HB2014

East Lansing, MI
10-14 November 2014

54th ICFA
Advanced Beam Dynamics
Workshop on High-Intensity,
High Brightness and
High Power Hadron Beams

Beam loss mechanism, measurements and simulations at the LHC (quench tests)

Mariusz Sapinski, CERN BE/BI
for many people participating in quench tests

CERN

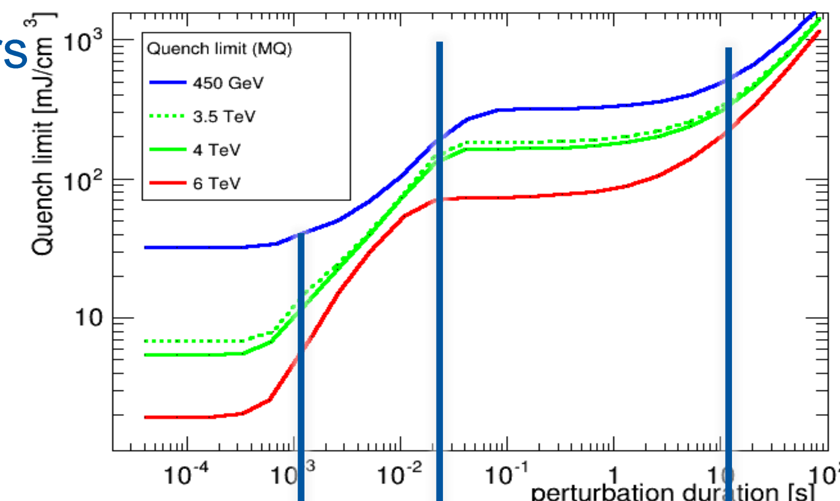
Outline

- Beam Losses in LHC
- Beam loss measurement techniques
- Quench experiments:
  - Methodology: tracking, particle-shower and electro-thermal simulations
  - History
  - Steady-state collimation quench test
  - Orbit bump quench test in millisecond timescale
- Conclusions

Beam losses in LHC

- Normal losses: luminosity, **collimation**, instabilities during ramp, squeeze, collision processes.
- Normal losses increase by 10x in 2012 due to smaller β* and tight collimators
- Abnormal losses: failure of machine components, Unidentified Falling Objects **(UFO)** losses.
- Categorize losses for their duration:

Cycle phase	% of lost intensity (aver/max)
capture	0.5 / 2%
ramp	1.2 / 15%
squeeze +adjust	1.7 / 10%



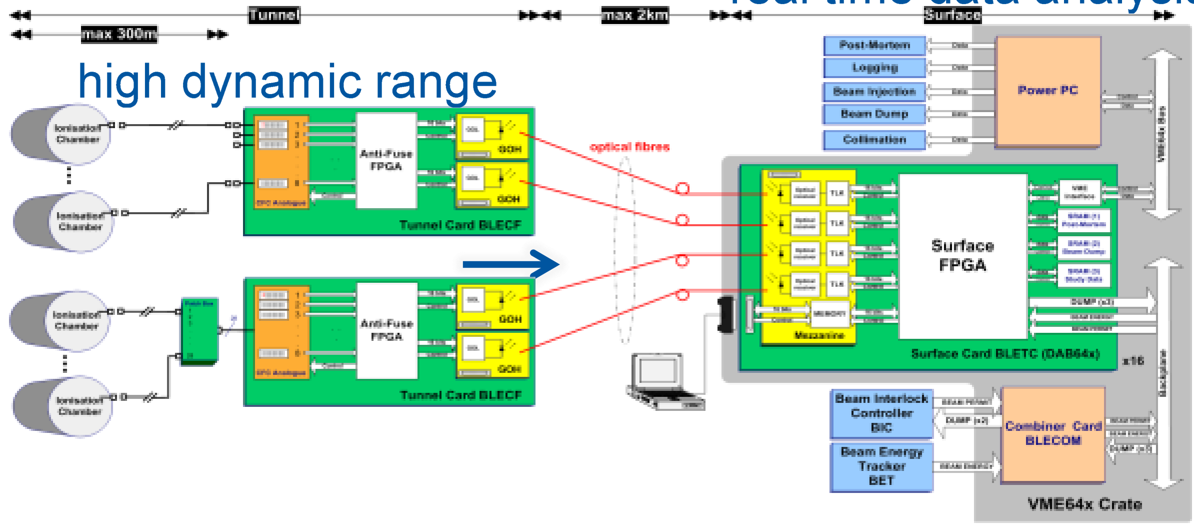
failures:	inj/dump	UFO	RF, quench	cryo, fb
protection:	collimation	BLM	many syst.	+OP
quench level	dry ΔH	LHe	LHe satur.	steady

Measurement techniques

- Standard system, temporal resolution ~ 40 µs

real time data analysis

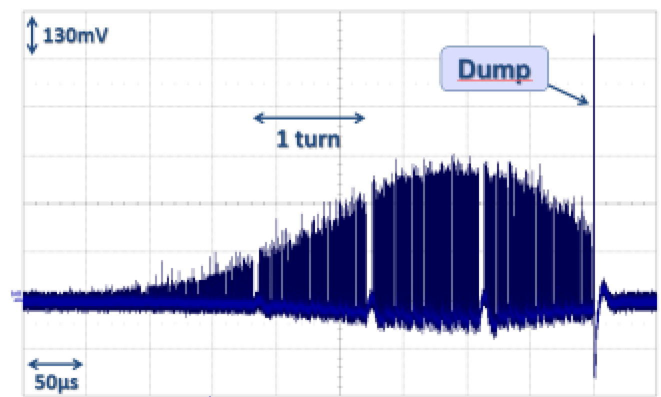
high dynamic range



- For bunch-by-bunch measurements:

  diamond detectors read by oscilloscopes

  bunch structure of the beam



Diamond BLM in IR7

Measurement techniques

Energy deposition in the coil

measurement

is more precise

when detectors are closer to

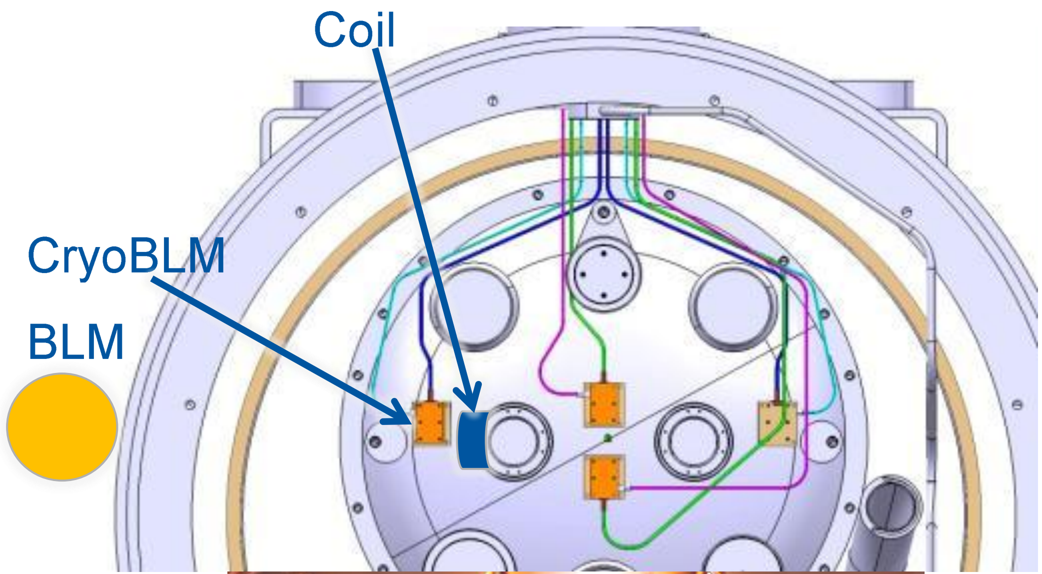
coil and particle shower core:

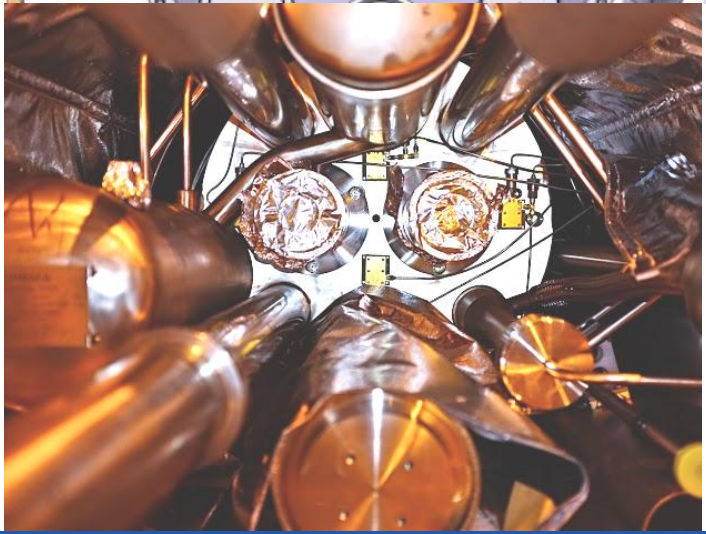
Cryogenic BLMs:

- semiconductor detectors (size!)
- radiation hardness in 2 K

  (irradiation experiment)
- pilot installation on two of LHC

  dipoles





Beam Loss experiments

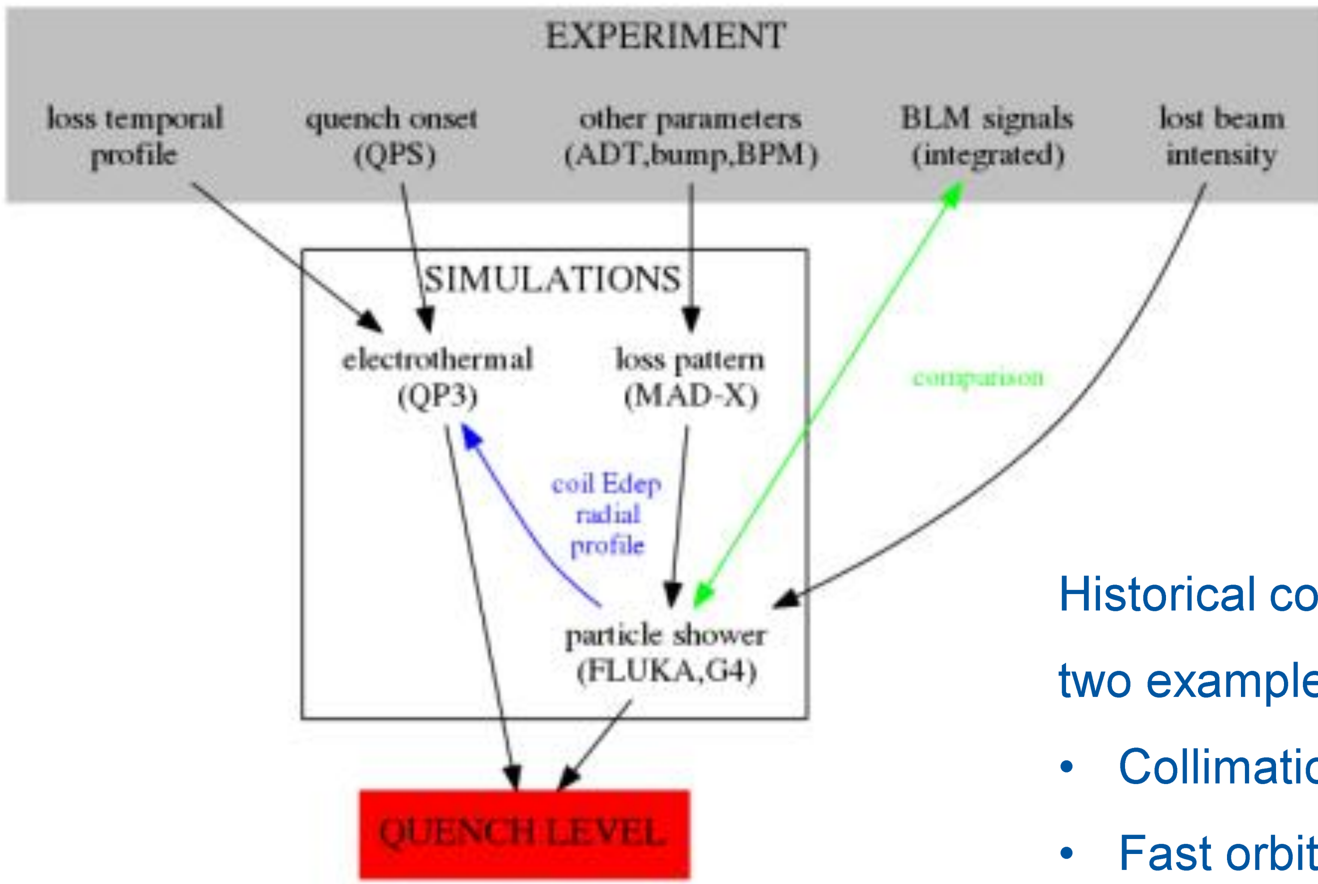
- Beam stability measurements
- Aperture checks
- Collimation setup (now also collimator BPMs)
- Calibration of the radiation detectors
- …
- **Quench tests**

Quench tests are probably most complex beam-loss experiments, their goals:

- **determination of quench-preventing BLM beam-abort thresholds**
- **determination of beam-induced (realistic) quench levels**

Quench tests scheme

- Carefully designed experiments
- Complex analysis scheme
- **17 quench tests during Run 1**
- Analysis Working Group (> 2 years)

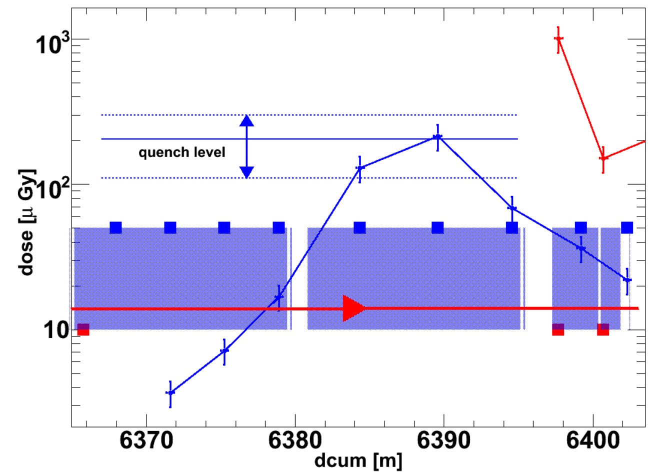


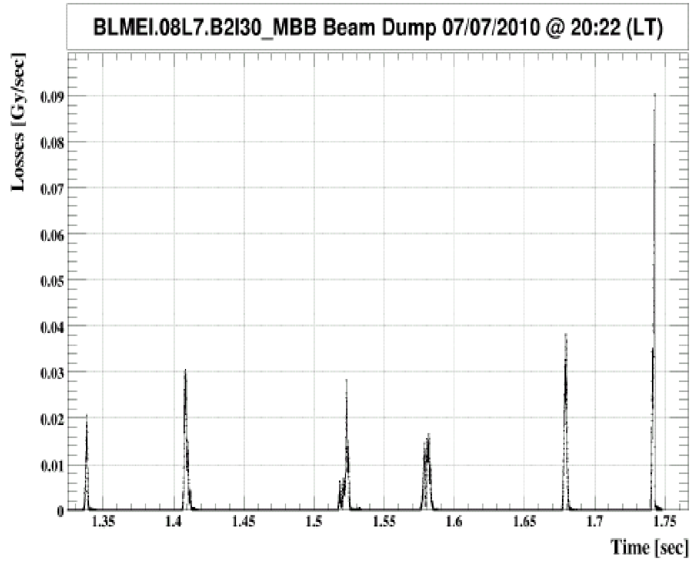
Historical context and two examples:

- Collimation test
- Fast orbit bump test

Historical context

- 2008: Aug 9th, first beam-induced quench during beam commissioning (fast events)
- 2010: LHC intensity ramp-up, safety reviews:
    - July 7th: fist beam-dumping UFO
    - September: Ebeam > 3 MJ
    - October: 1st quench test campaign:
        - local steady state and UFO losses
        - Result: correction of BLM thresholds
- 2011: first global collimation test
- 2012: physics production year
- 2013: 2nd quench test campaign: 48 hours, 4 advanced experiments





Steady-state collimation quench test

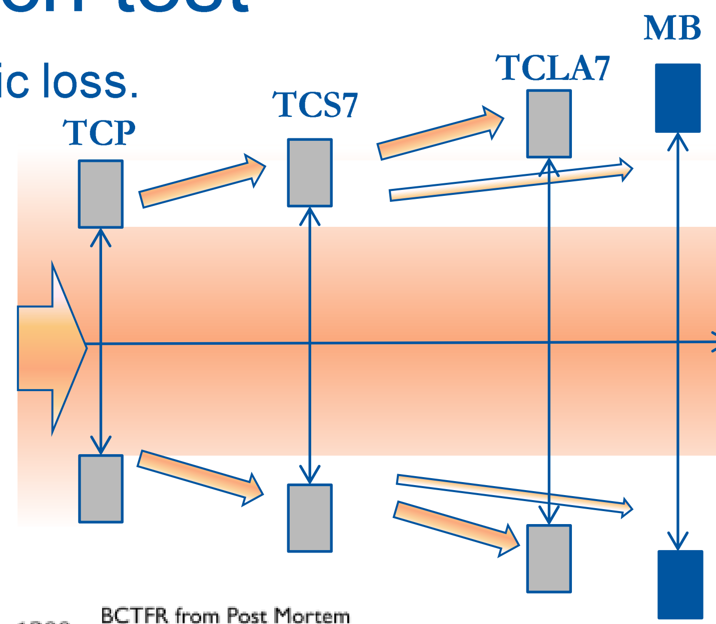
Goal: measure steady-state quench level for realistic loss.

