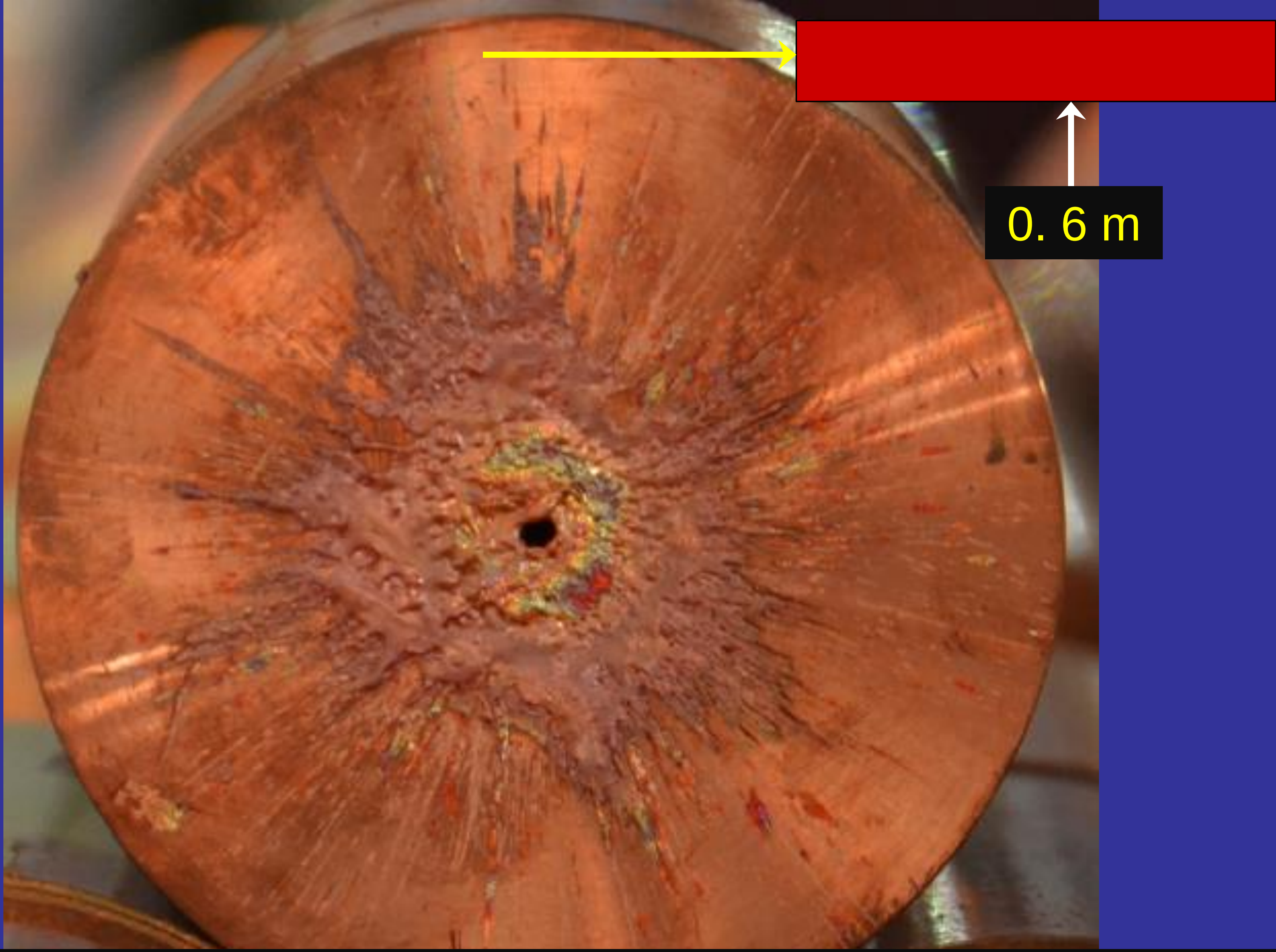
Machine Protection

Rüdiger Schmidt, CERN

CAS on Intensity Limitations in Particle Beams

Geneva, November 2015



Copper part of a target at a depth of 0.6 m, irradiated with one SPS beam pulse (1.5 MJ, 7 µs, 450 GeV, 0.2 mm)

Outline

- Particle beams and damage mechanisms
- Hazards and Risks
- Hazards when operating with particle beams
- Worst case scenario
- Machine Protection and Interlocks

See also material in Joint International Accelerator School on
"Beam Loss and Accelerator Protection"
http://uspas.fnal.gov/programs/JAS/JAS14.shtml Proceeding to be published by 2016

Protection from Energy and Power

- **Risks** come from **Energy** stored **in an accelerator** (Joule), and **Power** when **operating** an **accelerator** (Watt)
  - "Very powerful accelerator" … the power flow needs to be controlled
- Particle accelerators use **large amount of power** (few to many MW)
  - Where does the power go in case of failure?
- An **uncontrolled release** of energy or power flow can lead to **unwanted consequences**
  - Damage of equipment and loss of time for operation
  - Risk of activation of equipment when operating with particle beams

This is a particular **challenge** for complex systems such as **accelerators**

Direct energy transfer from beam to equipment

- Regular particle losses during operation
  - Particle losses due to residual gas
  - Particle losses due to collisions (in a collider)
  - Particles losses at the aperture (e.g. due to emittance growth and other effects)
  - Particle beams directed onto a target
- Accidental particle losses - due to a large number of possible failure mechanisms
  - Particles can be deflected into the aperture
  - Targets, collimators and beam dumps: beam characteristics not matching the target, e.g. beam size at a spallation target too small

Machine protection is essentially to prevent consequences of accidental beam losses

Indirect energy transfer from beam to equipment

- Power deposited by electromagnetic interaction between beam and environment (RF, beam instrumentation, vacuum chamber, kicker magnets, …)
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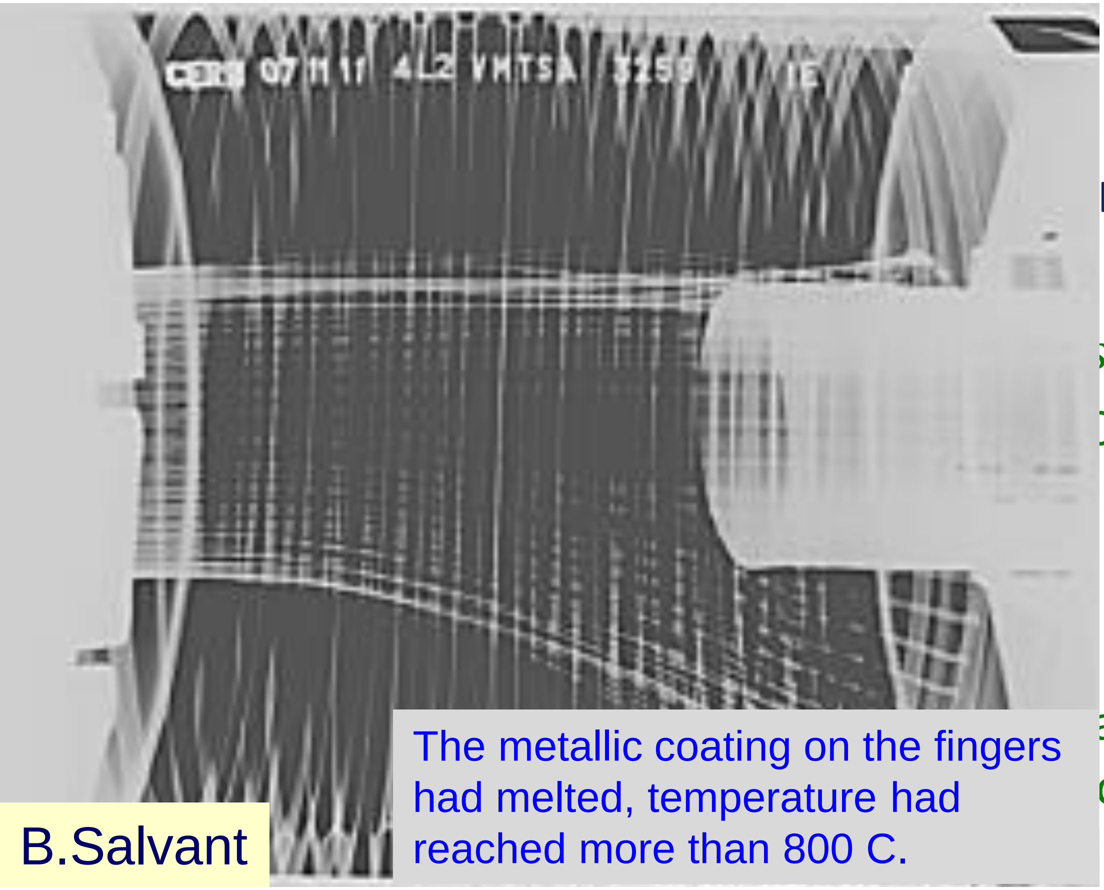


The metallic coating on the fingers had melted, temperature had reached more than 800 C.

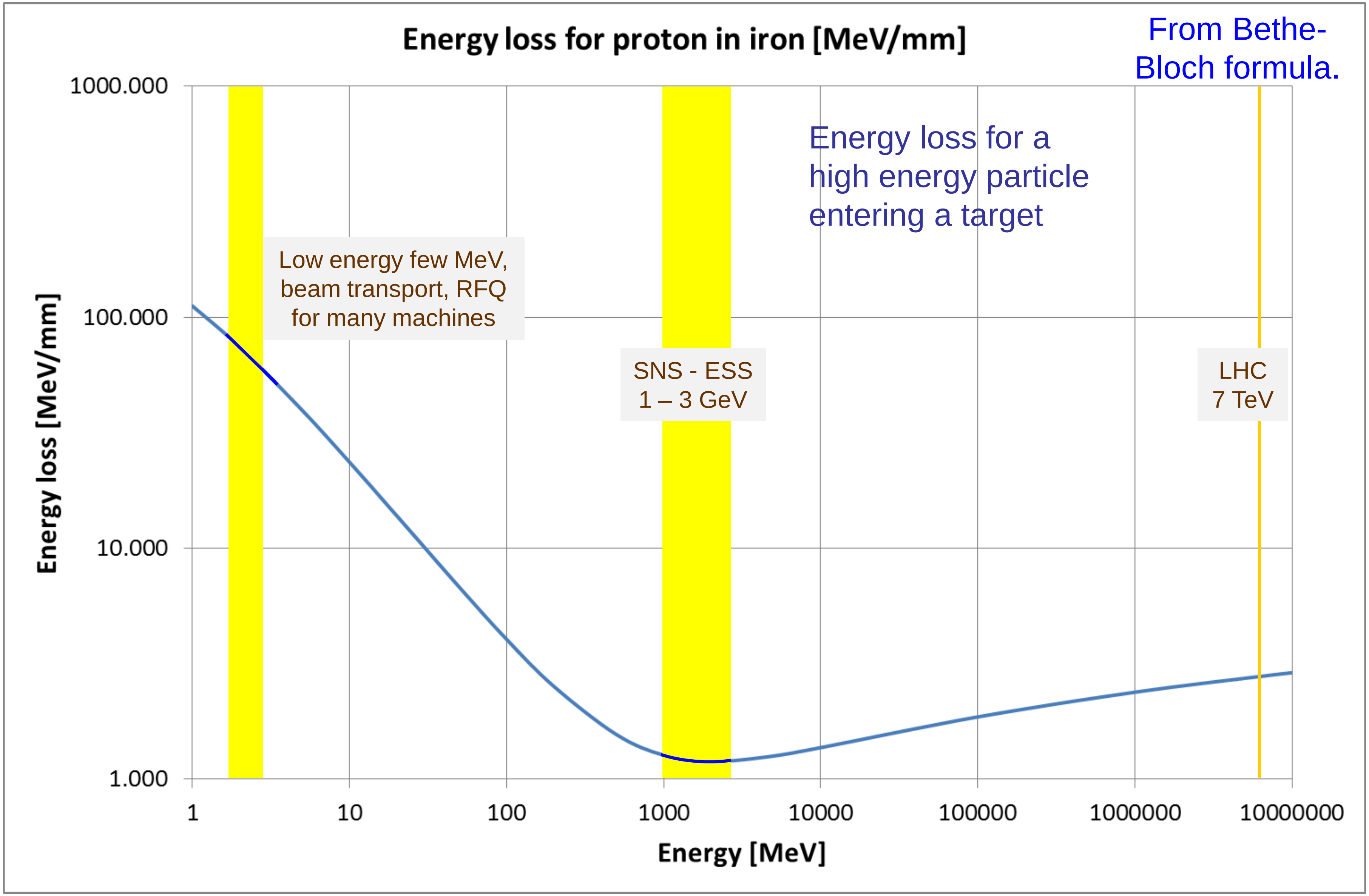
Particle losses and consequences

Beam loss and consequences

- Charged particles moving through matter interact with electrons of atoms in the material, exciting or ionizing the atoms => energy loss of traveling particle described by **Bethe-Bloch formula**.
- If the particle energy is high enough, it leads to particle cascades in materials, increasing the deposited energy
  - 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
  - Superconducting magnets could quench (beam loss of ~mJ to J)
  - Superconducting cavities performance degradation by some 10 J
  - Material can vaporise, melt, deform or lose its mechanical properties
  - Risk to damage sensitive equipment for less than one kJ, risk for damage of any structure for some MJ (depends on beam size)
  - Activation of material, risk for hand-on-maintenance
  - Single event upsets in electronics equipment

Energy loss: example for one proton in iron

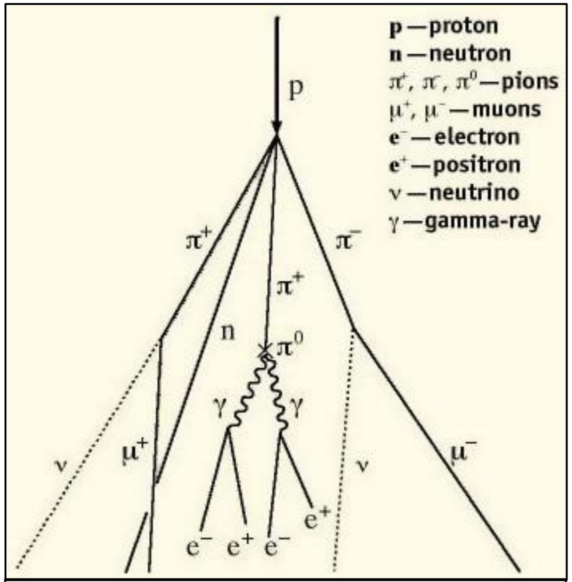
(stainless steel, copper very similar)



Heating of material with high energy protons

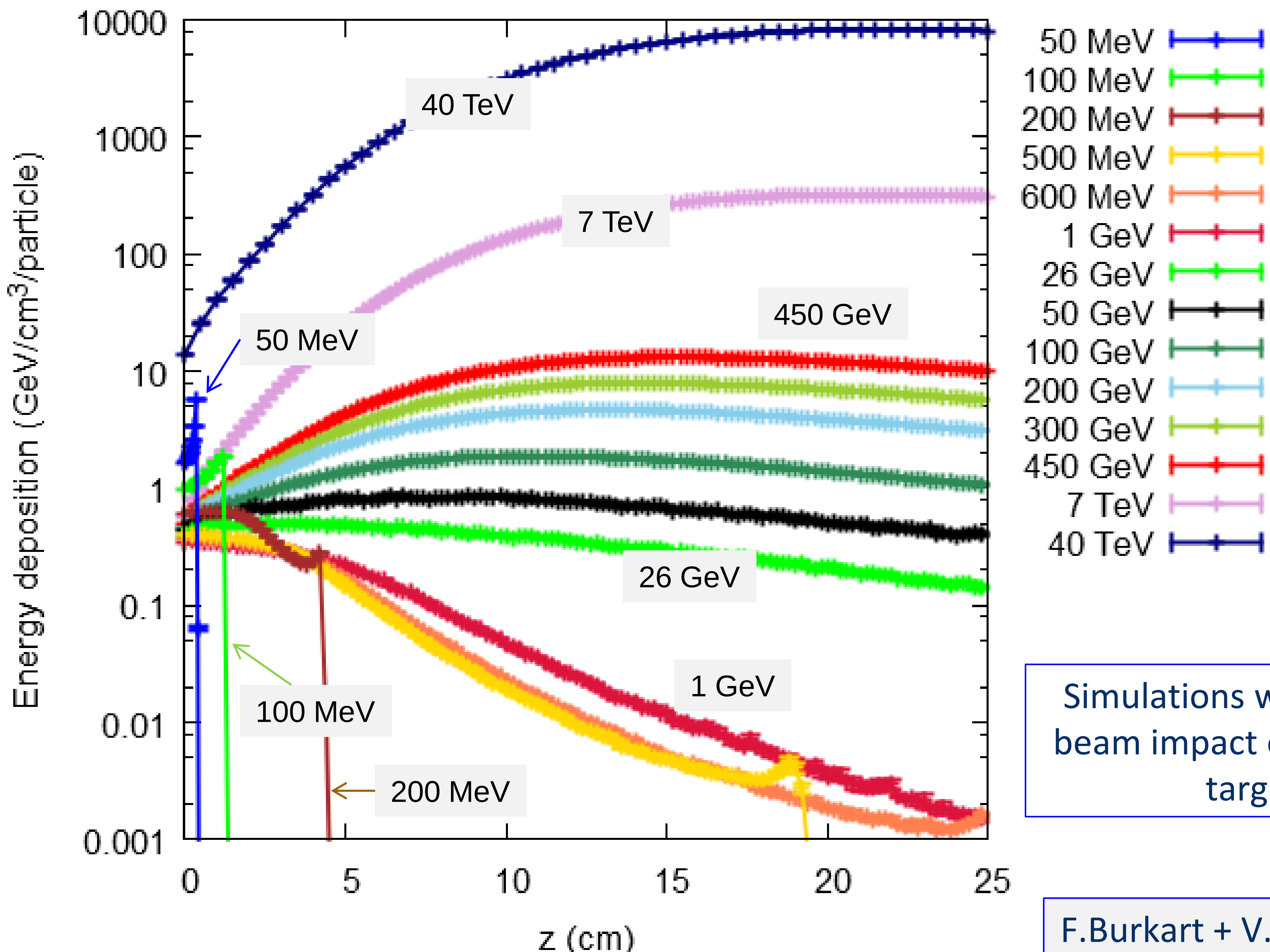
Nuclear inelastic interactions (hadronic shower)

- Creation of pions when going through matter
- Causes electromagnetic shower through decays of pions
- Exponential increase in number of created particles
- Final energy deposition to by a large number of electromagnetic particles
- Scales roughly with total energy of incident particle
- Energy deposition maximum deep in the material
- Energy deposition is a function of the particle type, its momentum and parameters of the material (atomic number, density, specific heat)
- No straightforward expression to calculate energy deposition
- Calculation by codes, such as FLUKA, GEANT or MARS



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

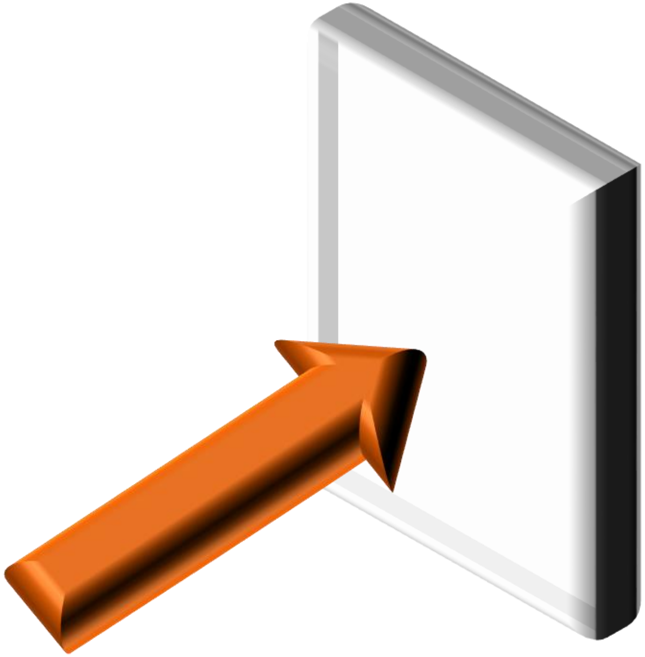
Proton energy deposition for different energies

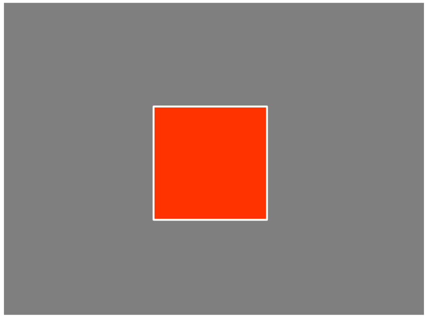


Simulations with FLUKA, beam impact on a copper target

F.Burkart + V.Chetvertkova

Beam loss and consequences





- Proton beam travels through a thin window of thickness d
- Assume a beam area of $4\ \sigma_x \times \sigma_y$, with σ_x, σ_y rms beam sizes (Gaussian beams)
- Assume a homogenous beam distribution
- The energy deposition can be calculated, mass and specific heat are known
- The temperature can be calculated (rather good approximation), assuming a fast loss and no cooling

Heating of material with low energy protons (3 MeV)

Temperature increase in the material: $dT_{Fe} := \dfrac{N_p \cdot dEdx_{Fe}}{c_{Fe\_spec} \cdot F_{beam} \cdot \rho_{Fe}}$

Temperature increase for a proton beam impacting on a Fe target:

Beam size: $\sigma_h = 1.00 \cdot mm$ and $\sigma_v = 1.00 \cdot mm$

Iron specific heat: $c_{Fe\_spec} = 440 \cdot \dfrac{J}{kg \cdot K}$

Iron specific weight: $\rho_{Fe} = 7860 \cdot \dfrac{kg}{m^3}$

Energy loss per proton/mm: $dEdx_{Fe} = 56.696 \cdot \dfrac{MeV}{mm}$

Number of protons: $\boxed{N_p = 1.16 \times 10^{12}}$

Energy of the proton: $E_p = 0.003 \cdot GeV$

Temperature increase: $\boxed{dT_{Fe} = 763\,K}$

Damage of a pencil 7 TeV proton beam (LHC)

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: $\frac{c_{Cu\_spec} \cdot \Delta T}{E_{max\_Cu}} = \boxed{1.28 \times 10^{10}}$

Copper

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 kg graphite 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: $\frac{c_{C\_spec} \cdot \Delta T}{E_{max\_C}} = \boxed{5.33 \times 10^{11}}$

