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Magnet Quenches with Beam

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with input from
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+ many others

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Switzerland

Outline

- Motivation:
  Why do we want to quench intentionally?
- Revision of Numbers & Layouts:
  Where will we try to quench?
- How to do the test
- Other requirements
- Conclusion

Motivation: Safe & Efficient LHC Operation

- **Safe operation**
  - Protect magnets against quenches → relevant for this talk
  - Protect machine against damage
- **Operation Efficiency**
  - Minimize number of quenches
  - Minimize number of unnecessary beam dumps

→ Know the quench level
→ Ability to detect if quench level is being reached

Pilot	$5 \cdot 10^{9}$
Nominal (1b)	$1.1 \cdot 10^{11}$
Nominal batch from SPS (288b)	$3 \cdot 10^{13}$
Nominal total (2808b)	$3 \cdot 10^{14}$

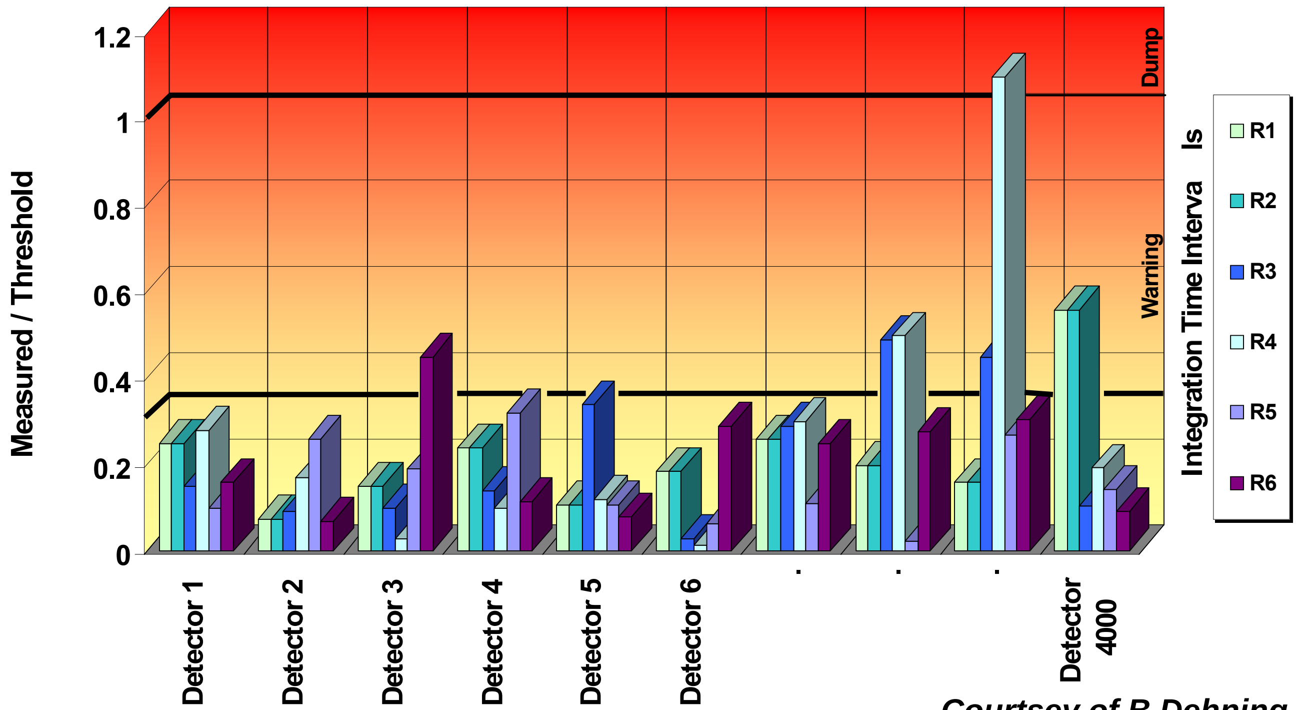
Quench Level, fast losses (< 0.1ms), 450GeV	$\sim 5 \cdot 10^{9}$
Damage Level, fast losses (< 0.1ms), 450GeV	$\sim 1 \cdot 10^{12}$

Systems in the LHC to guarantee safe & efficient operation:

- BLM (Beam Loss Monitor) system:
  allows to protect before quench occurs → active protection!
- Quench protection system:
  protects magnets against further damage while/after quench occurs
- Collimation system
- …

