Status of Machine Protection Studies

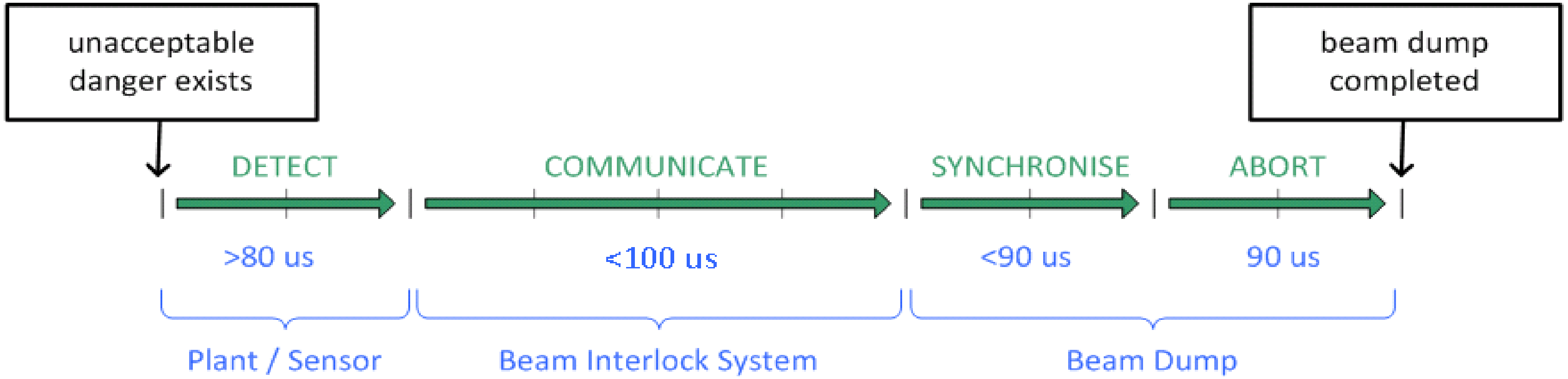
D. Wollmann, M. Zerlauth, J.Wenninger, R.Schmidt, V.Chetverkova, R.Bruce, S.Redaelli, A.Lechner, T.Baer and many more

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

- Recap of assumptions for (HL-)LHC MP systems
- ATS optics: 90 degree phase advance between MKD (IR6) and TCT/triplet in IP5 (B2):
  - Verification of protection margins with closed orbit bump.
  - Inversion of crossing and separation plane.
  - Damage levels for TCTs with new materials?
- Crab cavity failures – modeling, tracking/simulations
- Magnet damage limits
- Availability and quench limits

Recap of current assumptions for LHC MP systems



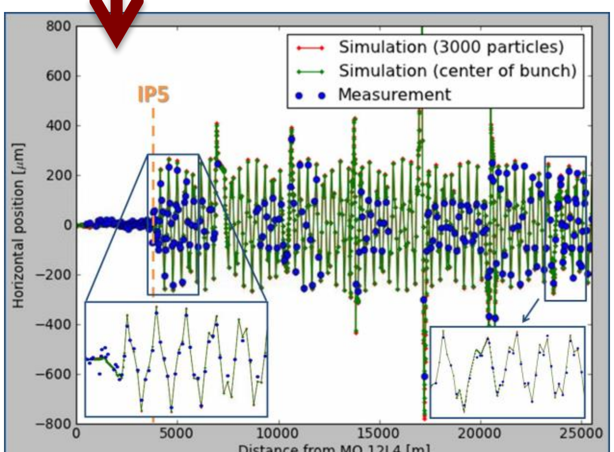
- **Ultra- Fast failures (< 3 turns)**:
  - Beam injection from SPS to LHC.
  - Beam extraction into dump channel.
  - Missing beam-beam kick after dump of one beam.

Upgrade or replacement of **passive protection** devices (TDI, TCDQ, Collimators etc.) [WP5, WP10, WP14, …]

Asynchronous dump failure for HL-LHC parameters / ATS TCT material studies [WP5]

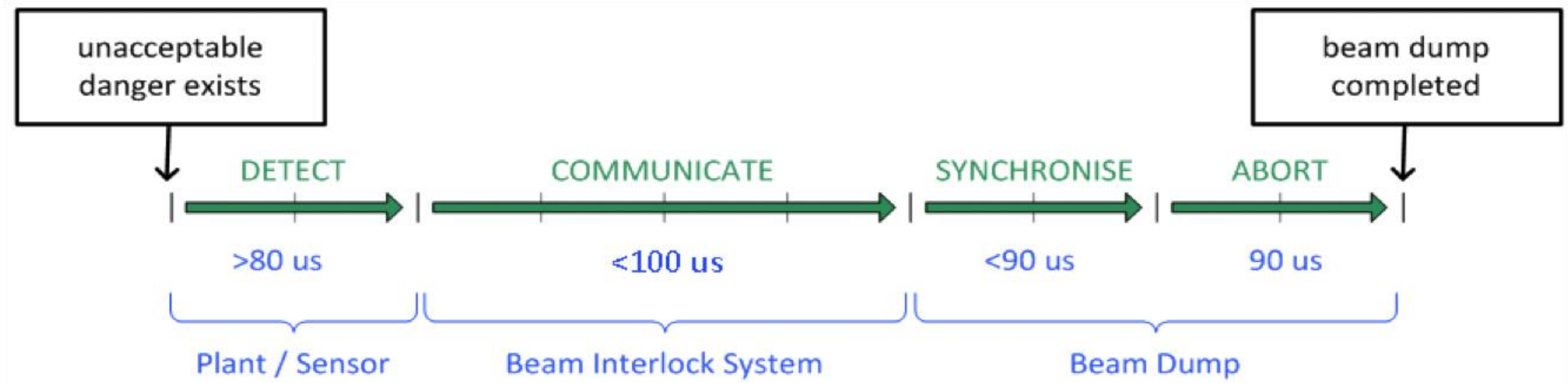
Trajectory perturbation of beam 1 after dump of beam 2, 4TeV, 0.9e11p/b, 84b, 25ns, IP5-xing=68urad, 13.12.2012 08:26:54

T.Baer

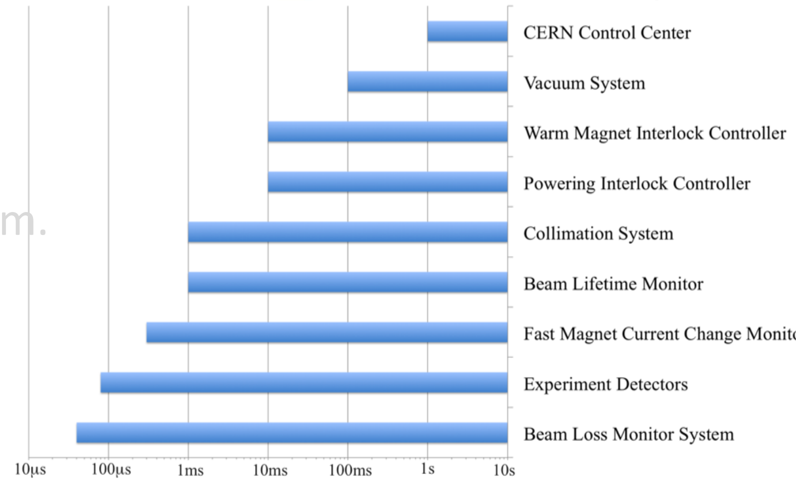


0.6σ single turn orbit perturbation **measured** @4TeV ➔ increase to **0.9-1.1σ expected** for HL-LHC

