CERN

BIQ Workshop, September 15

Quench Test Analysis Results

Collaboration of many teams: BLM, Collimation, FLUKA, LIBD, OP, RF, etc.

B. Auchmann, T. Baer, M. Bednarek, G. Bellodi, C. Bracco, R. Bruce, F. Cerutti, V. Chetvertkova, B. Dehning, P. P. Granieri, W. Hofle, E. B. Holzer, A. Lechner, E. Nebot Del Busto, A. Priebe, S. Redaelli, B. Salvachua, M. Sapinski, R. Schmidt, N. Shetty, E. Skordis, M. Solfaroli, D. Valuch, A. Verweij, J. Wenninger, D. Wollmann, M. Zerlauth, and more…

CERN

Overview

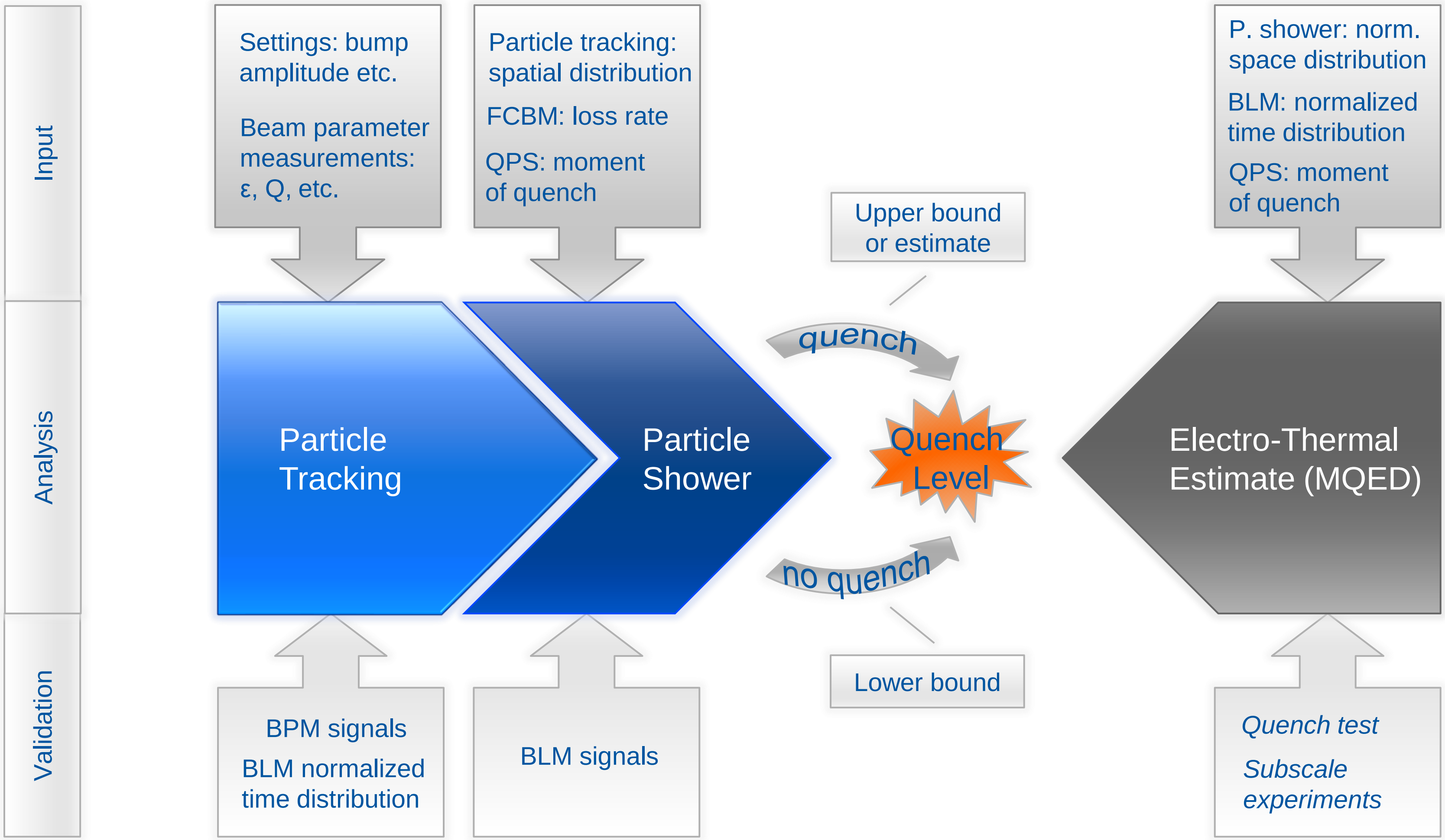
- Summary of quench-test results per time regime.

Regime	Method	Energy	Temperature
short	kick	450 GeV	1.9 K
short	collimation	0.45/6 TeV	4.5 K
intermediate	wire scanner	3.5 TeV	4.5 K
intermediate	orbit bump	4 TeV	1.9 K
steady-state	collimation	4 TeV	1.9 K
steady-state	dyn. orbit bump	3.5 TeV	1.9 K
steady-state	orbit bump	4 TeV	1.9 K

- What are the implications for BLM settings?

Quench Test Analysis

What is the energy deposition in the coil at the moment of quench?



Short-duration losses (0 – 50 µs)

Strong-Kick Event (07/09/2008)

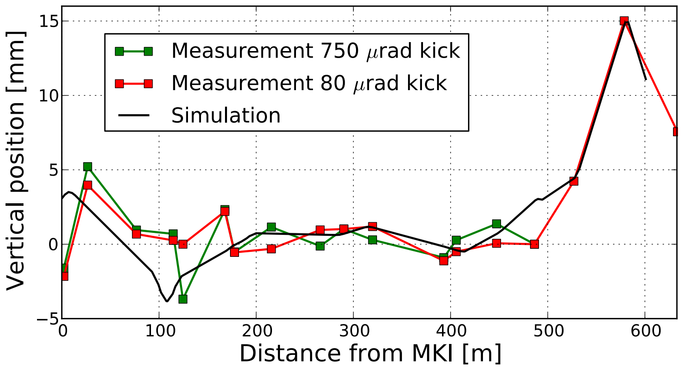
Particle-tracking	Particle-shower	Electro-thermal
Injection to beam screen	Same Magnet	Strand enthalpy

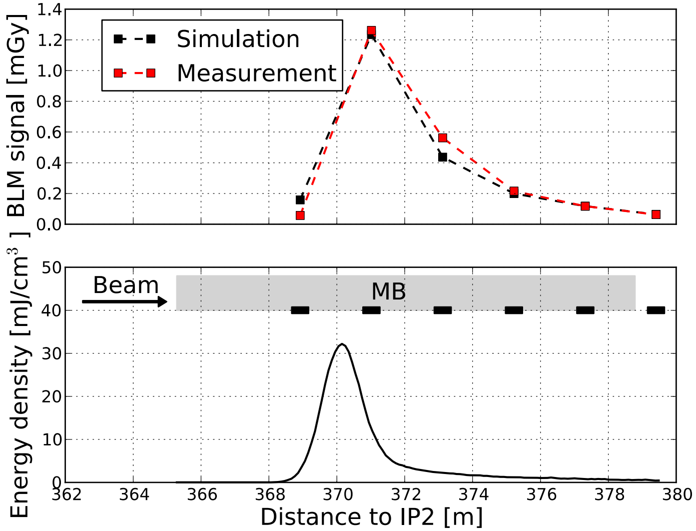
P. Show. [mJ/cm^3]	El.-Therm. [mJ/cm^3]
≤36	38

Challenge: getting the beam trajectory up to the kick right.

