11T Magnet Operating Margin

Presented by L. Bottura

With contributions from A. Devred, E. Felcini S. Izquierdo Bermudez,
F. Savary, D. Schoerling, R. Van Weelderen, G. Willering

Scope of this talk

- Focus on the operating margin of the MBH (11T) Nb_3Sn coil, heat transfer from the coil to the superfluid helium bath and comparison to MB Nb-Ti coil
- Values of heat loads due to collimation loss are provided by HL-LHC WP5, and recently summarized by S. Redaelli and C. Bahamonde, et al. in TCC 54, 2/8/2018
- Analysis of heat transfer in the helium bath in the cold mass was already presented by R. Van Weelderen, et al. in TCC 54, 2/8/2018
- The **ultimate and bold** goal is to provide the expected quench limits for the MBH (11T) Nb_3Sn magnets

Outline

- Background
- Available measurements on Nb_3Sn magnets
- Analysis and forecast
- Conclusions

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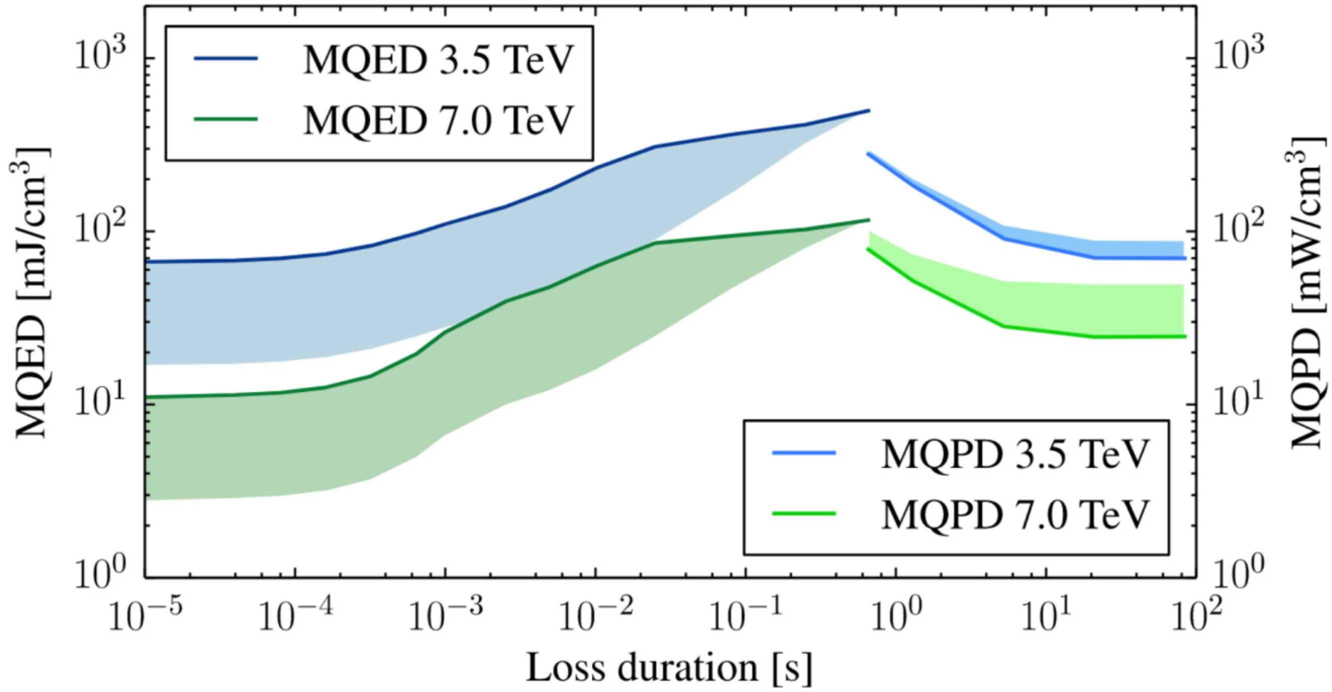
Background – 1/4

B. Auchmann et al., Phys. Rev. ST Accel. Beams, 18, 061002 (2015)



- Present LHC quench limits (Nb-Ti magnets)
  - 20 to 45 mW/cm^3 steady state losses (average over cable cross section)
    - “Measured” 20 to 30 mW/cm^3 at 6.37 TeV, a factor of two lower than the optimistic estimate
  - 3 to 10 mJ/cm^3 energy for fast losses (average over cable cross section)

