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Performance of the Quench Protection Heater for the HL-LHC Beam Separation Dipole

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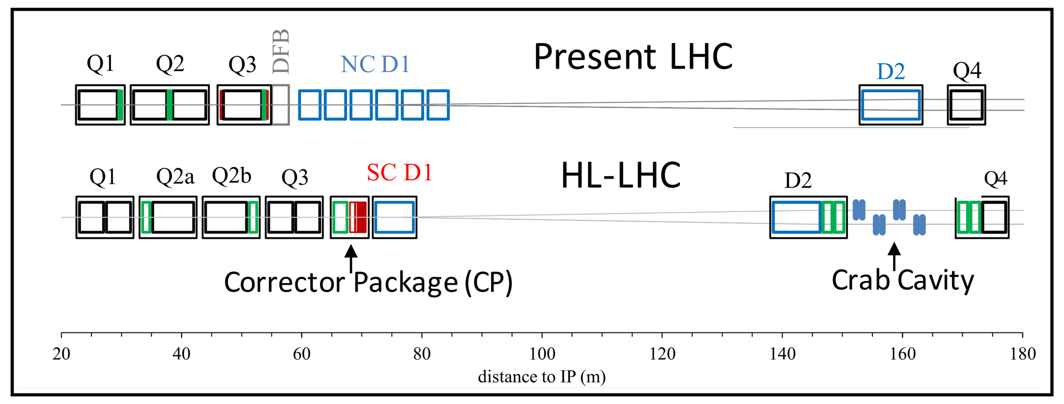
Abstract

A new quench protection heater of D1, MBXF, was designed and tested during the cold test of the 2nd and 3rd models (MBXFS2 and 3). Combining data taken since the test of the 1st model magnet (MBXFS1), we confirmed the maximum hotspot temperature are well below 300 K for both the low field (1 T) and high field (5 T) quenches. In addition, a simulation model was developed and tuned with the obtained data for the full-scale prototype magnet. The hotspot temperature after quench initiation was then computed with the new heater circuit and found to be below 300 K even for the case of failure in firing the heater.

Introduction



General parameters of MBXF

Design parameter	Full scale	Short model
Operating temperature (K)	1.9	
Nominal current (A)	12047	
Field (T)	5.60	
Field integral (T·m)	35	9.5
Magnetic length (m)	6.26	1.67
Differential inductance (mH)	24.86	6.63
Stored energy (MJ)	2.13	0.568
Conductor parameter		
Strand material	NbTi	
Strand diameter (mm)	0.825	
Cu/no Cu	1.95	
RRR	> 150	
Number of strands	36	
Strand twist pitch (mm)	100	
Bare cable width (mm)	15.1	
Bare cable mid. thickness (mm)	1.480	

- **Requirements to the D1 (MBXF) magnet for the HL-LHC upgrade**
  - Match the aperture with those of the triplets :60 mm → 150 mm
  - Shorten the total length of the magnet to accommodate new crab cavities and new inner triplets: 14 m → 7 m
    - This is realized by utilizing SC (NbTi) technology so as to increase the field integral to 35Tm
  - **Magnet protection system: Quench protection heater (QH)**

➡No external dump resistor will be used

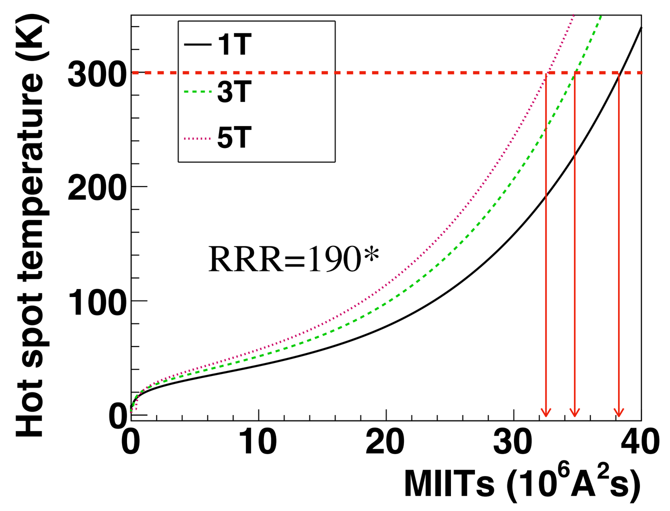
➡Reliability of the protection system with QH has to be checked prior to the magnet production

