Machine Protection

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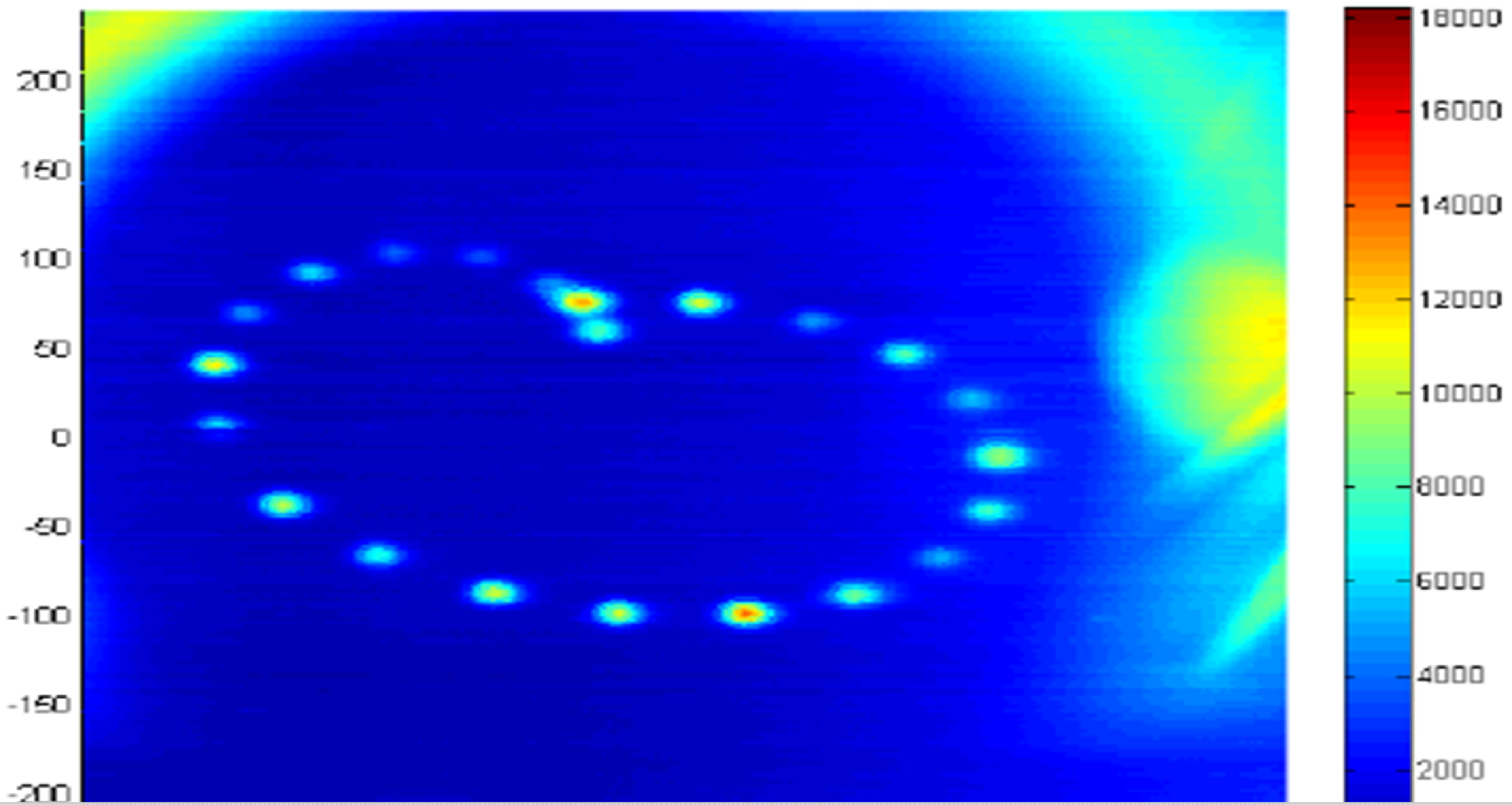
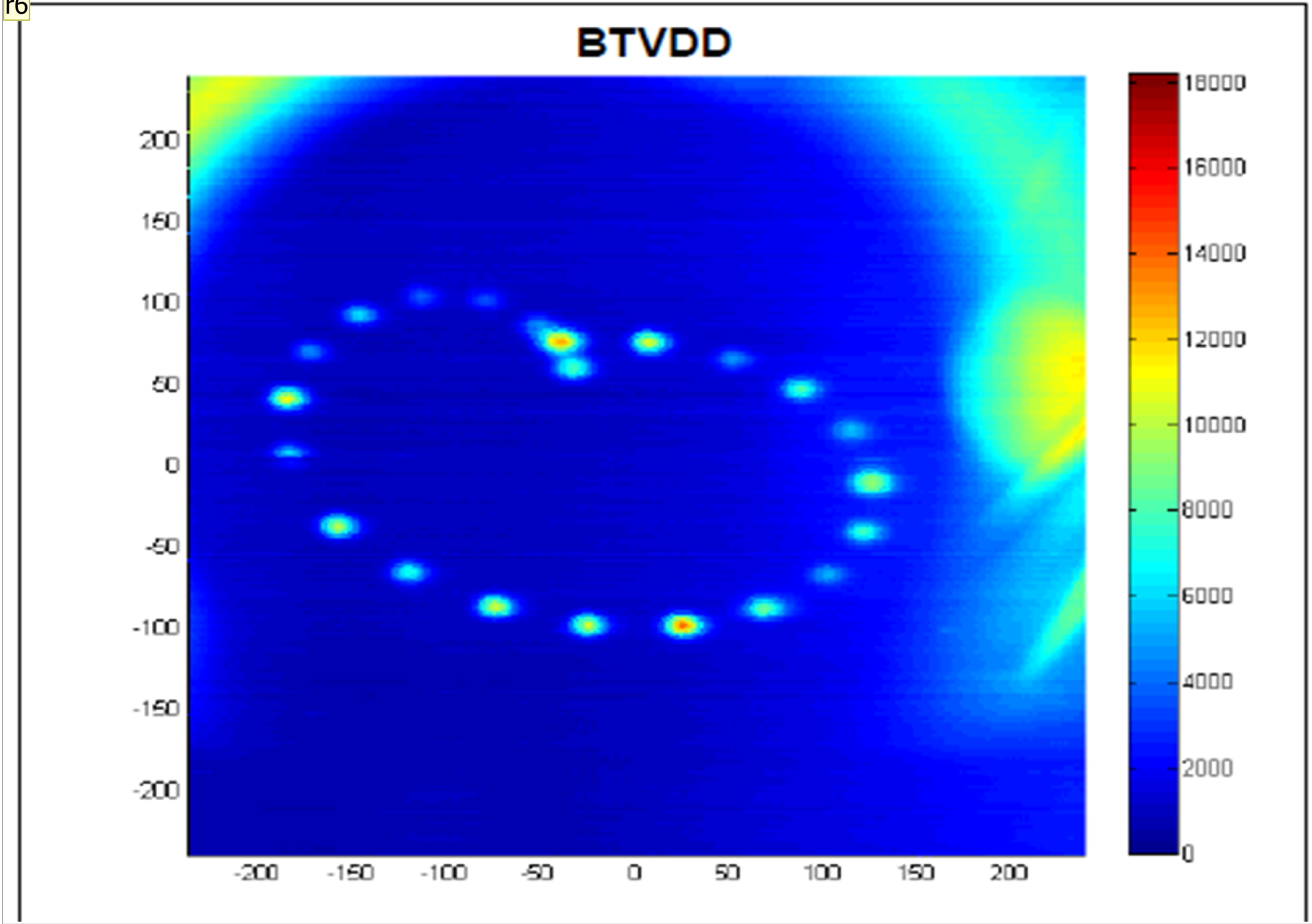
517. WE-Heraeus-Seminar 18/10/2012



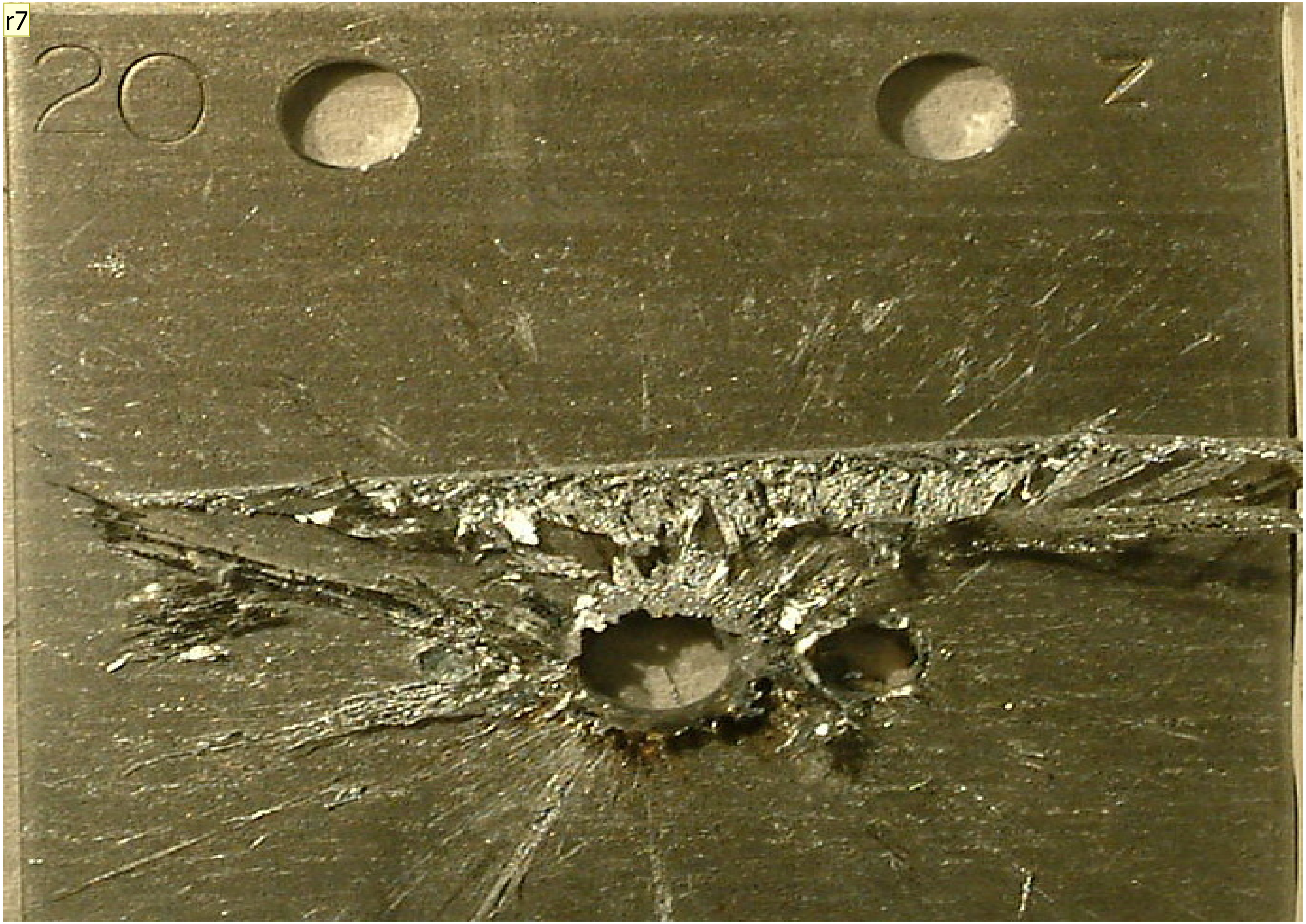
- Accidental beam losses and Machine Protection
- Continuous beam losses and Collimation

r6



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

r6 Illustrations and examples mostly from CERN
rudi; 23.05.2008



Proton bunches at the end of their life during an SPS test: damage to metal structure

Folie 3

r7 Illustrations and examples mostly from CERN
rudi; 23.05.2008

Content

- Overview: Energy and Power in accelerators

- Beam losses and damage potential
- Beam losses, collimation and machine protection
- Some examples of failures from LHC
- Collimators, beam absorbers and beam cleaning

- Wrap up on Machine Protection

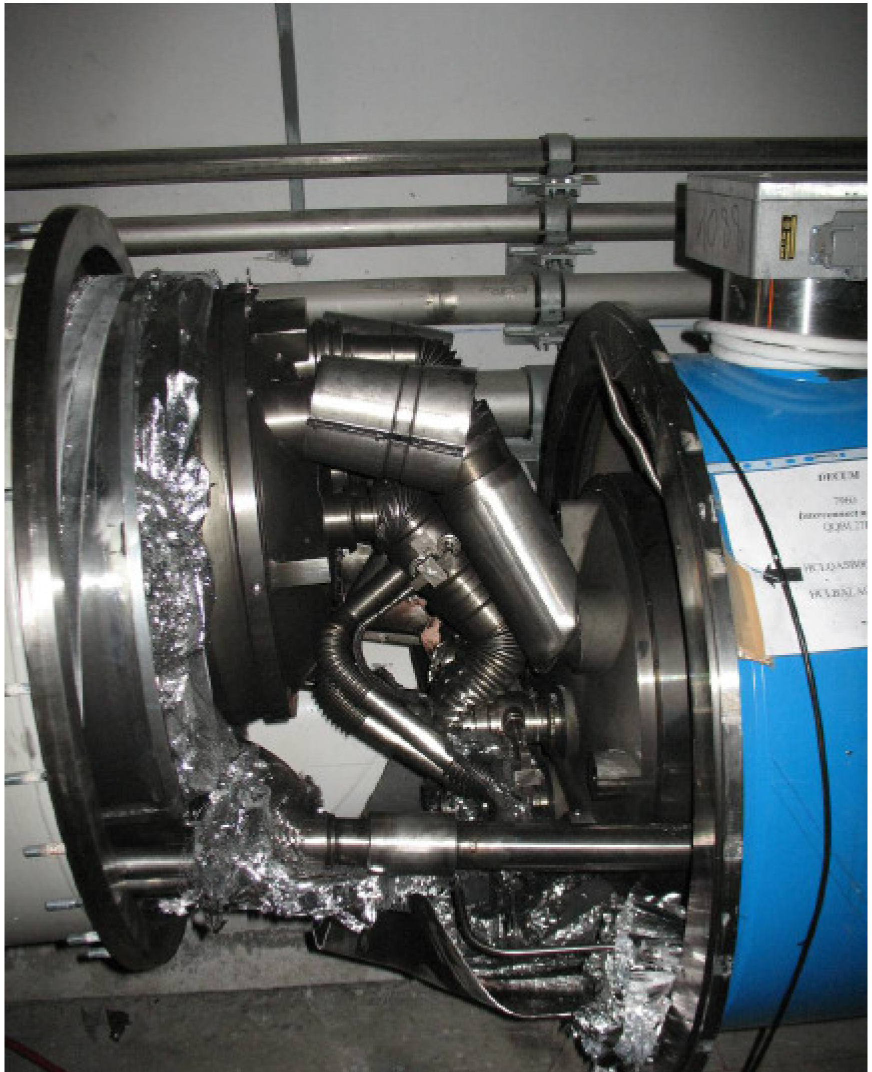
Most examples from LHC …. apologies to other accelerators….
LHC allows illustration of many principles

Overview: Energy and Power in accelerators

Protection from Energy and Power

- Risks come from Energy stored in a system (Joule), and Power when operating a system (Watt)
  - "very powerful accelerator" … the power flow needs to be controlled
  - !!! watch out: energy (e.g. 7 TeV) and stored energy (e.g. 362 MJ) !!!
- An uncontrolled release of the energy or an uncontrolled power flow can lead to unwanted consequences
  - Loss of time for operation or damage of equipment
- This is true for all systems, in particular for complex systems such as accelerators
  - For the RF system, power converters, magnet system (e.g. magnet protection for superconducting magnets), ….
  - For the beams
- The 2008 accident during LHC operation happened during test runs without beam

Damage of LHC during the 2008 accident



Accidental release of an energy of 600 MJoule stored in the magnet system - No Beam

Machine Protection for Particle Beams

Many accelerators operate with high beam intensity and/or large stored energy:

•For synchrotrons and storage rings, the energy stored in the beam is increased during the years (from ISR to LHC)

