Quench thresholds of LHC magnets
-
measurements and simulations

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OUTLINE

- BLM and QPS systems as the LHC magnet main protection
- Overview of Quench Tests
- Quench thresholds of BLM system
- Steady State Quench Test:
  - Experiment on 17th October 2010
  - Geant4 simulations
- Loss pattern optimization and simulation validation
- Fast Losses Quench Test in 2013
- Summary

INTRODUCTION

The LHC superconducting magnets protection

Beam Loss Monitoring System (BLM)	**Quench Protection System (QPS)**

Beam Loss Monitoring System (BLM)

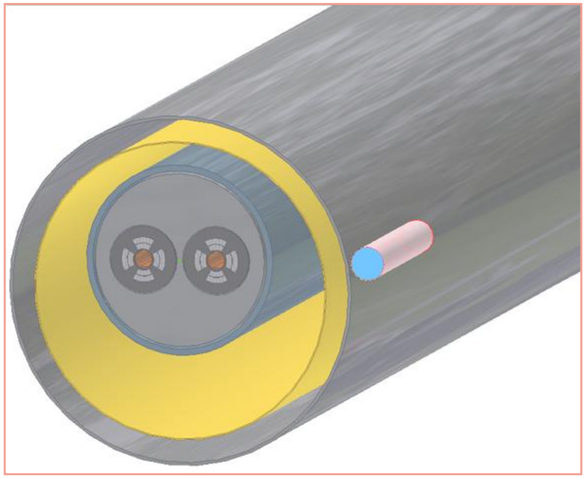
- **Based on ionization chambers located outside the magnet cryostats**
- **Measures radiation dose of secondary particle shower**
- **If a threshold value is exceeded, the beam dump is triggered**
- **The beam can be extracted from the accelerator before quenching occurs**

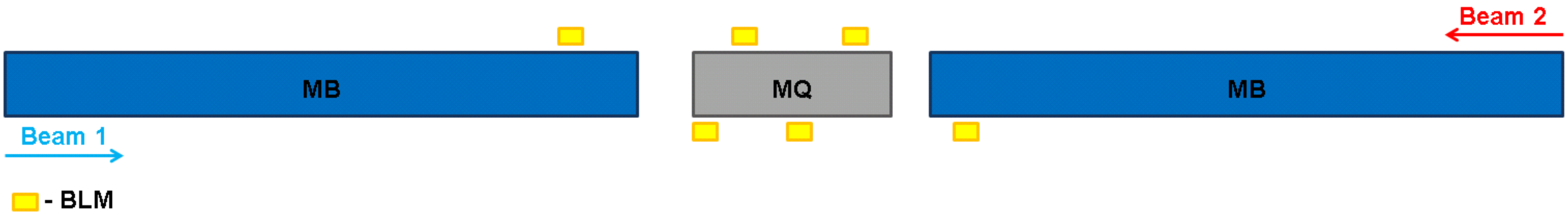
Quench Protection System (QPS)

- **Based on voltage measurements between two parts of superconducting coils**
- **If the voltage difference exceeds 100 mV for a time longer than 10 ms, the quench heaters are fired to dissipate the energy stored in the magnetic field over the whole volume of the coil**
- **The system reacts when a resistive volume is already developed**

Beam loss monitoring system (BLM)

- Each LHC arc Main Quadrupole is equipped with 6 monitors (3 per beam)
- Thresholds are set with correspondence to current knowledge on the quench limit (particle energy, loss duration)
- A precise correlation between energy deposited inside the superconducting coils and BLM signals is required for a proper threshold estimation





QUENCH TESTS OVERVIEW

- Fast Losses QT (injection & dump = single turn)

No	Quenching magnet	Energy [TeV]	Beam	Date
1	MB.A8L3	0.45	B1V	9.08.2008
2	MB.B10R2	0.45	B1V	7.09.2008
3	MB.A12L6	0.45	B1H	20.11.2009
4	MB.A15R2	0.45	B1V	4.12.2009
5	MB.A20R1+others	0.45	B1H	18.04.2010
6	MQ.14R2	0.45	B2V	6.10.2010
7	MQ.14R2	0.45	B2V	6.10.2010
8	MQ.14R2	0.45	B1H	6.10.2010
9	MBRB (RD4.L4)	3.50	B2	1.11.2010
10	MQ.14R2	0.45	B1H	3.07.2011

- Steady State QT (with circulating beam)

No	Quenching magnet	Energy [TeV]	Beam	Date
1	MQ.14R2	3.50	B2V	17.10.2010

There were also other Quench Tests but unsuccessful (no quench)

Quench Tests overview

- Fast Losses QT (injection & dump = single turn)

No	Quenching magnet	Energy [TeV]	Beam	Date
1	MB.A8L3	0.45	B1V	9.08.2008
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3	MB.A12L6	0.45	B1H	20.11.2009
4	MB.A15R2	0.45	B1V	4.12.2009
5	MB.A20R1+others	0.45	B1H	18.04.2010
6	MQ.14R2	0.45	B2V	6.10.2010
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9	MBRB (RD4.L4)	3.50	B2	1.11.2010
10	MQ.14R2	0.45	B1H	3.07.2011

- Fast Losses QT (circulating beam)

No	Quenching magnet	Energy [TeV]	Beam	Date
2	MQ.12L6	4.00	B2H	winter 2013

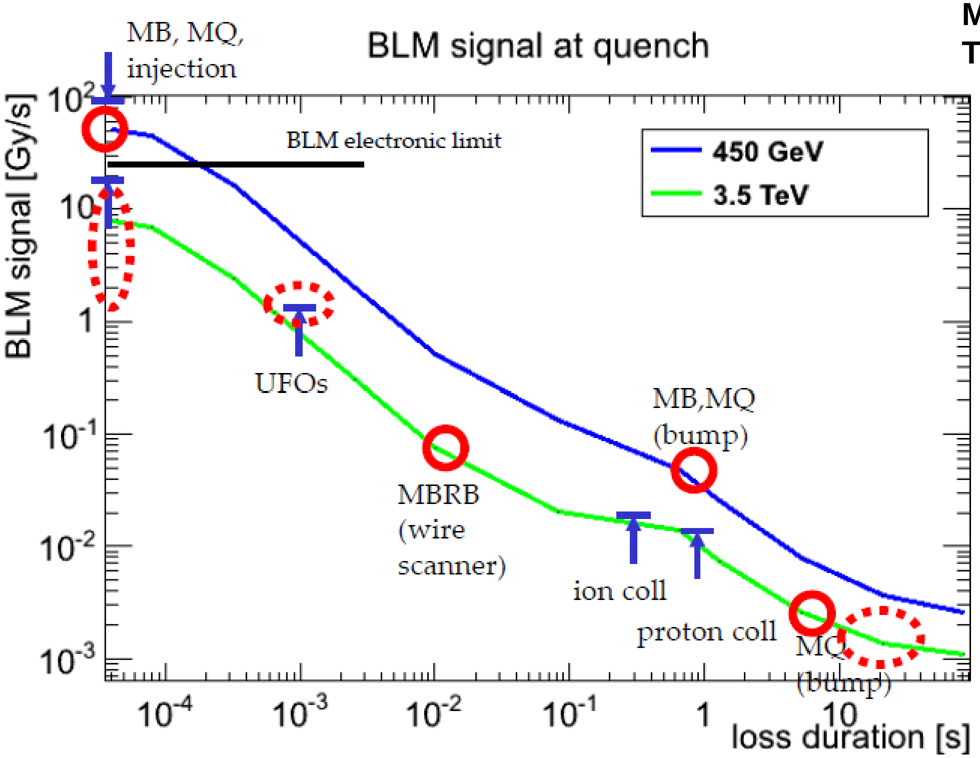
?