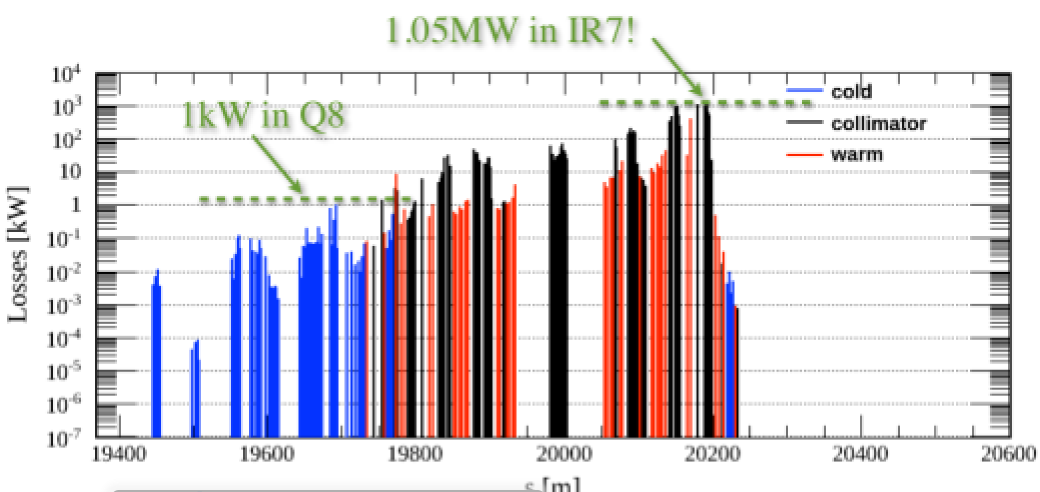
Method: generate losses on collimators

2011: crossing 3rd order resonance, no quench

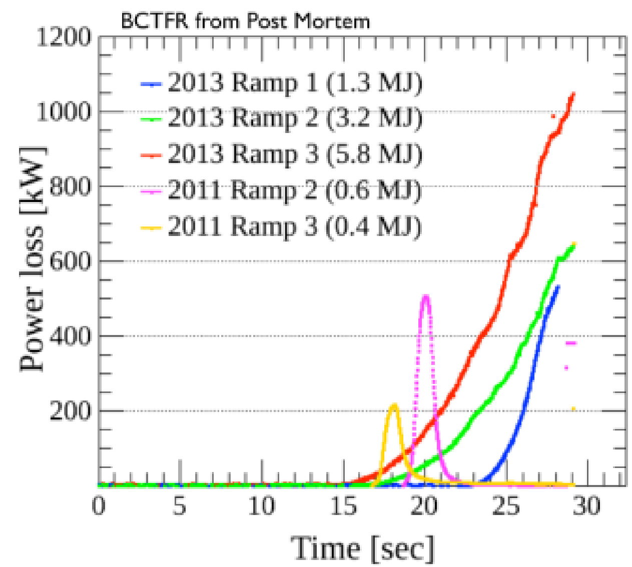
2013: transverse damper, white noise excitation

- power loss on the primary collimators to 1 MW.
- very relaxed collimator settings to increase loss leak to cold magnets. → Still no quench





B. Salvachua et al.

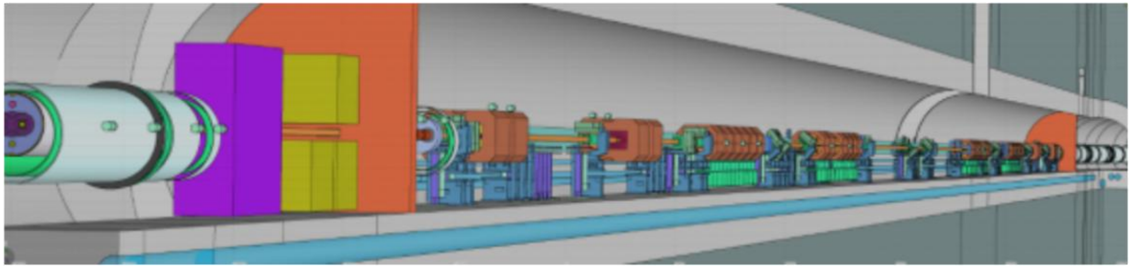


Analysis

Tracking simulation: use SixTrack: multi-turn tracking code successfully used to design the collimation system.

Particle shower simulation: construction of huge FLUKA geometry, 700 m of the tunnel.

Electro-thermal: quench level depends on the efficiency of the cooling to the helium bath, measured in lab experiments



Result:

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

Conclusion: Experiment+ParticeShower consistent with El.-Therm. but no quench level validation

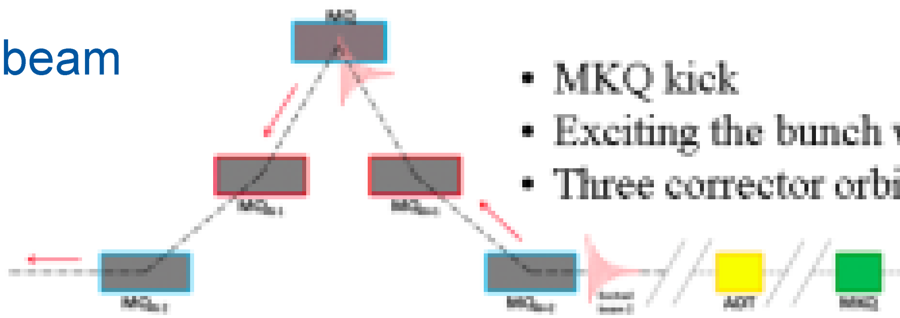
A. Lechner, E. Skordis

Simulated BLM signal on BLMs factor ~2-3 lower than measured.

Millisecond timescale quench test (I)

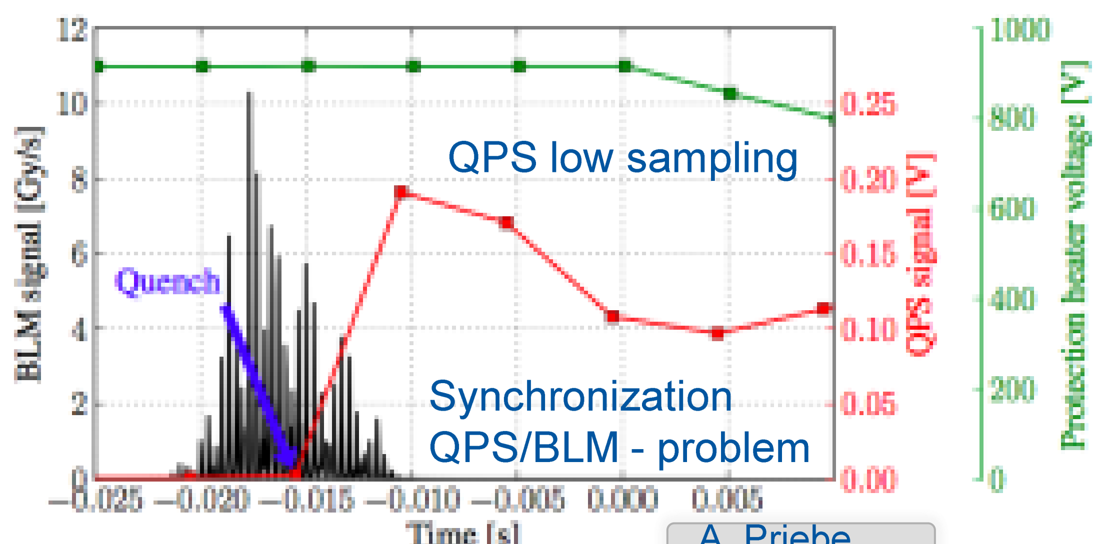
Goal: asses quench level for UFO-timescale (millisecond) losses

Method: make orbit bump and use transverse damper to excite (coherently) the beam oscillations.



Disadvantages:

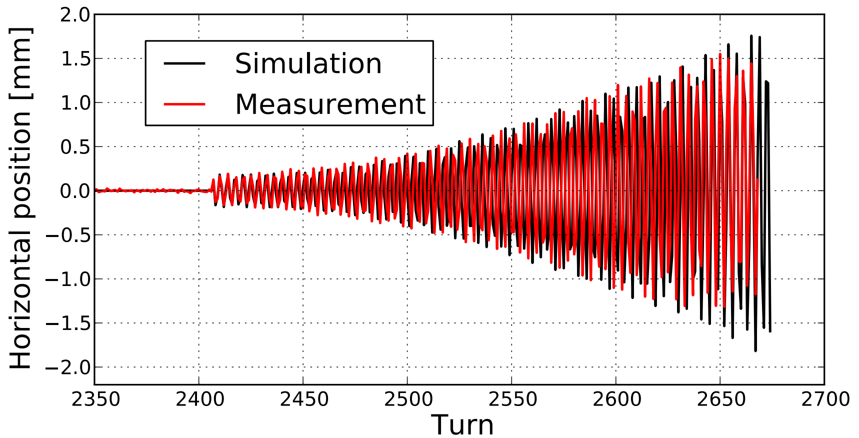
- Cannot aim dipole (UFO)
- Spiky loss structure
- Duration ~10 ms (UFO < 1 ms)
- Beam intensities 10 times less than pilot bunch (scraped on collimators)

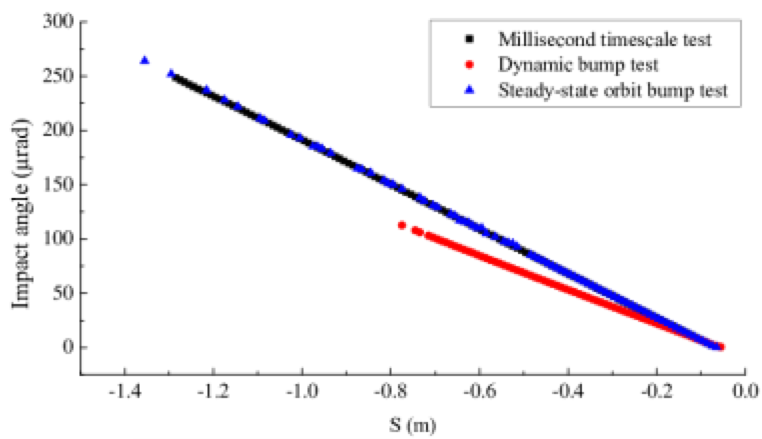


Analysis (I)

Tracking simulation: modified MAD-X.