Advantage: data for validation available.

Uncertainties in particle-tracking input used to obtain best agreement.





Short-duration losses (0 – 50 µs)

Impact on Collimator, Q6 Quench (15/02/2013)

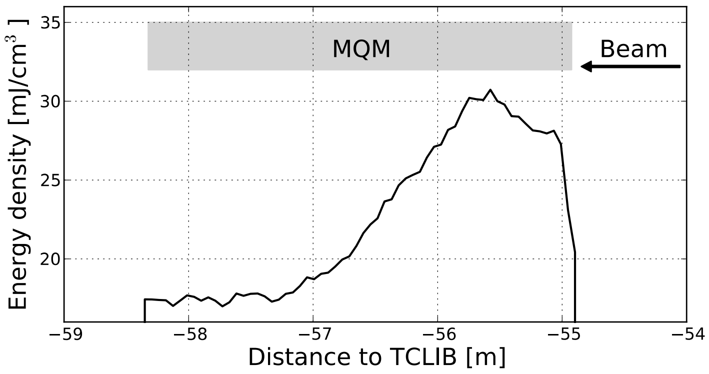
Particle-tracking	Particle-shower	Electro-thermal
Impact on collimator	55 meters of beam line	Strand enthalpy

Current [A]	P. Show. [mJ/cm^3]	El.-Therm. [mJ/cm^3]
2000	>29	20
2500	≤31	16

Challenge: BLM saturation ➔ no validation data for FLUKA simulation.

In the end, we trust the electro-thermal model.

Future test of this kind (Q4, LIBD team) should employ BLMs with higher sensitivity and dynamic range.



Intermediate-duration losses (50 µs – 5 s)

Wire-Scanner QT (01/11/2010)

Particle-tracking	Particle-shower	Electro-thermal
Impact on wire scanner	Dozens of meters of beam line	Cooling to saturated He 4.5 K. Loss peak in ends.

MBRB

v_w [m/s]	N_q/N_w [%]	P. Show. [mJ/cm^3]	El.-Therm. [mJ/cm^3]
0.15	n/a	>18	37^{+0}_{-11}
0.05	30	20	35^{+0}_{-11}
0.05	45	30	42^{+0}_{-16}

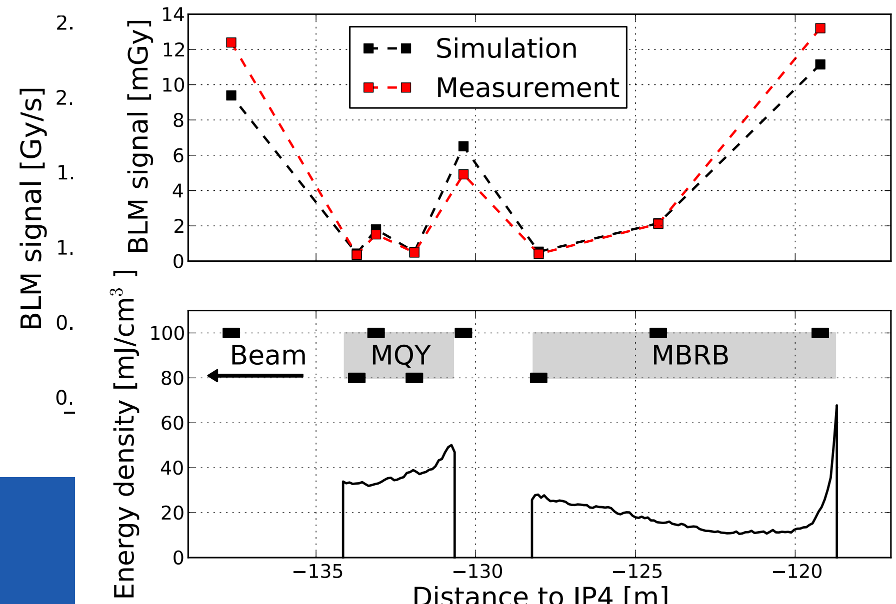
MQY

v_w [m/s]	P. Show. [mJ/cm^3]	El.-Therm. [mJ/cm^3]
0.05	>50	52

Challenges:

- Determination of the number of protons lost in the wire scanner, due to wire sublimation and vibration.
- Uncertainty on moment of quench.
- Peak losses in the coil ends ➔ uncertainty on cooling conditions and coil field.

Future tests should make use of oscilloscopes.



Intermediate-duration losses (50 µs – 5 s)

Orbit-Bump QT (15/02/2013)

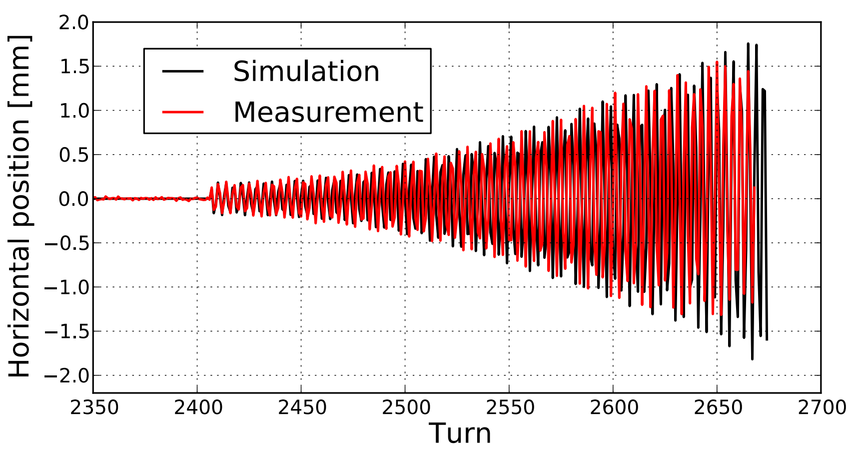
Particle-tracking	Particle-shower	Electro-thermal
Tracking hundreds of turns, MKI, ADT	Same Magnet	Cooling of µs loss peaks into He II

