State-of-the-art and Future Challenges for Machine Protection Systems

IPAC14, Dresden, 20th June 2014

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Acknowledgements: R. Schmidt, M. Zerlauth, D. Wollman, S. Redaelli, G. Valentino, B. Dehning, C. Bracco, J. Uythoven, V. Kain (CERN), M. Werner, T. Lensch (DESY), G. Stancari (FNAL)

- [x] Introduction
- [ ] Material robustness
- [ ] Instrumentation
- [ ] Collimation and halo
- [ ] Availability, safety and operation
- [ ] Conclusion

MPS is…

- An accelerator consist of an ensemble of equipment. The components must be protected when powered – without beam.
  - *Superconducting magnets/cavities can quench with / without beam !*

  $\Rightarrow$ Equipment protection

- The beam adds an extra damage potential for a subset of the accelerator components – those exposed to beam.

  $\Rightarrow$ Machine protection

Machine protection is the collection of measures that protect an accelerator from beam induced damage

- Not a universal definition !
- In this presentation I will discuss Machine Protection in relation with beam

Risks and protection

- Protection is required when there is some risk.

Risk = probability of an incident
x consequences (money, downtime, radiation doses).

- Probability of an uncontrolled beam loss:
  - What are the failures that lead to beam loss into equipment?
  - What is the probability for the failure modes?

- Consequences:
  - Damage to equipment.
  - Downtime of the accelerator for repair.
  - Activation of material, dose to personnel.

MP designers mitigate probability *and* consequences

Define matrix of occurrence frequency and cost
⇒ protection requirements

⇔ SIL concept for safety

**Safety Integrity Level*

Damage potential of beams

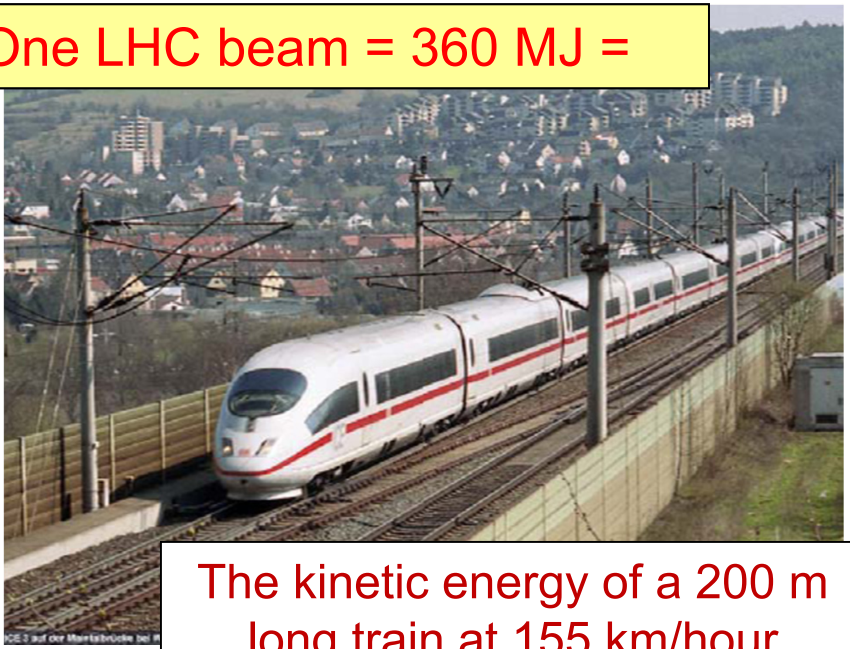
- Beam momentum
- Particle type

  Protons – ions – electrons - photons.
- Energy stored in the beam

  1 MJ can heat and melt 1.5 kg of copper.

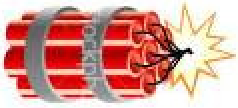
  1 MJ = energy stored in 0.25 kg of TNT.
- Beam power
- Beam size
- Time structure of beam

One LHC beam = 360 MJ =



The kinetic energy of a 200 m long train at 155 km/hour

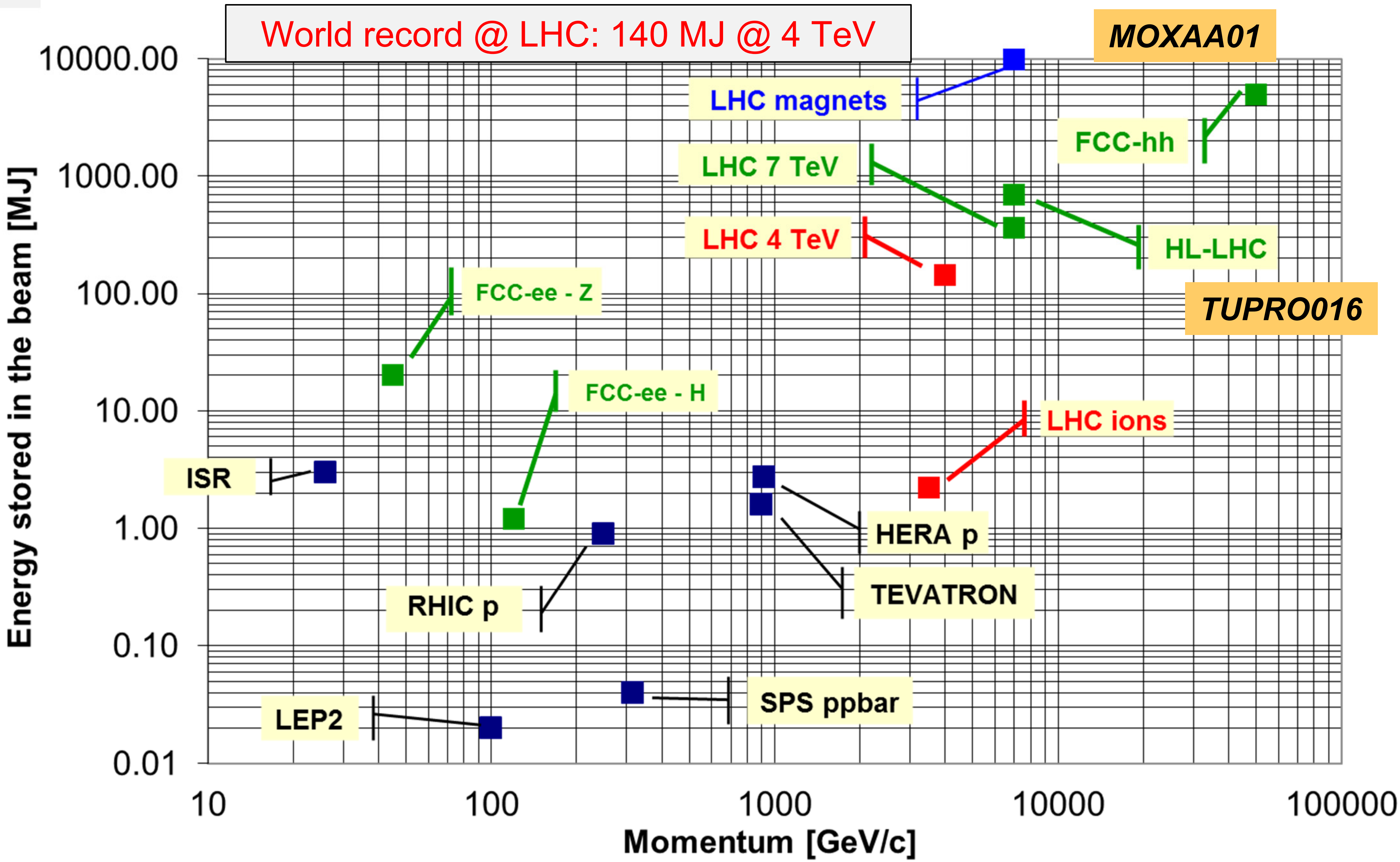
90 kg of TNT



Different accelerators (colliders, linacs, hadron - lepton) cannot always be compared directly!

