Quench Limits
Magnets and Cryogenics

Presented by L. Bottura, based on contributions from:

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Scope of the talk

- Update on the quench limits of the LHC superconducting magnets
  - Nb-Ti (MB)
  - Nb_3Sn (MBH)
- Limits on the cryogenic heat removal
  - Coil to helium
  - Helium circuit
- Conclusions

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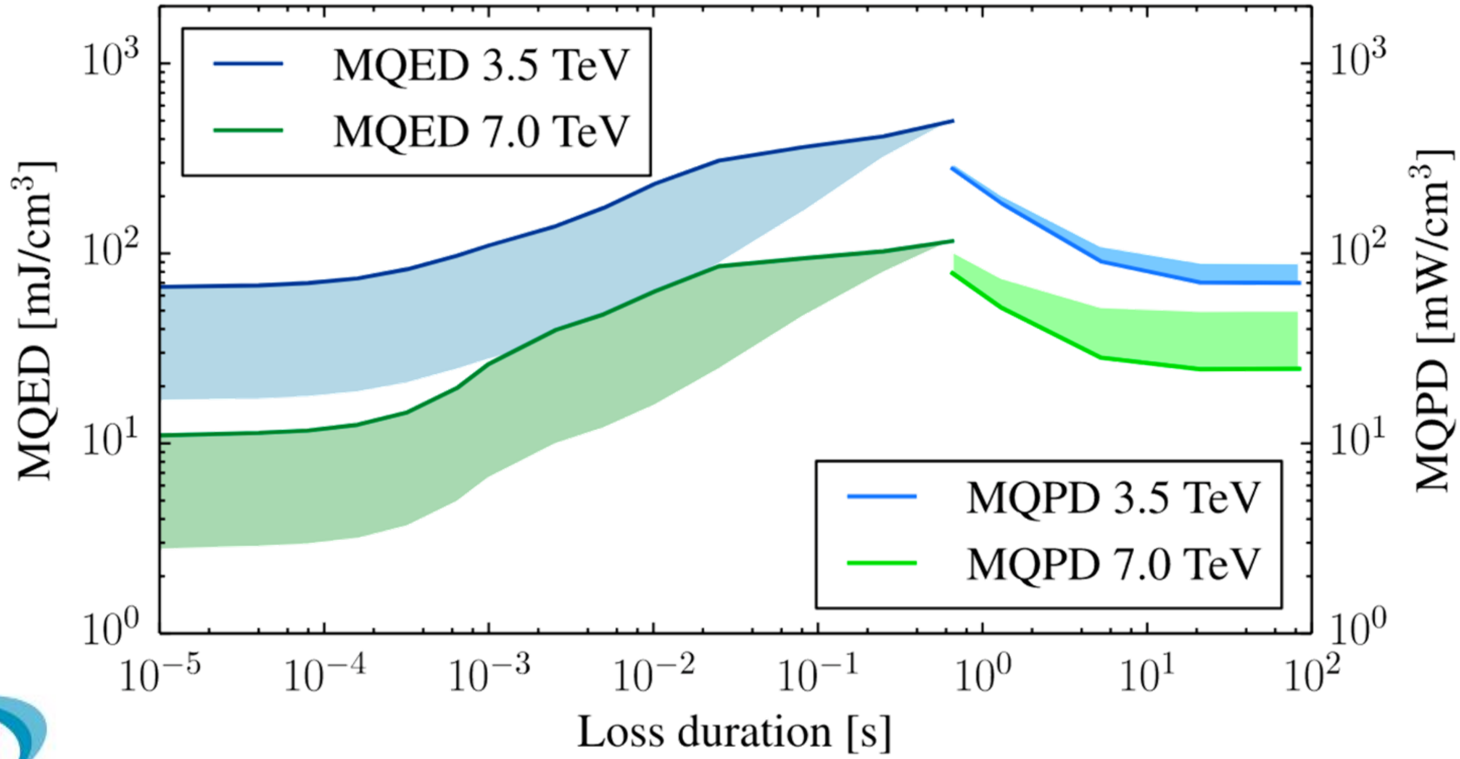
Nb-Ti magnets (MB)

- Estimate and measurement of quench limits:
  - Steady state losses: expected 20 to 45 mW/cm³ vs. "measured" 20 to 30 mW/cm³ at 6.37 TeV (average over cable cross section)
  - Fast losses: 3 to 10 mJ/cm³ (average over cable cross section)

Average values in the coil cross section



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

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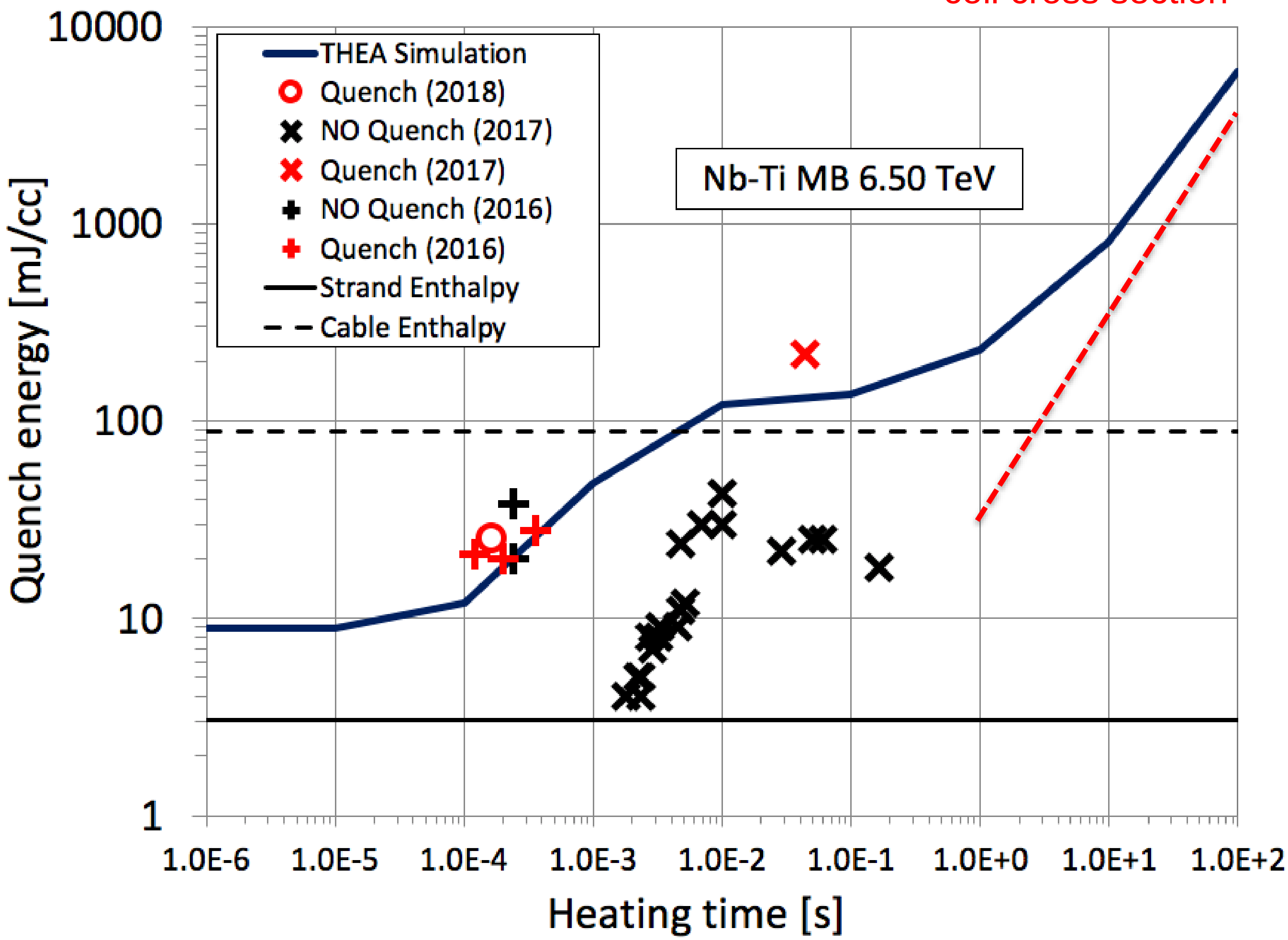
Improved estimates for Nb-Ti (MB)