Background – 2/4

L. Bottura et al., Cryogenics, 46, 481-493 (2006)

Available online at www.sciencedirect.com
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Cryogenics 46 (2006) 481–493
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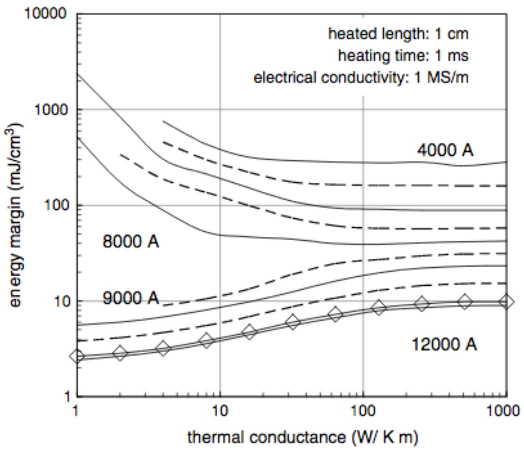
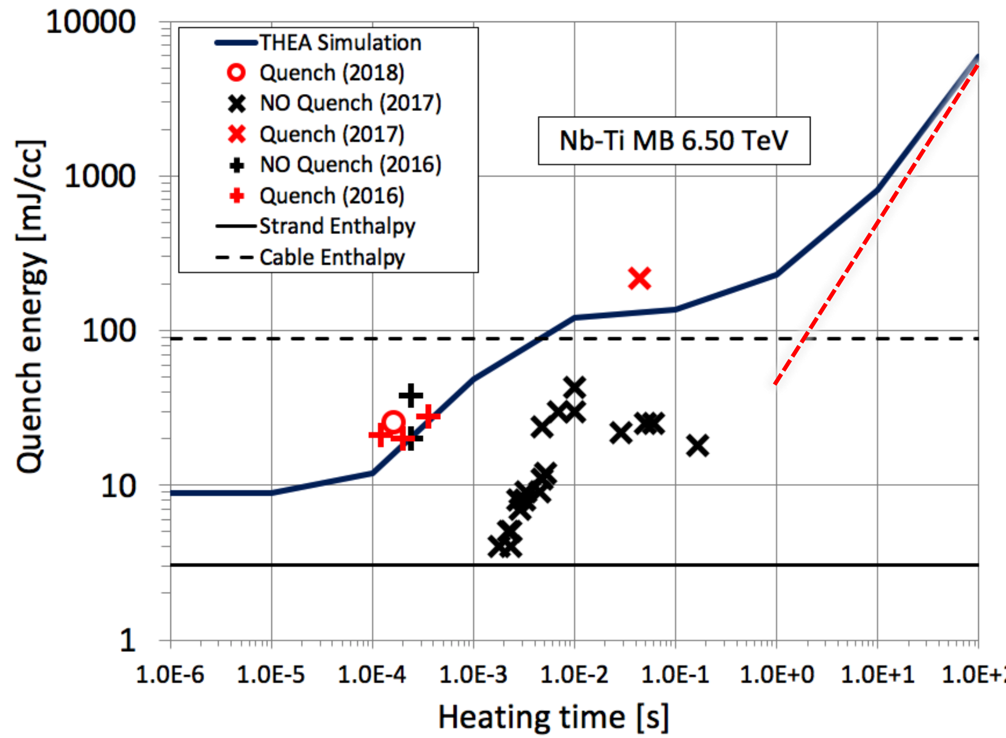
Stability analysis of the LHC cables

L. Bottura *, M. Calvi, A. Siemko

Stability
"BCS"





- Good agreement between multi-strand 1D model of stability and results derived from the quench tests in the LHC !
  - It is important to consider the details of the cable strands, geometry, field and heat distributions
  - The presence of the interstitial helium leads to a large enhancement of stability
  - The transient heat transfer model is a critical matter, especially for fast (1 ms) and ultra-fast (1μs) characteristic times

Background – 3/4

- Collimation loss expected at MBB.B8 (7 TeV)
  - Values as defined by C. Bahamonde, et al. in TCC 54, 2/8/2018, and previous analyses
  - Local and total loss depend on the assumption on the Beam Life Time (BLT)

	BLT = 1 hour		BLT = 12 min	
Protons	Coil peak: Coil total: Cold mass total:	2 mW/cm^3 11 W (0.2 mW/cm^3) 34 W	Coil peak: Coil total: Cold mass total:	11 mW/cm^3 54 W (1 mW/cm^3) 170 W
Ions	Coil peak: Coil total: Cold mass total:	4 mW/cm^3 20 W (0.4 mW/cm^3) 66 W	Coil peak: Coil total: Cold mass total:	21 mW/cm^3 98 W (1.8 mW/cm^3) 330 W

Thermal loads in the 11T magnet in MBB.B8 for different assumptions on the BLT

I am not entering in the discussion on BLT

Background – 4/4

- Cooling of the cold mass (from coil to HX)
  - Reference values have been given by R. Van Weelderen, et al. in TCC 54, 2/8/2018 for protons and ions and two different hypotheses on the BLT
  - Heat removal from cold mass is OK for BLT=1 hour
  - Temperature will drift for BLT=12 min (the coils will heat nearly adiabatically, beam dumped in 10 s)