Motivation: Beam Loss Monitor system

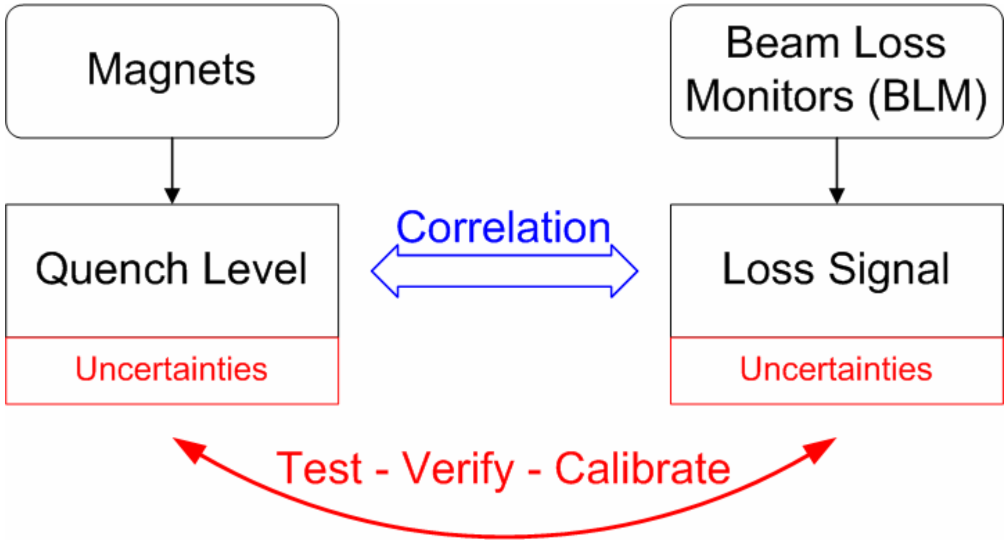
- Designed to allow prevention against quench & damage
- Loss detection outside the cryostat
- If losses exceed threshold → trigger beam dump
- Expected BLM signals from impacting protons by GEANT/FLUKA simulations



Courtsey of B.Dehning

- Calibration of the BLM system!
  - absolute & in terms of quench level

Motivation: Why quench test?



A dedicated magnet quench test allows us to:

- Verify or establish „real-life“ quench levels
- Verify simulated BLM signal (and loss patterns)
- **Establish thresholds = establish the correlation between quench level and BLM signal = Calibration!**
- In particular: What BLM signal refers to the quench level of a certain magnet type?

Accurately known quench levels will increase operational efficiency!

Quench Levels I/II

- LHC-Project-Report 44: "Quench levels and transient beam losses in LHC magnets", J.B. Jeanneret, D.Leroy, L.Oberli, T.Trenkler
- Number of protons required to induce a quench is $n_q = \frac{\Delta Q_c}{\varepsilon}$
- Fast losses, no temperature equalisation

$$\Delta Q_{critical} = \Delta H_{wire} \text{ and } \varepsilon = \varepsilon_{peak}$$

- ε_{peak} , peak energy deposition of one proton in most exposed cable

$$\varepsilon_{peak,local} = 3.8 \times 10^{-11} J \cdot cm^{-3}$$

$$\varepsilon_{peak,\ dist.} = 3.8 \times 10^{-11} J \cdot m \cdot cm^{-3}$$

- Enthalpy reserve at 450 GeV: $\Delta H_{wire} = 38\, mJ \cdot cm^{-3}$

➡ **Quench level in # of protons: 10^9p locally or 10^9p/m distributed**

- Ongoing studies and simulations [1,2,3]

[1] R.Bruce, (S.Gilardoni, J.M.Jowett): Simulation of ion beam losses in LHC magnets, CERN-THESIS-2005-053

[2] A.Siemko: Beam loss induced quench levels, Chamonix XIV, CERN-AB-2005-014, p.296ff.

[3] A.Siemko: Status of the LHC magnet quench level calculations, LTC 19.10.2005

Quench Levels II/II

By courtsey of D.Bocian/M.Calvi/A.Siemko

Magnet type	Cable type	T [K]	Enthalpy [mJ/cm^3]			
			Injection energy, low current		Top energy, nominal current	
			Fast perturbation	Slow perturbation	Fast perturbation	Slow perturbation
			<100 μs	**>100 ms**	**<100 μs**	**>100 ms**
MB	Type-1	1.9	31.3	148.5	1.54	56.55
MB	Type-2	1.9	29.2	141.2	1.45	56.41
MQ	Type-3	1.9	29.5	150.7	4.24	70.53
MQM	Type-7	1.9	30.3	127.8	1.51	49.97
MQM	Type-7	4.5	28.2	47.6	2.41	9.87
MQY	Type-5	4.5	28.4	48.5	2.89	12.15
MQY	Type-6	4.5	32.1	57.8	3.80	15.31
MCB(H&V)	Corr-1	1.9	23.2	23.2	4.20 / 7.23	13.39 / 16.78
MCBC(H&V)	Corr-2	1.9	23.1	23.1	2.50 / 3.87	8.45 / 9.93
MCBC(H&V)	Corr-2	4.5	21.6	21.6	4.65	13.41
MCBY(H&V)	Corr-2	1.9	23.3	23.3	3.32 / 5.46	11.28 / 13.50
MCBY(H&V)	Corr-2	4.5	21.5	21.5	4.29	12.56
MCBXH	Corr-4	1.9	33.1	33.1	9.67 / 14.11	24.60 / 28.53
MCBXV	Corr-4	1.9	33.2	33.2	10.42	26.10
MQT	Corr-3	1.9	32.2	32.2	5.45 / 7.83	14.08 / 15.66
MQTLI	Corr-3	1.9	32.2	32.2	5.45 / 7.83	14.08 / 15.66
MQTLH	Corr-3	4.5	29.7	29.7	5.54 / 12.24	12.67 / 23.95

