6th QTAWG meeting, March 28, 2014

Quench Test Analyses: An Overview

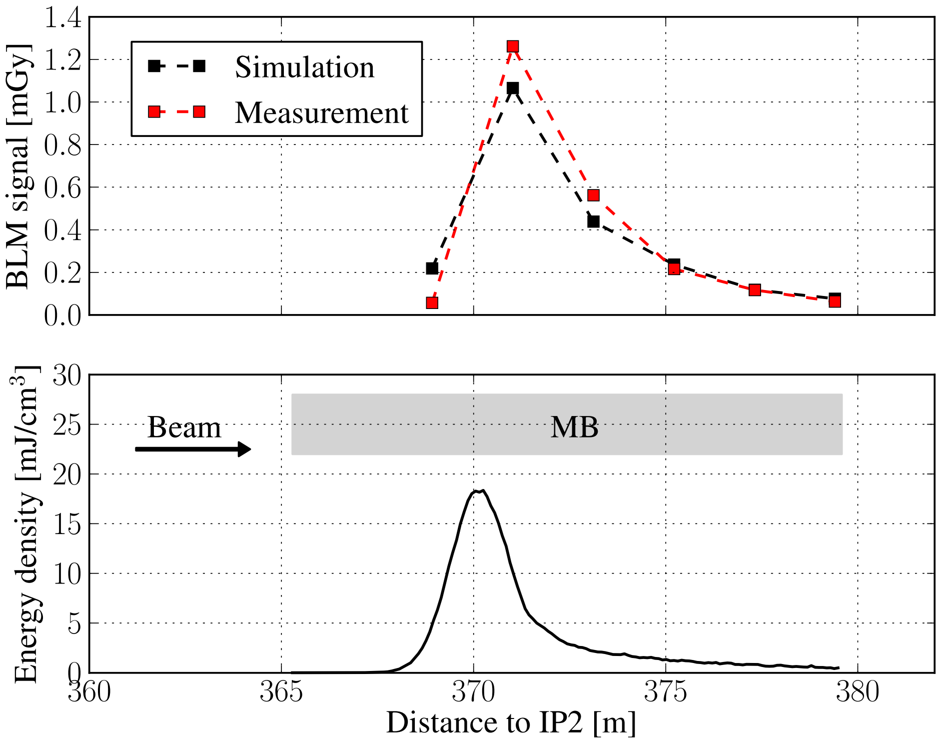
Overview

- 6 tests/events have been analyzed.

Regime	Method	CERN naming	Magnet type	Temperature
short	kick	750 µrad kick event	MB	1.9 K
short	collimation	Q6 QT	MQM	4.5 K
intermediate	wire scanner	Wire scanner QT	MBRB	4.5 K
intermediate	wire scanner	Wire scanner QT	MQY	4.5 K
intermediate	orbit bump	Fast-loss ADT QT	MQ	1.9 K
steady-state	collimation	Collimation	MB	1.9 K
steady-state	orbit bump	Steady-state loss ADT QT	MQ	1.9 K
steady-state	dyn. orbit bump	Dyn. orbit bump QT	MQ	1.9 K

Strong-Kick Quench Event

- Recall: 2008 a large orbit kick during injection studies caused a quench in an MB.
- Reasons to include the event:
  - Information on quench level at injection energy and for fast losses at 1.9 K.
  - Presumably straight-forward beam dynamics (20-m drift space between corrector and MB).



Results and Discussion

- Uncertainty on initial conditions and corrector strengths in MAD-X model.
- Resulting uncertainty FLUKA longitudinal and transverse loss distribution.
- Electro-thermal MQED estimate based on strand enthalpy.

TABLE I. Comparison of FLUKA upper bound (UB) and the electro-thermal MQED estimate.

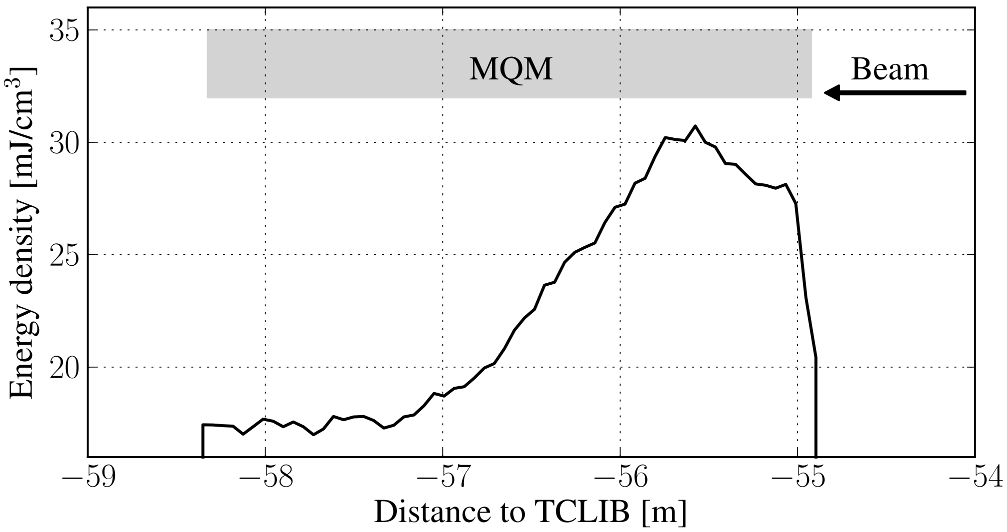
FLUKA UB [mJ/cm^3]	MQED [mJ/cm^3]
18^{+7}_{-0}	38

- More data for MAD-X validation would be required.
- MQED estimate probably within the error margin.