	BLT = 1 hour	BLT = 12 min
Protons	Q8-Q9: ∞ (85 W) Q10-Q11: ∞ (88…95 W)	Q8-Q9: 40 mins (333 W) Q10-Q11: 30 mins (348…383 W)
Ions	Q8-Q9: few hours (120 W) Q10-Q11: 2 hours (162…177 W)	Q8-Q9: 20 mins (508 W) Q10-Q11: 10 mins (718…793 W)

Time expected to reach T_λ in half cells Q8-Q9 and Q10-Q11 as a function of BLT

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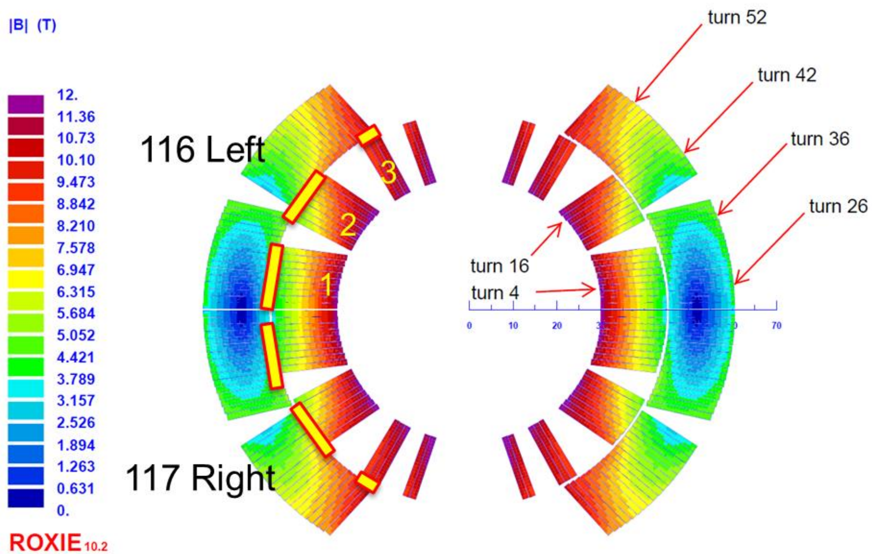
Available measurements

- "DC stability" measurements using inter-layer quench heaters DP106 as a heat source
- "Ramp rate" studies in short models SP106 and SP107 at 1.9 K and 4.3 K
- "AC loss" measurements in short models (SP102, SP104, SP105, DP101, SP106, SP107) and long prototype (MBHP01)
- Measurement of heat transfer in cable stacks and coil parts (CryoLab)
- Measurements of heat transfer in other Nb_3Sn dipole models (e.g. VLHC models at FNAL)
- Measurement of stability in wires and cables

