Beam Loss and Machine Protection Lecture I

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Summer Student Lectures 2017

DANGER

DO NOT OPERATE THIS MACHINE WITHOUT PROPER PROTECTION

Protection is required if there are risks

What are the risks ?

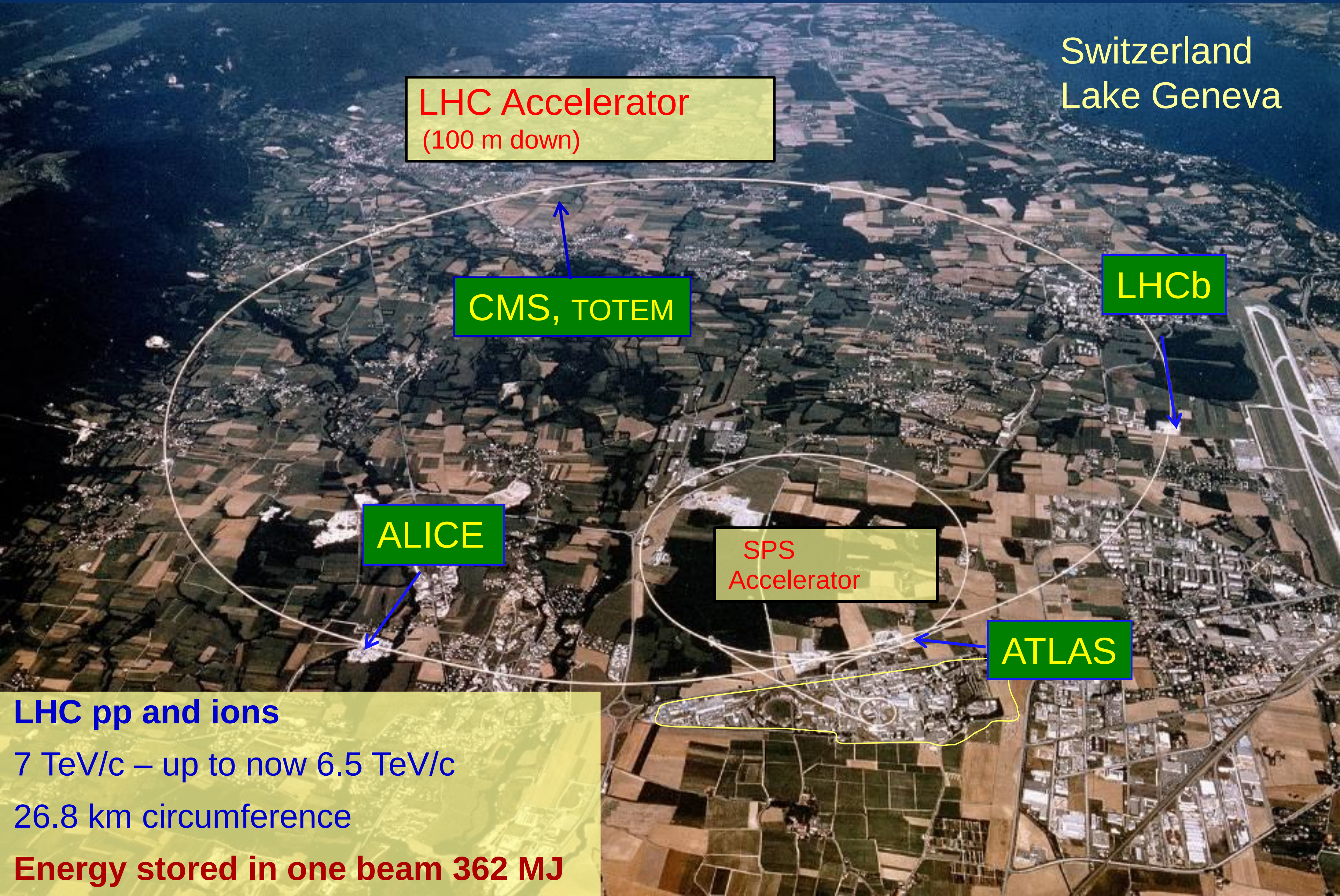
What protection ?

Risk 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
- An uncontrolled release of the energy, or an uncontrolled power flow can lead to unwanted consequences
  - Damage of equipment and loss of time for operation
  - For particle beams, activation of equipment
- In particular relevant for complex particle accelerators
  - For equipment, such as **RF system**, **power converters**, **magnet system** …
  - For **particle beams**
- Particle accelerators use large amount of power (few MW to many MW)

Where does the energy go in case of failure?

Proton collider LHC – 362 MJ stored in one beam



LHC pp and ions

7 TeV/c – up to now 6.5 TeV/c

26.8 km circumference

Energy stored in one beam 362 MJ

Energy in the LHC collider

Nominal energy per proton is 7 TeV

Very high luminosity

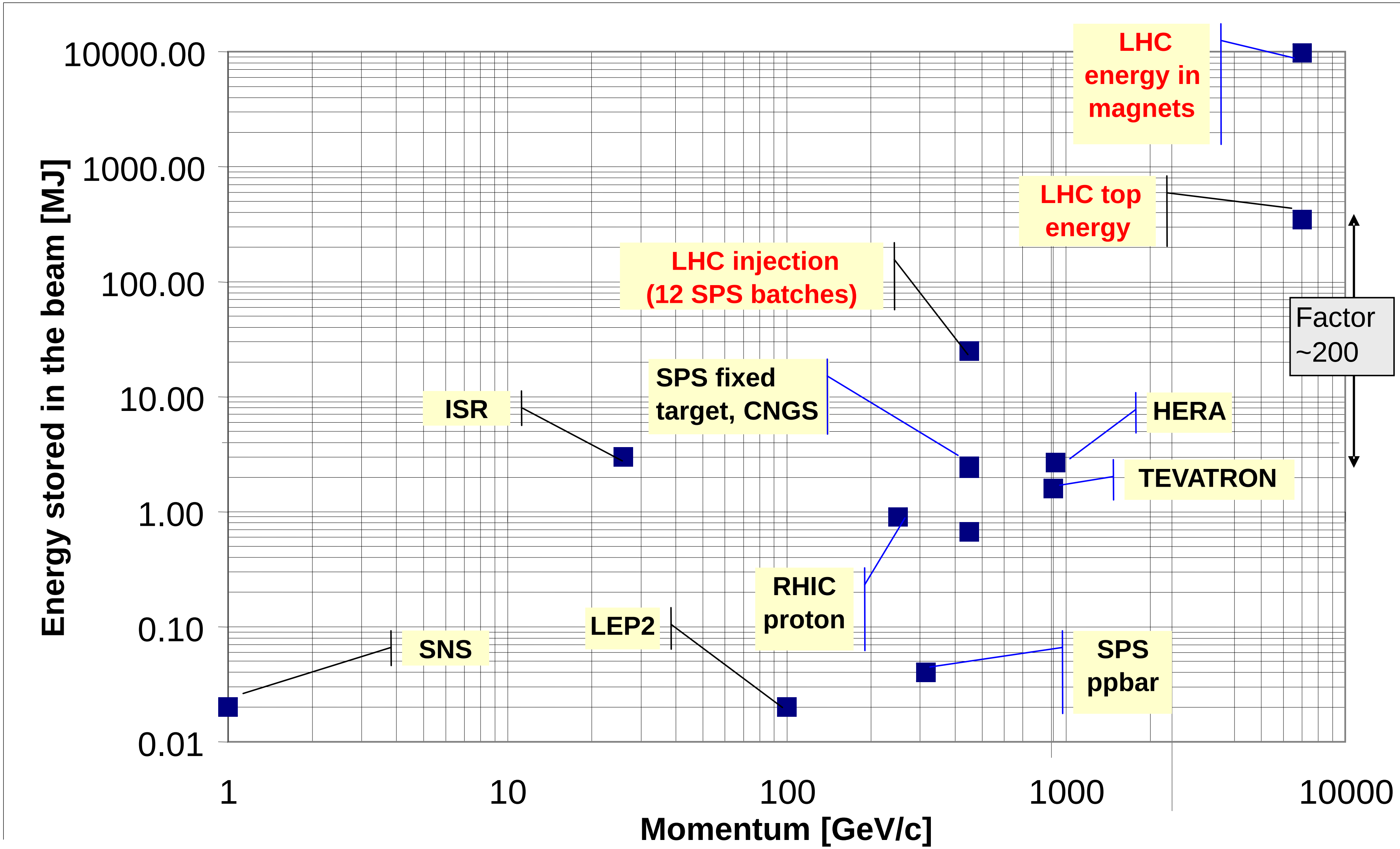
Many many many many protons (about $3 \cdot 10^{14}$ in each beam)

Energy in beam = Number of protons · Proton energy

Superconducting magnets

Energy in magnets $\simeq \boldsymbol{B^2 \cdot V}$

Energy stored in beam and magnets

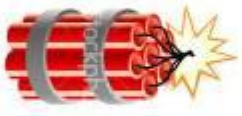


based on graph from R.Assmann

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 !!

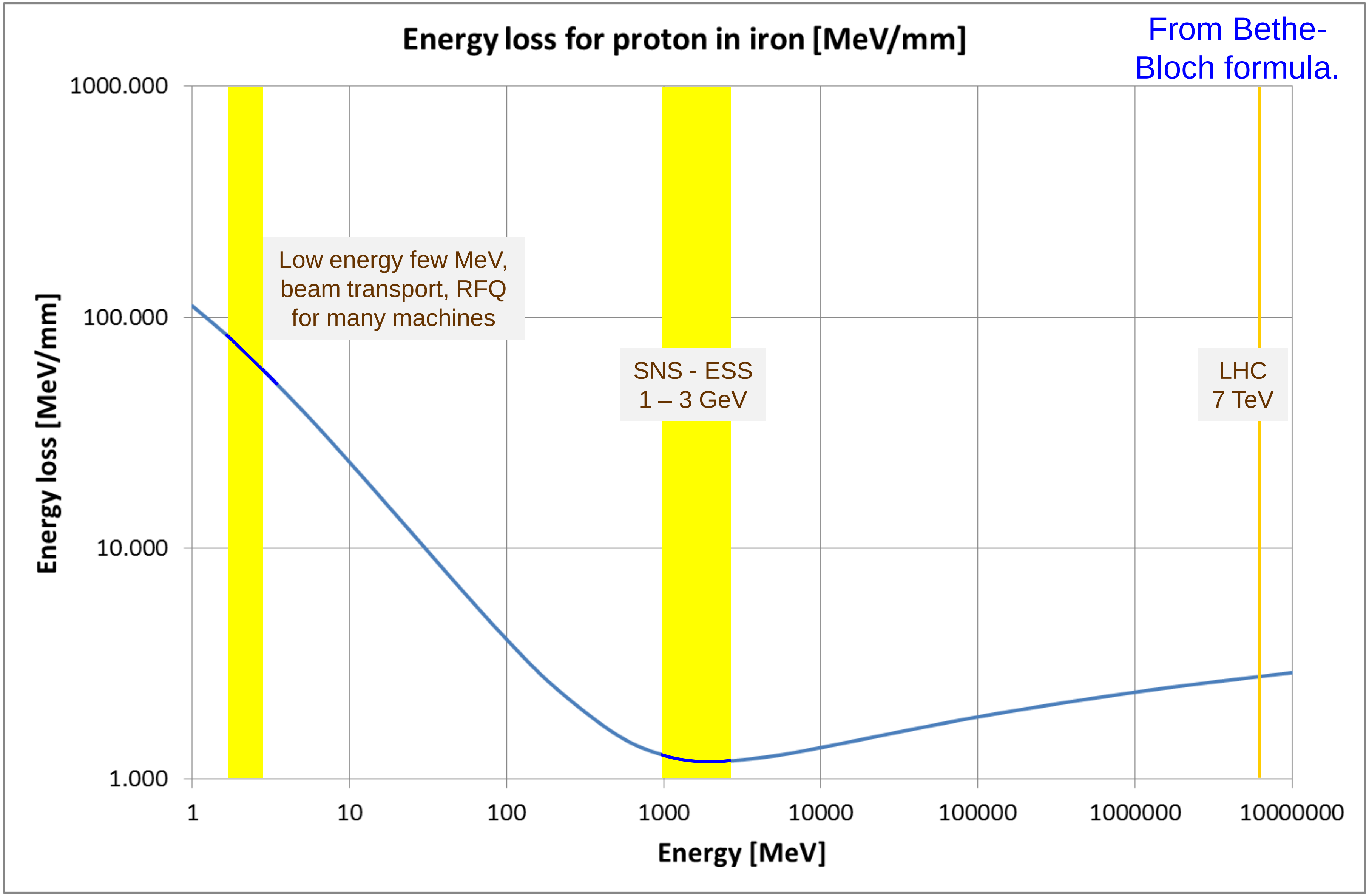
(Accidental) beam loss and consequences

Beam losses and consequences

- Charged particles moving through matter: interaction with electrons of atoms in the material, exciting or ionizing the atoms => **energy loss** is described by **Bethe-Bloch formula**.
- If the particle energy is high enough, particle collisions lead to **particle cascades**, 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**
  - 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)
  - superconducting magnets could quench (beam loss of ~mJ to J)
  - superconducting cavities performance degradation by some 10 J
  - activation of material, risk for hand-on-maintenance

Ionisation energy loss for one proton in iron

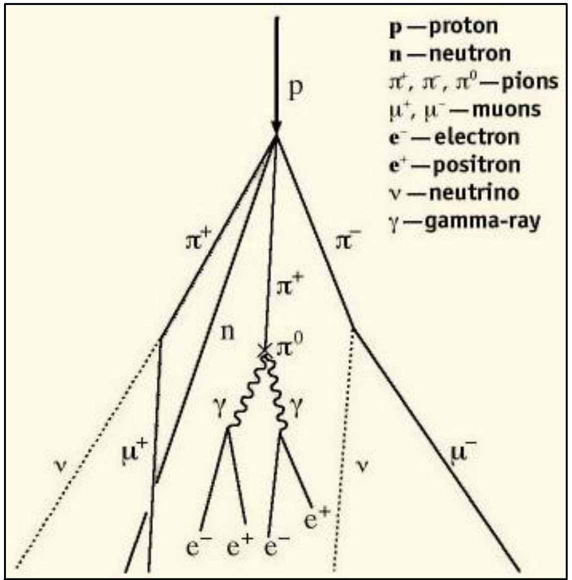
(stainless steel, copper very similar)



Heating of material with high energy protons

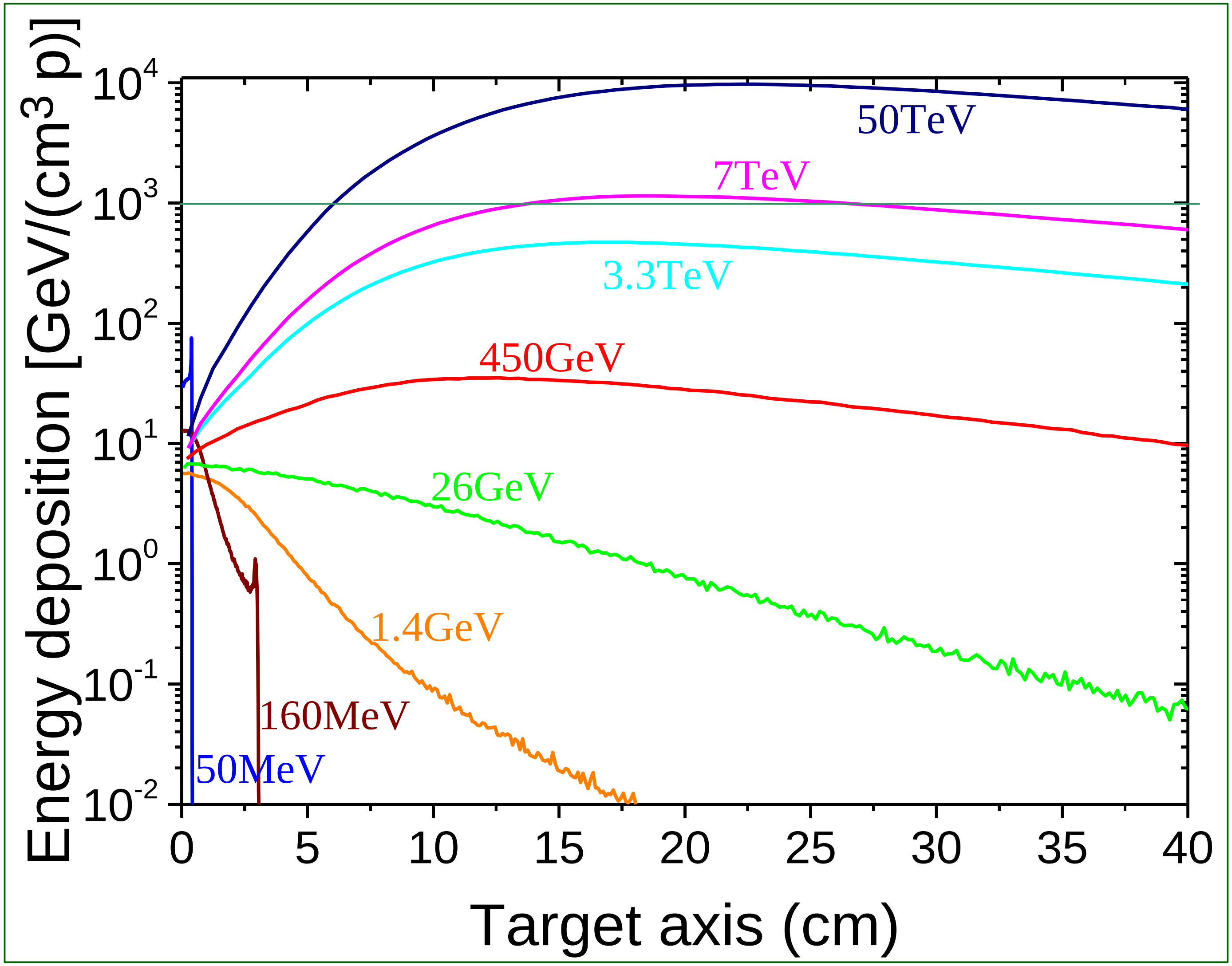
Nuclear inelastic interactions (hadronic shower)