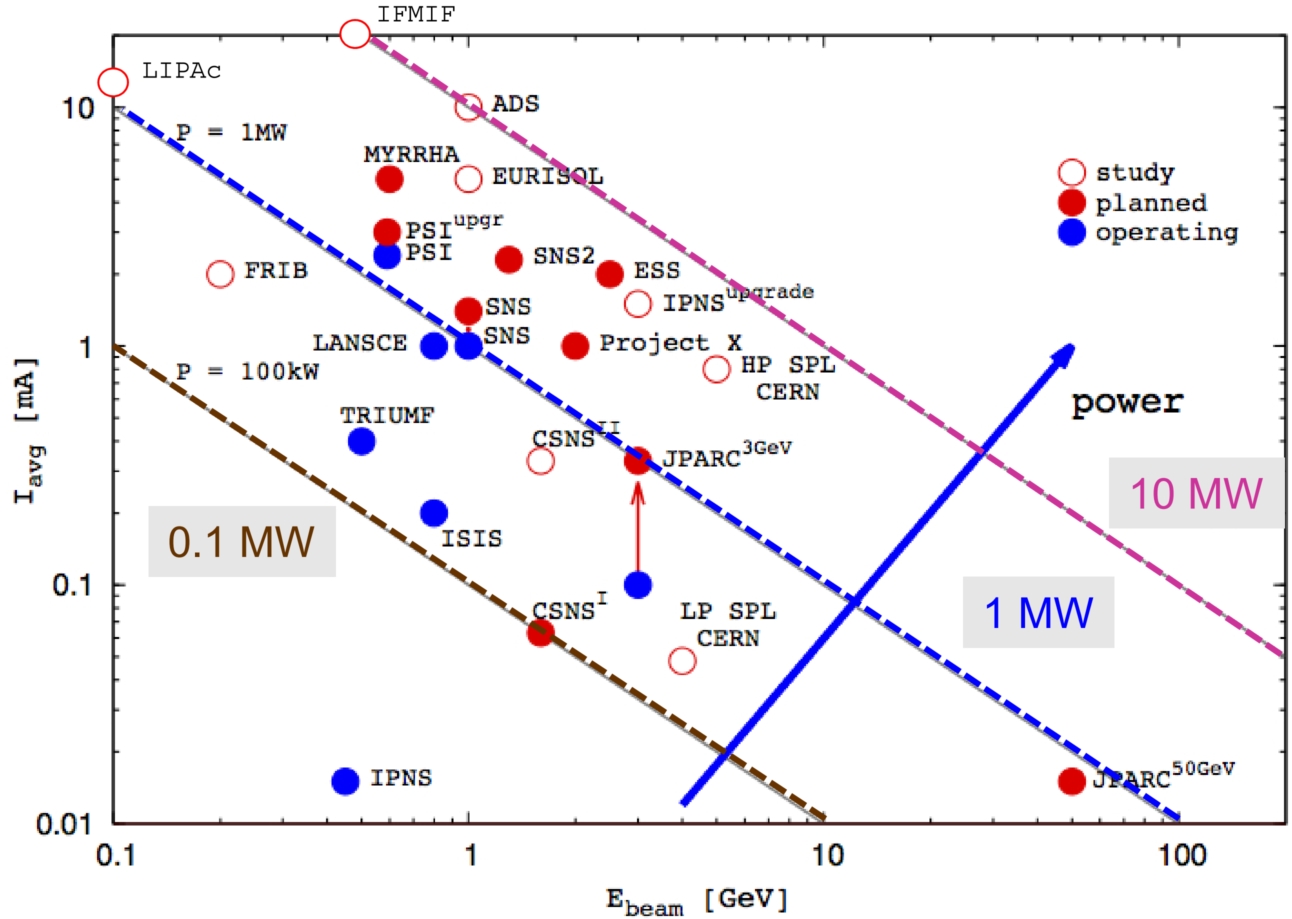
MPS challenges can be quite different !

Stored energy – colliders



Planned projects: 1-10 MW range

J. Wei -MOYBA01



ILC ~ 20 MW

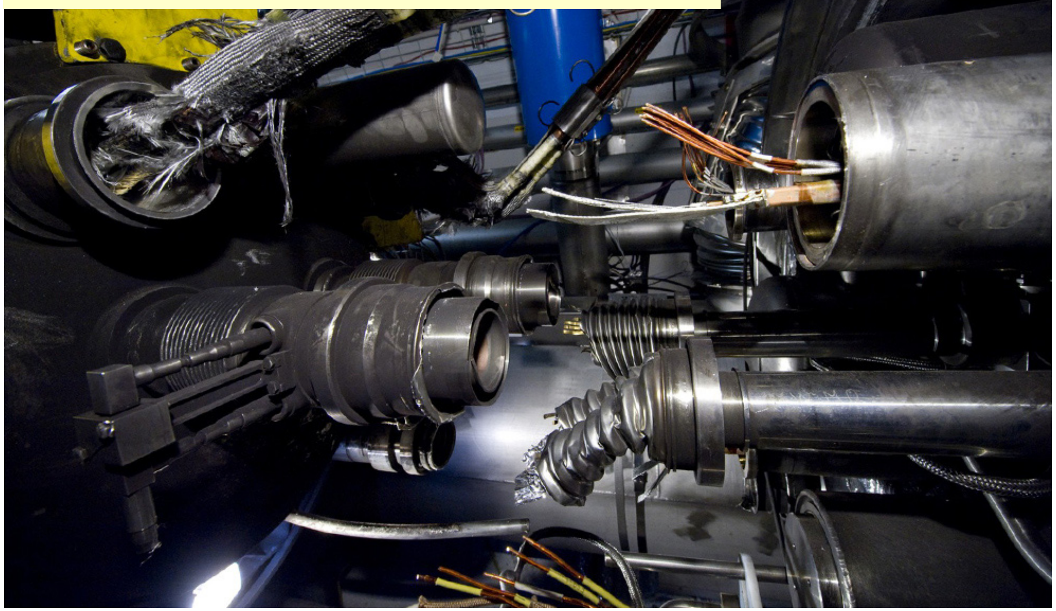
Courtesy M. Lindroos

The 2008 LHC accident happened during test runs without beam.

A magnet interconnect was defect and the circuit opened. An electrical arc provoked a He pressure wave damaging ~600 m of LHC, polluting the beam vacuum over more than 2 km.

Collateral damage from the helium pressure wave dominates !

Arcing in the interconnection



Release of 600 MJ at LHC

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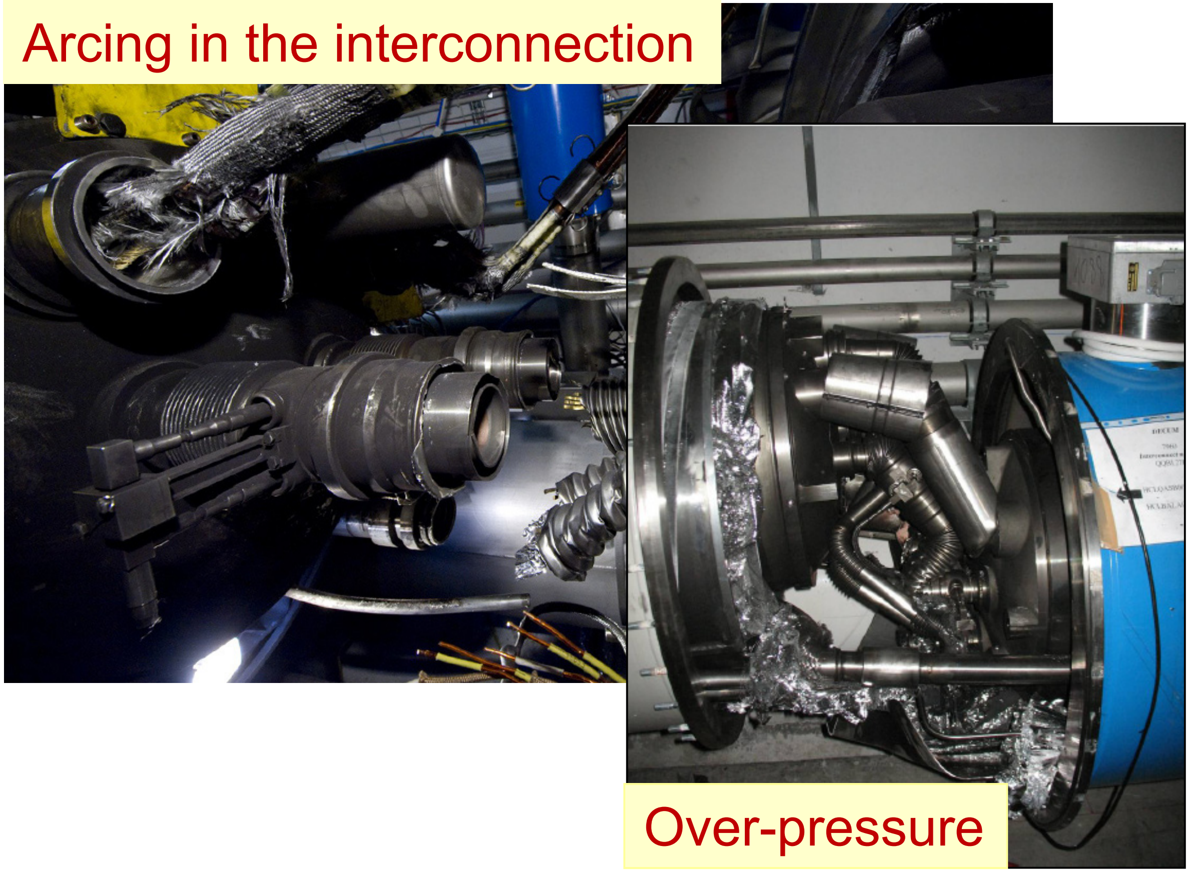