- Good reproduction of orbit position in BPMs
- Poor reproduction of temporal high-frequency BLM signal
- Extensive **parametric study** of tune, orbit bump amplitude, beam size, damper gain
- Loss pattern: angle strictly dependent on longitudinal position (integrated magnetic field).
- Surface roughness (even 30μm deviation) can affect significantly the loss pattern)





V. Chetvertkova

Analysis (II)

Particle shower simulation: detailed FLUKA geometry

Electro-thermal: heat transfer to helium bath is complex, cooling mechanisms show hysteresis. Spiky structure of loss may keep nucleate boiling active.

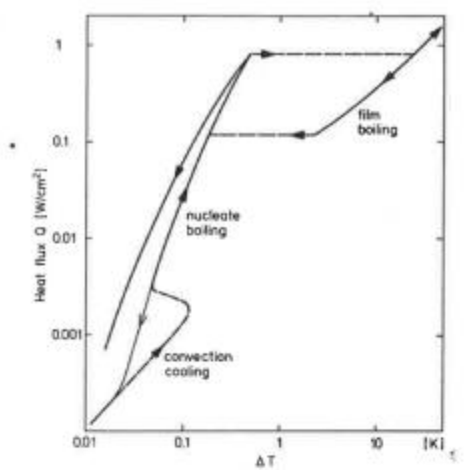
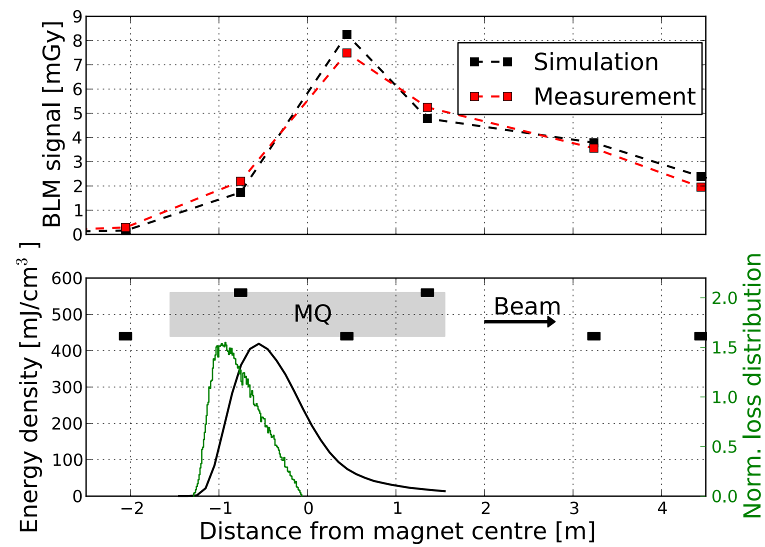


Fig. 1 - Steady-state heat transfer characteristic. The curve is artificially composed of experimental results in Refs. 6,7,11.

Conclusion: Experiment+ParticleShower gives 4 times higher quench level than El.-Thermal



N. Shetty

Result:

N_p	N_q	P. Show. [mJ/cm³]	El.-Therm. [mJ/cm³]
3.5×10^8	n/a	>198	$71^{+?}_{-10}$
8.2×10^8	5.3×10^8	$\boxed{250}$	$58^{+?}_{-8}$
8.2×10^8	8.2×10^8	≤405	$80^{+?}_{-10}$

B. Auchmann

Lessons learned

1. Design your test such, that there is **no-quench and quench attempt** (e.g. slowly increase intensity of lost beam)
2. Synchronization QPS/BLM is crucial for fast tests:
   - Oscilloscope connected to BLM and QPS
3. BLMs cannot resolve loss pattern details below a 1-2 meters in case of low angle loss on smooth vacuum chamber:
   - Measure the **surface roughness** to um scale (?)
   - Introduce known aperture limits (?).
4. **Parametric study** at the simulation level – very important.
5. **Transverse damper** is a very helpful tool to generate controlled losses.
6. **Particle tracking** usually more difficult than particle shower.
7. Complex regions – additional uncertainty for Particle Shower and El-Thermal

Literature

1. Workshop on Beam Induced Quenches –proceedings in preparation, 2014
2. "Testing Beam-Induced Quench Levels of LHC Superconducting Magnets in Run 1", paper soon to be submitted to PRST-AB
3. B. Salvachua et al., Handling_1MW_Losses_with_the_LHC_Coll_System, IPAC14, MOPRO043
4. B. Dehning et al., Beam-induced Quench Tests of LHC Magnets, IPAC14, MOOCB01
5. N. Shetty et al., Energy Deposition and Quench Level Calculations for Millisecond and Steady-state Quench Tests of LHC Arc Quadrupoles at 4 TeV, IPAC14, MOPRO019
6. C. Bracco et al.,Test and Simulation Results for Quenches Induced by Fast Losses on a LHC Quadrupole, IPAC14
7. V. Chetvertkova et al.,MadX Tracking Simulations to Determine the Beam loss Distributions for the LHC Quench Tests with ADT Excitation, IPAC14, THPRI094
8. R. Bruce et al., Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider, Phys. Rev. ST Accel. Beams 17, 081004 (2014)
9. A. Priebe, Quench tests of lhc magnets with beam: studies on beam loss development and determination of quench levels, PhD, CERN-THESIS-2014-013
10. M. Sapinski et al., LHC magnet quench test with beam loss generated by wire scan , IPAC11

… and more!

Summary

1. LHC normal losses account for a few percent intensity loss before collisions.
2. Losses have increased by factor 10 after optimization for luminosity-production.
3. Standard BLM system works very well, developments towards fast diagnostics and measurements closer to the loss location.
4. UFO losses maybe the largest thread to physics run at 6.5 TeV.
5. 17 quench tests performed during Run 1, some very sophisticated.
6. Analysis is very complex and multi-disciplinary.
7. Steady-state quench levels: understood within factor 2.
8. UFO-timescale losses (0.1 ms-10 ms) – factor 4 discrepancy.

Thank you for your attention!

spare slides

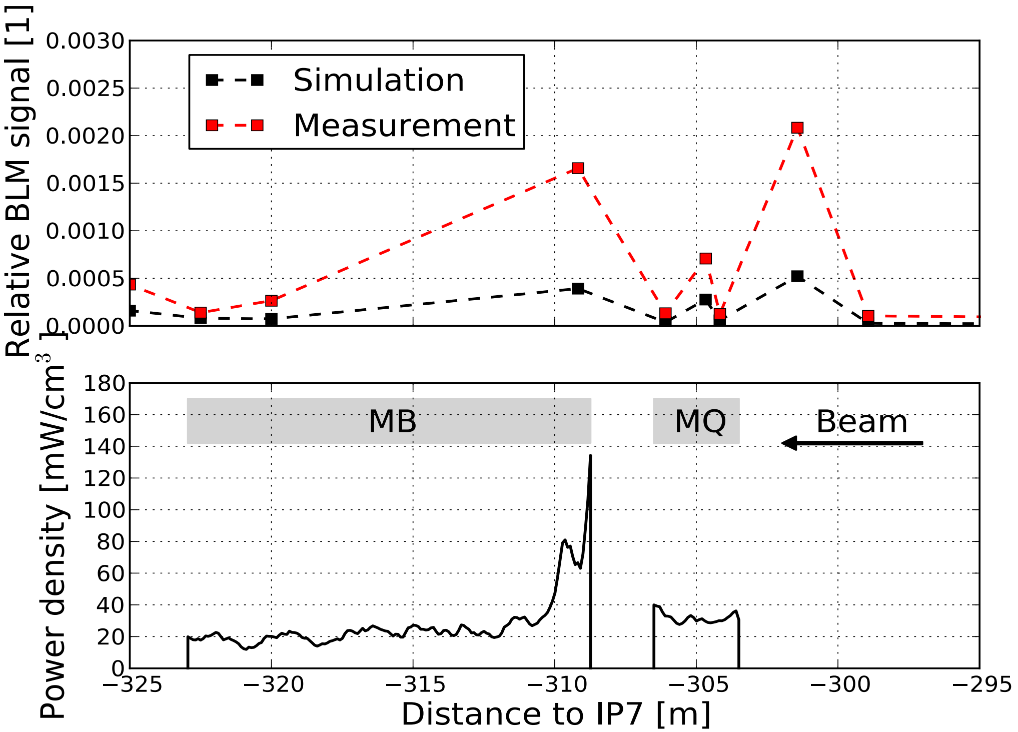
Remark

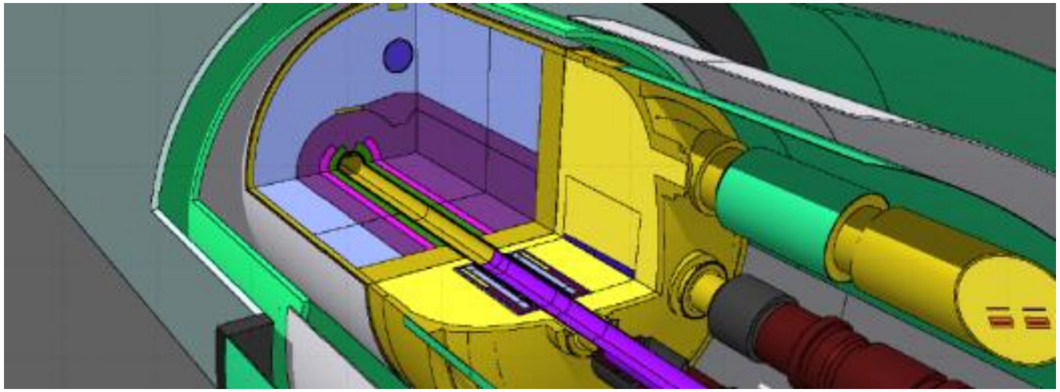
Loss in complex region!

