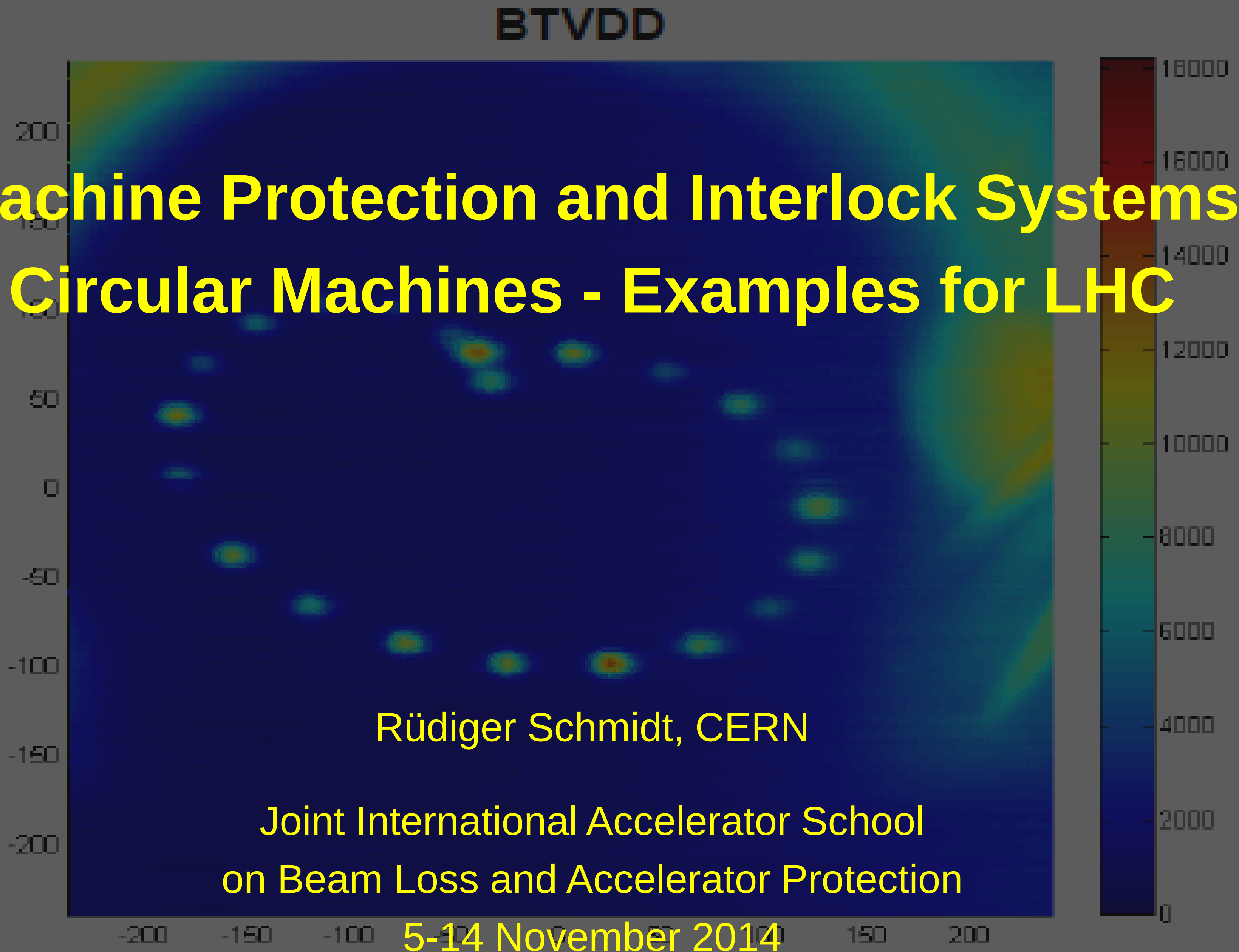
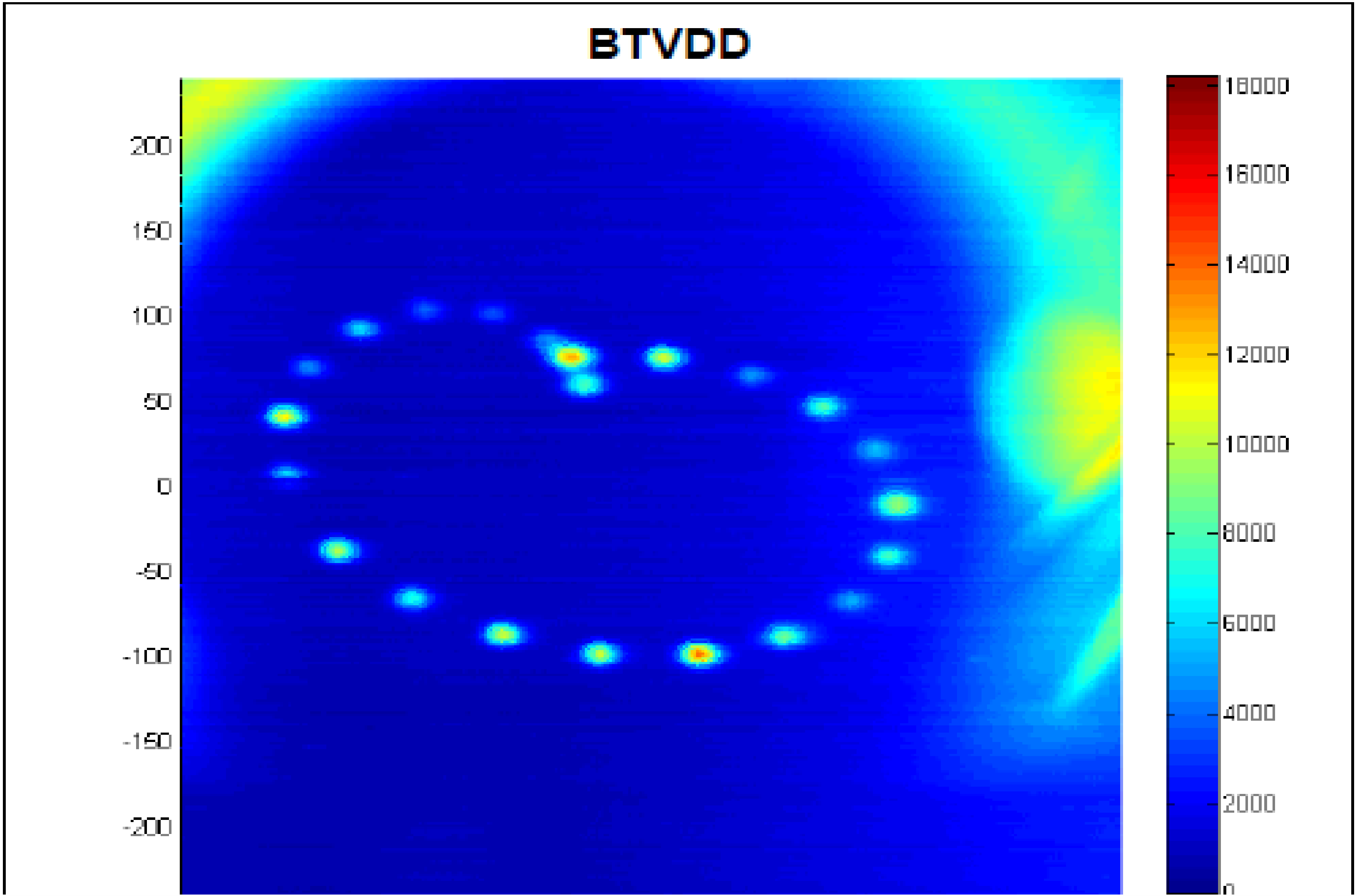
Machine Protection and Interlock Systems Circular Machines - Examples for LHC

Rüdiger Schmidt, CERN

Joint International Accelerator School
on Beam Loss and Accelerator Protection
5-14 November 2014





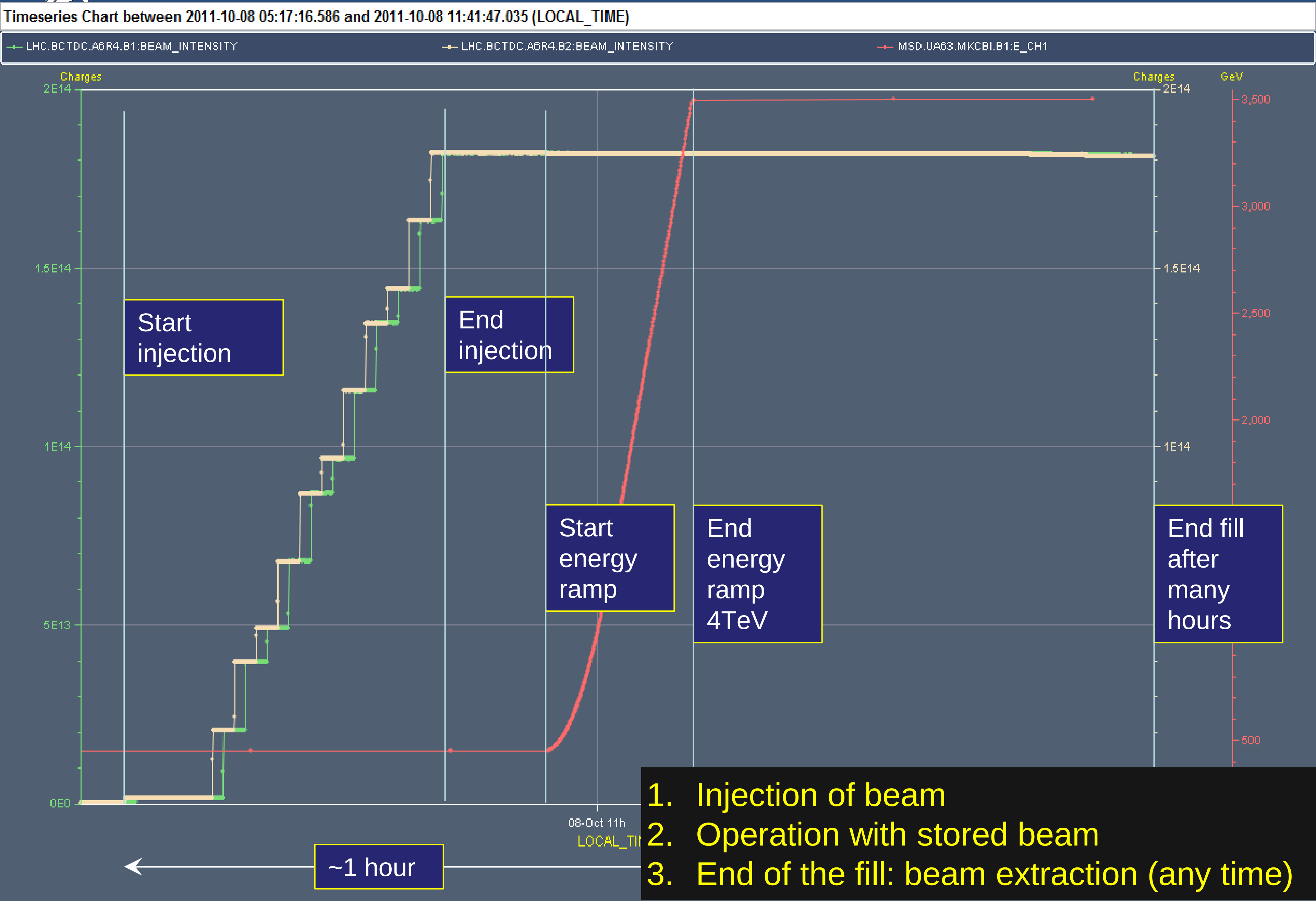
Proton bunches at the end of their life in LHC: screen in front of the beam dump block

Approach to designing a protection system

1. Identify hazards: what failures can have a direct impact on beam parameters and cause loss of particles (….hitting the 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

Back to square 1: continuous effort, not only once….

Operational modes in a circular accelerator



Timeseries Chart between 2011-10-08 05:17:16.586 and 2011-10-08 11:41:47.035 (LOCAL_TIME)

Start injection

End injection

Start energy ramp

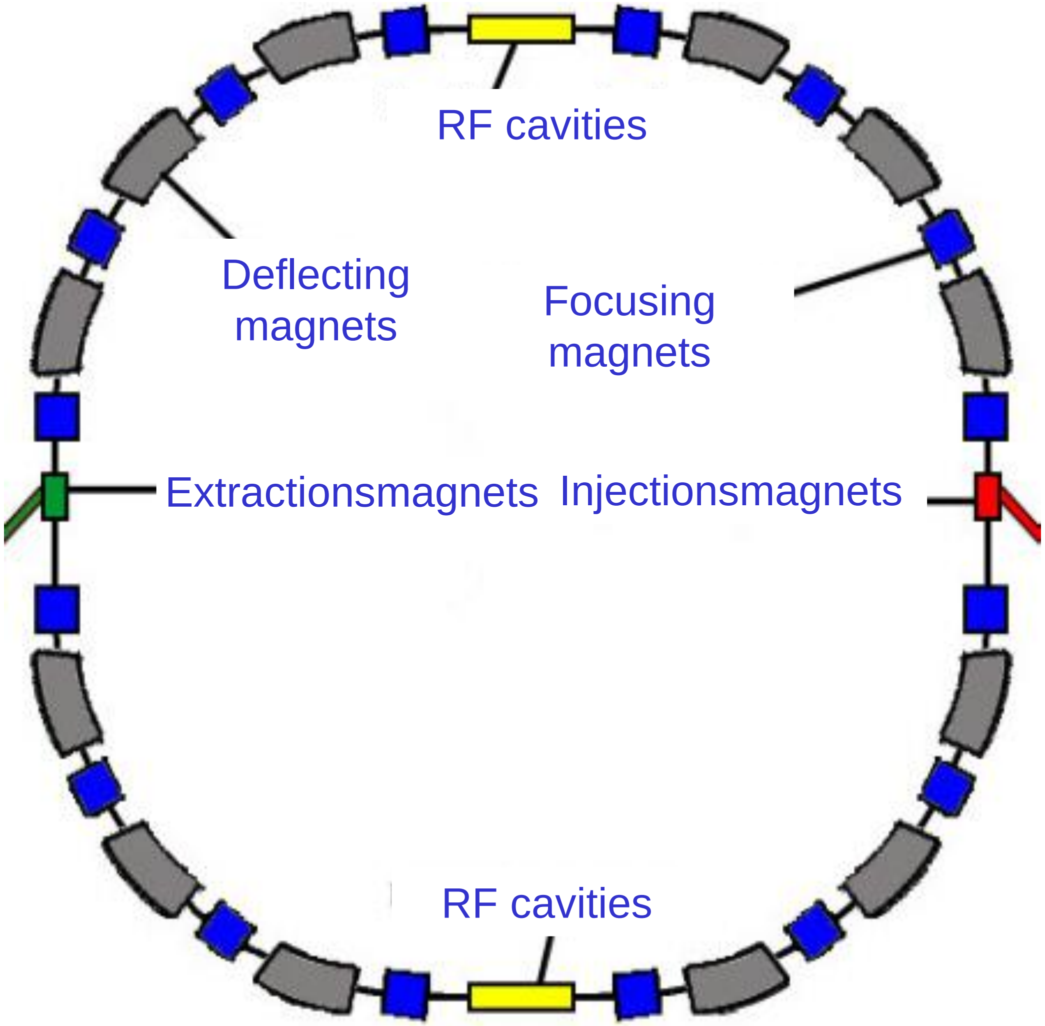
End energy ramp 4TeV

End fill after many hours

~1 hour

1. Injection of beam
2. Operation with stored beam
3. End of the fill: beam extraction (any time)

Components of a circular accelerator

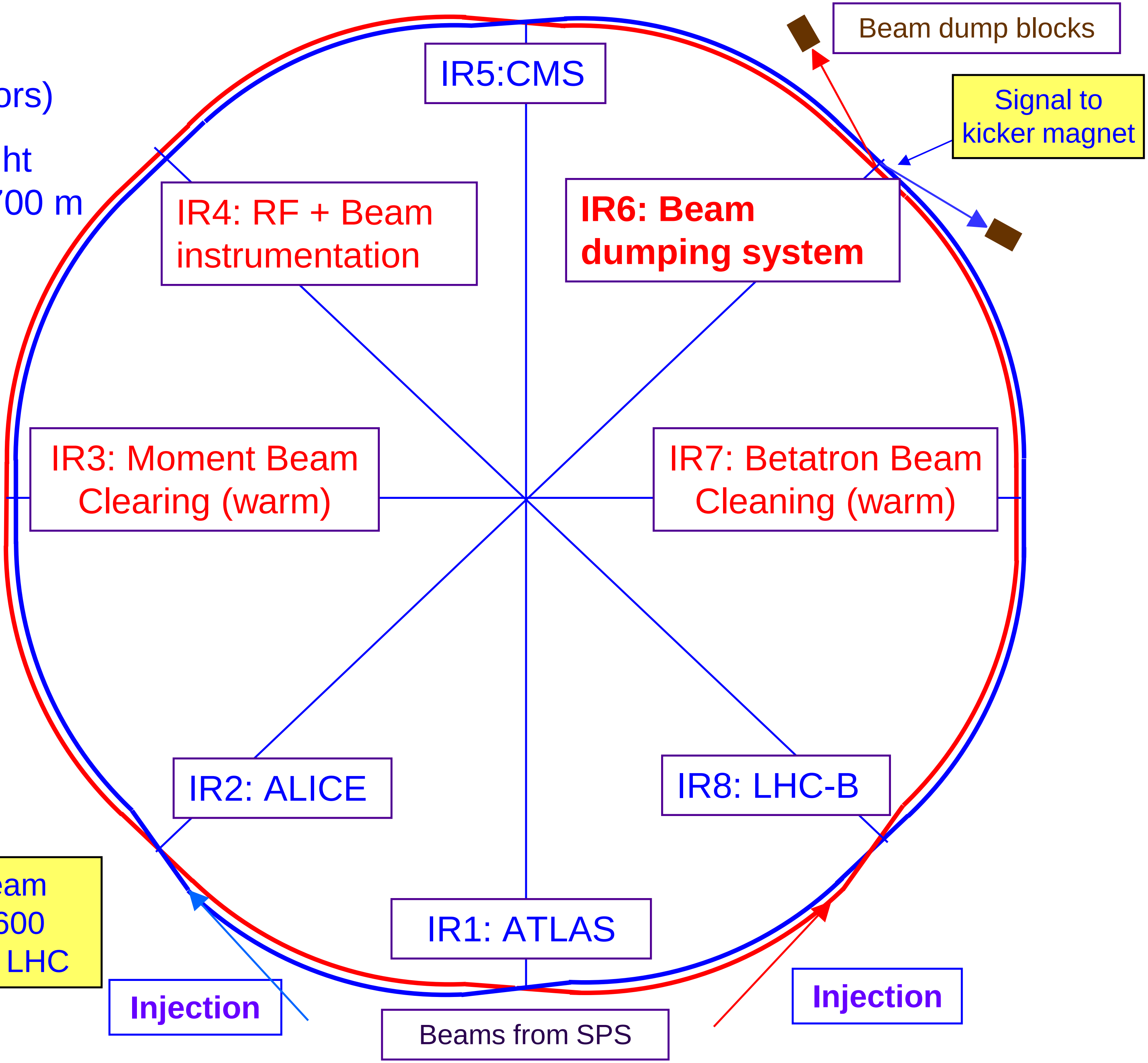


- Deflection magnets
- Magnets to focus beams and other magnets
- RF cavities
- RF system
- Vacuum system
- Injection magnets (pulsed)
- Extraction magnets (pulsed)
- Beam instrumentation
- Experiments
- Control system
- Power converter

LHC Layout

eight arcs (sectors)

eight long straight section (about 700 m long)



Beam dump blocks

Signal to kicker magnet

IR5:CMS

IR4: RF + Beam instrumentation

IR6: Beam dumping system

IR3: Moment Beam Clearing (warm)

IR7: Betatron Beam Cleaning (warm)

IR2: ALICE

IR8: LHC-B

IR1: ATLAS

Injection

Injection

Beams from SPS

Detection of beam losses with >3600 monitors around LHC

Hazards Overview

Classification of failures

- Type of the failure
  - Hardware failure (power converter trip, magnet quench, AC distribution failure such as thunderstorm, object in vacuum chamber, vacuum leak, RF trip, kicker magnet misfires, ….)
  - Controls failure (wrong data, wrong magnet current function, trigger problem, timing system, feedback failure, ..)
  - Operational failure (chromaticity / tune / orbit wrong values, …)
  - Beam instability (due to too high beam current / bunch current / e-clouds)

- Parameters for the failure
  - Time constant for beam loss
  - Probability for the failure
  - Damage potential

} Risk =Probability * Consequences

Time constant for failures

Single-passage beam loss in the accelerator complex (ns - μs)

- transfer lines b … fr … o a target station (target … or … p block)
- failures of kick … xt … er magnets, for example fo
- failures in linea … u … s
- too small beam size at a target station

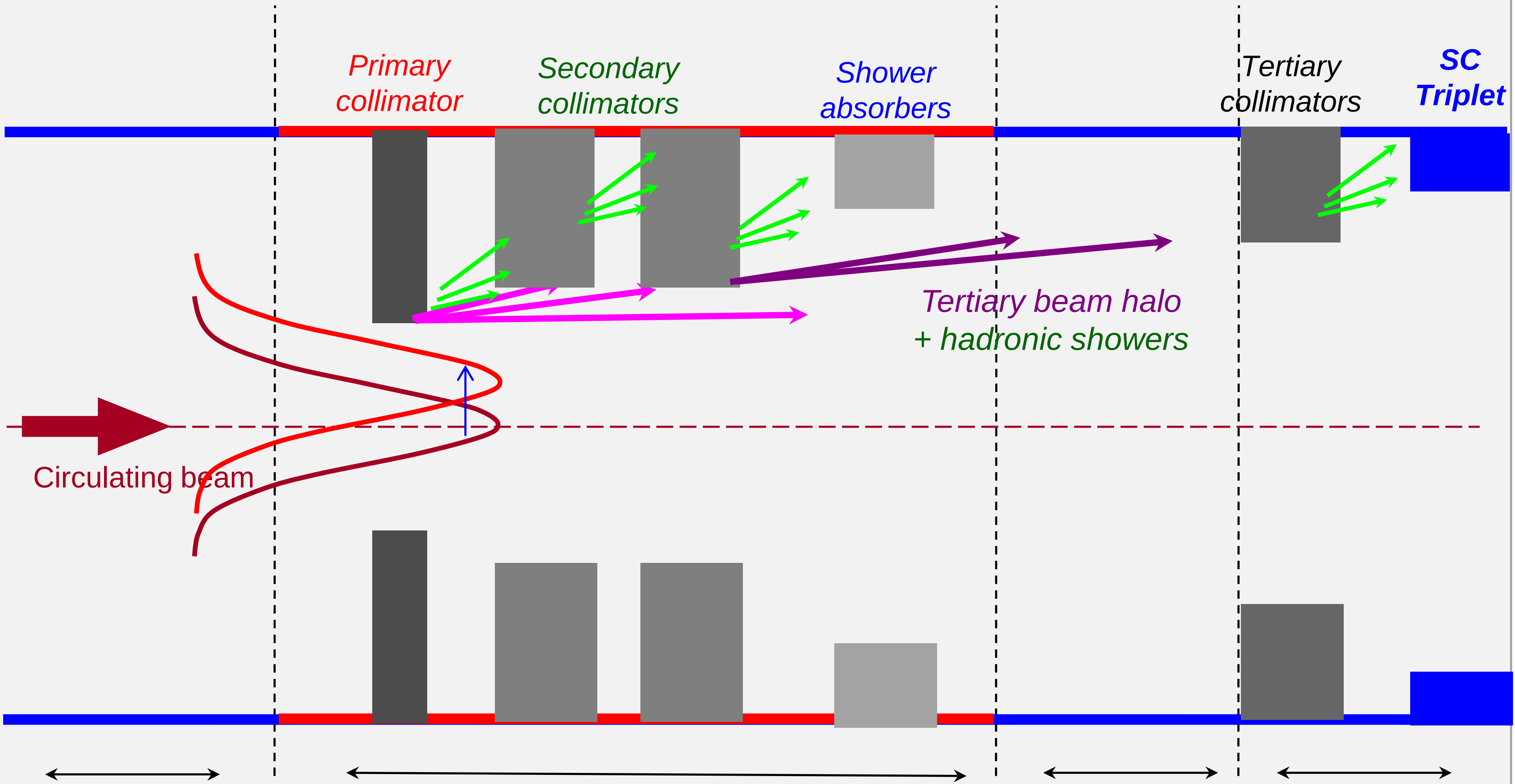
Very fast beam loss (ms)

- e.g. multi turn beam losses in circular accelerators
- due to a large number of possible failures, mostly in the magnet powering system, with a typical time constant of ~1 ms to many seconds

Fast beam loss (some 10 ms to seconds)

Slow beam loss (many seconds)

Where does the beam go?

