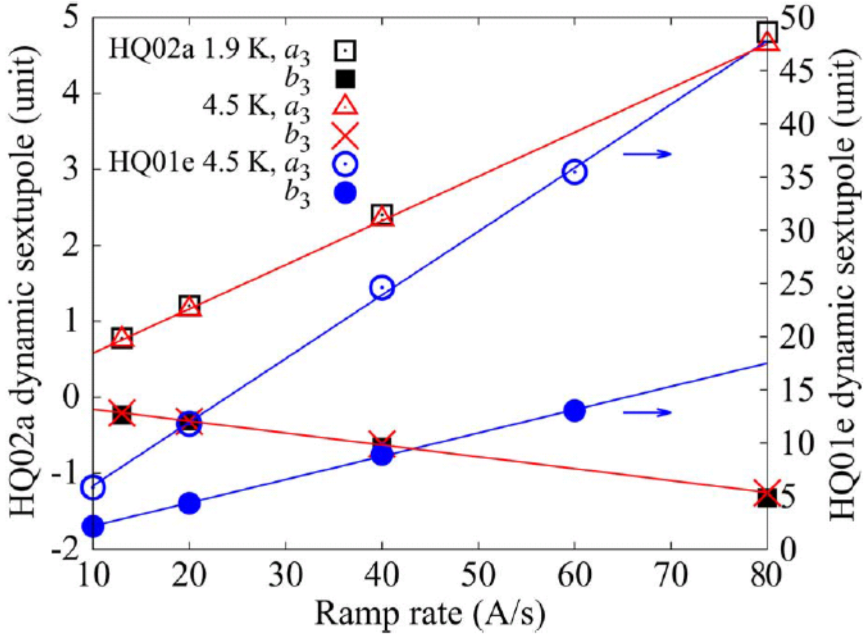
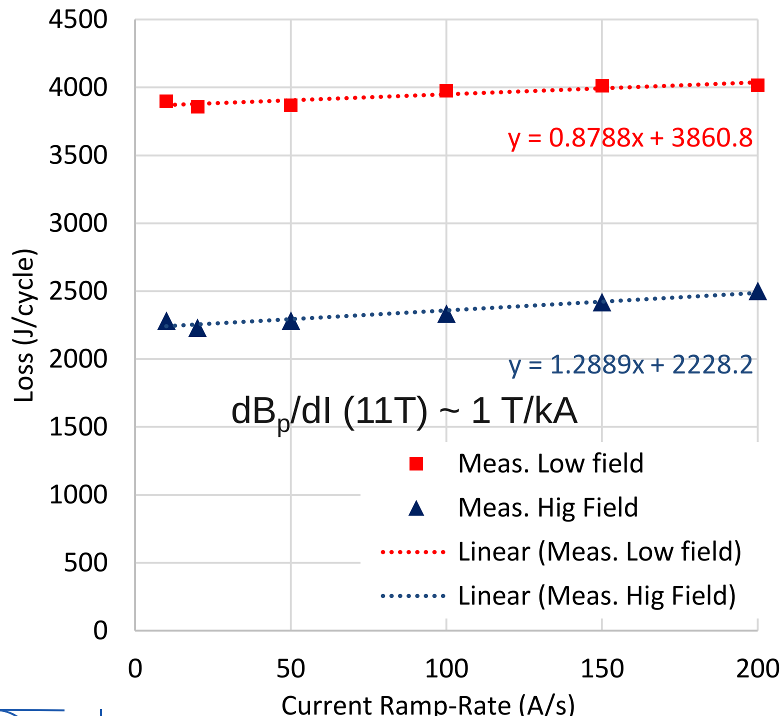


Fig. 8. Comparison of dynamic sextupoles as a function of ramp rate betwee HQ02a (primary y-axis) and HQ01e (secondary y-axis) at 10 kA. The soli lines are least-square linear fits of the data. $R_{\mathrm{ref}} = 40$ mm.

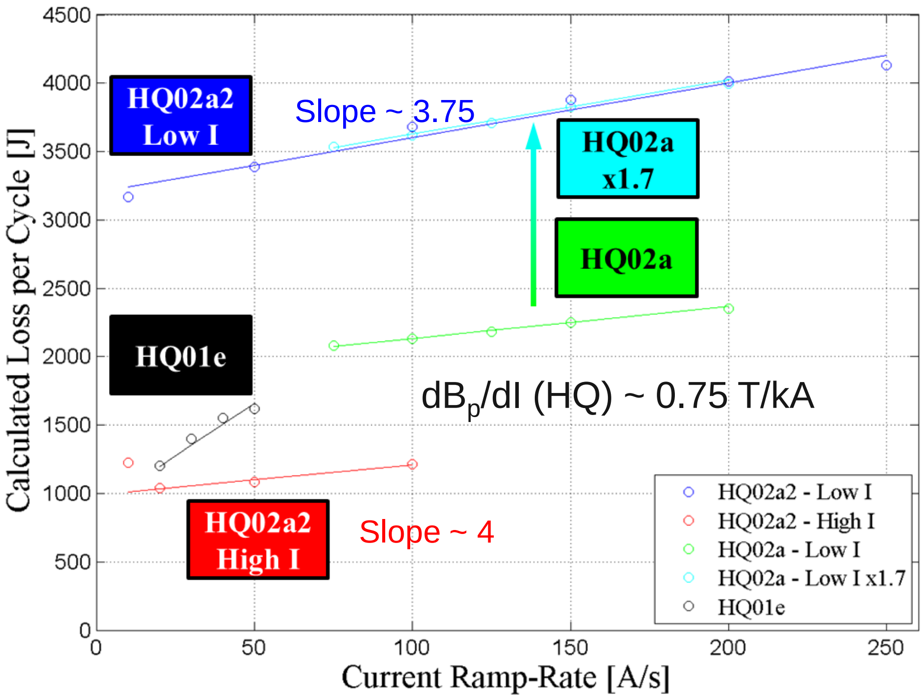
AC loss measurements

- Slope on the AC – loss measurements is ~ 2-3.5 times flatter than measurements on HQ.
- Comparing to HQ, R_c should be about 100 times more, this is too much, additional model validation needed!



HQ [E. Ravaioli]:

- ISCL
  - Rc ~ 0.3 µΩ for un-cored cable (HQ01)
  - Rc ~ 3 µΩ for cored cable (HQ02)
- IFCL
  - Effective transverse resistivity ~ 7.1·E-11 Ωm



Measurements:
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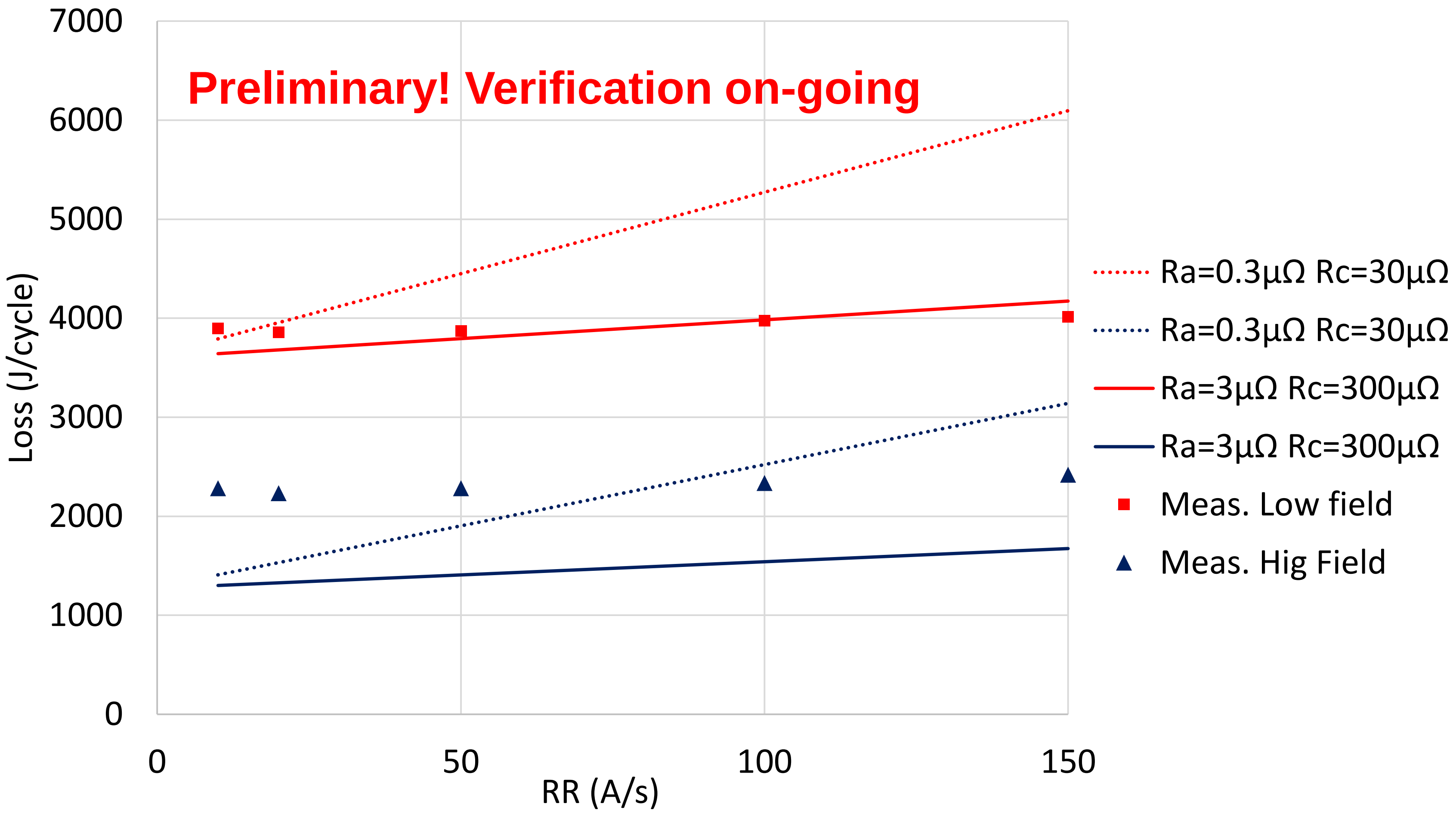
Susana Izquierdo Bermudez