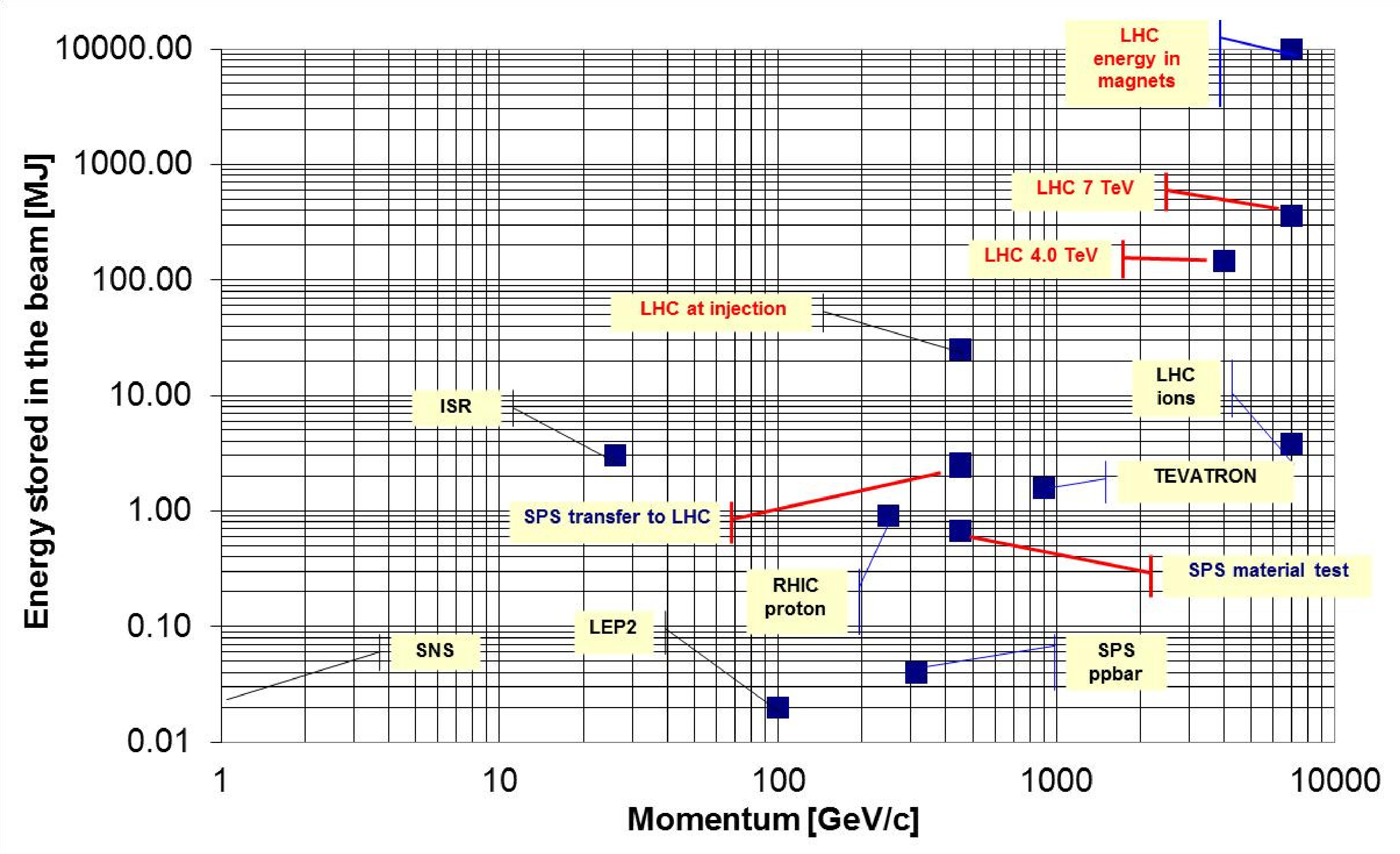
•For linear accelerators and fast cycling machines, in particular high intensity proton and ion accelerators, the beam power increases

The emittance becomes smaller (resulting in a beam size down to nanometer:

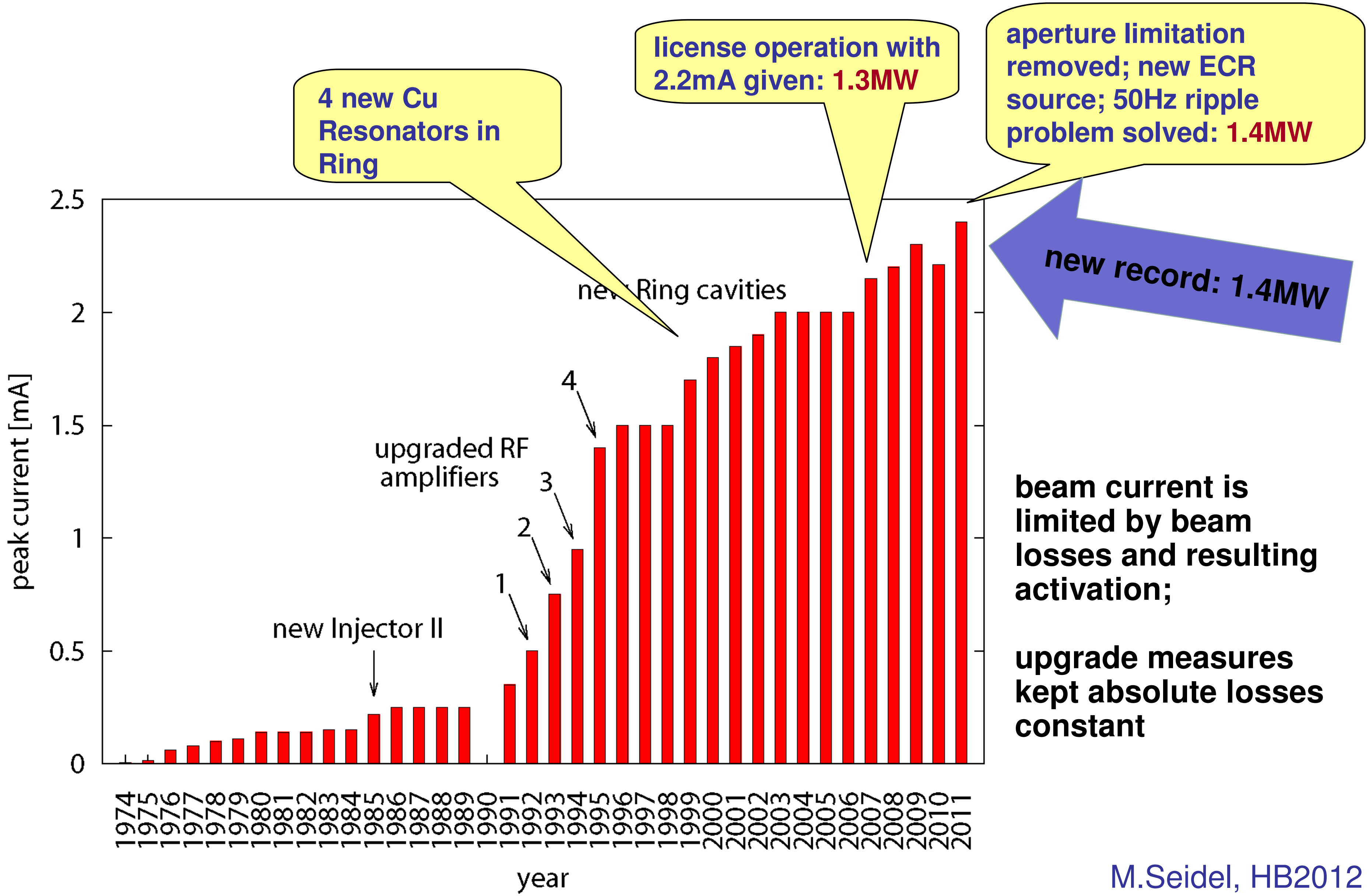
•Increasingly important for future projects, with increased beam power / energy density (W/mm^2 or J/mm^2) for ILC, CLIC and XFEL) - less relevant for hadron accelerators

•Beam induced heating due to high beam current via EM fields: see G.Arduinis presentation – not discussed here

Livingston type plot: Energy stored magnets and beam



Power in the PSI cyclotron accelerator



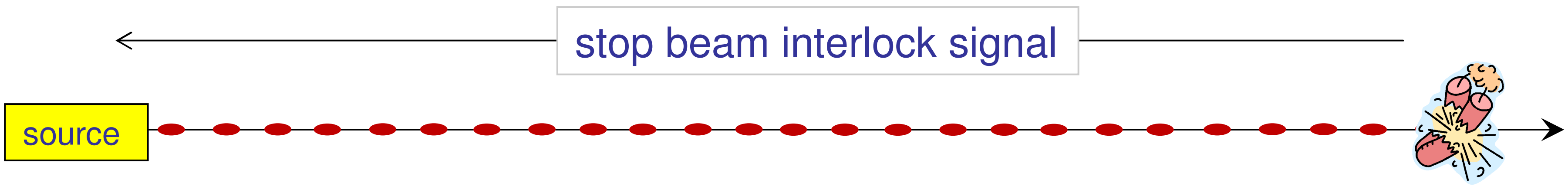
beam current is limited by beam losses and resulting activation;

upgrade measures kept absolute losses constant

M.Seidel, HB2012

High power accelerators …

- Operate with beam power of 1 MW and more
- SNS – 1 MW, PSI cyclotron – 1.3 MW, ESS – planned for 5 MW, FRIB (ions)– planned for 0.4 MW
- In case of an uncontrolled beam loss during 1 ms, the deposited energy is 1 kJ to 5 kJ, for 100 ms 100 kJ to 500 kJ
- It is required to switch off the source a.s.a.p. after detecting uncontrolled beam loss
- The delay between detection and "beam off" to be considered



dT = dT_detect failure + dT_transmit signal + dT_stop source + dT_stop impact

Beam losses

In accelerators, particles are lost due to a variety of reasons: beam gas interaction, losses from collisions, losses of the beam halo, …

- Continuous beam losses are inherent to the operation of accelerators
  - Taken into account during the design of the accelerator
- Accidental beam losses are due to a multitude of failures mechanisms
- The number of possible failures leading to accidental beam losses is (nearly) infinite

Beam losses, machine protection and collimation

Continuous beam losses: **Collimation** prevents too high beam losses around the accelerator (beam cleaning)

A collimation system is a (very complex) system with (massive) material blocks installed in an accelerator to capture halo particles

Such system is also called (beam) Cleaning System

Accidental beam losses: "**Machine Protection**" protects equipment from damage, activation and downtime

Machine protection includes a large variety of systems, including collimators (or beam absorbers) to capture mis-steered beam

Regular and irregular operation

Regular operation	Failures during operation
Many accelerator systems Continuous beam losses Collimators for beam cleaning Collimators for halo scraping Collimators to prevent ion-induced desorption	Beam losses due to failures, timescale from nanoseconds to seconds Machine protection systems Collimators Beam absorbers

Beam losses and damage

Beam losses and consequences

- Particle losses lead to ionisation and particle cascades in materials that deposit energy in the material
  - the maximum energy deposition can be deep in the material at the maximum of the hadron / electromagnetic shower
- The energy deposition leads to a temperature increase
  - material can vaporise, melt, deform or lose its mechanical properties
  - risk to damage sensitive equipment for some kJ …10 kJ, risk for damage of any structure for some MJoule (depends on beam size)
  - superconducting magnets could quench (beam loss of ~mJ to J)
- Activation of equipment due to beam losses (acceptable is ~1 W/m for high energy protons, should be "As Low As Reasonably Achievable" - ALARA)
  - very serious limitation of the performance of high power accelerators (PSI cyclotron, SNS, …..)

Energy deposition and temperature increase

- There is no straightforward expression for the energy deposition of particles in matter
- The energy deposition is a function of the particle type, its momentum, and the parameters of the material (atomic number, density, specific heat)
- Programs such as FLUKA, MARS, GEANT and similar codes are being used for the calculation of energy deposition and activation
- Other programs are used to calculate the response of the material (deformation, melting, …) to beam impact (mechanical codes such as ANSYS, hydrodynamic codes such as BIG2, AUTODYN and others)

Question: what is dangerous (stored beam energy, beam power)? When do we need to worry about protection?

What parameters are relevant?

- Energy stored in the beam
  - one MJoule can heat and melt 1.5 kg of copper
  - one MJoule corresponds to the energy stored in 0.25 kg of TNT
- Beam power
  - one MW during one second corresponds to a MJ
- Particle type
  - activation is mainly an issue for hadron accelerators
- Momentum of the particle
- Time structure of beam
- Beam size
- Beam power / energy density ($MJoule/mm^2$, $MWatt/mm^2$)

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

Machine protection to be considered for an energy stored in the beam > 1 kJ … 10 kJ
Very important if beam > 1 MJ

SPS experiment: Beam damage with 450 GeV proton beam

Controlled SPS experiment

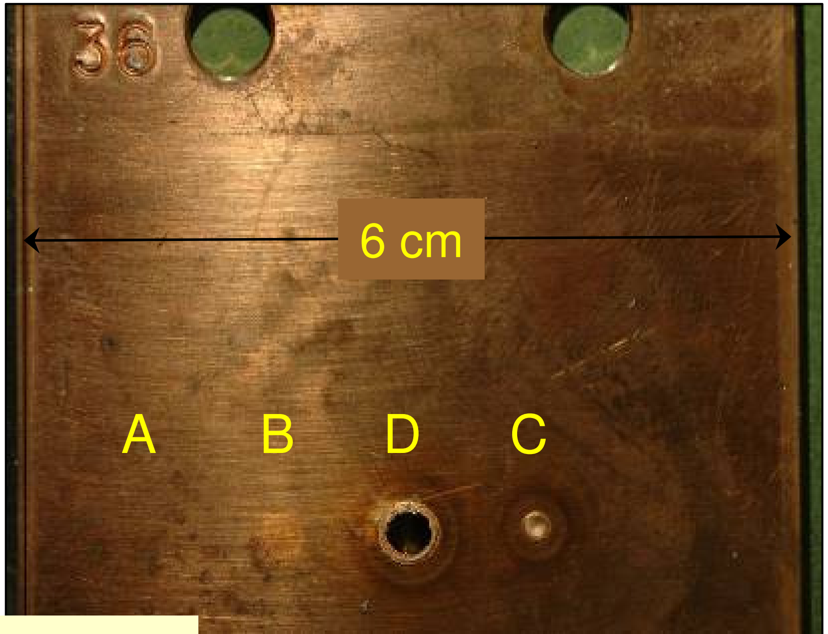
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

above damage limit for copper

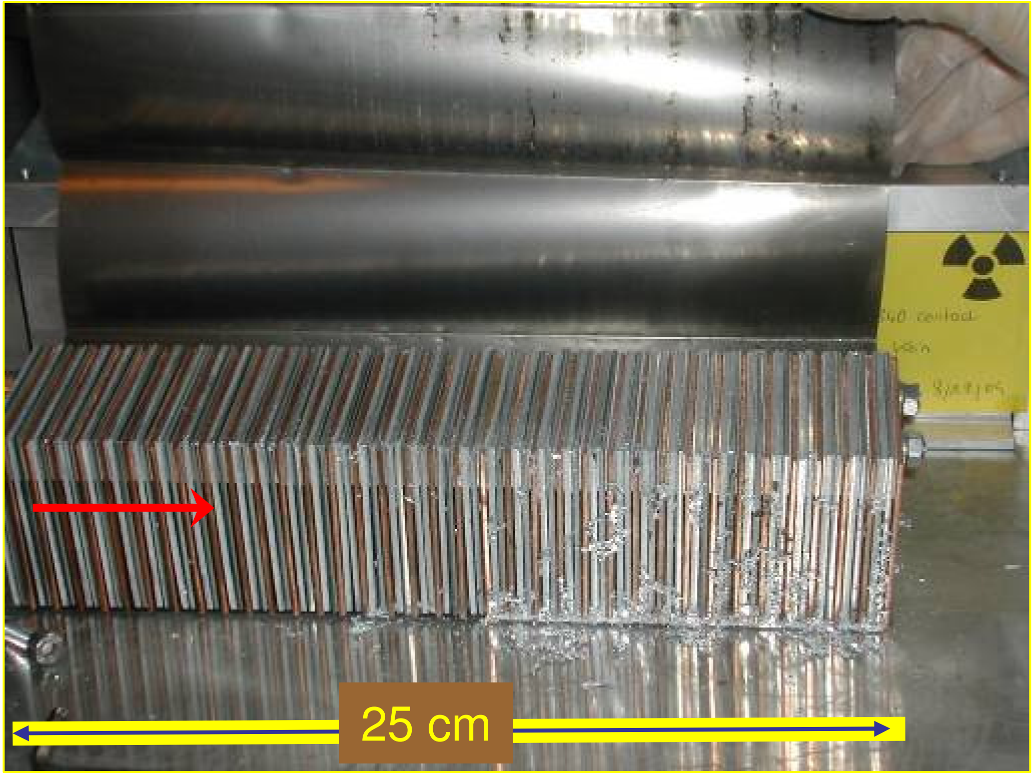
stainless steel no damage

- $2 \cdot 10^{12}$ protons

below damage limit for copper



V.Kain et al



- Damage limit ~200 kJoule
- 0.1 % of the full LHC 7 TeV beams
- factor of ~10 below the energy in a bunch train injected into LHC

Protons versus Ions - LHC parameters

	Protons	Ions (Pb)
Max. dipole field	8.33 T	8.33 T
Energy per nucleon	7 TeV	2.759 TeV
Number of bunches	2808	592
Particles per bunch	$1.15 * 10^{11}$	$7 * 10^{7}$
Energy per bunch	129 kJ	6.44 kJ
Energy in one beam	362 MJ	3.81 MJ

- In the worst case, the proton beam could damage the accelerator beyond repair, one bunch can drill a hole into the vacuum chamber
- The ion beam can damage the accelerator, the worst case damage potential is much less
- For one ion bunch with 6.44 kJ stored energy, is there any risk?

Concept of set-up (safe) beam

- High intensity beams: the full machine protection system must work reliably, all interlocks should fully function
- Commissioning starts with low-intensity (safe) beams, as well as during machine development periods
- During initial commissioning working with all interlocks is not practical (…common practice is to strap interlocks)
- LHC solution
  - With low intensity (safe) beams, interlocks can be masked (disabled)
  - With high intensity beams the masks are automatically removed (the criticality of the beam is measured
    - $Criticality = beam\ current \times energy^{1.8}$
- What intensity is "safe"?