Recap of current assumptions for LHC MP systems



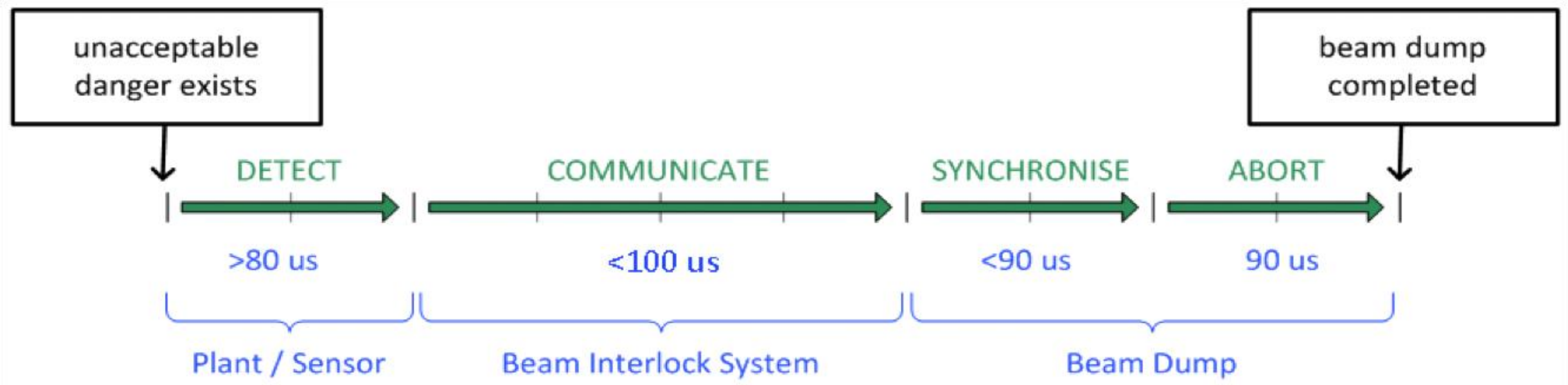
- Ultra- Fast failures (< 3 turns):
  - Beam injection from SPS to LHC.
  - Beam extraction into dump channel.
  - Missing beam-beam kick after dump of one beam.
- **Fast failures (< few milliseconds)**:
  - Detected by: BLMs (>40us), FMCM (~100us), Beam Life Time monitor (~200-300us), …
  - Equipment failure with **fast effect on orbit**: e.g. **D1** separation dipole (IP1/5) fastest failure with circulating beam.
  - **UFOs**.
  - Crab Cavity failure modes



Reaction time sufficient for HL-LHC optics (25% faster failure) even without replacing D1 by superconducting magnet.

Could/will? replace D1 as fastest LHC failure with circulating beam

Recap of current assumptions for LHC MP systems



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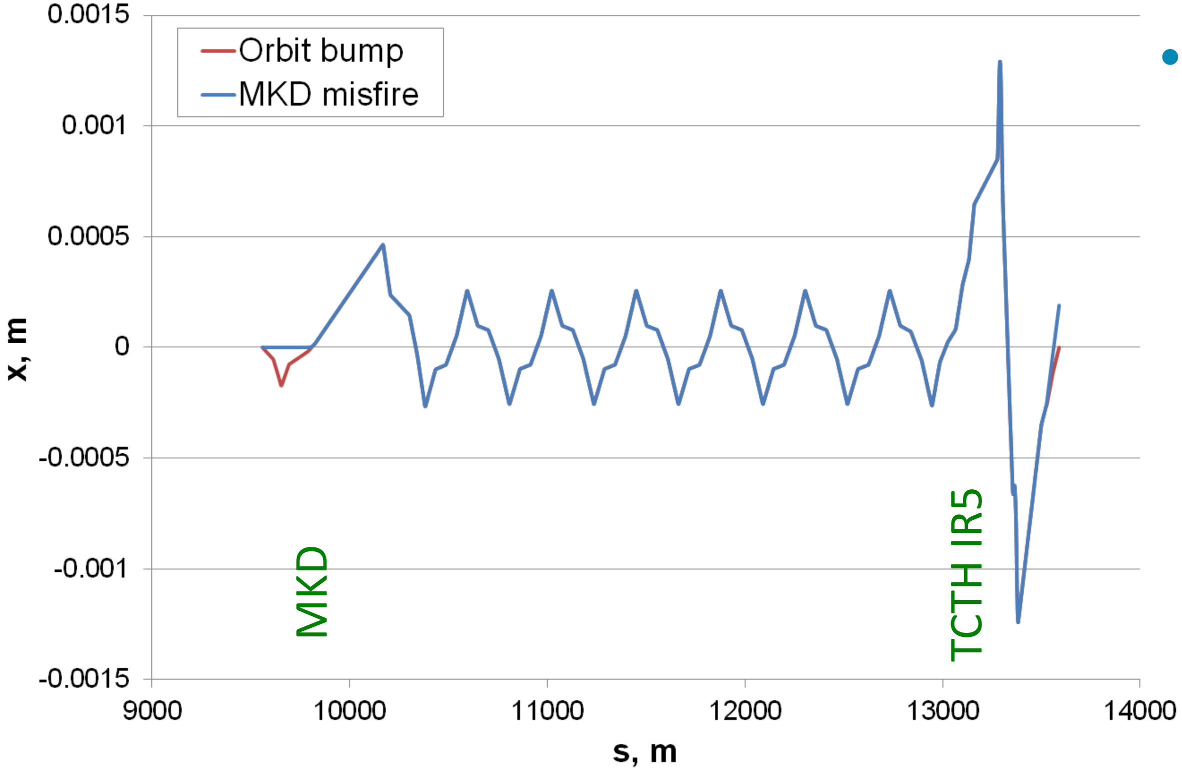
  - Missing beam-beam kick after dump of one beam.
- Fast failures (< few milliseconds):
  - Detected by: BLMs (>40us), FMCM (~100 us), Beam Life Time monitor (~100μs), …
  - Equipment failure with **fast effect on orbit**: e.g. **D1** separation dipole fastest failure with circulating beam.
- **Slow Failures (> few milliseconds)**:
  - Instabilities, Magnet quenches, Moving devices, …
  - Multi-fold redundancy (BLM, PC, QPS, RF, …)

→ Not expected to have significant impact on MP considerations for HL-LHC, **BUT** likely to become an **increasing challenge** for **Machine Availability**!

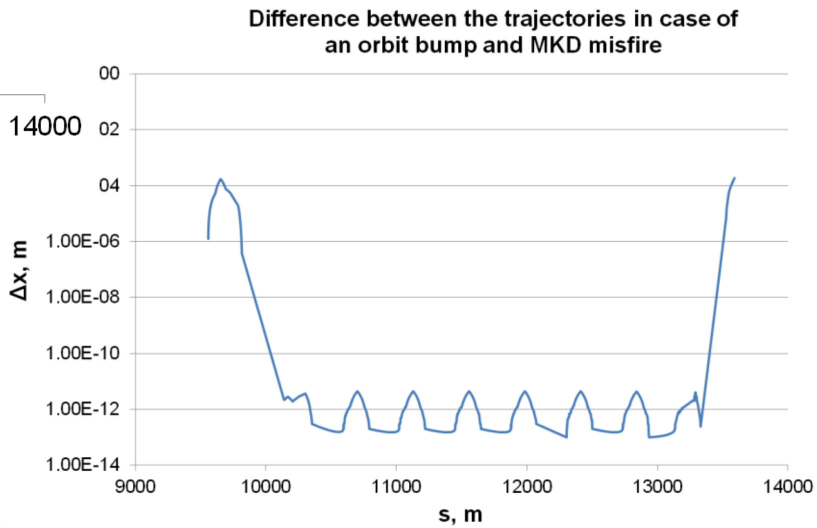
Phase advance between MKDs (IP6) and TCTs/triplet in IP5 (ATS, B2)

- Novel method based on closed orbit bump for verification of protection margins of collimators and beam absorbers between dump (IP6) and triplet (IP5). [V. Chetvertkova et al.]
- Inversion of crossing and separation plane for HL-LHC ATS optics to gain margin in aperture? (email discussion G. Arduini, R. Bruce, R. de Maria, S. Redaelli, D. Wollmann)
- Update on TCT damage levels? Damage levels for TCTs with new materials?