CERN

Short-Duration Collimation QT

- Formerly Q6 QT.
- Are the non-saturated BLM signals to be trusted?
- Geometry of FLUKA model needed refinement.
- Electro-thermal MQED estimate based on strand enthalpy.



Results and Discussion

- MQED at 2000 A is below the FLUKA lower bound.
- Is there still a missing geometrical feature?
- Could the non-saturated BLM signals be correct?

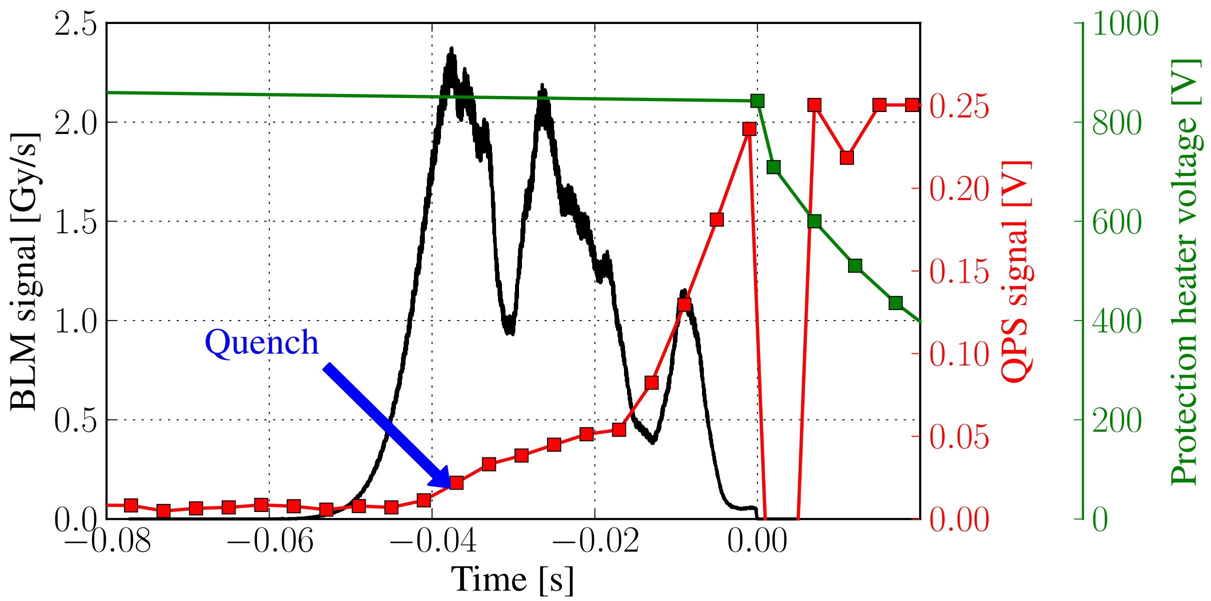
TABLE II. Comparison of FLUKA lower bound (LB) and upper bound (UB) and the electro-thermal MQED estimate.

Current [A]	FLUKA LB [mJ/cm^3]	FLUKA UB [mJ/cm^3]	MQED [mJ/cm^3]
2000	29	n/a	20
2500	n/a	31	16

- Any feature that could shield losses is relevant for collimation quench tests.