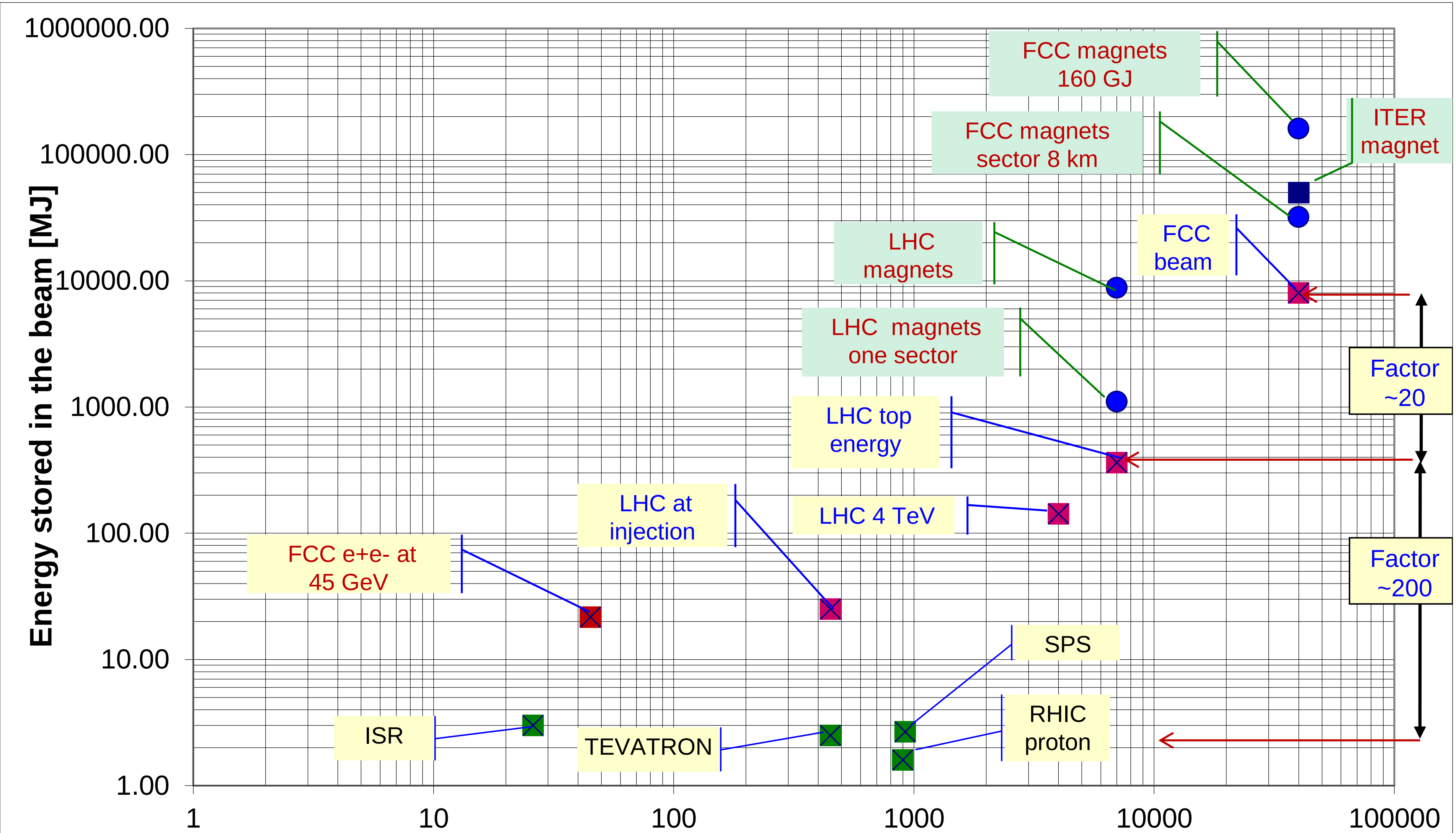
graphite

Beam loss and consequences

- Calculate the response of the material (deformation, melting, …) to beam impact (mechanical codes such as ANSYS, hydrodynamic codes such as BIG2 and others)
- Beams at very low energy have limited power…. however, the energy deposition is very high, and can lead to (limited) damage in case of beam impact
  - Issue at the initial stage of an accelerator, after the source, low energy beam transport and RFQ
  - Limited impact (e.g. damaging the RFQ) might lead to long downtime, depending on spare situation
- Beams at very high energy can have a tremendous damage potential
  - For LHC, damage of metals for ~10^{10} protons at top energy (7 TeV)
  - One LHC bunch has about $1.5 \cdot 10^{11}$ protons, in total up to 2808 bunches
  - In case of catastrophic beam loss, possibly damage beyond repair

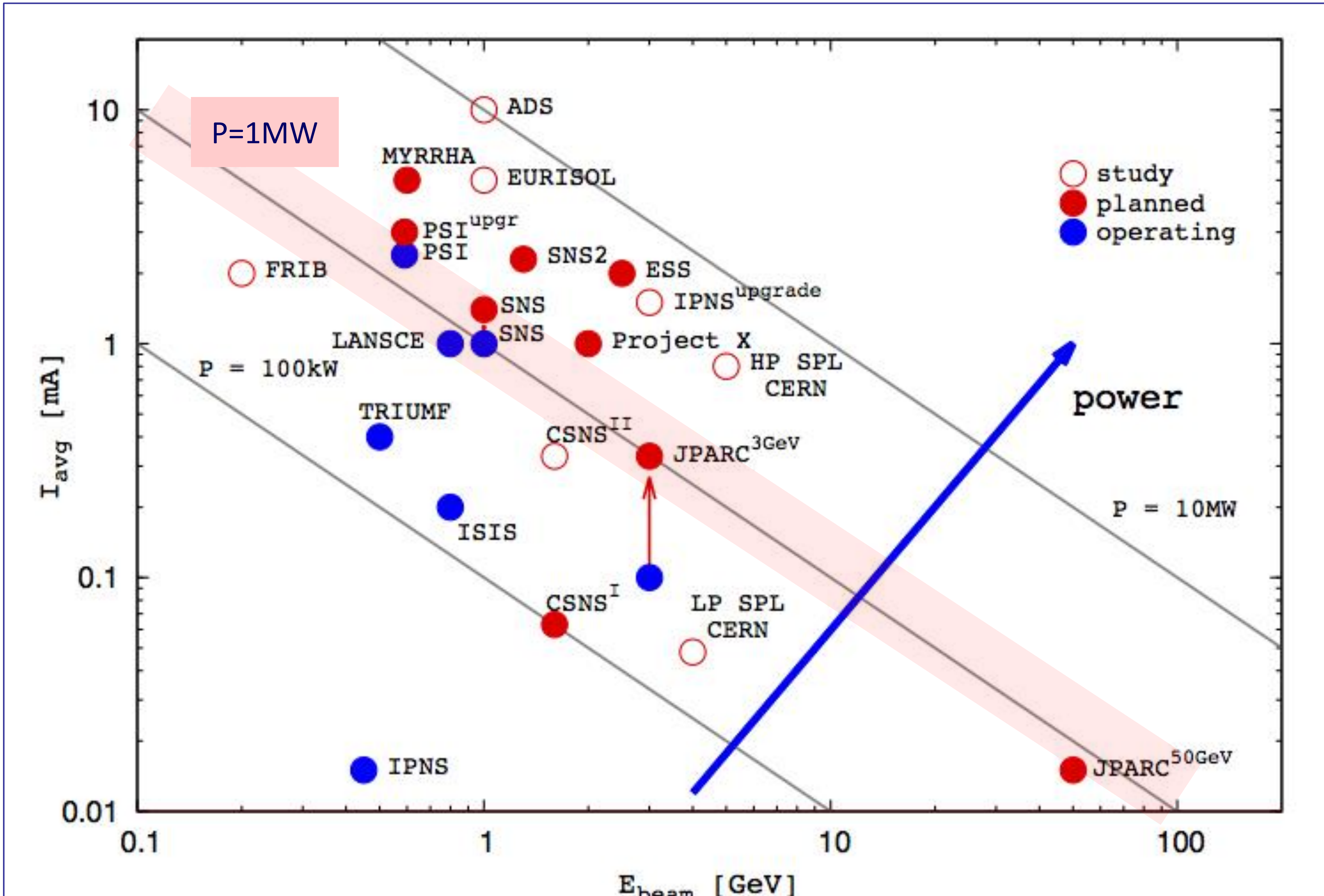
What accelerators?

Energy versus momentum



Stored Energy for (one) Beam and Magnets

High Intensity Proton Accelerators



What does it mean .... MJoule ?

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

360 MJ: the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT

- 8 litres of gasoline

- 15 kg of chocolate

It matters most how easy and fast the energy is released !!

Hazards and Risks

Synchrotrons

Linear accelerators

Hazard and Risk

- **Hazard:** a situation that poses a level of threat to the machine. Hazards are dormant or potential, with only a theoretical risk of damage. Once a hazard becomes "active“: **incident / accident**.
- **Consequences** and **Probability** of an accident create **Risk**:

Risk = Probability · Consequences

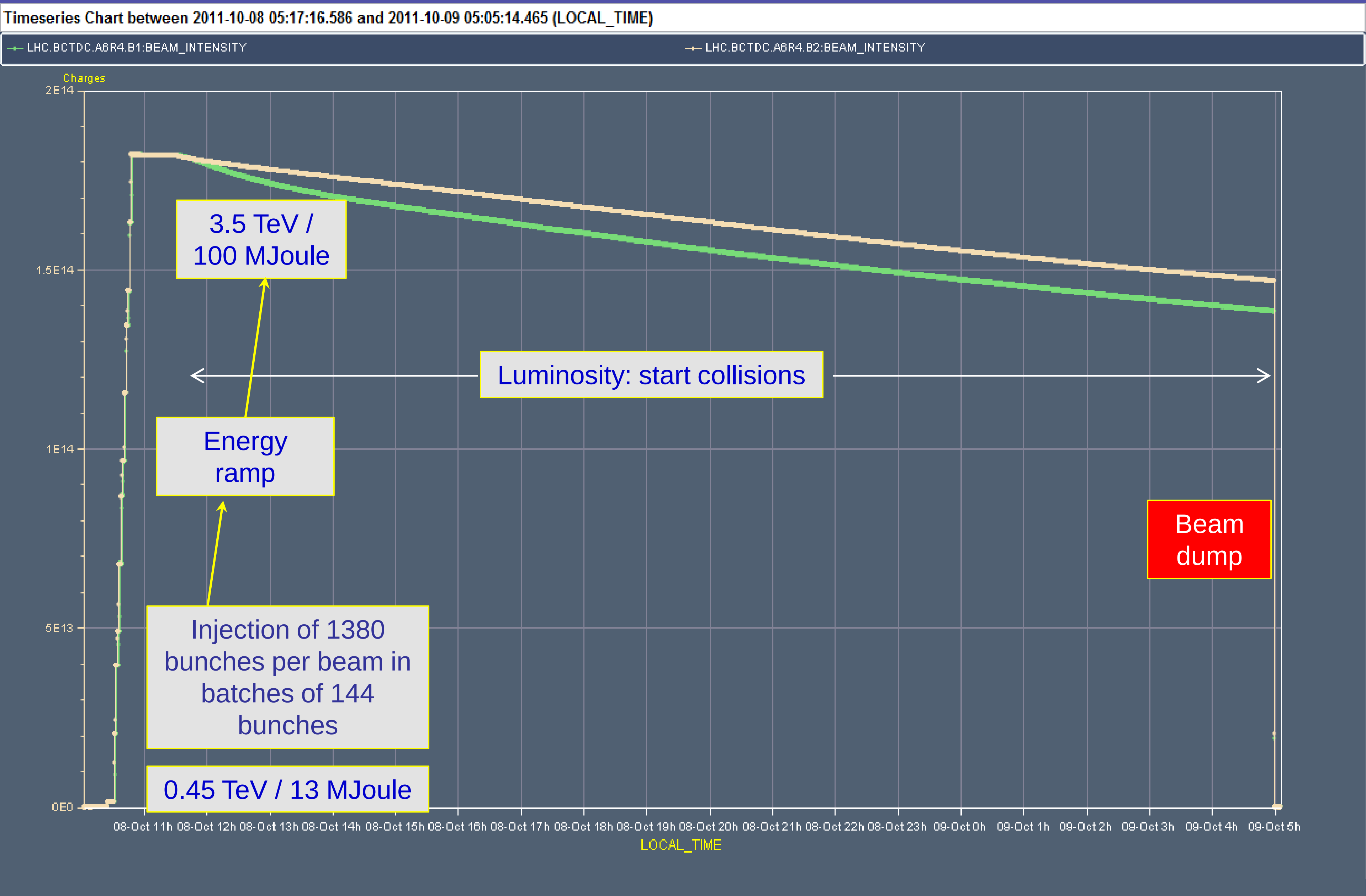
Related to complex research instruments

- **Consequences** of a failure in a hardware systems or uncontrolled beam loss (in €, downtime, radiation dose to people, reputation)
- **Probability** of such event
- The higher the **Risk**, the more **Protection** is required

Hazards related to particle beams

- **Accidental beam losses due to failures**: understand hazards, e.g. mechanisms for accidental beam losses
  - Hazards become accidents due to a failure, machine protection systems mitigate the consequences
- **Understand mechanisms for damage** of components by direct beam loss
- **Regular beam losses** during operation
  - To be considered since this leads to activation of equipment and possibly quenches of superconducting magnets
  - Radiation induced effects in electronics (Single Event Effects)
- Understand effects from **electromagnetic fields and synchrotron radiation** that potentially lead to damage of equipment

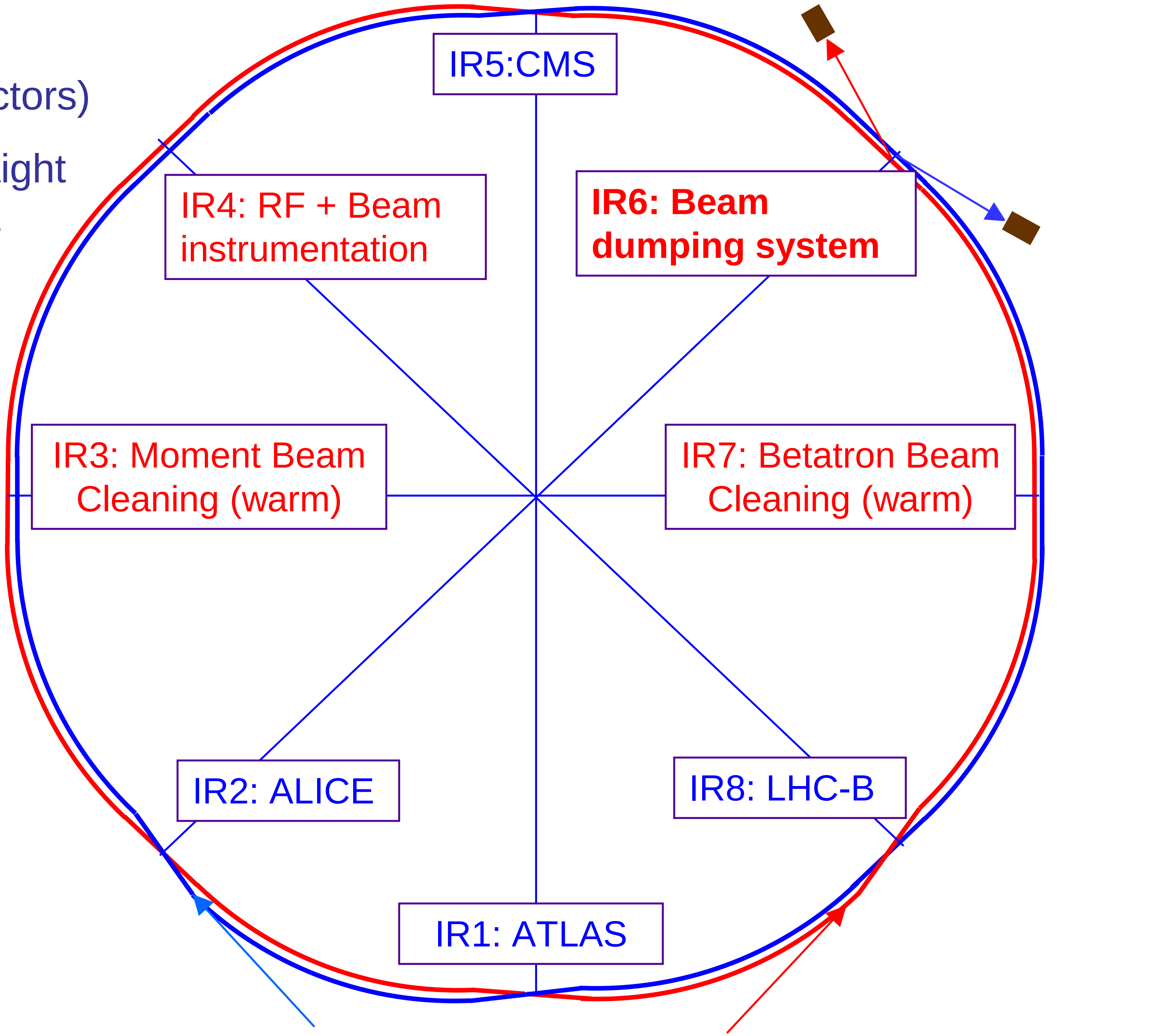
Luminosity fill in 2011 (18 hours)



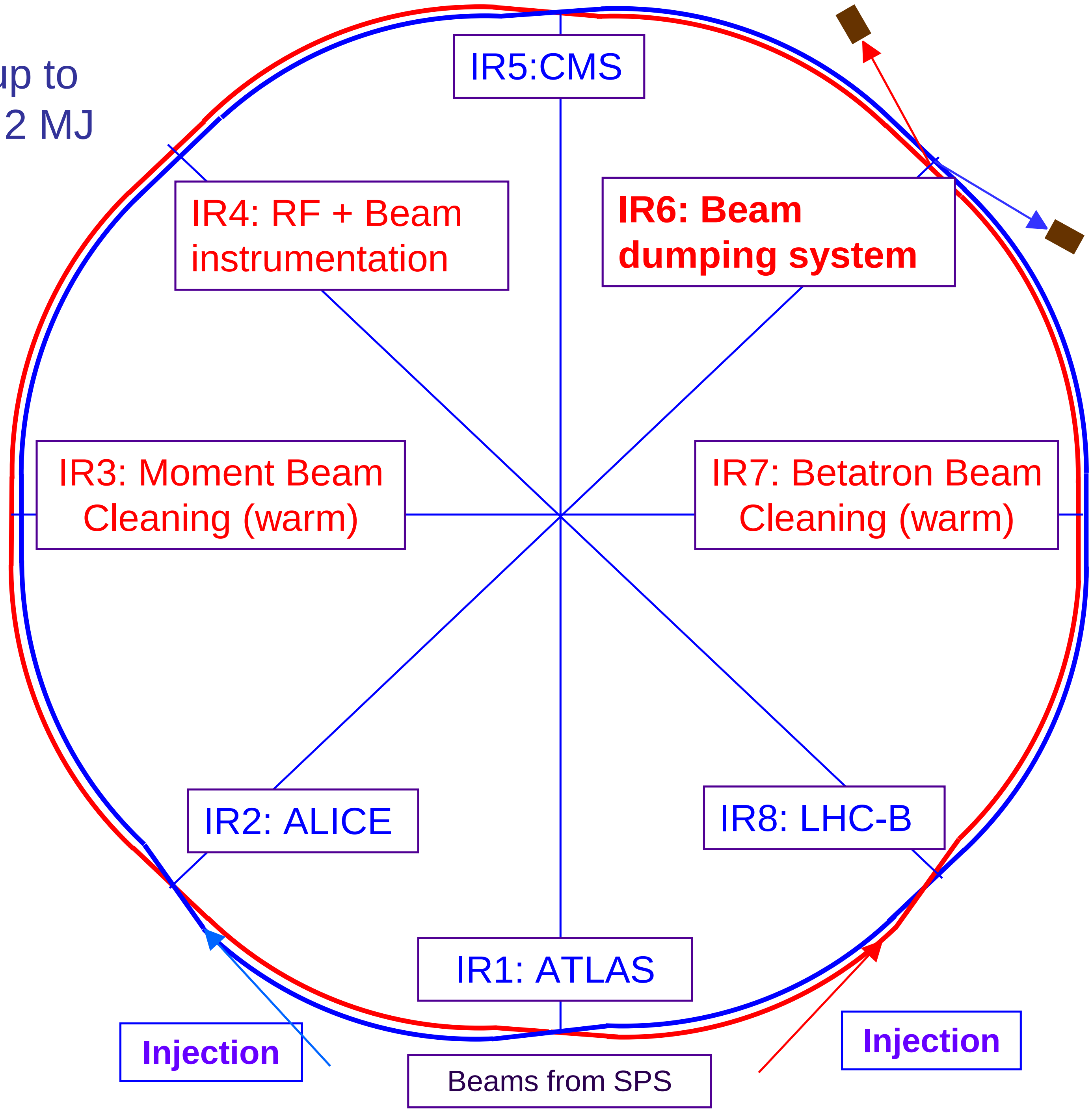
LHC Layout

eight arcs (sectors)

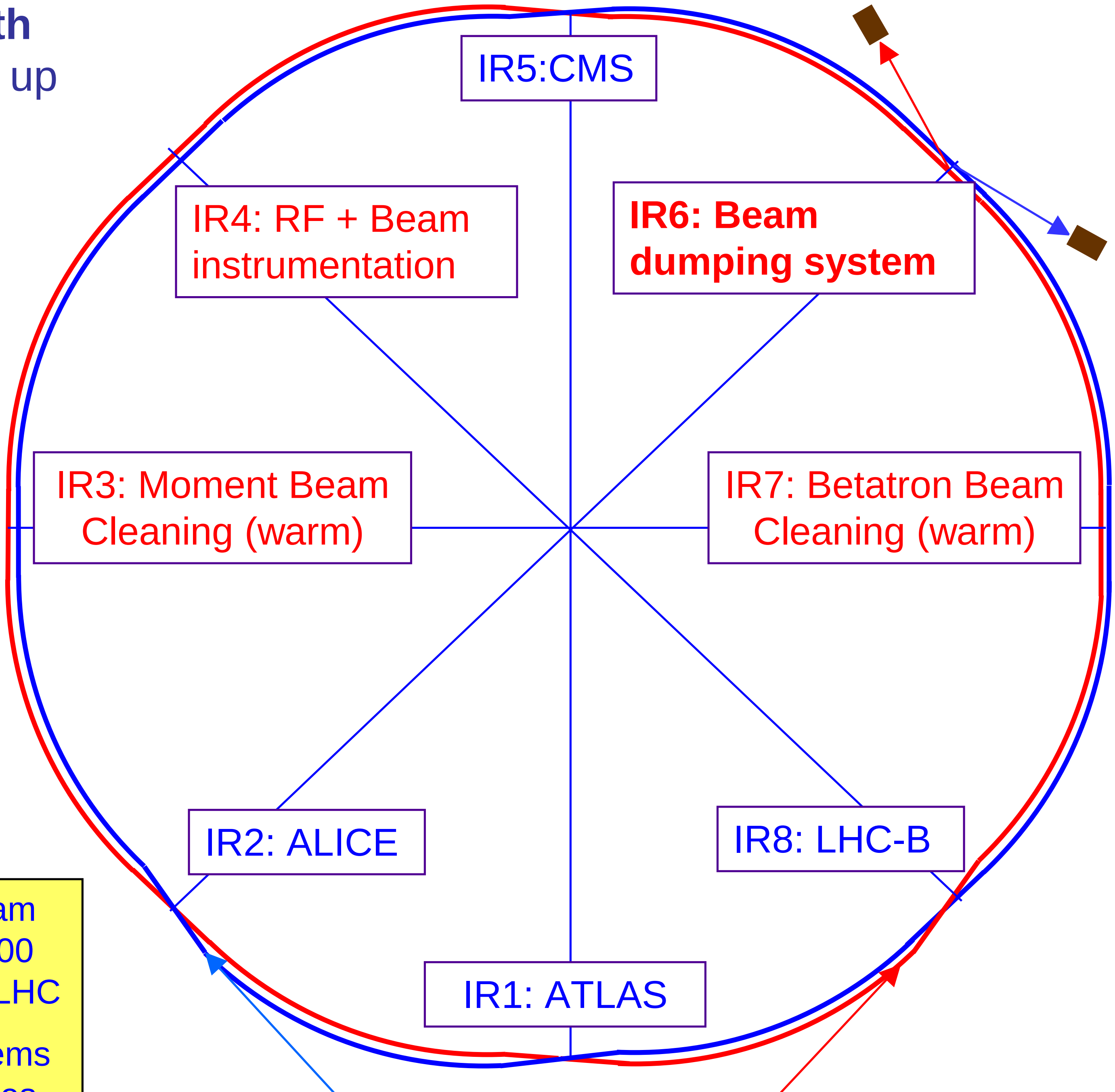
eight long straight section (about 700 m long)



Injection of batches with up to 288 bunches, 2 MJ



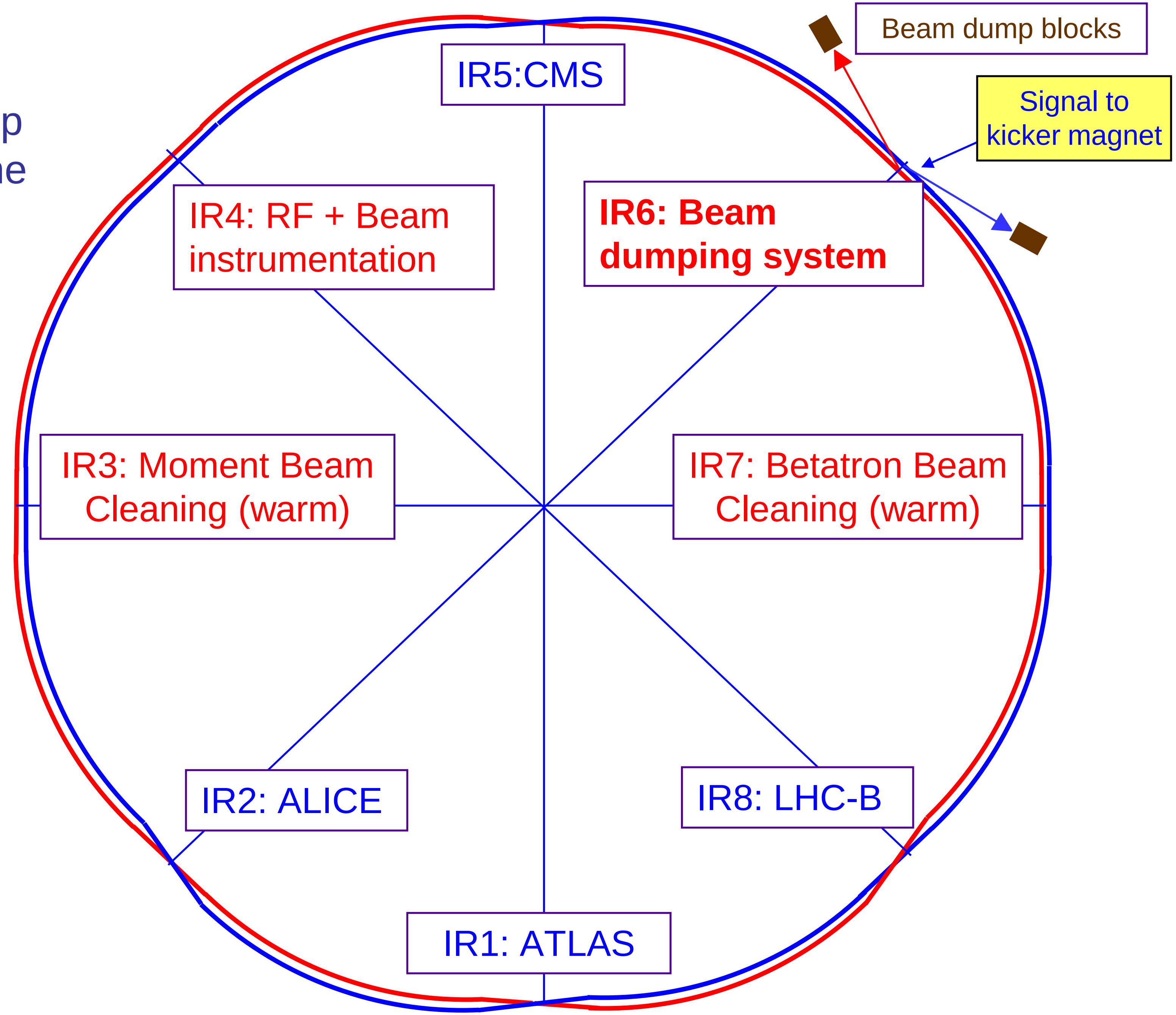
Operation with stored beam, up to 362 MJ per beam