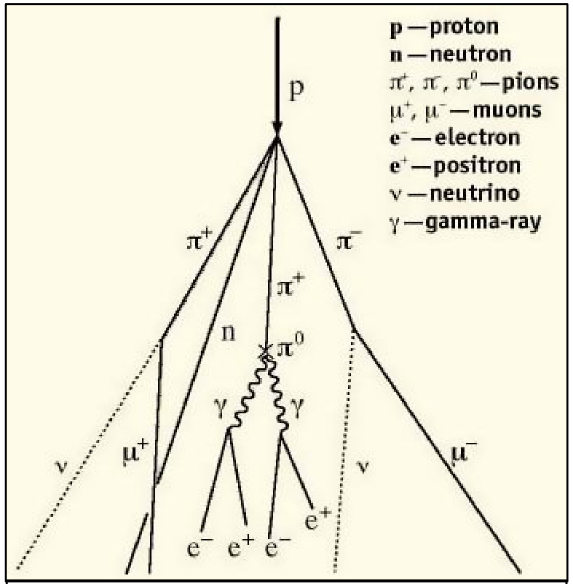
Energy deposition in target: protons and ions

- The interaction of protons and ions with matter has similarities, but also differences aspects
- Ionisation energy loss
  - Creates many soft electrons, which makes the final energy deposition close to the point of creation => very localized energy deposition
  - Scales with Z^2, approximately described by Bethe-Bloch formula for relativistic particles:

$$-dE/dx = \frac{4\pi}{m_e \cdot c^2} \cdot \frac{n_t \cdot Z_p^2}{\beta_p^2} \cdot \left(\frac{e_0^2}{4 \cdot \pi \cdot \varepsilon_0} \right)^2 \cdot \left[\ln \left[\frac{2 \cdot m_e \cdot c^2 \cdot \beta_p^2}{I_t \cdot \left(1 - \beta_p^2\right)} \right] - \beta_p^2 \right]$$

Energy deposition in target: protons and ions

- Nuclear inelastic interactions (hadronic shower)
  - Causes electromagnetic shower through decays of pions
  - Exponential increase in number of created particles
  - Final energy deposition to large fraction done by large number of electromagnetic particles
  - Scales roughly with total energy of incident particles
  - Ions can be approximated as independent nucleons
- Ions nuclei can break up in the high-intensity electromagnetic field for ultra peripheral collisions without direct overlap
- In ion-ion collisions, the nucleus can change the charge/mass ratio, e.g.



http://williamson-labs.com/ltoc/cbr-tech.htm

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^+$$

Damage of a pencil 7 TeV proton beam (LHC)

copper

Maximum energy deposition in the proton cascade (one proton) $E_{max\_Cu} := 1.5 \cdot 10^{-5} \frac{J}{kg}$

Specific heat of copper is $c_{Cu\_spec} = 384.5600 \frac{1}{kg} \frac{J}{K}$

To heat 1 kg copper by, say, by $\Delta T := 500K$, one needs: $c_{Cu\_spec} \cdot \Delta T \cdot 1kg = 1.92 \times 10^{5} J$

Number of protons to deposit this energy is: $\frac{c_{Cu\_spec} \cdot \Delta T}{E_{max\_Cu}} = 1.28 \times 10^{10}$ Copper

graphite

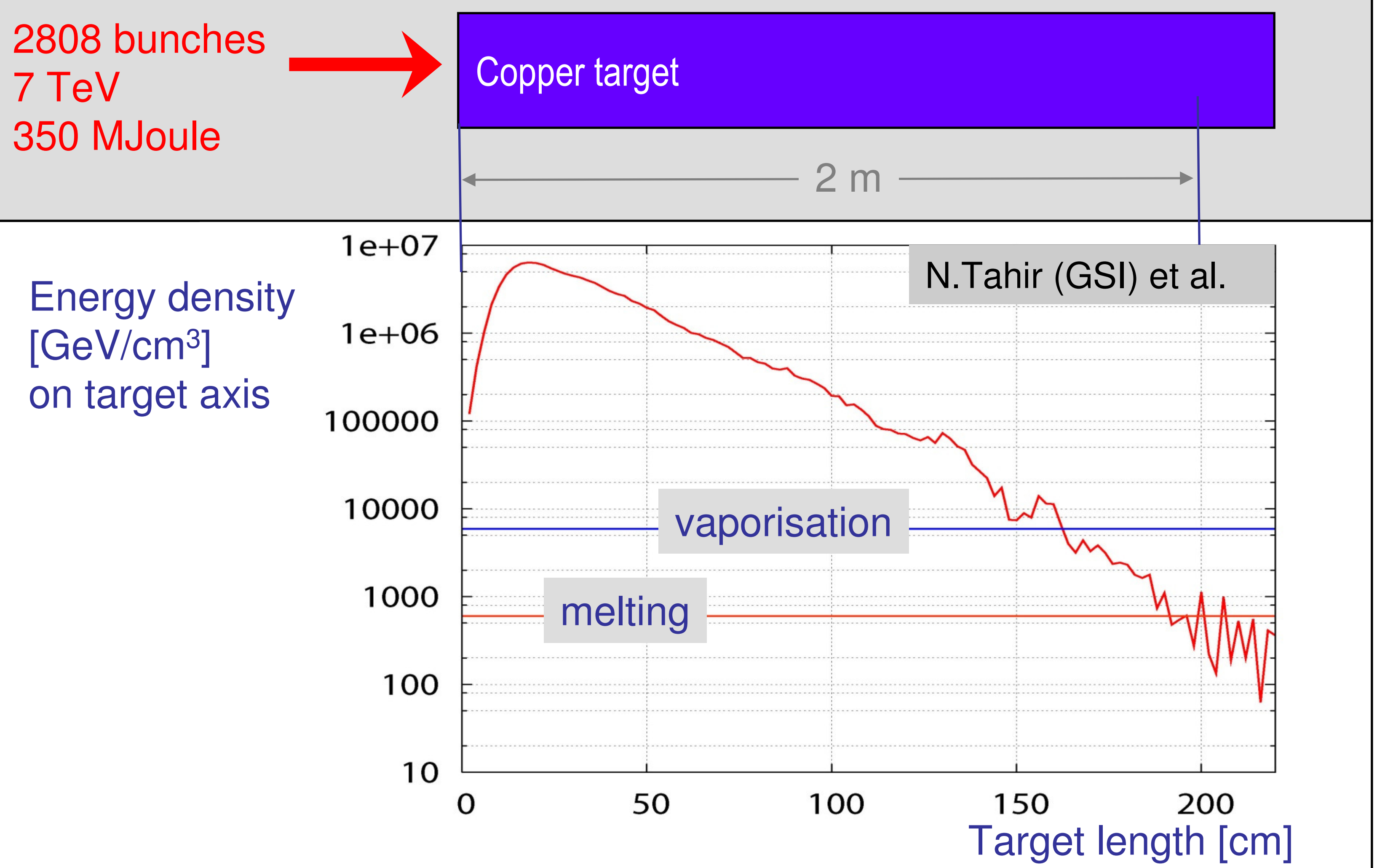
Maximum energy deposition in the proton cascade (one proton) $E_{max\_C} := 2.0 \cdot 10^{-6} \frac{J}{kg}$

Specific heat of graphite is $c_{C\_spec} = 710.6000 \frac{1}{kg} \frac{J}{K}$

To heat 1 kggraphite by, say, by $\Delta T := 1500K$, one needs: $c_{C\_spec} \cdot \Delta T \cdot 1kg = 1.07 \times 10^{6} J$

Number of protons to deposit this energy is: $\frac{c_{C\_spec} \cdot \Delta T}{E_{max\_C}} = 5.33 \times 10^{11}$ graphite

Full LHC beam deflected into copper target

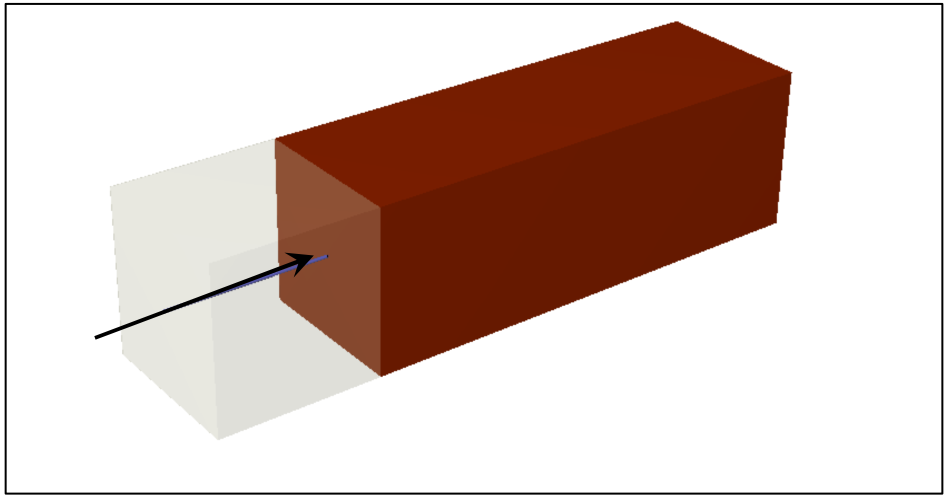


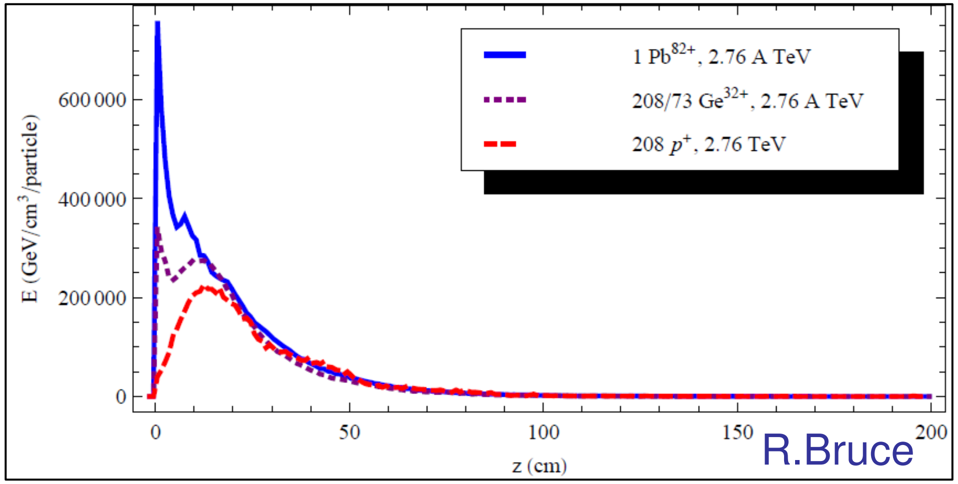
FLUKA and hydrodynamic codes: the LHC beam will tunnel about 30 m into solid copper for full beam impact

Impact of high energy high intensity proton beams on targets, N.A.Tahir et al, PRSTAB IPAC 2011 Conference Edition

Energy deposition in target: Ions

- Relevant ion-matter interactions implemented in programs such as FLUKA
- Simple case: beams of Pb ions and protons hitting homogenous copper target at straight angle
- Gaussian beam with σ = 40 µ sigma hitting Cu target
- Three different particle species simulated: Pb82+, Ge32+ and p+, all at 2.76 TeV/nucleon
- Sharp peak for ions near to entry point
- Second peak after some 20 cm
- Energy deposition from Pb roughly factor 4 higher than energy deposition from protons





Beam losses, collimation and protection

Continuous beam losses: Collimation

Limitation of beam losses is in order of 1 W/m (high energy protons) to avoid activation and allow hands-on maintenance

- avoid beam losses around the accelerator
- define the aperture by collimators
- capture continuous particle losses with collimators at specific locations

Continuous beam with a power ~1 MW (SNS, JPARC, ESS)

- a loss of 1% corresponds to 10 kW – not to be lost along the beam line to avoid activation of material, heating, quenching, …
- assume a length of 200 m: 50 W/m, not acceptable
- ideas for accelerators of 5 MW, 10 MW and more….

LHC stored beam with an energy of 360 MJ for 7 TeV operation

- assume lifetime of 10 minutes corresponds to beam loss of 500 kW, not to be lost in superconducting magnets
- reduce losses by four orders of magnitude

….but also: capture fast accidental beam losses

Accidental beam losses: Machine Protection

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

- transfer lines between accelerators or from an accelerator to a target station (target for secondary particle production, beam dump block)
- failures of kicker magnets (injection, extraction, special kicker magnets, for example for diagnostics)
- failures in linear accelerators
- too small beam size at a target station

Very fast beam loss (ms)

- in circular accelerators (multiturn) and in linacs
- 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)

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 / bunch current / e-clouds)
- Parameters for the failure
  - time constant for beam loss
  - probability for the failure
  - damage potential

  } defined as risk (probability for the failure, damage potential)
- Machine state when failure occurs
  - beam transfer, injection and extraction (single pass)
  - acceleration
  - stored beam

Example for Active Protection - Traffic

- A monitor detects a dangerous situation

- An action is triggered

- The energy stored in the system is safely dissipated

Example for Passive Protection

- The monitor fails to detect a dangerous situation

- The reaction time is too short

- Active protection not possible – passive protection by bumper, air bag, safety belts

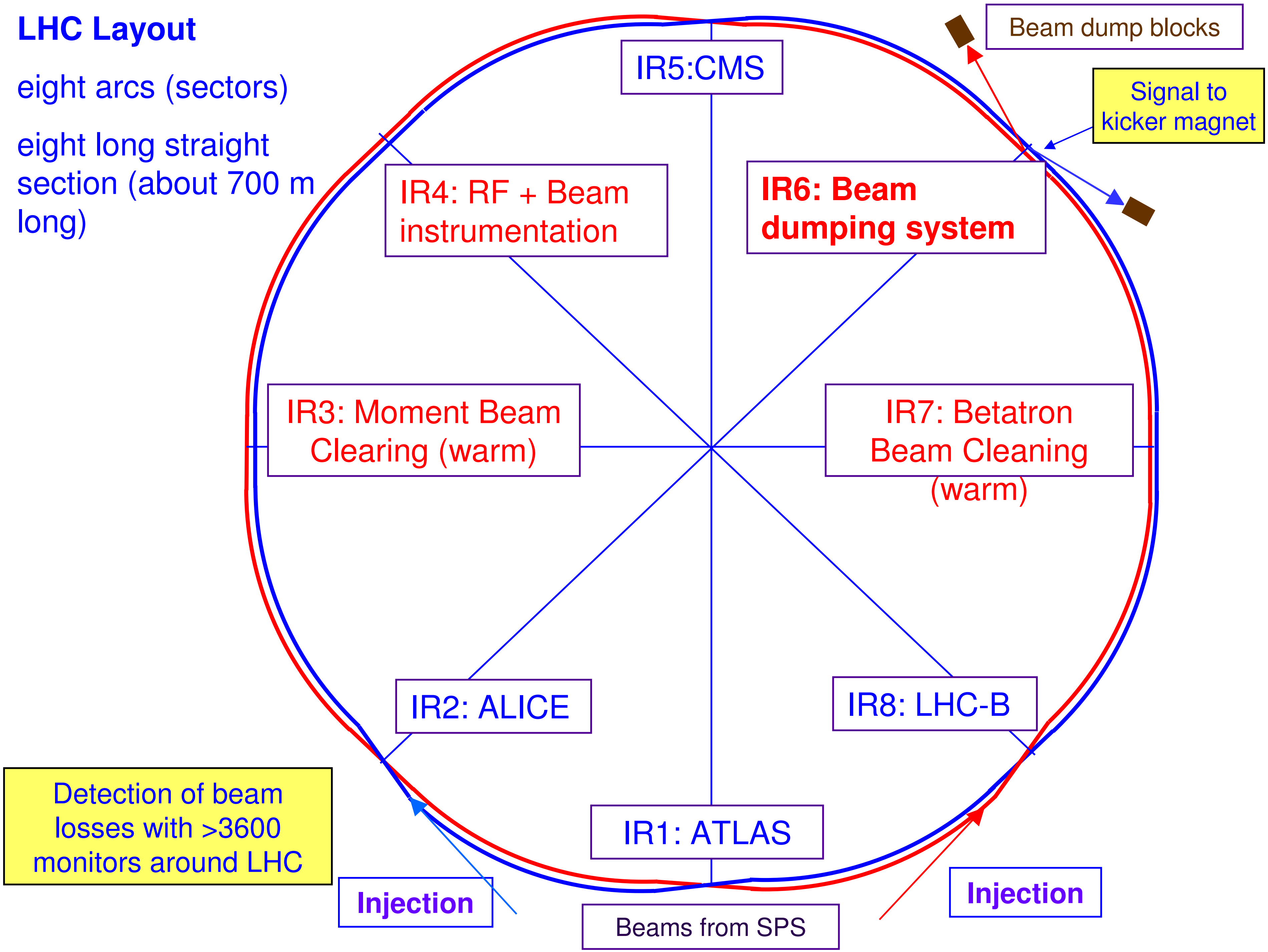
Strategy for protection: Protection Systems

- 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
  - stop injection
  - extract beam into beam dump block
  - stop beam by beam absorber / collimator
- Elements in the protection systems
  - hardware monitoring and beam monitoring
  - beam dump (fast kicker magnet and absorber block)
  - collimators and beam absorbers
  - beam interlock systems linking different systems

LHC Layout

eight arcs (sectors)