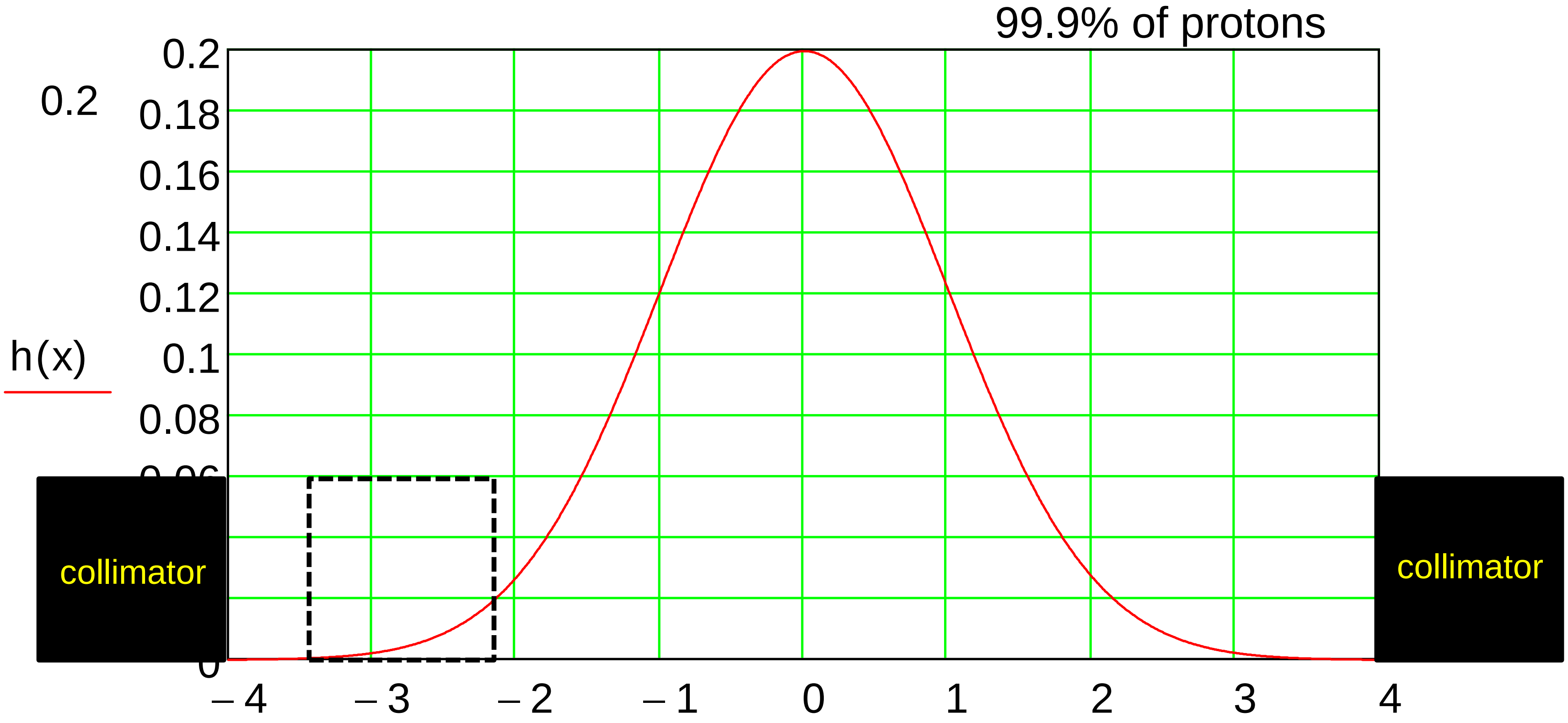


Cold aperture

Warm aperture

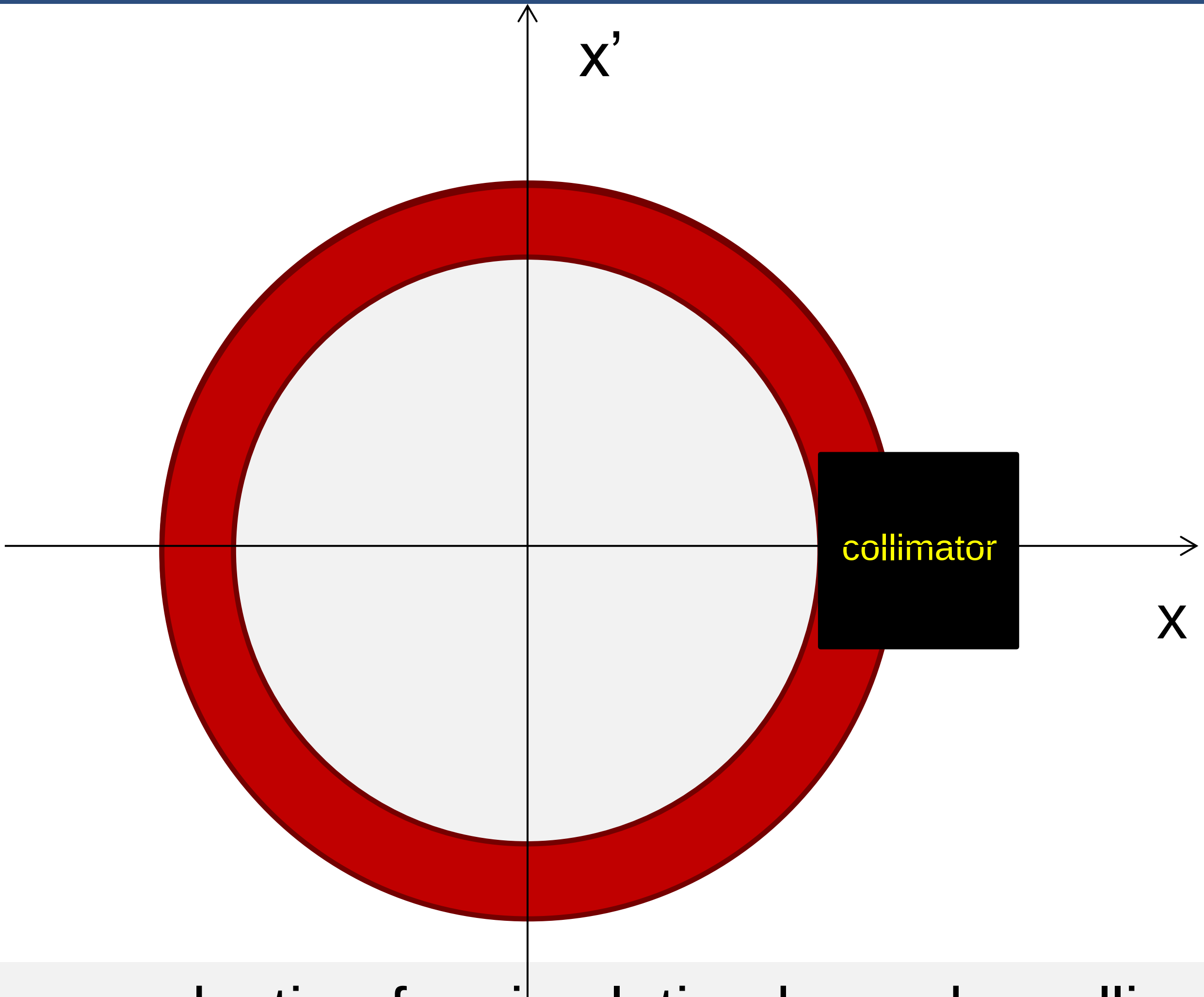
Illustration drawing

Gaussian beam collimated at 4 σ



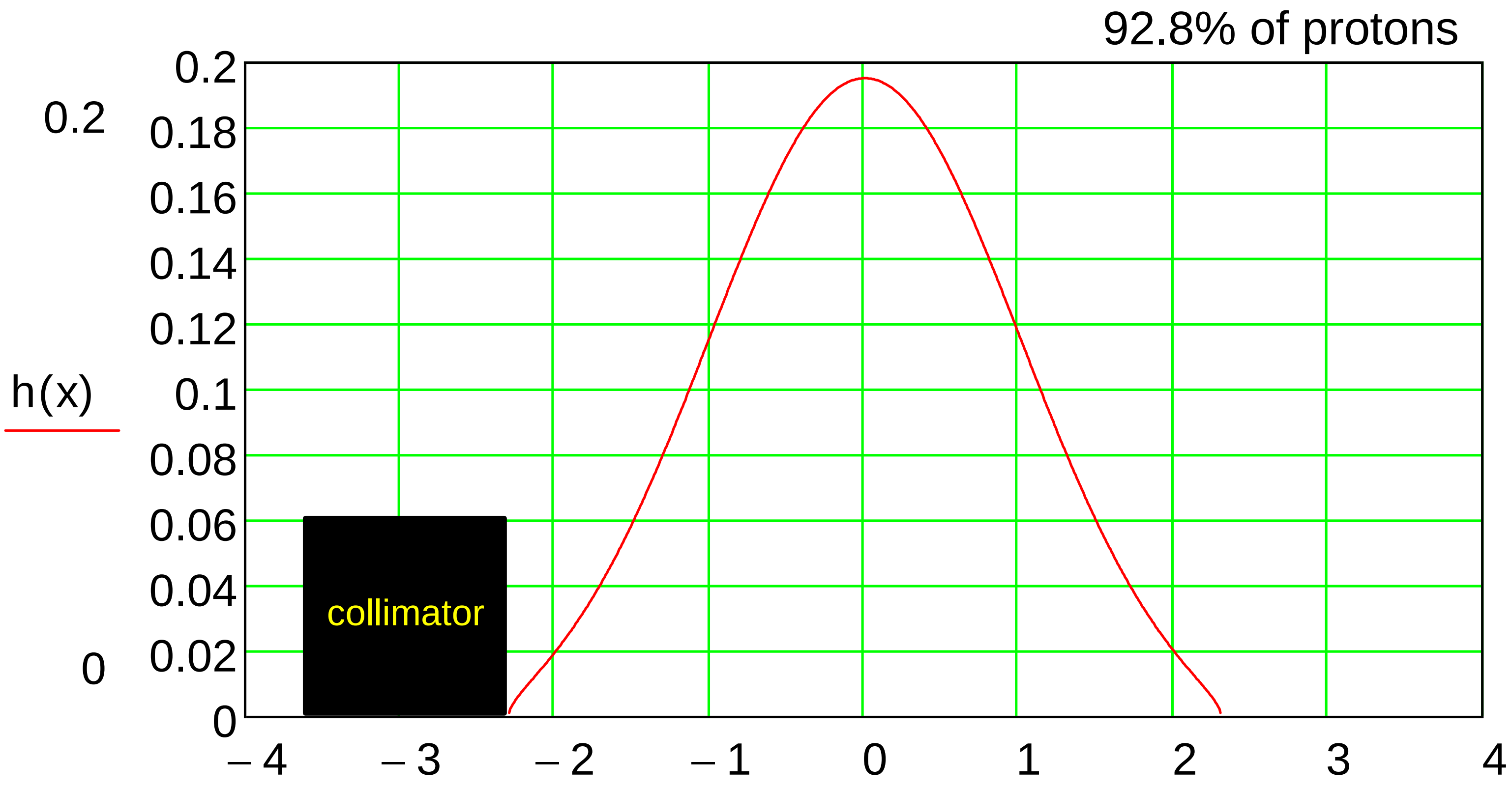
Example: a collimator is positioned at 4 σ, and we assume a dipole magnet failure. The beam starts to move, assume by 1.7 σ. All particles beyond 2.3 σ are lost.

Phase space reduction by collimator



Phase space reduction for circulating beam by collimator (multi-turn effect, different for transfer line or linac!)

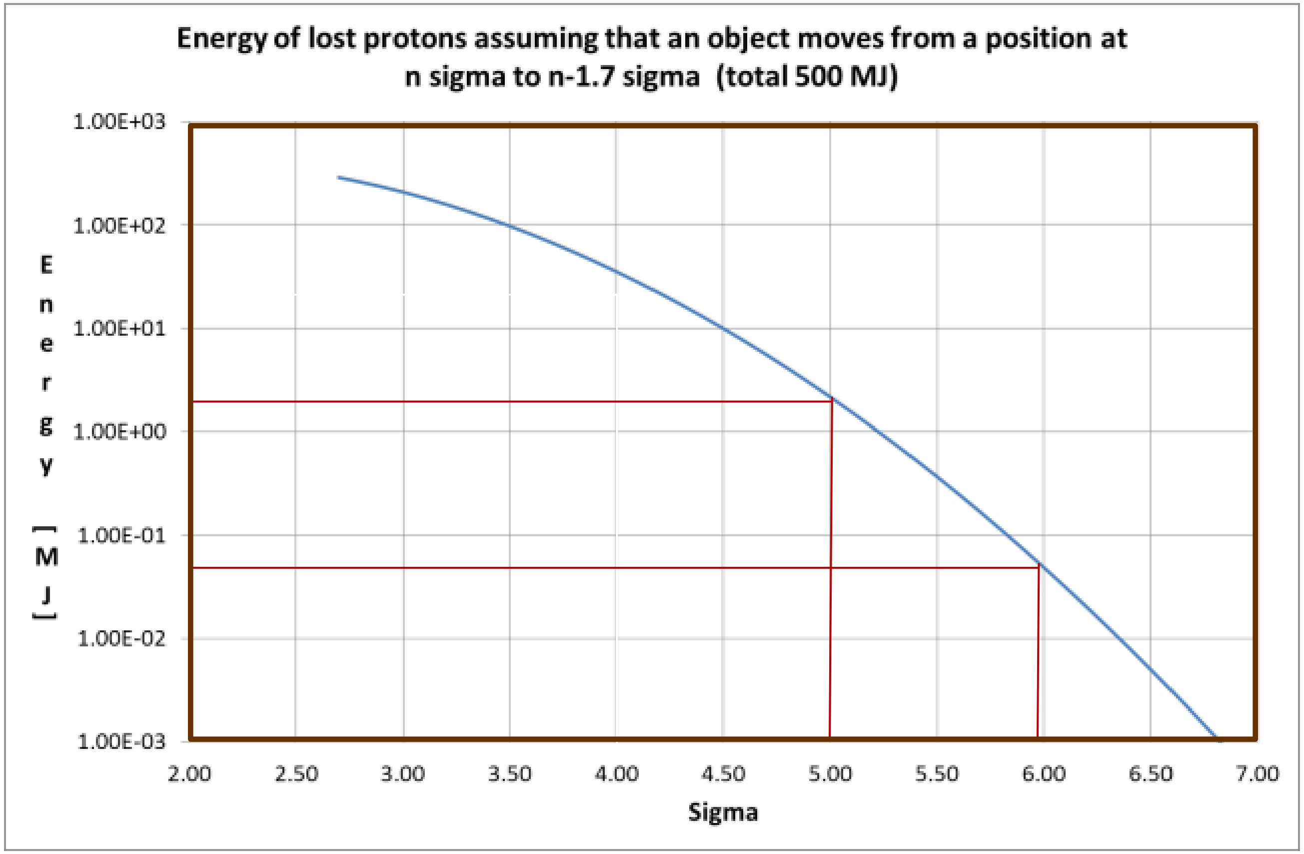
Gaussian beam with a collimator at 2.3 σ



- Assume that the total energy stored in the beam is 500 MJoule (HL-LHC)
- Assume a movement of the closed orbit by 1.7 σ
- Assume that all particles above 2.3 σ are lost => corresponds to energy deposition of 35 MJ

Gaussian beam, 1.7 σ are cut

- Assume that a collimator is at 4 σ, and a fast failure happens cutting into the tails by 1.7 σ. The energy loss corresponds to 35 MJ.
- For a collimator at 5 σ and a cut by 1.7 σ, the energy loss is ‘only’ 2.2 MJ.
- For a collimator at 6 σ and a cut by 1.7 σ, the energy loss is less than 0.1 MJ



What can change beam parameters?

- Magnetic fields (dominant elements in any circular accelerator)
  - Normalconducting magnets
  - Superconducing magnets
  - Can be dipoles, quadrupoles, sextupoles, etc.
- Electric fields
  - Electric fields for transverse deflection (e.g. electrostatic separators)
  - RF cavities – longitudinal field for acceleration
  - Transverse feedback systems
  - RF cavities (crab cavities), transverse field for deflection (for HL-LHC)
- Elements in the beam pipe
  - Residual gas (pressure of 10^{-6} to 10^{-12} mBar)
  - Elements that can move into the beam pipe
  - Elements that can be accidentally in the beam pipe
- Beam instabilities

Magnetic and electrical fields

- Slow changing dipole fields (magnets in the accelerator) => change the closed orbit
- Fast changing dipole fields (kicker magnets) => introduce betatron oscillations
- Quadrupole fields: change optics, might drive beam on resonances, might lead to instabilities
- Sextupole fields: change chromaticity, might drive beam on resonances, might lead to instabilities

For LHC, a PhD study showed that some dipole magnets (except kickers) have the fastest impact on the beam

- Define failure cases
- Calculate impact on particles
- Consider aperture when particles are lost

Redundancy of the LHC machine protection systems in case of magnet failures, A. Gomez Alonso, CERN-THESIS-2009-023 - Geneva : CERN, 2009.

Very fast beam loss

Failure in a magnet circuit

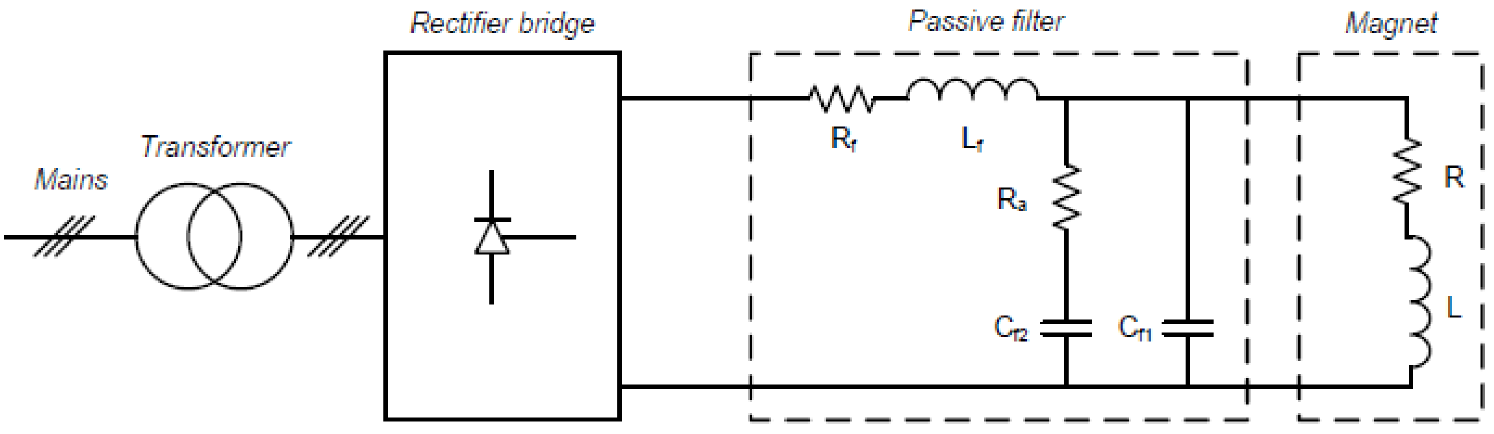


Figure 4.1: Output stage of a power converter

- Magnet parameters: $Inductance\ L\ and\ Resistance\ R$
- Power converter parameters: $Current\ I\ and\ Voltage\ V$
- Magnets rarely fail, failures are from the mains, the power converter, a quench, water cooling, controls or operation
- In case of a failure, the current and the field in the magnet changes
- A power converter can be very complex, but modelling the failure for the purpose of machine protection considerations can be simplified

1700 power converters for 60 A to 13 kA

13 kA

600 A

60 A

4…8 kA

Failure in a normal conducting magnet circuit

Normal operation at constant current with the nominal voltage V_{nom} and the resistance R :

$$I_{nom} = \frac{V_{nom}}{R}$$

Some failure scenarios

1. Failure: power supply trips and voltage V_{fail} goes to zero
    - Typical failure during a thunderstorm
2. Failure: controls requests power supply to go to maximum voltage, or voltage with opposite polarity
    - There can be cases that are worse than a trip to $V = 0V$
    - Limit voltage of power supply to what is needed, not more

Assume a failure and the power converter voltage changes to V_{fail}:

$$I(t) = I_{nom} \times (e^{-\frac{t}{\tau}} + \frac{V_{fail}}{V_{nom}} \times (1 - e^{-\frac{t}{\tau}})) \quad \text{with} \quad \tau = L/R$$

Recall some equations

Deflection angle of a magnet:

$$\alpha = \frac{B \times L}{E} \times c \times e_0$$

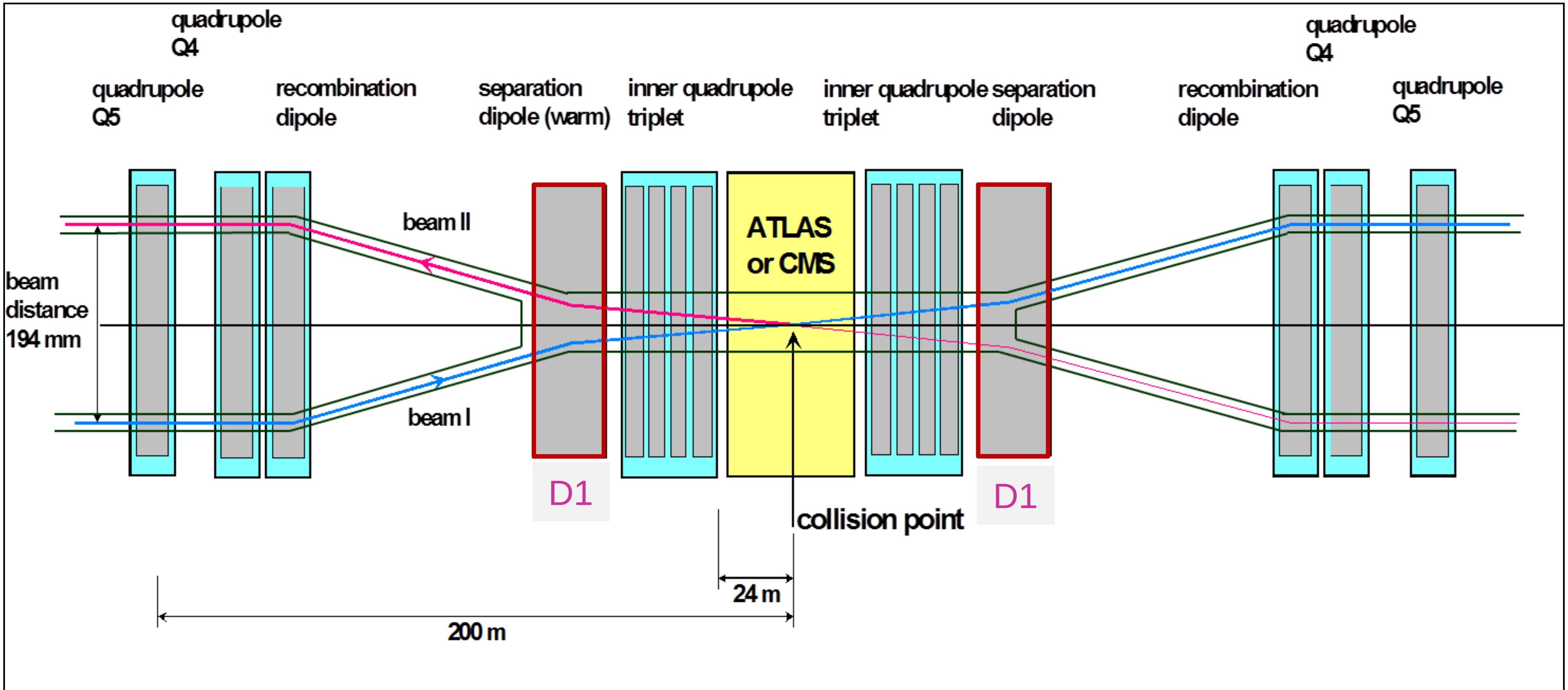
With B the magnetic field, L the length of the magnet, and E the beam energy and $c \times e_0$ constants (speed of light, elementary charge)

Change of closed orbit as a function of the deflection angle of a magnet:

$$x = \frac{\sqrt{\beta_1 \times \beta_2}}{2 \times \sin(\pi Q)} \times \alpha$$

With $\beta_{1,2}$ the beta functions at the location of the magnet, and the location of the observation point, Q the betatron tune and α the deflection angle in [rad]

LHC experimental long straight sections and D1



Example for an LHC insertion with ATLAS or CMS

- The 2 LHC beams are brought together to collide in a ‘common’ region
- Over ~260 m the beams circulate in one vacuum chamber with ‘parasitic’ encounters (when the spacing between bunches is small enough)
- D1 separates the two beams

Failure of a D1 magnet at LHC

Inductance of 12 magnets powered in series: $L_{D1} := 1.74\mathrm{H}$

Resistance of 12 magnets powered in series: $R_{D1} := 0.78\Omega$

Energy of LHC protons at collision energy: $E_{lhc\_c} = 7.0000 \cdot \mathrm{TeV}$ and Time for one revolution:

$T_0 := 89 \cdot 10^{-6}\mathrm{s}$

Nominal field at 7 TeV: $B0_{D1} := 1.38\mathrm{T}$

Length of one magnet: $L_{D1} := 3.4\mathrm{m}$

Nominal deflection angle: $\alpha_{D1} := \dfrac{B0_{D1} \cdot 12 \cdot L_{D1}}{E_{lhc\_c}} \cdot c \cdot e_0$ => $\alpha_{D1} = 2.41 \times 10^{-3}$

Time constant in case of powering failure: $\tau_{D1} := \dfrac{L_{D1}}{R_{D1}}$ => $\tau_{D1} := 2.53\mathrm{s}$

Error in deflection after $N := 10$ turns: $t_x := N \cdot 89 \cdot 10^{-6} \cdot \mathrm{s}$

$$B_{D1} := B0_{D1} \cdot \left(1 - e^{\frac{-t_x}{\tau_{D1}}}\right)$$

$$\frac{B_{D1}}{B0_{D1}} = 3.52 \times 10^{-4}$$

Failure of a D1 magnet at LHC

Error in angle:

$$\alpha_{err} := \alpha_{D1} \cdot \frac{B_{D1}}{B0_{D1}}$$

$$\alpha_{err} = 8.4812 \times 10^{-7}$$

Change of the position orbit at a location of the LHC with $\beta_{D1} := 4000\text{m}$, $\beta_{test} := 100\text{m}$:

$$x_{D1} := \frac{\sqrt{\beta_{D1} \cdot \beta_{test}}}{2 \cdot \sin(\pi \cdot Q)} \cdot \alpha_{err}$$

$x_{D1} = 0.3243 \cdot \text{mm}$ Beam position change after 0.9 ms, about 1.4 σ

Beam size at a location with $\beta_{test} = 100.0\,\text{m}$ assuming a normalised emittance

$$\varepsilon_n = 3.75 \times 10^{-6}\,\text{m}$$

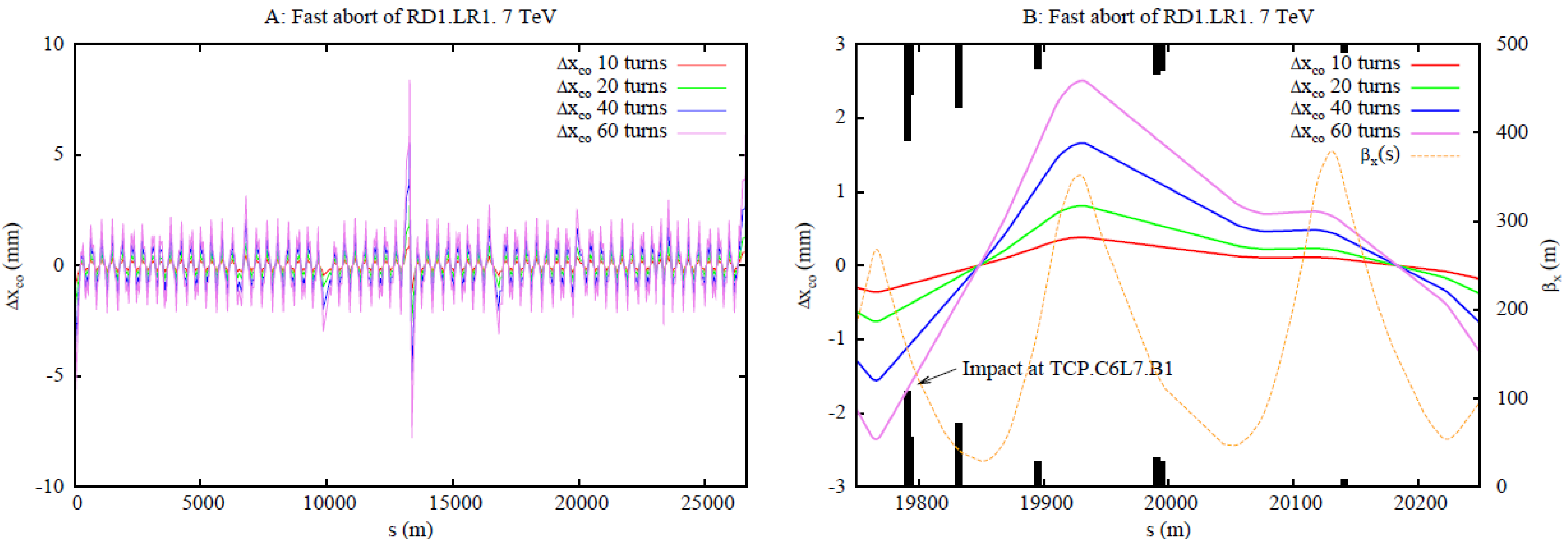
The gamma factor for an energy of $E_{lhc\_c} = 7.0000 \cdot \text{TeV}$ => $\gamma_c = 7459.9105$

$$\sigma_{100m} := \sqrt{\frac{\varepsilon_n}{\gamma_c} \cdot \beta_{test}}$$

$$\sigma_{100m} = 0.2242 \cdot \text{mm}$$

Simulation using MADX of this failure

- This failure (and many other failures) were simulated using MADX
- A failure of D1 is the most critical failure



Andres Gomez Alonso

Consequences for machine protection

- In case of a trip of the D1 magnet the orbit starts to move rather rapidly (1 sigma in about 0.7 ms)
- In 10 ms the beam would move by 14 sigma, already outside of the aperture defined by the collimators
- For this failure, the beam has to be extracted in a very short time
- Probability that this will happen during the lifetime of LHC is high
- Detection of the failure by several different systems (diverse redundancy)
  - Detection of the failure of a wrong magnet current, challenging, since a fast detection on the level of 10^{-4} is required
  - Done with a specifically designed electronics (FMCM = Fast Magnet Current Monitor) – M.Werner (DESY) et al.
  - Beam loss monitors detect losses when the beam touches the aperture (e.g. collimator jaw, but also elsewhere)
- LHC MPS was designed for this type of failure => J.Wenninger

Failure in a superconducting magnet circuit

- Magnet parameters: $Inductance\ L$ (in general very high)
- $Resistance\ R$: magnet resistance is zero, resistance given by connecting cables (very small)
- In case of powering failure, the decay of the magnet field takes a long time (can be up to many hours)
- In case of a quench: it depends how the quench is created. In general, the magnet starts to quench at a specific location, and the quench spreads out. The resistance increases with time.