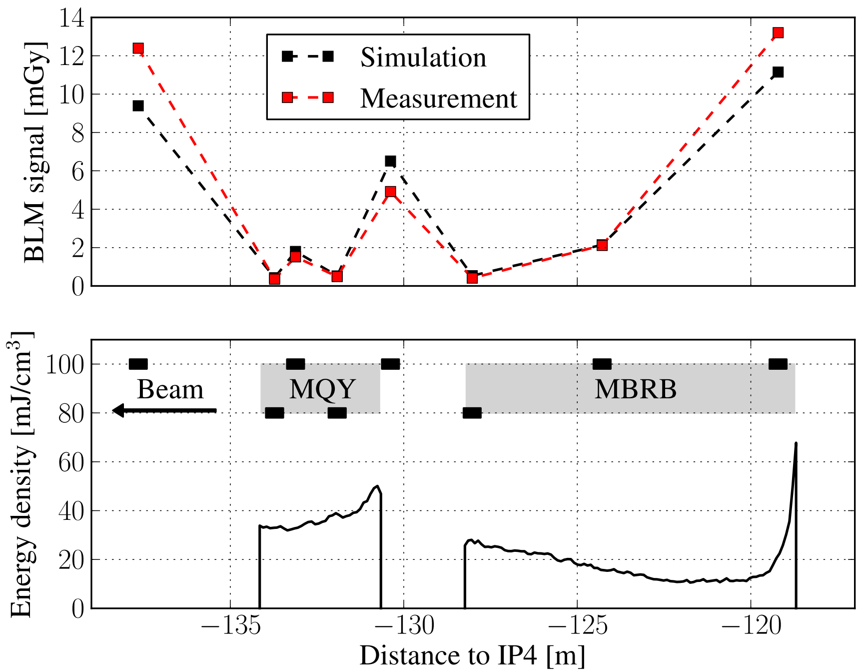
Wire-Scanner QT

- Wire sublimation and low velocities lead to vibrations and non-Gaussian time-dependence of losses.
- Precise moment of quench cannot be determined.
- Involved calculation of number of lost protons in the last (quenching) test.



Wire Scanner QT

- Good agreement with BLM vindicates the calculation of protons lost.
- Losses in MQY (Q5) and MBRB (D4) studied.
- Losses in MBRB occurred in magnet ends:
  - FLUKA does not provide the correct coil geometry.
  - The electro-thermal model suffers from unknown field and cooling conditions.



Results and Discussion

- Unknown timing of quench requires parametric study.
- Unkown field and cooling induce uncertainties in electro-thermal model.
- FLUKA error due to end geometry unknown.

TABLE III. Comparison of FLUKA lower bound (LB) and upper bound (UB) on the electro-thermal MQED estimate in the MBRB coil.

v_w [m/s]	N_q/N_w [%]	FLUKA LB [mJ/cm^3]	FLUKA UB [mJ/cm^3]	MQED [mJ/cm^3]
0.15	n/a	18	n/a	37^{+0}_{-11}
0.05	30	n/a	20	35^{+0}_{-11}
0.05	45	n/a	30	42^{+0}_{-16}

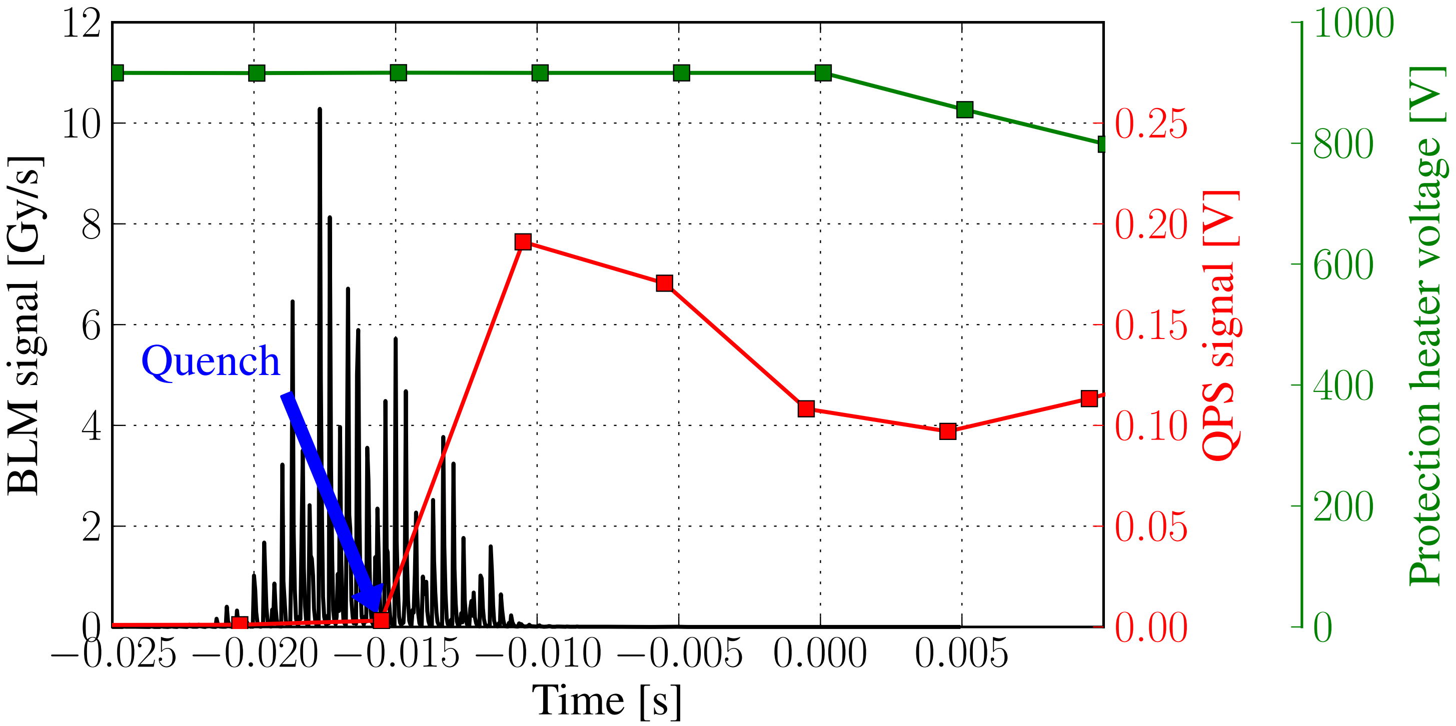
TABLE IV. Comparison of FLUKA lower bound (LB) on the electro-thermal MQED estimate in the MQY coil.

