From 10^{-12} TeV to 10^{16} TeV

Introduction to accelerator physics and technology:
The Large Hadron Collider

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RTG Fall Workshop der Universität Freiburg 4-6 October 2017

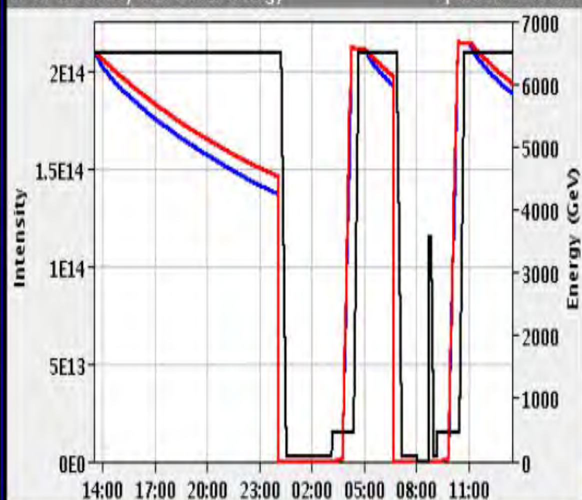
LHC Page1 Fill: 6271 E: 6499 GeV t(SB): 02:09:16 04-10-17 13:28:30

PROTON PHYSICS: STABLE BEAMS

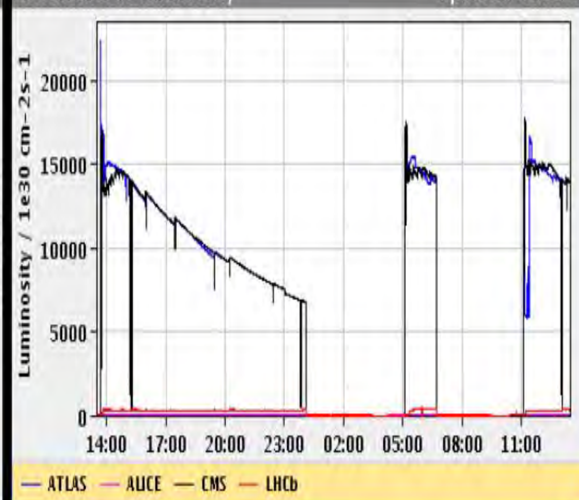
Energy:	6499 GeV	I(B1):	1.89e+14	I(B2):	1.93e+14

Inst. Lumi [(ub.s)^-1]	IP1: 13930.70	IP2: 9.16	IP5: 13924.44	IP8: 320.91

FBCT Intensity and Beam Energy Updated: 13:28:30



Instantaneous Luminosity Updated: 13:28:30



BIS status and SMP flags

	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

Comments (04-Oct-2017 13:14:48)

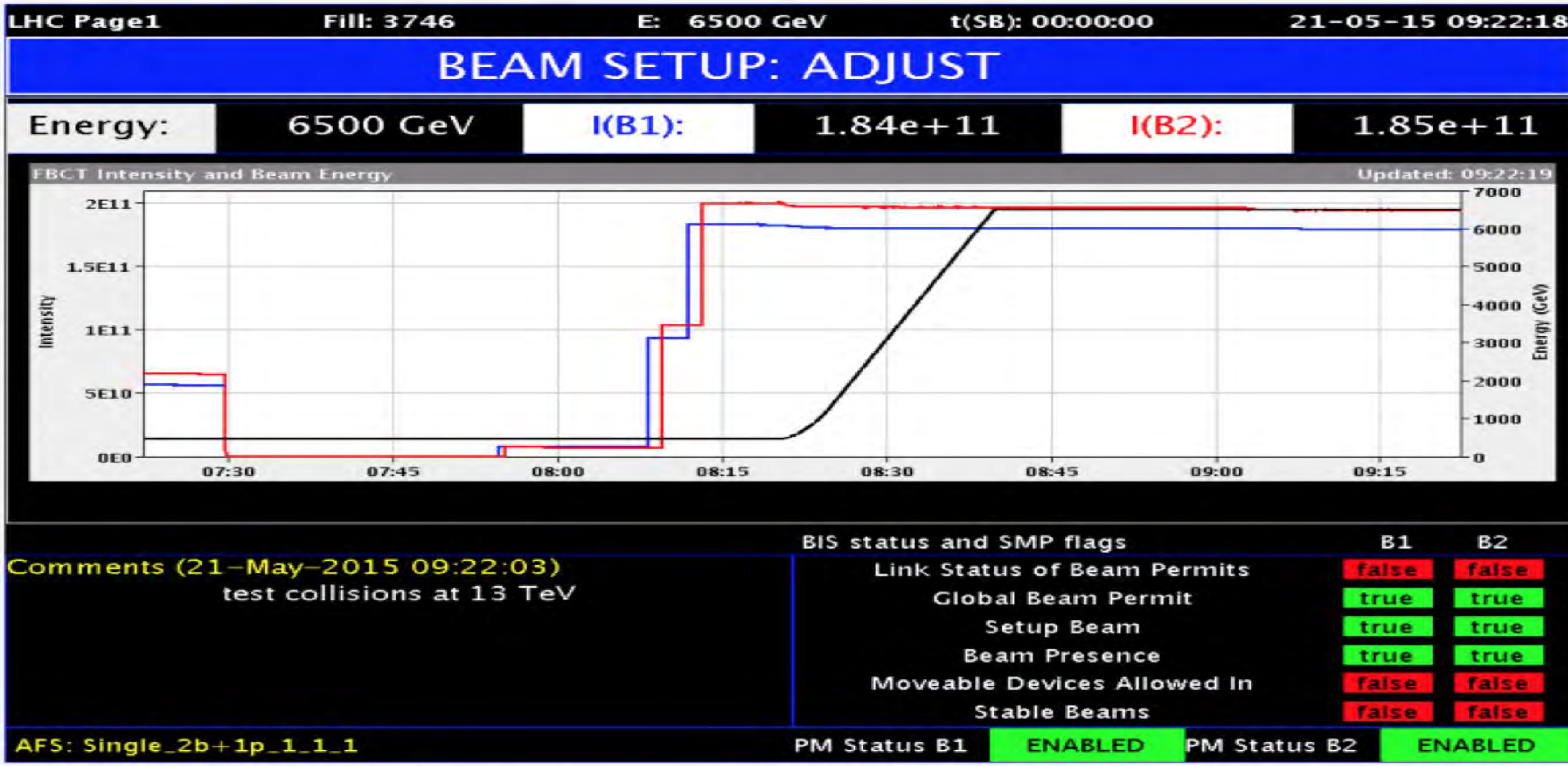
Roman pots in
changing crossing angle to 140 urad
refill for Physics (8b4e BCS)

AFS: 25ns_1836b_1824_1052_1688_96bpi_20i8b4e PM Status B1 ENABLED PM Status B2 ENABLED

FR 16:18

First images of collisions at 13 TeV

by Cian O'Luanaigh



Test collisions continue today at 13 TeV in the Large Hadron Collider (LHC) to prepare the detectors ALICE, ATLAS, CMS, LHCb, LHCf, MOEDAL and TOTEM for data-taking, planned for early June (Image: LHC page 1)

To accelerate particles to much lower energy

……. 6.5 TeV for a proton, for an ion >500 TeV

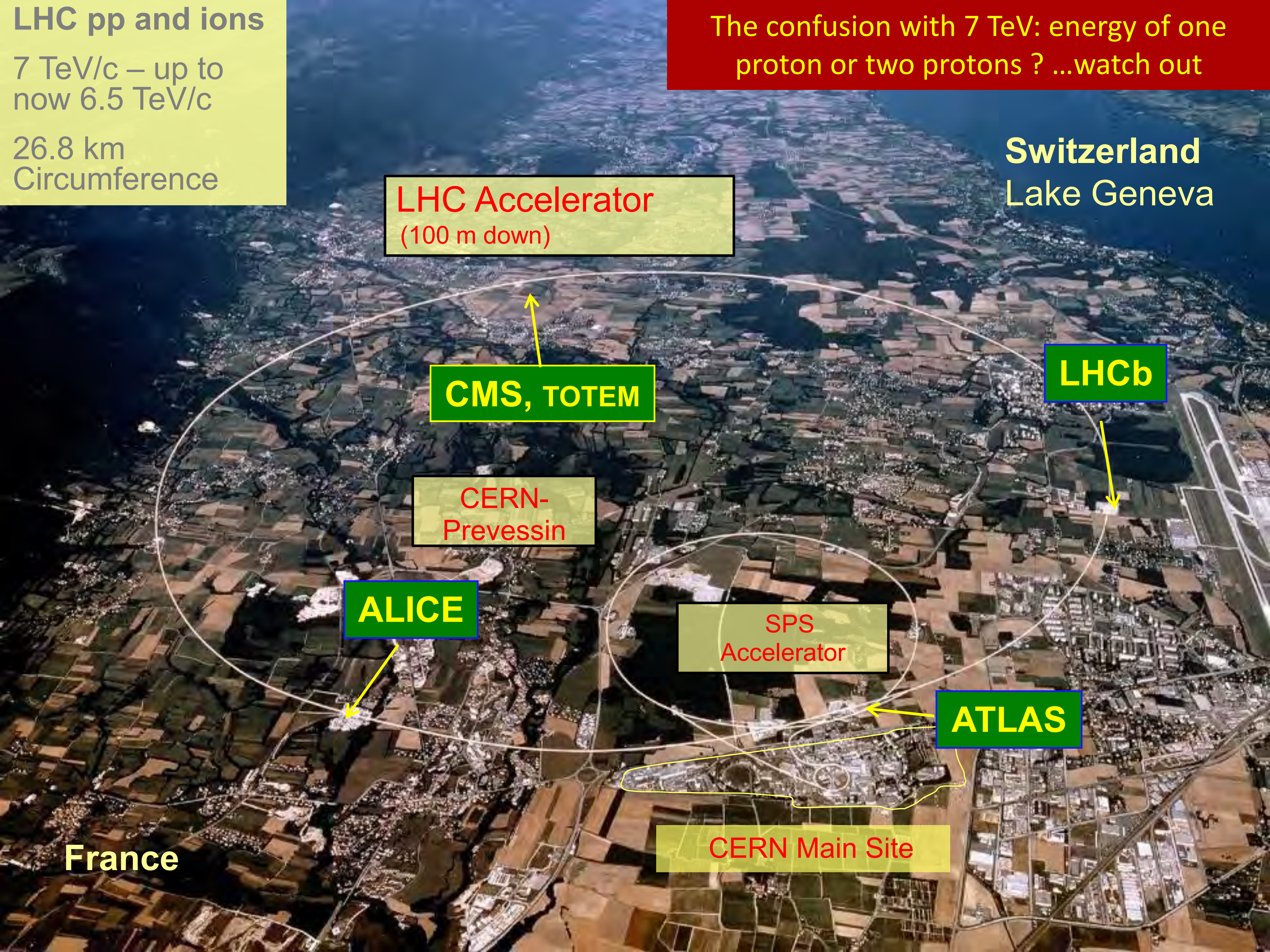
Energy stored in the entire proton beam = $2*10^{15}$ TeV

LHC pp and ions

7 TeV/c – up to now 6.5 TeV/c

26.8 km Circumference

The confusion with 7 TeV: energy of one proton or two protons ? …watch out



Energy and Luminosity

Energy and Luminosity

- Particle physics requires an accelerator colliding beams with a centre-of-mass energy **substantially exceeding 1 TeV**
- In order to observe rare events, the luminosity should be in the order of **10^{34} [$cm^{-2}s^{-1}$]** (challenge for the LHC accelerator)
- Event rate:

$$\frac{N}{\Delta t} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma[cm^{2}]$$

- Assuming a total cross section of about 100 mbarn for pp collisions, the **event rate** for this luminosity is in the order of 10^9 events/second (challenge for the LHC experiments)
- Nuclear and particle physics require heavy ion collisions in the LHC (quark-gluon plasma ....)

Integrated Luminosity and Availability

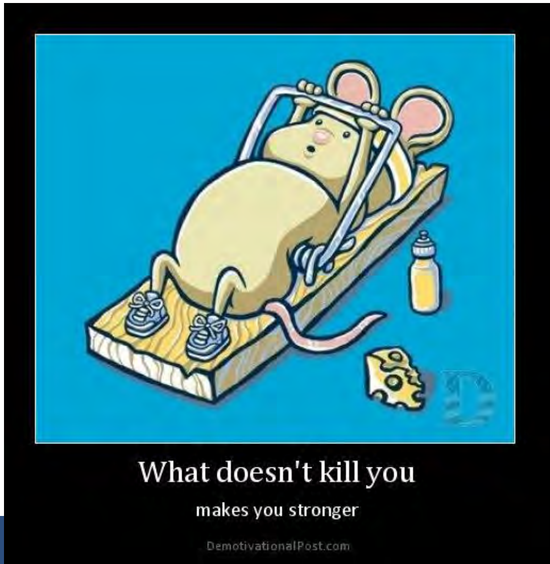
- The total number of particles created at an accelerator (e.g. the total number of Higgs bosons) is proportional to the Integrated Luminosity:

$$\int L(t) \times dt$$

- It has the unit of [cm^{-2}] and is expressed in Inverse Picobarn or Inverse Femtobarn
- The availability of the accelerator plays an essential role: all systems must work correctly, very challenging for such complex machine
- Example: https://lhc-statistics.web.cern.ch/LHC-Statistics/

LHC: A long story starting in the distant past

- First ideas to first protons: from 1984 to 2008
- Enthusiasm…. first beam in 2008
- Despair (due to the hopefully last) accident in 2008



The LHC: just another collider ?

	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Lumi $[cm^{-2}s^{-1}]$	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	$4.3\ 10^{32}$	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	$5.1\ 10^{31}$	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	$1.5\ 10^{32}$	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	7000 Now 6500	26800	8.3	**10^{34}** Now 1.7×10^{34}	**362** now 300
Factor			7	4	2	**50**	**100**

Overview

- Accelerator physics crash course - DONE
- Energy and Luminosity - DONE
- Accelerator physics crash course part II
- Acceleration and deflection of charged particles
- Energy and Luminosity Challenges
- Short Beam Dynamics course
- Particle Energy and Superconducting Magnets
- Understanding LHC operation
- Challenges for high intensity beams operation
- Preparing for the next 20 years: HL-LHC…..
- Preparing for the next 50 years: HE-LHC, FCC study…..

Accelerator Physics Crash Course Part II

what is accelerator physics?

what species are accelerator physicists?

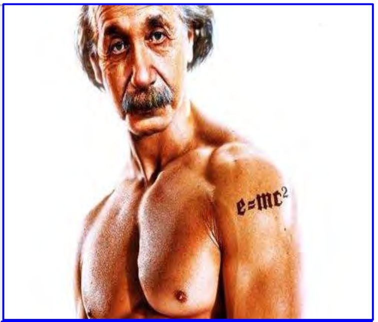
Accelerator Physicist

Plumber of the year

…building very long, exceptionally cold and extremely complex machines

The physics and engineering required to plan, develop, construct and operate particle accelerators

- Electrodynamics
- Relativity
- Particle physics, nuclear physics and radiation physics
- Thermodynamics
- Mechanics
- Quantum Mechanics
- Physics of nonlinear systems
- Material science, solid state physics and surface physics
- Vacuum physics
- Plasma physics and laser physics



A rather clever plummer is needed

Plus a lot of technology: mechanical engineering, electrical engineering, computing science, metrology, civil engineering

Also important: Management, reliability engineering and system engineering

Acceleration and deflection of charged particles

How to get to high energy?

How to make many collisions (~10^9/s)?

The force on a charged particle is proportional to the charge, the electric field, and the vector product of velocity and magnetic field:

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

For an electron or proton the charge is:

$$q = e_0 = 1.602 \cdot 10^{-19} \ [C]$$

Acceleration (increase of energy) only by electrical fields – not by magnetic fields:

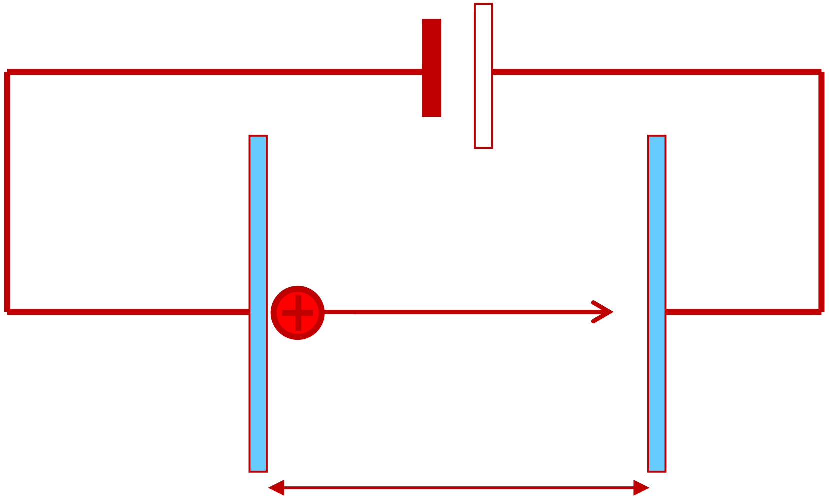
$$\Delta E = \int_{s1}^{s2} \vec{\mathbf{F}} \cdot \mathbf{d}\vec{\mathbf{s}}$$

$$\frac{dE}{dt} = \vec{\mathbf{v}} \cdot \vec{\mathbf{F}}$$

$$\frac{dE}{dt} = q \cdot (\vec{\mathbf{v}} \cdot \vec{\mathbf{E}} + \vec{\mathbf{v}} \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}})) = q \cdot \vec{\mathbf{v}} \cdot \vec{\mathbf{E}}$$

$$U = \int_{s1}^{s2} \vec{\mathbf{E}} \cdot \mathbf{d}\vec{\mathbf{s}}$$

$$\Delta E = \int_{s1}^{s2} \vec{\mathbf{F}} \cdot \mathbf{d}\vec{\mathbf{s}} = \int_{s1}^{s2} q \cdot \vec{\mathbf{E}} \cdot \mathbf{d}\vec{\mathbf{s}} = q \cdot U$$