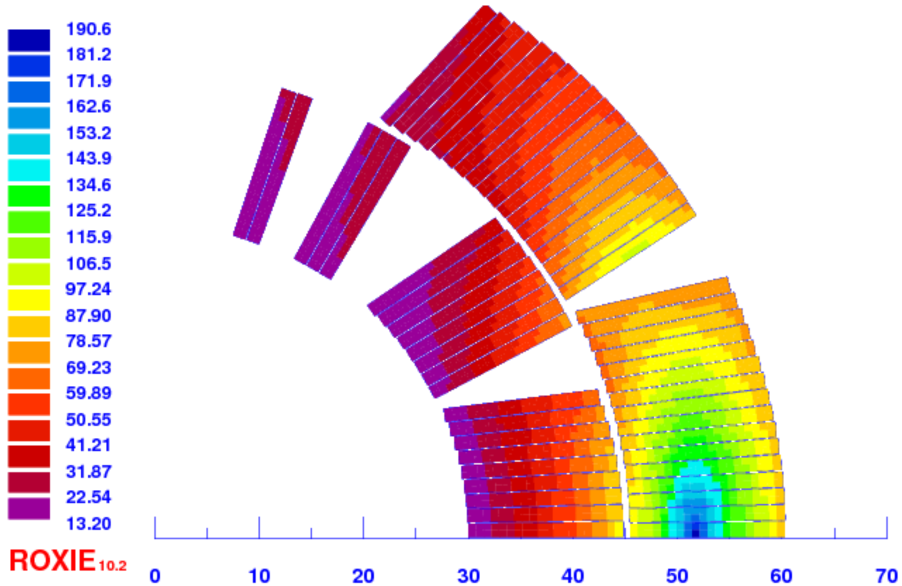
AC loss measurements (2/2)



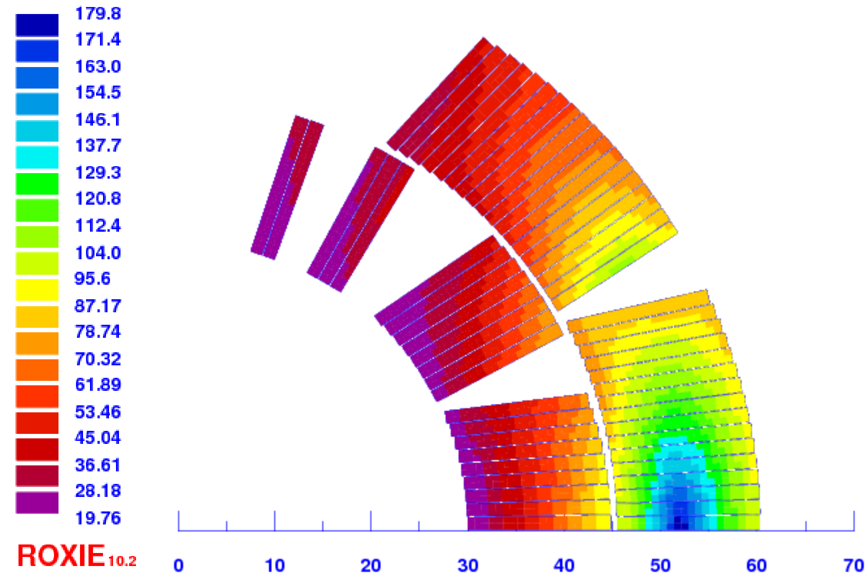
Ramp rate study

- No quench at 200 A/s up to nominal current.
- Quench at 300 A/s at 10.8 kA.

Enthalpy margin (mJ/cm^3) at I = 11.85 kA



Enthalpy margin (mJ/cm^3) at I = 10.8 kA



Minimum required energy to quench	@ 11.85 kA	@ 10.8 kA
Total energy(J)	113	170
Coil volume (mm^3)	8584	8584
Deposited energy (mJ/cm^3)	13	20

- Based on the AC-loss measurements
  - Loss RR=200 A/s from 0 to I_{nom} ~ 200 J
  - Loss RR=300 A/s from 0 to I_{nom} ~ 300 J
- So we are not very far…

Energy extraction test

Energy extraction tests to asses contribution of IFCC and ISCC dynamic effects:

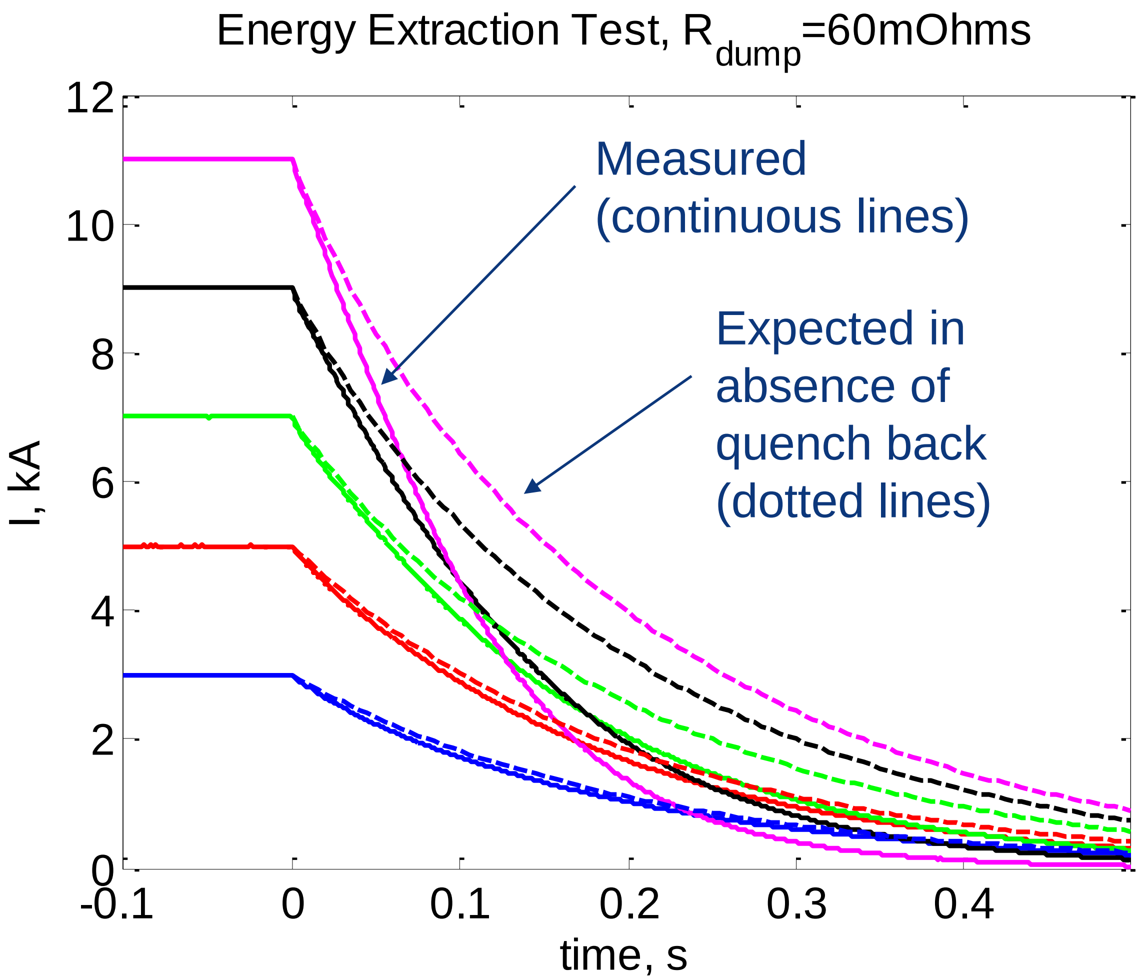
- EE discharge at different current levels at different current level and with different values of extraction resistor; manually triggering the EE, without firing QH.
- Measure voltage and current to observe the presence of quench back.
- Current levels and energy extraction resistance defined to assure QI < 12 MIITs and V < 1 kV

Quench Load [MIITs]	**Initial current [kA]**					
R_EE [mOhm]	**3**	**5**	**7**	**9**	**11**	**Max I (kA) for V < 1kV**
10	**5.3**	*14.8*	*28.9*	*47.8*	*71.4*	*100.0*
20	**2.7**	**7.4**	*14.5*	*23.9*	*35.7*	*50.0*
40	**1.3**	**3.7**	**7.2**	**11.9**	*17.8*	*25.0*
60	**0.9**	**2.5**	**4.8**	**8**	**11.9**	*16.7*
120	**0.4**	**1.2**	**2.4**	**4**	**5.9**	*8.3*