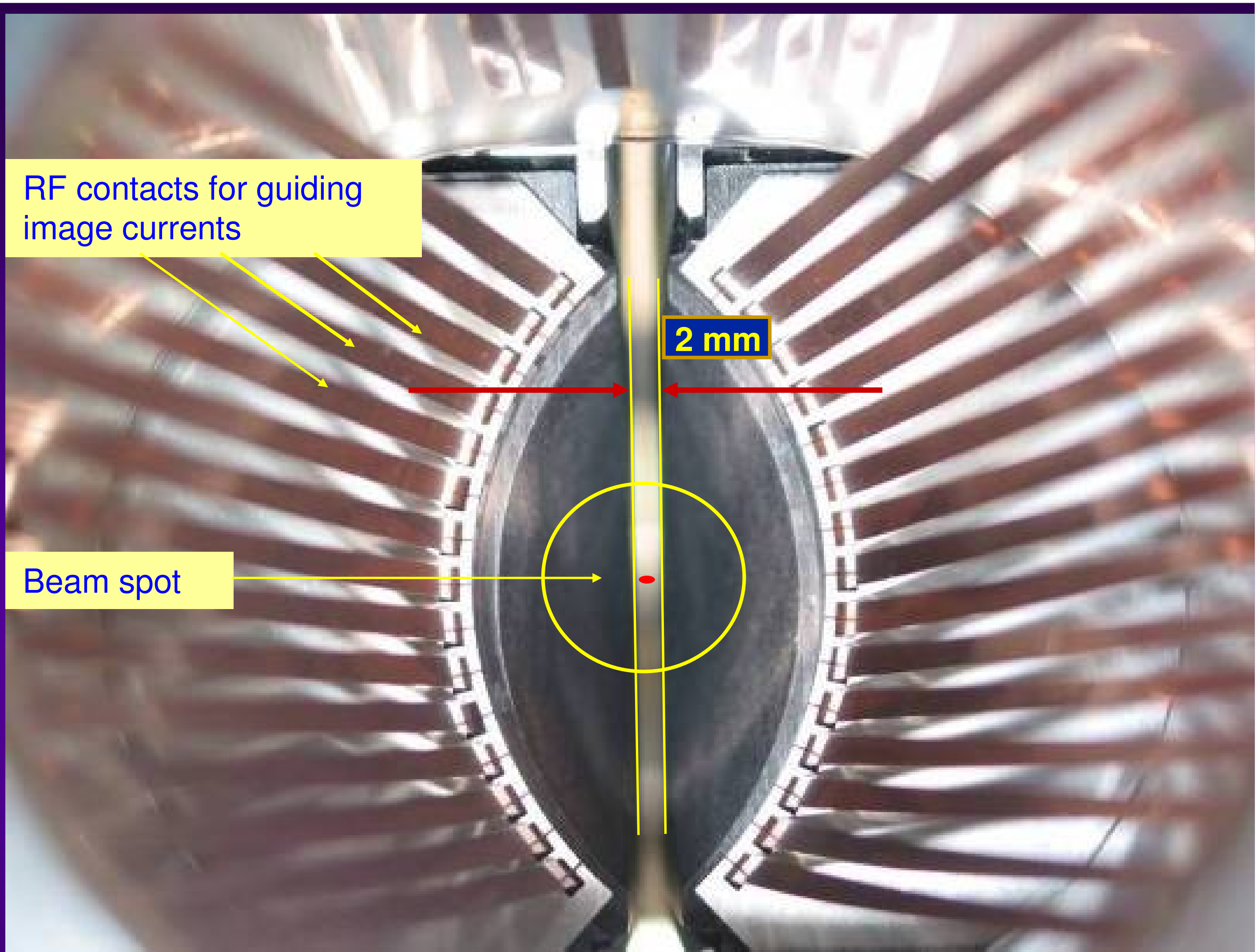
eight long straight section (about 700 m long)

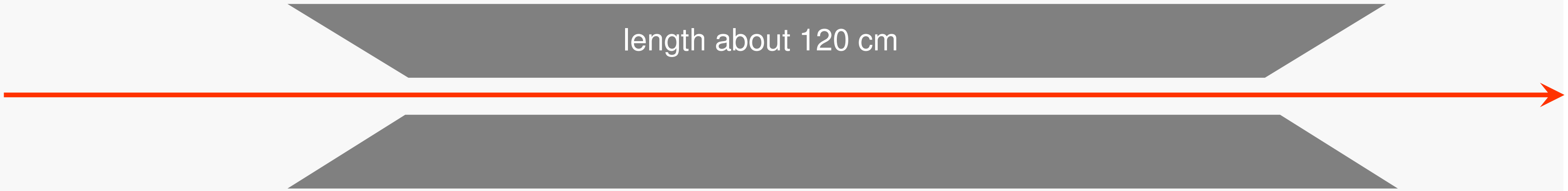


View of a two sided collimator

for LHC

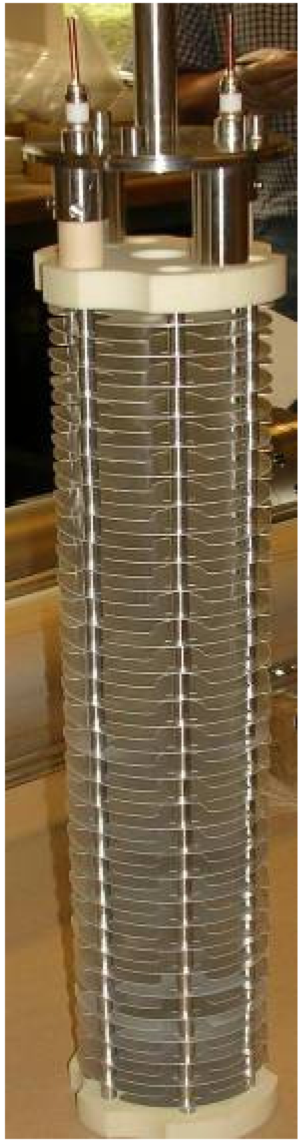
about 100 collimators are installed



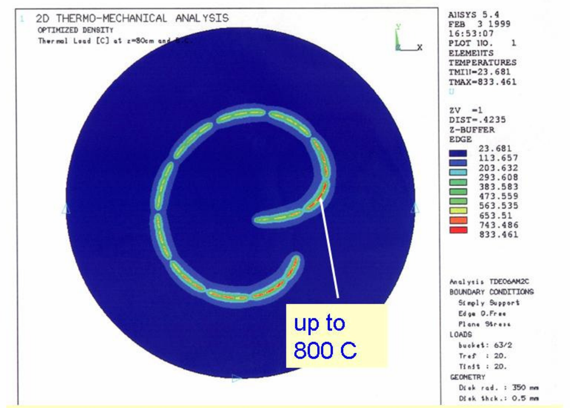


Beam Loss Monitors

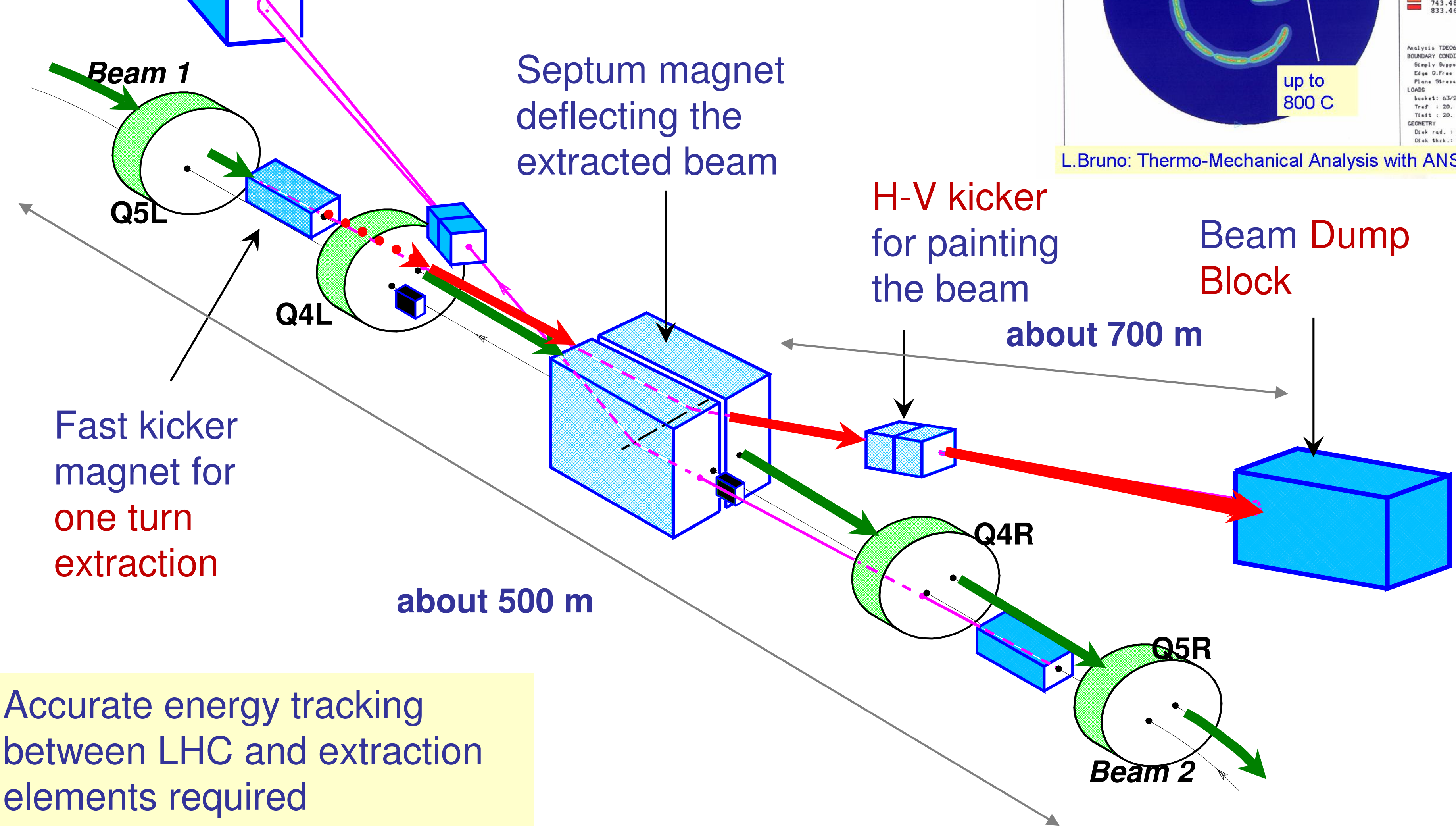
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are ~3600 chambers distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !



Schematic layout of LHC beam dumping system



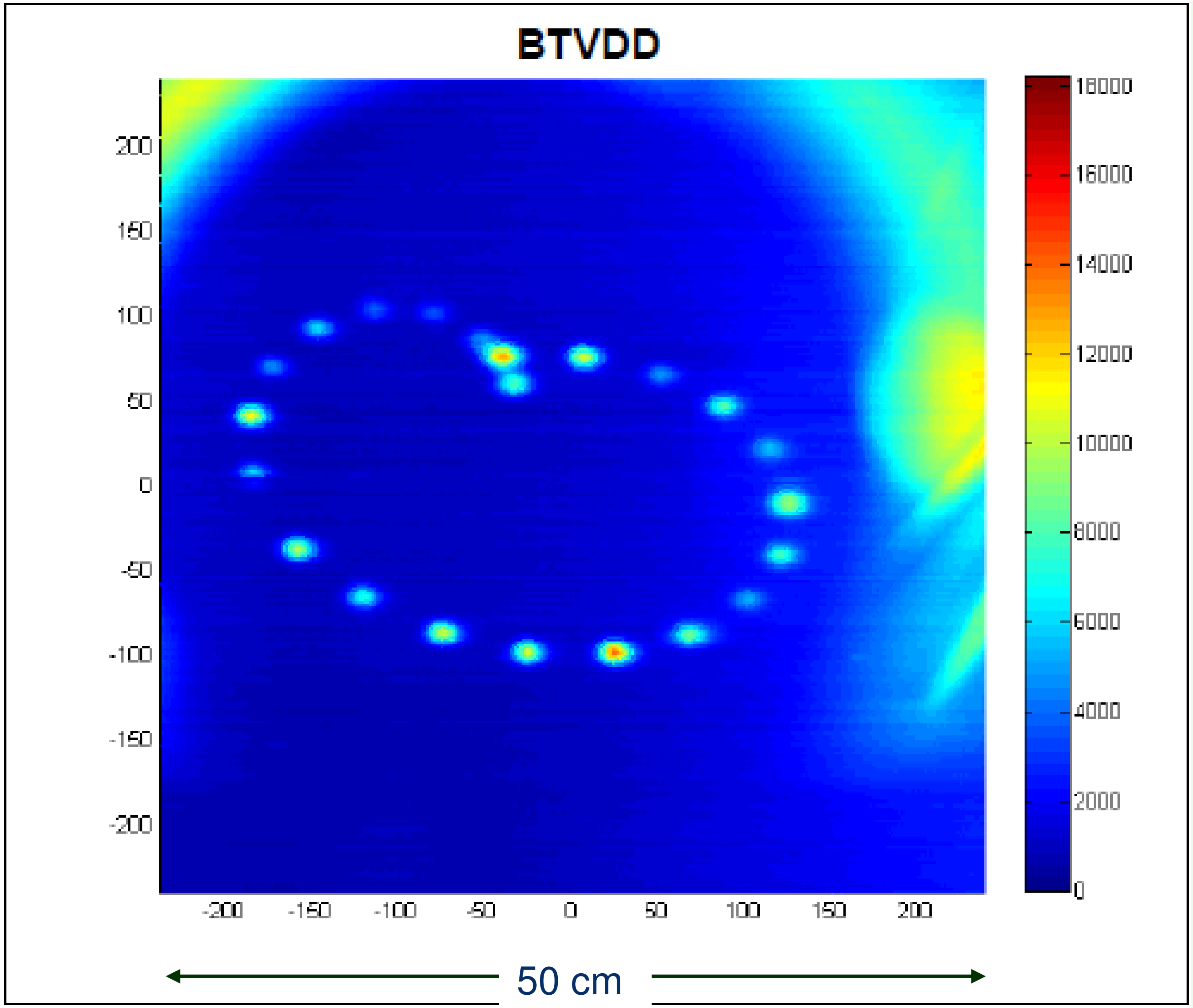
L.Bruno: Thermo-Mechanical Analysis with ANSYS



Accurate energy tracking between LHC and extraction elements required

LHC beam dumping system

Beam dump



- Screen in front of the beam dump block
- Each light dot shows the passage of one proton bunch traversing the screen
- Each proton bunch has a different trajectory, to better distribute the energy across a large volume

Some examples for failure from LHC

Failures: examples for LHC

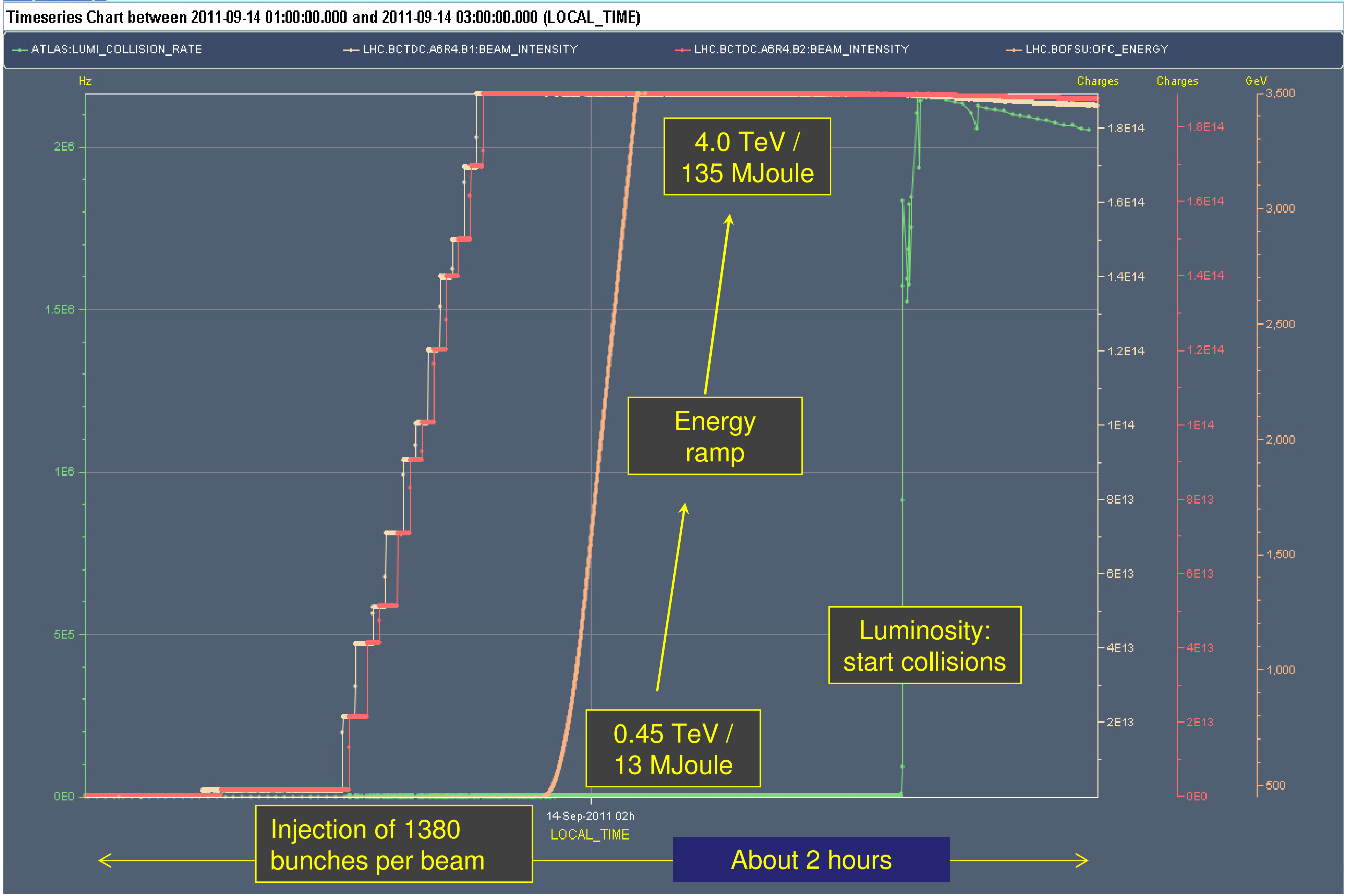
Assume that two 100 MJoule beams (= 2*25 kg TNT) are circulating with the speed of light through the 56 mm diameter vacuum chamber and 2 mm wide collimators

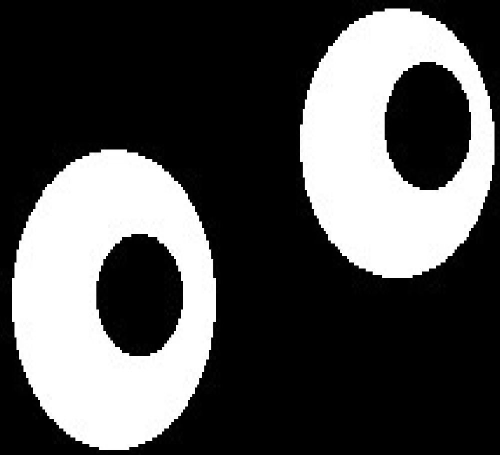
1. Suddenly the AC distribution for CERN fails – no power!
2. An object falls into the beam

Assume we injection beams for the next fill…..