Verification of protection margins IP6 (MKD/TCDQ) → IP5 (TCT/triplet) with closed orbit bump

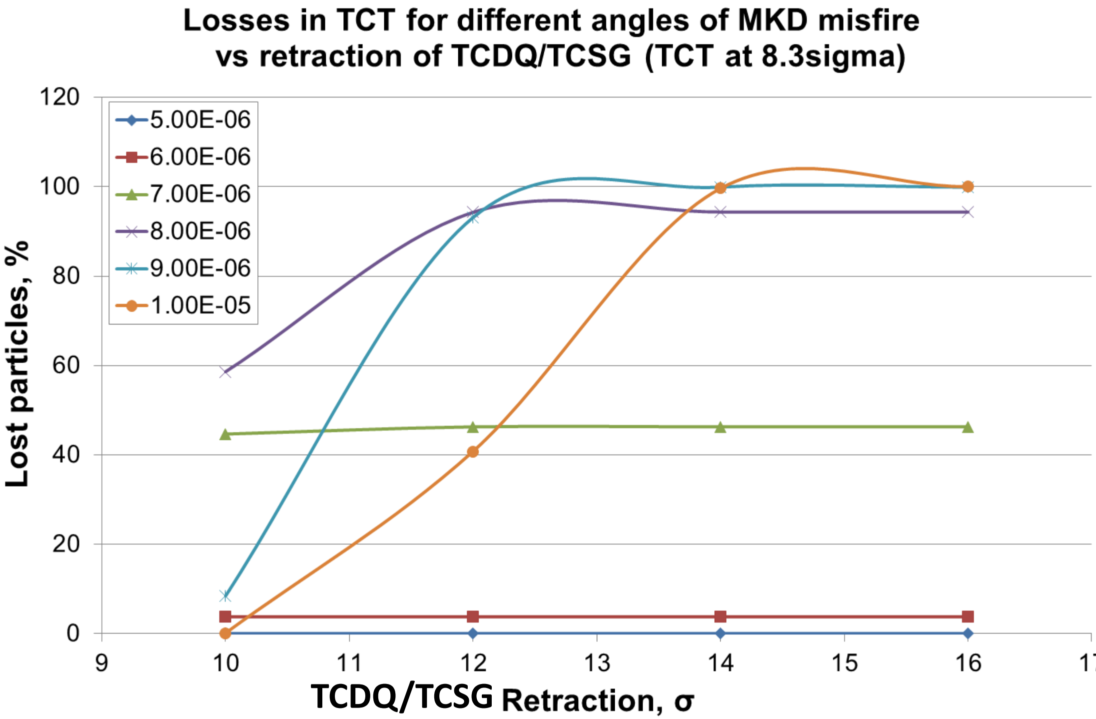


- Particle trajectories with closed orbit bump and during MKD misfire are practically equivalent.



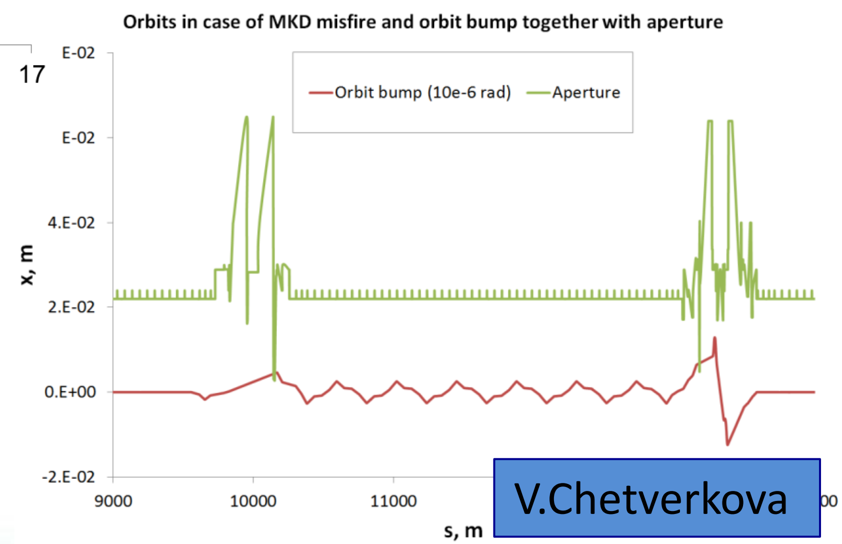
V.Chetverkova

Verification of protection margins IP6 (MKD/TCDQ) → IP5 (TCT/triplet) with closed orbit bump



Measurements with several pilot bunches:

- Implement bump.
- Reduce retraction between TCDQ/TCSG and TCT respectively TCT and triplet aperture in increments.
- Blow out one pilot bunch after each change.



V.Chetverkova

- Test method in ATS MD in 2015.
- Study if method can be extended to B2 IP6->IP1 and nominal LHC optics B1 IP6-IP1.

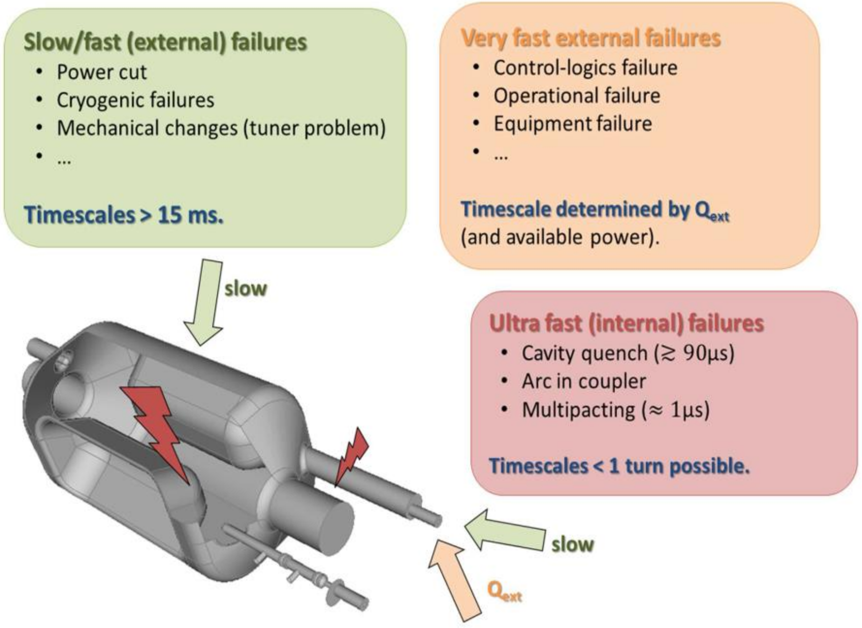
Inversion of crossing and separation plane

Email Gianluigi:

- In the present layout/optics we have a vertical/horizontal crossing angle in IP1/5 respectively
- From the discussions that followed the validation of the ATS for 2015 I understood that we might have to go to horizontal/vertical in IP1 and 5 as we have little margin to change the phase advance between point 6 and 5 for beam 2 while we have more margin for the phase advance between 6 and 1 for beam 1 and for HL-LHC we do not have the constraint of the orientation of the beam screens.
- This is to avoid (to my understanding) dangerous situations in case of an asynchronous dump.
- Do you agree? Do you think it would be good to discuss this in a joint meeting and then bring it up at the PLC so that we can then update the optics layout for the next version taking this into account?

Crab cavity failures – modeling, tracking in simulations

- SixTrack with crab cavities (T.Baer and B.Yee Rendon):
  - **Who** maintains and updates? (→ WP5, WP8?, ABP)
  - Important to keep **possibility to study the effects of fast failures**, based on first measurements in experiments (SM18, SPS).
  - Can/will crab cavity module be **implemented** into the SixTrack **repository**?