- Superconducting magnets require a magnet protection system that detects any quench – this signal should also be used to dump the beam

Quench of a superconducting magnet

- No analytical equation for the current as a function of time
- Below, measurements from LHC magnets
- Approximation by a Gaussian is reasonable
- In general, less critical than the trip of a normal conducting

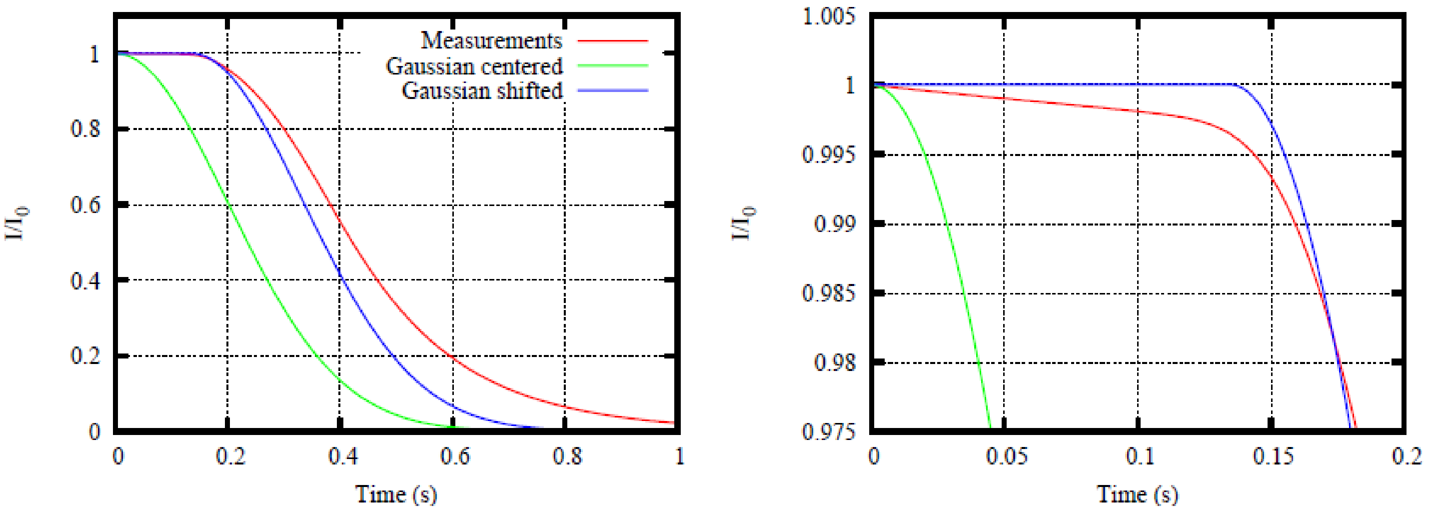
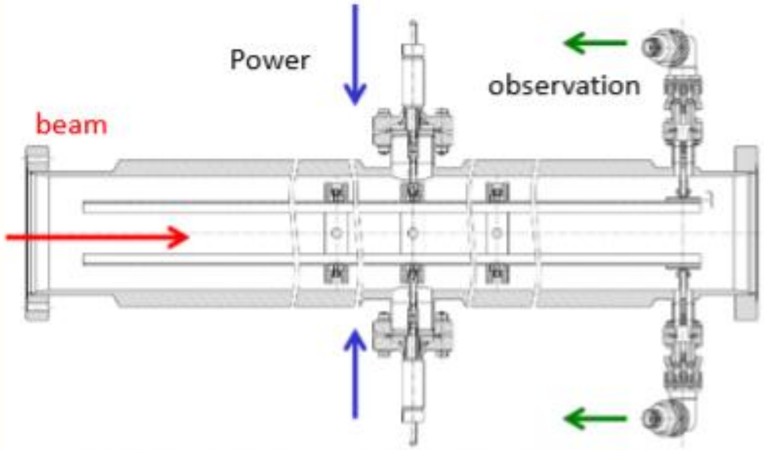


Figure 4.5: Current decay for a quench in RD2.L5. The measured data show a small linear drop until the whole magnet is quenched and then follow a Gaussian decay. The characteristics of the linear drop depend on the evolution of the quench in each particular case and on the reaction time of the QPS. In this particular case, the analytical approach with $\sigma = 200$ ms yields a decay that is slightly faster than the measured one.

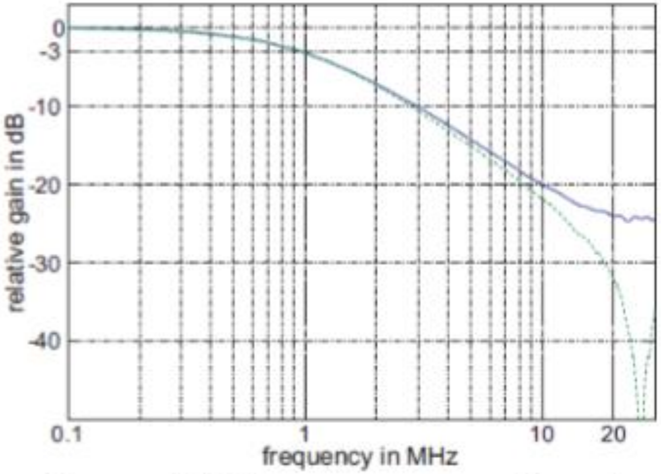
W. Hofle Progress in Transverse Feedbacks ... for Hadron Machines IPAC'13 Shanghai, China
May 13-17, 2013

ADT Power and Kicker System



ADT kicker. The beam is kicked by electric field

- Kicker length: each kicker 1.5 m
- Max voltage: 10.5 kV
- **2μrad** kick to 450 GeV beam
- Gain up to beyond 20 MHz
- 16 kickers,
- 32x30 kW tetrode amplifiers
- Bandwidth up to 20 MHz



Measured ADT frequency response. Green: bare power amplifier, blue: power amp + kicker.

LHC transverse Feedback (ADT) kickers and amplifiers in tunnel point 4 of LHC, RB44 and RB46

Built in collaboration with JINR, Dubna, Russia; E. Gorbachev et al. LHC Proj. Rept.-1165 CERN (2008)

LHC

9

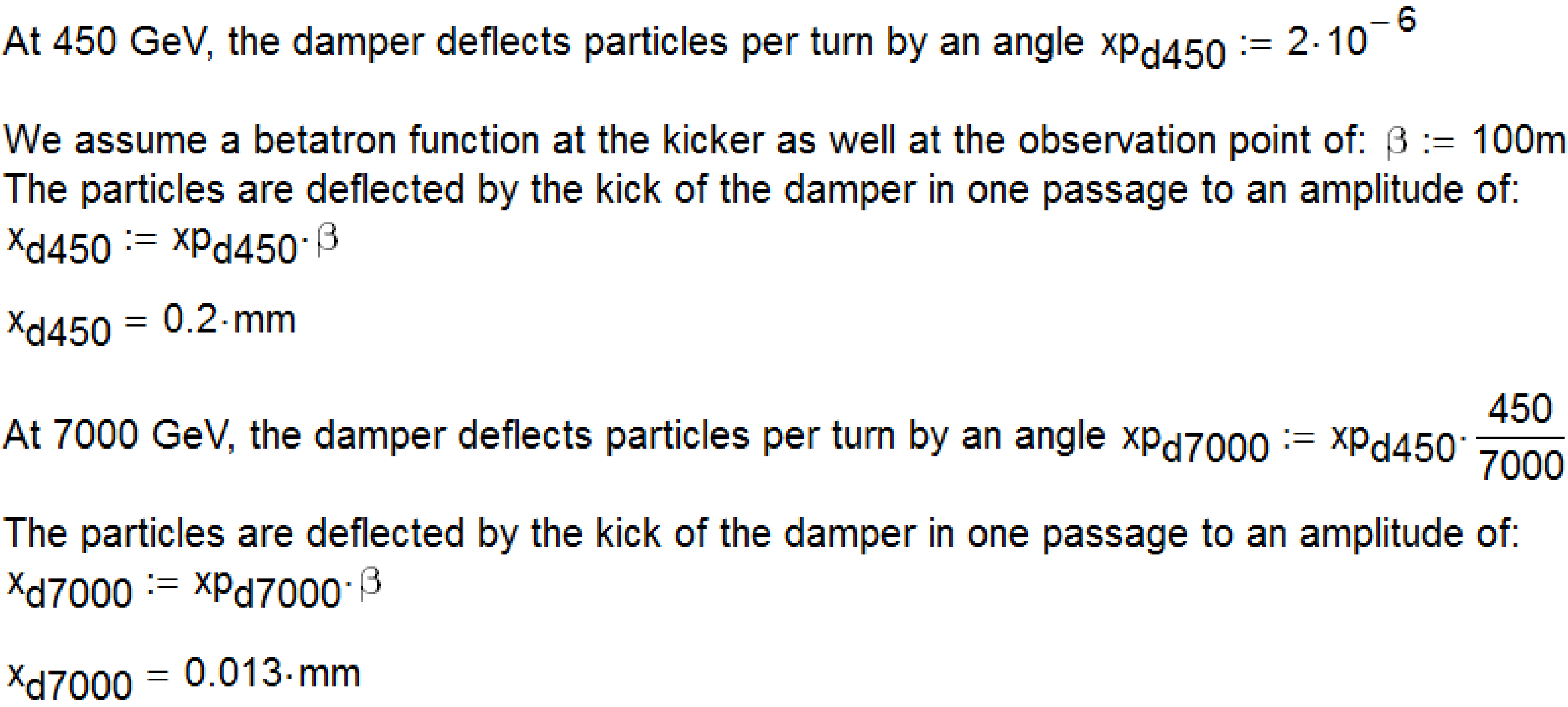
W.Hoefle, IPAC 2013

Transverse damper (feedback)

- The transverse damper is used to damp instabilities, to damp injection oscillations and has several other applications
  - Abort-gap and injection cleaning
  - Blow-up for loss maps and aperture studies
  - Tool to produce losses for quench tests
  - Diagnostics tool to record bunch by bunch oscillation
  - Tune measurement (under development)
- The damper creates an electrical field for deflecting the particles and can deflect the beam with an angle of 2 murad/passage at 450 GeV

In the worst case, the deflection of the transverse damper can add up coherently

Excitation of betatron oscillation



At 450 GeV, the damper deflects particles per turn by an angle $xp_{d450} := 2 \cdot 10^{-6}$

We assume a betatron function at the kicker as well at the observation point of: $\beta := 100m$

The particles are deflected by the kick of the damper in one passage to an amplitude of:

$x_{d450} := xp_{d450} \cdot \beta$

$x_{d450} = 0.2 \cdot mm$

At 7000 GeV, the damper deflects particles per turn by an angle $xp_{d7000} := xp_{d450} \cdot \frac{450}{7000}$

The particles are deflected by the kick of the damper in one passage to an amplitude of:

$x_{d7000} := xp_{d7000} \cdot \beta$

$x_{d7000} = 0.013 \cdot mm$

Effect of the damper: worst case calculation

In the worst case, we assume an entirely coherent excitation (the effect of the kick adds up).

We assume a normalised emittance of the beam of: $\varepsilon_n := 3.75 \cdot 10^{-6} m.$

$E_{lhc} := 7000GeV$

Gamma: $\gamma := \frac{E_{lhc}}{m_p \cdot c^2}$

Emittance: $\varepsilon := \frac{\varepsilon_n}{\gamma}$

The beam size at a position with a beta function of: $\beta = 100\,m$ is given by: $\sigma := \sqrt{\varepsilon \cdot \beta}$

Beam size: $\sigma = 0.224 \cdot mm$

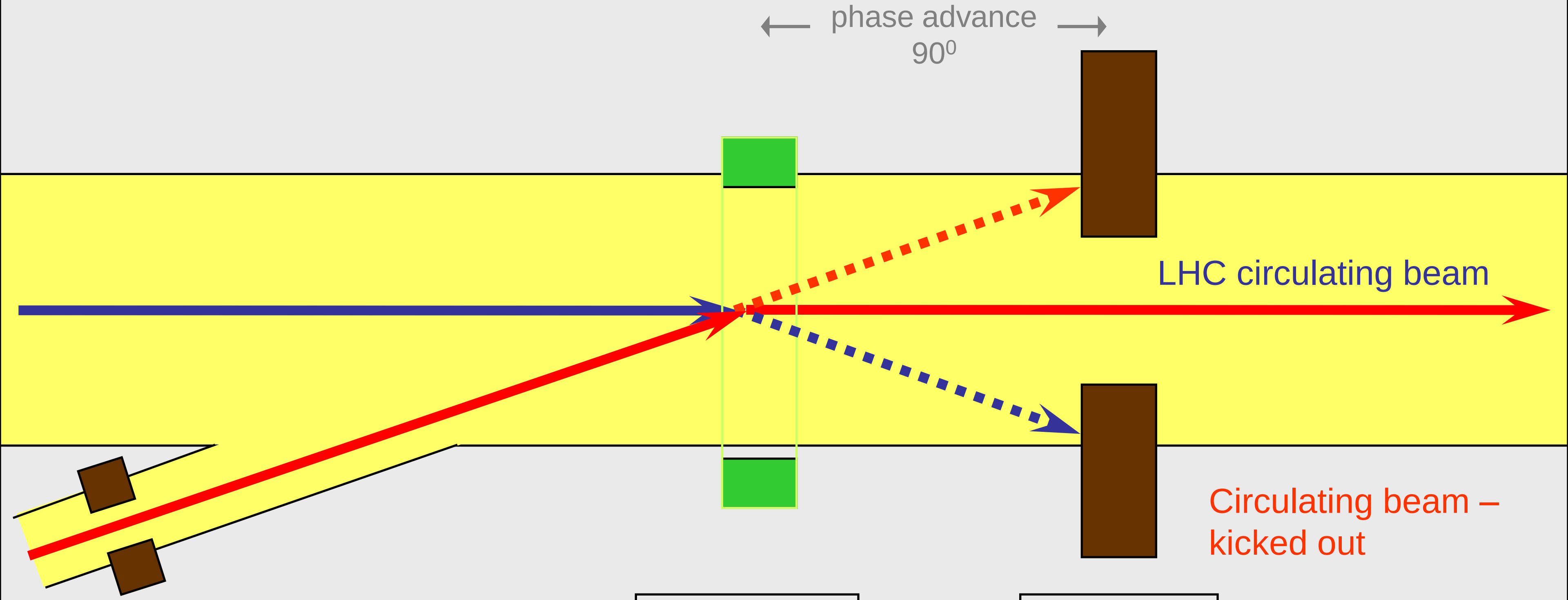
The increase of the amplitude per turn is given by: $x_{d7000} = 0.013 \cdot mm$

It takes a number of turns that the beam is displaced by one sigma: $N_{turns\_1\sigma} := \frac{\sigma}{x_{d7000}}$

$N_{turns\_1\sigma} = 17.438$

Fast kicker magnets for injection and extraction

Fast kicker magnets: Protection at injection



Set of transfer line collimators (TCDI) ~5σ

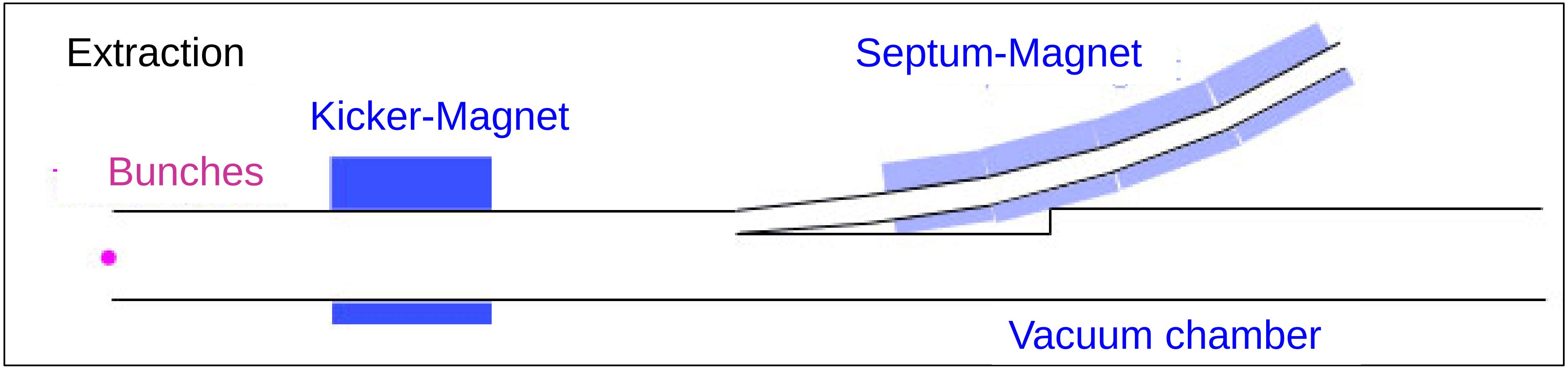
Injection Kicker

Injection absorber (TDI) ~7σ

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

Fast kicker magnets: Principle at extraction

- Kicker magnets: very short pulse, deflecting by a small angle
- Septum magnets: “DC” magnets (can be slowly pulsed), no magnetic field on circulating beam

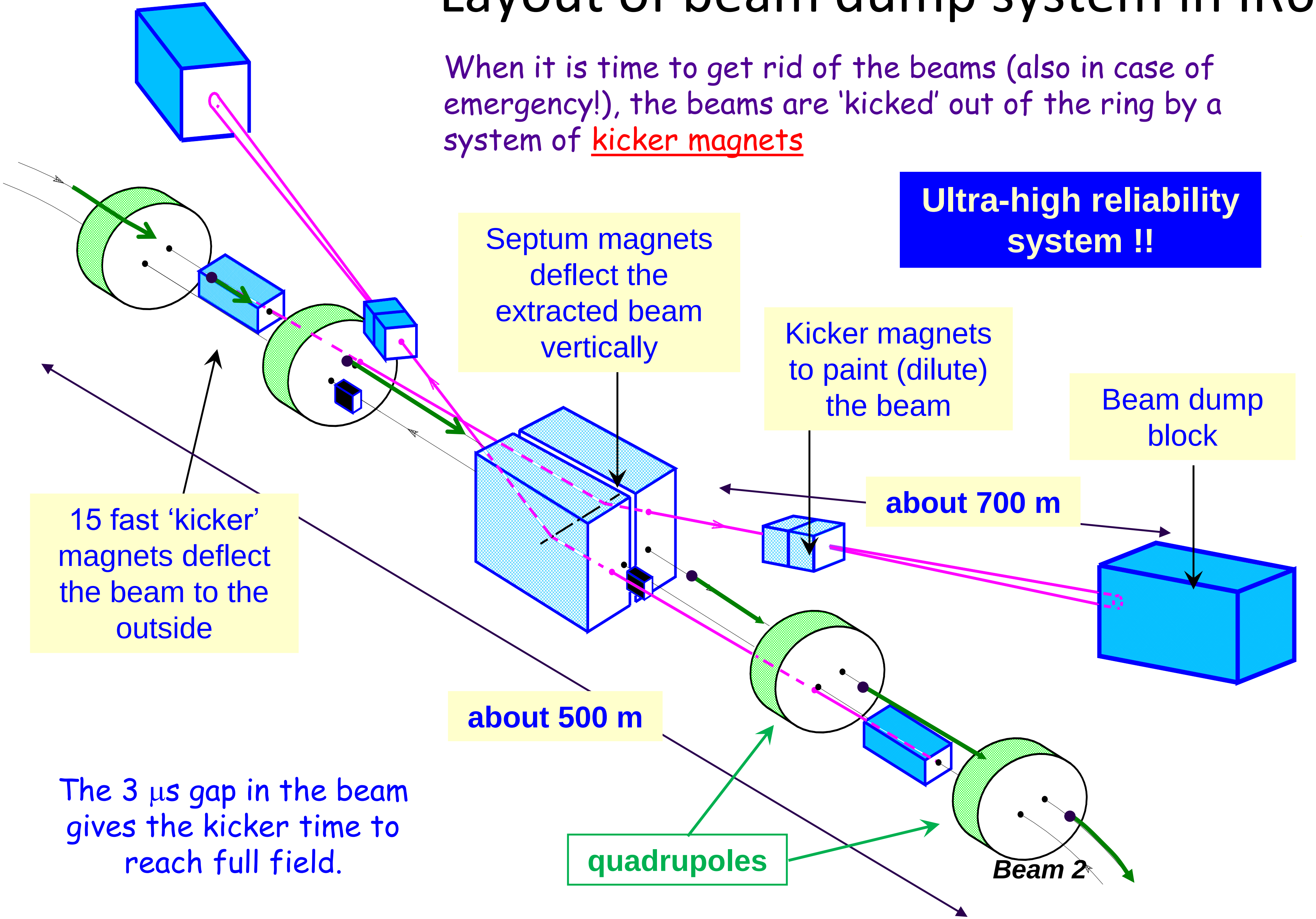


- Deflection angle must be independent of particle energy
- The strength of the kicker magnet and the septum magnet need to follow the energy ramp
- If this does not work – bye bye LHC…..

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

Ultra-high reliability system !!



Septum magnets deflect the extracted beam vertically

Kicker magnets to paint (dilute) the beam

Beam dump block

about 700 m

15 fast 'kicker' magnets deflect the beam to the outside

about 500 m

quadrupoles

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

Injection and extraction

- At injection, a batch of 288 bunches is injected at an energy of 450 GeV – always with the same energy
- The injection elements must have always the same strength
- The energy stored in the batch is about 2 MJ
- Injection happens very frequently, in order to fill each of the two beams with up to 2808 bunches

- Extraction, can happen at any energy from 450 GeV to 7 TeV
- The energy stored in the beam is up to 364 MJ
- The strength of the kicker field depends on the energy, the angle must remain constant
- The **current of the main dipole magnets in 4/8 sector** of the LHC **is measured** – and used **to ensure the correct tracking** of the kicker and septum strength

Some remarks for fast kickers

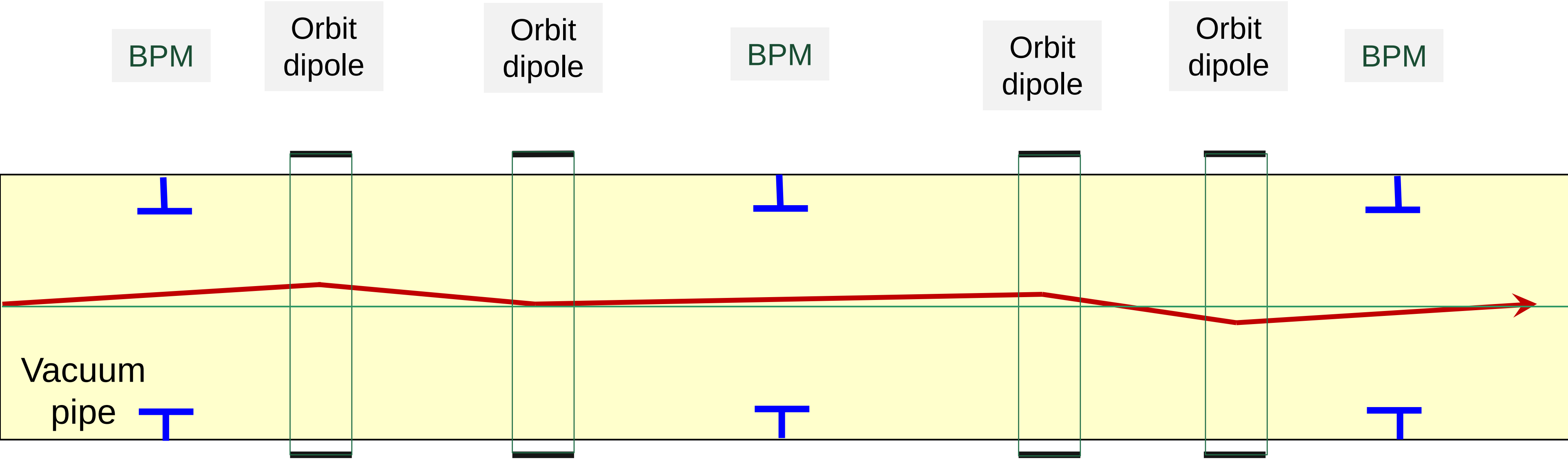
- Avoid very fast deflecting magnets when possible (no aperture kicker magnets)

- Ensure that the deflecting angles are correct
- Ensure that the time when the kicker fires is correct
  - Failure cases to be considered
- The injection kicker should NEVER deflect the beam when the accelerator is not at injection energy => **after starting the ramp switch off the kicker**
- There are some failures that cannot be avoided – ensure that these failures are mitigated and do not damage equipment

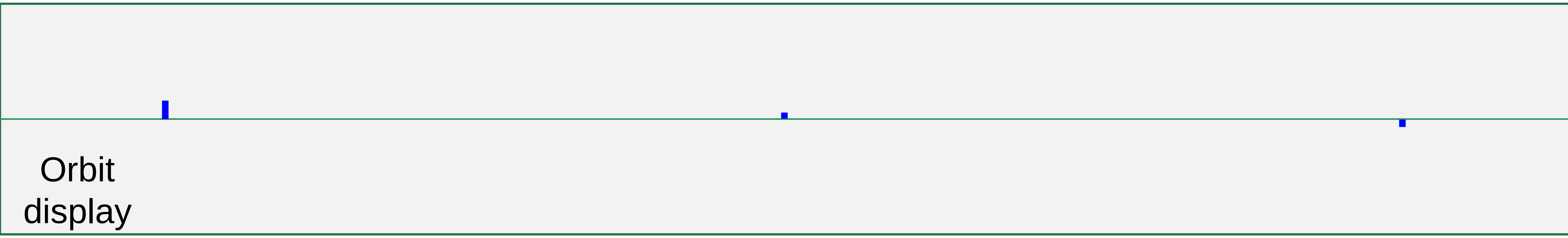
Examples for why magnets behave badly …

1. Failure of the power converter, water cooling or quench
2. Wrong command entered by operator (e.g. request for angle change of 0.01 mrad instead of 0.001 mrad)
3. Timing event to start current ramp does not arrive, or at the wrong moment
4. Controls system failure (….data not send, or send incorrectly)
5. Wrong conversion factor (e.g. from mrad to Ampere)
6. Feedback system failure
7. Failure of beam instrumentation