- 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 large fraction done by 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 simulation codes, such as FLUKA, GEANT or MARS



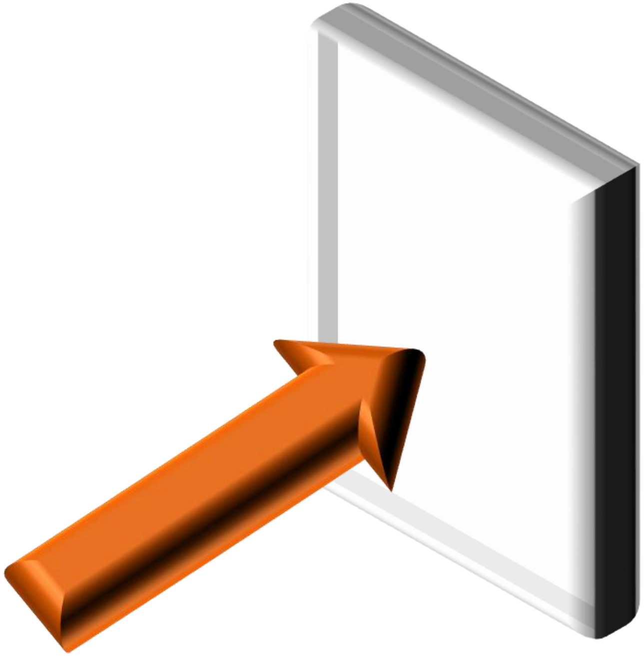
http://williamson-labs.com/ltoc/cbr-tech.htm

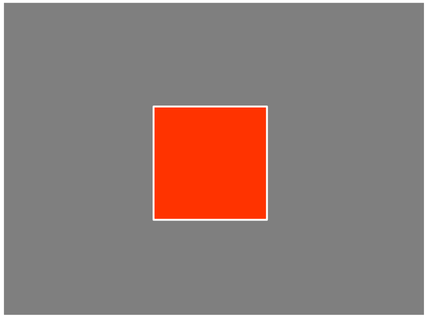
Energy loss of a proton shower in copper



Y.Nie

Beam losses in a thin window





- 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
(Iron 3 MeV, thin window)

Temperature increase in the material: $dT = (N_p \cdot dEdx)/(c_p \cdot F_{beam} \cdot \rho)$

Assume beam size with $\sigma_h = 1mm$ and $\sigma_v = 1mm$

Assume iron with the specific heat of $c_p = 440 \frac{J}{kg \cdot K}$

Assume iron with the specific weight of $\rho = 7860\ kg/m^3$

Energy loss per proton and mm: $dEdx = 59.7\ \frac{MeV}{mm}$

Number of protons : $1.16 \cdot 10^{12}$

Energy of protons : $3\ MeV$

Temperature increase: $dT = 763\ K$

Beam losses and consequences at 7 TeV

Maximum energy deposition for one proton in copper: $E_{maxCu} = 1.5 \cdot 10^{-5}\, J/kg$

Specific heat of copper: $c_{Cu\_spec} = 384.6 \frac{J}{kg \cdot K}$

Energy to heat 1 kg of copper by $\Delta T = 500\ {}^{0}K$

$$c_{Cu\_spec} \cdot \Delta T \cdot 1\ kg = 1.92 \cdot 10^{5}\ Joule$$

Number of protons required to deposit this energy in copper:

$$(c_{Cu\_spec} \cdot \Delta T)/E_{maxCu} = 1.28 \cdot 10^{10}$$

For graphite: $E_{maxC} = 2.0 \cdot 10^{-6}\, J/kg$ $c_{C\_spec} = 710.6 \frac{J}{kg \cdot K}$

Number of protons required to deposit this energy in carbon:

$$(c_{C\_spec} \cdot \Delta T)/E_{maxC} = 5.33 \cdot 10^{11}$$

Beam losses 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/energy…. however, the energy deposition per proton 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
  - 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

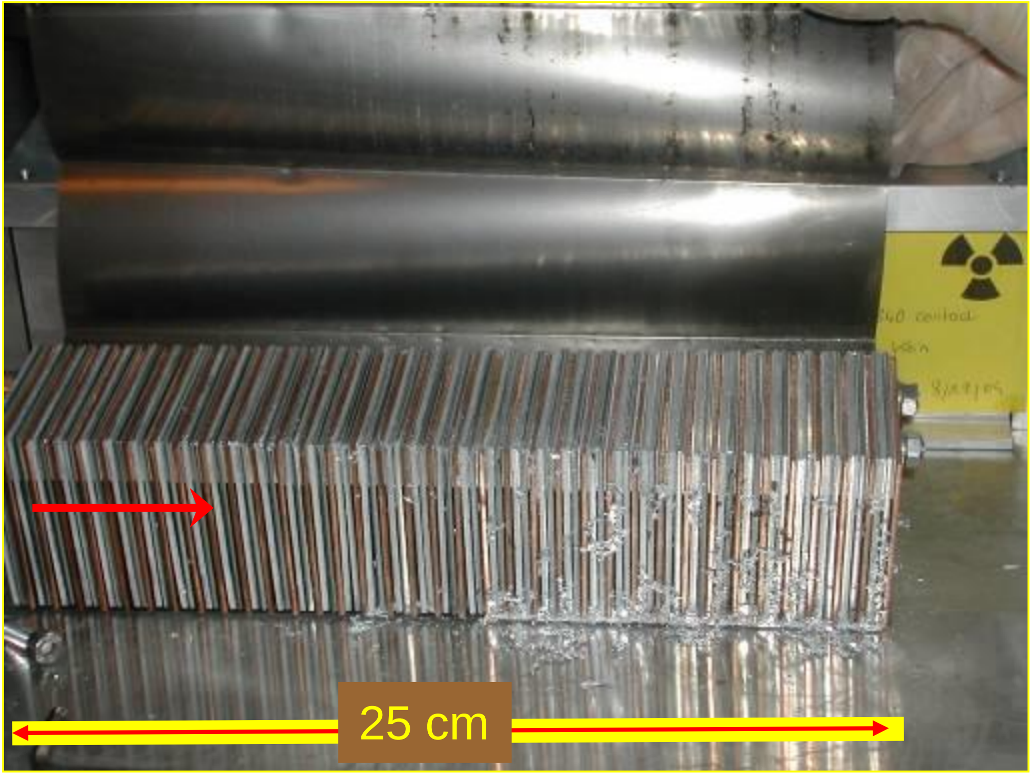
SPS experiment: Beam damage with 450 GeV protons

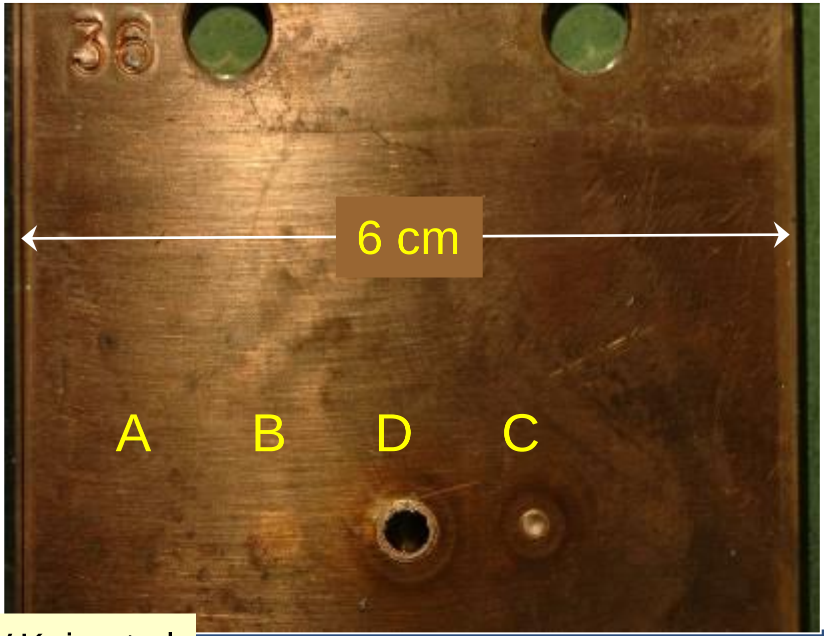
Controlled SPS experiment

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

stainless steel no damage

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

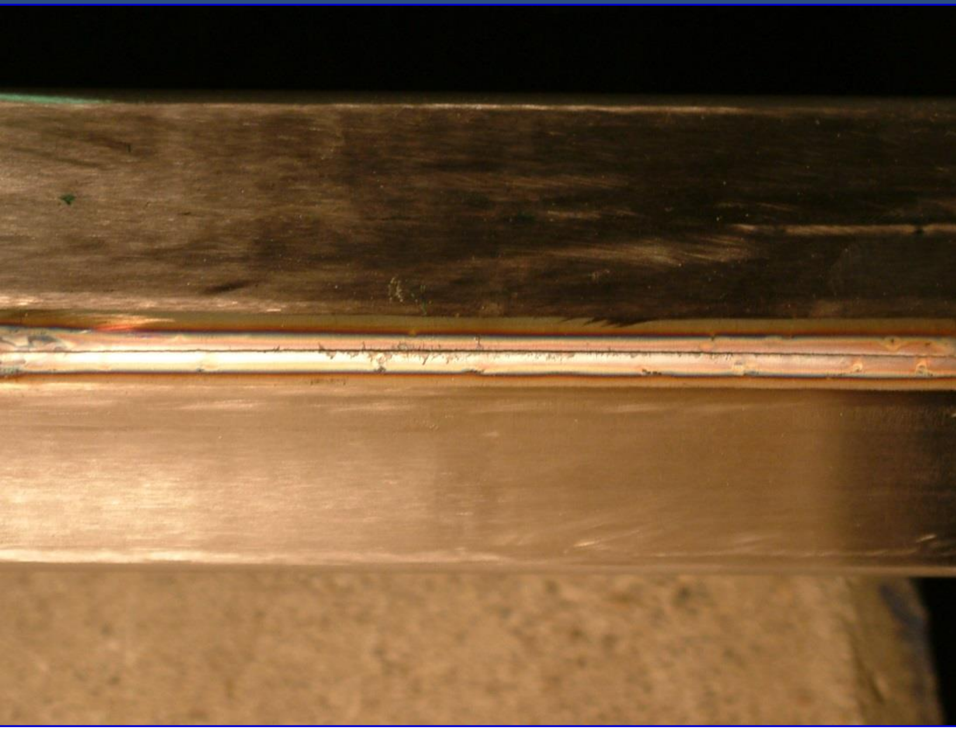


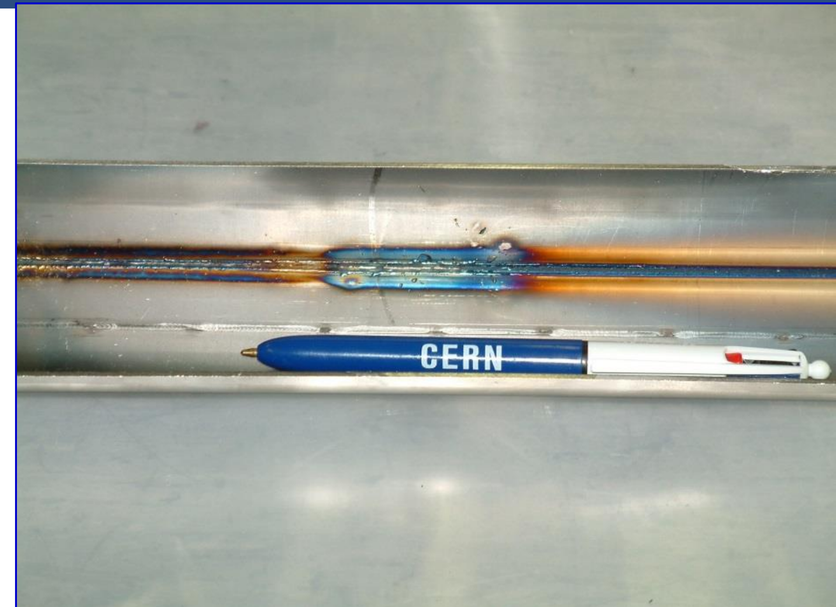


- 0.1 % of the full LHC 7 TeV beams
- factor of three below the energy in a bunch train injected into LHC
- damage limit ~200 kJoule

V.Kain et al

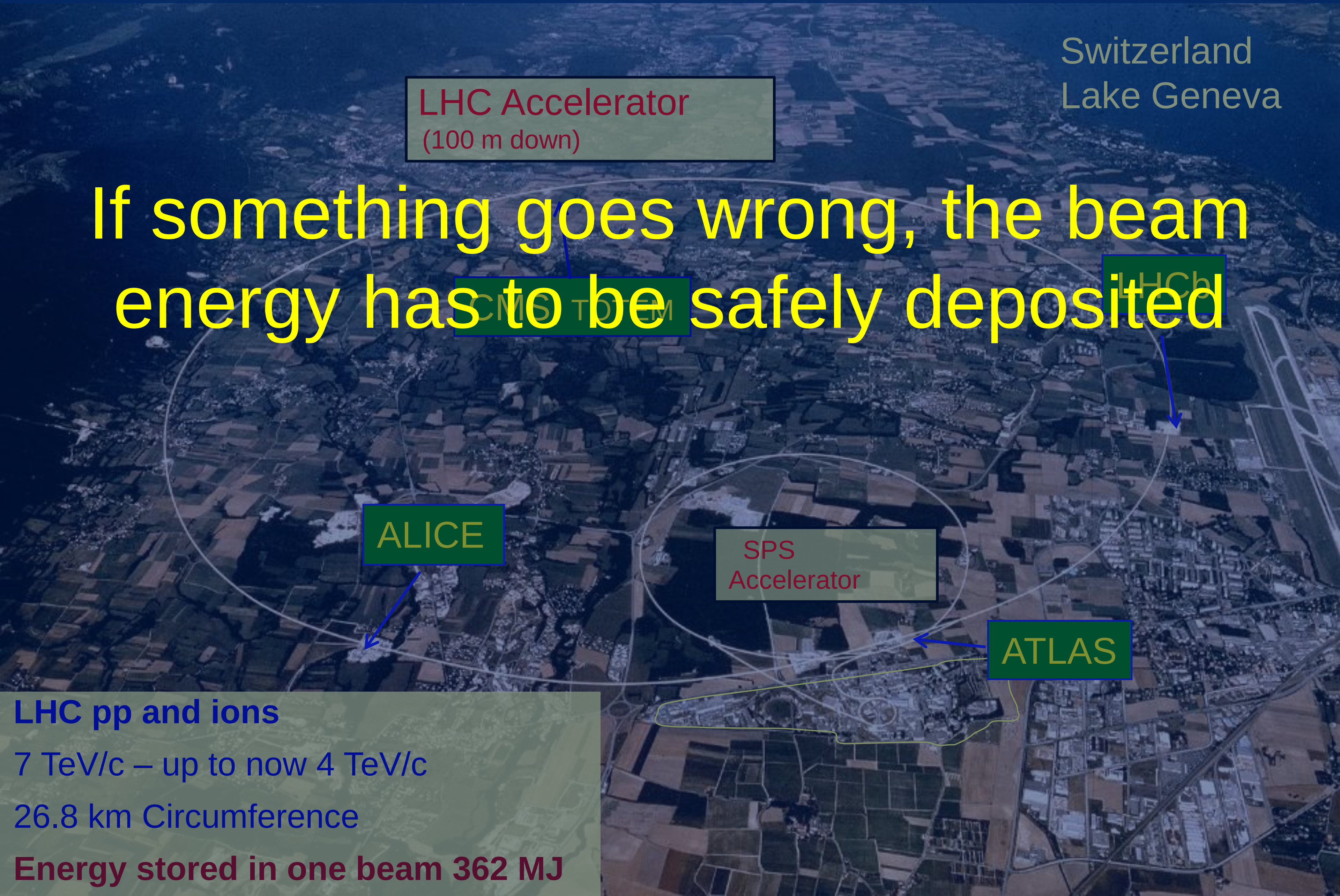
Vacuum chamber in SPS extraction line incident





- 450 GeV protons, 2 MJ beam in 2004
- Failure of a septum magnet
- Cut of 25 cm length, groove of 70 cm
- Condensed drops of steel on other side of the vacuum chamber
- Vacuum chamber and magnet needed to be replaced