preliminary results! *for details see* *

➡ Required proton density still expected to be ~10^9p/m

** A.Siemko: Status of the LHC magnet quench level calculations, LTC 19.10.2005*

Aperture LHC injection 450 GeV

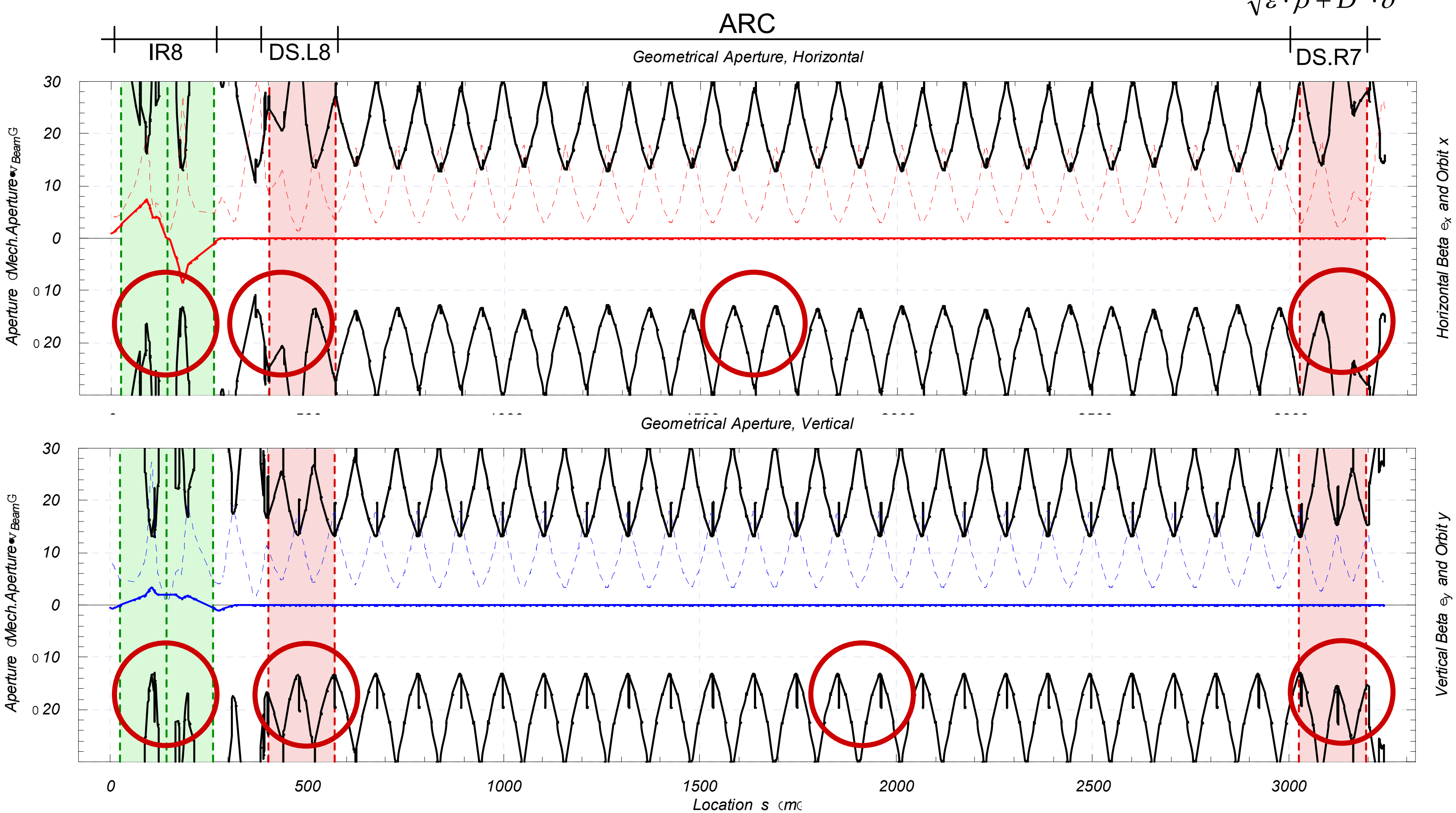
Cold aperture limits at injection:

- Triplet quadrupoles
- Dispersion suppressor quadrupoles
- Arc quadrupoles
- (Main dipoles)