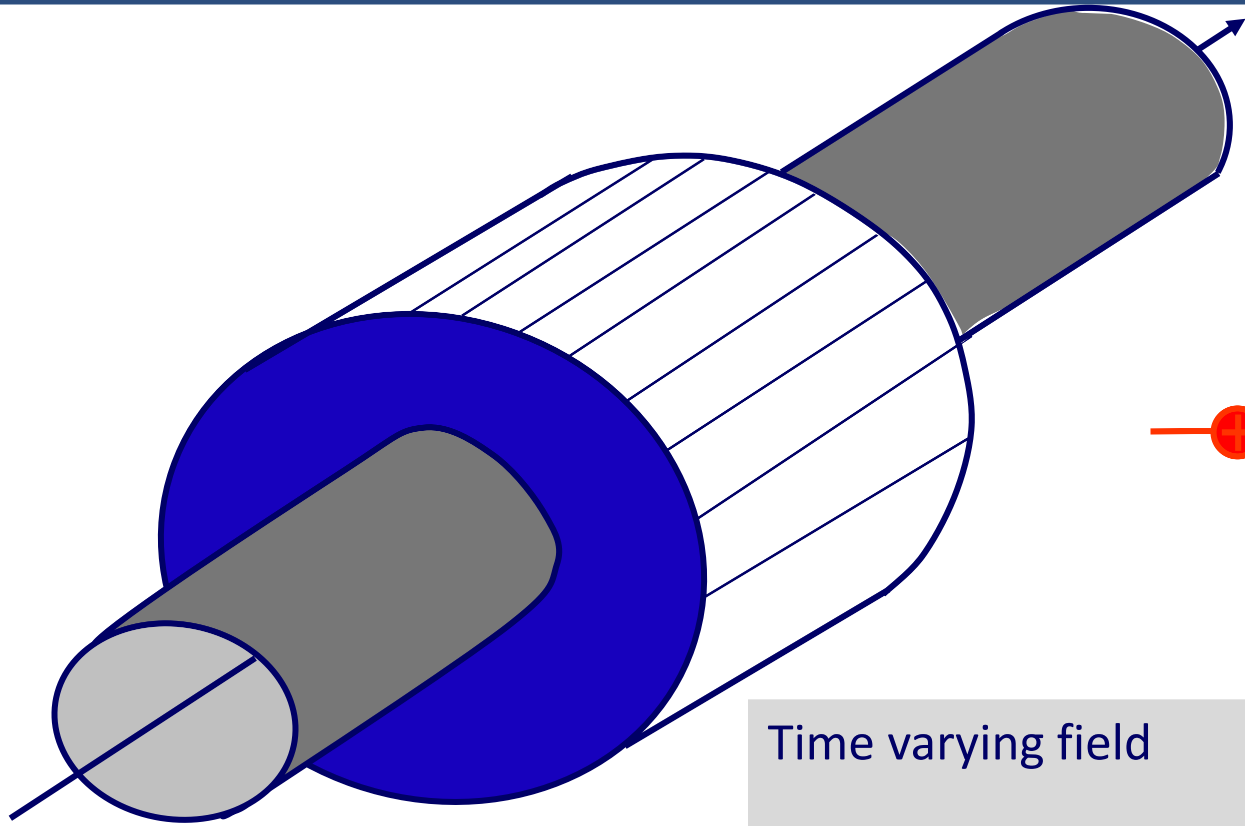
1 MeV requires
U = 1 MV

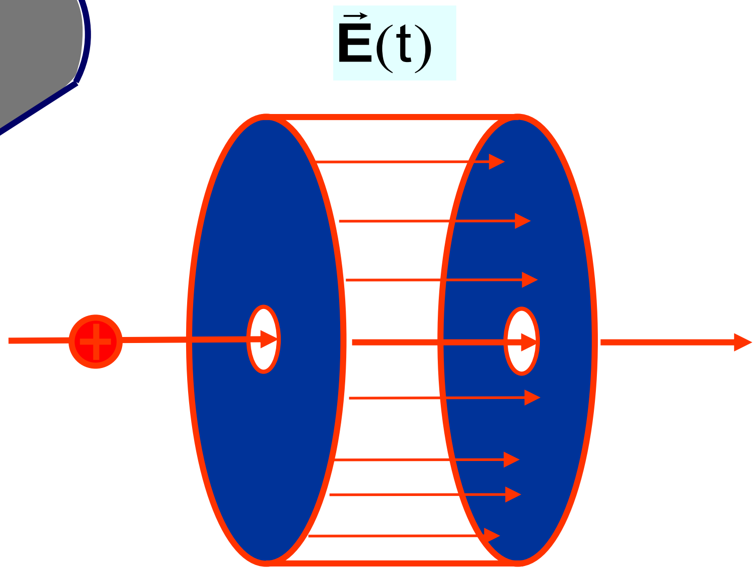
Acceleration of elementary particles to high energy in an electrical field,
e.g. 1 GeV => 1 GV

- No constant electrical field above some Million Volt (break down)

=> Use of time dependent electrical field

Particle acceleration with RF cavity





LHC RF frequency 400 MHz (typical frequency for an accelerator)

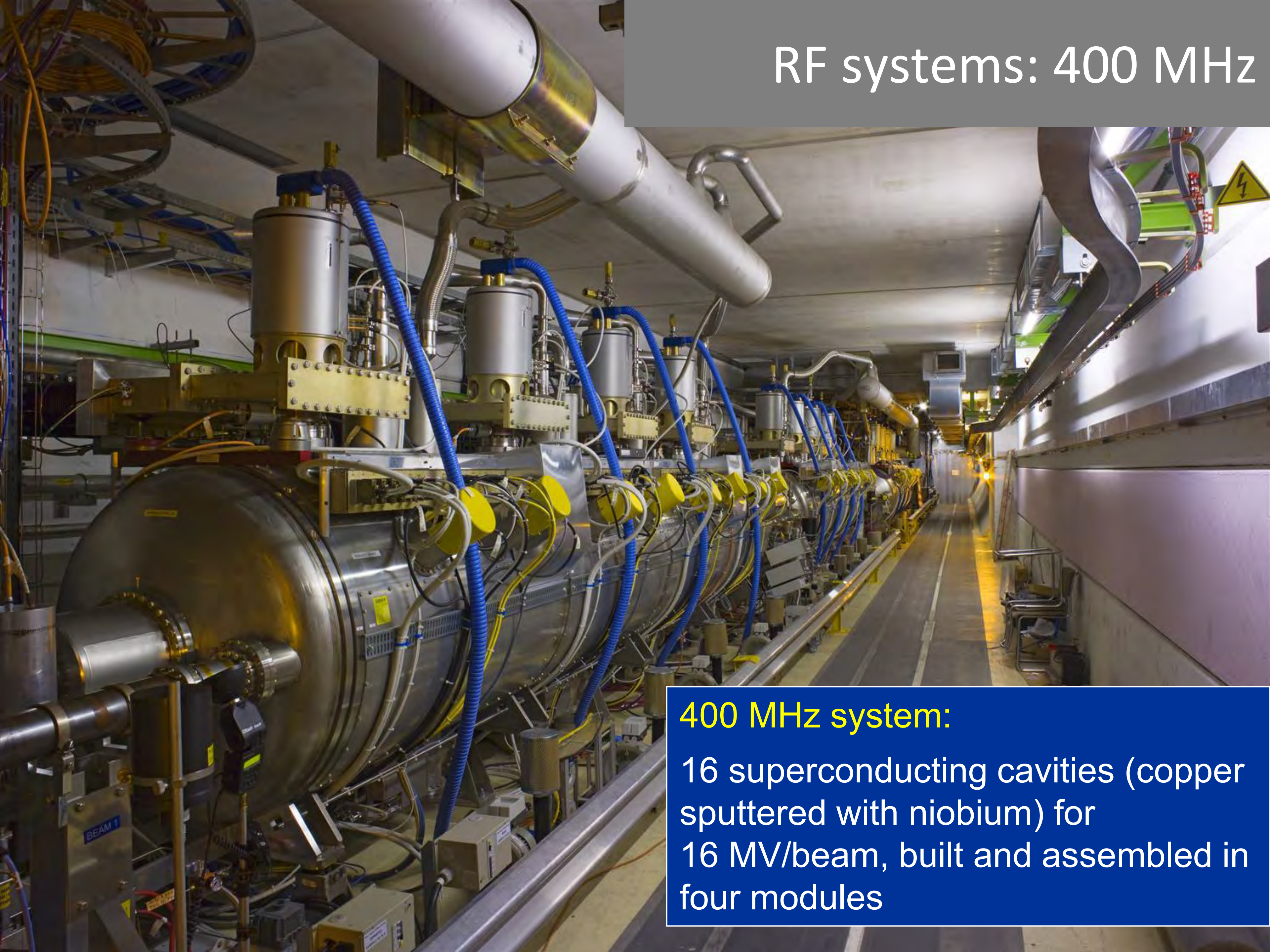
Time varying field

$$E_z(t) = E_0 \times \cos(\omega t + \phi)$$

Maximum field about 30-40 MV/m

Beams are accelerated in bunches (no continuous beam)

RF systems: 400 MHz



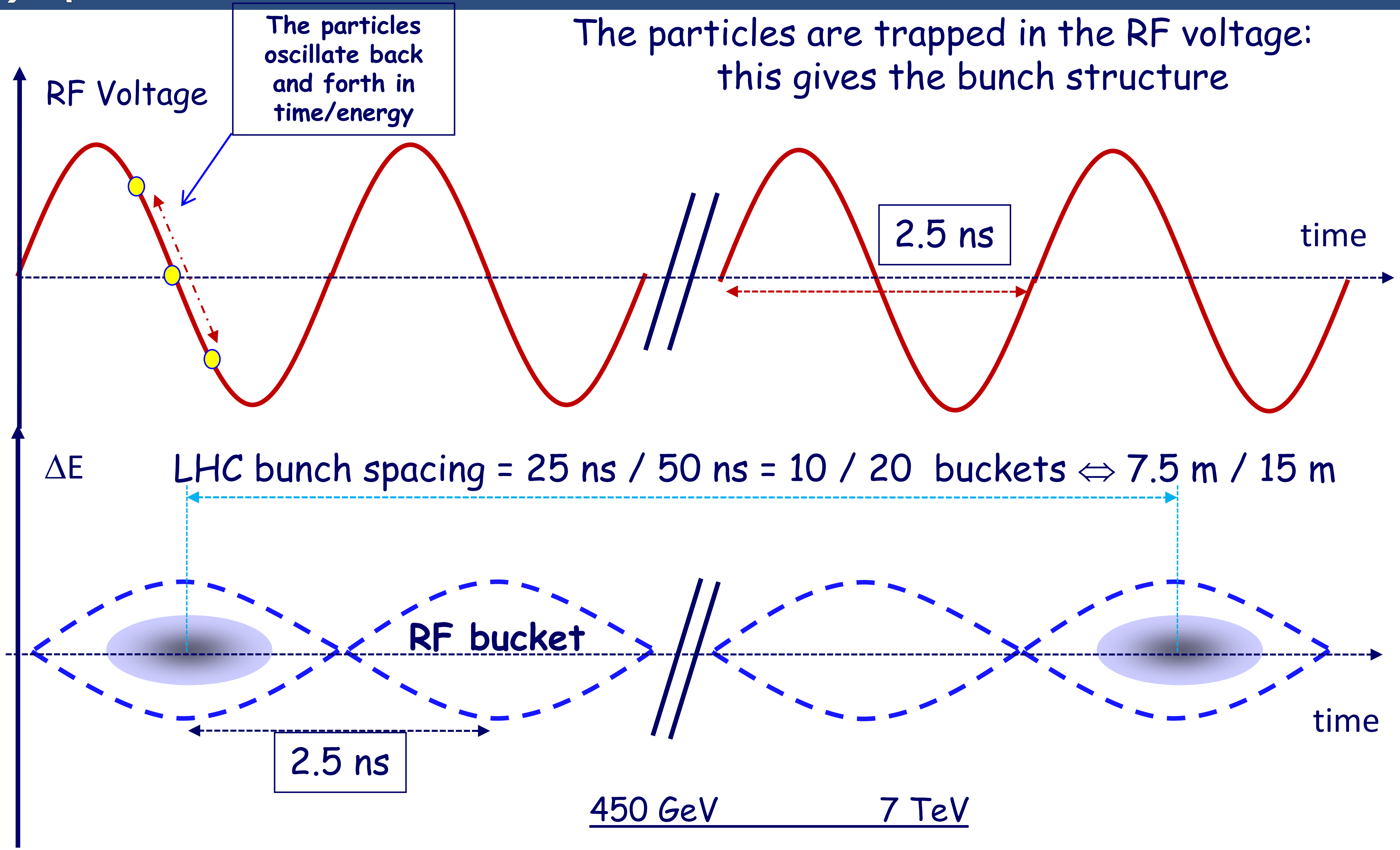
400 MHz system:

16 superconducting cavities (copper sputtered with niobium) for 16 MV/beam, built and assembled in four modules

Capture of Surfers by a water wave for acceleration

400 MHz RF buckets and bunches

The particles are trapped in the RF voltage: this gives the bunch structure



	450 GeV	7 TeV
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

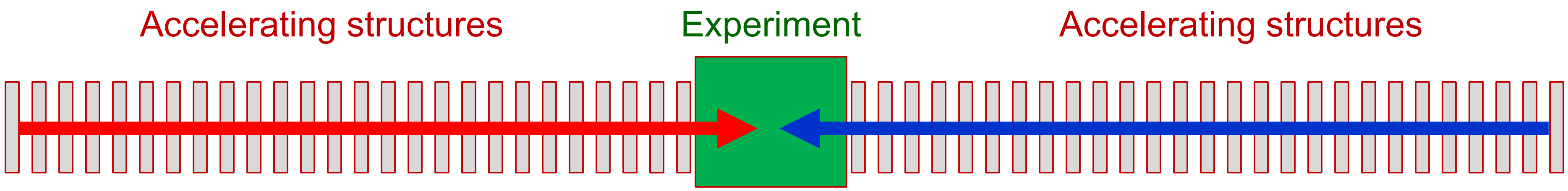
To collide particles at very high energy

Linear collider versus Circular collider

Linear accelerator: use accelerating structure once

Accelerating beams to high energy in a linear collider:

- The beams are accelerated during one passage and the particles are colliding only once at the center of the experiment



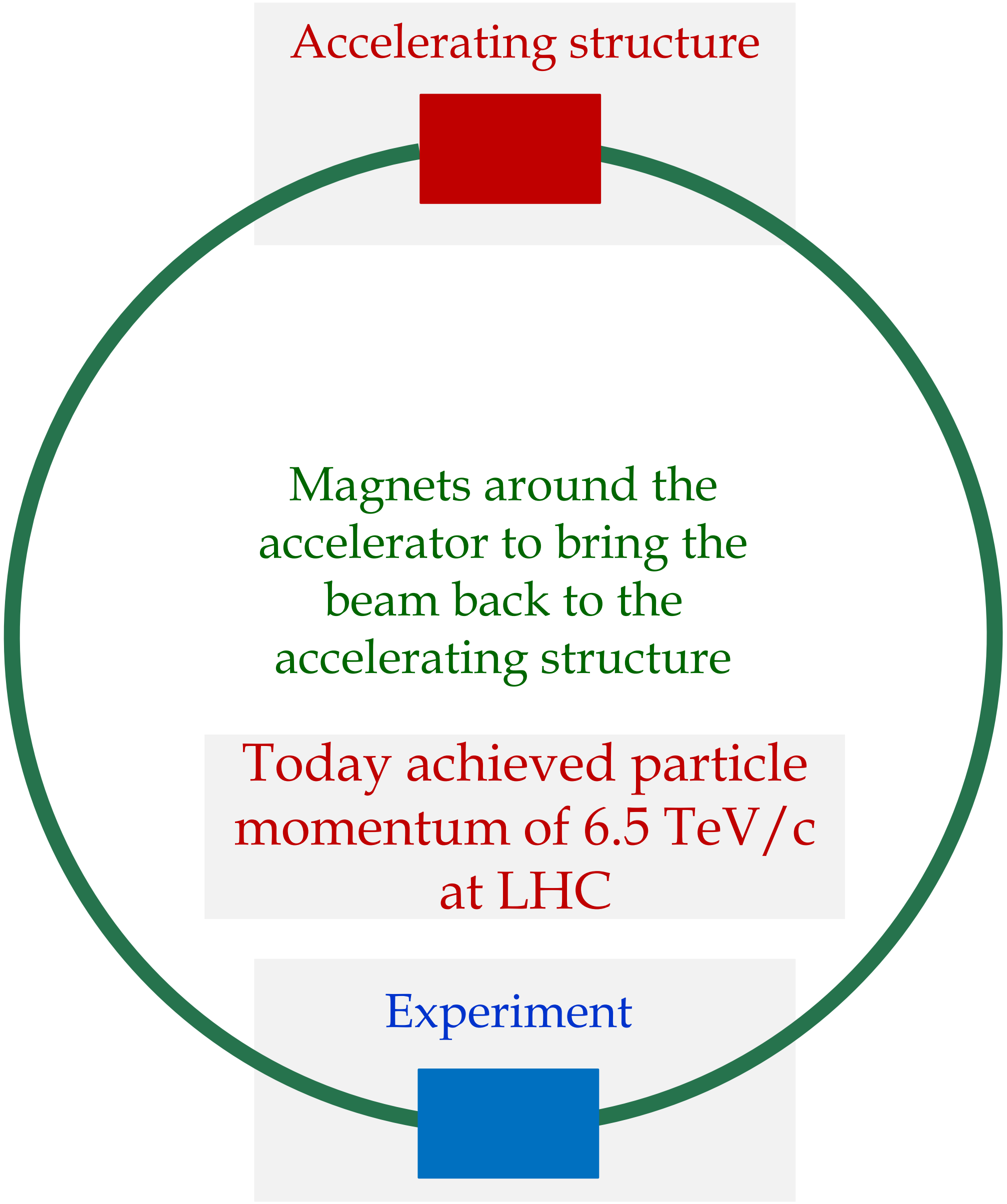
Acceleration of particles with time-varying electrical field

- Limit 30-40 MeV/m with superconducting cavities
- Limit about 100 MeV/m with other technologies, not yet used (CLIC)
- Some 100 GeV … ~TeV conceivable for e+e- colliders
- Reaching an energy of 14 TeV c.m. (such as LHC) would require an accelerator with a length > 400 km (with 40 MV/m)
- Long-term: acceleration in a plasma … not ready for a HEP collider

Circular accelerator: re-use accelerating structure

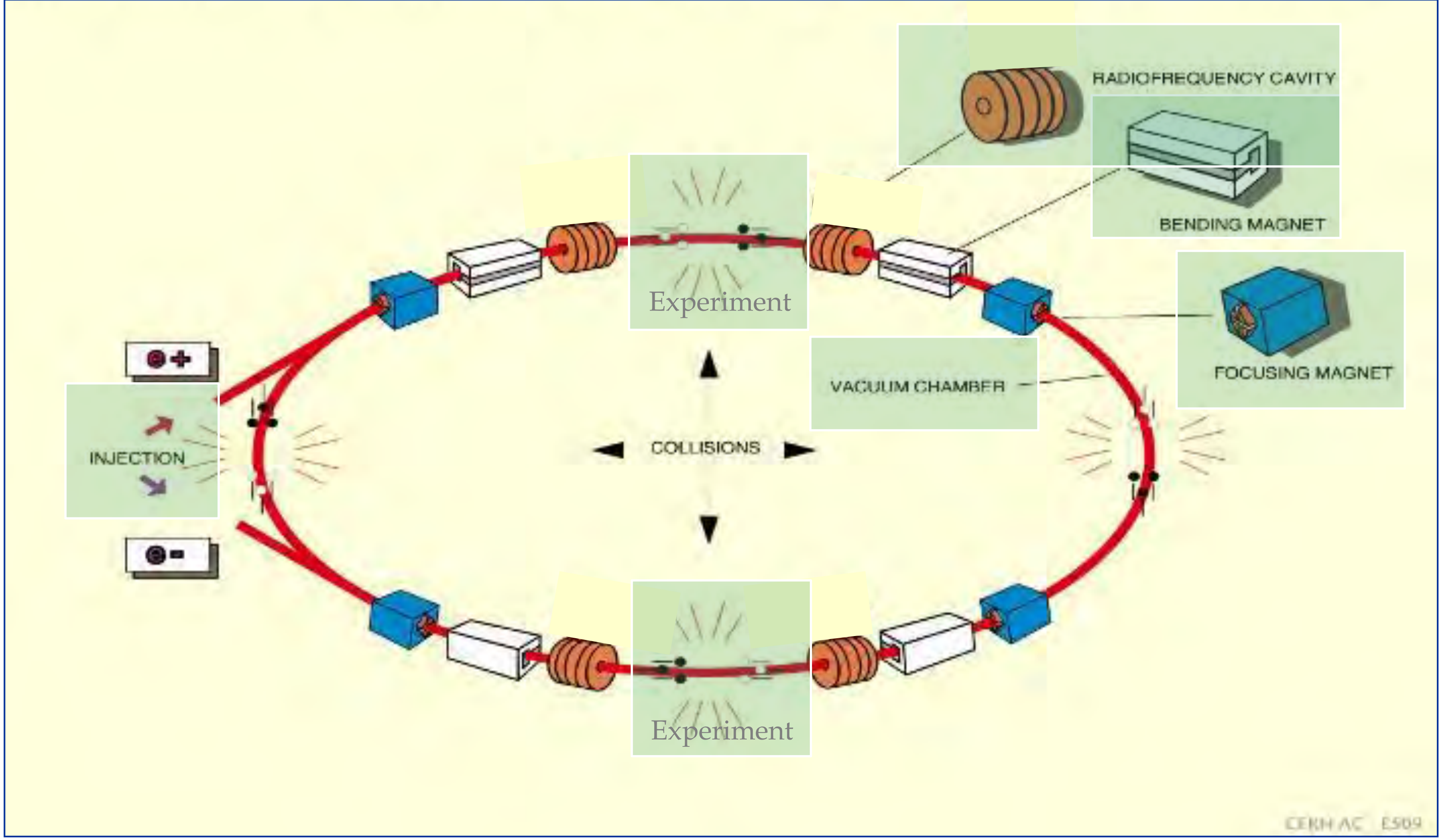
Accelerating beams to high energy in a synchrotron