Proton collider LHC – 362 MJ stored in one beam



If something goes wrong, the beam energy has to be safely deposited

LHC pp and ions

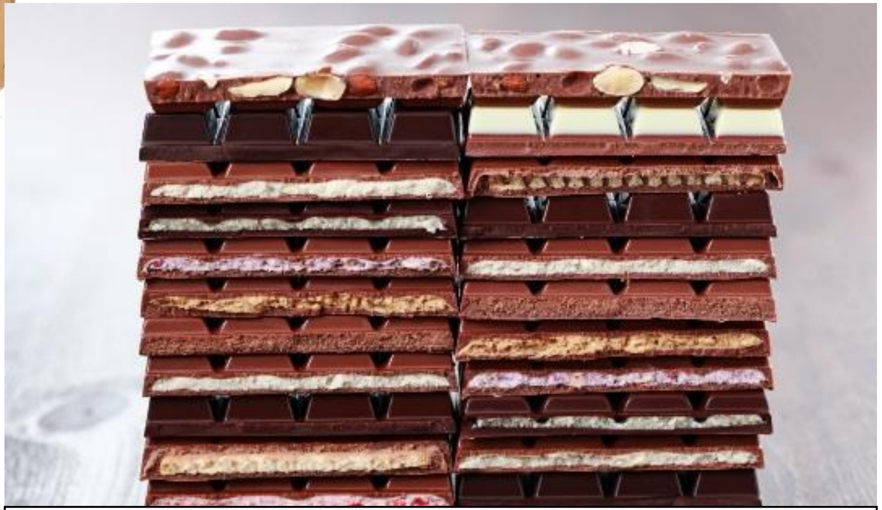
7 TeV/c – up to now 4 TeV/c

26.8 km Circumference

Energy stored in one beam 362 MJ

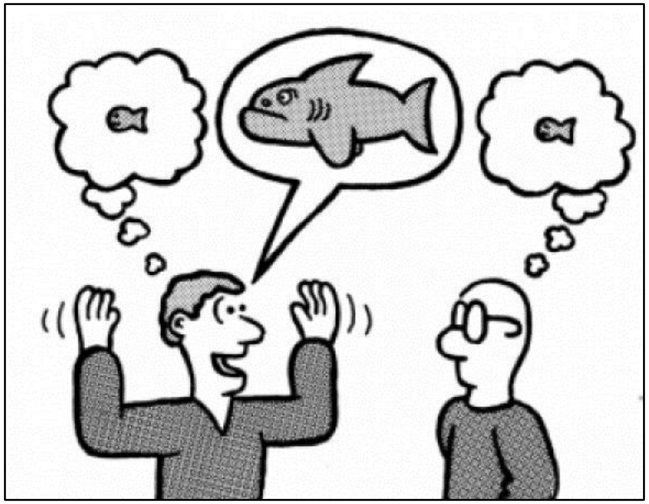
The energy stored in the LHC dipole magnets of 9 GJ corresponds to the energy of 2000 kg TNT

Airbus A330 at 700 km/h

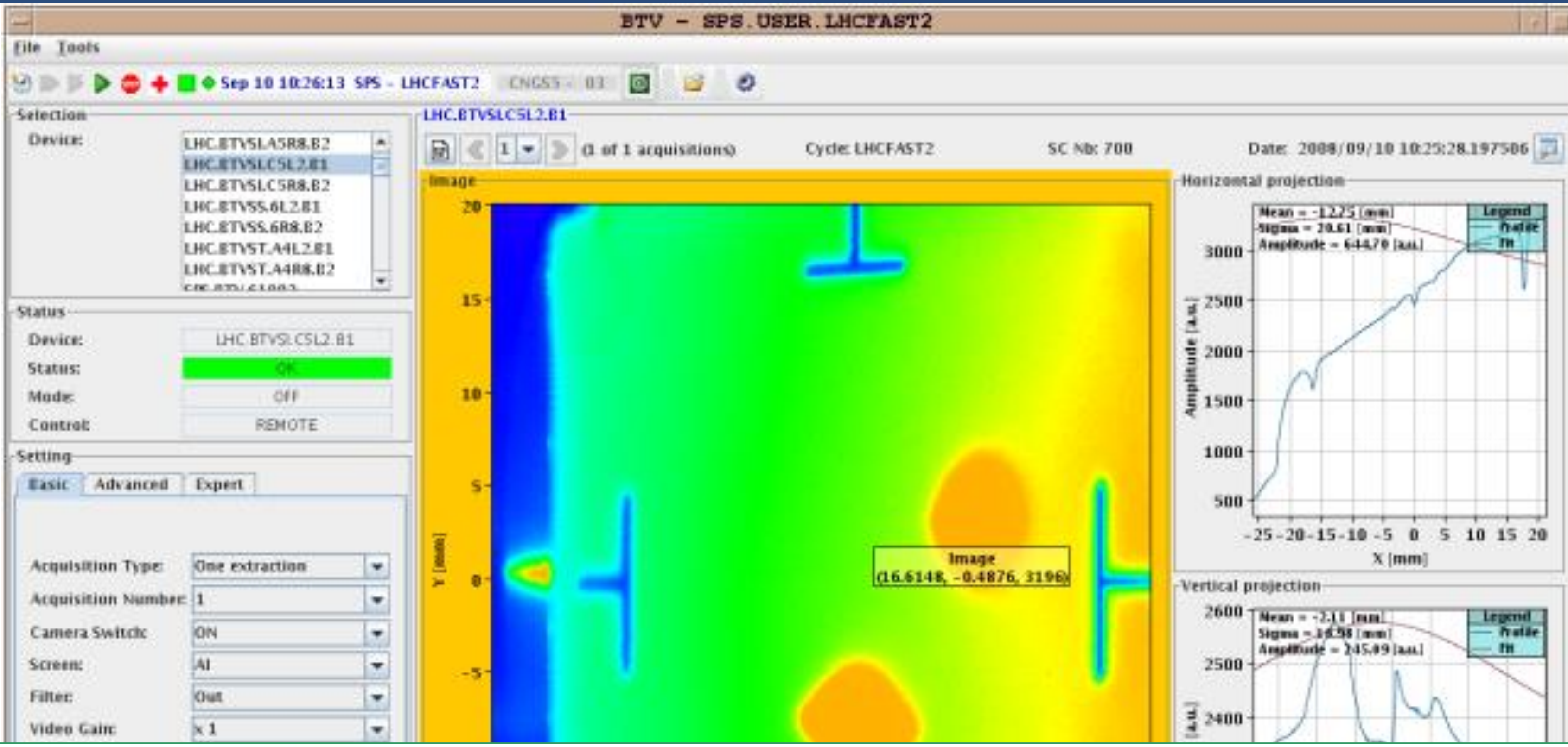


450 kg of chocolate

“…..do not exaggerate -
large accelerators are operating since many years without accidents…….”



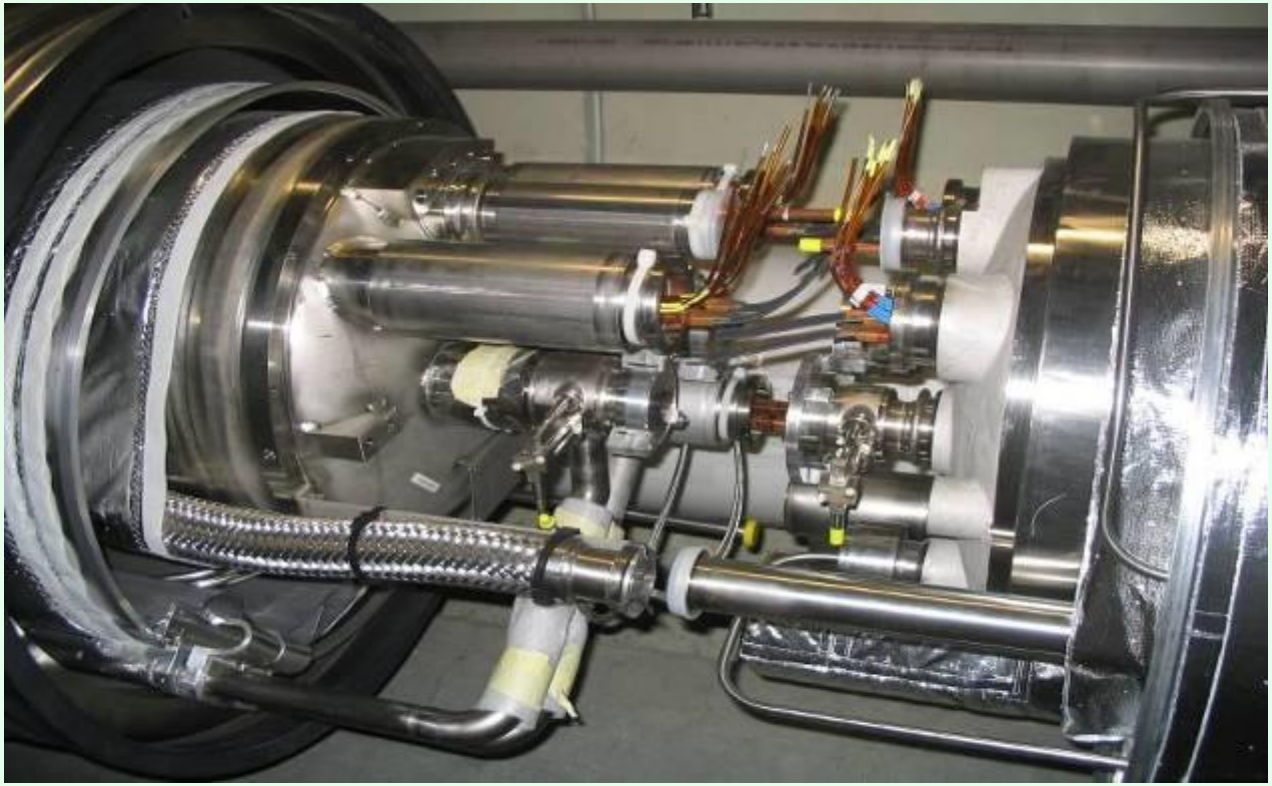
10 September 2008: Success!



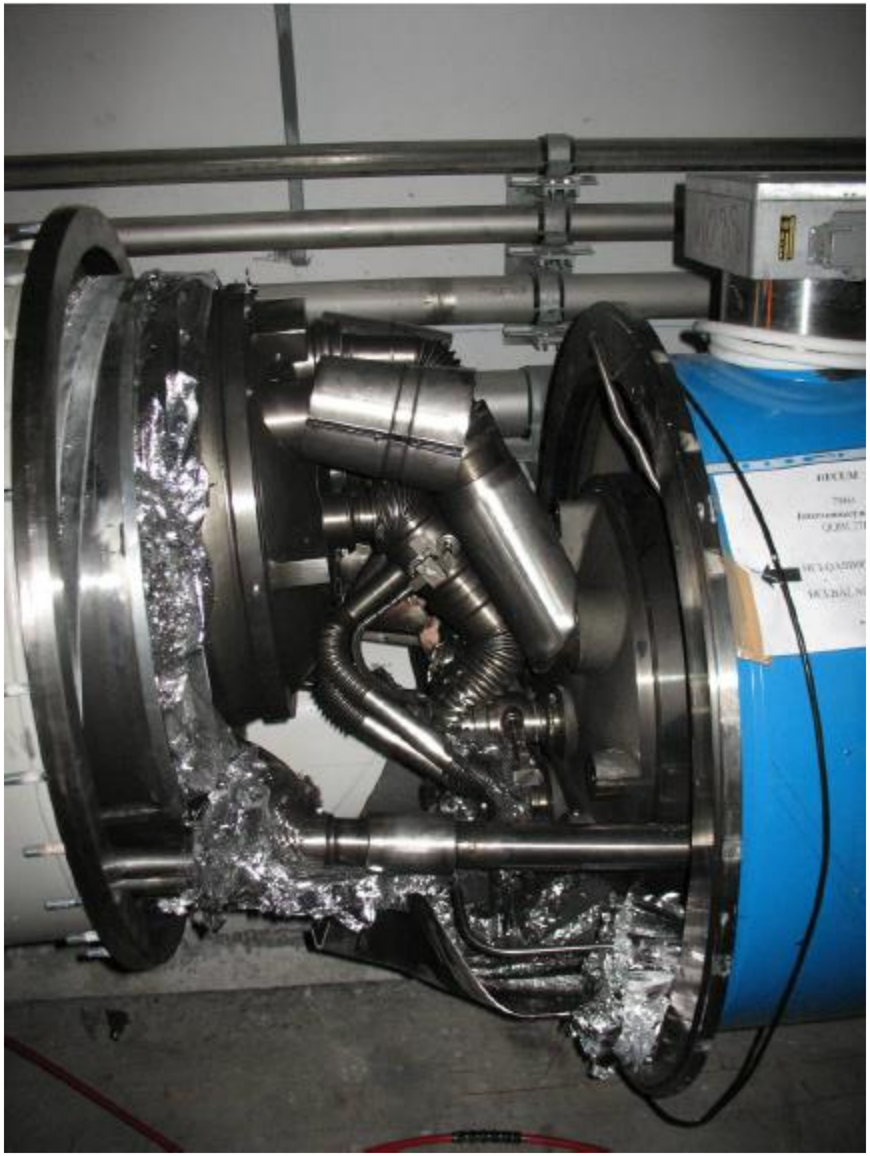
Unfortunately, nine days later...

The incident of 19 September 2008

- **10000** high current superconducting **cable joints** – all soldered in situ in the tunnel and **one** of these connections was **defective**



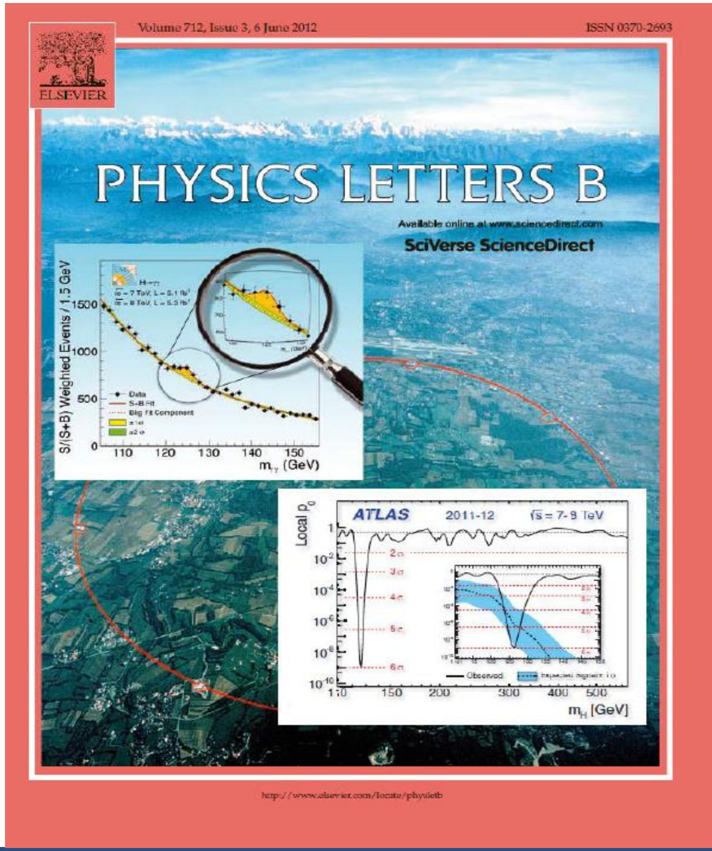
One joint ruptured, with 600 MJ stored in the magnets – 70% of this energy was dissipated in the tunnel, electric arcs, vaporizing material, and moving magnets around



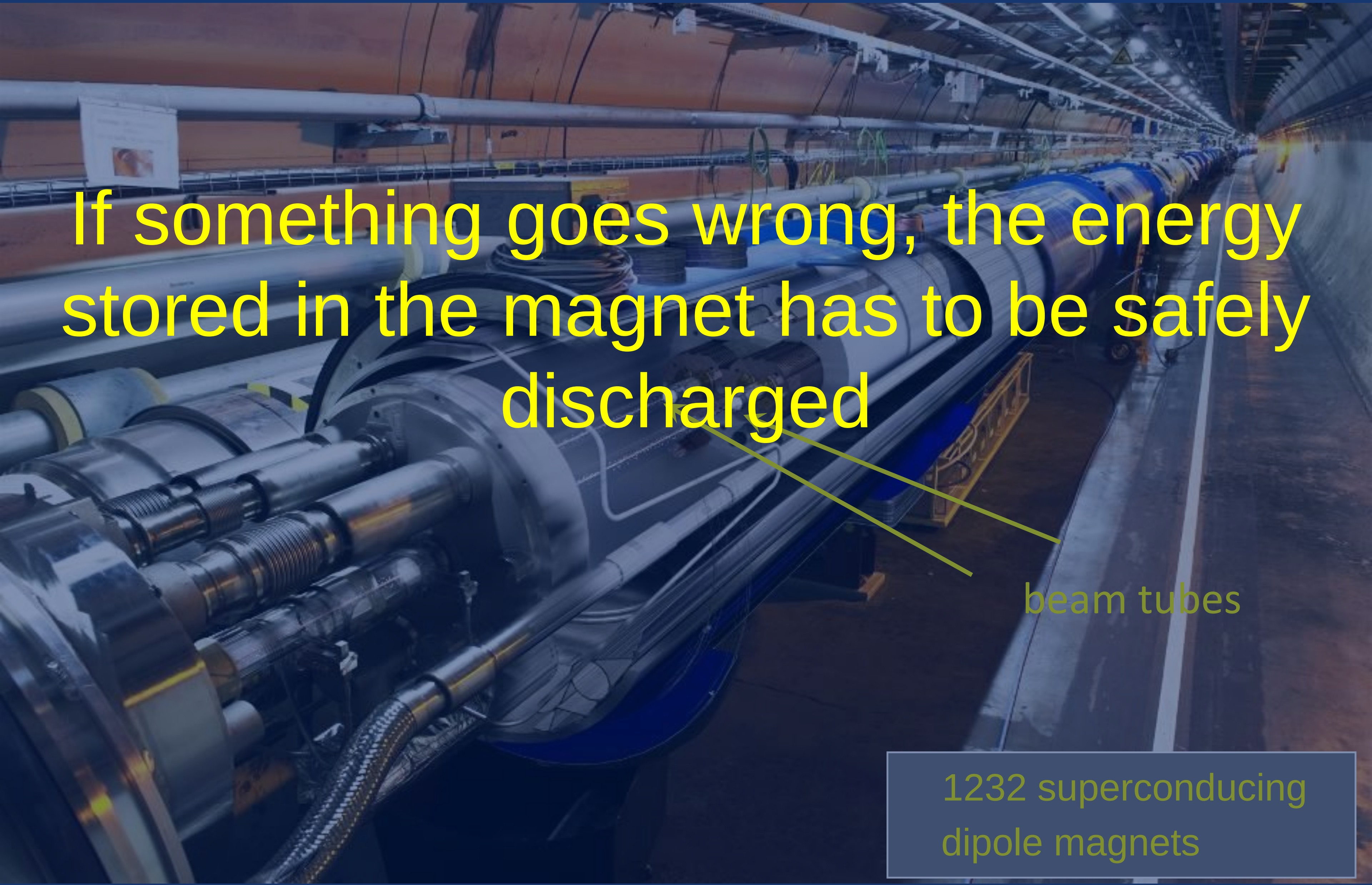
Recovery from the accident

- Damage has a large impact on the availability of an accelerator
- For the LHC, it took a long time (about one year) to repair the magnets