Estimation of the hot spot temperature (T_{max}): **MIITs relation**

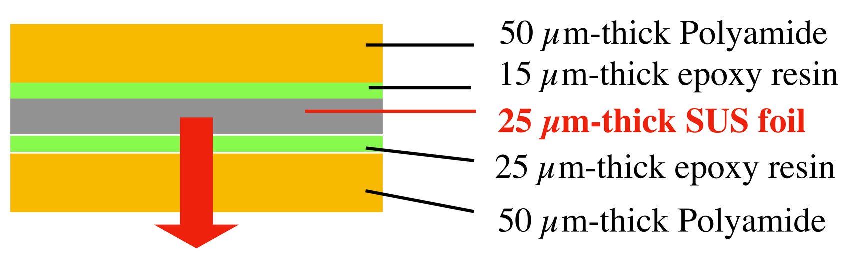
$$\mathrm{MIITs} = A^2 \int_{T=1.9\ \mathrm{K}}^{T_{max}} \frac{S(T)}{\rho_E(T,B,\mathrm{RRR})}\, dT = \int_{-t_{det}(I,B)}^{0} I^2 dt + \int_{0}^{\infty} I^2(t) dt \ ,$$

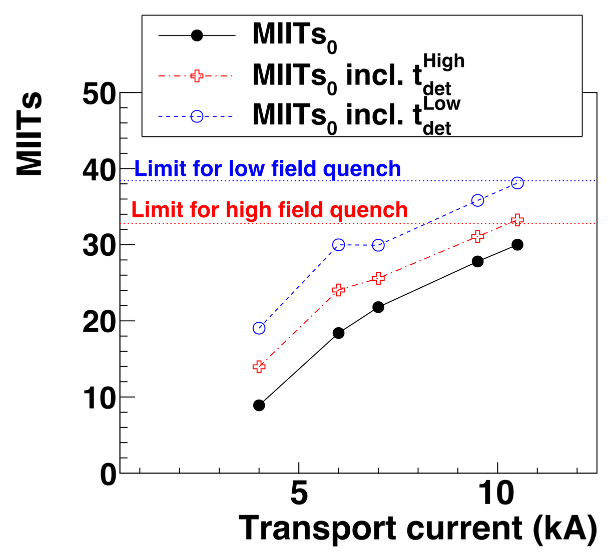
t_{det}: time to detect a magnet quench
A : cross section of the cable
S : volumetric heat capacity of the cable
ρ_E: electric resistivity of the cable

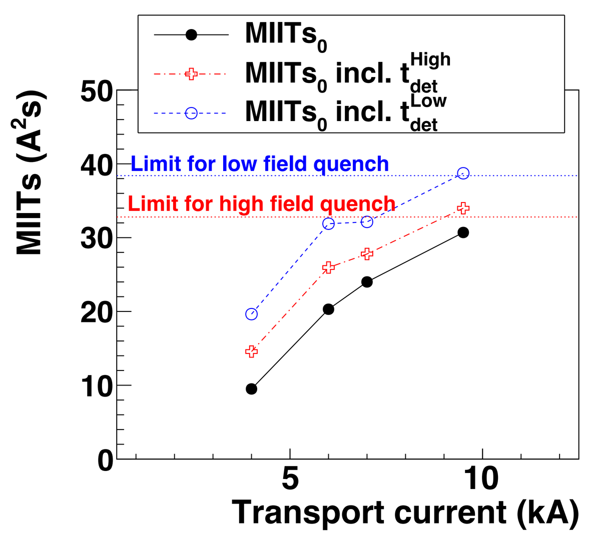
- In our criteria, an experimental limit of T_{max} is set to **300 K**
- T_{max} is estimated for various magnet field strengths using the parameter set listed in the left table, and is shown in the right fig.
- Maximum allowable MIITs can be defined at T_{max} =300 K as shown in the right figure



Results of the 1st model (MBXFS1)