Maximum energy deposit in magnet ending:

- Decaying field
- Coil: stress, uncertain amount of liquid He
- Many elements, difficult to model

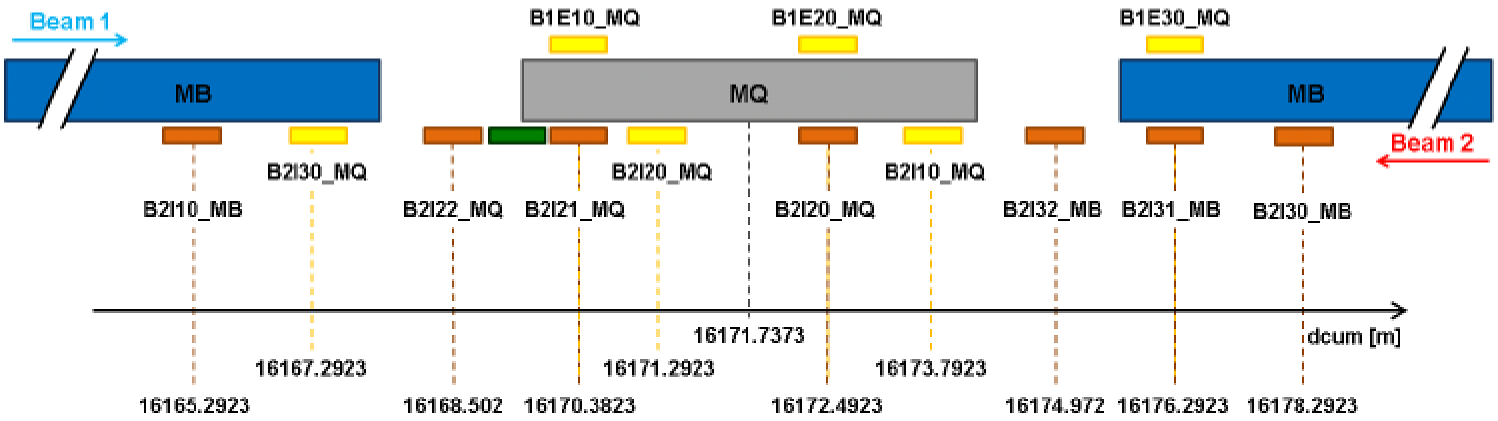
Additional uncertainties in Electro-Thermal and Particle Shower simulations.

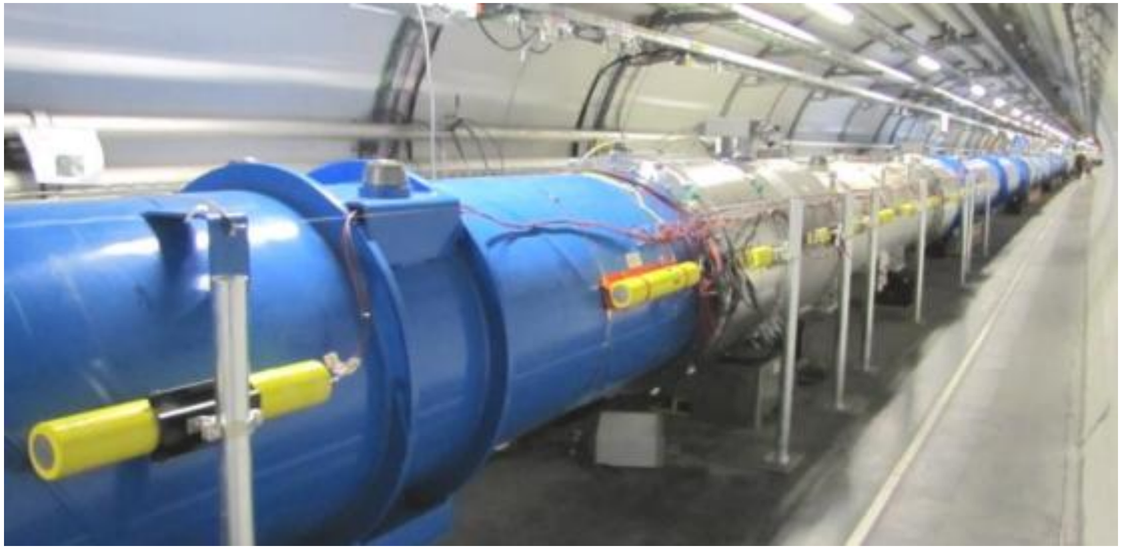




Millisecond timescale quench test (II)

Additional BLMs:

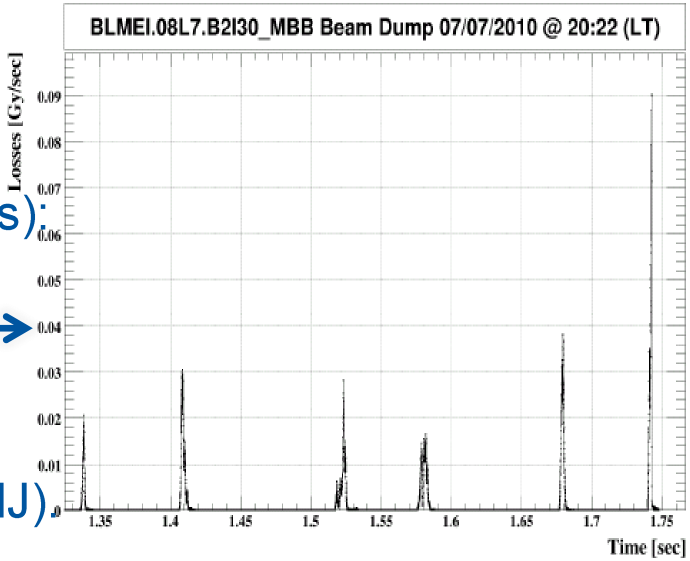




2010: intensity ramp-up

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
14th October	248	233	1e32
8th October	248	233	8.8e31
4th October	204	186	7e31
29th September	152	140	5e31
25th September	104	93	3.5e31
23rd September	56	47	2e31
22nd September	24	16	4.6e30

24 MJ

15 MJ

3.5 MJ

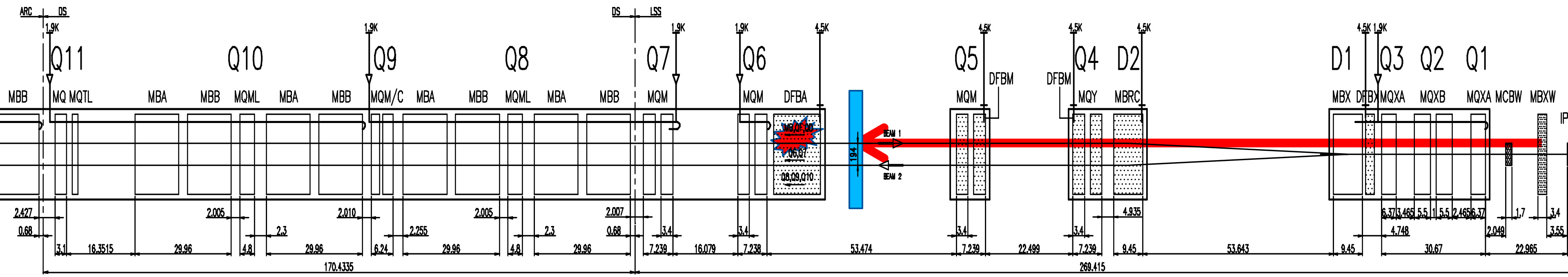
Clear need to verify BLM thresholds at UFO and steady-state timescales!