- A new layer of protection system for the superconducting magnets and bus-bars was installed
- Energy was limited to 3.5 TeV
- Re-start up about one year later
- During a two years shut-down from 2013-2014 the interconnects were finally repaired
- Now operating at 6.5 TeV
- **Performance is excellent**



LHC tunnel with dipole magnets



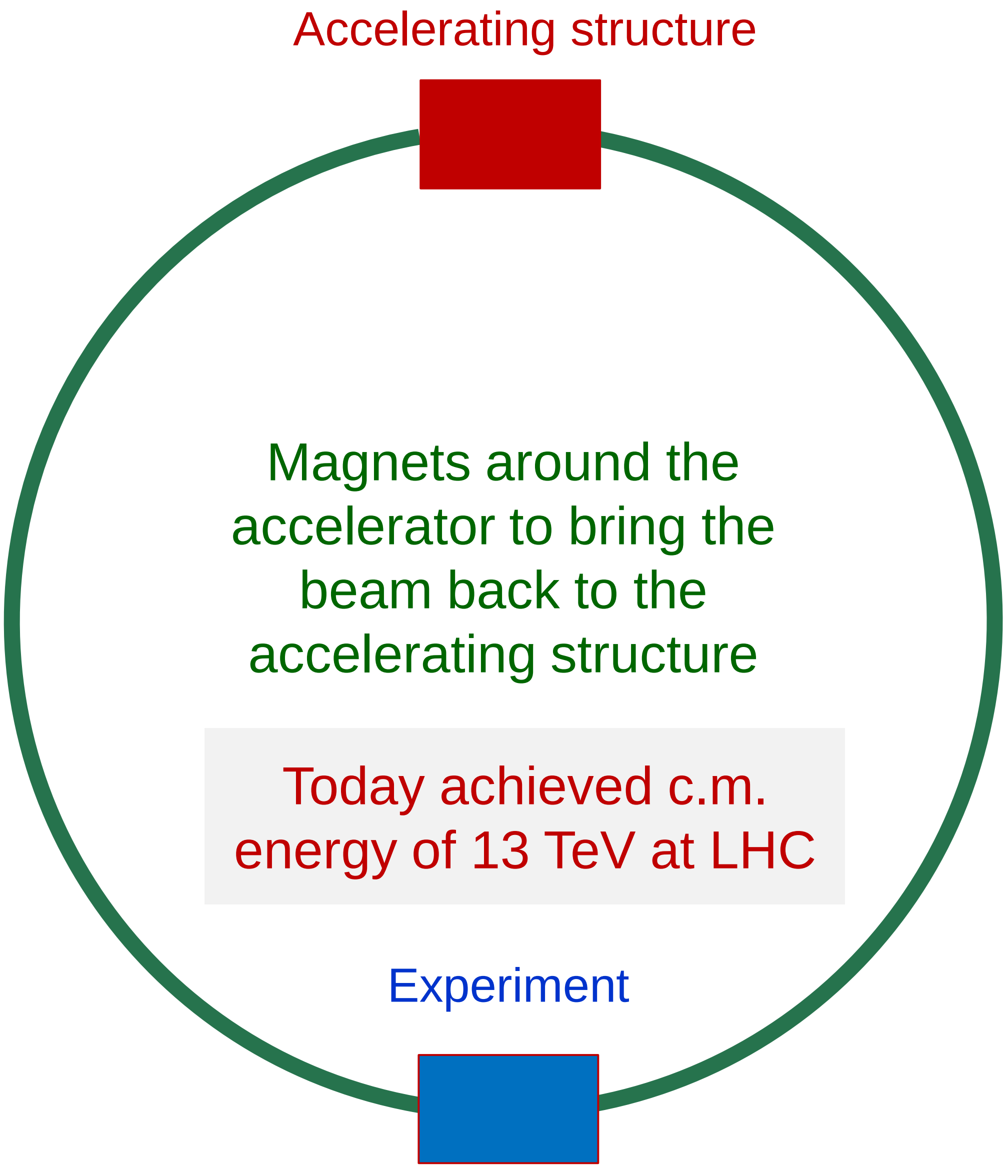
If something goes wrong, the energy stored in the magnet has to be safely discharged

Machine Protection in a Synchrotron

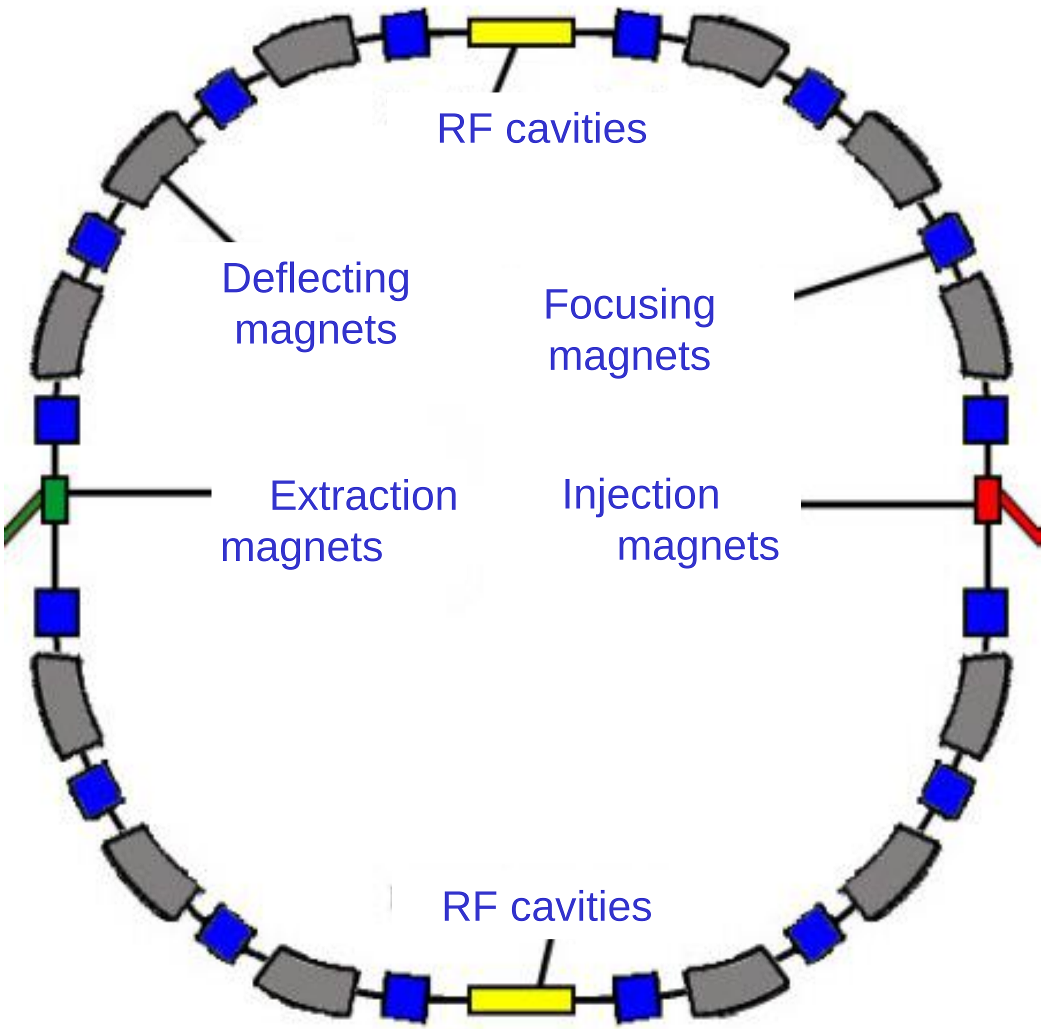
Circular accelerator: re-use accelerating structure

Accelerating beams to high energy in a synchrotron

- **Beam are injected** into the accelerator
- The particles make many turns
- The magnetic field is slowly increased, and particles are accelerated and gaining energy when travelling through the accelerating structure
- The beams are stored for many hours at top energy, bunches collide each turn
- **The beams are extracted** into a dump block



Components of a synchrotron

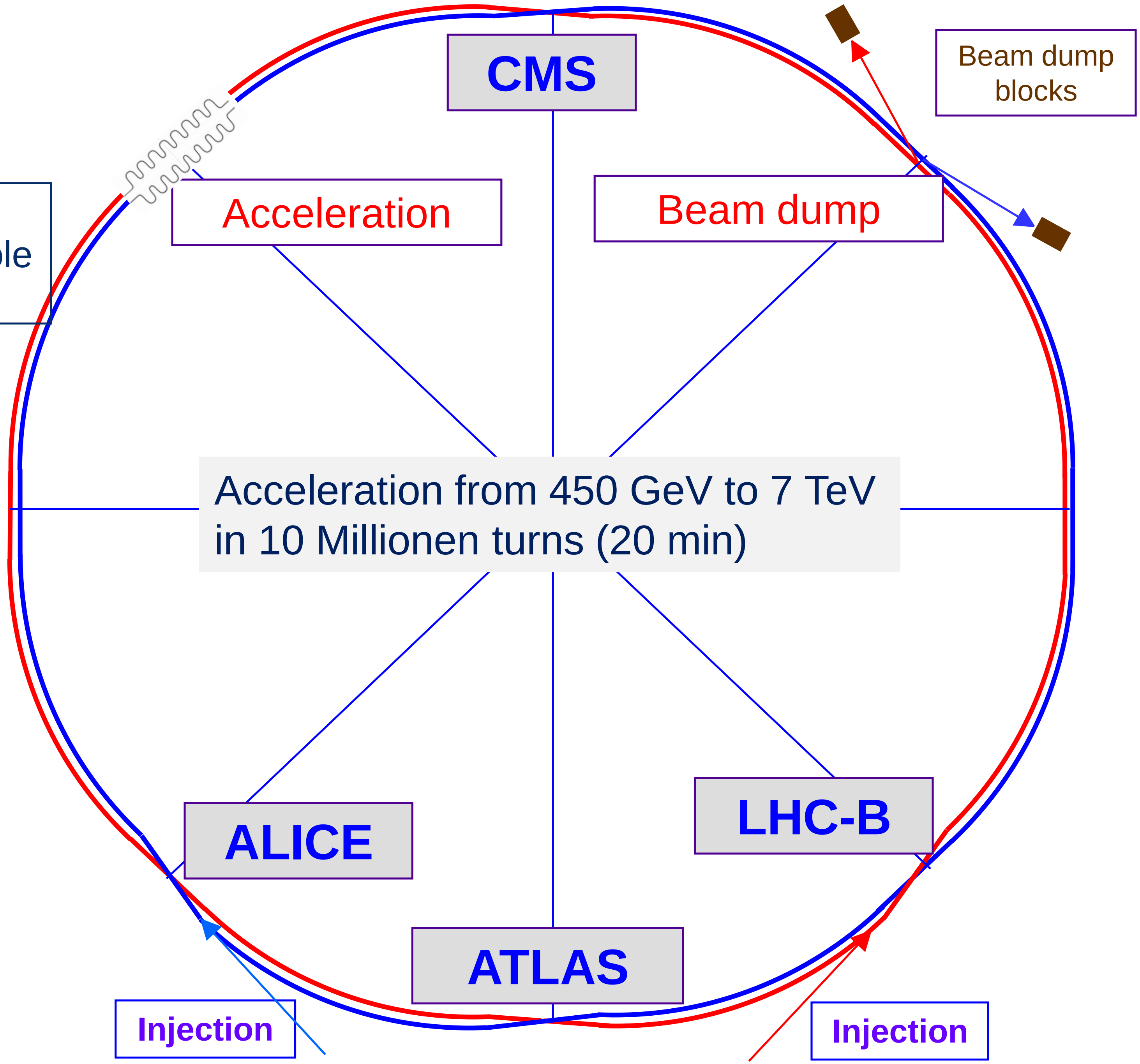


Components of a synchrotron:

- 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

In the arcs:
1232 deflecting dipole magnets

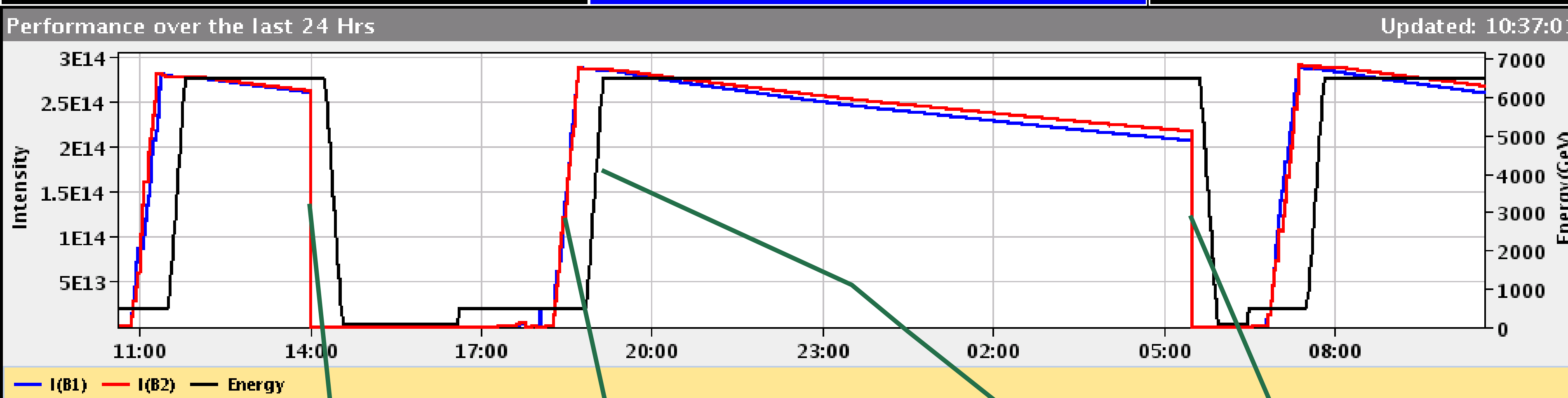


- 27 km
- 2 beams
- 11246 turns/ second
- 8 arcs
- 8 straight sections

29-Jun-2017 10:37:03 Fill #: 5883 Energy: 6499 GeV I(B1): 2.60e+14 I(B2): 2.68e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	13032.950	2.633	12733.096	443.098
BRAN Luminosity [(ub.s)^-1]	14023.1	3.1	10934.7	328.1
Fill Luminosity (nb)^-1	124302.242	24.180	118534.438	3590.458
Beam 1 BKGD	1.811	3.198	1.442	0.014
Beam 2 BKGD	2.899	0.043	1.351	0.074

LHCb VELO Position IN Gap: -0.0 mm | STABLE BEAMS | TOTEM: STANDBY



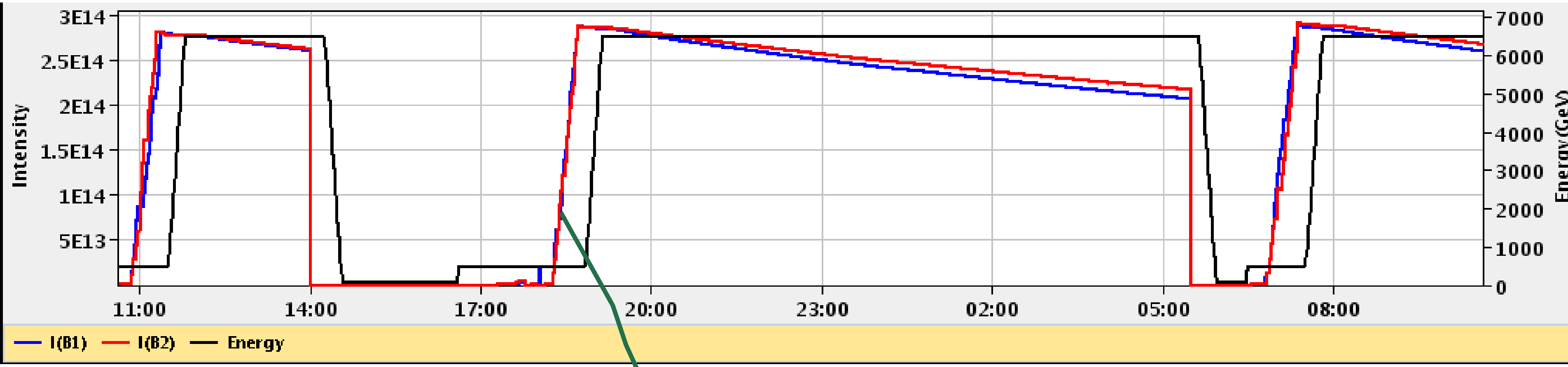
Ramp from 450 GeV to 6.5 TeV => total energy for each beam is 290 MJ

Failure: what to do with 290 MJ ?