DC stability

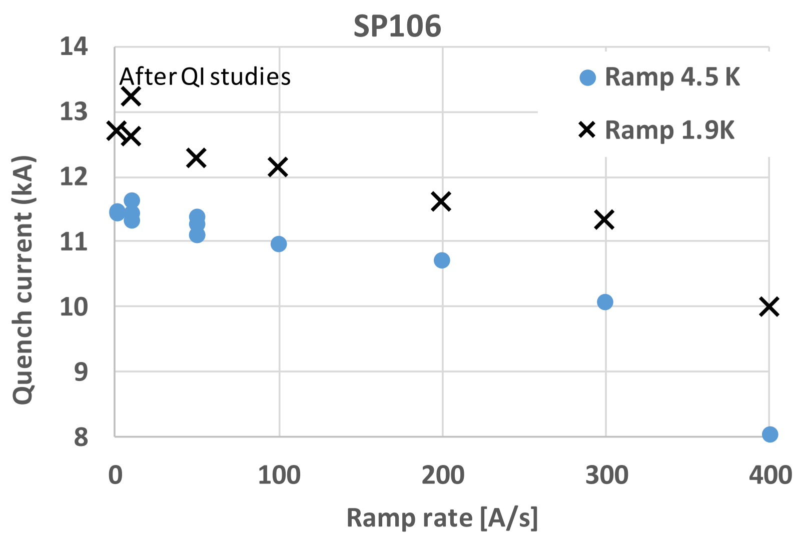


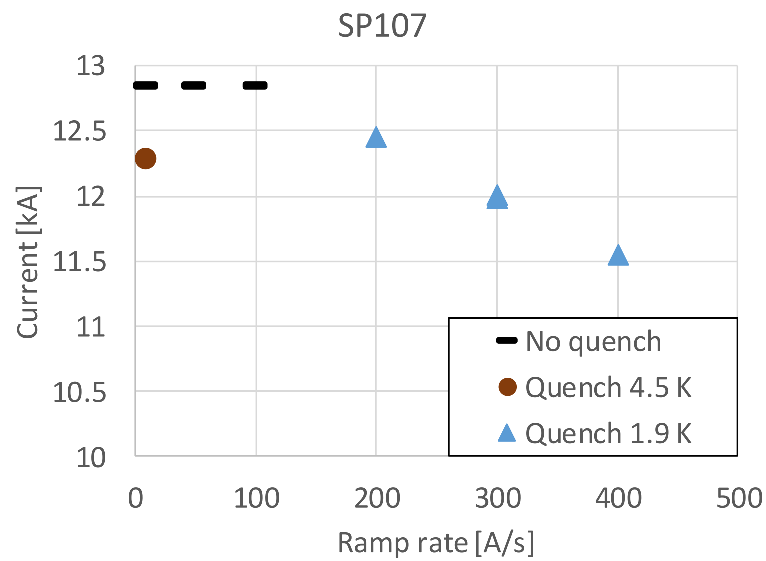
			power per quadrant					
cycle #	coil #	Temperature K	Power-stable W/m	Power-Quench W/m	Power-average W/m	Iquench kA	Iss kA	Iquench/Iss -
1	116	4.5	5.9	5.9	**5.9**	11.644	13.55	0.86
2	117	4.5	7.7	9.7	**8.7**	11.5	13.55	0.85
3	117	4.5	9.7	12	**10.9**	11	13.55	0.81
4	117	1.9	5.9	7.7	**6.8**	12.85	14.95	0.86
5	116	1.9	12	12	**12**	12.27	14.95	0.82
6	117	1.9	10.9	11.9	**11.4**	11.85	14.95	0.79

- The model magnet is powered at constant operating current
- The inter-later quench heaters is switched-on to provide a steady-state heating
- A quench is recorded at a certain value of current and power, providing the operating limit
- When running at nominal current (11850 A), the magnet sustains a steady power input of 8x11.4 W/m (90 W/m)
- Note that the magnet reaches close to nominal operating current at 4.3 K and can still sustain 8x5.9 W/m (47 W/m)
- Recall that the power is limited by the cooling capacity of the He bath: heat removal is limited to about 10 W/m at 1.9 K

