Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Machine Protection Concepts

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Outline

- Beam Stored Energy
- Protection of Beam, Experiment and Machine
- Machine Protection System (MPS) Landscape
- Collimation and Active Protection
- Tevatron MPS Concepts and 2003 Beam Accident
- LHC 2008 Incident
- MPS Strategy and Design Guidelines
- LHC MPS Performance
- MPS in the HL-LHC Era and Beyond

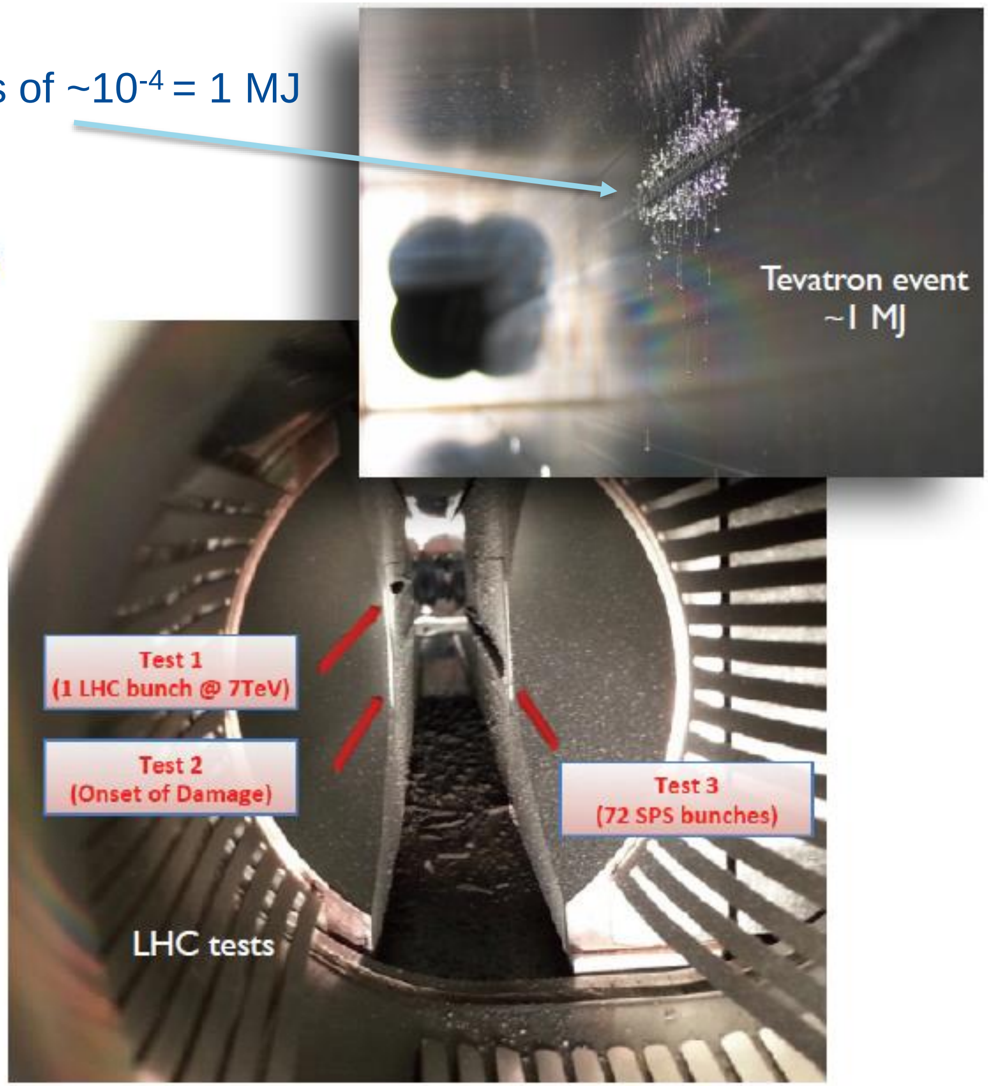
Acknowledgements: D. Cossairt, R. Schmidt, D. Steel, J. Wenninger

Beam Stored Energy

- Example: FCC parameters
- >8 GJ kinetic energy per beam
  - **Airbus A380 at 720 km/h**
  - 24 times larger than in LHC at 14 TeV
  - Can melt 12 tons of copper
  - Or drill a 300 m long hole
  - ⇒ Machine protection

Beam loss of ~10^{-4} = 1 MJ

- Also *small* loss is important
  - *e.g*. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background for the experiments
  - Activation of the machine
  - ⇒ Collimation system



Protection of Beam, Experiment and Machine

$p\bar{p}$ colliders (S$p\bar{p}$S & Tevatron)

1. Protect the beam: ~10^{-5} useful antiprotons per proton on target, takes many hours to produce them & setup collisions → no unintentional beam aborts
2. Protect the experiments: backgrounds and the most expensive near beam detector components
3. Protect the machine components (superconducting magnets, collimators, beam diagnostics etc.) from uncontrolled beam loss

pp colliders (LHC & beyond)

1. Protect the machine components (superconducting magnets, collimators, beam diagnostics etc.) from uncontrolled beam loss
2. Protect the experiments: backgrounds and the most expensive near beam detector components
3. Protect the beam: minimize beam aborts to maximize the integrated luminosity

Hazard, Risk and Protection at Accelerators

Hazard: a situation that poses a level of threat to the accelerator. It is dormant or potential, it turns to **incident** or **accident** once a hazard becomes “active”.

Accident quantification: Risk = Consequences × Probability

Consequences of a failure (in Euro, downtime, radiation dose to people or environment, reputation) in hardware systems or uncontrolled beam loss.

The higher the **Risk**, the more **protection** is needed:

- Protection of people during operation (highest priority) – keep them away from the accelerator when beam is running (access system), taking care also of electrical, pressure, oxygen deficiency and other hazards.
- Protection of the environment.
- Protection of accelerator and experiment equipment.

Motivation for Protection Systems

1. All technical systems cause some downtime
2. A protection system will always contribute to downtime
3. If the risk is low, it might be better to operate without or with a reduced protection system (see the Tevatron example)
4. If the risk is significant, protection systems is mandatory
5. If the downtime due to expected damage is larger than the downtime due to the protection system, such system is mandatory
6. The investment required for repair in case of damage needs to be considered

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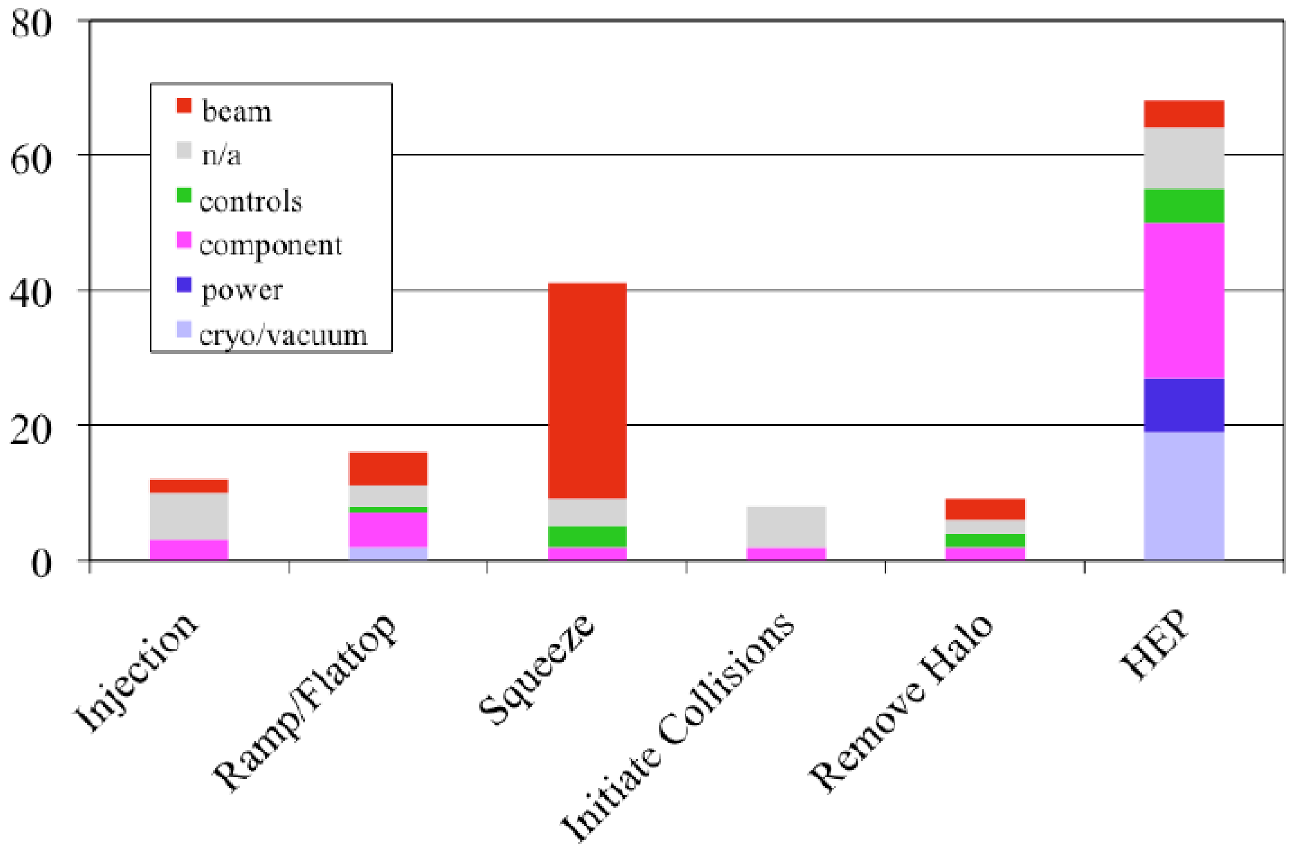
Tevatron 1.96-TeV $p\bar{p}$ Collider Magnet Quenches