Remarks: Quench protection enabled, so in case of a natural quench the magnet is protected.
10 mOhms dump resistor test to be performed only if enough time available

Legend: **Tests to be performed**
Not to be performed because QI>12MIITs
Not to be performed because Vmax>1kV

Energy extraction test



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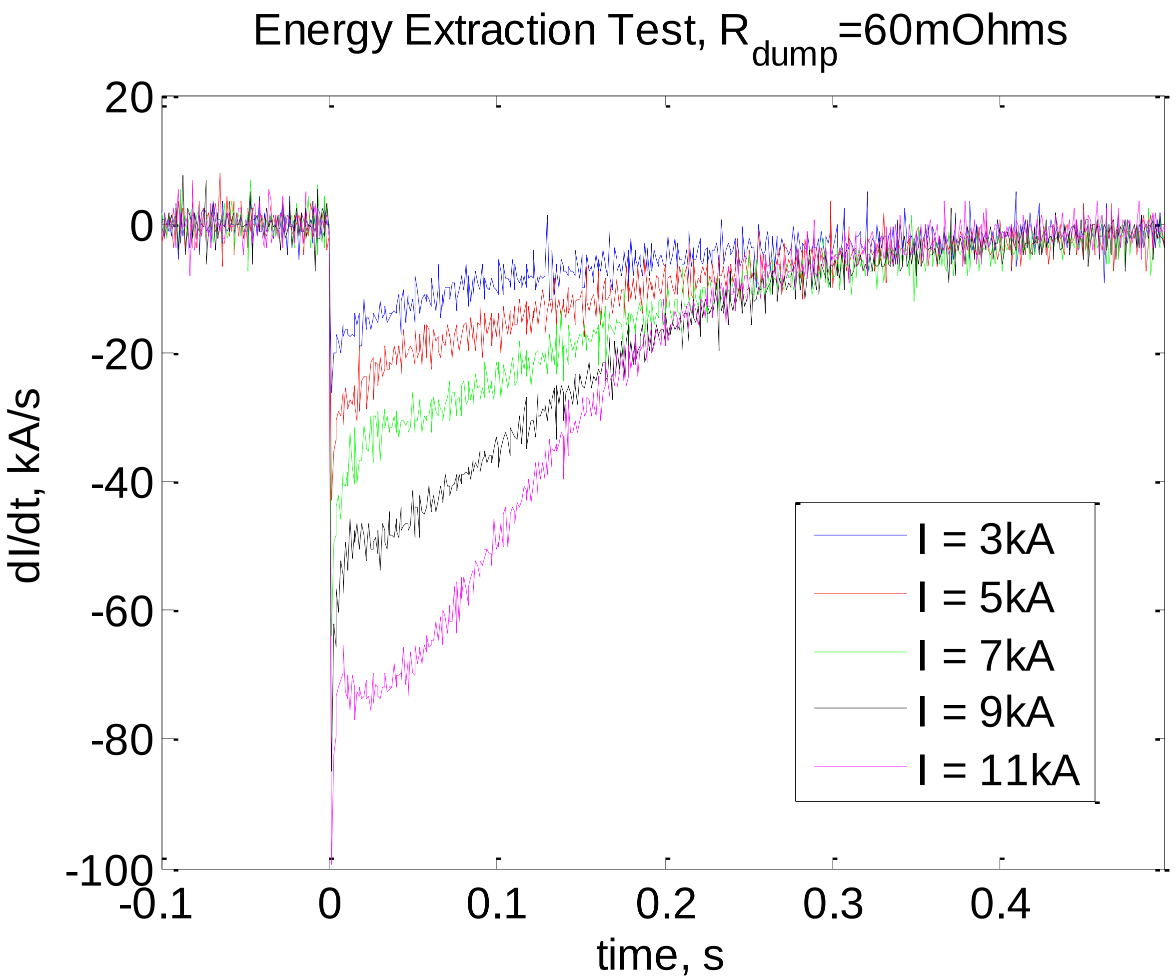
Energy extraction test



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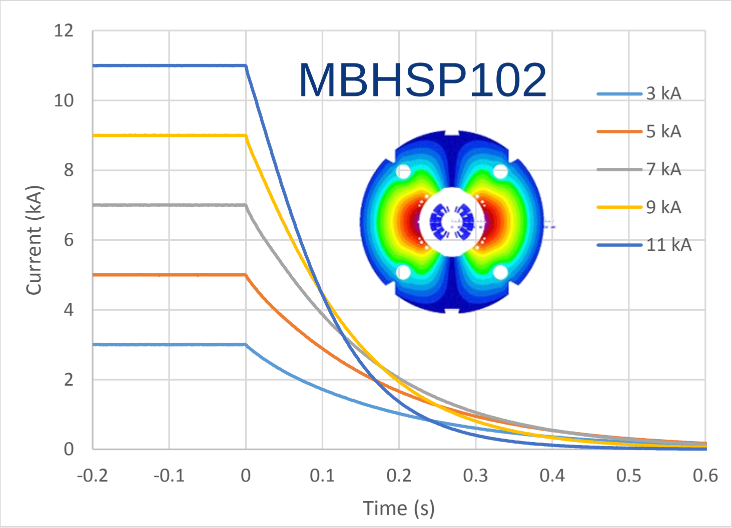
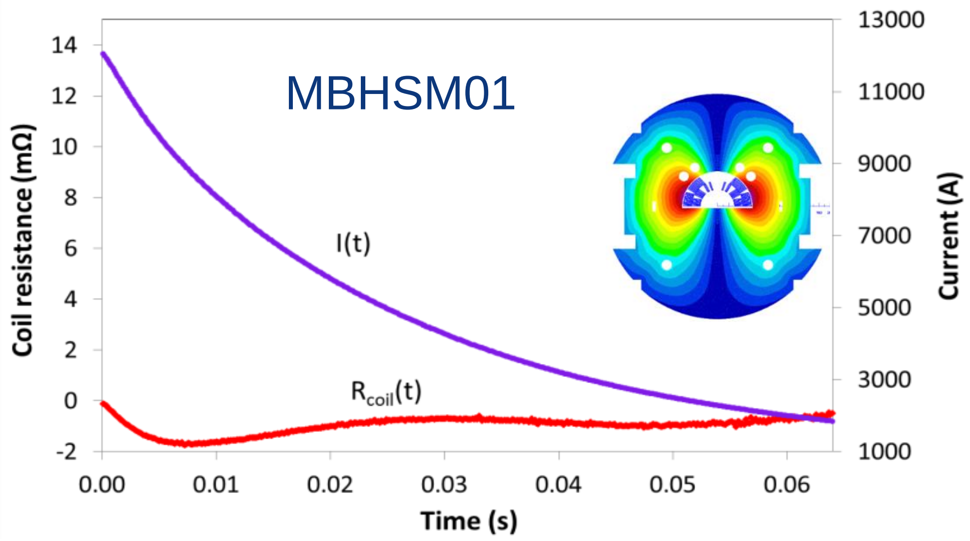
Energy extraction test

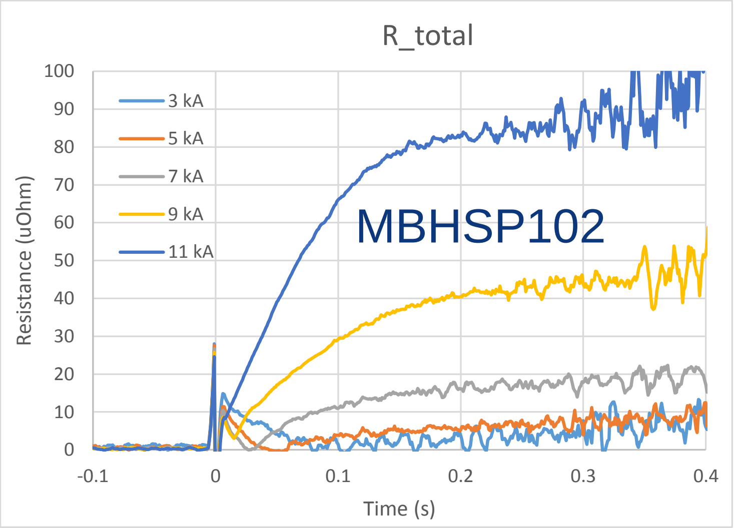
Similar test were performed in FNAL in MBHSM01, and not trace of quench back was present…

why?