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

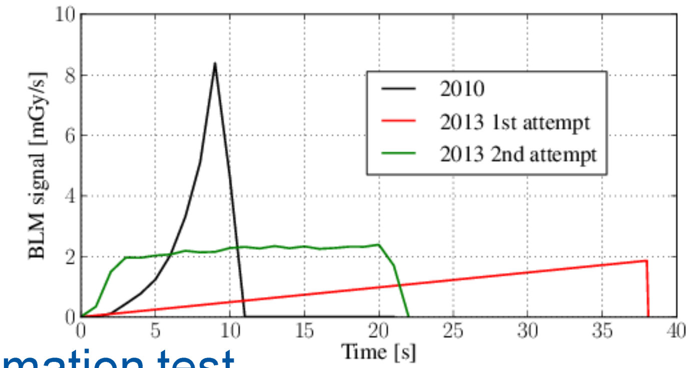
End of Run Quench Test campaign - 2013

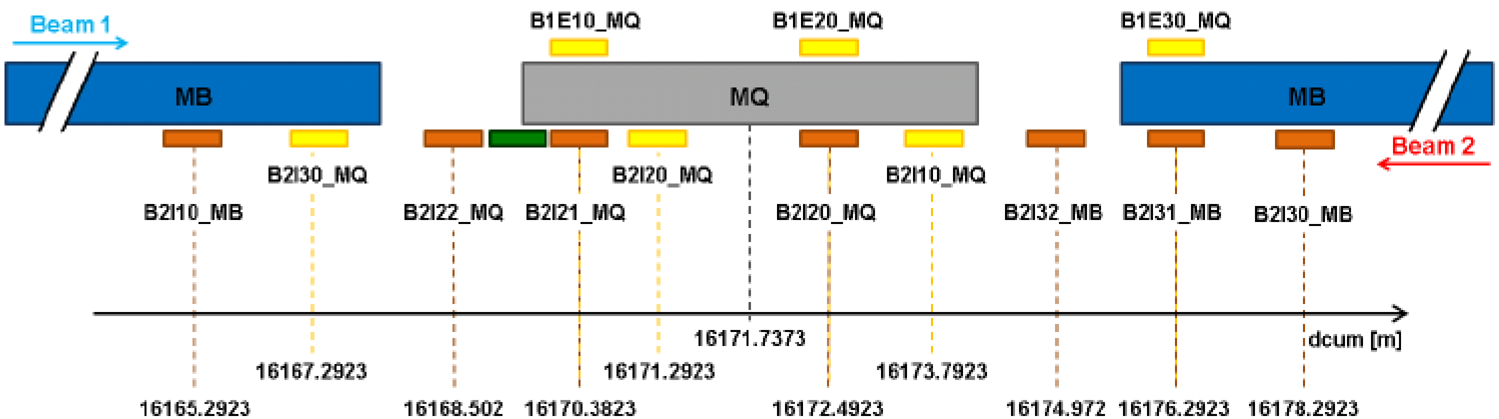
Situation:

- 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 than 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 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



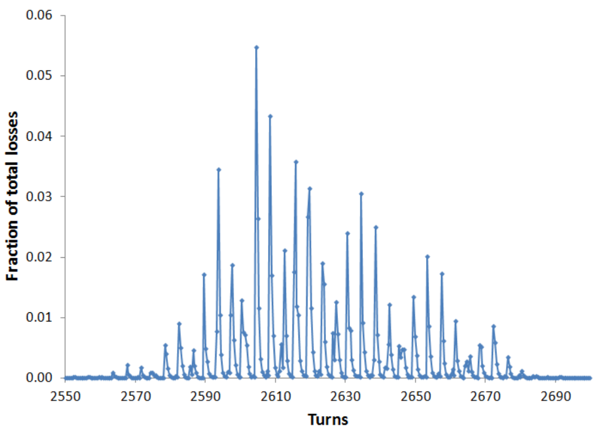


V. Chetvertkova et al., IPAC14
N. Shetty et a. IPAC14

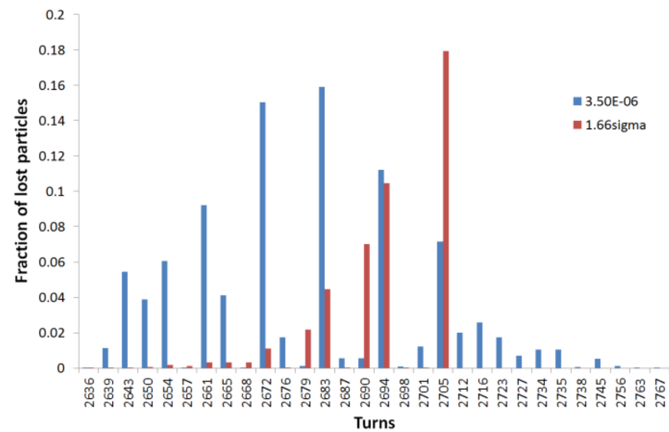
Millisecond timescale quench test (II)

- Reproduction of high-sampling frequency BLM data

data

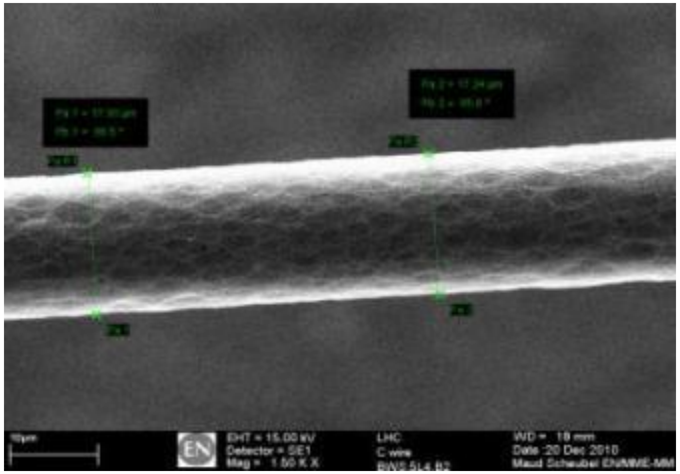


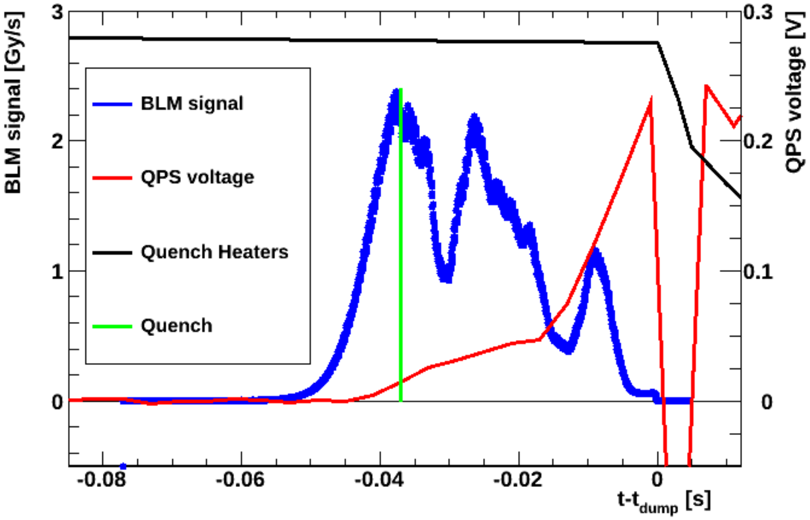
MAD-X simulations



The first quench test campaign – 2010 millisecond timescale losses:

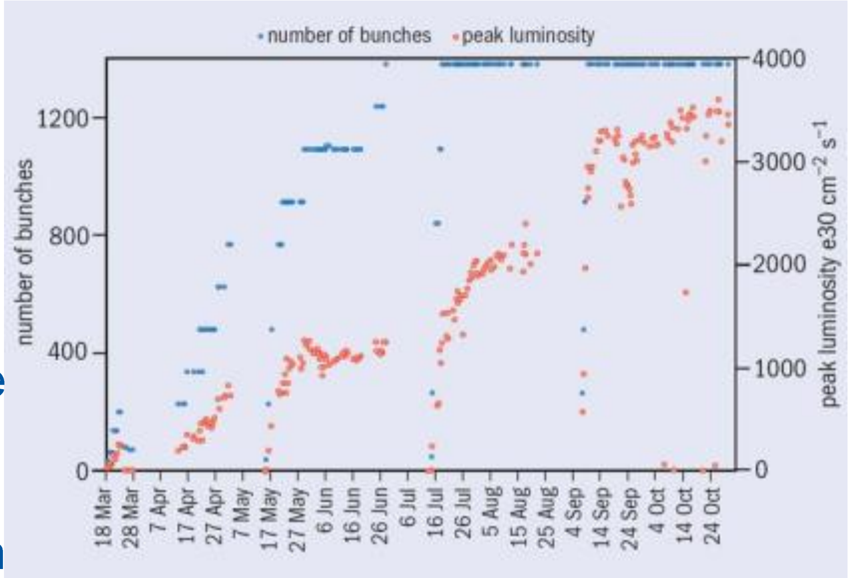
- Loss generated by a wire scan
- Advantages:
  - Simple, not much prep needed,
  - obtained temporal profile should correspond to UFO loss profile (gaussian)
- Disadvantages:
  - Can target only one magnet – recombination dipole D4
  - Magnet is 4.5 K (not representative), there is no functional spare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





M. Sapinski et al., IPAC11

Tests in 2011



<u>Situation:</u>

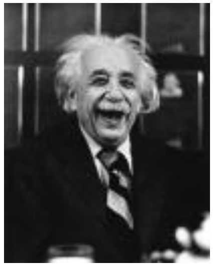
- Beam energy: 3.5 TeV
- Intensity ramp from 368 to 1380 bnches
- Time to address the machine performance limits: quench limit in case of distributed steady-state losses: collimation cleaning and luminosity – important for Phase 2 of collimation system.
  - Steady-state collimation quench tests
- Investigating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

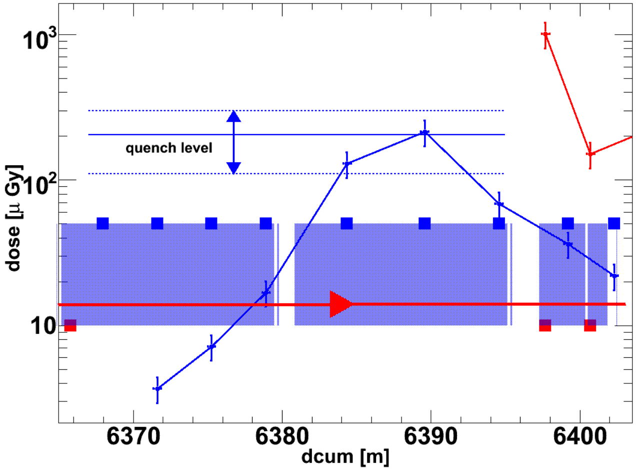
The first beam-induced quench - 2008

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.