3. Serious failure during injection – the injection kicker fails

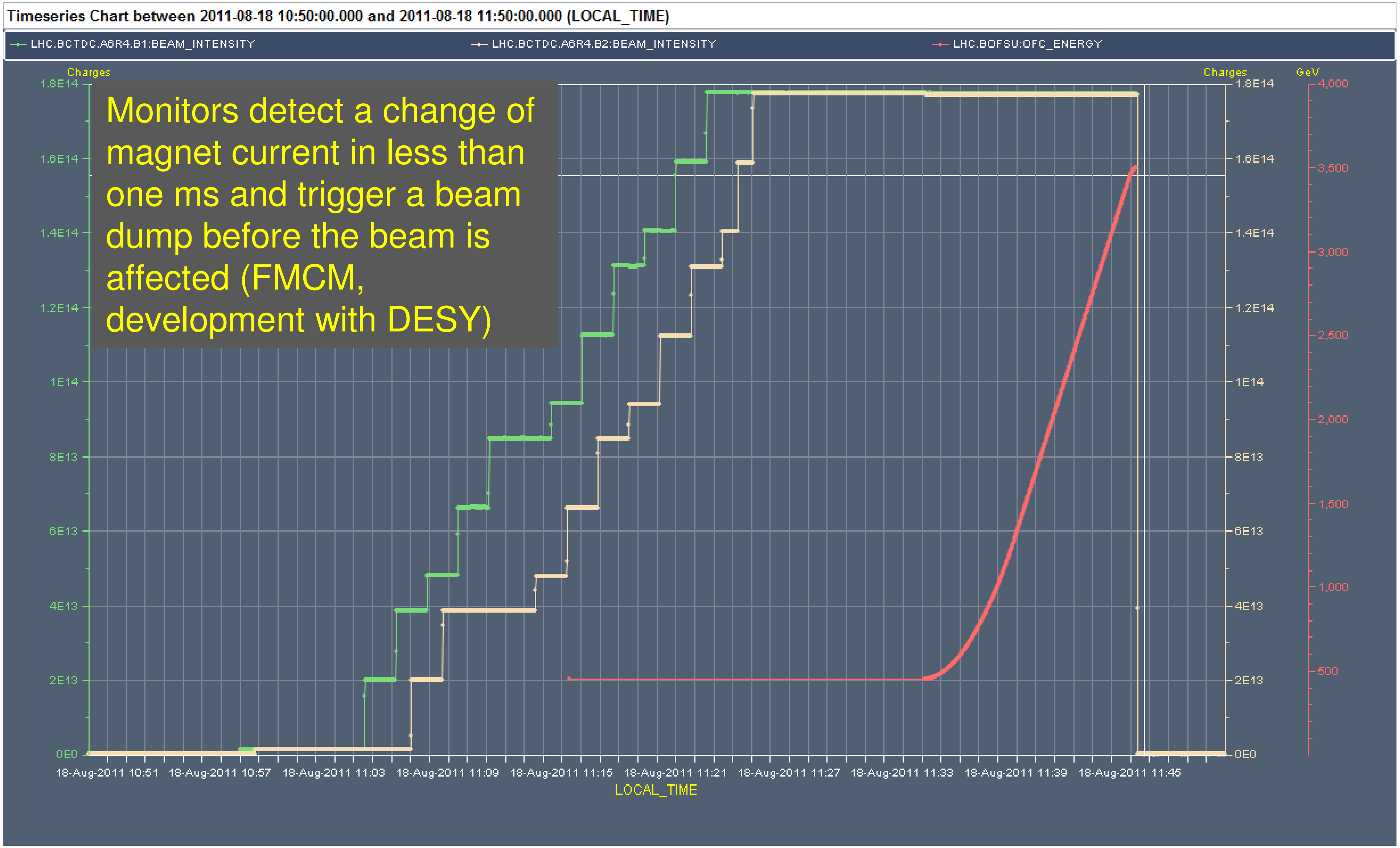
LHC from injection to collisions





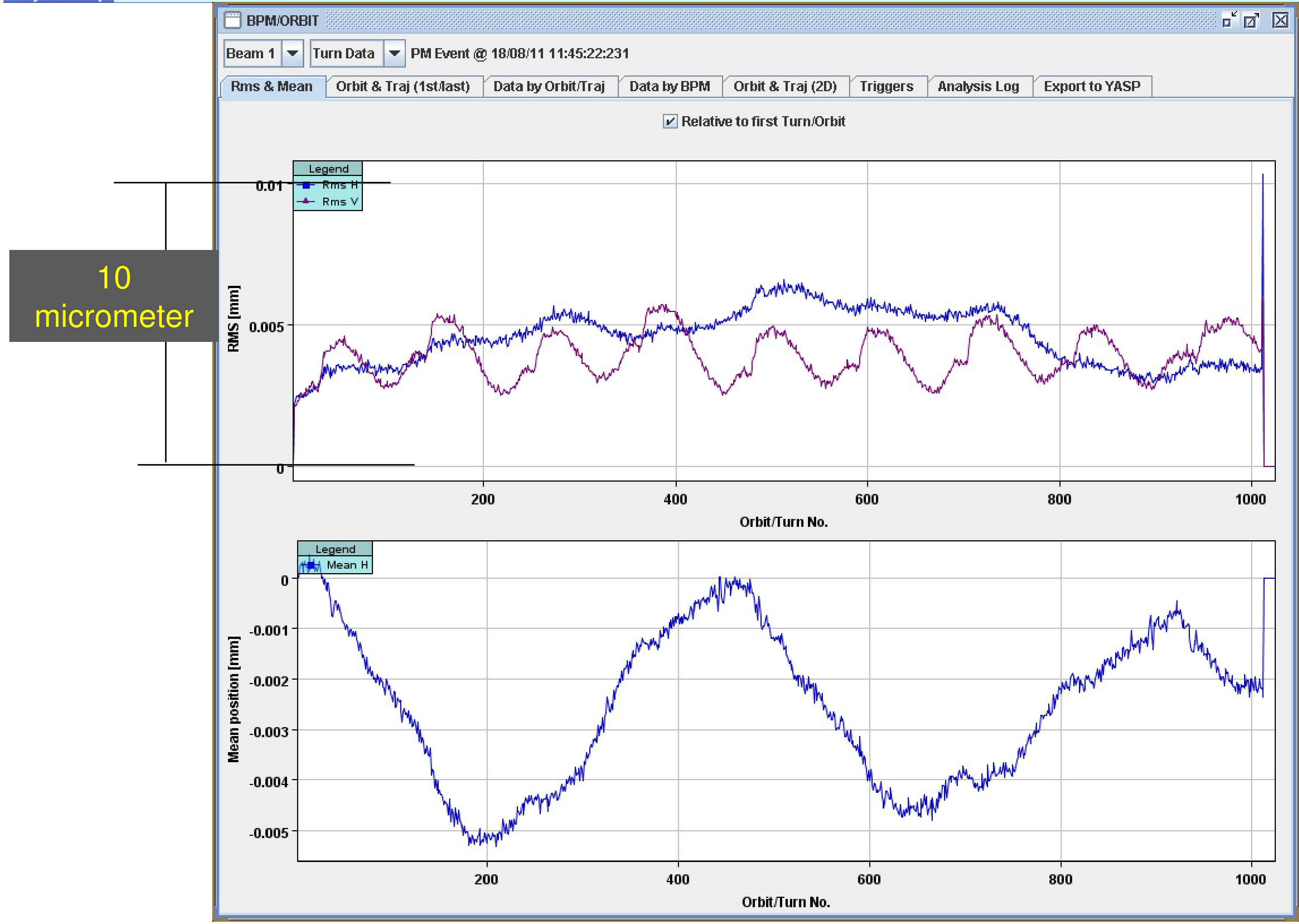
1. Suddenly the AC distribution for CERN fails – no power for LHC!

Total power cut at LHC - 18 August 2011, 11:45



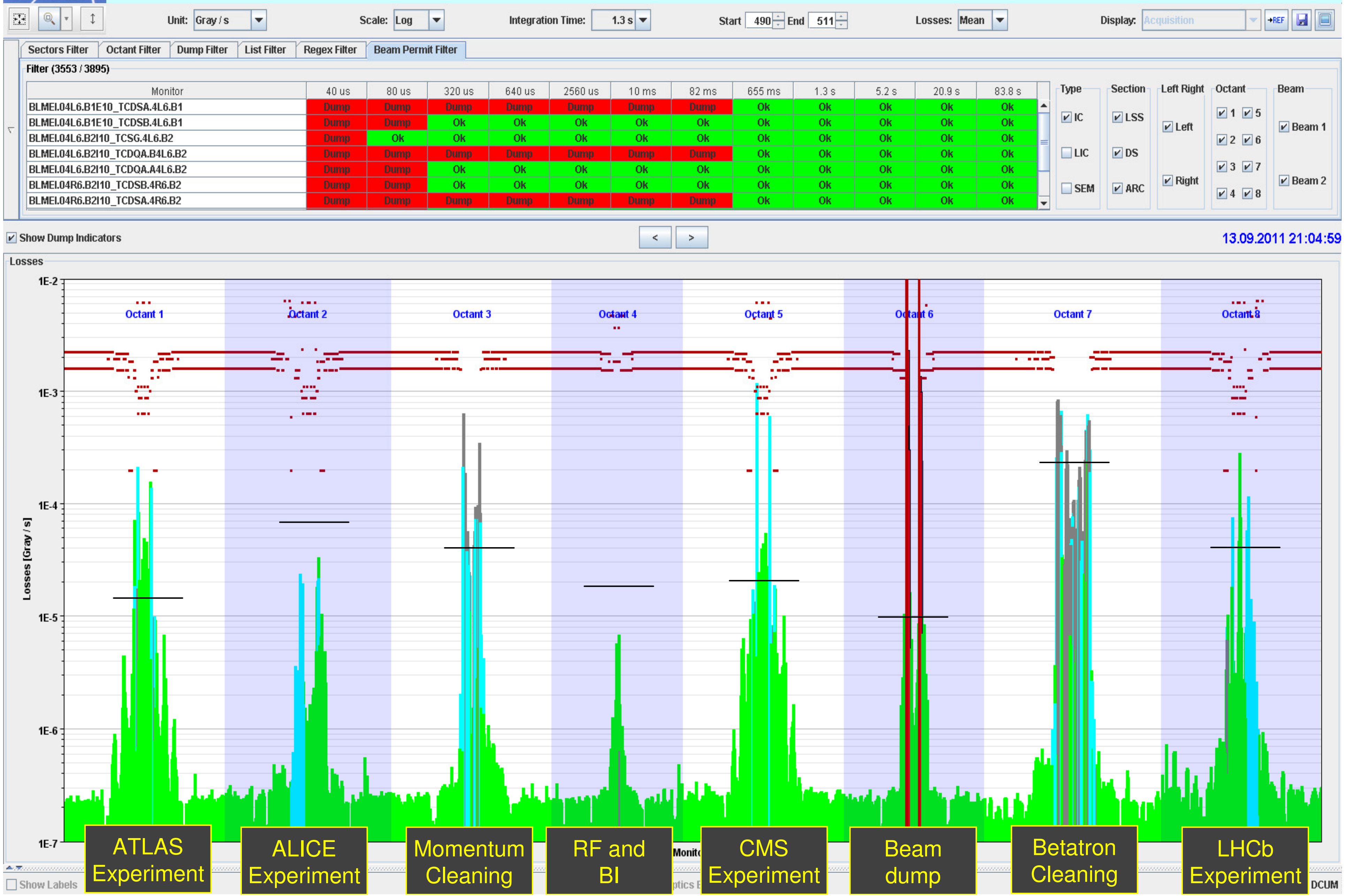
Monitors detect a change of magnet current in less than one ms and trigger a beam dump before the beam is affected (FMCM, development with DESY)