Guram **Chlachidze**



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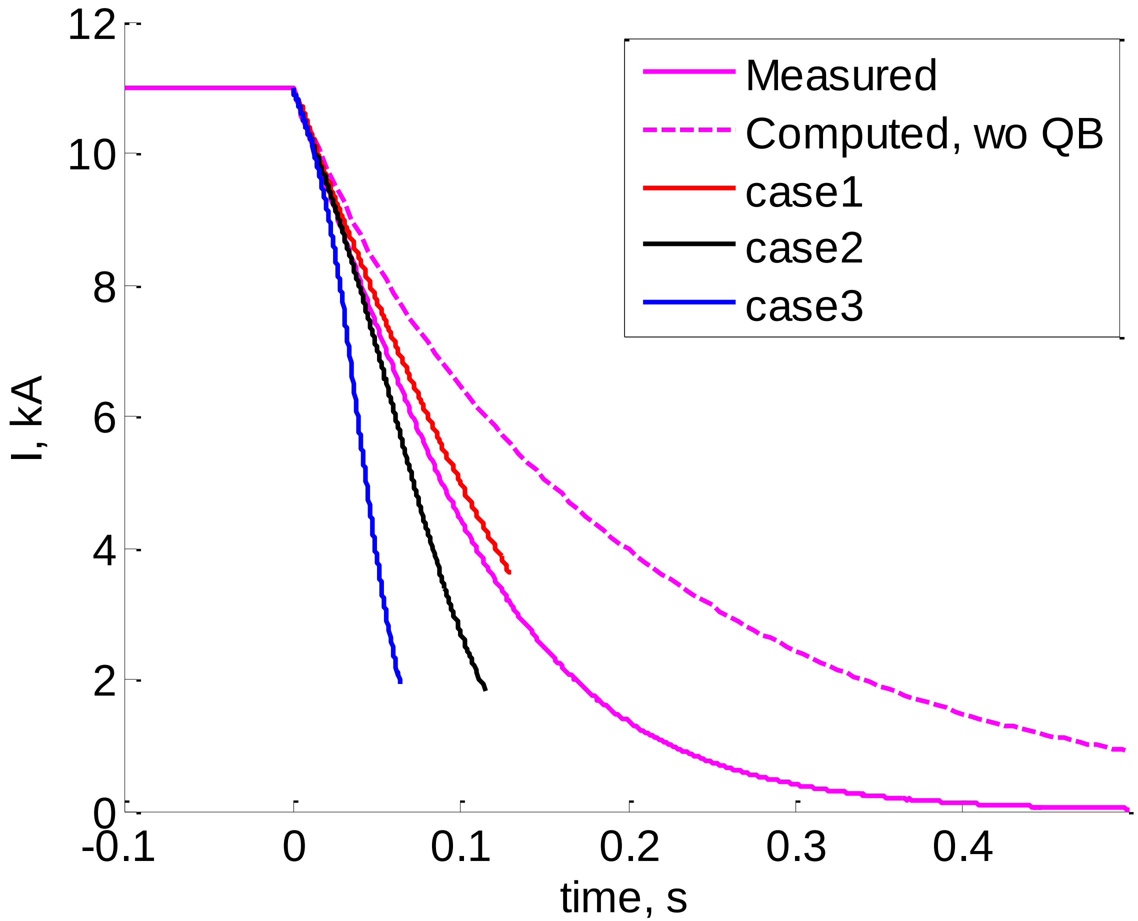
Energy extraction test

In order to follow experimental data → Rc ~ 3 μΩ and τ ~ 5s

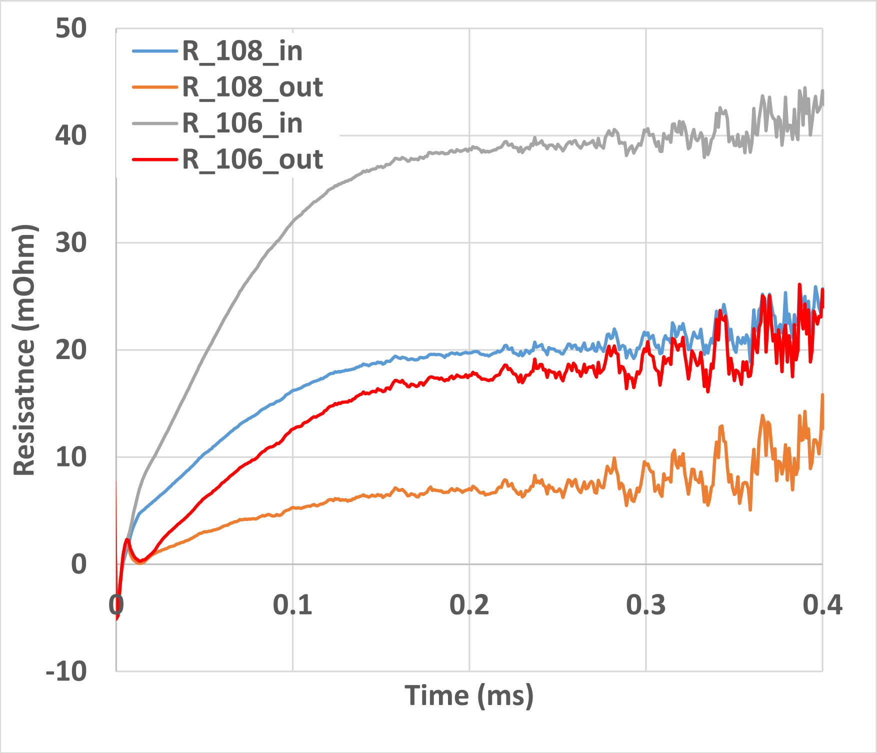
- Values are close to those measured in HQ
- They don't seem consistent with the AC loss and magnetic measurements.

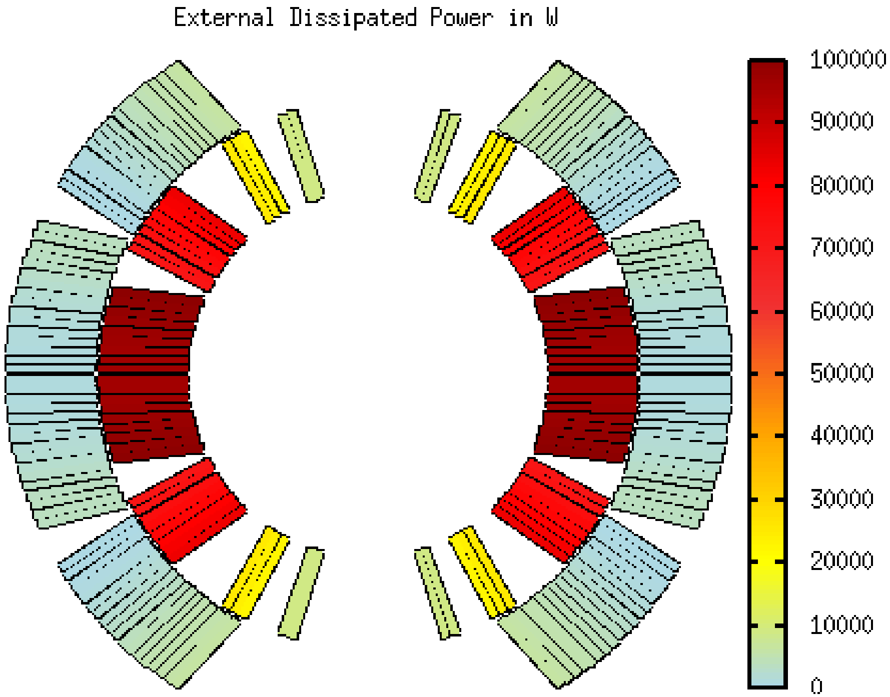
	Rc (μΩ)	τ (s)
case 1	3	5
case 2	30	0.5
case 3	300	0.05



Energy extraction test

- Most of the energy is dissipated in the inner layer, as expected.
- The differences in conductor resistivity for the two coils is visible in the experimental data





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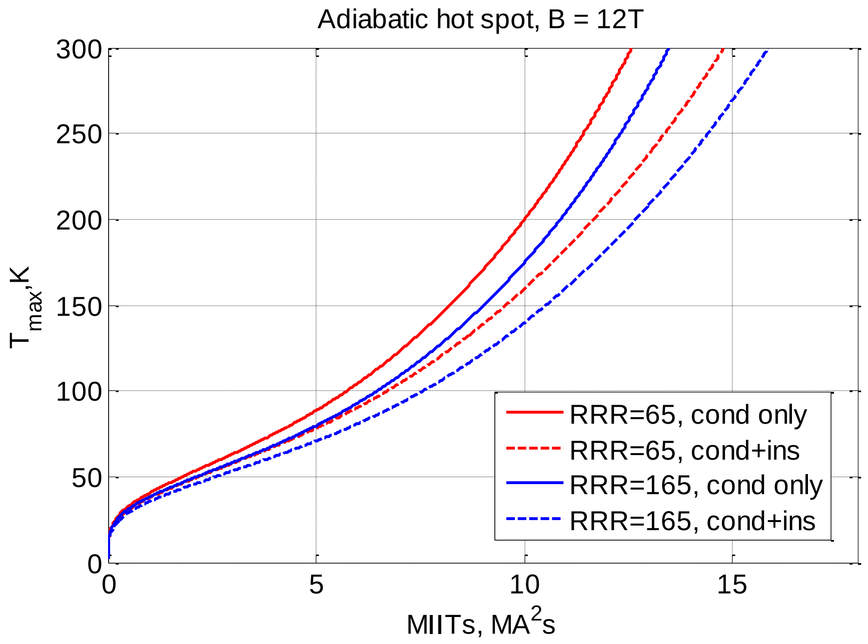
Quench Integral Studies

Quench integral (QI) studies and quench propagation (from the OL to the IL) study:

- Dump delay of 1000 ms ("No Dump" configuration). Quench heater current = 150 A.
- All quench heaters fired, no dump
- Test performed at 6 kA, 8 kA and 10 kA