- Beam are injected into the accelerator
- The particles make many turns
- The magnetic field is slowly increased, and particles are accelerated when travelling through the accelerating structure
- The beams can be extracted, or stored for many hours at top energy, bunches collide each turn
- **Major limitations: emission of synchrotron radiation and strength of the magnetic field**



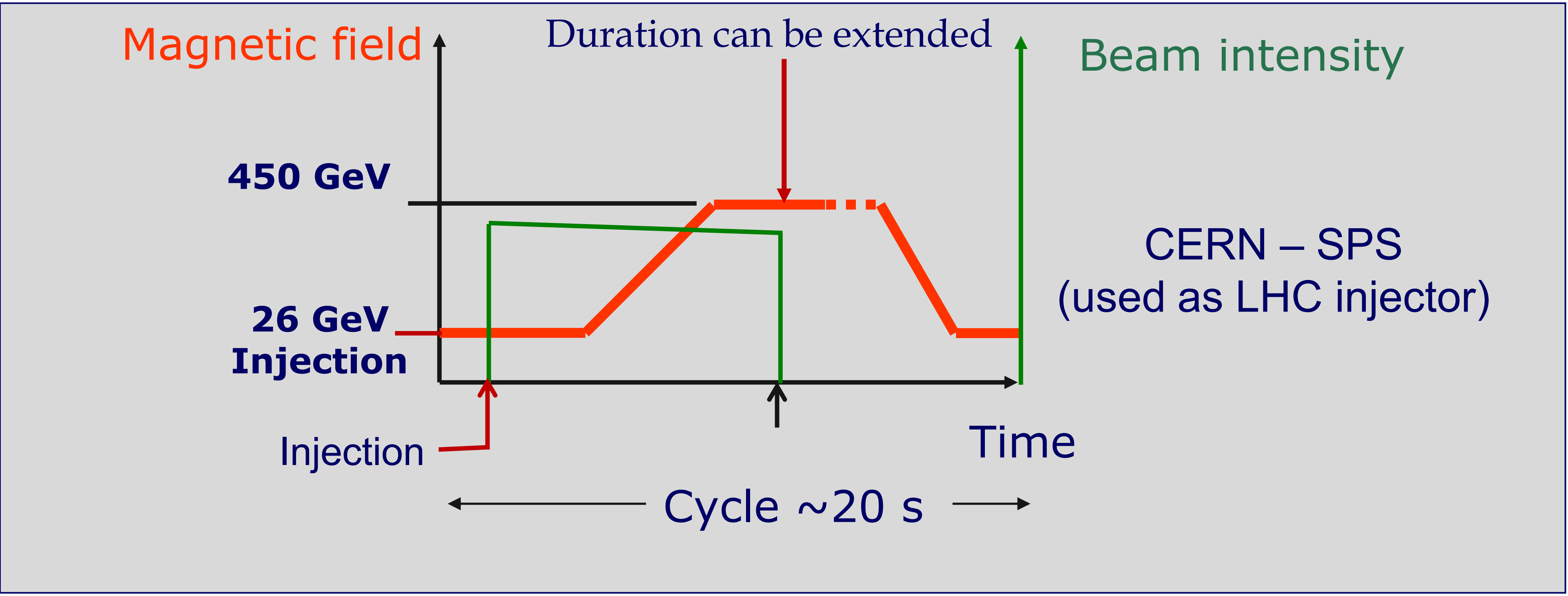
Synchrotron – circular accelerator

LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 6.5 TeV takes about 20 minutes



Operational cycle of a synchrotron

- Injection at low energy
- Ramping of magnetic field and acceleration by RF field
- Operation (collisions) at top energy



Particle Energy Challenge

Major limitation: Synchrotron Radiation

- Electromagnetic radiation is emitted when charged particles are accelerated radially: synchrotron radiation.
- Power of synchrotron radiation for one particle with the energy $\boldsymbol{E}$ and the mass $\boldsymbol{m}$ in a deflecting field with the bending radius $\boldsymbol{\rho}$ assuming the charge e_0 :

$$P = \frac{e_0^2 \cdot c}{6 \cdot \pi \cdot \epsilon_0 \cdot (\boldsymbol{m} \cdot c^2)^4} \times \frac{\boldsymbol{E}^4}{\boldsymbol{\rho}^2}$$

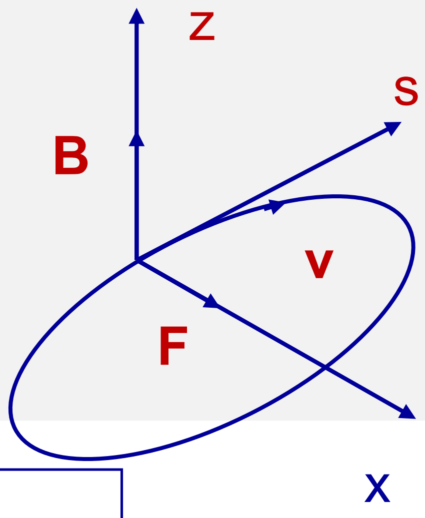
- LEP with electron-positron beams at 100 GeV/c: 16000 kW
- LHC with proton-proton beams at 7000 GeV/c and about 100 times more particles: 2.2 kW

Major limitation: Strength of deflecting field

The force on a charged particle is proportional to the charge, the electric field, and the vector product of velocity and magnetic field given by Lorentz Force:

Momentum of a particle in a magnetic field:

$$p = B \cdot \rho \cdot e_0$$



Example for LHC

- Radius ρ = 2805 m fixed by LHC (former LEP) tunnel
- Magnetic field B = 8.33 Tesla (NbTi magnets) with high field superconducting magnets
- **Maximum momentum 7000 GeV/c**

LEP / LHC in tunnel with a length of 27 km

Particles	Momentum [GeV/c]	Energy loss per turn [GeV]	Energy loss per turn [%]	Energy loss [MeV/m]	Bending field [T]
e+e-	102.00	3.22	3.16	0.172	0.12
p	7000.00	6.29E-06	0.00	0.000	8.30

LEP / LHC tunnel: limitations for protons

Particles	Momentum [GeV/c]	Energy loss per turn [GeV]	Energy loss per turn [%]	Energy loss [MeV/m]	Bending field [T]
e+e-	102.00	3.22	3.16	0.172	0.12
p	7000.00	6.29E-06	0.00	0.000	8.30
p	14000.00	1.02E-04	0.00	0.000	16.60
p	187232.00	3.22	0.00	0.172	222.00

Assume protons in LHC with synchrotron radiation loss GeV/turn as electrons in LEP: magnetic field more than one order of magnitude above what is possible today (16 TeV could possibly be conceived)

LEP / LHC tunnel: limitations for e+e-

Particles	Momentum [GeV/c]	Energy loss per turn [GeV]	Energy loss per turn [%]	Energy loss [MeV/m]	Bending field [T]
e+e-	102.00	3.22	3.16	0.172	0.12
p	7000.00	6.29E-06	0.00	0.000	8.30
p	14000.00	1.02E-04	0.00	0.000	16.60
p	187232.00	3.22	0.00	0.172	222.00
e+e-	7000.00	71385649.93	1019795.00	3818950.942	8.30
e+e-	175.00	27.89	15.93	1.492	0.21

Electrons with same magnetic field as protons in LHC: energy loss in a few cm.

……. and with a large reduced field, but somewhat higher than LEP, still much too high

Luminosity challenge

How to make many collisions ($\sim 10^9$/s)?

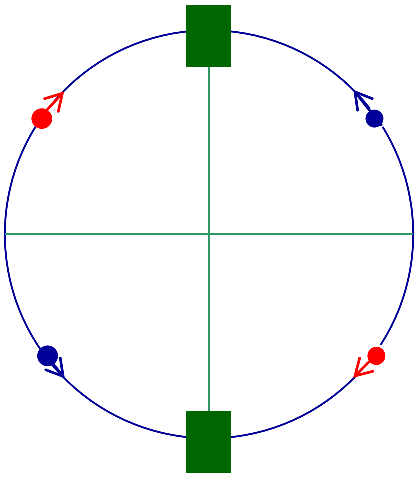
How to get to many many many many collisions ?

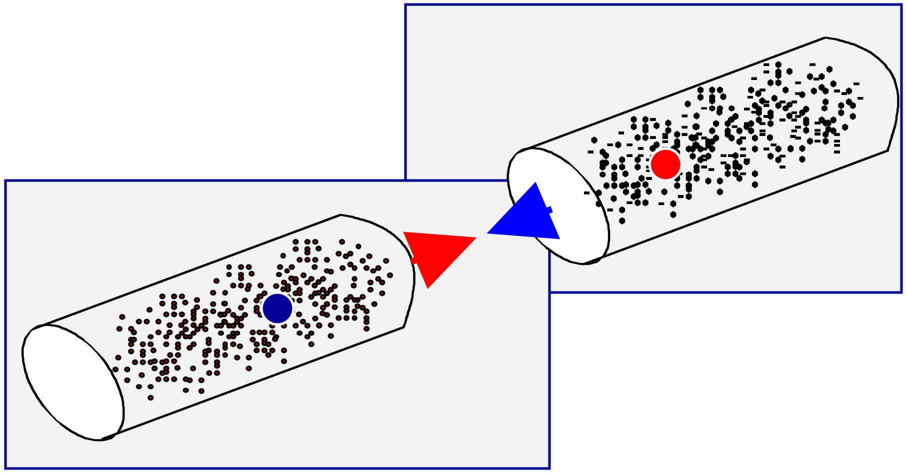
$$\frac{N}{\Delta t} = L[cm^{-2}\,s^{-1}] \cdot \sigma[cm^2]$$

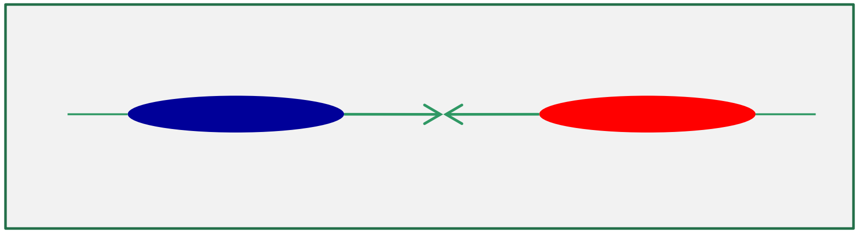
Luminosity parameters for a circular collider

Head-on crossing: $$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y}$$

N …	number of protons per bunch
f …	revolution frequency
n_b …	number of bunches per beam
$\sigma_x \cdot \sigma_y$ …	beam dimensions at interaction point







LHC Luminosity: parameters for head on collisions

Number of protons per bunch **$1.1 \cdot 10^{11}$** (limited to about $3 \cdot 10^{11}$ due to the beam-beam interaction and beam instabilities)

f = **11246 Hz**

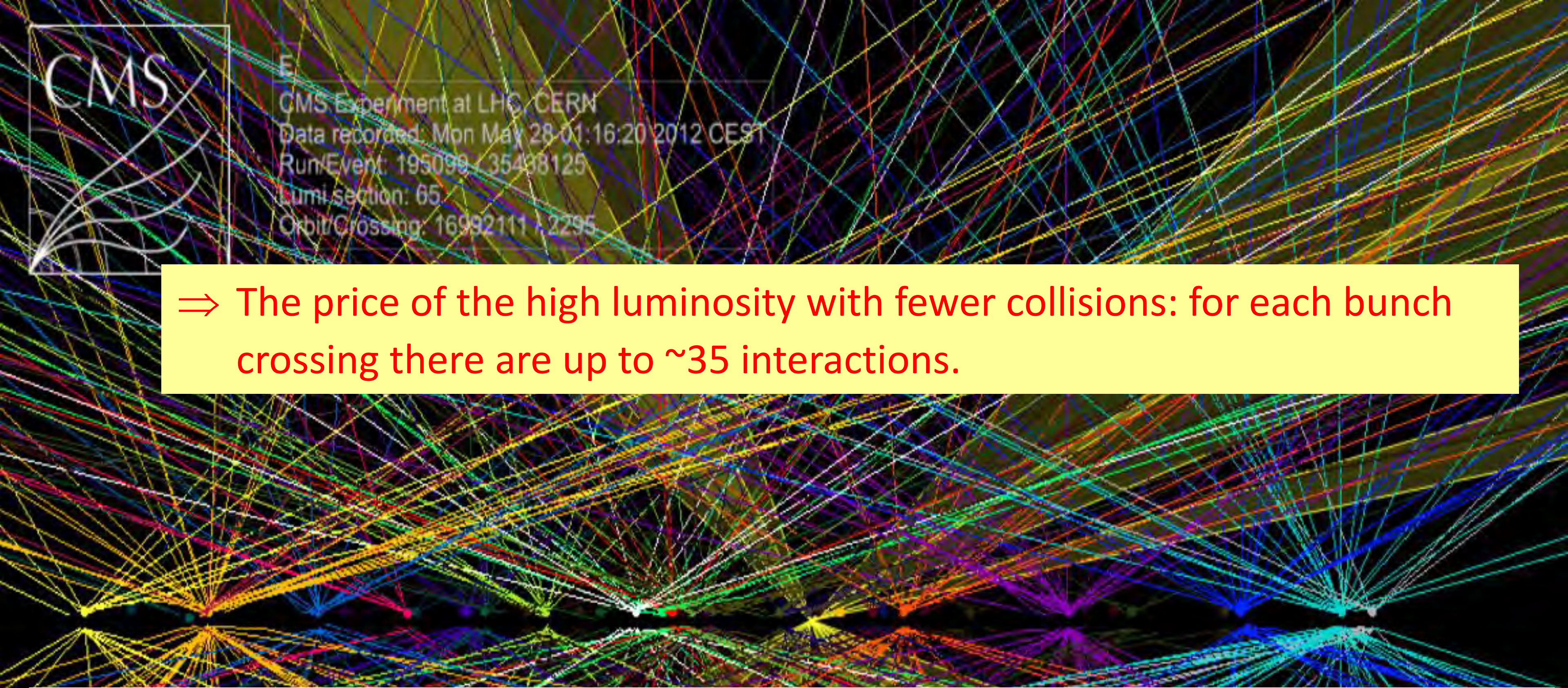
Beam size given by injectors and by space in vacuum chamber

Beam size **16 μm**, for β = 0.5 m (β* is a function of the lattice)

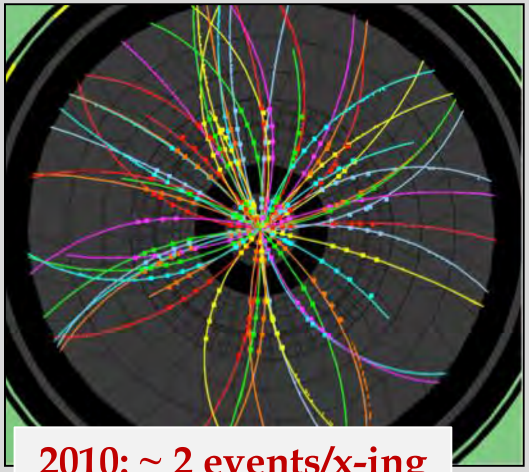
$$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y} = 3.5 \times 10^{30}\ [cm^{-2}\ s^{-1}]$$ (n_b = 1, one bunch)

~2800 bunches (every 25 ns one bunch) **$L = 10^{34}$ [$cm^{-2}s^{-1}$]**

Watch out for another limitation: **Event pile-up**



⇒ The price of the high luminosity with fewer collisions: for each bunch crossing there are up to ~35 interactions.



2010: ~ 2 events/x-ing

2011: ~ 10 events/x-ing

2012: ~ 20 events/x-ing

Crossing parameters with many bunches

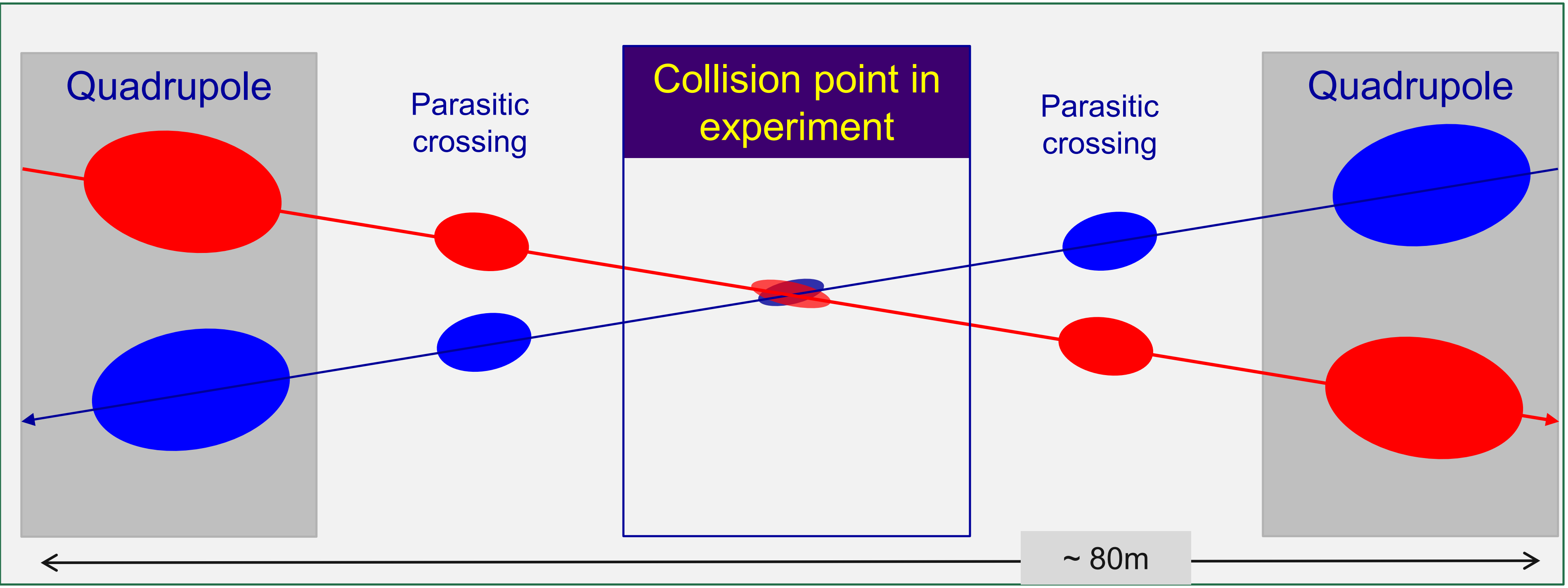
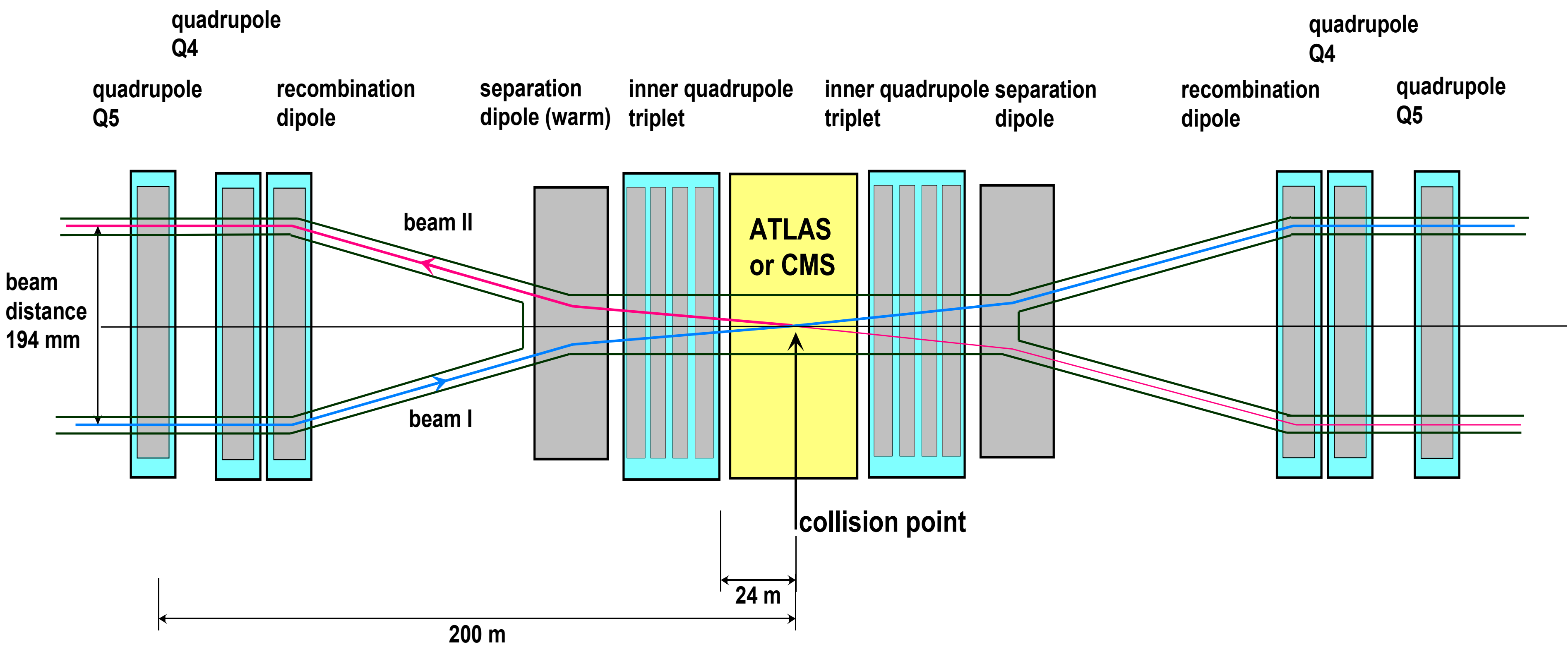


