CERN
CH-1211 Geneva 23
Switzerland

Technology
Department

CERN TE/Group
TE/MPE

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Technical Note

UPPER LIMITS FOR SYMQ THRESHOLDS OF THE MAIN DIPOLE CIRCUITS IN THE LHC

Abstract

This note serves as a basis for the determination of post-LS1 thresholds for the SymQ quench protection system. It presents the results of an investigation of the upper limits for SymQ thresholds; it is, therefore, not a recommendation for the actual setting of SymQ thresholds, which shall be chosen as low as reasonably possible, and at least below the limiting values presented here.

Prepared by :	*Checked by :*	*Approved by :*
D. Egede Rasmussen TE-MPE **B. Auchmann TE-MPE** **A. Verweij TE-MPE**		**A. Siemko TE-MPE**

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1. CONTENTS

2. INTRODUCTION

The QPS of the main dipole circuits measures the differential voltage drop across the two aperatures of each magnet, hence cancelling out the inductive voltage during a current ramp. In the symmetric quench scenario both apertures of a main dipole are quenching at the same time, most likely by a wave of warm helium. This scenario is undetectable by comparison of apertures. Protection against such symmetric quenches relies on the SymQ board which measures the voltage drop across the entire magnet and compares it to 3 adjacent magnets for inductive voltage cancellation. Slight differences and transmission line effects make this detection scheme vulnarable to fast transients. 'Sunglasses' were therefore introduced to avoid false triggering at the start of a Fast Power Abort [1]. The 'sunglasses' concept applies an elevated threshold during a period of 1.3 s starting as soon as a fast power abort (FPA) is initiated, in order to avoid triggering on inductive voltage transients. The pre-LS1 SymQ threshold was set to 0.8 V with an elevated threshold of 1.3 V during the `sunglasses'-period [2]. The elevated thresholds during the `sunglasses'-period may be justified by the fact that symmetric quenches during the first 1.3 s after an FPA are highly unlikely.

For the increased energy levels of the post-LS1 operation these thresholds needs to be re-evaluated. In our study with the ROXIE quench module we have studied three locations for the initial quench of the magnet [3][4]:

- the quench initiates in the high field zone of the outer layer and propagates in both directions (OLHF);
- the quench initiates in the high field zone of the inner layer and propagates in both directions (ILHF);
- the quench arrives to the low field zone of the outer layer and continues propagating uni-directionally (OLLF).

Moreover, symmetric quenches at different current levels and for different threshold values were studied.

A SymQ threshold consists of a voltage threshold, U_{th}, and an evaluation time, Δt_{eval}. The evaluation time is the duration between the moment that the voltage signal U_{res} exceeds U_{th} and the moment that QPS triggers the quench heaters. For pre-LS1 operation the evaluation time was Δt_{eval}=20 ms and this value was also used in this investigation of the U_{th} limits.

In this note, a maximum safe hotspot temperature of 350 K was used for the magnet coils. In the absence of hard experimental evidence, the maximum safe hotspot temperature is subject to much debate, but we believe that the above given values are rather conservative since they are well below the melting temperature of the cable insualtion. Moreover, symmetric quenches are very rare, so a magnet will not be exposed to this kind of hot-spot temperature repeatedly.

In ROXIE the cable insulation and the helium in the inter-strand voids is lumped together with the heat capacity of the cable. This type of model is too simplistic and tuning of the longitudinal and transverse heat propagation is therefore needed. The tuning of the model and simultion of a symmetric quench was subdivided in 3 steps:

1. A simple 1-D model for longitudinal quench propagation validation, see Section 3.
2. A (2+1)-D model for transverse quench propagation validation and simulation of initial voltage rise, see Section 4.
3. A 2-D model of the main dipole magnet for tuning of the heater-efficiency delay and to determine the maximum temperature in case of a symmetric quench, see Section 5.

All the parameters of the tuned ROXIE models are documented in the appendix.

3. LONGITUDINAL QUENCH PROPAGATION MODEL

The time to reach the voltage threshold after quench initiation depends mainly on the quench propagation speed and the copper resistivity. It takes time for the heat to propagate through the cable insulation to the adjacent turns of the magnet and in the first 5-15 ms the quench only propagates along the cable. The ROXIE model is tuned to data from training quenches in SM18. Figure 3-1 shows voltage rise measurements from several training quenches in SM18 at various currents between 9 kA and 13 kA.