SPS Test Program And Objectives

Objectives:

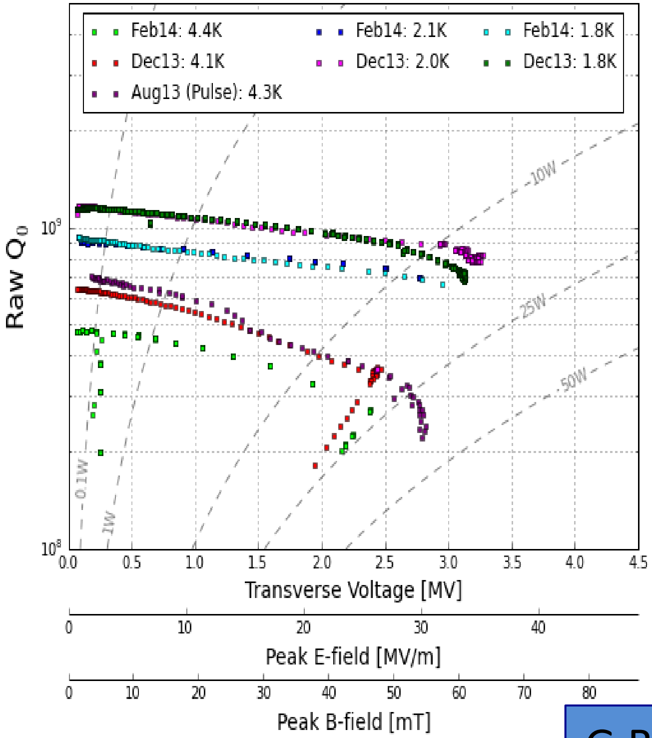
- Demonstration of cavity deflecting field with proton beam including injection, energy ramp and coast at energies ranging from 26-450 GeV.
- Verification and control of cavity field (amplitude and phase), frequency, tuning sensitivity, input coupling, power overhead and HOM signals. Establish and test operational cycle with crab cavities.
- Demonstrate the possibility to operate w/o crab cavity action (make them invisible) by both counter-phasing the two cavities or by appropriate detuning (to parking position) at energies ranging from 26-450 GeV.
- Measurements of beam orbit centering, crab dispersive orbit and bunch rotation with available instrumentation such as BPMs and head-tail monitors.
- Demonstrate MFB operation.
- Demonstrate non-correlated operation of two cavities in a common CM – trigger quench in one cavity without inducing quench in the other.
- Define and implement interlock hierarchy. Verification of machine protection aspects and functioning of slow and fast interlocks.
- Test HOM coupler operation with high beam currents, different filling schemes and associated power levels. Measurement of impedance and instability thresholds for nominal mode and HOMs.
- Measure emittance growth induced by the crab cavities as far as possible.

G.Burt

High Luminosity LHC

SPS Test Program And Objectives

- CCs tested in SM18 are equipped with up to 30 relative density monitors to localize and analyze quench behavior, work ongoing to resolve time structure based on power signals
- During SPS tests 1 (aiming to be ready for installation in EYETS early 2017) dedicated MD slot foreseen for machine protection (LLRF failure modes, diagnostics,..)
- PhD student to work on quench types, genuine input on what CC can really do expected in 2015
- Trigger work on quench modeling for sc cavities, e.g. Uni Wuppertal (G.Mueller), HZ Berlin BESSY (Jankowiak)?



G.Burt

Study of Magnet Damage limits – Scientific Motivation

- Transient beam losses cause local shock heating in sc. magnets → shock wave:
  - Damage of insulation (to ground, turn-by-turn)
  - Degradation of sc. properties of cable,
  - Degradation of mechanical stability.
- Max. allowed shock heating un-know: 50 – 1000J/cm^3
- Improved understanding required as input for upgrade of passive protection elements due to increased beam brilliance from LHC injectors.

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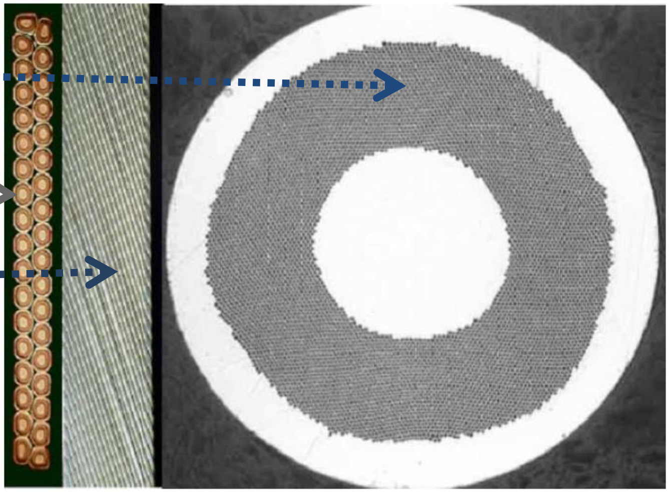
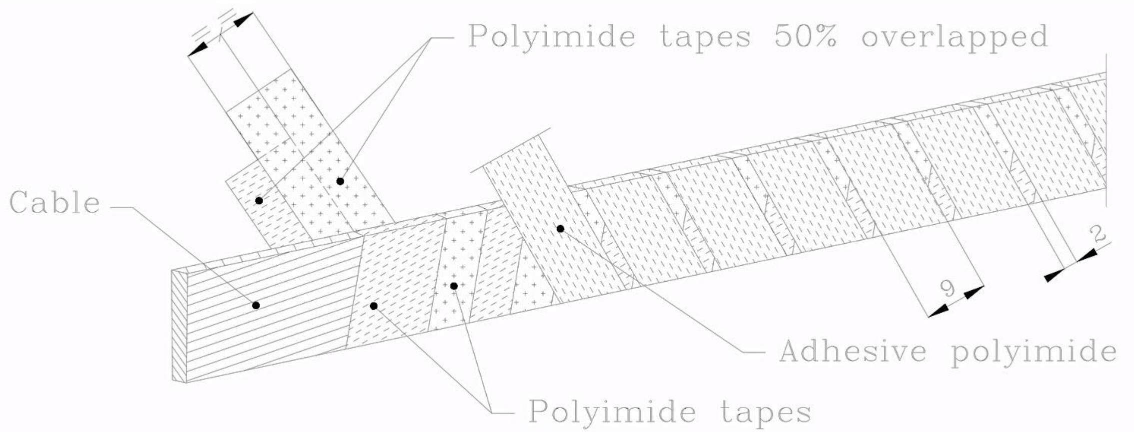
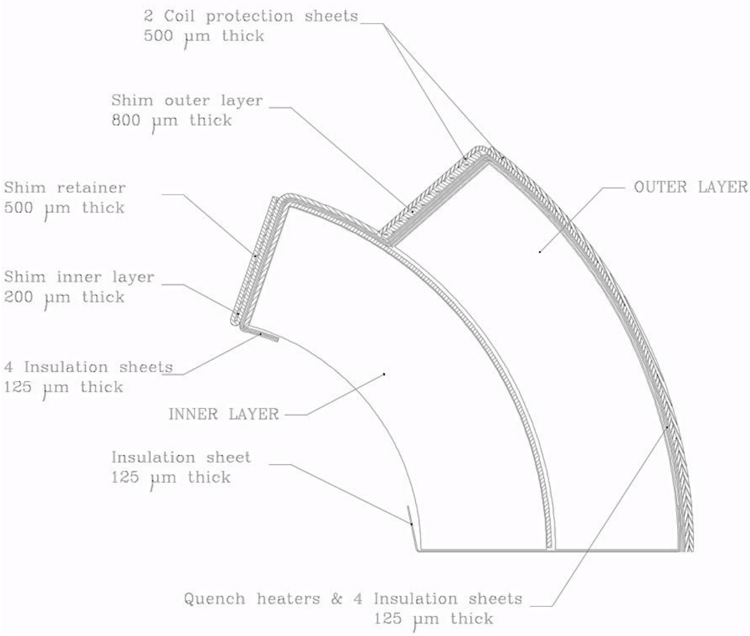
Critical parts of sc magnet (1)

- Sc. filaments
- Sc. strands
- Cables
- Insulation (cable-cable, cable to ground, cable to quench heater, …)