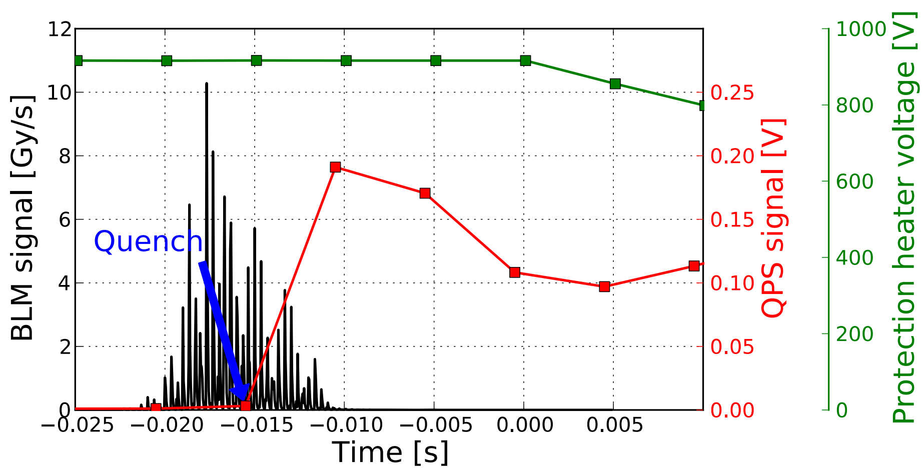
N_p	N_q	P. Show. [mJ/cm^3]	El.-Therm. [mJ/cm^3]
3.5×10^8	n/a	>198	$71^{+?}_{-10}$
8.2×10^8	5.3×10^8	250	$58^{+?}_{-8}$
8.2×10^8	8.2×10^8	≤405	$80^{+?}_{-10}$

Uncertainty on moment of quench.

Loss spikes of several µs ➔ even larger uncertainty on cooling model.

Particle tracking tuned to fit BPM data.

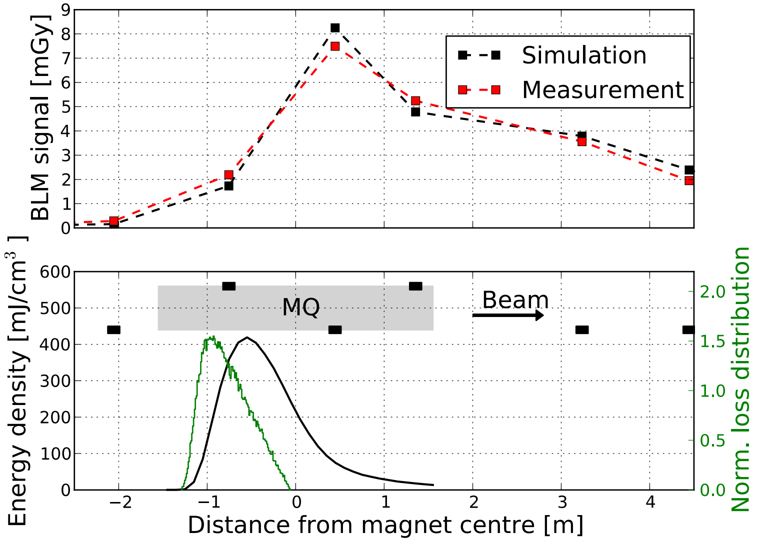




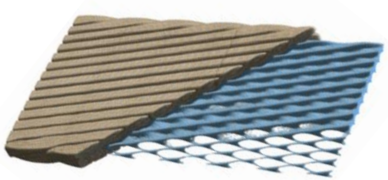
Intermediate-duration losses (0.5 ms – 5 s)

Orbit-Bump QT (15/02/2013)

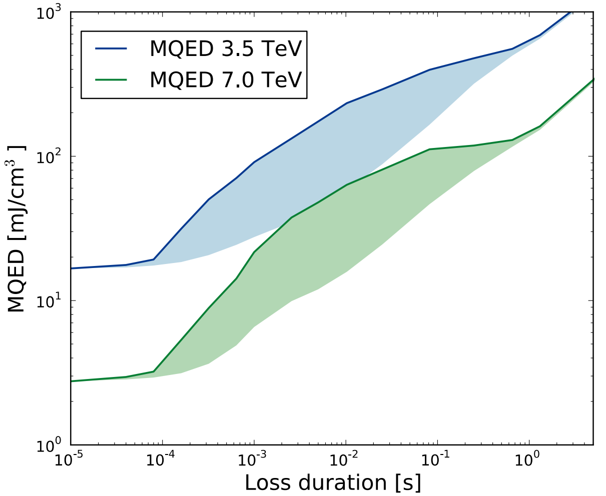
- Excellent agreement with BLM data.
- High confidence in FLUKA energy deposition.
- Electro-thermal model underestimates the quench level by factor 4!
- How does this scale to 6.5 TeV?
- Subscale experimental work needed!
- µs-duration peaks may increase the quench level w.r.t. a Gaussian distribution.
- Is the test representative for UFOs?
- *Still 250 mJ/cm3 is the best number we have.*



N_p	N_q	P. Show. [mJ/cm^3]	El.-Therm. [mJ/cm^3]
3.5×10^8	n/a	>198	$71^{+?}_{-10}$
8.2×10^8	5.3×10^8	250	$58^{+?}_{-8}$
8.2×10^8	8.2×10^8	≤405	$80^{+?}_{-10}$



Courtesy:
Chr. Scheuerlein



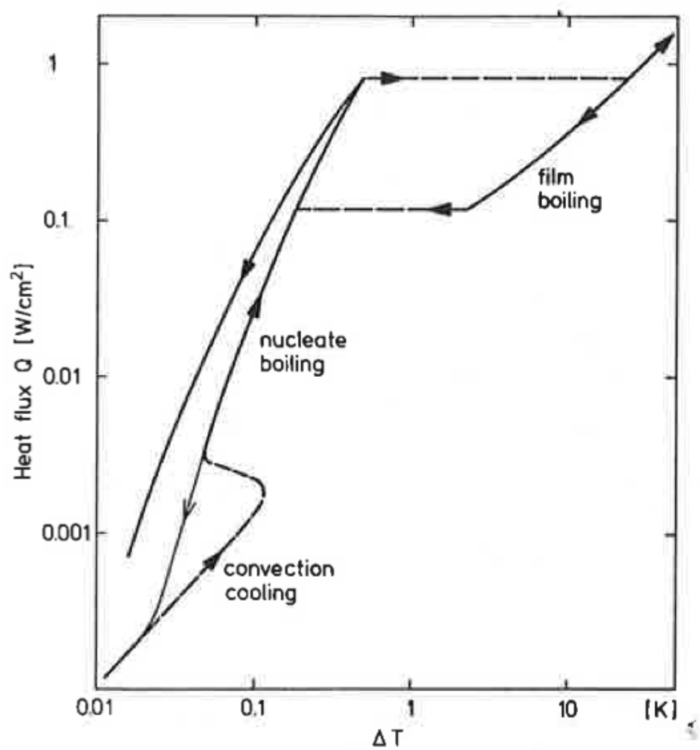


Fig. 1 - Steady-state heat transfer characteristic. The curve is artificially composed of experimental results in Refs. 6,7,11.