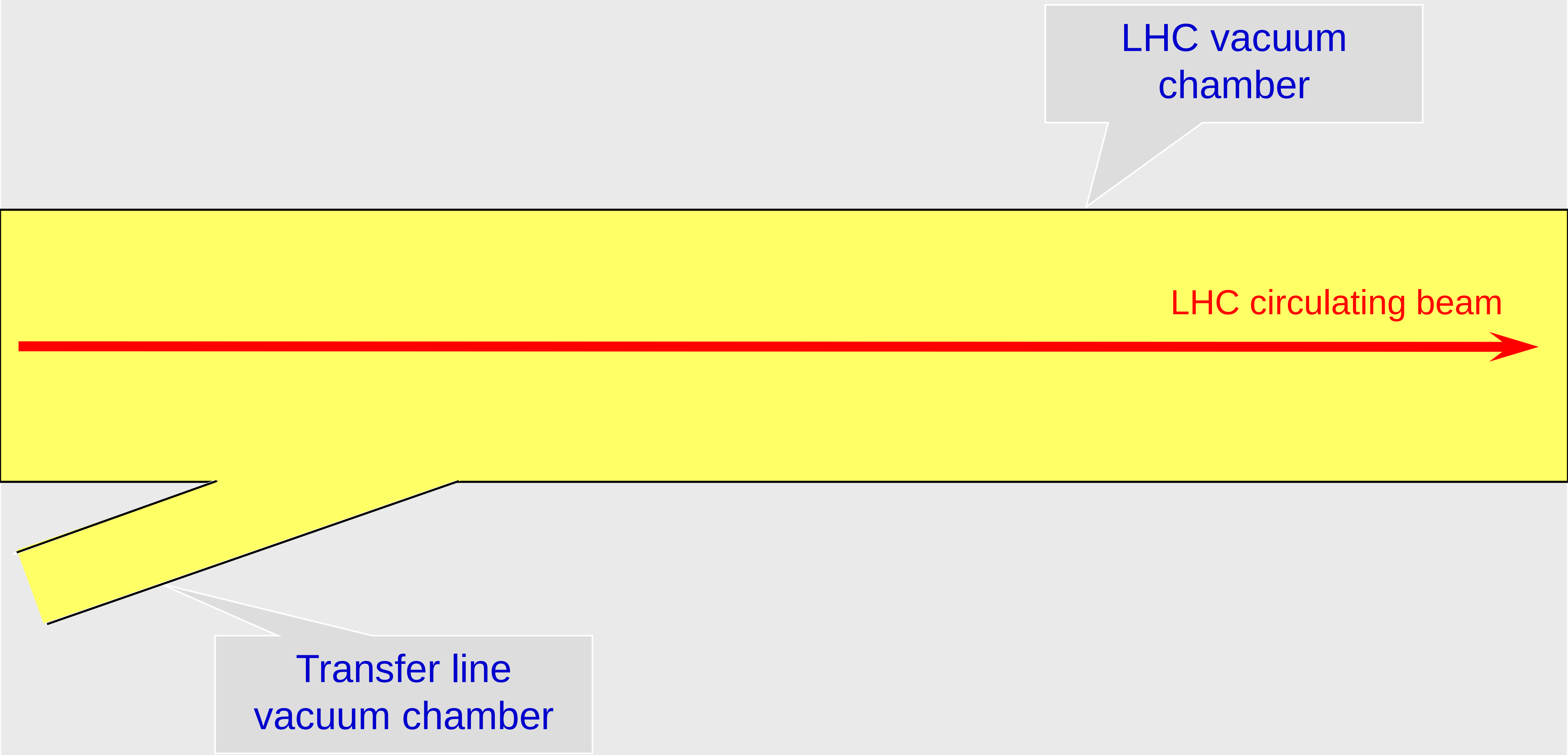
Detection of beam losses with >3600 monitors around LHC

Many other systems can detect failures

Extraction of the beam into the beam dump blocks, after the end of a luminosity run, and in case of failure

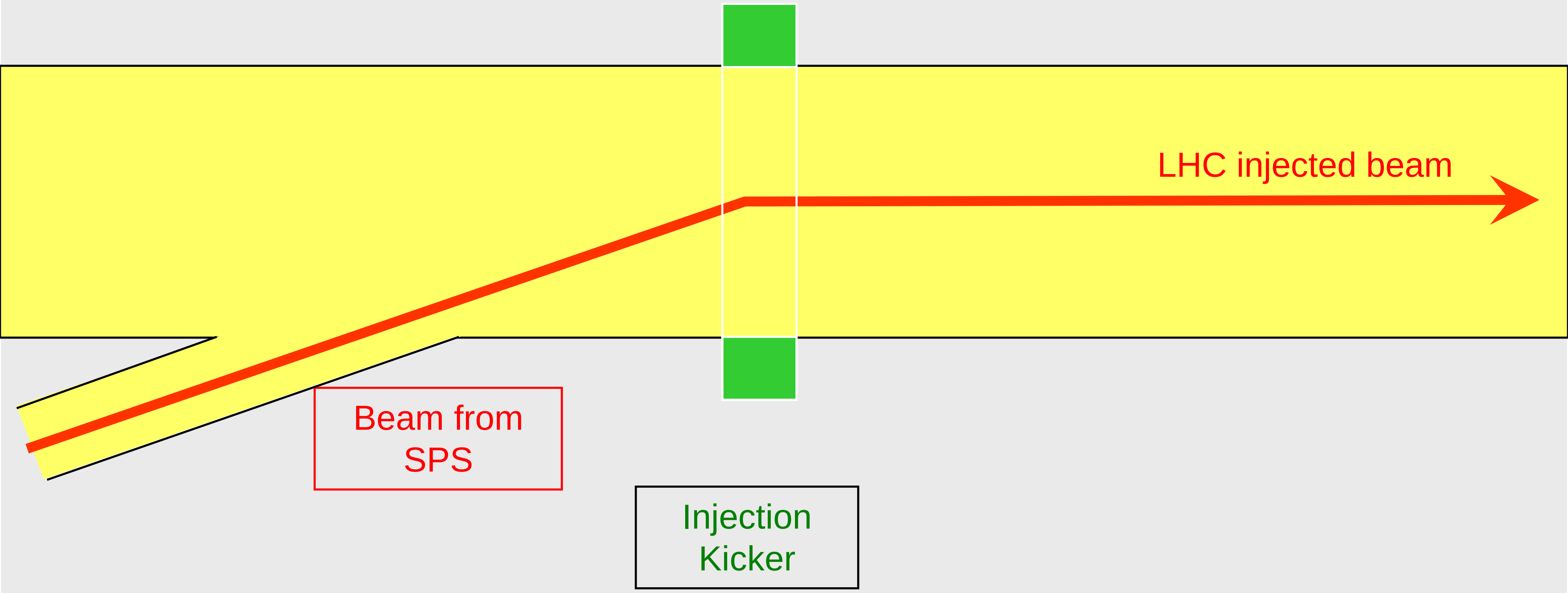


Protection at injection



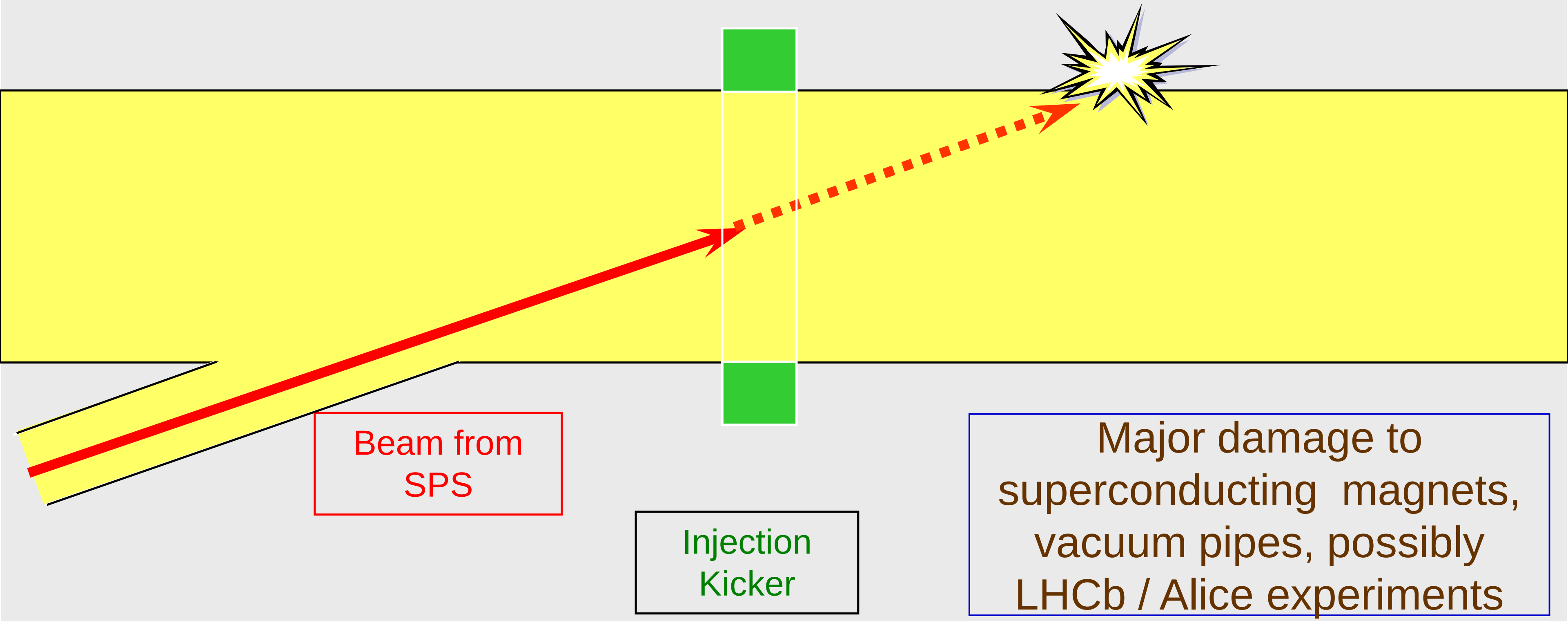
Circulating beam in LHC

Protection at injection



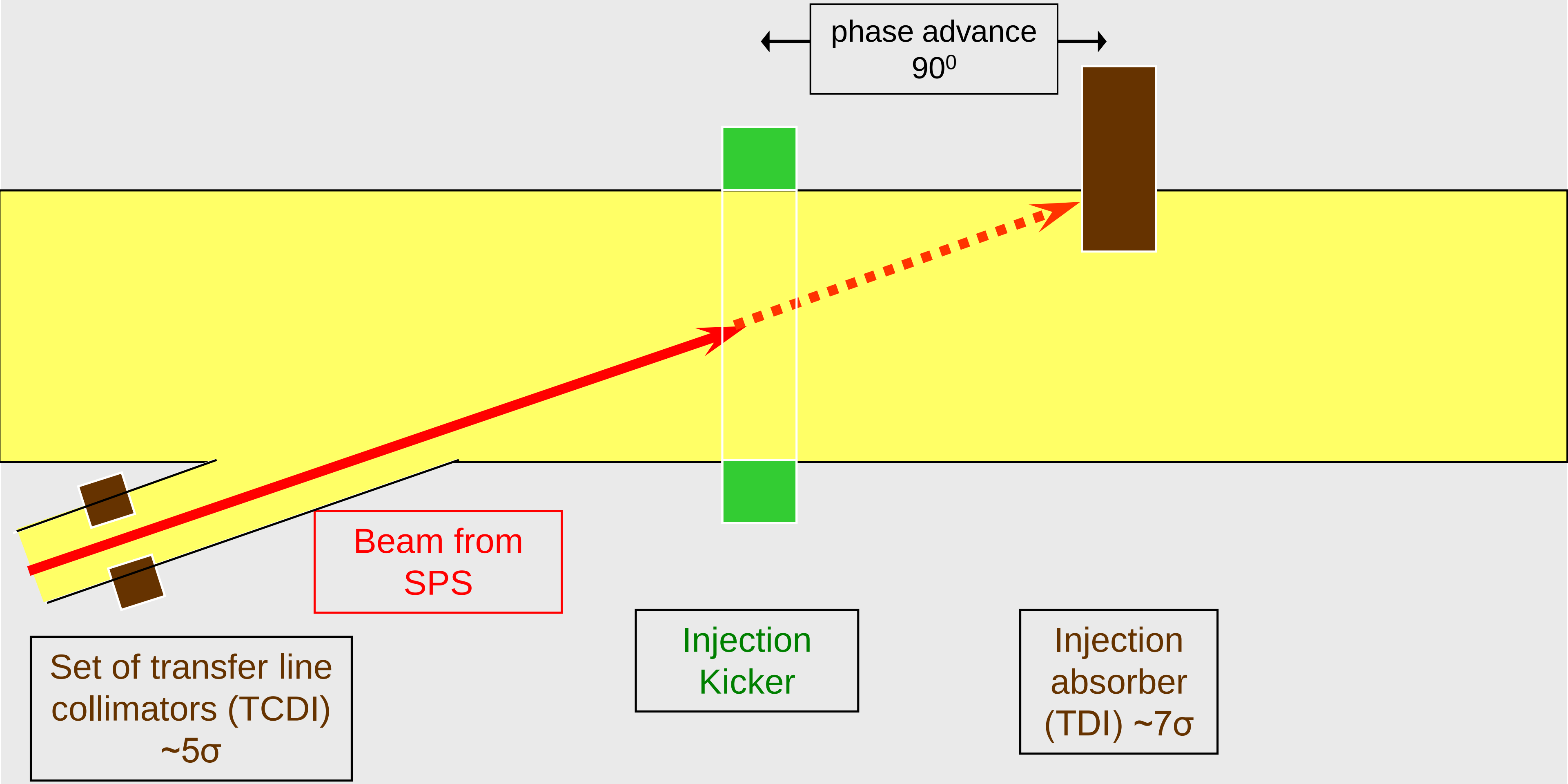
Beam injected from SPS and transfer line

Protection at injection



Kicker failure (no kick)

Protection at injection

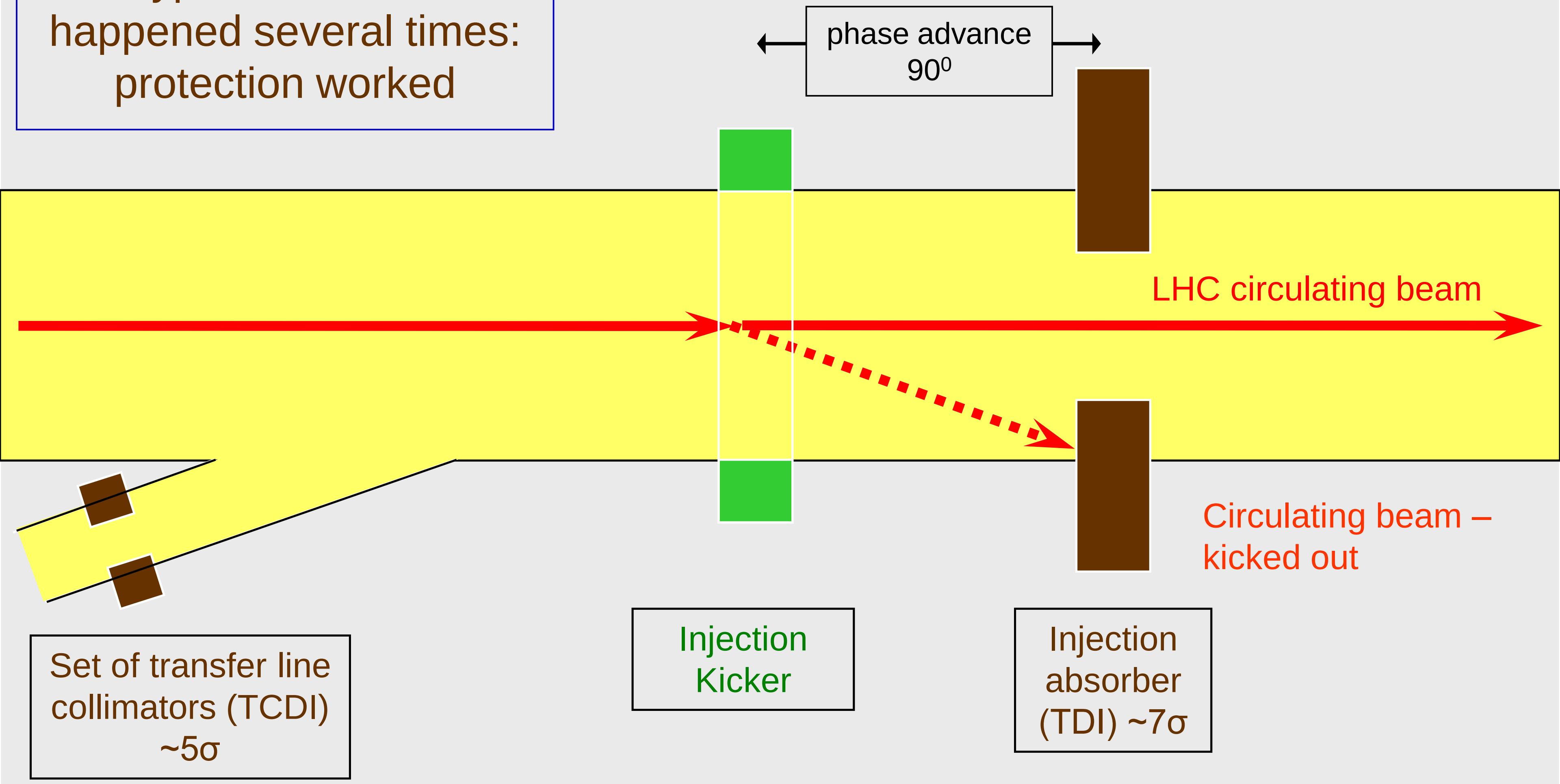


Beam absorbers take beam in case of kicker misfiring

Transfer line collimators ensure that incoming beam trajectory is ok

Protection at injection

This type of kicker failure happened several times: protection worked

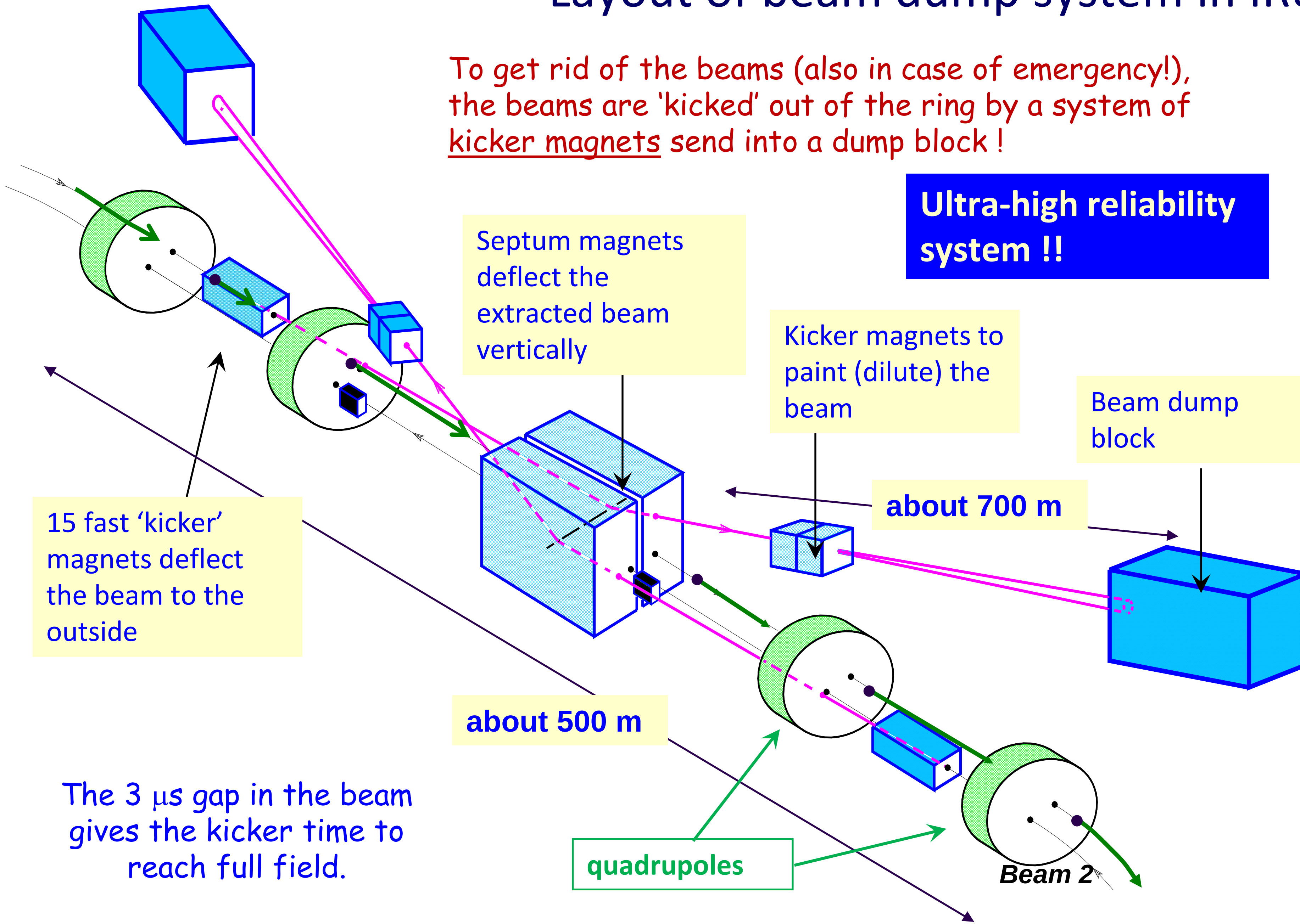


Beam absorbers take beam in case of kicker misfiring on circulating beam

Layout of beam dump system in IR6

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 send into a dump block !

Ultra-high reliability system !!