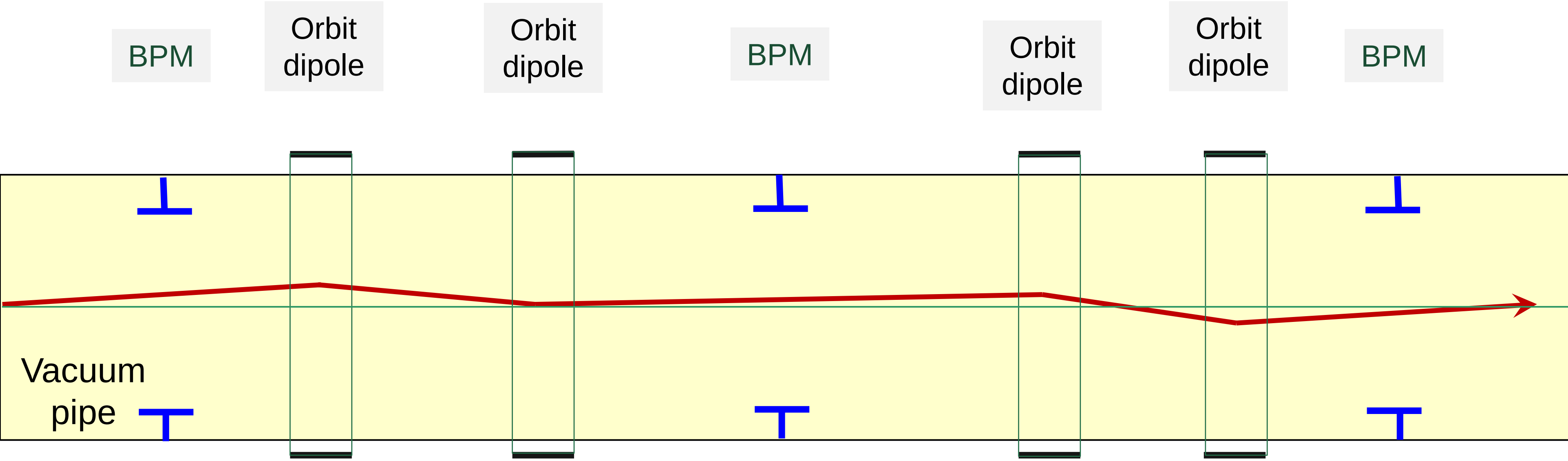
Closed orbit or trajectory



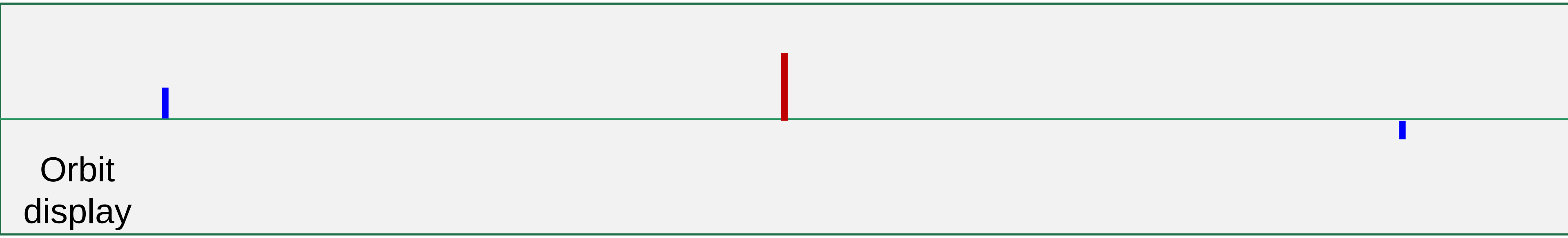
Display of beam position



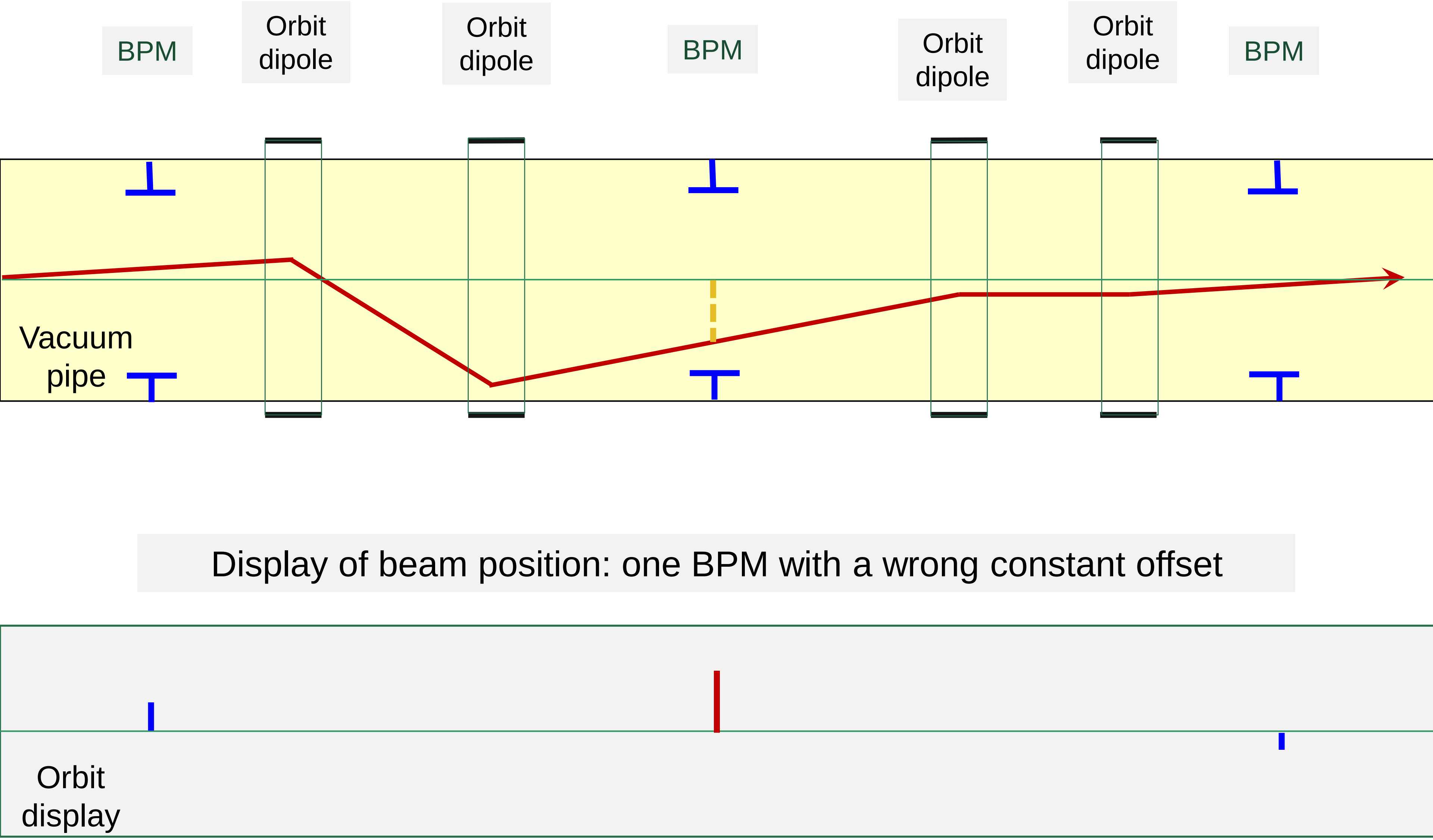
Closed orbit or trajectory



Display of beam position: one BPM with a wrong constant offset

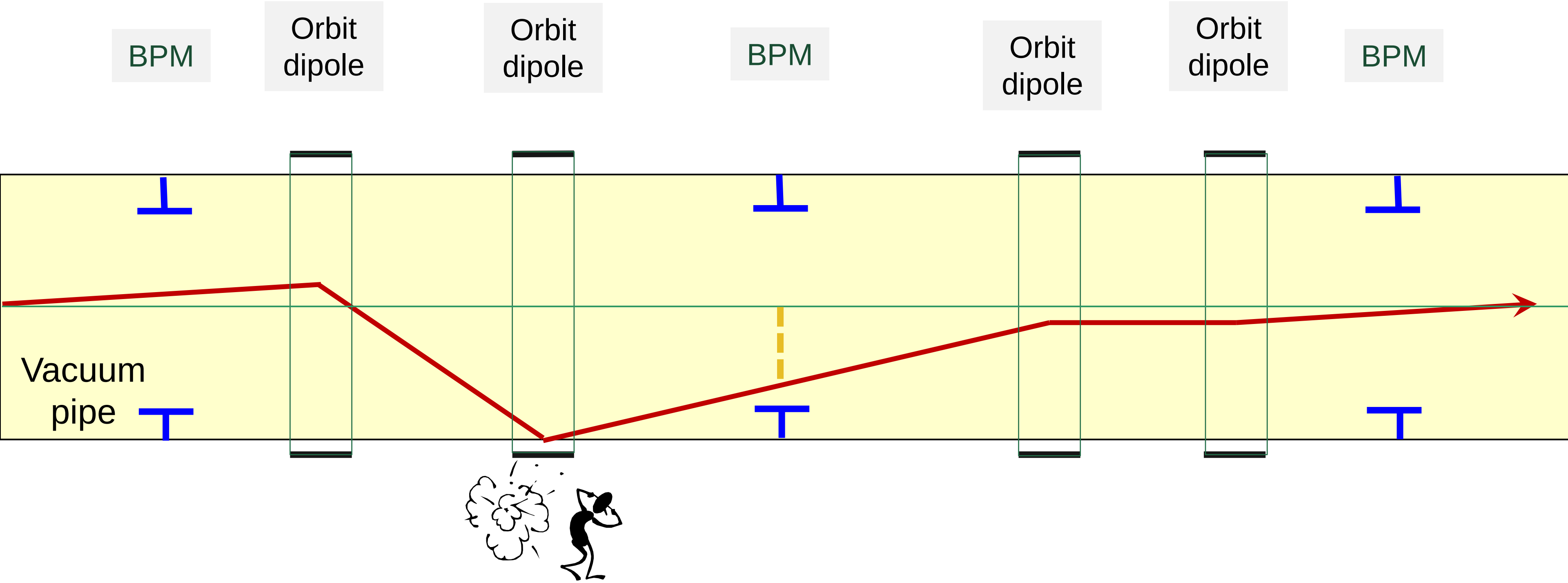


Action of orbit correction program: one step

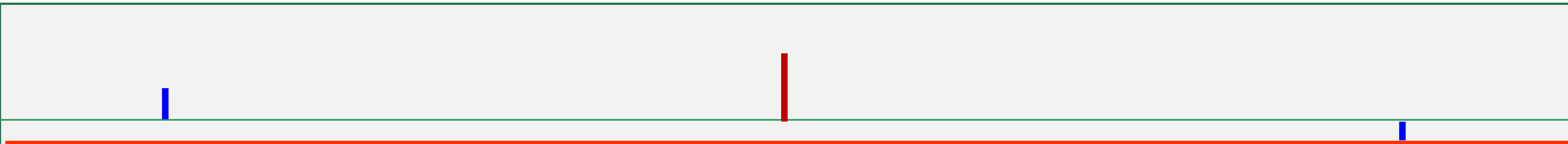


Display of beam position: one BPM with a wrong constant offset

Action of orbit correction program: next steps

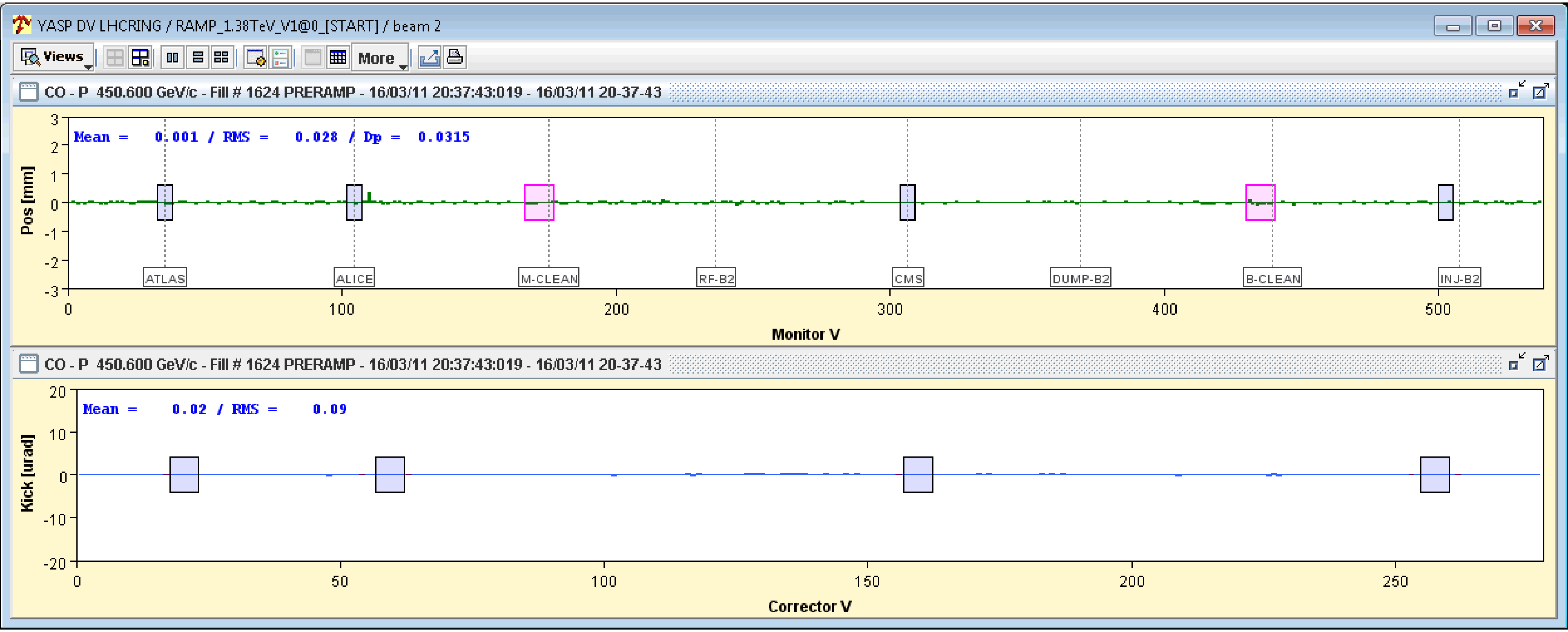


Display of beam position: one BPM with a wrong constant offset



Watch out for closed orbit bumps reducing the aperture (software interlock using strength of orbit corrector magnets)

Pi bump development (by OFB)



CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:43:019 - 16/03/11 20-37-43

Mean = 0.001 / RMS = 0.028 / Dp = 0.0315

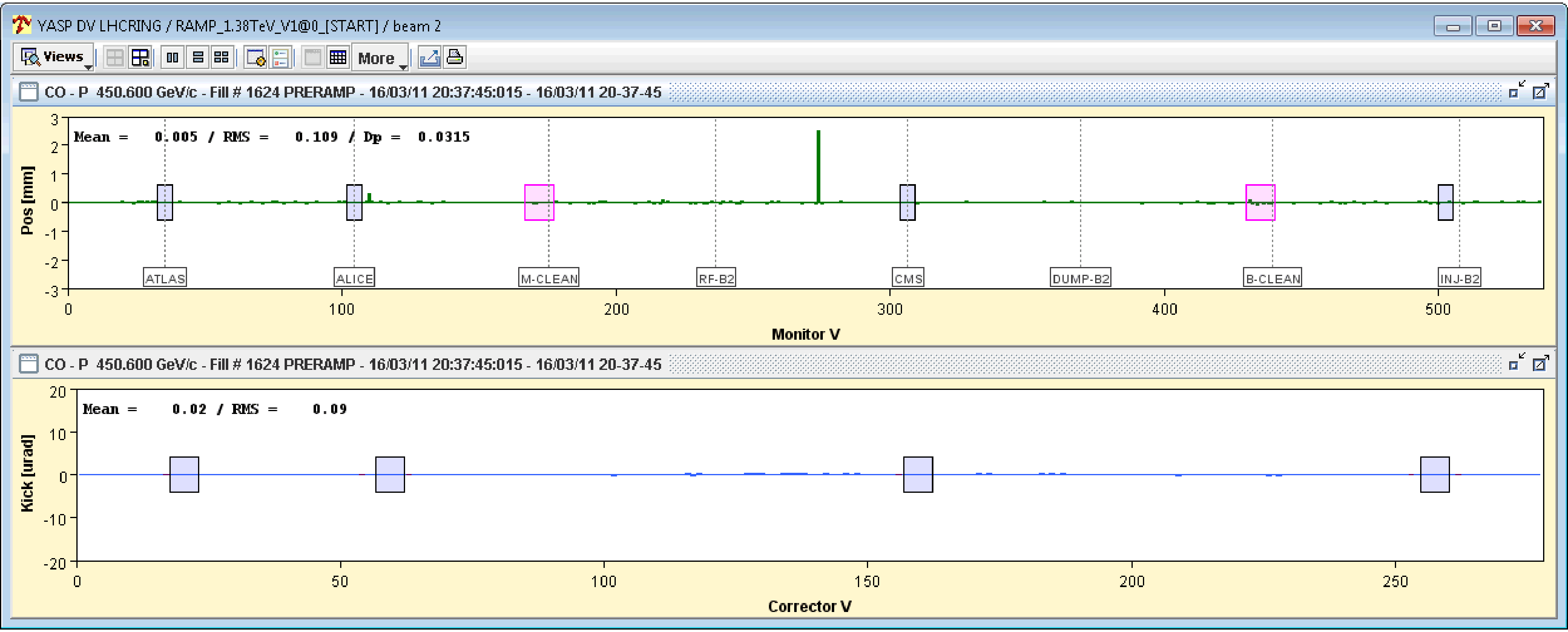
CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:43:019 - 16/03/11 20-37-43

Mean = 0.02 / RMS = 0.09

Following slides from Jorg Wenninger

Pi bump development

+ 2 seconds



YASP DV LHCRING / RAMP_1.38TeV_V1@0_[START] / beam 2

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:45:015 - 16/03/11 20-37-45

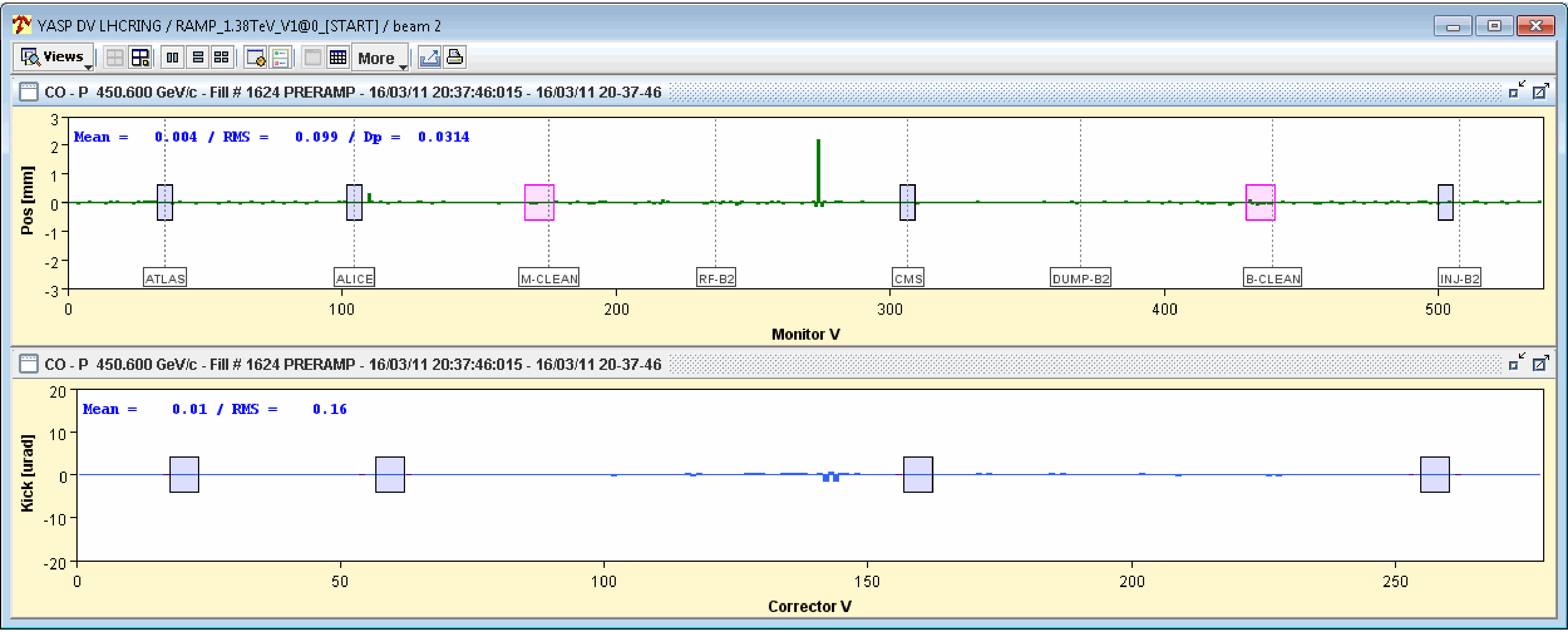
Mean = 0.005 / RMS = 0.109 / Dp = 0.0315

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:45:015 - 16/03/11 20-37-45

Mean = 0.02 / RMS = 0.09

Pi bump development

+ 1 second


YASP DV LHCRING / RAMP_1.38TeV_V1@0_[START] / beam 2

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:46:015 - 16/03/11 20-37-46

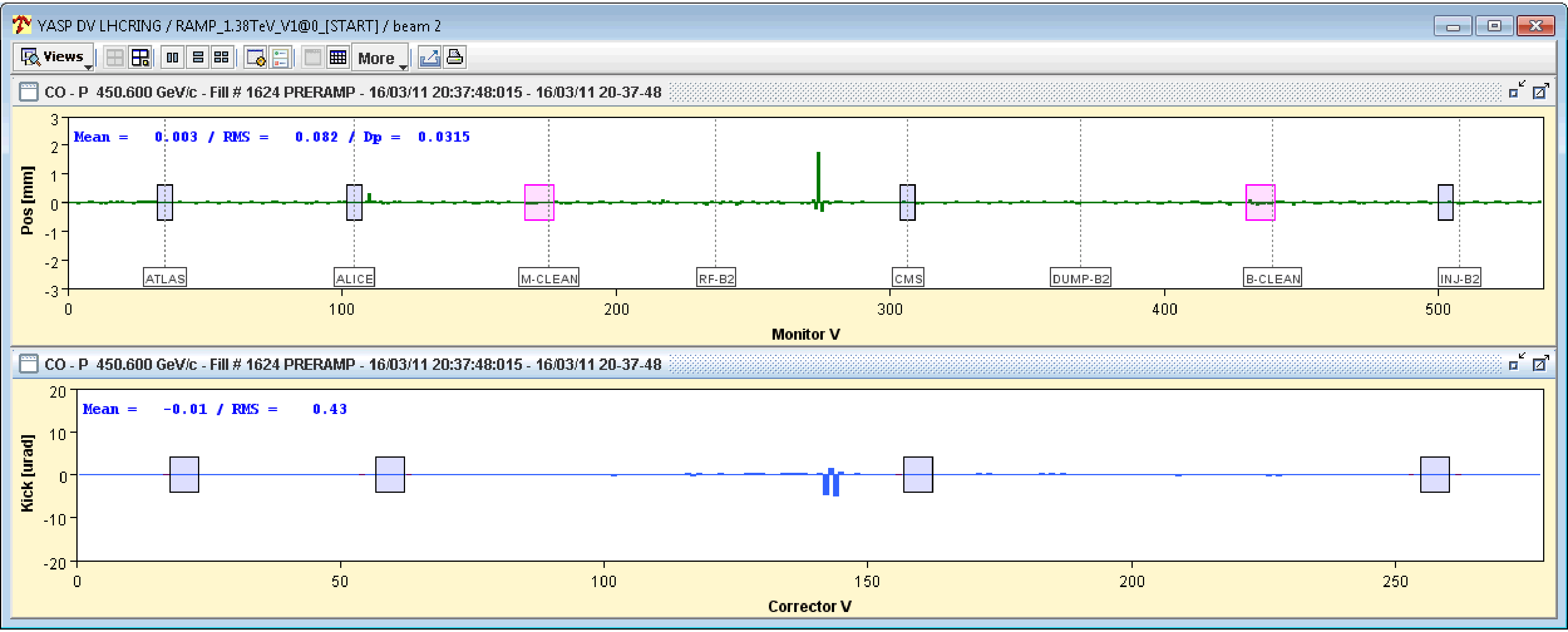
Mean = 0.004 / RMS = 0.099 / Dp = 0.0314