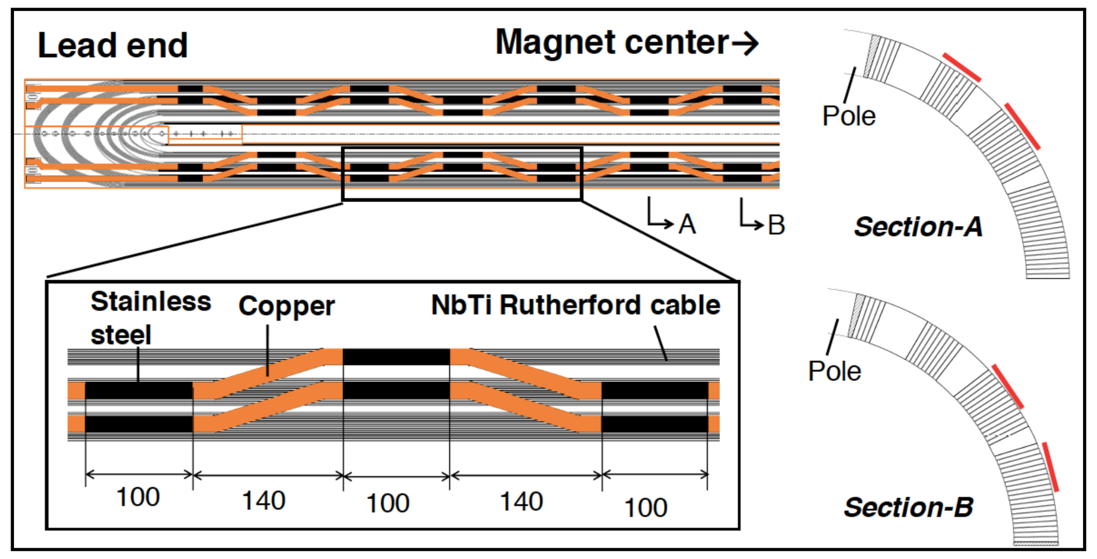




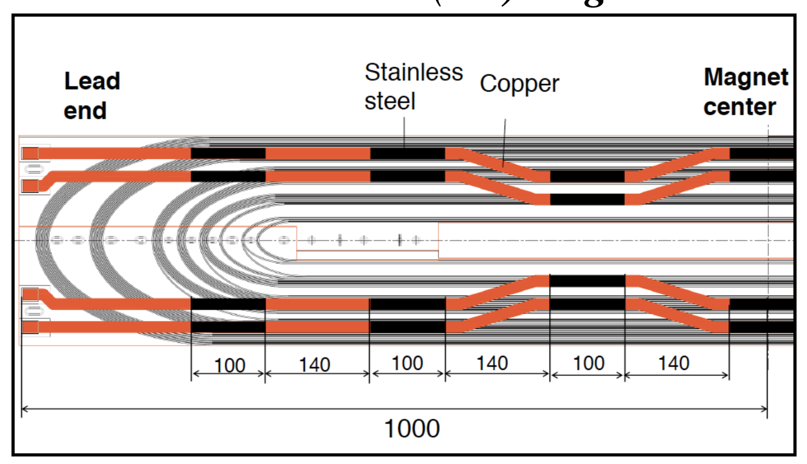
- The full energy dump test was performed using the single strip heater for the 1st model magnet.
- Additional MIITs is added to take account of duration t_{det}
  - Two cases : High field (B=5T) quench (t^{High}_{det}) or low field (B=1T) quench (t^{Low}_{det})
- **In any quench cases, the total MIITs exceeds the limit at I=10.5 kA (9.5 kA) when firing 4 (2) QPHs**
- **QH has to be re-designed to protect the magnet!!**