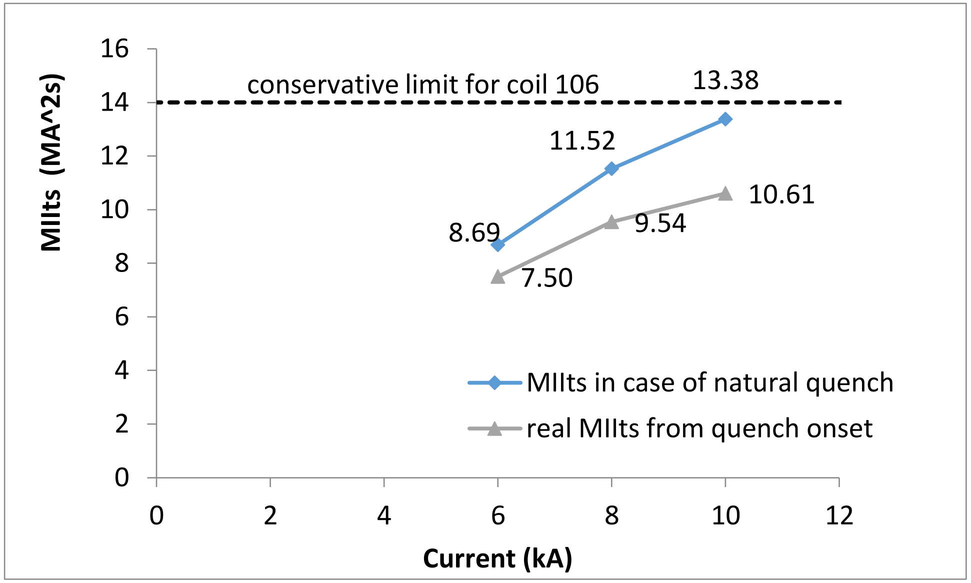
QI limits:

- Due to the differences in the RRR, QI conservative limit is different for both coils:
  - QI(coil 106) < 14 MIITs
  - QI(coil 108) < 15 MIITs
- The magnet should be protected in case of natural quench, so the additional time for detection and heater delay has to be taken into account when defining the safe operation parameters

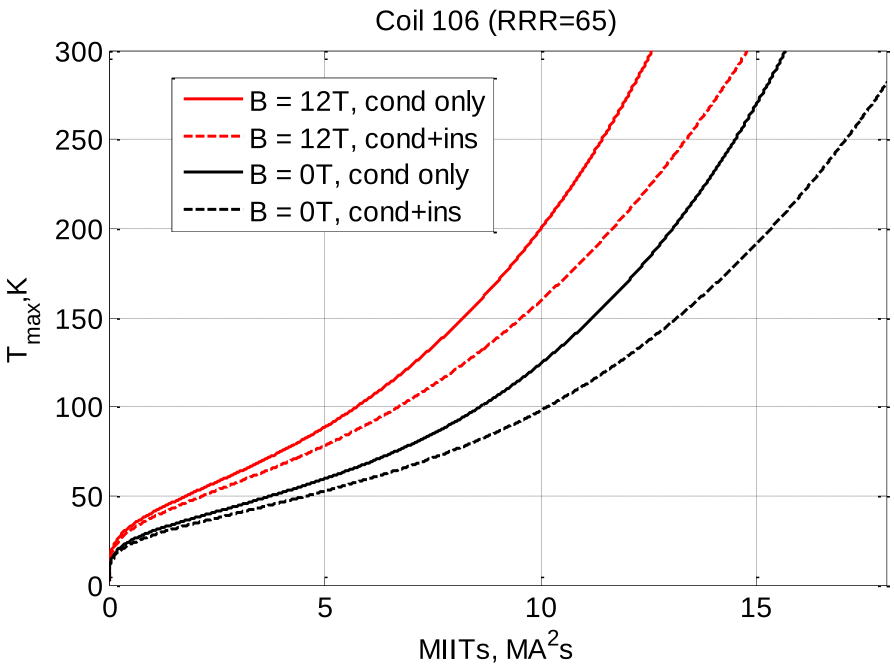


Quench Integral Studies

- Test was done only up to 10 kA because it was not considered to be safe to perform the test at nominal current in case of a natural quench.
- Measured MIITs at 10 kA from the quench onset are 10.6 MA^2s, in case on a natural quench, about 30 ms are needed to detect and provoke a quench in the magnet, getting close to the 14 MIITs limit.