- Steady State QT (with circulating beam)

No	Quenching magnet	Energy [TeV]	Beam	Date
1	MQ.14R2	3.50	B2V	17.10.2010
2	MQ.12L6	4.00	B2H	winter 2013

?

QUENCH THRESHOLD OF BLM SYSTEM



M.Sapinski, "Proposal for Beam Induced Quench Tests at the end of 2013 run", LMC 154, 24.10.2012

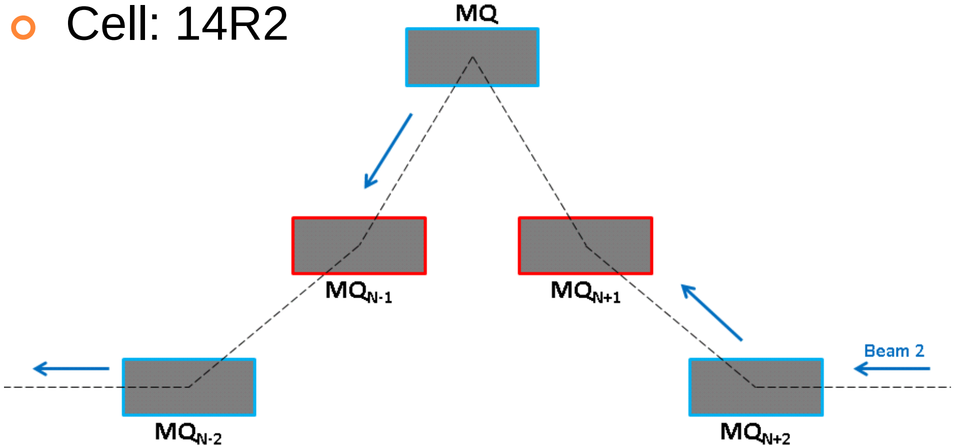
- Beam induced quenches
- Quench Test or losses which established lower limit for quench level
- Measurements to be done in 2012/13, important for LHC after LS1

Quench Test are important to revise currently applied models of quench limits

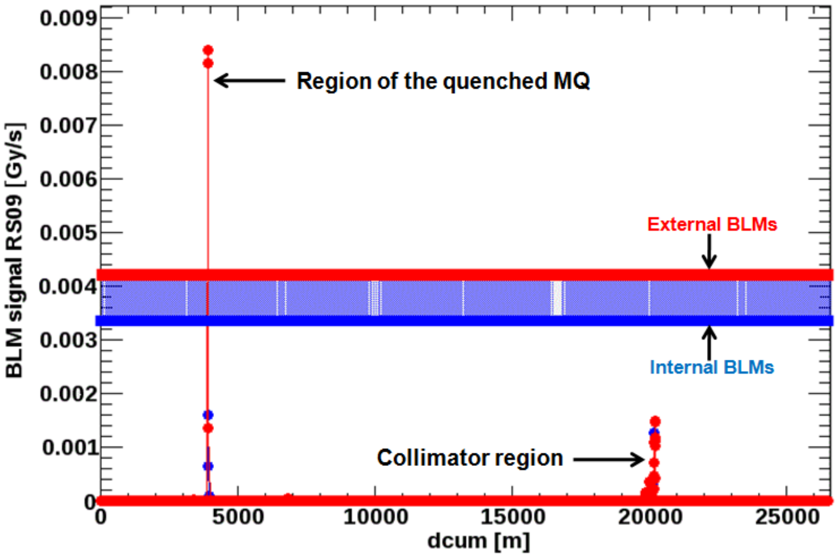
Increase of the LHC efficiency = reduction of false beam dumps

STEADY STATE QUENCH TEST - EXPERIMENT

- Performed on 17th October 2010
- Energy: 3.5 TeV
- Beam: 2
- Plane: vertical
- No of lost protons: $1.1 \cdot 10^{10}$
- Loss duration: 5.6 s
- Circulating beam
- Cell: 14R2

