Beam Loss and Machine Protection
Lecture II

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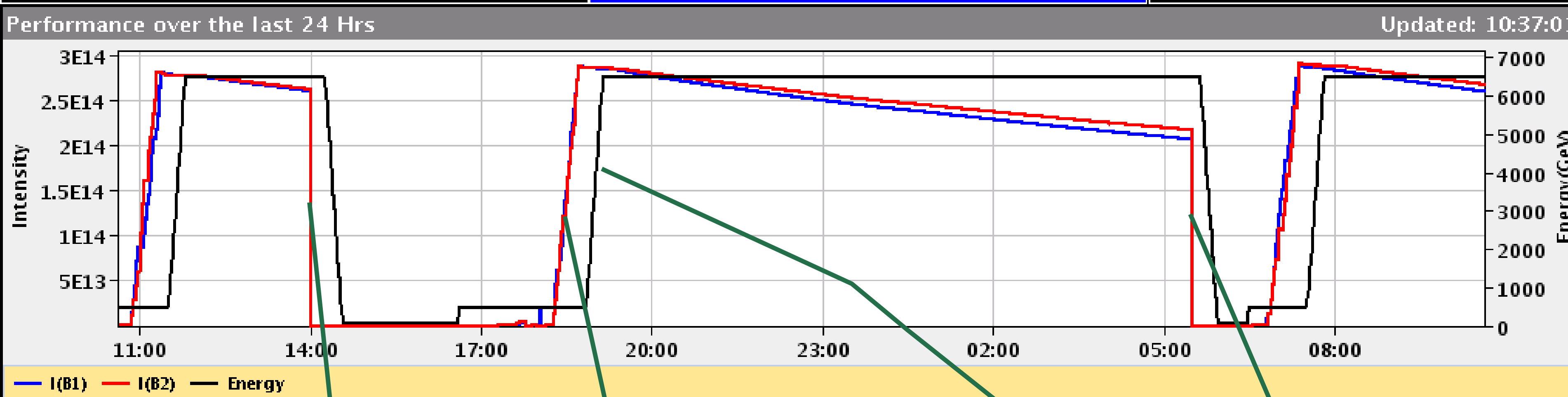
Summer Student Lectures 2017

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



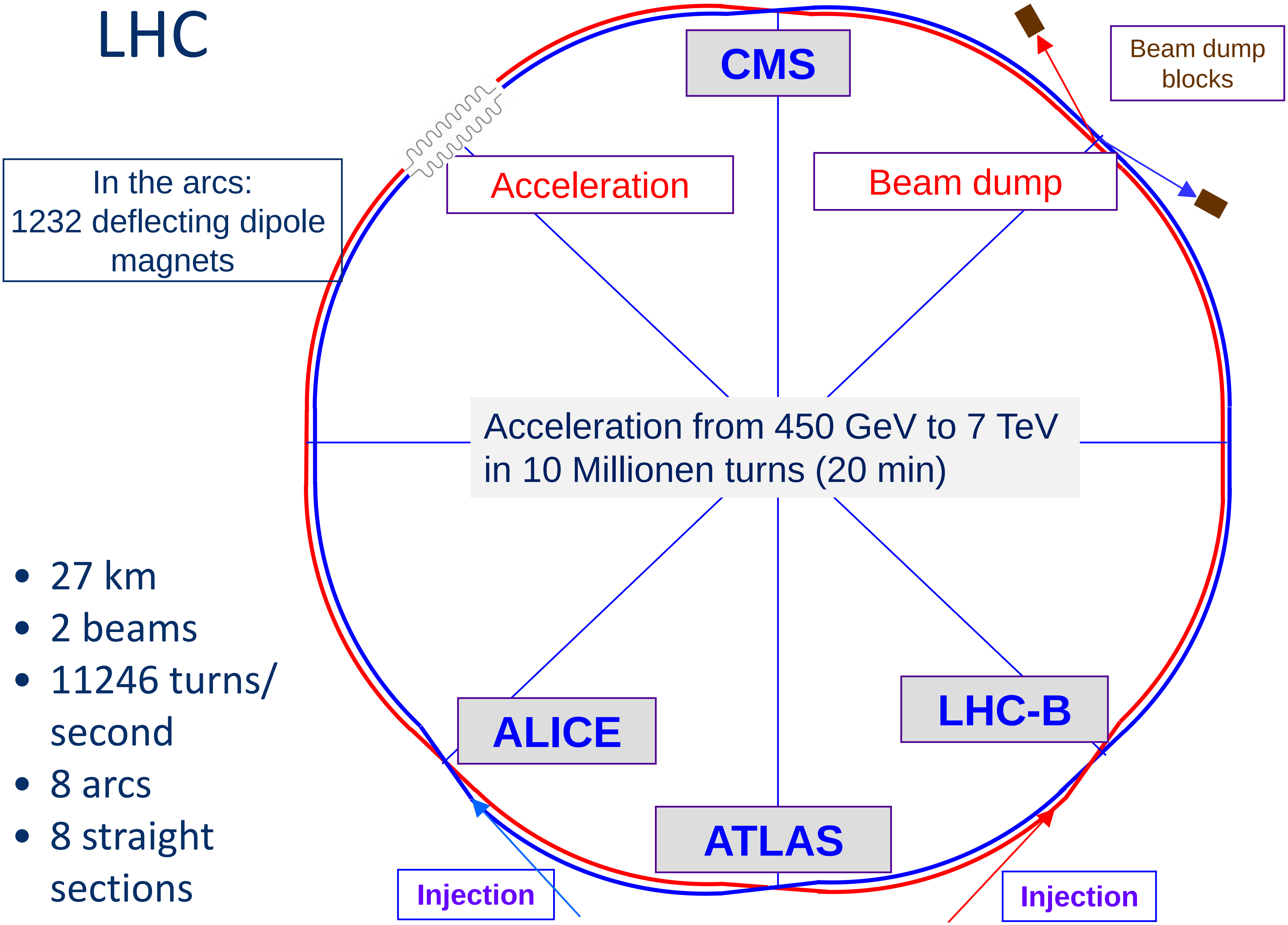
Ramp from 450 GeV to 6.5 TeV => total energy for each beam is 290 MJ

Failure: what to do with 290 MJ ?

Injection of 10 * 144 bunches = 144 *1.2 MJ

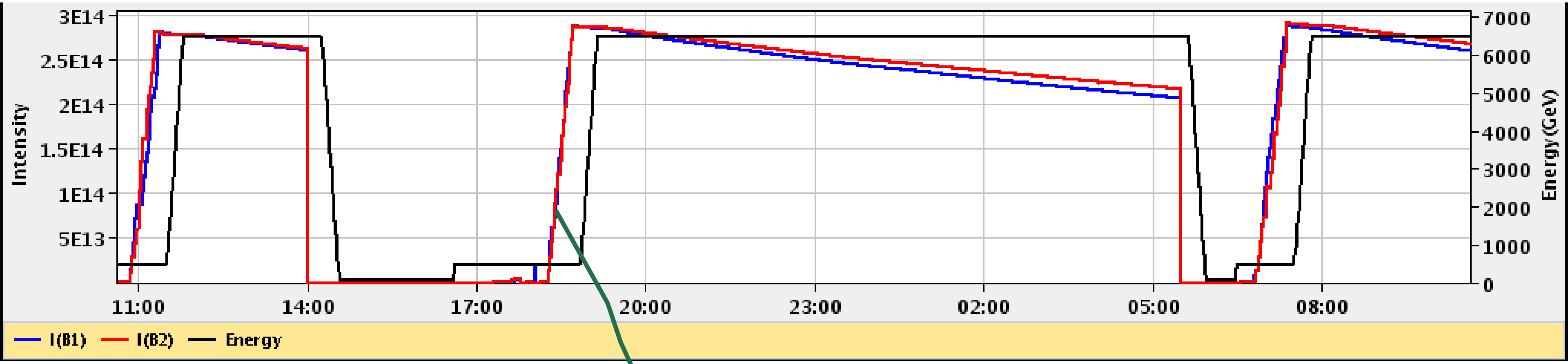
End of the fill: what to do with the beams?

LHC



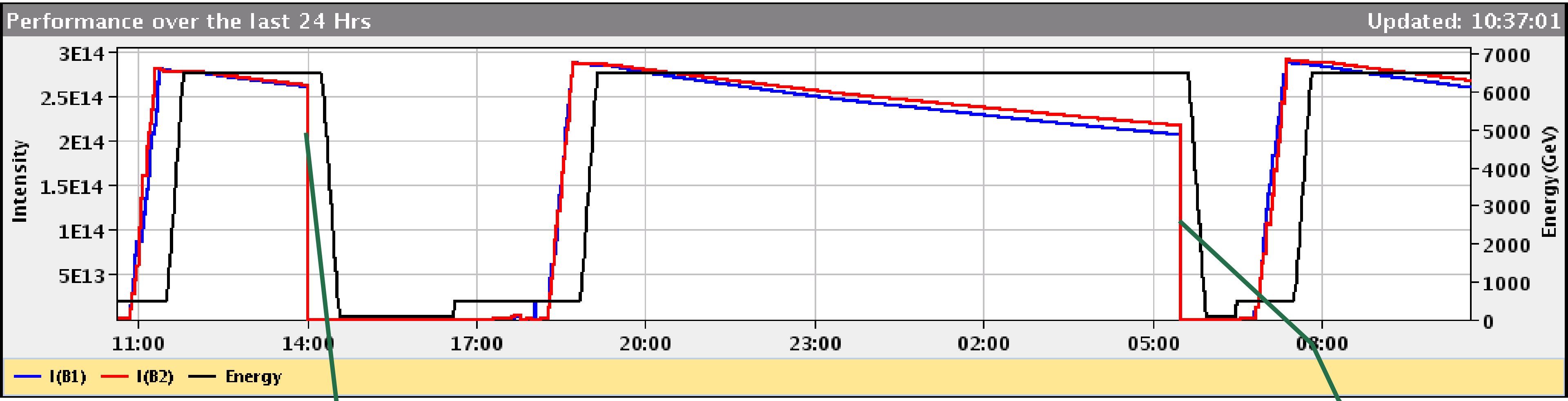
- 27 km
- 2 beams
- 11246 turns/ second
- 8 arcs
- 8 straight sections

Machine Protection at Injection



Injection of 10 * 144 bunches = 144 *1.2 MJ

Getting rid of the beams – the beam dumping system



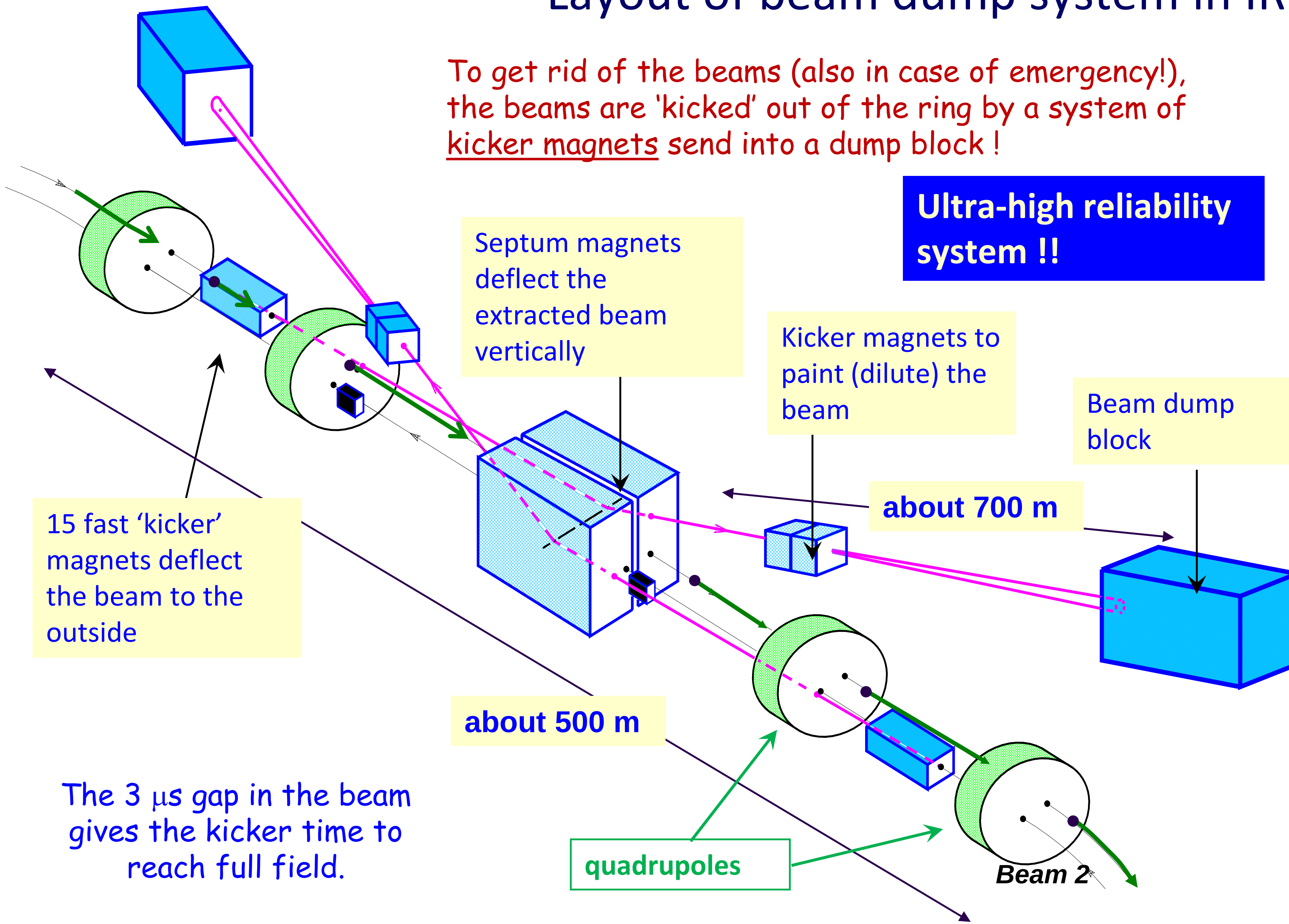
Failure: what to do with 290 MJ ?