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:46:015 - 16/03/11 20-37-46

Mean = 0.01 / RMS = 0.16

Pi bump development

+ 2 seconds



YASP DV LHCRING / RAMP_1.38TeV_V1@0_[START] / beam 2

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:48:015 - 16/03/11 20-37-48

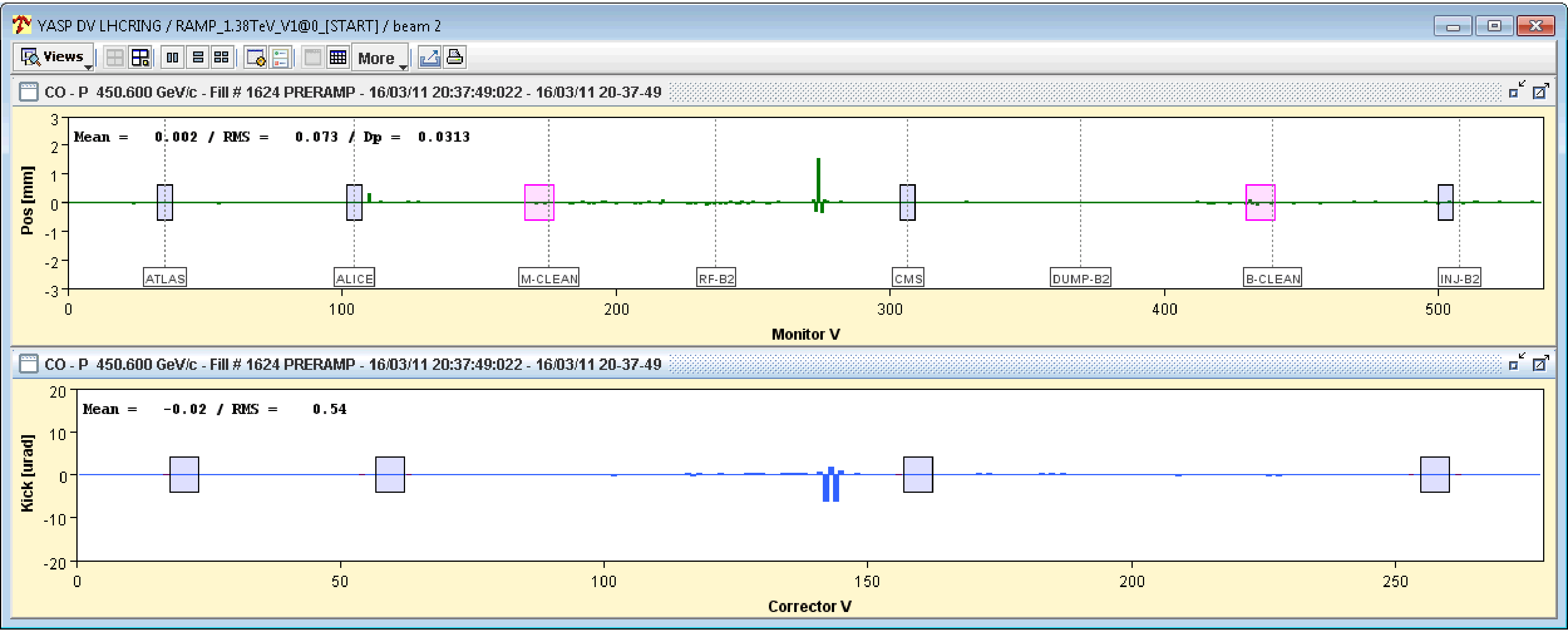
Mean = 0.003 / RMS = 0.082 / Dp = 0.0315

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:48:015 - 16/03/11 20-37-48

Mean = -0.01 / RMS = 0.43

Pi bump development

+ 1 second



YASP DV LHCRING / RAMP_1.38TeV_V1@0_[START] / beam 2

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:49:022 - 16/03/11 20-37-49

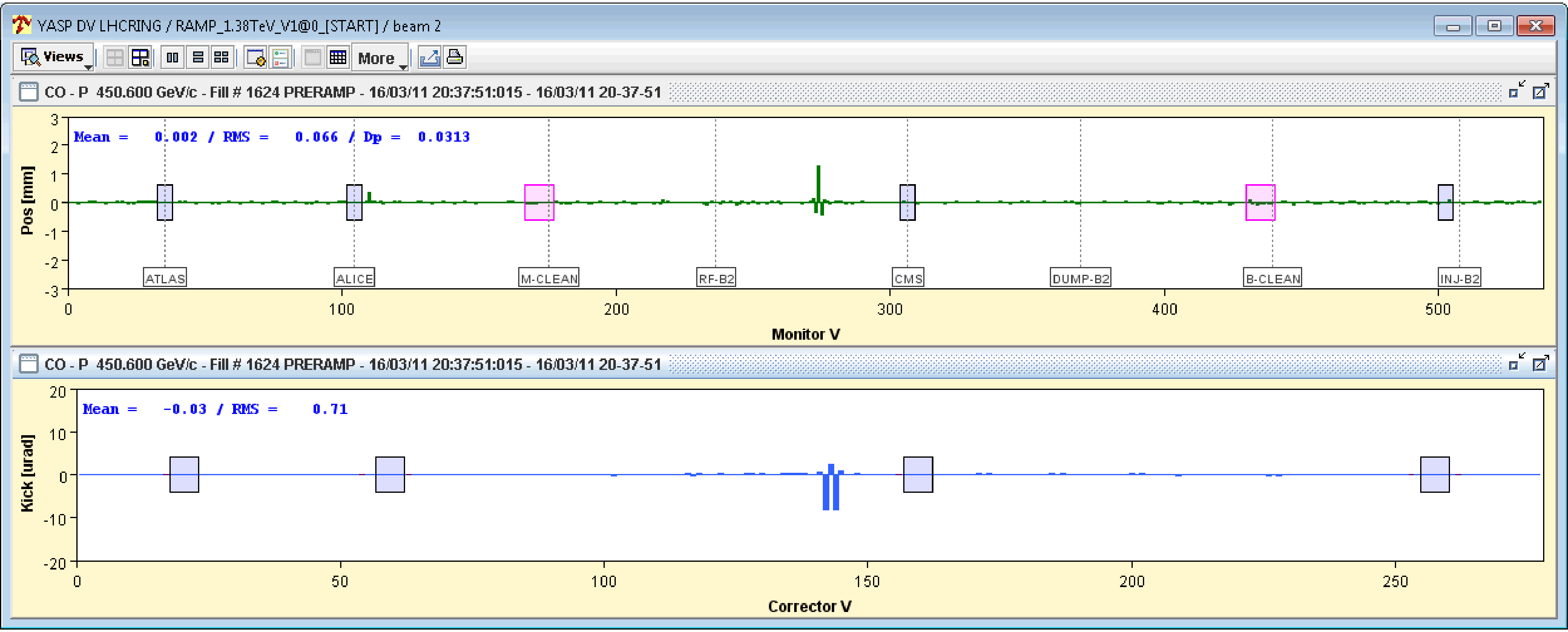
Mean = 0.002 / RMS = 0.073 / Dp = 0.0313

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:49:022 - 16/03/11 20-37-49

Mean = -0.02 / RMS = 0.54

Pi bump development

+ 2 seconds



YASP DV LHCRING / RAMP_1.38TeV_V1@0_[START] / beam 2

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:51:015 - 16/03/11 20-37-51

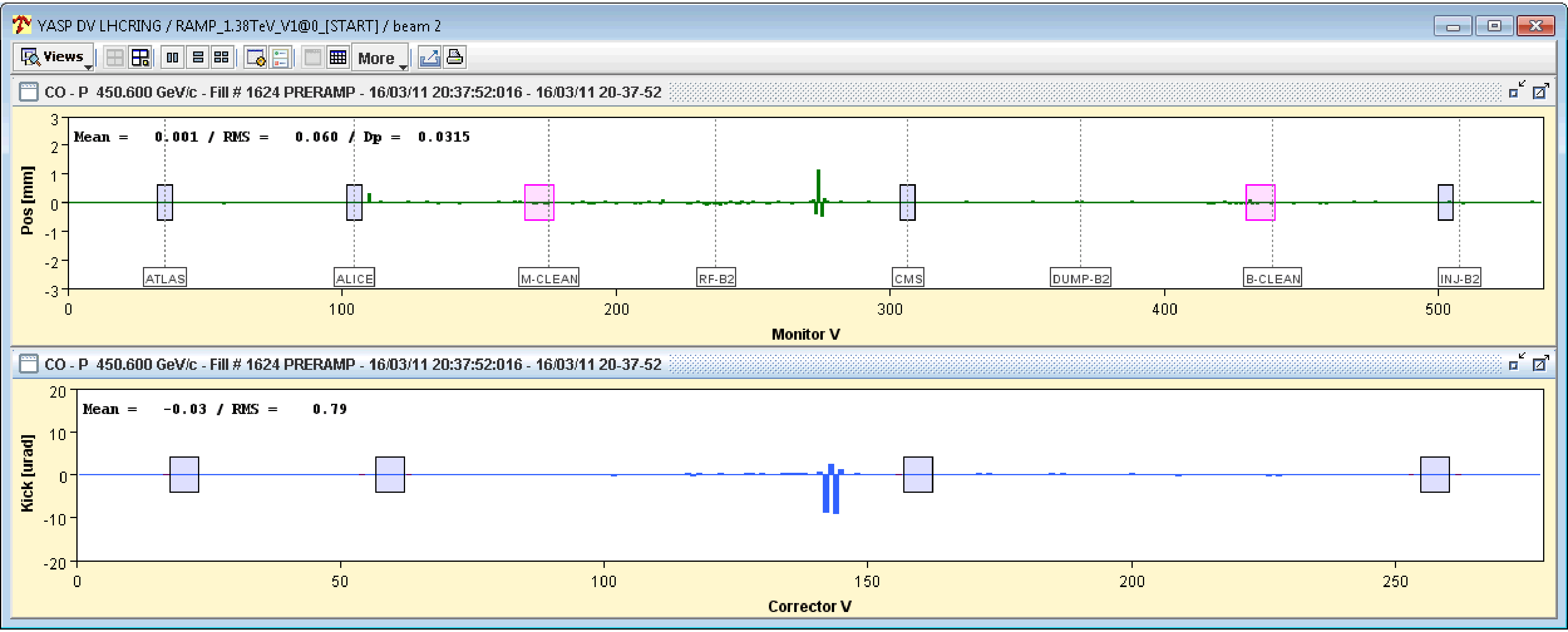
Mean = 0.002 / RMS = 0.066 / Dp = 0.0313

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:51:015 - 16/03/11 20-37-51

Mean = -0.03 / RMS = 0.71

Pi bump development

+ 1 second



YASP DV LHCRING / RAMP_1.38TeV_V1@0_[START] / beam 2

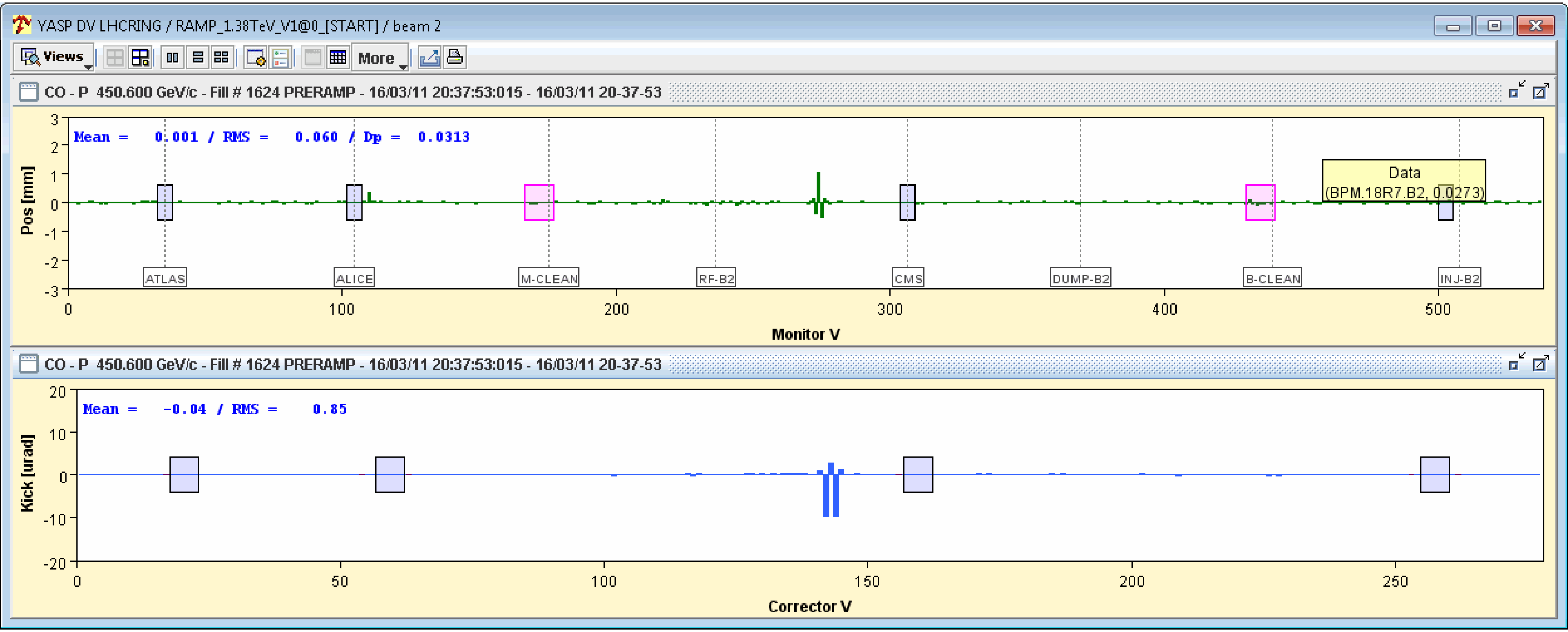
CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:52:016 - 16/03/11 20-37-52

Mean = 0.001 / RMS = 0.060 / Dp = 0.0315

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:52:016 - 16/03/11 20-37-52

Mean = -0.03 / RMS = 0.79

Pi bump development



YASP DV LHCRING / RAMP_1.38TeV_V1@0_[START] / beam 2

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:53:015 - 16/03/11 20-37-53

Mean = 0.001 / RMS = 0.060 / Dp = 0.0313

Data
(BPM.18R7.B2, 0.0273)

CO - P 450.600 GeV/c - Fill # 1624 PRERAMP - 16/03/11 20:37:53:015 - 16/03/11 20-37-53

Mean = -0.04 / RMS = 0.85

Characteristic pattern of a pi bump (arc). Mitigated now by software interlock.

Objects that might block beam passage

Equipment designed to move into the beam pipe (movable devices)

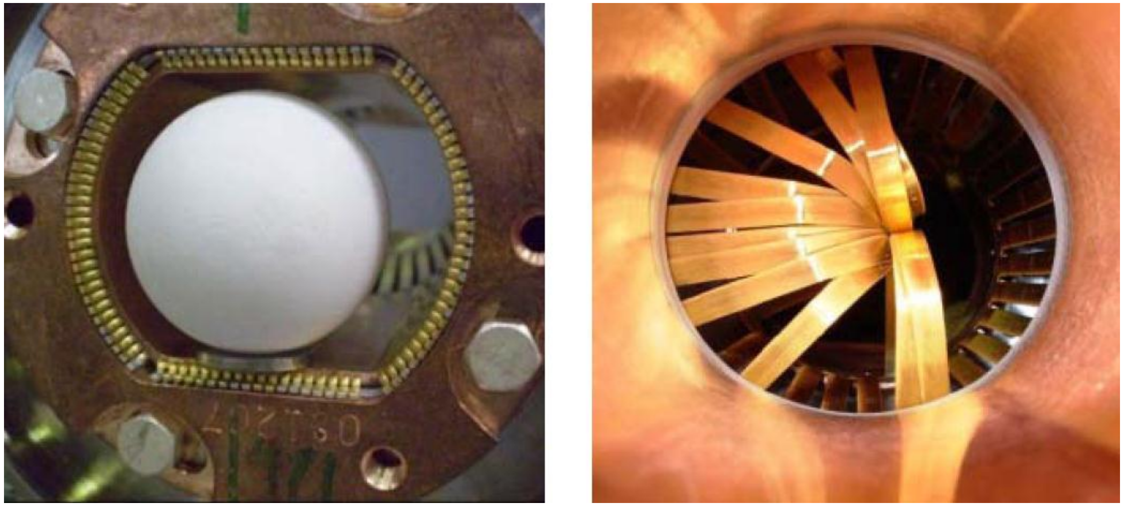
- Vacuum valves as part of the vacuum system
- Collimators and beam absorbers
- Beam instrumentation
  - Screens for observation of the beam profile
  - Mirrors to observe synchrotron light
  - Wire scanners to measure the beam profile
- Experiments, e.g. so-called Roman Pots to observe small angle scattered particle from an the interaction point in experiments

Elements that should never be in the beam pipe

  - Heineken beer bottle….
  - RF fingers
  - Other material
  - Gas above nominal pressure. …

Objects in the beam pipe

- Left over in vacuum tube from activities that require opening the beam vacuum system
- Elements that are getting into the pipe due to a failure (e.g. during cool-down in a superconducting accelerator or during operation)



- At LHC, during cool-down, RF fingers moved into the LHC beam pipe
- Due to high beam current, elements deformed and there is the risk that they obstruct the beam pipe

Wire scanners and machine protection

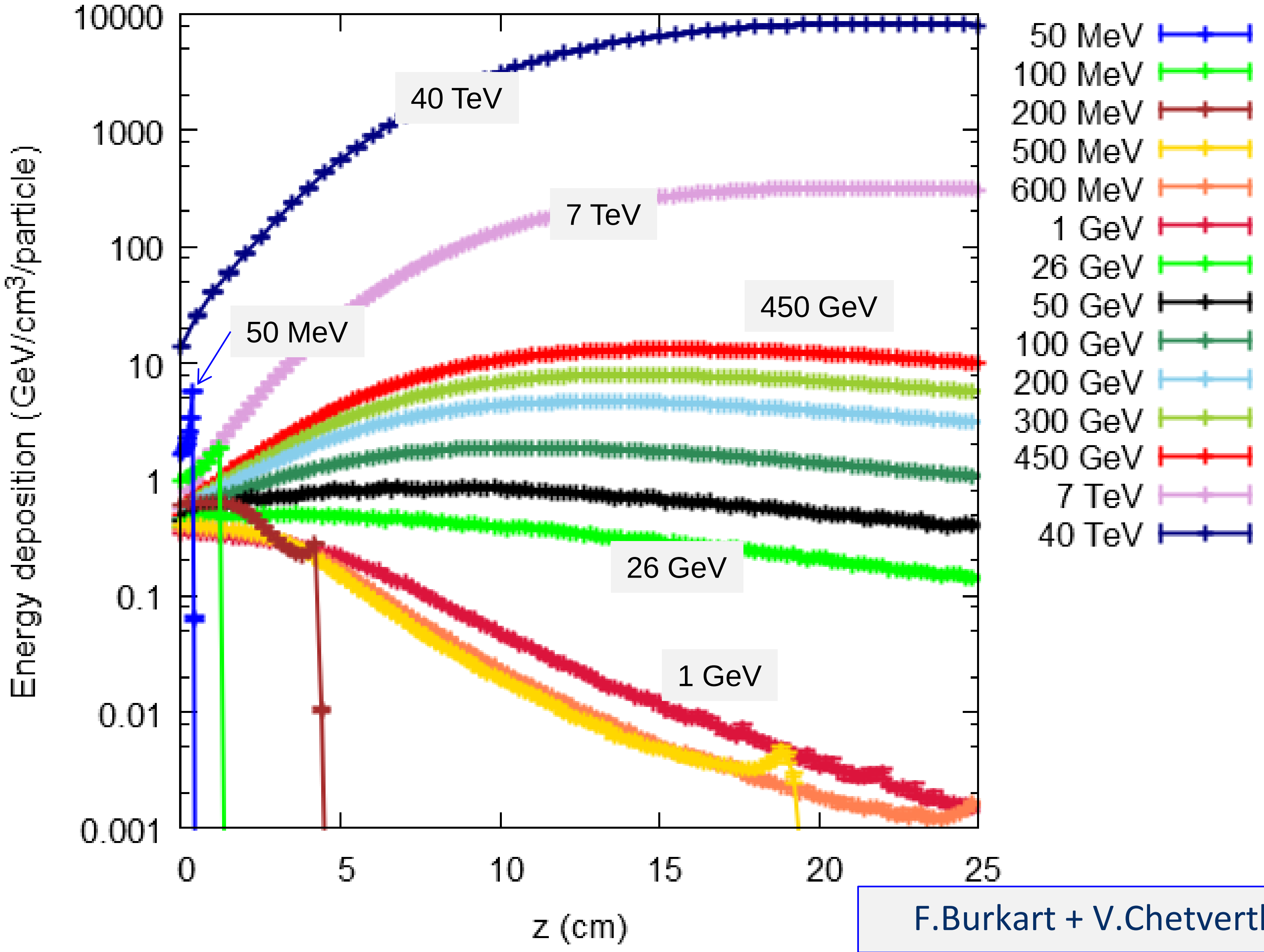
- Wire scanners: a thin carbon or tungsten wire moves through the beam, the particle shower or the secondary emission is measured
- With too high energy density of the beam
  - The wire risks to melt, protection of the instrument is required
  - Superconducting magnets in the vicinity risk to quench (downtime for the accelerator to be avoided)
- The energy density depends on the intensity and on the beam size – for hadron beams the size decreases with energy
- Consequences of such failure are minor (instrument not be available)
- Probability that an operator sends the wire through high intensity beam is high
- The risk is relatively small
- A protection system with a low protection level is acceptable

Collimators and machine protection

- Collimators and beam absorbers are essential elements for machine protection
- Collimators protect, but also need protection from High Energy Beam (in particular at injection and extraction)
- They should be at the correct position with respect to the beam
- Usually closest collimators are at about 6 sigma from the beam
  - At LHC, the absolute position depends on the energy
  - The collimators are moved closer to the beam during the energy ramp
- How to interlock the collimator position…
  - Timing event
  - Check by independent method: energy function
  - Can also be done when the optics changes and collimator position needs to be adjusted
- Roman pots must be outside of collimator aperture

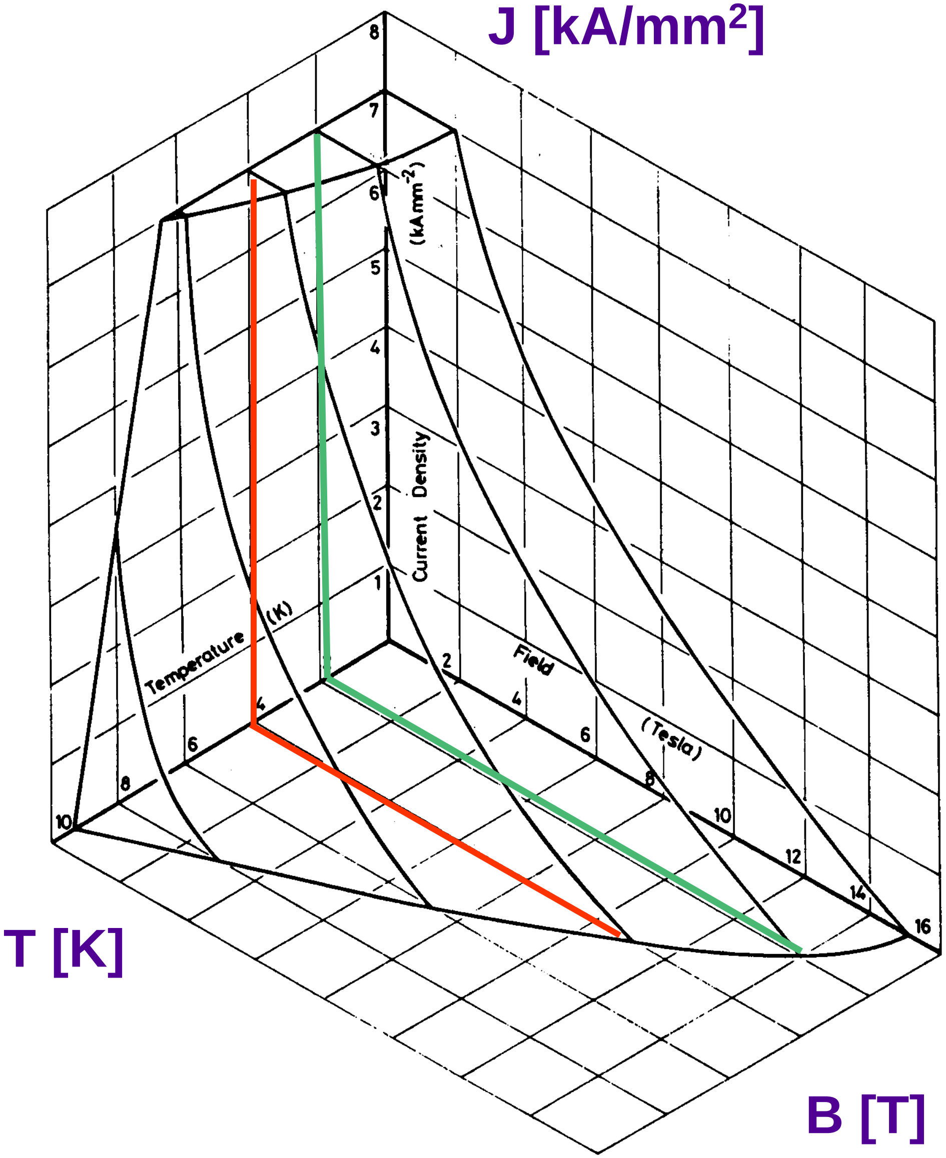
Consequences

Proton energy deposition for different energies



F.Burkart + V.Chetvertkova

Beam losses and magnet quench



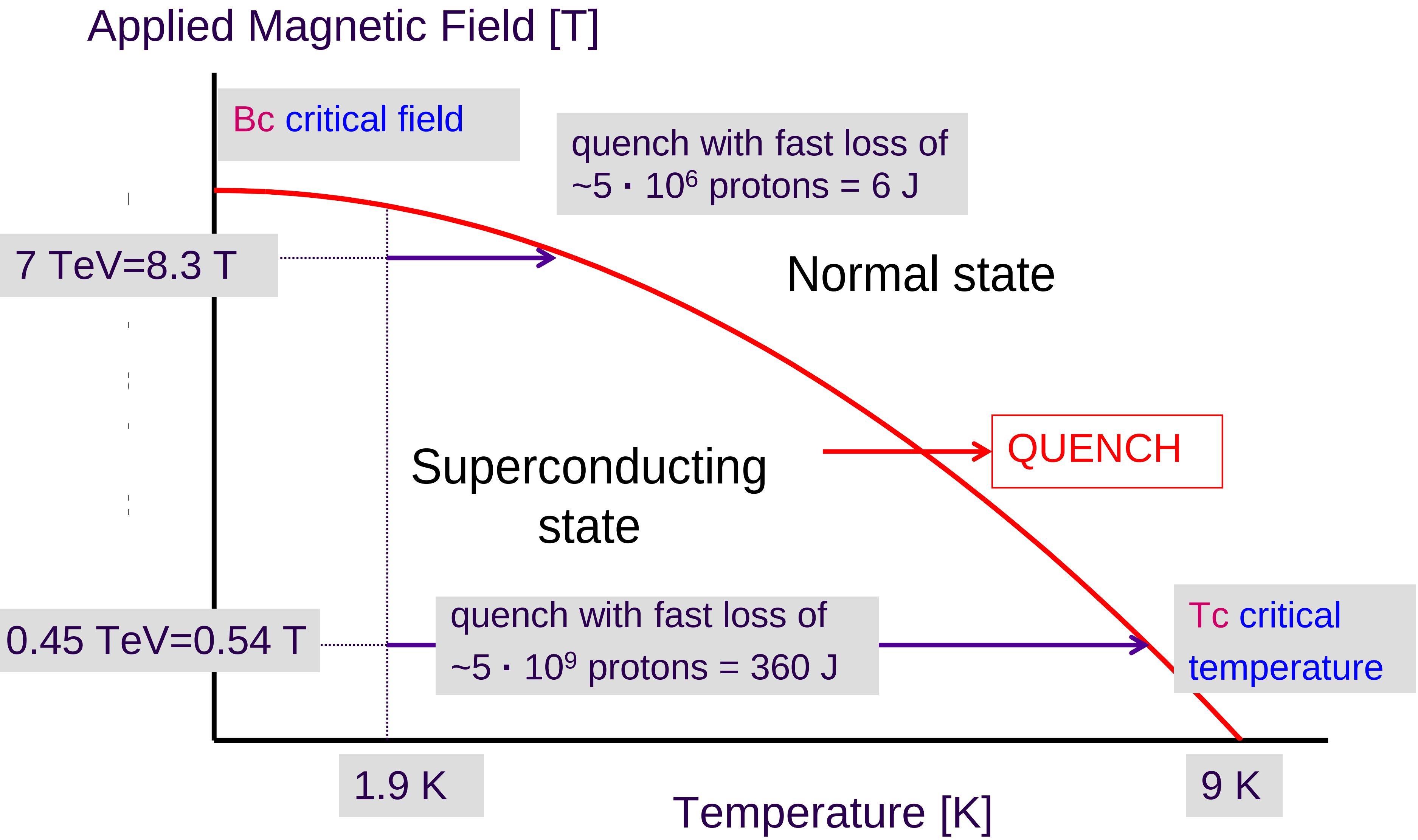
Operating parameters of superconductors (NbTi)