Orbit for last 1000 turns before power cut

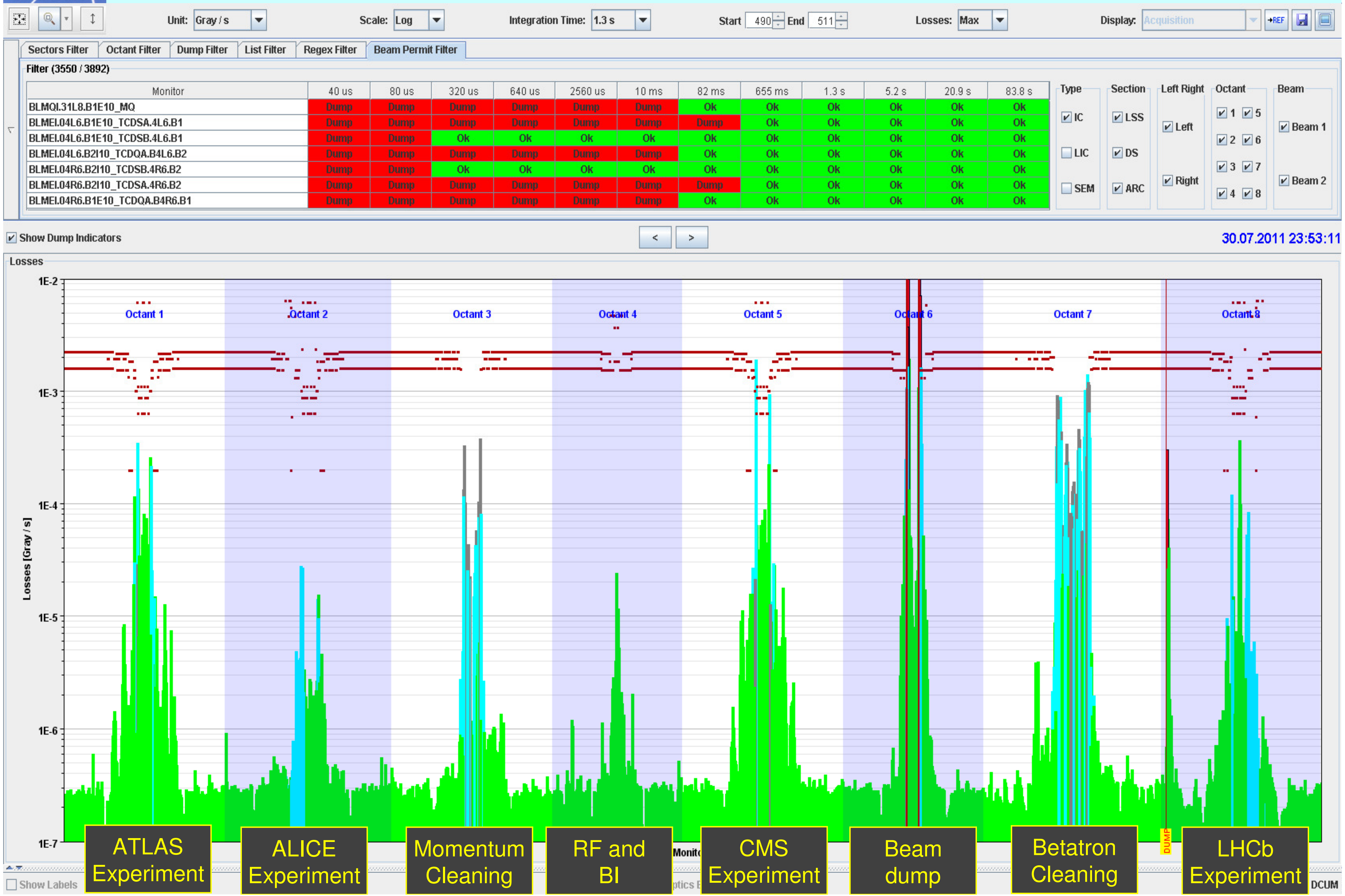


2. An object falls into the beam

Continuous beam losses during collisions

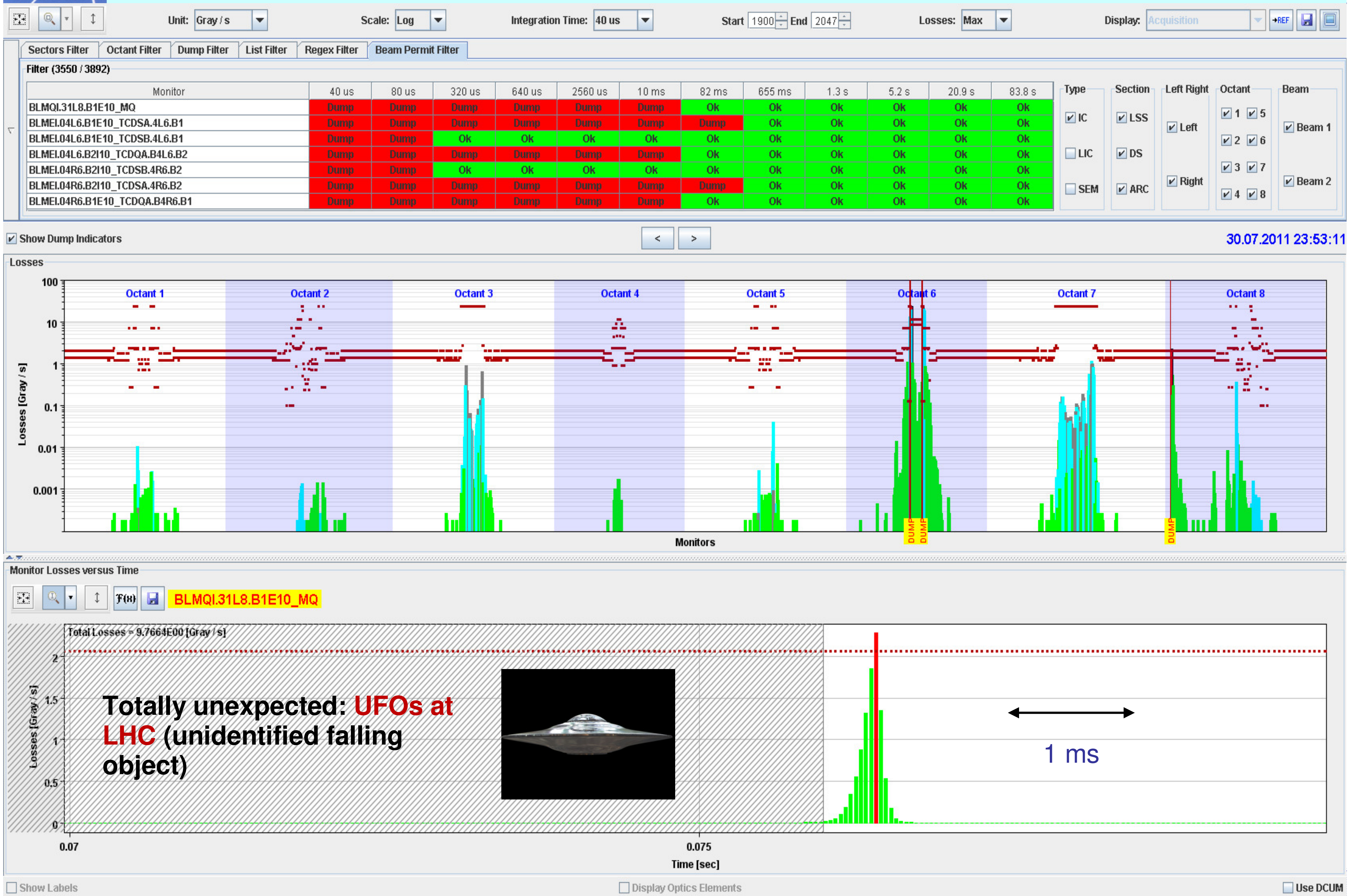


Accidental beam losses during collisions



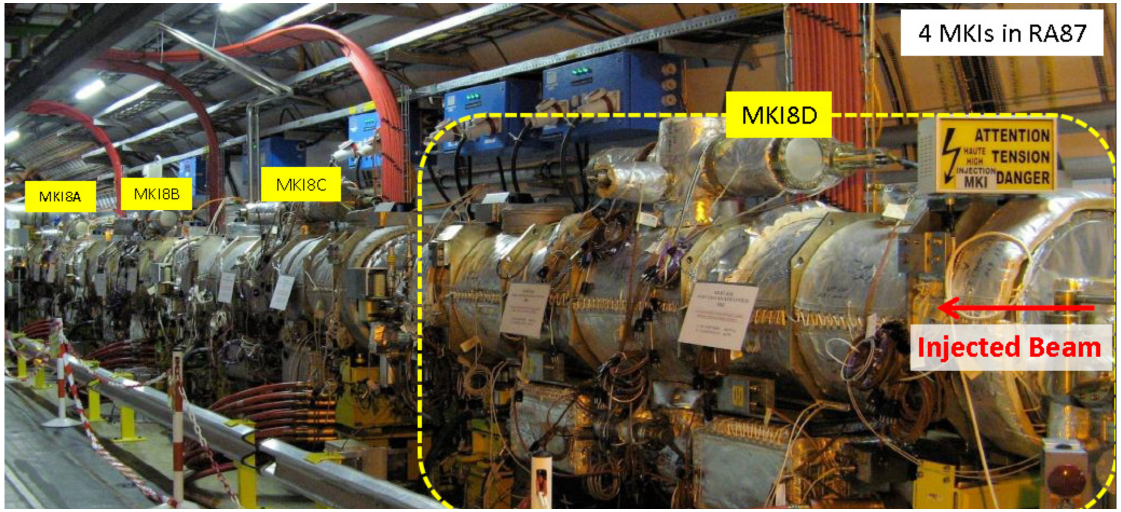
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B1E10_TCDQA.B4R6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok

Zoom one monitor: beam loss as a function of time



Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B1E10_TCDQA.B4R6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok

Totally unexpected: UFOs at LHC (unidentified falling object)



3. Serious failure during injection – the injection kicker fails

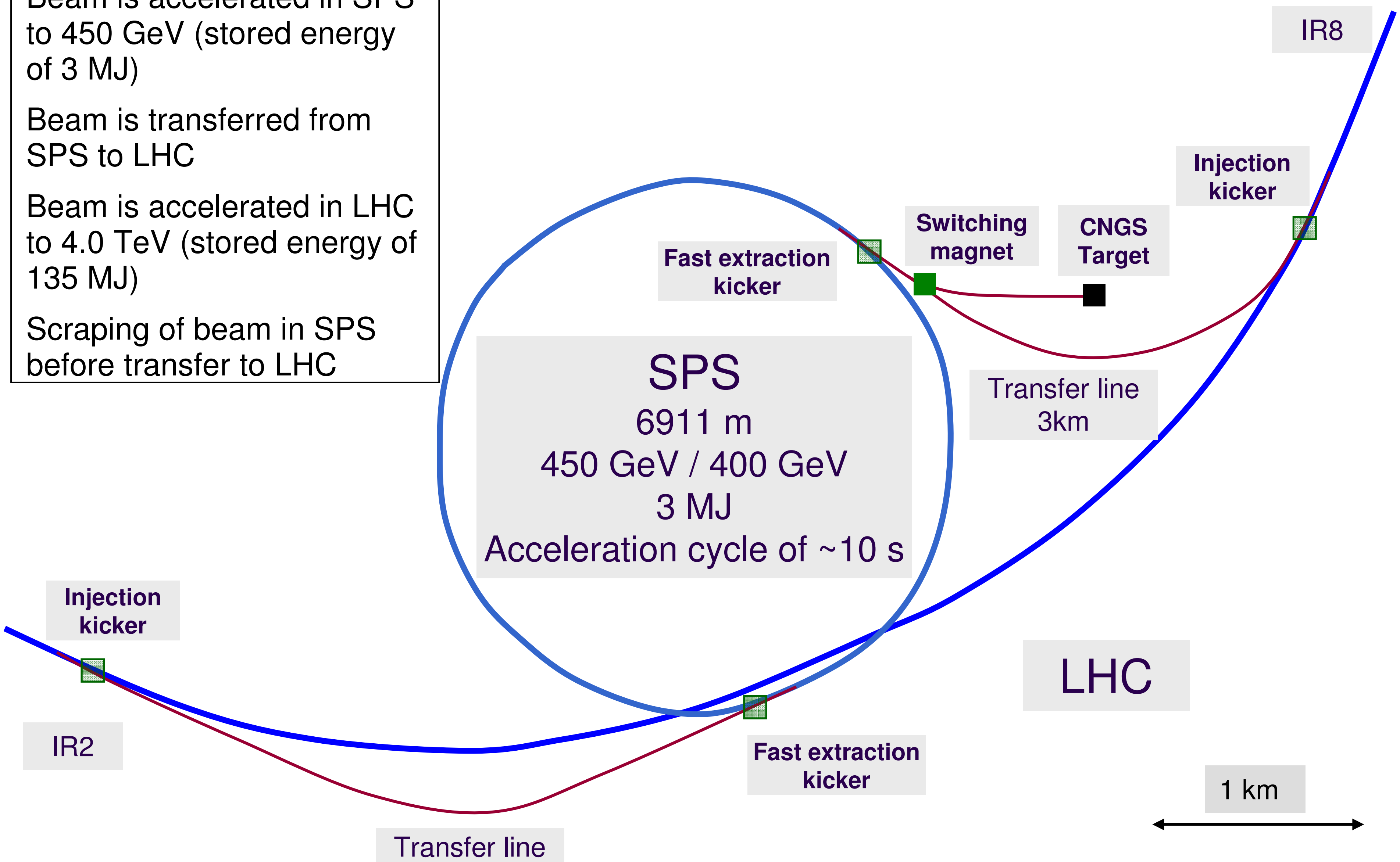
SPS, transfer line and LHC

Beam is accelerated in SPS to 450 GeV (stored energy of 3 MJ)

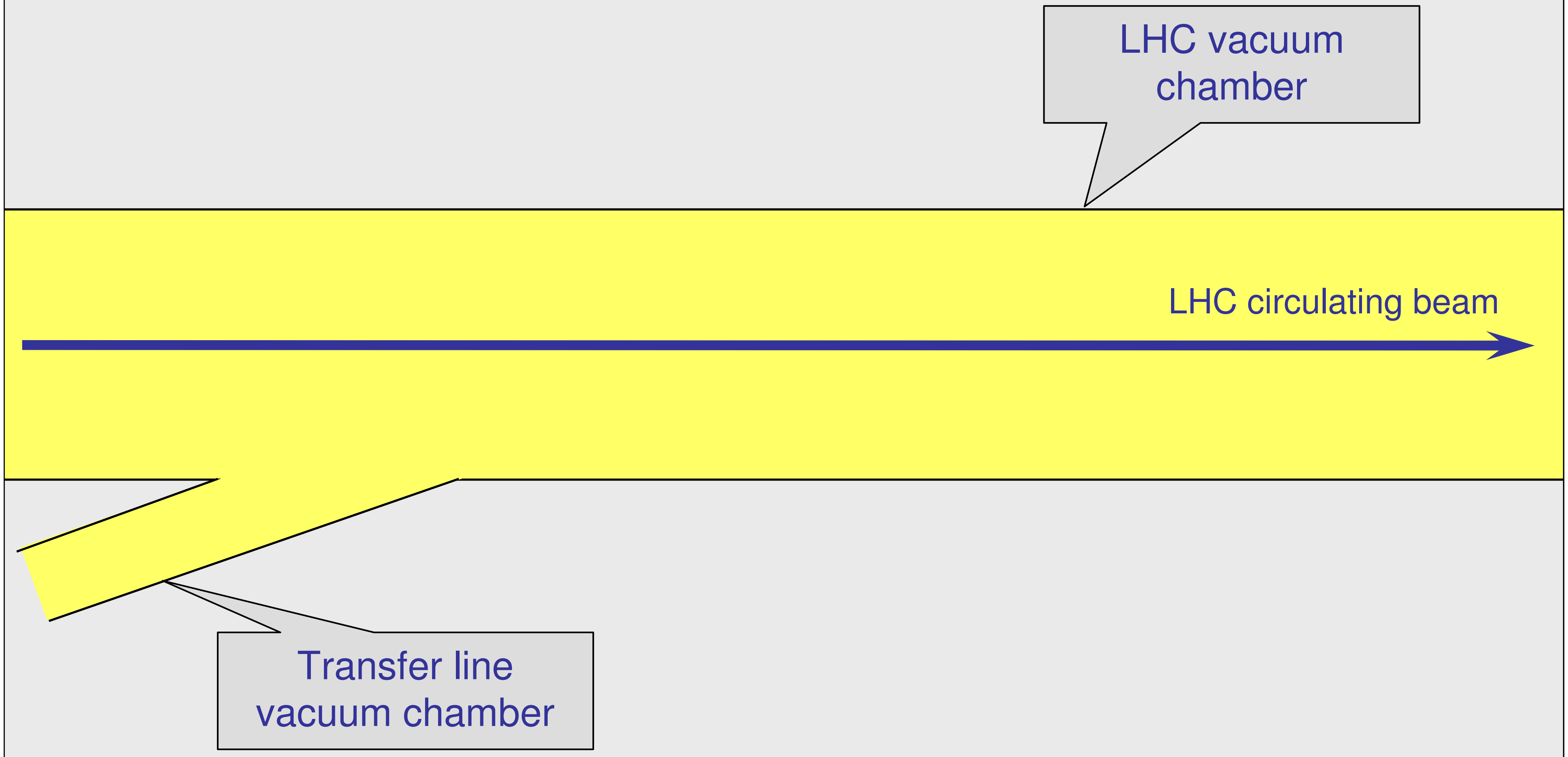
Beam is transferred from SPS to LHC

Beam is accelerated in LHC to 4.0 TeV (stored energy of 135 MJ)