Characterization of Tevatron magnet quenches between October 2007 and March 2011. Out of 154 total, 32 were during low-beta squeeze (3 to 4% luminosity loss), 5 during acceleration, 3 during halo removal and 4 at HEP collisions. Cryo recovery at HEP was 3 hours. D. Still & A. Valishev

Machine Protection System (MPS)

- If something goes wrong, the beam energy has to be safely deposited (aborting the beam to an external absorber)
- If something goes wrong, the energy stored in each of the magnet has to be safely discharged (1232 superconducting dipole magnets in LHC)
- Obviously, if something goes wrong, injection has to be stopped

Beam Loss Timescale: Specs for MPS at LHC

- Single-pass (ns to μs)
  - Beam transfer lines (injection, extraction, beam abort, fixed target experiments)
  - Kicker magnet failures (injection, extraction, special kickers – diagnostics)
  - Accidental local (~200 ns, 60 m)
- Very fast (ms) transient
  - 10 turns or so in LHC
  - Large number of possible failures in technical systems (e.g., magnet powering)
- Fast (10 ms to sec)
  - Large number of possible failures in technical systems
- Slow (many sec)
  - Beam-gas scattering, non-linear dynamics, experiment cross-talk
  - Tails from collimators (collimation inefficiency)

Beam Collimation: 0.5 MW to 5 TW at LHC

- Beam cleaning (halo scraping): reduction of slow loss (beam-gas scattering, non-linear dynamics etc.) to minimize radiation loads to superconducting and warm magnets, detector backgrounds and mitigate radiological issues

- Passive protection of machine and detector components against irregular fast losses and failures; always needed in case of MPS failures and if the MPS response time is two long

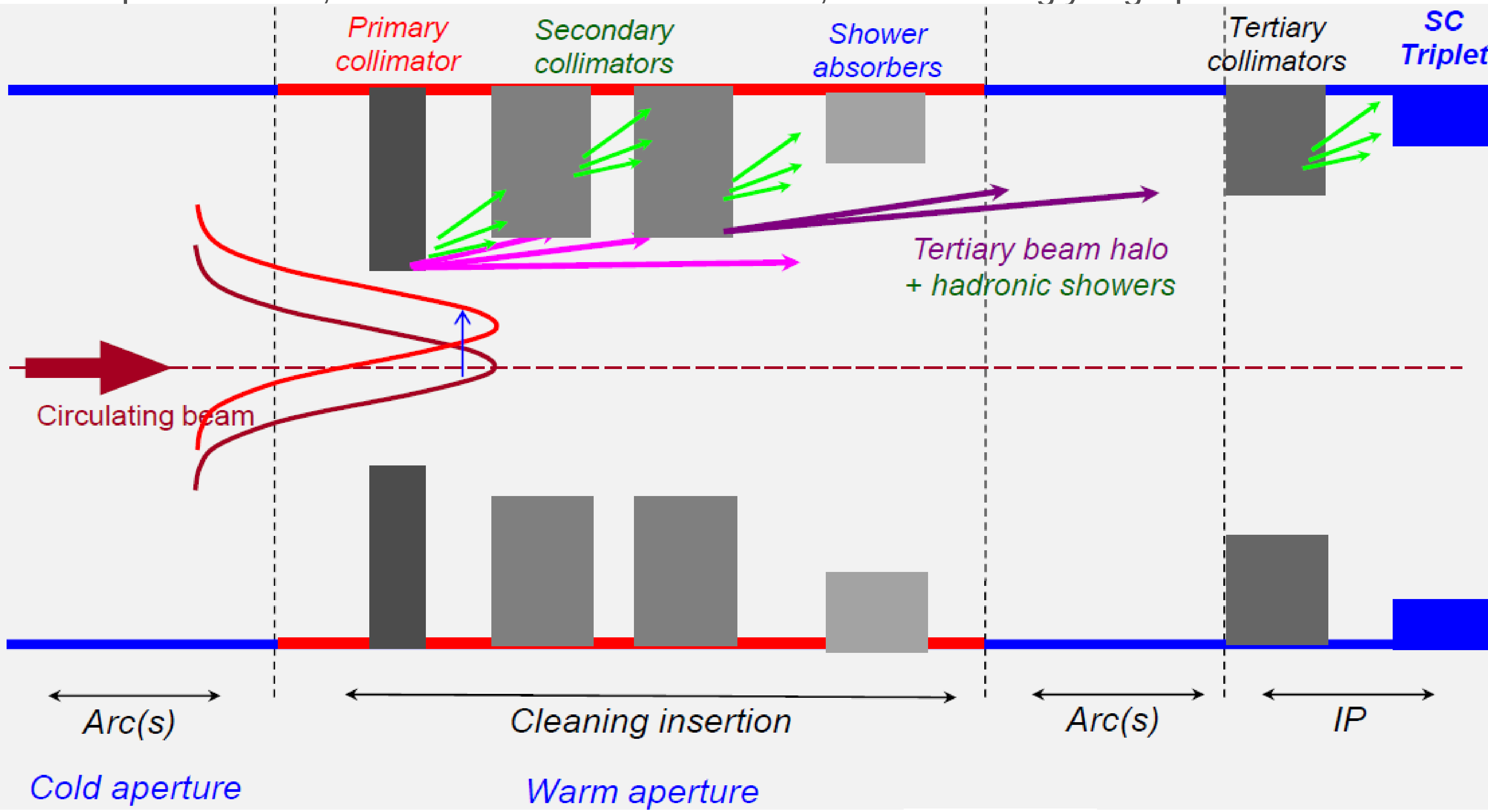
Specified 7 TeV maximum allowed beam losses:

– Slow:	0.1% of beam per s for 10 s	**0.5 MW**
– Transient:	5×10^{-5} of beam in ~10 turns (~1 ms)	**20 MW**
– Accidental:	up to 1 MJ in 200 ns into 0.2 mm^2	**5 TW**

Stored energy at max beam energy: LHC 362 MJ, FCC > 8 GJ

Multi-Stage Beam Collimation

Built for the first time at the Tevatron Collider in 1995. Built and installed at the LHC complex in 2008; now 110 movable collimators, with amazingly high performance



Active Protection

- A system is monitored, the monitor delivers some values (e.g. beam loss monitors measuring beam losses)
- The acceptable range of values is predefined (e.g. maximum beam losses within a time interval)
- If a value is out of the predefined range (e.g., after an equipment failure): take action (dump the circulating beam, stop injection, etc)
- The information has to travel from the monitor to the activator (extraction system, injection inhibit) → interlock system
- There is some **reaction time required for the response** (depending on the system this can range between some ns and many seconds)