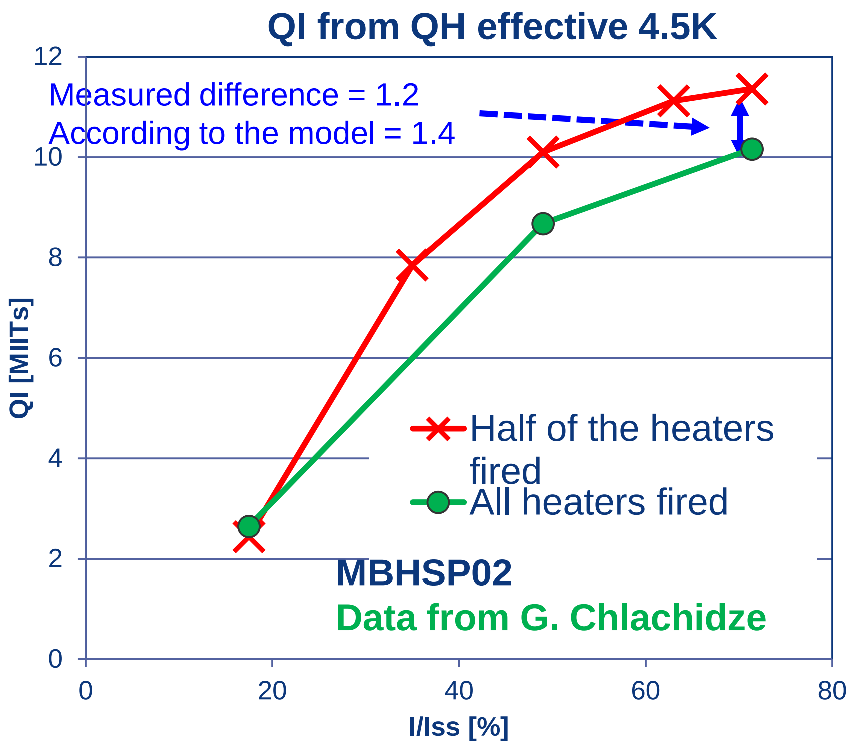


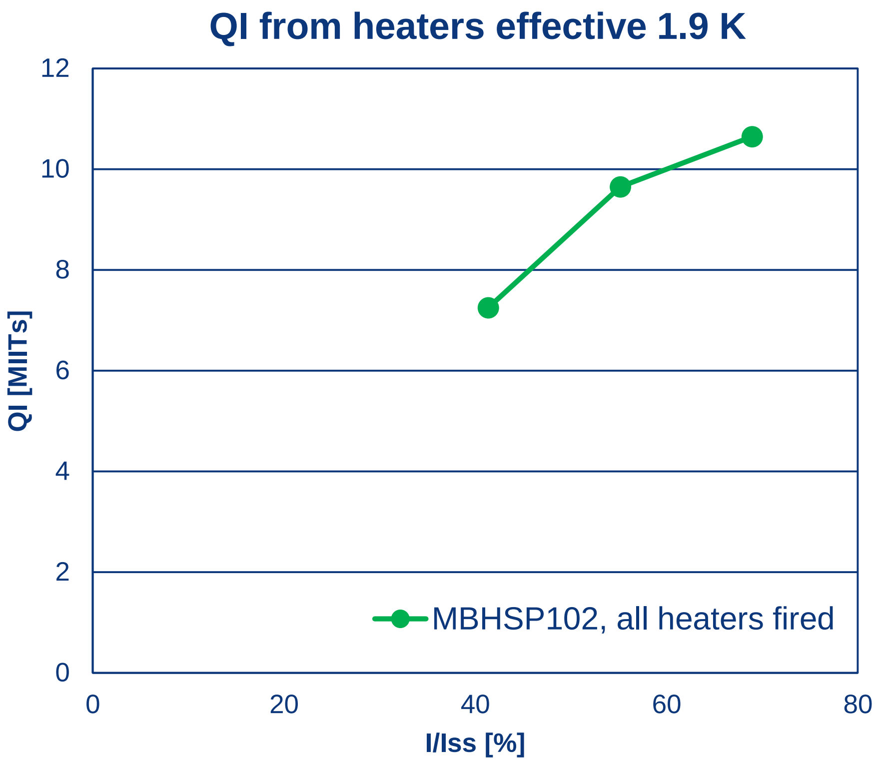
Gerard Willering



Quench Integral Studies

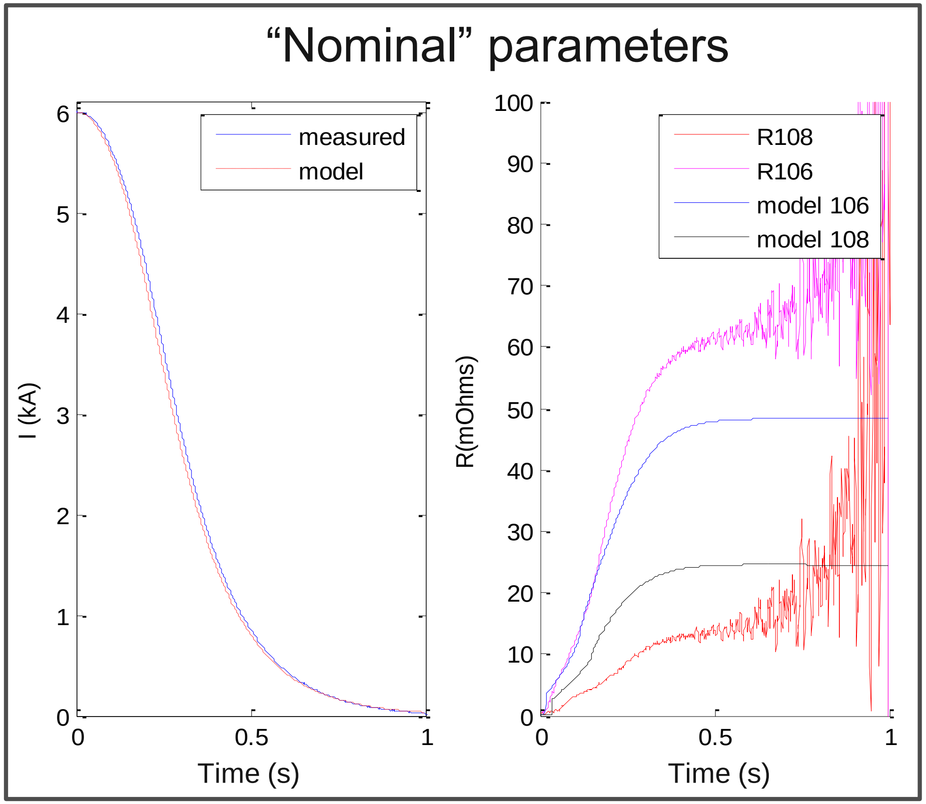
Results are consistent with FNAL measurements on MBHSP02

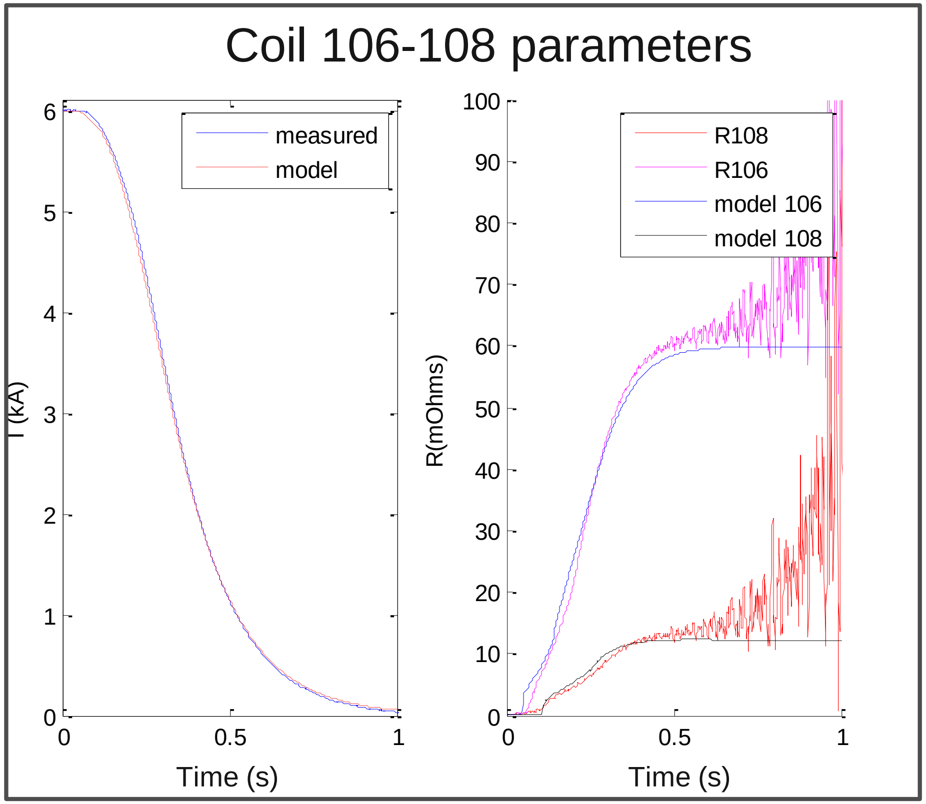




Quench Integral Studies

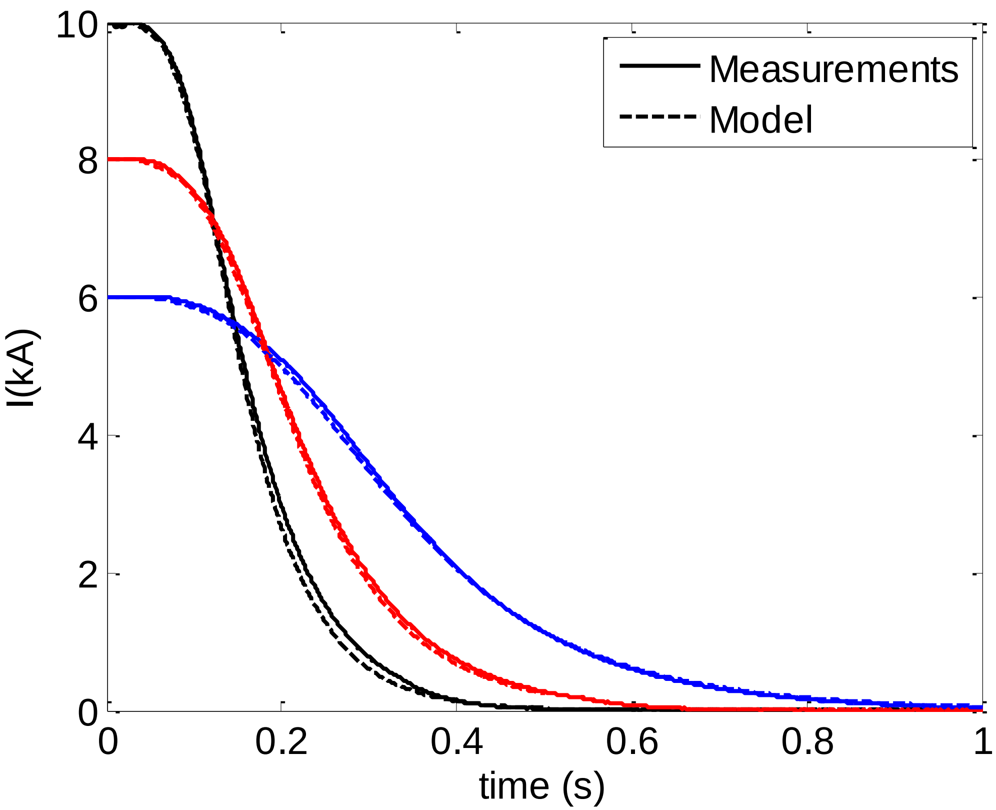
- Even if the current decay is fairly good reproduced by the model using the “nominal” parameters, in order to reproduce the actual resistance growth in the two coils it is important to consider:
  - Difference in RRR and resistivity
  - Difference in heater efficiency





Quench Integral Studies

- Error between modelled and measured current decay < 5 % for all the current levels