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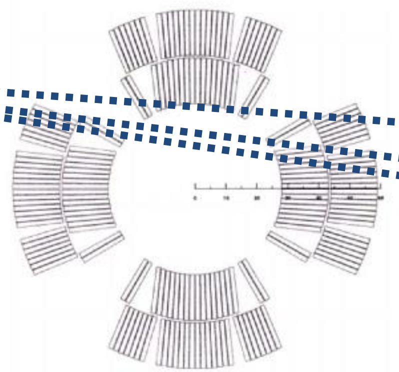
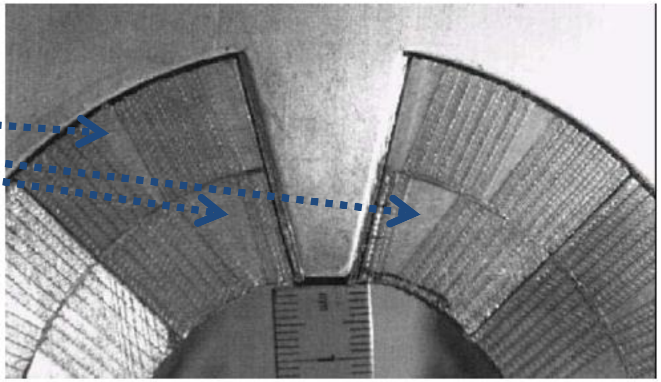
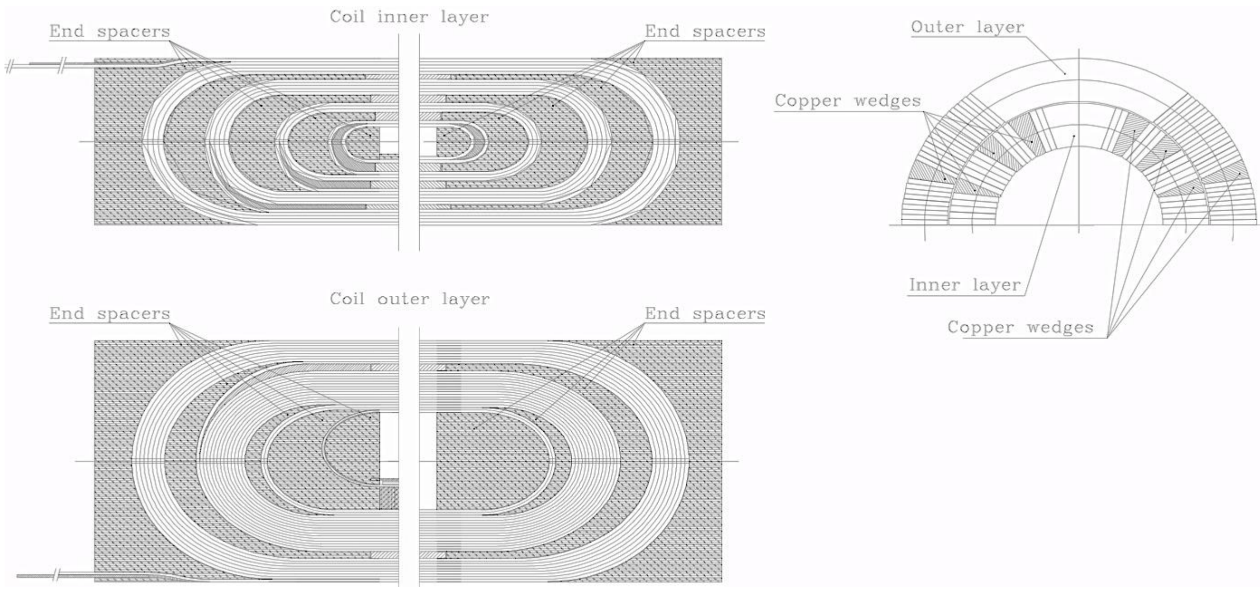
Critical parts of sc magnet (2)

- Wedges and end spacers.
- Helium between layers.
- Structural stability through epoxy.
- Splices.
- …







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Scientific Motivation – Ultra fast failures

- Asynchronous beam dump: tolerated failure mode (1x per year), magnet quenches to be expected; will Q4/Q5 experience damage with future increased beam intensities? → limit of bunch intensities or re-design mask required?
- Injection failures: regular failure mode (several times per year), quenches to be expected; will D1 experience damage? → limit bunch intensity of re-design of mask required?
- Three 120A inner triplet corrector circuits found open after MKI flashover 28.07.2011 → damage mechanism not understood → comparable limitations for other magnets?

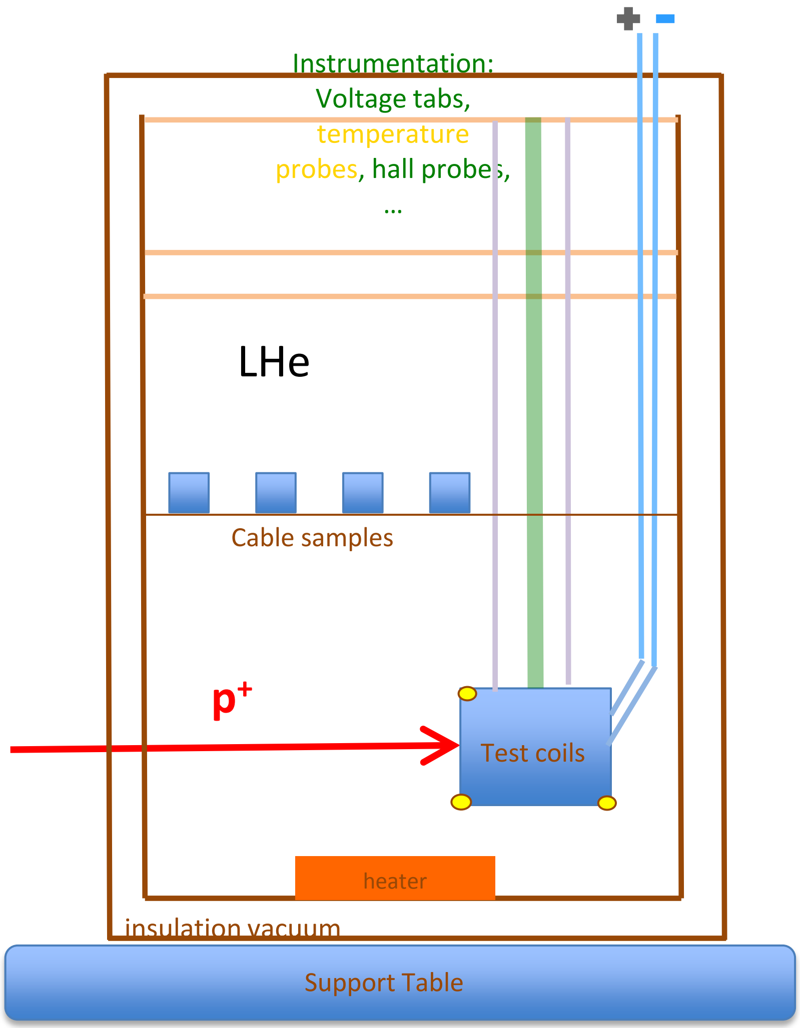
Scientific Motivation – transient beam losses

- Quench limits of sc. magnets well understood.
- Damage limits of materials well understood.
- Damage limits of sc. magnets before structural damage of materials (melting etc.) not known.

- → Measure damage limits of sc. magnets due to transient beam impacts.
- Beam time requested at CERN's HiRadMat facility for second part of 2015.

