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Dariusz.Bocian@cern.ch

Enthalpy Limit Calculations for transient perturbations in LHC magnets

D. Bocian[1] / AB-BI, M.Calvi and A. Siemko / AT-MTM

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Summary

The results of enthalpy limit calculations of LHC magnets are presented. The enthalpy limits of bare cables and helium surrounding the cable strands were calculated from the material properties. The results of calculations give the range of the expected energy deposition limits in the LHC superconducting cables for fast and slow beam losses.

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[1] H. Niewodniczański Institute of Nuclear Physics PAN, Krakow, Poland

1 Introduction

The energy deposited by the beam in the LHC superconducting magnet coils 5 could increase the temperature of the superconducting cable above the critical temperature and it could results in quench[2] of the magnet. The knowledge of the stability margin of the LHC superconducting magnets with respect to beam induced heat depositions is required for the commissioning and the exploitation of the LHC 5. In this paper the stability margins of the LHC magnets, calculated from the material properties, are presented. The calculations taking into account only enthalpies of the bare cable and in case of main LHC magnets, the helium surrounding the cable strands. No heat flow in the bare cable itself and from the cable into the helium is regarded. The results of calculations give the range of the expected energy deposition limits in the LHC superconducting cables for fast and slow beam losses.

2 Superconducting cables characteristic

The main LHC superconducting magnet coils are built from the Rutheford type cables and the corrector magnets coils are made from bulk type cables. A photo and schematic cut view of the Rutheford type superconducting cable cross section is shown in Fig. 1. The strands are made of NbTi filaments inserted inside a Copper matrix. The helium occupies the space between the strands and between the strands and the insulation.

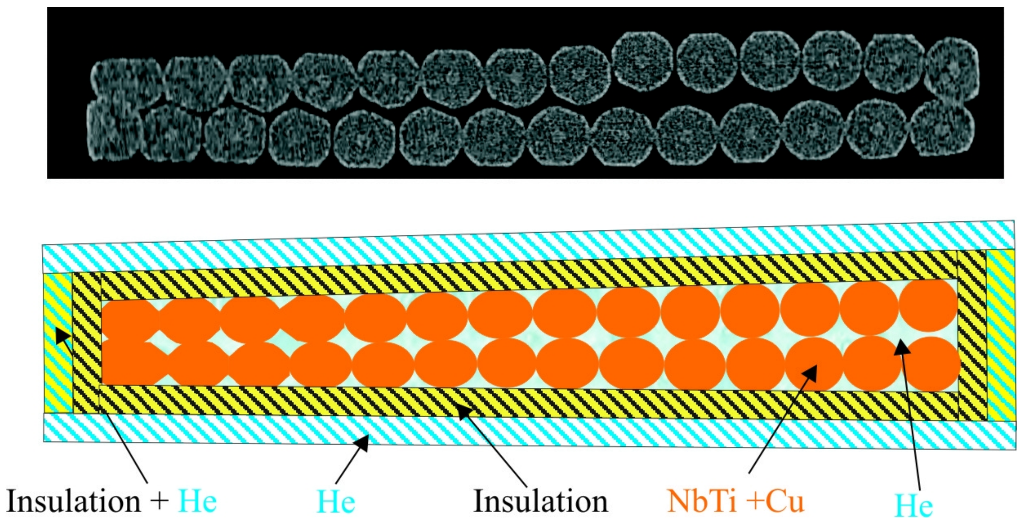

Fig. 1 Superconducting cable photo and schematic cut view

A rough estimation of the strands cross-section can be obtained from the cable geometry. The calculations are valid for ideal, plastically non-deformed strands. These calculations have taken into account that strands in the cable are twisted and transposition pitch is different for each type of the cable. This means that the cross-section of the strands has ellipsoid shape with the major axis determined by transposition pitch and the cable width and minor axis determined by strand radius. The area enclosed by an ellipse is πab, where a and b are the ellipse's semimajor and semiminor axes respectively. The helium volume inside of the superconducting cable was calculated with the method described in 5. Table 1 and summarize the results of the cable cross-section calculation.

[2] A quench is a transition of a conductor from the superconducting to the normal conducting state. Such a transition occurs in accelerator magnets if one of three parameters: temperature, magnetic field or current density, exceeds a critical value.

Table 1 Main LHC superconducting magnet cable cross-sections.