The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

Superconducting magnets produce high field with high current density

Lowering the temperature enables better usage of the superconductor, by broadening its working range

Margin of a superconducting magnet at LHC



Applied Magnetic Field [T]

Bc critical field

quench with fast loss of
~5 · 10^6 protons = 6 J

7 TeV=8.3 T

Normal state

QUENCH

Superconducting
state

0.45 TeV=0.54 T

quench with fast loss of
~5 · 10^9 protons = 360 J

Tc critical
temperature

1.9 K

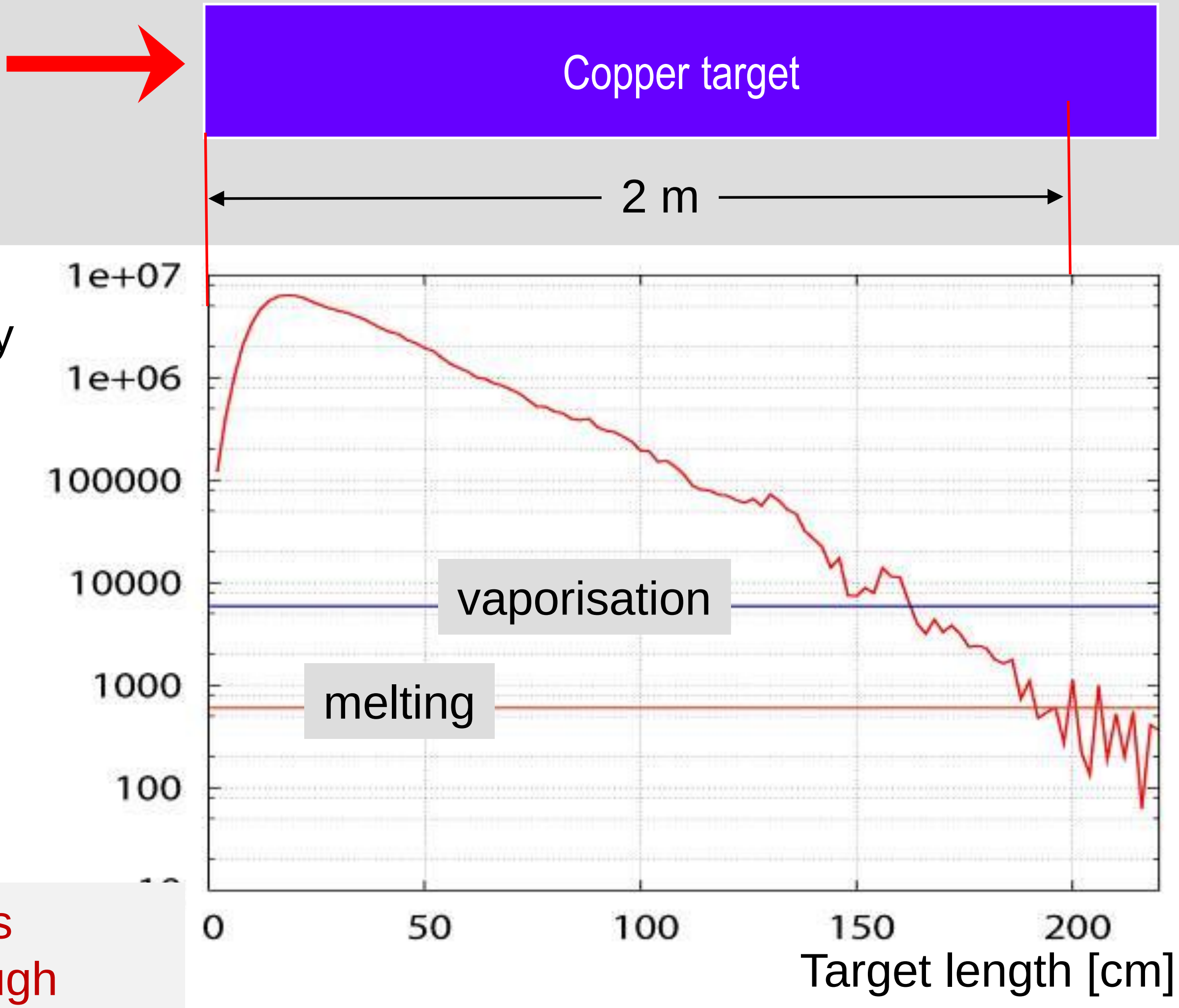
9 K

Temperature [K]

Full LHC beam deflected into copper target

2808 bunches
7 TeV
350 MJoule

Energy density
[GeV/cm³]
on target axis



The 7 TeV LHC beam is expected to travel through about 30 m of copper (graphite is similar)

N.Tahir (GSI) et al.

Consequences: Research required

- Damage for high energy protons, beam size order of 1 mm
  - For other parameters, the table will look different
- Some fields can be filled – many are speculative
- Would be wonderful to have such table
- In general, for protection a conservative is required (for high risk)

Fast beam impact, energy [J] - beam size order of 1 mm - high energy protons	Superconducting magnets	Vacuum chamber and normal conducting elements	Collimators (graphite)	Collimators (metal)	Superconducting cavities
1.E+00	🟩	🟩	🟩	🟩	🟩
1.E+01	🟧 Quench of a magnet (LI 7TeV)	🟩	🟩	🟩	🟩
1.E+02	🟧 Quench of a magne		🟩	🟩	🟨 Effects on superconducting cavities
1.E+03	🟧 Quench of a magne		🟩	🟩	🟥
1.E+04	🟧 Quench of a magne		🟩	🟨	🟥
1.E+05	🟨 Not known		🟩	🟥	🟥
1.E+06	🟨 Not known	🟨 exposure SPS-TT40 accident	🟩	🟥	🟥
1.E+07	🟥	🟥	🟥	🟥	🟥

??

Machine protection and Interlocks at LHC

Strategy for protection and related systems

- Avoid that a specific failure can happen
- Detect failure at hardware level and stop beam operation
- Detect initial consequences of failure with beam instrumentation ….before it is too late…
- Stop beam operation
  - inhibit injection
  - extract beam into beam dump block
  - stop beam by beam absorber / collimator
- Elements in the protection systems
  - equipment monitoring and beam monitoring
  - beam dump (fast kicker magnet and absorber block)
  - collimators and beam absorbers
  - beam interlock systems linking different systems

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.

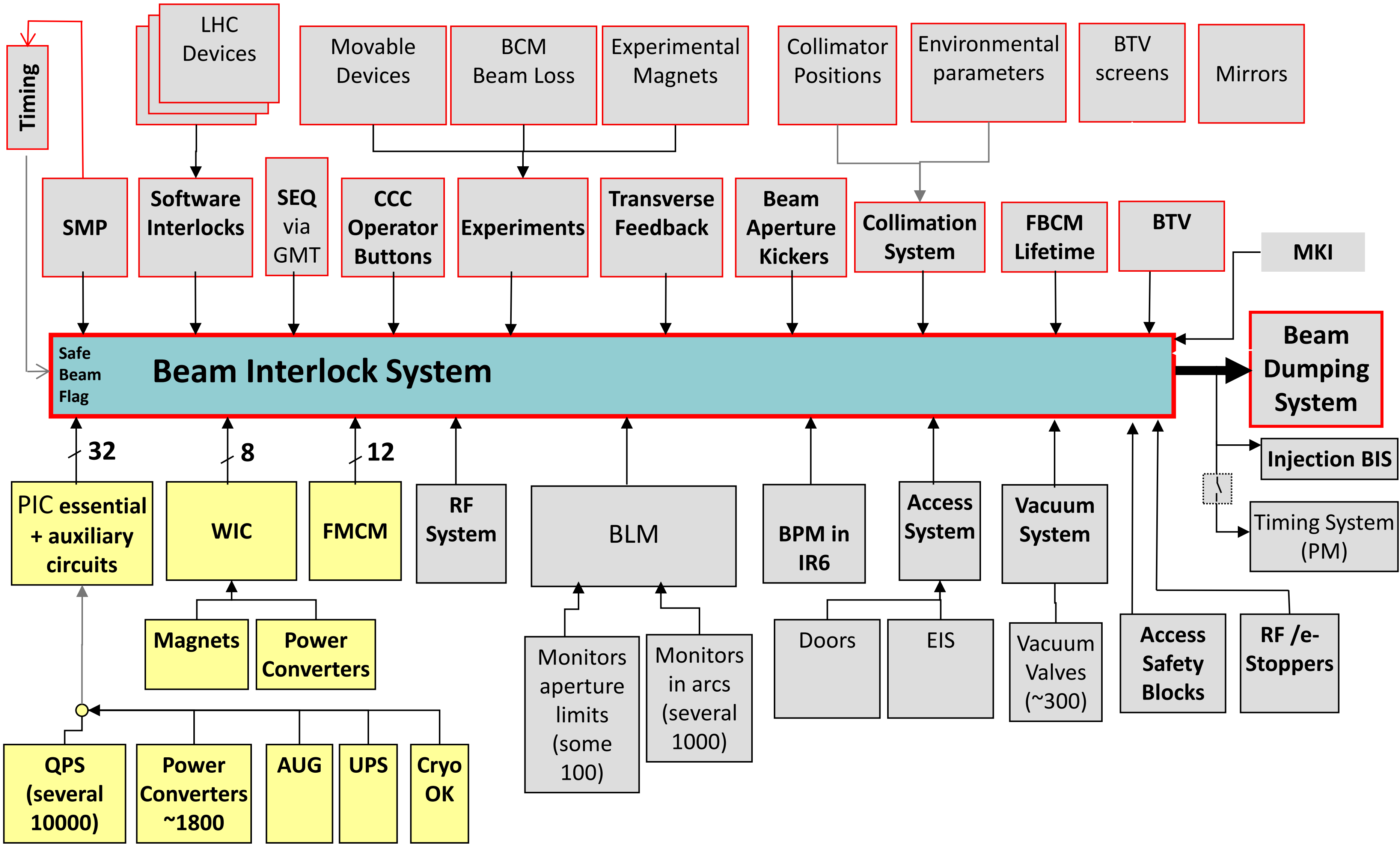
Collimator and Beam Absorbers

Machine Interlock Systems at LHC

- Beam Interlock System
  - Ensures that the beams are extracted into the beam dump blocks when one of the connected systems detects a failure
- Powering Interlock System
  - Ensures communication between systems involved in the powering of the LHC superconducting magnets (magnet protection system, power converters, cryogenics, UPS, controls)
- Normal conducting Magnet Interlock System
  - Ensures protection of normal conducting magnets in case of overheating
  - Ensures communication between systems involved in the powering of the LHC normal conducting magnets (magnet protection system, power converters, UPS, controls)

Separate machine interlocks strictly from interlock for personnel safety (as pointed out in the discussions, there might be a grey area between Machine Protection and Protection of Personnel)

LHC Interlock Systems and inputs



Timing

LHC Devices

Movable Devices

BCM Beam Loss

Experimental Magnets

Collimator Positions

Environmental parameters

BTV screens

Mirrors

SMP

Software Interlocks

SEQ via GMT

CCC Operator Buttons

Experiments

Transverse Feedback

Beam Aperture Kickers

Collimation System

FBCM Lifetime

BTV

MKI

Safe Beam Flag

Beam Interlock System

Beam Dumping System

Injection BIS

Timing System (PM)

32

8

12

PIC essential **+ auxiliary circuits**

WIC

FMCM

RF System

BLM

BPM in IR6

Access System

Vacuum System

Magnets

Power Converters

Monitors aperture limits (some 100)

Monitors in arcs (several 1000)

Doors

EIS

Vacuum Valves (~300)

Access Safety Blocks

RF /e- Stoppers

QPS (several 10000)

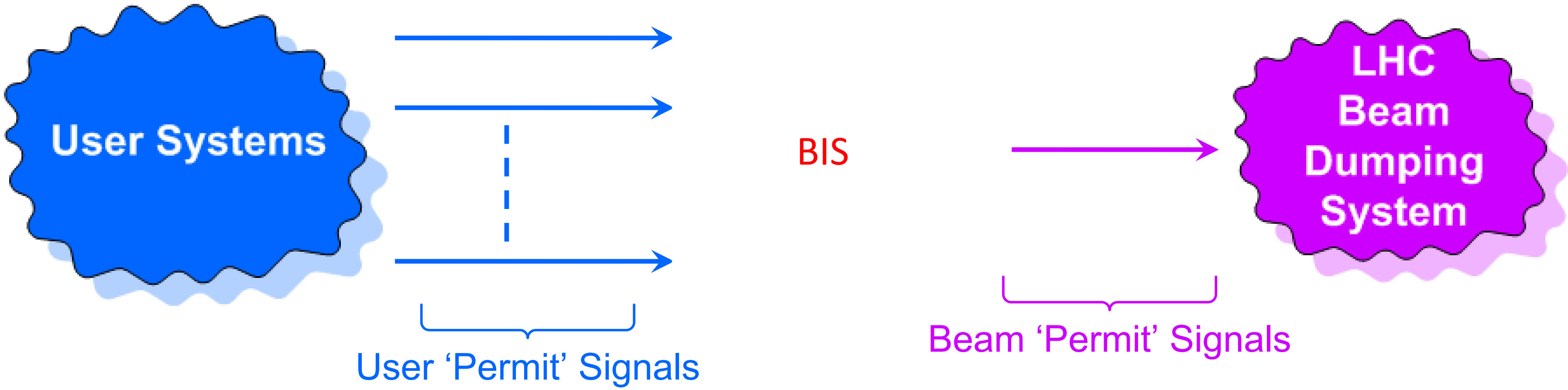
Power Converters ~1800

AUG

UPS

Cryo OK

Beam Interlock System Function



User Systems

BIS

LHC Beam Dumping System

User ‘Permit’ Signals

Beam ‘Permit’ Signals

~200 User Systems distributed over 27 kms

Both-Beam

LHC has 2 Beams

Some User Systems give simultaneous permit

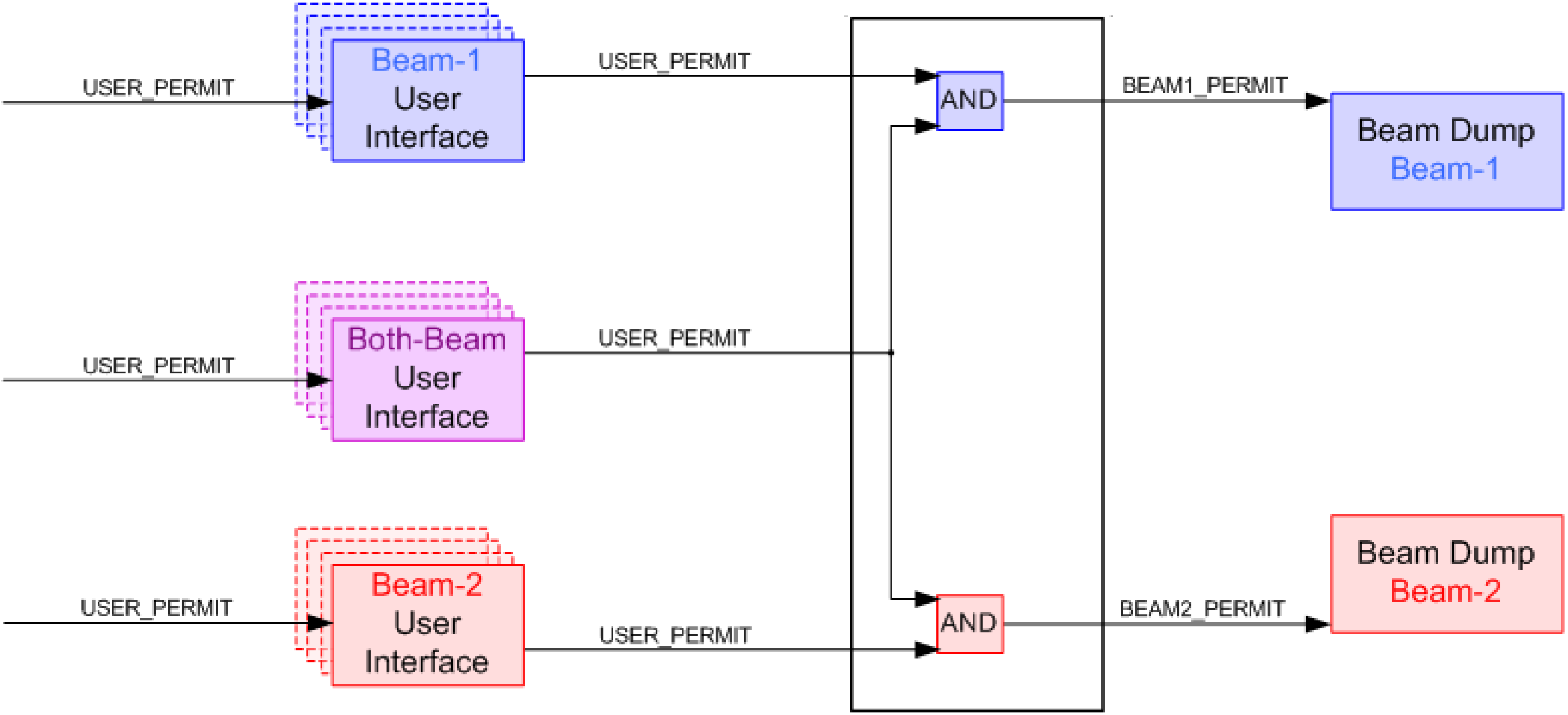
Others give independent permit

Beam-1

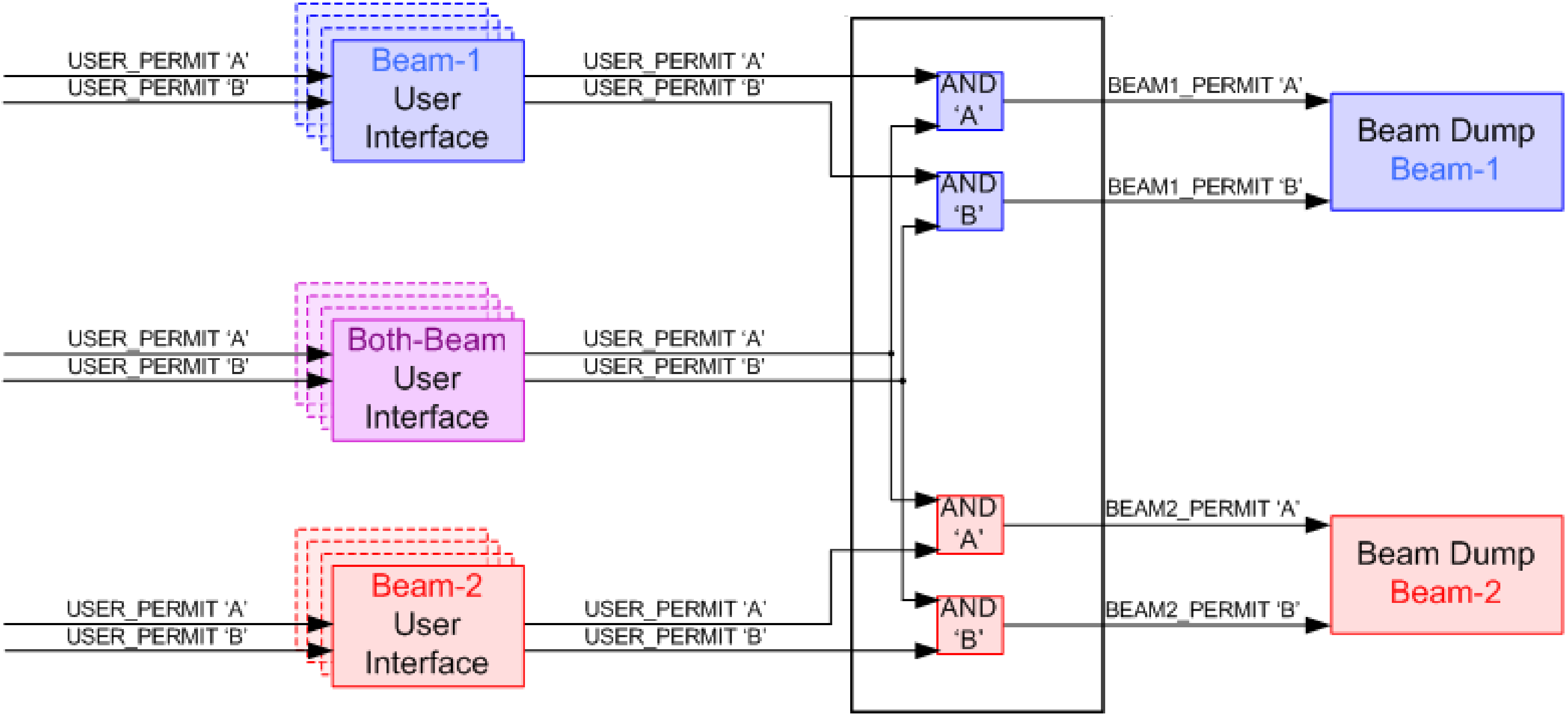
Beam-2

Following slides from Ben Todd

Signals


USER_PERMIT
Beam-1
User
Interface
USER_PERMIT
AND
BEAM1_PERMIT
Beam Dump
Beam-1
USER_PERMIT
Both-Beam
User
Interface
USER_PERMIT
USER_PERMIT
Beam-2
User
Interface
USER_PERMIT
AND
BEAM2_PERMIT
Beam Dump
Beam-2

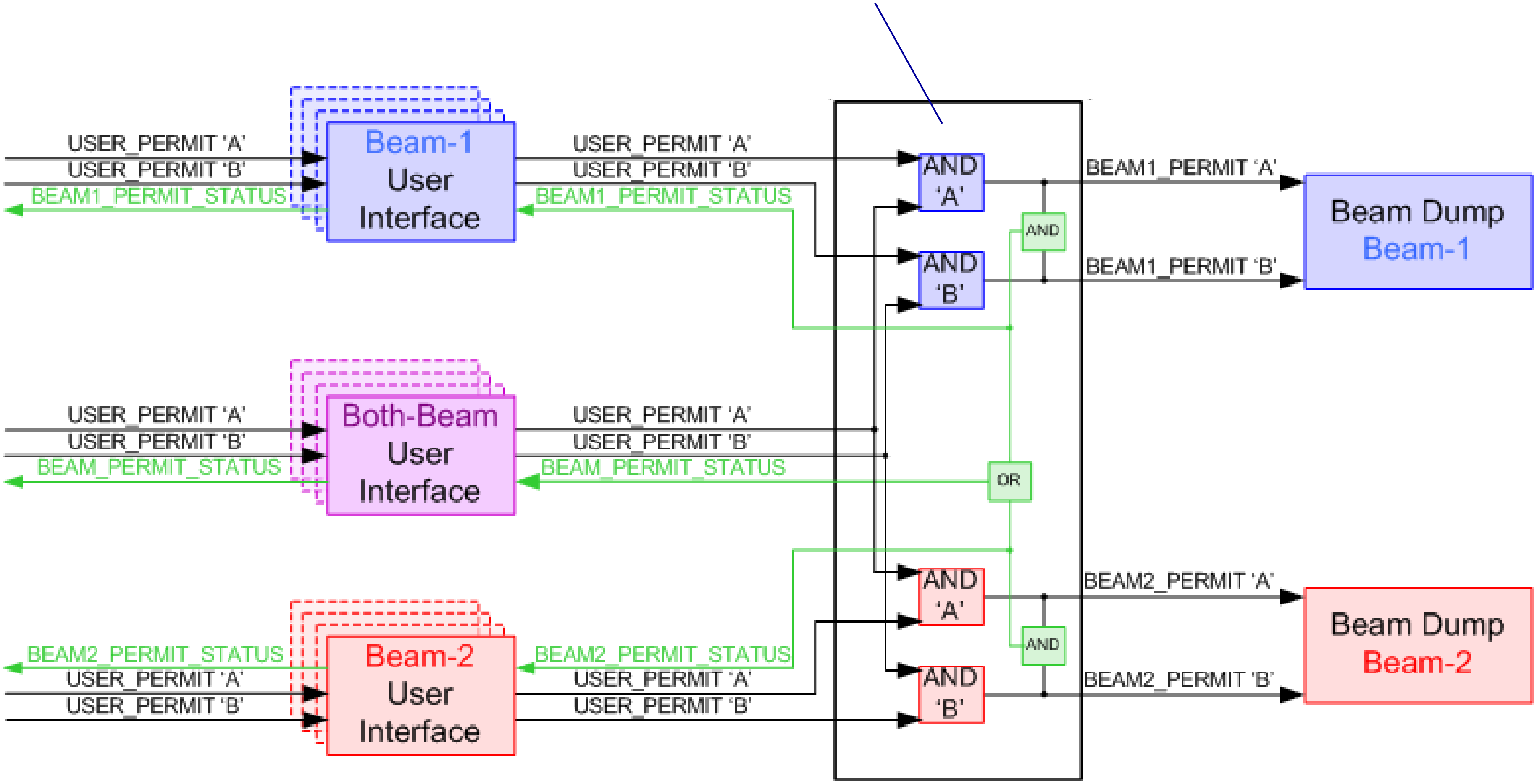
Signals with redundancy



Signals with redundancy and feedback to users

Hardware MATRIX = 9500 Complex Programmable Logic Device (CPLD)

Hardware Description Language (VHDL)



USER_PERMIT 'A'
USER_PERMIT 'B'
BEAM1_PERMIT_STATUS
Beam-1 User Interface
USER_PERMIT 'A'
USER_PERMIT 'B'
BEAM1_PERMIT_STATUS

USER_PERMIT 'A'
USER_PERMIT 'B'
BEAM_PERMIT_STATUS
Both-Beam User Interface
USER_PERMIT 'A'
USER_PERMIT 'B'
BEAM_PERMIT_STATUS

BEAM2_PERMIT_STATUS
USER_PERMIT 'A'
USER_PERMIT 'B'
Beam-2 User Interface
BEAM2_PERMIT_STATUS
USER_PERMIT 'A'
USER_PERMIT 'B'