➡ Beam losses at these locations

➡ Quench

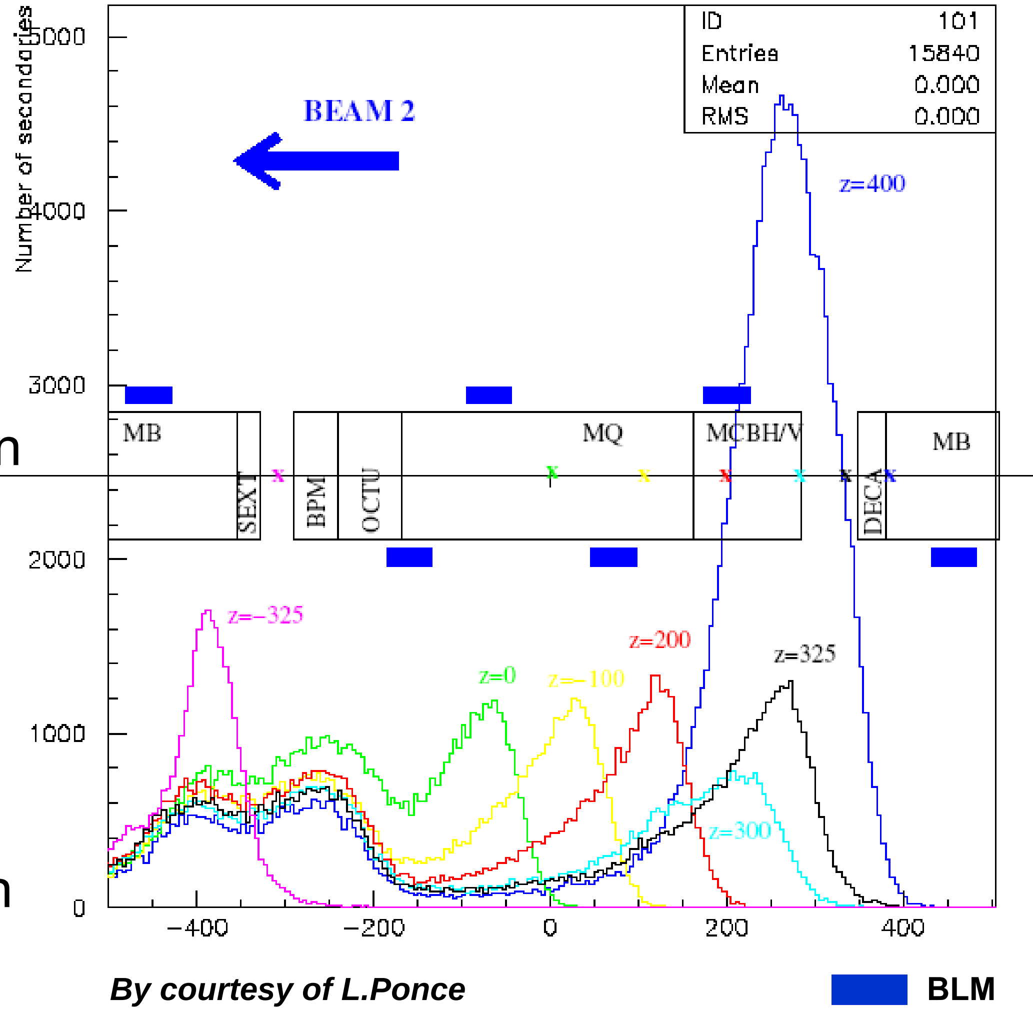
$$N_\sigma = \frac{A_{x|y} - \delta_{mech./align.}}{\sqrt{\varepsilon \cdot \beta + D^2 \cdot \delta^2}}$$



Beam Loss Monitor (BLM) Layout

- ARC BLM layout at the main quadrupoles
- 6 BLMs per quadrupole location
- Mounted in horizontal plane
- BLM signal due to local proton impact
  @ 0.25 mrad

- Shower of secondaries > 1m
- BLM signal could give information on impact position



By courtesy of L.Ponce

How to do the quench test: Overview

- Simple idea: Steer beam into aperture and cause magnet quench
- 36h time-slot foreseen for quench tests,
  rather towards the end of the sector test preferably as several 8-10h shifts
- Recovery time after a quench is expected to be roughly 2h*.
  This is an assumption!
- ~ 10 quenches are planned.
- Ideally 10 quenches at the same magnet with reproducible beam conditions in order to calibrate the BLMs!
- 36h – 10x2h = 16h of possible beam in LHC sector
- 16h/10 = ~ 1.5h/quench attempt for beam set-up and parameter variations

➡ thorough, detailed planning
stable beam conditions
including injector chain

** Actual recovery time will be established during the test. Assumptions range from 15min – 5h*

How to do the quench test: Optics & Beam

- Beam steered into aperture via 3 corrector magnet bump, (or directly by only one corrector magnet if necessary). Maximum kick angle:

$$\Delta\Theta_{\max}^{450\,GeV} = \frac{B \cdot \Delta s}{p/c} = 1.26\ mrad$$

- Intensity: $N_{proton} = (2)\ 5\times10^{9} - 1\times10^{11}\ p$
  - Single bunch
  - Variation in steps of ~20% achieved either by
    - Vary PS Booster intensity
    - Scraping the beam in the SPS

    } both!

- Emittance: $\varepsilon_{norm.} \approx 0.5 - 3.5 \cdot 10^{-6}\ m \cdot rad$
  - Expected range due to scraping

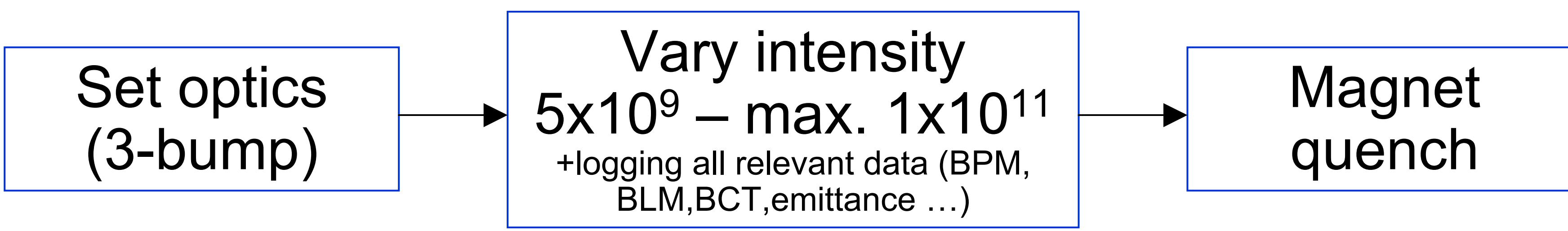
- Impact angle:
  - Depends on the actual magnet chosen and the corresponding corrector magnet layout

How to do the quench test: Implementation

Initial conditions & requirements:

- Pilot beam $5x10^9$, LHC injection optics
- No separation bumps, crossing angle, or spectrometer bump (LHCb)
- Clean conditions, orbit corrected (to better +/- 3 mm?).
- BPM data/logging available ➡ Trajectory
- BLM data/logging available
- BCT in TI8 (end) available + preferably one at the end of sector?
- Wire scanner in the SPS ➡ Emittance
- Additional “mobile” BLMs at chosen locations
- Shot-to-shot time ~15-20 sec. (SPS cycle):
  Assumption: No accumulation (history) in SC magnets expected!