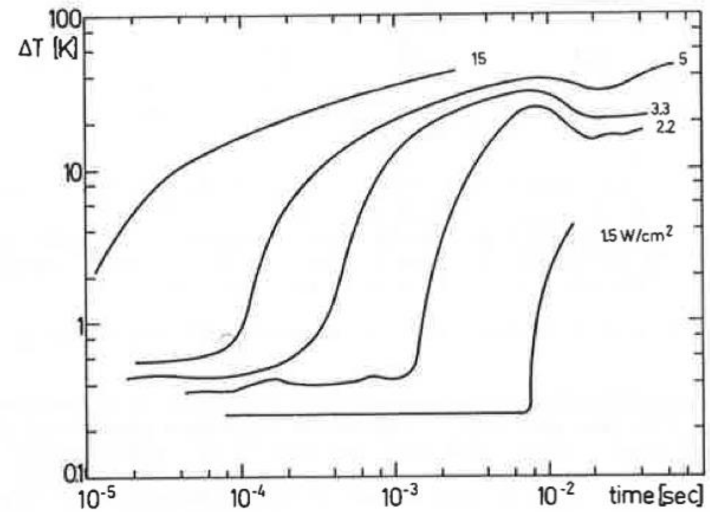


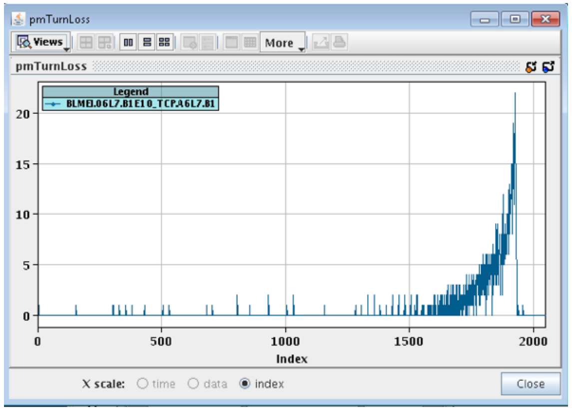
Fig. 9 - Transient heat transfer experiment using a monofilamentary NbTi/Cu superconductor (NbTi diam. 36 μm, Cu diam. 52 μm) both as a heater and a thermometer. The plot shows surface temperature traces for various heat fluxes Q. From Ref. /34/.

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.

Intermediate-duration losses (0.5 ms – 5 s)

Future tests

- Repetition of wire scanner test unlikely
  - 4.5 K is better understood and less relevant.
  - UFOs are less likely due to lower number of magnets.
  - Uncertainty due to quench in coil ends cannot be mitigated.
- Repetition of orbit-bump quench test
  - Use oscilloscope.
  - Perform beam-parameter measurements right before test.
  - Improve ADT understanding and modeling.
  - The uncertainty due to μs spikes does not go away.
- Fast current-change in warm D1 magnet
  - Shown to produce smooth losses on collimator in the ms range.
  - In combination with local orbit bump could be used to quench MQ?
  - Requires in depth study.



FMCM Beam Tests for D1 IR1/5
2/12/2009, 0h21m29s

Steady-state losses (5 s – infty)

Collimation QT (15/02/2013)

Particle-tracking	Particle-shower	Electro-thermal
Inelastic collisions in IR7 collimators	Hundreds of meters	“Fish-bone” efficiency, peak in ends

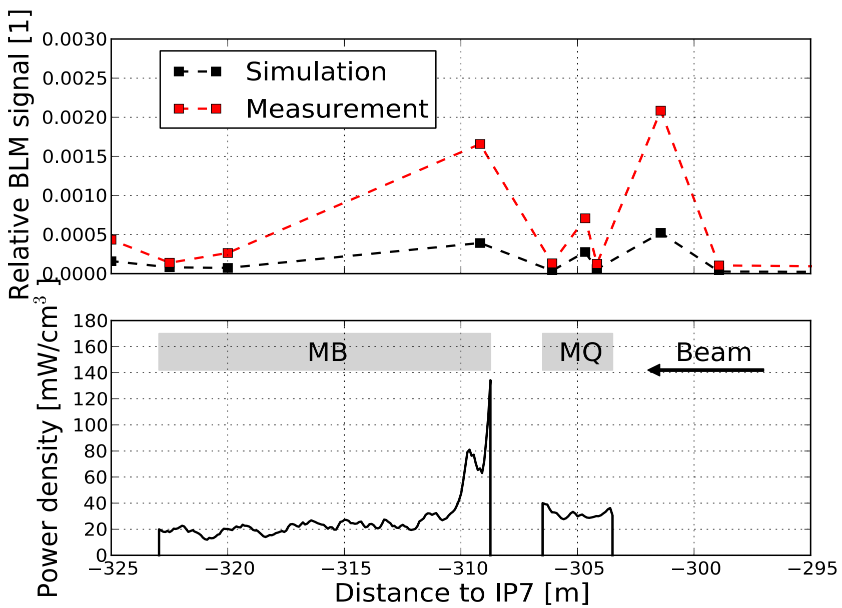
P. Show. [mW/cm^3]	El.-Therm. [mW/cm^3]
> 50	115^{+25}_{-0}

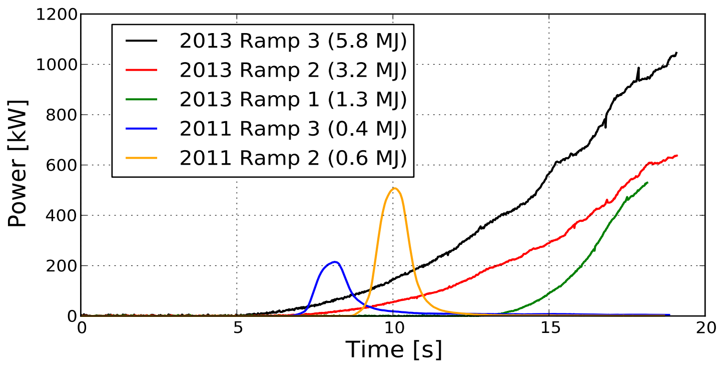
No quench, hence no validation of quench level.

Peak losses in MB coilends.