	A_{metal} (mm^2)	A_{Cu} (mm^2)	A_{NbTi} (mm^2)	$A_{polyimide}$ (mm^2)	A_{Helium} (mm^2)
Type-1	25.79	16.06	9.73	5.46	2.01
Type-2	20.10	13.29	6.81	5.33	1.49
Type-3	20.10	13.29	6.81	4.51	1.63
Type-4 & 7	6.74	4.29	2.45	1.88	0.43
Type-5	6.34	4.04	2.31	1.79	0.42
Type-6	9.63	6.13	3.50	1.87	0.84

Table 2 LHC corrector cable cross-sections. Superconductor NbTi with Ti=47% by weight.

Cable type	A_{metal} (mm^2)	A_{Cu} (mm^2)	A_{NbTi} (mm^2)	A_{PVA} (mm^2)
Corr-1	0.110	0.088	0.022	0.0382
Corr-2	0.214	0.172	0.043	0.0630
Corr-3	0.689	0.424	0.265	0.2232
Corr-4	1.301	0.800	0.500	0.3000

3 Enthalpy limit calculations

The enthalpy limit is calculated from the basic thermodynamic law describing relation of the enthalpy and heat capacity. In the calculations, following formulae was used:

$$\Delta H = \int_{T_b}^{T_{cs}} C_{eff}\, dT \qquad \textbf{Eq. 1}$$

where the effective volumetric heat capacity $C_{eff} = C_p \cdot \rho$ (C_p- heat capacity at constant pressure, ρ-density) is calculated as follows:

$$C_{eff} = \frac{\sum_{i=1}^{n} C_{p_i} \cdot \rho_i \cdot A_i}{\sum_{i=1}^{n} A_i} \qquad \textbf{Eq. 2}$$

where i indicates Copper, NbTi and Helium in case of Rutheford type cable. The reference density value of Cu is 8930 kg/m^3, NbTi is 6138 kg/m^3 5 and Polyimide insulation is 1420 kg/m^3 5. The density of helium is taken from 5. The temperature margin values were obtained from 5 and are listed in Appendix A. The quench limits in the Table 3 and Table 4 are given for the peak magnetic field strength in the magnets (see Appendix A) and for two of the beam energy settings - injection and collision. For each of the energy the two sets of numbers, corresponding to the beam loss duration, are shown. Fast perturbation means no heat transfer to the helium in the cable and only heat reserve of the bare cable is calculated. For the slow perturbation heat reserve of helium is added. Superfluid helium has a large heat capacity hence the differences between the 2 sets of numbers. For time periods between the 2 extremes (fast and slow perturbations, there will be a partial affect from the helium – this is non-trivial to calculate as it depends upon modelling the superfluid He and its properties. and Table 4 summarize the results of enthalpy limit calculation. The names Type-1 to Type-6 and corr-1 to corr-4 corresponds to the cable types in the coils of the magnets. When two types of the cables appear with the same name of the magnet, it means that coil consists of two types of the cables.

The quench limits in the Table 3 and Table 4 are given for the peak magnetic field strength in the magnets (see Appendix A) and for two of the beam energy settings - injection and collision. For each of the energy the two sets of numbers, corresponding to the beam loss duration, are shown. Fast perturbation means no heat transfer to the helium in the cable and only heat reserve of the bare cable is calculated. For the slow perturbation heat reserve of helium is added. Superfluid helium has a large heat capacity hence the differences between the 2 sets of numbers. For time periods between the 2 extremes (fast and slow perturbations, there will be a partial affect from the helium – this is non-trivial to calculate as it depends upon modelling the superfluid He and its properties.

Table 3 Enthalpy limits of the main LHC superconducting magnets

			Enthalpy [mJoule/cm³]			
			Beam energy = 450 GeV		Beam energy = 7000 GeV	
Magnet	Cable type	T_{bath}	Fast perturbation <10 µs	Slow perturbation >100 ms	Fast perturbation <10 µs	Slow perturbation >100 ms
MB	Type-1	1.9K	*31,29*	*148,53*	*0,93*	*56,26*
MB	Type-2	1.9K	*29,24*	*141,21*	*0,90*	*53,70*
MQ	Type-3	1.9K	*29,45*	*150,69*	*1,41*	*72,09*
MQM(C, L)	Type-7	1.9K	*30,31*	*127,78*	*1,06*	*50,11*
MQM(L)	Type-7	4.5K	*28,22*	*47,58*	*1,63*	*6,35*
MQY	Type-5	4.5K	*28,43*	*48,55*	*2,46*	*8,78*
MQY	Type-6	4.5K	*32,06*	*57,76*	*4,95*	*15,84*