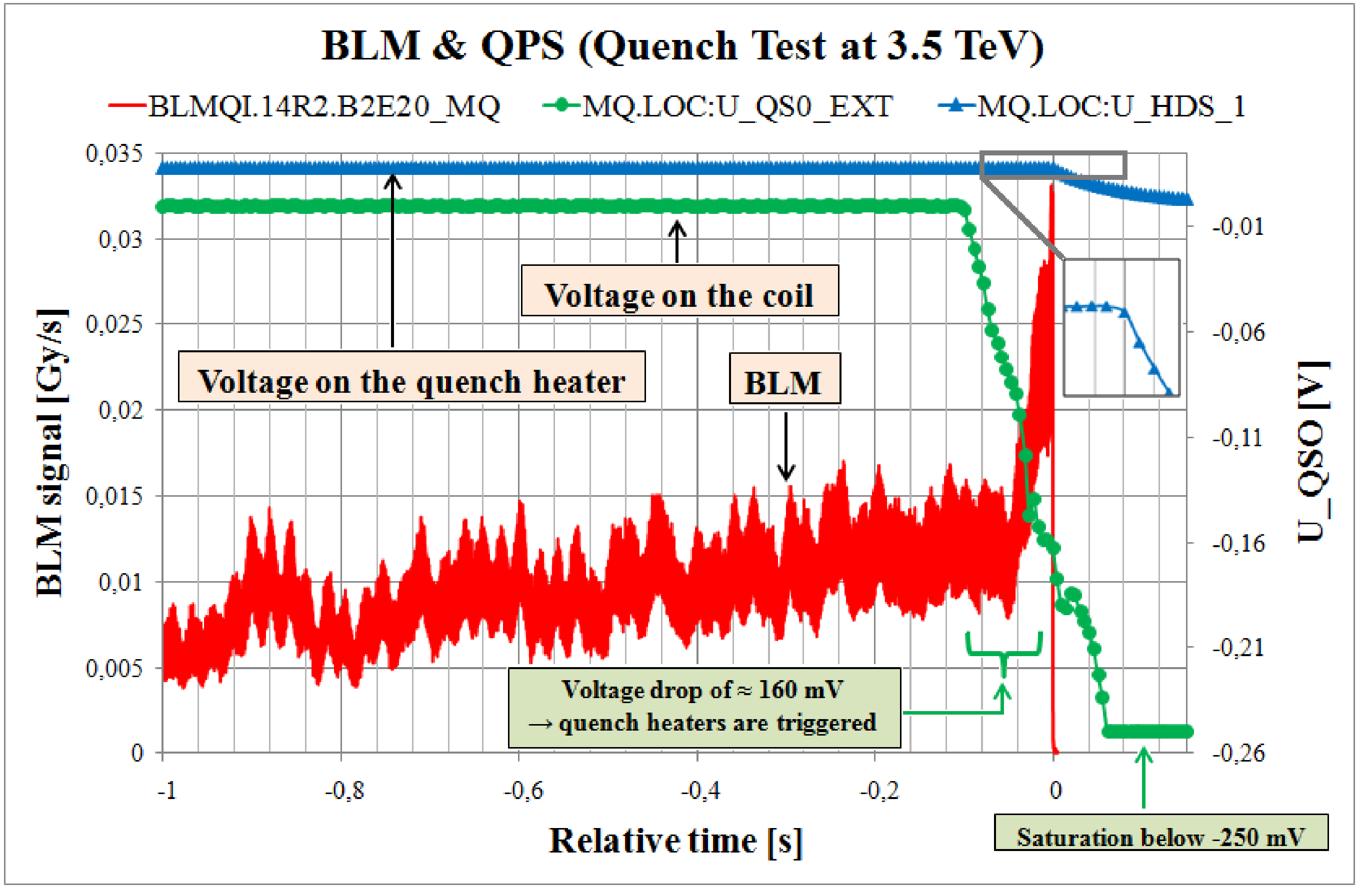


3-corrector orbital bump



Steady State Quench Test - Experiment

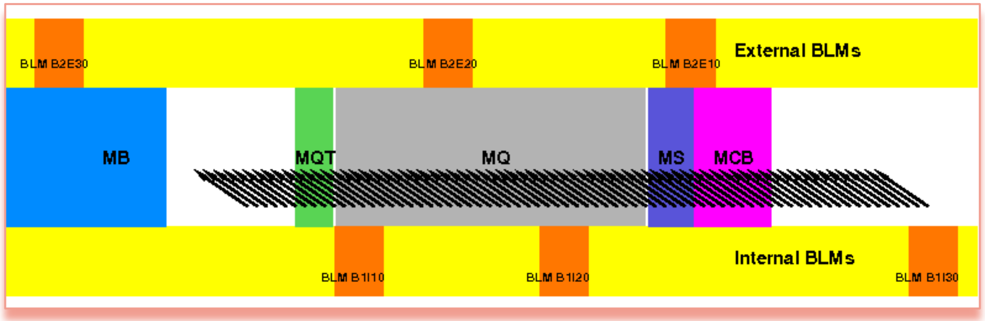
BLM threshold RS01 (40μs) = 4.68 Gy/s



- BLM monitor factors increased by a factor of 3 to permit the quench
- Real quench: the beam dump triggered by the QPS

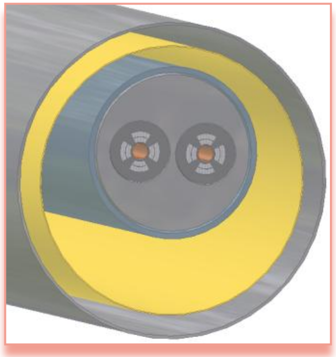
STEADY STATE QUENCH TEST – SIMULATIONS

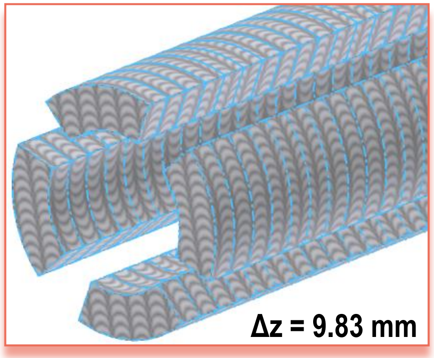
- Geant4 simulations
- The LHC halfcell: C14R2
- Detailed magnet representation
- Long pseudo-monitors
- Impacting angle: 202 μrad
- 71 point like losses → flexibility
- Correlation: E_{dep} = f(BLM)

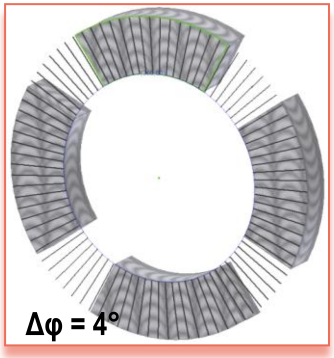


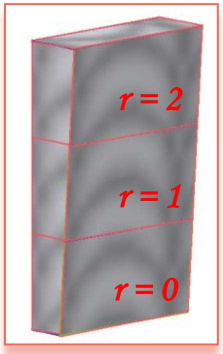
OBJECTIVE:

Best fitting loss scenario









STEADY STATE QUENCH TEST – SIMULATIONS

How to find the best agreement between simulations and experimental data?

Simulation-experiment similarity estimator:

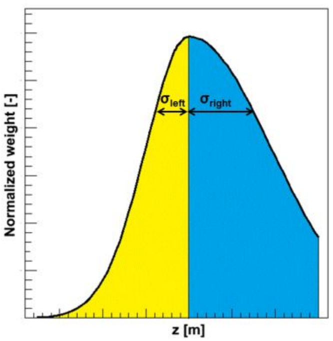
$$\Sigma^{norm}_{\mu,\sigma_r,\sigma_l} = \sum_{i=1}^{6}\left(\frac{BLM_i^{sim} - BLM_i^{exp}}{BLM_i^{sim}}\right)^2$$

Looking for: minimum

BLM_i^{sim} - simulated signal of *i*-th BLM

BLM_i^{exp} - measured signal of *i*-th BLM

Optimized parameters:



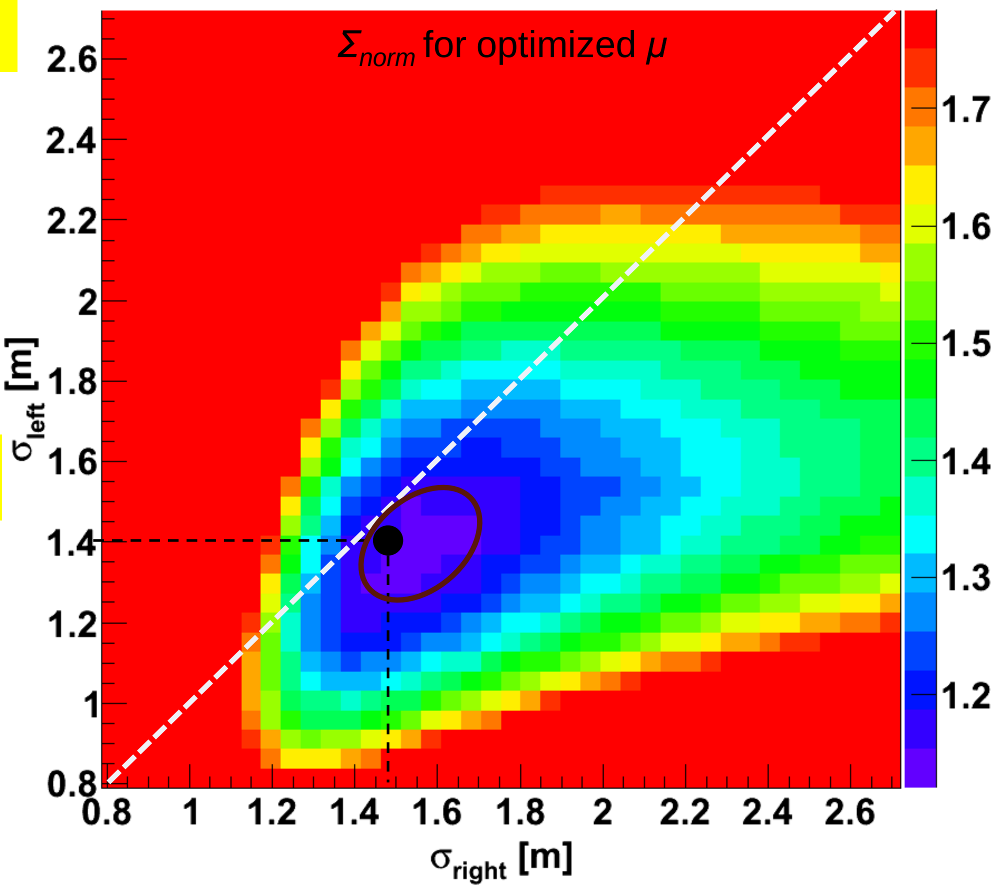
Asymmetrical Gaussian

- Σ_{norm} = 1.12

→ μ = (0.4±0.1) m

→ σ_{right} = (1.54±0.15) m

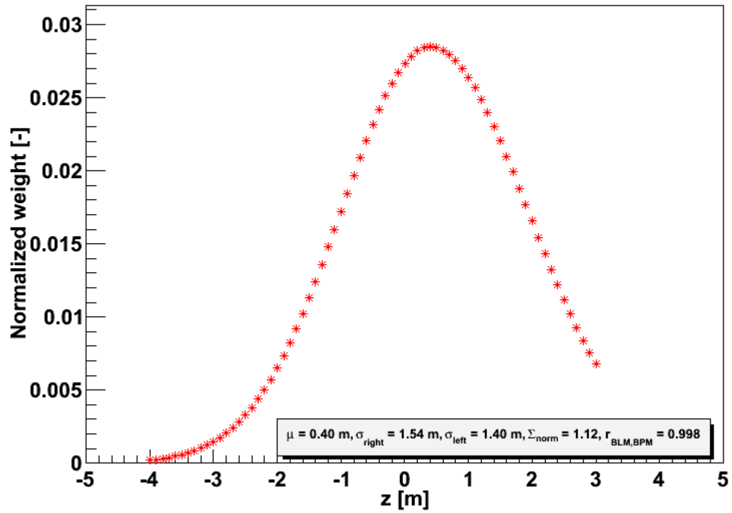
→ σ_{left} = (1.40±0.14) m

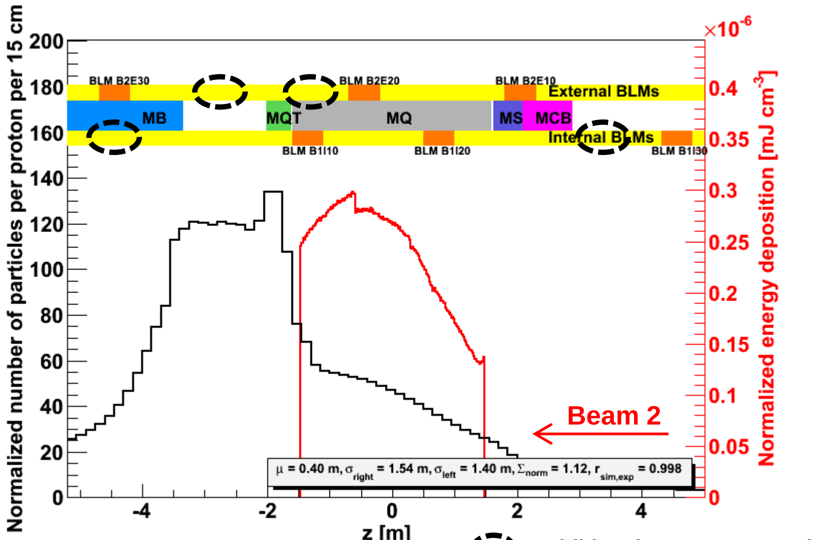


- $\sigma_{right} > \sigma_{left}$ (reasonable due to the impact of magnetic field)
- ≈ 1% (0.05 m^2) of the map is characterized by $\Sigma_{norm} \leq 1.15$

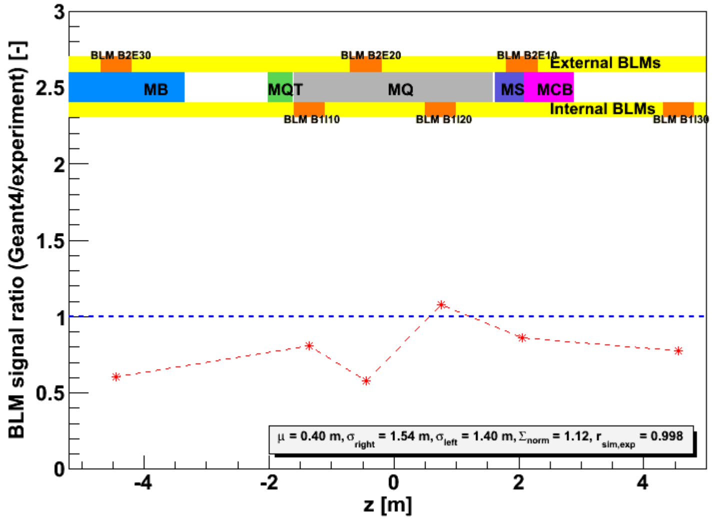
Steady state quench test – simulations

Integrated loss pattern (no time evolution) over 6 s





- additional BLMs to be installed before the next QT



- Optimized three free parameters:
  - → $\mu = 0.4$ m
  - → $\sigma_{right} = 1.54$ m
  - → $\sigma_{left} = 1.40$ m
  - $\Sigma_{norm} = 1.12$
  - $r_{exp,sim} = 0.9978$
- Max of E_{dep} at the end of MQ
- The highest number of secondary particles in the interconnection region (MB-SSS)

PLANS FOR THE FUTURE

- In the LHC, UFOs are the Undefined Falling Objects

- UFOs are expected to be a major luminosity limitation in the future
- UFOs rate increases with the beam energy
- BLM thresholds should be increased to avoid undesirable beam dumps

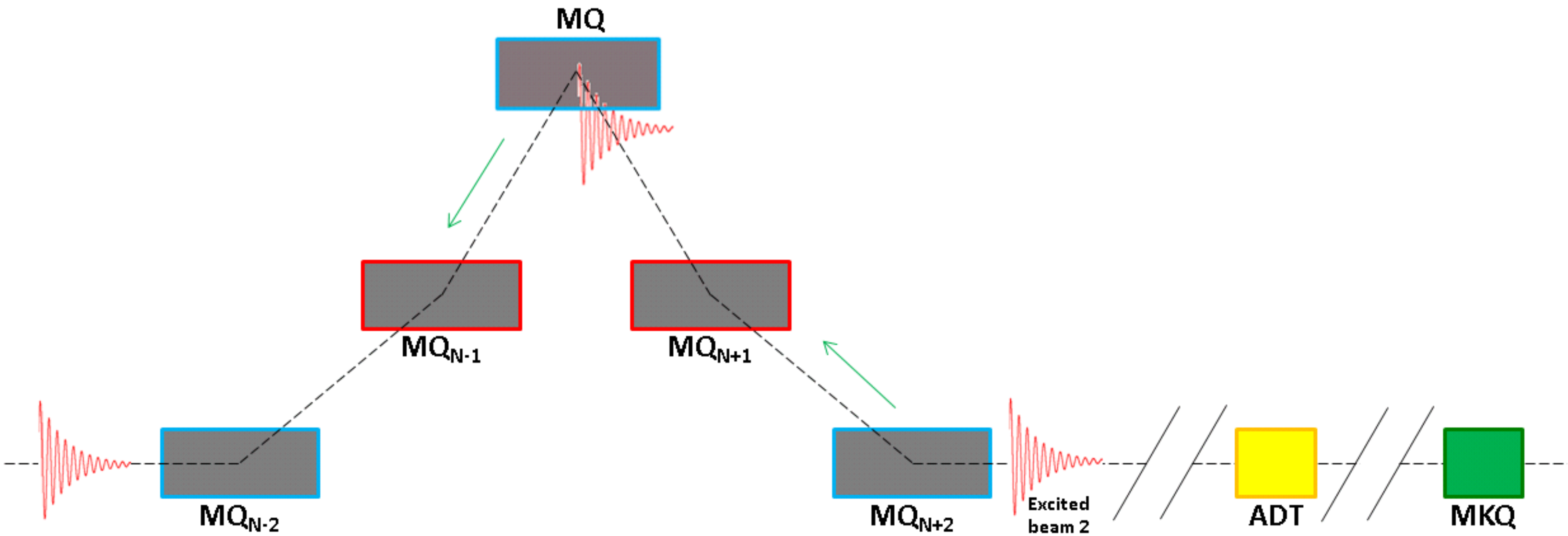
UFO's properties

- Temporal loss distribution has **Gaussian shape**
- Loss duration in order of **milliseconds**