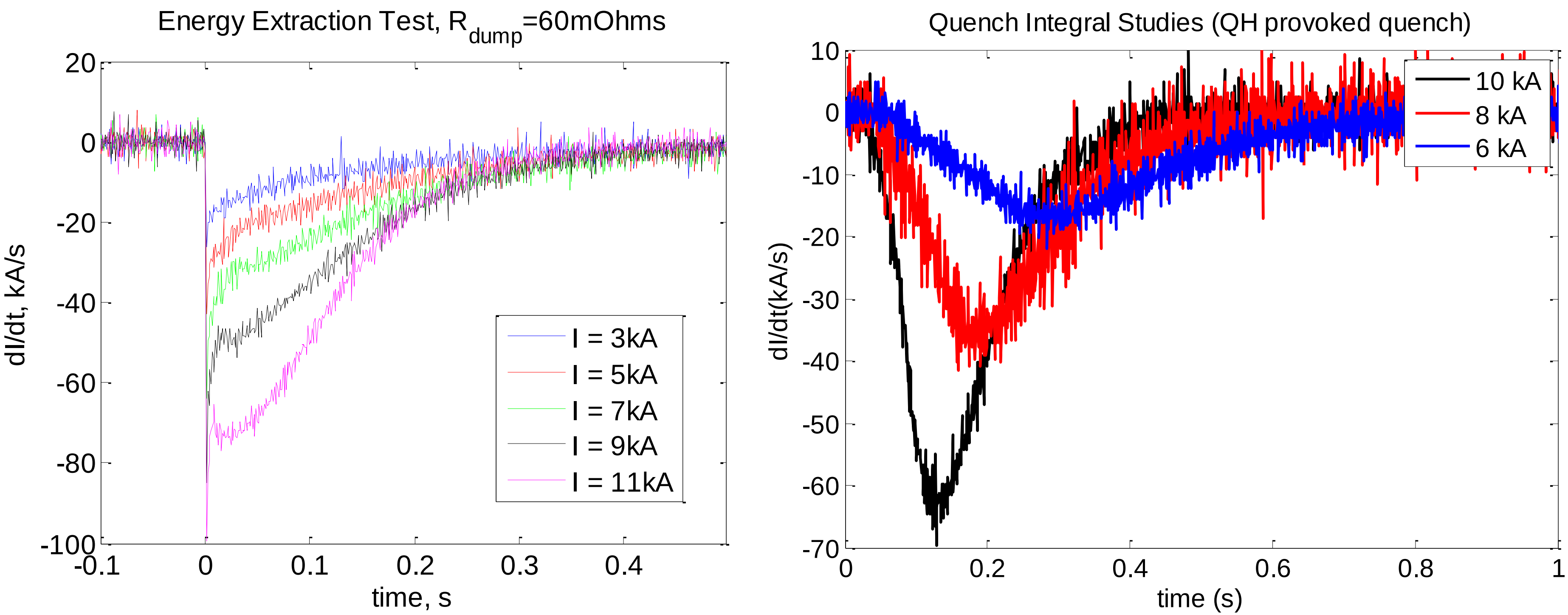


Conclusions/Final Remarks

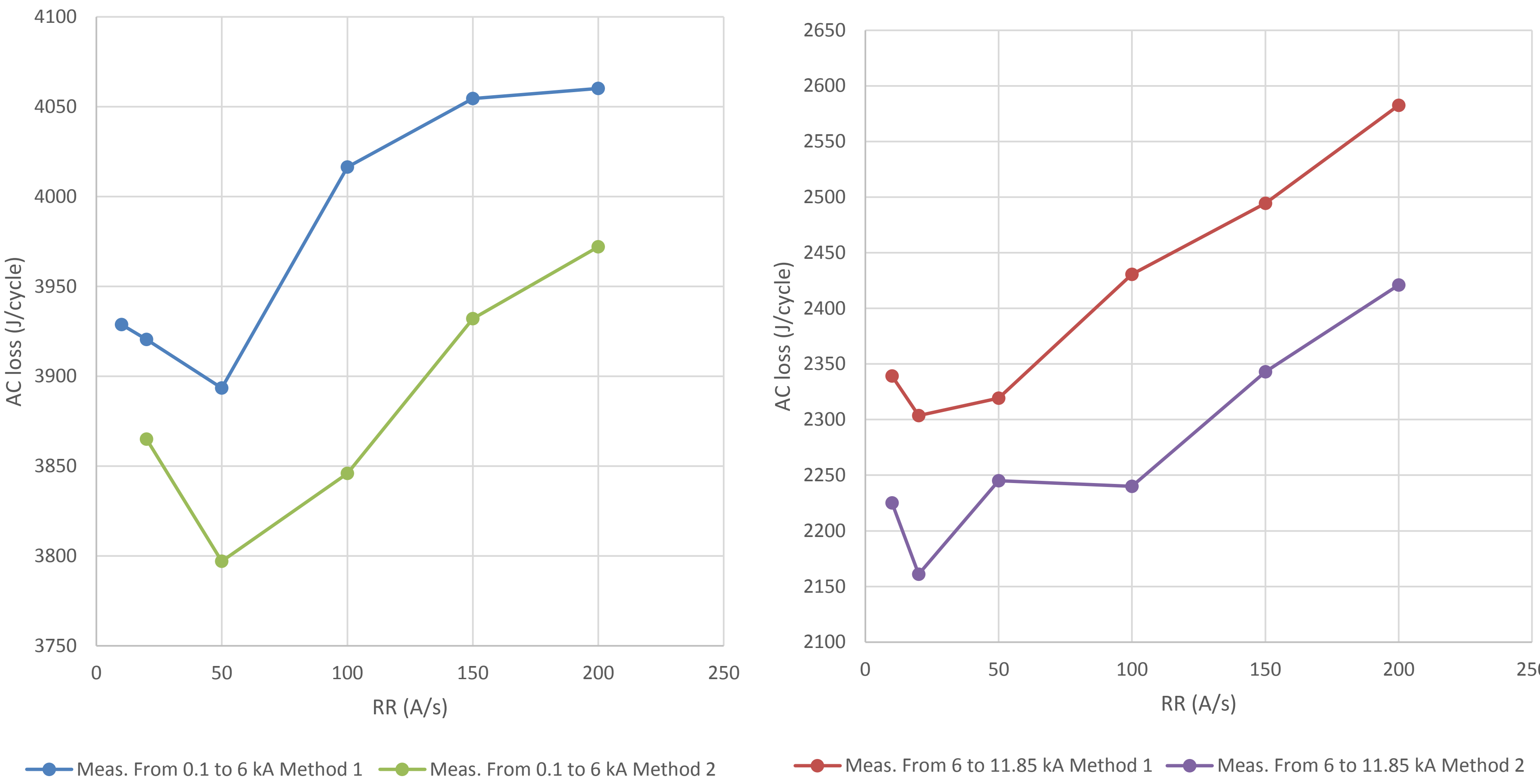
- The important differences in the two conductors and coil insulation lay out complicates the quench protection analysis
- Behaviour of coil 106 is very reproducible in aperture MBHSP101 and MBHSP102
- Heater performance of coil 108:
  - Heater onset is as expected (very close to coil 107 measured in MBHSP101 with the same insulation lay out)
  - Heater efficiency is lower than expected. Not clear reason to explain the differences between low field quench heater delay observed in coil 107 and 108.
- AC loss contribution needs to be further investigated:
  - Based on energy extraction tests, Rc should be in the order of 3 – 5 μΩ , close to HQ values
  - Magnetic measurements and AC loss measurements show Rc 100 times higher according to the model. These are only preliminary numbers and further analysis in needed to verify the model

Additional slides

Energy extraction test



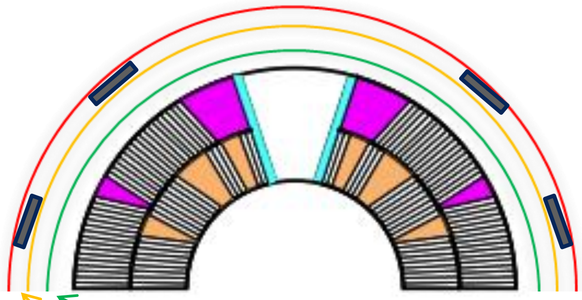
AC loss


4100
4050
4000
3950
3900
3850
3800
3750
AC loss (J/cycle)
0
50
100
150
200
250
RR (A/s)
Meas. From 0.1 to 6 kA Method 1
Meas. From 0.1 to 6 kA Method 2
2650
2600
2550
2500
2450
2400
2350
2300
2250
2200
2150
2100
AC loss (J/cycle)
0
50
100
150
200
250
RR (A/s)
Meas. From 6 to 11.85 kA Method 1
Meas. From 6 to 11.85 kA Method 2

Heat transfer from heater to coil

Example for the **DS-11T** (CERN):

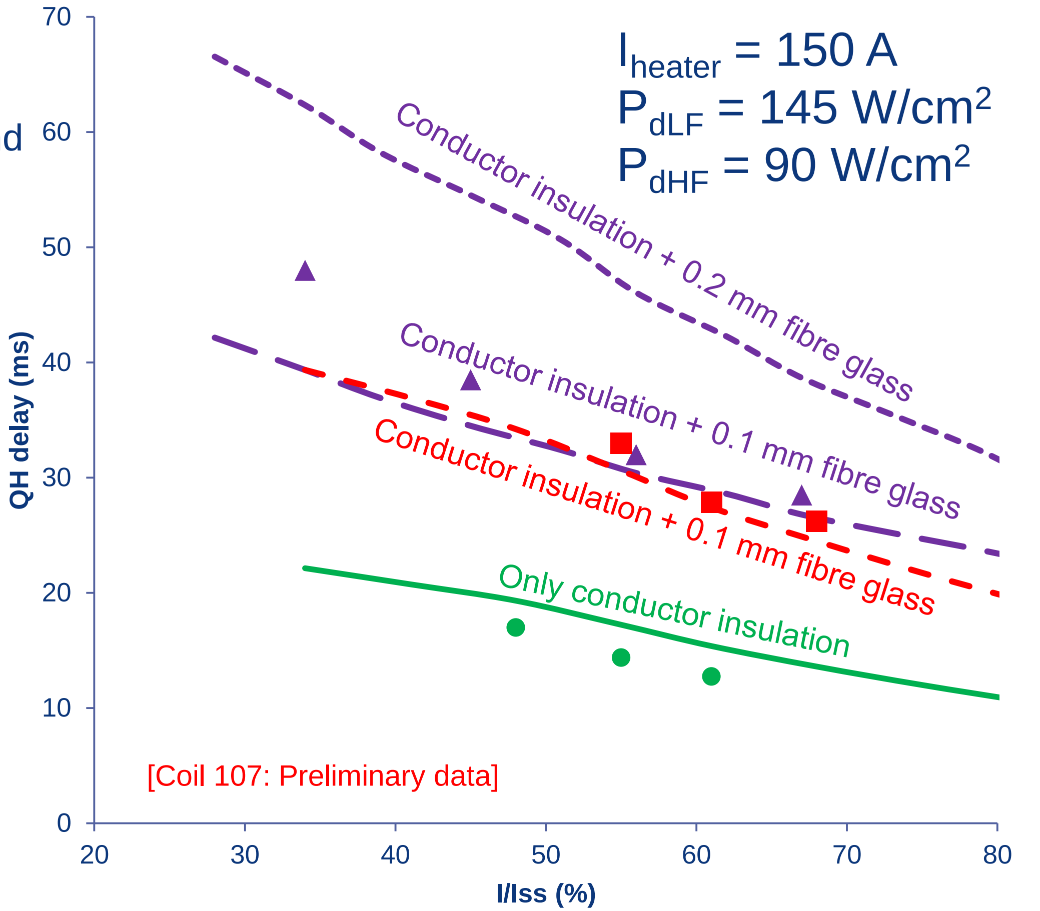
- Heaters are glued on top of the coil after impregnation
- The amount of insulation between heater and coil is the critical parameter