High Luminosity LHC

Experimental setup



Samples:

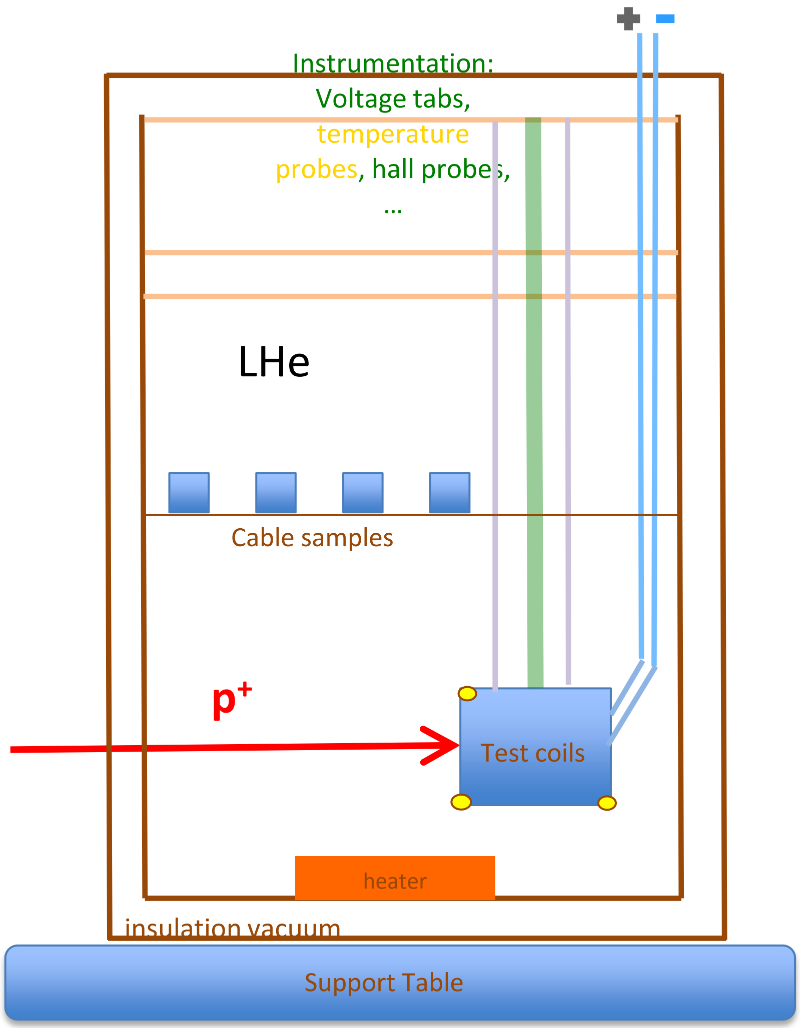
- 4 coil samples (in-situ measurement: electrical integrity /insulation, critical current; PM analysis: microscopic studies)
- ~20 cable samples (PM analysis: magnetization, microscopic measurements)
- LHe cryostat (~500l, max. 3 x refilling)
- X-Y table, which allows rotation of max. 120degree.

Instrumentation:

- Diamond detectors (particle showers).
- CERNOX temperature sensors.
- HV measurement (after each shot)
- Critical current measurement (after each shot)

V. Raginel, D.Wollmann

Requested Beam Parameters



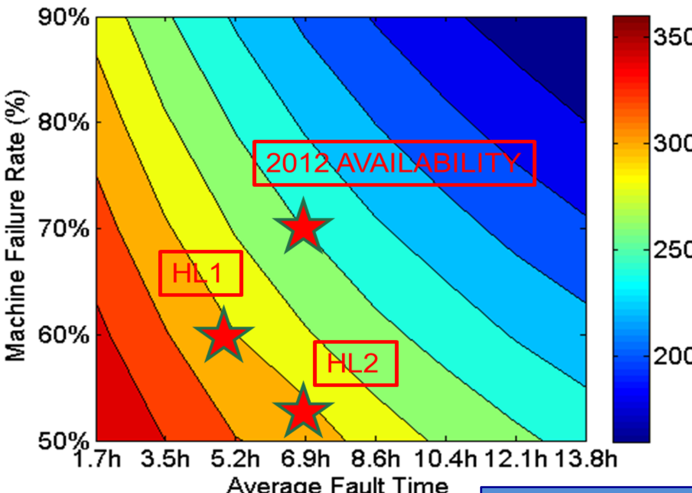
- Pulse intensity: 1e9 -1e13p
- Bunch intensity: 1e9 – 1.5e11
- Spot size: 1-2mm ($sigma_{x,y}$)
- Number of pulses:
  - 20 shots per sample coil (increasing energy deposition with hot spot temperatures from 50 to 400K).
  - 1 shot per cable sample (hot spot temperature varying from 50 to 400K).
- Integral intensity < 4e14 p

→ exact shot intensities will be calculated with FLUKA.

V. Raginel, D.Wollmann

Machine availability

- Increasing integrated luminosity in HL-LHC only possible with **longer time** in collision → Machine **availability** becomes key factor.
- To achieve 300fb^{-1}/year **global increase of availability by 20%** required (in addition to already planned improvements; 200 days operation).
- 1/3 of failures/fault time due to R2E affects (→ mitigations during LS1 and run2 [FGC lite]), **2/3 due to other effects**.
- **Effects besides R2E** are likely to play a dominating role in the future → **extend availability studies** to append allowed un-availability per system and extend to **more systems**.
  - Possible **shortening of LHC cycle** by installing 2 quadrant PCs for MQs→ ~10% gain for stable beams time.
  - Reduction of (generous) **safety margins** in interlock levels (Vacuum thresholds, BLMs, …) could reduce machine failure rate.



A.Apollonio

Quench and magnet protection

- **Beam induced quench workshop** 15.-16.09. @ CERN:
  - Experience with beam losses and beam-loss monitoring has been combined at CERN.
  - CERN has taken the analyses of beam-loss events (based on the superior diagnostic data) to a new level.
  - Modeling of stability limits in He-II-cooled Rutherford cable is still exceedingly difficult.
  - BLM thresholds try to incorporate all of the above in order to maximize availability and keep the LHC safe.
- Development of **novel tools for modeling** superconducting magnets and circuits, with particular attention to beam induced quenches has started → collaboration with University of Darmstadt, Germany.
- **CLIQ** (coupling-loss induced quench system):
  - 1000+ CLIQ tests on solenoid magnets performed.
  - 50+ CLIQ tests on HL-LHC quadrupole model magnets (1-2 meters, Nb-Ti and Nb3Sn).
  - CLIQ-based protection of the full-size **HL-LHC quadrupole magnet** is being simulated and designed.
  - Next CLIQ testing campaigns (December/January): **15 m LHC Main Dipole**, LHC spare quadrupoles, 11 T dipole, 170 H solenoid, …?

History of Quench Tests and Analysis (M. Sapinski)

BLM, collimation, and LIBD teams pushed from the beginning for controlled beam-loss experiments causing quenches, with the goal to explore quench levels in the machine for different scenarios.

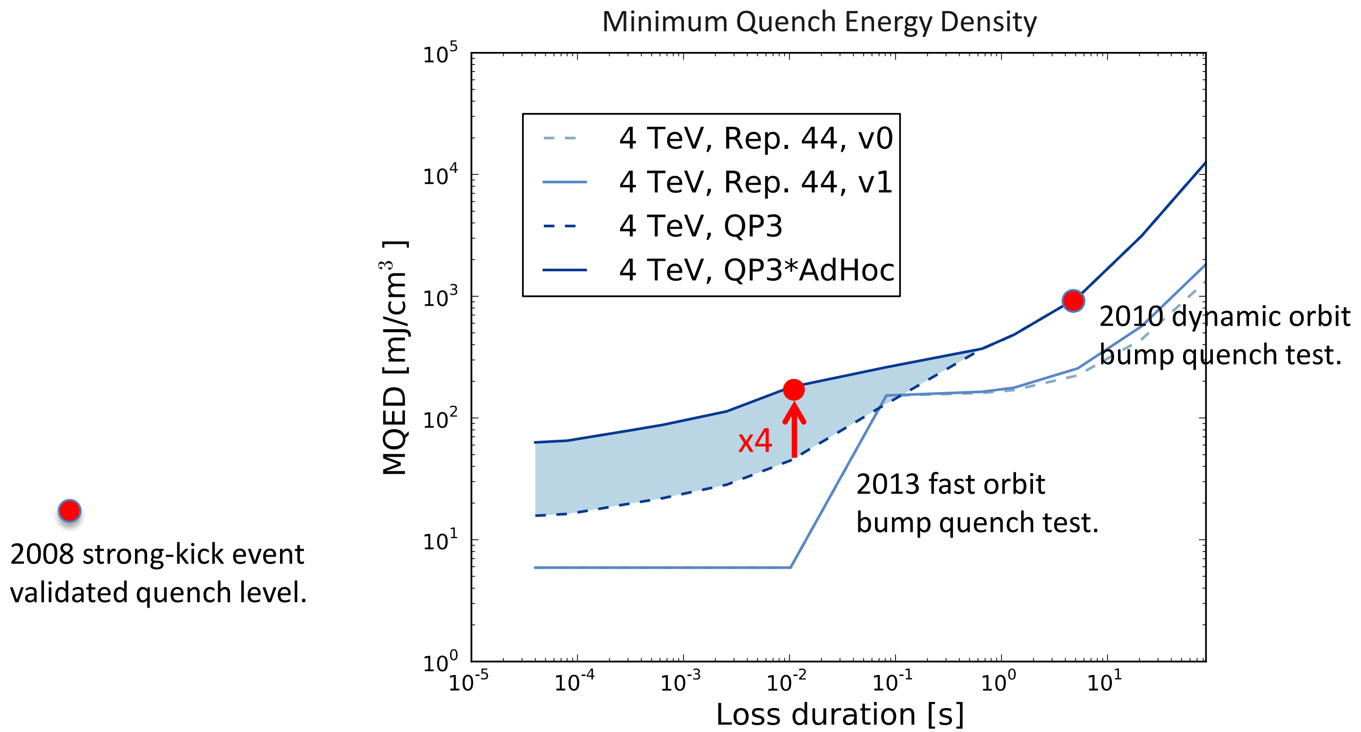
With every year the methods grew more sophisticated, both, in beam-loss generation and analysis technique.