Injection of 10 * 144 bunches = 144 *1.2 MJ

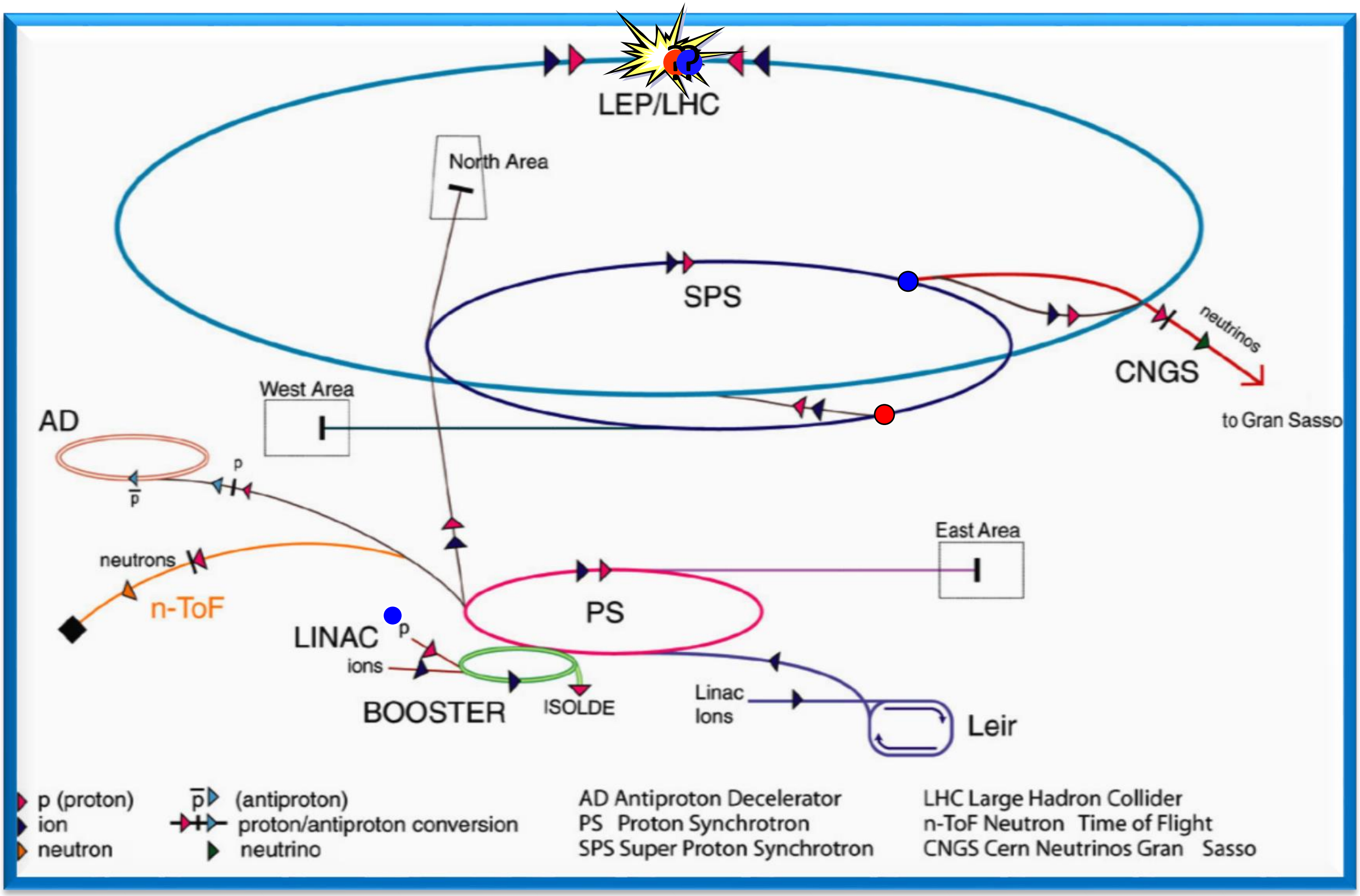
End of the fill: what to do with the beams?

Machine Protection at Injection



Injection of 10 * 144
bunches = 144 *1.2 MJ

CERN accelerator complex



High intensity beam from SPS to LHC at 450 GeV via TI2 and TI8, LHC accelerates to 7 TeV

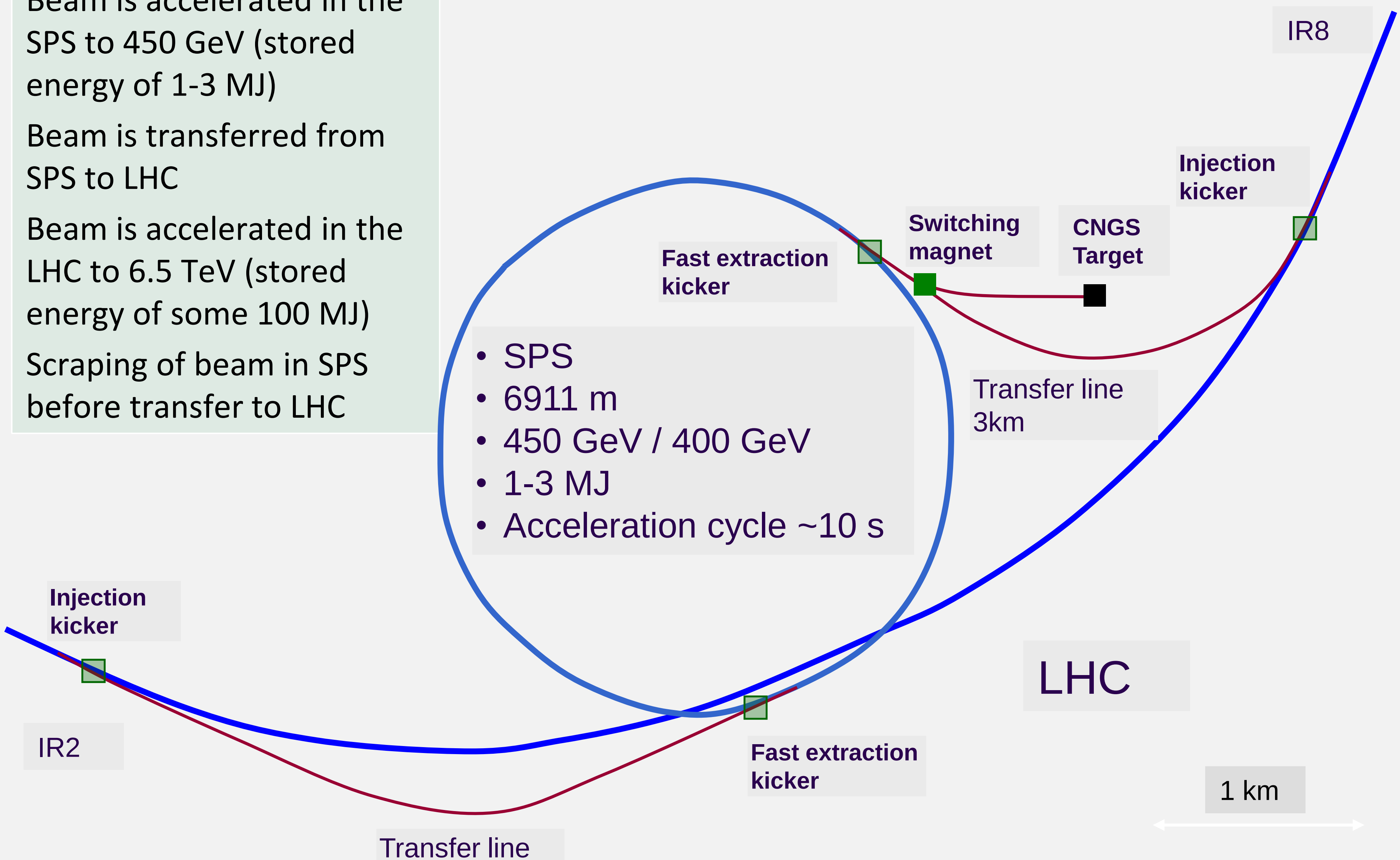
SPS, transfer line and LHC

Beam is accelerated in the SPS to 450 GeV (stored energy of 1-3 MJ)

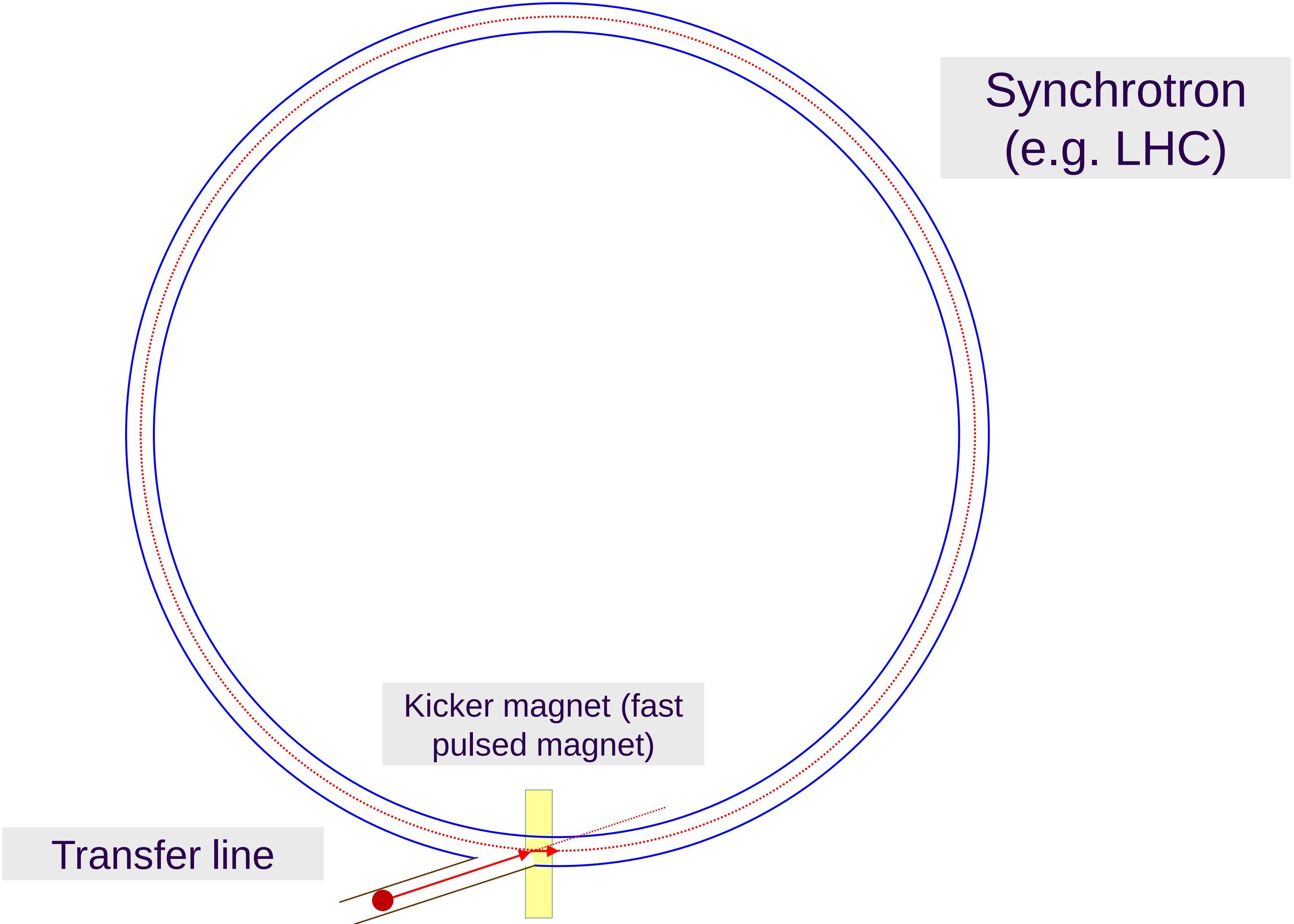
Beam is transferred from SPS to LHC

Beam is accelerated in the LHC to 6.5 TeV (stored energy of some 100 MJ)

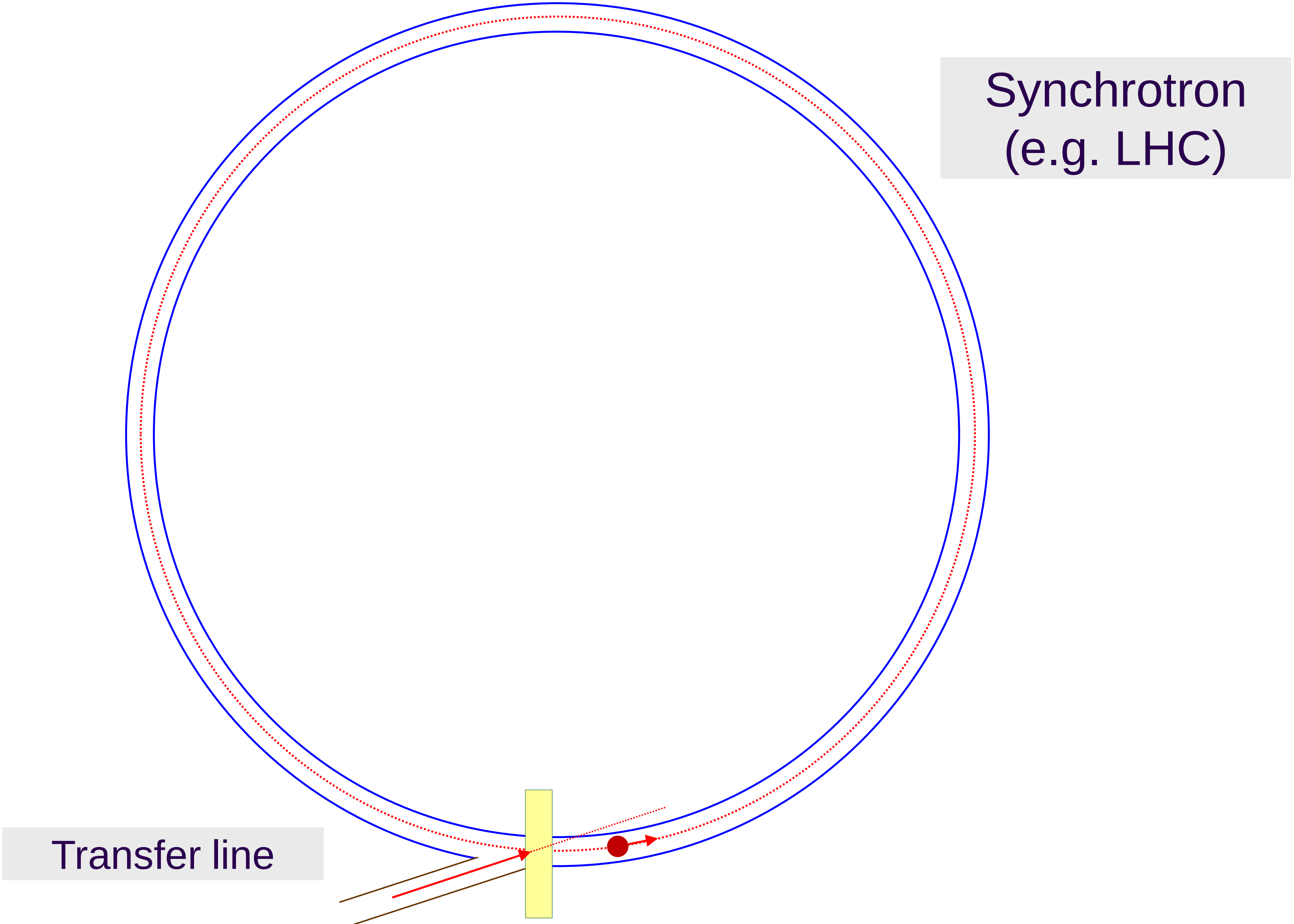
Scraping of beam in SPS before transfer to LHC