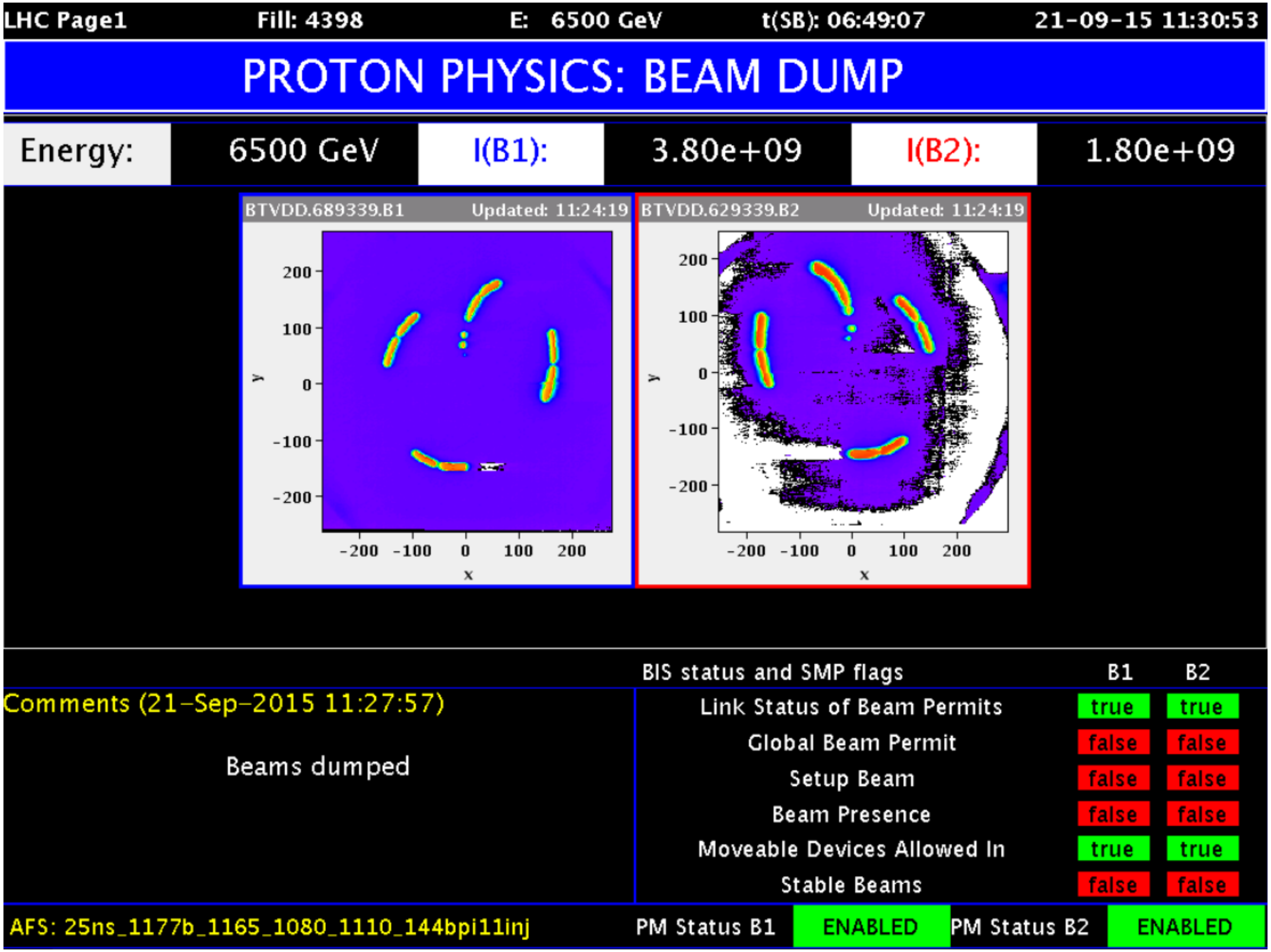


The 3 μs gap in the beam gives the kicker time to reach full field.

Beam dump line

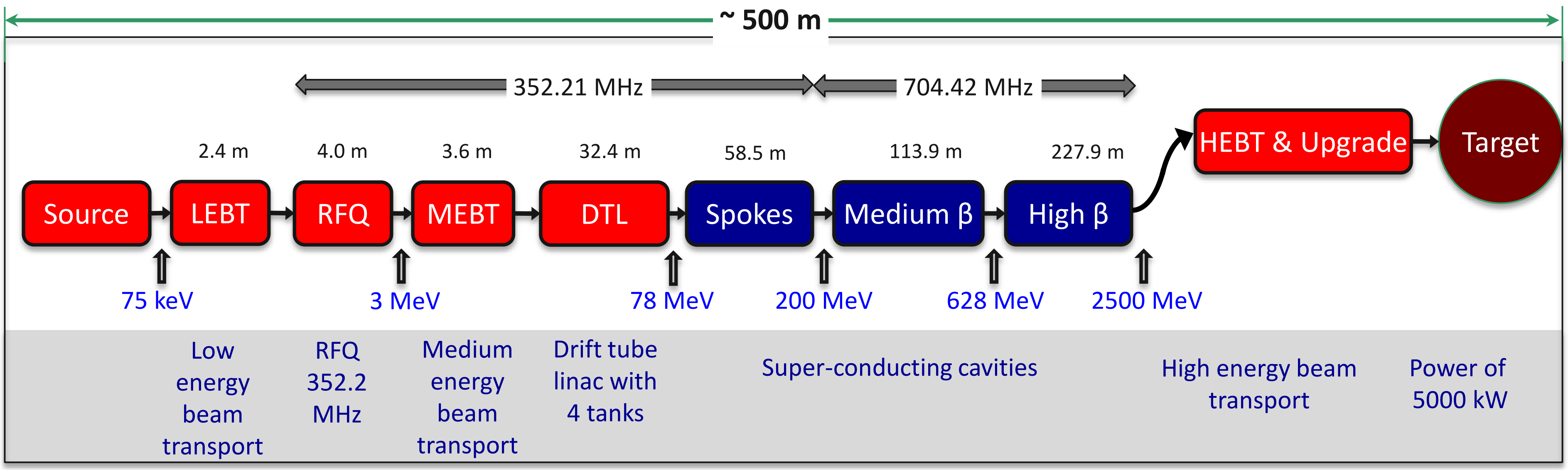
700 m long tunnel to beam dump block- beam size increases

Beam dump with 1380 bunches



Beam spot at the end of the beam dumping line, just in front of the beam dump block

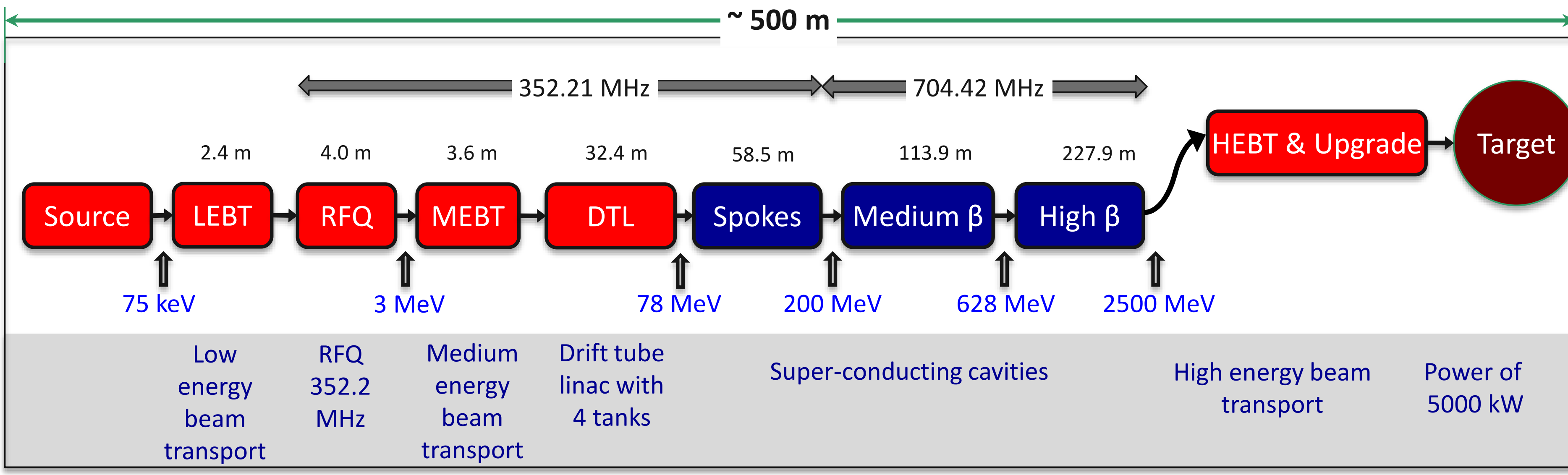
ESS Lund / Sweden – 5 MW beam power



Example for a high intensity linear accelerator (similar to SNS and J-PARC)

- Operating with protons
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Average power of 5 MW**
- Peak power of 125 MW
- One pulse = 357 kJ

ESS Lund / Sweden – 5 MW beam power



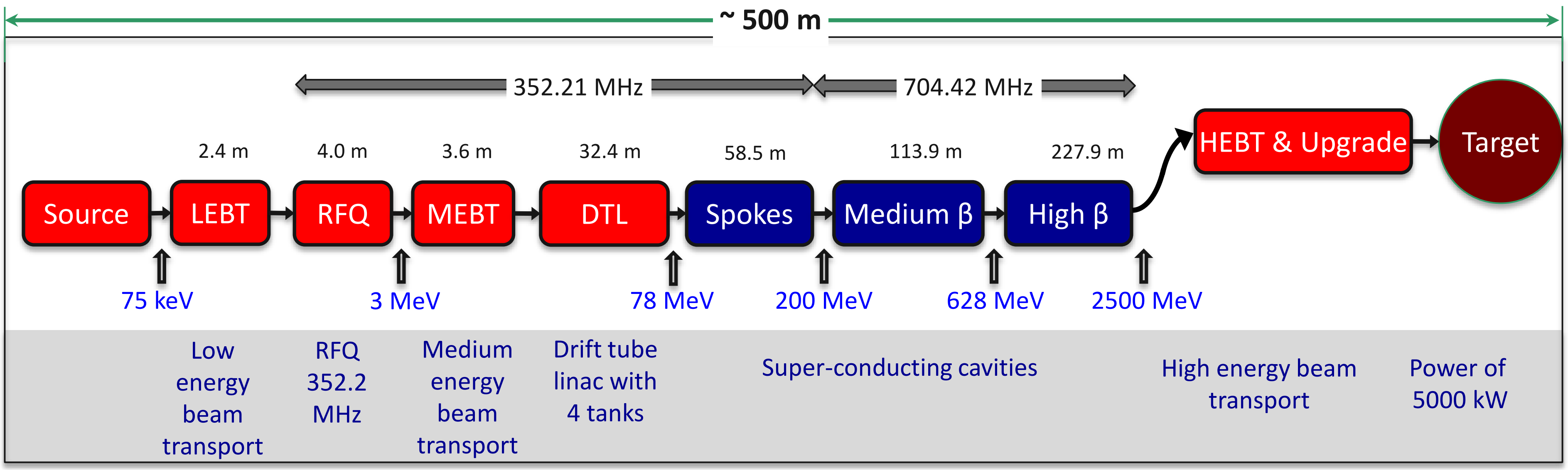
The energy stored in the beam at a given moment is relatively small

- Low energy part
- Medium energy part
- High energy part

In case of a failure, the beam needs to be switched off at the source

- Operating with protons
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Average power of 5 MW**
- Peak power of 125 MW
- One pulse = 357 kJ

ESS Lund / Sweden – 5 MW beam power



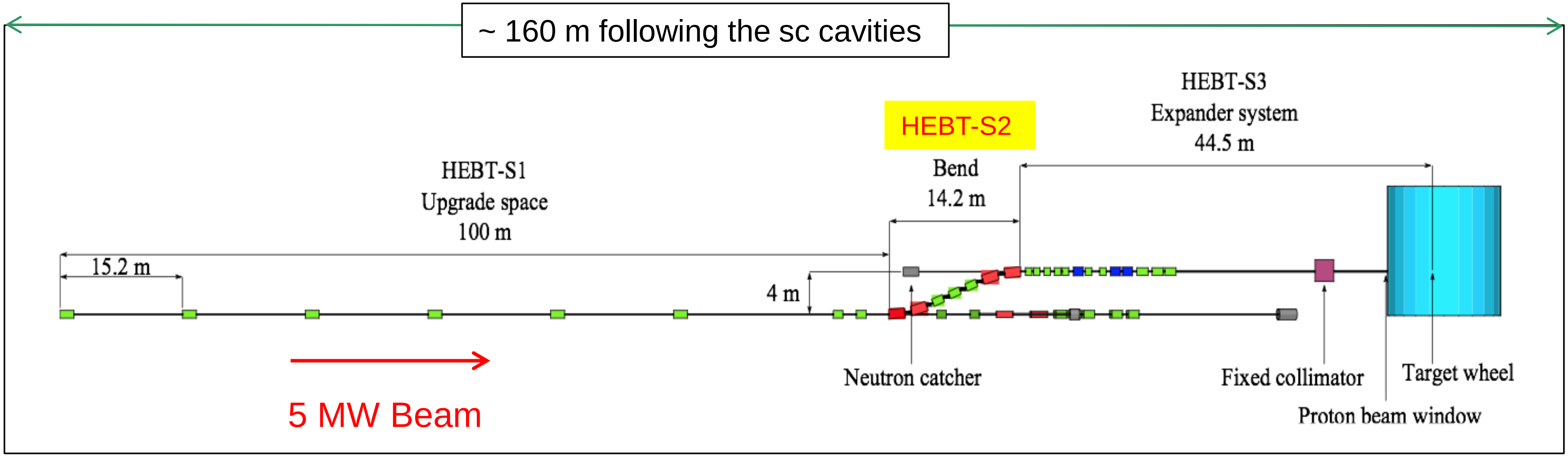
In between two pulses (about 70 ms), ensure that the parameters of the accelerator allow for correct beam transmission – or do not start with the next pulse.

If something is wrong and not detected before the pulse by monitors, stop beam as soon as possible

- Operating with protons
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Average power of 5 MW**
- Peak power of 125 MW
- One pulse = 357 kJ

Example for a failure at ESS

- Bending magnet in an accelerator deflecting the beam
- Assume that the power supply for the bend in HEBT-S2 fails and the magnets stops deflecting the beam
  - Probability: MTBF for power supply is 100000 hours = 15 years
- The beam is not deflected and hits the vacuum chamber
  - Consequences: what is expected to happen? Damage of magnet, vacuum pipe, possibly pollution of superconducting cavities



Accelerators that require protection systems I

- Hadron synchrotrons with large stored energy in the beam
  - Colliders using protons / antiprotons (RHIC, LHC, FCC)
  - Synchrotrons accelerating beams for fixed target experiments (SPS)
- High power proton accelerators (e.g. spallation sources) with beam power of some 10 kW to above 1 MW
  - Risk of damage and activation
  - Spallation sources, up to (and above) 1 MW beam power (SNS, ISIS, PSI cyclotron, JPARC, and in the future ESS, FRIB, MYRRHA and IFMIF)
- Synchrotron light sources and FELs with high intensity beams and secondary photon beams
  - LCLS, FLASH 90 kW, European XFEL 600 kW, JLab FEL 1.5 MW,
- Energy recovery linacs
  - Daresbury prototype: one bunch train cannot damage equipment, but next train must not leave the (injector) station

Accelerators that require protection systems II

- Linear e+e- colliders / accelerators with very high beam power densities due to small beam size
  - High average power in linear accelerators: ILC 11 MW, CLIC
  - One beam pulse can lead already to damage

- “Any time interval large enough to allow a substantial change in the beam trajectory of component alignment (~fraction of a second), pilot beam must be used to prove the integrity” from Next Linear Collider paper 1999

Worst case accidents

Proton collider

Hydrodynamic tunnelling

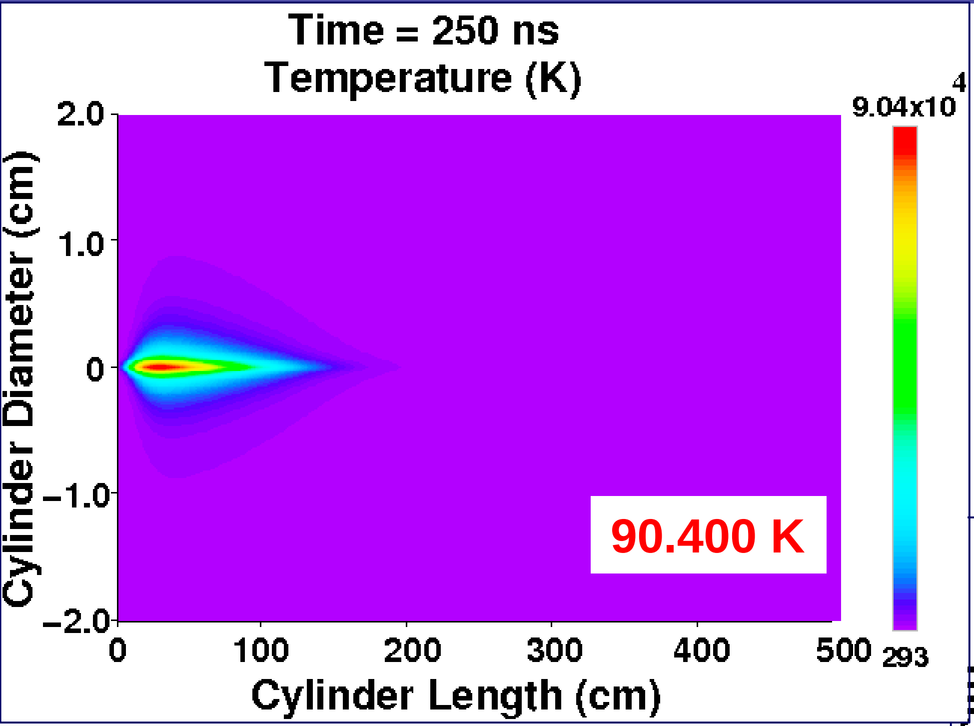
- The beam impacts on a target, e.g. due to a failure of the injection of extraction kicker
- For LHC, bunches arrive every 25 or 50 ns
- The time structure of the beam plays an essential role
- The first bunches arrive, deposit their energy, and lead to a reduction of the target material density
- Bunches arriving later travel further into the target since the material density is reduced (predicted already for SSC, N.Mokhov et al.)

Copper or carbon target

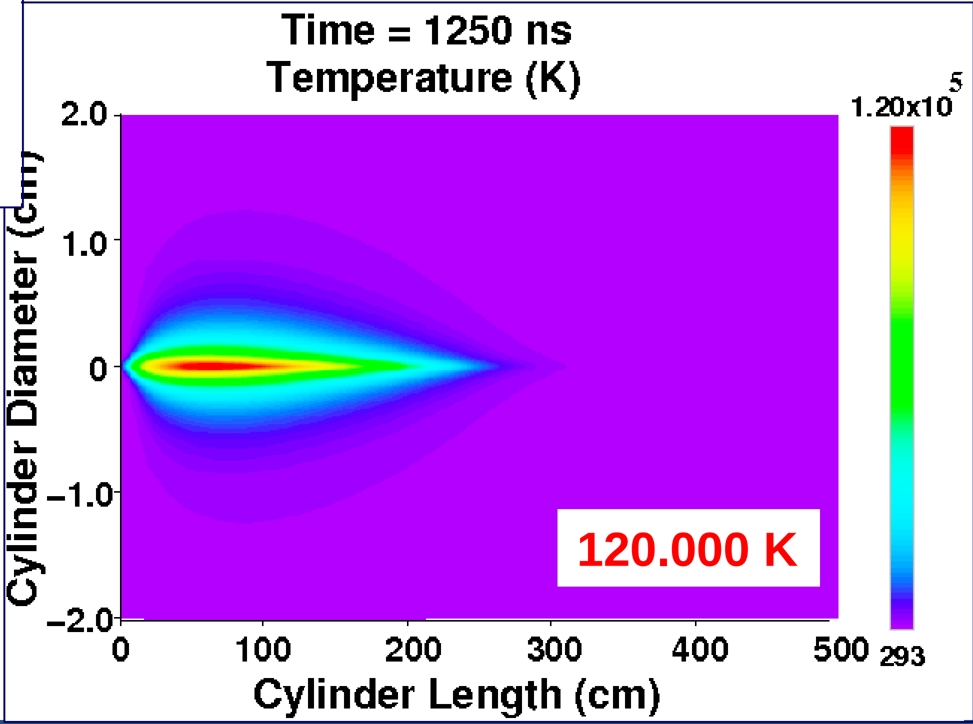
How to perform calculations?

- Assume **LHC Beam impacts** on **Solid Cylindrical Target**
  - 2808 bunches with 1.1×10^{11}protons, $\sigma = 0.5$ mm, 25 ns bunch distance, target length of 6 m, Radius = 5 cm, Density = 2.3 g/cm3
- The energy deposition for few bunches is calculated with FLUKA
- The hydrodynamic code BIG2 uses the 3d energy deposition to calculate temperature, pressure and density of the target
- The programs are run iteratively
  - FLUKA 3d energy loss data is used as input to BIG2
  - BIG2 3d density data is used as input for FLUKA
- The modified density distribution is used in FLUKA to calculate the energy loss corresponding to this new density distribution
- The new energy loss distribution is used in BIG2 which is run for time step
- LHC: **tunnelling of the beam through about 30 m** is expected

FCC: Temperature profile

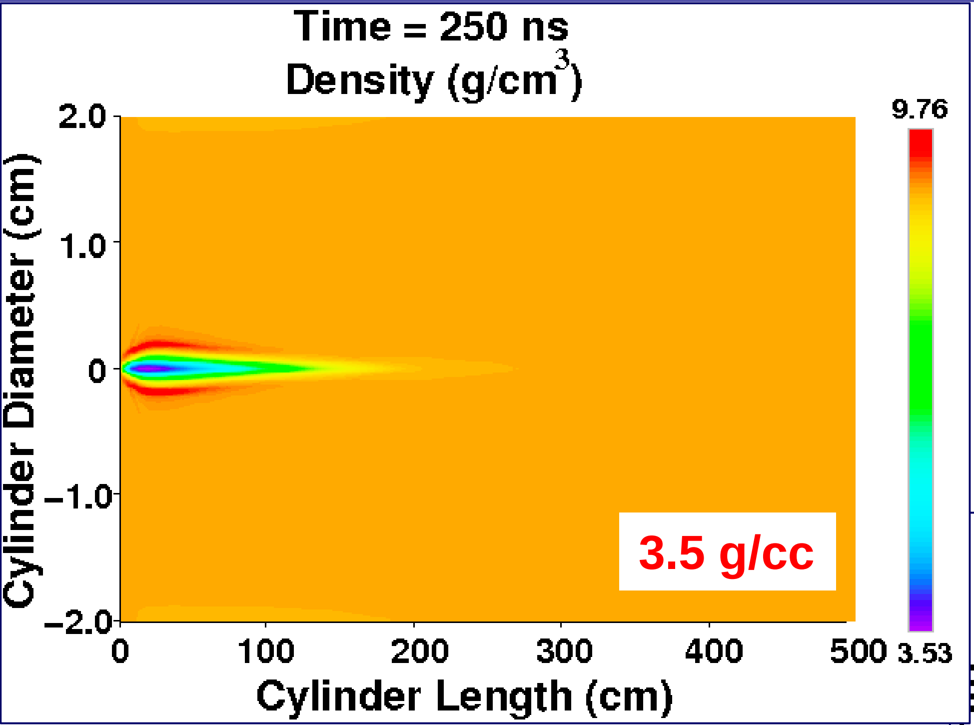


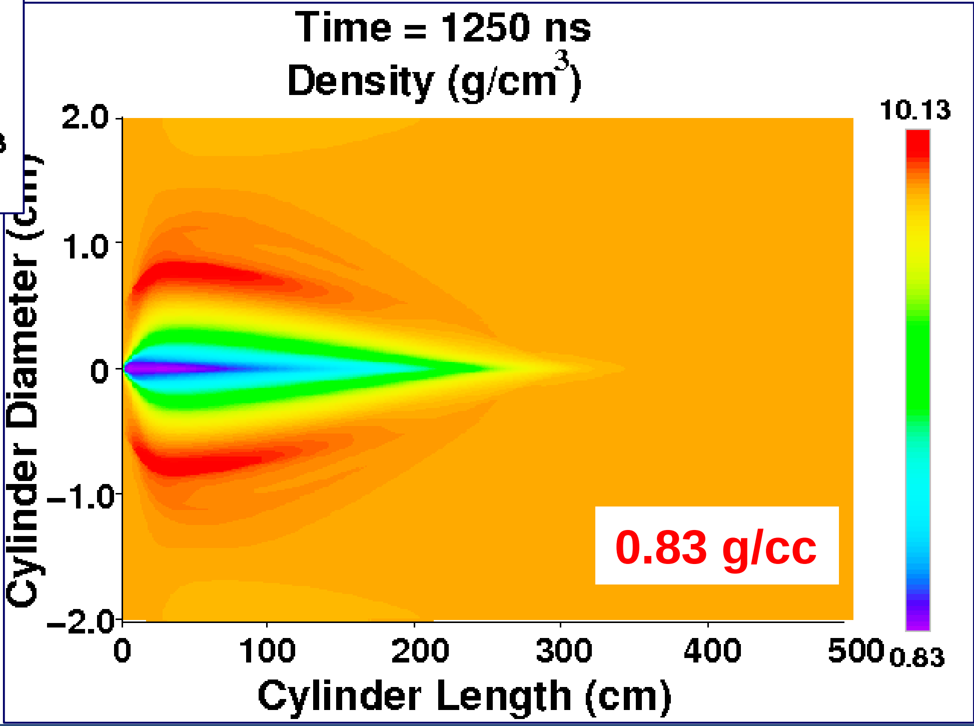
- FCC 100 km long accelerator.
- Particle energy of 40 TeV.
- Copper, Length = 5 m, Radius = 2 cm.
- The simulation took about 15 months.