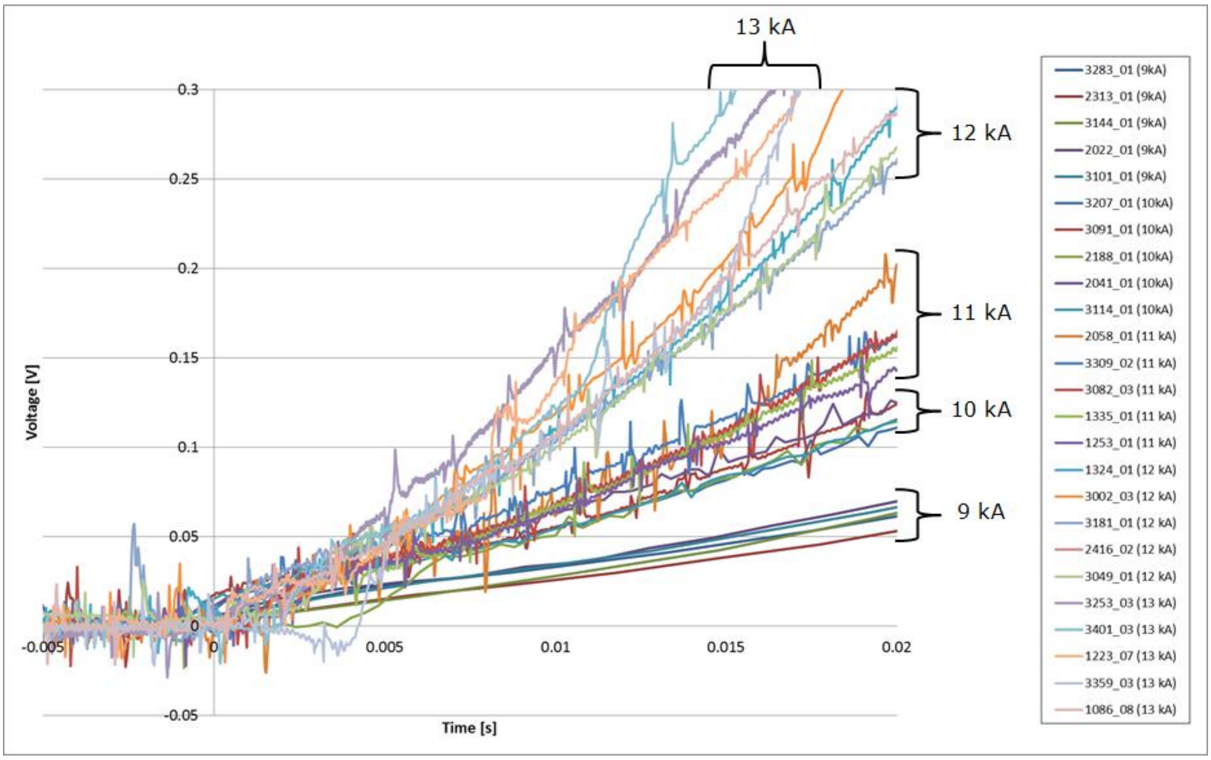

Figure 3-1 – Voltage rise measurements from training quenches in SM18 at various current levels.

From Figure 3-1 it is cannot be determined unambiguously when turn-to-turn popagation starts, but as the simulation results will show there is clearly an acceleration of the voltage rise which can not be explained solely by longitudinal propagation.

The superconducting cables of the two layers of the main dipole magnets have different geometries. The cable in the inner layer has a larger cross-section, which (even though the field in the inner layer is larger than in the outer layer) results in slower propagation and, hence, in a slower voltage rise than for the outer layer. Looking at the individual current levels in Figure 3-1 it is not possible to distinguish separate groups of signals with different slopes. It is therefore assumed that all the training quenches occurred in the same layer of the magnet. For a more precise tuning of the model further data mining is needed, so that it can be determined in which layer the quench initiates.

The fastest voltage rise in the model is observed for quenches in OLHF. The most conservative approach in terms of detection time is, therefore, to tune the model to stay below all the measured voltage curves of Figure 3-1 for OLHF quenches.

For the tuning of the longitudinal quench propagation a simple ROXIE model with only one cable and a defined external field was used. The tuning was done by multiplying the longitudinal heat conductivity by a fitting factor. The results are presented in Figure 3-2 and Figure 3-3 for 9 kA and 13 kA respectively. With a tuning factor of 2 the model of the outer layer follows the measured curves on the conservative side for 5 ms at 13 kA and 10 ms at

9 kA, after which turn-to-turn propagation is assumed to account for the deviation between measurement and the ROXIE 1-D model.

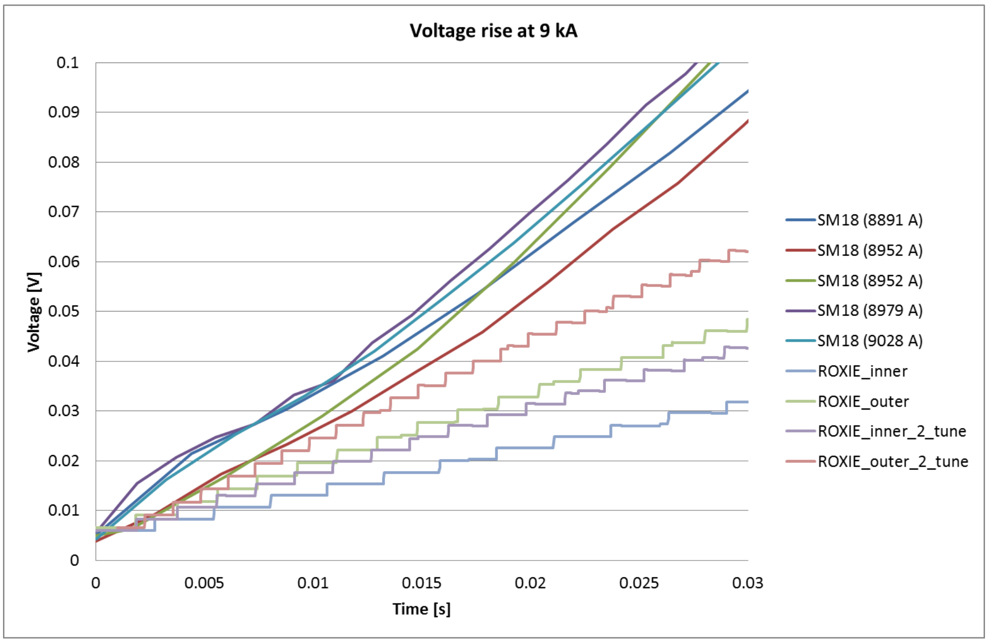

Figure 3-2 – Voltage rise measurements from SM18 quenches at 9 kA plotted with results of ROXIE simulations with and without tuning. All simulations are performed in the HF turn.