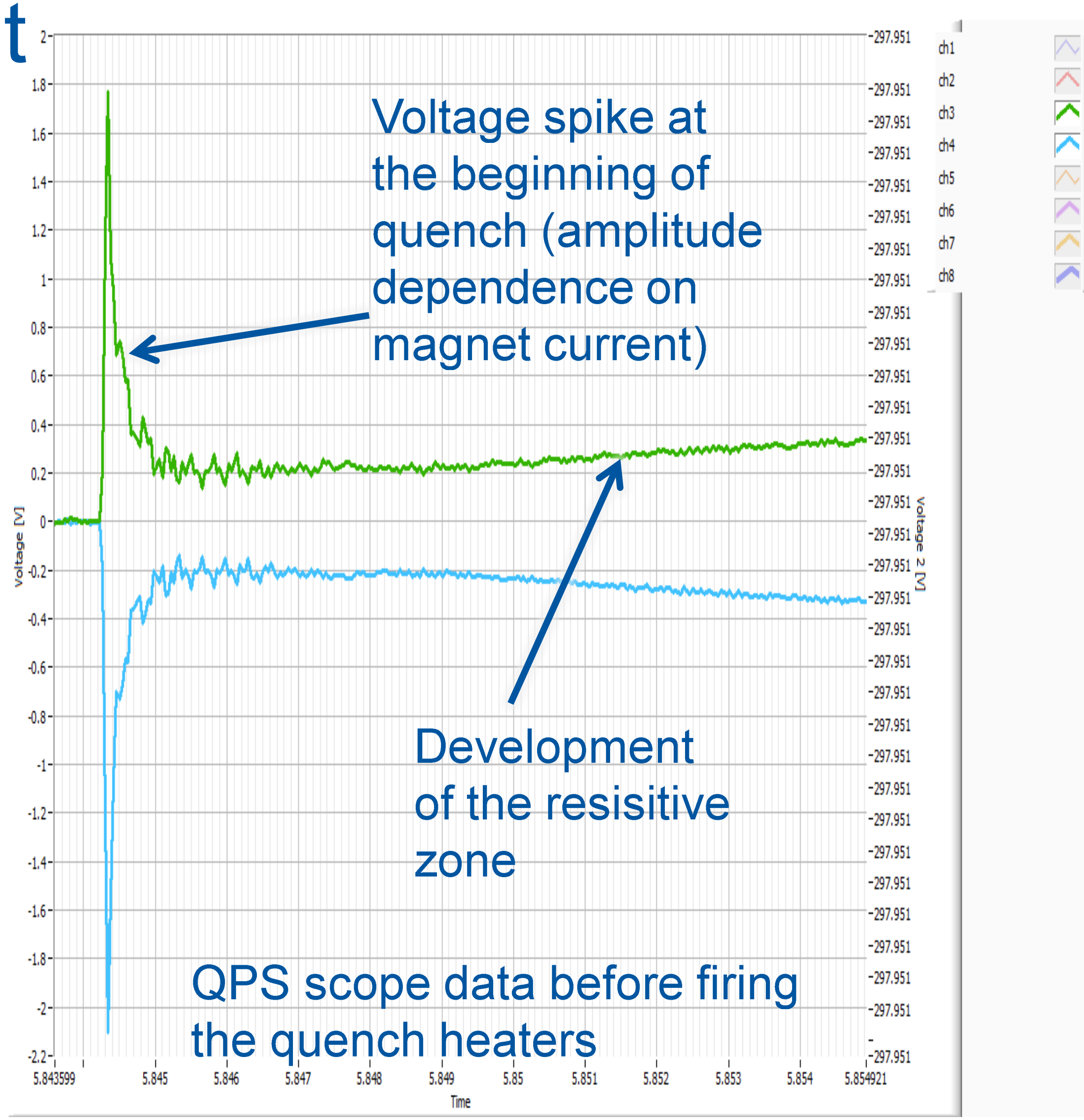


September 7th - another, similar quench. We call it **strong-kick event** because beam hit MB beam screen with angle 750 μrad. Such large impact angle allows for more precise simulations (see following presentations).
September 10th: beams circulating in LHC

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

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

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.*

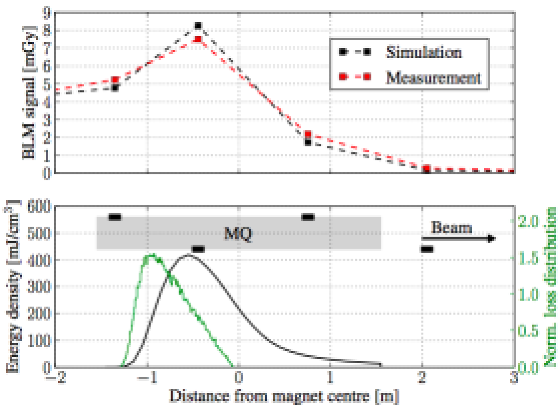
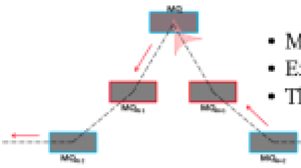


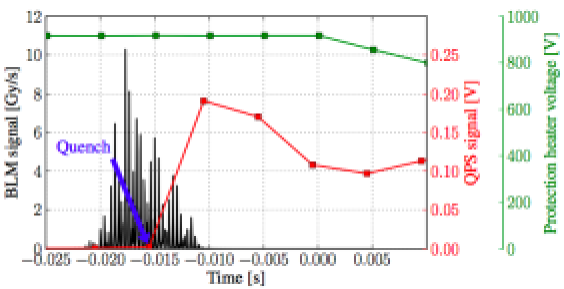
TABLE III. Comparison of FLUKA lower bound (LB) and estimate on the electro-thermal MQED estimate in the MBRB coil.

v_w [m/s]	N_q/N_w [%]	FLUKA LB [mJ/cm^3]	FLUKA [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}



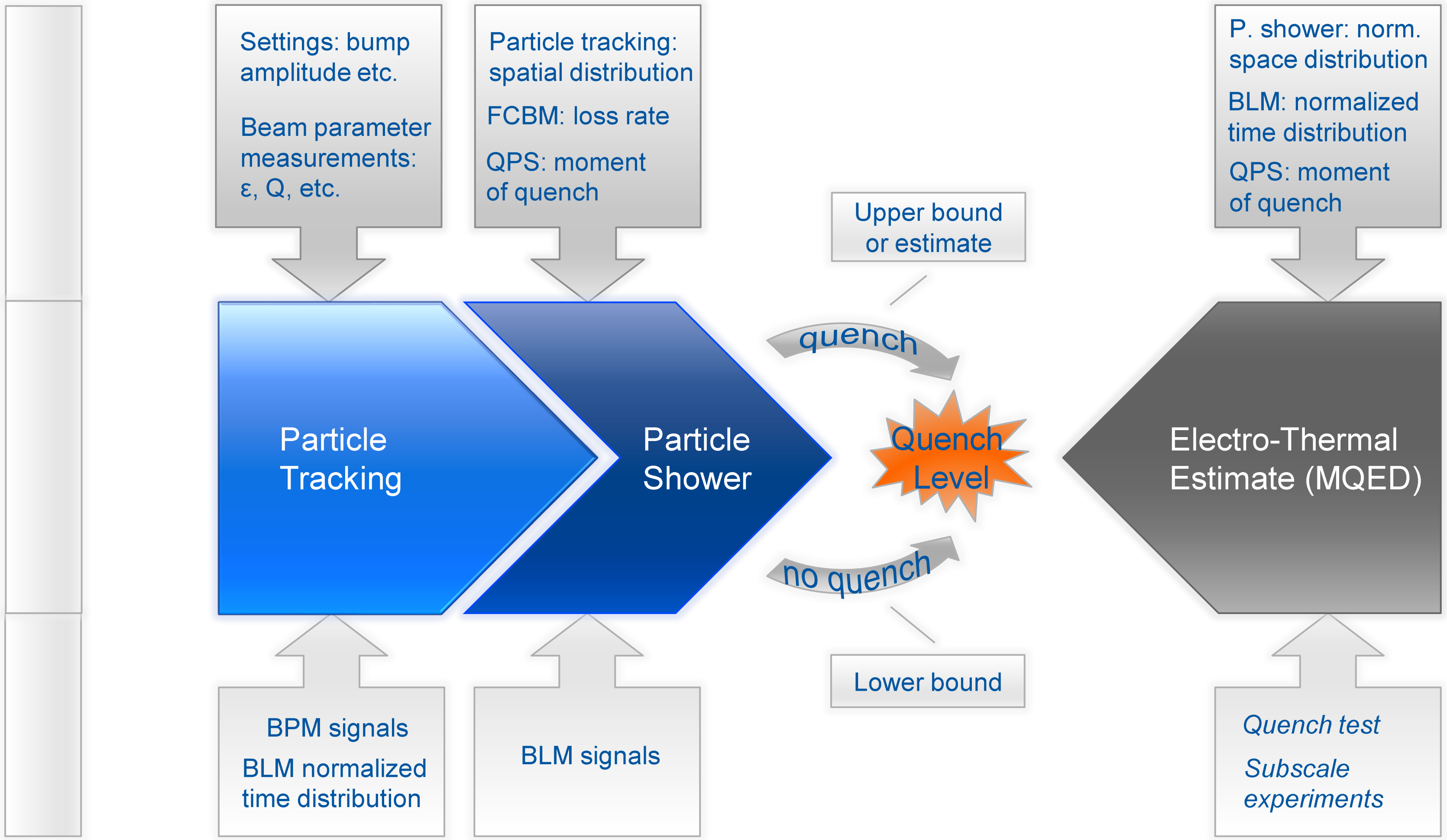
- MKQ kick
- Exciting the bunch with the ADT sign flip mode
- Three corrector orbit bump