Quench Test Procedure:

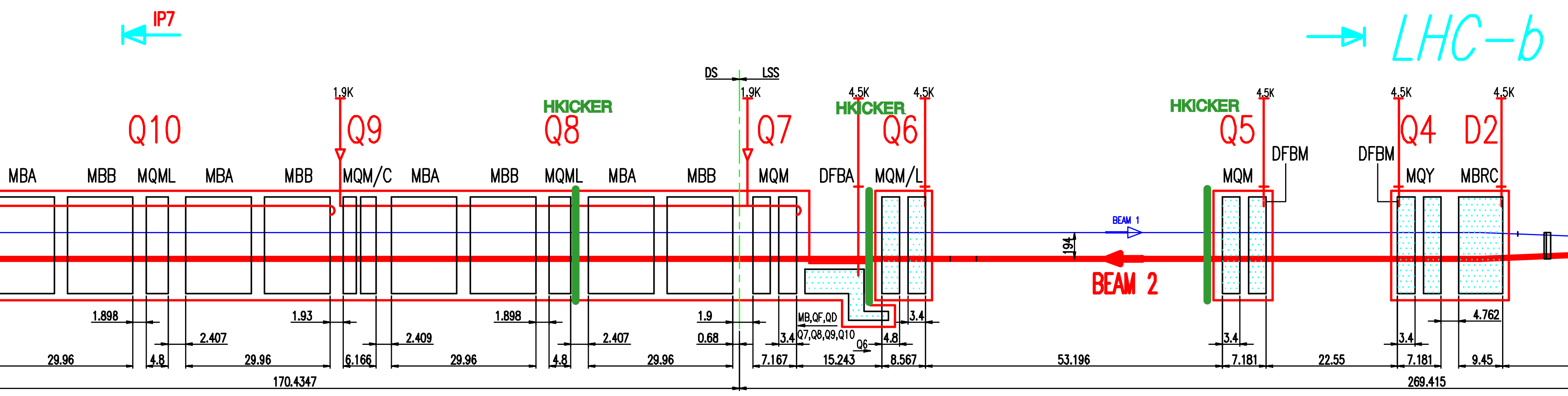


How to do the quench test: Which magnets?

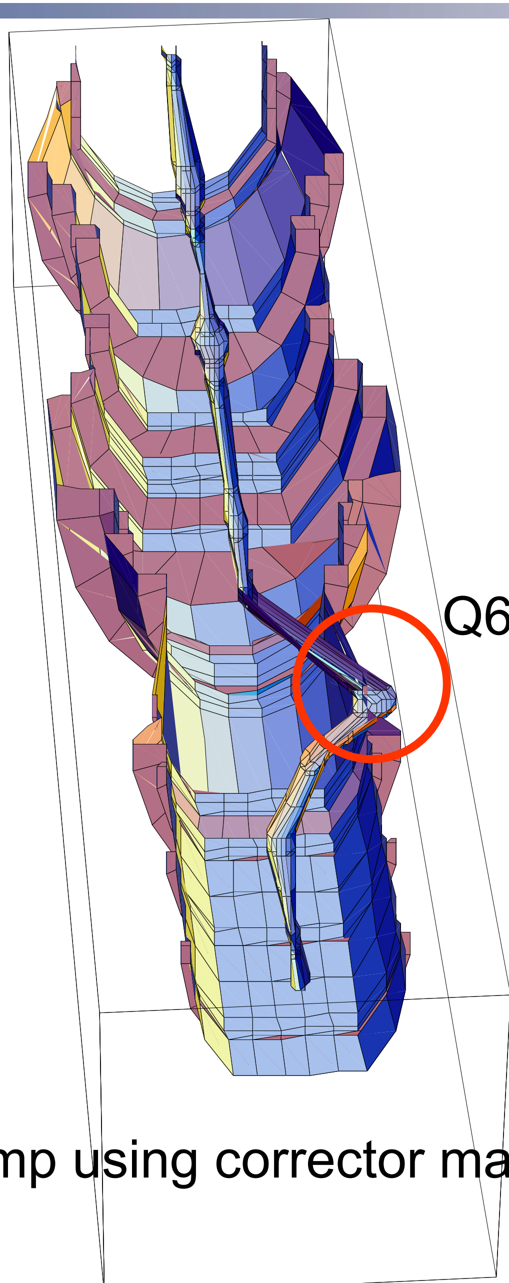
	Magnet Type	Temp. [K]	Quench Level [mJ/cm^3]	What/Where	Why
Main magnets					
	MQM	4.5	28.2 @ 0.1ms	MQM(L).6L8.B2 quadrupole Q6	• low quench level • aperture limit at injection • "standalone" magnet, **separate powering and cooling**
	MQTL	4.5	29.7 @ 0.1ms	MQTLH.x6R7 quadrupole Q6	• low quench level • strongly requested by collimation team • "standalone" magnet, **separate powering and cooling** • **Test at nominal current!**
	MQ	1.9	29.5 @ 0.1ms	Main arc quadrupoles	• low quench level • aperture limit at injection
	MB	1.9	31.3 @ 0.1ms	Arc dipoles	• cover large fraction of the machine • cold aperture at injection limited in the arcs (quadrupoles + dipoles)
Further candidates					
	MQY	4.5	32.1 @ 0.1ms	Q4	low quench level
	MQM/L	1.9	30.3 @ 0.1ms	Q7/8/9/10 dispersion suppressor quads	low quench level
	MQT	1.9	32.2 @ 0.1ms	Tuning quads	low quench level
	MCBX	1.9	33.1 @ 0.1ms		low quench level
	MCBY	1.9	33.2 @ 0.1ms		low quench level
	MCBH, MCBV		23.2 @ 0.1ms	orbit correctors, arc	low quench level may quench before main magnets