v_w [m/s]	FLUKA LB [mJ/cm^3]	MQED [mJ/cm^3]
0.05	50	52

- Functioning oscilloscope is mandatory!

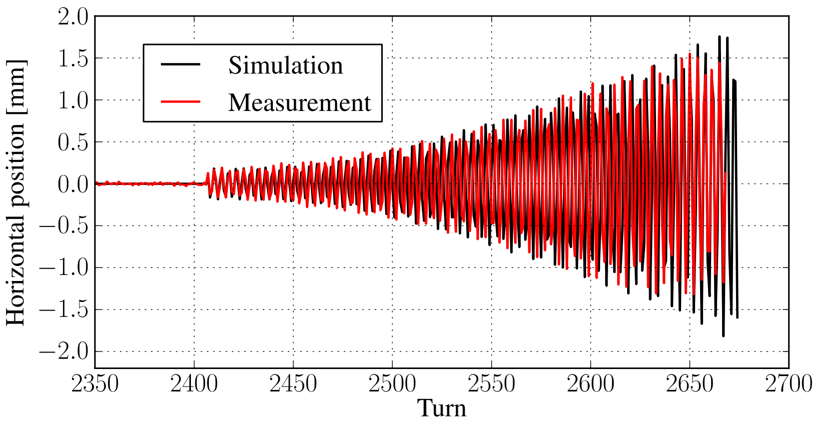
Intermediate-Duration Orbit-Bump QT

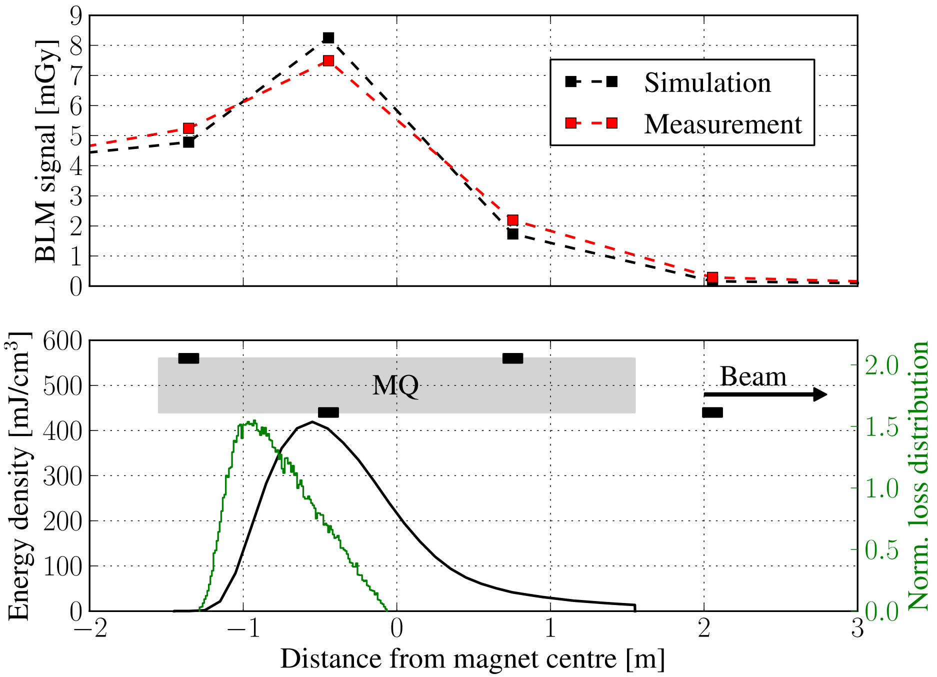
- Orbit-bump + MKI kick + ADT in sign-flip mode create 10 ms of losses with short spikes ever 4 turns.
- Time of quench again not accurately known.



Intermediate-Duration Orbit-Bump QT

- MAD-X model tuned to match BPM data.
- Good FLUKA BLM agreement.