R. Schmidt

Transient Beam Loss Handling at the Tevatron

- Early days of Tevatron fixed target
  - ➢ Protect against any possible quench
  - ➢ Unnecessary abort wastes a single beam pulse
- Early days of Collider (6×6 , 900 GeV, ~2E12)
  - ➢ Tevatron can survive a quench
  - ➢ An abort turns off collider for ~ 1 day
  - ➢ A quench is no worse than an abort
- Run II Intensities(36×36, 980 GeV, ~1E13)
  - ➢ There is enough beam to damage Tevatron again
  - ➢ Improve protection of Tevatron components
  - ➢ Do not cause unnecessary down time

Beam Abort System at the Tevatron

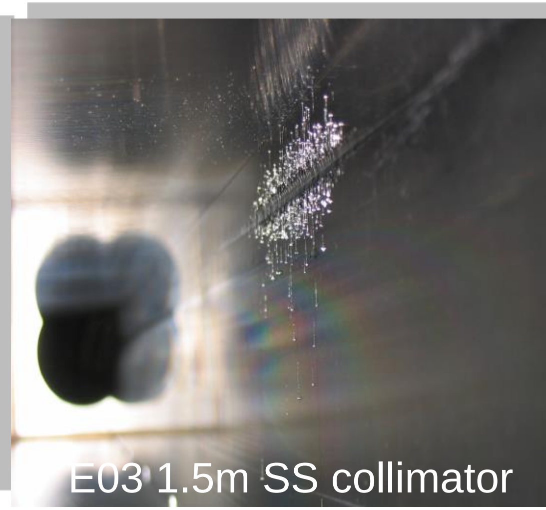
- Abort Inputs
  - QPM (Quench Protection Monitor controlling superconducting state of the magnets)
  - Beam Loss Monitors (masked during stores)
  - Power supplies (etc.)
- Abort Loop
  - Hardware fail-safe loop
  - Can abort beam within a couple revolutions (40 μs)
  - Aborts synchronized to single beam abort gap

Beam-Induced Accident at the Tevatron in 2003

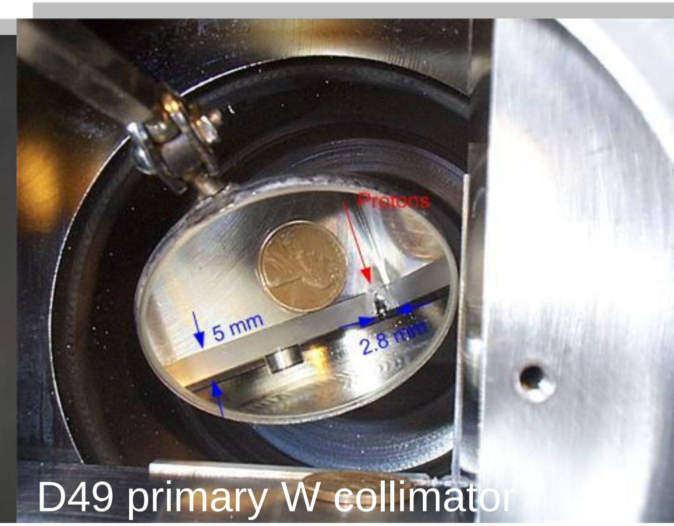
There were 24 cryogenic refrigerator houses for the Fermilab Tevatron ring. One house cryogenically kept about 40 superconducting magnets. On December 5, 2003, the Tevatron suffered a 16 house quench (**2/3** of the 6-km ring) during the end of a proton-antiproton colliding beam store.

That followed by the damage of **2 collimators** used for halo reduction at the CDF and DØ interaction points. In addition, two cryogenic spool pieces with **3 correction elements** were also damaged as a result of helium evaporation and pressure rise during the quench, requiring **10 days of Tevatron downtime** for repairs.

C18 spool



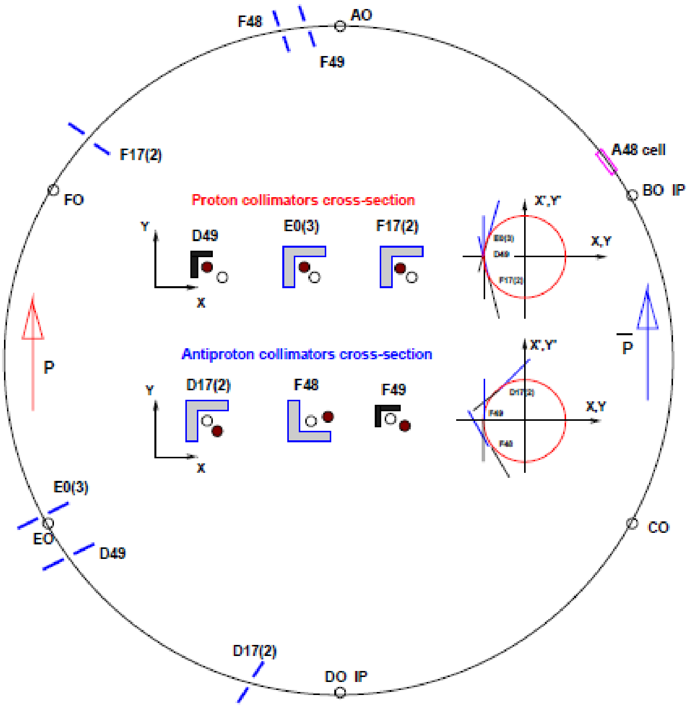
E03 1.5m SS collimator



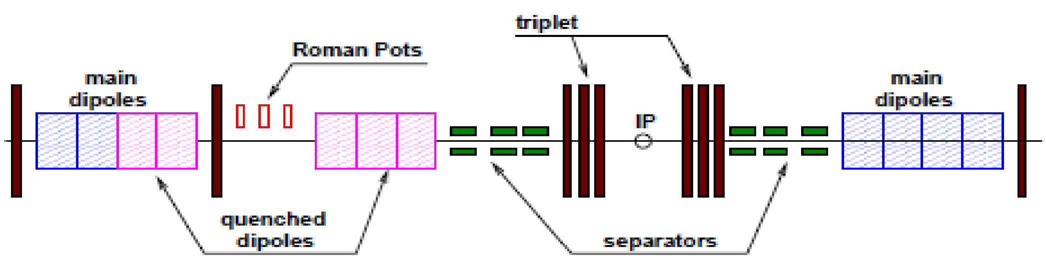
D49 primary W collimator

Sequence of Events

The large quench was found to be initially caused by a CDF Roman Pot reinserting itself quickly back into the beam after it had been issued retract commands.



- Losses generated quickly and quench A48U
- Field in 5 dipoles starts decaying (500 A/sec)
- Orbit moves everywhere
- Beam moves through D49 primary collimator, E11 spool piece, and E03 Collimator.
- Protons are extinguished in E03 collimator in about several turns
- QPM detects quench in A48
- Abort kickers fire
- This all occurs within 16 msec