G. Willering, et al., unpublished data, 2018

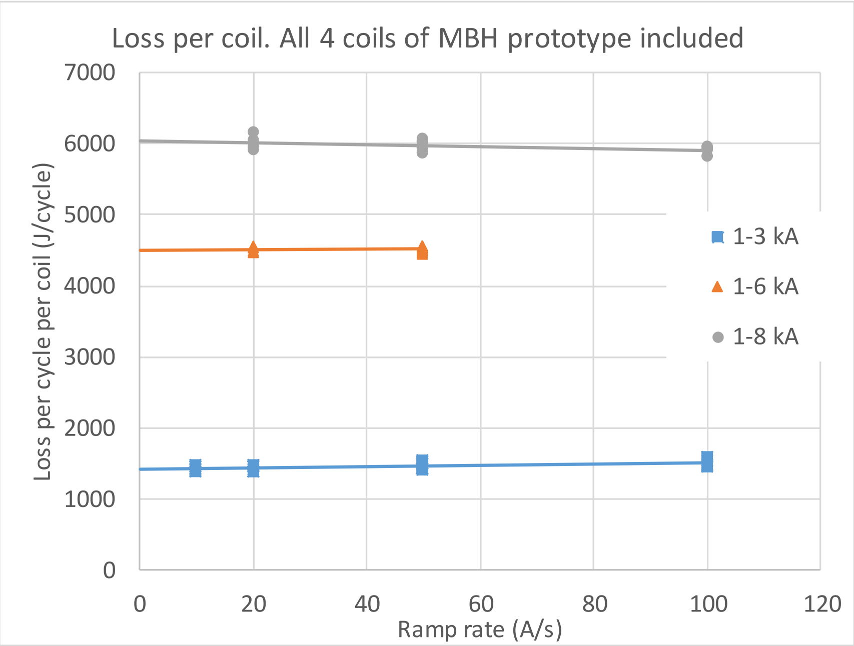
Ramp-rate studies

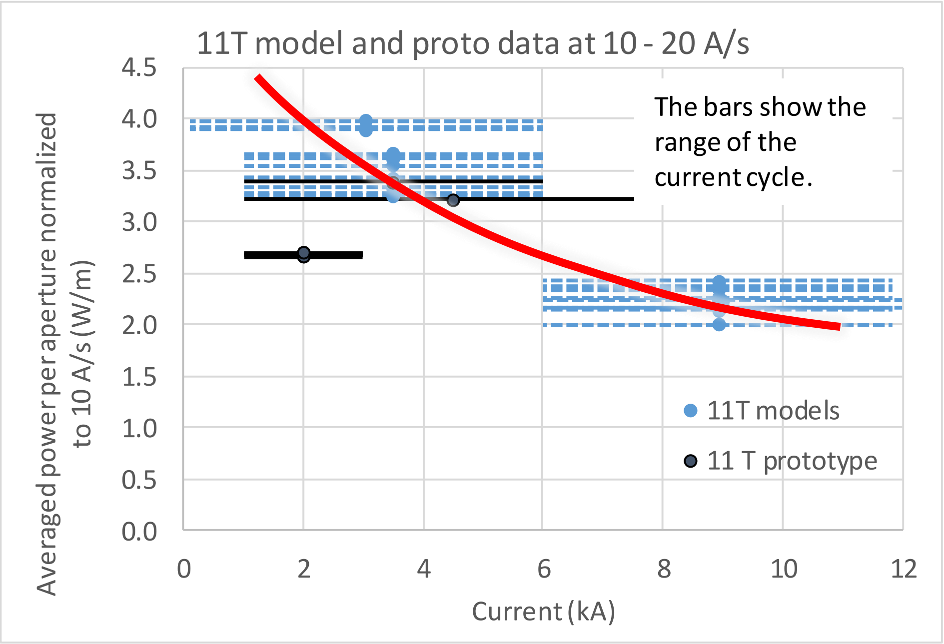




- The “trained” magnet is set at the operating temperature (1.9 K or 4.3 K) and ramped with constant ramp-rate to quench
- AC loss, and possibly other phenomena (eddy currents heating, current redistribution in case of uneven cable or joint properties) cause (usually) a reduction of the quench current at increasing ramp-rate
- Knowing the AC loss by independent measurements it is possible to convert dI/dt (A/s) in heating power q’ (W/m)

AC loss measurements

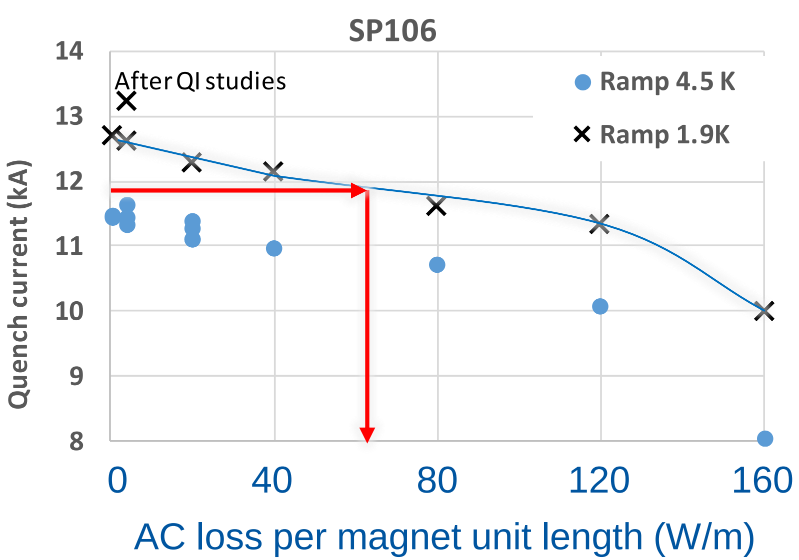


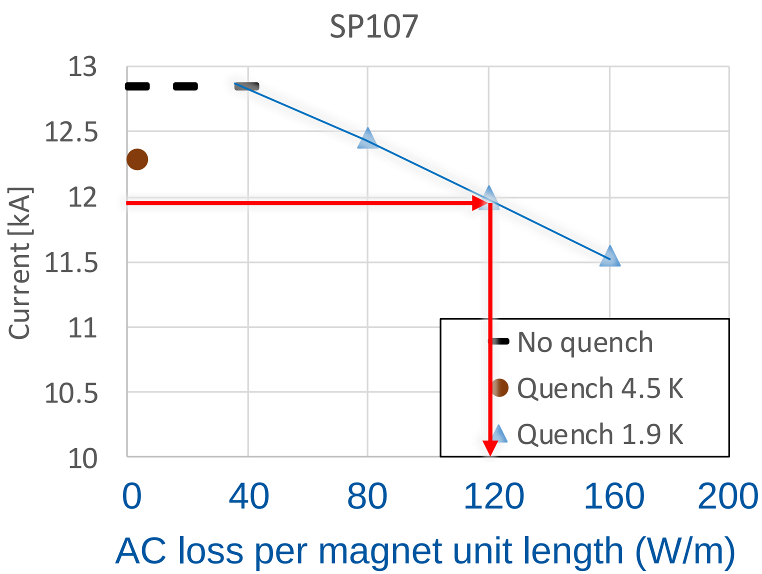


- The AC loss per cycle, as measured in 11T models and prototypes, show negligible ramp-rate dependence, which is consistent with filament hysteresis being the dominating mechanism
- About 4 W/m (low current) to 2 W/m (high current) are generated at 10 A/s in a magnet aperture (2 coils)