New QH design

For full-scale magnet



For short-scale (2m) magnet



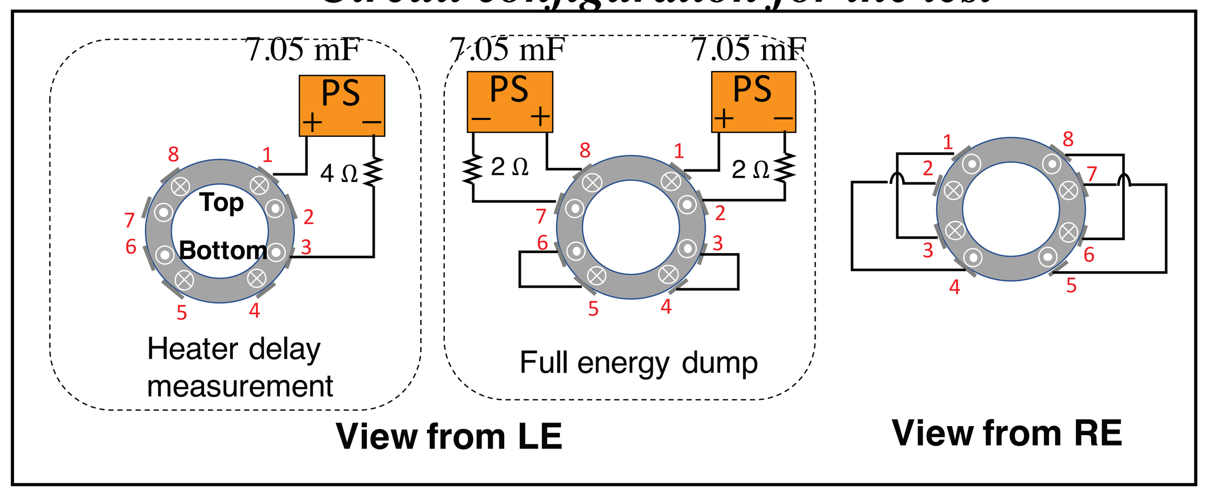
- A longitudinal length of SUS patch is >100 mm to cover a strand twist pitch
- A zigzag pattern is adopted to increase heater coverage
- A total resistance of the heater (R_{QH}) is close to that of the 2m-long single heater strip to achieve a similar peak power density :

$$P_{peak} = \frac{R_{QH} I_{QH}^2}{A_{heater}}$$

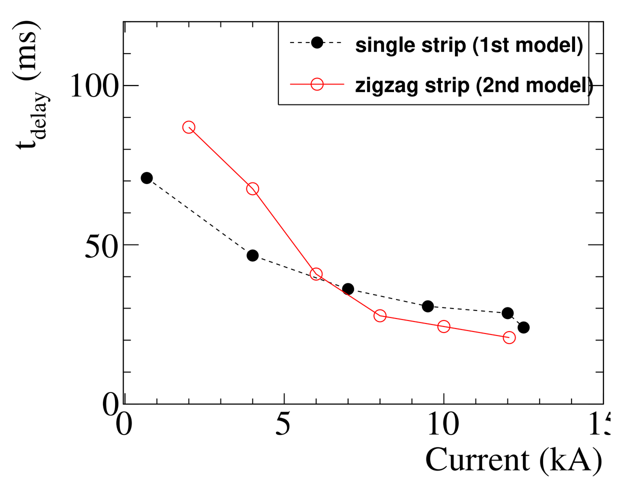
I_{QH}: Peak current flowing into the heater
A_{heater} : Heater area

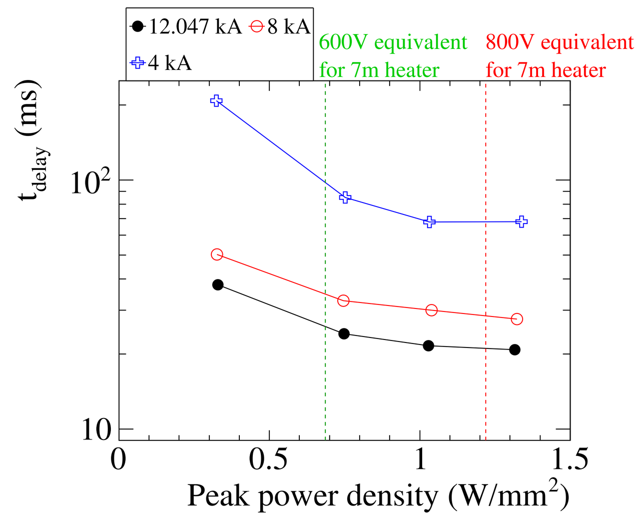
Evaluation of the new QH performance during the test of MBXFS2 and 3

