Workshop on Beam Induced Quenches, Sept. 15, 2014

# Setup of LHC Quench Experiments


**Mariusz Sapinski**

**on behalf of many contributing people from various CERN departments:**

**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, A. Priebe, S. Redaelli, B. Salvachua, R. Schmidt, N. Shetty, E .Skordis, M. Solfaroli, D. Valuch, A. Verweij, J. Wenninger, D. Wollman, M. Zerlauth and others.**

# Situation before the LHC startup

- Knowledge about beam-induced quenches summarized in **Note 44**
- Basic loss scenarios have been identified:
    - Orbit bump
    - Leakage from collimation system
- Basic Geant3 and Geant4 (**Note 422**)
- simulations have been performed
- FLUKA simulations in the triplet region was ongoing
- BLMs were divided into families and thresholds were set using existing knowledge and a lot of scientific guessing

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

*Large Hadron Collider Project* **LHC Project Report 44**

**QUENCH LEVELS AND TRANSIENT BEAM LOSSES IN LHC MAGNETS**

J.B. Jeanneret, D. Leroy, L. Oberli, T. Trenkler

**Abstract**

The last evaluation of quench levels related to transient beam losses was done in 1987 [1]. The subject is reevaluated with a more detailed approach of the thermodynamics of the superconducting cables in response to a transient heat load associated to beam losses.

LHC Project Note 422
July 15, 2009

**Energy deposition in LHC MB magnet and quench threshold test with beam.**

Bernd Dehning, Agnieszka Priebe, Mariusz Sapinski *
CERN CH-1211 Geneva 23, Switzerland

Keywords: superconducting magnets, quench prevention

Summary

In this study a particle shower development in the Main Dipole magnet due to the losses of the LHC beam particles is simulated with Geant4 Monte Carlo code. The signals observed in Beam Loss Monitors located outside the magnet cryostat are related to the energy deposited in the magnet coil. The beam abort thresholds in the Beam Loss Monitors corresponding to quench-provoking temperature increase of the magnet coil are determined. This thresholds depend on the beam energy, loss duration and the loss dimension. The results of the simulations are compared with the first and the second beam-induced quench of the Main Dipole.

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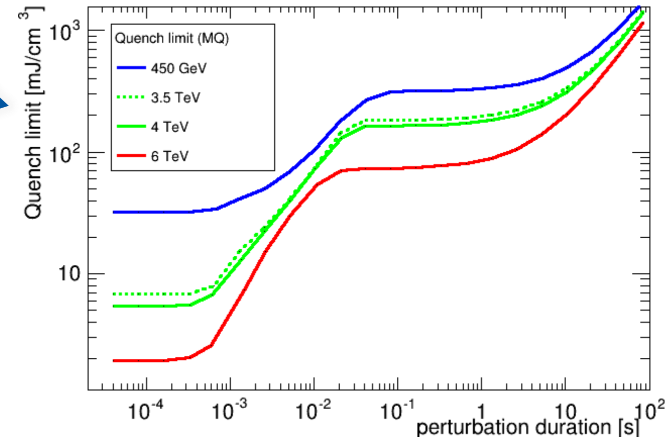



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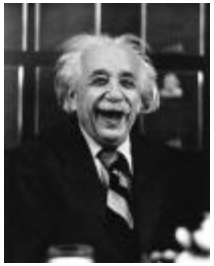
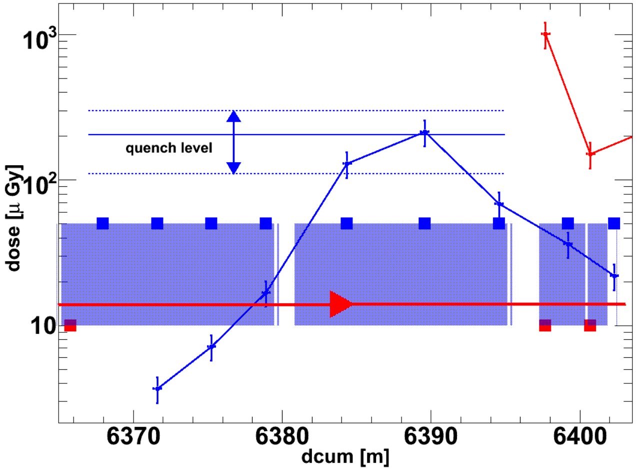
# The first beam-induced quench - 2008

On August 9th, 2008, during the aperture scan, the pilot bunch ($4 \cdot 10^9$ protons) accidentally hit a main dipole magnet.

This was the **first beam-induced quench.**

We were very happy because BLM signals were closer than factor 2 to what we expected at quench.





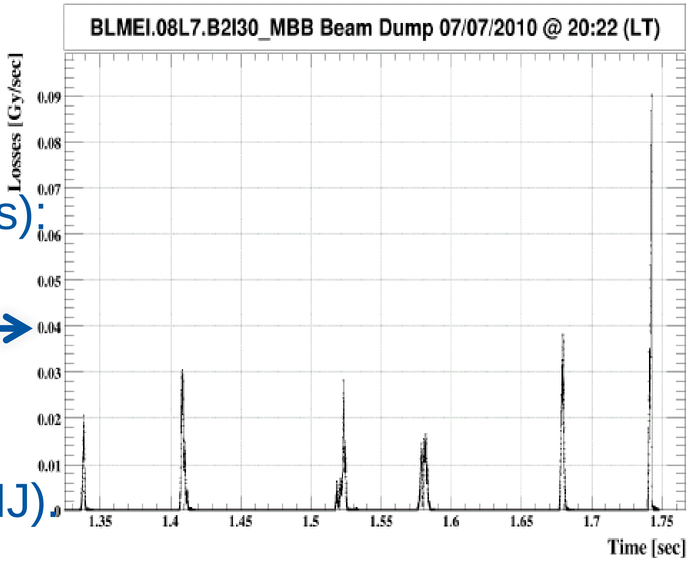

September 7th - another, similar quench. We call it **strong-kick event** because beam hit MB beam screen with angle 750 µrad. Such large impact angle allows for more precise simulations (see following presentations).
September 10th: beams circulating in LHC

Two other events like that (in 2009) confirmed that BLM are correct
**at injection energy and for ultra-fast losses!**

# The first quench test campaign - 2010

Very interesting year:

- March 20th: first collisions at 3.5 TeV (pilot bunches)
- In preparation to intensity ramp-up (bunch trains): many machine safety reviews
- July 7th: fist beam-dumping UFO →
- after external MPP review in September 6-8: a green light to going beyond 3 MJ of energy stored in beams (damage to equipment at ~1 MJ).