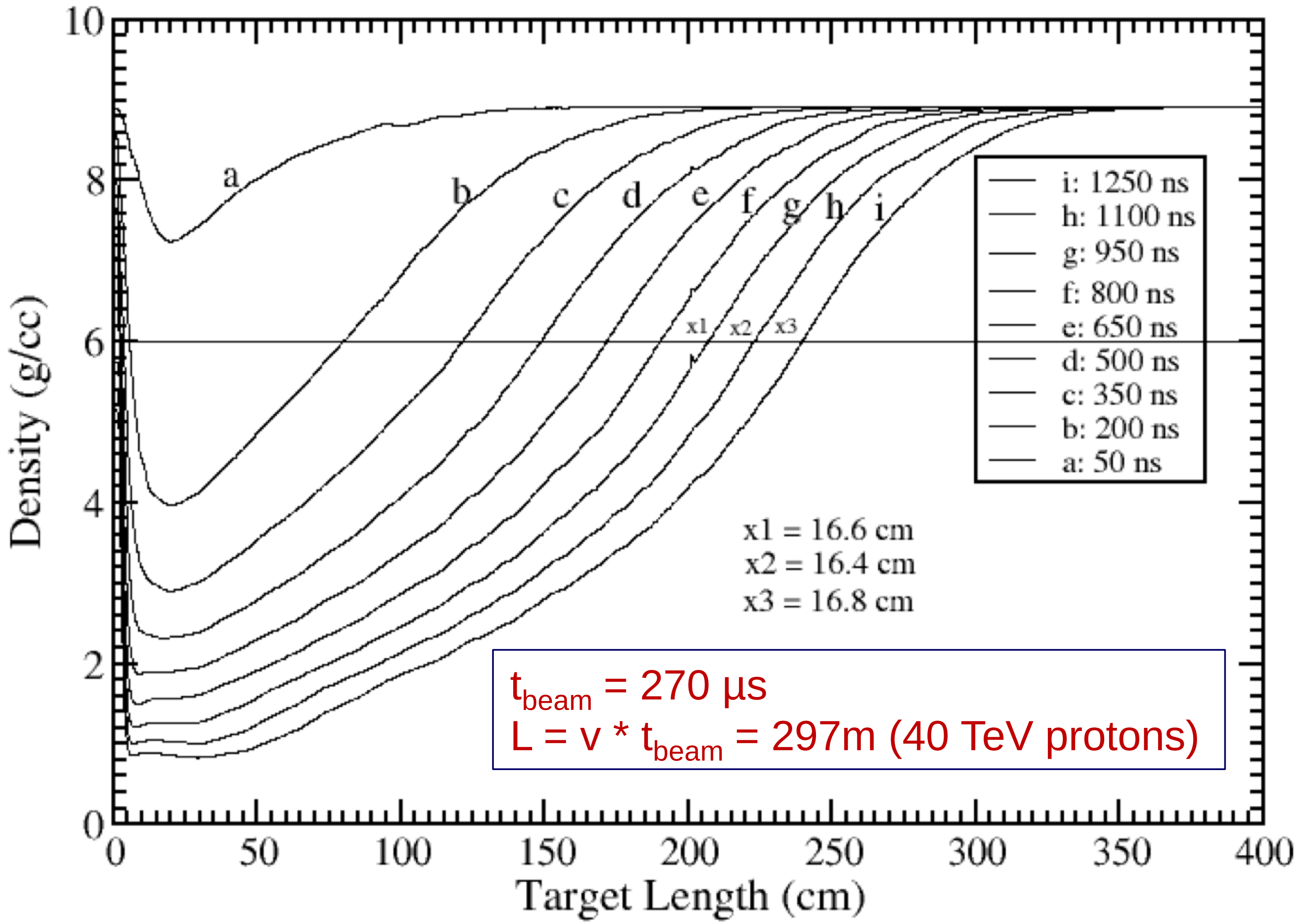
Naeem Tahir, Florian Burkart

Density profile





Density profile on axis



t_{beam} = 270 µs

L = v * t_{beam} = 297m (40 TeV protons)

Principle of the code validation experiment

using a copper target

Copper Target length of about 2 m

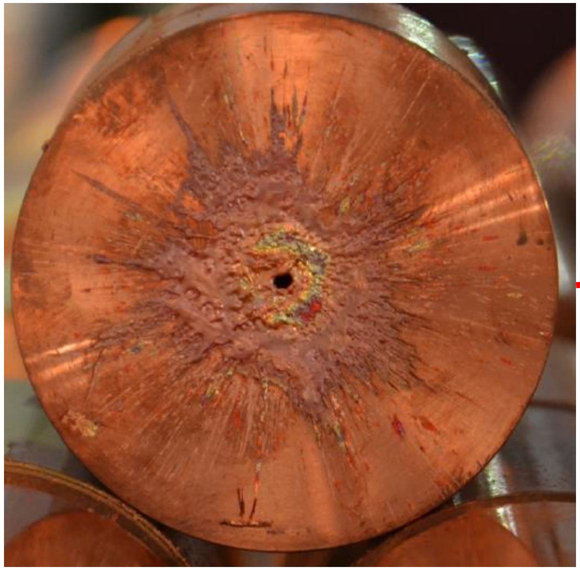
Target 1: 144 bunches ~1.9E11@50ns, 2.0mm σ -> no tunnelling expected

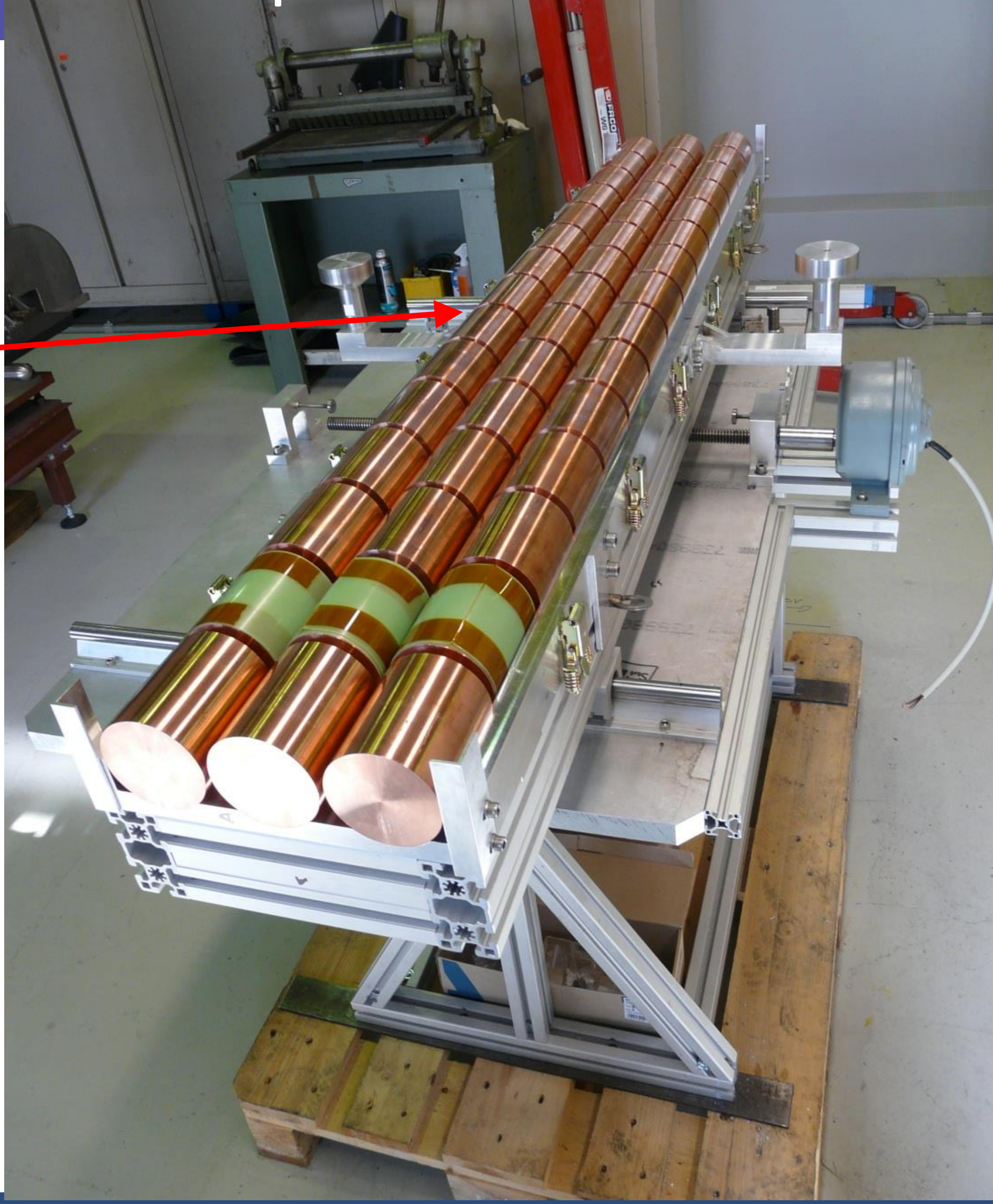
Target 2: 108 bunches ~1.9E11@50ns, 0.2mm σ -> tunnelling expected

Target 3: 144 bunches ~1.9E11@50ns, 0.2mm σ -> tunnelling expected

Juan Blanco, Florian Burkart, et al.

Copper target before the experiment

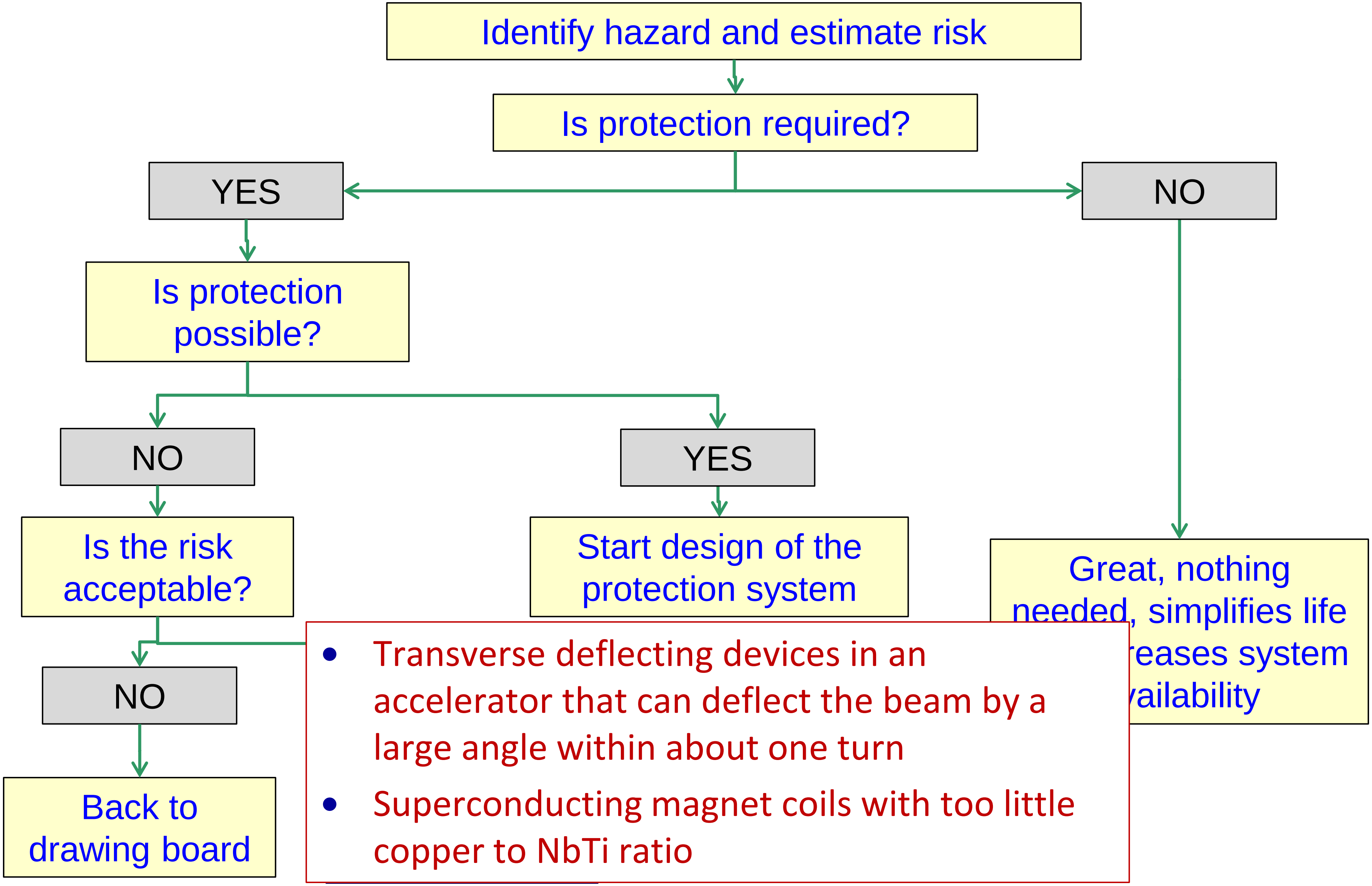




- The range of the beam in target 3 is larger than in target 1 and 2
- Clear indication for tunnelling

Machine Protection

Analysing need for machine protection



- Transverse deflecting devices in an accelerator that can deflect the beam by a large angle within about one turn
- Superconducting magnet coils with too little copper to NbTi ratio

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)
- Failures in the injectors and transfer lines to be considered
- Parameters for the failure
  - Probability for the failure
  - Damage potential
  - **Time constant for beam loss**

Risk = Probability * Consequences

Multi passage beam loss in a synchrotron

- Very fast beam loss (few ms)
  - Large number of possible failures, mostly in the magnet powering system, with a typical time constant of some ms to many seconds

- Fast beam loss (some 10 ms to seconds)
  - Beam instabilities

- Slow beam loss (many seconds)

Detect failure and trigger beam dump

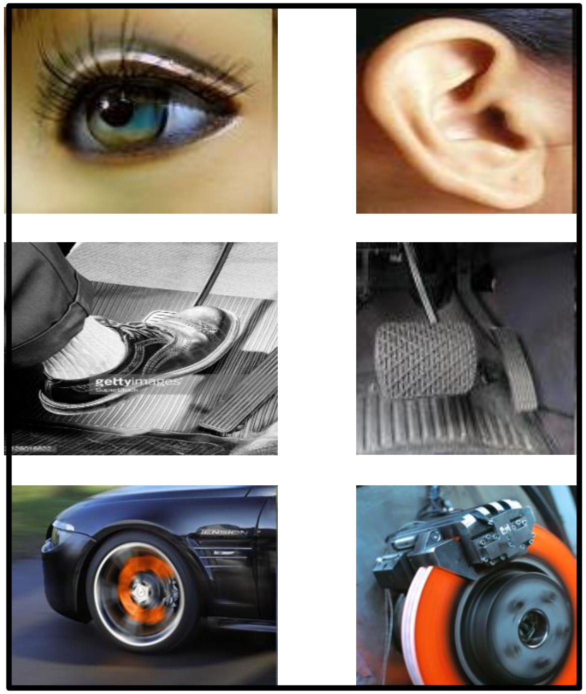
Single-passage beam loss in an accelerator complex (ns - μs)

- Linear accelerators
  - Beam is injected, but there is a failure present in the accelerator
  - Before a pulse, ensure that the parameters of the accelerator allow for correct beam transmission
  - If something is wrong and not detected before the pulse, stop beam as soon as possible at the source
- Transfer lines between accelerators (e.g. SPS to LHC)
  - Before a transfer, ensure that the parameters of the accelerator allow for correct beam transmission
  - Use beam absorbers to capture mis-steered beam
- Failures of kicker magnets (injection, extraction, special kicker magnets, for example for diagnostics)
  - Use beam absorbers to capture mis-steered beam

Active and Passive Protection

Active protection

- A sensor detects a dangerous situation
- An action is triggered by an actuator
- The energy stored in the system is safely dissipated



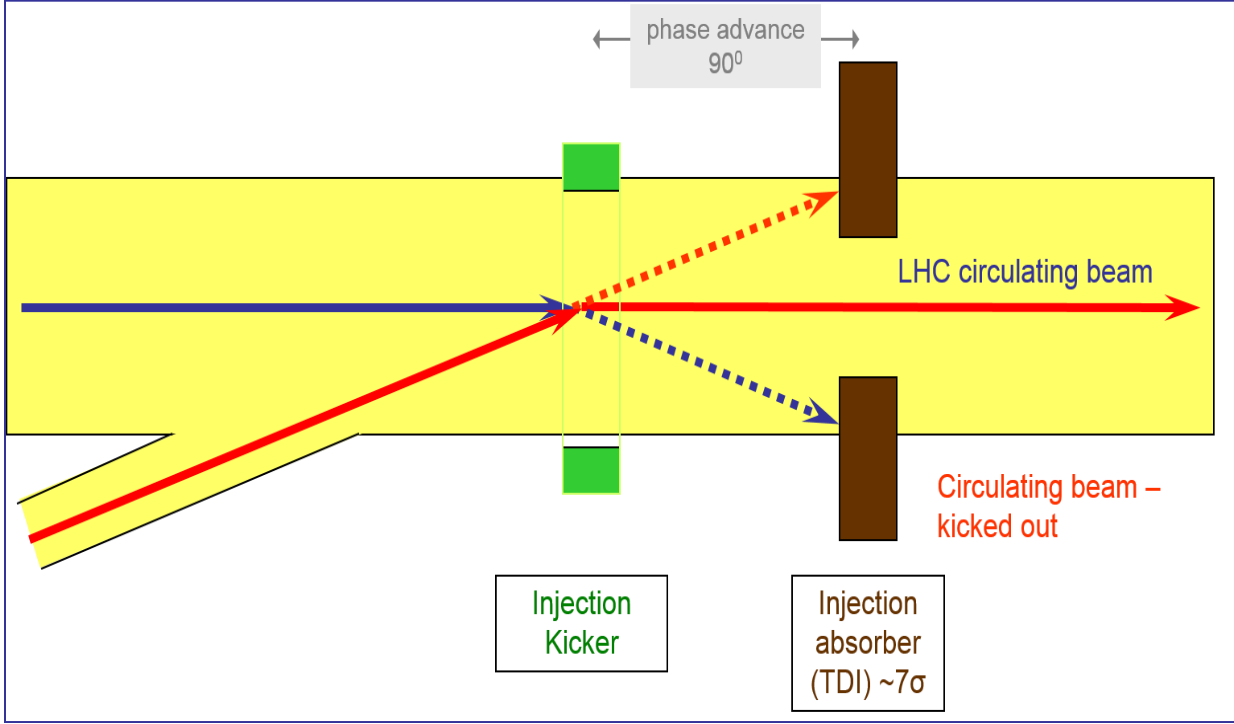
Passive protection

- Preferred if possible to operate without active protection
- Active protection not possible, e.g. the reaction time is too short
- Monitors fail to detect a dangerous situation (redundancy)

Passive protection

- Is always necessary when the time required for the response is too short (…remember the limitation of the speed of light)
- One example is the fast injection of a high intensity beam into a synchrotron with a fast kicker magnet

- If beam can damage hardware, **protection absorbers** are required
- For movable absorbers: need to be made sure that they are at the **correct position** of the absorber with respect to the beam during injection



LHC strategy for machine protection

• Definition of aperture by collimators.	**Beam Cleaning System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Collimator and Beam Absorbers**
• 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** **Stop beam at source**
• 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**

Three Principles for Machine Protection

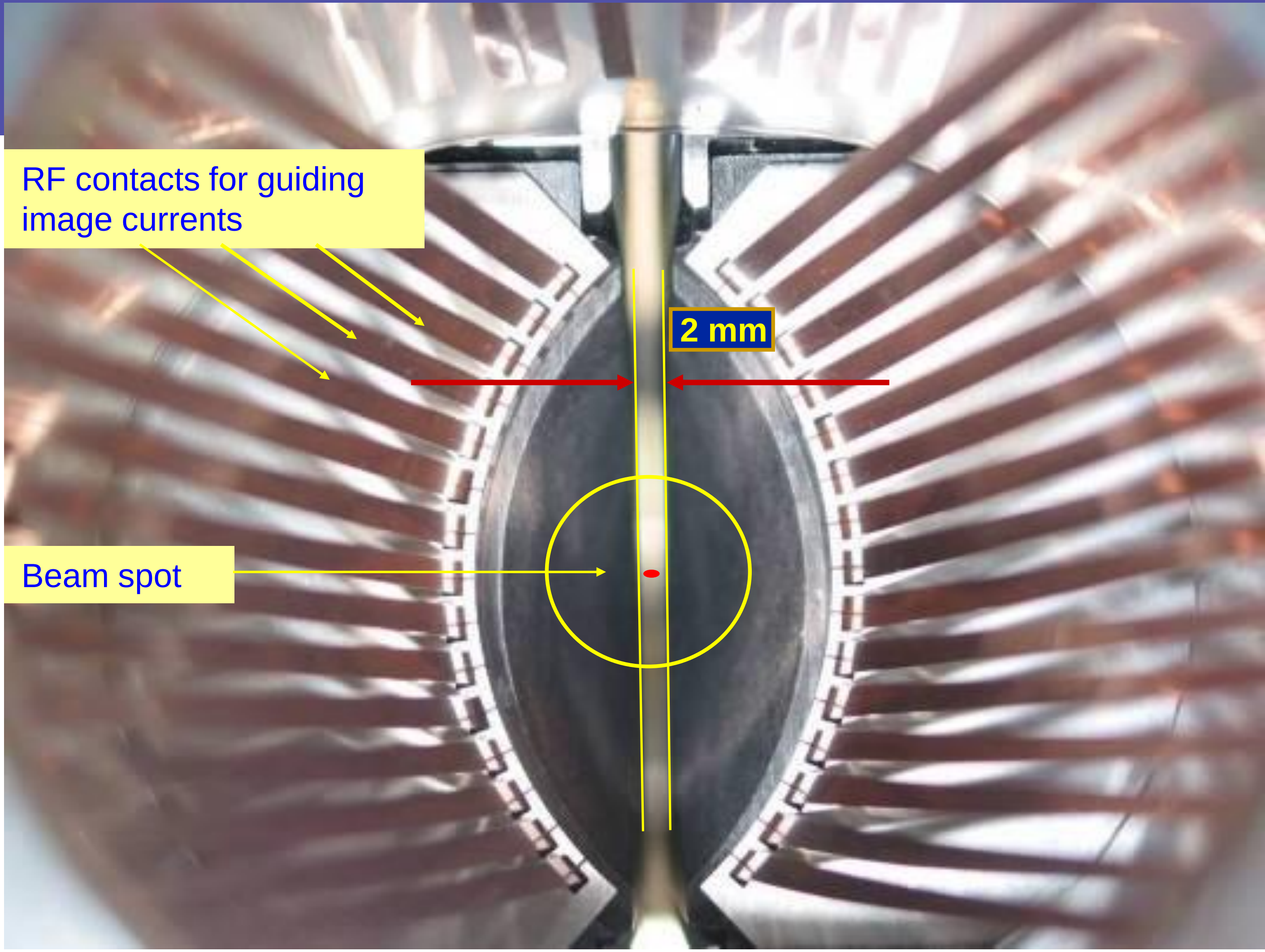
1. **Protect the equipment** (machine protection systems + interlock systems)

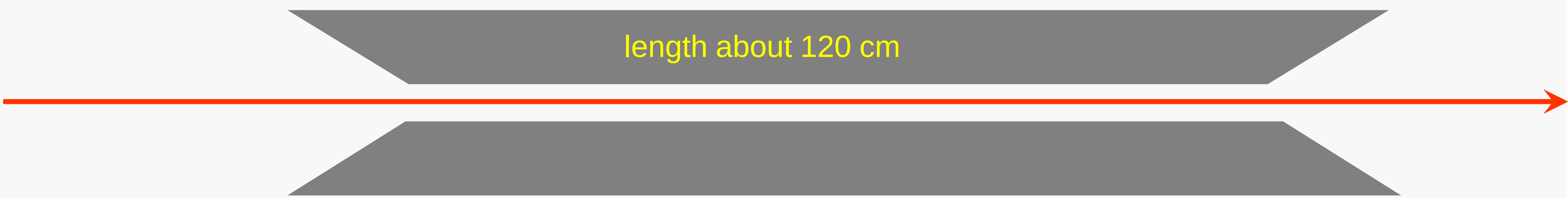
2. **Protect the process** (high availability systems)
   - Machine protection systems will always contribute to downtime
   - Protection action ONLY if a hazard becomes active (e.g. something went wrong threatening to damage equipment)