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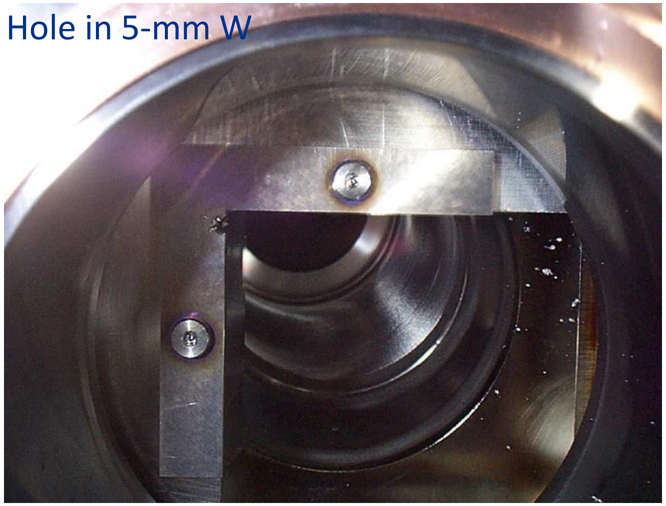
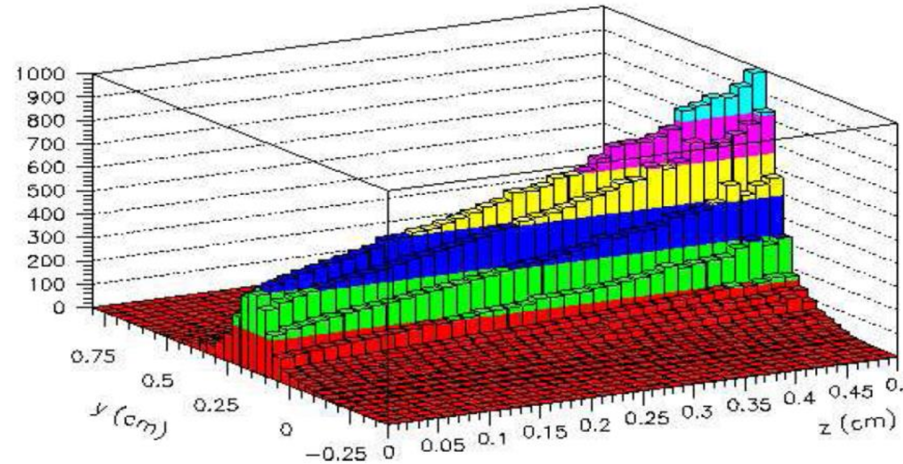
Modelling of Tungsten Collimator Ablation





Detailed modelling of dynamics of beam loss (STRUCT), energy deposition (MARS14) as high as 1 kJ/g, and time evolution over 1.6 ms of the tungsten collimator ablation (FRONTIER), explained what happened

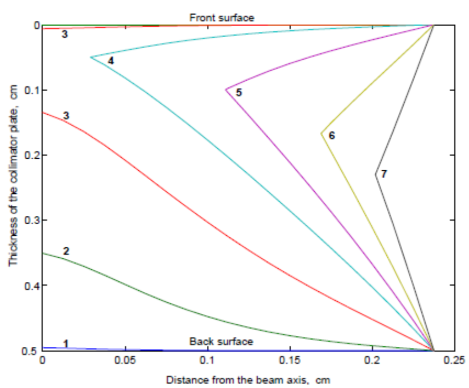
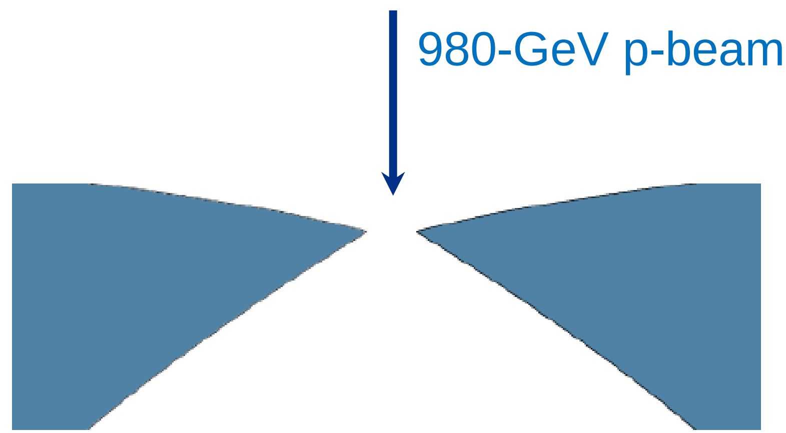


Figure 7: Evolution of the front and back surfaces of the collimator plate at $t = 0.4_{[1]} - 1.6_{[7]}\ ms$ with Δt=0.2 ms.



What Has Been Done after the Accident (1)

- **Roman Pots:** the controllers have been fixed, drivers changed and hard stops installed
- **AC Power in Kicker Room:** reconfigured so the kicker and the CAMAC Abort controls are on a separate feed from the sub-station
- **Timing Generator**: the CAMAC abort system now generates an abort pulse – phase locked to the abort gap – if the accelerator timing system clock is lost
- **Multi-House Quench**: implantation of a new fast detection buffer inside the Quench Protection Monitor system (QPM) that samples quench data at 5kHz (instead of the original 60 Hz) and determines a quench and pull the abort in 2 msec instead of 16 msec before the change

What Has Been Done after the Accident (2)

- **BLM System:** upgrade
- **Vacuum System Failures:** it took 200 ms for the abort to be generated in the old system. A new chassis that monitor the voltages going to the valves have been designed, built and installed. If the voltage is removed, this generates an abort command in ~7 ms. It was verified this works appropriately. Twenty four crates have been installed during the shutdown
- **Controls:** The beam abort loop was comprised of a loop of C200 family modules (one in each sector) that provides a permit (antifire) signal for the kickers. Each upstream module was input into the next downstream module. Modifications have been made to ensure the startup state for the masks. The timer circuitry was also modified
- **Correctors:** checked and confirmed that these are OK

Brand New Example: PIP-II MPS Concept

PIP-II is the Fermilab 800 MeV superconducting Linac project

The main goal of the MPS is to protect the machine from beam induced damage; thereby inhibiting the beam in case of excessive beam loss, equipment failures, or operator request. In achieving that objective, the system will also provide the following features:

- Manage beam intensity and permit limits of MPS designated devices while providing post mortem data to the control system.
- Provide a comprehensive overview of the machine state and readiness status to subsystems and the broader complex.
- Provide a global synchronization trigger for beam related system fault analysis.
- Provide linac beam status to the accelerator complex control system.
- Provide high availability and fail-safe operation where possible.
- Manage and display MPS alarms.
- The MPS is not a personnel safety system.

LHC Incident of September 19, 2008

The most serious machine incident

- Last commissioning step of one out of the 8 main dipole electrical circuit in sector 34 : ramp to 9.3kA (5.5 TeV).
- At 8.7kA an electrical fault developed in the **dipole bus bar** located in the interconnection between quadrupole Q24.R3 and the neighboring dipole.

  Later correlated to a local resistance of ~220 nΩ – nominal value 0.35 nΩ.

- An electrical arc developed which punctured the helium enclosure.

  Secondary arcs developed along the arc.

  Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs.

- Large amounts of Helium were released into the insulating vacuum.

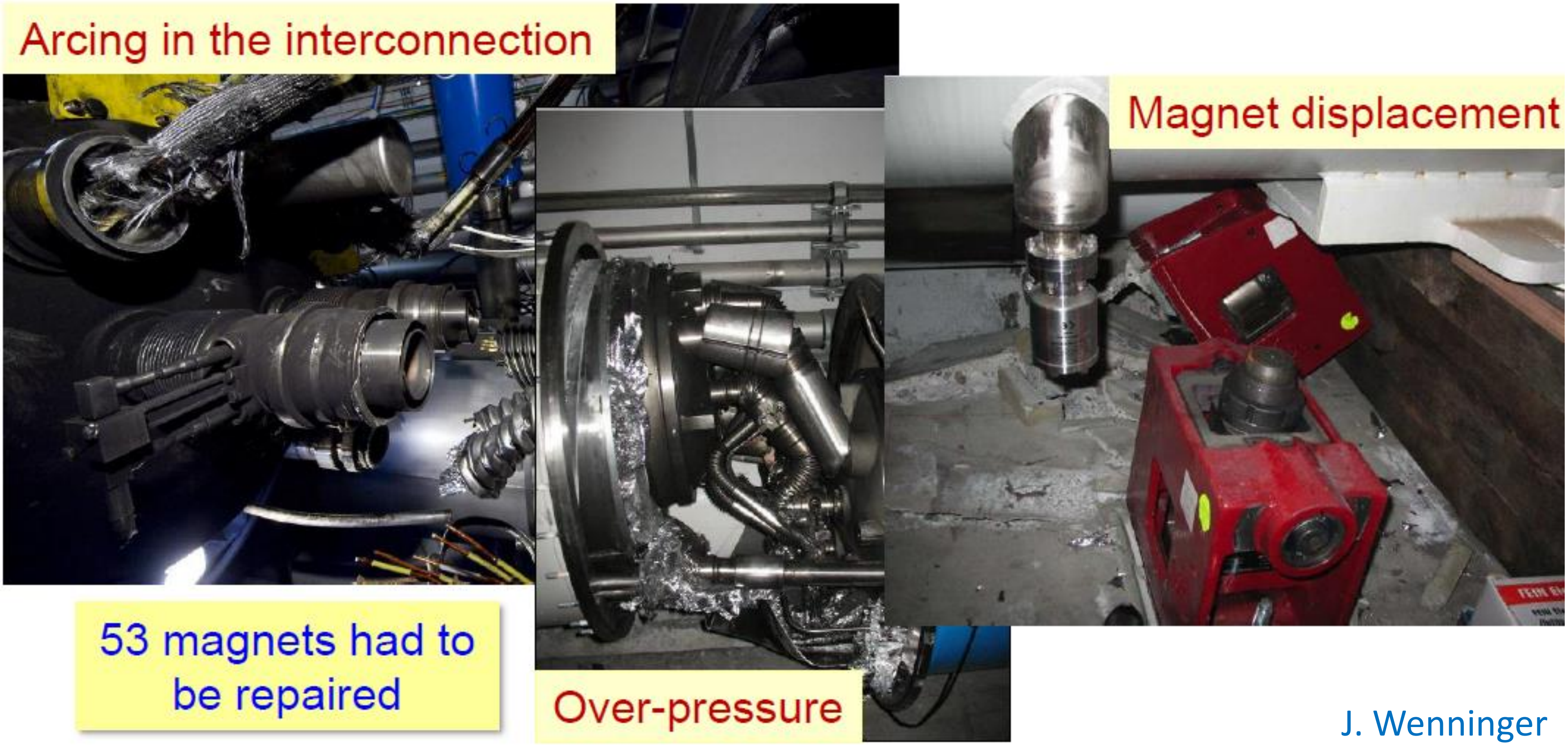
  In total 6 tons of He were released.