Over-pressure

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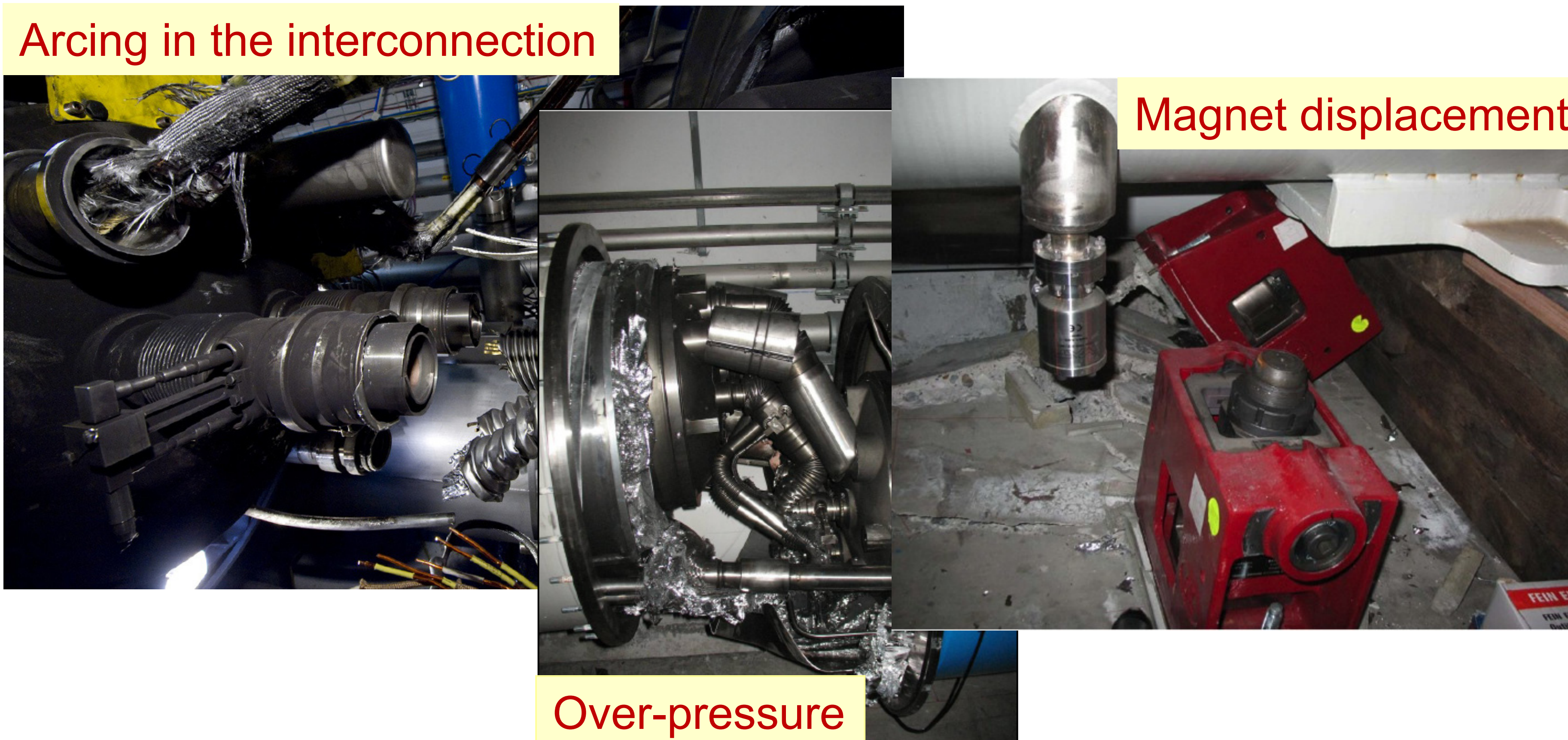

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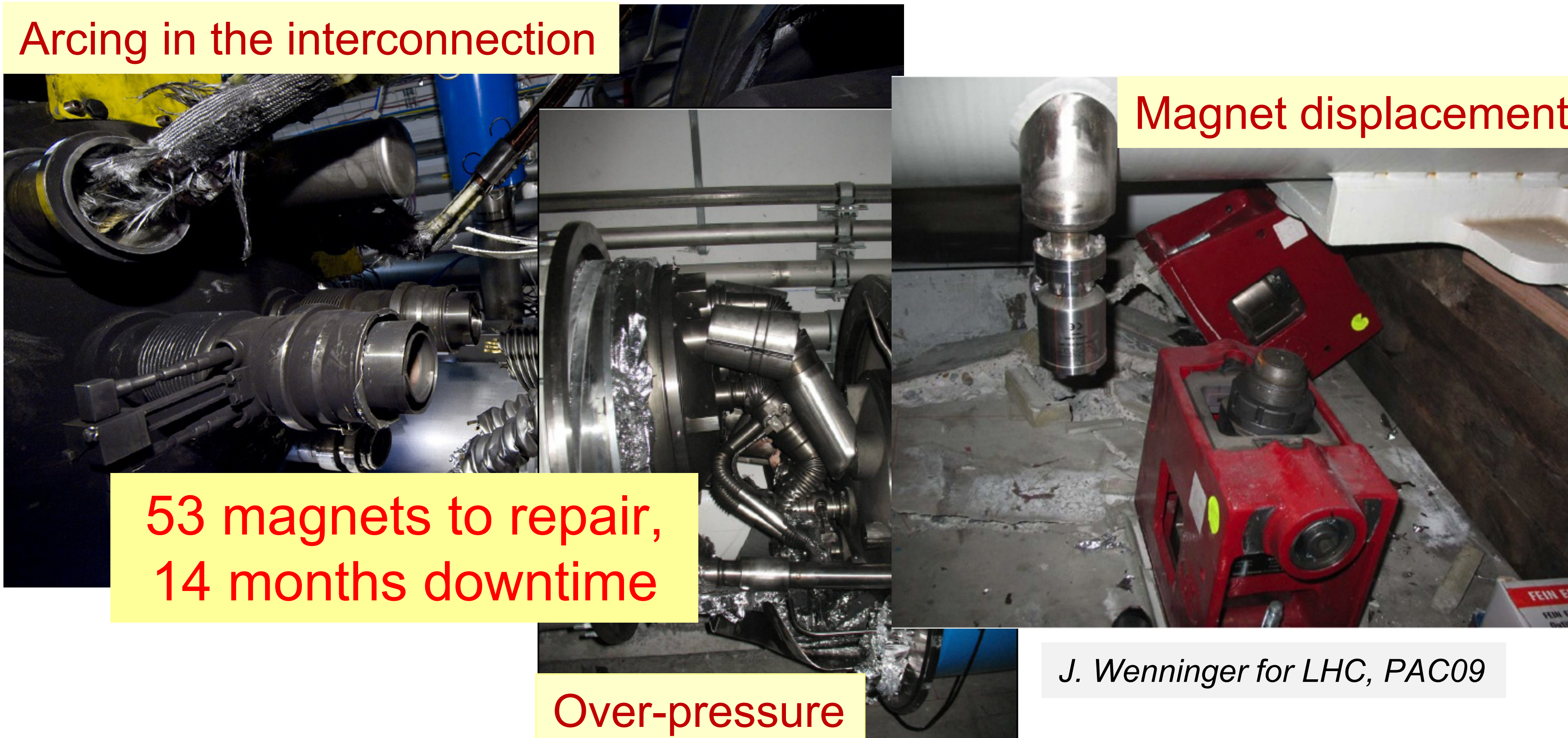

Magnet displacement

53 magnets to repair,
14 months downtime

Over-pressure

J. Wenninger for LHC, PAC09

Example from the other end of the scale…

- ***SNS short errant beams*** (~10 μs) : beam outside the normal operation envelope. Issues with beam intensity loss well below ‘classical damage’ level:

  W. Blokland & C. Peters, IBIC13

  - *Errant beam loss in SC Linac leads to accumulating damage,*
  - *Degradation of SC Linac cavity performance over time.*

  ⇒ Detailed investigations to improve the situation. Majority of trips located in room temperature linac.

- ***Damage to undulator magnets*** at FELs / light sources.

  L. Froehlich, FEL2012

  - *Degradation with low loss /radiation levels.*

Petra III - WEPRE035

Modern Machine Protection System : P³

- **Protect the machine**
  - Highest priority is to avoid damage of the accelerator.

- **Protect the beam**
  - Complex protection systems may reduce the accelerator availability, an aspect that must be taken into account at the design phase.
  - Trade-off between protection and operation.
    - Availability (targets): ~99% light sources, ~95% spallation sources like SNS, ESS, LHC so far modest 35%.

- **Provide the evidence**
  - Clear (post-mortem) diagnostics must be provided when:
    - the protection systems stop operation,
    - something goes wrong (failure, damage, but also ‘near miss’).