Table 4 Enthalpy limits of the LHC corrector magnets

			Enthalpy [mJoule/cm³]	
Magnet	**Cable type**	$\mathbf{T_{bath}}$	Beam energy = 450 GeV	Beam energy = 7000 GeV
			Orbit correctors	
MCB	corr-1	1.9K	*23,21*	*4,77*
MCBC	corr-2	1.9K	*23,13*	*4,20*
MCBC	corr-2	4.5K	*21,60*	*5,69*
MCBY	corr-2	1.9K	*23,30*	*5,21*
MCBY	corr-2	4.5K	*21,51*	*5,28*
MCBXH	corr-4	1.9K	*33,11*	*10,91*
MCBXV	corr-4	1.9K	*33,22*	*11,66*
			Multipole correctors	
MCD	corr-3	1.9K	*32,88*	*10,65*
MCO	corr-2	1.9K	*23,72*	*7,64*
MCOSX	corr-2	1.9K	*23,98*	*9,46*
MCOX	corr2	1.9K	*23,98*	*9,37*
MCS	corr-3	1.9K	*32,99*	*12,27*
MCSSX	corr-2	1.9K	*23,98*	*9,50*
MCSX	corr-2	1.9K	*23,81*	*7,02*
MCTX	corr-2	1.9K	*23,30*	*4,89*
			Lattice correctors	
MO	corr-3	1.9K	*32,76*	*10,55*
MQS	corr-3	1.9K	*32,20*	*5,81*
MQSX	corr3	1.9K	*32,20*	*6,32*
MQT	corr-3	1.9K	*32,20*	*5,81*
MQTLI	corr-3	1.9K	*32,20*	*5,81*
MS	corr-3	1.9K	*32,08*	*5,00*
MSS	corr-3	1.9K	*32,08*	*5,00*
			Q6 at IR3 and IR7	
MQTLH	corr-3	4.5K	*29,72*	*5,69*

4 Conclusions

The calculations presented in this note give the first estimation of the stability margin of the main LHC superconducting magnets and the corrector magnets as well. The numbers can be used to evaluate the fraction of quench limit from any given energy deposit in the coils for LHC superconducting magnets. Further research on stability margin calculation including heat transfer model for transient beam losses is going on. The results will be reported in the next papers.

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5 Bibliography

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Appendix A CHARACTERISTIC OF LHC MAGNETS

Tab A. 1 LHC main magnets characteristic at the collision optics (E_{beam}=7000 GeV).

Magnet type	Cable type	T_{bath} (K)	I_{op} (A)	B (T)	T_{cs} (K)	ΔT (K)
MB	Type-1	1.9	11850	8.58	3.51	1.61
MB	Type-2	1.9	11850	7.41	3.51	1.61
MQ	Type-3	1.9	11870	6.85	3.88	1.98
MQM	Type-7	1.9	5390	6.30	3.62	1.72
MQM	Type-7	4.5	4310	5.04	4.94	0.44
MQMC	Type-4	1.9	5390	6.30	3.62	1.72
MQML	Type-4	1.9	5390	6.30	3.62	1.72
MQML	Type-4	4.5	4310	5.04	4.94	0.44
MQY	Type-5	4.5	3610	5.13	5.12	0.62
MQY	Type-6	4.5	3610	6.16	5.45	0.95

Tab A. 2 Corrector magnet characteristic and cable types used in the LHC magnets – collision optics.