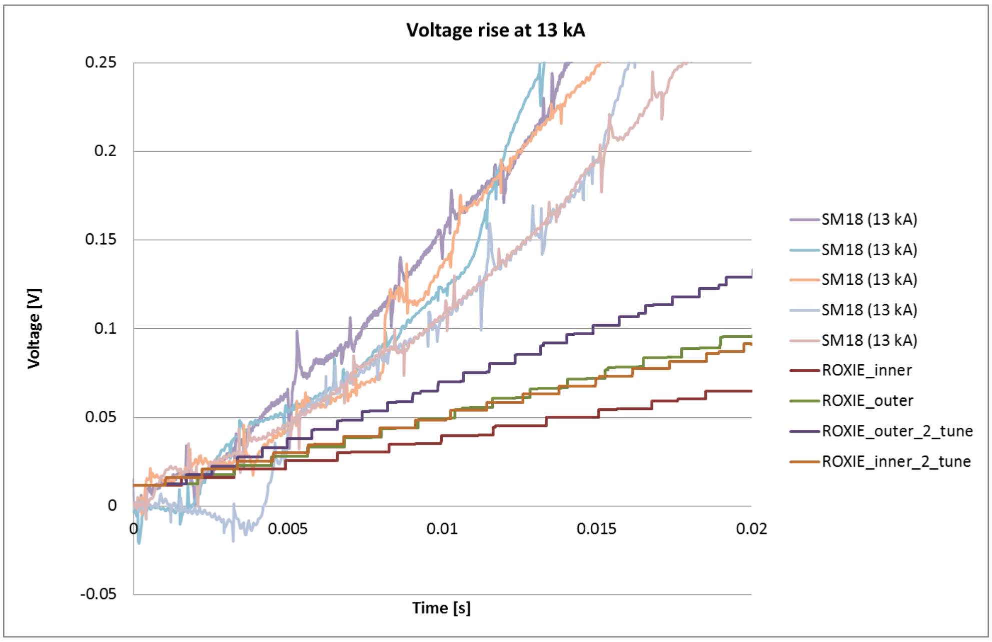

Figure 3-3 - Voltage rise measurements from SM18 quenches at 13 kA plotted with results of ROXIE simulations with and without tuning. All simulations are performed in the HF turn.

4. TRANSVERSE QUENCH PROPAGATION MODEL

For the validation of the transverse quench propagation a full (2+1)-D ROXIE model was used. The term (2+1)-D is used instead of 3-D because the field distribution in the model is based on a 2-D simulation and does not change along the magnet.

Like for the longitudinal case the experimental data and the simulations are tuned by multiplying the transverse heat by a fitting factor. The full (2+1)-D model also contains the tuned longitudinal heat conductivity obtained in the previous section.

The best fit is obtained with a tuning factor of 20 for transverse heat conductivity, accounting among others, for the absence of helium microchannels in the ROXIE model, which accelerates the turn-to-turn propagation. The results are presented in Figure 4-1 and Figure 4-2 for 9 kA and 11.85 kA (nominal current) respectively.

Using this simple tuning approach the model does not scale correctly with current, resulting in a voltage rise which is too rapid at lower current levels. As shown in Figure 4-1, a simulated quench initiating in the high field zone of the outer layer (OLHF) at 9 kA is a bit fast, yet still within the range of the measured voltage rise curves from SM18. However, as simulation results of Section 5 will show, the worst-case condition is a quench in OLHF at nominal current where the voltage rise of the model is slower and the simulated detection time longer than the measuremed one; see Figure 4-2. Hence, the model is still conservative.