PLANS FOR THE FUTURE

Fast Losses Quench Test – the end of LHC run 2013

- Preparations: 2 MDs – ADT Fast Losses Test and the ADT combined with MKQ Fast Losses Test
- Loss duration: ≈ 1 ms
- Beam: 2, horizontal (based on MD results, UFO loss orientation, machine protection)
- Cell: 12L6
- Challenges: beam intensity (below $2 \cdot 10^9$ protons the beam is not seen by many systems, models predict that quench should occur with $\approx 10^8$)



SUMMARY

Quench Tests

are very

important for

my PhD

… but seriously …

Summary

- Quench Tests are extremely important to estimate the quench levels and update existing thresholds for fast and steady state losses.
- Accurate thresholds are needed to combine a safe machine operation with a reduction of undesired beam dumps.
- Fast Losses Quench Test will allow better understanding of UFO-like losses which are expected to be a major luminosity limitation of the LHC after LS1.
- Geant4 simulations show good agreement with experimental data. The integrated over time loss pattern was presented. An analysis of loss time evolution is ongoing.

THANK YOU FOR YOU ATTENTION !

Questions?

Comments?

Remarks?

Back-up slides

Steady state quench test – simulations

How to find the best correlation between simulations and experimental data?

- Simulation-experiment similarity estimator

$$\Sigma^{norm}_{\mu,\sigma_r,\sigma_l} = \sum_{i=1}^{6} \left(\frac{BLM_i^{sim} - BLM_i^{exp}}{BLM_i^{sim}} \right)^2$$

Looking for: minimum

- Correlation coefficient

$$r_{BLM_{exp},BLM_{sim}} = \frac{\sum_{i=1}^{6} \left(BLM_i^{sim} - \overline{BLM}_{sim}\right)\left(BLM_i^{exp} - \overline{BLM}_{exp}\right)}{\sqrt{\sum_{i=1}^{6} \left(BLM_i^{sim} - \overline{BLM}_{sim}\right)^2 \sum_{i=1}^{6} \left(BLM_i^{exp} - \overline{BLM}_{exp}\right)^2}}$$

Looking for: maximum

(value the closest to 1)

STEADY STATE QUENCH TEST – SIMULATIONS

How to find the best correlation between simulations and experimental data?

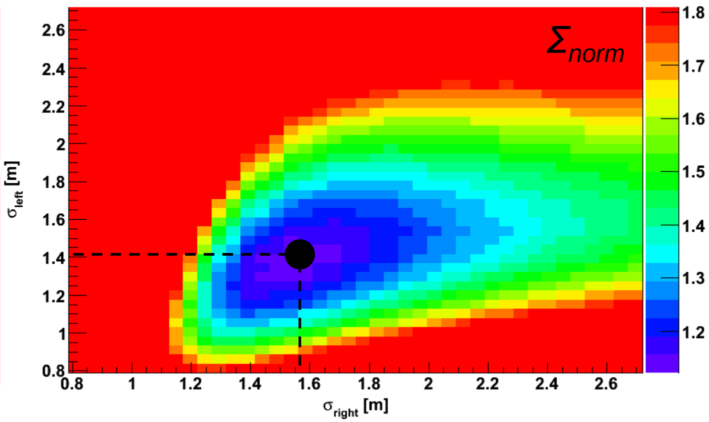
- Results based on Σ_{min} estimation

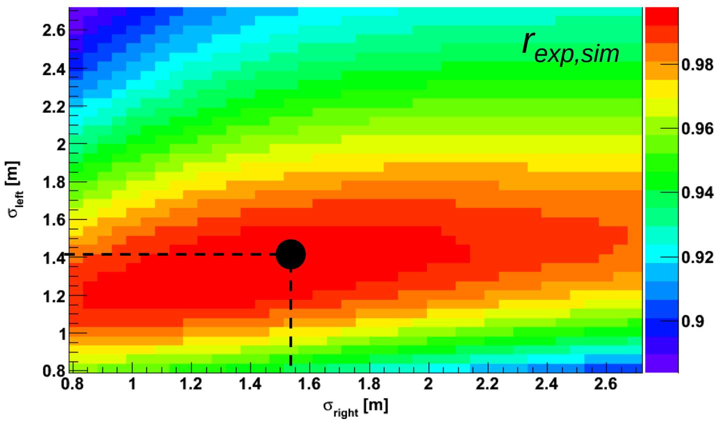
  - $\Sigma_{norm} = 1.12$
  - $r_{exp,sim} = 0.998$

  → $\mu = 0.4$ m

  → $\sigma_{right} = 1.54$ m

  → $\sigma_{left} = 1.4$ m





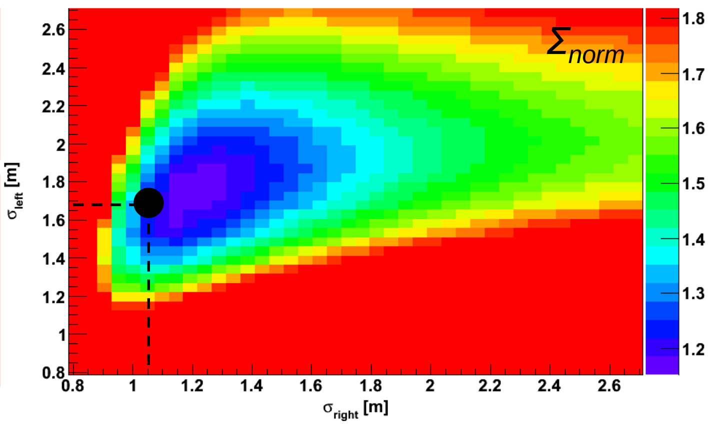
- Results based on $r_{exp,sim,max}$ estimation

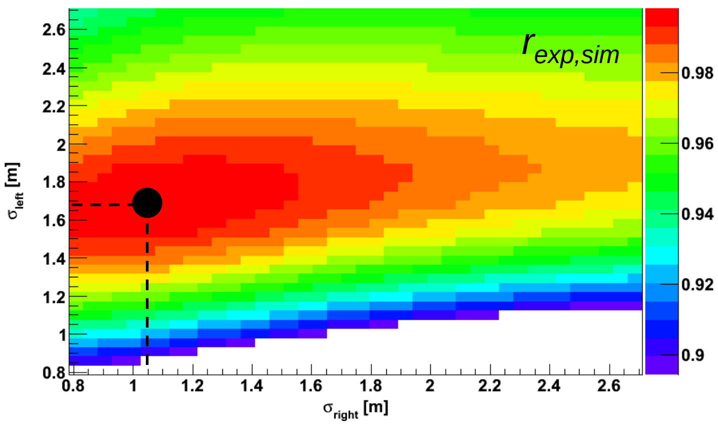
  - $\Sigma_{norm} = 1.22$
  - $r_{exp,sim} = 0.999$