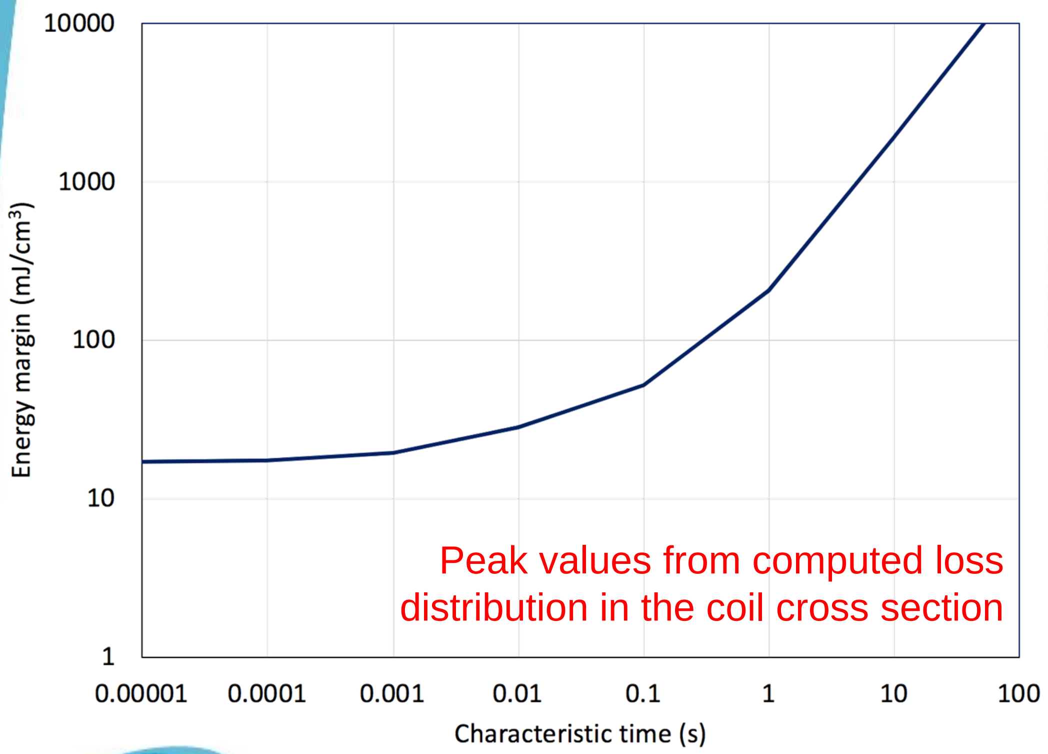
Peak values from computed loss distribution in the coil cross section

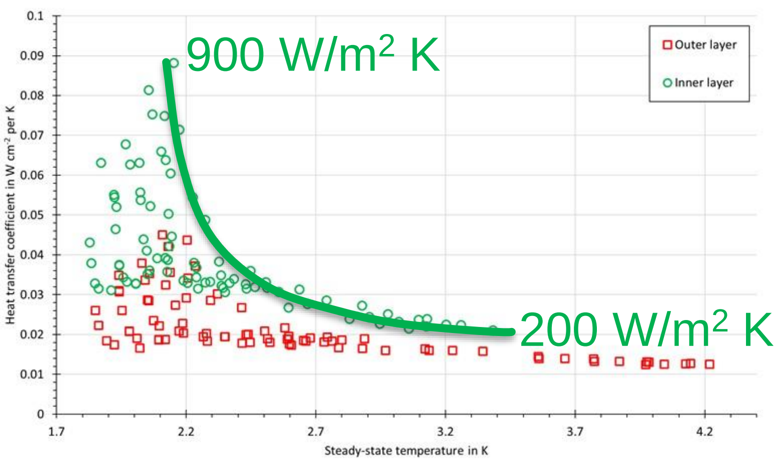


L. Bottura, M. Breschi, E. Felcini, A. Lerchner, "Stability modeling of the LHC Nb-Ti Rutherford cables subjected to beam losses", Submitted for publication to PR-STAB, January 2019

Nb_3Sn magnets (MBH)

- Estimate of quench limits:
  - Steady state losses: expected 100 mW/cm³ to 200 mW/cm³ (**localized peak loss**)
  - Fast losses: 20 mJ/cm³ (**localized peak loss**)