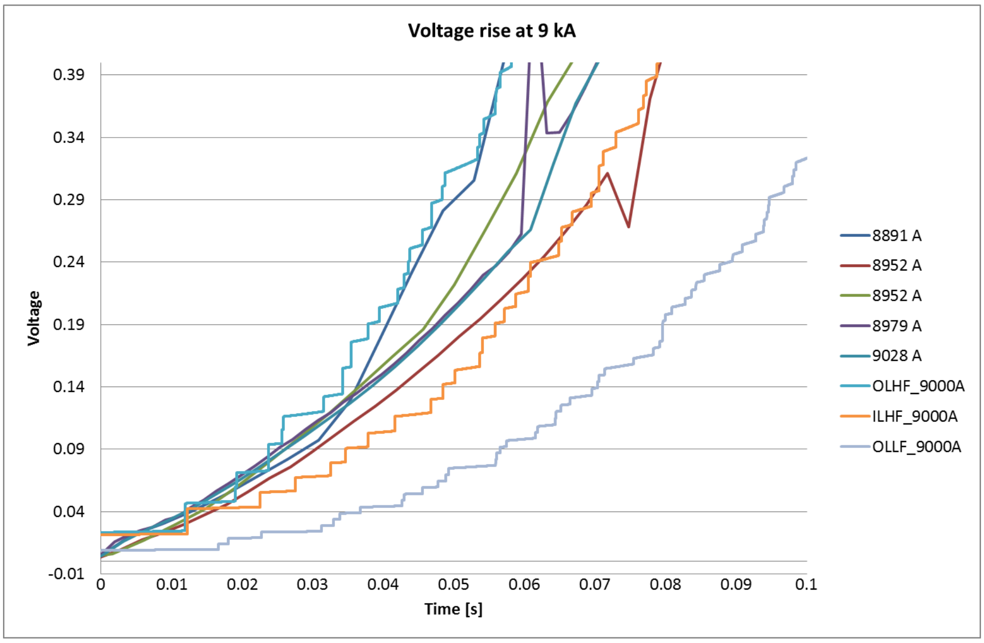

Figure 4-1 – Measured and simulated voltage rise for training quenches at 9 kA. Simulations were performed for quench initiation in the high field zone of the outer layer (OLHF) and inner layer (ILHF), as well as the low field zone of the outer layer (OLLF).

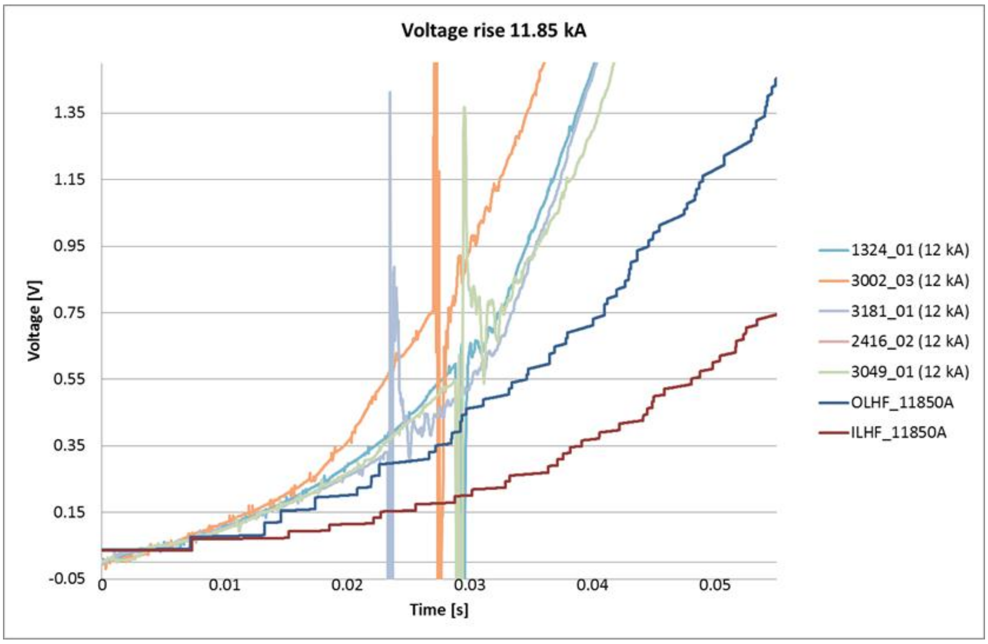

Figure 4-2 - Measured and simulated voltage rise for training quenches at 11.85 kA (nominal). Simulations performed for quench initiation in the high field zone of the outer layer (OLHF) and inner layer (ILHF).

5. 2-D MODEL SIMULATION RESULTS

In principle, the full (2+1)-D model can be used to calculate the full evolution of the quench and determine the peak temperature. However, calculation times for this full model are long and in order to reduce simulation times a different aproach is used. This aproach involves determining the time to detection using the (2+1)-D model and then do a 2-D simulation of the full event to determine the peak temperature. Table 5-1 shows the time to detection determined from the (2+1)-D model.

SymQ threshold	ILHF @ 11.85 kA time to threshold	OLLF @ 11.85 kA time to threshold	OLHF @ 11.85 kA time to threshold	OLHF @ 9 kA time to threshold	OLHF @ 6 kA time to threshold
[V]	**[s]**	**[s]**	**[s]**	**[s]**	**[s]**
0.1	0.007	0.021	0.007	0.019	0.048
0.2	0.019	0.032	0.013	0.026	0.07
0.5	0.029	0.051	0.022	0.044	0.117
0.8	0.042	0.062	0.029	0.058	0.227
0.9	0.044	0.064	0.030	0.061	0.235

Table 5-1 – Simulated times to reach threshold using the (2+1)-D model.

For the 2-D simulations the threshold is set to a virtual value of 0 V and the above time to reach the actual threshold is added to the evaluation time of 20 ms. Furthermore, a heater-switching delay of 5 ms is considered. The heat conductivity between the heaters and the cable is tuned with a scaling factor of 0.43 to fit the delay times to measurements [5].