  → $\mu = 0.9$ m

  → $\sigma_{right} = 1.05$ m

  → $\sigma_{left} = 1.68$ m



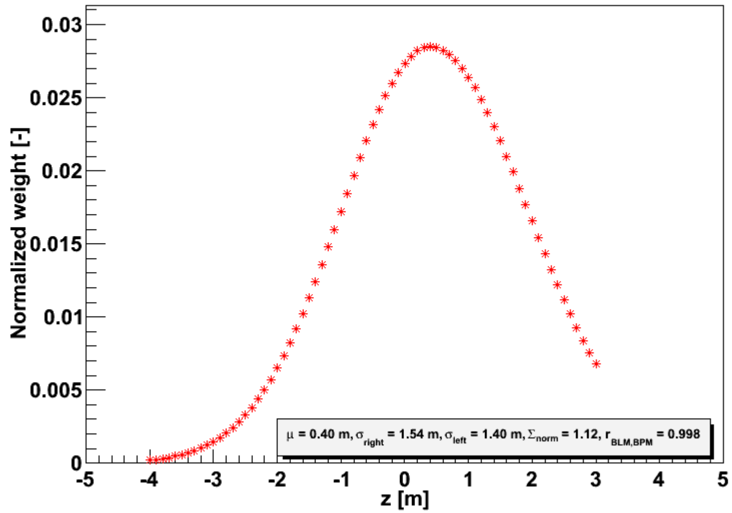


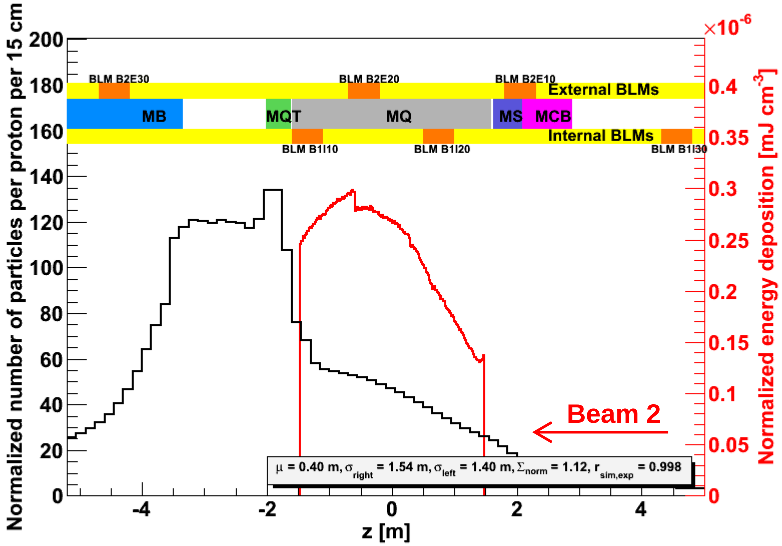
Both factors indicate that the loss occurred inside the MQ with

$\sigma_{right} = (1.3\pm0.4)$ m and $\sigma_{left} = (1.5\pm0.2)$ m

STEADY STATE QUENCH TEST – SIMULATIONS

Integrated loss pattern (no time evolution) over 6 s

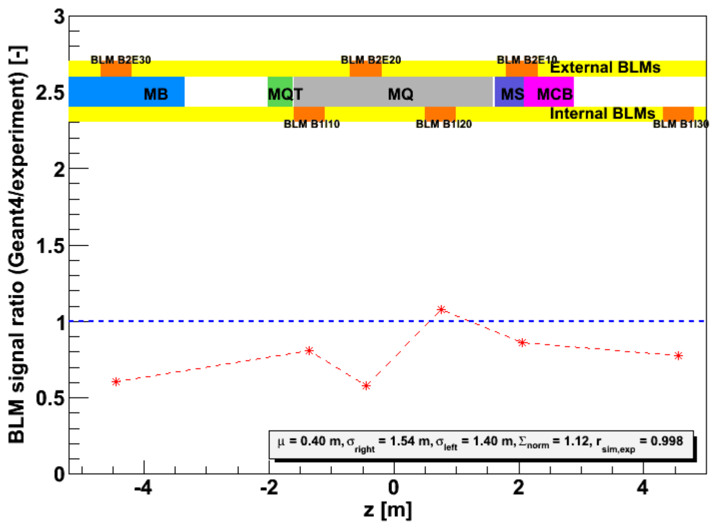




- Optimized three free parameters:

→ $\mu = 0.4$ m
→ $\sigma_{right} = 1.54$ m
→ $\sigma_{left} = 1.40$ m

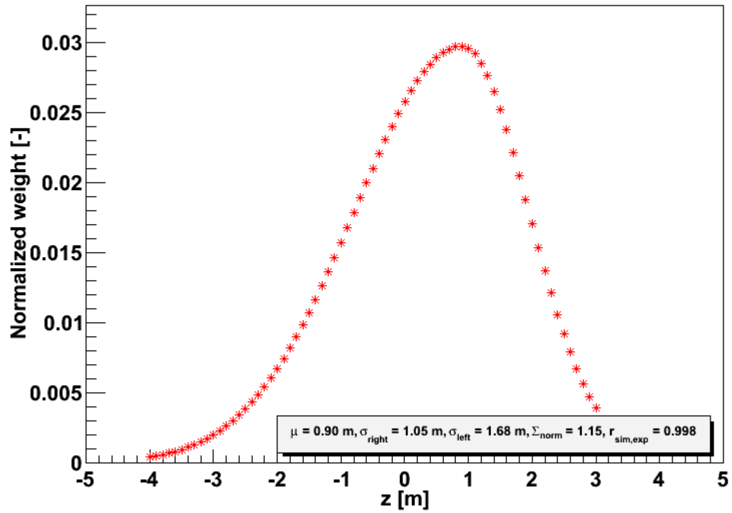
• $\Sigma_{norm} = 1.12$
• $r_{exp,sim} = 0.9978$

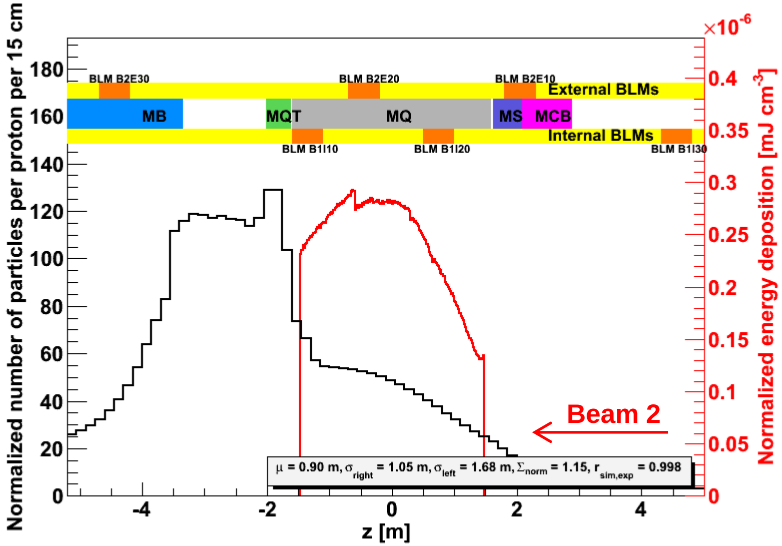


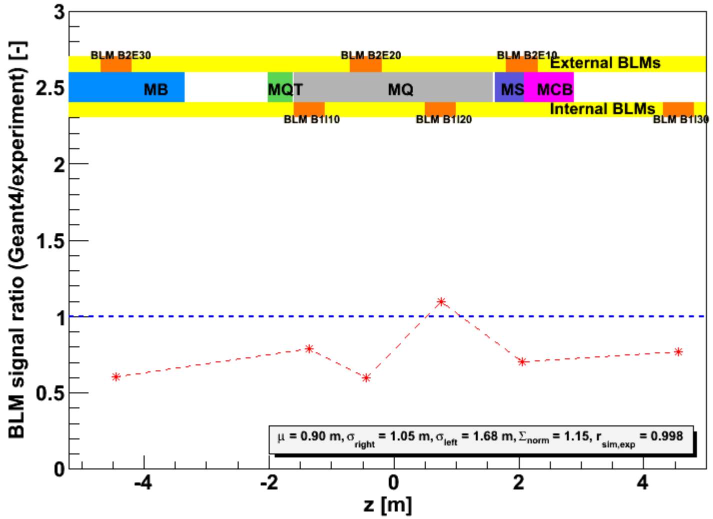
- Max of E_{dep} at the end of MQ
- The highest number of secondary particles in the interconnection region (MB-SSS)