Transient Nucleate Boiling

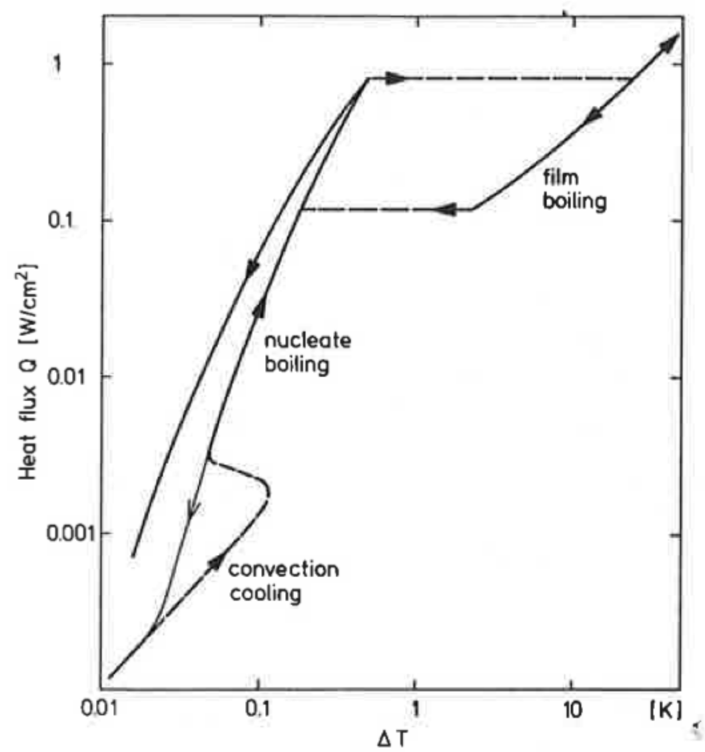


Fig. 1 - Steady-state heat transfer characteristic. The curve is artificially composed of experimental results in Refs. 6,7,11.

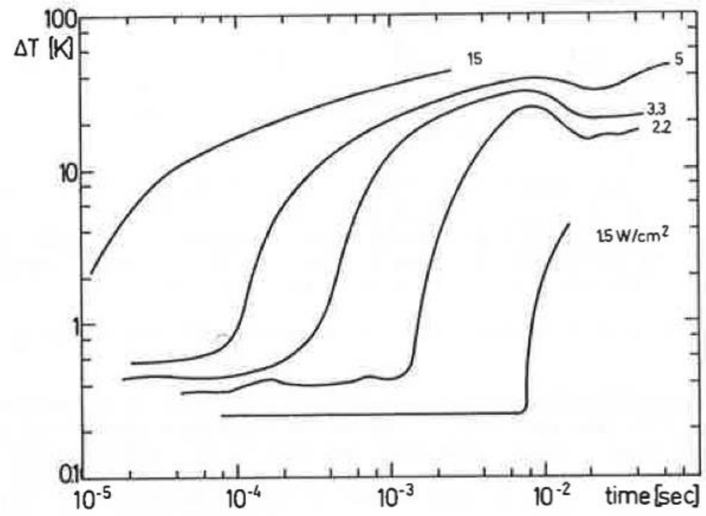


Fig. 9 - Transient heat transfer experiment using a monofilamentary NbTi/Cu superconductor (NbTi diam. 36 μm, Cu diam. 52 μm) both as a heater and a thermometer. The plot shows surface temperature traces for various heat fluxes Q. From Ref. /34/.

C. Schmidt, *Review of Steady State and Transient Heat Transfer in Pool Boiling He I*. Saclay, France: International Institute of Refrigeration: Commision A1/2-Saclay, 1981, pp. 17–31.

Results and Discussion

- Nucleate boiling is the most efficient cooling regime.
- Large heat fluxes are possible for short durations.
- Could this explain the large discrepancy between FLUKA LB and MQED estimate (without nucleate boiling)?