Circuit configuration for the test



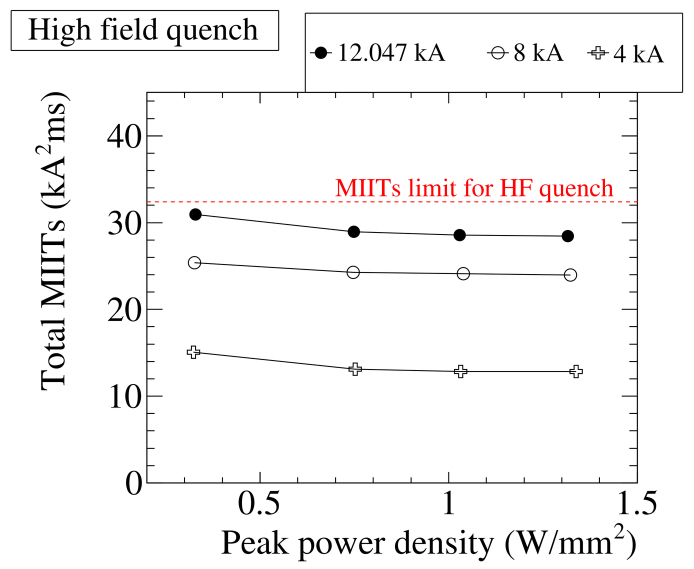
Heater delay measurement

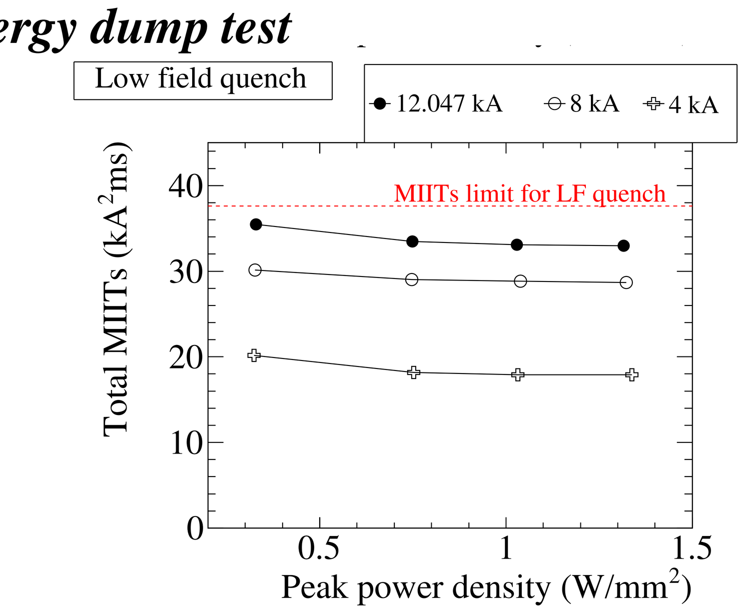




- Left: Comparison of the heater delay (t_{delay}):
  - Shorter t_{delay} was achieved for the higher current
- Right: P_{peak} dependence of t_{delay}
  - t_{delay} curve is almost flat for >1W/mm²
  - Full-scale QH (800V full charge) is expected to give a similar heater delay of ~20 ms