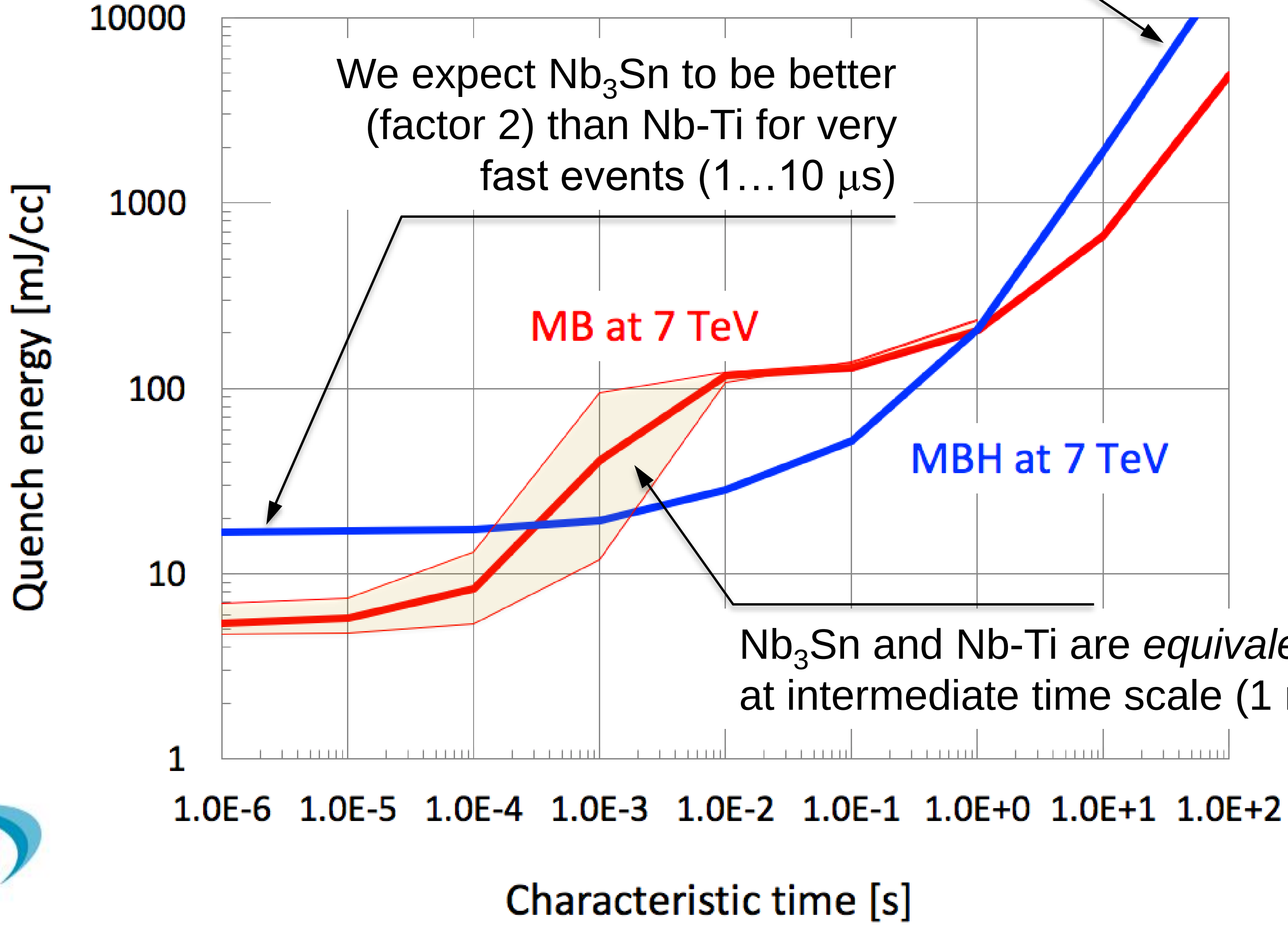
Steady state heat transfer measurements from Mario David Grosso Xavier (CERN), Private Communication, 2018

Model from: M. Breschi, et al., IEEE TAS, 27(4), 2017, 4002105

Nb_3Sn vs Nb-Ti

Peak values from computed loss distribution in the coil cross section

We expect Nb_3Sn to be significantly better (factor 3…5) for steady state loss



Nb_3Sn and Nb-Ti are *equivalent* at intermediate time scale (1 ms)

Quench limits summary

Peak energy density (mJ/cm³)
Fast time scale (≈ 1 μs)

MB	MBH
9	18

Factor 2

Uniform energy density(mJ/cm³)
Fast time scale (≈ 1 μs)

MB	MBH
3…10	15

Peak power density (mW/cm³)
Slow time scale (≈ 1 s)

MB	MBH
65	190

Factor 3

Uniform power density(mW/cm³)
Slow time scale (≈ 1 s)

MB	MBH
20…30	70

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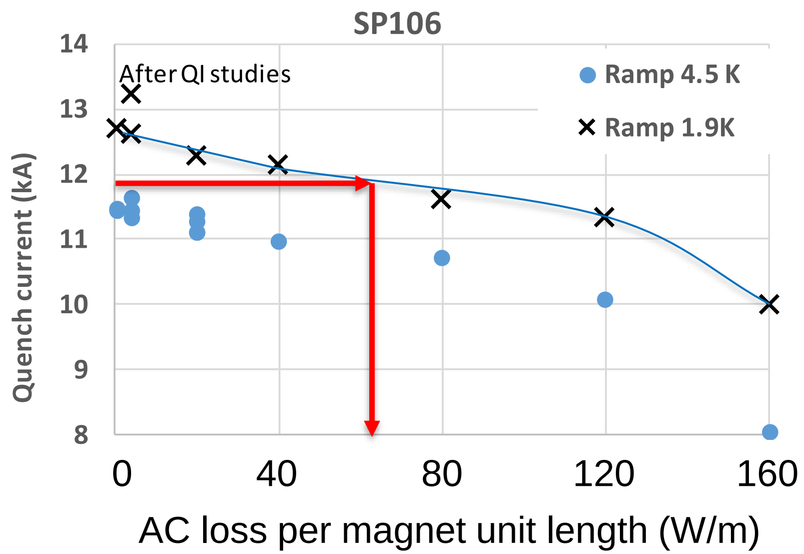
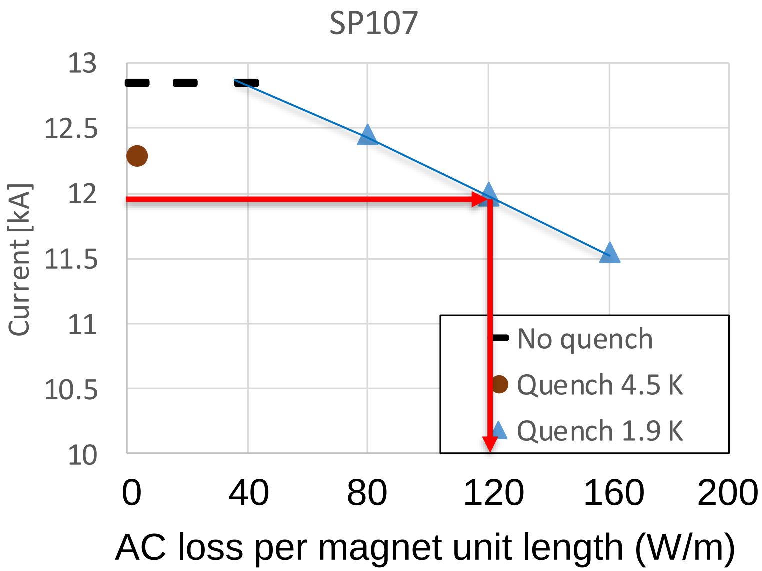
Coil to helium: *ramp-rate studies*