All the 2-D simulations were performed with a RRR of 150. A RRR of 150 is in the low extreme of what can be expected in the LHC main dipoles. A lower RRR will increase the jouleheating and thereby also the peak temperature. On the other hand a low RRR will also decrease the detection time, but because the (2+1)-D model was tuned to measurement the RRR does not effect the detection time in this model.

The simulations were performed at three different locations; ILHF, OLLF and OLHF. In Figure 5-1 the current decay of the simulation results are presented along with the current decay measured during a training quench in SM18. All the simulations result in slower current decays than those measured in SM18, confirming the conservative nature of the model. Note that also the quench-back effect was not considered in the model.

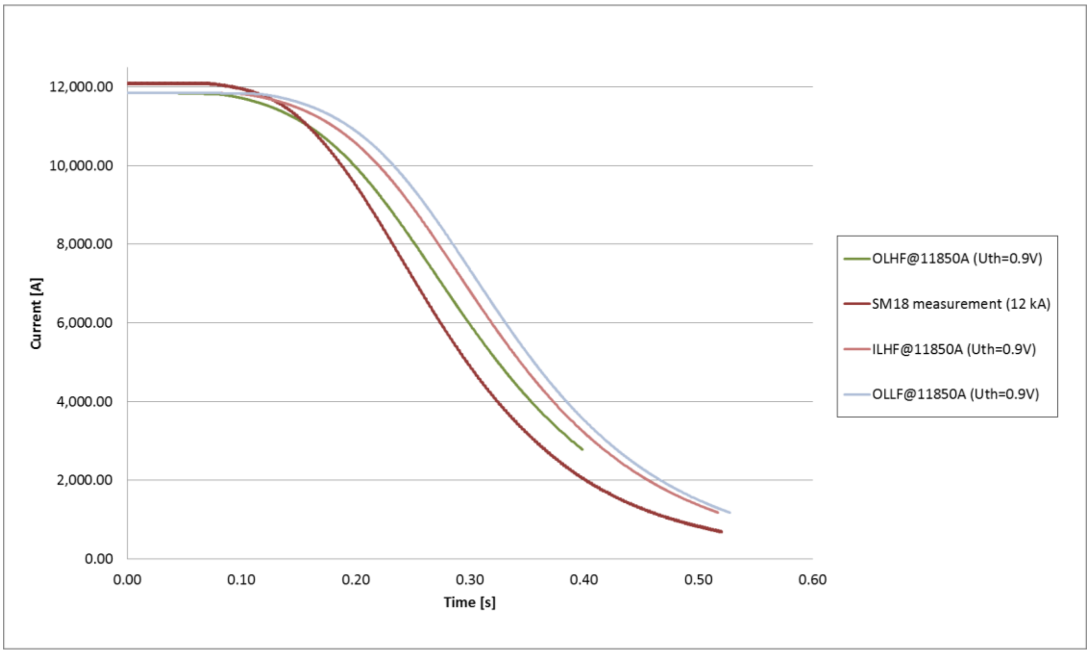

Figure 5-1 – Simulated current decays using the 2-D model and measured current decay from a typical SM18 training quench.

The resulting peak temperatures at nominal current for the different quench locations and a SymQ threshold of 0.9 V are presented in Figure 5-2. In Figure 5-3 the simulated peak temperatures for a quench in OLHF at vairous current levels are presented.

The worst-case is a quench at nominal current initiating in OLHF. For a SymQ threshold of 0.9 V this results in a peak temperature of 342 K.

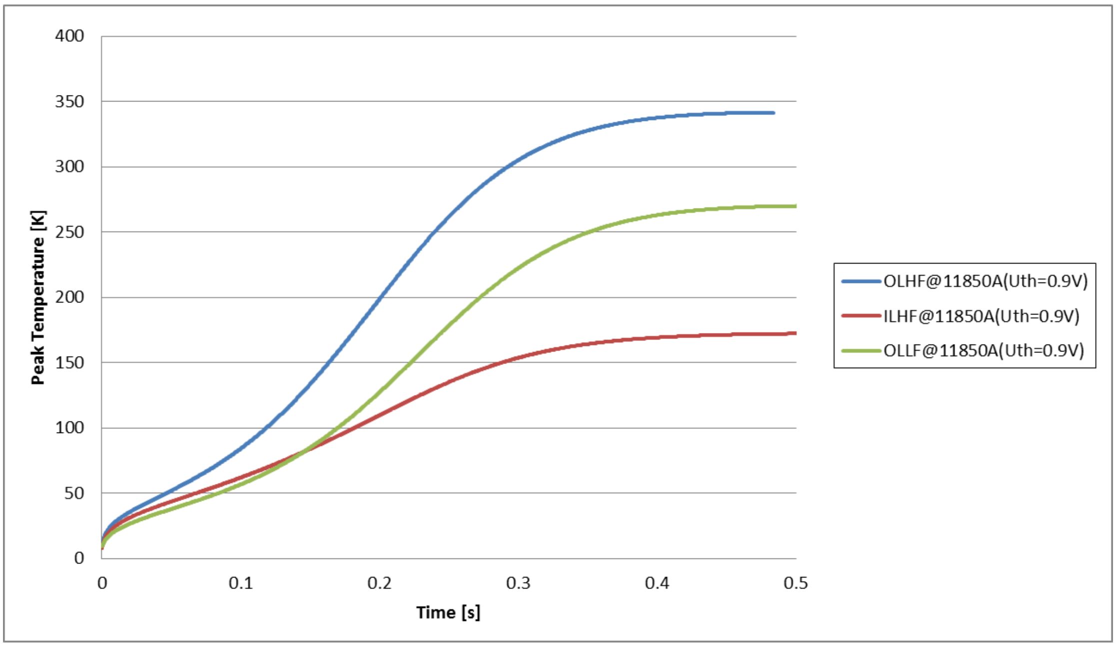

Figure 5-2 – Simulated peak temperature in case of a symmetric quench for various quench initiation locations and a SymQ threshold of 0.9 V.