G. Willering, H. Bajas and S. Izquierdo Bermudez, unpublished data, 2018

Ramp-rate studies implication





- Use the value of 2 W/m at 10 A/s to convert dI/dt in AC loss per unit length
- The models show that they can operate stably at nominal conditions (11850 A, 1.9 K) under a steady state heat load of 50 W/m to 120 W/m
- Recall that the power is limited by the cooling capacity of the He bath: heat removal is limited to about 10 W/m at 1.9 K

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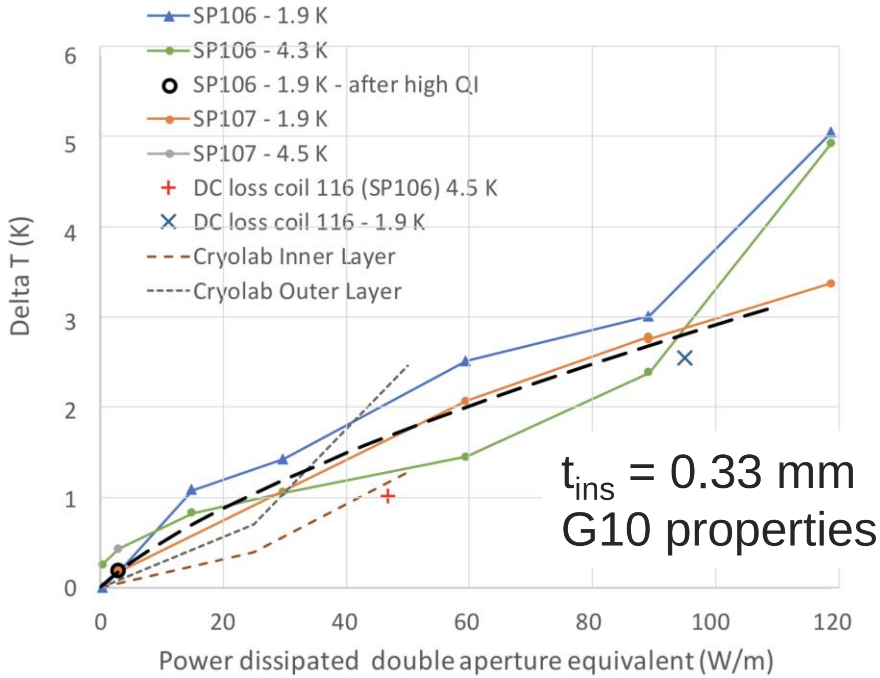
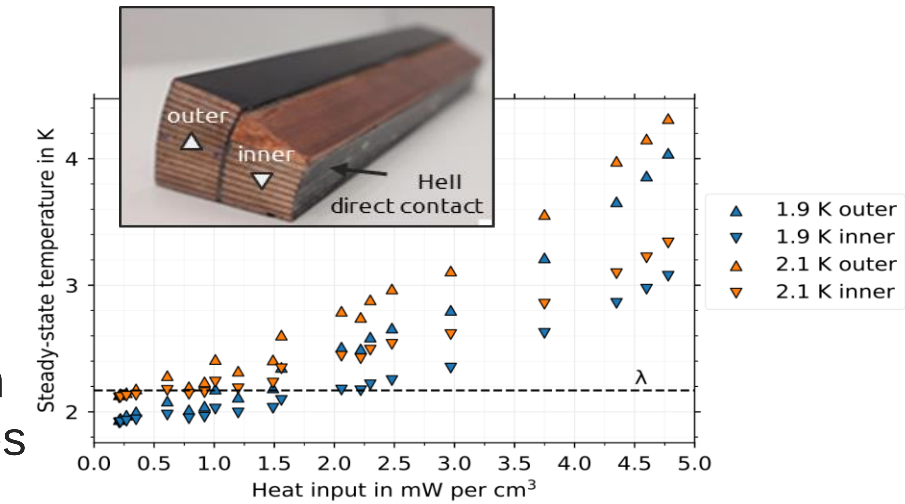
Temperature increase





R. Van Weelderen,TCC 54, August 2 2018

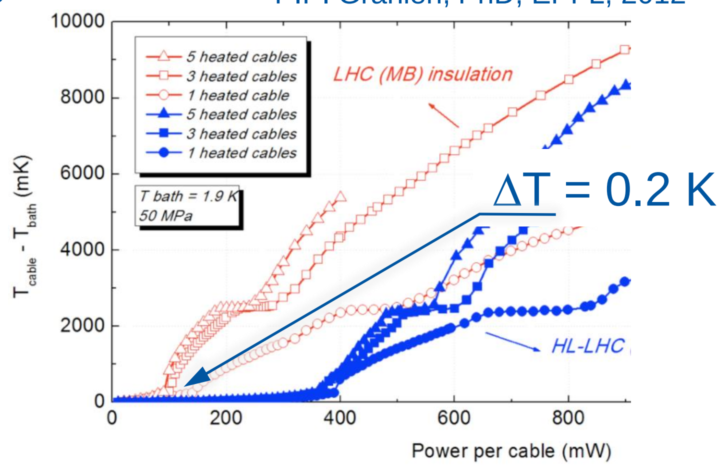
- All data available, of different origins, are relatively consistent as to the steady-state heat transfer properties of the coil
- The temperature increase can be explained by thermal conduction across the conductor insulation (fiber-glass/epoxy composite) with thermal conductivity (0.02…0.04 W/m K) and thickness (0.2…0.4 mm) consistent with expectations