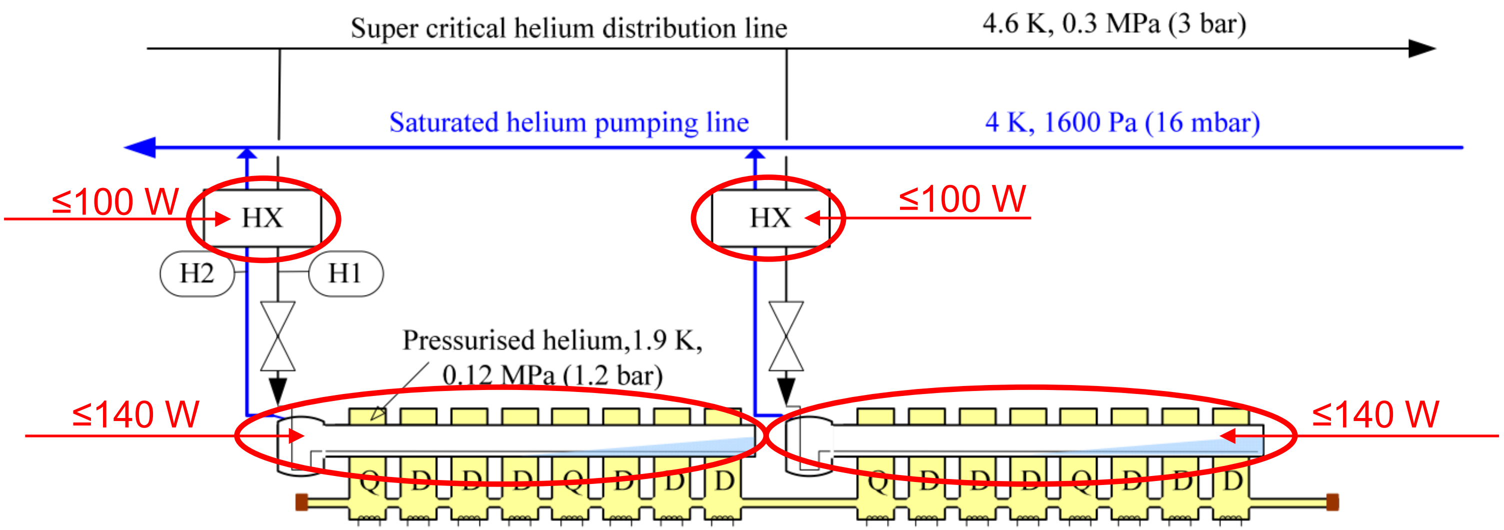




- The AC loss deposited in the 11T coils at 10 A/s is around 2 W/m per unit length of magnet (two apertures)
- The models show that they can operate stably at nominal conditions (11850 A, 1.9 K) under a steady state heat load of 50 W/m to 100 W/m
- This corresponds to a total sustainable heat load from the coil to the helium bath of 550 W to 1100 W per cryo-collimation unit (2x5.5 m long MBH magnets)

Why is this so much better than in Nb-Ti MB ? See backup slides

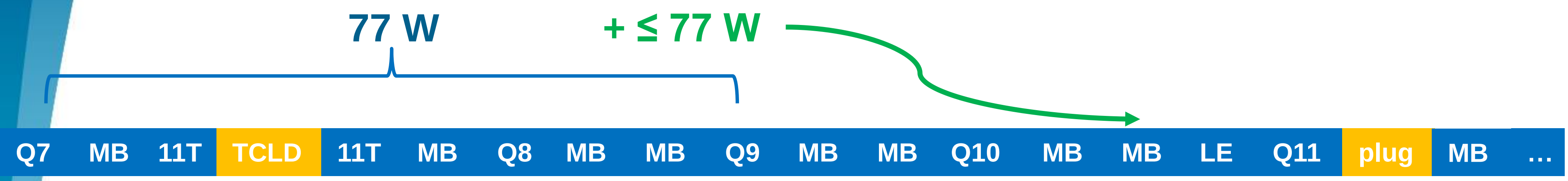
Cooling of an LHC cell



- An LHC cell has the following heat removal limits:
  - Design limit for the bayonet heat exchanger, protruding through all cold masses: 7 g/s, or ≤ 140 W (at 1.9 K, pumping)
  - Design limit of very low pressure counter-flow heat exchanger installed in the QRL-service module: 5 g/s, or ≤ 100 W (at 1.9 K, pumping)
  - Every 2nd LHC-cell, cooling exchange between cells is blocked by hydraulic restrictions, thus reducing the possibility to *spread-out* heat loads

After Rob Van Weelderen, HL-LHC TCC 2/8/2018

Cryogenic configuration in DS



- Available steady-state cooling power per cell:
  - Static heat loads (0.25 W/m)(1): 23 W/cell
  - Beam-gas interaction heat load(2): 0 W/cell
  - Available collimation heat load: 77 W/cell
- Contingency:
  - Some additional heat load (< 77W) can be taken by the neighboring cell, provided the total heat load on two cells is less than 200 W

(1) Loss data from CERN-ATS-2010-016

(2) Considering beam-gas based on present LHC vacuum (factor 200 lower than TDR)