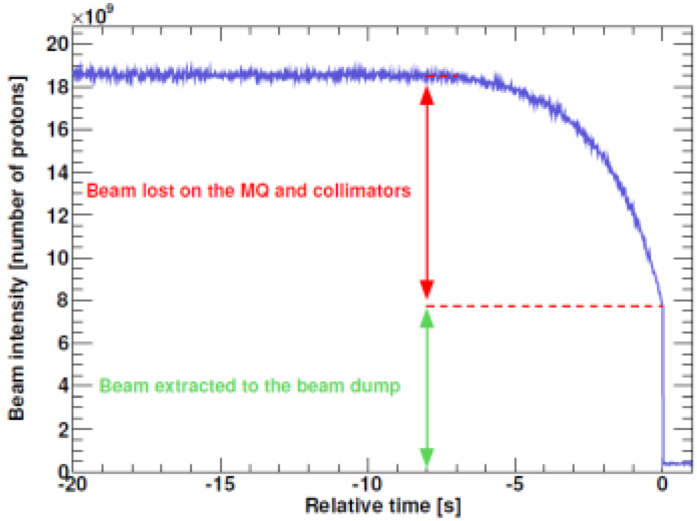



| | | | | |
|---|---|---|---|---|
| 25th October | 368 | 348 | 2.07e32 | |
| 16th October | 312 | 295 | 1.35e32 | 24 MJ |
| 14th October | 248 | 233 | 1e32 | |
| 8th October | 248 | 233 | 8.8e31 | 15 MJ |
| 4th October | 204 | 186 | 7e31 | |
| 29th September | 152 | 140 | 5e31 | |
| 25th September | 104 | 93 | 3.5e31 | |
| 23rd September | 56 | 47 | 2e31 | 3.5 MJ |
| 22nd September | 24 | 16 | 4.6e30 | |

**Clear need to verify BLM thresholds at UFO and steady-state timescales!**

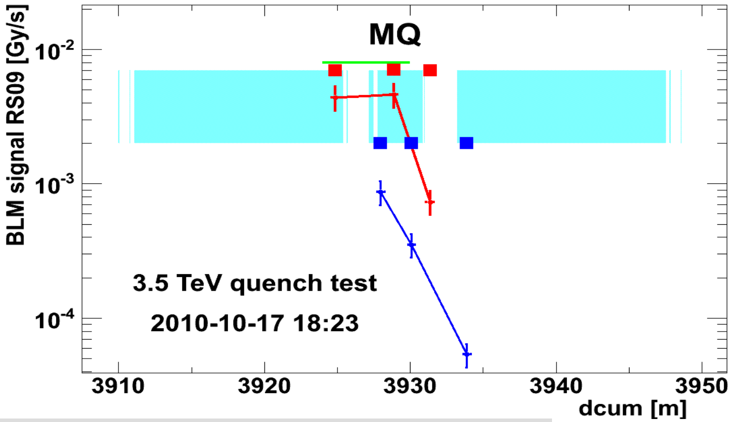
# The first quench test campaign – 2010
# Steady-state losses:

- Dynamic 3-corrector orbit bump technique
- Advantages:
  - Simple, no much prep needed
- Disadvantages:
  - Not-constant loss rate
  - Can target only quadrupole magnet
- 3 quenches at 450 GeV
  - Loss duration ~ 1s
- 1 quench at 3.5 TeV
  - Loss duration ~ 5s




__Consequence:__

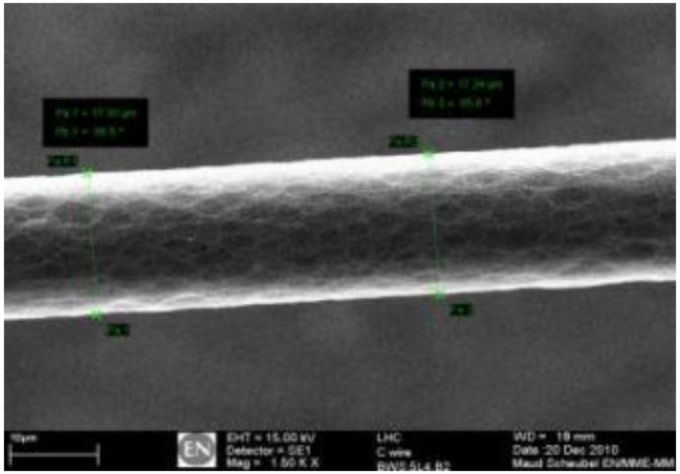
- **Correction of BLM thresholds for steady-state regime for the rest of Run 1**