Year	Method	Analysis
2008	Accidental kick	Geant4, D. Bocian quench levels
2010	First beam-dumping UFO	Start thinking about QT in the UFO time-scale
2010	Dynamic orbit-bump (1-6 s)	Geant4, QP3
2010	Wire-scanner (20 ms)	Geant4, QP3
2011	Collimation quench tests with p and Pb (1-10 s)	No quenches. Very short losses for Pb.
2011	Shot on TDI (x ns)	No quench in Q6.
2013	End of run campaign: • Shot on TDI (x ns) • Fast-loss ADT excitation (10 ms) • Slow-loss ADT excitation (20 s) • Collimation with ADT (15 s)	MAD-X, SixTrack, FLUKA, QP3, THEA Full analysis in QTAWG ~ 1 year.

Applying AdHoc factor to QuenchLevel

Outcome of the orbit-bump quench test: Factor 4 higher quench level in the 10-millisecond time range and possibly below.

We propose to start after LS1 with an optimistic correction of electro-thermal model between 40 µs and 10 ms.



CONCLUSIONS

- Work ongoing on several fronts to help defining requirements for new (HL-)LHC protection elements (injection protection, absorbers,..)
- Major effort still ongoing to define and implement new quench limits into protection systems. New limits will be experimentally confirmed (and officially published) after first months of run2 experience
- Awaiting first experimental results from SM18/SPS tests for CC before investigating (major) upgrades of interlock systems
- Will need better quantification of margins in many domains to increase machine availability in view of HL-LHC (TCTs, quench limits, interlock levels, orbit,…)

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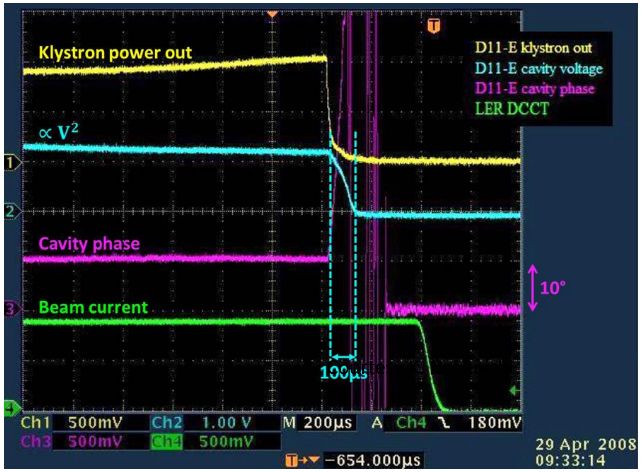
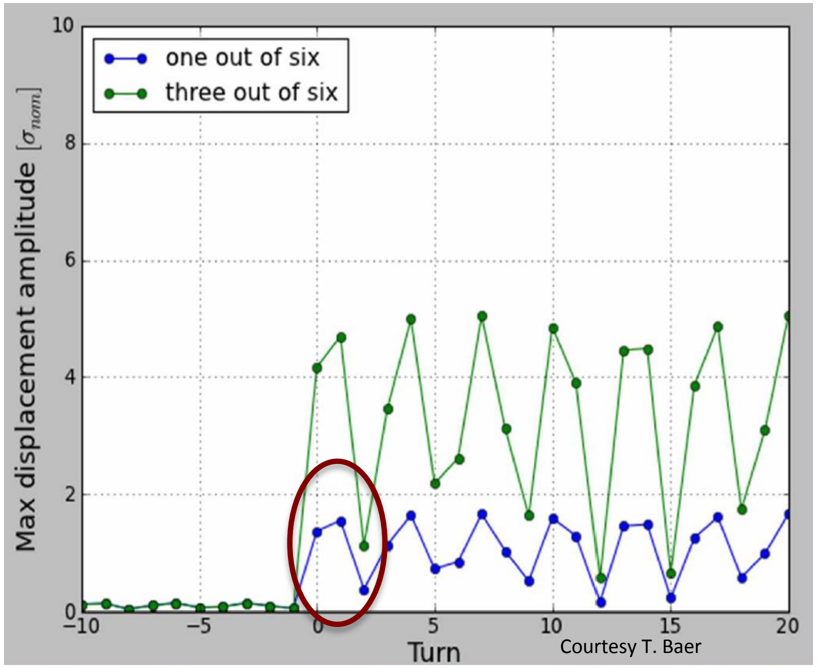
Backup slides

New ultra fast failures due to Crab Cavities

- 3 CCs per side of IP1/5.
- 3.3MV pro module.
- Voltage decay within **100μs** and large oscillations observed in KEKB.