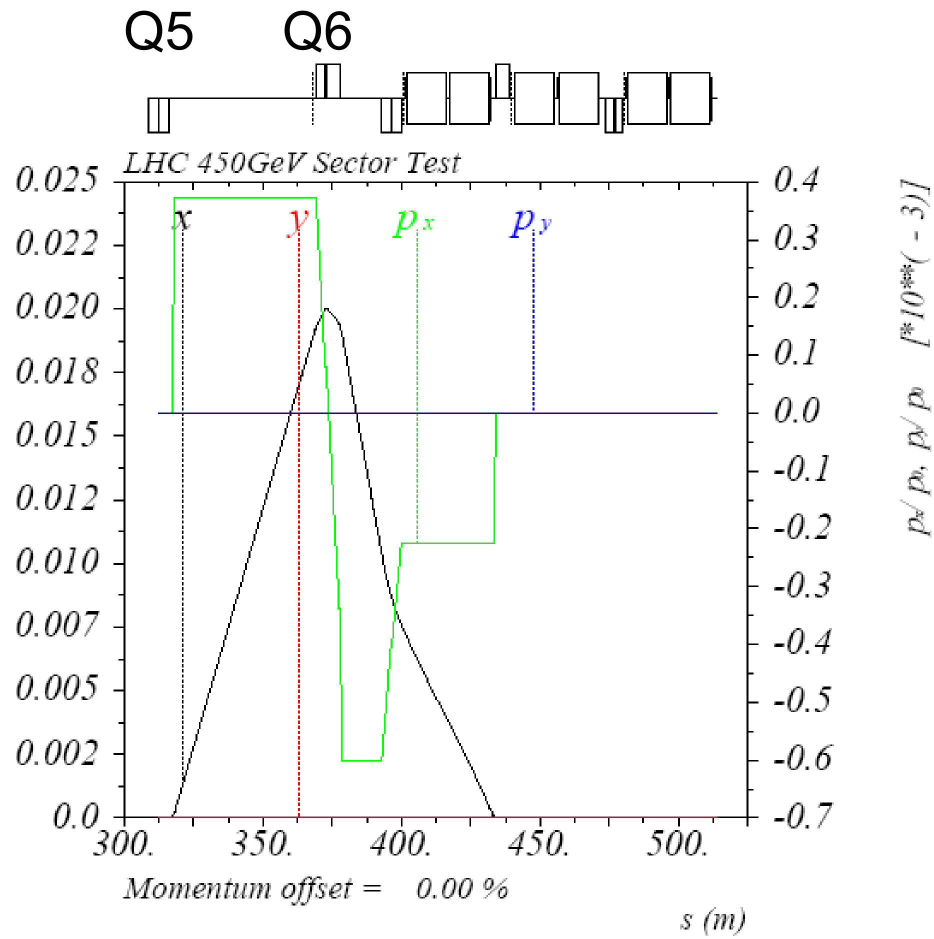
How to do the quench test: Layout

- MQM (Q6) only left of IP8
- MQTLH (Q6) only right of IR7, last magnet before the beam bump!
  - Can be tested at injection current & **nominal current**!
- MQ and MB at any location in the arc equal, but preferably near the temporary beam dump, hence right of IR7 (MB.12, MB.13, …)
- NOT quenching anything before or near IP8, because we do not want to create any further radiation/activation in this area.