AND 'A'
AND 'B'
AND
OR
AND 'A'
AND 'B'
AND

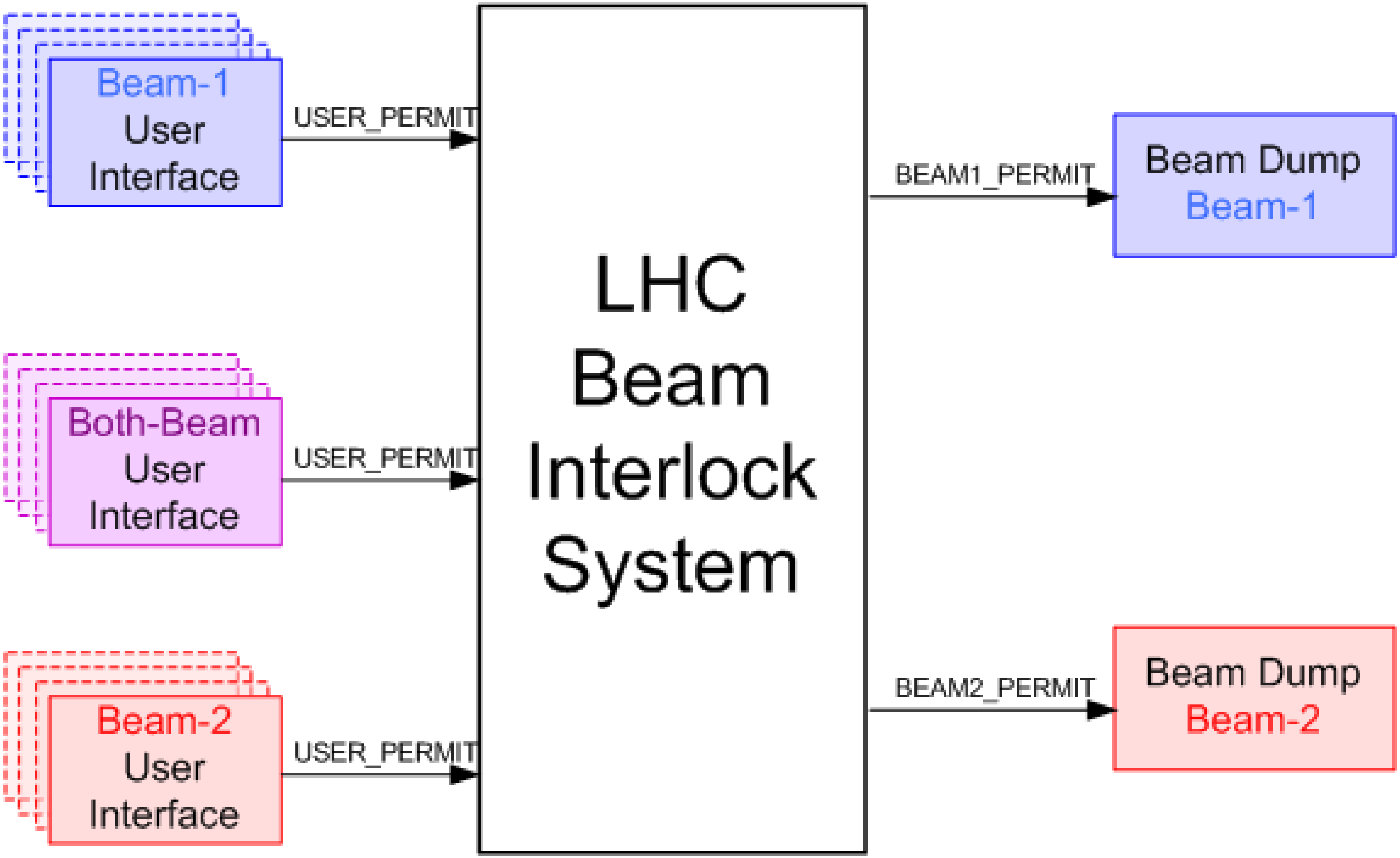
BEAM1_PERMIT 'A'
BEAM1_PERMIT 'B'
Beam Dump Beam-1

BEAM2_PERMIT 'A'
BEAM2_PERMIT 'B'
Beam Dump Beam-2

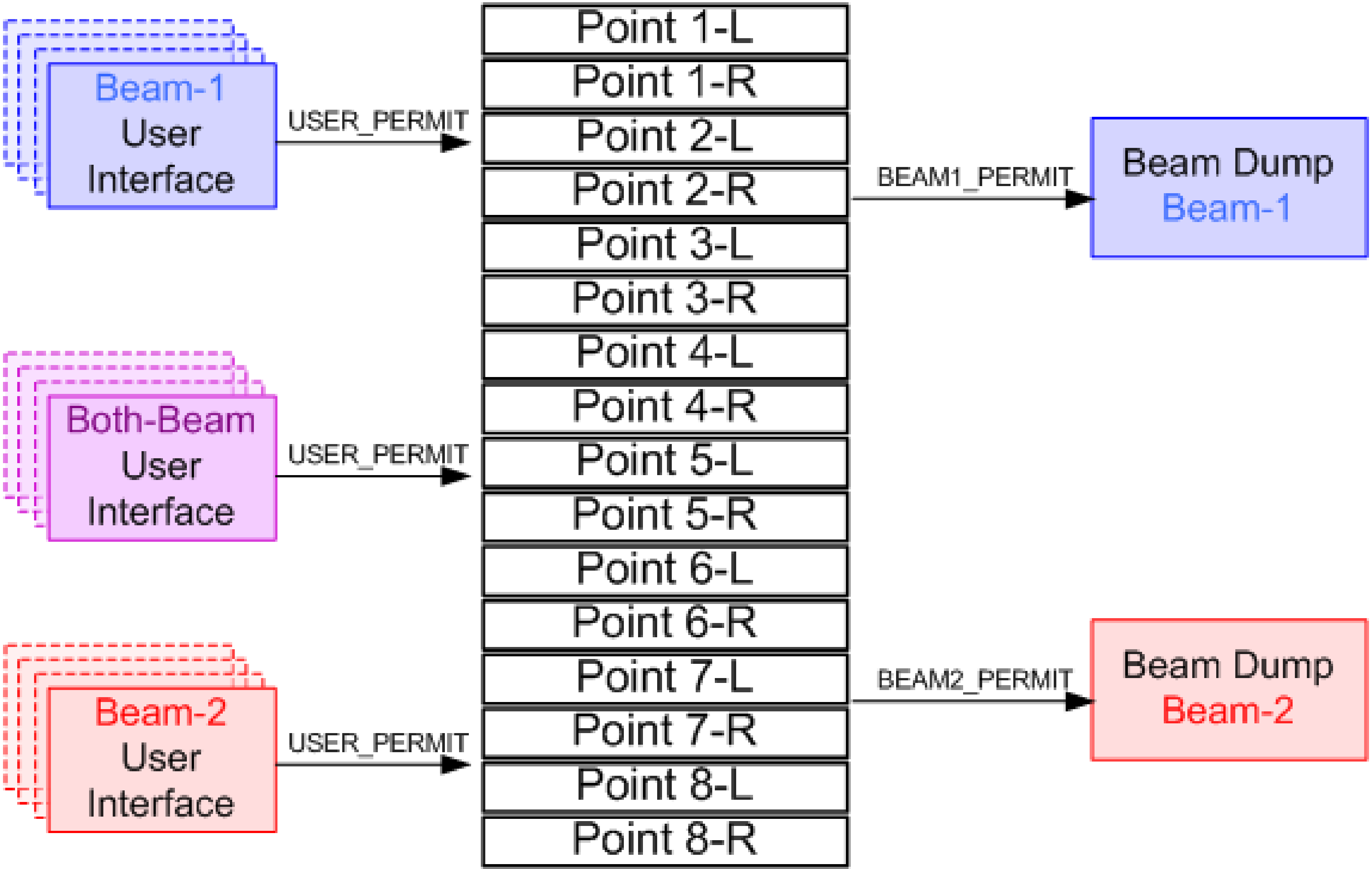
NON-CRITICAL / Monitoring = DIFFERENT device

Layout

In LHC, BIS forms a transparent layer from User System to Beam Dump



Layout



Beam-1
User
Interface

Both-Beam
User
Interface

Beam-2
User
Interface

USER_PERMIT

USER_PERMIT

USER_PERMIT

Point 1-L
Point 1-R
Point 2-L
Point 2-R
Point 3-L
Point 3-R
Point 4-L
Point 4-R
Point 5-L
Point 5-R
Point 6-L
Point 6-R
Point 7-L
Point 7-R
Point 8-L
Point 8-R

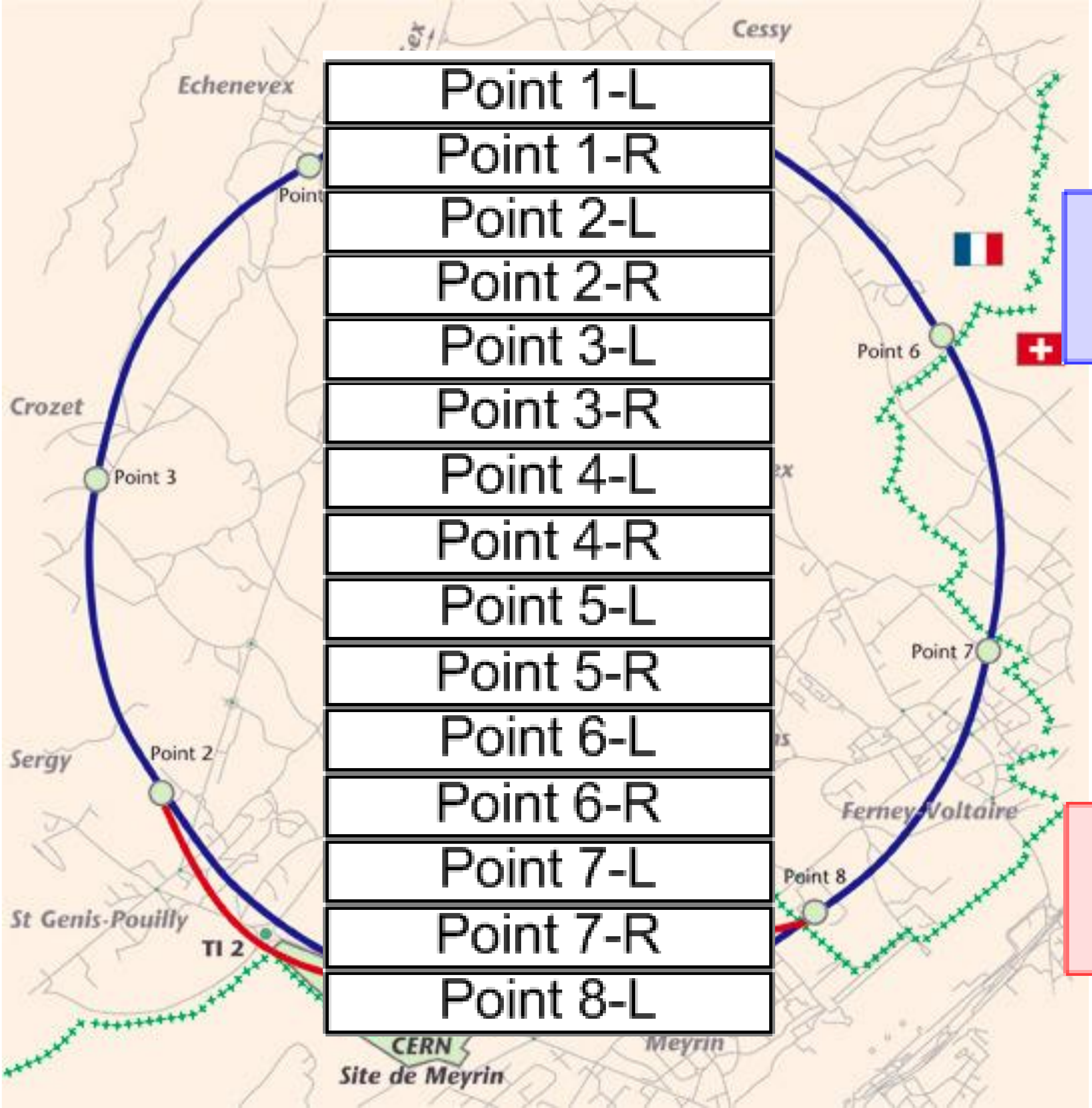
BEAM1_PERMIT

BEAM2_PERMIT

Beam Dump
Beam-1

Beam Dump
Beam-2

Layout



Point 1-L
Point 1-R
Point 2-L
Point 2-R
Point 3-L
Point 3-R
Point 4-L
Point 4-R
Point 5-L
Point 5-R
Point 6-L
Point 6-R
Point 7-L
Point 7-R
Point 8-L

Beam Dump
Beam-1

Beam Dump
Beam-2

Beam Permit Loops & BICs

4 fibre-optic channels from Point 6
1 clockwise &
1 anticlockwise for **each** Beam

Square wave generated at IP6
-Signal can be cut by any Controller
-Signal can be monitored by any Controller

When any of the four signals is
absent at IP6, BEAM DUMP!

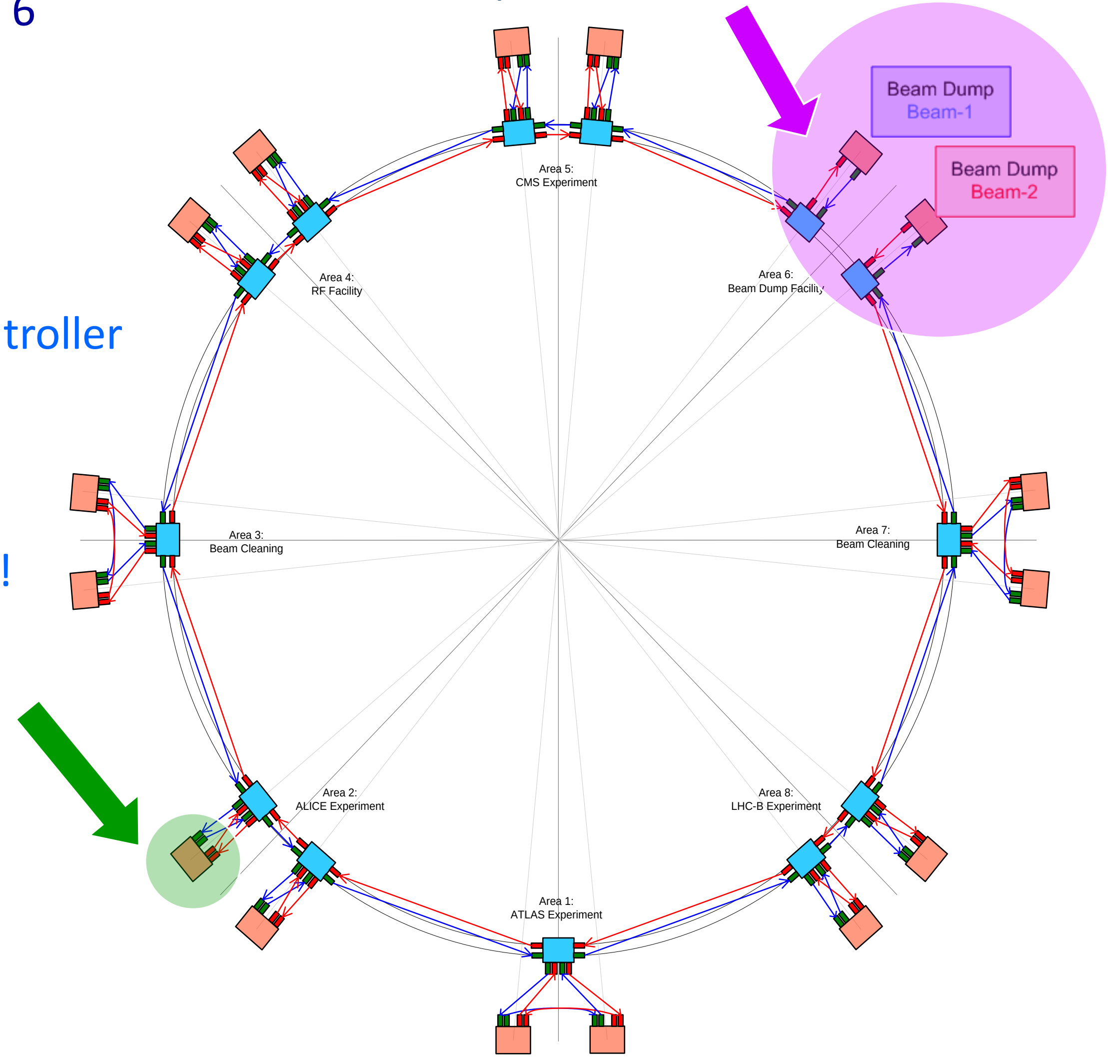
Beam-1 / Beam-2 are Independent!

Beam Interlock Controllers (BIC)

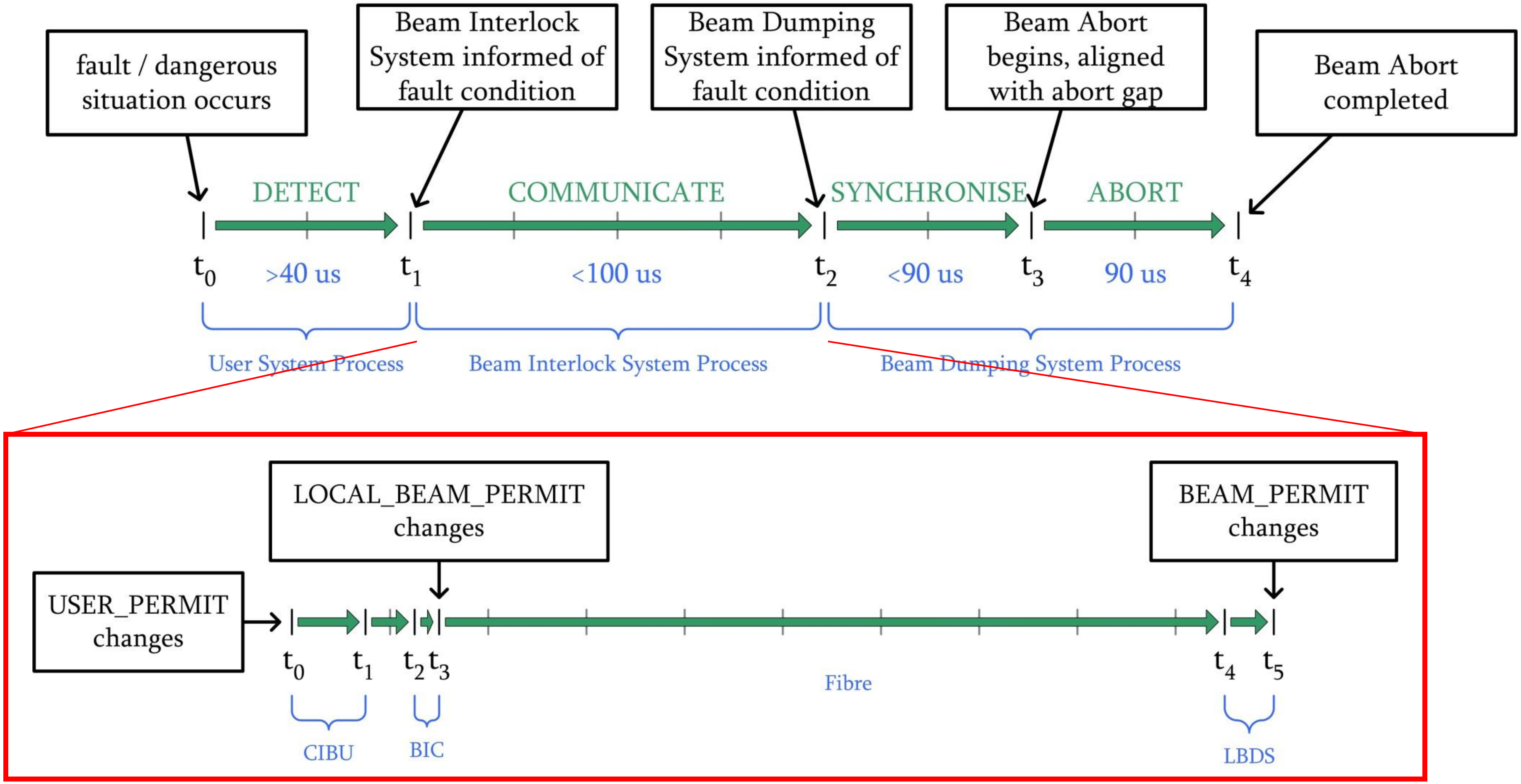
16 BICs per beam
- Two at each Insertion Point

Up to 20 User Systems per BIC
6 x Beam-1
8 x Both-Beam
6 x Beam-2

Beam Dump Beam-1 and Beam-2



LHC Function



fault / dangerous situation occurs

Beam Interlock System informed of fault condition

Beam Dumping System informed of fault condition

Beam Abort begins, aligned with abort gap

Beam Abort completed

DETECT

COMMUNICATE

SYNCHRONISE

ABORT

t_0 >40 us t_1 <100 us t_2 <90 us t_3 90 us t_4

User System Process

Beam Interlock System Process

Beam Dumping System Process

LOCAL_BEAM_PERMIT changes

BEAM_PERMIT changes

USER_PERMIT changes

t_0 t_1 t_2 t_3 t_4 t_5

CIBU

BIC

Fibre

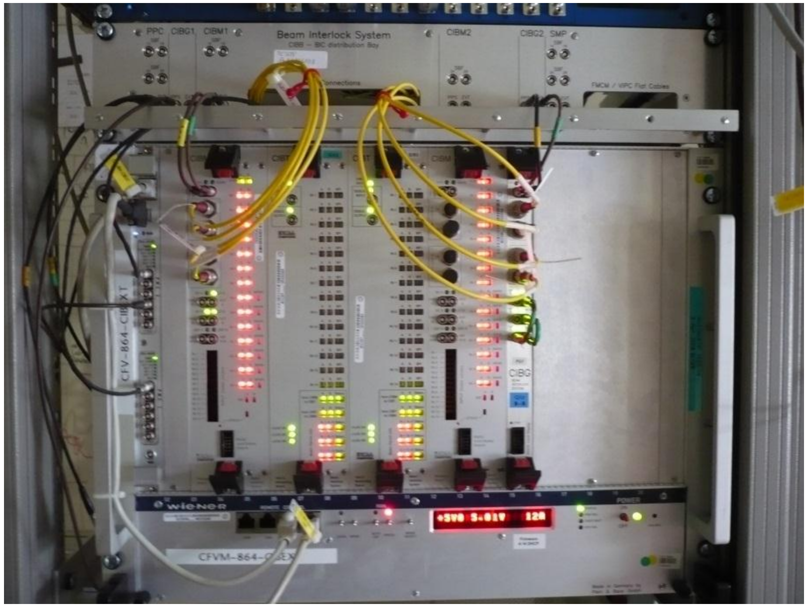
LBDS

Typical Hardware

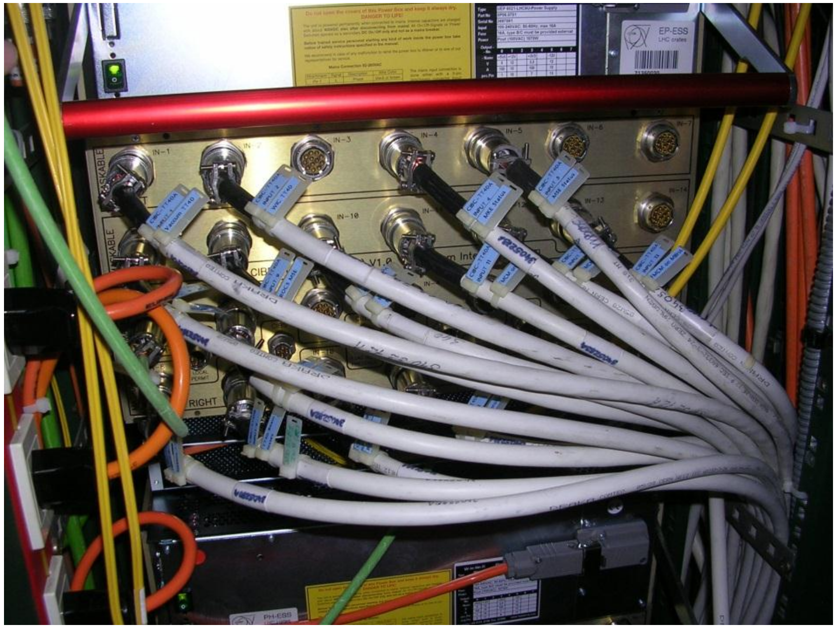
Partially located in
Radiation environment

User Interface

BIC (Front)



BIC (Rear)



Specification

- Fast = 100µs over 27 km

- Redundant User Permit = Safe
- Redundant Power Supplies = Available

- Critical is Hardware Only

- Critical physically separated from non-critical

- NO remote update of critical
- CAN remote update non-critical

- Modular in-house design
- 20 year lifespan

- Every Board Tested during fabrication
- Every Controller exhaustive critical test before installation

- Installed system can be fully tested on demand

- Pre operational checks
- Full online consistency monitoring during operation
- Post operational checks

‘Standard’ design

- In the world of industry different standards exist to guide engineers in the design of safety systems
  - IEC61508, …
- Accelerators are very special machines
- Safety must be ensured for
  1. Personnel
  2. Environment
  3. Machine
  4. “Beam”
- Common standards are applied to personnel and environmental protection systems
- Machine related protection can follow a relatively free approach to the design (still inspired by standards…)
  - Depends on the primary focus of the system

Evaluation of risk

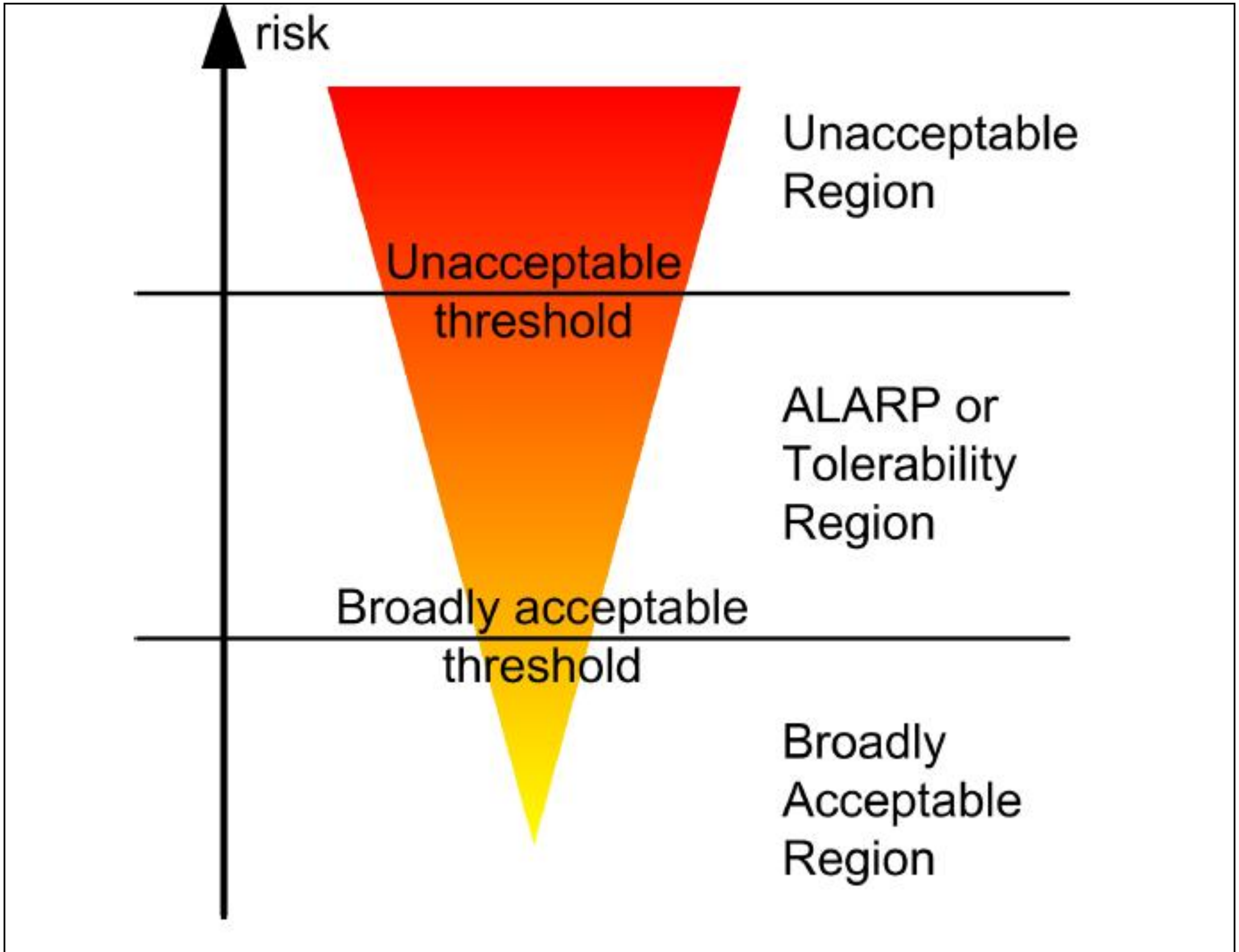
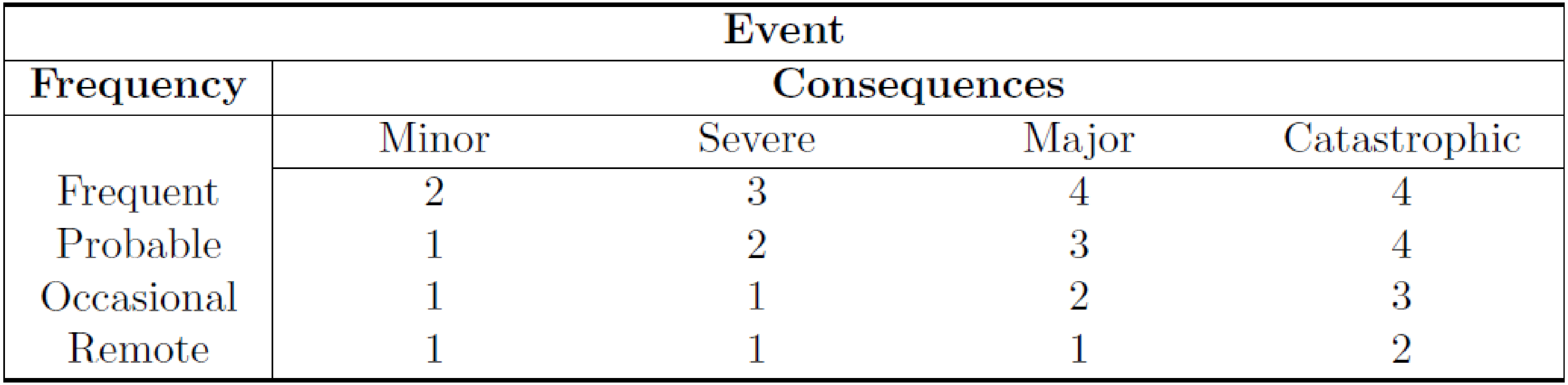


Figure 4.8: Diagram of the ALARP principle.