3. **Provide the evidence** (post mortem, logging of data)
   - Provide post mortem buffers in equipment (record data, and stop after protection action kicks in) – 70% of LHC luminosity fills dumped prematurely
   - Synchronisation of different systems is ultra – critical, to understand what happened
   - Post operational checks by the controls system

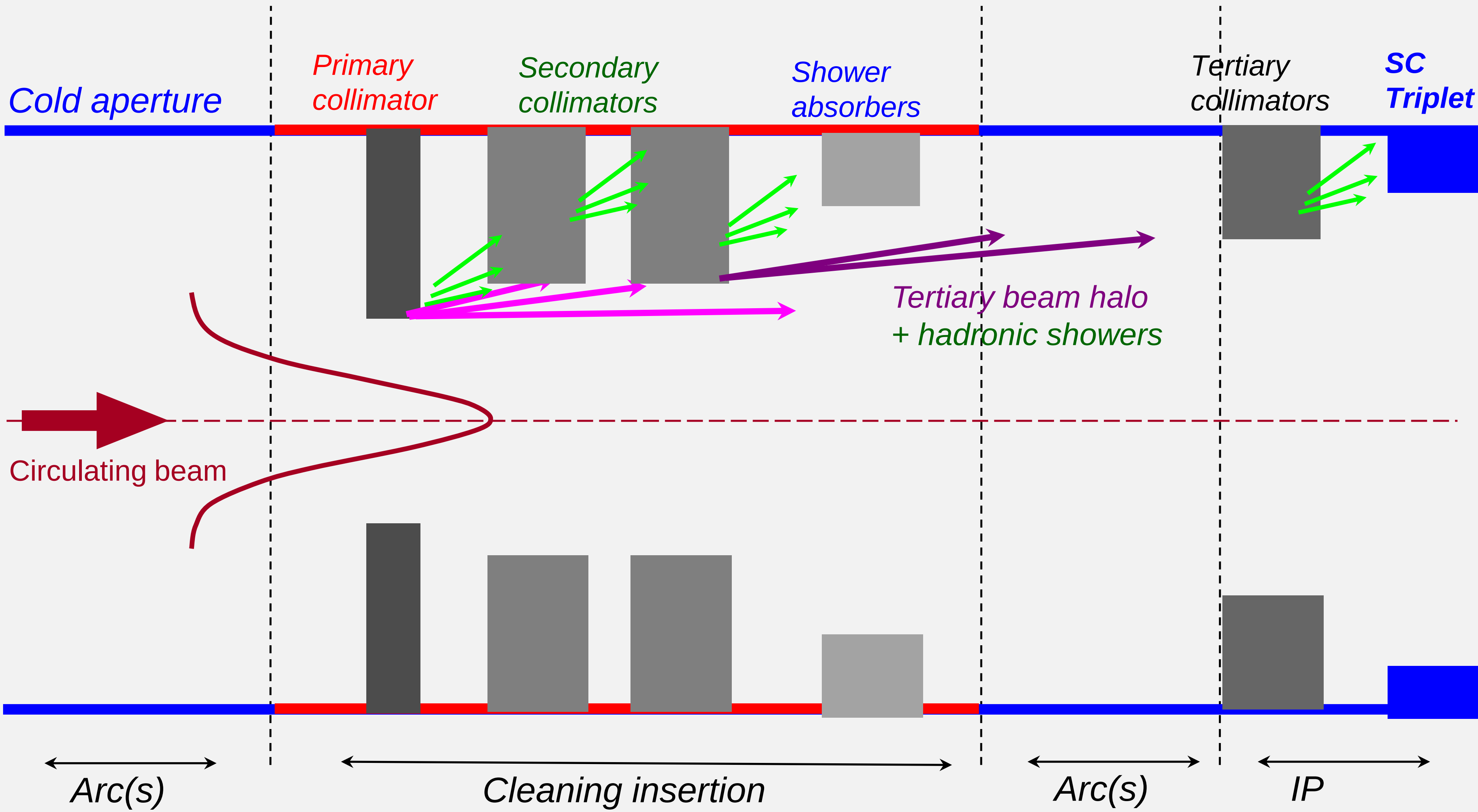
View of a two sided collimator

about 100 collimators are installed in LHC





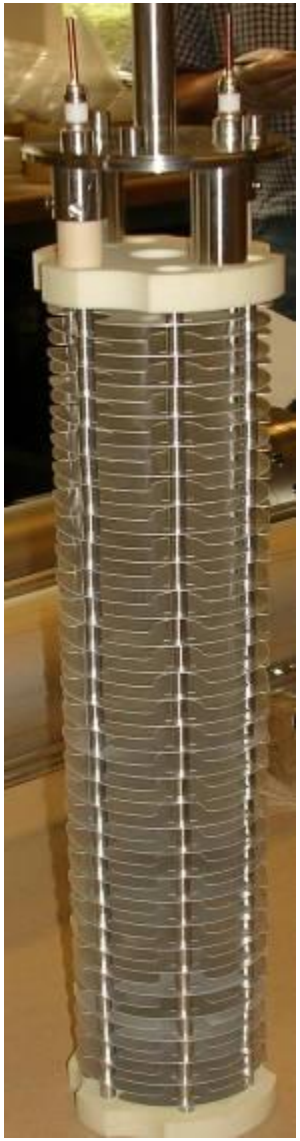
Betatron beam cleaning



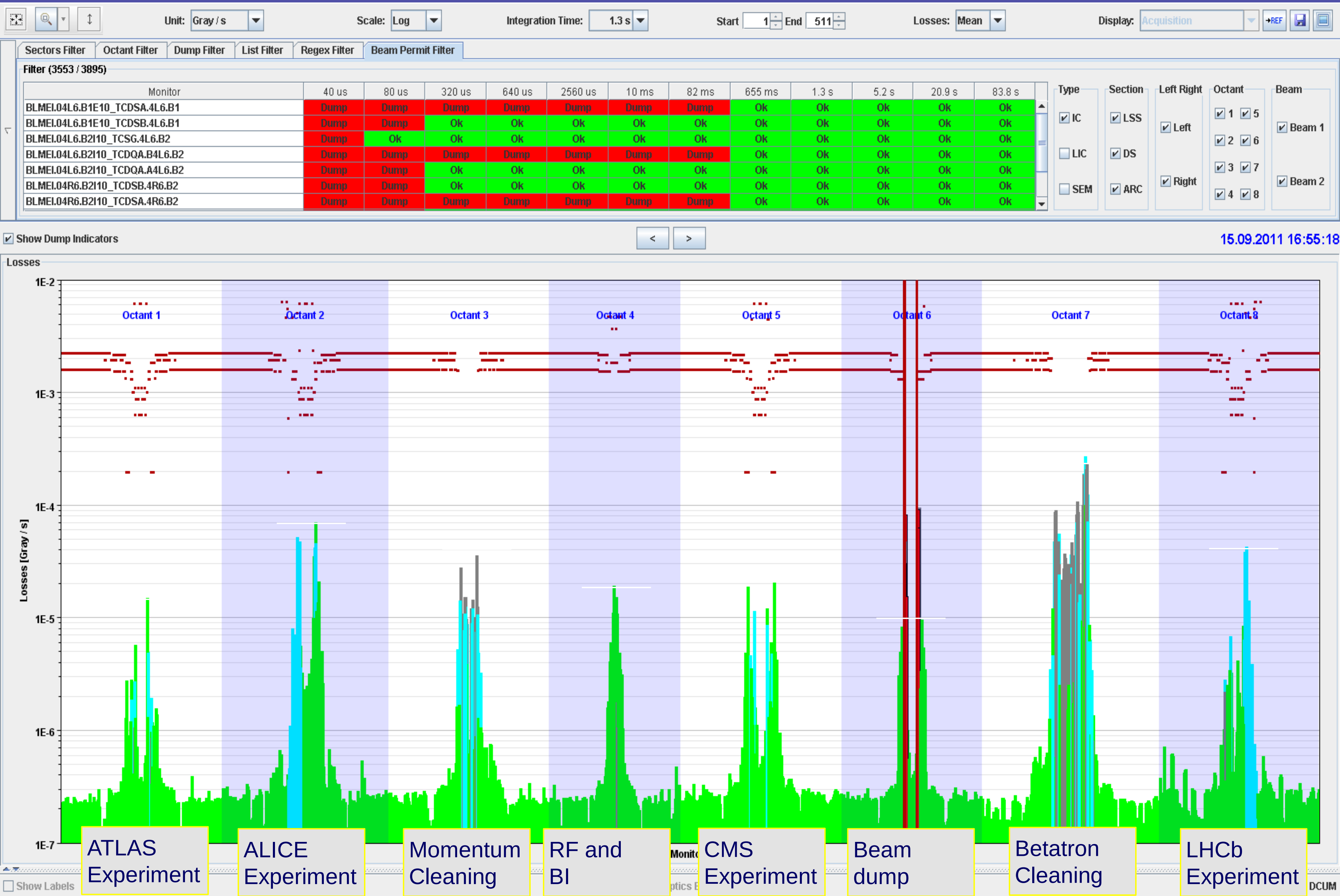
About 99.99% of the particle lost are captured in the cleaning insertion

Illustration drawing

- 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 !
- Very important beam instrumentation!



BLM system: beam losses before 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
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_TCSG.4L6.B2	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.A4L6.B2	Dump	Dump	Ok	Ok	Ok	Ok	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

Continuous beam losses during collisions

Unit: Gray / s Scale: Log Integration Time: 1.3 s Start 490 End 511 Losses: Mean Display: Acquisition

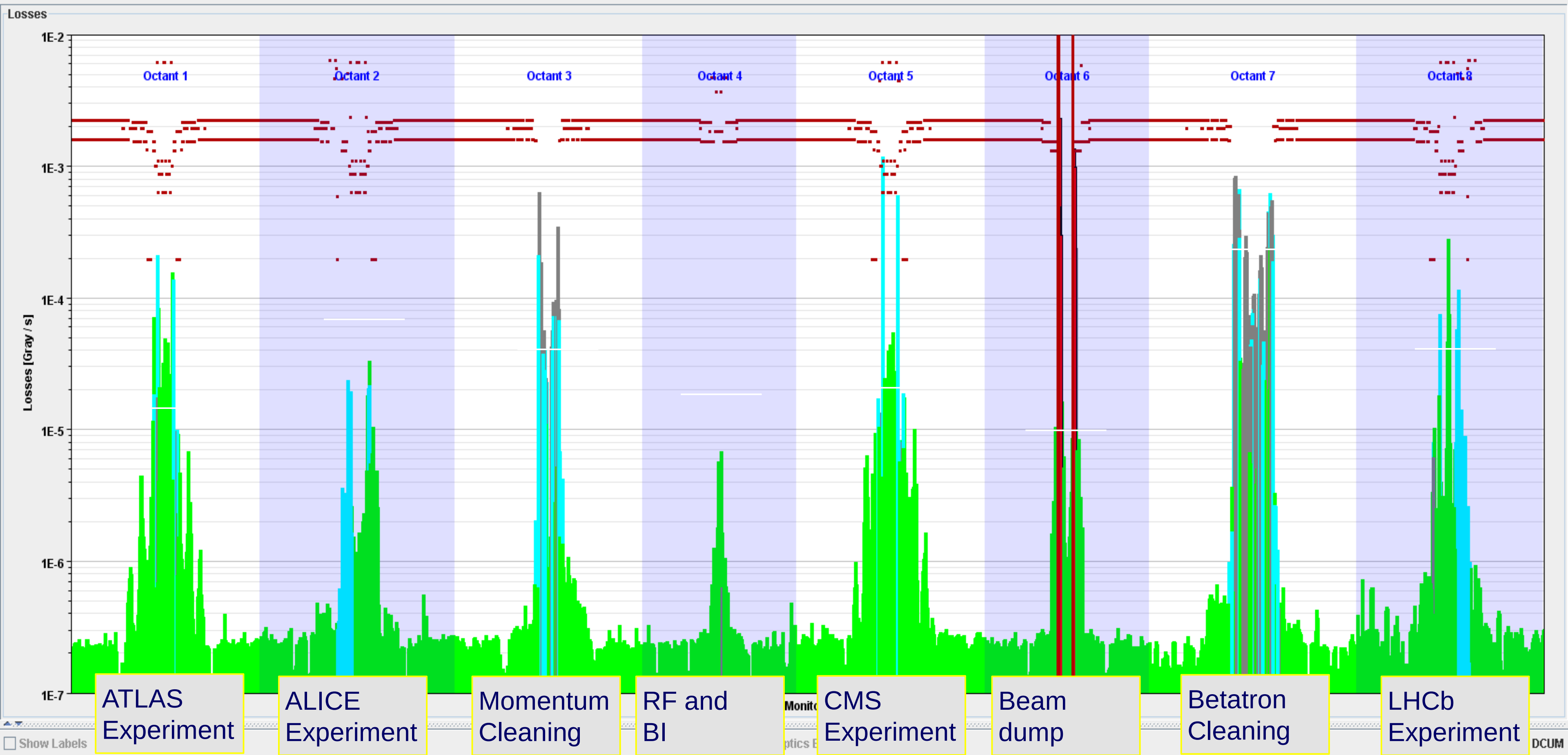
Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

Filter (3553 / 3895)

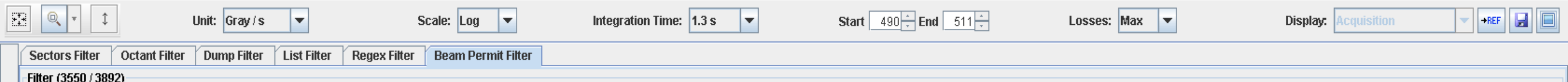
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCSG.4L6.B2	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.A4L6.B2	Dump	Dump	Ok	Ok	Ok	Ok	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

Type: IC, LIC, SEM — Section: LSS, DS, ARC — Left Right: Left, Right — Octant: 1, 2, 3, 4, 5, 6, 7, 8 — Beam: Beam 1, Beam 2

Show Dump Indicators 13.09.2011 21:04:59



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
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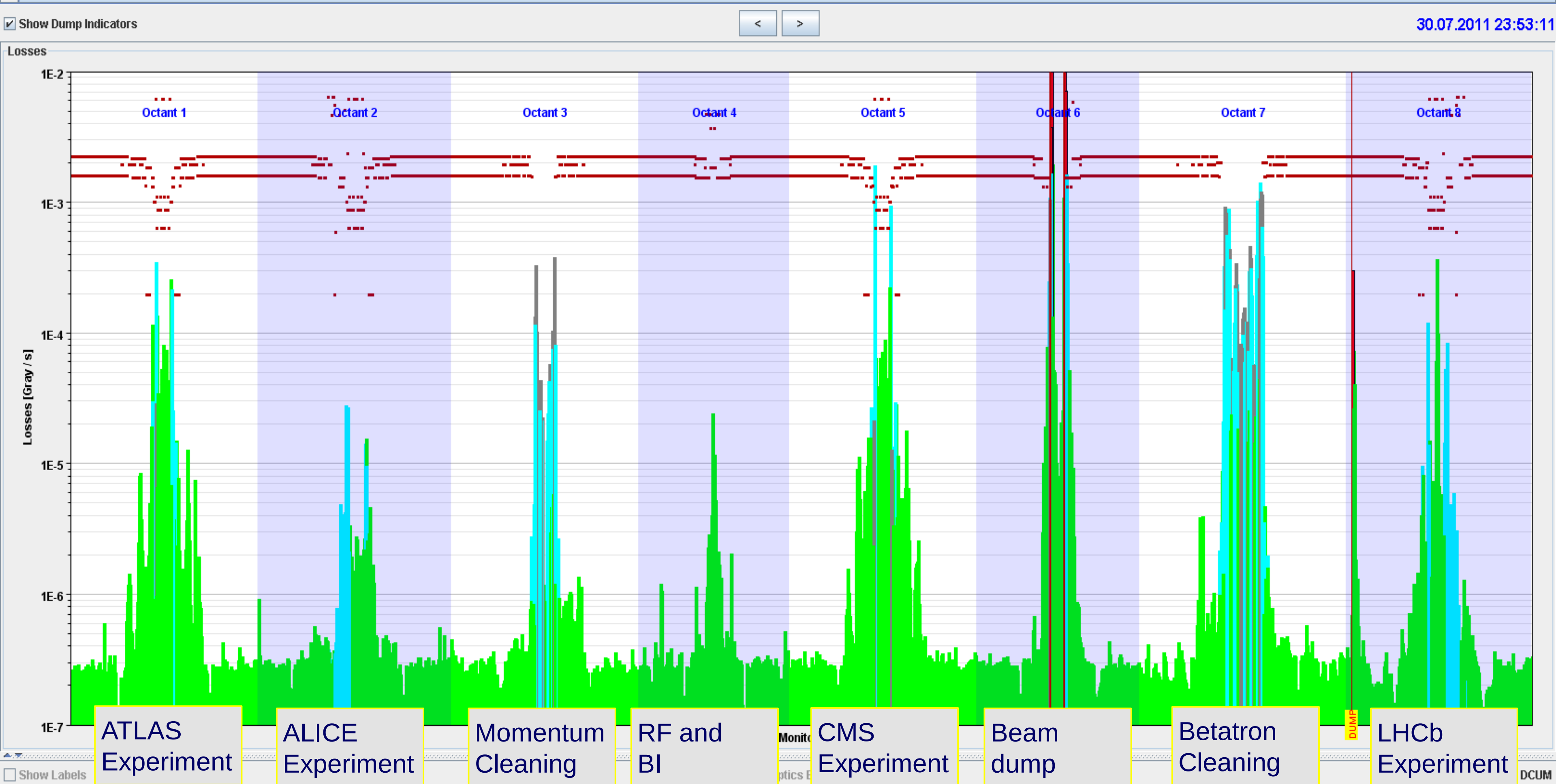
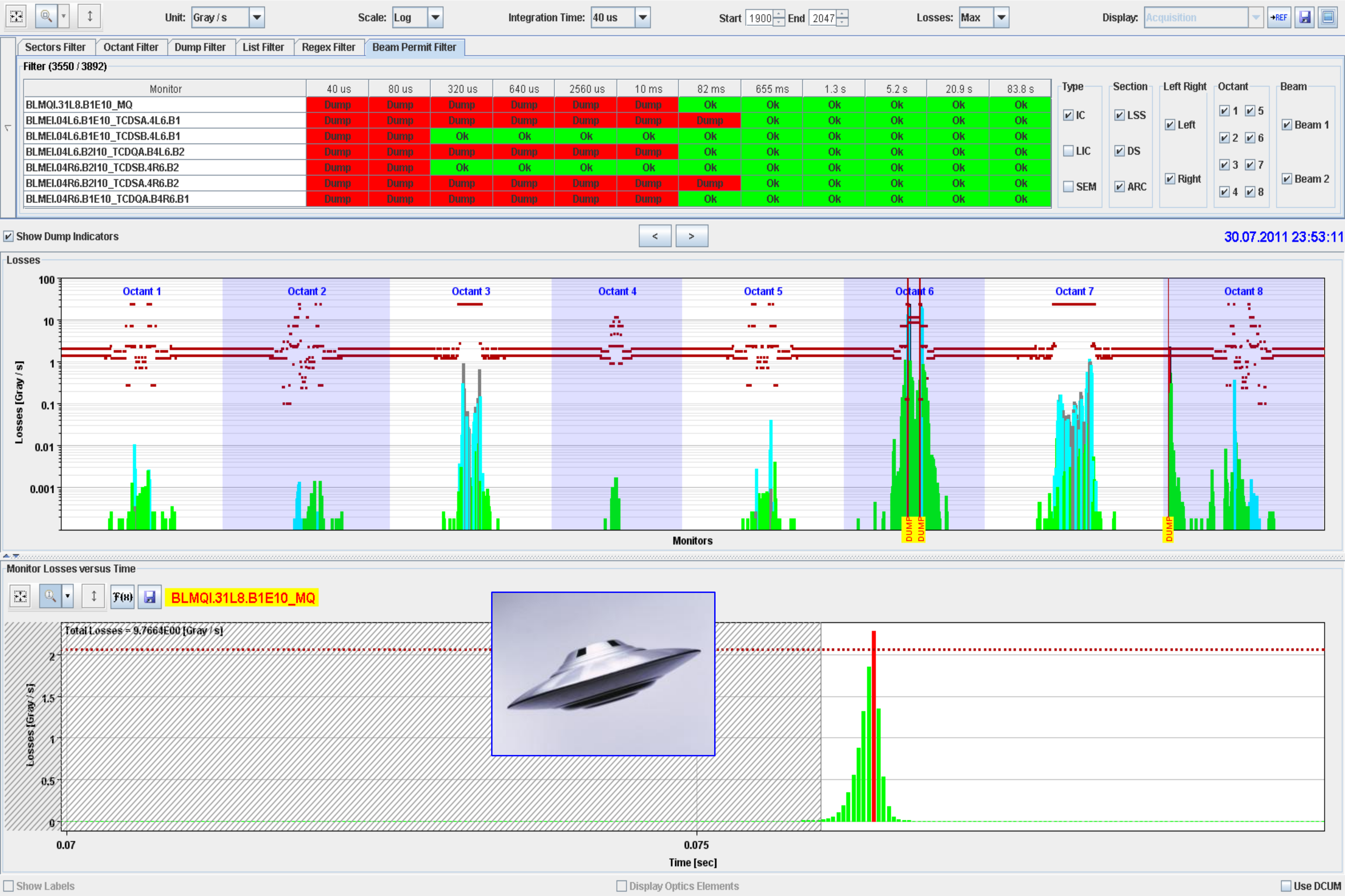


Accidental beam losses : UFOs



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

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

- ESS (4 % duty cycle): in case of an uncontrolled beam loss during 1 ms, the deposited energy is up to 130 kJ, for 1 s it is up to 5 MJ
- Inhibit the beam after detecting uncontrolled beam loss – how fast?

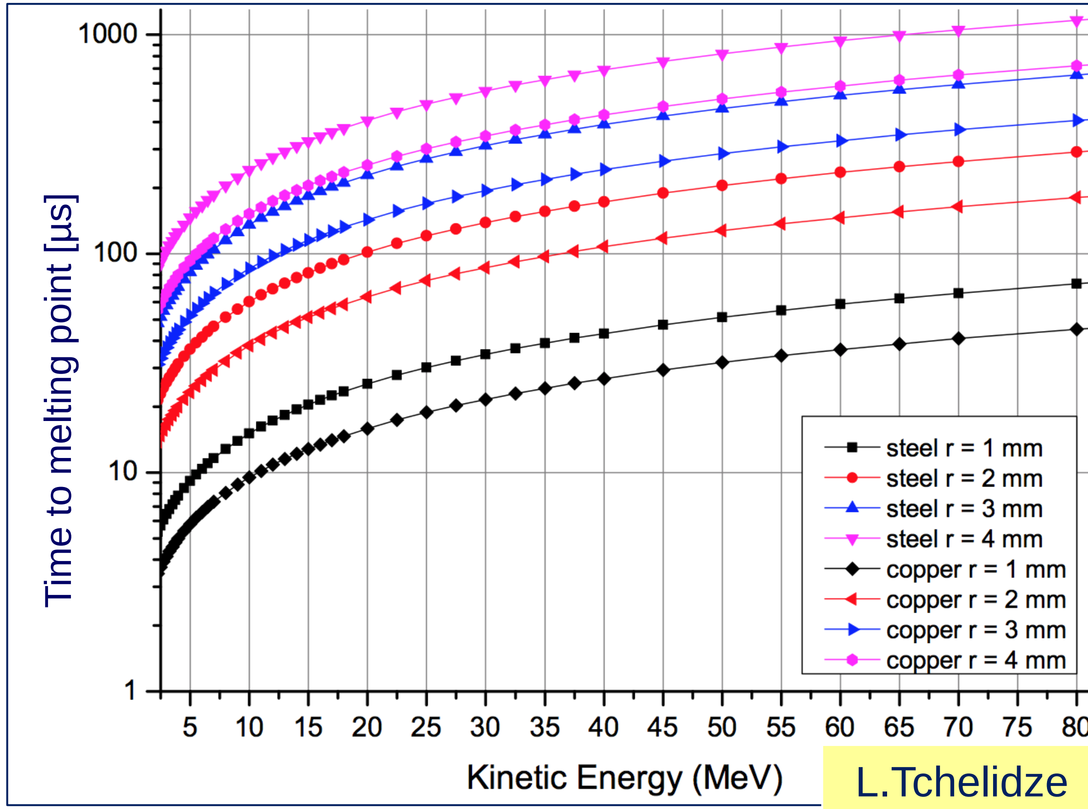
- The delay between detection and "beam off" to be considered

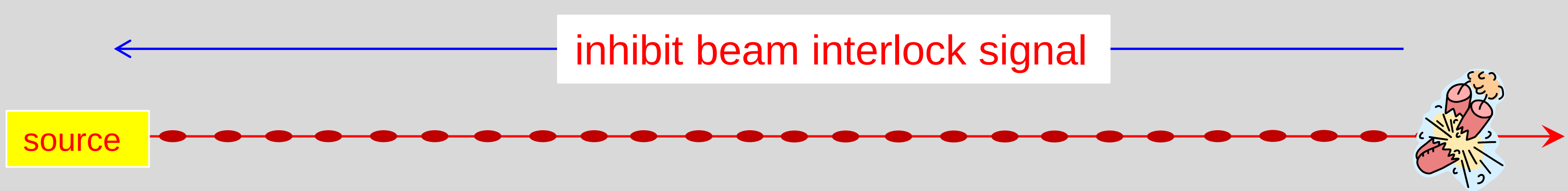
Example for ESS

Example:

After the DTL normal conducting linac, the proton energy is 78 MeV. In case of a beam size of 2 mm radius, melting would start after about 200 μs.