Impressive overall agreement, but important discrepancy at location of peak losses.

6.5 TeV test will give more information, together with improved SixTrack routines.





Steady-state losses (5 s – infty)

Dynamic orbit bump QT (17/10/2010)

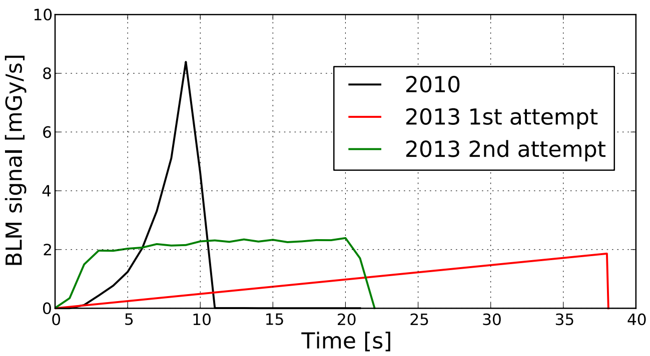
Particle-tracking	Particle-shower	Electro-thermal
Involved model of slow bump increase	Same Magnet	Cooling-channel efficiency

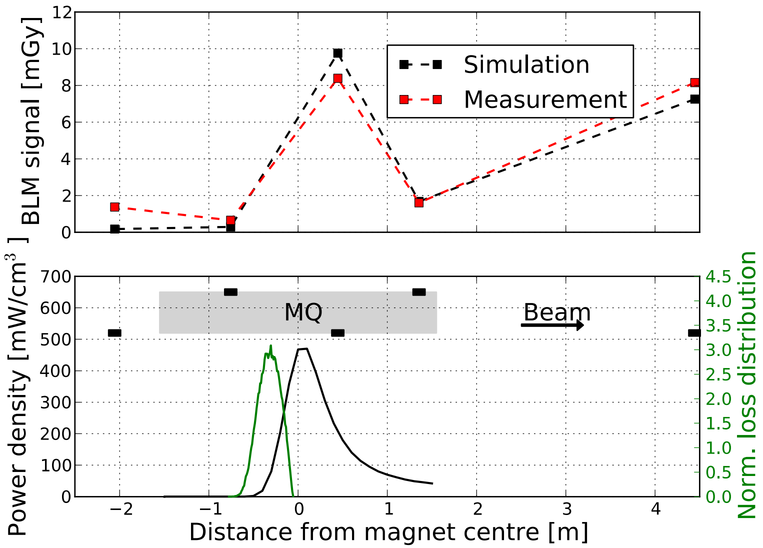
P. Show. [mW/cm^3]	El.-Therm. [mW/cm^3]
208	180^{+35}_{-0}

Vertical orbit bump.

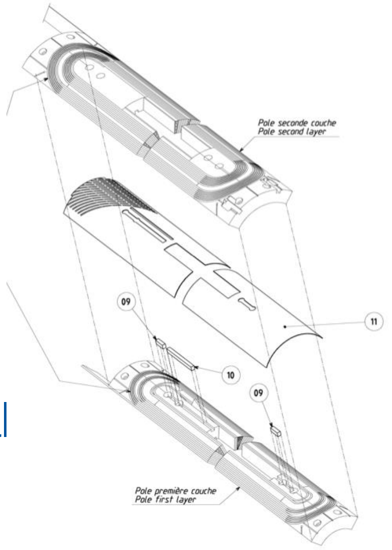
Excellent agreement with BLM signals.

Remarkable agreement FLUKA/electro-thermal model.





Steady-state heat-transfer model

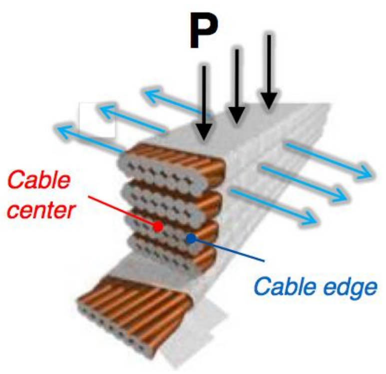


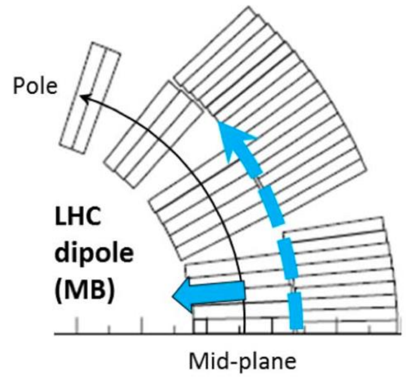
Measured heat-extraction from stack-test.

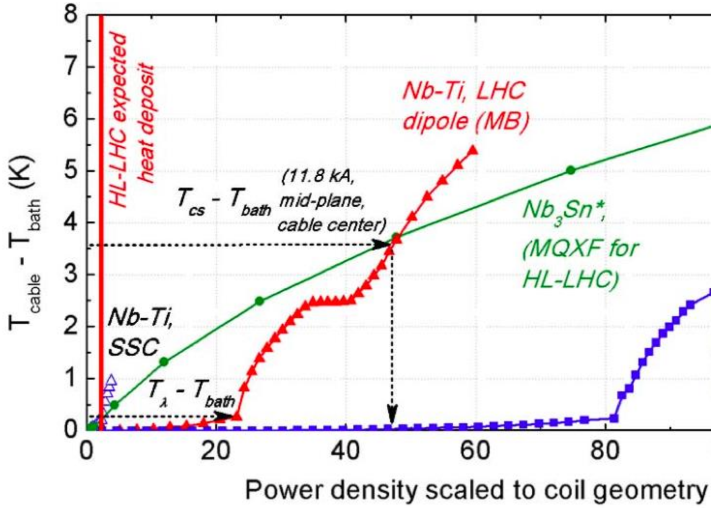
“Fish-bone” structure raises question how to extrapolate stack data to coil inner layer.

- Assumption 1: Steady-state heat transfer is unidirectional
- Assumption 2: Fish-bone side is efficient up to $T_s = T_\lambda$.

No entirely predictive model available.







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.