Steady state quench test – simulations

Integrated loss pattern (no time evolution) over 6 s







- Optimized three free parameters:

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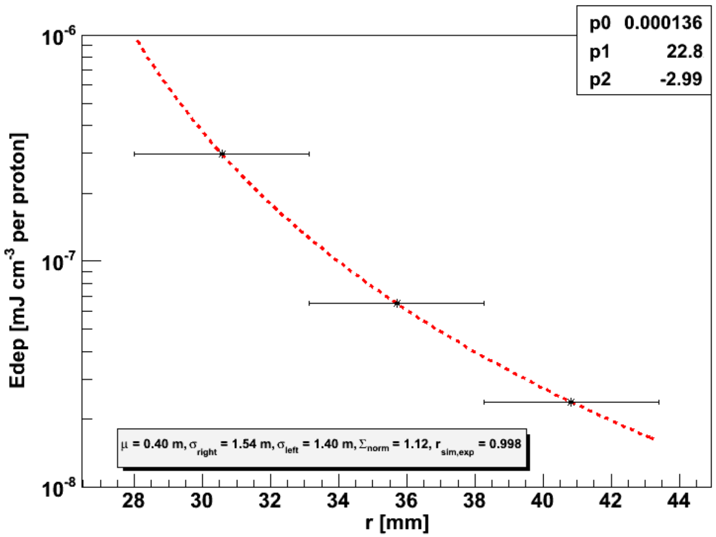
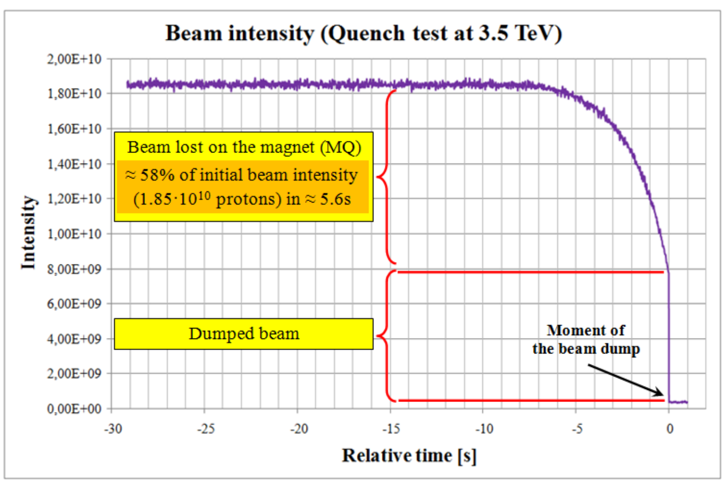
  - $\sigma_{right} = 1.05$ m
  - $\sigma_{left} = 1.68$ m

  - $\Sigma_{norm} = 1.22$
  - $r_{exp,sim} = 0.9985$

- Max of E_{dep} at the end of MQ
- The highest number of secondary particles in the interconnection region (MB-SSS)

Steady state quench test – Quench level





- Radial energy distribution and loss distribution in time are two main inputs to QP3 heat transfer code
- Power law function

$$E_{dep} = p_0\,(r - p_1)^{p_2}$$

r – radius of the coil

p_0, p_1, p_2 – fit parameters

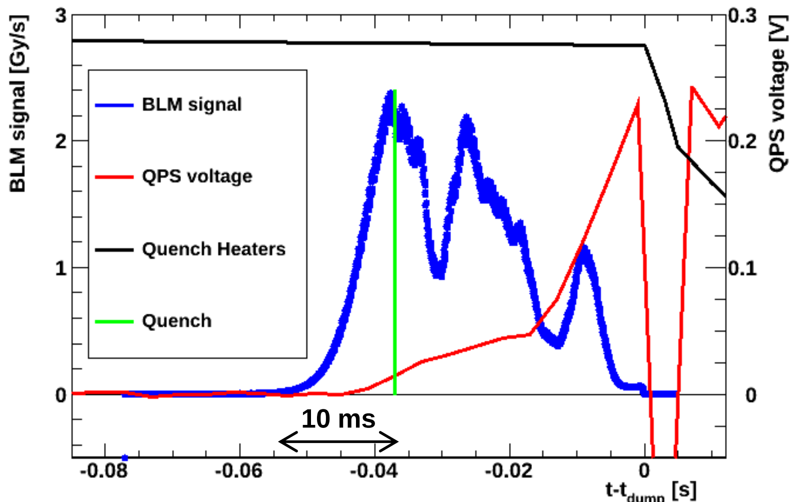
- The LHC MQ cables consist of two layers, each with 18 strands.
- Average energy needed to quench the magnet:

E_{avg} [J cm^{-3}]		
Geant4	QP3	Ratio
1.62	0.54	3

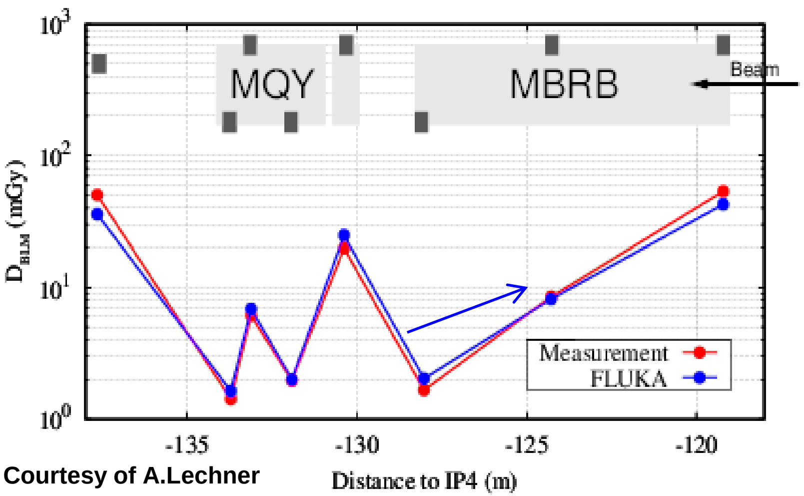
- This difference can be partly explained by the different meaning of quench limit for Geant4 and QP3.