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

Layout of beam dump system in IR6

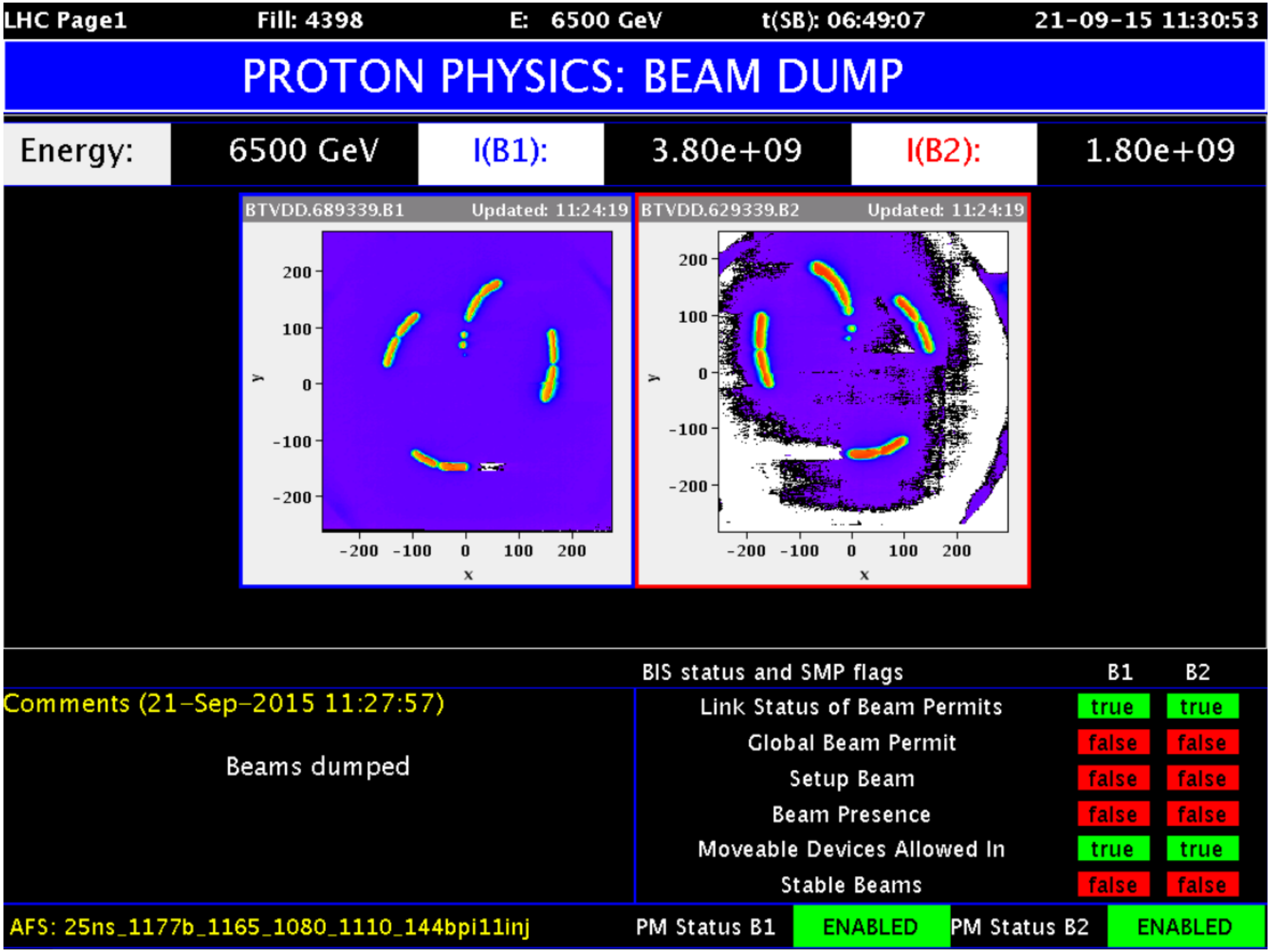
To get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets send into a dump block !

Ultra-high reliability system !!



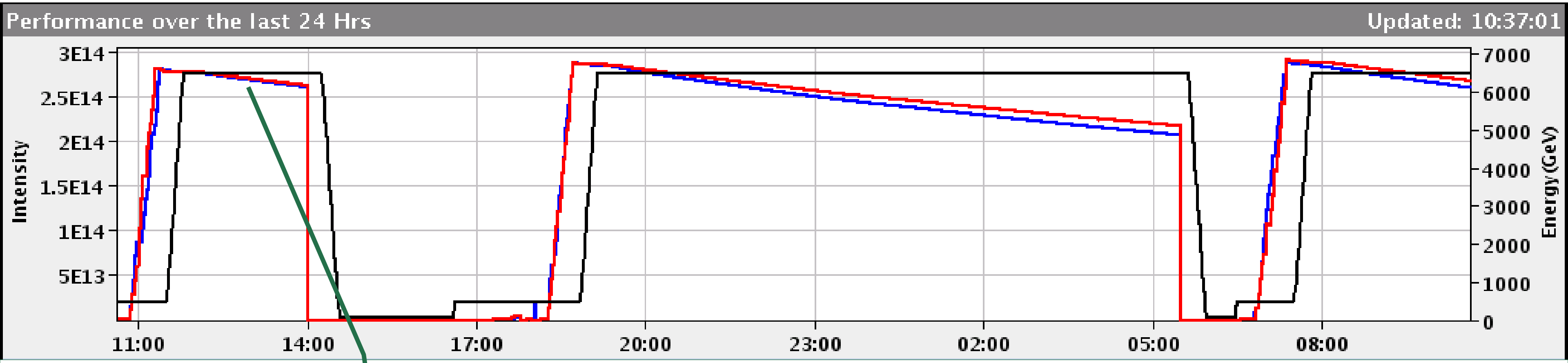
The 3 μs gap in the beam gives the kicker time to reach full field.

Beam dump with 1380 bunches

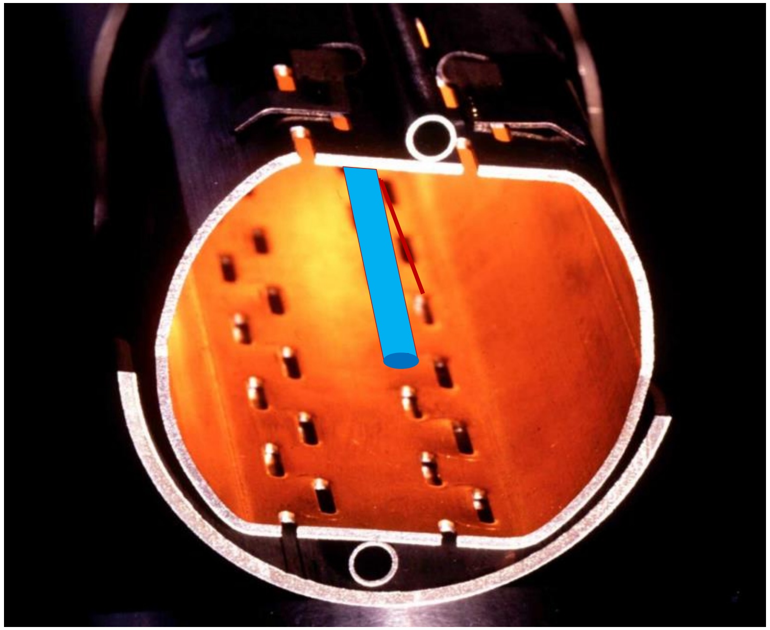


Beam spot at the end of the beam dumping line, just in front of the beam dump block

Circulating beams….



Failure with 290 MJ energy in circulating beams



The protons in LHC need to travel in the beam pipe for a distance of about 100 times the distance between sun and earth

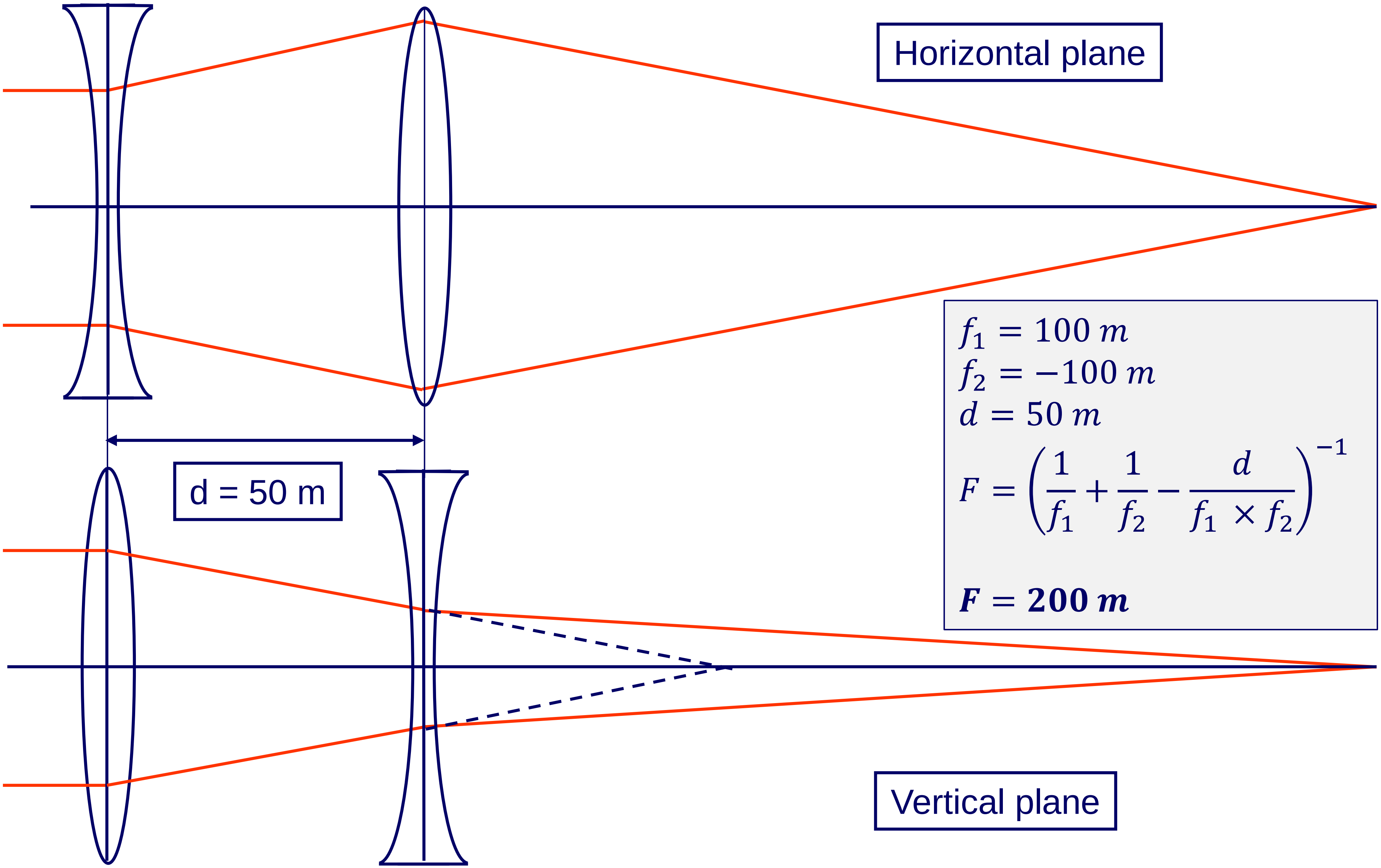
Reminder accelerator physics and beam dynamics

Need for getting protons on a circle: dipole magnets

Need for focusing the beams with lenses:

- Particles with different injection parameters (angle, position) separate with time
  - Assuming an angle difference of 10^{-6} rad, two particles would separate by 1 m after 10^6 m. At the LHC, with a length of 26860 m, this would be the case after 50 turns (5 ms !)
- Particles would „drop“ due to gravitation
- The beam size must be well controlled
  - At the collision point the beam size must be tiny
- Particles with (slightly) different energies should stay together

Focusing by two quadrupole magnets, thin lenses

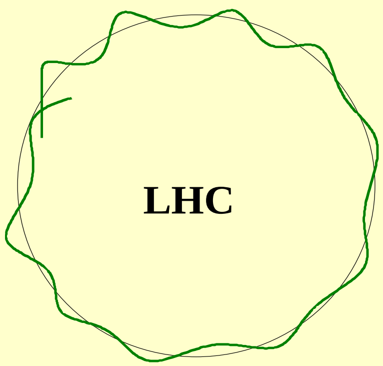


$f_1 = 100\ m$
$f_2 = -100\ m$
$d = 50\ m$

$$F = \left(\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \times f_2}\right)^{-1}$$

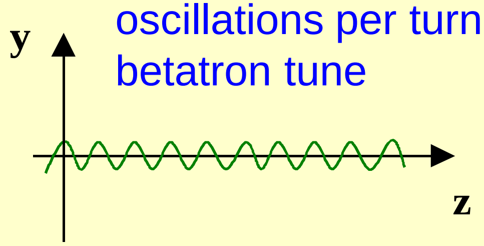
$\boldsymbol{F = 200\ m}$

Particle stability and magnets

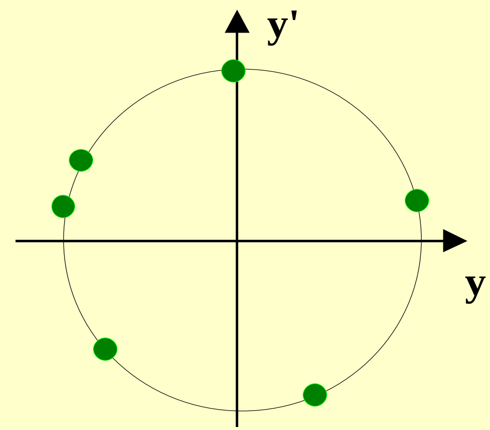


Particle oscillations in quadrupole field (small amplitude)

Number of oscillations per turn: betatron tune



Harmonic oscillation after coordinate transformation



Circular movement in phase space

- All particles in a circular accelerator oscillate around a trajectory in the accelerator: the **closed orbit**
- With correct coordinate transformation, these **betatron oscillations** have sinusoidal shape
- This is exactly true for a system with linear fields (only quadrupolar fields), and only approximately true for non-linear field

Magnets and beam transport

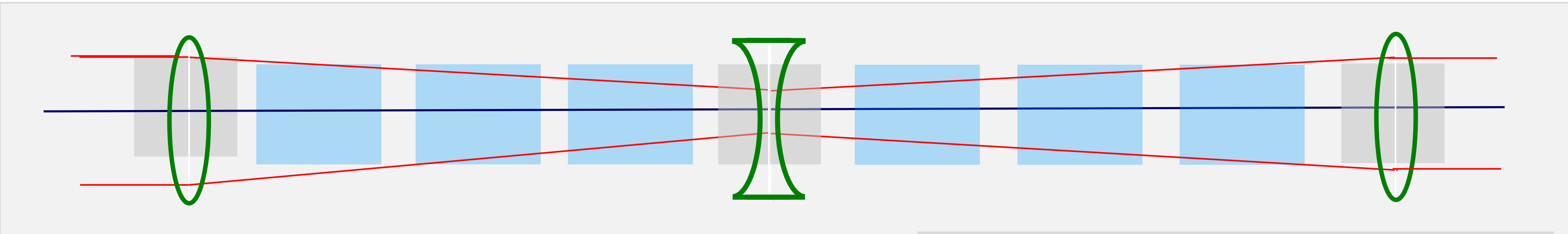
- Dipole magnets
  - To make a circle around LHC
- Quadrupole magnets
  - To keep beam particles together
  - Particle trajectory stable for particles with nominal momentum

Linear

- Sextupole magnets
  - To correct the trajectories for off momentum particles
- Multipole-corrector magnets
  - Sextupole - and decapole corrector magnets at end of dipoles
- Particle trajectories can become instable after many turns (even after, say, 10^6 turns)

Non-linear

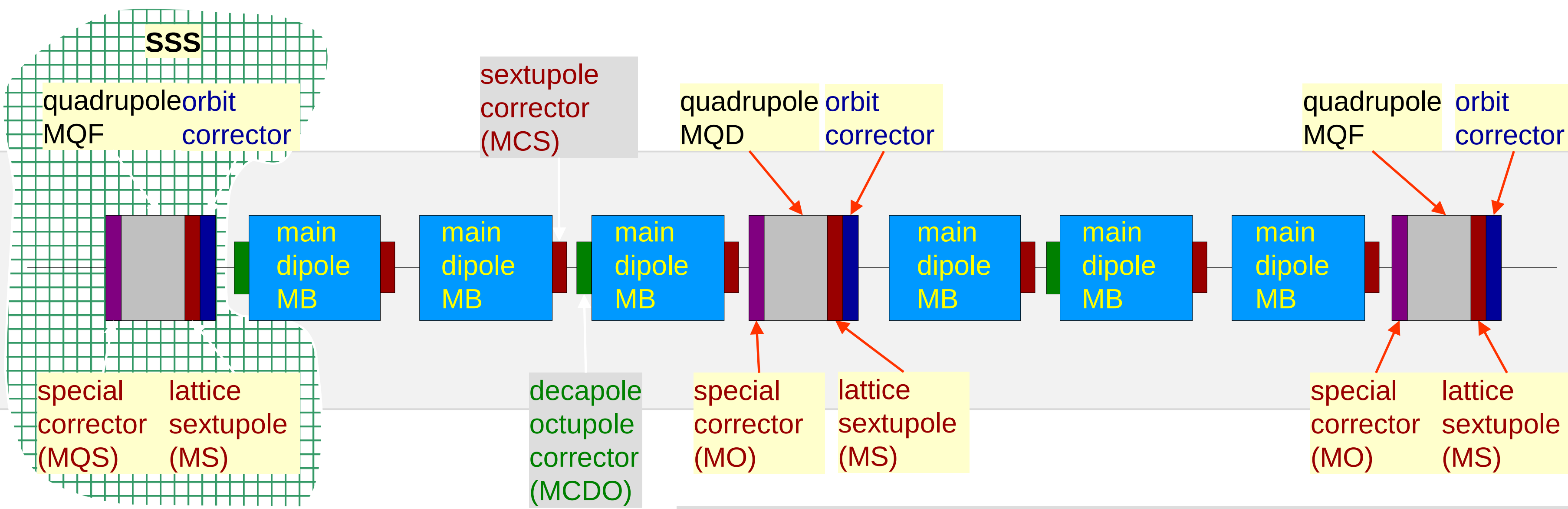
A (F0D0) cell in the LHC arcs



Vertical / Horizontal plane (QF / QD)