Illustration drawing

- Large beam size in adjacent quadrupole magnets
- Crossing angle to avoid additional collision points
- Separation between beams needed, about 10 σ (σ = rms beam size)
- Limitation with aperture in quadrupoles

Experimental long straight sections



Example for an LHC insertion with ATLAS or CMS

- The 2 LHC beams are brought together to collide in a 'common' region
- Over ~260 m the beams circulate in one vacuum chamber with 'parasitic' encounters (when the spacing between bunches is small enough)
- Total crossing angle of about 300 μrad

Event pile up in LHC experiments

Assuming nominal parameters, for one bunch crossing, the number of colliding proton pairs (events) is given by:

$$L = \frac{N^2 \times f \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y}$$

Event pile up for one bunch crossing:

Total cross section: $\sigma_{tot} := 100\,\mathrm{mBarn}$

$\sigma_{tot} = 1 \times 10^{-25}\,\mathrm{cm}^2$

Luminosity: $L = 1 \times 10^{34}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$

Number of events per second: $L \cdot \sigma_{tot} = 1 \times 10^{9}\,\frac{1}{\mathrm{s}}$

$frev_{lhc} = 1.1246 \times 10^{4}\,\frac{1}{\mathrm{s}}$ and $N_{bunches\_1beam} = 2808$

Number of events per bunch crossing: $L \cdot \frac{\sigma_{tot}}{frev_{lhc} \cdot N_{bunches\_1beam}} = 31.7$

Challenges for high luminosity operation

Large beam intensity => Energy stored in beams

- **Dumping the beam** in a safe way in case of failure
- **Avoiding beam losses**, in particular in the superconducting magnets (beam induced magnet quenching (for LHC, when 10^{-8}-10^{-7} of beam hits magnet at 7 TeV/c)
- **Radiation**, in particular in experimental areas from beam collisions (beam lifetime is dominated by this effect)

Beam dynamics

- **Instabilities** and **Electron Cloud**
- **UFOs**
- **Beam-beam** effects

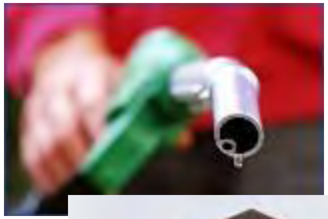
Energy stored in the beam

For LHC at 7 TeV/c the energy stored in the beam is equal to 362 MJ for nominal parameters

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 362 MJoule stored in one LHC beam

362 MJoule: the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate



It's how ease the energy is released that matters most !!

Some essential parameters for accelerators

- Particle type (e+, e-, p, antiproton, ion, …)
- Energy / momentum of a particle
- Beam intensity / beam current
- Beam size => beam emittance
- Trajectory / closed orbit

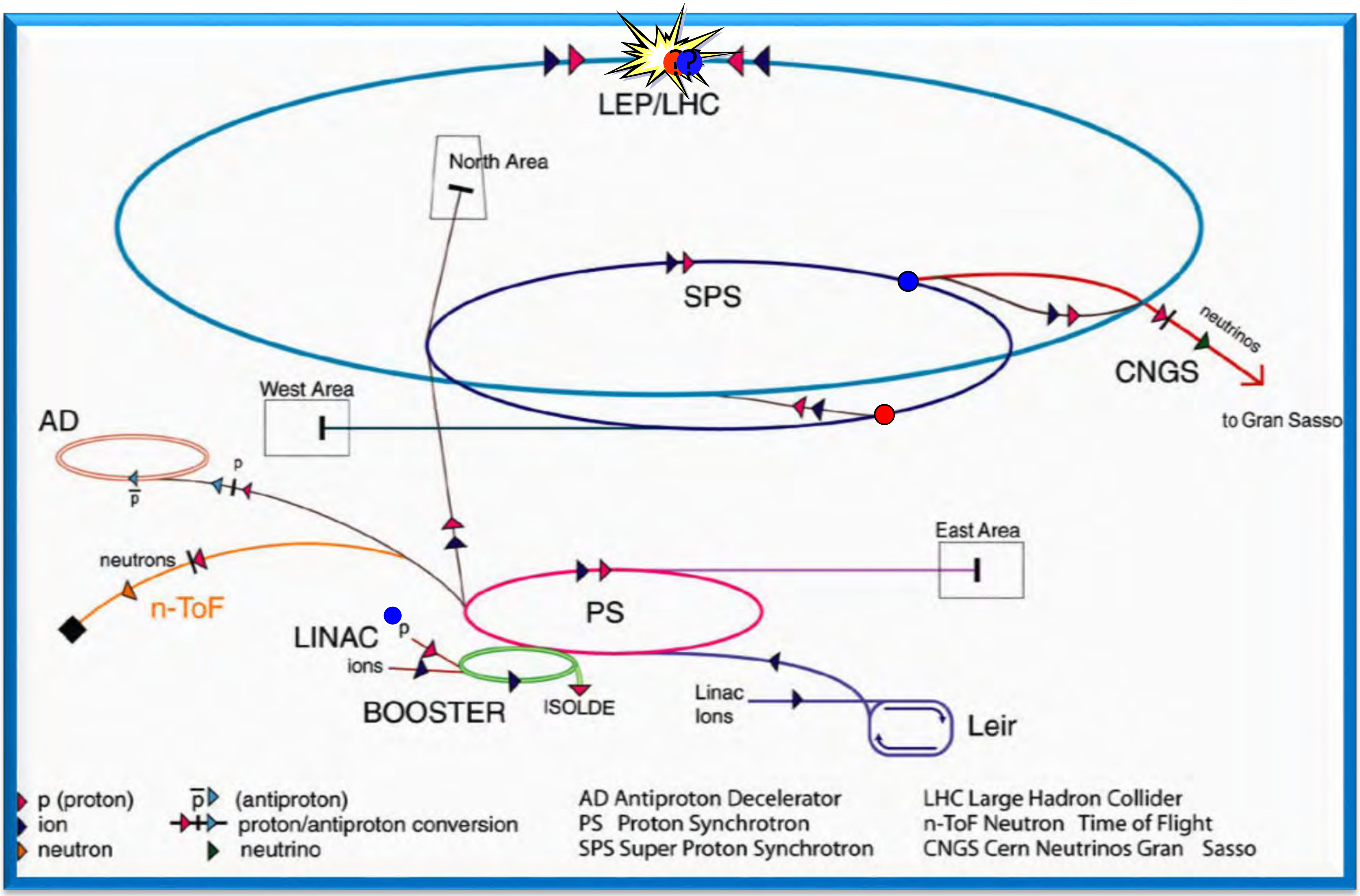
- Betatron oscillations
- Betatron tune (Q value)

$$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y}$$

Short Beam Dynamics Course

How to transport many particles through an accelerator complex?

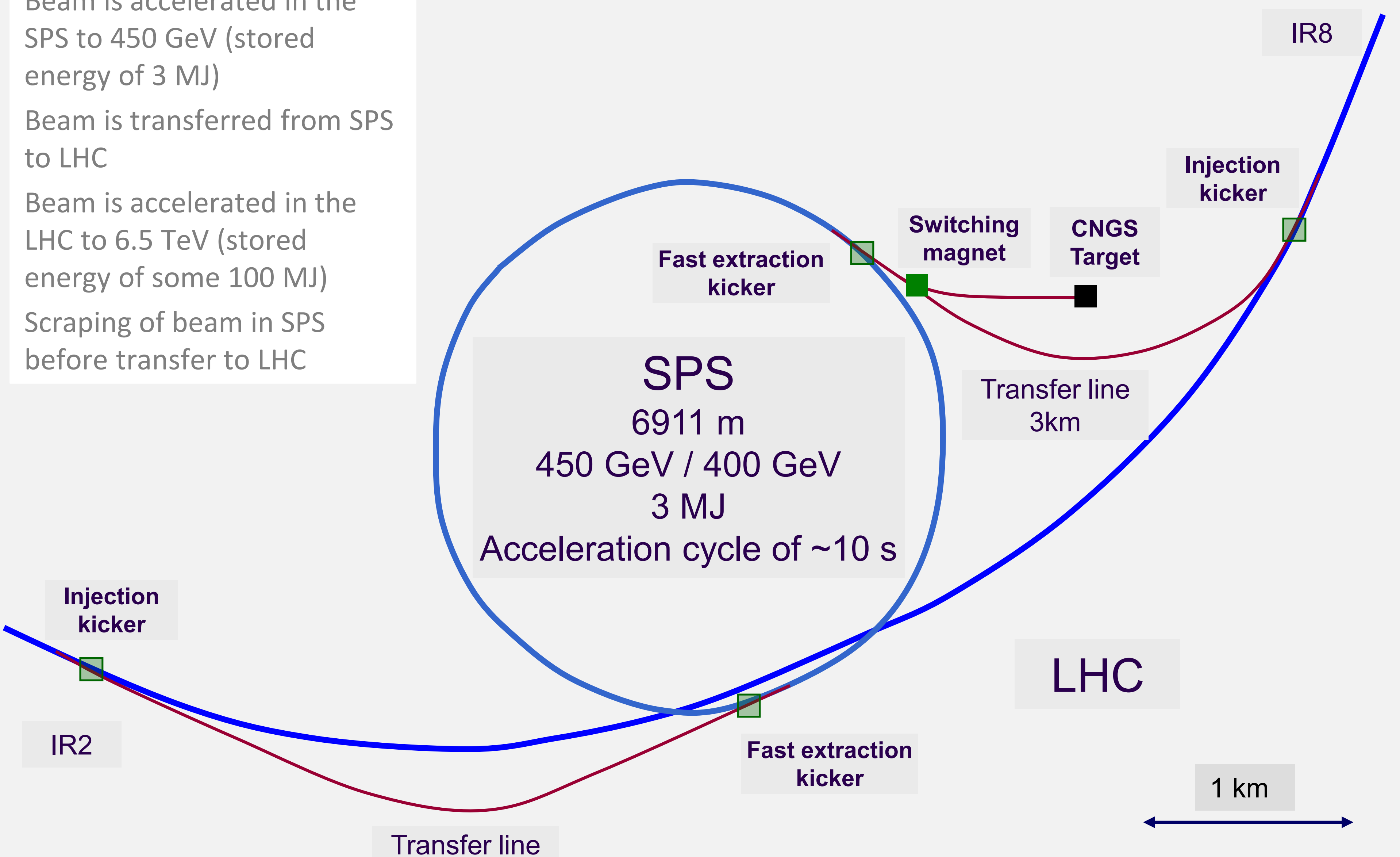
CERN accelerator complex



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 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



Need for getting protons on a circle: dipole magnets

Need for focusing the beams with lenses:

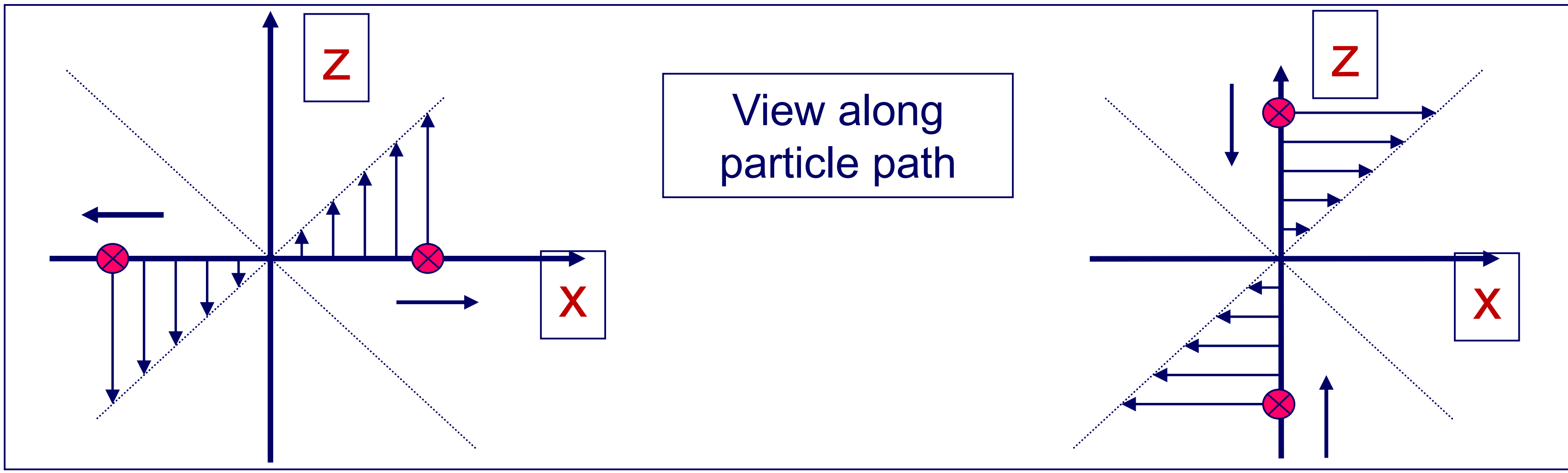
- Particles with different injection parameters (angle, position) separate with time
  - Assuming an angle difference of 10^{-6} rad, two particles would separate by 1 m after 10^{6} m. At the LHC, with a length of 26860 m, this would be the case after 50 turns (5 ms !)
- Particles would „drop“ due to 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

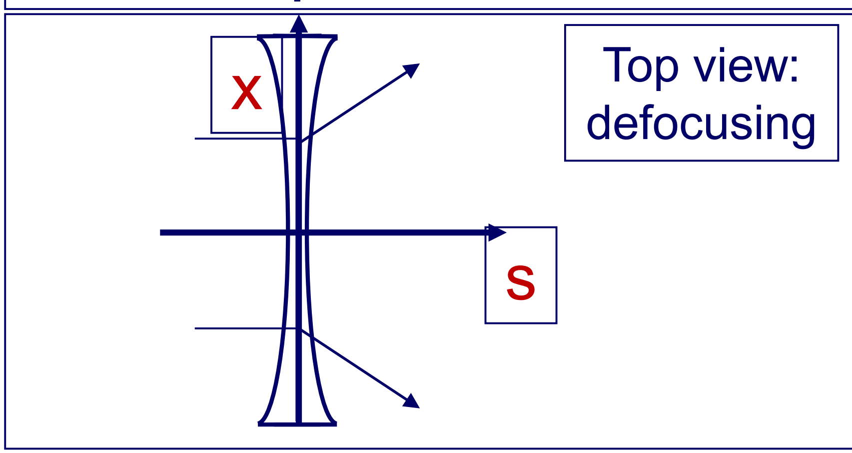
Force by quadrupole magnets

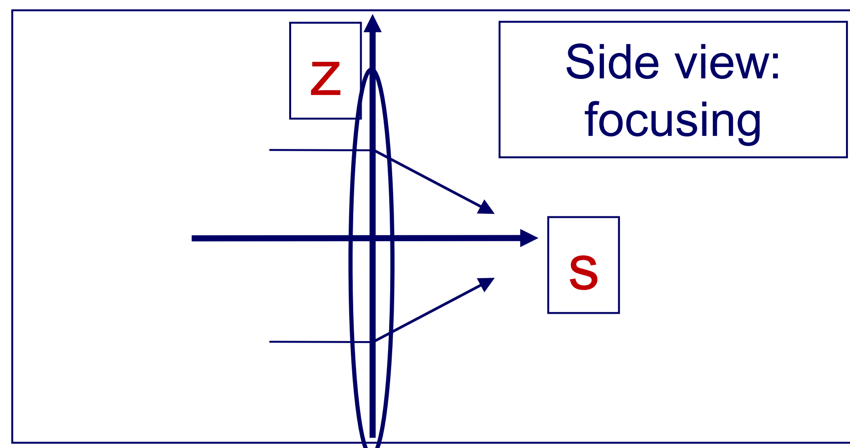
$$B_z(x) = const \times x$$
$$B_x(z) = const \times z$$