Safety / Protection Integrity Level

- **RISK = Consequences · Probability**
- IEC 61508 is an international standard of rules applied in industry, Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems (E/E/PE, or E/E/PES))
- Ideas from Safety Integrity Level (SIL) concept of the IEC 61508 were applied => **PIL**
- If a hazard becomes active…..



Event				
Frequency	**Consequences**			
	Minor	Severe	Major	Catastrophic
Frequent	2	3	4	4
Probable	1	2	3	4
Occasional	1	1	2	3
Remote	1	1	1	2

M.Kwiatkowski, Methods for the application of programmable logic devices in electronic protection systems for high energy particle accelerators, CERN-THESIS-2014-048

Frequency of a hazard becoming an accident

Frequent	Hazard expected to become active at least once every 100 days
Probable	Hazard expected to become active at least once between every 100 days to 1000 days
Occasional	Hazard expected to become active at least once between every 1000 days to 10000 days
Remote	Hazard is not expected to become active in 10000 days (unlikely during lifetime of LHC)

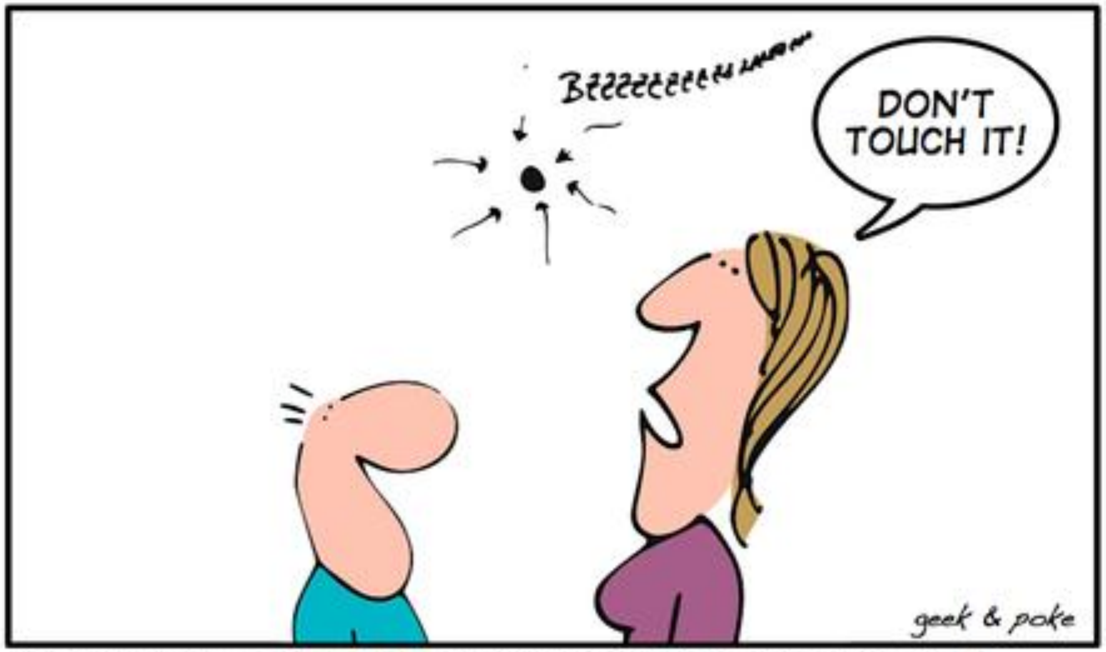
Consequences of a hazard becoming an accident

Catastrophic	if the consequence requires more than 200 days of repair or the cost of the repair is greater than 50 MCHF.
Major	if the consequence requires between 20 to 200 days of repair or the cost of the repair is between 1 MCHF and 50 MCHF.
Severe	if the consequence requires between 2 to 20 days of repair or the cost of the repair is between 100 kCHF and 1 MCHF.
Minor	if the consequence requires less than 2 day of repair or the cost of the repair is less than 100 kCHF.

This is not a unique table, and here the number are defined for LHC

Risk and Protection Integrity Level

- What is the risk that a probe beam will be injected into empty LHC and be lost during the first turn?
- What is the risk that a power converter fails and the full LHC beam is deflected?
- What is the risk for a wire scanners moving through the high intensity beam?
- What is the risk that the entire LHC beam will be deflected by a black hole generated in a proton-proton collision into ATLAS?



NOW THAT THE LARGE HADRON COLLIDER HAS STARTED WE CAN WATCH THE FIRST BLACK HOLES HANGING AROUND IN THE WILD

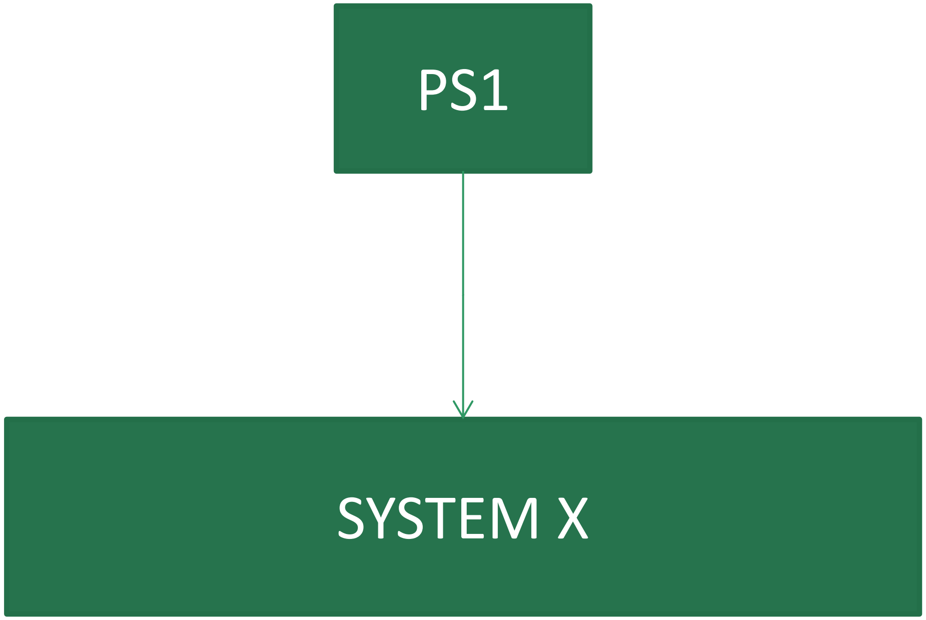
Design guidelines for protection systems

- Failsafe design
  - Detect internal faults
  - Possibility for remote testing, for example between two runs
  - If the protection system does not work, better stop operation rather than damage equipment
- Critical equipment should be redundant (possibly diverse)
- Critical processes not by software (no operating system)
  - No remote changes of most critical parameters
- Calculate safety / availability / reliability
  - Use established methods to analyse critical systems and predict failure rate
- Managing interlocks
  - Disabling of interlocks is common practice **(keep track!)**
  - LHC: masking of some interlocks possible for “setup beap” beams

Design guidelines for protection systems

- Avoid (unnecessary) complexity for protection systems
- Having a vision to the operational phase of the system helps….
- Test benches for electronic systems should be part of the system development
  - Careful testing in conditions similar to real operation
- Reliable protection does not end with the development phase. Documentation for installation, maintenance and operation of the MPS are required
- The accurate execution of each protection function must be explicitly tested during commissioning
- Requirements are established for the test interval of each function
- Most failure are due to power supplies, mechanical parts and connectors

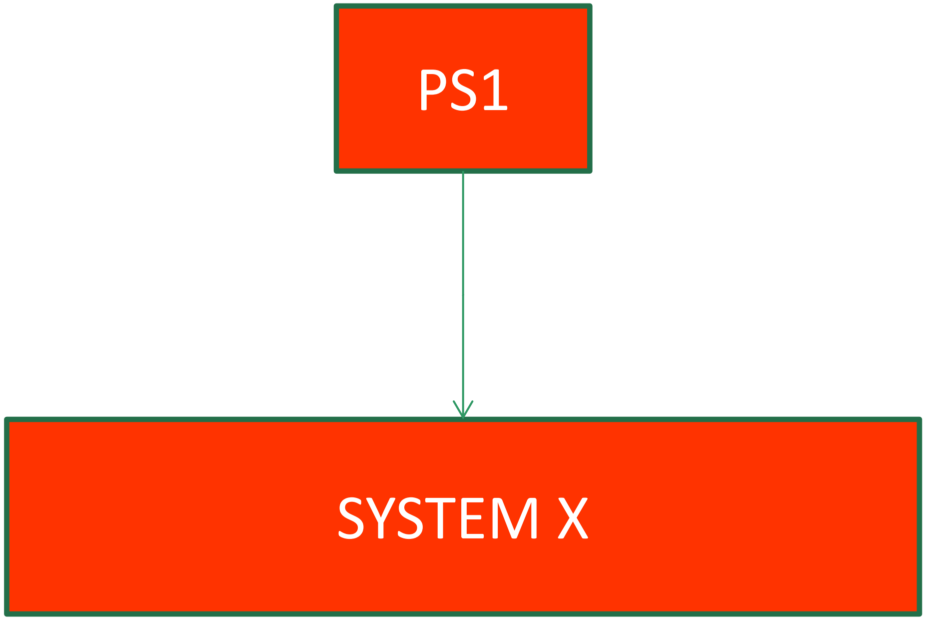
Powering critical equipment



PS1

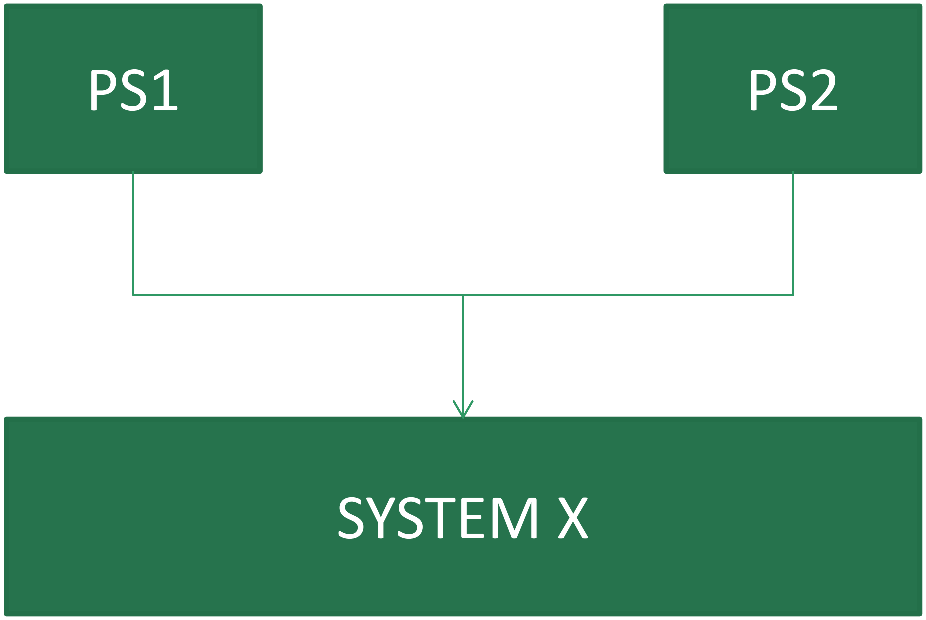
SYSTEM X

Powering critical equipment



MTBF = 20 years
Time for operation = 20 years
Probability of failure = 58%

Redundant Powering

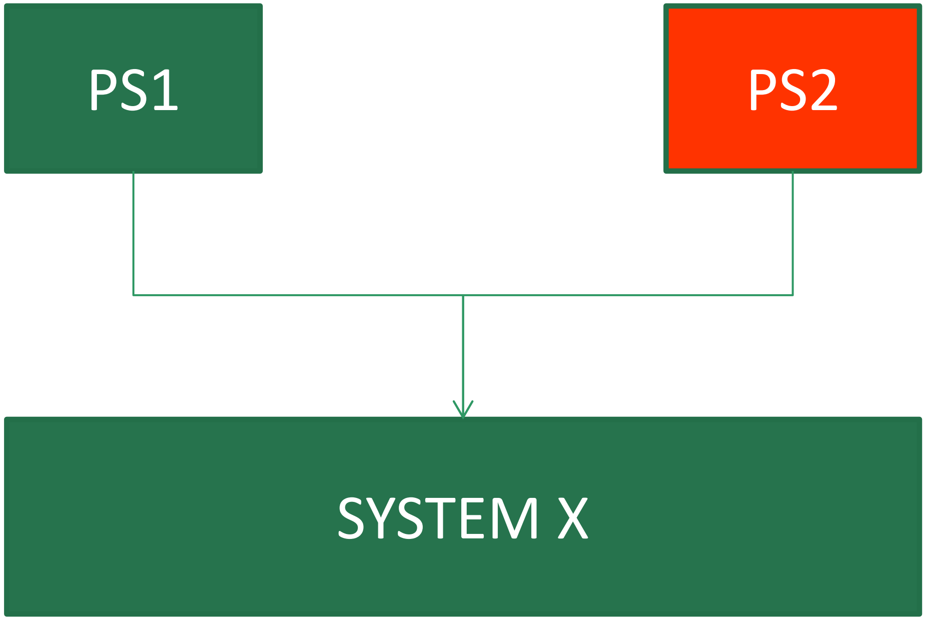


PS1

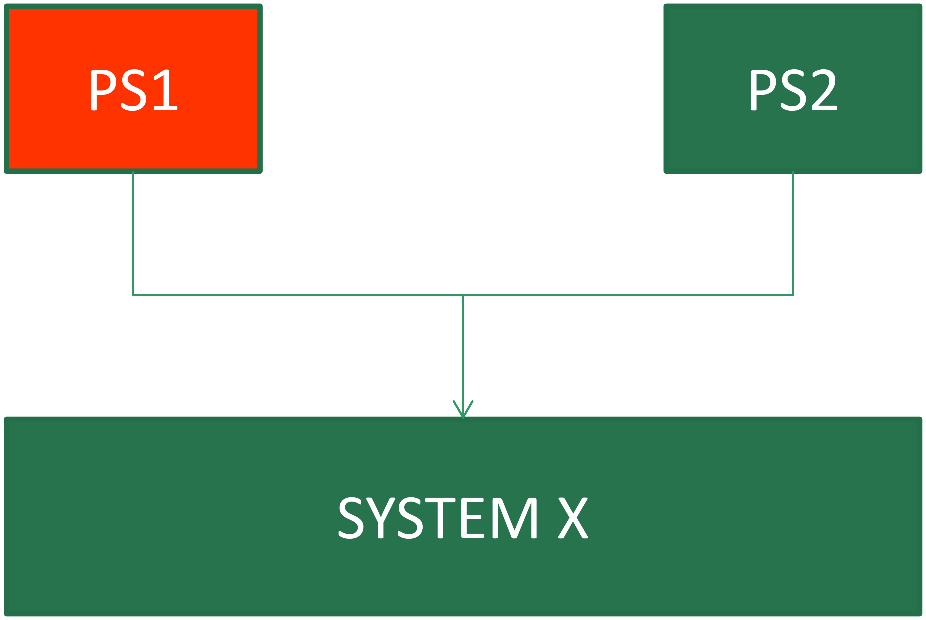
PS2

SYSTEM X

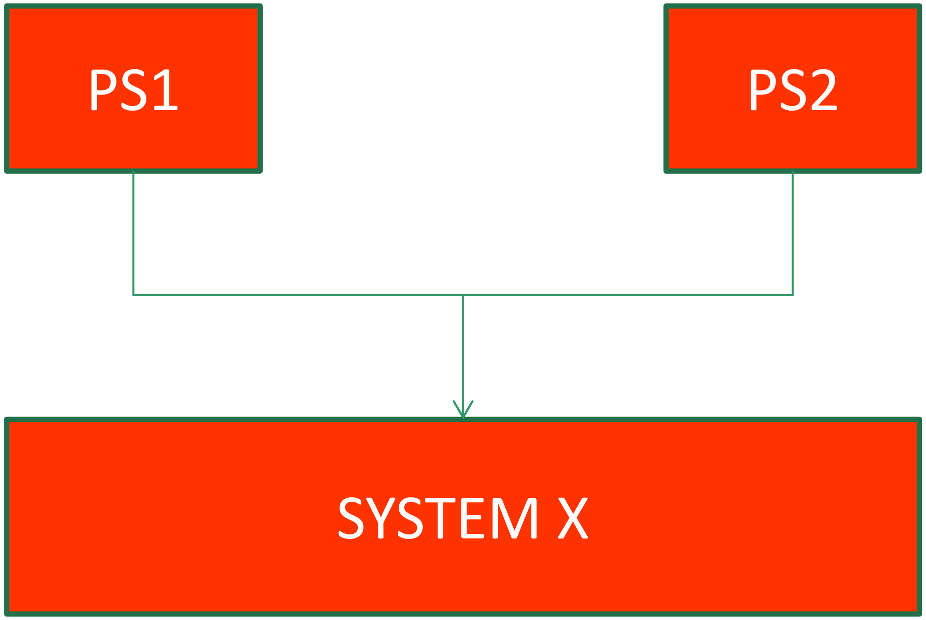
Redundant Powering



Redundant Powering



Redundant Powering

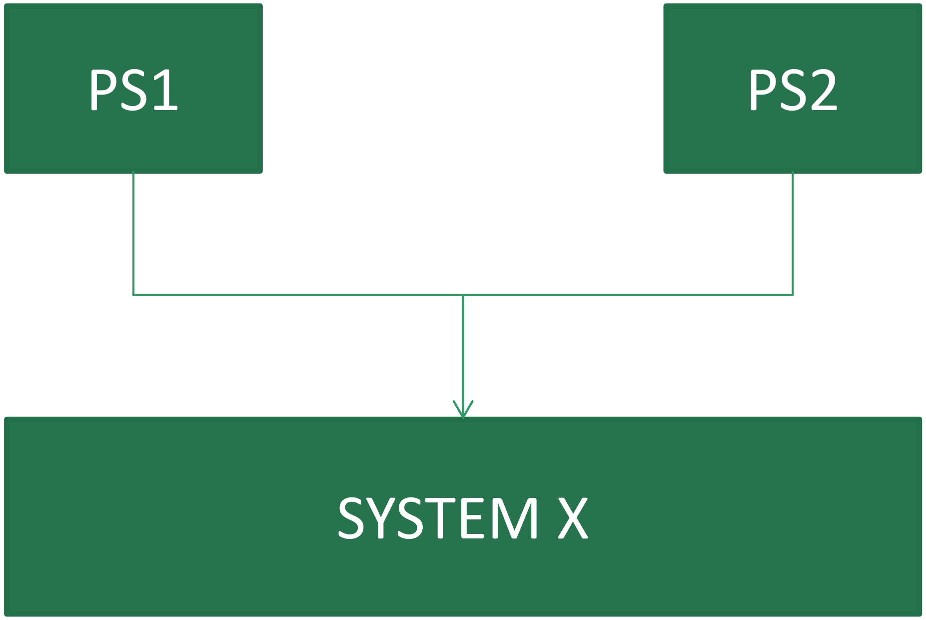

PS1

PS2

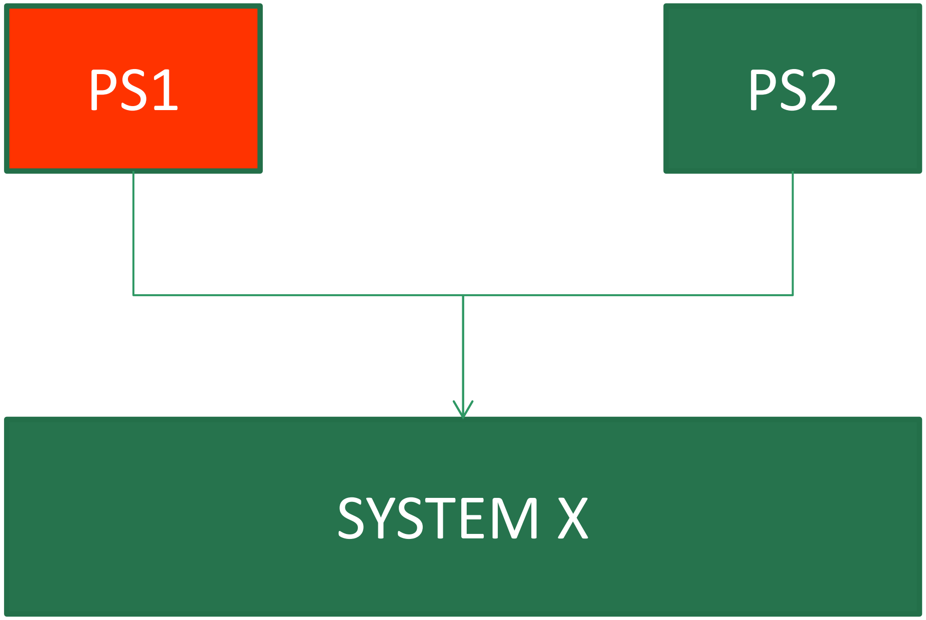
SYSTEM X

MTBF = 20 years
Time for operation = 20 years
Probability of failure = 66%

Redundant Powering: detect and repair

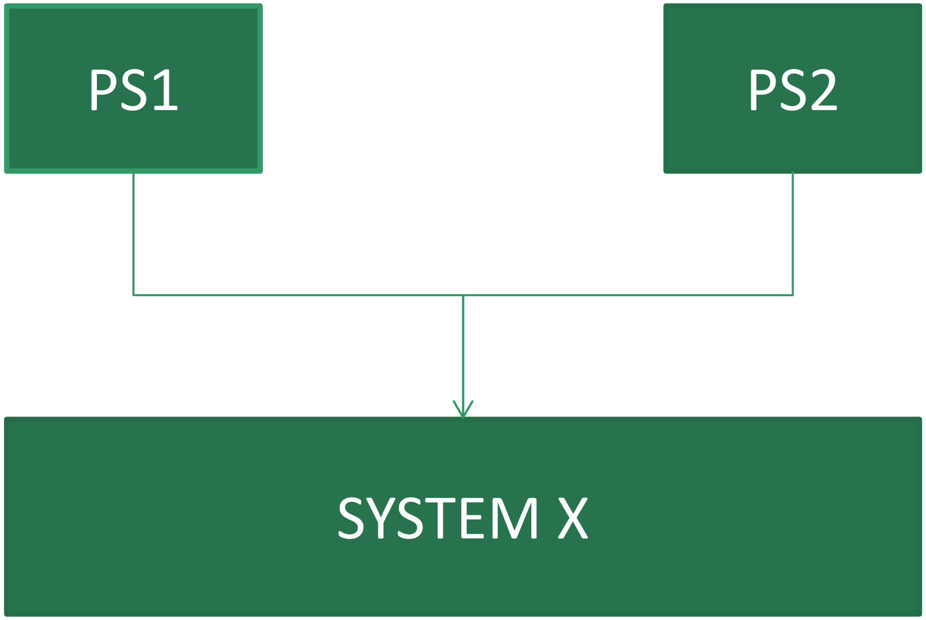


Redundant Powering: detect and repair



Detect the failure and repair the unit

Redundant Powering: detect and repair



MTBF = 20 years
Time for operation = 20 years
Detect and repair interval = 1 months
Probability of failure = 98%

Dependability of MPS

- Dependability: new challenge for accelerator laboratories
- Requires different approach in engineering, operation and management
- Safety culture: has been developed over the last, say, 10 years
  - Largely helped by the accident in 2008
- Excellent experience: no damage, no near miss
- Availability and Safety are in trade-off relationship - given safety is met, the goal is to make the system as available as possible for experiments
  - Avoid 'false beam dumps' + minimize downtime
  - Room for improvements
- Lessons to be learned for future accelerators to ensure safe operation with high availability (e.g. **A**ccelerator **D**riven **S**pallation)

Summary

Machine protection

- is not equal to equipment protection
- requires the understanding of many different type of failures that could lead to beam loss
- requires comprehensive understanding of all aspects of the accelerator (accelerator physics, operation, equipment, instrumentation, functional safety)
- touches many aspects of accelerator construction and operation
- includes many systems
- is becoming increasingly important for future projects, with increased beam power / energy density (W/mm^2 or J/mm^2) and increasingly complex machines

References

- See at the end of the first talk…