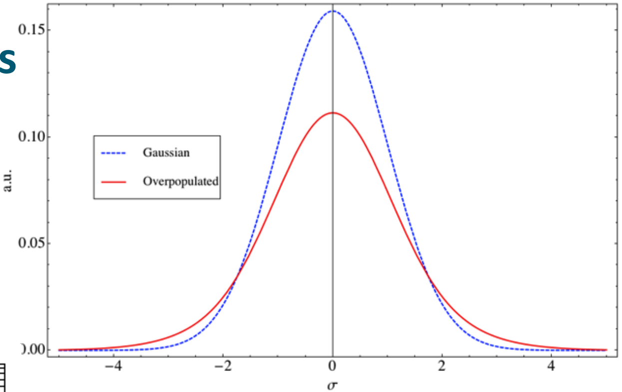


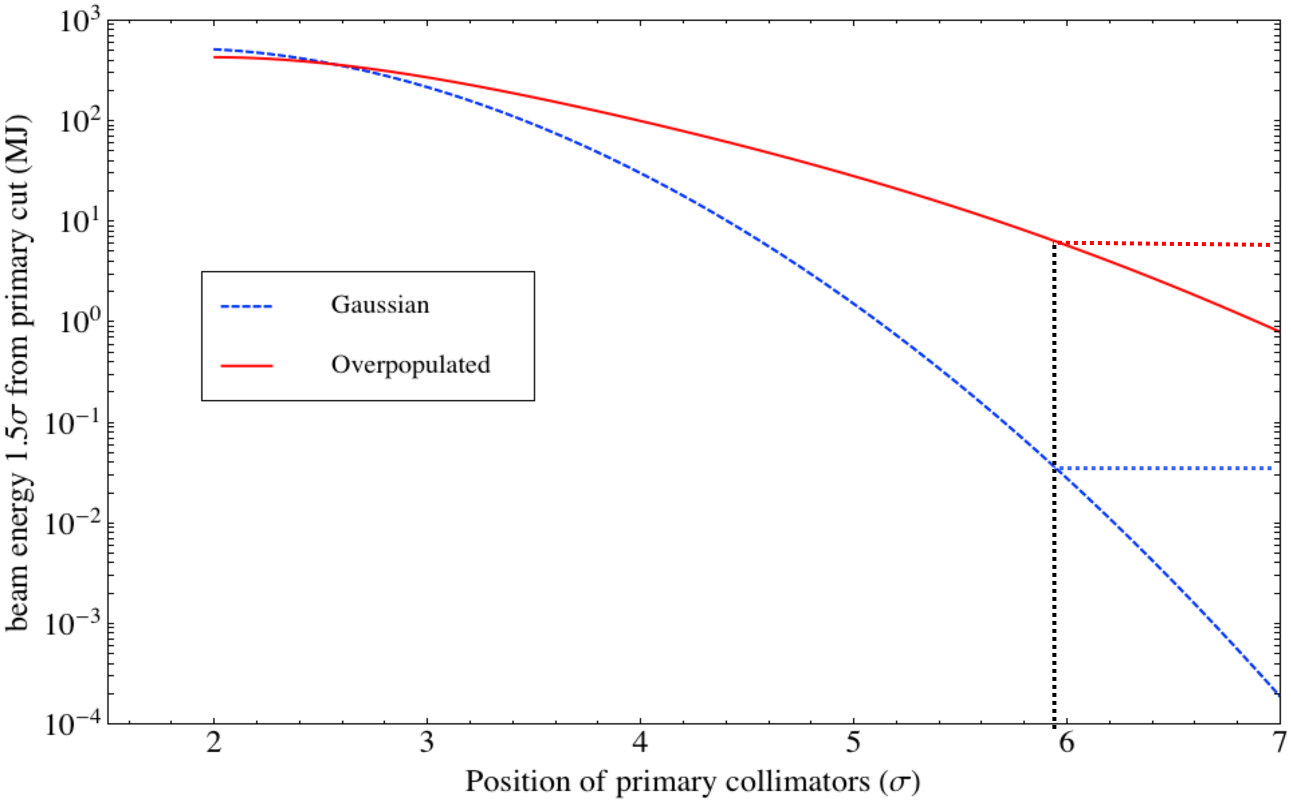
- Tracking simulations predict **orbit distortion of 1.5σ** within the **first turn** after the instantaneous drop of the deflecting **voltage in a single CC**.
- Orbit distortion **modulated by β-tron tune**.



Expected energy lost due to 1.5σ beam shift

- Measurement in LHC showed beams with **overpopulated tails** (2% of beam outside 4σ). [F. Burkart, CERN Thesis 2012 046]
- Fraction of beam **1.5σ inside** of the primary collimators (6σ): 4e-5 (28kJ) ➔ **8e-3 (5.8MJ).**





- Tracking studies show that **~1/3** of this beam is lost within the first 3 turns.

(See **B.Y. Rendon et al.** *Simulations of Fast Crab Cavity failures in the High Luminosity Large Hadron Collider)*

- Thus, **2MJ** of beam impacting on collimators ➔ above damage limit.

High Luminosity LHC

Possible mitigation strategies

- **More and weaker** (less voltage) crab cavities per side of IP.
- Very **fast LLRF** control.
- Partial **depletion of halo** (1.5s outside of primary collimators): Hollow electron-lens, tune modulation, excitation of halo particles with ADT, … .
- Monitoring and **interlocking** of halo population.

New schemes may need 4 CC with max 6.6 MV → **double** kick expected.

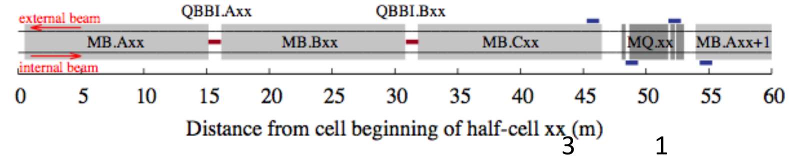
Reduced detection time budget and redundancy in BLMs (depends on halo).

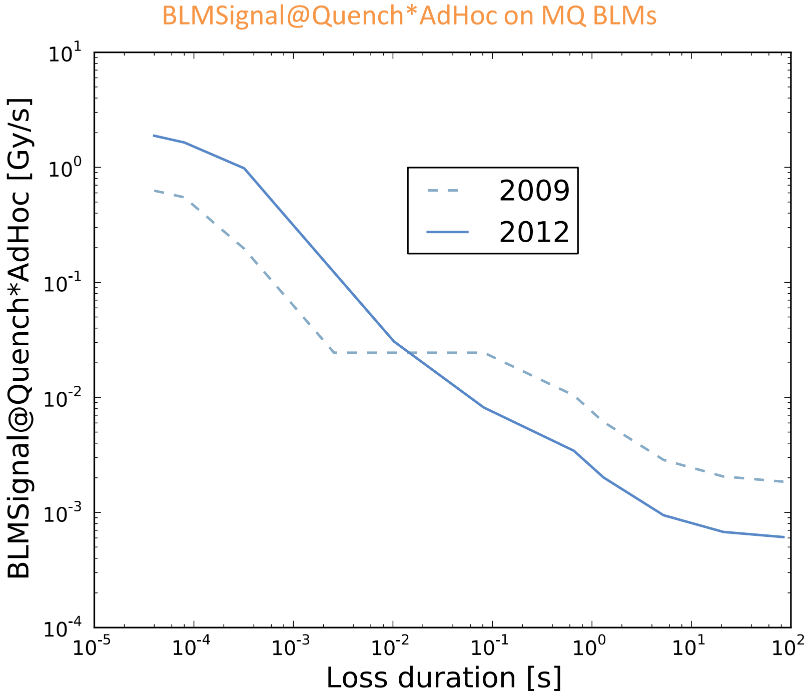
High **reliability** method required**.**

- **Tests of crab cavities** in SM18 and the SPS ongoing or in preparation → confirm **worst case** voltage and phase **failures** (incl. time scales).
- **Efficiency** of hollow e-lens or alternative methods in LHC has to be shown.

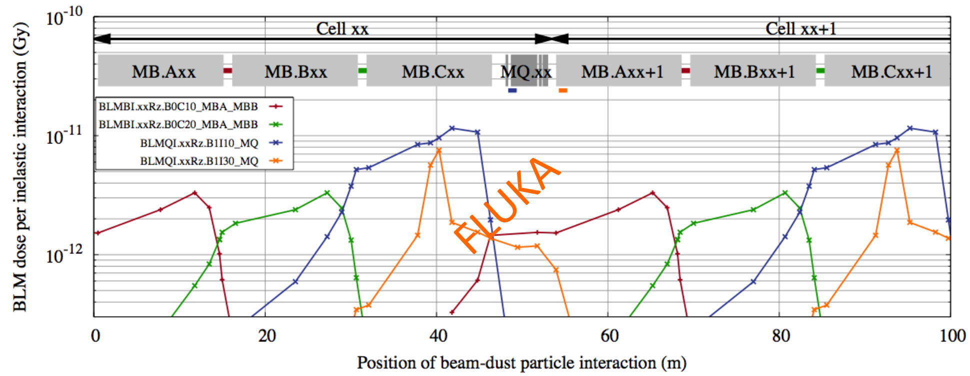
Arc thresholds

BLM-thresholds after LS1





BLMResponse



EnergyDeposit

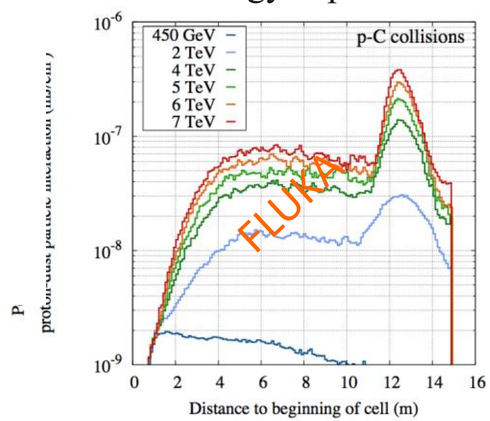


Figure: Peak energy density in MB coils per proton–dust particle interaction for different beam energies. The dust particle is assumed to be composed of carbon.

QuenchLevel