Inhibiting beam should be in about 10% of this time.

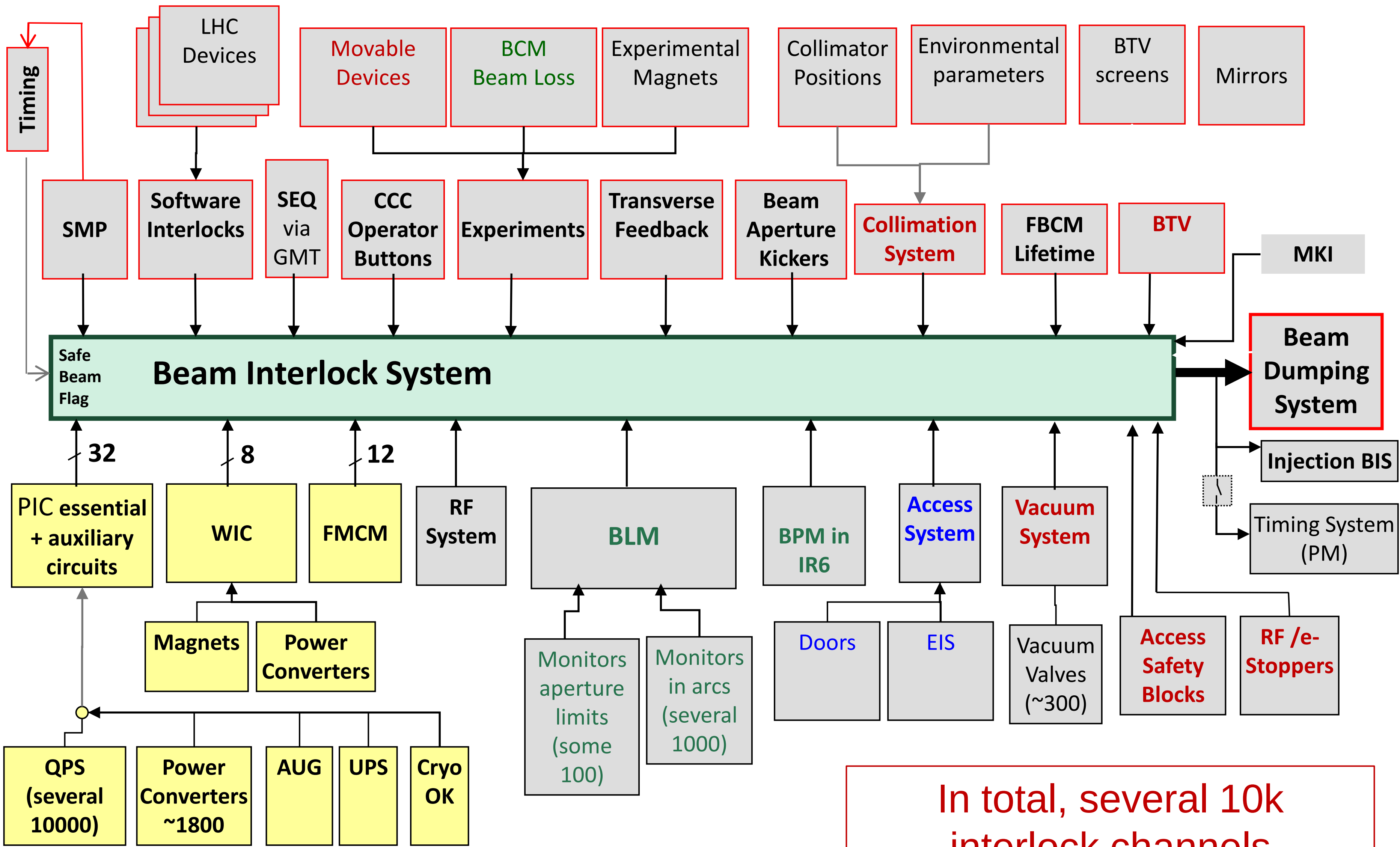




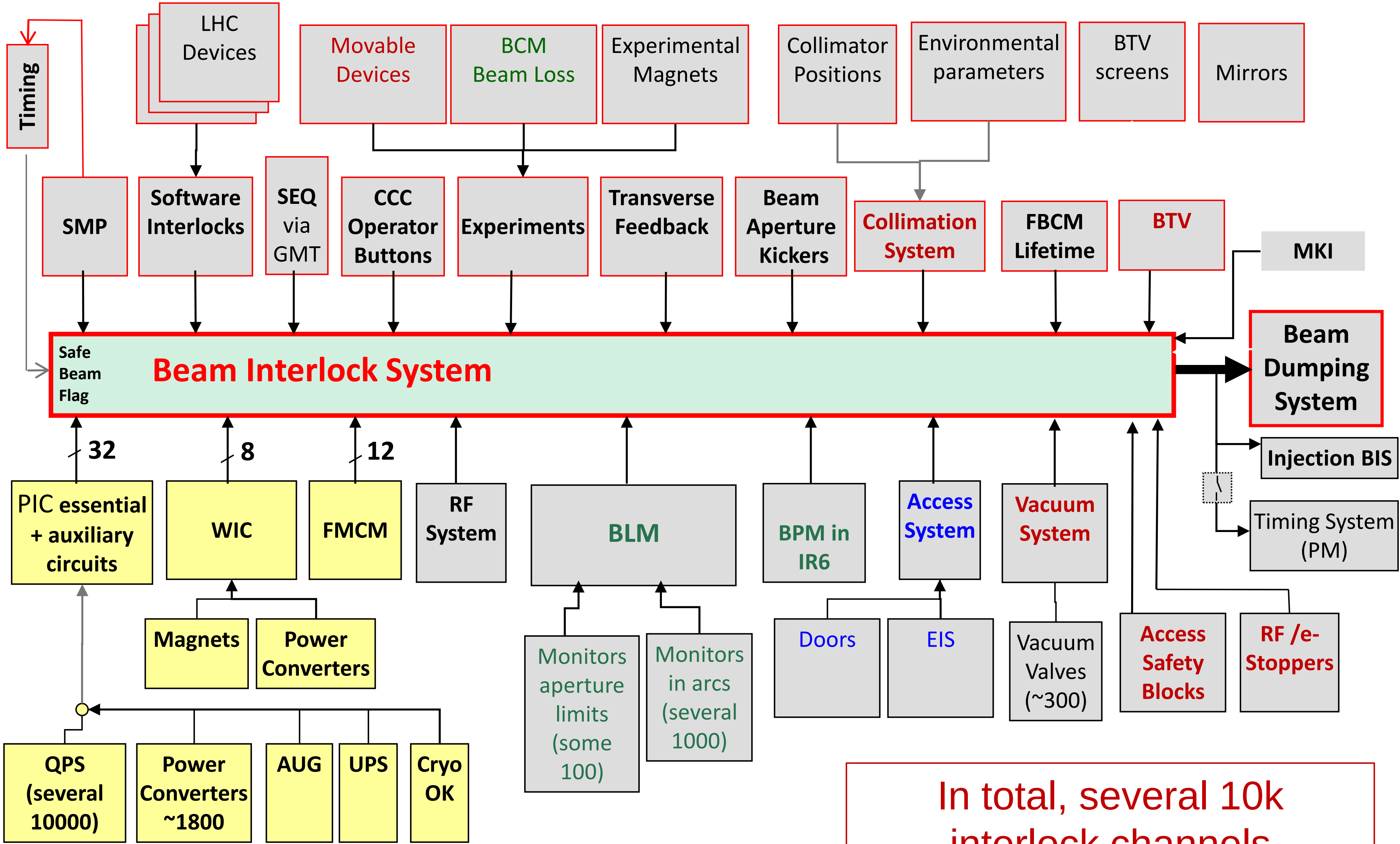
dT = dT_detect failure + dT_transmit signal + dT_inhibit source + dT_beam off

Interlock Systems

LHC Interlock Systems and inputs

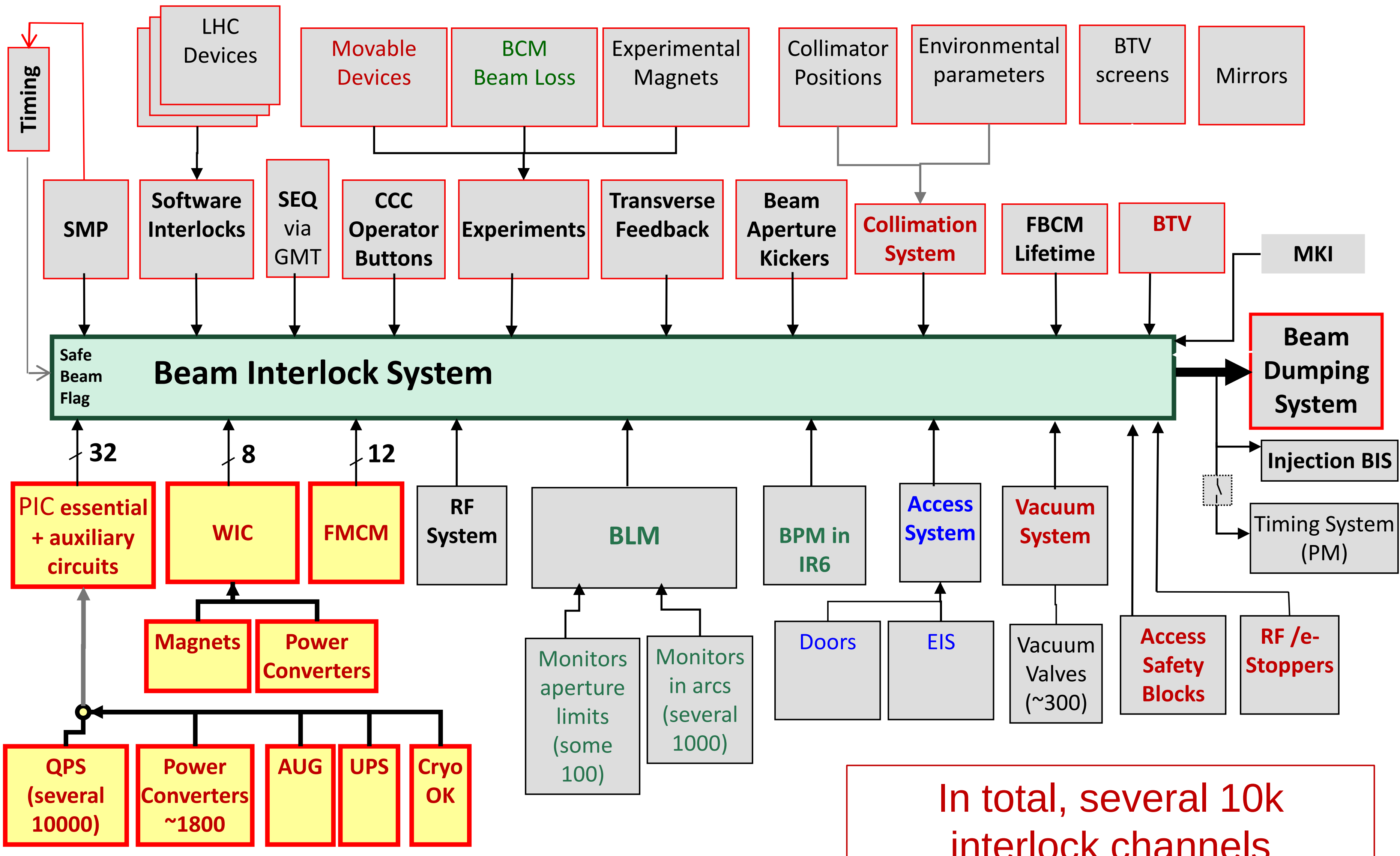


In total, several 10k interlock channels



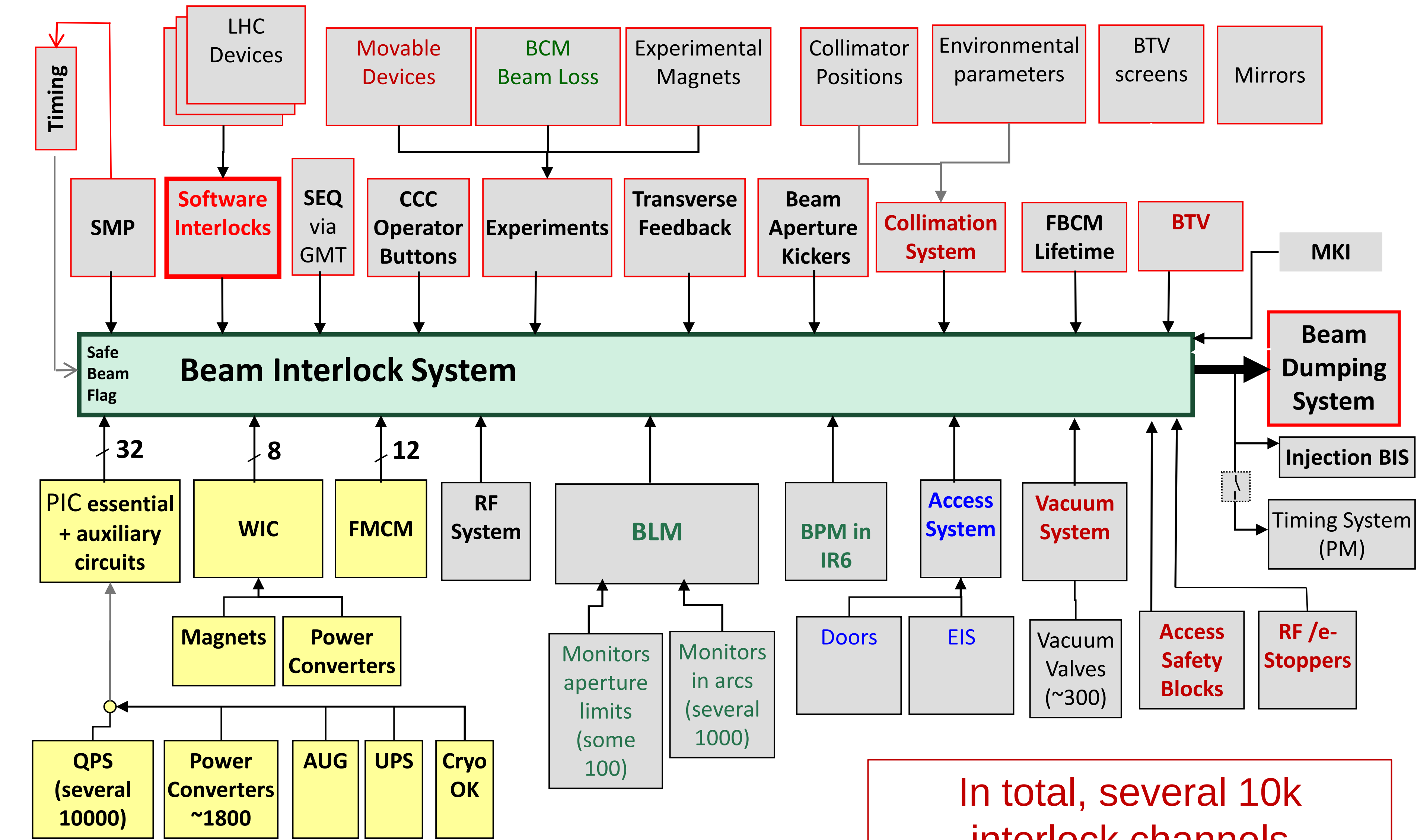
In total, several 10k interlock channels

Powering Interlock Systems



In total, several 10k interlock channels

Software Interlock System



In total, several 10k interlock channels

MP systems: design recommendations

- **Avoid** (unnecessary) **complexity** for protection systems
- **Failsafe** design
  - Detect internal faults
  - Possibility for remote testing, for example between two runs
- Critical equipment should be **redundant** (possibly diverse)
- Critical processes not by software and operating system
- No remote changes of most critical parameters
- **Calculate safety / availability / reliability**
  - Use methods to analyse critical systems and predict failure rate
- **Managing interlocks**
  - Bypassing of interlocks is common practice **(keep track!)**
  - LHC: bypassing of some interlocks possible for “setup beams”
- **Time stamping** for all system with adequate **synchronisation**

Machine 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

Thank you very much for your attention

Important tool for you working on protection

Niels Bohr and A. Einstein

Horseshoe

- Einstein was visiting in the home of Nobel Prize winner Niels Bohr, the famous atom scientist.
- As they were talking, the friend kept glancing at a horseshoe hanging over the door. Finally, unable to contain his curiosity any longer, he demanded:
- “Niels, it can’t possibly be that you, a brilliant scientist, believe that foolish horseshoe superstition! ? !”
- “Of course not,” replied the scientist. “But I understand it’s lucky whether you believe in it or not.”

Acknowledgement

- Many colleagues at CERN, working on machine protection and interlocks
- Several colleagues from other labs – profiting from their experience and many discussions, in particular from DESY, BNL and ESS

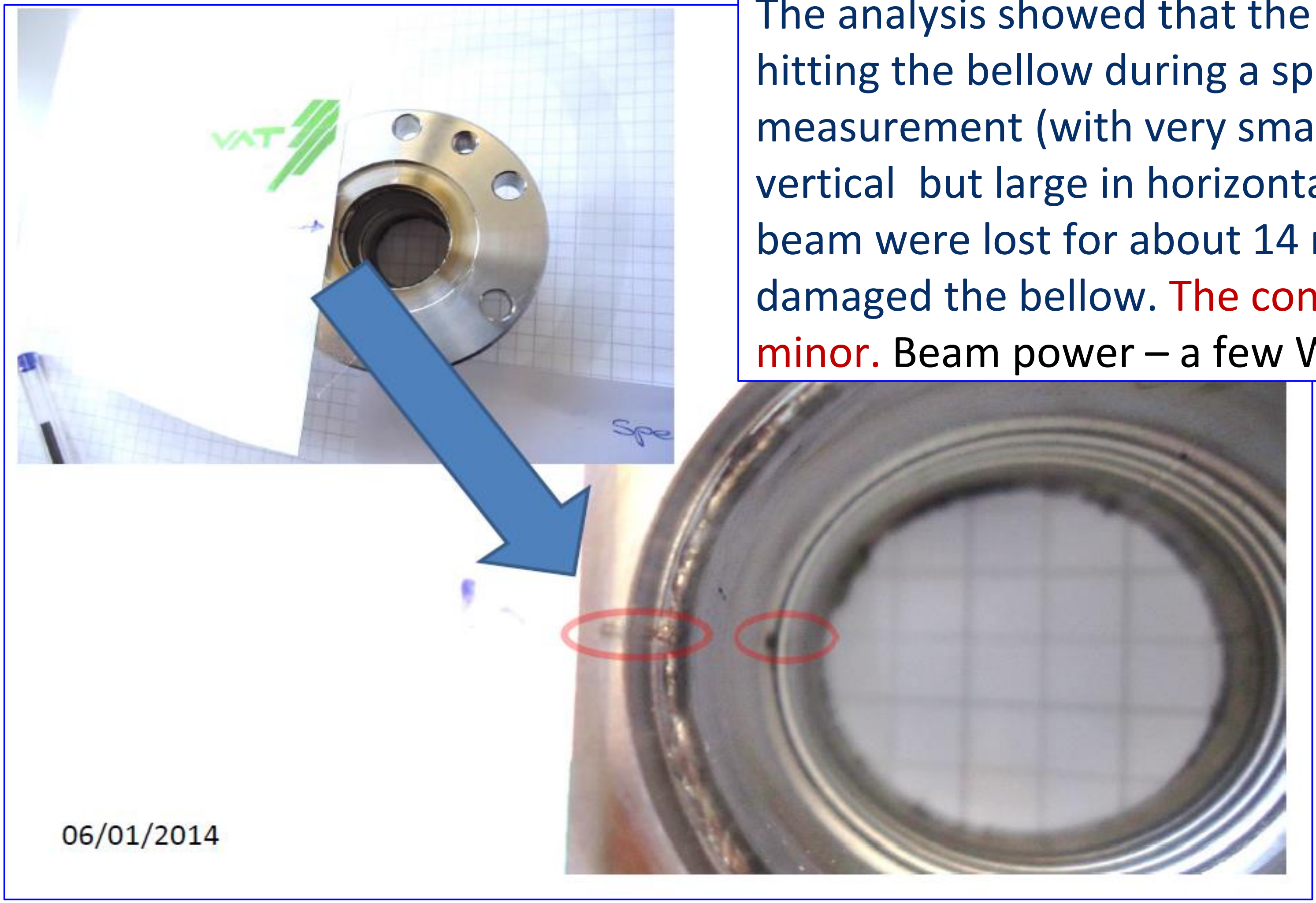
- A special thanks to some of my colleagues at CERN, e.g. Bruno Puccio, Jörg Wenninger, Markus Zerlauth and Daniel Wollmann,

Reserve

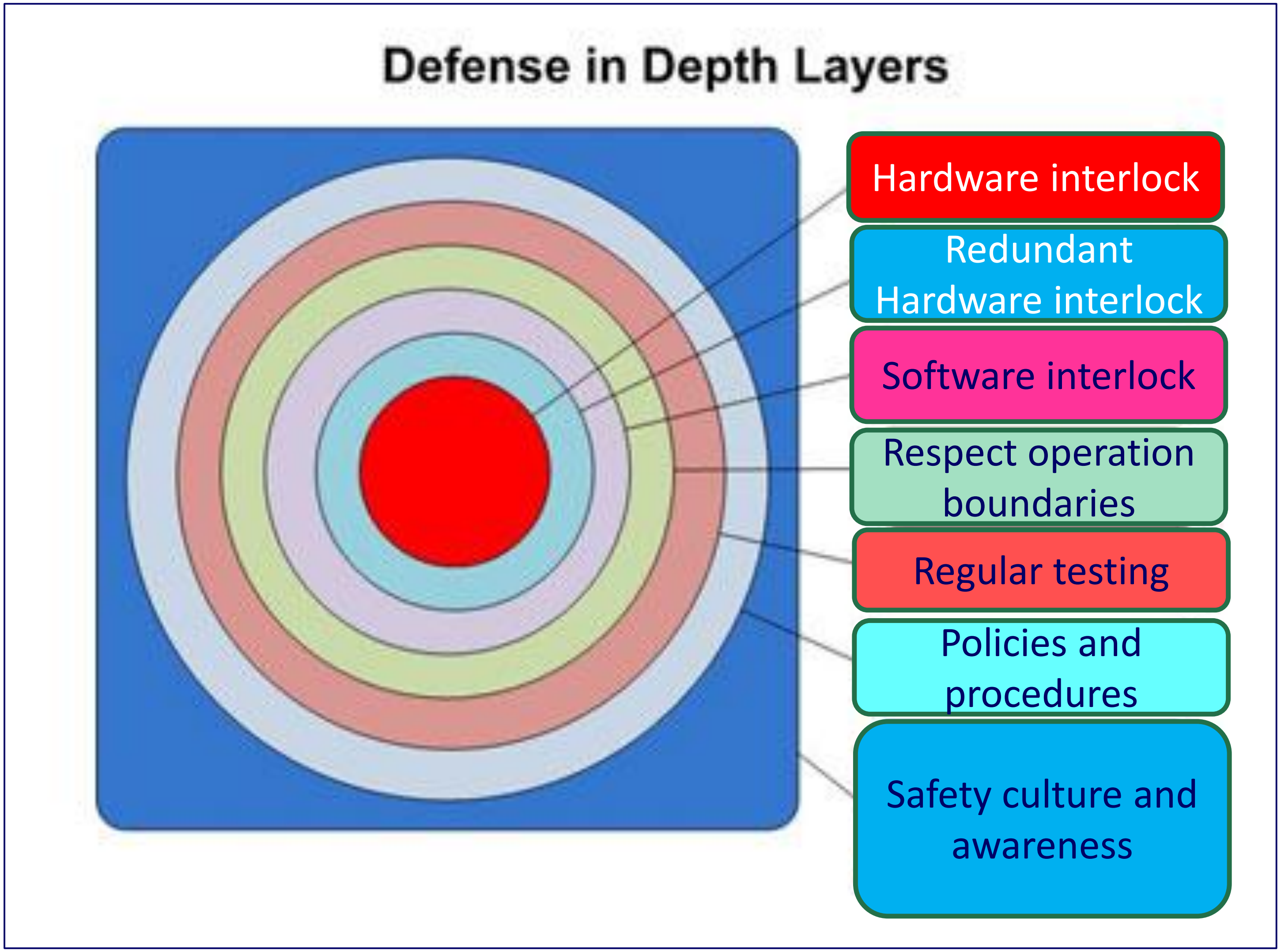
CERN-LINAC 4 during commissioning at 3 MeV

December 2013 a vacuum leak on a below developed in the MEBT line.