This incident involved magnet powering, but no beam!

J. Wenninger

Release of 600 MJ at LHC

The Helium pressure wave damaged ~600 m of LHC, polluting the beam vacuum over more than 2 km.



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Consequences

- Machine down for more than 1 year for repair and re-commissioning
- Major upgrades to protection system of the magnets (surveillance of the busbar stabilizer)
- Major upgrades to pressure release and magnet anchoring
- Limitation of the machine energy to 3.5 TeV instead of 7 TeV
- Almost 2-year long shutdown (2013-2014) to repair all magnet interconnections
- **Bonus:** commissioning and early operation in "easier" conditions 3.5–4 TeV *vs* 7 TeV, lower fields, increased quench-resistance; ➔ no beam-induced quench in Run 1 (2010-2013) with stored energy up to 70 times above previous state-of-the art

J. Wenninger

Launching MPS Design

1. Identify hazards: what failures can have a direct impact on beam parameters and cause loss of particles on aperture
2. Classify the failures in different categories
3. Estimate the risk for each failure (or for categories of failures)
4. Work out the worst case failures
5. Identify how to prevent the failures or mitigate the consequences
6. Design systems for machine protection (e.g., 3600 BLMs around LHC plus much more)

R. Schmidt

Classification of Failures

- Type of the Failure
  - Hardware: power converter trip, magnet quench, AC distribution (thunderstorm etc.), object in beam pipe, vacuum leak, RF trip, kicker misfire etc.
  - Controls: wrong data, wrong magnet current function, trigger problem, timing system, feedback failure etc.
  - Operational: chromaticity/tune/orbit wrong values
  - Beam instabilities: e-clouds or too high beam/bunch current
  - Objects in the beampipe: movable devices, RF fingers, gas above nominal pressure, some beam instrumentation, Roman Pots
- Parameters of the Failure
  - Time constant of beam loss
  - Location of beam loss (normally, in the predefined places)
  - Probability for the failure
  - Damage potential

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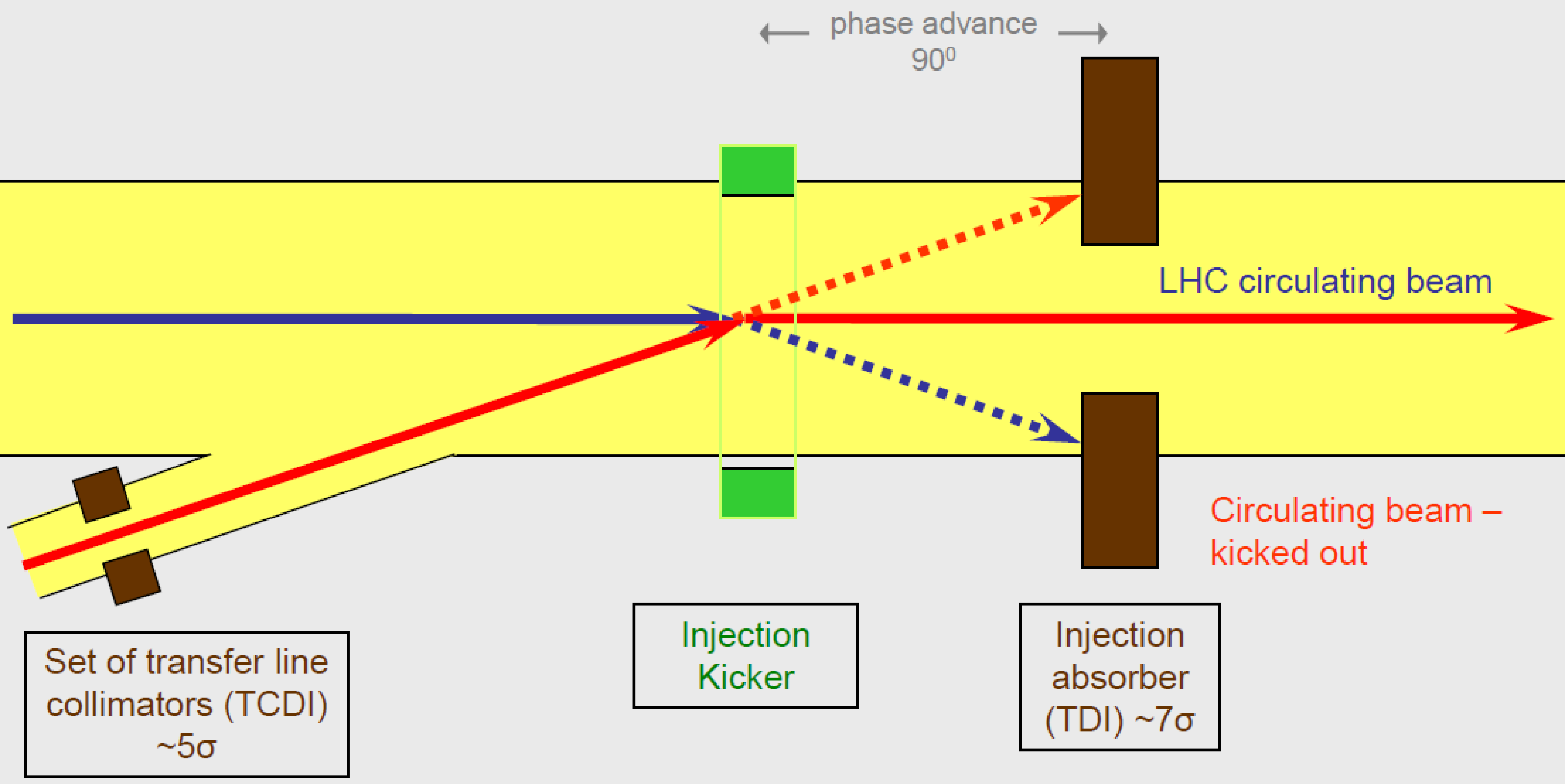
Protection at Injection to LHC