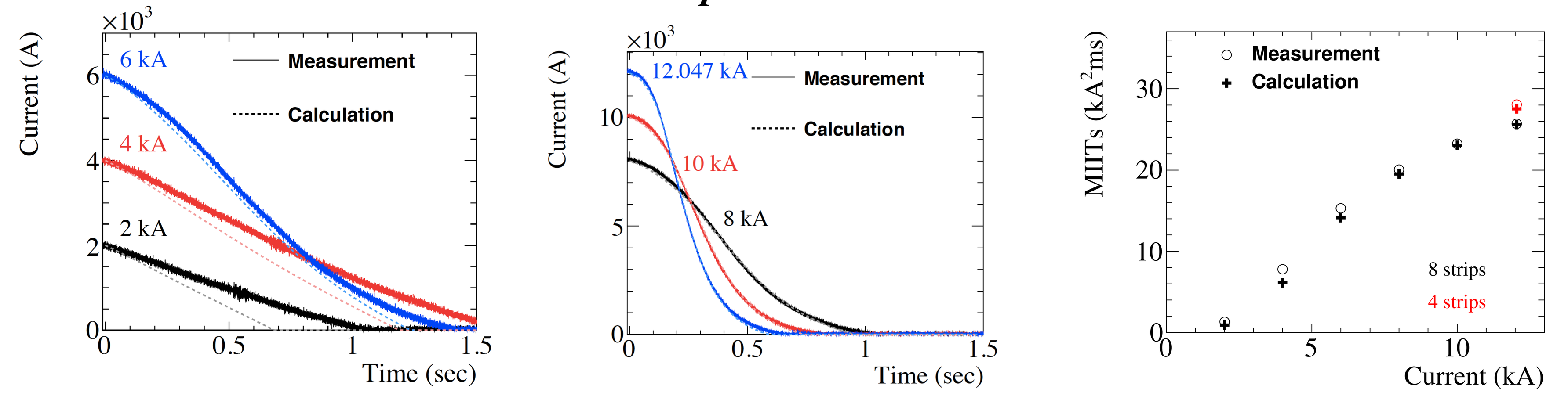
Full energy dump test





- Measured total MIITs (incl. detection time, t_{det}) for high field (left) and low field (right) quenches
- **In conclusion, the new heater demonstrates that overall MIITs are well below the limit (T=300 K) even the charge voltage of PS is half (400 V)**

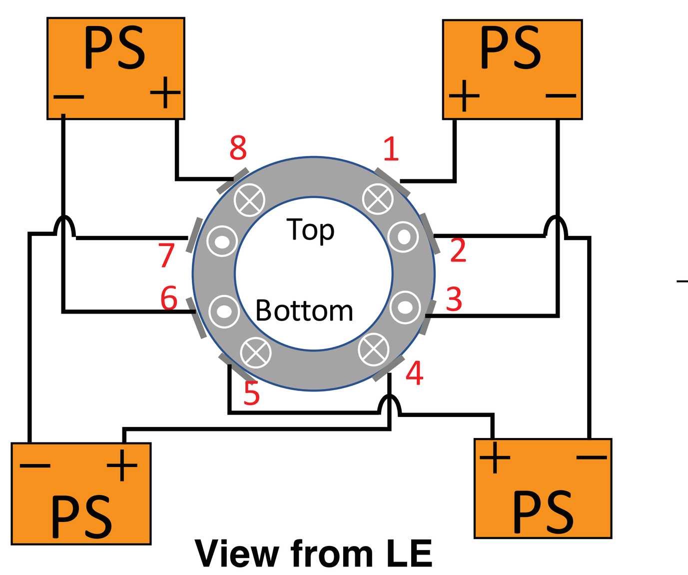
Comparison with the simulation



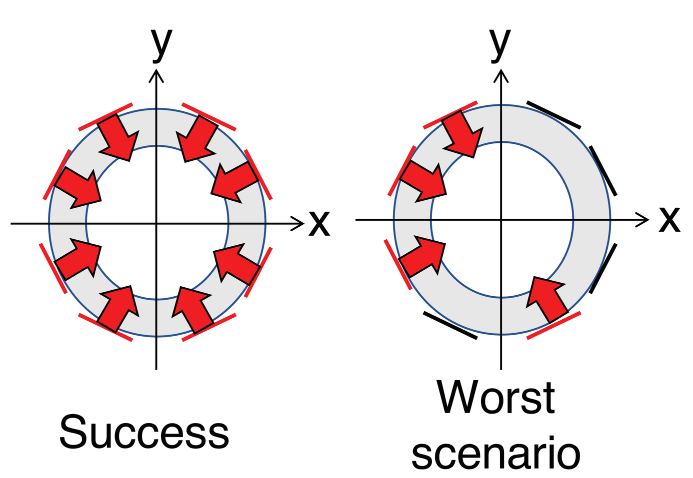
- Measured current dump, which was obtained during the full energy dump test of MBXFS2, was compared to the simulated one
- **Our simulation predicts the current profile and MIITs precisely especially for the higher magnet current**
- **We conclude that our simulation can also predict the full-scale QH performance for nominal operating condition (I=12.047 kA)**

Full-scale QH performance (Simulation)

Present plan of the heater circuit



Expected failure case



- The heater circuit is devised so as to reduce the total MIIts as much as possible in any heater failure scenarios
- **Assuming RRR of the conductor is 150, the computed hotspot temperature is confirmed to be below 300 K even for the worst case**

Expected MIITs and hotspot temperature (T_{max}) at I =12.047 kA

	Expected total MIITs and T_{max}	
	HF quench (5 T)	LF quench (1 T)
Success	28.9 / 235 K	33.4 / 229 K
Worst case	31.9 / 297 K	36.4 / 289 K

Conclusion

- A new heater was designed and tested with MBXFS2 and 3
- Measured total MIITs were below the limits, and our simulation model also supports the obtained data
- Performance of the full-scale QH with the new design was also evaluated on the simulation basis and T_{max} is confirmed to be below 300 K even for the worst case