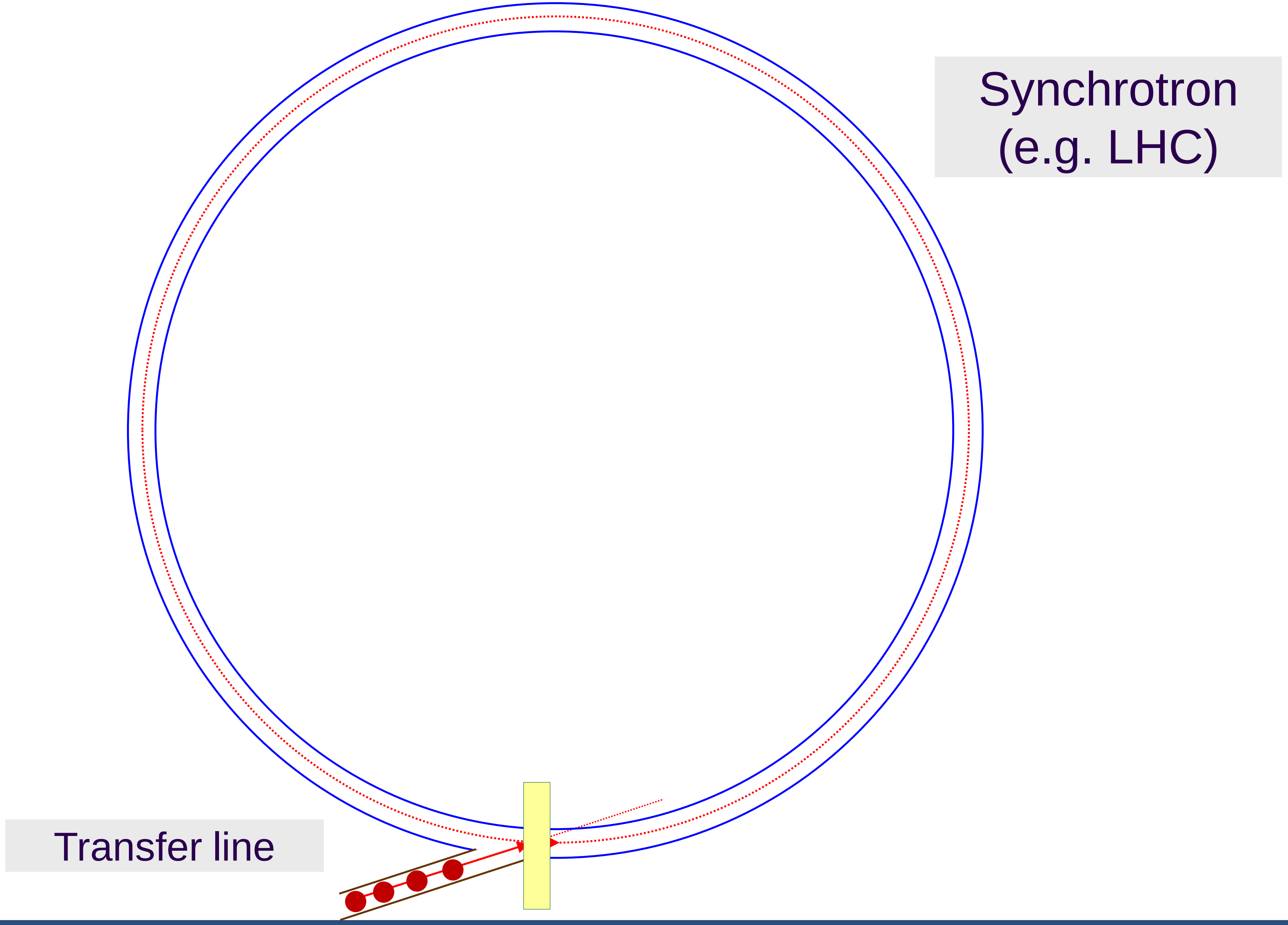
Before injection of one bunch into LHC



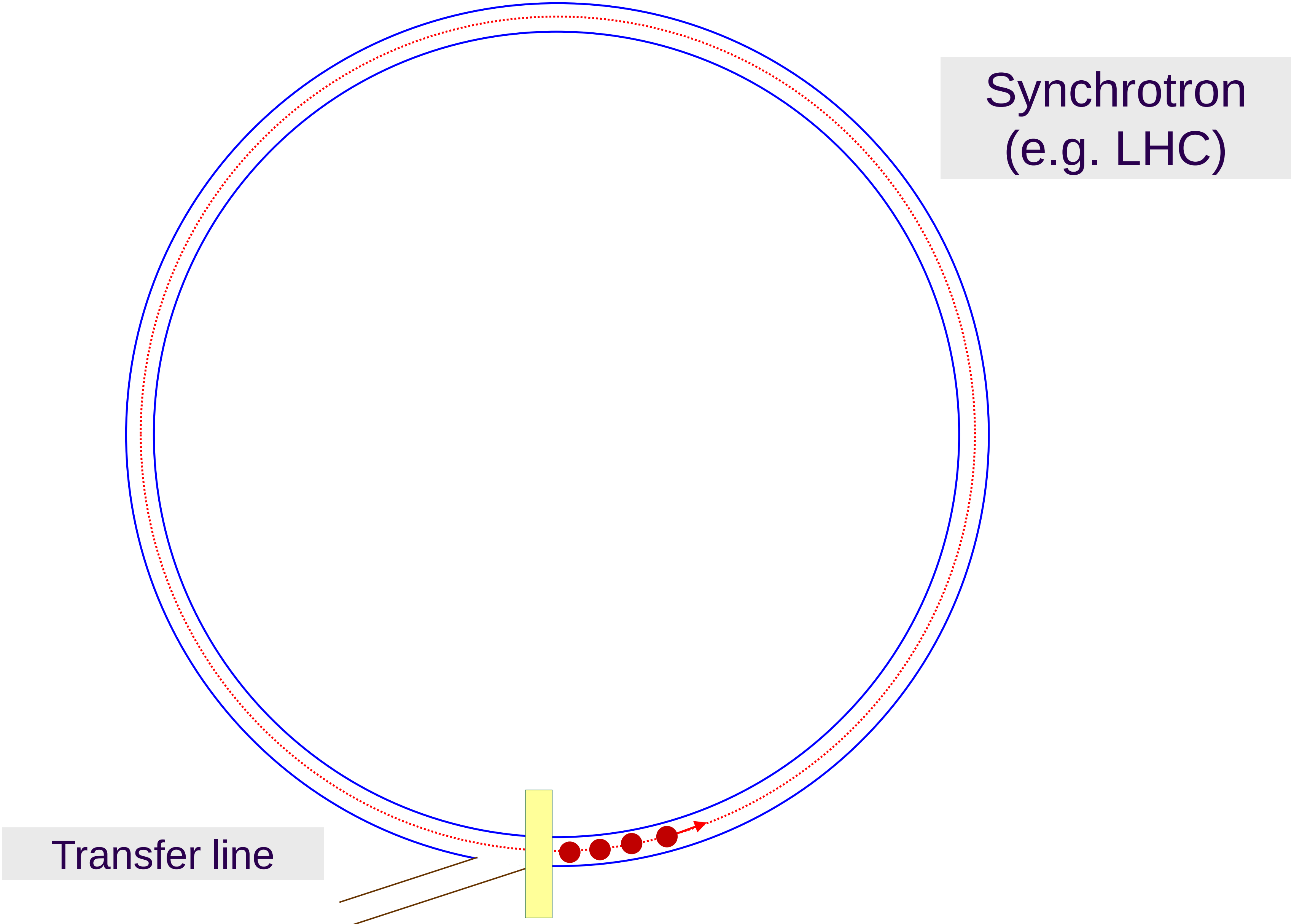
After injection of one bunch into LHC



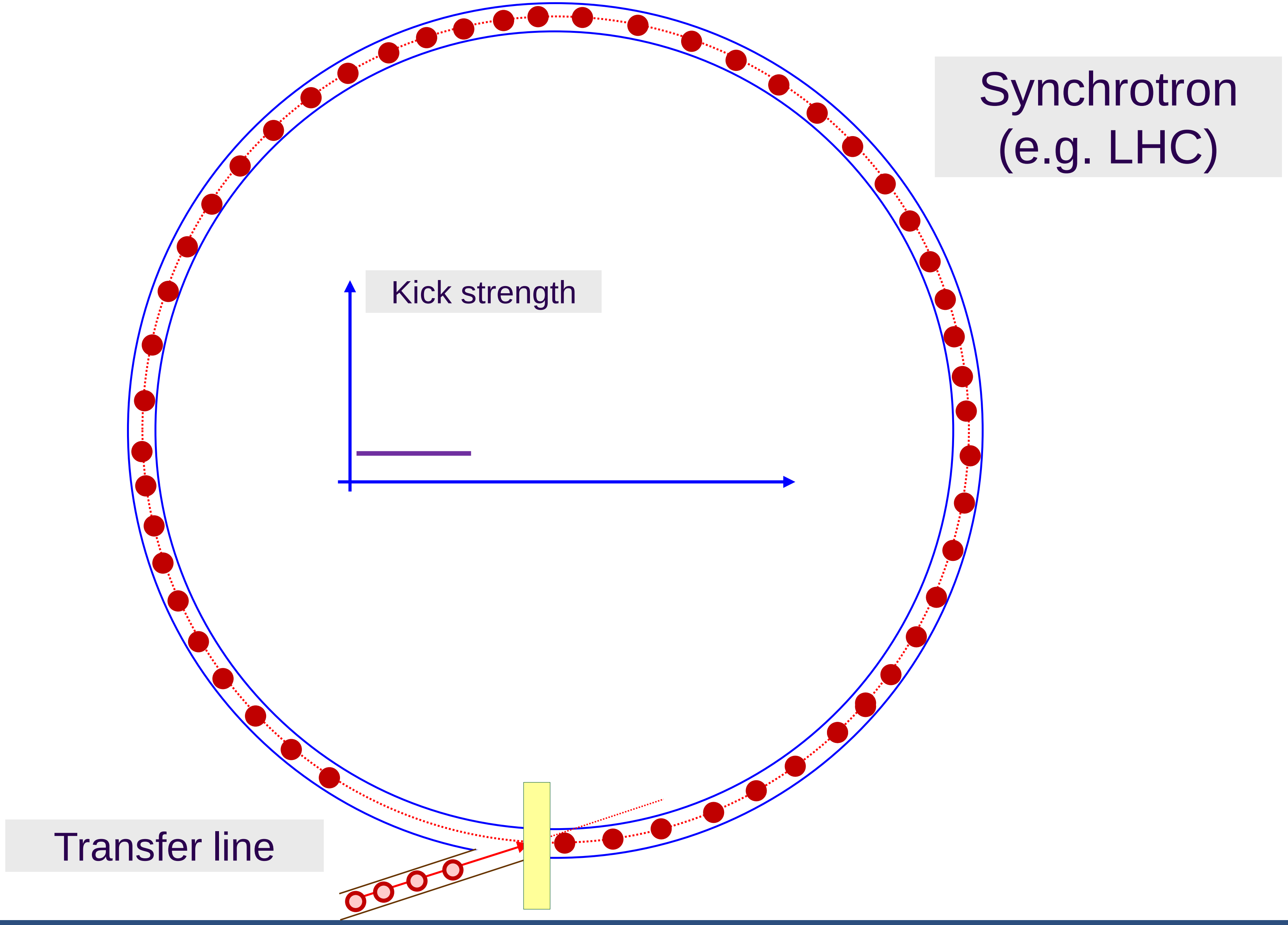
Before injection of a bunch train into LHC



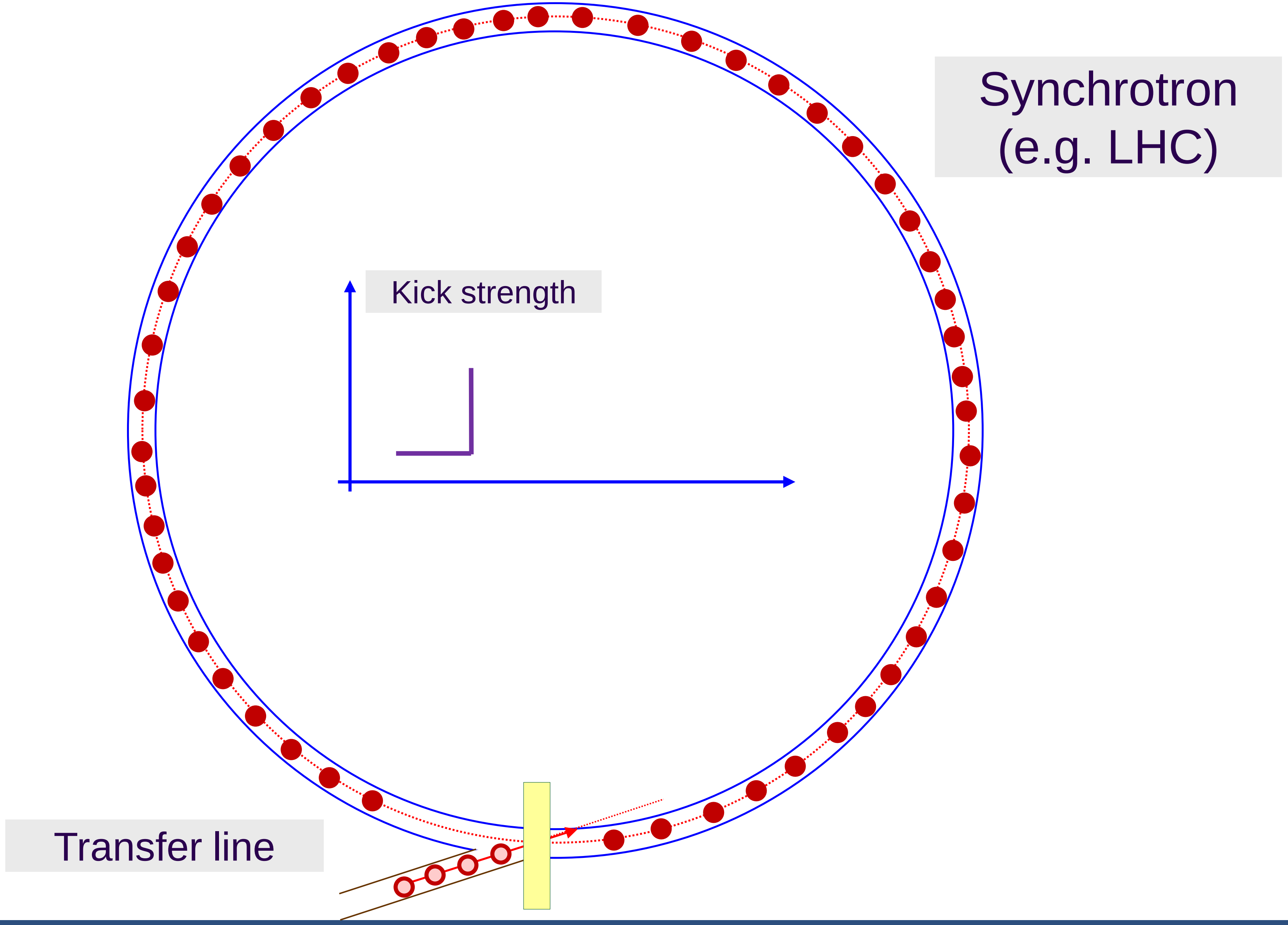
After injection of a bunch train into LHC



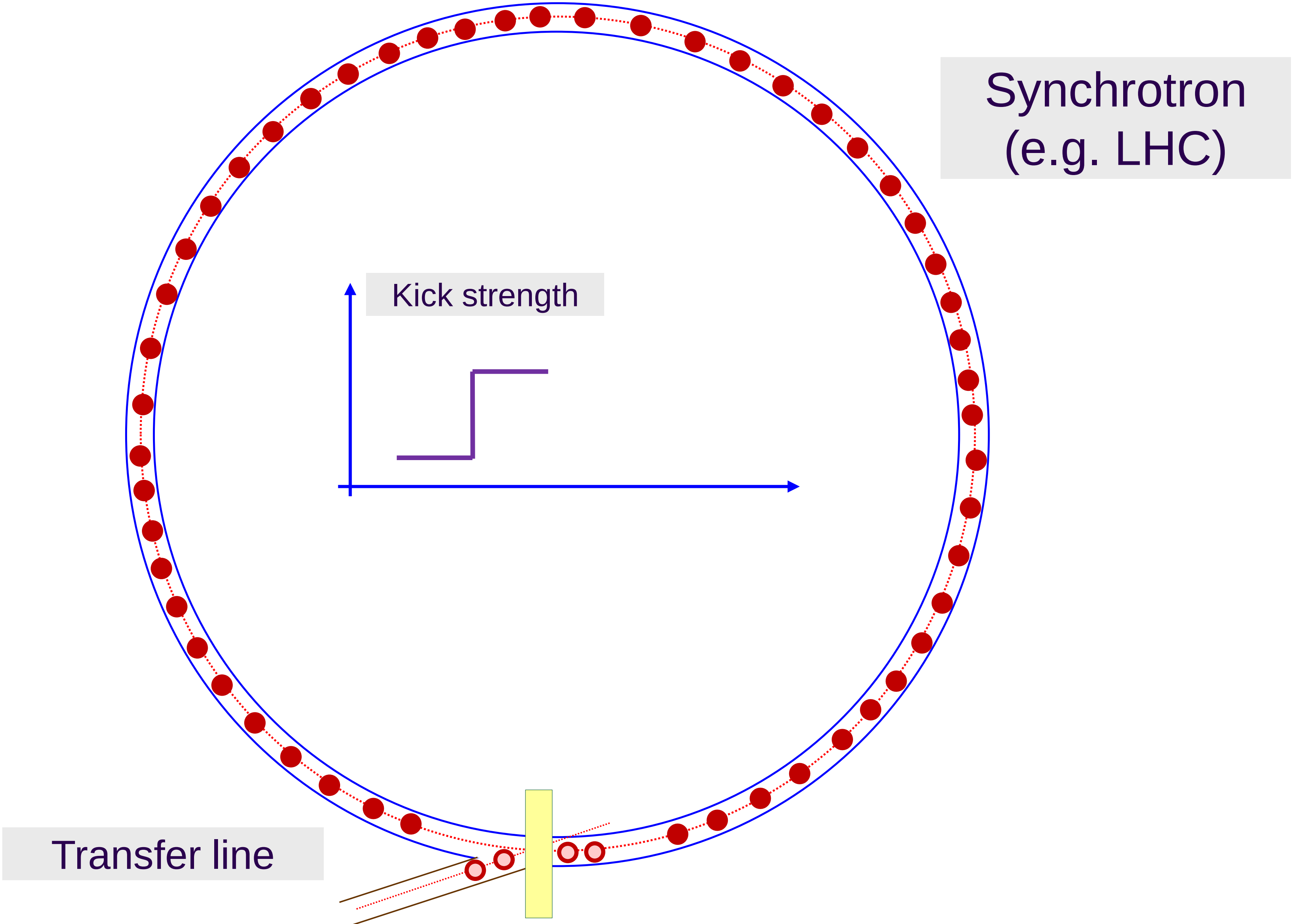
Before injection of a bunch train, LHC already filled