From Maxwell's equations

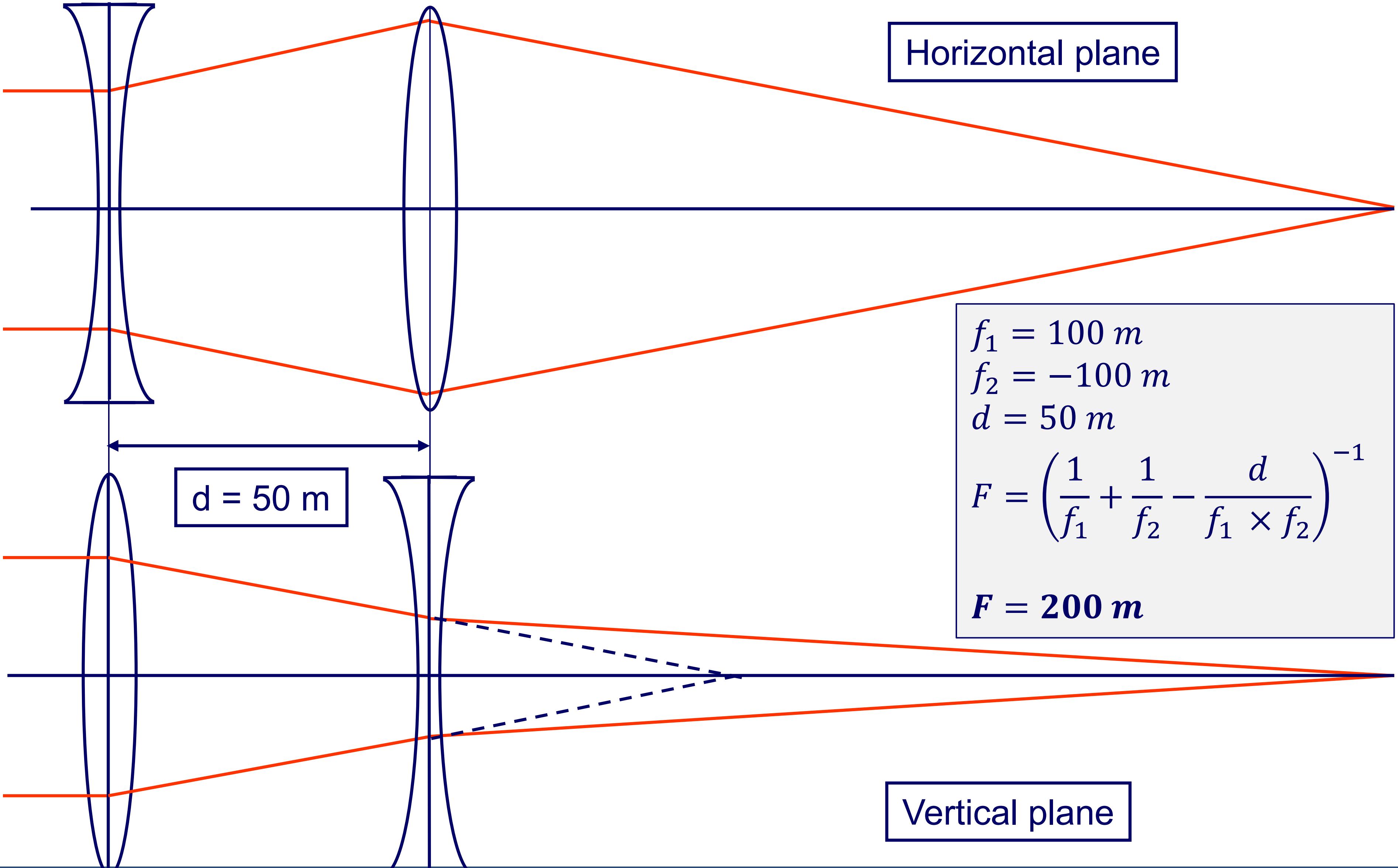
Here: a particle with positive charge travels in s-direction, into the table







Focusing by two quadrupole magnets, thin lenses



$f_1 = 100\ m$

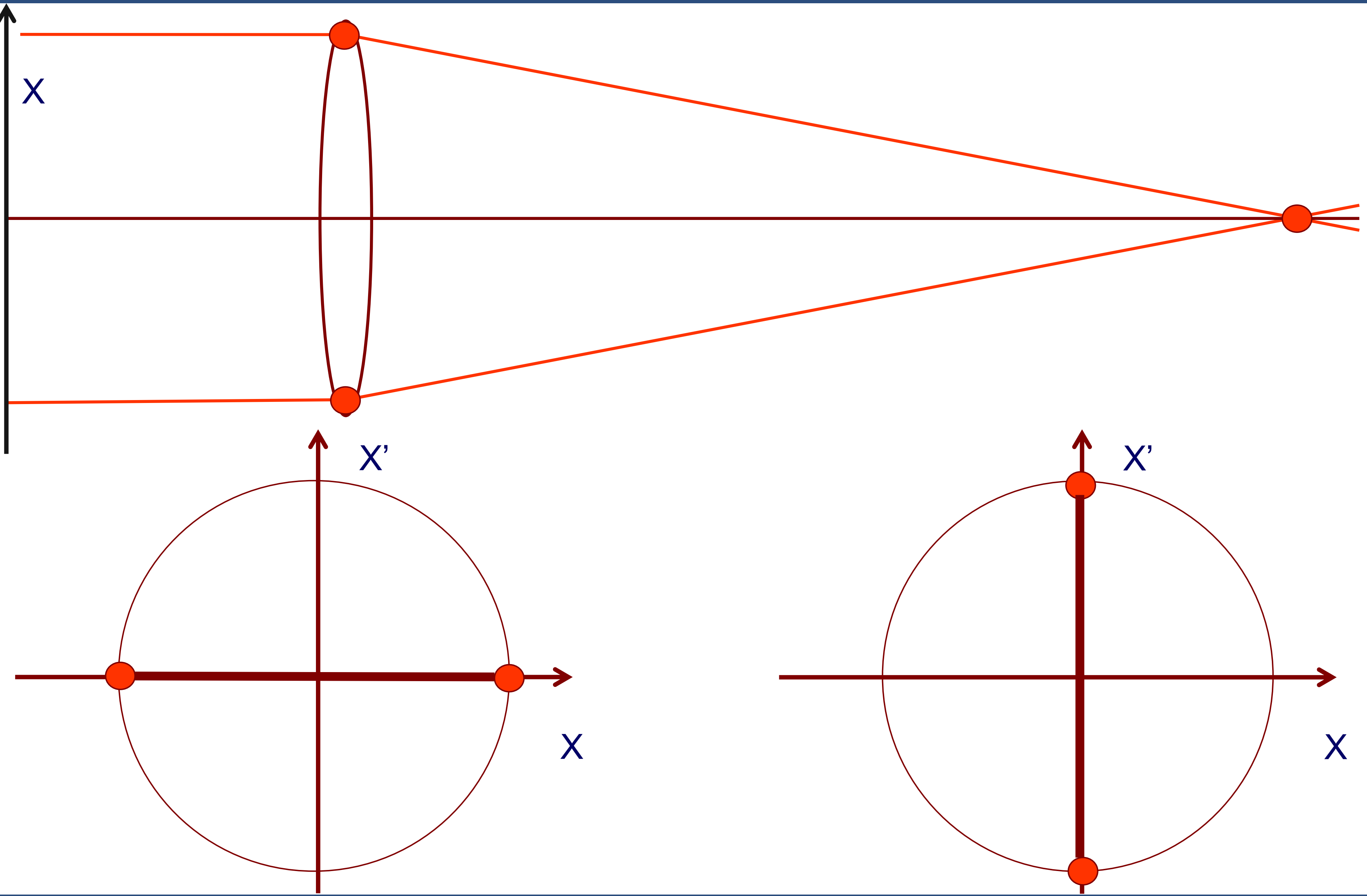
$f_2 = -100\ m$

$d = 50\ m$

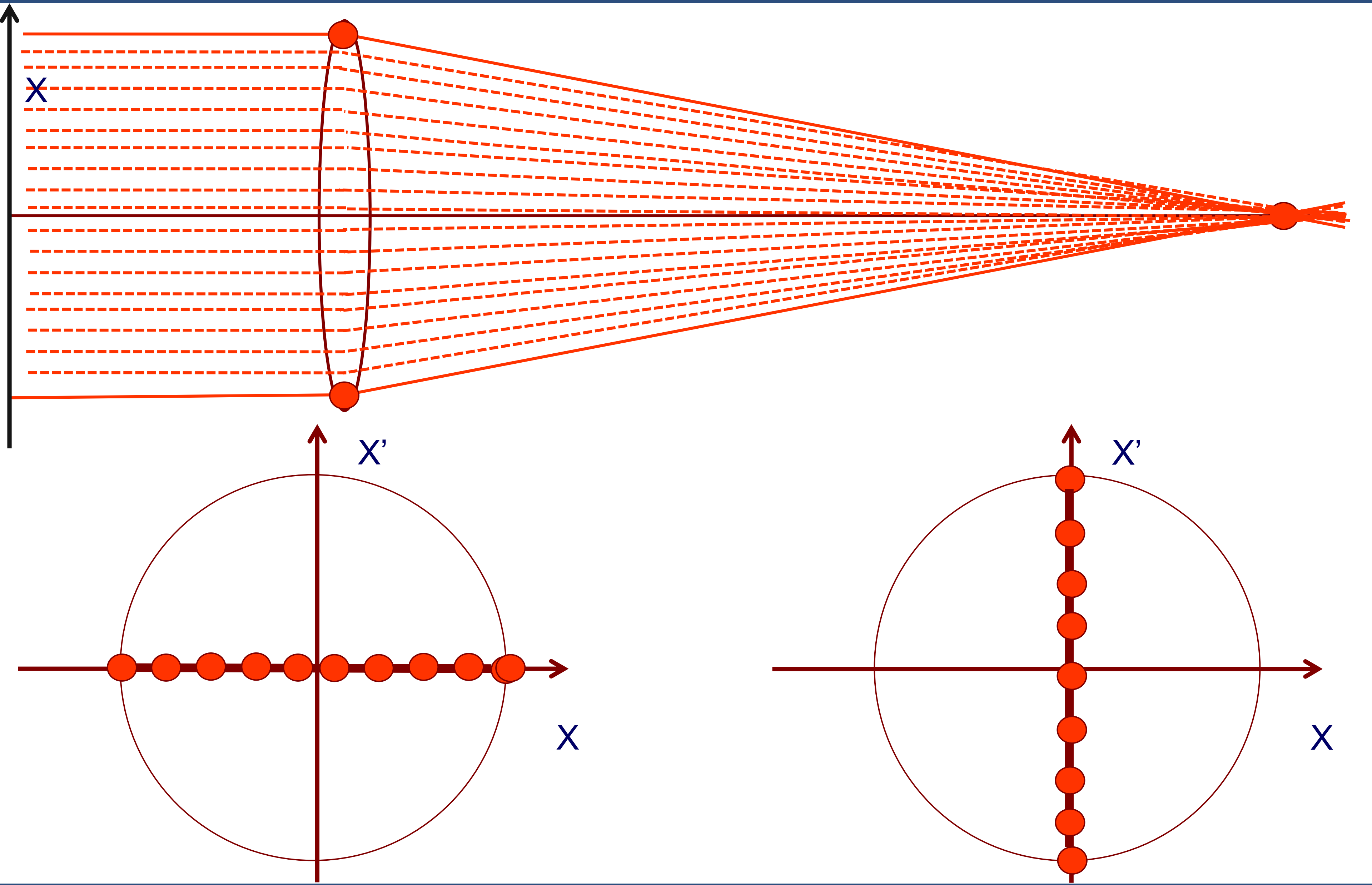
$$F = \left(\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \times f_2}\right)^{-1}$$

$$\boldsymbol{F = 200\ m}$$

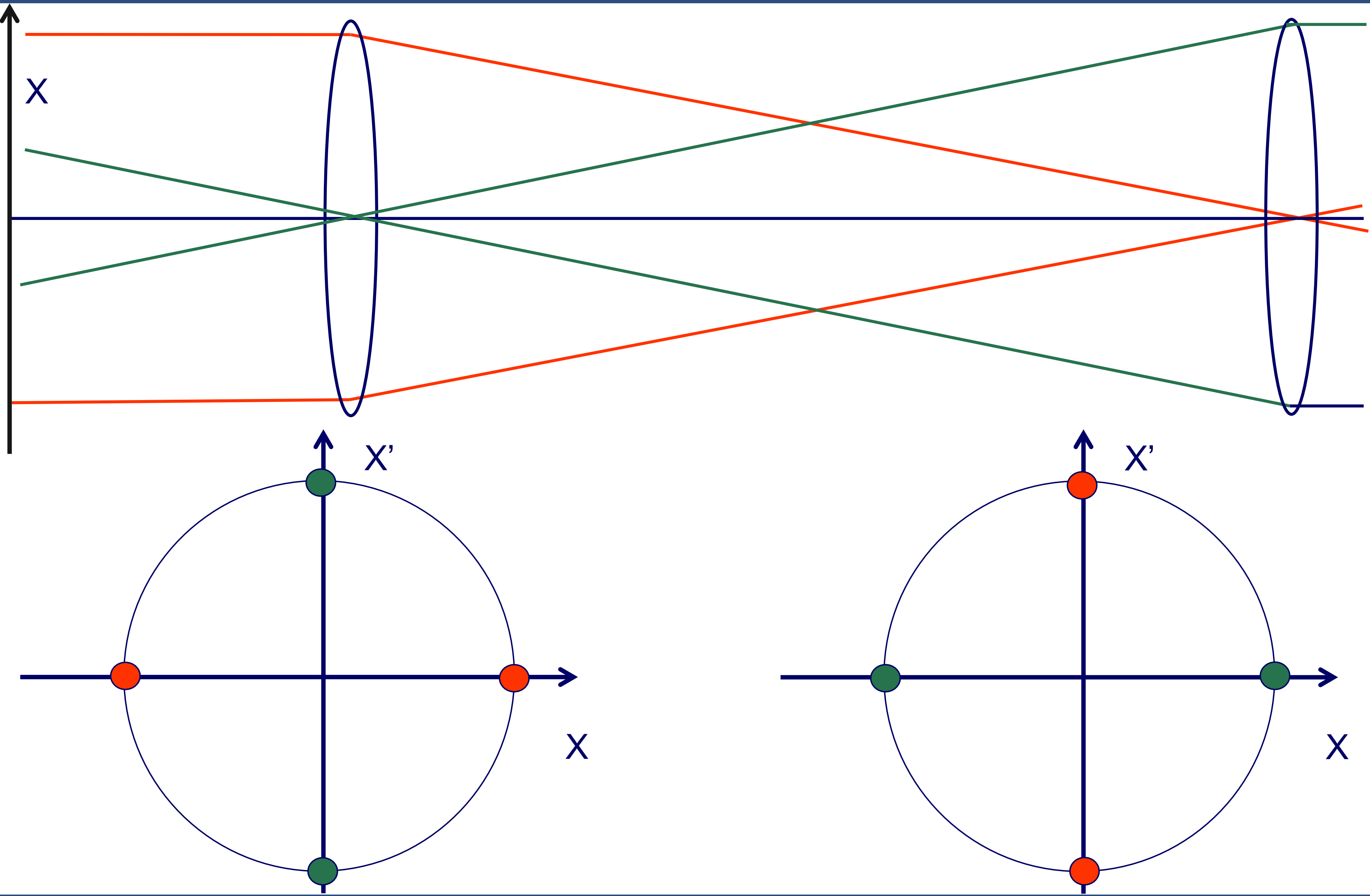
Phase Space of an ensemble of particles



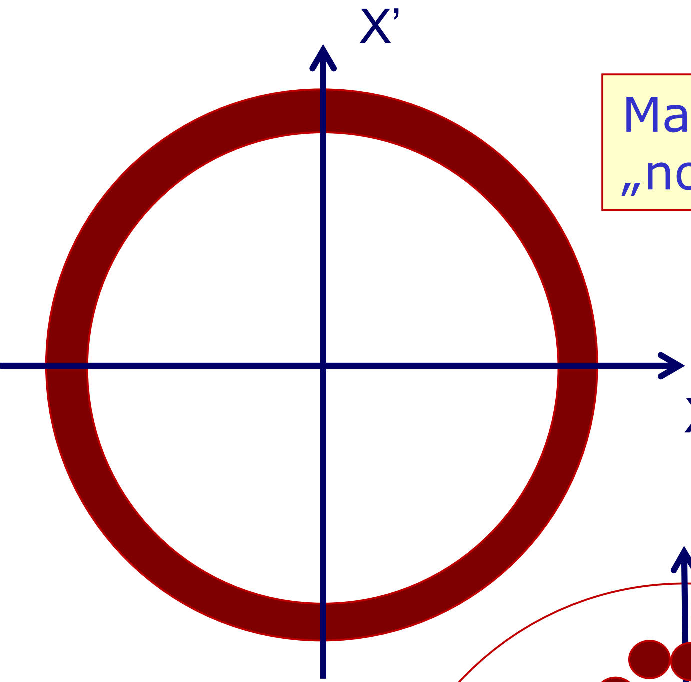
Phase Space of an ensemble of particles



Phase space of an ensemble of particles

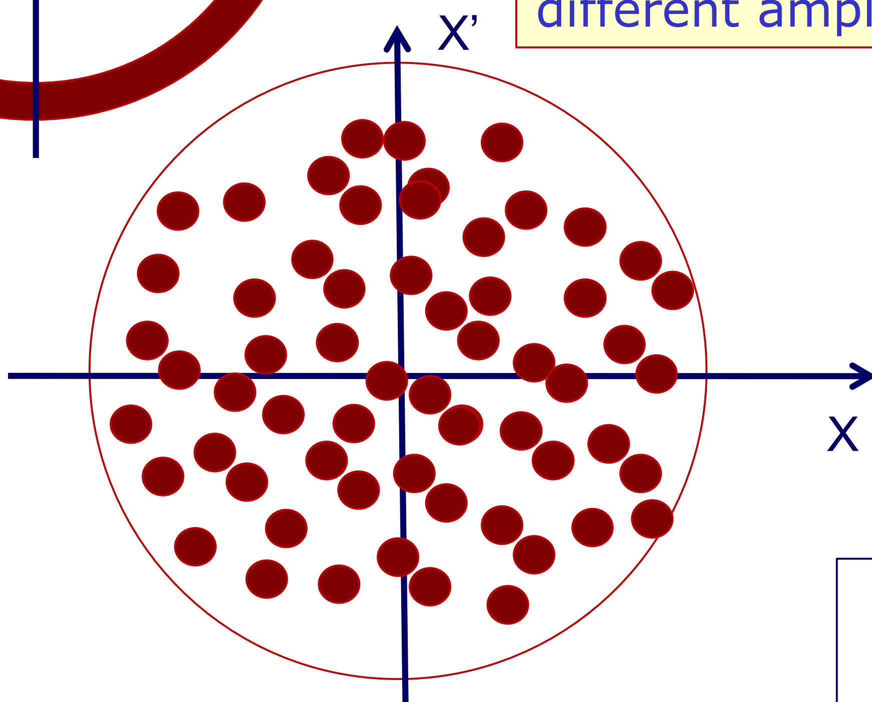


Phase space of an ensemble of particles



Many particles, same „normalised" amplitude

Real beam: many particles, different amplitudes

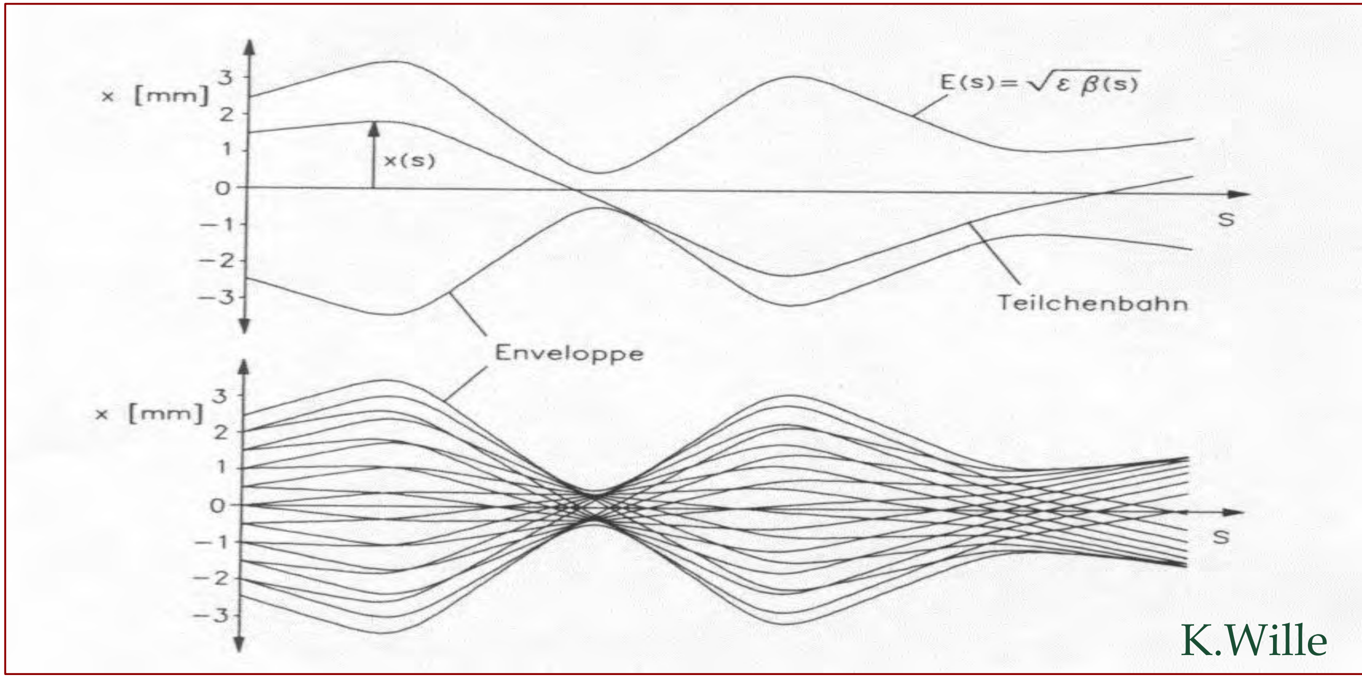


This conservation law: phase space volume occupied by a collection of systems evolving according to Hamilton's equations of motion is preserved in time