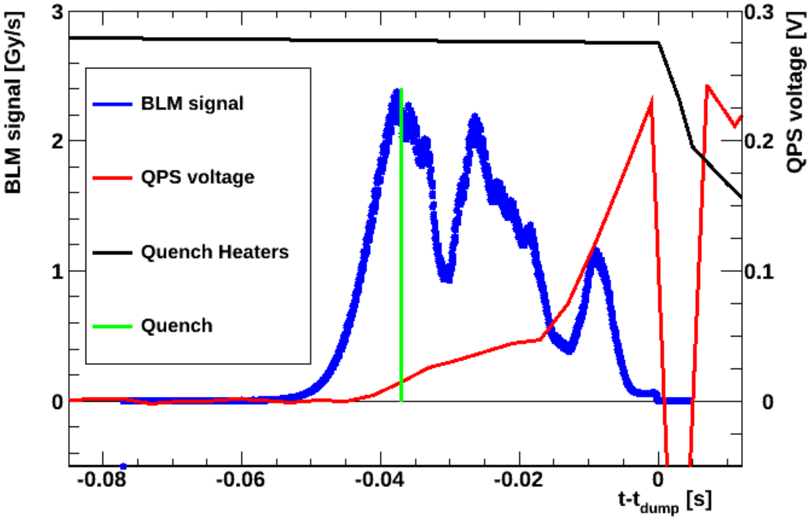



A. Priebe et al., IPAC11 and IEEE Trans. on Appl. Supercond, Vol: PP, Issue: 99

# The first quench test campaign – 2010 millisecond timescale losses:

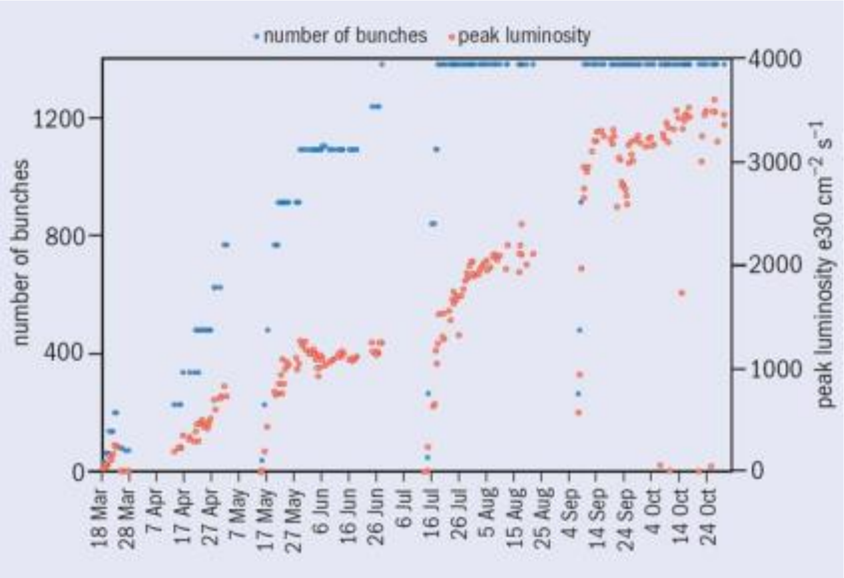
- Loss generated by a wire scan
- Advantages:
  - Simple, not much prep needed,
  - obtained temporal profile should correspond to UFO loss profile (gaussian)
- Disadvantages:
  - Can target only one magnet – recombination dipole D4
  - Magnet is 4.5 K (not representative), there is no functional spare magnet
  - Can damage the wire scanner.






M. Sapinski et al., IPAC11

# Tests in 2011




<u>Situation:</u>

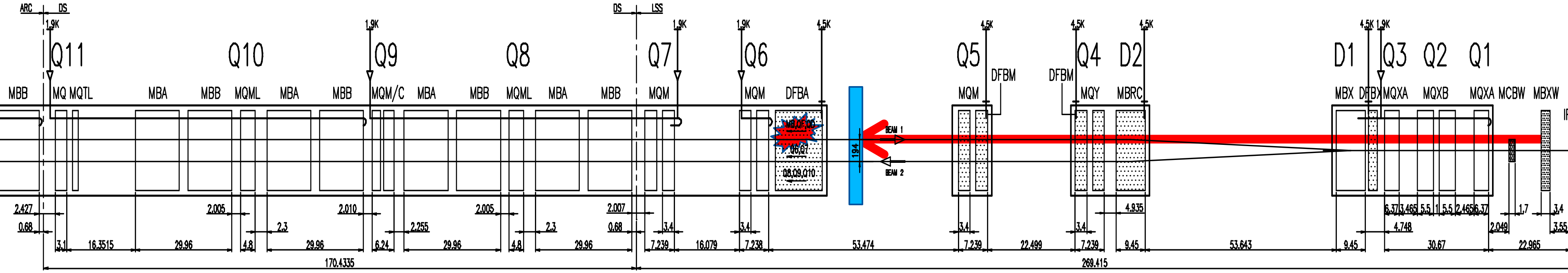
- Beam energy: 3.5 TeV
- Intensity ramp from 368 to 1380 bnches
- Time to address the machine performance limits: quench limit in case of distributed steady-state losses: collimation cleaning and luminosity – important for Phase 2 of collimation system.
  - Steady-state collimation quench tests
- Investigating potential consequences of asynchronous dump:
  - In July: 1$^{st}$ ultra-fast collimation quench test for estimation of magnet quenches in case of asynchronous beam dump

# Tests in 2011
# Steady-state collimation tests:

- Method: crossing 3rd order resonance with enough beam to generate quench-provoking losses, starting on collimators
- Protons in May:
  - In 3rd attempt reached 510 kW loss on primary collimators
  - Loss duration ~1s
  - No quench
- Pb ions in December:
  - 4 attempts, high loss every time in different location leading to premature beam dumps
  - Losses significantly shorter than for protons - unexplained
  - No quench

# Tests in 2011
# Fast collimation quench test:

- Method: shooting on closed collimator quenching the magnet behind

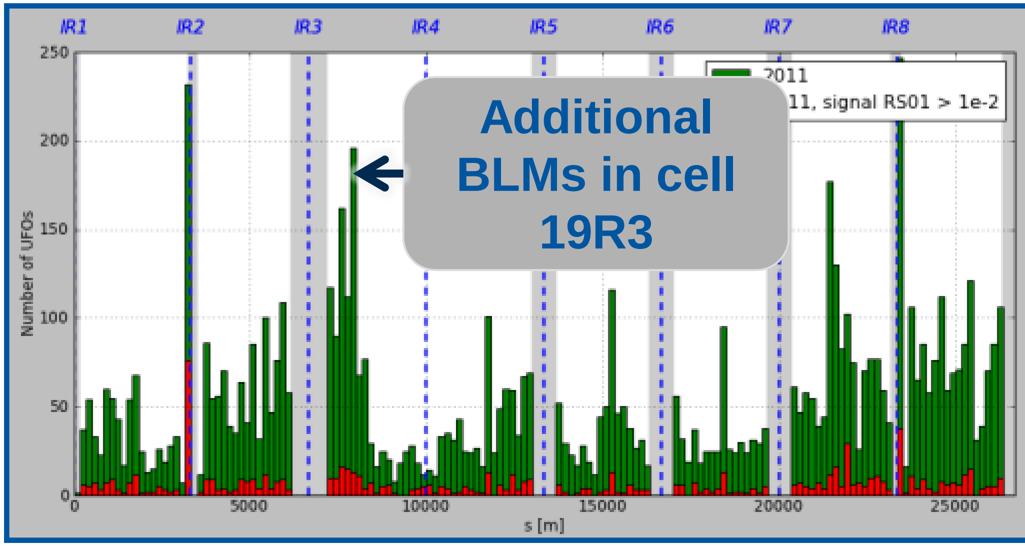



- Observation of QPS signal with a scope
- Quench not observed at expected value
- Stopping the test for further analysis before proceeding with current increase