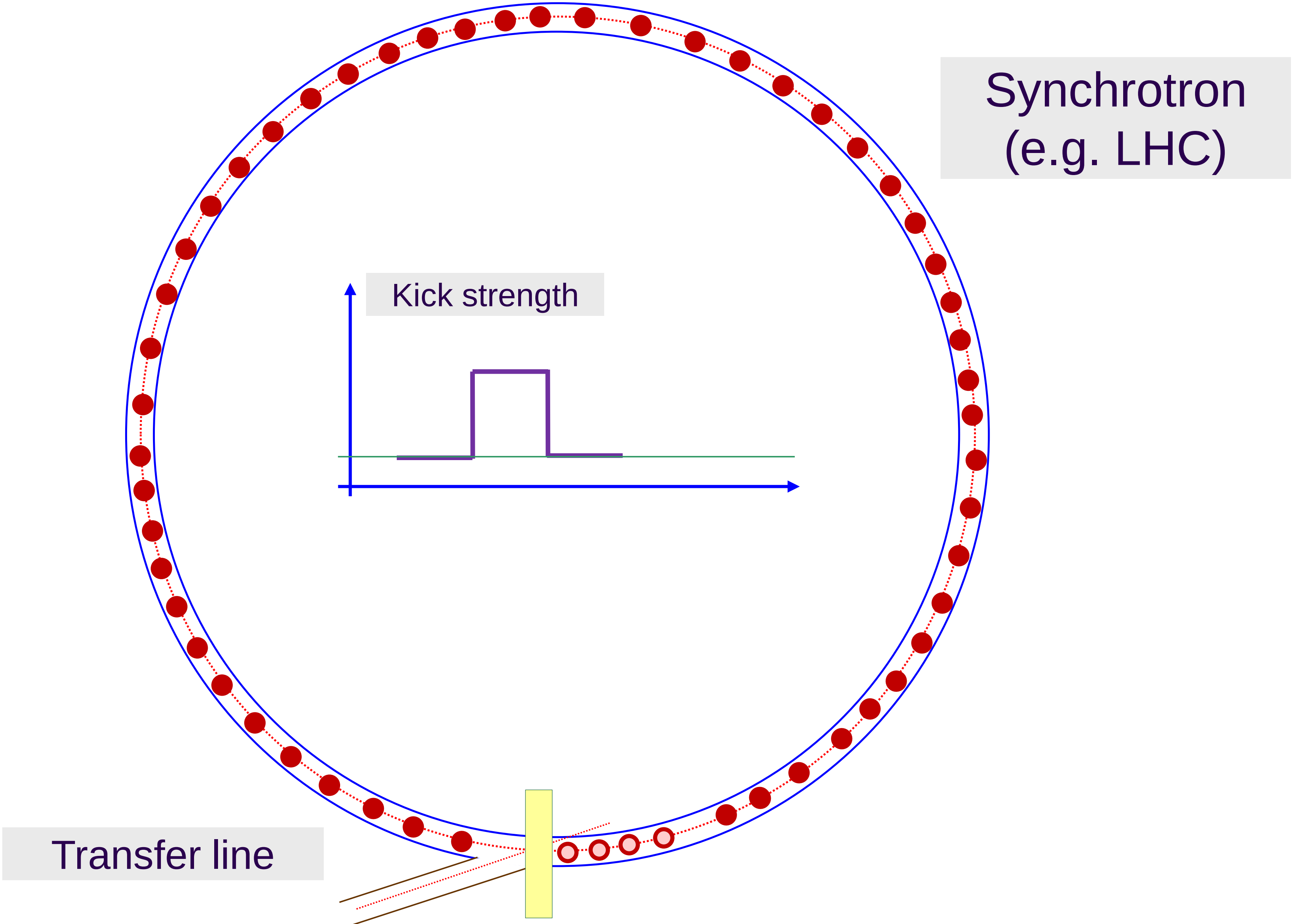
Before injection of a bunch train, LHC already filled



During injection of a bunch train, LHC already filled



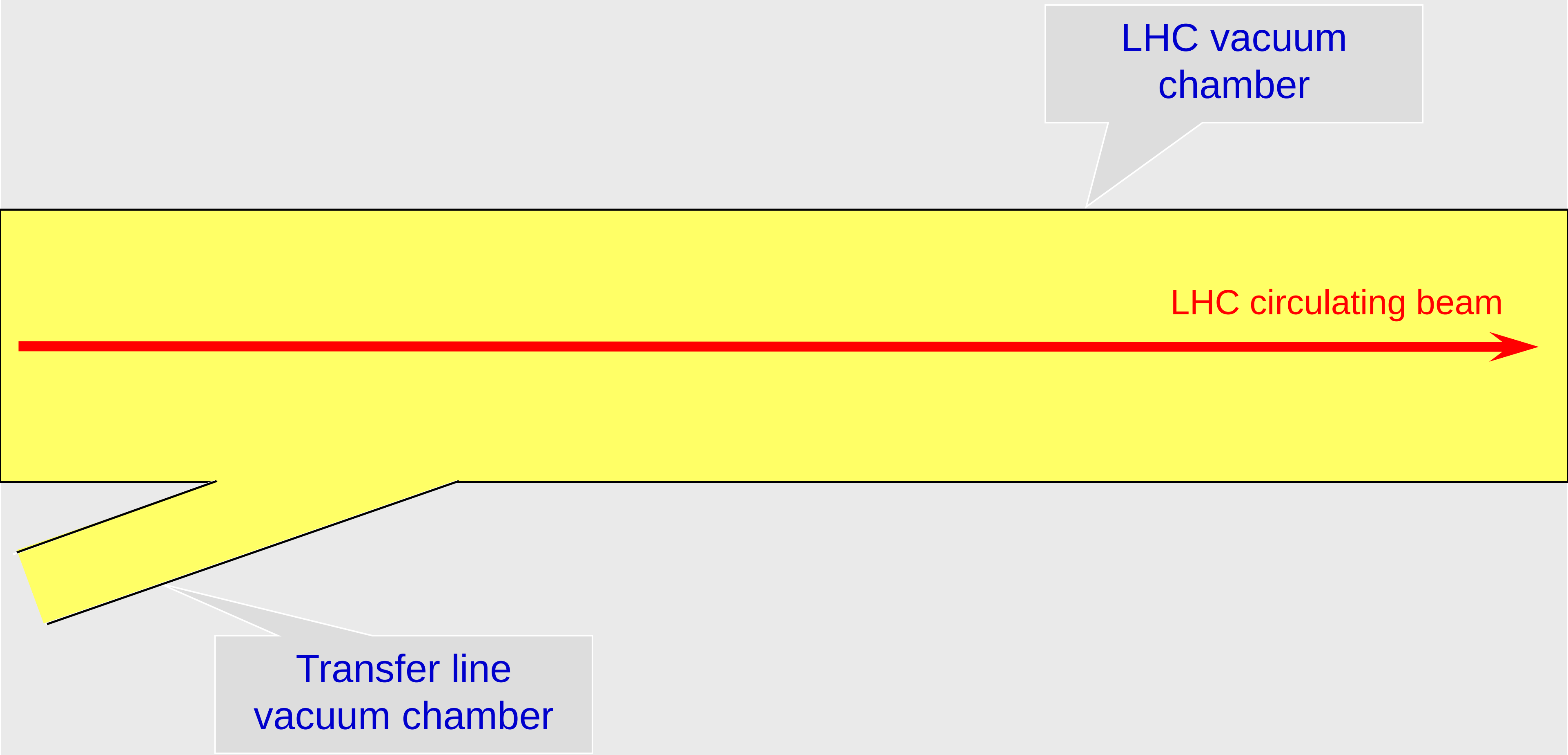
After injection of a bunch train, LHC already filled



Question

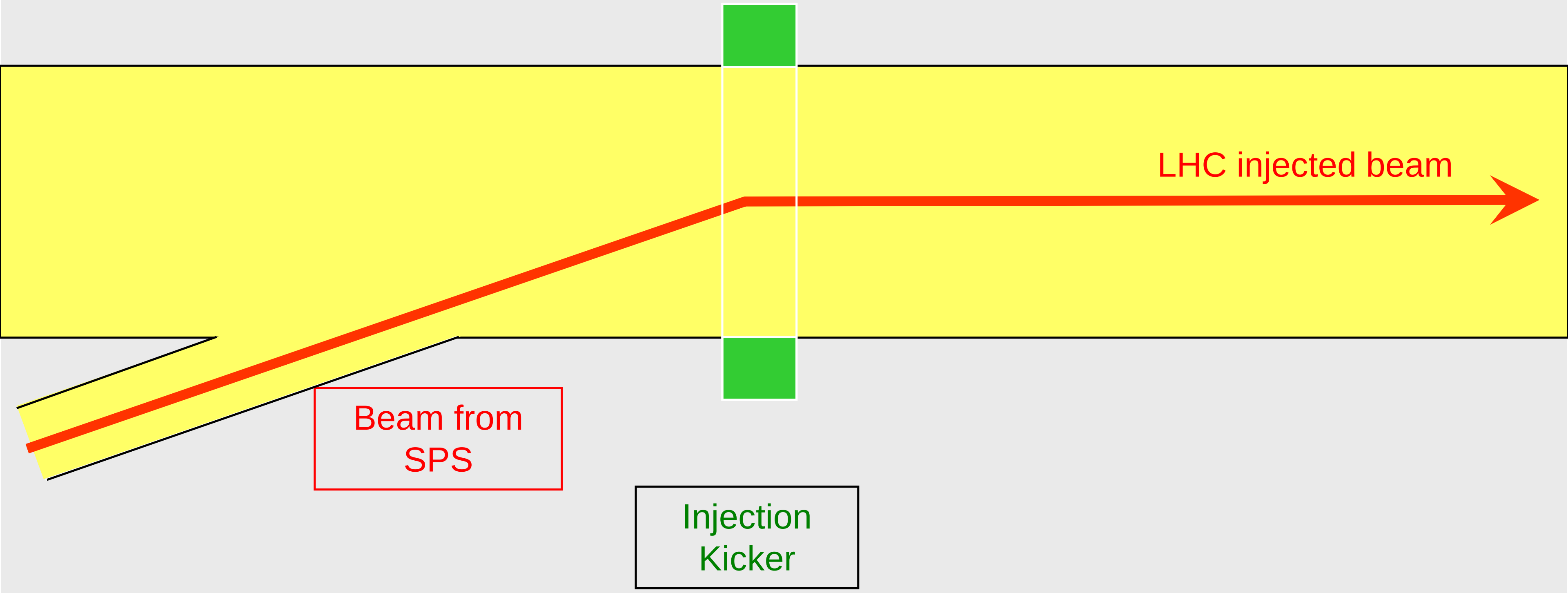
What can go wrong during injection ?

Protection at injection



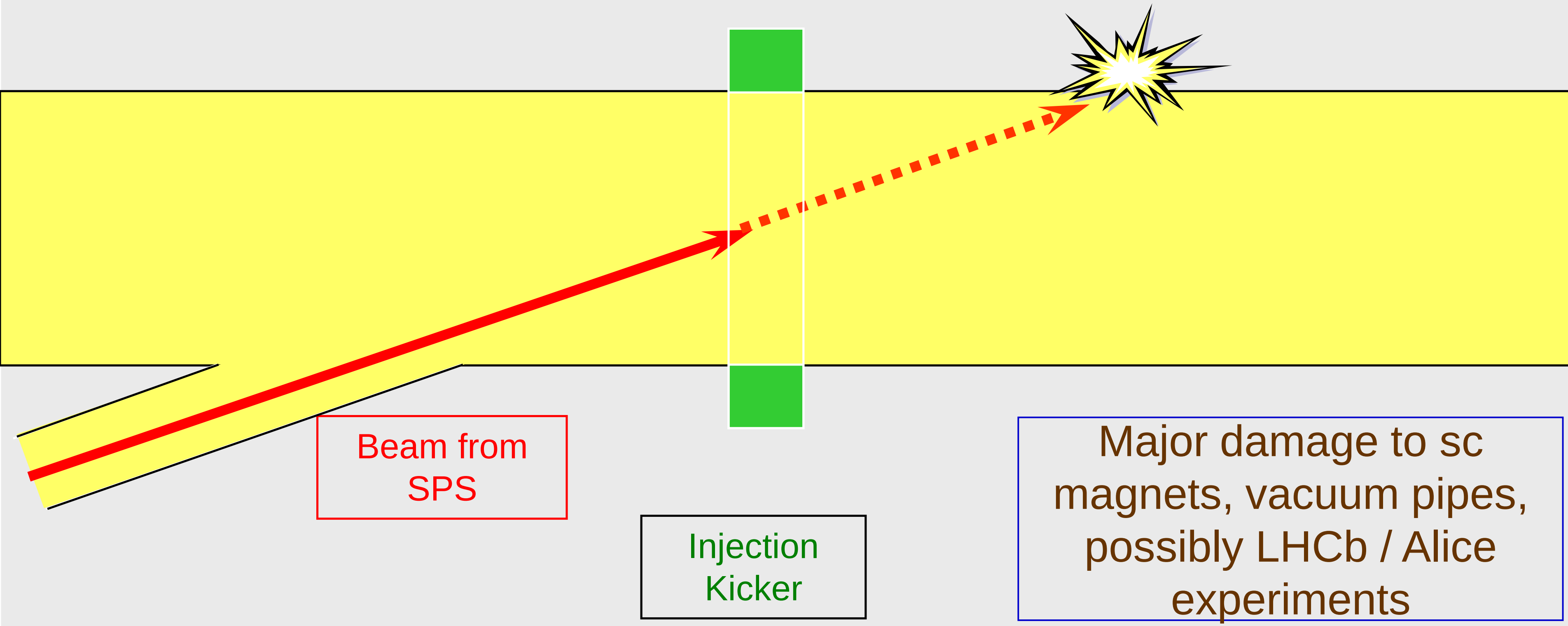
Circulating beam in LHC

Protection at injection



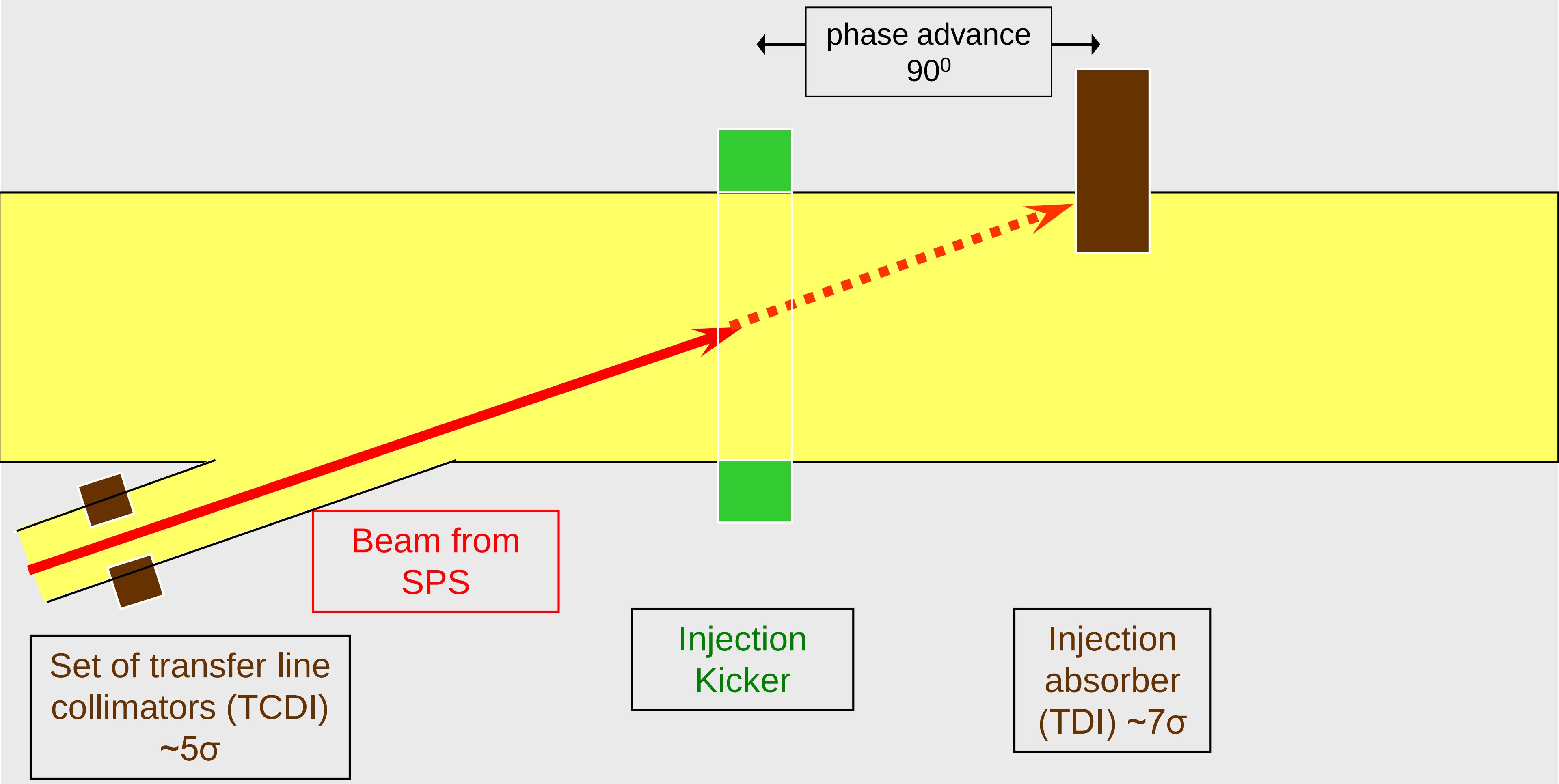
Beam injected from SPS and transfer line