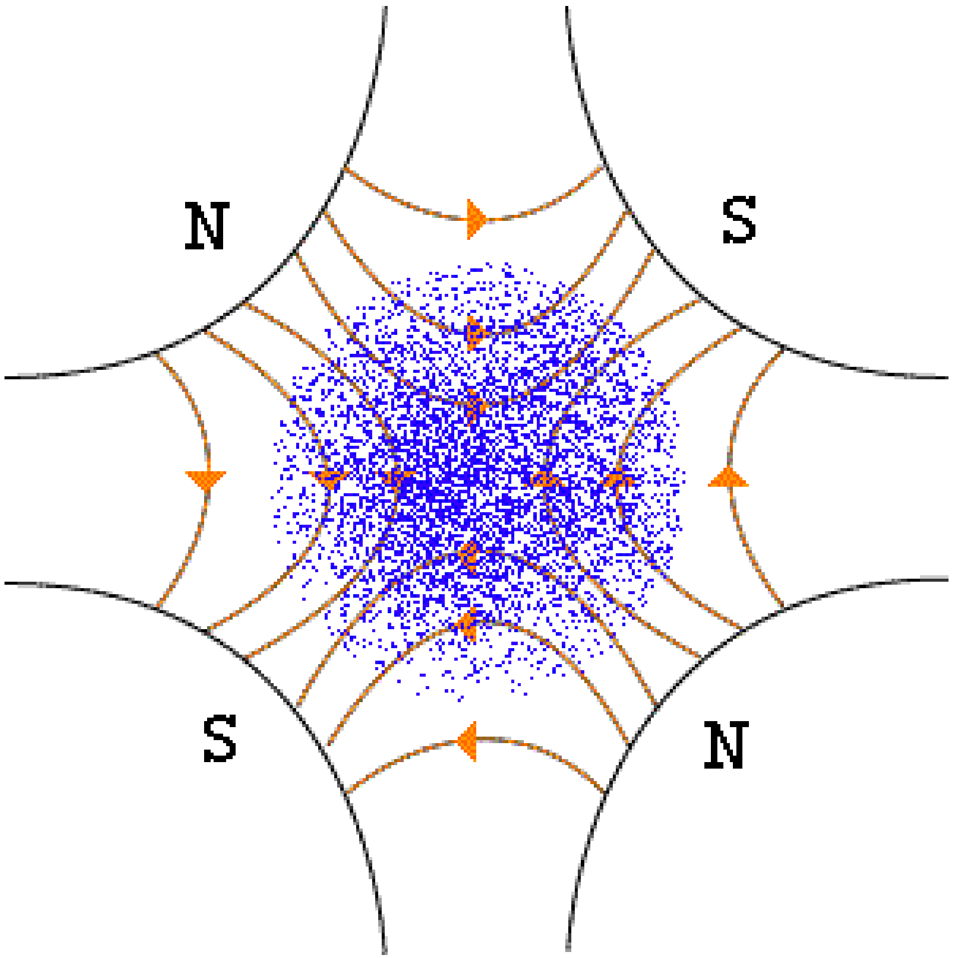
Quadrupole magnets controlling the beam size „to keep protons together" (similar to optical lenses)

LHC Cell - Length about 110 m (schematic layout)



10000 magnets powered in 1700 electrical circuits

Visualisation

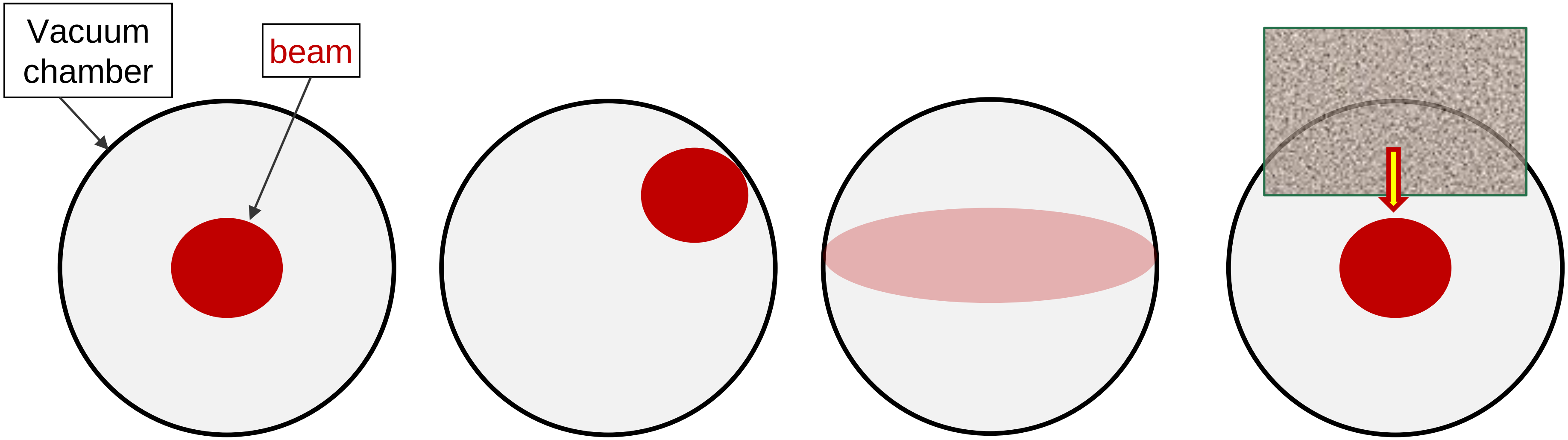


What can happen to beams in a circular accelerator?

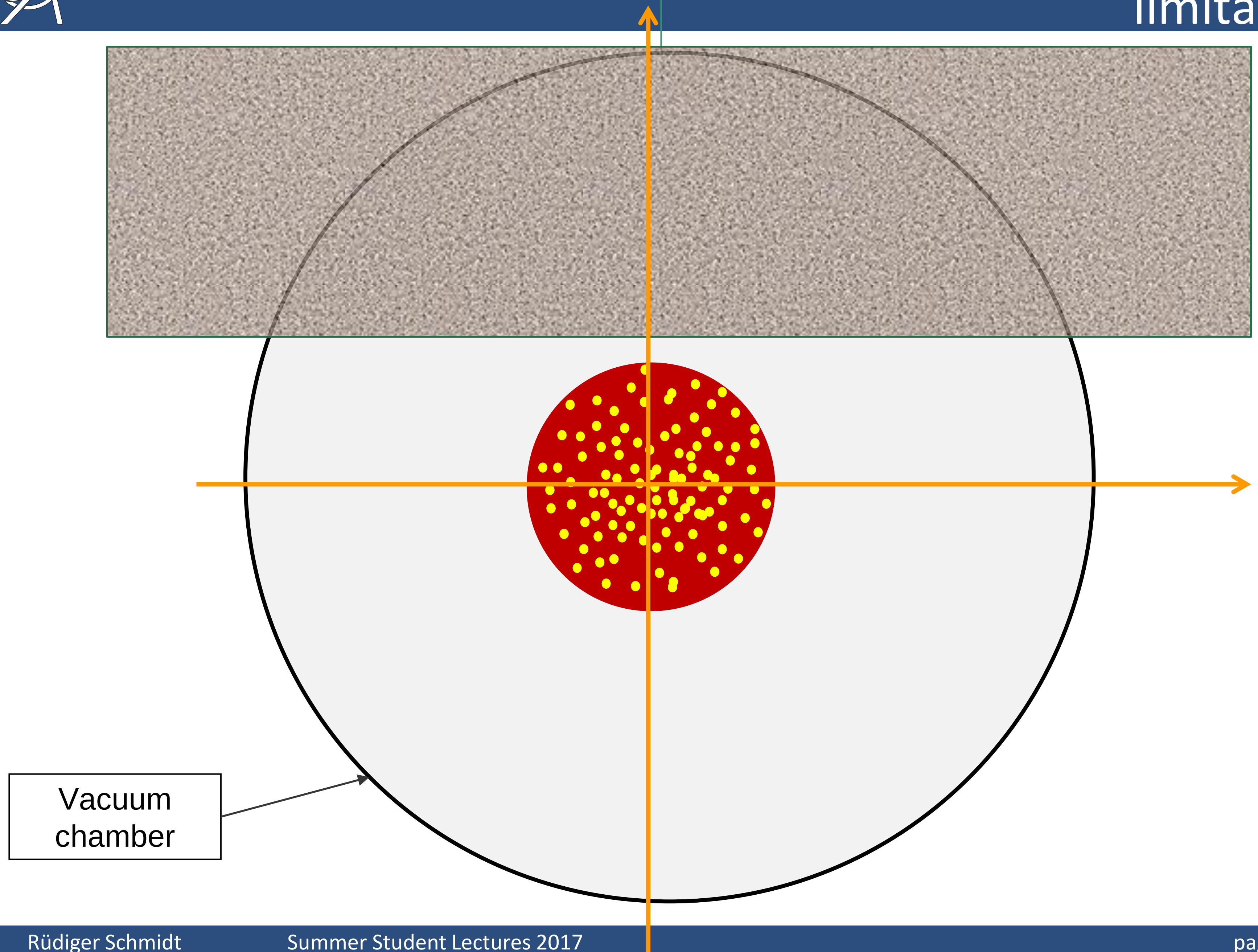
Assume that the beam is happily circulating in the accelerator: what mechanism can cause beam losses?

A) Particles are leaving the nominal trajectory (which is in general an oscillation around the centre of the vacuum chamber) and touch the aperture

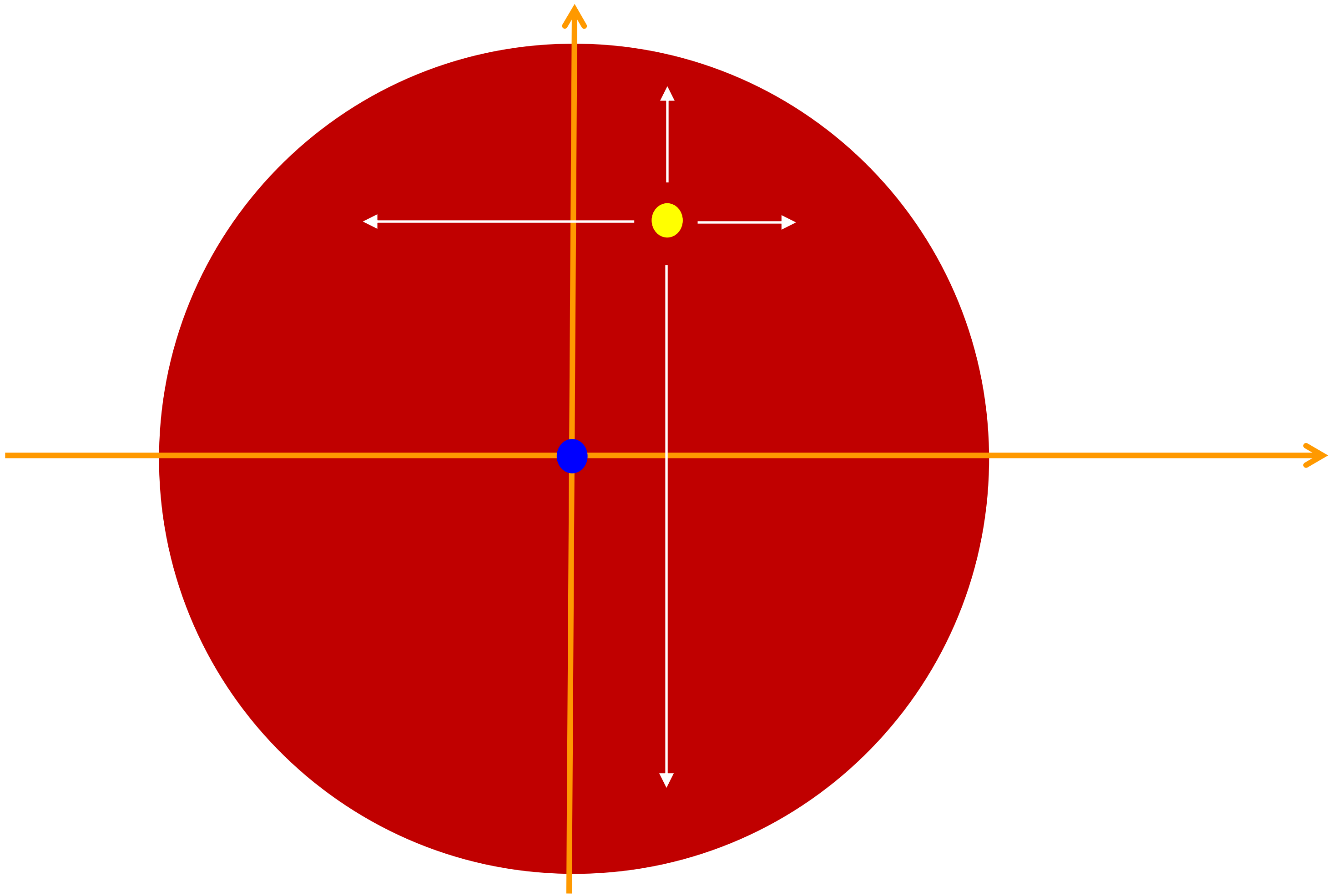
B) Mechanical objects touch the beam (beam instrument, vacuum valve, other objects, …)