Modern Machine Protection System : P^3

- **Protect the machine**
  - Highest priority is to avoid dam…

- **Prot…**
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- **P…**
  - C… …ortem) diagnostics must be provided when:
    - the protection systems stop operation,
    - something goes wrong (failure, damage, but also 'near miss').

Machine protection is not limited to designing a fast interlock !

Machine protection must be closely integrated into the machine design !

Circular - linear

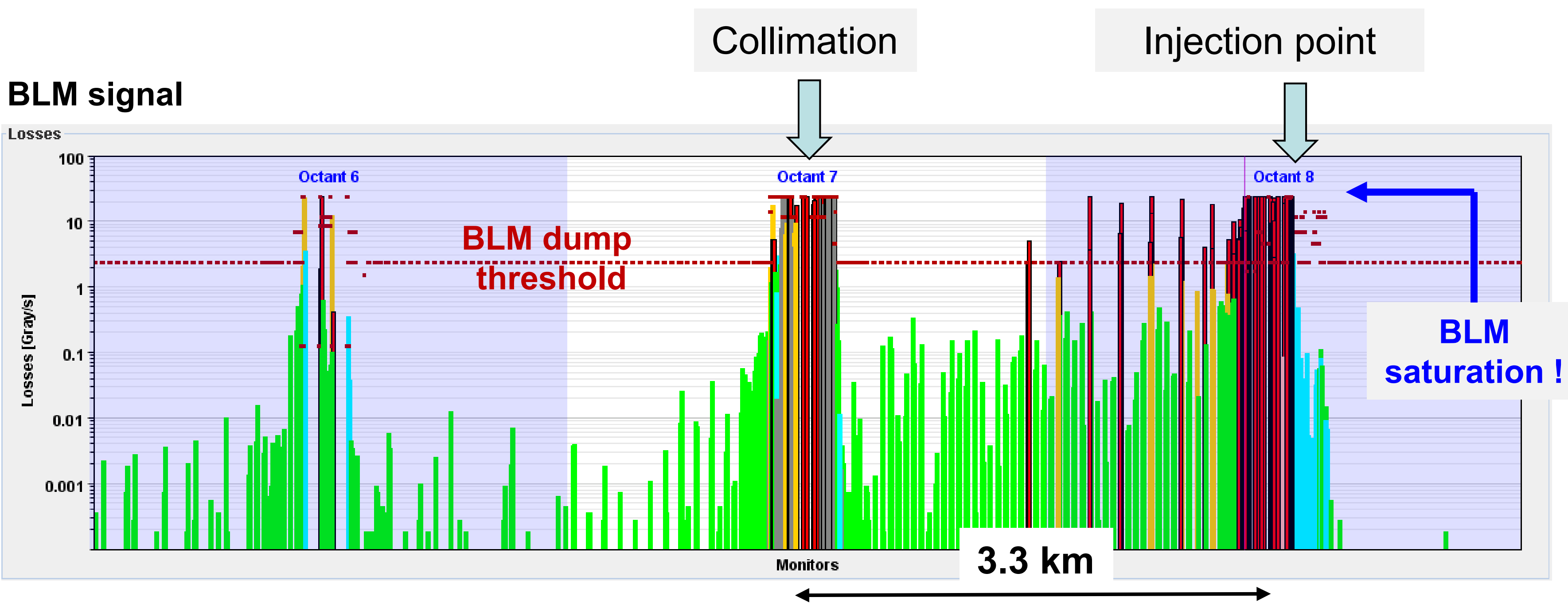
- Circulating beams: with the notable exception of kicker magnet failures (injection / dump) the impact of a failure on the beam usually develops progressively – many turns
  - *Provides room for reaction by the MPS*.
- Linacs, beam transfer: once the beam is produced or the transfer is initiated the beam cannot be stopped anymore.
  - *Avoid incorrect element settings before launch.*
  - *Mitigation by active and passive protection, probe beams / bunches, intermediate dumps.*

LHC beam: stored - transfer

- Despite storing up to 140 MJ at 4 TeV, not a single superconducting magnet was quenched with circulating beam – threshold ~ few 10's of mJ.
- Many magnets were however quenched at injection, mainly due to (expected) injection kicker failures.
  - *The beam (~2 MJ) is safely absorbed in injection dump blocks, but the shower leakage quenches magnets over ~1 km.*

MOPRO019-20

FCC-hh injected intensity @ 3 TeV limited by MPS concerns !



- ☐ Introduction
- ☑ Material robustness
- ☐ Instrumentation
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- ☐ Availability, safety and operation
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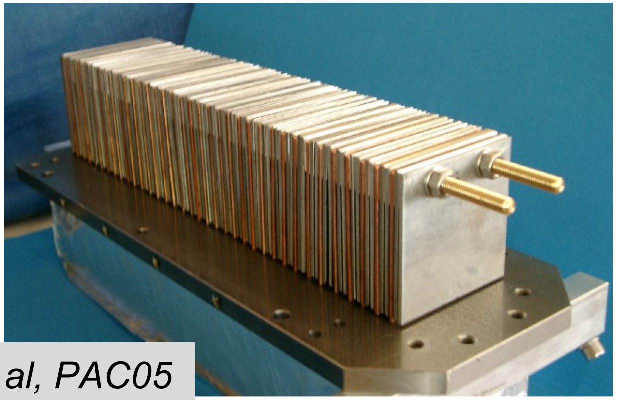
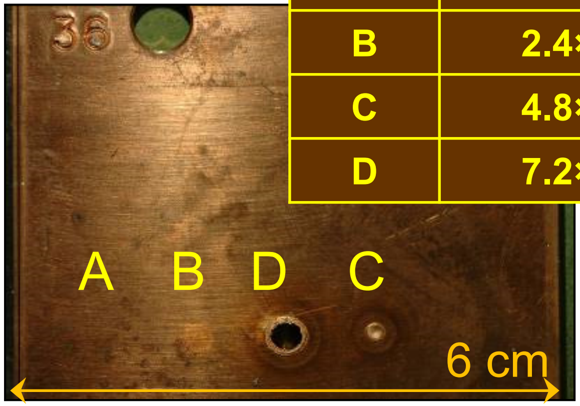
Material limits – passive protection

- An important aspect for collimators, absorbers, dumps and targets is the survival due to nominal or abnormal impacts.
  - *LHC dump block must withstand up to 700 MJ → strong dilution !*
- For high intensity & energy proton beams, current material limits are around 3-4 MJ – low density and high resistance to shocks. **MOPRI086**
- In the past decade a lot of effort was invested to better understand the interaction of high energy / high density beams with matter.
  - *Ad-hoc test for LHC @ 450 GeV*

Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

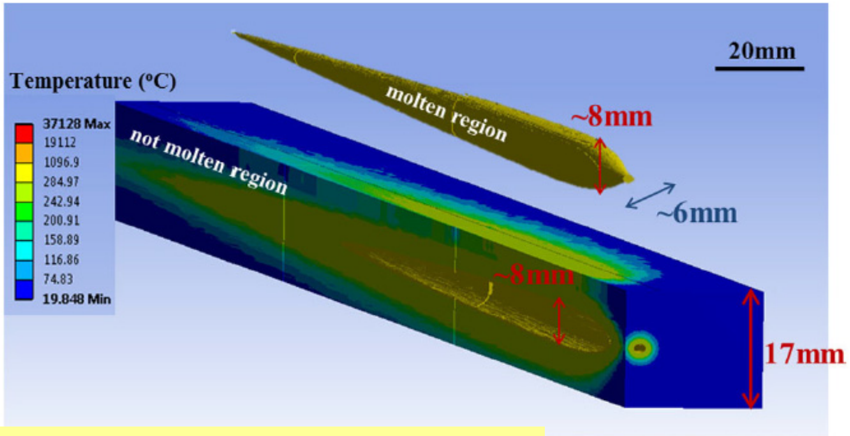


V. Kain et al, PAC05

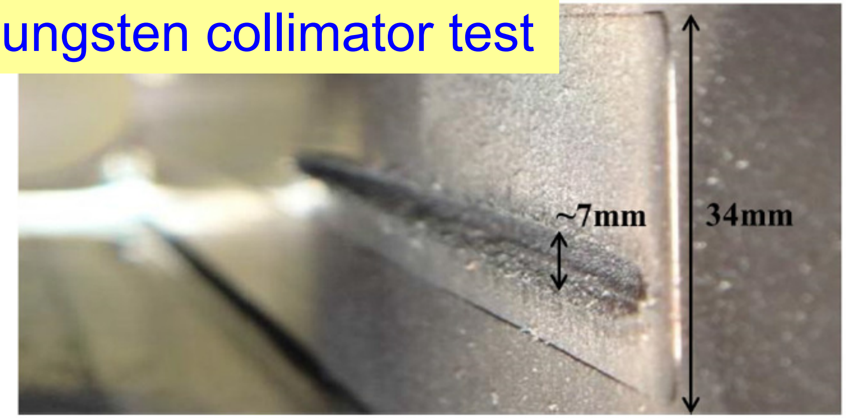


- New beam line at the SPS @ CERN coupled to a high radiation to materials test facility - **HiRadMat**.
  - *2-3 MJ beam, 7-8 μs (fast extraction).*
  - *Tunable beam intensity and density.*