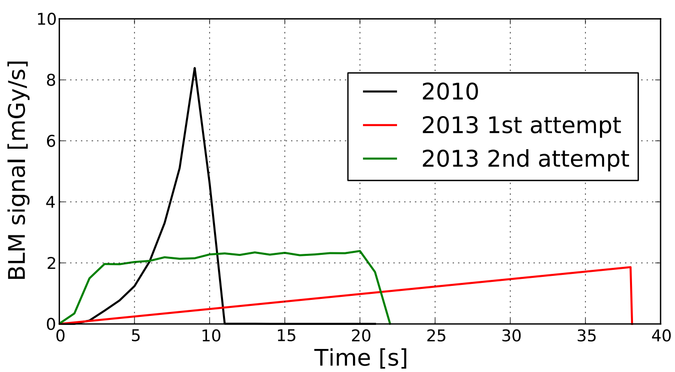
Steady-state losses (5 s – infty)

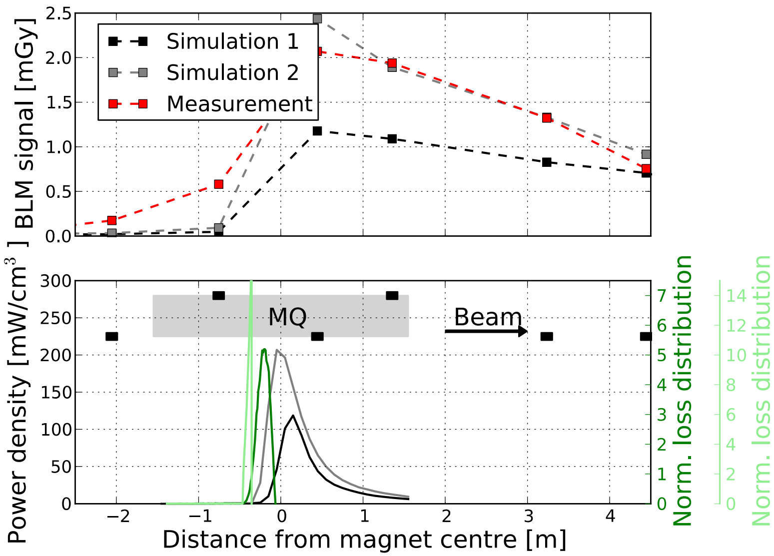
Static orbit bump QT (15/02/2013)

Particle-tracking	Particle-shower	Electro-thermal
Involved model of bump and ADT excitation	Same Magnet	Cooling-channel efficiency

attempt	P. Show. [mW/cm^3]	El.-Therm. [mW/cm^3]
1st	$>33^{+22}_{-0}$	80^{+20}_{-0}
2nd	41^{+33}_{-0}	70^{+18}_{-0}

Given the excellent agreement FLUKA/BLM in previous orbit-bump tests, something unknown must influence the particle distribution.
Hence the study of 30-µm-thick, 20-cm-long aperture restriction.



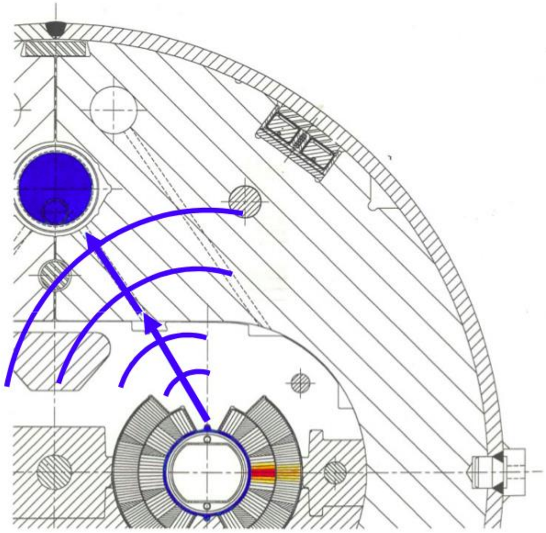


Steady-state losses (5 s – infty)

Repetition of test in different aperture or different magnet could verify/falsify the aperture-restriction assumption.

Analysis needed to study whether heat transport to heat exchanger could be a limiting factor.

Model is based on measurements on MB cable. How does this scale to MQXA, MQXB, MQY, MQM and their different insulation schemes?



Courtesy D. Bocian.

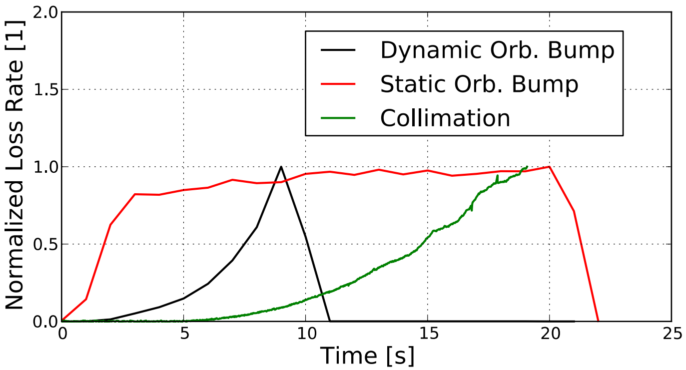
Magnet	Coil insulation	Operating temperature	Injection			Collision			Conditions/Reference
			Temperature margin	Heat reserve (transient losses)	Peak power density	Temperature margin	Heat reserve (transient losses)	Peak power density	
MB	2x50mu (50% overlap) + 73 mu (2 mm gap)	1.9 K	7 K	38 mJ/cm3	10 mW/cm3	1 K	0.8 mJ/cm3	5 mW/cm3	LPR 44; Meuris et al. (1999)
MQXA	2x25mu (50% overlap) + 60 mu (2 mm gap)	1.9 K	8.2 K	55 mJ/cm3		1.3 K	1.3 mJ/cm3	4 mW/cm3	Kimura et al, IEEE Tran SC., 9(1999)1097
MQXB	2x25mu (55% overlap) + 50 mu (2 mm gap)	1.9 K	8 K	50 mJ/cm3		1.2 K	1.2 mJ/cm3	0.4 mW/g	Mohkov et al., LPR 633
MQM	2x25mu (50% overlap) + 55 mu (2 mm gap)	1.9 K	7.5 K	50 mJ/cm3	10 mW/cm3	1 K	1.0 mJ/cm3	5 mW/cm3	
MQM	2x25mu (50% overlap) + 55 mu (2 mm gap)	4.5 K	6.5 K	75 mJ/cm3		1.2 K	5 mJ/cm3	2 mW/cm3	
MQY	2x25mu (50% overlap) +55 mu (2 mm gap)	4.5 K	6.5 K	75 mJ/cm3		1.4 K	5 mJ/cm3	2 mW/cm3	
MQTL	B-stage epoxy impregnated	4.5 K	6.5 K	75 mJ/cm3		2 K	5 mJ/cm3	1.0 mW/cm3	R.Wolf, Pr comm., 28 July 2004