Zooming in – illustration of beam with aperture limitation



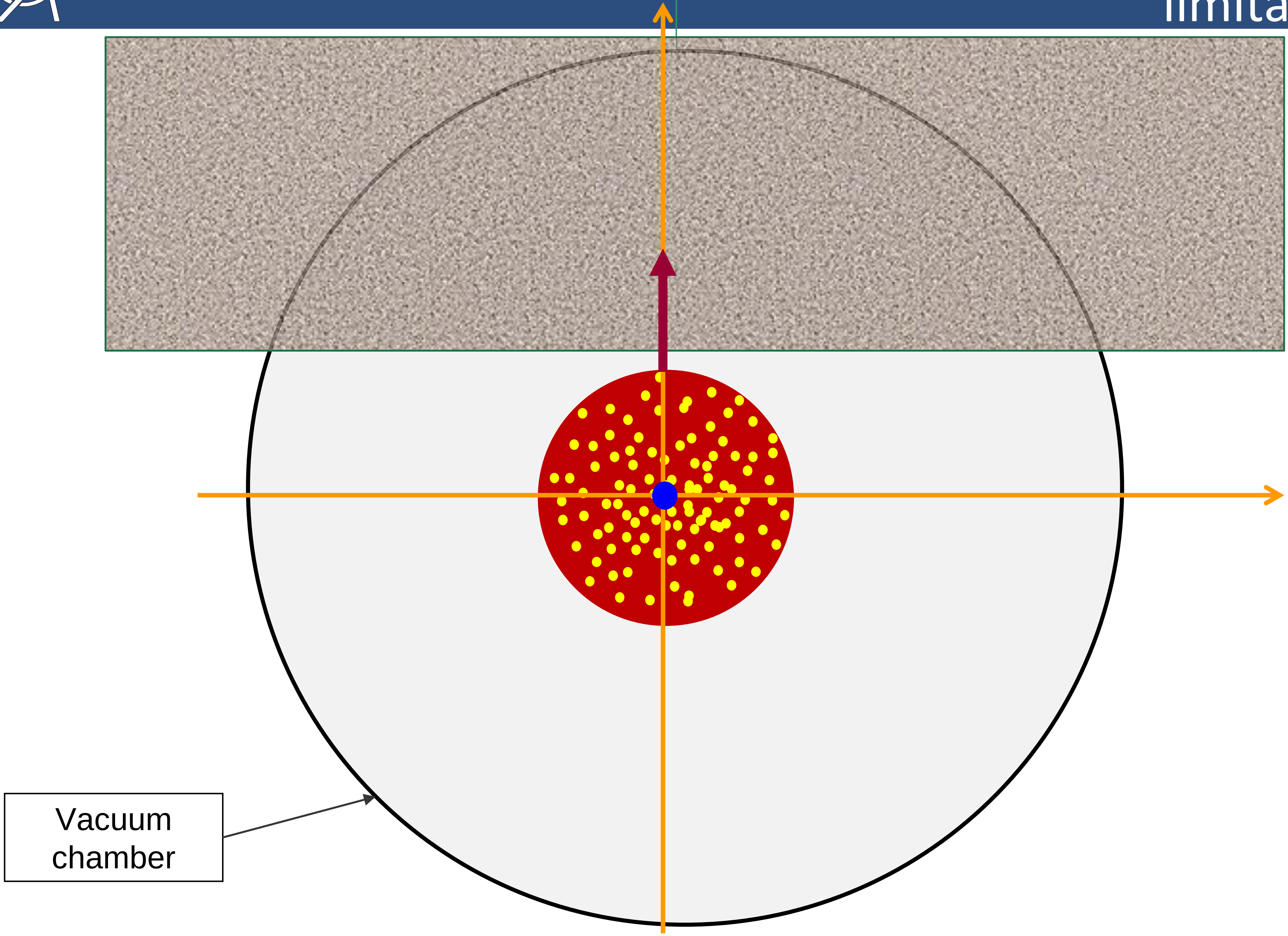
Zooming further into the beam



Blue - particle on closed orbit

Yellow - particle performing betatron oscillations around the closed orbit

Zooming in – illustration of beam with aperture limitation

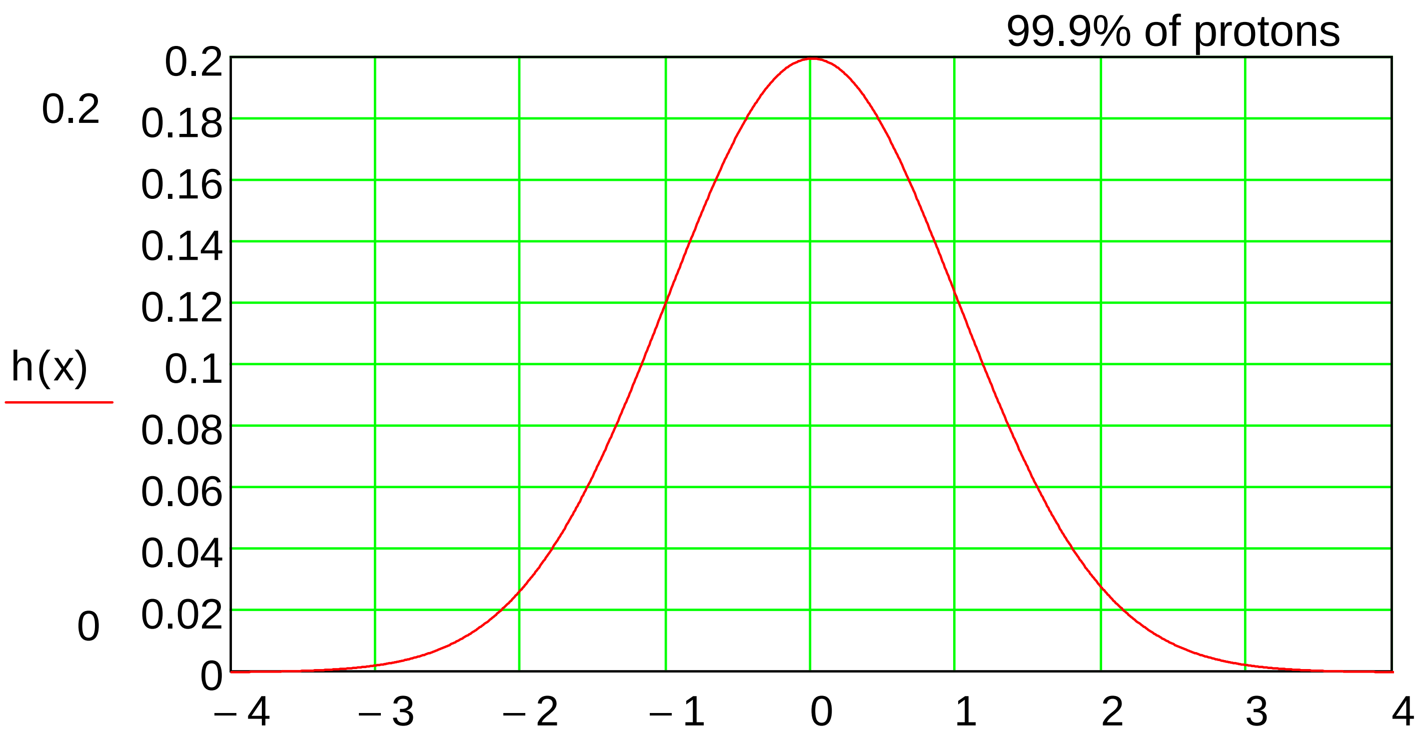


Question

Assume that the beam moves slowly further out.
The centre of the beam (closed orbit – yellow cross) is moving…

When are all particles lost?

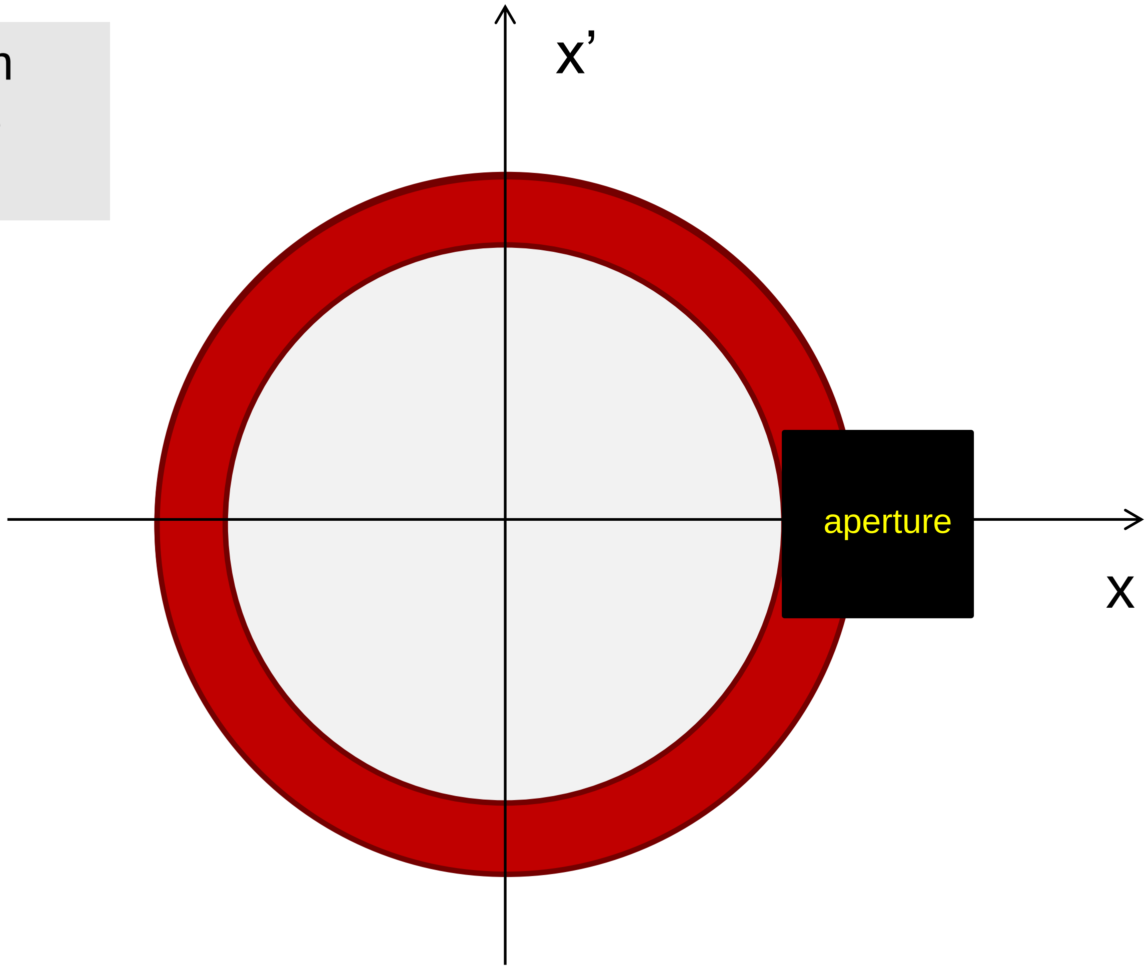
Gaussian beam and aperture



99.9% of all particles are inside a boundary of 4 σ
Depending on the accelerator and its operational parameters, the aperture can be much larger than 4 σ - but not smaller

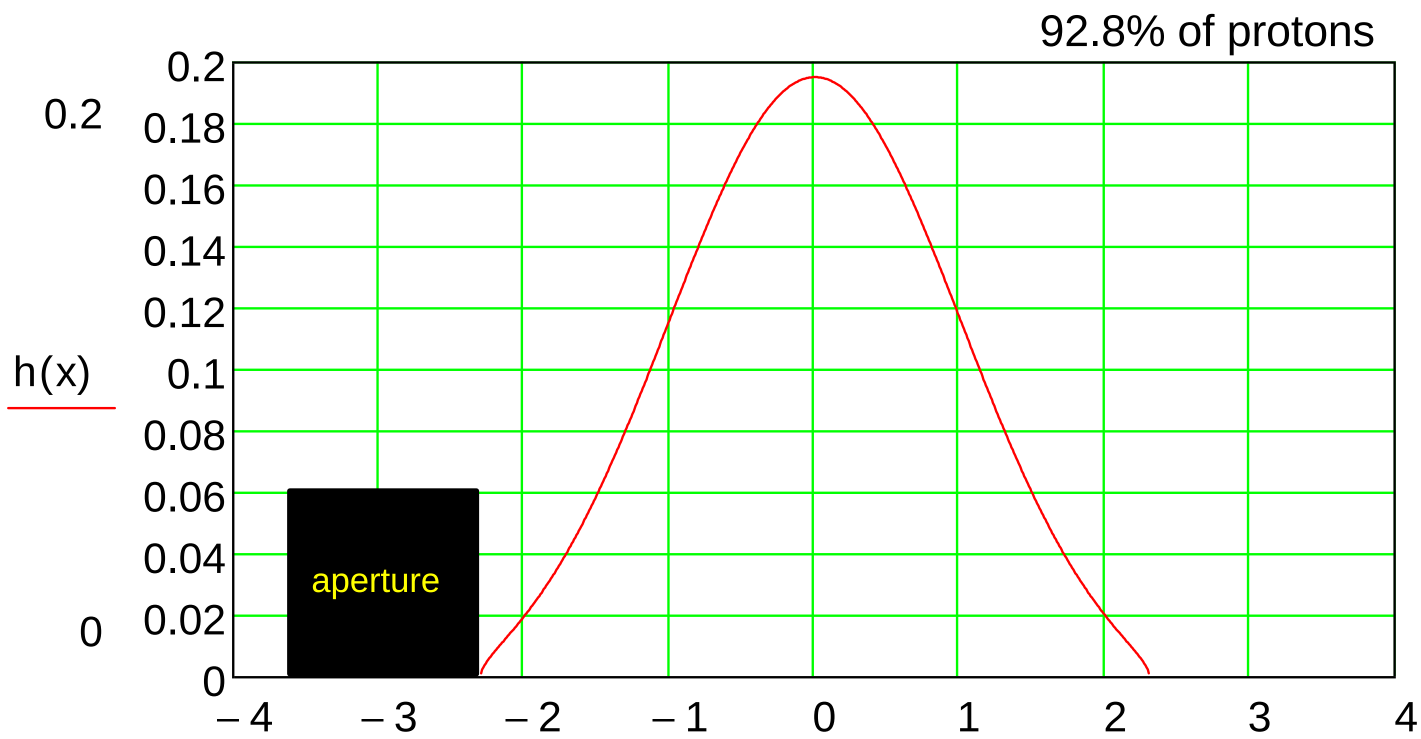
Phase space reduction by collimator

Example: the beam moves towards the aperture.



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

Gaussian beam with an aperture at 2.3 σ



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

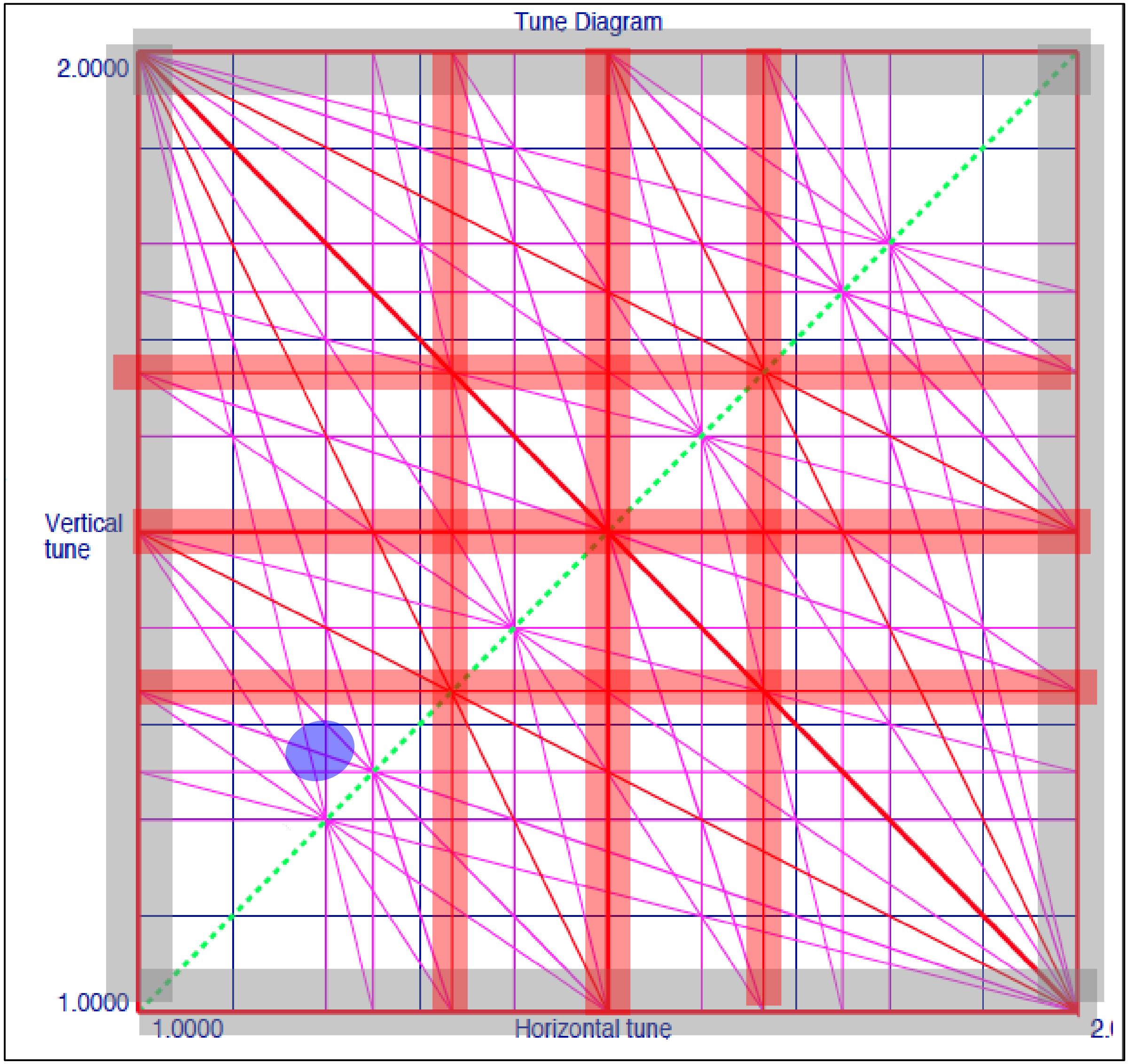
Beam loss mechanism

- What is required for beams not touching the aperture:
  - No mechanical elements in the beam pipe
  - Well corrected closed orbit
  - Correct betatron tunes
  - Correct chromaticity (in general, tune spread limited between resonances)
  - Beam intensity below instability threshold