Protection at injection



Kicker failure (no kick)

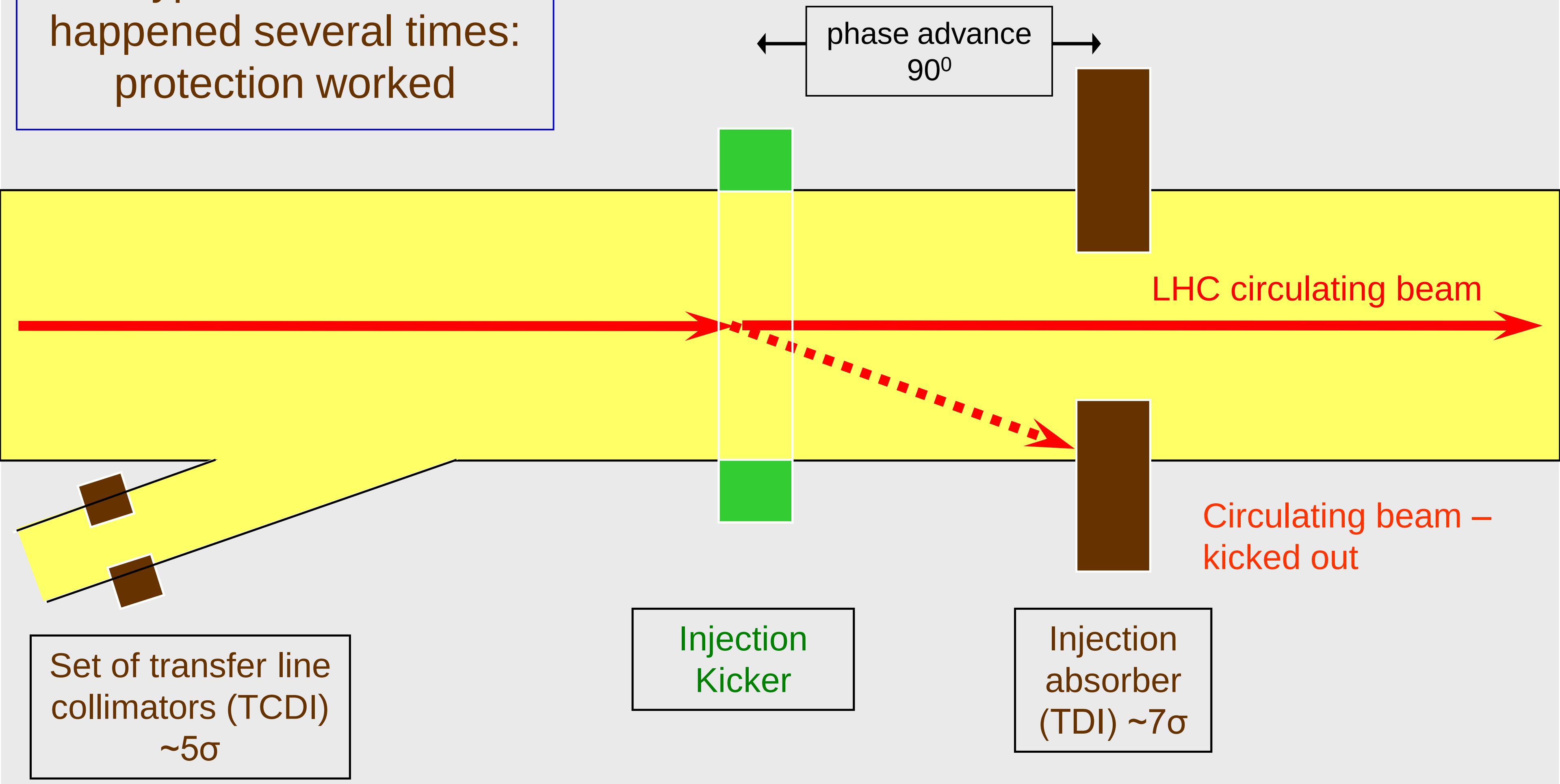
Protection at injection



Beam absorbers take beam in case of kicker misfiring
Transfer line collimators ensure that incoming beam trajectory is ok

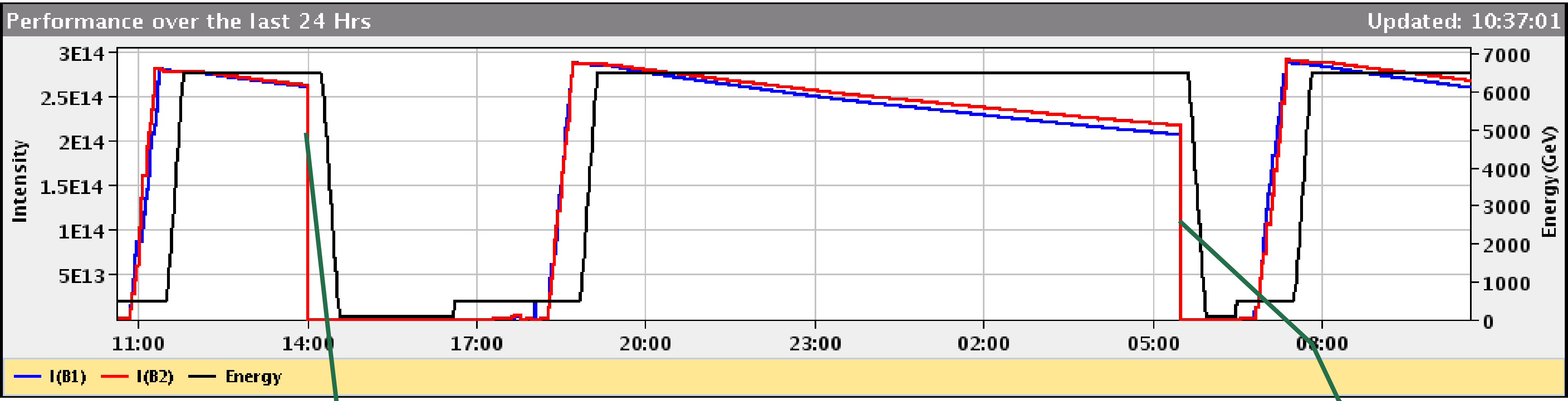
Protection at injection

This type of kicker failure happened several times: protection worked



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

Getting rid of the beams – the beam dumping system



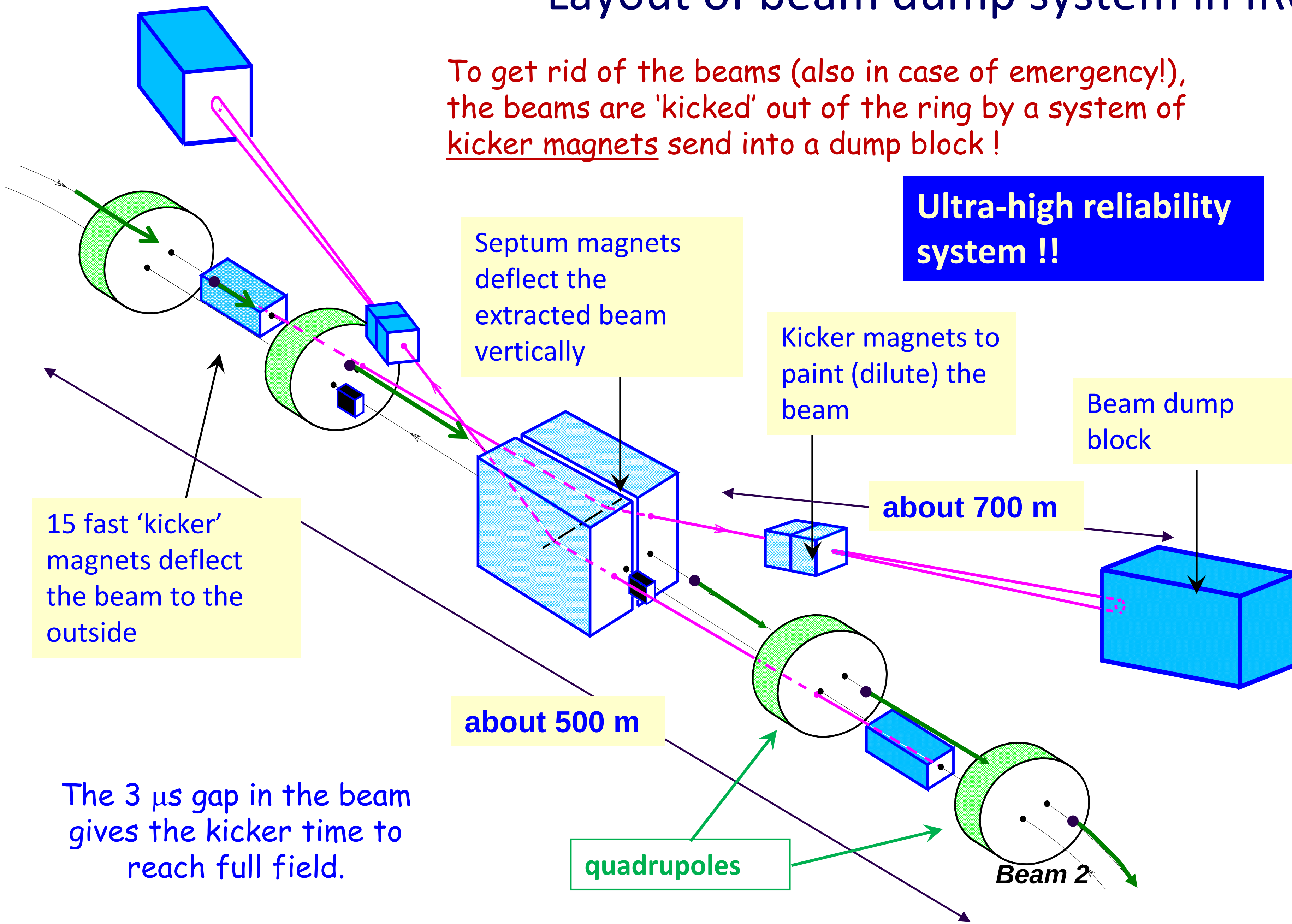
Failure: what to do with 290 MJ ?

End of the fill: what to do with the beams?

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 !

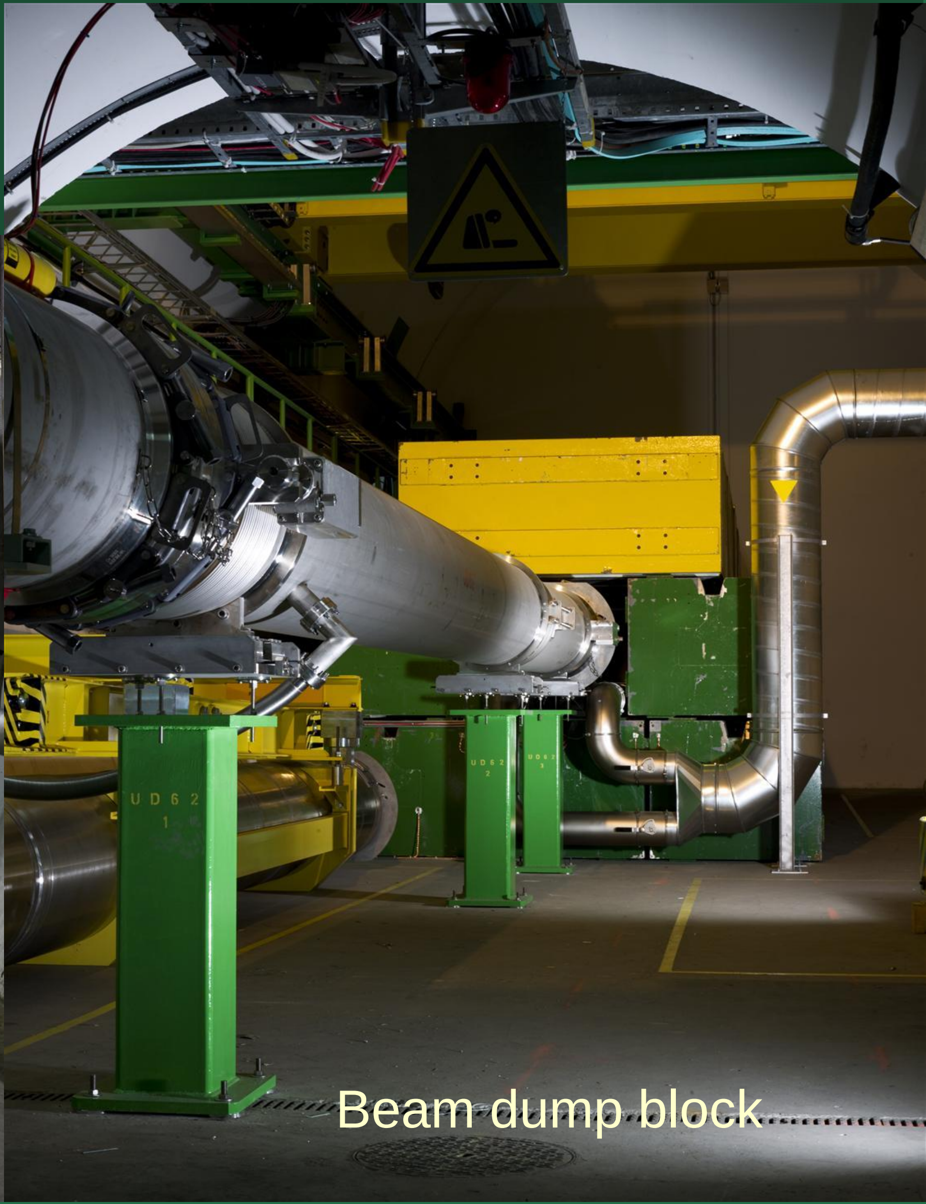
Ultra-high reliability system !!



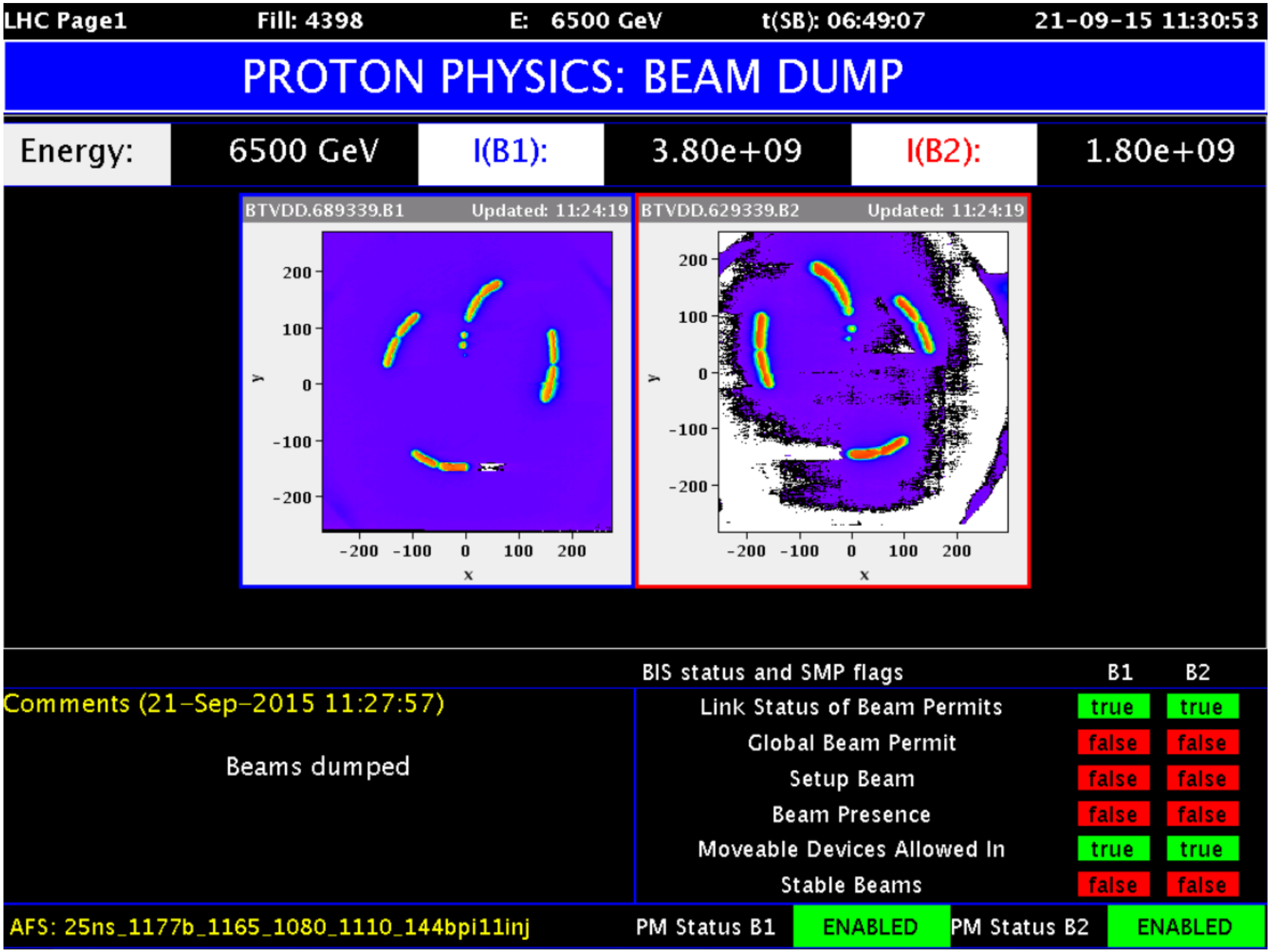
The 3 μs gap in the beam gives the kicker time to reach full field.

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