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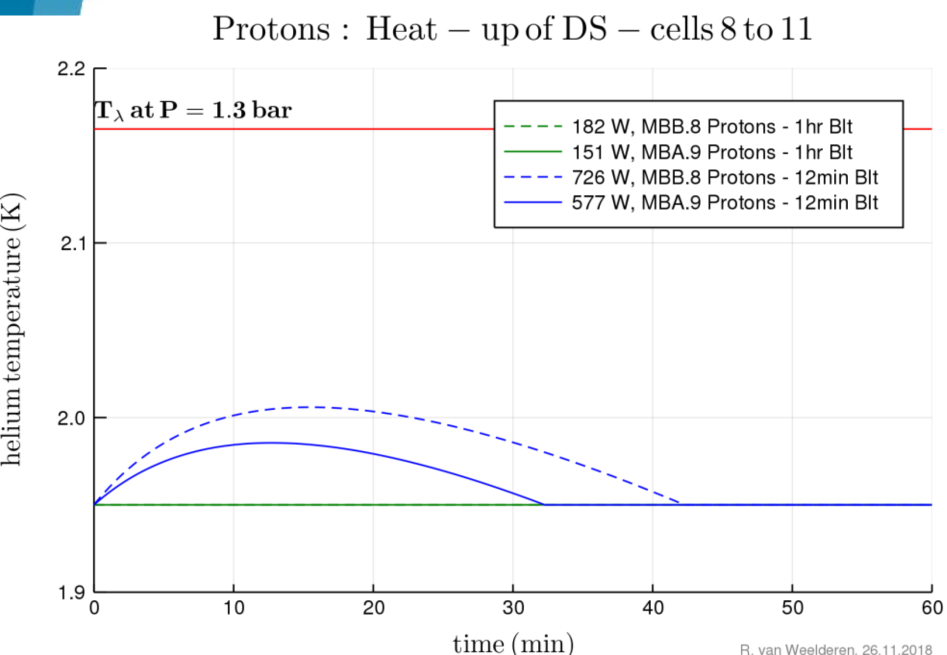
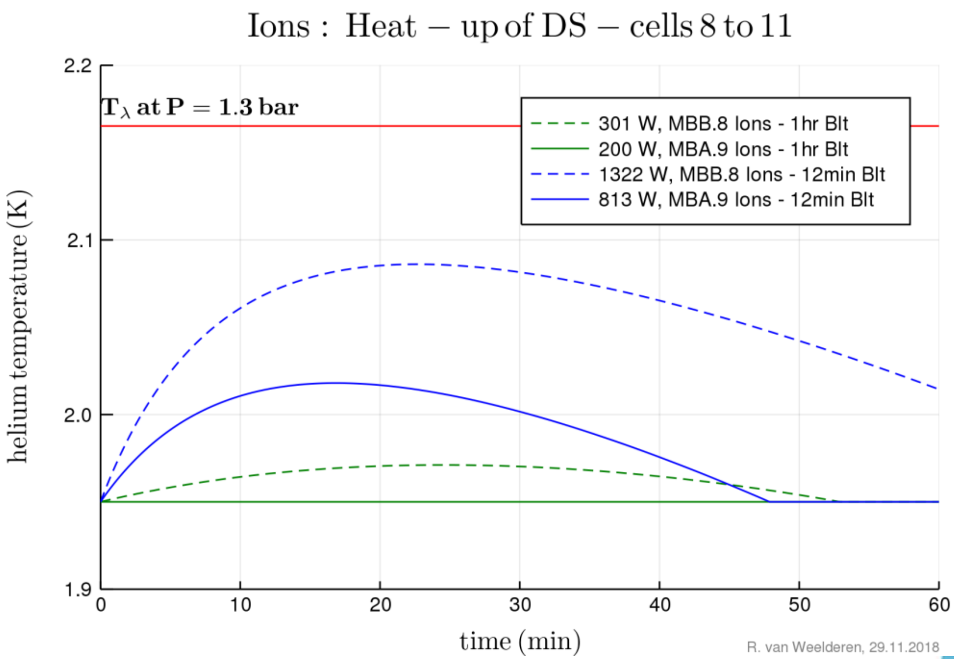
Transient heat removal





- Exceeding the steady-state heat removal limits (77W per cell) will cause the temperature of the helium to rise
- The balance of adiabatic temperature rise vs. concurrent drop of heat deposition for very short beam life time has been analyzed, and in no foreseen conditions the local temperature exceeds T_λ

After Rob Van Weelderen, HL-LHC TCC 29/11/2018

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Summary and conclusions

- Coil quench limits of MB confirmed, and quench limits of MBH estimated based on modeling and measurements (direct and indirect)
  - MBH are expected to be a factor 2 to 3 better than MB in terms of resilience to heat loads, both transients and steady state
- Cryogenic heat removal capability of the DS cells reviewed (cells 8 and 9)
  - 77 W/cell are available in steady-state for beam-losses, with the possibility to absorb some additional heat load in the neighboring cell (but in any case < 200 W total heat load)
  - Heat loads exceeding the above limit will lead to temperature increase, but the helium enthalpy locally available will be enough to withstand transients of several minutes at peaks of the order of 1 kW/cell

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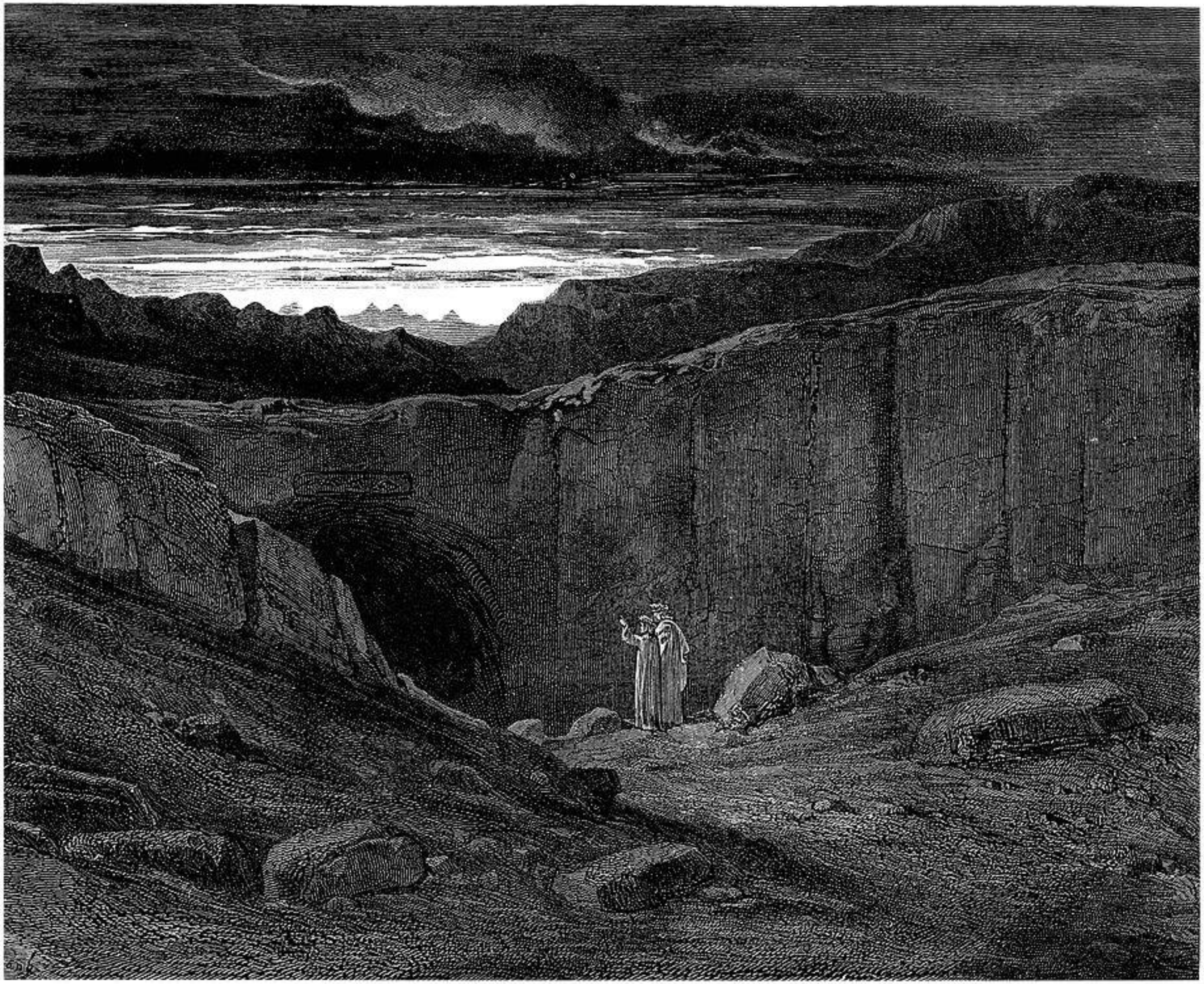