G. Willering, unpublished data, 2018

Temperature margin and heat removal

- From the previous analysis we demonstrate that the 11T magnet can operate stably at nominal current under a temperature increase of 2 to 3 K
- Findings are consistent with the observation that the 11T magnet reaches nominal operating current of 11850 A at 4.5 K
- This corresponds to a total sustainable heat loads of 250 W to 500 W per 5.5 m-long magnet, typically one order of magnitude larger than the maximum power that can be removed by the proximity cryogenic

P.P. Granieri, PhD, EPFL, 2012

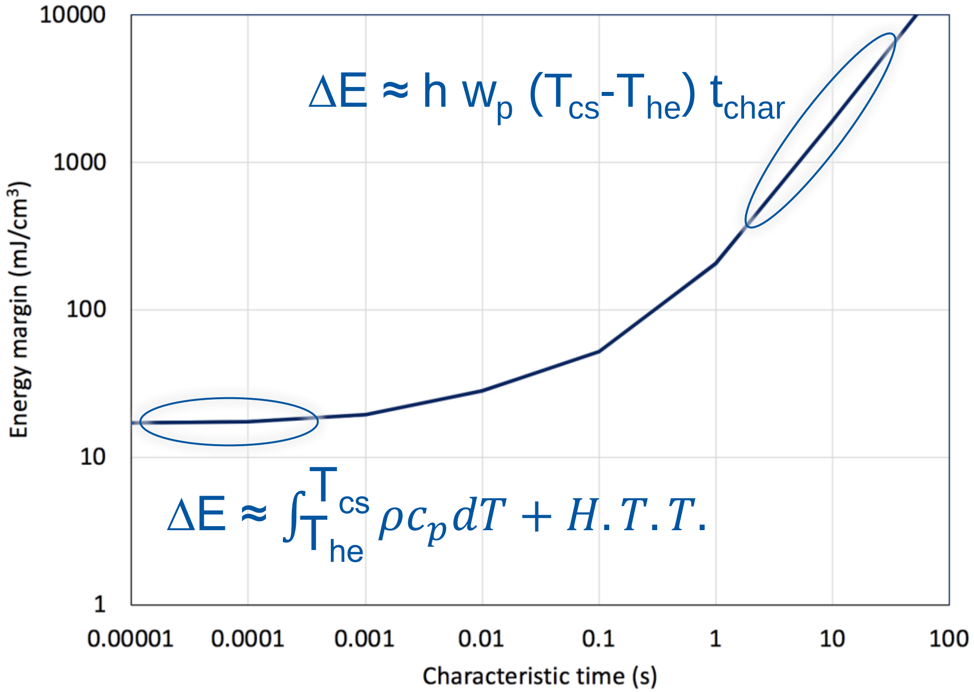


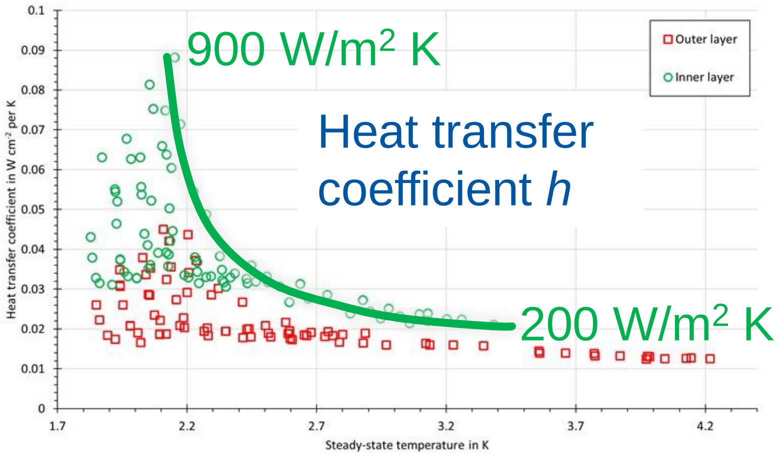
Operating temperature	1.9 K
MB margin (Nb-Ti)	1.5 K
MBH margin (Nb_3Sn)	4.5 K