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

Betatron oscillations for many particles

Beam size at longitudinal position s

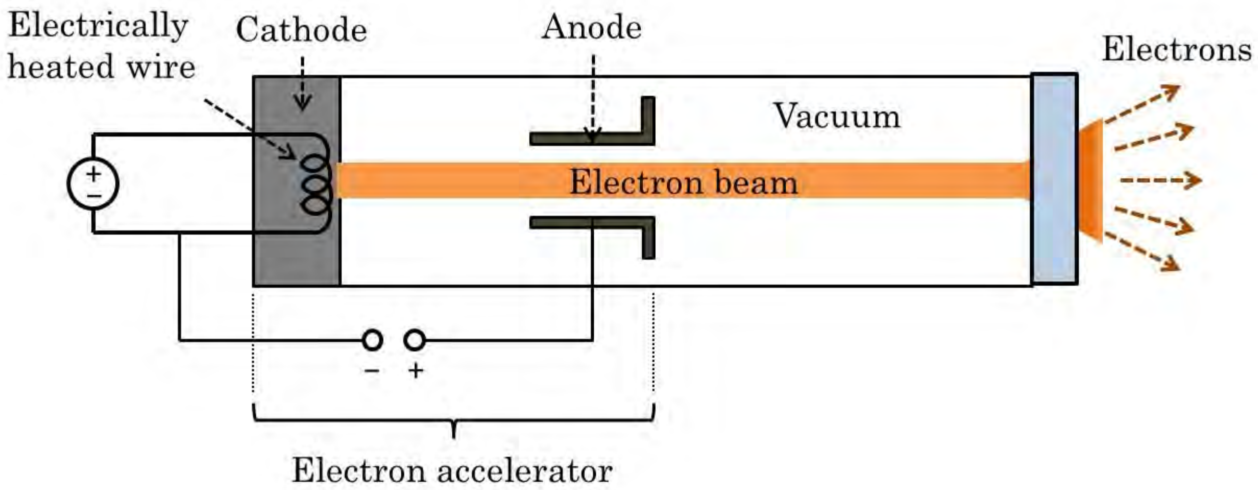


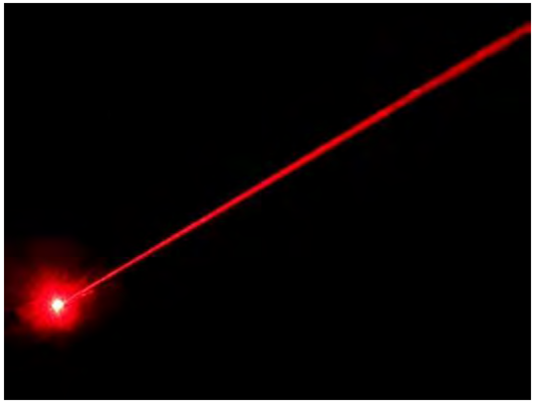
$$\sigma(s) = \sqrt{\epsilon \times \beta(s)} \text{ and } \sigma'(s) = \sqrt{\frac{\epsilon}{\beta(s)}} \text{ for each plane x and z}$$

$$\sigma(s) \cdot \sigma'(s) = \epsilon = \ constant$$

The emittances ϵ_x and ϵ_z are statistical values.

ϵ decreases proportional to the particle energy during acceleration (adiabatic damping) - for protons with negligible synchrotron radiation emission)

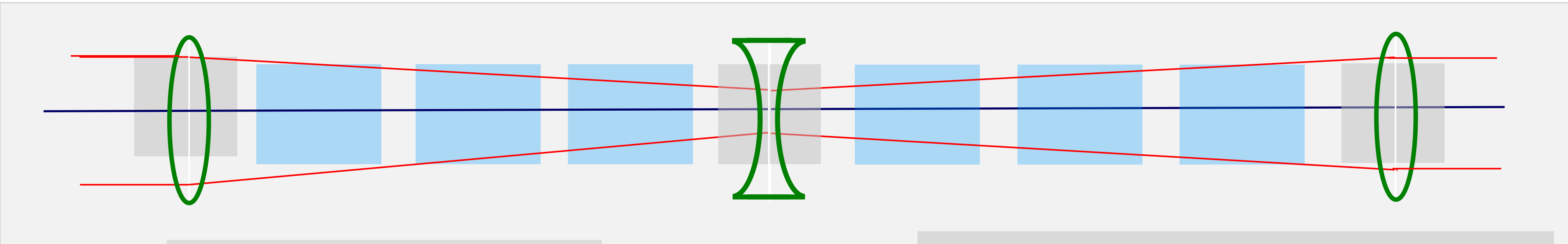

Electrically
heated wire
Cathode
Anode
Electrons
Vacuum
Electron beam
+
−
−
+
Electron accelerator



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
- Sextupole magnets
  - To correct the trajectories for off momentum particles
  - Particle trajectories stable for small amplitudes (about 10 mm)
- 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)

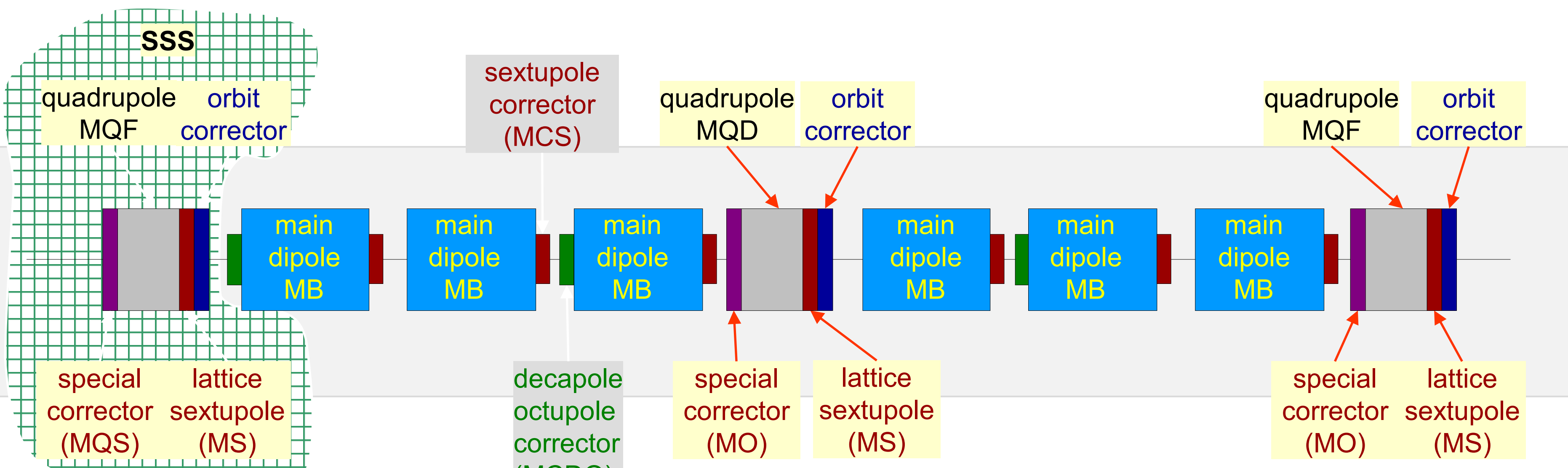
A (F0D0) cell in the LHC arcs



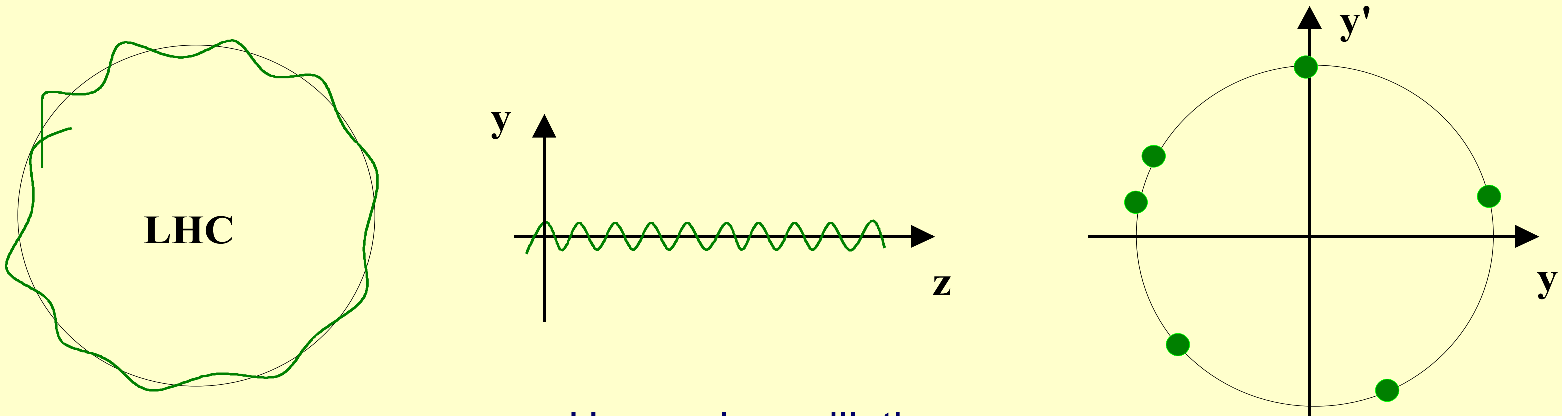
Vertical / Horizontal plane
(QF / QD)

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



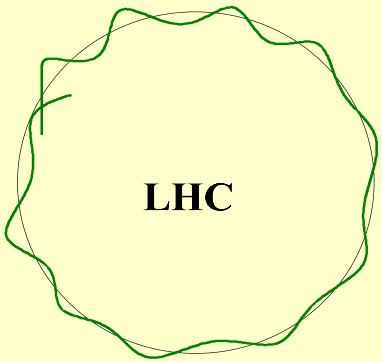
Particle oscillations in quadrupole field (small amplitude)

Harmonic oscillation after coordinate transformation

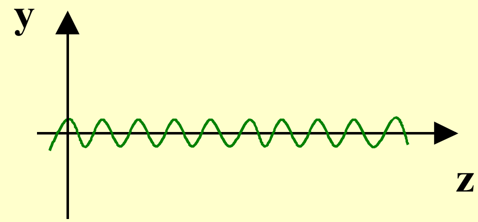
Circular movement in phase space

- 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

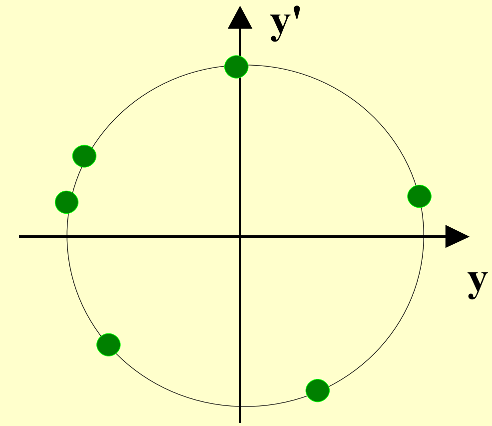
Particle stability and magnets



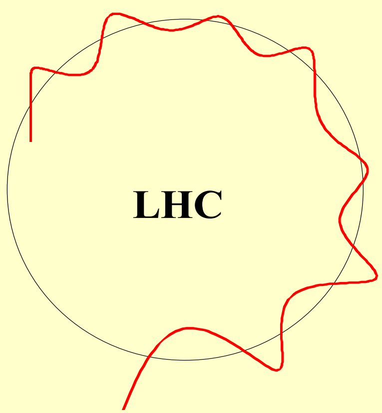
Particle oscillations in quadrupole field (small amplitude)



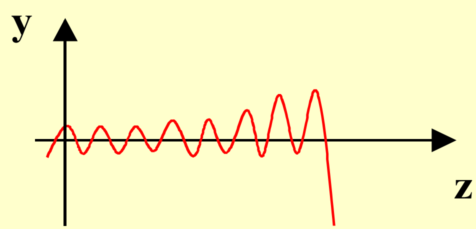
Harmonic oscillation after coordinate transformation



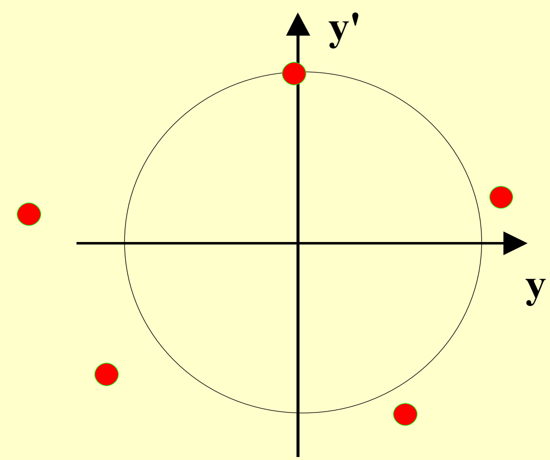
Circular movement in phase space



Particle oscillation assuming non-linear fields, large amplitude

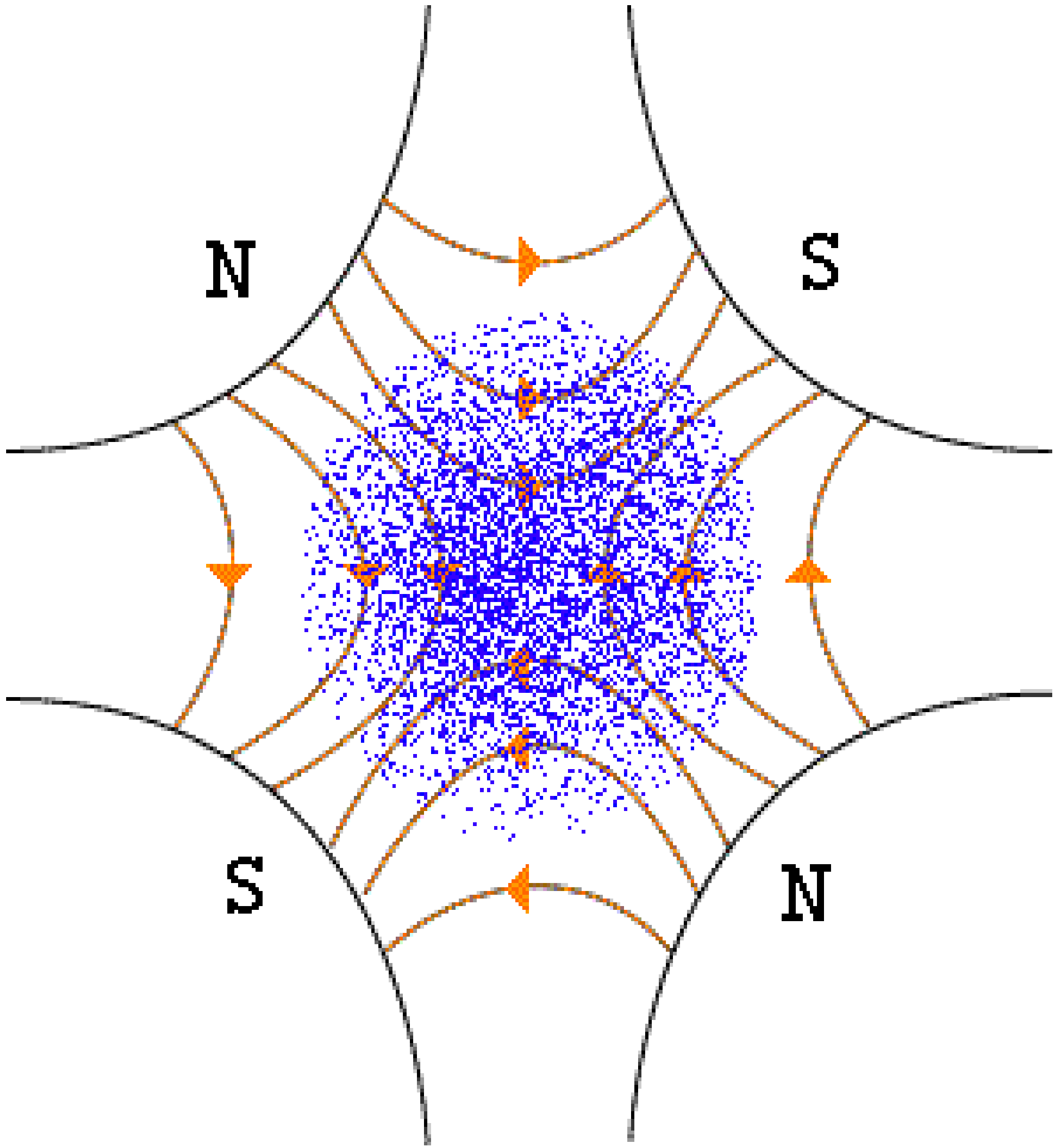


Amplitude grows until particle is lost (touches aperture)