- What can go wrong:
  - Some mechanical element accidently moves into the vacuum pipe
  - Horizontal or vertical dipole magnet has wrong field
  - Quadrupole magnet has wrong field
  - Sextupole magnets have wrong field – losses due to single particle effects or instabilities (multi particle effect)
  - Too high beam current for the operational point – losses due to single particle effect or instabilities

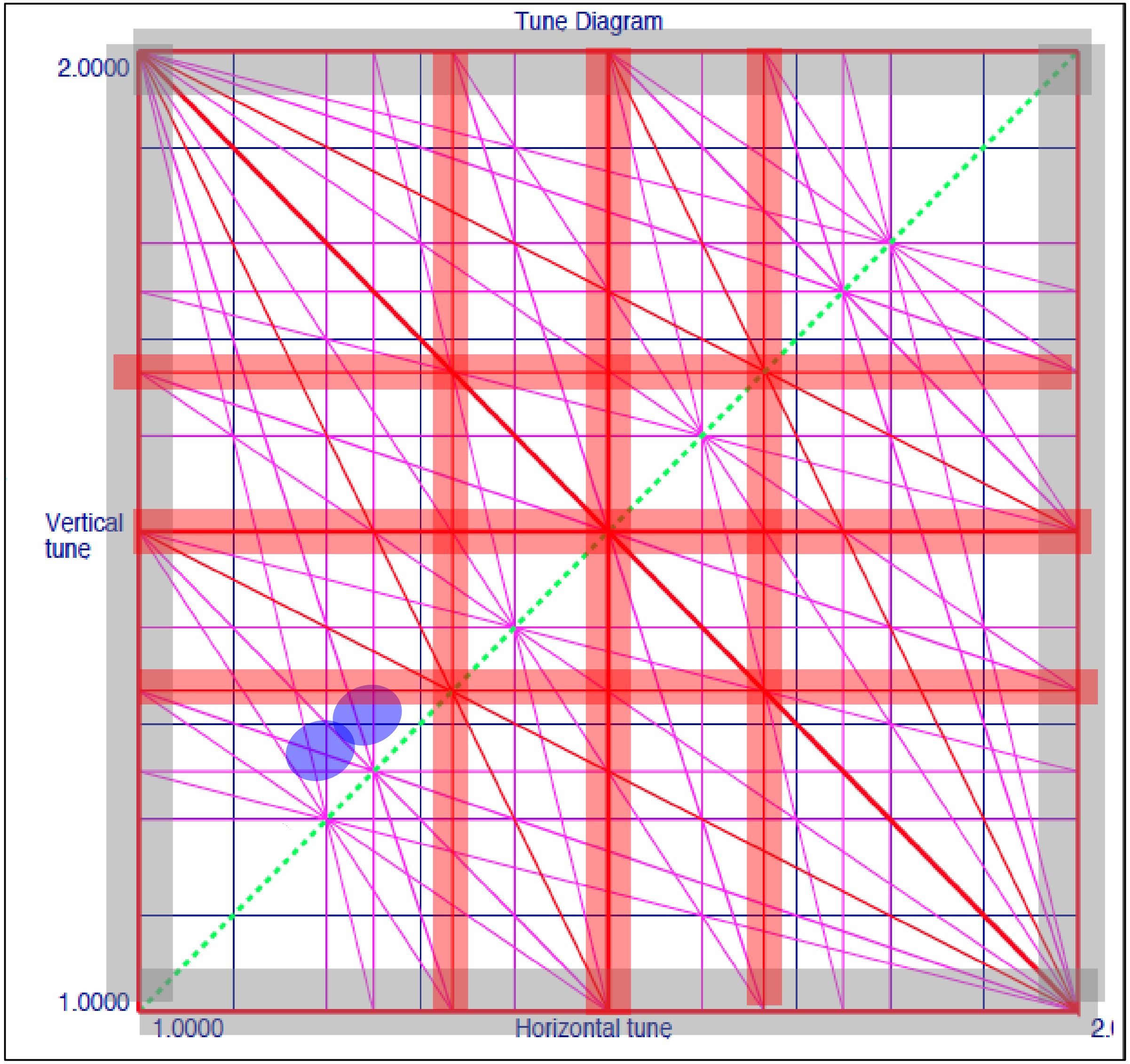
Betatron tune diagram

- Particles with integer, half-integer or third integer tunes risk to be lost
- Due to the chromaticity and energy spread particles have a different tune
- There are other effects that lead to a tune spread (beam-beam, nonlinear fields, effects due to high beam intensity)



Tune diagram and resonances

- Particles with integer, half-integer or third integer tunes risk to be lost
- Due to the chromaticity and energy spread particles have a different tune
- There are other effects that lead to a tune spread (beam-beam, nonlinear fields, effects due to high beam intensity)



Why does it go wrong?

For the LHC cycle, many million parameters during the acceleration cycle of 30 min (e.g. current versus time every 20 ms for 1700 power converters).

One single wrong parameter can cause beam losses

- **Failure of some hardware** (power converter / magnet)
- **Single event upset** due to radiation in control electronics
- Thunderstorm (**electrical system**) affecting powering
- **Software failure** (wrong magnet current programmed)
- **Operator** gives wrong command
- Too high beam intensity - **instability**
- **Feedback** system **failure**
- **Wrong timing-** functions not synchronised

Machine Protection

Accidental beam losses time scale
Active protection
Passive protection

Accidental beam losses

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, in particular due to RF systems
- too small beam size at a target station

Very fast beam loss (ms)

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

Fast beam loss (some 10 ms to seconds)

Slow beam loss (many seconds)

Number of protons in the two beams: $N_p = 6 \cdot 10^{14}$

Assume beam lifetime of 1 hour = 3600 seconds

Number of protons lost per second: $f_{p-lost} = 1.7 \cdot 10^{11}$ / second

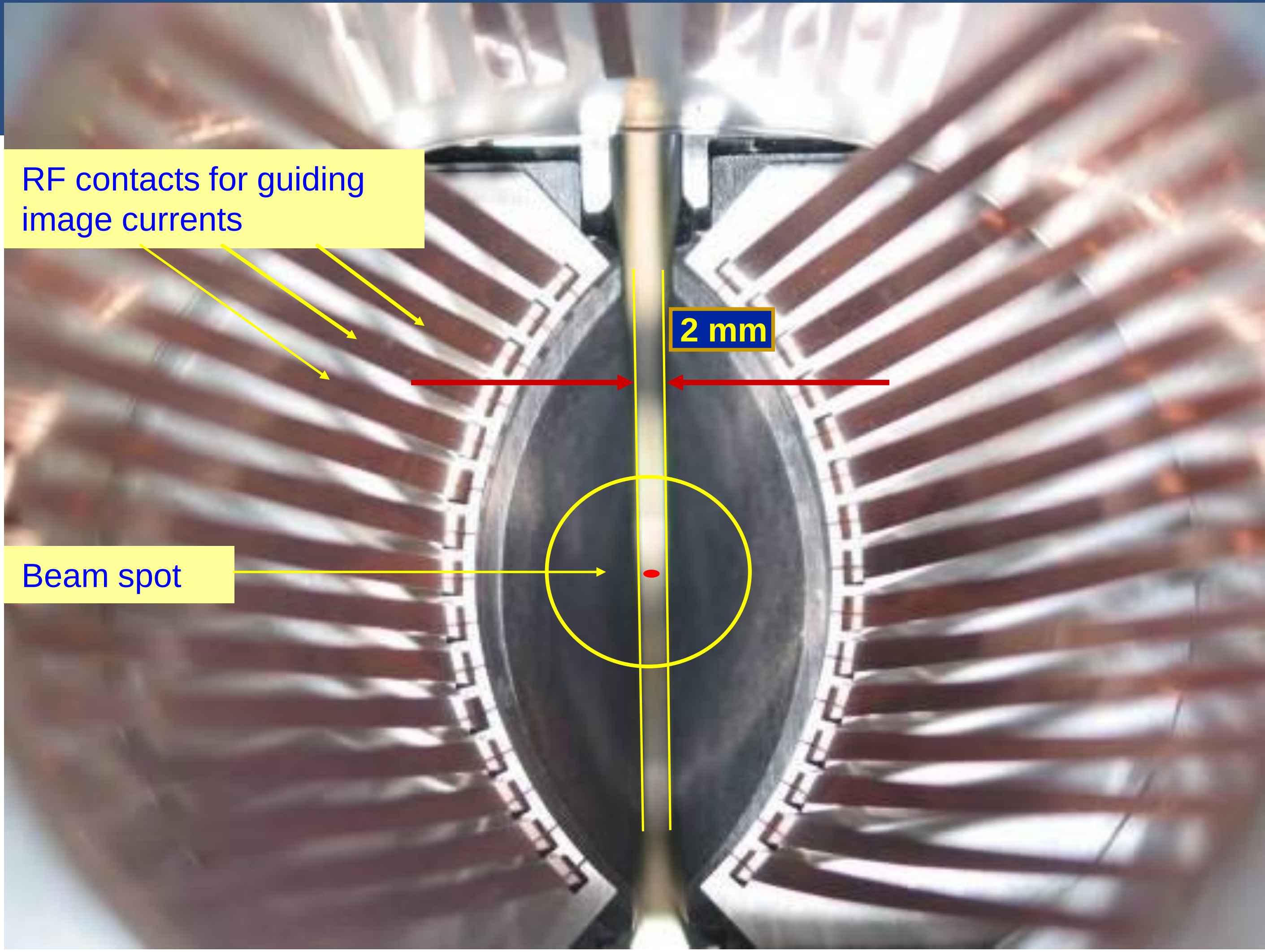
Quench limit of superconducting magnets at 6.5 TeV: some 10^6 protons

If nothing is done, magnets would quench

Beam cleaning system

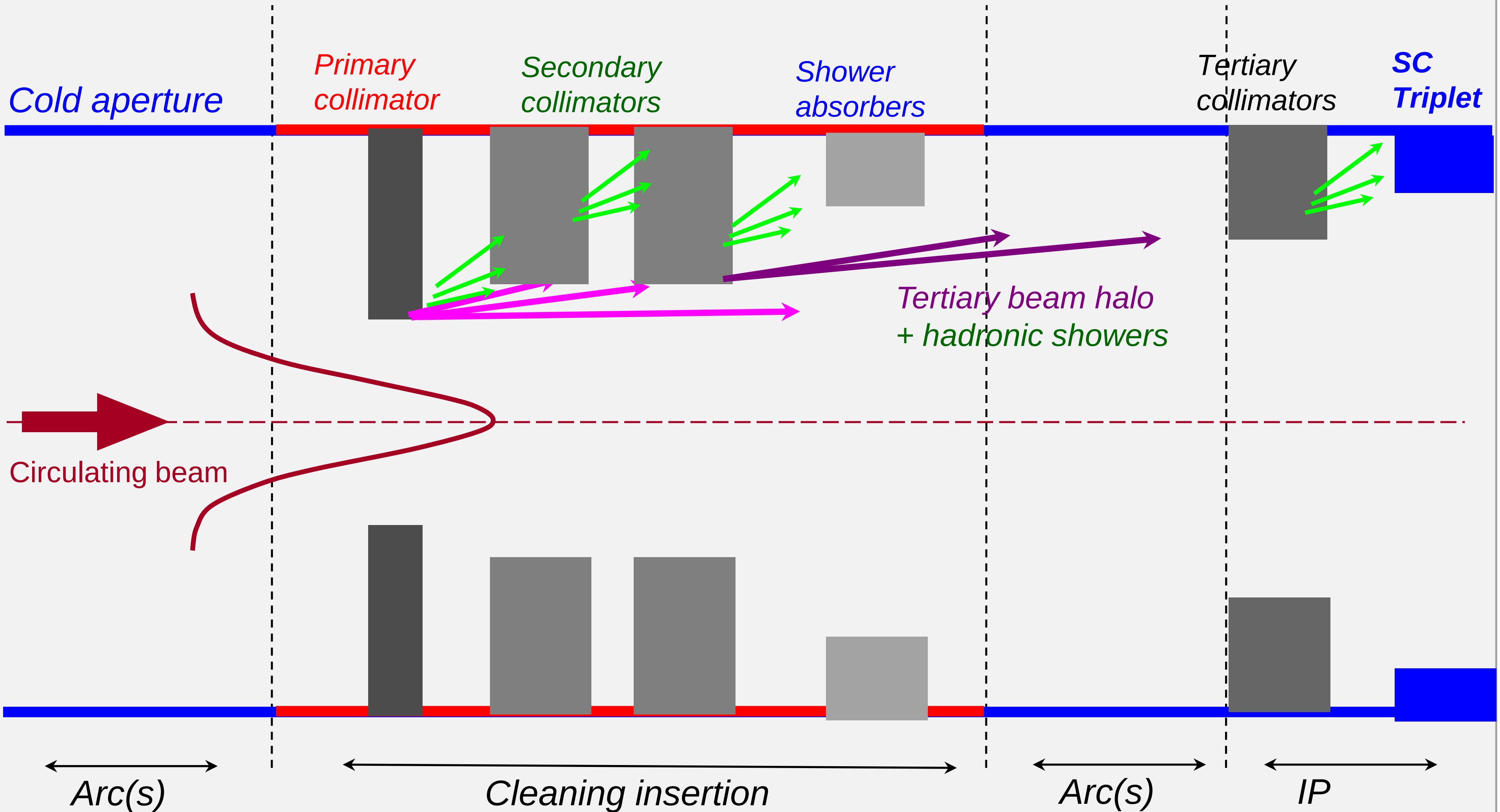
View of a two sided collimator

about 100 collimators are installed in LHC



Ralph Assmann

Betatron beam cleaning



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

Illustration drawing

Fast losses

Example for Active Protection - Traffic

- A monitor detects a dangerous situation

- An action is triggered

- The energy stored in the system is safely dissipated

Active protection

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

Example for Passive Protection - Traffic

- 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

Passive protection

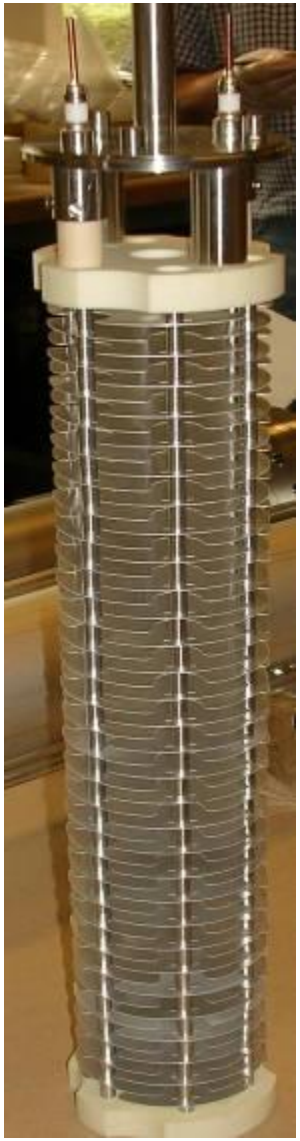
- Is always necessary when the time required for the response is too short (…remember the limitation of the speed of light)
- Might simplify the protection system
- One example is the **injection of high intensity beam** into the LHC
  - The injection is performed with a fast kicker magnet
  - It cannot be guaranteed that there is not kicker failure leading to a wrong deflection angle of the beam
  - The range of plausible failures (=deflection angles) needs to be defined
  - If the beam could damage hardware, protection absorbers are required
  - For movable absorbers: need to be made sure that they are at the correct position
- Another example is the extraction **(beam dump) system** of the LHC