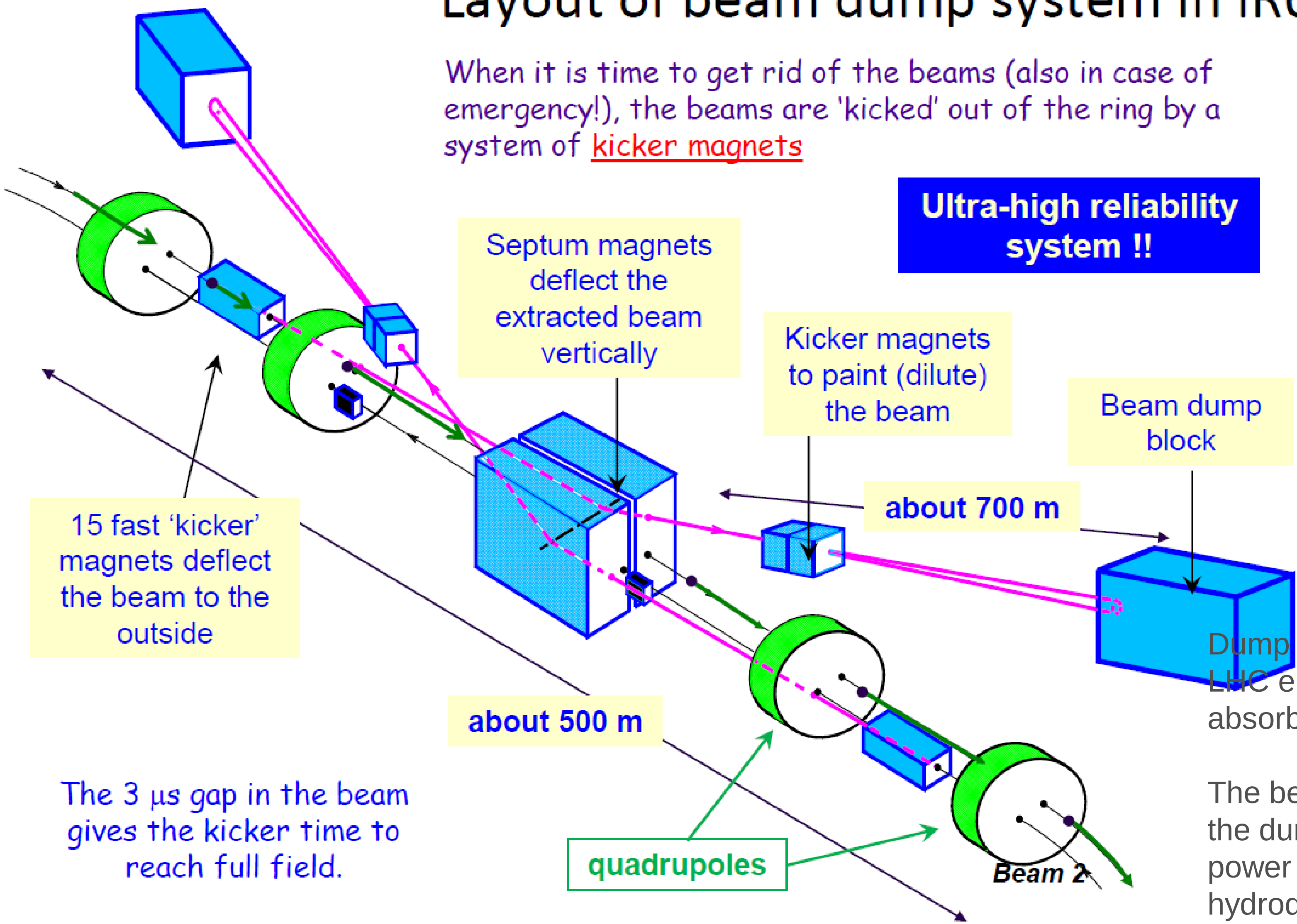


Beam absorbers take beam in case of kicker misfiring on circulating beam

LHC Beam Abort System

Layout of beam dump system in IR6

When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets



Dump block is the only LHC element capable of absorbing the full beam.

The beam is swept over the dump face to lower power density, otherwise hydrodynamic tunneling.

The 3 μs gap in the beam gives the kicker time to reach full field.

LHC Strategy for Machine Protection

• Definition of aperture by collimators.	**Beam Cleaning System**
• Early detection of equipment failures generates dump request, possibly before beam is affected.	**Powering Interlocks** **Fast Magnet Current change Monitor**
• Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.	**Beam Loss Monitors** Other Beam Monitors
• Reliable operation of beam dumping system for dump requests or internal faults, safely extracting beams onto the external dump blocks.	**Beam Dumping System**
• Reliable transmission of beam dump requests to beam dumping system. Active signal required for operation, absence of signal is considered as beam dump request and injection inhibit.	**Beam Interlock System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Collimator and Beam Absorbers**

R. Schmidt

Machine Interlock Systems at LHC

- Beam Interlock: Ensures beam extraction into the beam dump blocks when one of the MP systems detects a failure
- Powering Interlock: Ensures communication between systems involved in powering superconducting magnets (magnet protection, power converters, cryogenics, controls)
- Normal-Conducting Magnet Interlock: Ensures magnet protection in case of overheating and communication between systems involved in magnet powering
- Machine interlocks are strictly separated from interlock for personnel safety

Fermilab Machine Control and Safety Mechanisms

Administrative Controls

- Policies
- Procedures
- Signs
- Machine operators

Machine Protection Systems

- Beam permit system (BPS)
  - Beam alarms
  - Loss monitor inputs
  - Power supply monitoring
  - Vacuum valve positions
  - RF systems
  - Safety system (it provides input to BPS for monitoring purposes, but will terminate the beam directly and independently of all other systems)
  - Control system software monitoring
- Elements of the accelerator control system

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Fermilab Machine Controls (MC)

- MC are systems that are used to limit accidental beam losses. They may prevent a beam loss from occurring, may prevent subsequent beam losses from occurring, or may include monitoring secondary effects from significant beam losses, such as loss of vacuum, that then potentially result in actions that prevent further beam losses from occurring.

- While all of these machine controls are capable of terminating beam operations upon discovery of an excessive beam loss, the laboratory recognizes well that they all have failure modes and do not meet the level of rigor designed into to the Safety System.

- Administrative controls are obviously subject to well-known human performance factors that can lead to failures. Likewise, the automated machine protection systems, unlike the redundant Safety System items, are single output devices. Inputs to the MPS can be "masked" (i.e., taken off line) during beam tuning and troubleshooting activities and thus have the potential to not be "unmasked" when normal operations resume.

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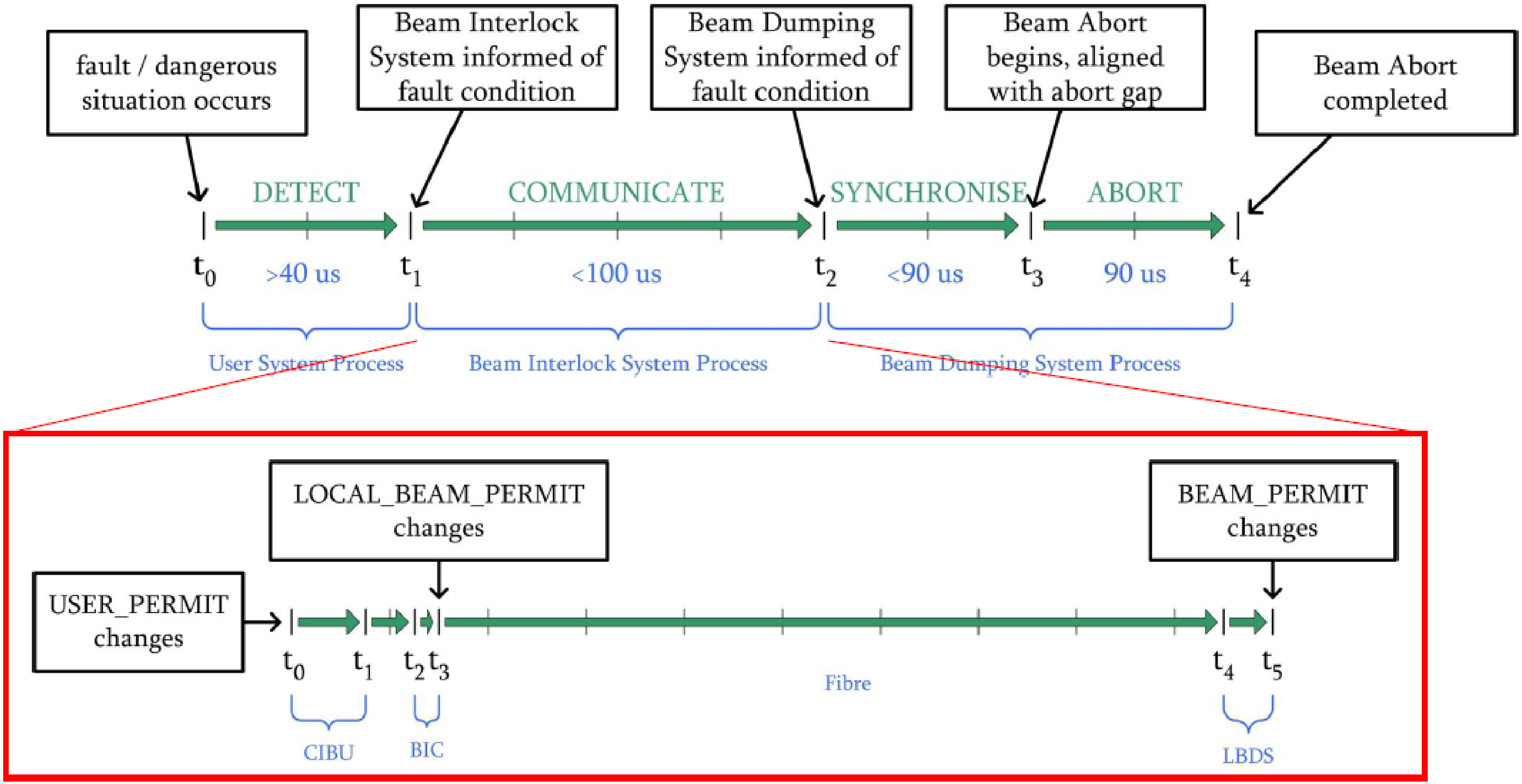
LHC MPS Flow