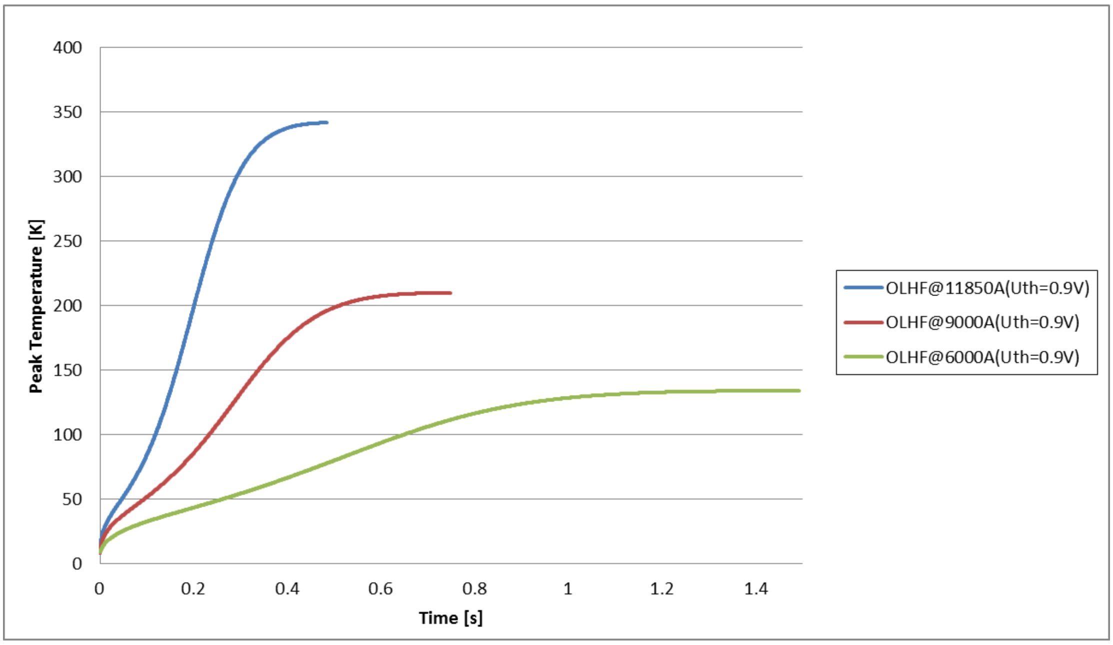

Figure 5-3 - Simulated peak temperatures for a quench in OLHF with a SymQ threshold of 0.9 V at various current levels.

In Figure 5-4 the peak temperature is presented for various SymQ thresholds. Because of the turn-to-turn propagation the voltgae rise across the magnet is accelerating. This means that as the threshold is increased the effect of the increase on the peak temperature becomes less pronounced. Hence, changing the threshold from 0.8 V to 0.9 V increases the peak temperature by only 3 K.

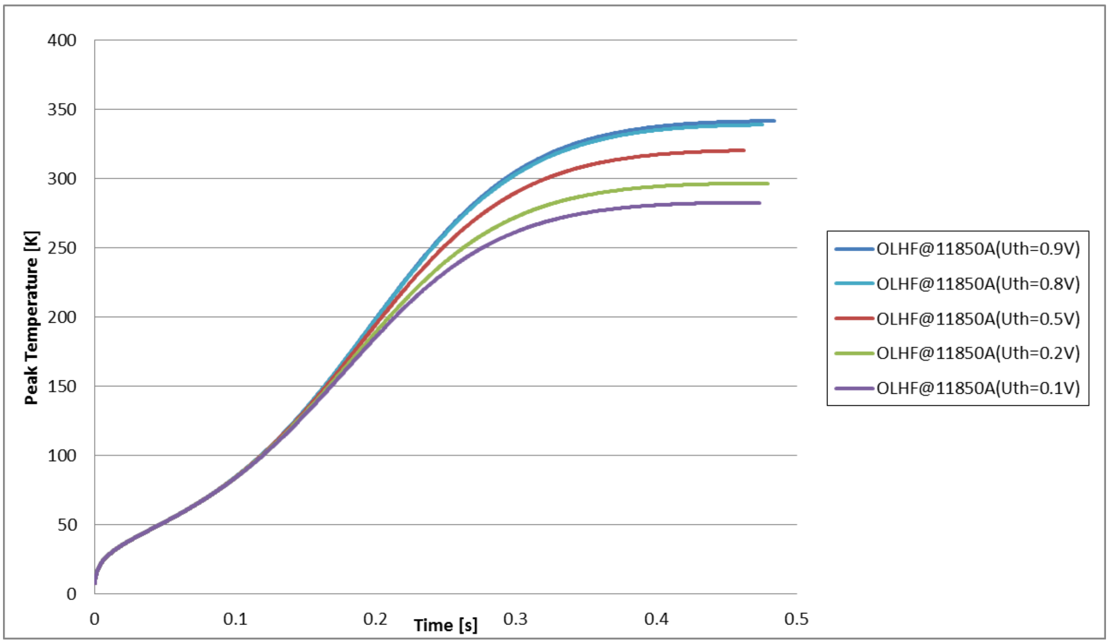

Figure 5-4 - Simulated peak temperatures for a quench in OLHF with various SymQ thresholds.