LHC strategy for machine protection

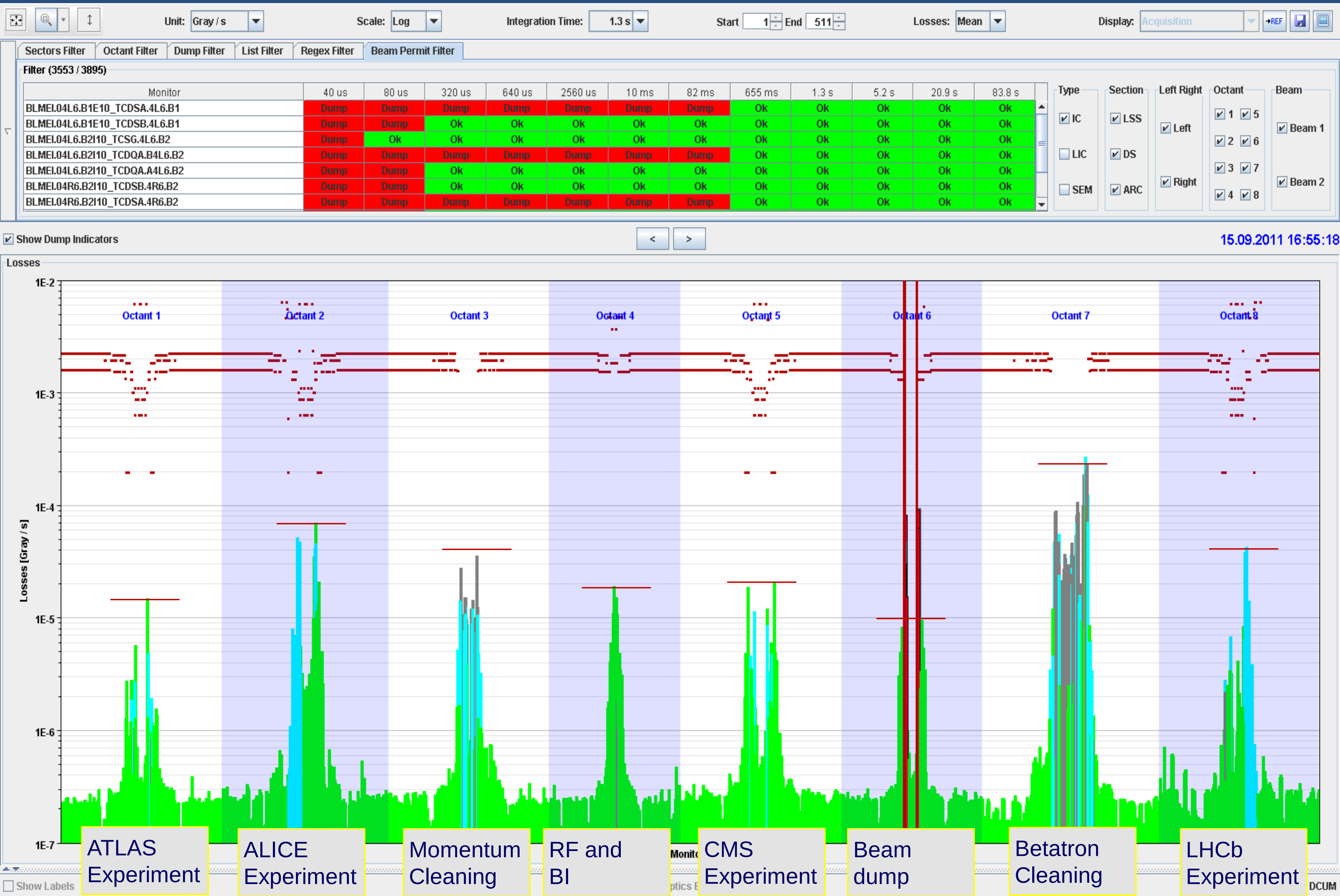
• Definition of aperture by collimators.	**Beam Cleaning System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Collimator and Beam Absorbers**
• Early detection of equipment failures generates dump request, possibly before beam is affected.	**Powering Interlocks** **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**

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 !
- Very important beam instrumentation!

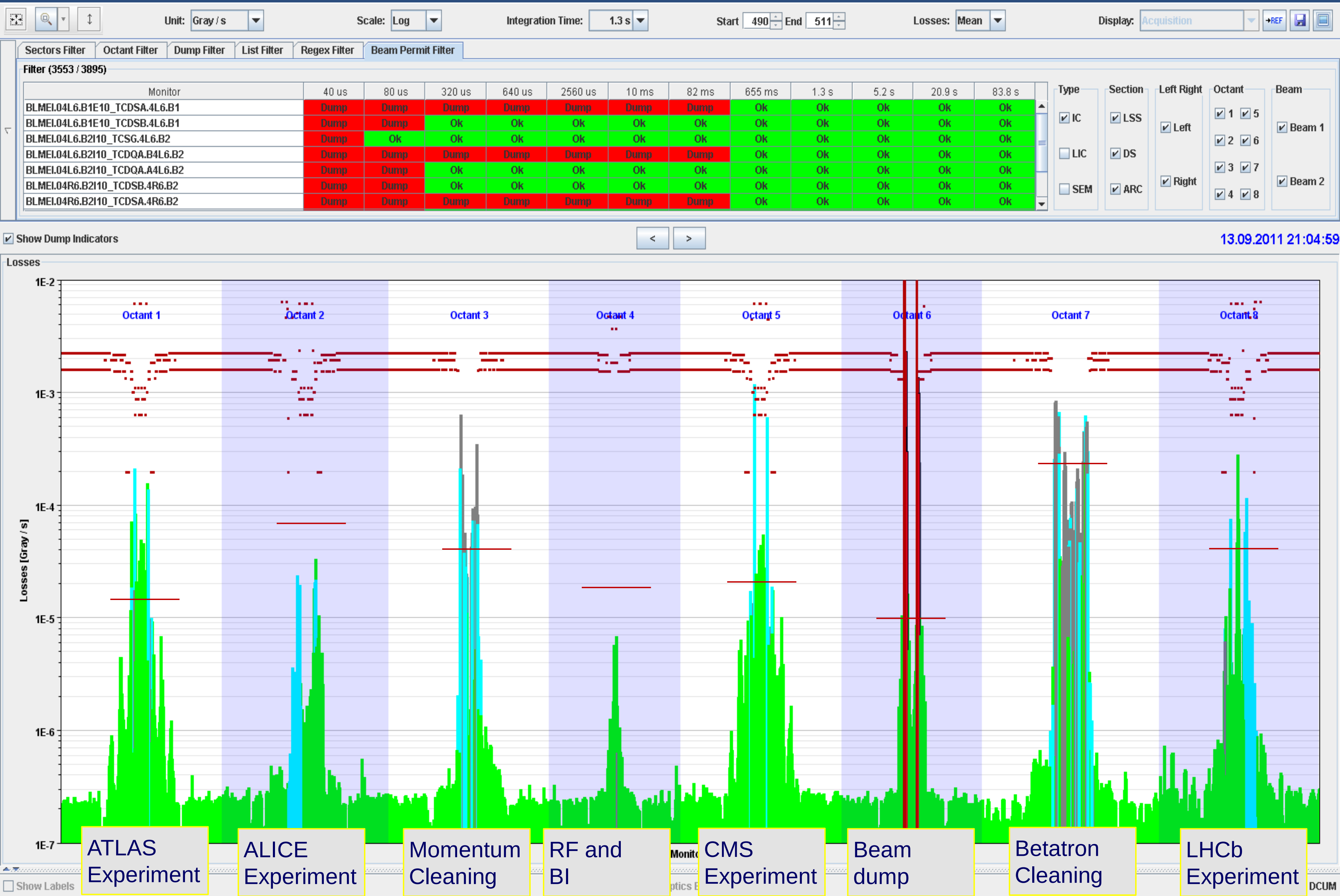


BLM system: beam losses before collisions



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



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

Accidental beam losses during collisions

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

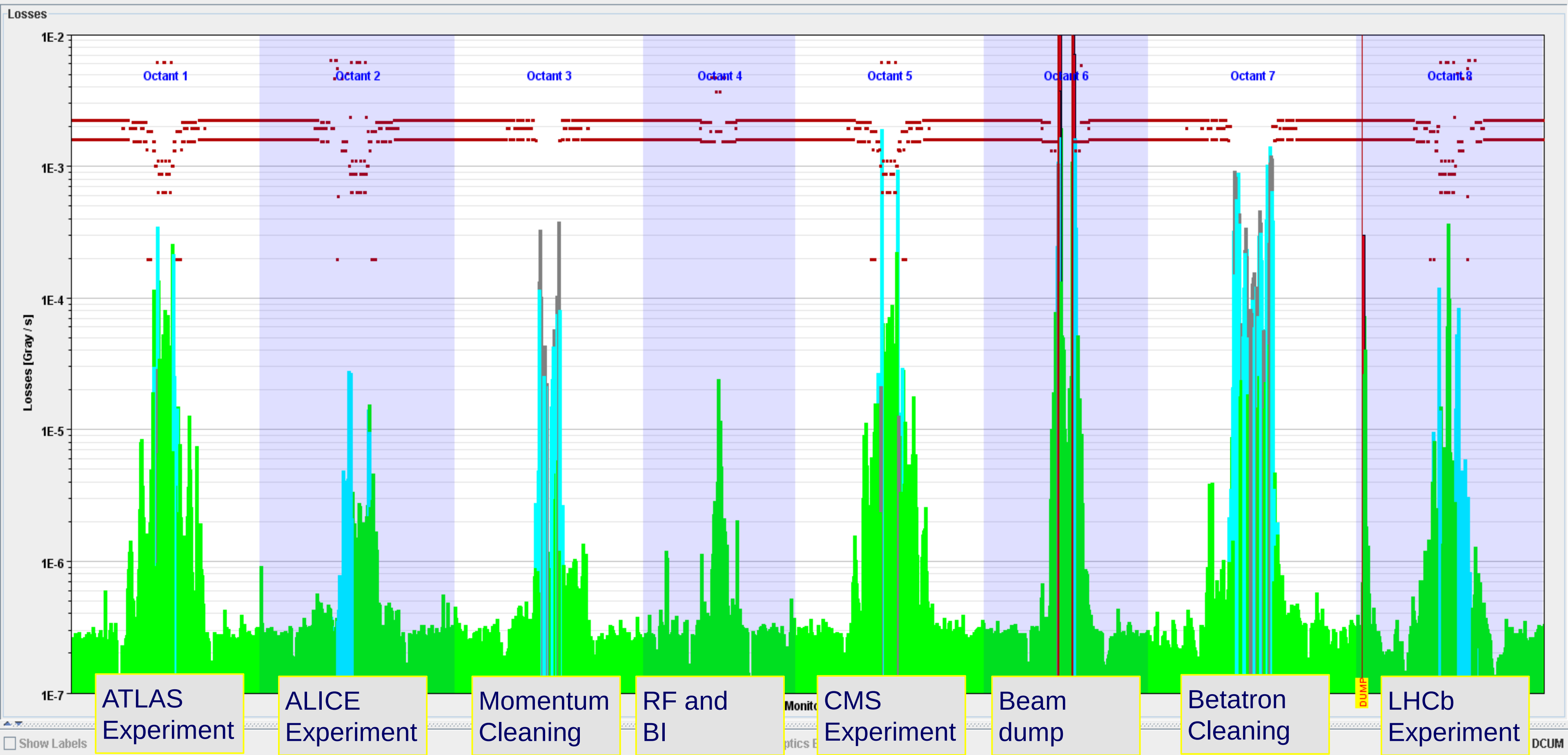
Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

Filter (3550 / 3892)

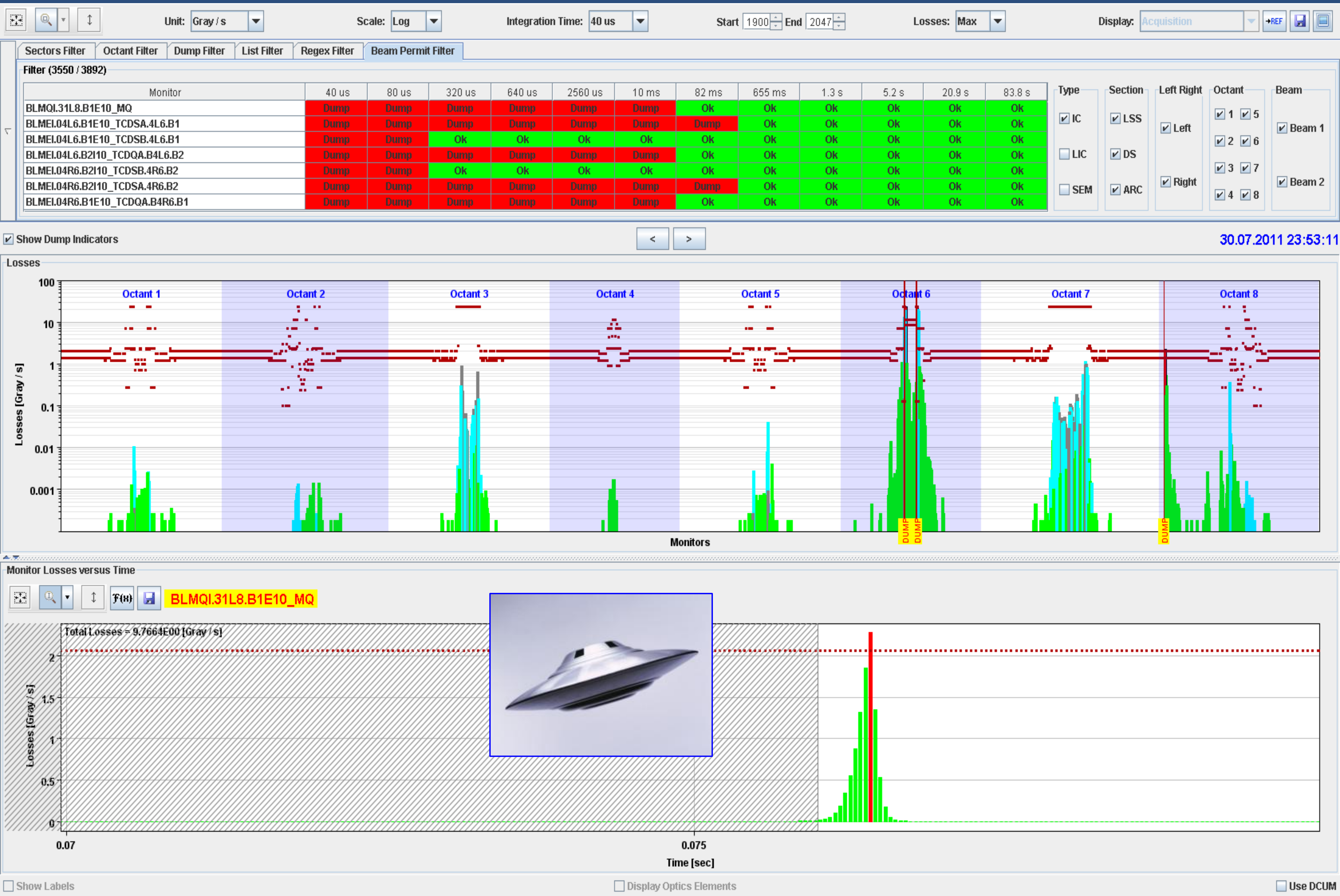
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	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