PRSTAB 17, 021004 (2014)



Tungsten collimator test



- Test of new materials, bench marking of simulation codes.
- Robust materials:
  - *CFC, graphite, boron nitrite.*
  - *Impedance $\Rightarrow$ coating.*

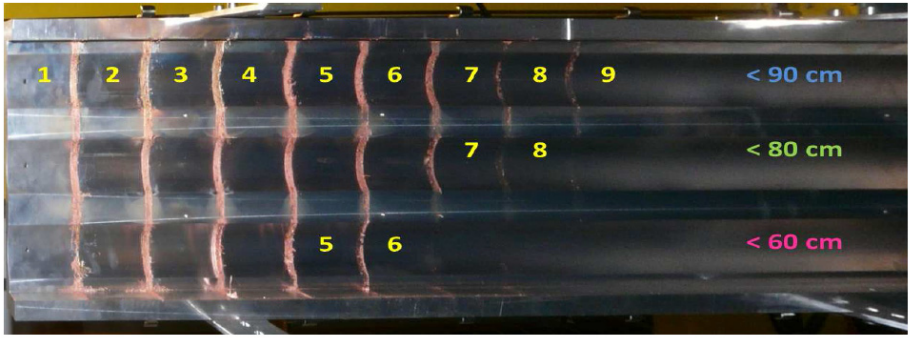
MOPRO038 ***THPRI096***

Hydrodynamic tunneling

- For high intensity beams made of long bunch trains **hydrodynamic tunneling** significantly increases the damage range in a material.
  - *Leading bunches melt the material and create a plasma, the following bunches see less material and penetrate deeper etc.*

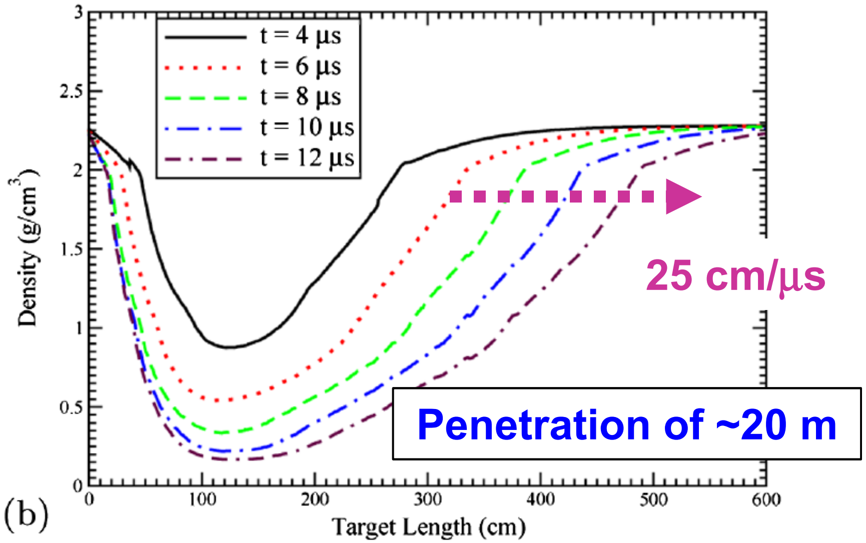
MOPME047

Experimental verification with SPS beam on Cu target @ HiRadMat



For the 50 TeV FCC-hh proton beam the penetration depth is > 100 m

LHC beam in carbon target

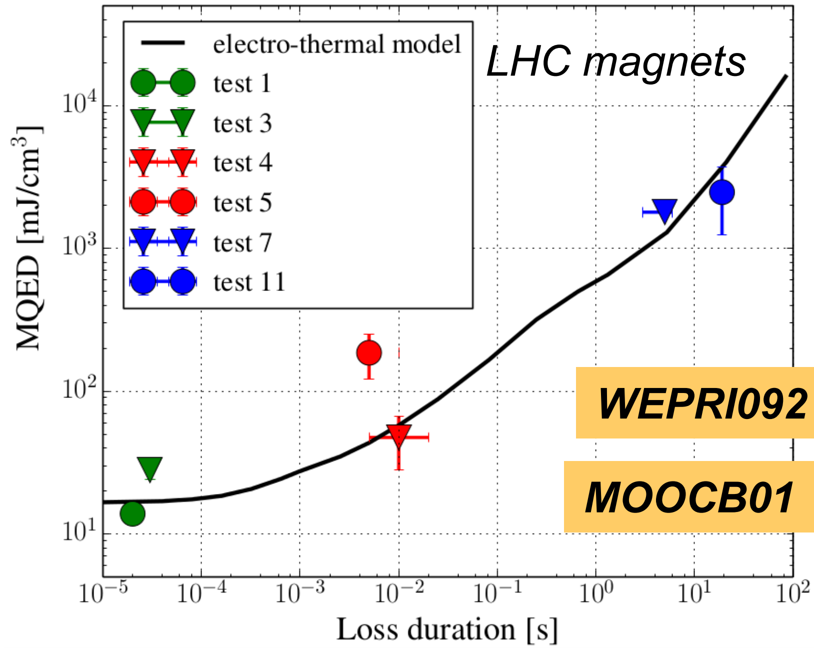


PRSTAB 15, 051003 (2012)

- Understanding quench levels of magnets are essential to set correct thresholds for beam loss monitors.
  - *Impact on availability – dump versus quench recovery.*
- Beam induced quenches involve complex simulations on the beam (tracking + FLUKA, GEANT, MARS…) and on the magnet side. And experimental tests are required.
  - *Influence of the loss time scale.*
  - *Series of beam tests at the LHC to prepare for higher energies.*

Workshop on beam induced quenches in preparation,

CERN 15th-16th September 2014



- ☐ Introduction
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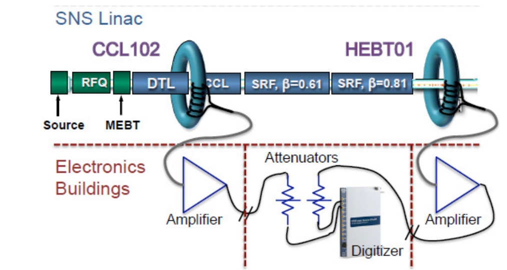
- Nowadays almost all beam instrument types are used in interlocks:
  - *BCTs (masking, linac losses, fast ring losses,…)*
  - *Beam loss monitors (not at very low energy!),*
  - *Beam position monitors,*
  - *Synchrotron light monitors.*

W. Blokland, C. Peters, IBIC13

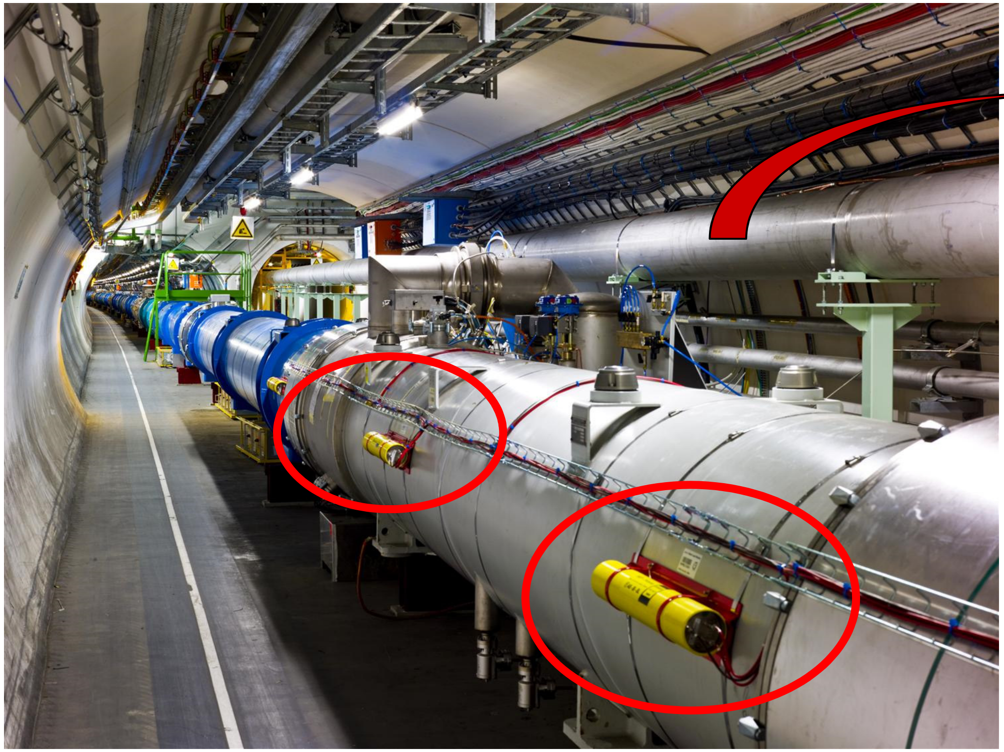


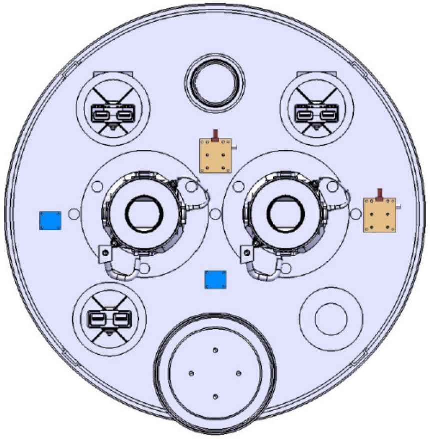
- A general challenge for beam instrumentation is to cope with an increasing *dynamic range* between safe commissioning beams and nominal beams – minimize systematic effects.
  - *Applies to ALL instruments – not just for MPS devices.*
  - *At LHC: 4 orders of magnitude !*
    - *Beam position measurements should be independent of bunch intensity and filling pattern.*
    - *Dynamic range of BLMs (→ see s. 12).*