N_p	N_q/N_p [%]	FLUKA LB [mJ/cm^3]	FLUKA [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	$80^{+?}_{-10}$



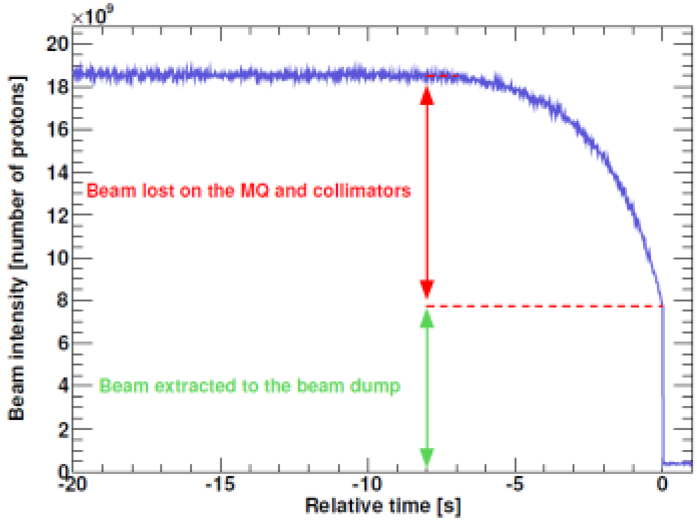
Quench Test Analysis

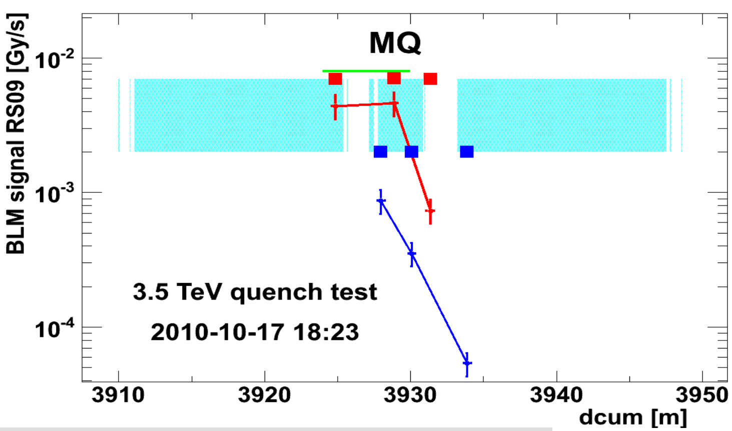
What is the energy deposition in the coil at the moment of quench?



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





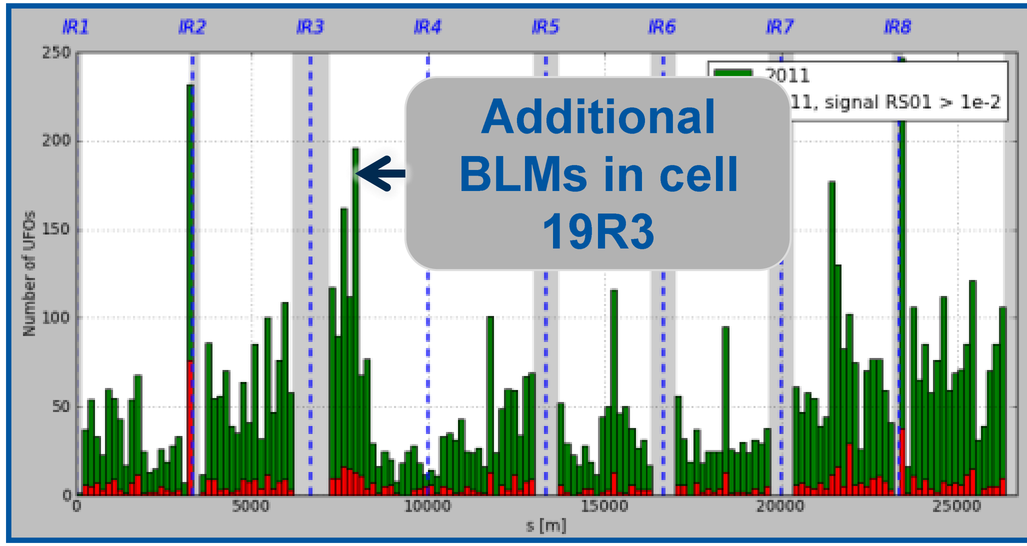
Consequence:

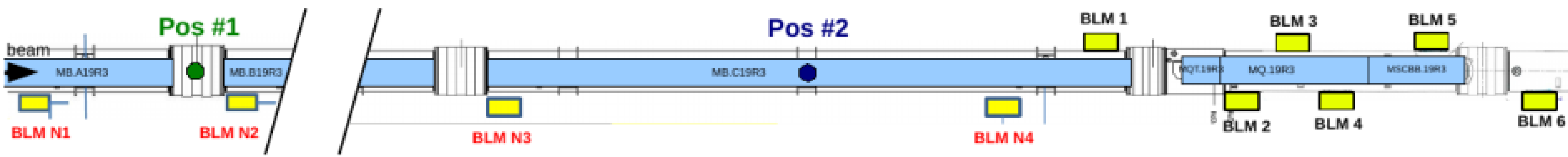
- **Correction of BLM thresholds for steady-state regime for the rest of Run 1**

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

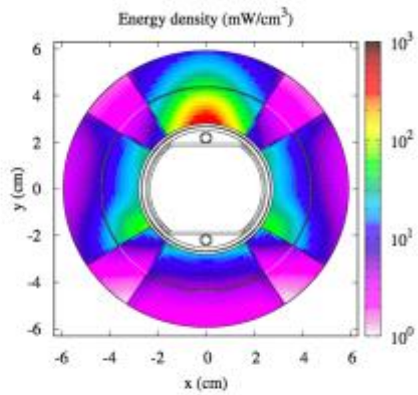
UFO fishing

- 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

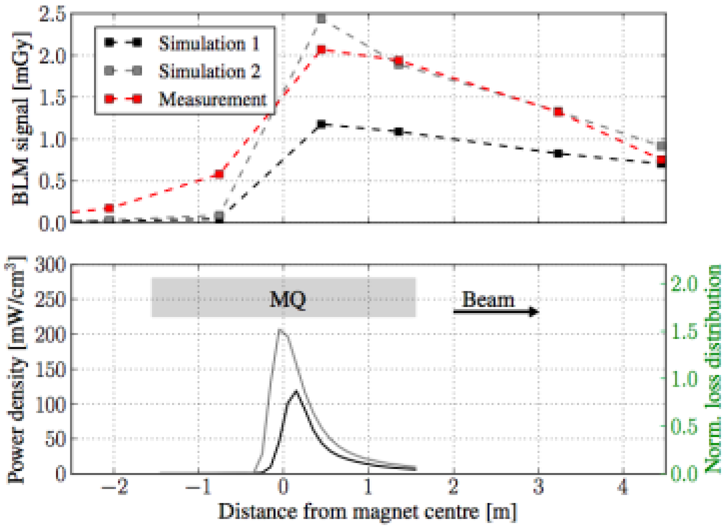




Steady-State Losses



- 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.*



Situation before the LHC startup

- Knowledge about beam-induced quenches summarized in **Note 44**, typical picture
- 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

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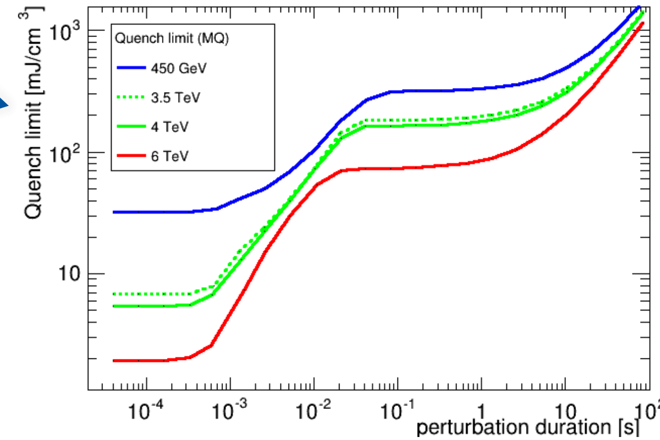

LHC Project Note 422

July 15, 2009

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

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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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