Type: IC, LIC, SEM — Section: LSS, DS, ARC — Left Right: Left, Right — Octant: 1–8 — Beam: Beam 1, Beam 2

Show Dump Indicators — 30.07.2011 23:53:11



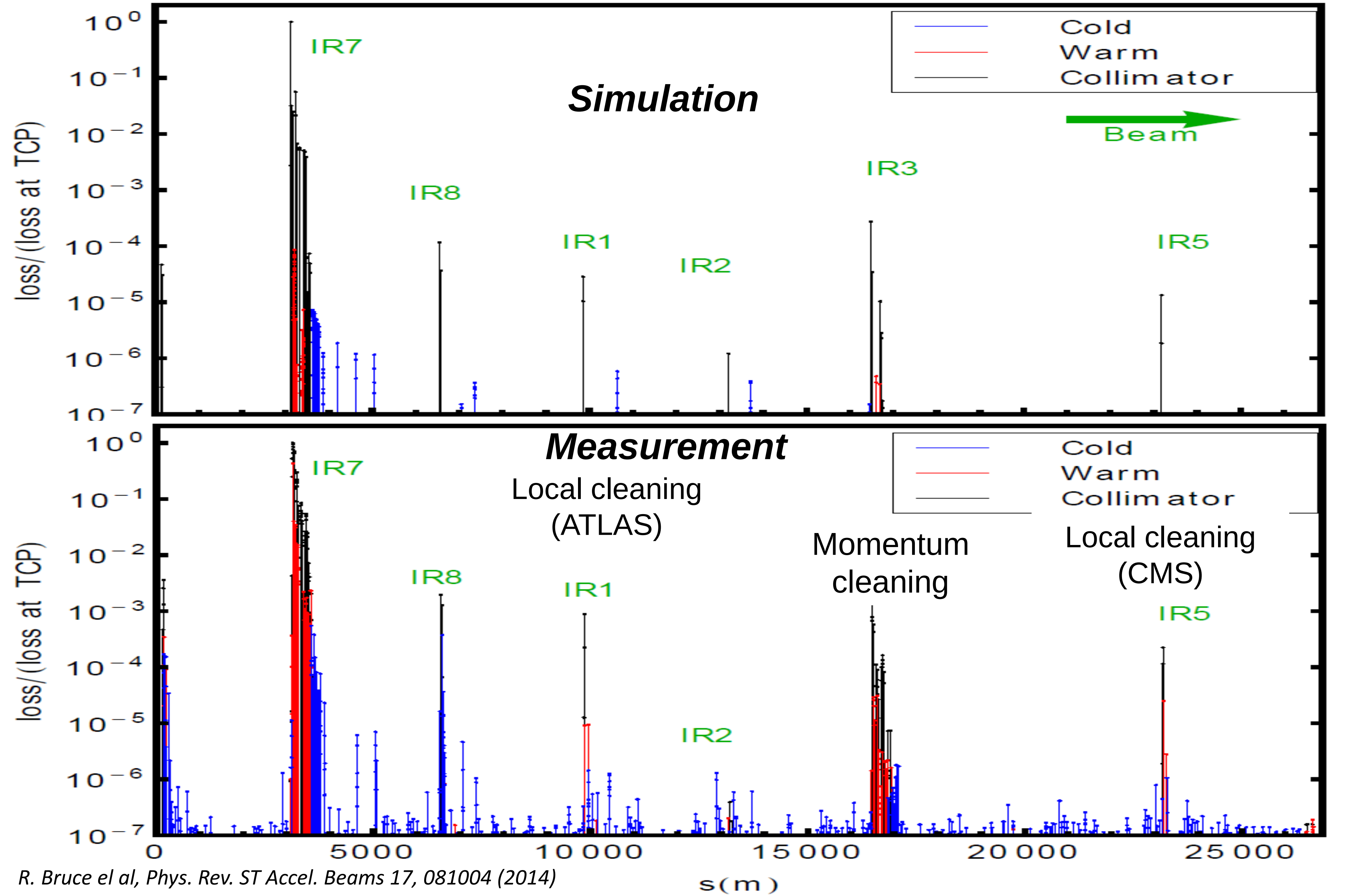
Accidental beam losses: UFOs



Cleaning system

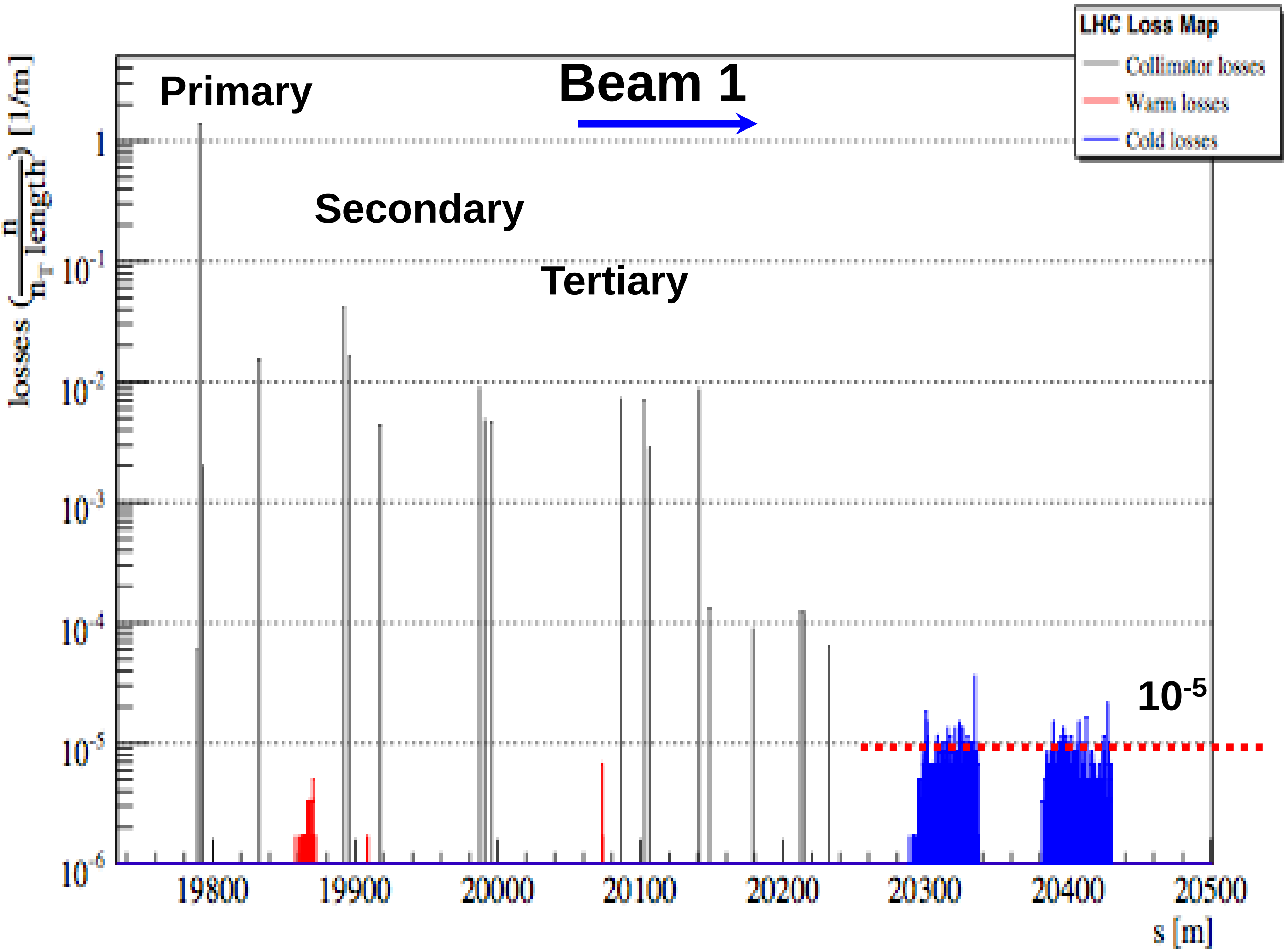
- To suppress slow losses in the cold part of the LHC
- In case of fast losses, protons touch collimators first and provide signal to Beam Loss Monitors

Collimation performance for 4 TeV proton beam



R. Bruce el al, Phys. Rev. ST Accel. Beams 17, 081004 (2014)

Zoom IR7 – cleaning efficiency



Achieve a few 10^{-5} in IR7.

Cold losses in experiments removed by local protection.

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

Acknowledgement

- Many colleagues at CERN, working on machine protection, beam cleaning 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, in particular Jörg Wenninger, Markus Zerlauth and Daniel Wollmann

Thank you very much for your attention


If you are working on protection…..

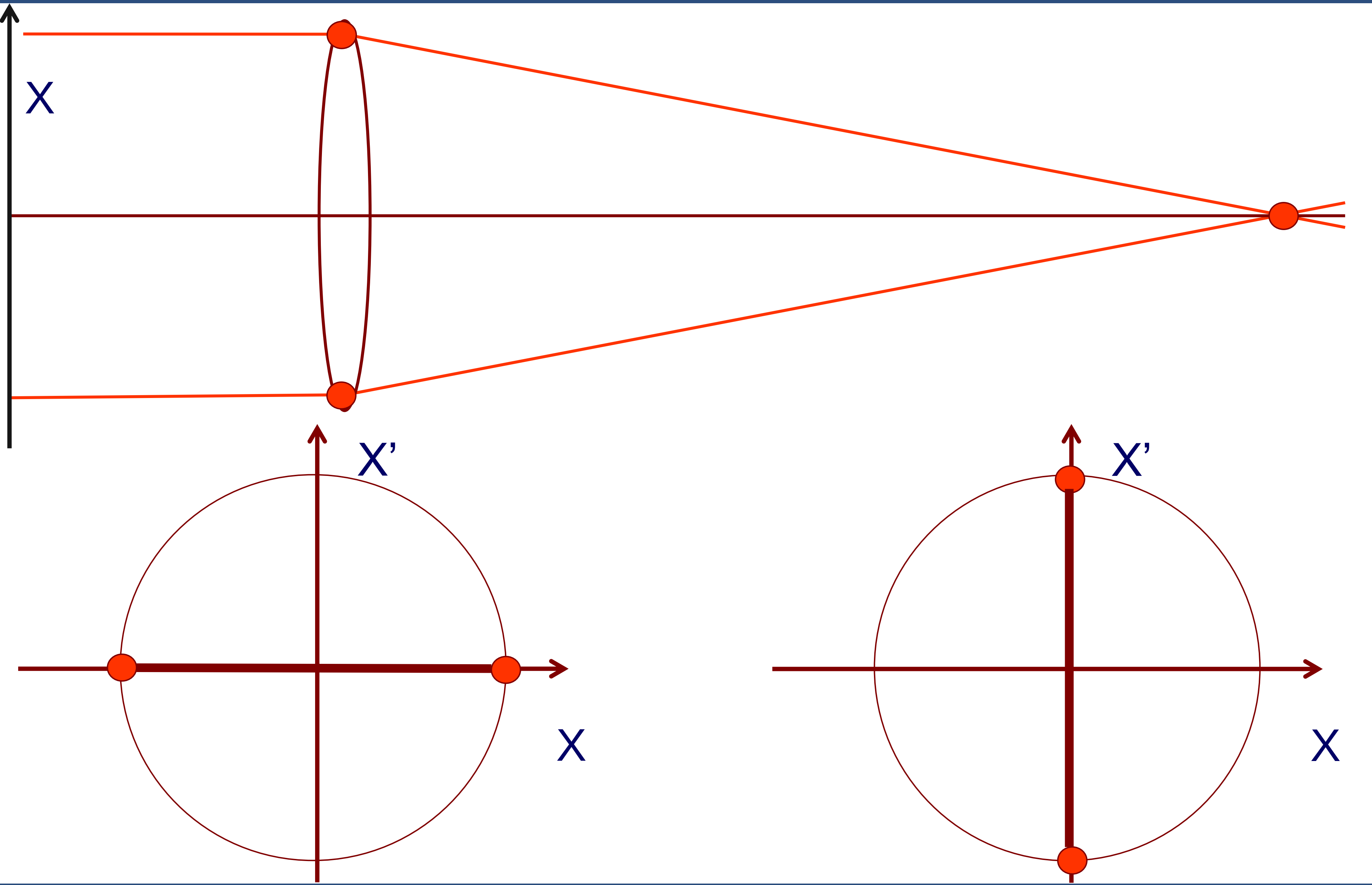
Niels Bohr and A. Einstein

Horseshoe

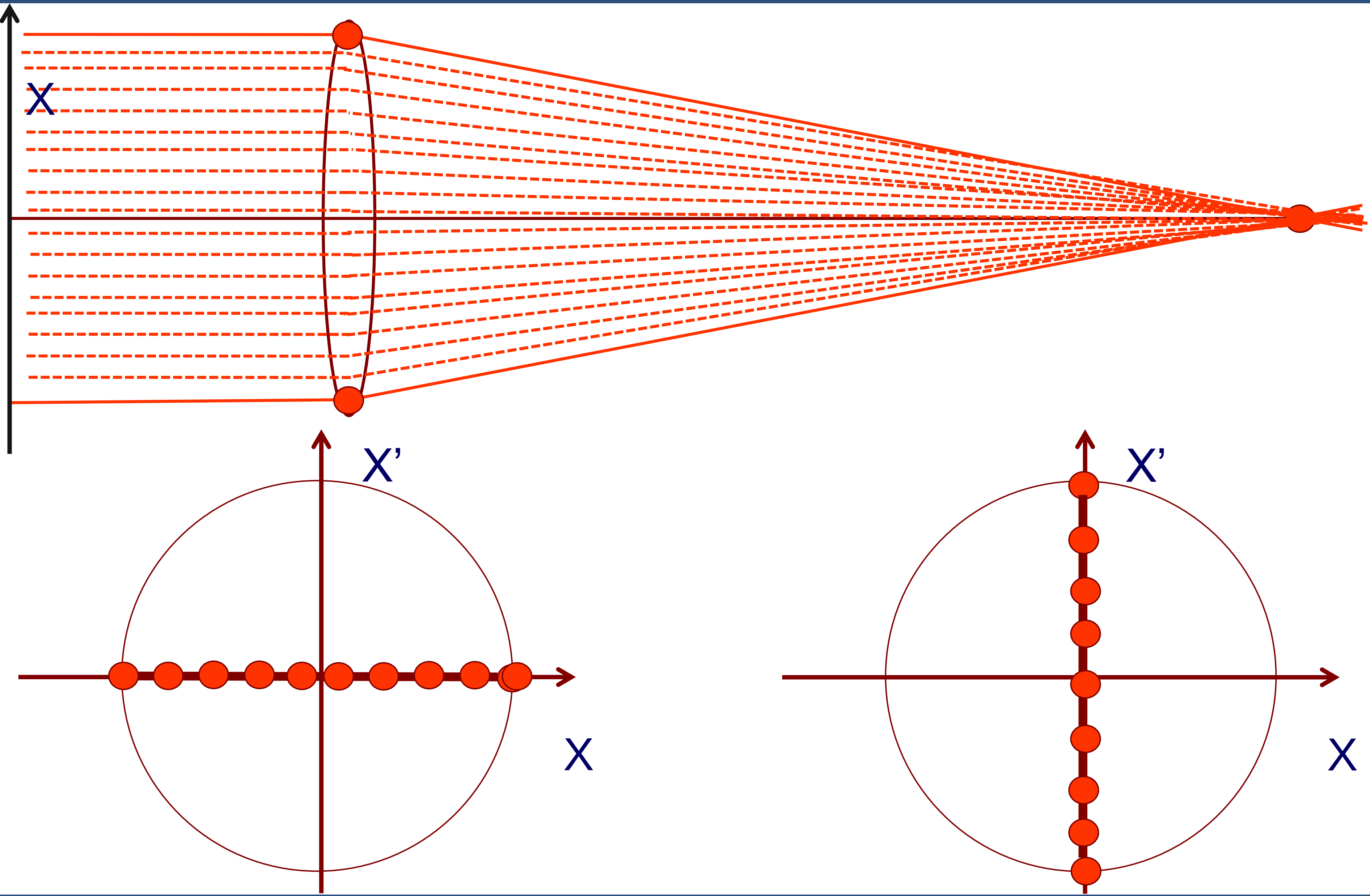
- Einstein was visiting the home of Nobel Prize winner Niels Bohr, the famous atom scientist.
- As they were talking, Einstein kept glancing at a horseshoe hanging over the door. Finally, unable to contain his curiosity any longer, he demanded: “Niels, it can’t possibly be that you, a brilliant scientist,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