6. CONCLUSION

A ROXIE model of quench propagation in a LHC main dipole magnet has been tuned to approximate in a conservative way the measured voltage rise from training quenches in SM18. After tuning, the model was then used calculate the maximum temperature of the coil assuming that the quench starts symmetrically between both apertures. Such calcualtions were done for various current levels and quench locations. With a SymQ threshold of 0.9 V the maximum temperature approaches the limiting value of 350 K.

By adding turn-to-turn propagation to the model the peak temperature is less dependent on the threshold value.

This is not a recommendation for the actual setting of SymQ thresholds, which shall be chosen as low as reasonably possible, and at least below 0.9 V.

7. WORKS CITED

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2. **Auchmann, B., Verweij, A.** *Estimate of a save threshold for the symmetric quench protection system @ 6 kA*, Geneva : CERN, 2010. EDMS id: 1065905.

3. **Schwerg, N., Auchmann, B. and Russenschuck, S.** *Quench Simulation in an Integrated Design Enviroment for Superconducting Magnets,* Geneva : CERN, 2007.

4. *http://cern.ch/roxie.* **ROXIE 10.2.** 2010.

5. **Rodriguez-Mateos, F. et al.** *Quench Heater Experiments on the LHC Main Superconducting Magnets,* Vienna, 2000.

8. APPENDIX

8.1 ROXIE CABLE DATA

8.1.1 CONDUCTOR

Name	Type	CableGeom.	Strand	Filament	Insul	Trans	QuenchMat.	T_o	Comment
LHCMBIN	1	CABLE01	LHCMBSTR1	NBTII	ALLPOLYIL	LHCTRANS1	MBIN	1.9	V6-1 DESIGN DIPOLE INNER
LHCMBOU	1	CABLE02	LHCMBSTR2	NBTIO	ALLPOLYOL	LHCTRANS2	MBOUT	1.9	V6-1 DESIGN DIPOLE OUTER

8.1.2 CABLE

Name	height	width_i	width_o	ns	transp.	degrd	Comment
CABLE01	15.1	1.736	2.064	28	115	0	MB INNER LAYER,STR01
CABLE02	15.1	1.362	1.598	36	100	0	MB OUTER LAYER,STR01

8.1.3 QUENCH

Name	SCHeat Capa	CuHeat Capa	CuTherm Cond	CuElec Res	InsHeatCapa	InsThermCond	FillHeatCapa	He%	Comment
MBIN	2	2	2	2	1	1	2	29.72	MB Dipole outer'
MBOUT	2	2	2	2	1	1	2	24.65	MB Dipole outer'

8.1.4 STRAND

Name	diam.	cu/sc	RRR	Tref	Bref	Jc@BrTr	dJc/dB	Comment
LHCMBSTR1	1.065	1.6	200	1.9	10	1433.3	500.34	LHC MB Arjan 150-250
LHCMBSTR2	0.825	1.9	200	1.9	9	1953	550.03	LHC MB Arjan 150-250

8.1.5 TRANSIENT

Name	Rc	Ra	fil.twistp.	fil.R0	fil.dR/dB	strandfill.fac.	Comment
LHCTRANS1	3.00E-05	0.0001	0.018	1.24E-10	9.00E-11	0.5	LHC cable resistances Arjan
LHCTRANS2	6.00E-05	0.0001	0.015	1.24E-10	9.00E-11	0.5	LHC cable resistances Arjan

8.1.6 FILAMENT

Name	fildiao	fildiai	Jc-Fit	fit-|	Comment
NBTII	7	0	FIT1	FIT1	NBTI INNER CABLES
NBTIO	6	0	FIT1	FIT1	NBTI OUTER CABLES