Lasciate ogne speranza, voi ch'intrate

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

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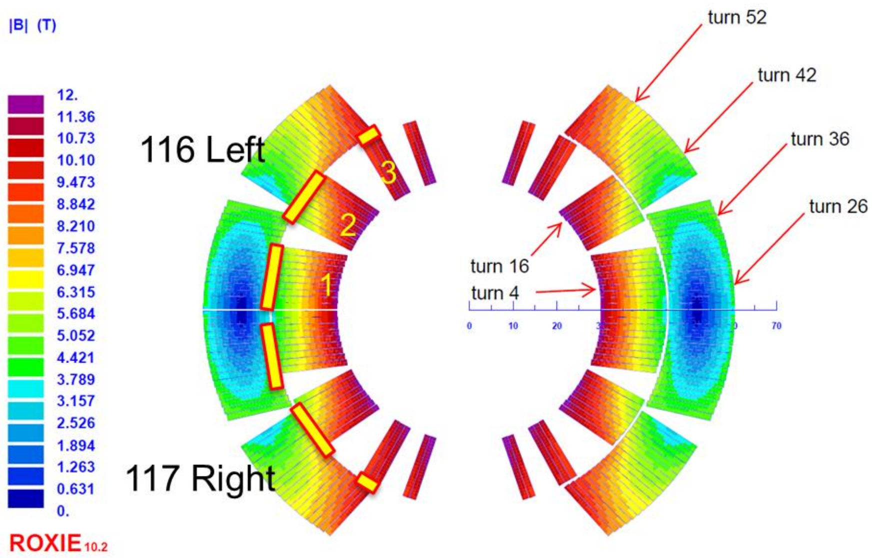
DC stability



			power per quadrant					
cycle	coil	Temperature	Power-stable	Power-Quench	Power-average	Iquench	Iss	Iquench/Iss
#	#	K	W/m	W/m	W/m	kA	kA	-
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

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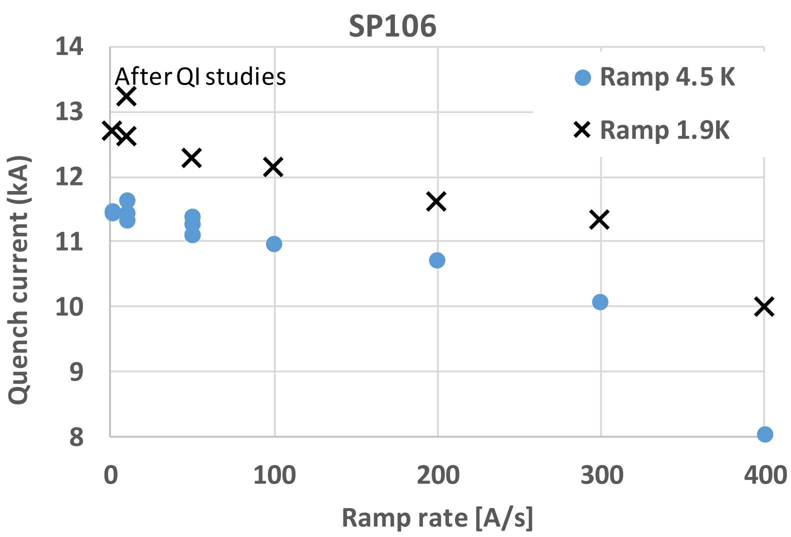
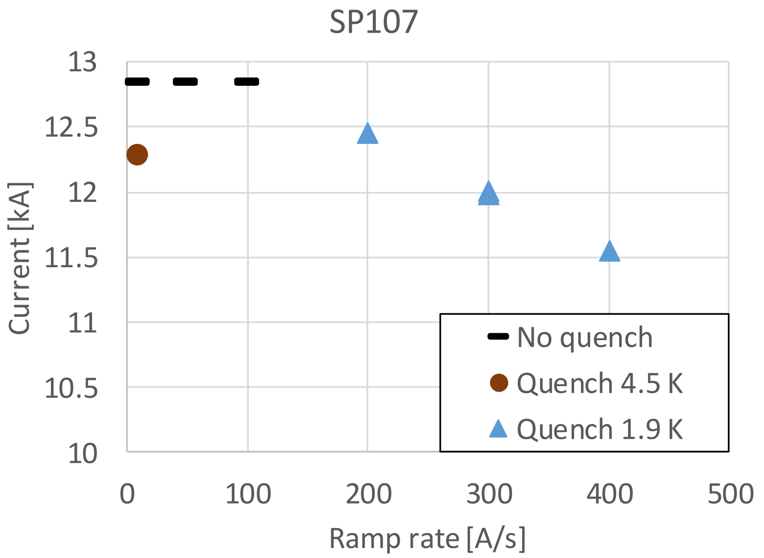
G. Willering, et al., Private Communication, 2018