CIBU=Controls-Interlocks-Beam-User BIC=Beam Interlock Controller LBDS=LHC Beam Dumping System

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Design Guidelines for MPS

- Fail-safety: detect internal faults, remote testing, stop operation if MPS off
- Redundant critical equipment
- No remote changes of most critical parameters
- Quantify safety, availability, reliability to predict failure rate
- Managing interlocks (e.g., their masking for beam setup)
- Test-benching of electronics
- Documentation for MPS design, installation, maintenance and operation is mandatory
- During commissioning, test accurate execution of each protection function
- Establish requirements for the test interval of each function
- Keep in mind that most failures (at LHC) are due to power supplies, mechanical parts and connectors

LHC MPS Topics in 2015

- ❑ Electronics of quench detection: radiation induced failures.
  - *No safety, repair during TS2.*
- ❑ TDI absorber failures > 400 deg.
  - *Limit on no. injected bunches.*
- ❑ BLM threshold changes
  - *Weigh unnecessary UFO dumps vs protection.*
- ❑ Issues with interlock BPMs
- ❑ Beam dump block N2 pressure.
  - *Discovered a weakness in the surveillance of the dump*.

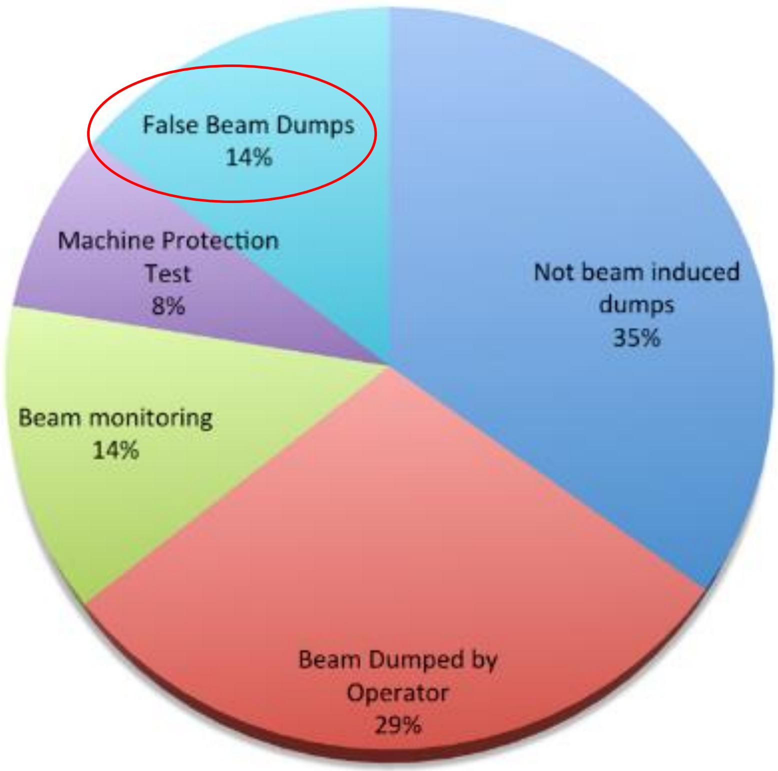
Efficient and fast reactions, mitigations were put in place
No problems during the intensity ramp up of the LHC in 2015

Chamonix 2016 Summary

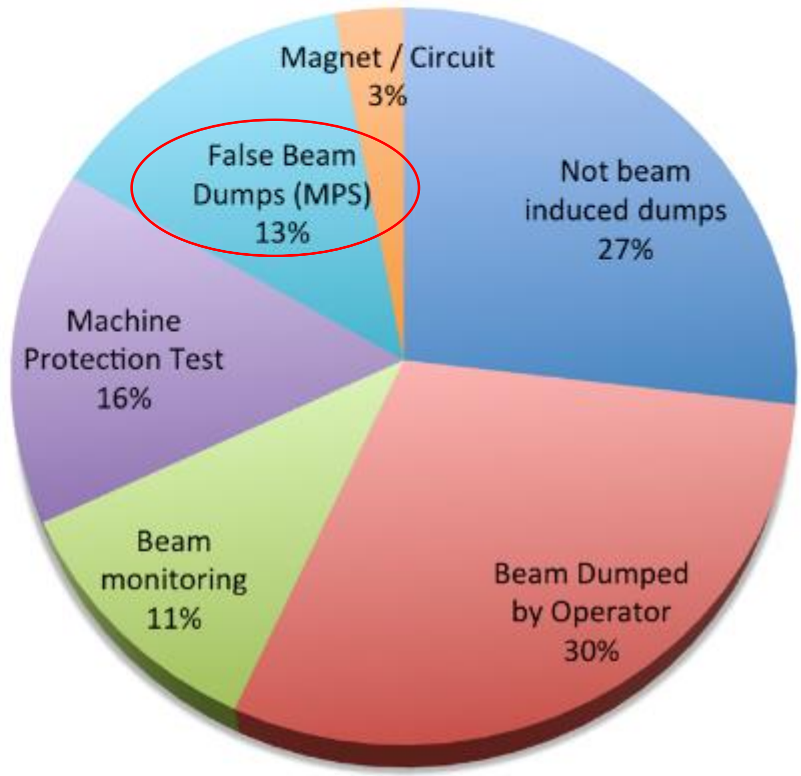
LHC MPS Dumps

Beam dump causes 2015 versus 2012 above injection

2012 (536)



2015 (442)