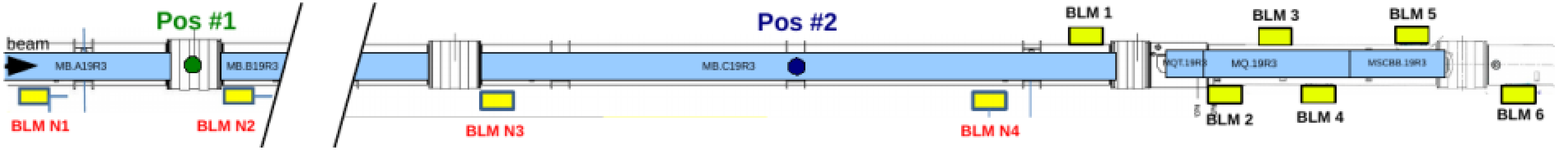
C. Bracco et al., IPAC12

# UFO fishing

- It is difficult to reproduce UFO in controlled experimental conditions
- But they happen by themselves, so:
  - Install additional instrumentation in a zone with high UFO activity
  - Wait for quench to happen.
- One arc cell chosen
- 4 additional BLMs installed
- No quench observed but




- Measurement and observations → reconfiguration of BLM system for Run2



# End of Run Quench Test campaign - 2013

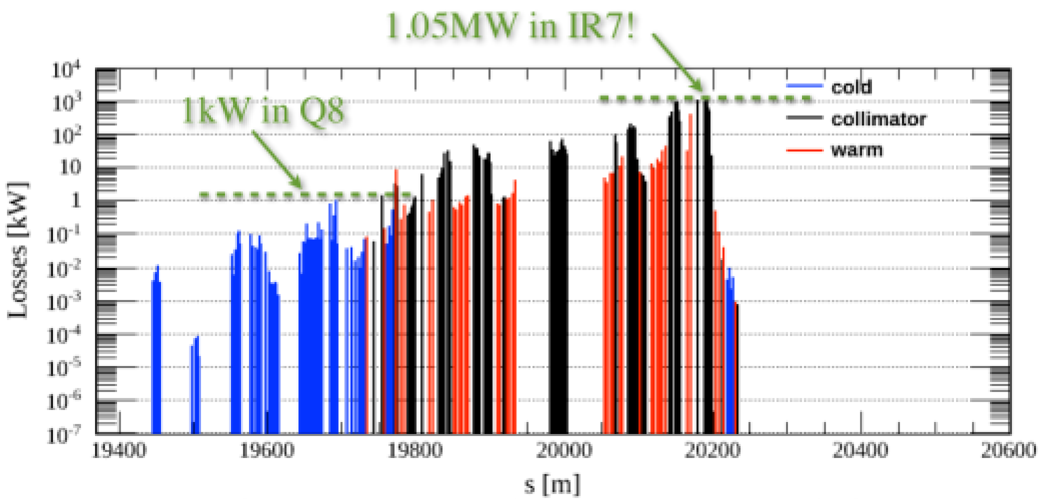

Situation:

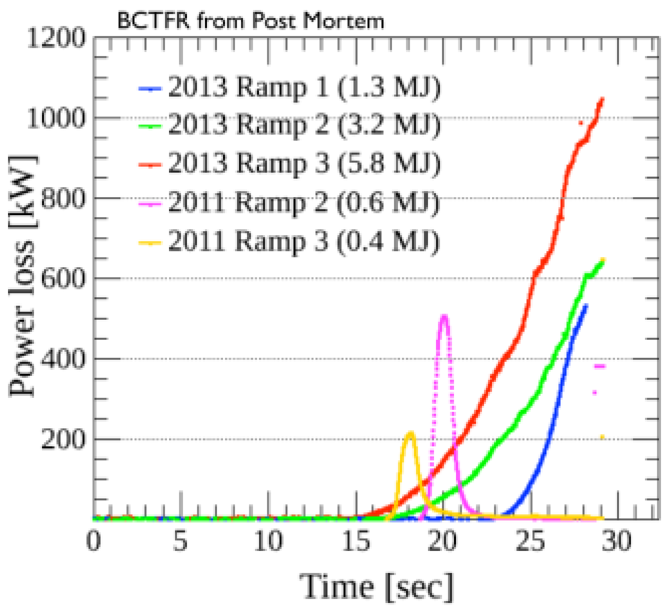
- Physics run finished, particle fever dropped
- Almost 2 year shutdown in perspective, but
- Unexplored beam parameters after: 360 MJ, 25 ns, 7 TeV
- **UFO and intensity/luminosity reach of the machine remain uncertain**
- New tool – transverse damper – commissioned and operational - better control of beam losses then ever before
- **48 hour period at the end of the Run dedicated to 4 quench tests**
- Preceded by **one year** of studies, tests, discussion (Quench Test Strategy Working Group)
- And it took **more than one year to analyze** the results! (Quench Test Analysis Working Group)

# End of Run Quench Test campaign – 2013
# Steady-state collimation

After careful analysis of experience from 2011:

- Increase the power loss on the primary collimators to 1 MW.
- Use transverse damper to make losses longer.
- Use very relaxed collimator settings to allow more energy leak to cold magnets.