Ramp-rate studies

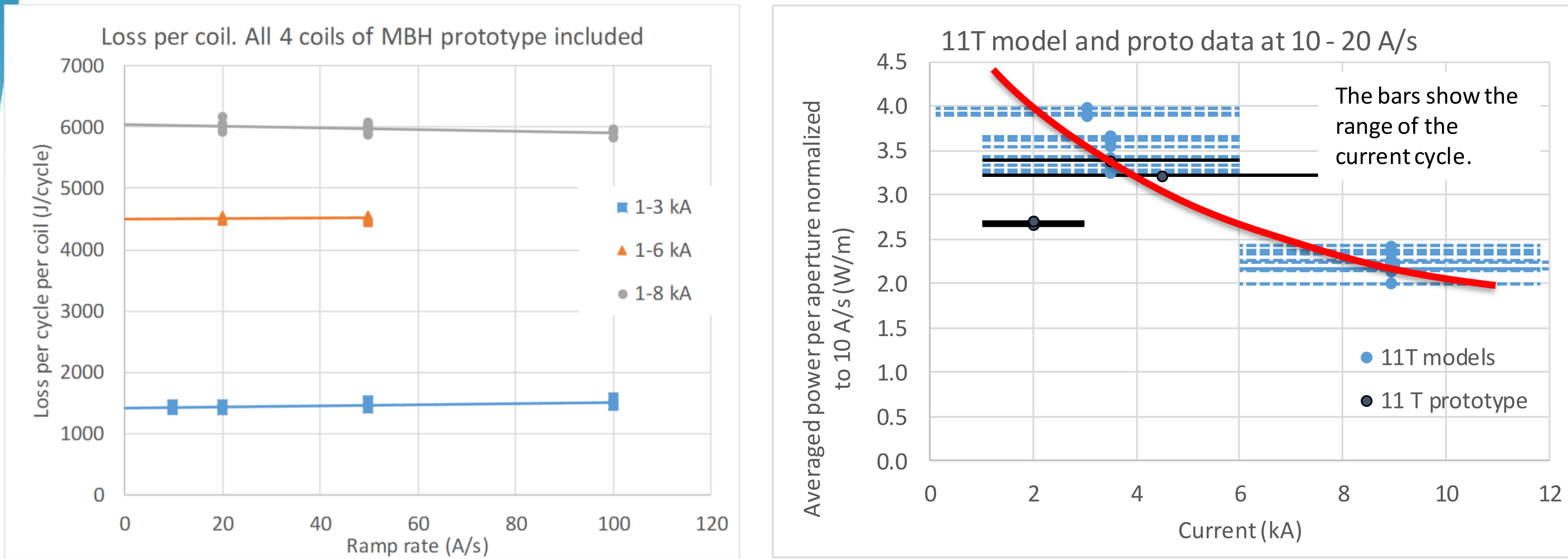




- The "trained" magnet is set at the operating temperature (1.9 K or 4.3 K) and ramped with constant ramp-rate to quench
- AC loss, and possibly other phenomena (eddy currents heating, current redistribution in case of uneven cable or joint properties) cause (usually) a reduction of the quench current 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)

G. Willering, et al., Private Communication, 2018

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)

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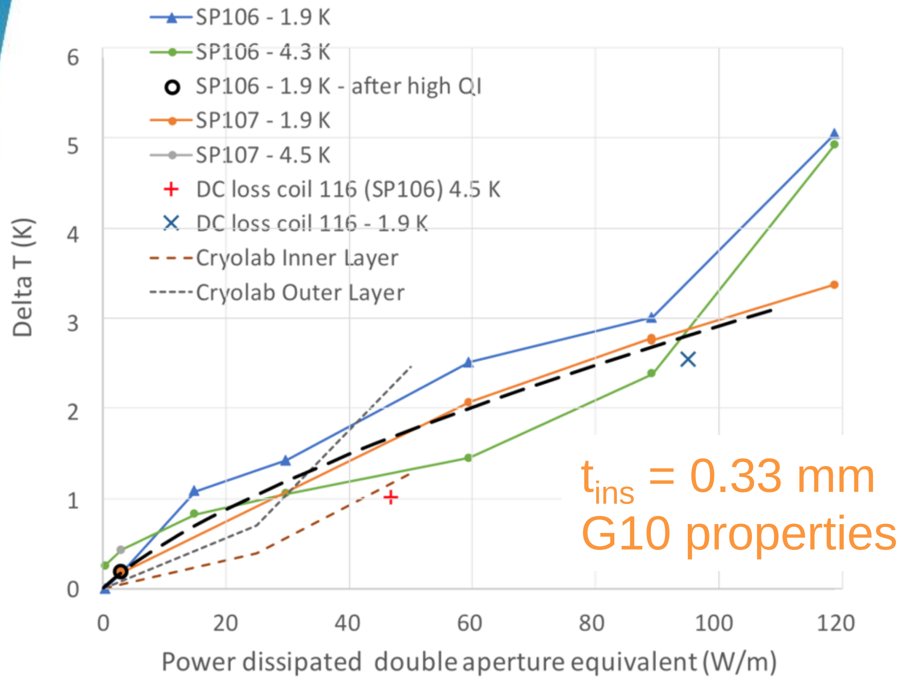
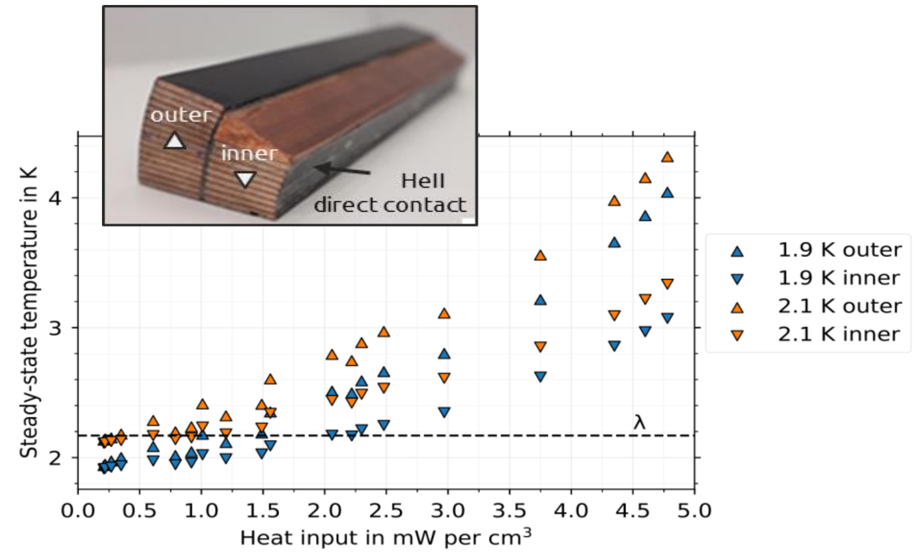
G. Willering, H. Bajas and S. Izquierdo Bermudez, Private Communication, 2018