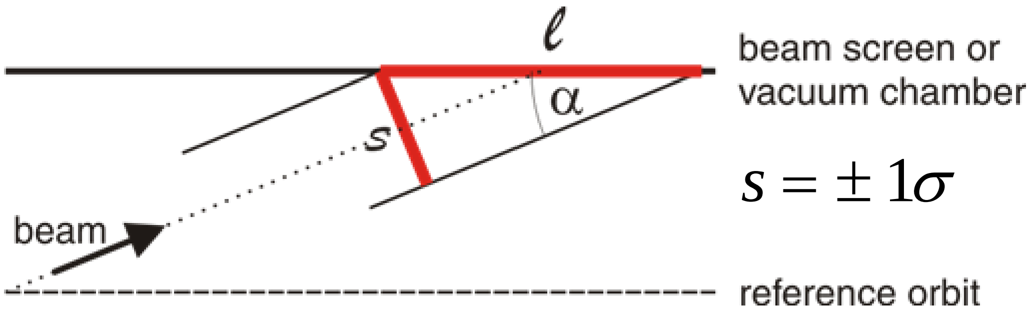
How to do the quench test: Example Q6





3-bump using corrector magnets MCBYH.5L8, MCBCH.6L8, MCBCH.8L8

How to do the quench test: Impact Length



$$s = \pm 1\sigma$$

$$l = \frac{2 \cdot \sqrt{\varepsilon \cdot \beta + D^2 \cdot \delta^2}}{\sin x'}$$

MQM MQ.6L8.B2:

β (m) beta	D (m) dispersion	δ momentum error	X' impact angle	ε emittance normalized	L (m) impact length
16	0.1	$1.5\ 10^{-3}$	$0.35\ 10^{-3}$	$1\ 10^{-6}$	**1.35**
16	0.1	$1.5\ 10^{-3}$	$0.35\ 10^{-3}$	$3.5\ 10^{-6}$	**2.13**
16	0.1	$0.5\ 10^{-3}$	$0.35\ 10^{-3}$	$1\ 10^{-6}$	**1.08**
16	0.1	$0.5\ 10^{-3}$	$0.35\ 10^{-3}$	$3.5\ 10^{-6}$	**1.97**

MB MB.C12R7.B2:

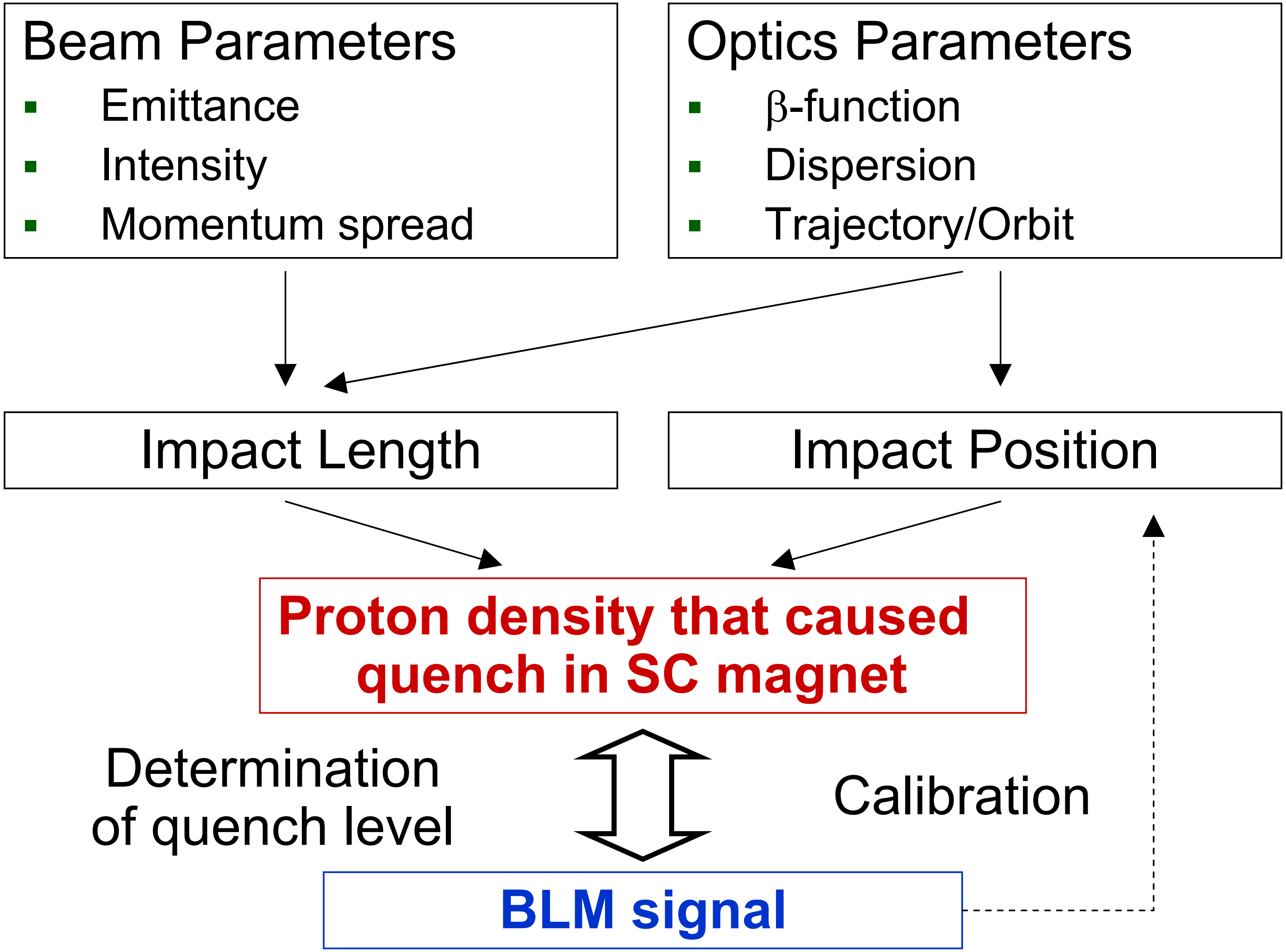
β (m) beta	D (m) dispersion	δ momentum error	X' impact angle	ε emittance normalized	L (m) impact length
135	1.65	$1.5\ 10^{-3}$	$1.23\ 10^{-3}$	$1\ 10^{-6}$	**4.12**
135	1.65	$1.5\ 10^{-3}$	$1.23\ 10^{-3}$	$3.5\ 10^{-6}$	**4.34**
135	1.65	$0.5\ 10^{-3}$	$1.23\ 10^{-3}$	$1\ 10^{-6}$	**1.60**
135	1.65	$0.5\ 10^{-3}$	$1.23\ 10^{-3}$	$3.5\ 10^{-6}$	**2.10**