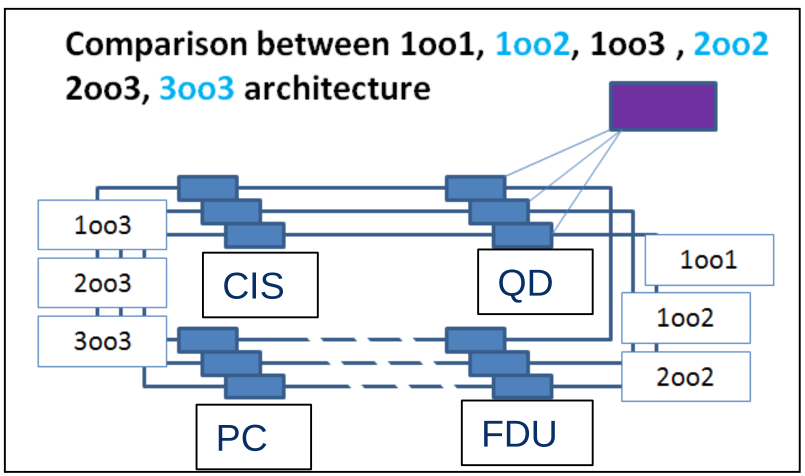
The analysis showed that the beam has been hitting the bellow during a special measurement (with very small beams in vertical but large in horizontal), ~16% of the beam were lost for about 14 minutes and damaged the bellow. The consequences were minor. Beam power – a few W.



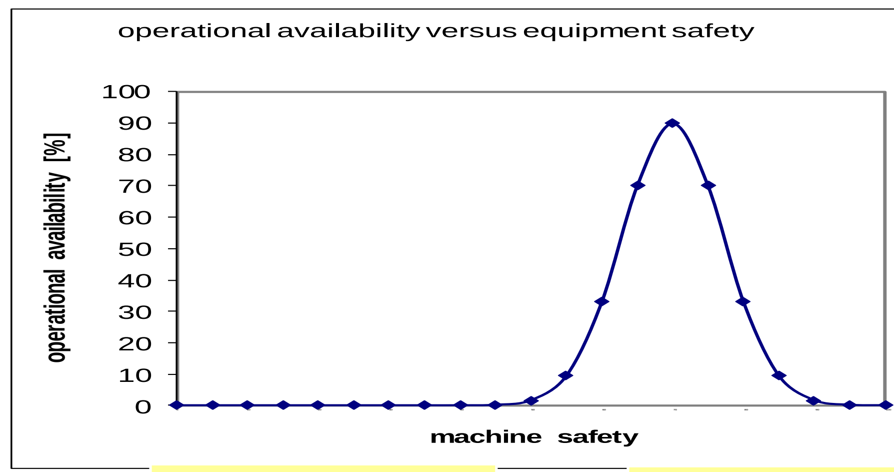
A.Lombardi


Defense in Depth Layers
Hardware interlock
Redundant Hardware interlock
Software interlock
Respect operation boundaries
Regular testing
Policies and procedures
Safety culture and awareness

- If the only objective is to maximising safety, this risks to reduce the overall availability – find a reasonable compromise
- For protection system: majority voting to be considered to increase failure tolerance
- Optimum has been found with 2oo3 voting systems
- Prototype powering interlock system developed for ITER



S. Wagner



Downtime for repairs due to insufficient protection systems

Downtime dominated by too complex Protection Systems

Design guidelines 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
- 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

The LHC machine need protection systems, but….

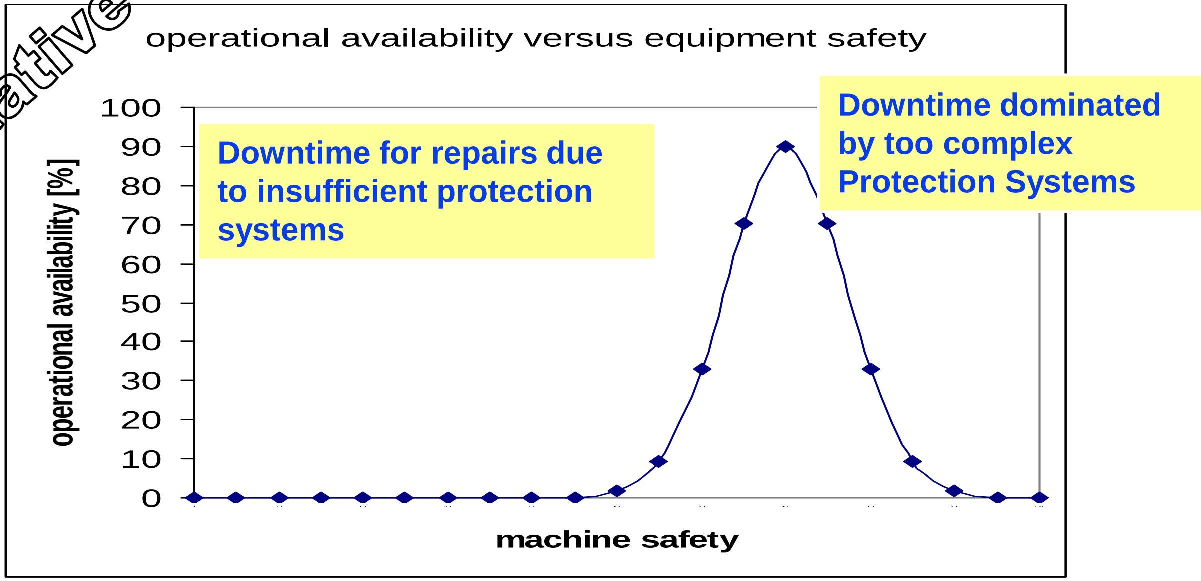
Machine Protection is not an objective in itself, it is to

maximise operational availability by minimising down-time (quench, repairs)

avoid expensive repair of equipment and irreparable damage

Operations workshop
R.Schmidt - Villars
30/01/2001

Qualitative



Side effects from LHC Machine Protection System compromising operational efficiency must be minimised

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**

……then **back to square 1**

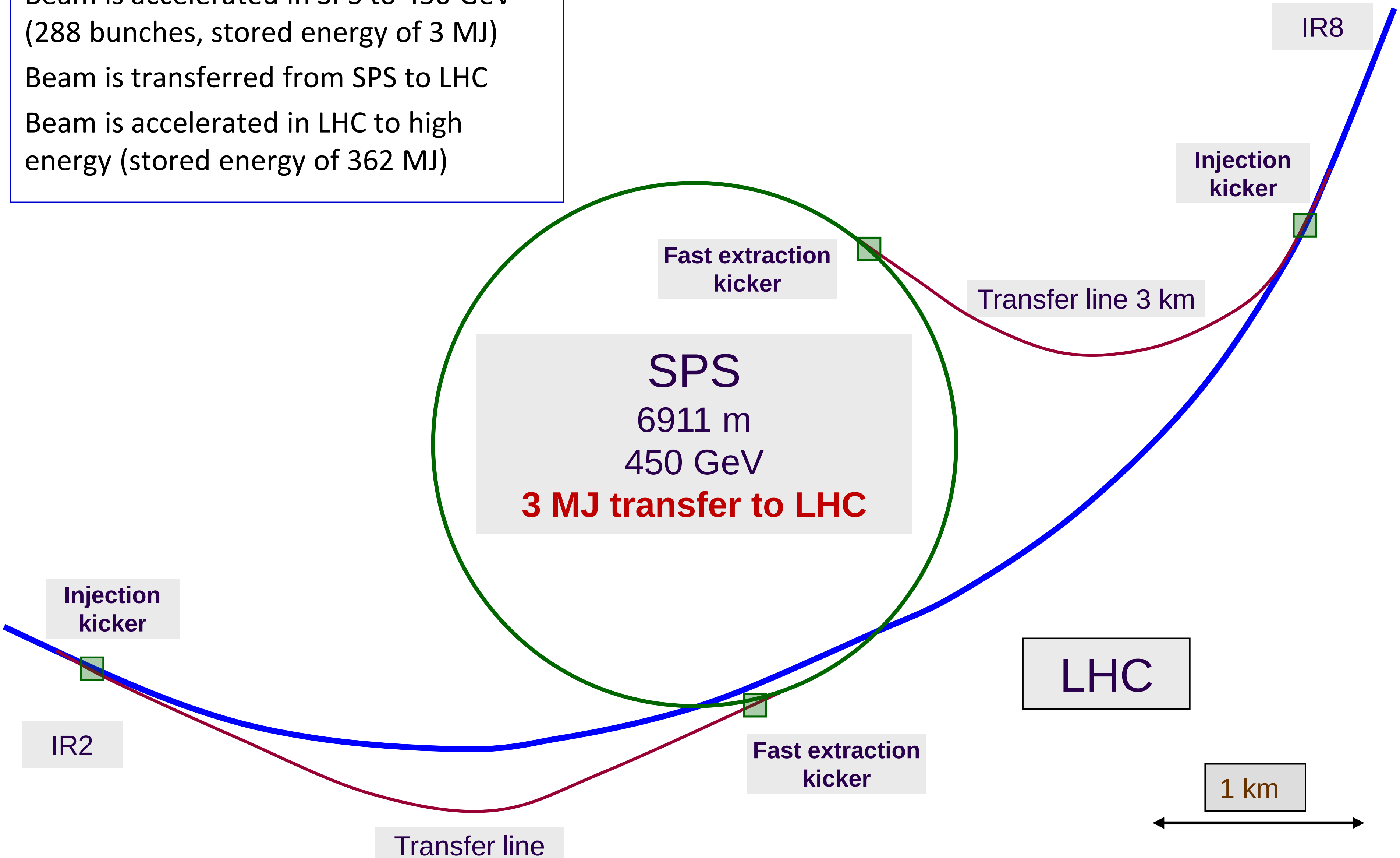
….starting in the early design phase, continuous effort, not only once….

Example for LHC: SPS, transfer line and LHC

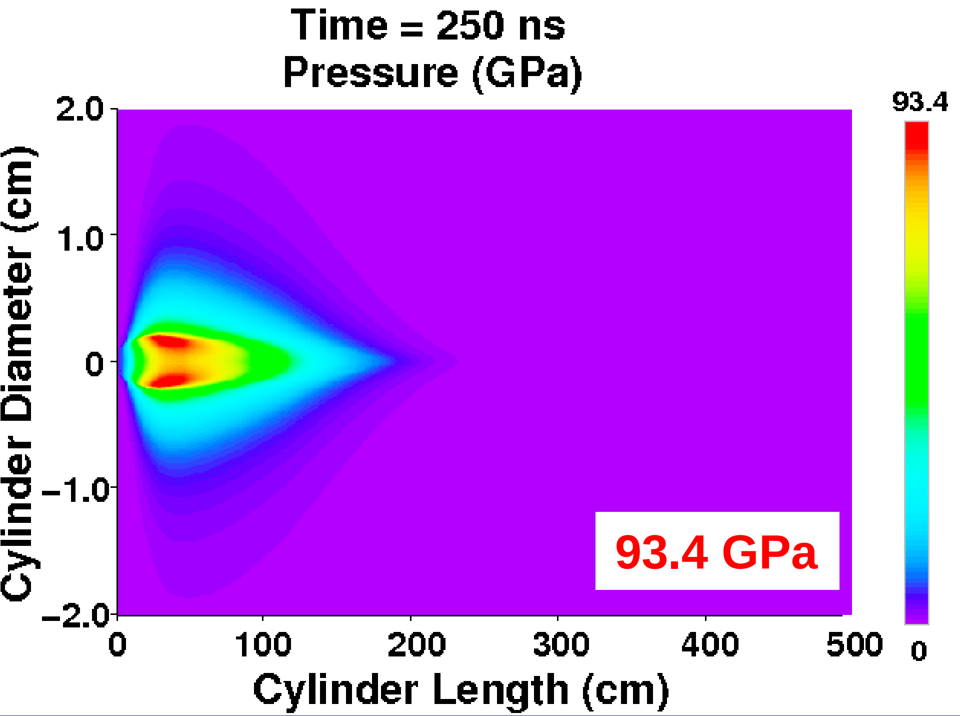
Beam is accelerated in SPS to 450 GeV (288 bunches, stored energy of 3 MJ)

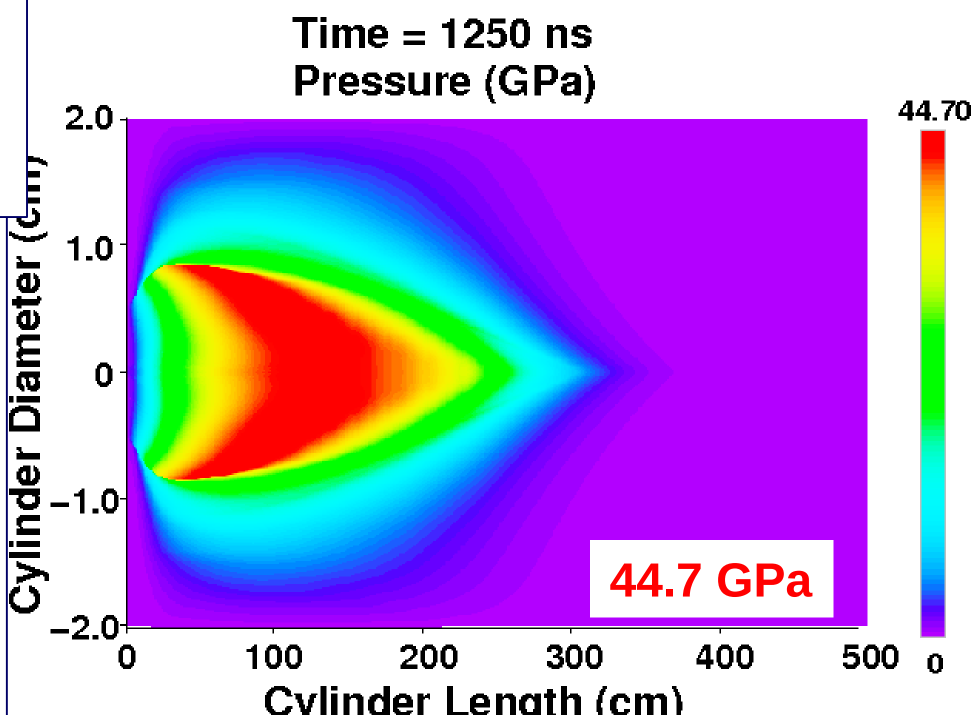
Beam is transferred from SPS to LHC

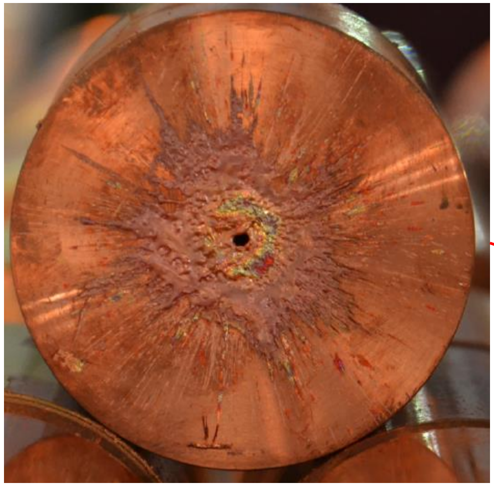
Beam is accelerated in LHC to high energy (stored energy of 362 MJ)

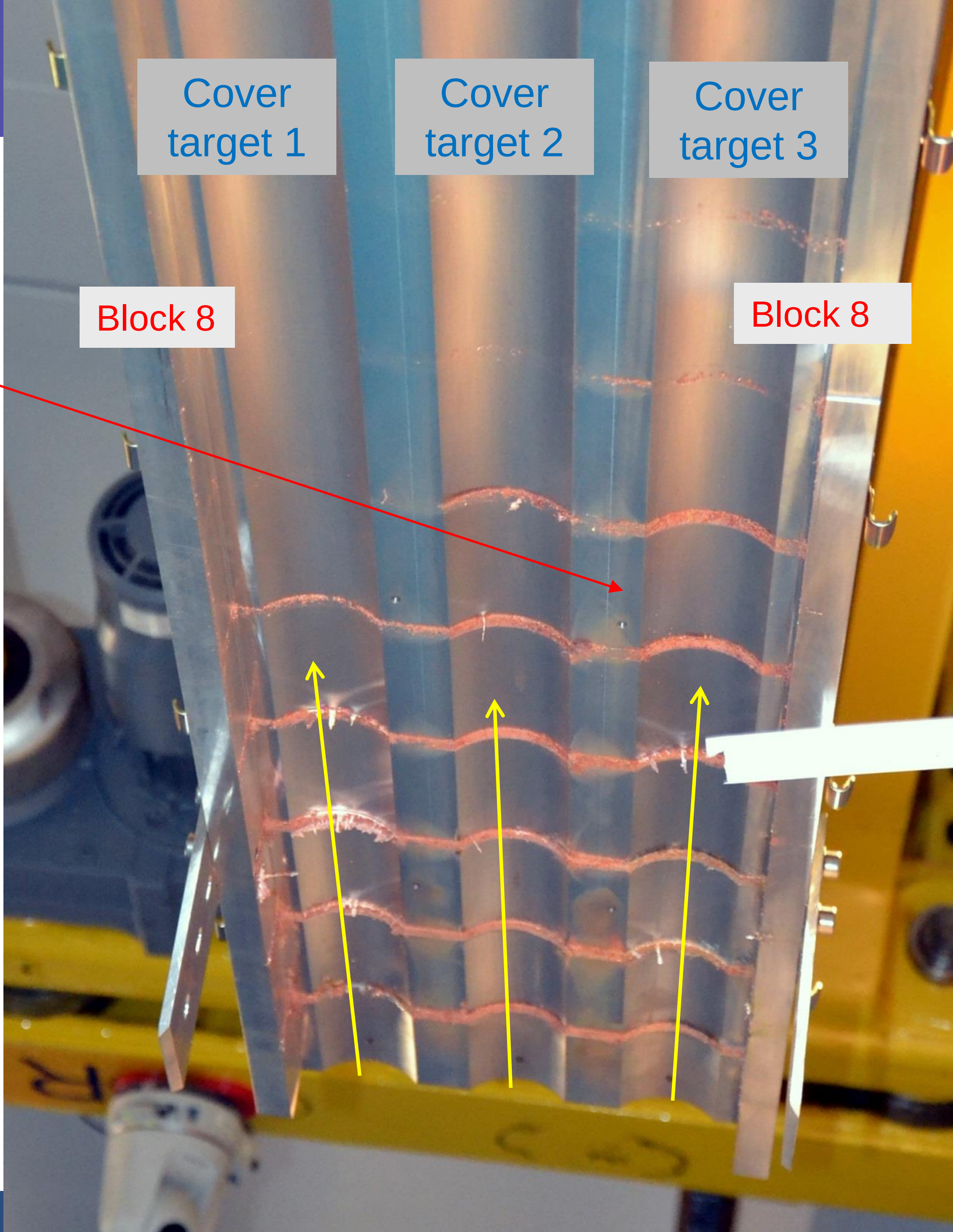


Pressure profile









- Cover of the targets: the molten copper escapes between the targets and leaves clear traces on the cover
- The range of the beam in target 3 is larger than in target 1 and 2
- Clear indication for tunnelling

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 a failure with beam instrumentation ….before it is too late…
- Stop beam operation
  - extract beam into beam dump block
  - inhibit injection
  - stop beam by beam absorber / collimator
- Elements in the protection systems
  - equipment monitoring and beam monitoring
  - extraction protection
  - Injection protection
  - collimators and beam absorbers
  - beam interlock systems linking different systems

Reaction time for Interlock systems

- **Fast** interlock systems
  - Reaction time can be down to some ns (typically µs)
- **Slow** interlock systems
  - From seconds down to several milliseconds

- **Interlock systems** based on **hardware** (Electronics / Asics)
- Interlock systems including **intelligent controllers** (**FPGA** Field Programmable Gate Array)
  - Extremely fast, ns
- **PLCs** **P**rogrammable **L**ogic **C**ontrollers (standard and safety PLCs)
  - Milliseconds to hundred milliseconds (safety PLCs)
- **Software** interlock systems
  - In the order of one second

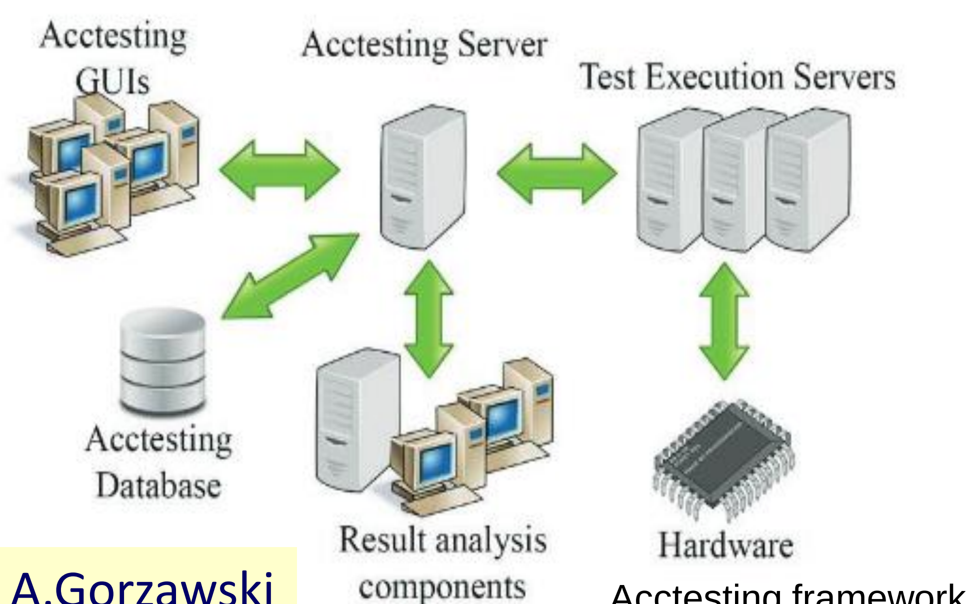
Interlocks systems: other considerations

M. Kwiatkowski
B. Todd

- **P**rotection **I**ntegrity **L**evel (**PIL**)
  - Derived from **S**afety **I**ntegrity **L**evel (SIL) - IEC 61508
  - PIL1 to PIL4: PIL1…lowest risk, PIL4…highest risk
- **Radiation** environment (e.g. Single Event Effects)
- **Communication** layer
  - Current loops, frequency loops, use of intelligent network such as Profibus, Profisafe, Ethernet, …..
  - Electrical, optical, wireless in the future (?)
- **Time for development** (in-house design of electronics, buying and programming PLCs, ….)
- **Lab environment**
  - Lab standards
  - Competence in the lab and maintainability
- Cost

- Design of the protection system: **testing to be considered**.
  - Correct commissioning and regular testing of protection system is vital to ensure reliable operation.
  - Repeated testing is very time consuming, can be extremely boring and prone to errors, in particular if done by humans.
  - Consider partial commissioning of accelerator (e.g. linacs)

- **Automatic test procedures** and automatic validation of the results via the controls system
- Framework for automatic testing used for LHC magnet system commissioning, about 10k tests performed.



A.Gorzawski

Acctesting framework

Machine Protection and Controls

Other aspects

- **Several million parameters** for the protection systems
  - Many parameters can only be defined with operational experience
  - Management of critical parameters
  - Access to these parameters
  - Ensure that parameters in database are the same as in hardware
- (Cyber) security – **access to critical parameters**
  - Highest PIL: not possible to modify parameters via controls system
  - Medium PIL: parameter can be changed via the control system, but strict controls for parameter changes, e.g. two people role
  - Low PIL: parameter can be changed via the control system
- **Several 10k interlock channels** that can prevent operation
  - Nightmare for starting-up of a system, in particular, if the risk is (close to) zero
  - Option for bypassing of interlocks to be included in the design