J-PARC - THPME130

'Cryogenic' BLMs

- To improve the sensitivity of BLMs: from the outside to the inside of the cryostats – avoid shielding from iron yokes.
  - *BLMs in cryogenic environment (LHe, silicon, diamonds).*
  - *First tests in the LHC in 2015.*
- Similar ideas at FRIB and IFMIF for high sensitivity halo monitors.

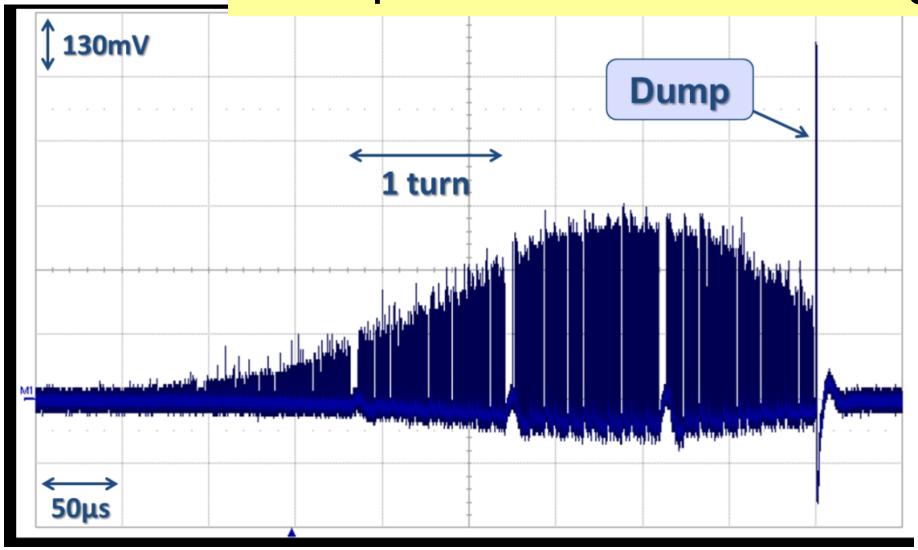




Beyond just protection

- The sensitivity and speed of certain BLMs (diamonds, scintillators) provide powerful diagnostics beyond the pure protection.
  - *LHC: CVD diamonds for bunch-by-bunch diagnostic – machine & experiments.*
  - *IFMIF : CVD diamonds μ–loss halo diagnostics and tuning, integrated into cryo-module as close as possible to the beam.*
  - *XFEL : Scintillator+PMT for bunch-by-bunch diagnostics.*

Dust particle – '*UFO*' – falling into the LHC beam.



Bunch by bunch losses @ LHC from diamond detectors close to primary collimators

T. Bär

Beam as witness

- Direct 'injection' of an intense beam into a synchrotron or a linac may be problematic or require large / extensive monitoring efforts.

  ⇒ concept of 'witness' beam / bunch

- The LHC with nominal injection of 3 MJ (>> damage threshold) uses the beam presence concept.
  - *Only a probe beam (typically 10^{10} protons, max 10^{11}) may be injected into an **EMPTY** ring.*
  - *Logic is implemented with a highly reliable and redundant 'presence' measurement – diode detection system.*
  - *Even a probe bunch was able to quench 4 magnets at injection !*

- CLIC and ILC foresee to use witness bunches (ahead of main train) or low intensity witness trains.

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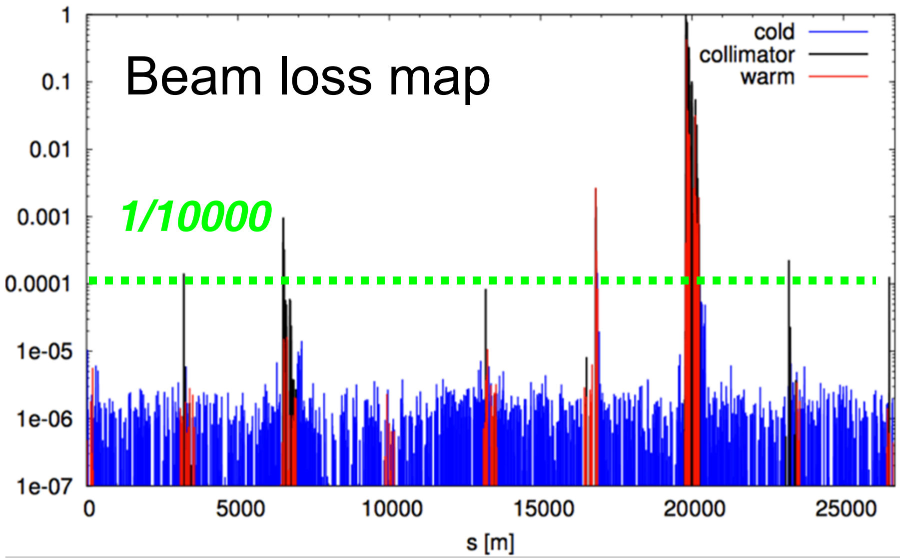
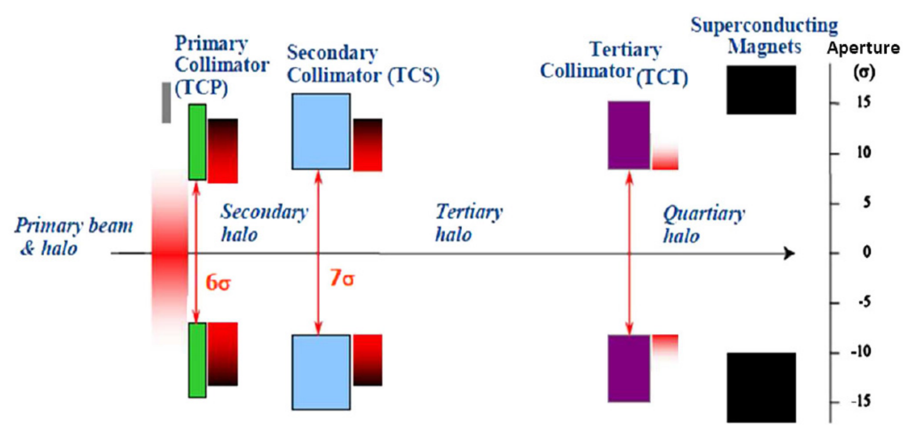
Collimating the halo

- At the LHC it was demonstrated that a multi-stage collimation system with >100 collimators can be operated efficiently and that it provides excellent and reproducible **cleaning** and **protection** – **no quench with circulating beam**.
  - *Cleaning efficiencies of ≈99.99% - verified regularly with defined procedure.*
    - Also for protection against asynchronous beam dumps – Carbon jaws.
  - *One alignment per year ⇔ **reproducible orbit, optics and collimator position**.*
  - *Alignment speed improvement by automation (from 20 mins to ~3 mins / collimator)*