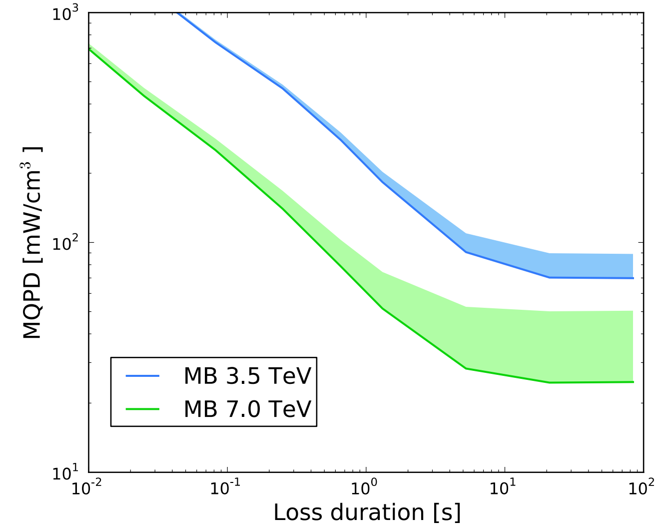
R. Ostojic, Insertion Magnets and Beam Heat Loads, at workshop "Beam generated heat deposition and quench levels for LHC magnets", 3-4 March 2005

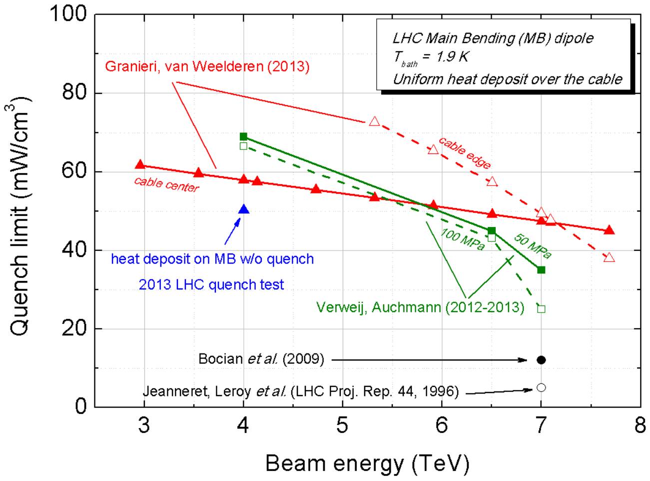
Steady-state losses (5 s – infty)

- Uncertainties due to “fish-bone” are more important at higher energies.
- Definitive validation not possible at 4 TeV.
- Based on static-orbit bump QT results we use the more conservative assumption.
- More input in tomorrow’s morning session!

Test	Energy [TeV]	Type	Ramp time [s]	MQPD [mW/cm³]	FLUKA [mW/cm³]
Dyn. Orbit Bump	3.5	MQ	6	180^{+35}	208
Collimation	4	MB	15	115^{+25}	n/a
Static Orbit Bump	4	MQ	infty	70^{+18}	41^{+33}







Courtesy P.P. Granieri

Steady-state losses (5 s – infty)

- Future tests
  - Repetition of orbit-bump test in
    - Different MQ
    - Also in MQM, MQY – even triplet magnets?
  - Collimation quench test
    - Will give improved analysis and, perhaps, a quench?

Overview

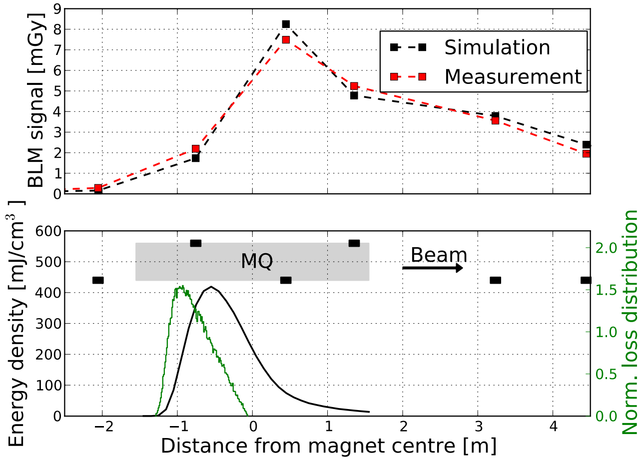
- Summary of quench-test results per time regime.

Regime	Method	Energy	Temperature
short	kick	450 GeV	1.9 K
short	collimation	0.45/6 TeV	4.5 K
intermediate	wire scanner	3.5 TeV	4.5 K
intermediate	orbit bump	4 TeV	1.9 K
steady-state	collimation	4 TeV	1.9 K
steady-state	dyn. orbit bump	3.5 TeV	1.9 K
steady-state	orbit bump	4 TeV	1.9 K

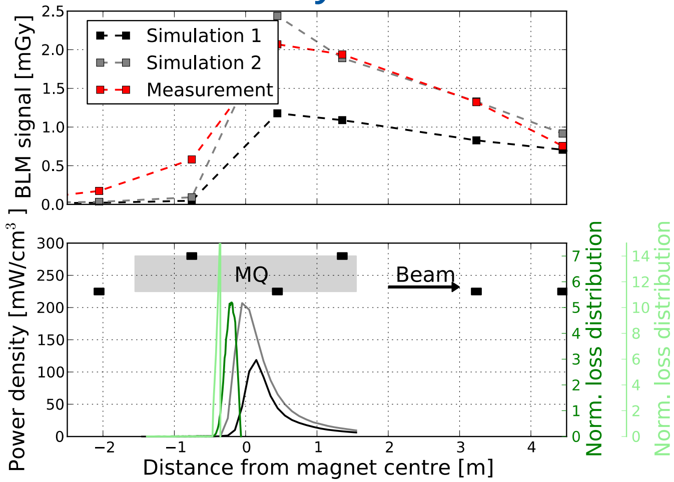
- What are the implications for BLM settings?

Summary orbit-bump scenarios

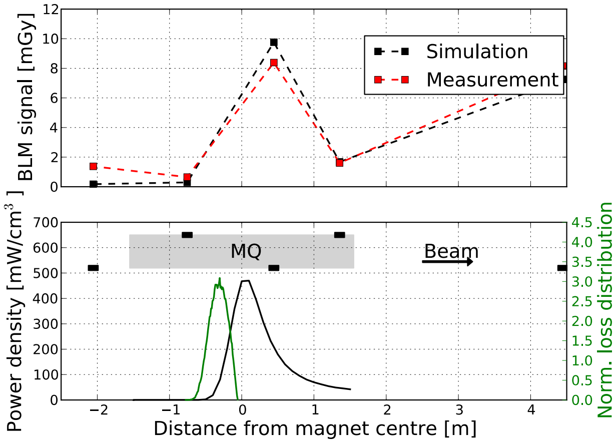
Intermediate-duration



Steady-state



horizontal



vertical

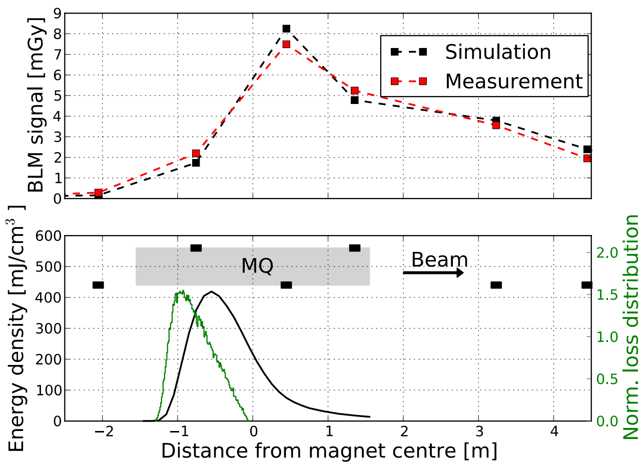
Stronger kicks lead to

- Faster losses
- Wider loss distributions
- Loss maximum closer to MQ beginning
- Larger impact angles
- Higher BLM signals.