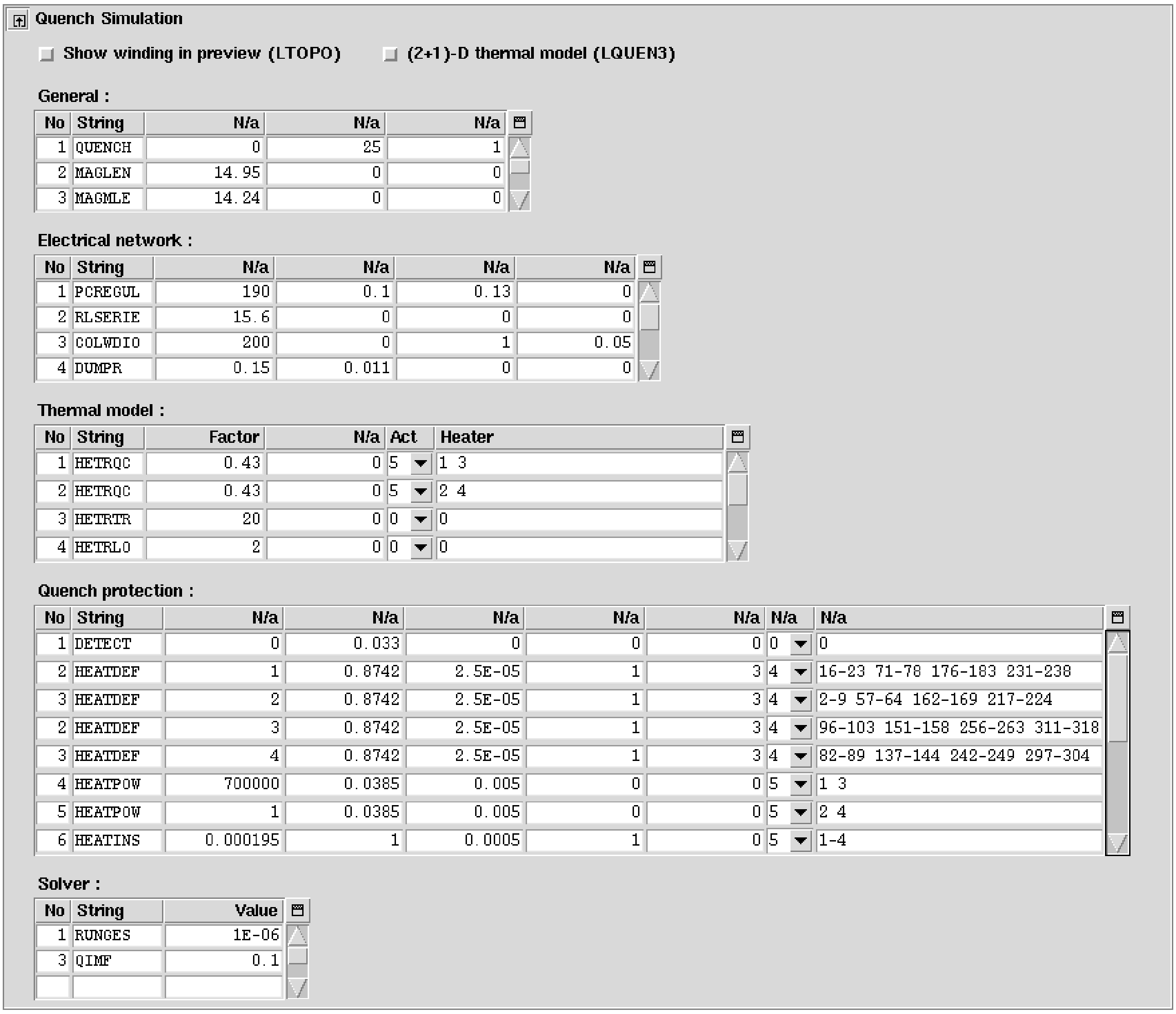
8.1.7 REMFIT

Name	Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Comment
FIT1	1	3.00E+09	9.2	0.57	0.9	2.32	27.04	14.5	0	0	0	0	MB FILAMENT TYPE

8.1.8 INSULATION

Name	Radial	Azimut	Comment
ALLPOLYIL	0.15	0.12	POLYIMID MB INNER
ALLPOLYOL	0.15	0.13	POLYIMID MB OUTER

8.2 ROXIE QUENCH SIMULATION SETTINGS



Quench Simulation

☐ Show winding in preview (LTOPO) ☐ (2+1)-D thermal model (LQUEN3)

General :

No	String	N/a	N/a	N/a
1	QUENCH	0	25	1
2	MAGLEN	14.95	0	0
3	MAGMLE	14.24	0	0

Electrical network :

No	String	N/a	N/a	N/a	N/a
1	PCREGUL	190	0.1	0.13	0
2	RLSERIE	15.6	0	0	0
3	COLWDIO	200	0	1	0.05
4	DUMPR	0.15	0.011	0	0

Thermal model :

No	String	Factor	N/a	Act	Heater
1	HETRQC	0.43	0	5	1 3
2	HETRQC	0.43	0	5	2 4
3	HETRTR	20	0	0	0
4	HETRLO	2	0	0	0

Quench protection :

No	String	N/a	N/a	N/a	N/a	N/a	N/a	N/a
1	DETECT	0	0.033	0	0	0	0	0
2	HEATDEF	1	0.8742	2.5E-05	1	3	4	16-23 71-78 176-183 231-238
3	HEATDEF	2	0.8742	2.5E-05	1	3	4	2-9 57-64 162-169 217-224
2	HEATDEF	3	0.8742	2.5E-05	1	3	4	96-103 151-158 256-263 311-318
3	HEATDEF	4	0.8742	2.5E-05	1	3	4	82-89 137-144 242-249 297-304
4	HEATPOW	700000	0.0385	0.005	0	0	5	1 3
5	HEATPOW	1	0.0385	0.005	0	0	5	2 4
6	HEATINS	0.000195	1	0.0005	1	0	5	1-4

Solver :

No	String	Value
1	RUNGES	1E-06
3	QIMF	0.1

Figure 8-1 – ROXIE simulation parameters for a SymQ threshold of 0.2 V.