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 ~ 10 ms

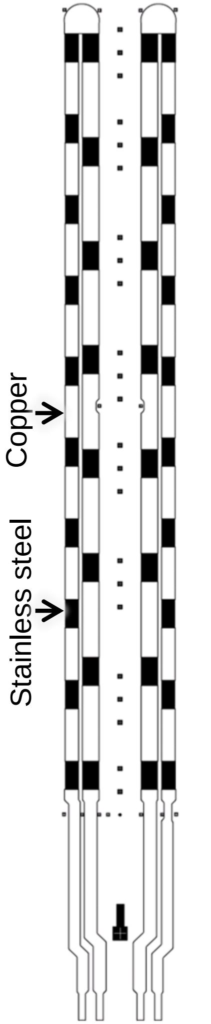
Quench heater onset



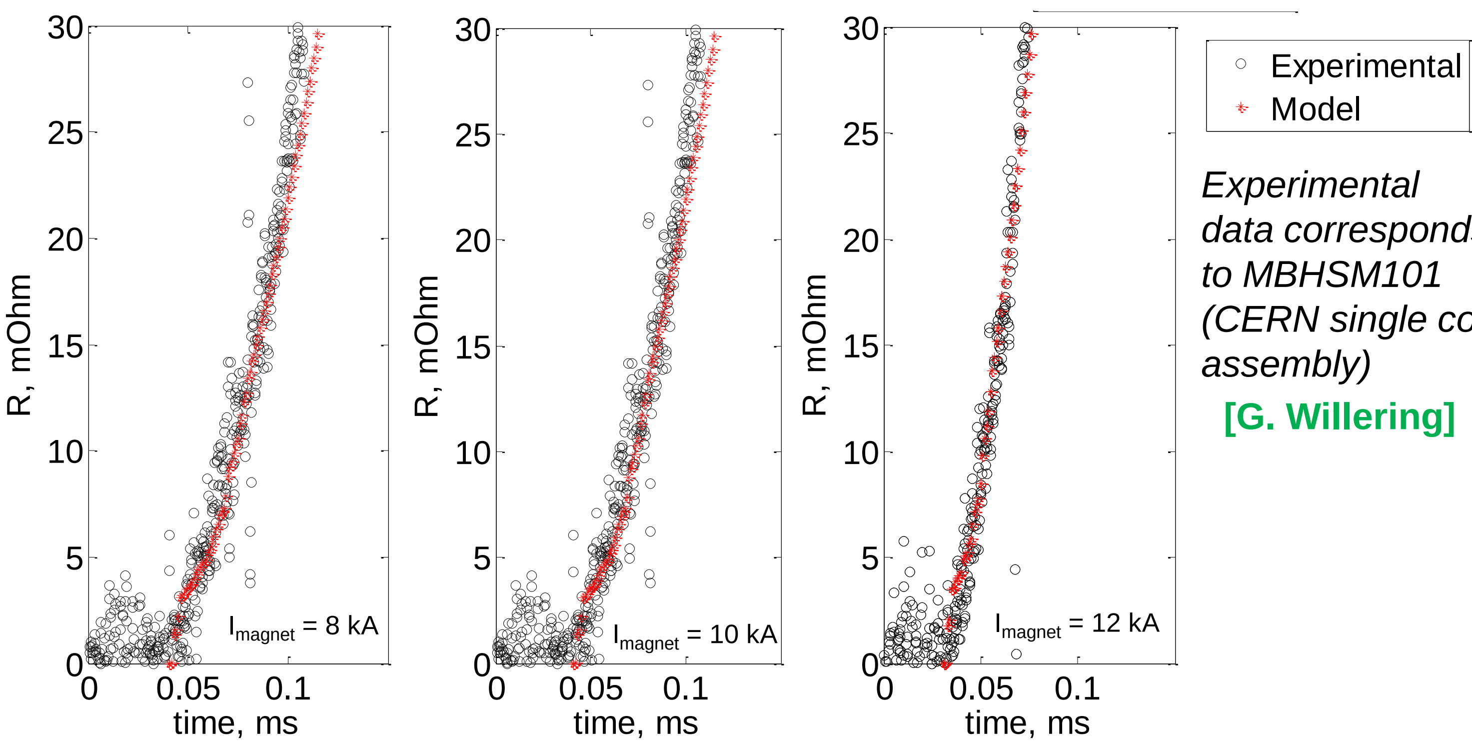
Model [J. Rysti]
Experimental data [J. Feuvrier, G. Willering]

Heat transfer from heater to coil

- Quench heaters are modelled in the global solution as a power input to the conductors in contact of the heater with the delay computed by the COMSOL 2D model (delay for the first conductor to quench)
- Quench propagates in between stations in ~5 ms.



Heater pattern

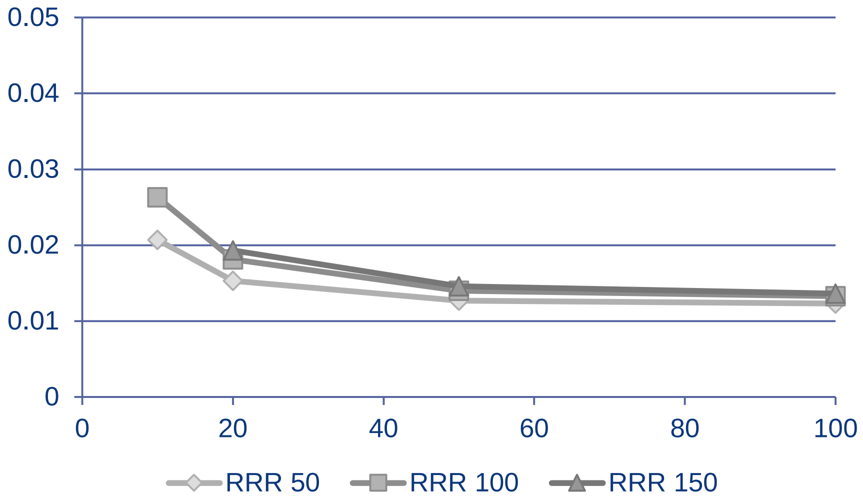


Experimental data corresponds to MBHSM101 (CERN single coil assembly)

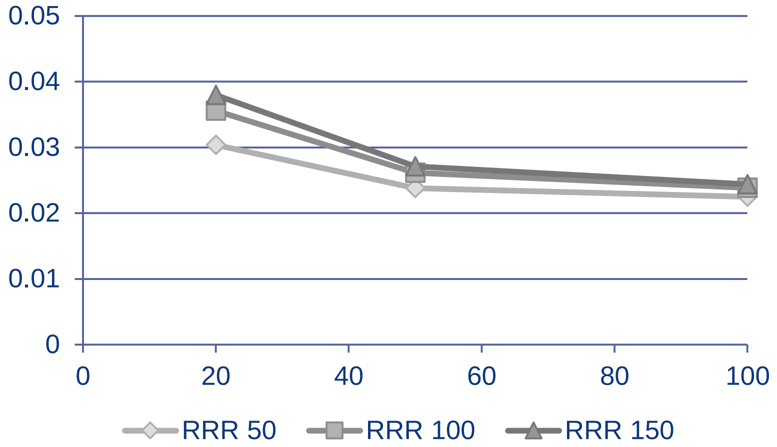
[G. Willering]

Quench heater efficiency

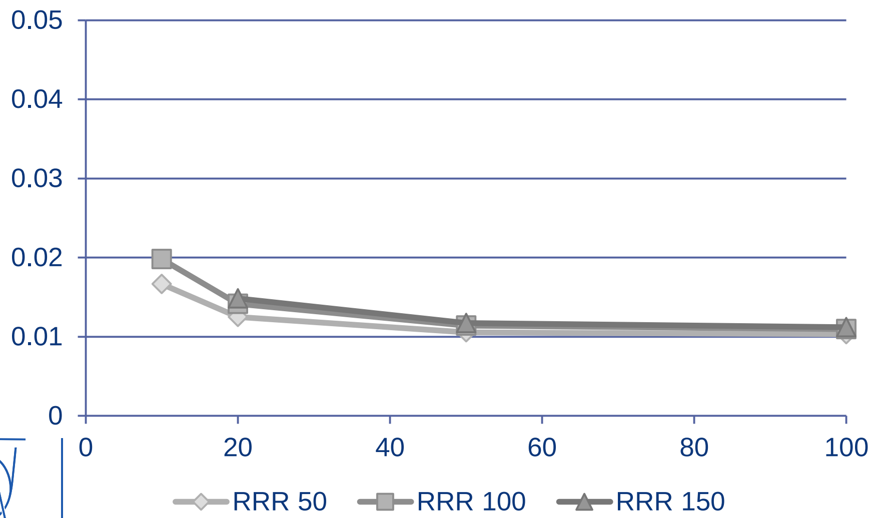
Coil 106, LF 11.85 kA



LF 11.85 kA



Coil 108, HF 11.85 kA



HF 11.85 kA