No circular movement in phasespace

Visualising bunch oscillation in accelerator

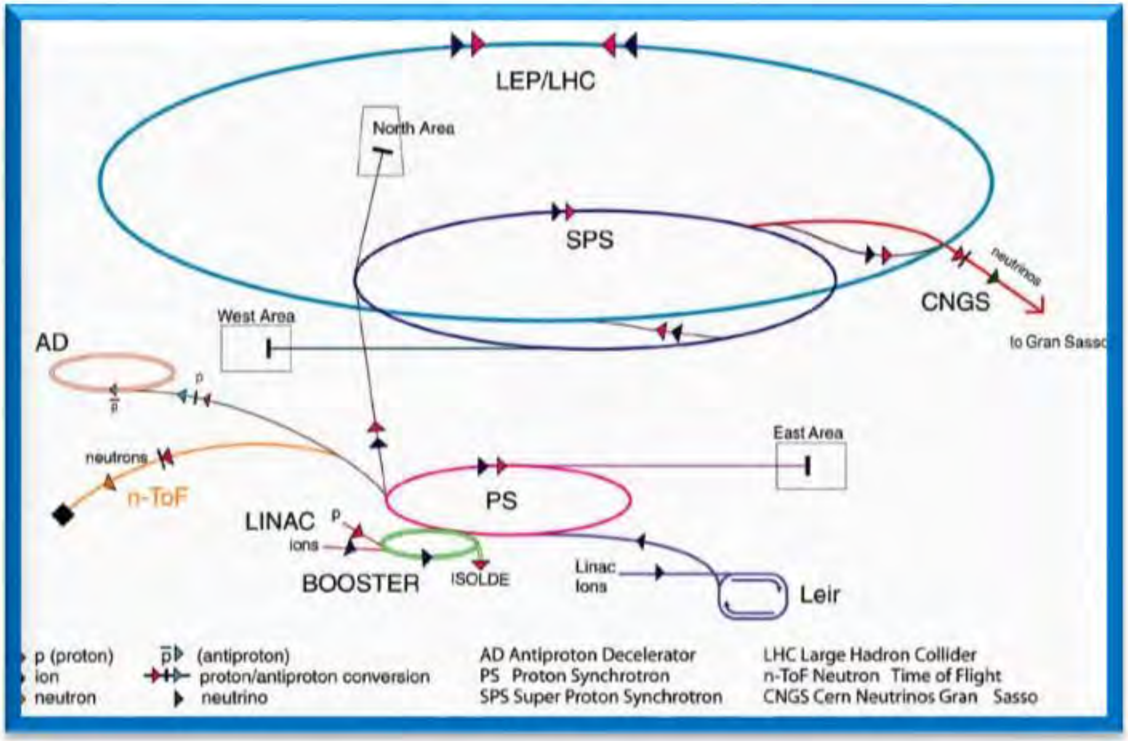


Particle energy and superconducting magnets

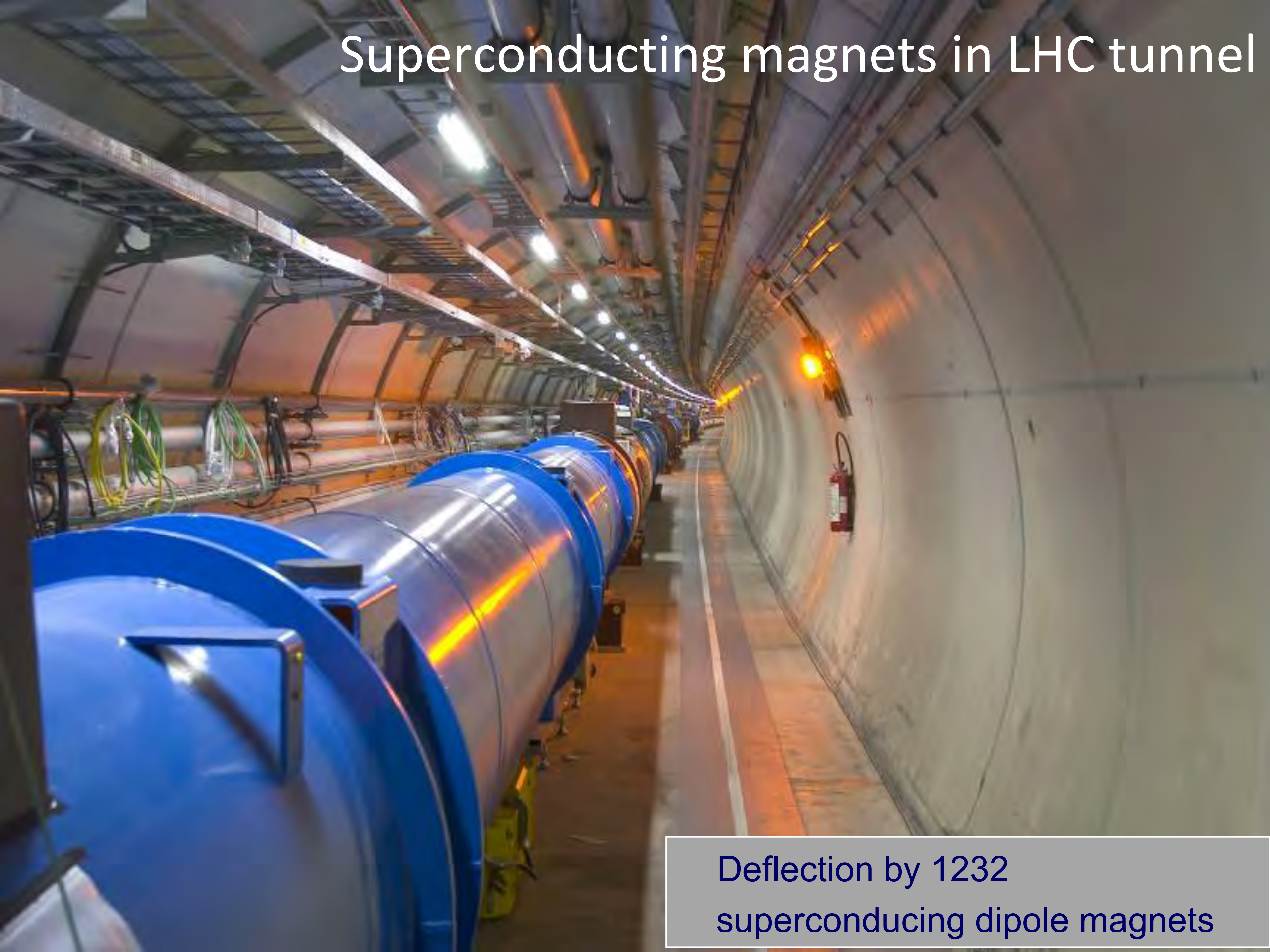
…….the magnetic field strength determines the beam energy

Question

Why so many accelerators ?



Superconducting magnets in LHC tunnel



Deflection by 1232 superconducing dipole magnets

Dipole magnets for the LHC

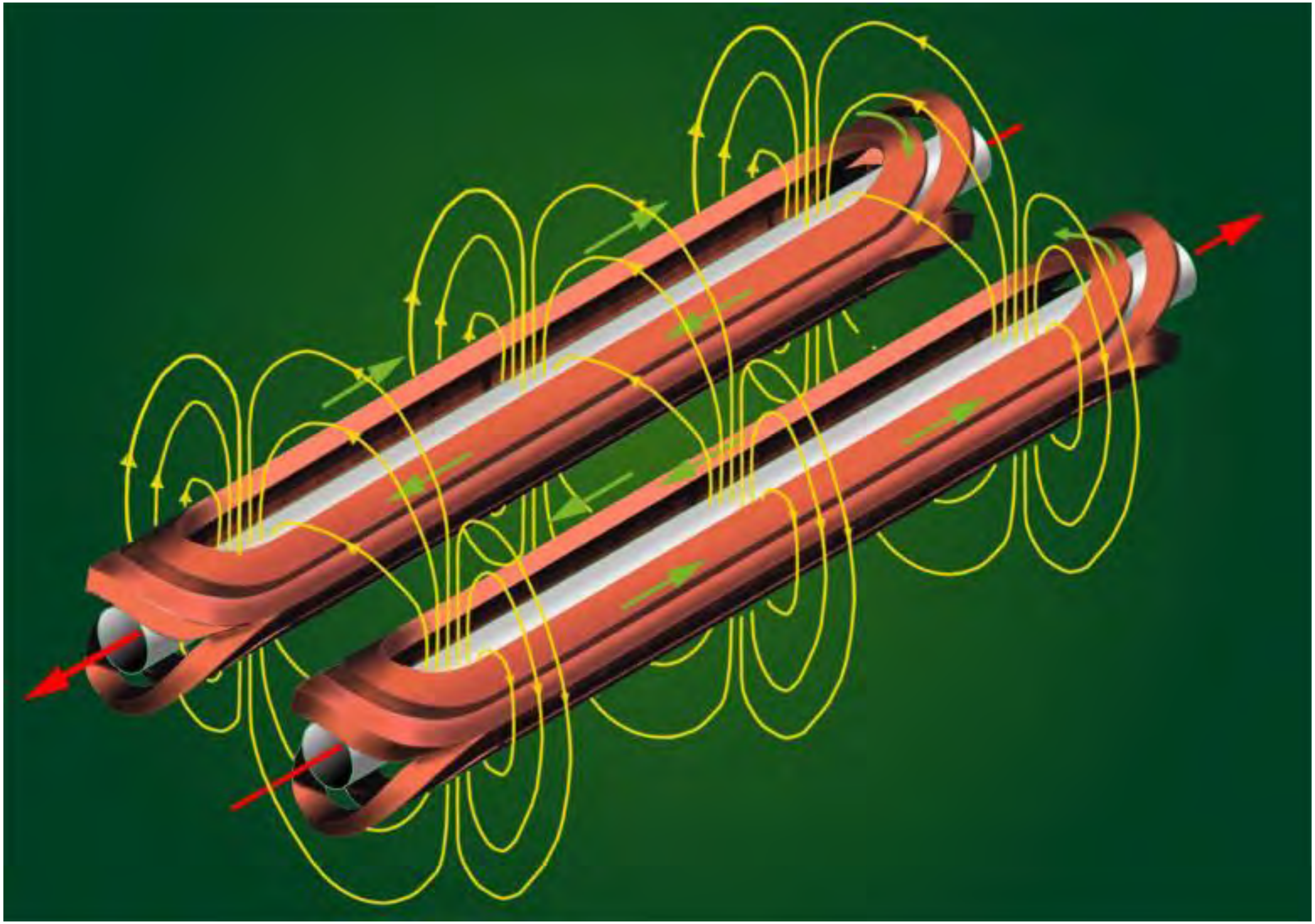
1232 Dipole magnets
Length about 15 m

Magnetic Field 8.3 T for 7 TeV

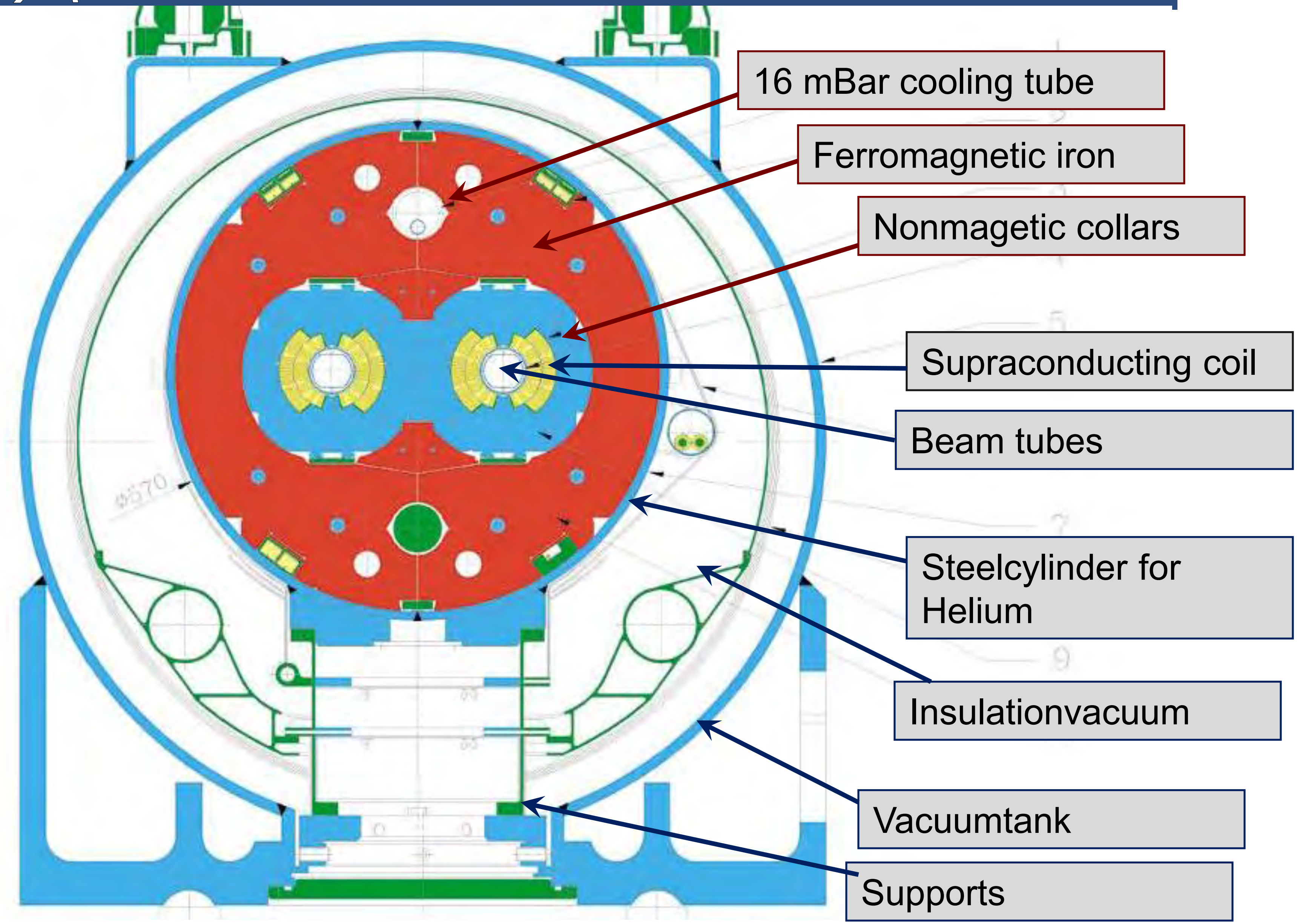
Two beam tubes with an opening of 56 mm

plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets)

Coils for Dipolmagnets

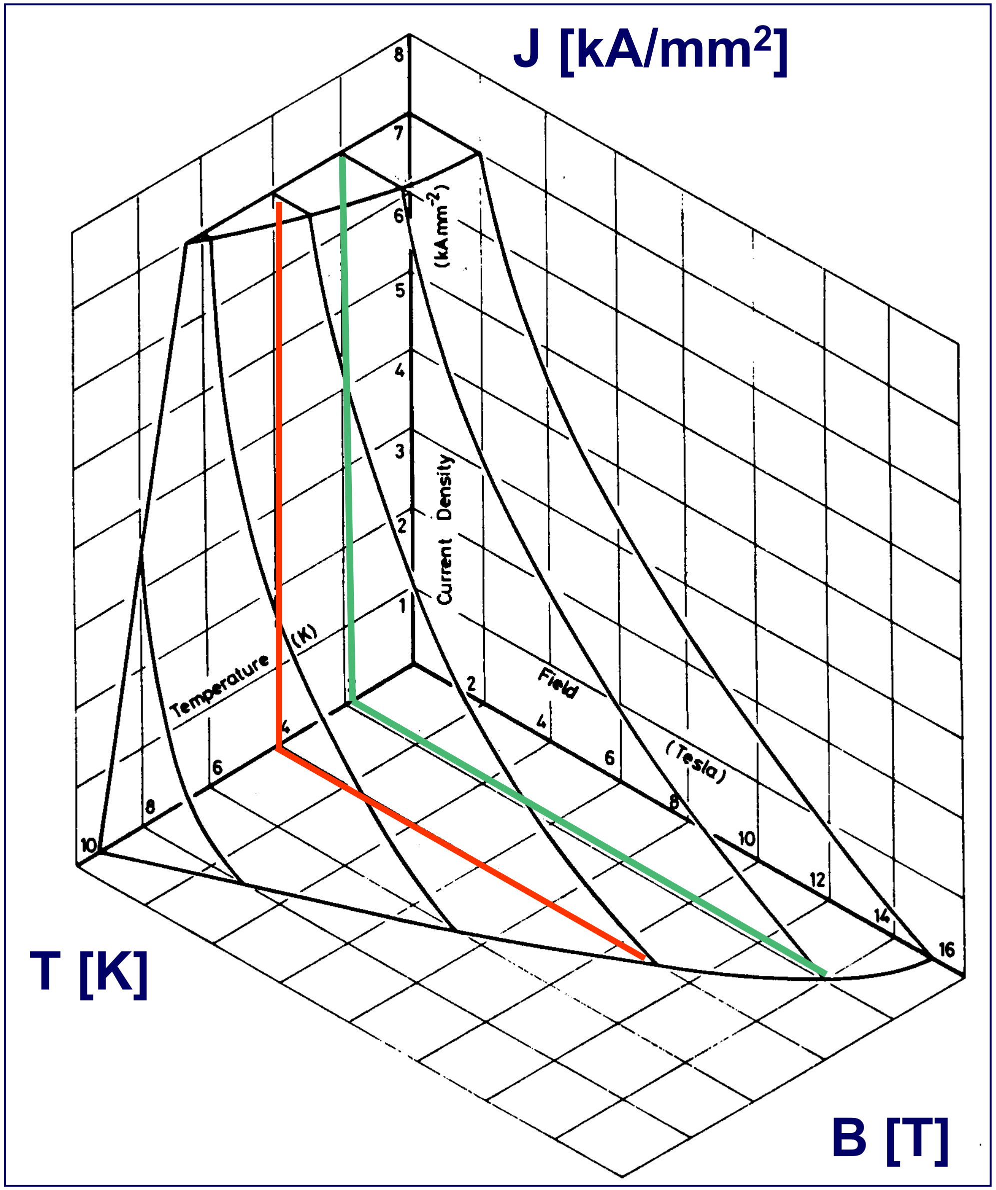


Dipole magnet cross section



Coils: dipole and quadrupole magnets

Operating temperature of superconductors (NbTi)