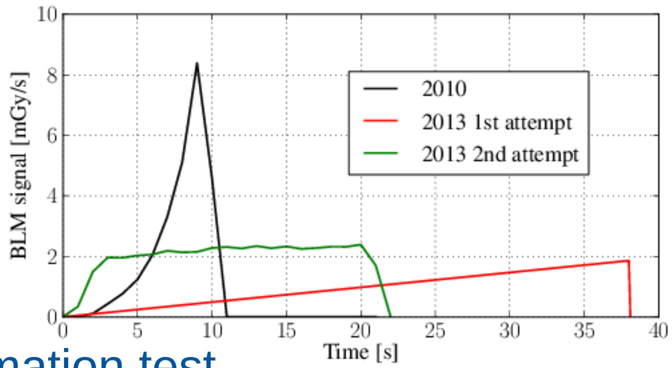


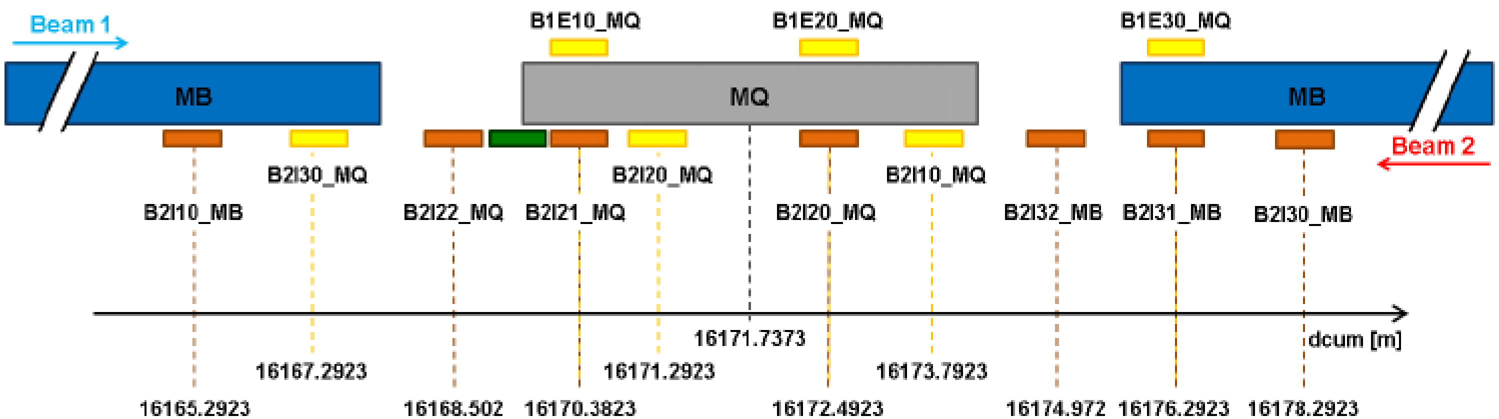

- No quench!
- Enormous FLUKA geometry for energy deposition analysis

B. Salvachua, IPAC14

# End of Run Quench Test campaign – 2013
# Steady-state orbit bump



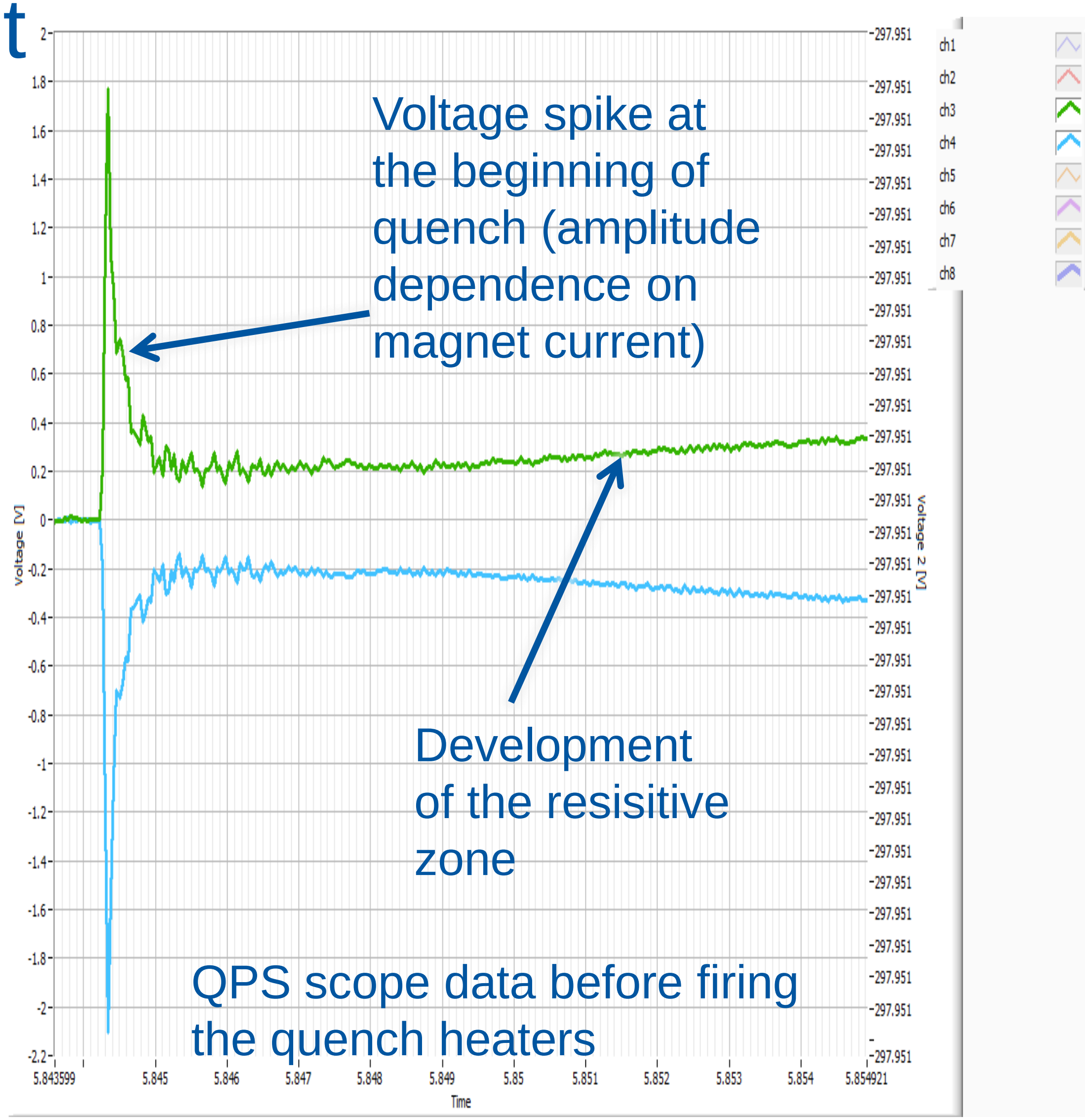

- Development of the idea of 2010 test
- Use transverse damper
- Install additional BLMs
- Localized steady-state loss is unlikely scenario
- But it could be expected that it gives more precise quench level estimation than collimation test
- Quench after ~20s of quite steady loss!
- Shows power of ADT as a tool, but also effect of preceding tail scrapping