Scraping of beam in SPS before transfer to LHC

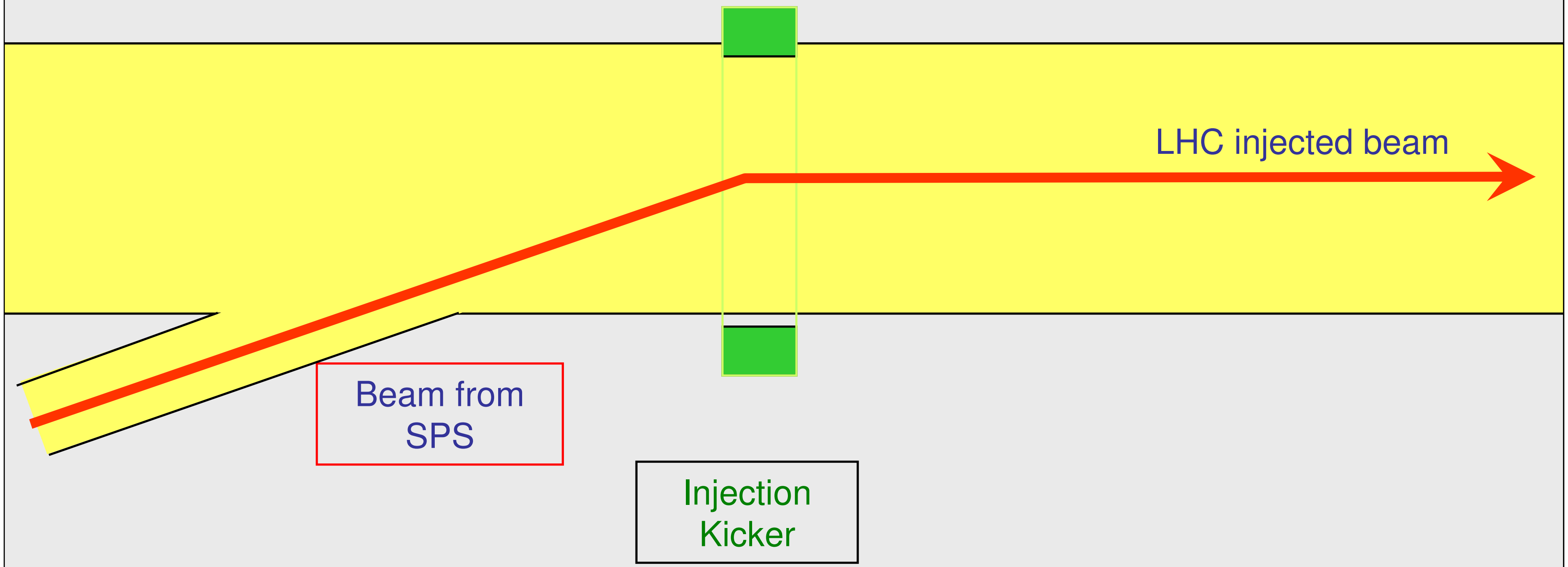


Protection at injection



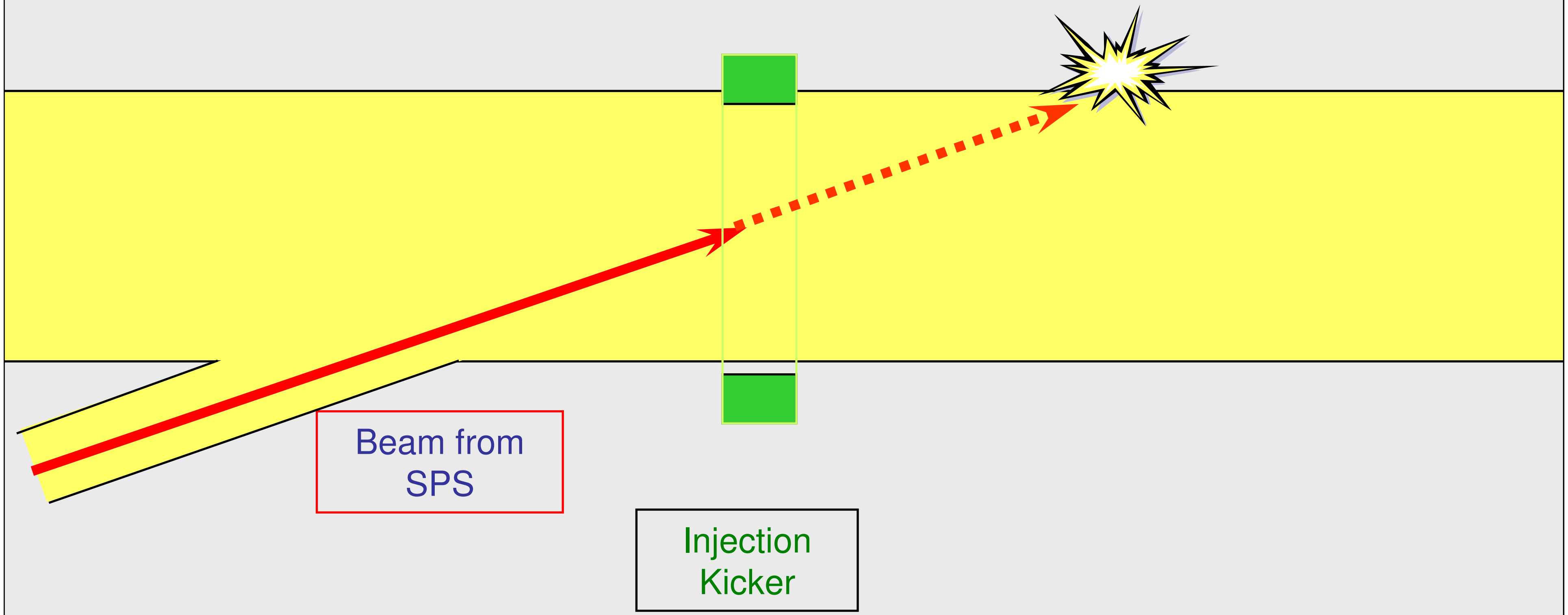
Circulating beam in LHC

Protection at injection



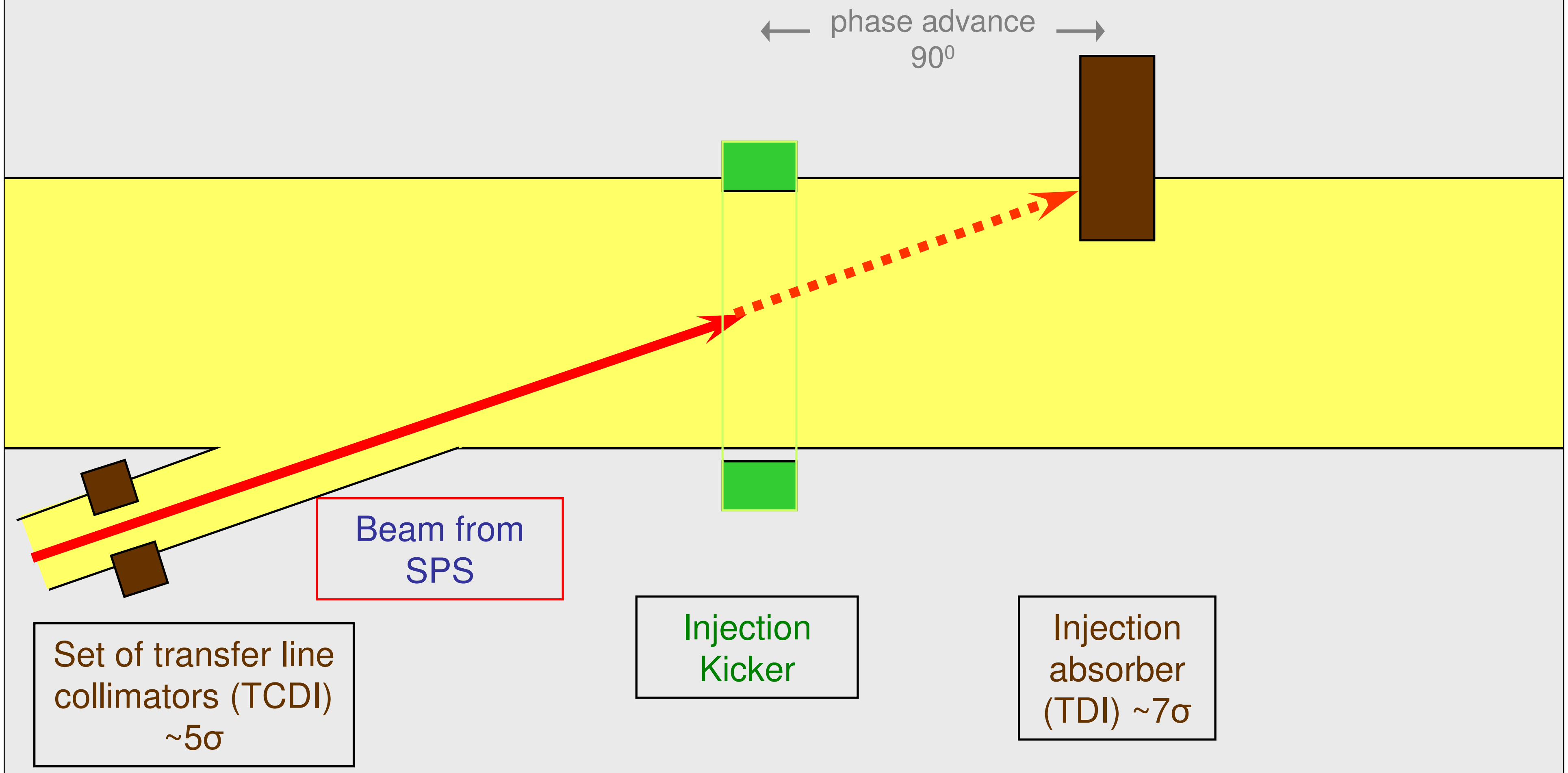
Beam injected from SPS and transfer line

Protection at injection



Kicker failure (no kick)

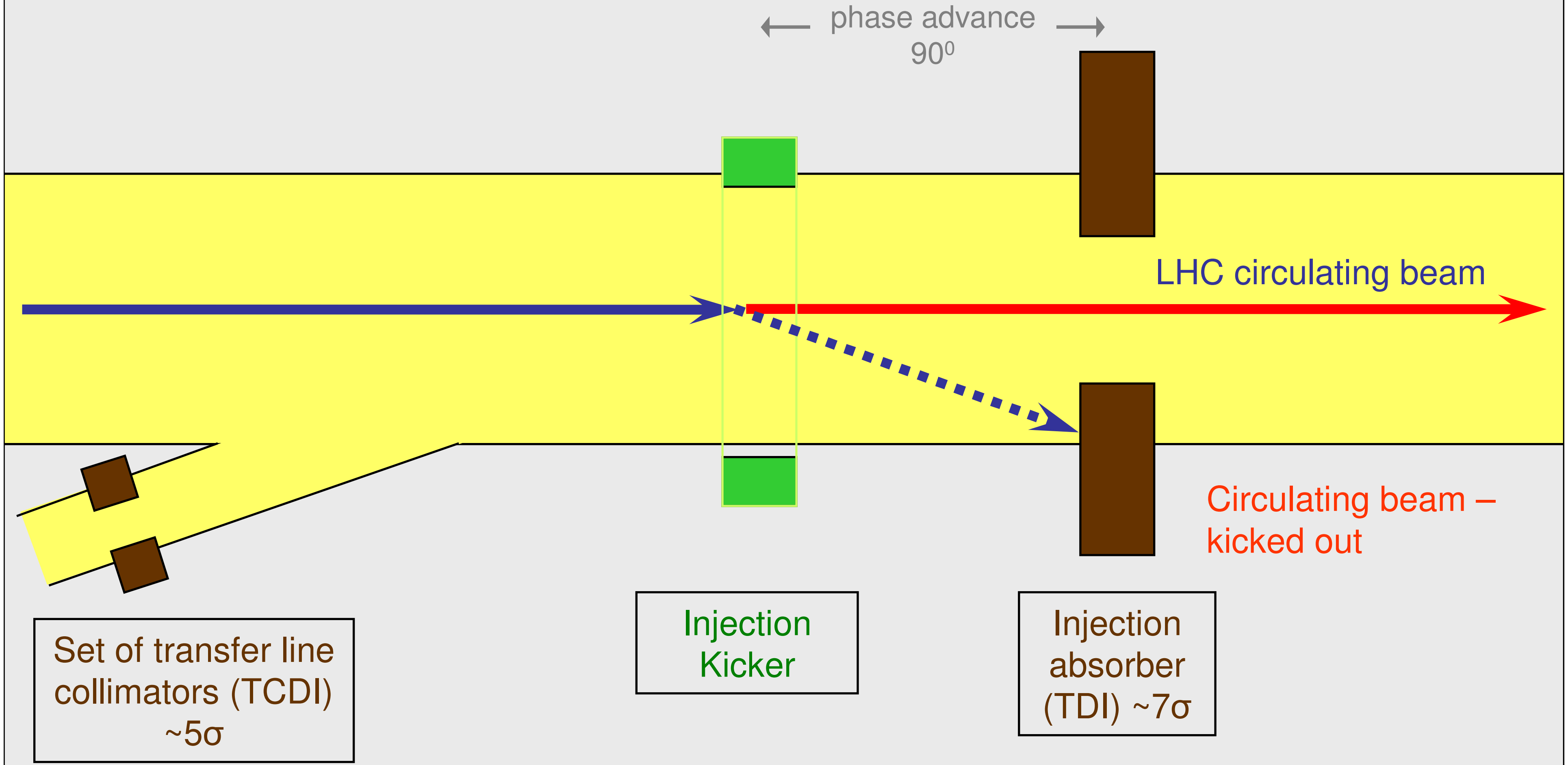
Protection at injection



Beam absorbers take beam in case of kicker misfiring

Transfer line collimators ensure that incoming beam trajectory is ok

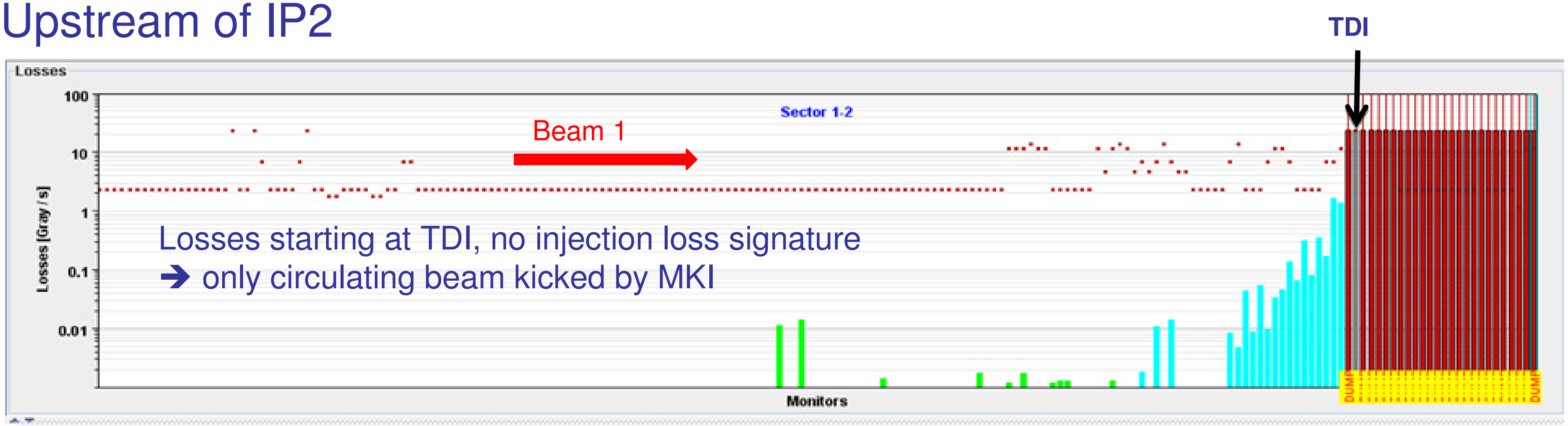
Protection at injection



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

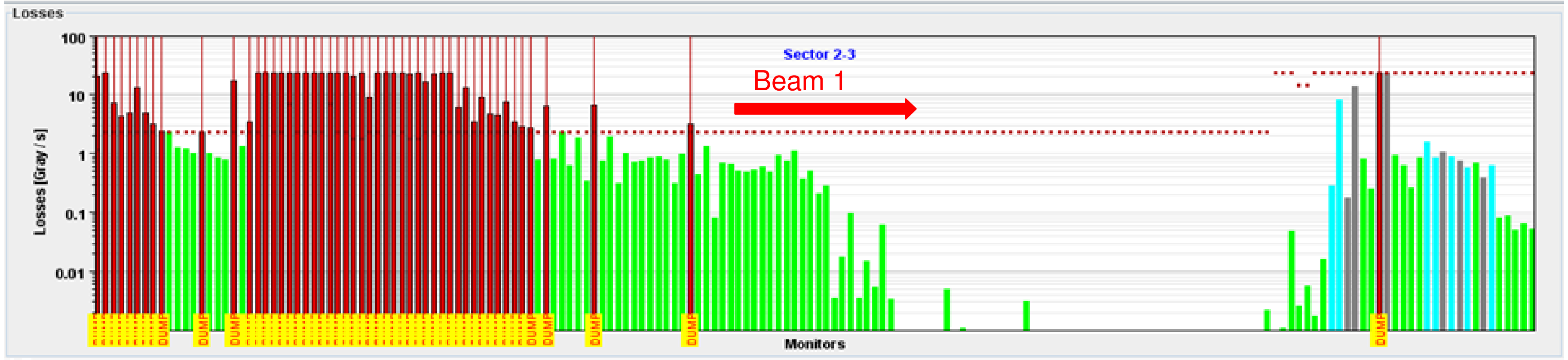
173 bunches grazing incident on injection absorber

Upstream of IP2



Downstream of IP2

Insertion losses: 3 magnets quenched (D1.L2, MQX.L2, D2.R2)



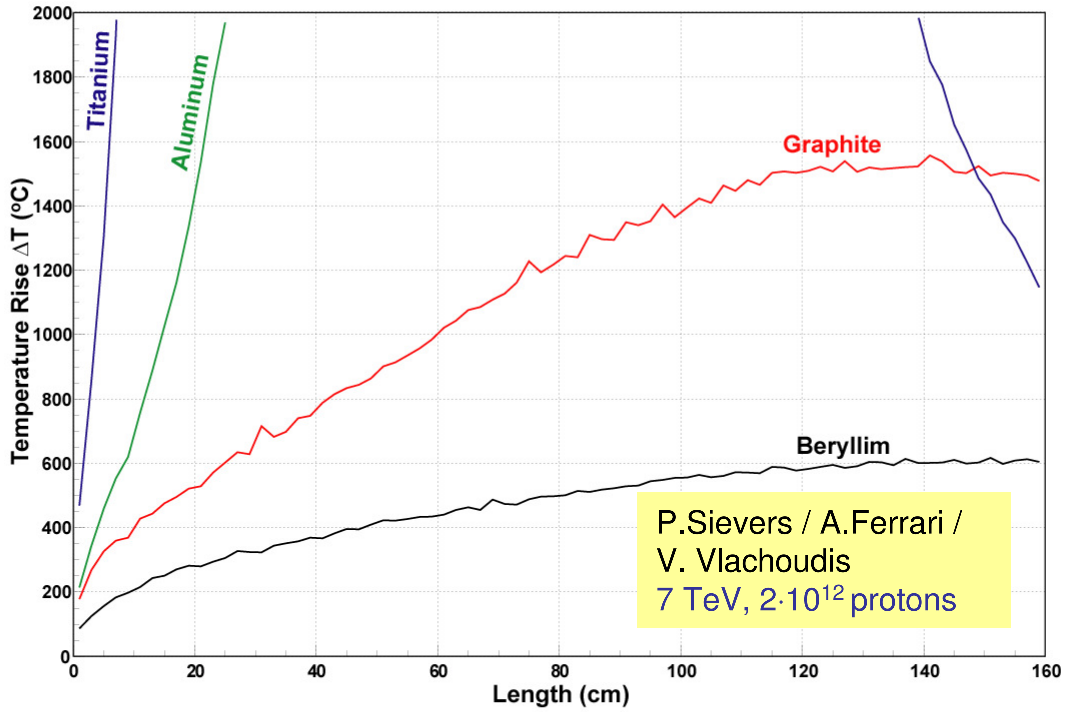
In comparison to flashover event of April 18th in P8 (LMC 20/04/11), cleaner in arc less magnet quenches (3), ALICE SDD permanent effect, open MCSOX.3L2 circuit

C.Bracco

Collimators, beam absorber and beam cleaning

Collimator material

- Full beam impact at injection: metal absorbers would be destroyed
- Other materials for injection absorber preferred, graphite or boron nitride for the injection absorber
- In case of a partial kick (can happen), the beam travels to collimators further down
- For collimators close to the beam, metal jaws would be destroyed
- Other materials for collimators close to the beam are preferred (carbon – carbon)



Collimation: why so many?