Reserve

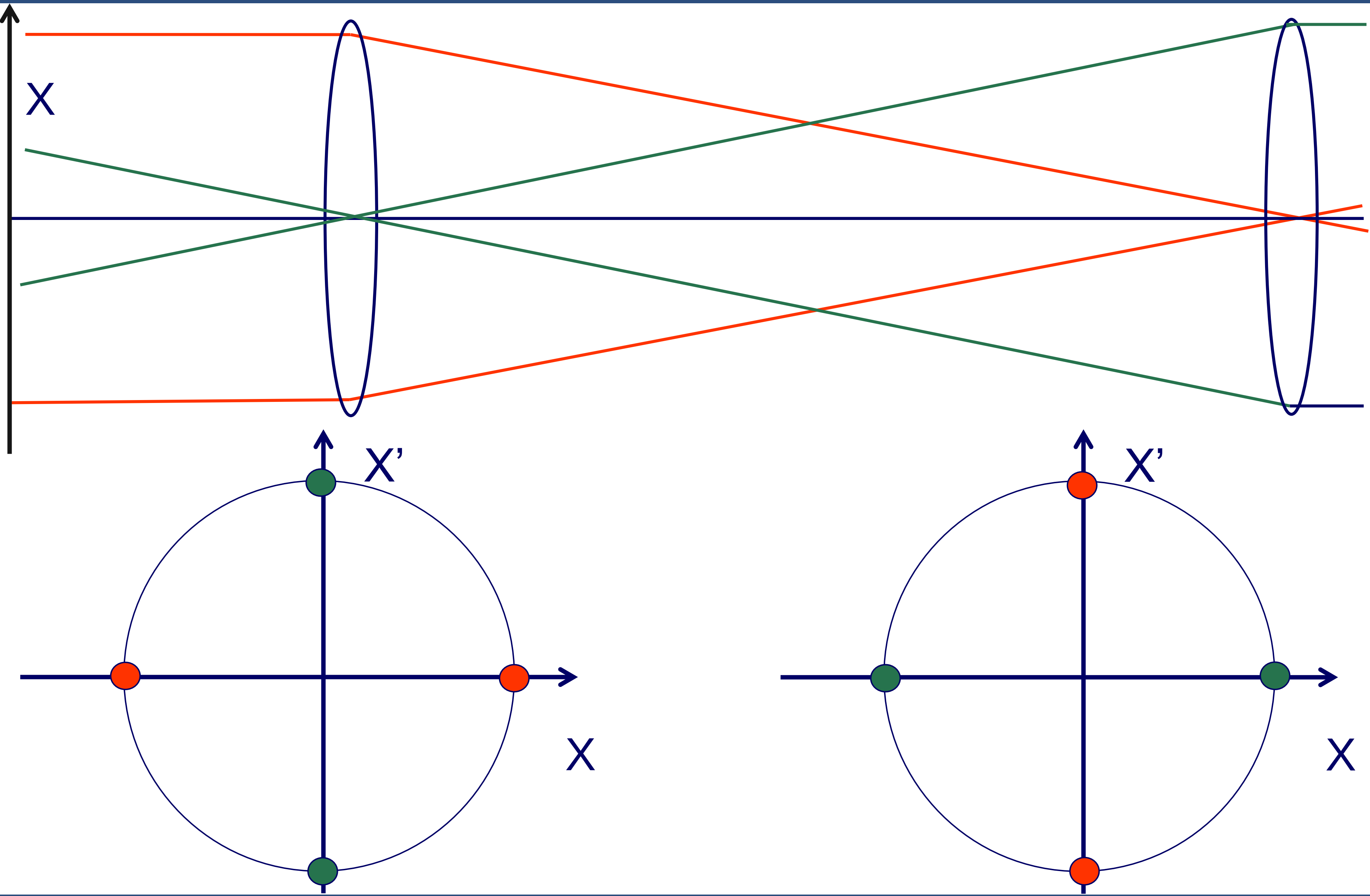
Phase Space of an ensemble of particles



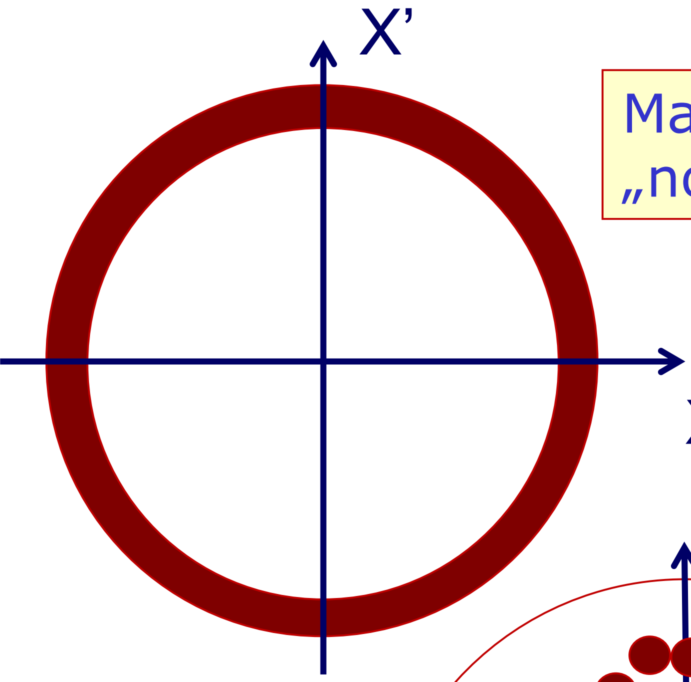
Phase Space of an ensemble of particles



Phase Space of an ensemble of particles

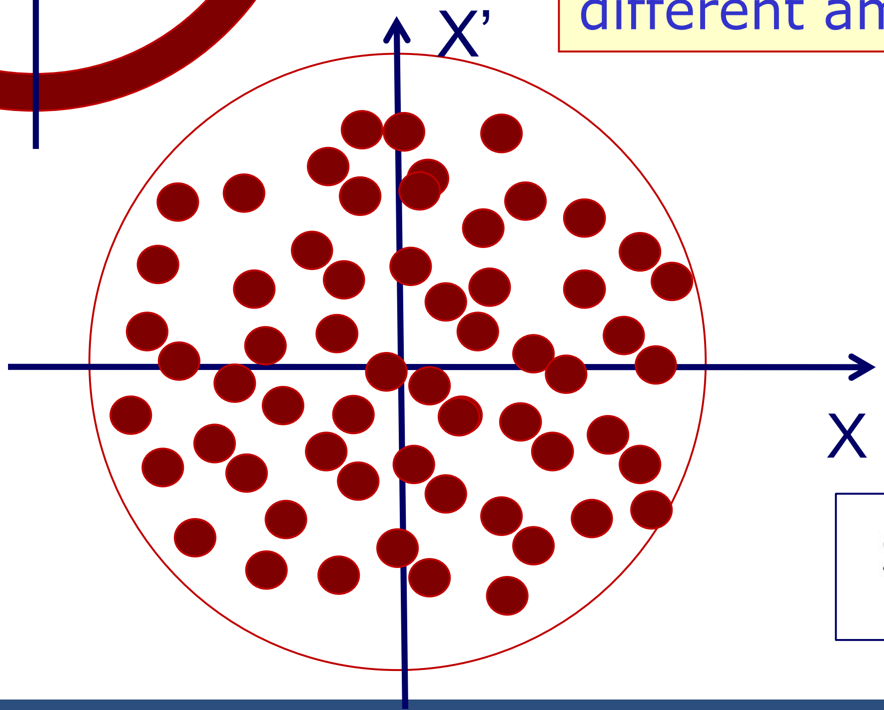


Phase Space of an ensemble of particles



Many particles, same „normalised" amplitude

Real beam: many particles, different amplitudes

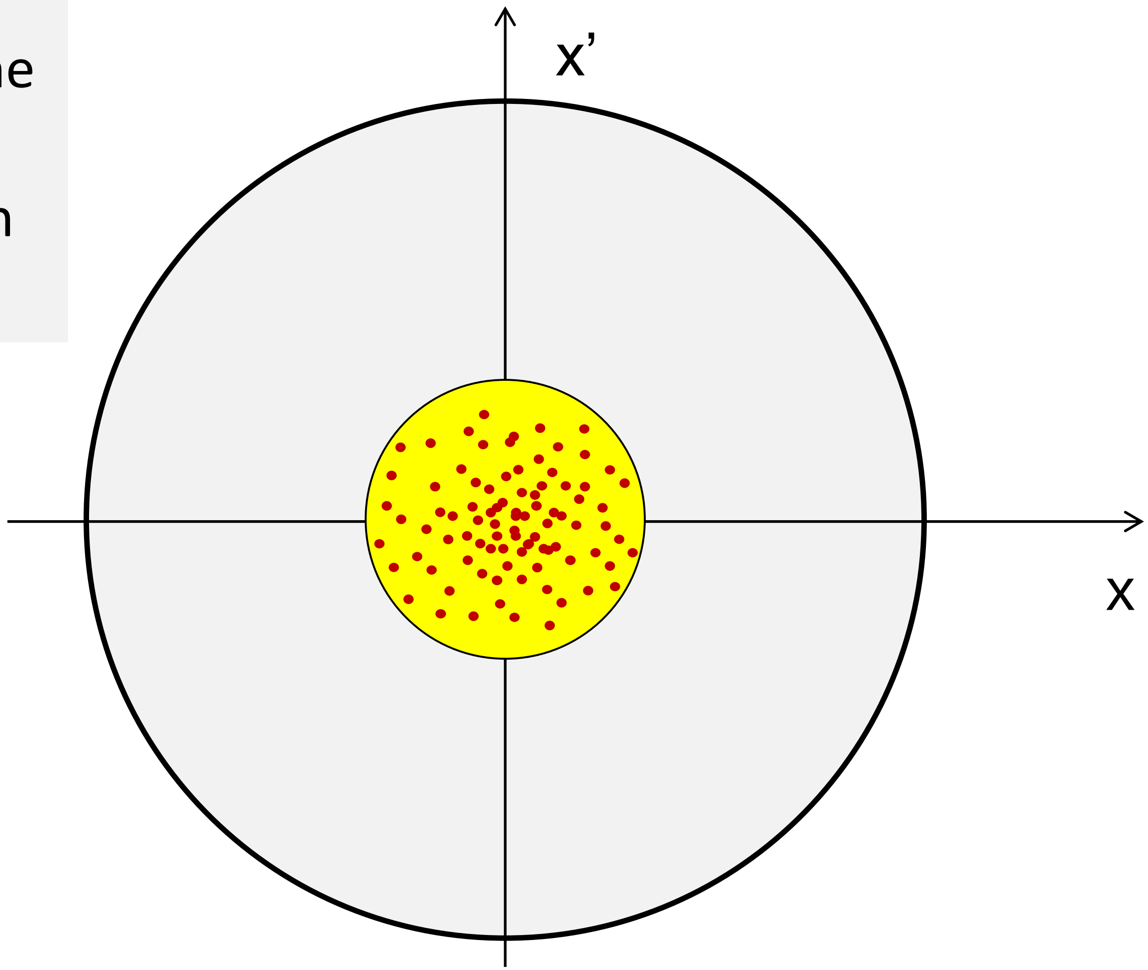


This conservation law: phase space volume occupied by a collection of systems evolving according to Hamilton's equations of motion is preserved in time

$$\frac{d\rho}{dt} = \frac{\partial \rho}{\partial t} + \sum_{i=1}^{n} \left(\frac{\partial \rho}{\partial q_i} \dot{q}_i + \frac{\partial \rho}{\partial p_i} \dot{p}_i \right) = 0.$$

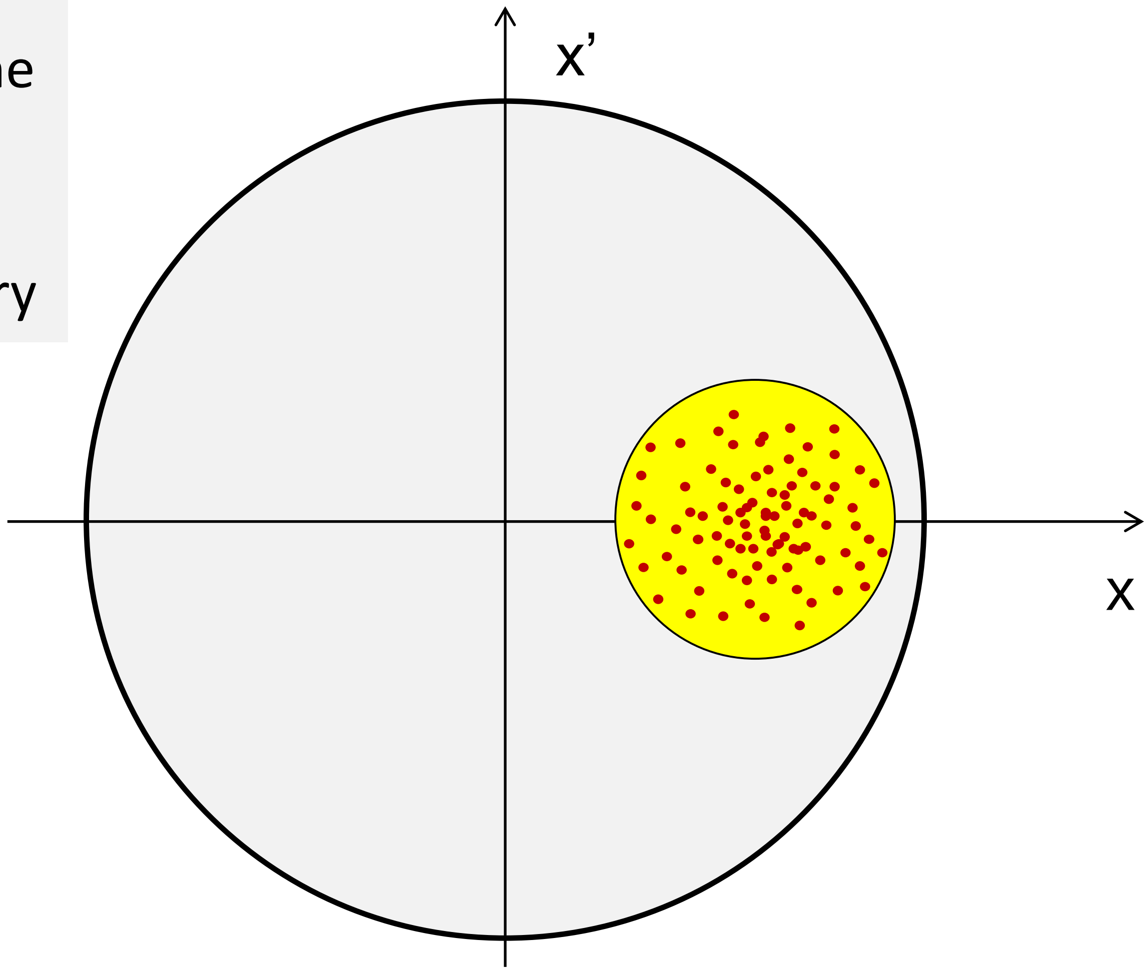
Effect of a dipole deflection – closed orbit centred

Phase space of particles inside the aperture at a certain location in the accelerator



Effect of a dipole deflection– closed orbit changes

Phase space of particles inside the aperture – beam move towards aperture boundary



Effect of a dipole deflection– closed orbit changes

Phase space of particles inside the aperture – beam move towards aperture boundary