V. Chetvertkova et al., IPAC14
N. Shetty et a. IPAC14

# End of Run Quench Test campaign – 2013
# Fast collimation test

- Repetition of 2011 test
- Going to higher magnet currents
- Quench at magnet current of 2500 A what corresponds to beam energy of 6 TeV

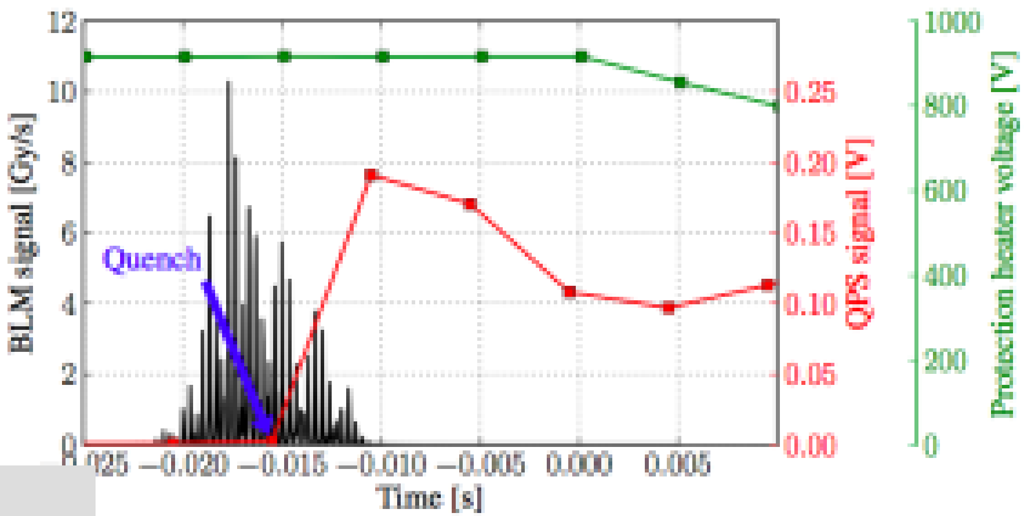



C. Bracco et al., IPAC14

# End of Run Quench Test campaign – 2013 Millisecond timescale test

New idea: use transverse damper to excite the beam oscillations.

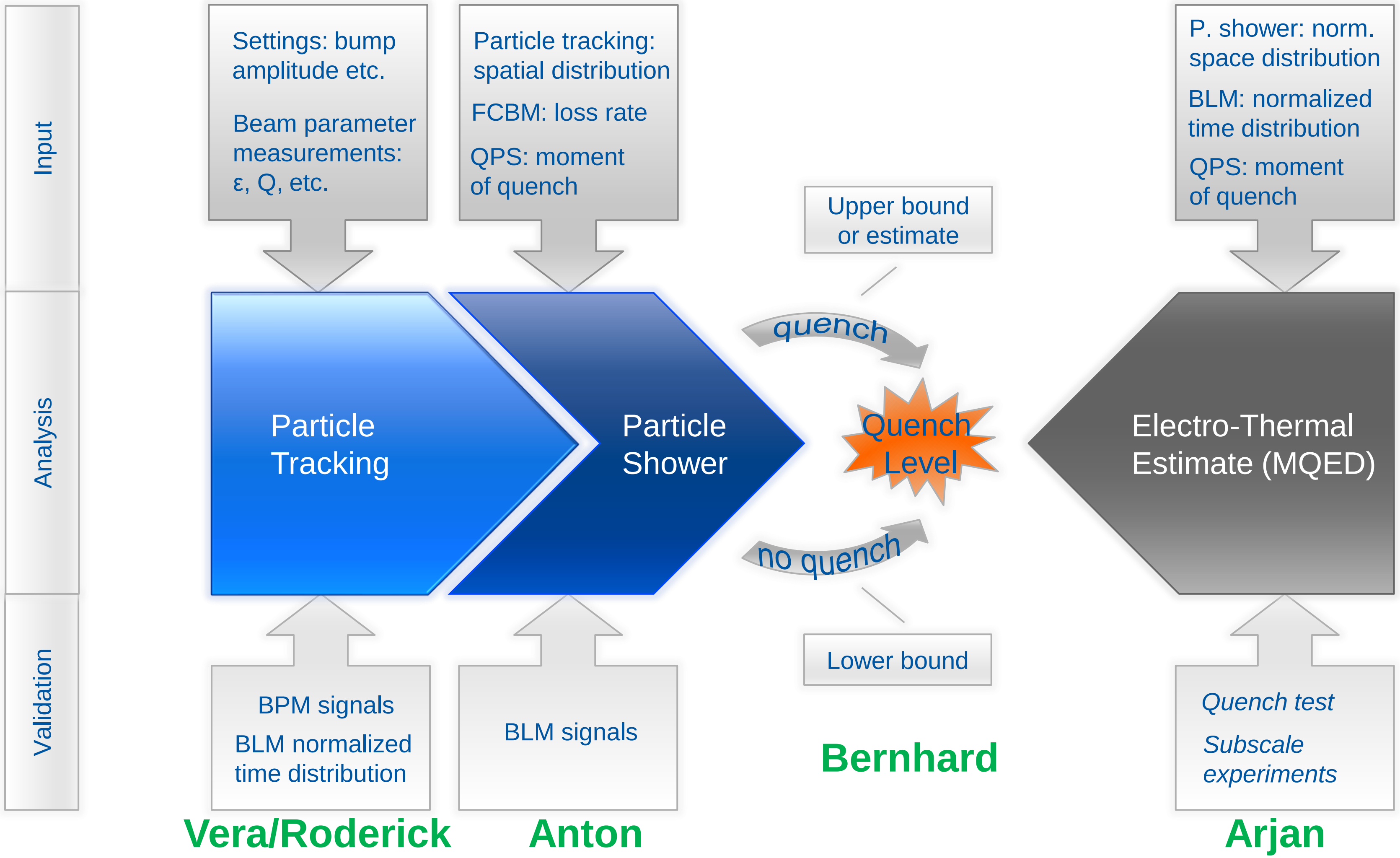
- It took 4 tests in 2012 to optimize this method
- Advantages:
  - Can aim any quadrupole
- Disadvantages:
  - Cannot aim dipole
  - Spiky loss structure
  - Duration ~10 ms (UFO < 10 ms)