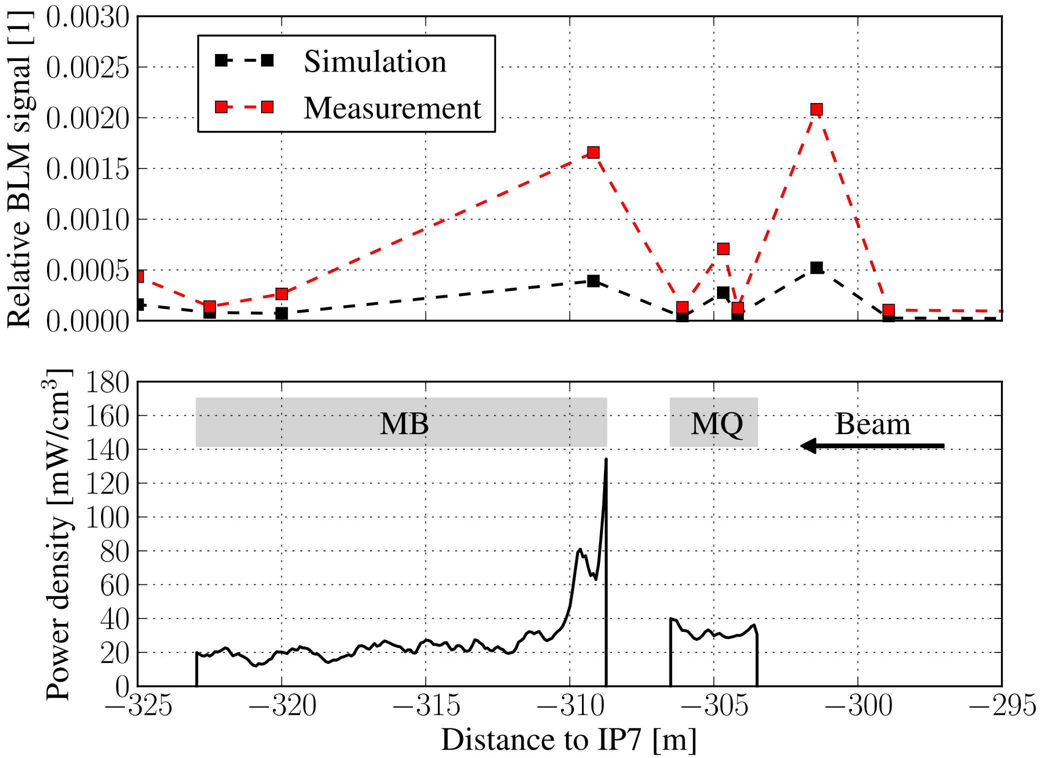
TABLE V. Comparison of FLUKA lower bound (LB) and upper bound (UB) on the electro-thermal MQED estimate in the MQ coil.

N_p	N_q/N_p [%]	FLUKA LB [mJ/cm^3]	FLUKA UB [mJ/cm^3]	MQED [mJ/cm^3]
3.5×10^8	n/a	198	n/a	$71^{+?}_{-10}$
8.2×10^8	62	n/a	250	$58^{+?}_{-8}$
8.2×10^8	99	n/a	405	$80^{+?}_{-10}$

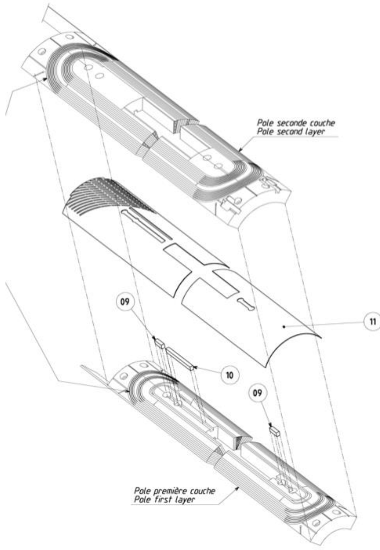
- Preliminary numerical experiments suggest MQED could be as high as 230 mJ/cm^3!
- Nucleate boiling may have very different effect for different loss durations in the 1-10 ms regime.

Collimation QT

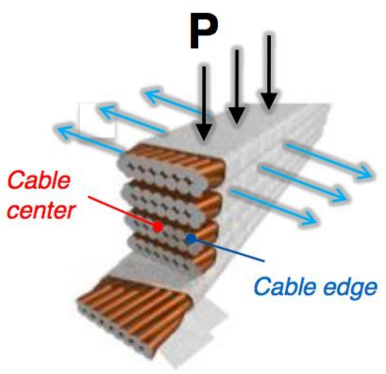
- Peak losses in the MB end.
- Local factor 4 in BLM vs. FLUKA despite overall good agreement.
- No upper bound from quench.

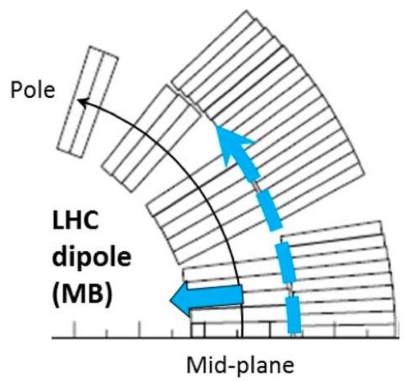


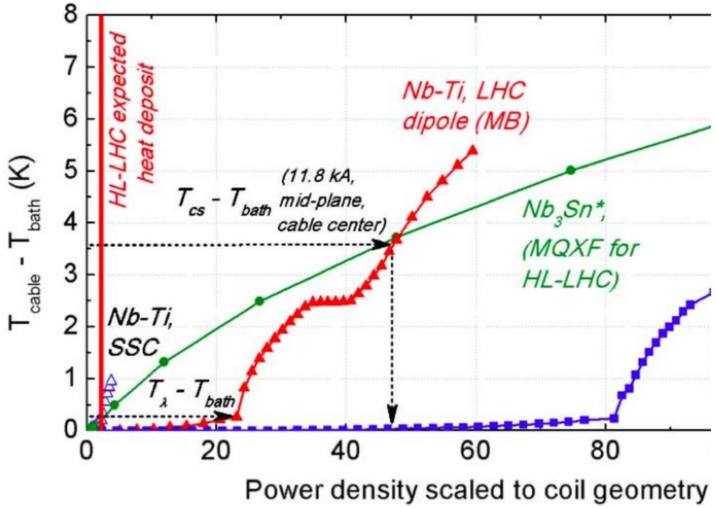
Electro-thermal analysis



- Measured heat-extraction from stack-test.
- “Fish-bone” structure raises question how to extrapolate stack data to coil inner layer.
- Assumption: Fish-bone is 100% efficient up to $T_s = T_\lambda$, and preserves that heat flux for $T_s > T_\lambda$.