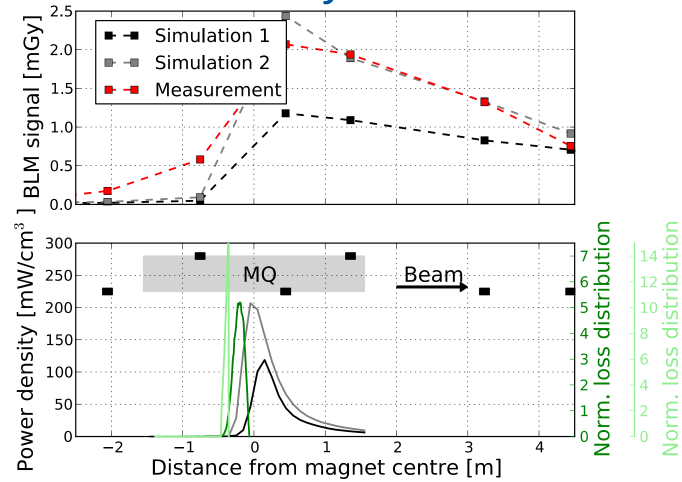
CERN

Summary orbit-bump scenarios

Intermediate-duration



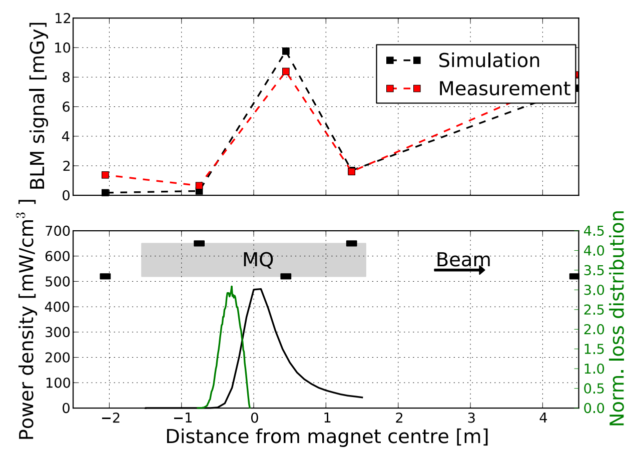
Steady-state



horizontal

$$\text{BLMSignal@Quench}(E,t) = \frac{\text{BLMResponse}(E,t) * \text{QuenchLevel}(E,t)}{\text{EnergyDeposit}(E,t)}$$

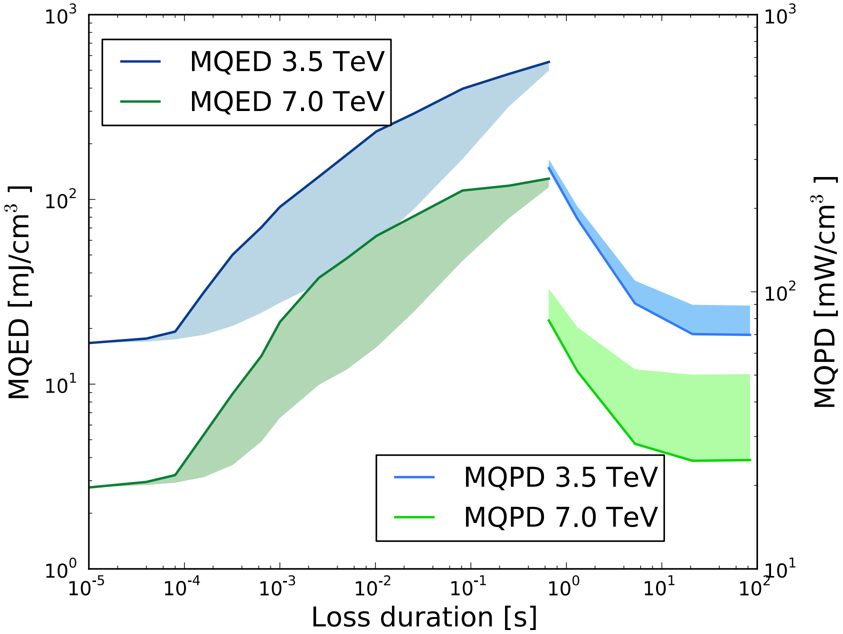
Plane	Regime	BLM Response [mGy/p]	Energy Deposit [mJ/(cm³p)]	Ratio [Gy cm³/J]
vertical	steady-state	3.26E-09	2.13E-07	1.53E-02
horizontal	intermediate -duration	9.10E-09	5.10E-07	1.78E-02
horizontal	steady-state	2.60E-09	4.00E-07	6.50E-03



vertical

What have we learned for BLM Quench Levels?

- Short duration:
  - Little uncertainty for fastest detectable losses.
- Intermediate duration:
  - Factor 4 uncertainty based on orbit-bump quench test.
  - For BLM thresholds we use higher level.
  - Unclear how this factor scales to 6.5 TeV.
  - UFOs during Run 2 and/or a future quench test will give more insight.
- Steady-state:
  - For BLM thresholds we use lower levels.
  - How to improve knowledge on MQXA, MQXB, MQY, MQM?
  - Sub-scale experiments (see Session III of this workshop) and quench tests at 6.5 TeV will bring further information.



MB estimated quench levels and uncertainties.

Conclusion

- The organization of quench tests and the analysis of beam-loss events are highly collaborative and multi-disciplinary efforts!
- In principle we should aim to understand beam-induced quenches in all aspects to within 20% - though it may still take some time to get there.
- On the long run we must aim to understand every beam-loss scenario for BLM thresholds to within this precision.
  - This will allow for better informed decisions whenever either a beam-induced quench or too many spurious triggers occur.
  - See tomorrow’s afternoon session for more on BLM thresholds!
- Sub-scale experimental work has to complement quench tests to pin down the quench levels in a single predictive model.
  - See tomorrow’s morning session on both, experimental and modeling work!

www.cern.ch