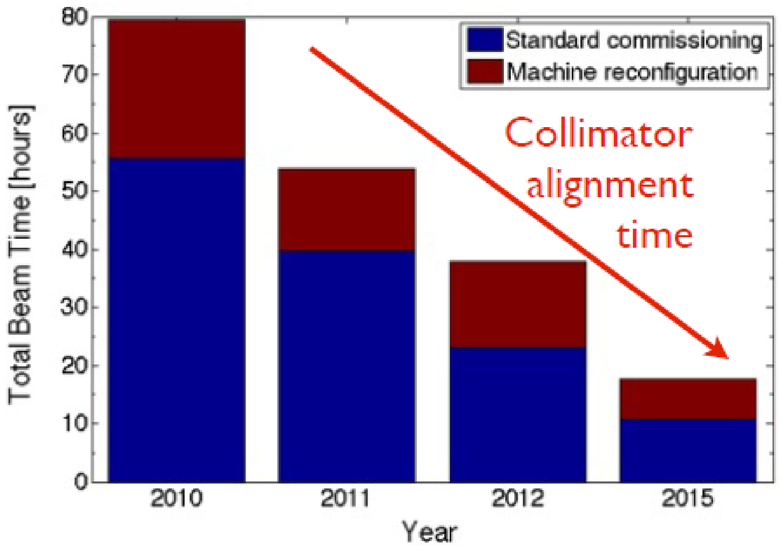


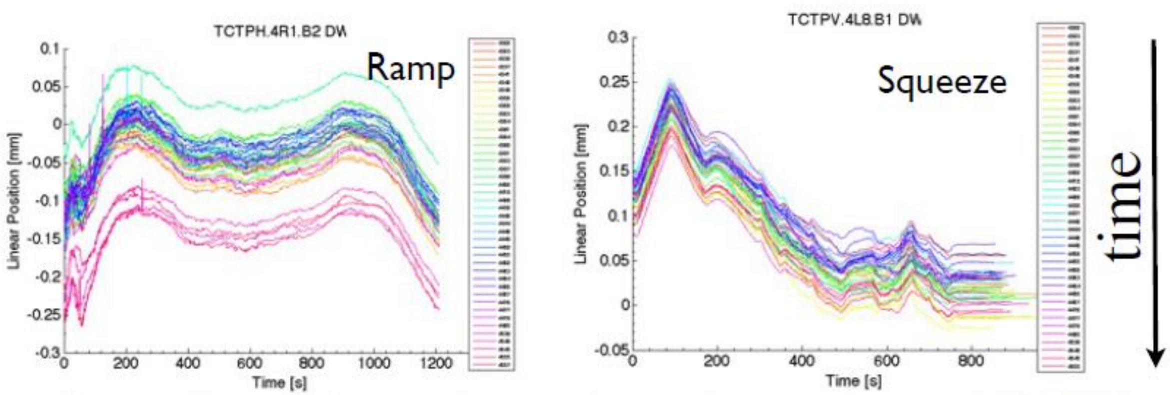
- False beam Dumps by Machine Protection Systems stable (LBDS, PIC, BLM, BIC, SIS, QPS, FMCM): 14 % in 2012 ➔ 13 % in 2015: OK

Chamonix 2016 Summary

LHC Collimation in 2015: Faster than Ever

- ❑ Thanks to experience and automation, the collimation setup and validation time was reduced by more than a **factor 4** since 2010.
- ❑ In 2015, 80% of the collimators were aligned with BLMs, 20% with BPMs.





- ❑ Systematic orbit offsets in the collimators during the cycle (ramp, squeeze) will be corrected in 2016…
- ❑ Preparing to interlock the beam position in collimators at lowest β^*.

Chamonix 2016 Summary

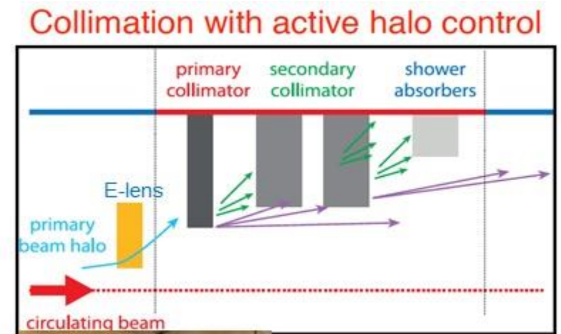
Protection Devices in the LIU & HL-LHC Project

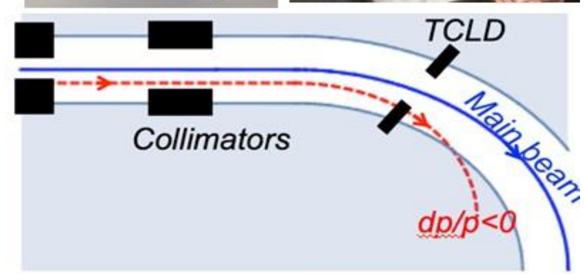
Protection devices in the whole accelerator chain will be upgraded for beams with higher intensity and brightness. Main examples:

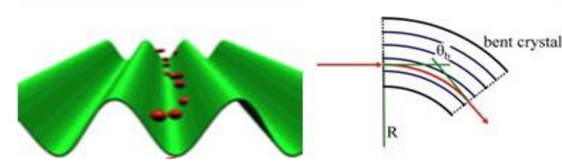
- **SPS internal dump** will be replaced with a re-designed version with improved shielding and vacuum performance
- **TCDI collimators** in the SPS-to-LHC transfer lines will be replaced with longer and more robust devices
- **TDI injection dumps** will be replaced with re-designed versions featuring better impedance, cooling and vacuum
- A large fraction of **LHC collimators** will be replaced with low-impedance ones; collimation still needs more work for the HL-LHC era

Chamonix 2017 Summary

Beam Halo Depletion in the HL-LHC Era







Chamonix 2017 Summary

<u>1. Active halo control</u> would allow **controlling diffusion speed** and **distributing losses** over time. **Overpopulated tails** (33 MJ outside 3.5 σ) combined with **fast failures** (e.g. by crab cavities) can cause high **losses into aperture** / collimation system.

Halo control via **e-lens** might be necessary to **mitigate fast failures and loss spikes**.

<u>2. Low impedance secondary collimators</u> (CFC) stabilize HL-LHC beams → **Prototype** collimators (MoGr, MoGr + TiN, MoGr + Mo) are being **installed** in LHC to **measure impedance** effects.

<u>3. Reduction of phase advance</u> (dump kickers to tertiary) or use of **more robust jaw material** allow for **tighter collimator settings** → nearly recover β^*=15 cm

4. **<u>Implementing BPM buttons</u>** in **all new collimators**: reduction of setup time

5. In IP7 dispersion suppressor, installation of **TCLD + 11 T dipoles** during LS2 will provide factor 3-4 margin (baseline) for protons.

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Towards FCC

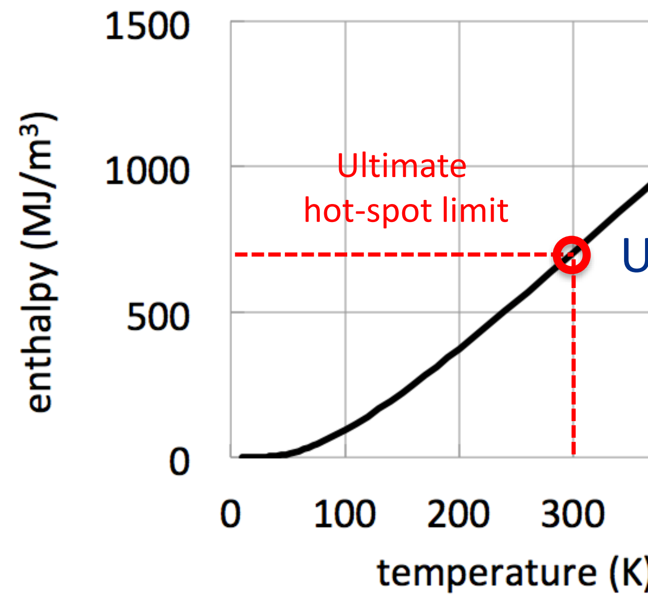
- Slow beam losses: decrease collimation cleaning inefficiency (to ≈ < 10^{-6})
- Fast losses: new ideas on MPS to protect a single magnet and magnet strings:
  dT/dt ≈ 1000…2000 (K/s), $\tau_{(300\ K)}$ ≈ 0.15…0.3 (s), E/l ≈ 1MJ/m

$$E/l \propto B^2$$

$$A_{coil} \propto \left(\frac{B}{J}\right)^n$$

In the range of typical magnet designs considered n≈1.5

$$e \approx \frac{E/l}{A_{coil}} \propto J^n B^{2-n}$$



L. Bottura

Typical energy densities e:

LHC MB(8.33T) ≈ 50 MJ/m^3
LHC MBH(11T) ≈ 85 MJ/m^3
FRESCA2(13T) ≈ 100 MJ/m^3

FCC MB(16T) ≈ 200 MJ/m^3

50 < 200 MJ/m^3 < UHSL