Very local impact of ~1m possible.

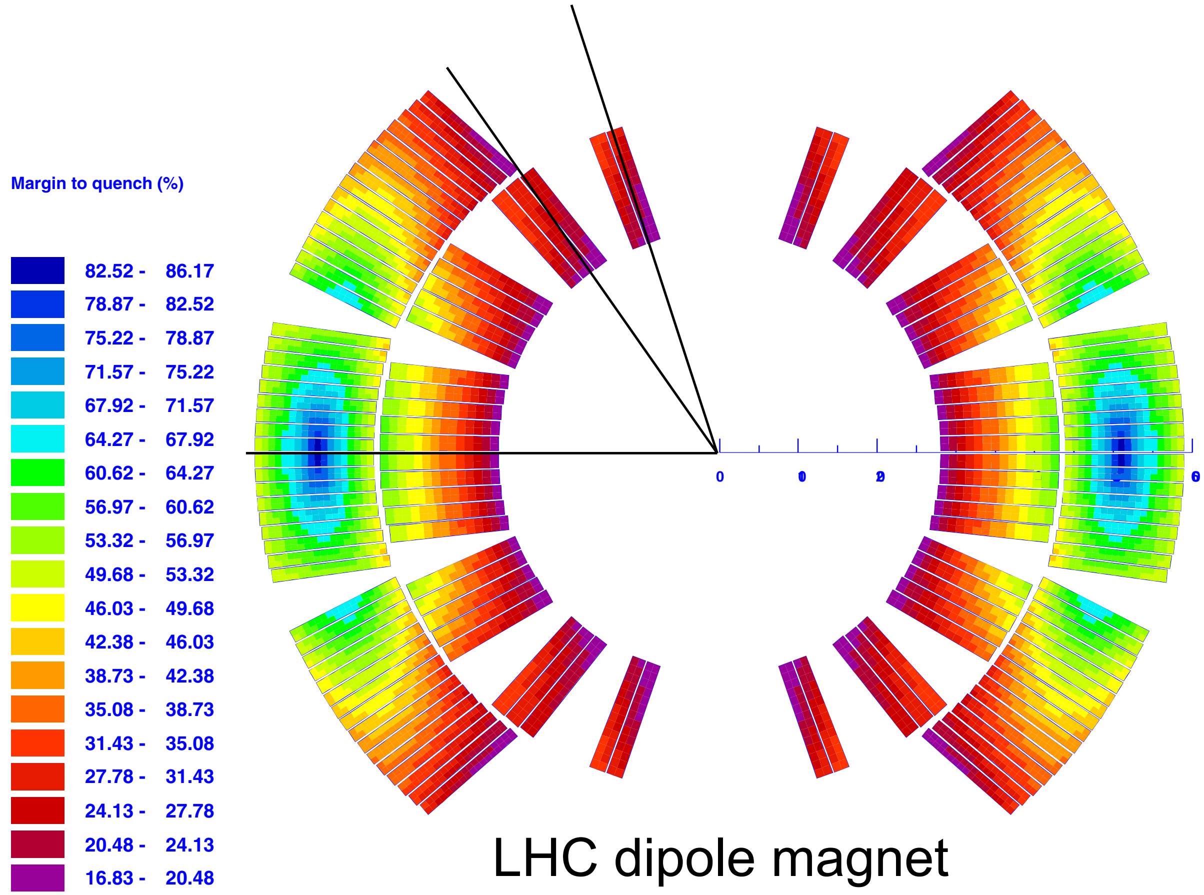
Dependence on emittance or beta is less influential than effect of momentum errors.

The impact length is however mostly dominated by the impact angle!

How to do the test: What we want to learn



How to do the test: Different quench behaviour?



LHC dipole magnet

By courtesy of S.Russenschuck

- Magnetic Flux density further in the coil depends on azimuth:
- We could test if quench behaviour is different at horizontal (0°) impact angle or vertical (55/72°) impact angle

Conclusions

- Controlled, defined test to establish
  - Absolute quench limits
  - BLM threshold values
  - Model and understanding of correlation of loss pattern, quench level, BLM signal

- This test is essential for an early calibration of the BLM system!

Conclusions & Follow-Up

- Refine & prepare optics solutions to steer beam into the various magnets
- Further GEANT/FLUKA simulations of beam loss patterns with the particular optics and layout of the impact situation during quench test
- Intensity variation relies on very-well commissioned scrapers in the SPS
- BLM data/logging available
- BPM data/logging available
- Quench Protection System: Need information if and where quench happened
- “Clean” beam conditions needed