Graphs and drawings from P.P. Granieri et al., “Deduction of Steady-State Cable Quench Limits for Various Electrical Insulation Schemes With Application to LHC and HL-LHC Magnets”, IEEE Trans. on App. SC, Vol. 24(3), June 2014.

Results and Discussion

- Lower MQPD estimate neglects fish-bone.
- Uncertainties due to quench in the ends not considered.
- Recall factor 4 scaling in BLM data.

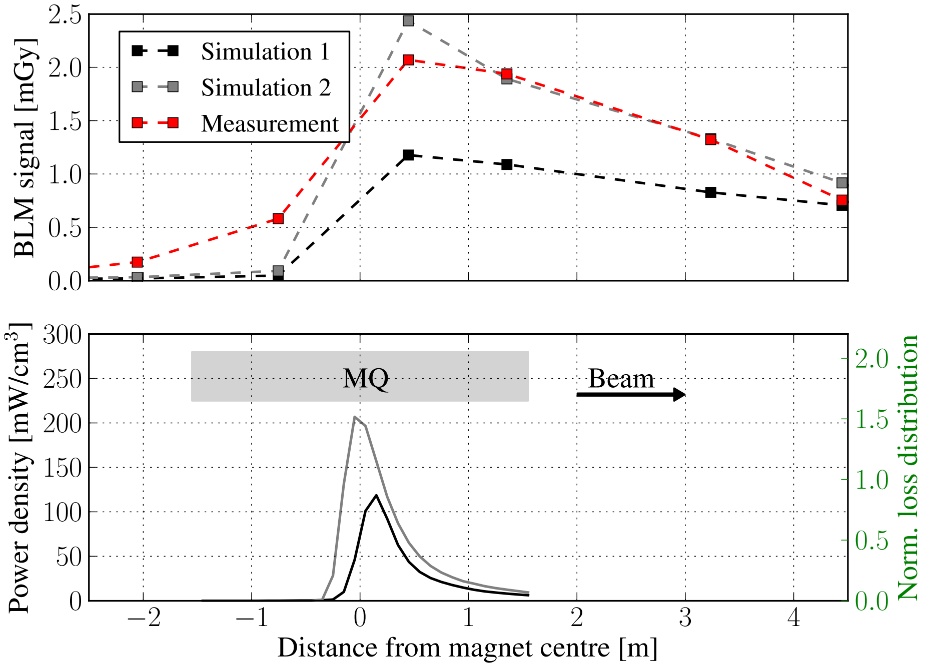
TABLE VI. Comparison of FLUKA lower bound (LB) and the electro-thermal MQPD estimate in the MB.A9L7 coil.

FLUKA LB [mW/cm^3]	MQPD [mW/cm^3]
50	140^{+0}_{-25}

- The electro-thermal model cannot be considered as validated.
- We need
  - better BLM agreement,
  - refined coil-end model,
  - and actual quench as upper bound.

Steady-State Orbit-Bump QT

- Orbit-bump and ADT in white-noise mode blow up the beam.
- Strong sensitivity of MAD-X model to steps of several 10 µm in the beam-screen surface.
- Simulation 2 includes 30 µm surface roughness to show that actual BLM signal lies within the uncertainty range of the model.



Results and Discussion

- FLUKA larger values include 30 µm surface roughness.
- Lower MQPD estimate neglects "fish-bone".

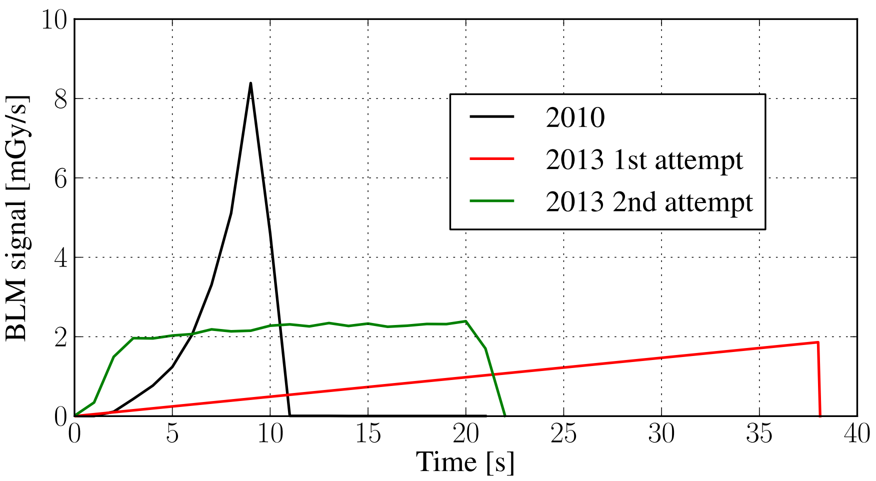


TABLE VII. Comparison of FLUKA lower bound (LB) and upper bound (UB) and the electro-thermal MQPD estimate.