V. Chetvertkova et al., IPAC14
N. Shetty et a. IPAC14

# Quench Test Analysis

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



# Conclusions

1. For ultra-fast losses two techniques are in the pocket: smashing the injected beam on a collimator or directly on the magnet.
2. For UFO-timescale losses (0.1 ms-10 ms) none of the proposed schemes is fully satisfactory.
3. Steady-state – two complementary techniques proposed, results quite satisfactory.
4. There are many experimental schemes, from simple to very challenging ones including multiple magnets, excitation devices etc.
   (and we have not explored all schemes yet – ideas are welcome for Run 2)
5. Transverse damper proven to be a very helpful tool.
6. Analysis of quench tests is very complex, includes:
   - particle tracking (see Vera's presentation)
   - particle shower simulations (see Anton's presentation)
   - Electro-thermal simulations (see Bernhard's presentation)
7. It takes a lot of time but you discover interesting things not always directly related to quench levels.
8. Next presentations will address the three main aspects of beam-induced quench tests.

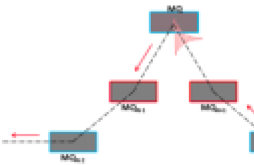
# Extra slides

# UFO Time-Scale Losses

- 2010:
  Wire-scanner quench test on D4 magnet
    - *D4 (@4.5 K) quenched.*
    - *Uncertainties due to timing and loss maximum in coil ends.*
- 2013 End-of-Run QT Campaign:
  ADT quench test
    - *MQ quenched.*
    - *Large uncertainty on moment of quench.*
    - *Large uncertainties in electro-thermal model.*
    - *Best approximation of UFO-type losses in 1.9 K magnets.*

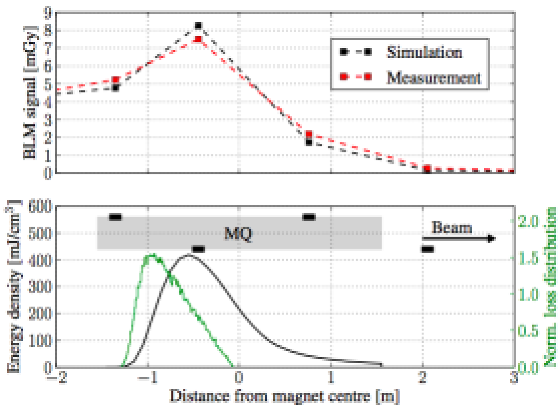
TABLE III. Comparison of FLUKA lower bound (LB) and estimate on the electro-thermal MQED estimate in the MBRB coil.

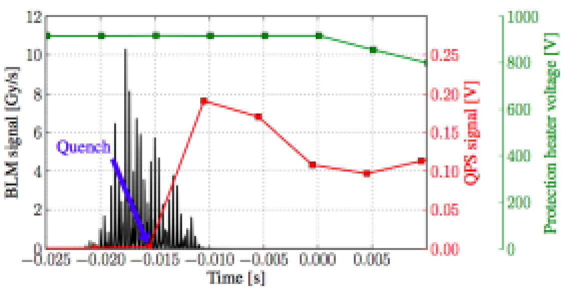
| $v_w$ [m/s] | $N_q/N_w$ [%] | FLUKA LB [mJ/cm³] | FLUKA [mJ/cm³] | MQED [mJ/cm³] |
|---|---|---|---|---|
| 0.15 | n/a | 18 | n/a | $37^{+0}_{-11}$ |
| 0.05 | 30 | n/a | 20 | $35^{+0}_{-11}$ |
| 0.05 | 45 | n/a | 30 | $42^{+0}_{-16}$ |




- MKQ kick
- Exciting the bunch with the ADT sign flip mode
- Three corrector orbit bump

| $N_p$ | $N_q/N_p$ [%] | FLUKA LB [mJ/cm³] | FLUKA [mJ/cm³] | MQED [mJ/cm³] |
|---|---|---|---|---|
| $3.5\times10^8$ | n/a | 198 | n/a | $71^{+?}_{-10}$ |
| $8.2\times10^8$ | 62 | n/a | 250 | $58^{+?}_{-8}$ |
| $8.2\times10^8$ | 99 | n/a | 405 | $80^{+?}_{-10}$ |