Heat transfer data & analysis



R. Van Weelderen,TCC 54, August 2 2018



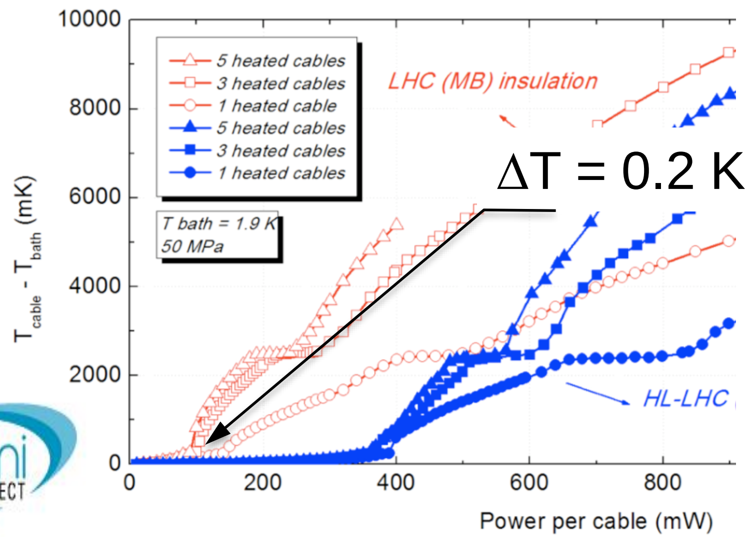
- All data available, of different origins, are relatively consistent as to the steady-state heat transfer properties of the coil
- The temperature increase can be explained by thermal conduction across the conductor insulation (fiber-glass/epoxy composite) with thermal conductivity (0.02…0.04 W/m K)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

G. Willering, et al., Private Communication, 2018

T-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
- Local heat transfer in MB and MBH is inherently very different:
  - MB – **superfluid counter-flow**, possible only for T<2.17 K ($\Delta T \approx 0.2$ K)
  - MBH – **solid conduction** driven by ΔT up to the current sharing temperature ($\Delta T \approx 4.5$ K)

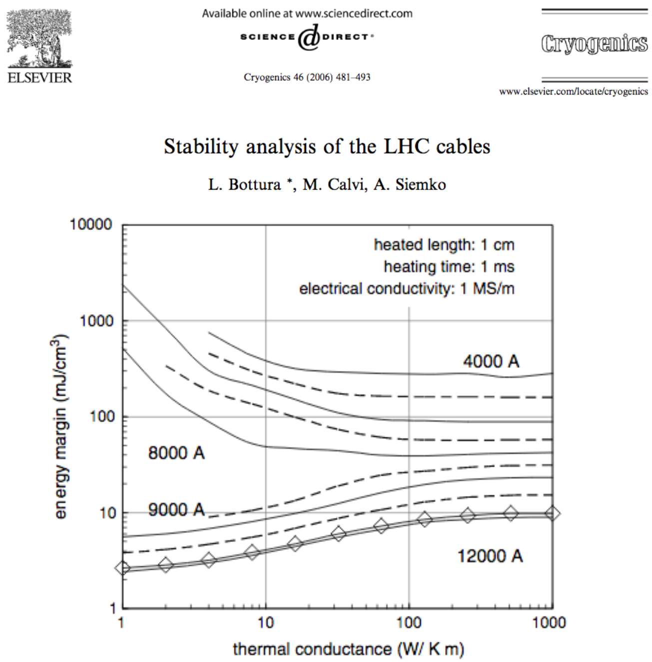
P.P. Granieri, PhD, EPFL, 2012



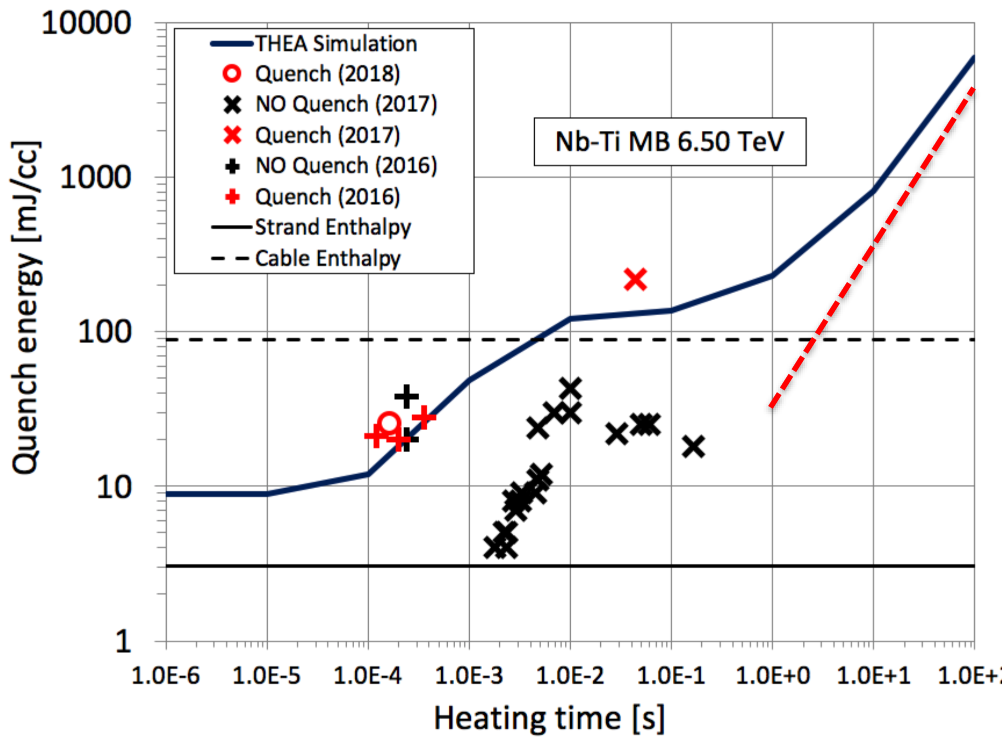
Operating temperature	1.9 K
MB margin (Nb-Ti)	1.5 K
MBH margin (Nb_3Sn)	4.5 K

Background on modeling

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



L. Bottura, et al., Submitted for publication to PR-STAB, January 2019



- 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

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