Answer A:

•For a transfer line or a linear accelerator, many collimators are required to remove particles at all phases

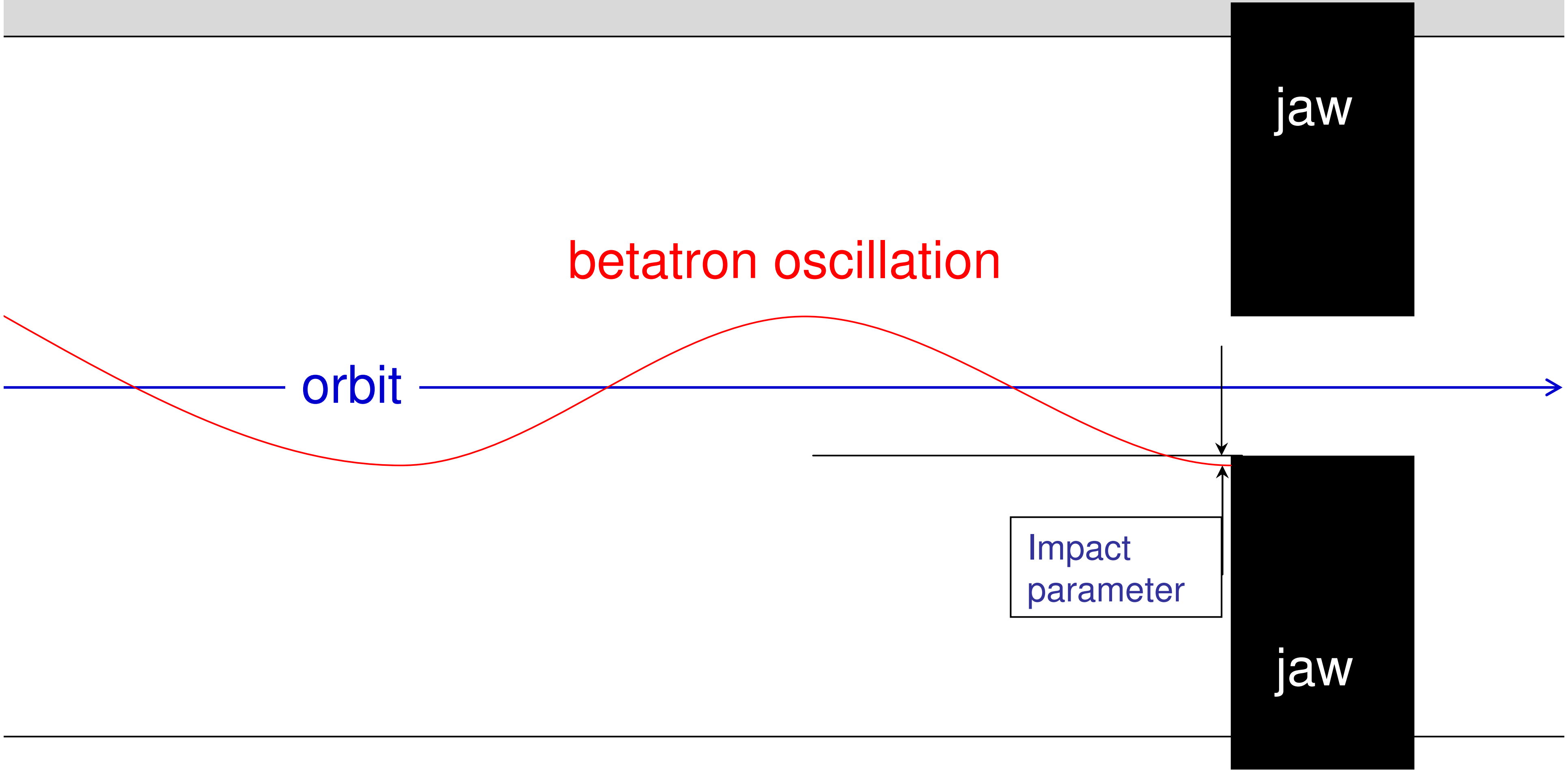
Answer B:

•Cite: "It is not possible to stop a high energy particle, it is only possible to make them mad"

•Collimators cannot stop a high energy particle

•The particle impact on a collimator jaw is very small, in the order of microns or even less

Collimation: why so many?



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•The particle impact on a collimator jaw is very small, in the order of microns or even less

•Particles scatter….. depends on particle type, energy and impact on collimator jaw

•Staged collimation system in a ring and in a transfer line

Betatron beam cleaning

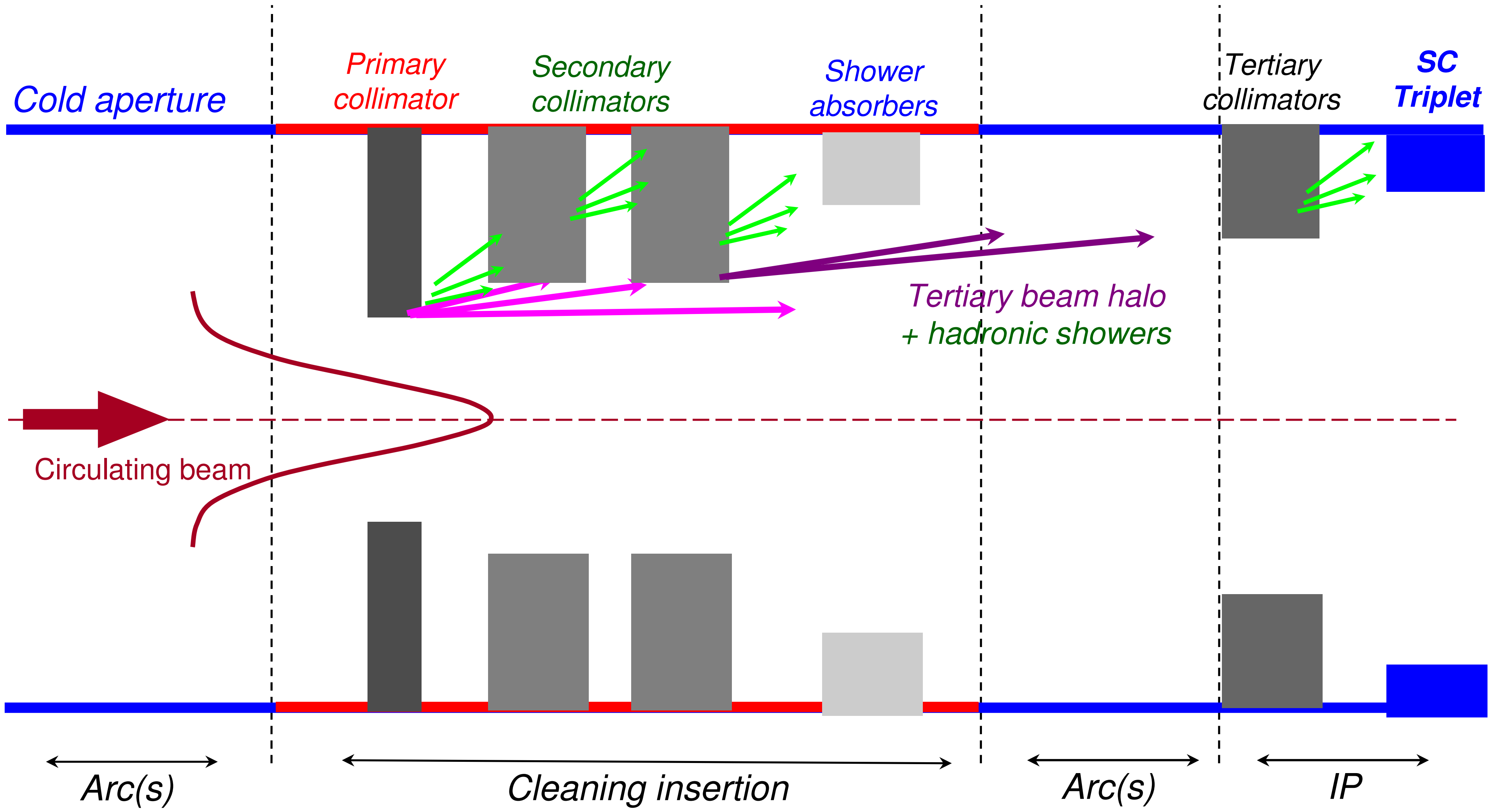
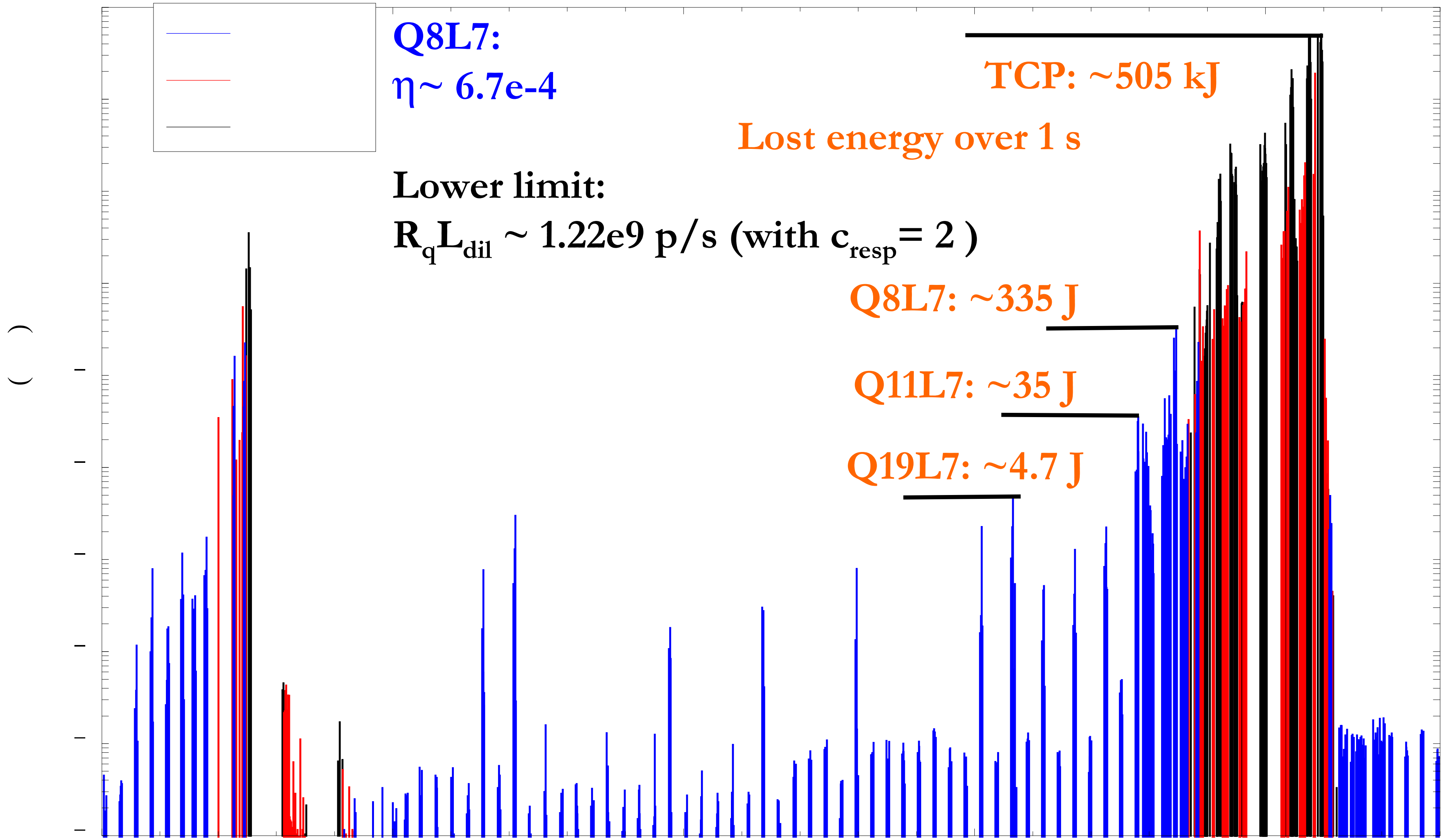


Illustration drawing

Measurement: 500 kJ proton losses at primary collimators (loss rate: 9.1e11 p/s) – IR7

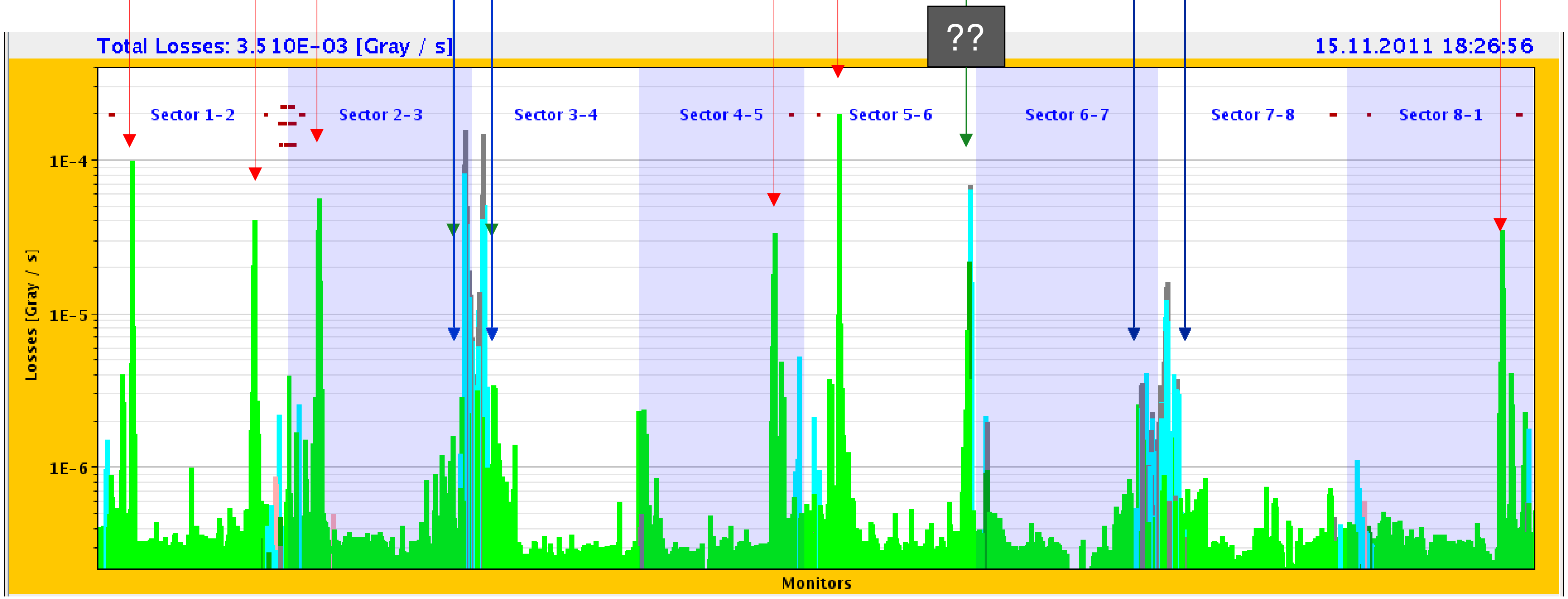


Losses during Pb-Pb Collisions in 2011

Bound-free pair production secondary beams from IPs

IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators

Losses from collimation inefficiency, nuclear processes in primary collimators



Limits efficiency of ion collimation, to about 100 times worse than protons

J.M. Jowett

Wrap up on Machine Protection

LHC strategy for machine protection

• Definition of aperture by collimators.	**Beam Cleaning System**
• Early detection of failures for equipment acting on beams generates dump request, possibly before the 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 extract the 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**

Accidental beam losses: Risks and protection

- Protection is required since there is some risk
- Risk = probability of an accident (in number of accidents per year)
  • consequences (in Euro, downtime, radiation dose to people)
- Probability of an accidental beam loss
  – What are the failure modes the lead to beam loss into equipment (there is an practical infinite number of mechanisms to lose the beam)?
  – What is the probability for the most likely failures?
- Consequences of an accidental beam loss
  – Damage to equipment
  – Downtime of the accelerator for repair (spare parts available?)
  – Activation of material, might limit operation and lead to downtime since access to equipment is delayed
- The higher the risk, the more protection becomes important

Some design principles 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
- Demonstrate safety / availability / reliability
  - use established methods to analyse critical systems and to predict failure rate
- Managing interlocks
  - disabling of interlocks is common practice **(keep track !)**
  - LHC: masking of some interlocks possible for low intensity / low energy beams

Beam instrumentation for machine protection

- Beam Loss Monitors
  - stop beam operation in case of too high beam losses
  - monitor beam losses around the accelerator (full coverage?)
  - could be fast and/or slow (LHC down to 40 μs)
- Beam Position Monitors
  - ensuring that the beam has the correct position
  - in general, the beam should be centred in the aperture
  - for extraction: monitor extraction bump using BPMs (redundant to magnet current)
- Beam Current Transformers
  - if the transmission between two locations of the accelerator is too low (=beam lost somewhere): stop beam operation
  - if the beam lifetime is too short: dump beam
- Beam Size Monitors
  - if beam size is too small could be dangerous for windows, targets, …

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

....is a fascinating subject…at least as long as nothing breaks

Acknowledgement

- Acknowledgements to many colleagues involved in LHC protection and operation
  - Beam instruments
  - Collimator and beam absorbers
  - Injection and beam dump
  - Interlocks
  - Operation

- Some colleagues concentrate on aspects of LHC as ion-ion and ion-proton collider
  - Ion operation in LHC is different from proton operation
  - Therefore particular thanks to Roderik Bruce and John Jowett

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Thank you very much for your attention