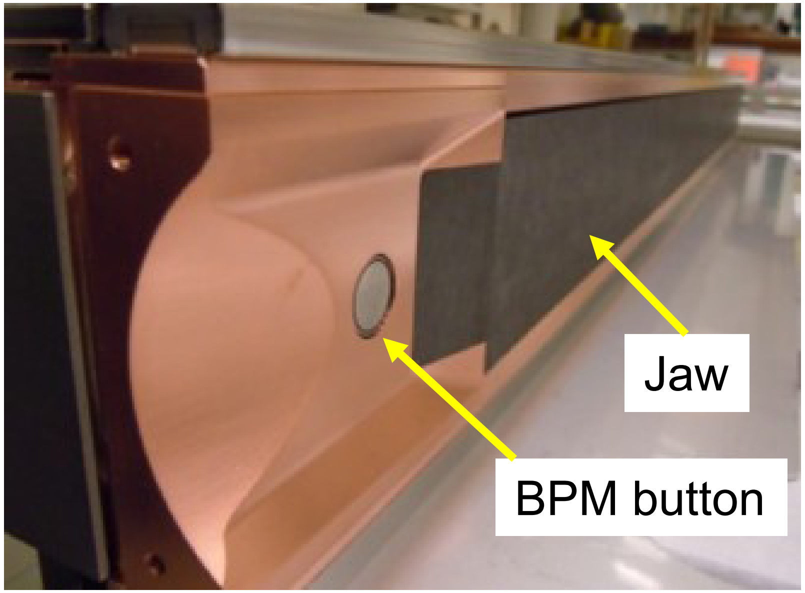
Courtesy S. Redaelli

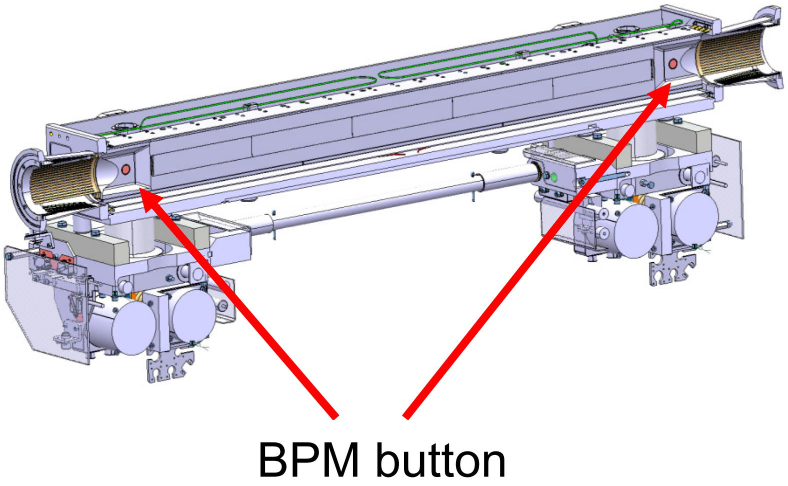


MOPRO043

Merging instrumentation and collimation

- Setting up many collimators with loss signals is very time consuming.
- Integration of BPMs into the jaws for next generation collimators (LHC):
  - *Direct monitoring of the beam position wrt jaw center.*
  - *Very fast setup (< 1 min/collimator), interlocking of beam wrt jaws.*
  - *High resolution on position with small gaps.*
- The first collimators with integrated BPMs will be used in operation at the LHC in 2015.

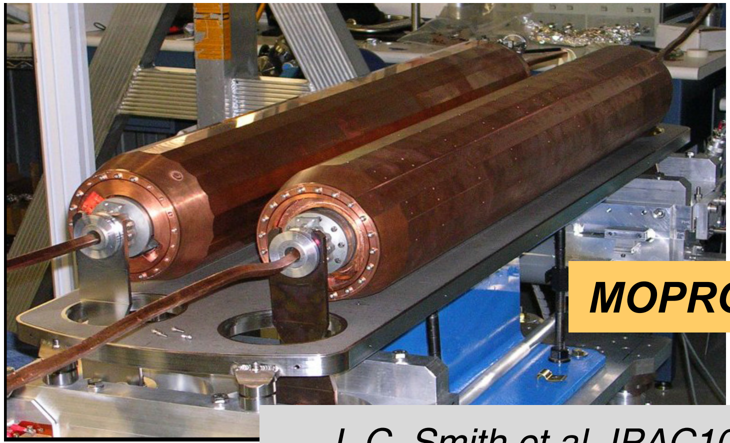




G. Valentino et al., PRSTAB 17, 021005

Other trends in collimation

- **Rotatable ('disposable') collimators**: less robust, but better impedance. Multiple surfaces to cope with limited number of 'incidents'.
  - *→ lower the impedance.*
  - *Development in progress for LHC prototype with 20 faces.*



MOPRO044

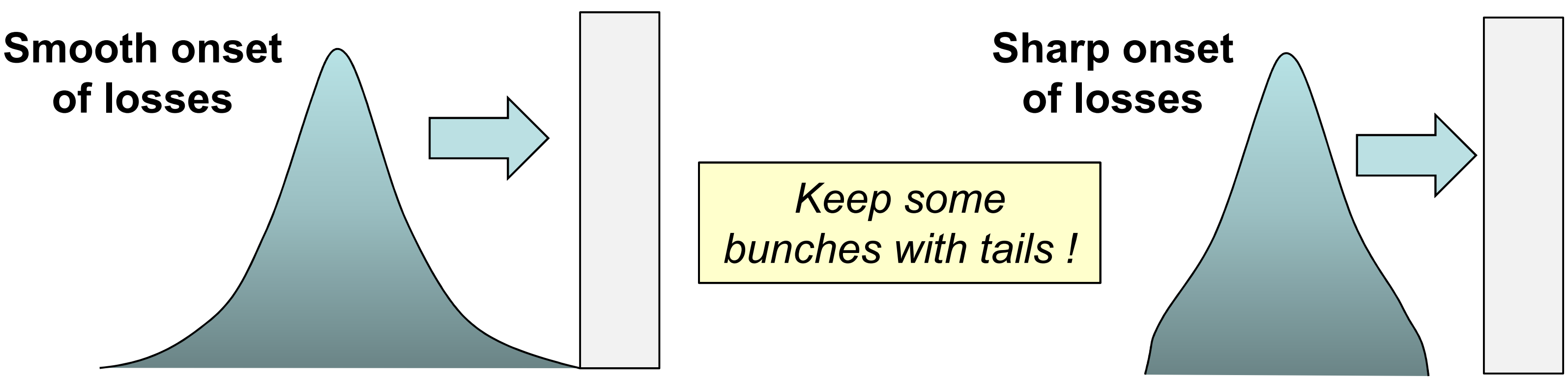
J. C. Smith et al, IPAC10

- **'Cryogenic' collimators**: catch losses in cold regions.
  - *Ion(Cryo)-catchers for SIS100.* **MOPRI105**
  - *Cryo-collimators for HL-LHC.* **MOPRO042**

- **Crystal assisted collimation**: improved collimation efficiency with bend crystal extraction of the halo under a secondary collimator.
  - *RHIC, Tevatron, test installation on one LHC beam for 2015.* **MOPRI110**

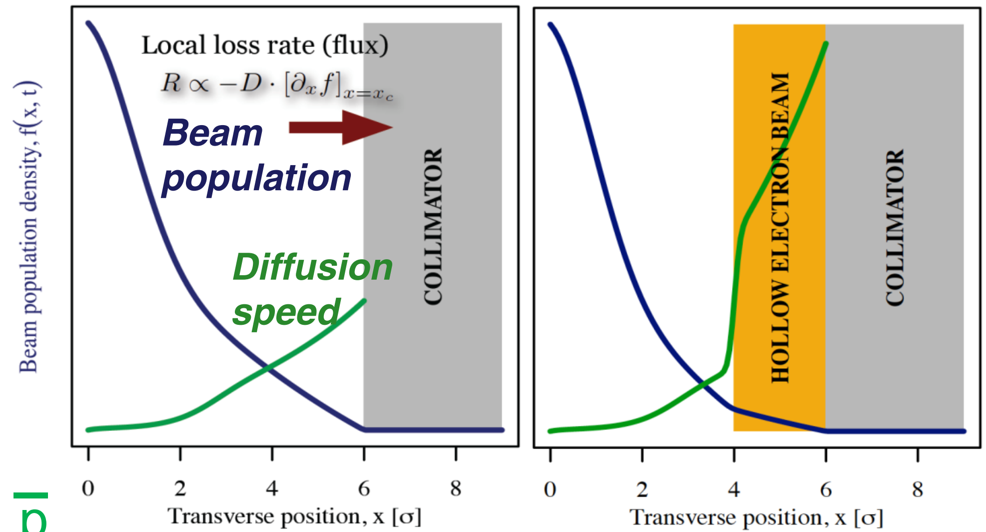
Beam halo

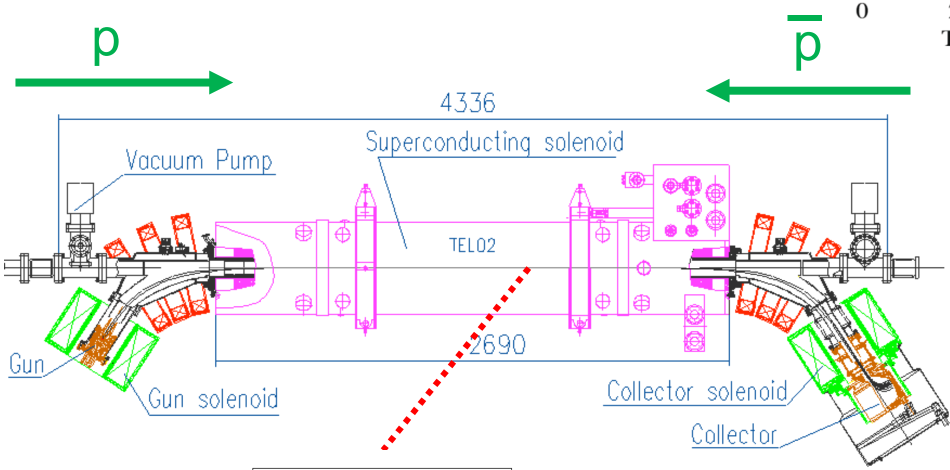
- Halo control and monitoring becomes an issue in many facilities.
  - *The HL-LHC beam halo (~4-5σ) will store ~10's MJ (scaling from 4 TeV).*
    - *A fast halo loss (by Crab Cavity failures) may lead to collimator damage !* **TUPRO003**
  - *Similar worries for IFMIF, LCLS etc.* *J. Marroncle et al, IBIC 2012* **MOPRO117**
- Halo cleaning by electron lenses for synchrotrons (pioneered at the Tevatron) and monitoring techniques (very sensitive and fast BLMs, synchrotron light monitors) are under development.
- Potential issue for MP without halo due to faster onset of critical loss rates! Reduced margin for reaction – rings.