attempt	FLUKA LB [mW/cm^3]	FLUKA UB [mW/cm^3]	MQPD [mW/cm^3]
1st	33^{+22}_{-0}	n/a	99^{+0}_{-20}
2nd	n/a	41^{+28}_{-0}	88^{+0}_{-18}

- This result cannot be seen as a validation of the fish-bone model.

Overview

TABLE VIII. Overview of the presented analyses. LB/QL and UB/QL are the ratios between, respectively, the lower and upper bounds from FLUKA, and the estimated quench levels. For consistency, LB/QL should be below 1 and UB/QL above. Bold font indicates inconsistencies.

Regime	Method	Type	Temp. [K]	I/I_{nom} [%]	LB/QL	UB/QL	Comment
short	kick	MB	1.9	6	n/a	$\mathbf{0.47}^{+0.19}_{-0}$	Tracking uncertainty.
short	collimation	MQM	4.5	46/58	**1.45**	1.94	Saturated BLM signals. No FLUKA validation.
intermediate	wire scanner	MBRB	4.5	50	$0.48^{+0}_{-0.21}$	$\mathbf{0.71}^{+0.44}_{-0}$	Timing uncertainty. Quench in ends. UB for $N_q/N_w = 45\%$.
intermediate	wire scanner	MQY	4.5	50	0.96	n/a	No upper bound.
intermediate	orbit bump	MQ	1.9	54	$\mathbf{2.79}^{+0.46}_{-?}$	$4.31^{+0.7}_{-?}$	Timing uncertainty. Nucleate boiling? UB for $N_q/N_p = 62\%$.
steady-state	collimation	MB	1.9	57	$0.36^{+0}_{-0.08}$	n/a	Peak loss in magnet ends. Cooling. Moderate FLUKA agreement with BLM signals. No upper bound.
steady-state	orbit bump	MQ	1.9	54	$0.33^{+0.36}_{-0}$	$\mathbf{0.47}^{+0.52}_{-0}$	Sensitivity to surface roughness. Cooling.
steady-state	dyn. orbit bump	MQ	1.9				Cooling.

Most cases show discrepancies between upper and lower bounds and quench-level estimate.

- In some cases consistent results are within the known margins of uncertainty.

Lessons learnt by method

- Orbit-bump and kick:
  - Require accurate MAD-X model.
  - Tolerances on beam screen and surface roughness increase the error bars.
- Wire scanner:
  - Slow movement and wire sublimation lead to vibrations.
  - Actual position induces quenches in the magnet ends (problems for FLUKA and electro-thermal model).
  - Oscilloscope required.
- Collimation:
  - Steady-state: QTs yield valuable information even without FLUKA/electro-thermal analysis.

Lessons learnt by analysis

- MAD-X:
  - Needs highly accurate knowledge of initial conditions.
  - Measure tune, emittance, etc. as close as possible to the test!
  - Determination of error bars via parametric studies.
- FLUKA:
  - Very precise geometrical models needed.
  - Large-scale model yields over-all good agreement – however, large error bar at peak-loss.
  - Improved model of coil ends would be needed.
- Electro-thermal:
  - Relevant cooling and field parameters not accurately known for peak losses in magnet ends.
  - For short-duration losses we trust the model.
  - For intermediate-duration losses at 1.9 K, nucleate boiling may increase MQED considerably. Loss spikes make the modeling of nucleate-boiling even more difficult.
  - For steady-state losses, the efficiency of “fish-bone” structure not yet tested.

Lessons learnt by regime

- Short duration:
  - We trust the MQED estimate.
- Intermediate-duration:
  - Install oscilloscopes to increase resolution and provide synchronization for BLM and QPS signals.
  - More tests at 4.5 K and 1.9 K producing smooth losses in the magnet straight sections.
- Steady-state:
  - Find means to improve MAD-X (orbit-bump) and FLUKA (collimation) models.

Next steps

1. Sections on strong-kick event and steady-state orbit-bump QT need to be finalized.
2. Results overview needs to be improved (graph?). Suggestions are welcome!
3. Internal review.
4. Anton et al. write a paper on FLUKA modeling, which shall be submitted at the same time as this paper.
5. Time permitting, the dynamic orbit-bump QT could be included.
6. Submission by end of April / middle of May.
7. Best-knowledge model is being finalized for BLM threshold calculations.