Magnet type	Cable type	T_{bath} (K)	I_{op} (A)	B (T)	T_{cs} (K)	ΔT (K)
Orbit correctors						
MCB(H&V)	Corr-1	1.9	55	3.15	5.36	3.46
MCBC(H&V)	Corr-2	1.9	100	3.65	5.21	3.31
MCBC(H&V)	Corr-2	4.5	74	2.68	6.29	1.79
MCBY(H&V)	Corr-2	1.9	88	3.60	5.49	3.59
MCBY(H&V)	Corr-2	4.5	72	2.96	6.18	1.68
MCBXH	Corr-4	1.9	550	4.02	6.21	4.31
MCBXV	Corr-4	1.9	550	3.71	6.35	4.45
Multipole correctors						
MCD	Corr-3	1.9	550	2.40	6.16	4.26
MCO	Corr-2	1.9	100	2.00	6.22	4.32
MCOSX	Corr-2	1.9	100	1.34	6.67	4.77
MCOX	Corr-2	1.9	100	1.37	6.65	4.75
MCS	Corr-3	1.9	550	1.90	6.46	4.56
MCSSX	Corr-2	1.9	100	1.32	6.68	4.78
MCSX	Corr-2	1.9	50	4.20	6.05	4.15
MCTX	Corr-2	1.9	80	4.10	5.39	3.49
Lattice correctors						
MO	Corr-3	1.9	550	2.43	6.14	4.24
MQS	Corr-3	1.9	550	4.10	5.18	3.28
MQSX	Corr-3	1.9	550	3.94	5.27	3.37
MQT	Corr-3	1.9	550	4.10	5.18	3.28
MQTLI	Corr-3	1.9	550	4.10	5.18	3.28
MS	Corr-3	1.9	550	4.37	5.02	3.12
MSS	Corr-3	1.9	550	4.37	5.02	3.12
Q6 at IP6						
MQTLH	Corr-3	4.5	400	4.10	5.74	1.24

Tab A. 3 LHC main magnets characteristic at the injection optics (E_{beam}= 450 GeV).

Magnet type	Cable type	T_{bath} (K)	I_{op} (A)	B (T)	T_{cs} (K)	ΔT (K)
MB	Type-1	1.9	761.79	0.55	8.83	6.93
MB	Type-2	1.9	761.79	0.48	8.81	6.91
MQ	Type-3	1.9	763.07	0.44	8.82	6.93
MQM	Type-7	1.9	346.50	0.40	8.80	6.90
MQM	Type-7	4.5	277.07	0.32	8.87	4.37
MQMC	Type-4	1.9	346.50	0.40	8.80	6.90
MQML	Type-4	1.9	346.50	0.40	8.80	6.90
MQML	Type-4	4.5	277.07	0.32	8.87	4.37
MQY	Type-5	4.5	232.07	0.33	8.89	4.39
MQY	Type-6	4.5	232.07	0.40	8.93	4.43

Tab A. 4 Corrector magnet characteristic and cable types used in the LHC magnets – injection optics.

Magnet type	Cable type	T_{bath} (K)	I_{op} (A)	B (T)	T_{cs} (K)	ΔT (K)
Orbit correctors						
MCB(H&V)	Corr-1	1.9	3.54	0.20	8.88	6.98
MCBC(H&V)	Corr-2	1.9	6.43	0.23	8.87	6.97
MCBC(H&V)	Corr-2	4.5	4.76	0.17	8.95	4.45
MCBY(H&V)	Corr-2	1.9	5.66	0.23	8.89	6.99
MCBY(H&V)	Corr-2	4.5	4.63	0.19	8.94	4.44
MCBXH	Corr-4	1.9	35.36	0.26	8.96	7.06
MCBXV	Corr-4	1.9	35.36	0.24	8.97	7.07
Multipole correctors						
MCD	Corr-3	1.9	35.36	0.15	8.94	7.04
MCO	Corr-2	1.9	6.43	0.13	8.94	7.04
MCOSX	Corr-2	1.9	6.43	0.09	8.97	7.07
MCOX	Corr-2	1.9	6.43	0.09	8.97	7.07
MCS	Corr-3	1.9	35.36	0.12	8.95	7.05
MCSSX	Corr-2	1.9	6.43	0.08	8.97	7.07
MCSX	Corr-2	1.9	3.21	0.27	8.95	7.05
MCTX	Corr-2	1.9	5.14	0.26	8.89	6.99
Lattice correctors						
MO	Corr-3	1.9	35.36	0.16	8.93	7.03
MQS	Corr-3	1.9	35.36	0.26	8.88	6.98
MQSX	Corr-3	1.9	35.36	0.25	8.88	6.98
MQT	Corr-3	1.9	35.36	0.26	8.88	6.98
MQTLI	Corr-3	1.9	35.36	0.26	8.88	6.98
MS	Corr-3	1.9	35.36	0.28	8.87	6.97
MSS	Corr-3	1.9	35.36	0.28	8.87	6.97
Q6 at IP6						
MQTLH	Corr-3	4.5	25.71	0.26	8.92	4.42