Hollow lens

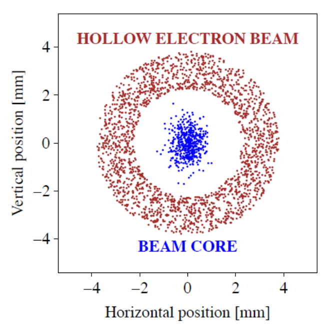
- Halo cleaning by electron lens demonstrated at Tevatron.
  - *Soft scrapper,*
  - *No material damage,*
  - *Tunable strength – diffusion speed*





- Such a lens is considered as an option for HL-LHC (CERN-LARP collaboration).

G. Stancari -TUOBA01



Stancari et al., Phys. Rev. Let. 107, 084802

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Availability and safety

- Peak performance is not everything, a high availability and safety are a key factor for modern machines.
- In many projects availability considerations are included from the design phase.
  - *100's to 1000's of inputs into the MPS.*
  - *Right level between too safe and too relaxed.*

ESS - MOPME047

SIS100 - THPME058

LINAC4 - THPRI020

- Different approaches can be used:
  - ***Failure mode, effects and criticality analysis** (FMECA) to asses safety and availability of the main systems,*
    - *Defines needs for redundancy, testing etc*
  - *Failure analysis based on IEC 61508 standard.*
  - *Reviews by colleagues in the field of MPS.*
  - *Input and review by **external consultants in the field of safety** (car industry, air traffic…). Fruitful exchange !*
    - *Approach to safety system analysis and design.*

Failure analysis

- For LHC the detailed failure analysis (FMECA) provided reasonable estimates for safety and false triggers (within factor 2 or better).
  - *But it requires significant efforts and a systematic approach !*
- A key benefit of a failure analysis:
  - *In depth analysis of the system,*
  - *Dangerous common mode failures may be revealed !*

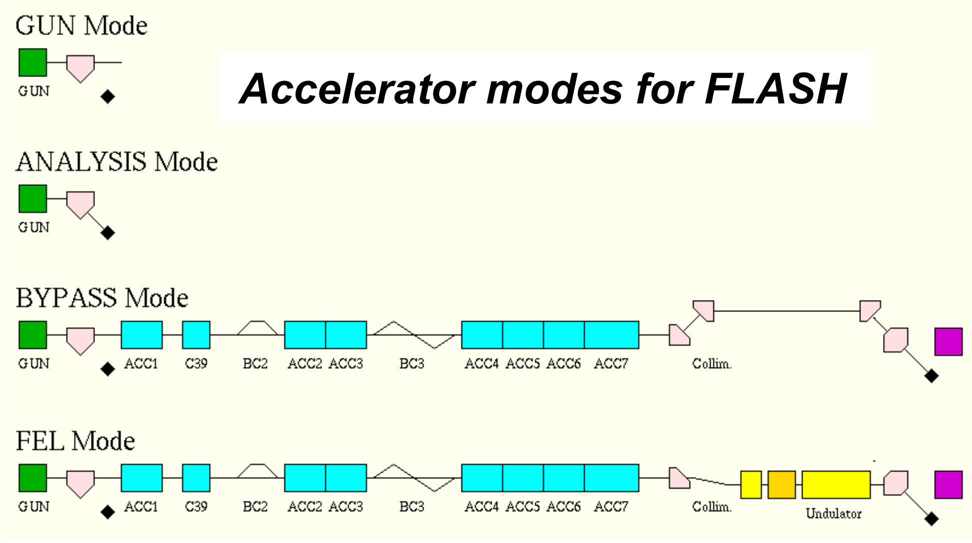

Wikipedia

Whether such an analysis is worth the effort depends evidently on the consequences !

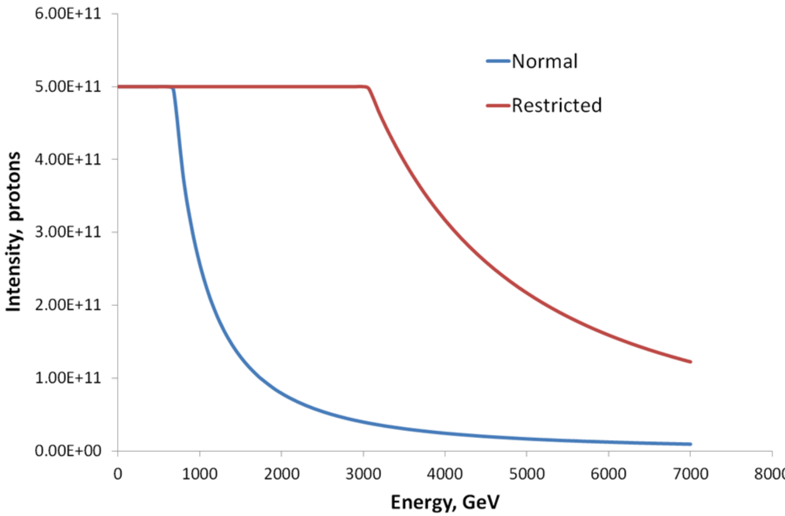
Masking and commissioning

- When designing an MPS one should consider commissioning, machine experiments, operation phases where flexibility is required.
  - *Need some way of relaxing or masking interlocks.*
- The concept of accelerator mode or a combination of beam intensity and energy in the interlock logic are typically used to mask out interlock channels.

Beware of failure modes introduced by this flexibility !



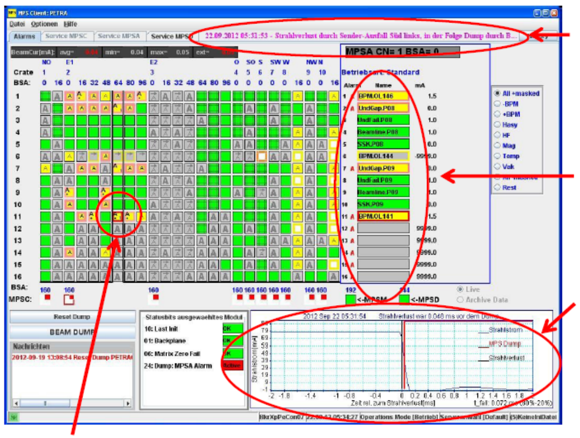
LHC limit for interlock masking



Diagnostics – post-mortem

- When the MPS fires post-mortem (PM) diagnostics must be provided to identify the root cause(s) – **all systems ! trigger and time reference !**
- For large MPS the analysis can be tedious, automatic analysis tools are developed to help the operator (and the MPS expert).

BEPCII – THOAA01



Rule based automated analysis of PM data at PETRA III

M. Bieler et al, ARW 2013

- **Post-operation checks** based on PM data can ensure that the MPS reacted as expected, that no redundancy was lost, etc.
  - *At the LHC automatic post operation checks (POC) are performed for the beam dumping system (equipment & beam data) – block operation is POC fails.*
  - *System 'as good as new'.*

Conclusion

- Requirements for high powers and large stored energy provides a steady flow of challenges for MPS.
- We will soon reach limits of materials, new concepts may be required – sacrificial devices.
- Monitoring of beam properties and equipment pushes to ever tighter tolerances with large dynamic ranges – instrumentation !!!
- Availability is a key aspect of a modern MPS – from the design !

US-CERN-JAPAN-RUSSIA Joint International Accelerator School

http://uspas.fnal.gov/programs/JAS/JAS14.shtml

Beam Loss and Accelerator Protection

November 5-14, 2014

Newport Beach, California, USA

This school is intended for physicists and engineers who are or may be engaged in the design, construction, and/or operation of accelerators with high power photon or particle beams and/or accelerator sub-systems with large stored energy.

The USPAS will offer a limited number of scholarships. Both U.S. and international participants are welcome to request a scholarship on their Application Form