CERN

NOTE: energy is intended as peak value as from loss distribution

Energy margin ΔE





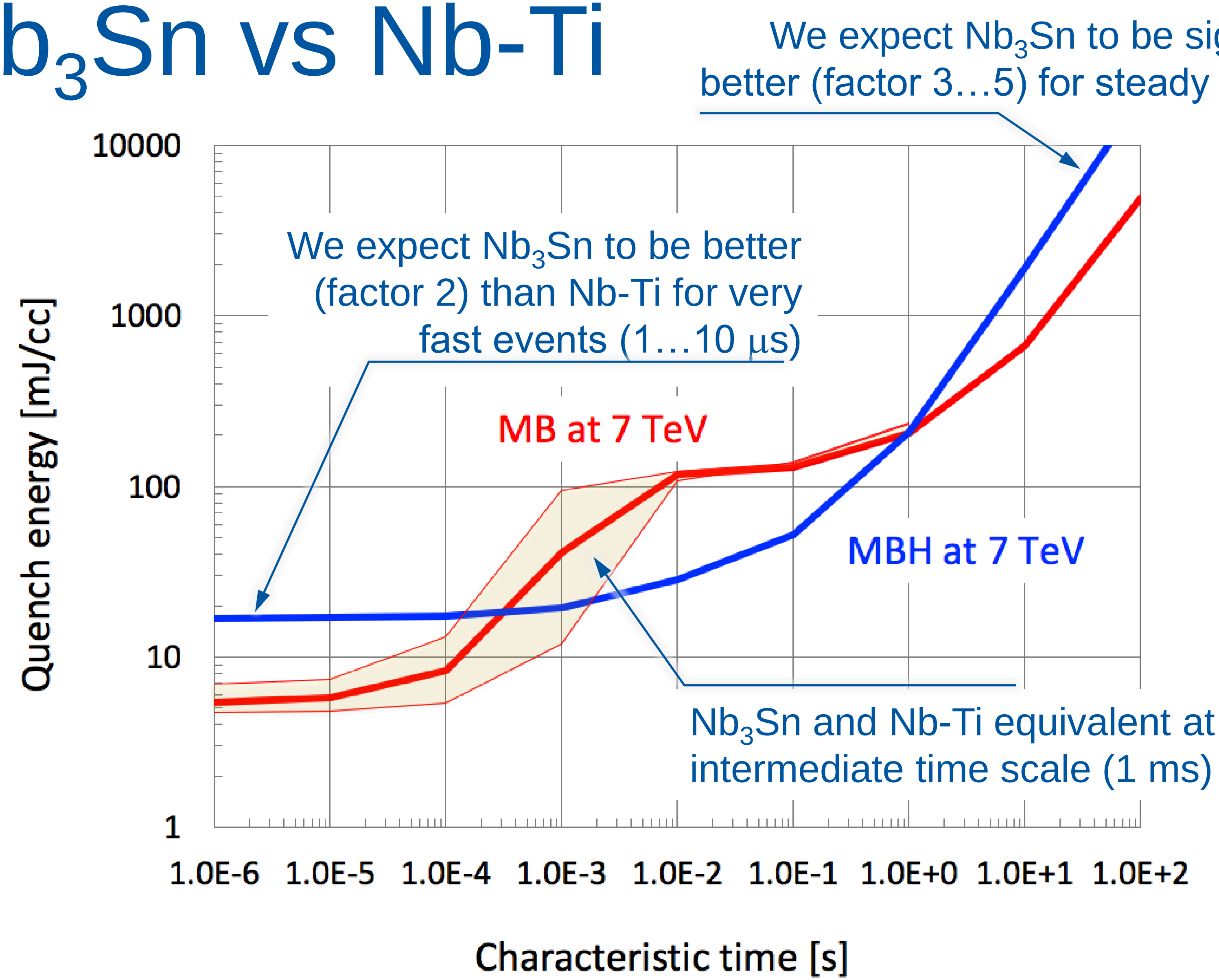
Mario David Grosso Xavier
Private Communication, 2018

- Expected MBH quench limits (Nb_3Sn magnets)
  - 100 mW/cm^3 to 200 mW/cm^3 **localized peak loss** for steady state beam losses
  - 20 mJ/cm^3 **localized peak loss** energy for fast beam losses

E. Felcini, unpublished data, 2018

NOTE: energy is intended as peak value as from loss distribution

Nb_3Sn vs Nb-Ti



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Conclusions

- From the point of view of operating margin and stability, MBH **meets the requested resilience to heat load for installation in MBB.B8**
- Compared to the Nb-Ti counterpart (LHC MB, kapton insulation scheme), Nb_3Sn magnets (MBH and QXF, glass-fiber/epoxy impregnation) appear to have superior characteristics:
  - A factor two more margin against very fast beam losses (1 …10 μs)
  - A factor three to five more margin against steady state/collimation beam losses (> 1 s, consistent with previous studies on VLHC model dipoles at FNAL)
- This is work in progress, still contains uncertainties and will require further measurements and validation on samples, short models, long magnets