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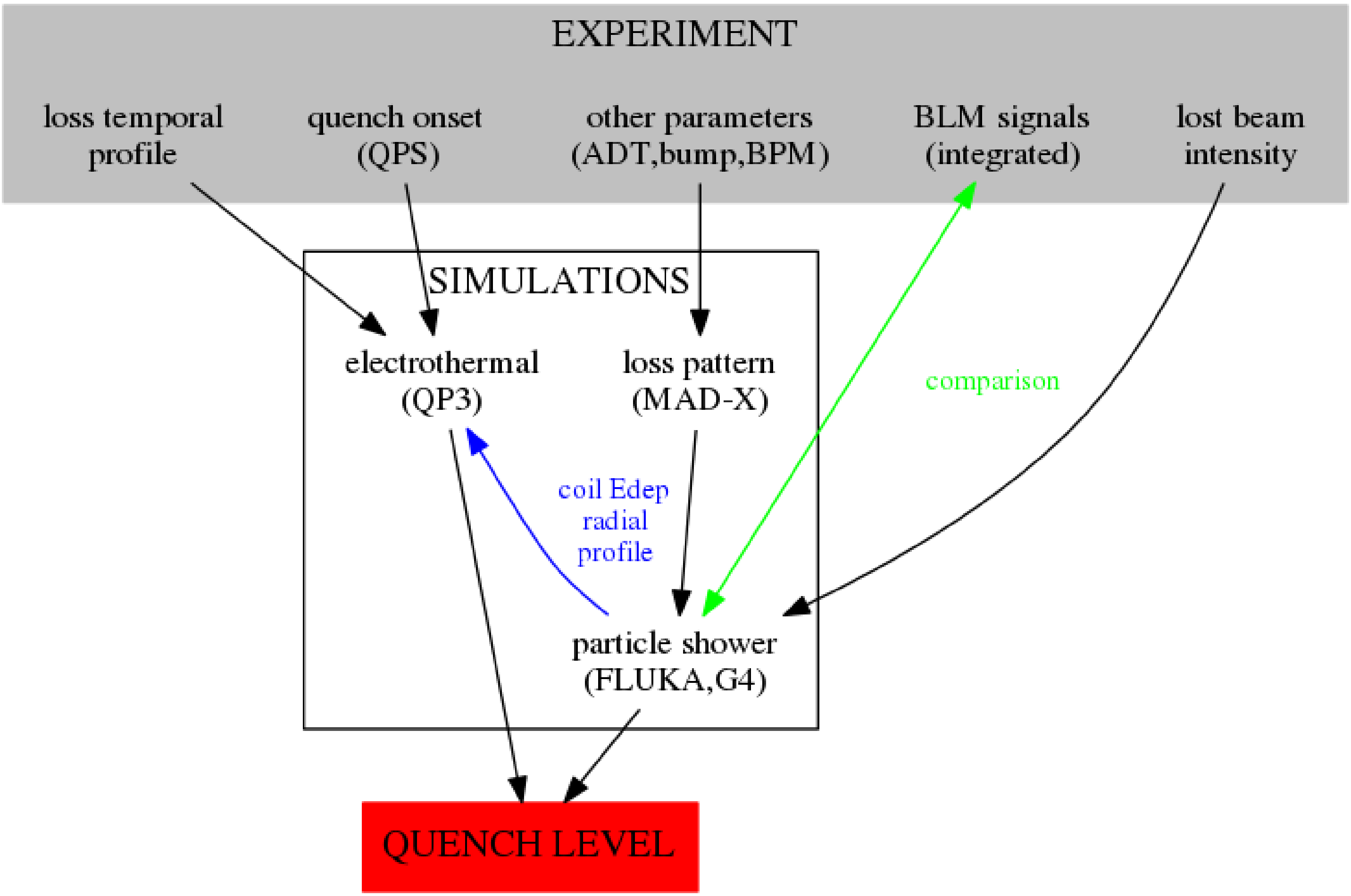
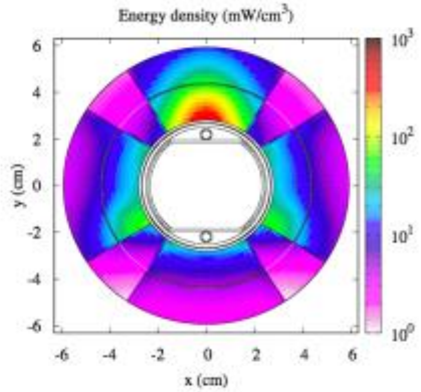
# Literature

1. A. Priebe, Phd
2. Conference papers
3. MD notes
4. Paper in preparation

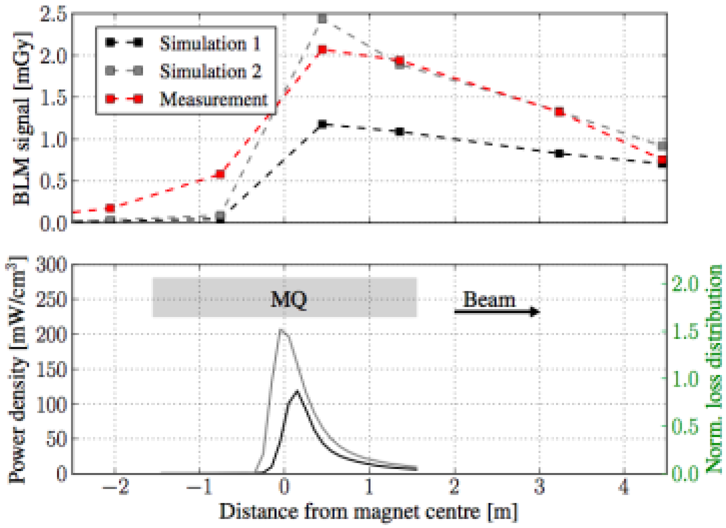
# Alternative analysis diagram



# Steady-State Losses




- 2010 Dynamic orbit bump quench tests at injection and 3.5 TeV
  - *Quenches in MQ at 450 GeV and 3.5 TeV.*
  - *Analysis results will be used to se low-energy arc and DS thresholds.*
  - *Documentation:*
    - A. Priebe, et al., Beam-induced Quench Test of a LHC Main Quadrupole, IPAC 2011.
    - A. Priebe, et al., Investigation of Quench Limits of the LHC Superconducting Magnets, IEEE Trans. On Appl. SC, Vol 23, No 3, June 2013.
    - A. Priebe, CERN-THESIS-2014-013.
    - PRSTAB paper to be submitted in autumn 2014.
- Collimation quench tests (see Collimation talk)
  - *No quenches occurred!*
- 2013 End-of-Run QT Campaign
  ADT quench test
  - *MQ quenched after 20 s of steady losses.*
  - *FLUKA/BLM discrepancy.*
  - *Modest (30 µm) step*
    *in surface roughness could produce a*
    *better fit to BLM data.*
  - *No full validation of electro-thermal model.*

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