FAST LOSSES QUENCH TEST PREPARATION

Wire Scanner Quench Test (1.11.2010)



M.Sapinski et al., "Quench Test Strategy WG - Introduction", QTSWG, 16.03.2012



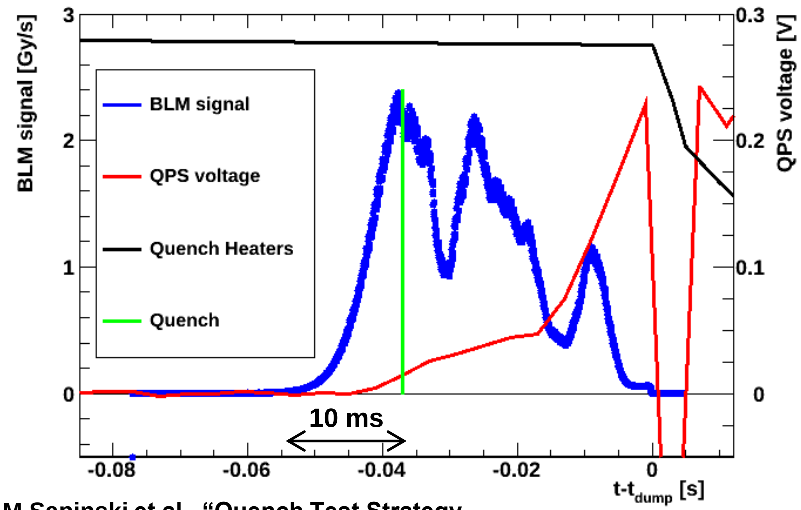
Courtesy of A.Lechner

- Quench on MBRB magnet after 10 ms
- Robust method (3.5 TeV)
- Good agreement between FLUKA simulations and experiment
- Method suspended
  - → MBRB operates at 4.5 K
  - → No good spare magnet in the case of damage

A new method needed for UFO-timescale losses studies

Fast losses quench test preparation

Wire Scanner Quench Test (1.11.2010)



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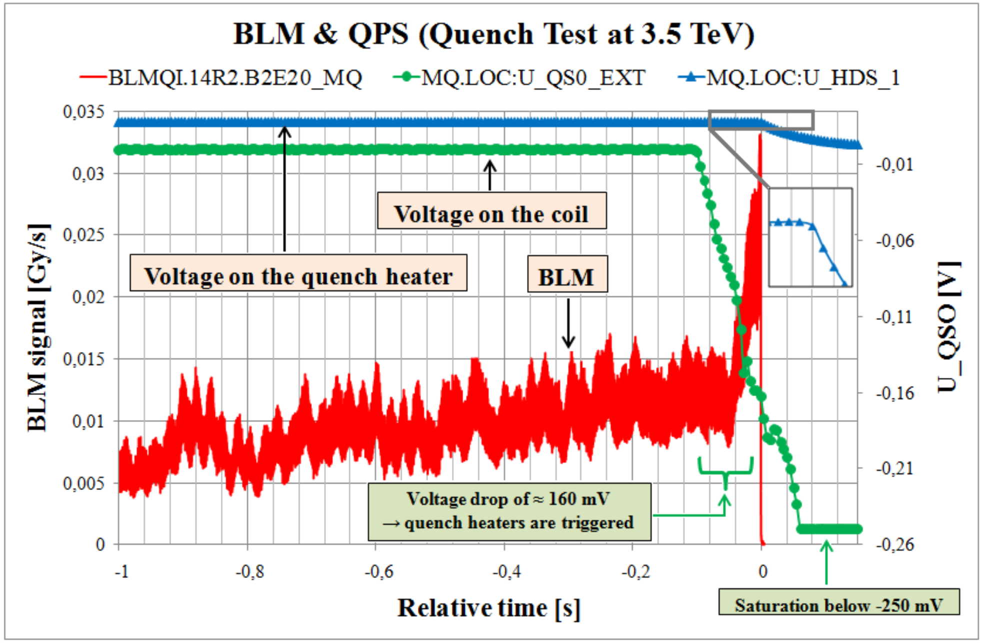
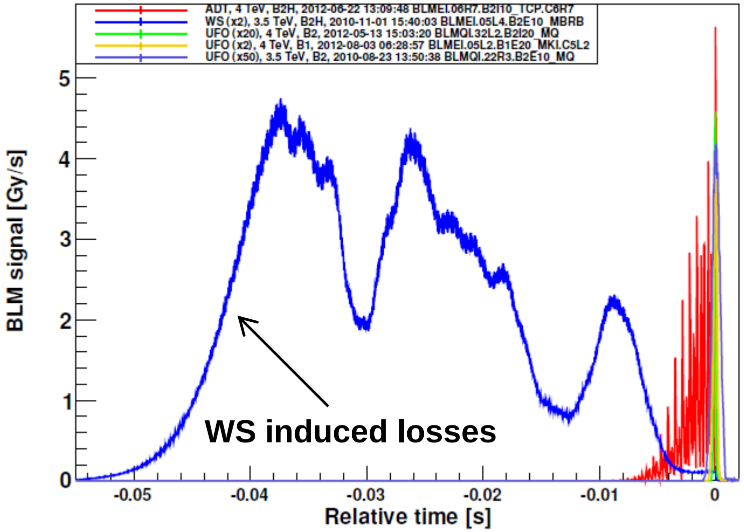
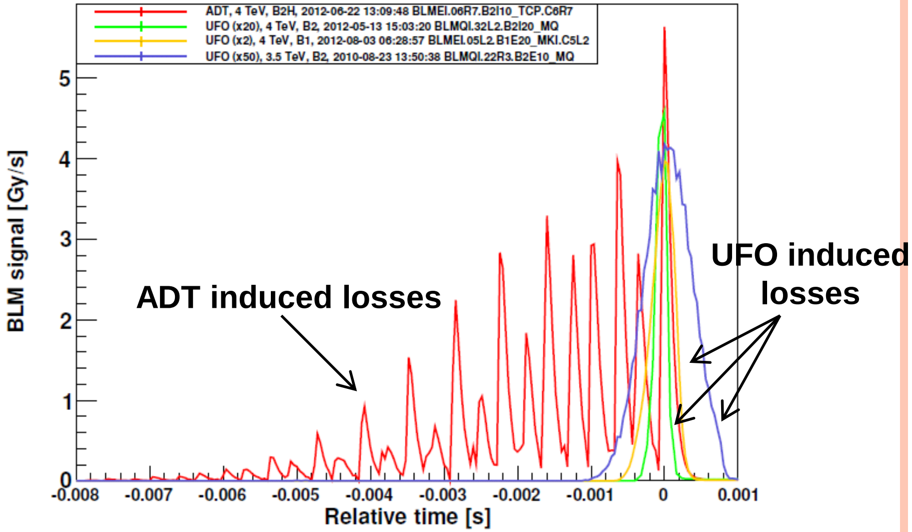


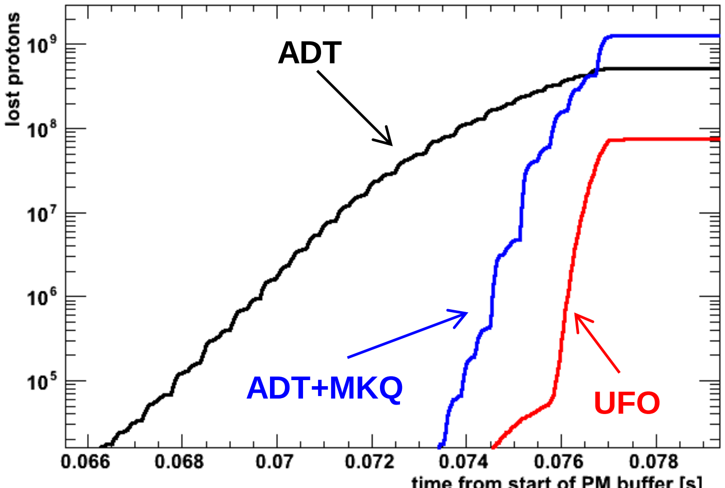
FAST LOSSES QUENCH TEST PREPARATION

ADT fast losses test (22.06.2012) results compared to Wire Scanner OT and UFOs





ADT +MKQ fast losses test (12.10.2012) results compared to ADT fast losses test and UFOs



M.Sapinski et al., "UFO timescale quench test preparation", LSWG, 26.10.2012

Conclusions

- The ADT sign flip method provides losses in the order of 7-8 ms
- A combination of the ADT with the MKQ (tune kicker) allows 3-ms loss induction