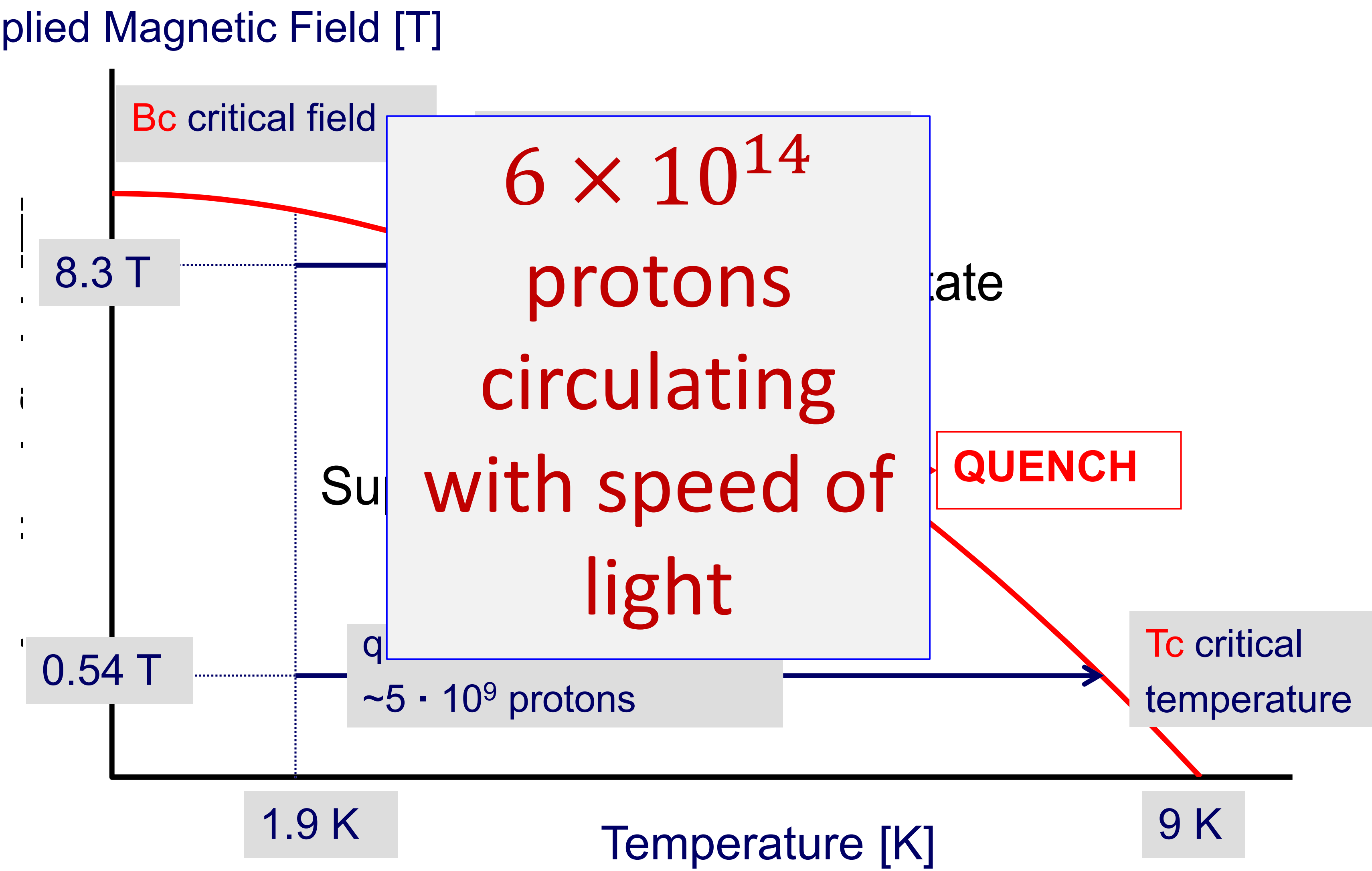


The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

Superconducting magnets produce high field with high current density

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

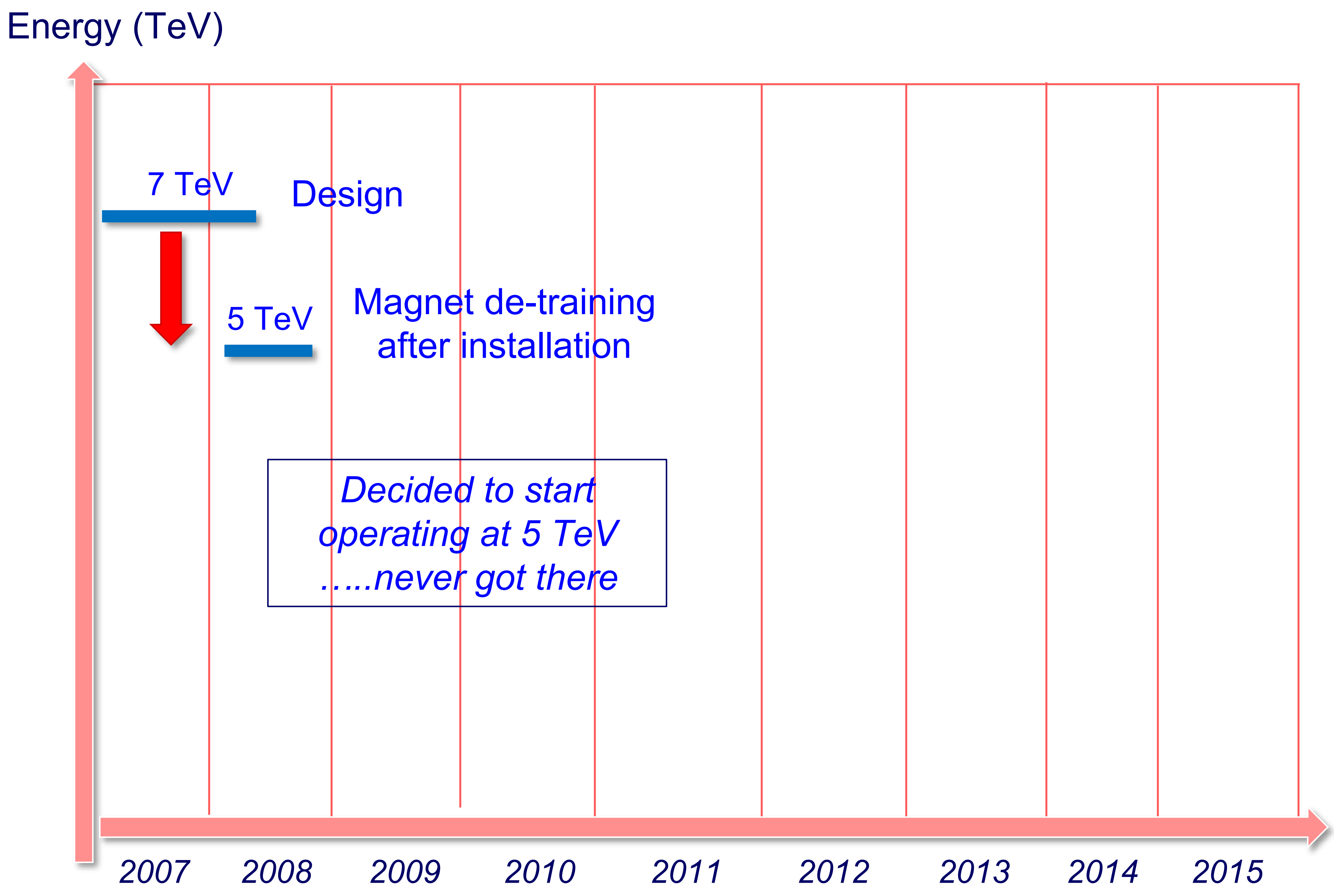
Operational margin of a superconducting magnet



2nd order phase transition, superfluid Helium at 2.19 K

Dipole magnets from surface to tunnel

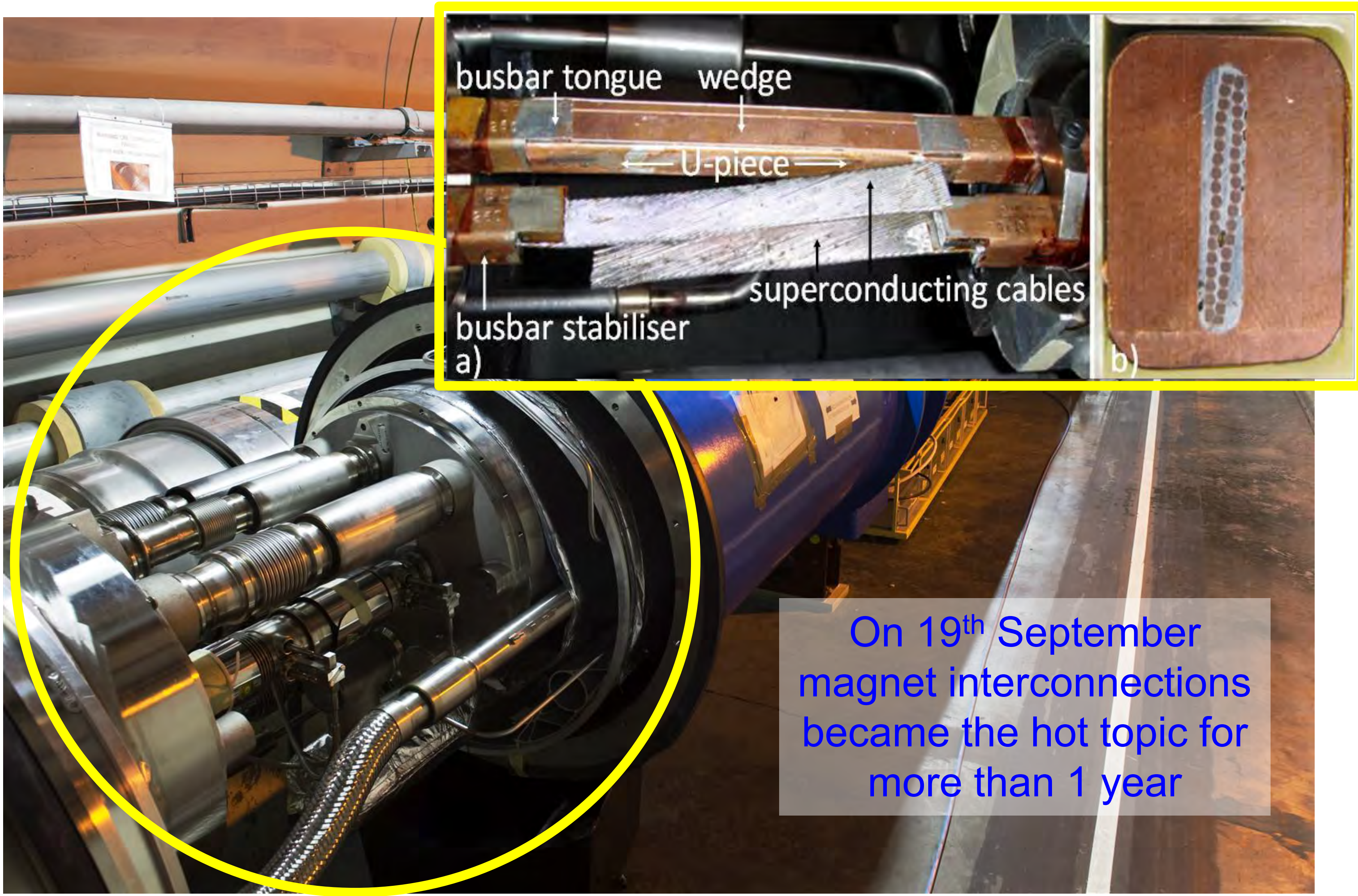
LHC energy evolution



September 10th 2008

A brief moment of glory

September 19th 2008



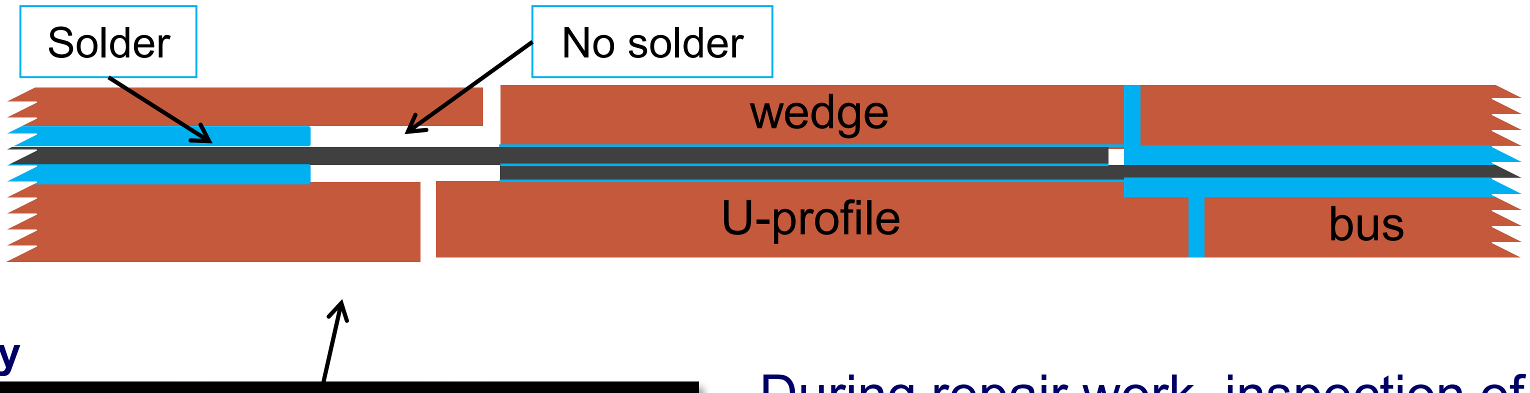
On 19th September magnet interconnections became the hot topic for more than 1 year

Incident September 19th 2008

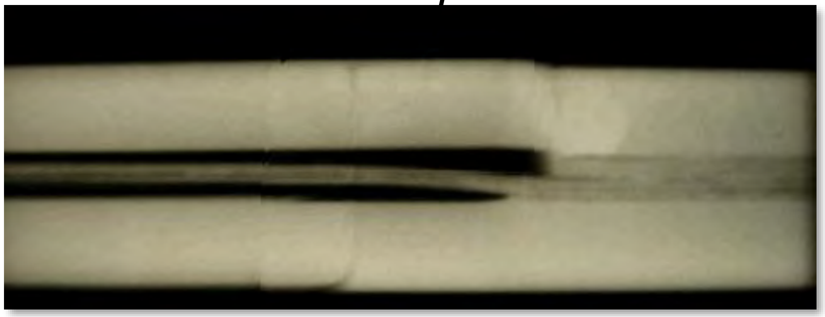
53 magnets had to be repaired

More problems on the joints

- The copper stabilizes the bus bar in the event of a cable quench (=bypass for the current while the energy is extracted from the circuit).
- Protection system in place in 2008 not sufficiently sensitive.
- A copper bus bar with reduced continuity coupled to a badly soldered superconducting cable can lead to a serious incident.



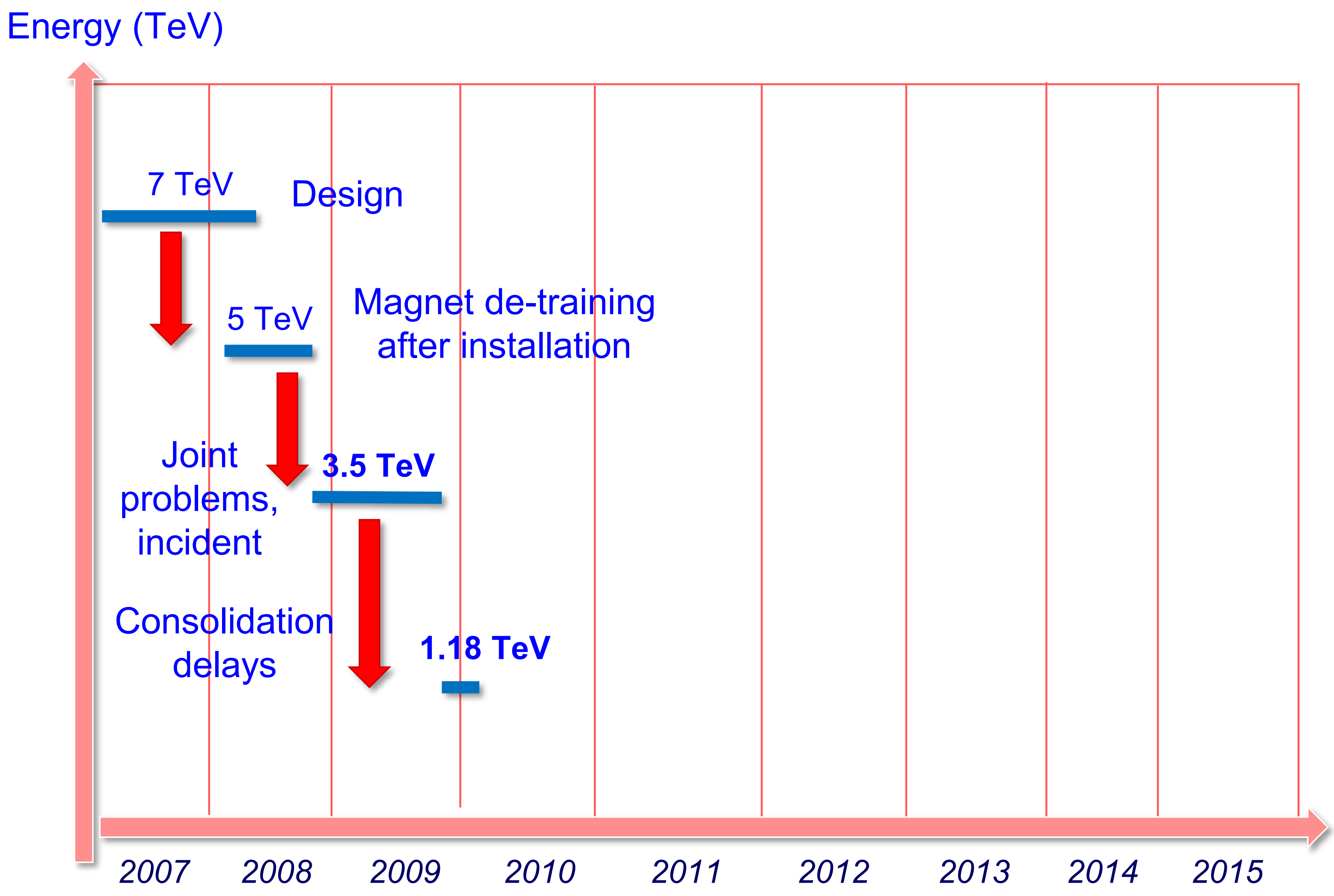
X-ray



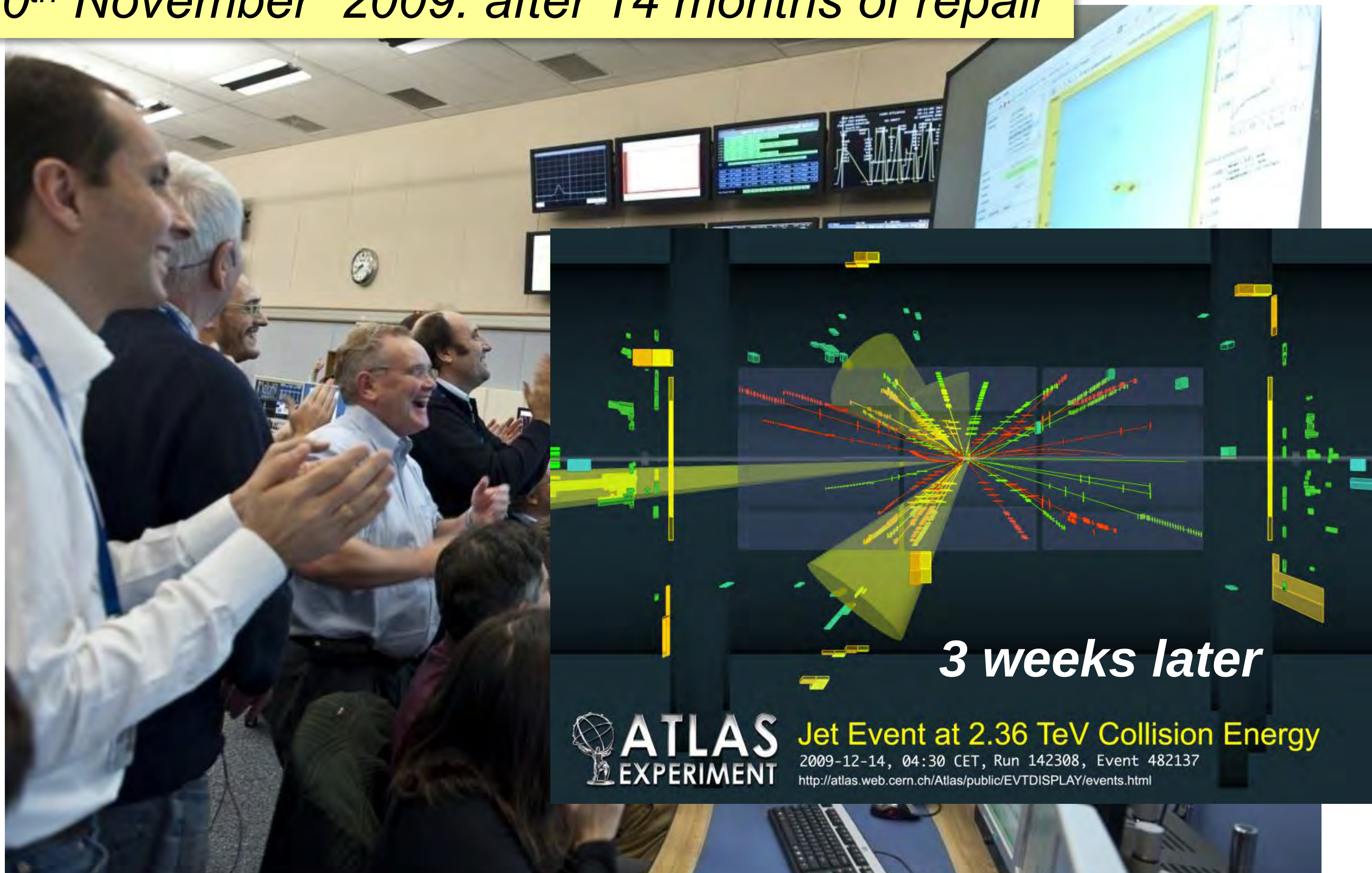
During repair work, inspection of the joints revealed systematic voids caused by the welding procedure.

Energy limitation for Run 1 !!

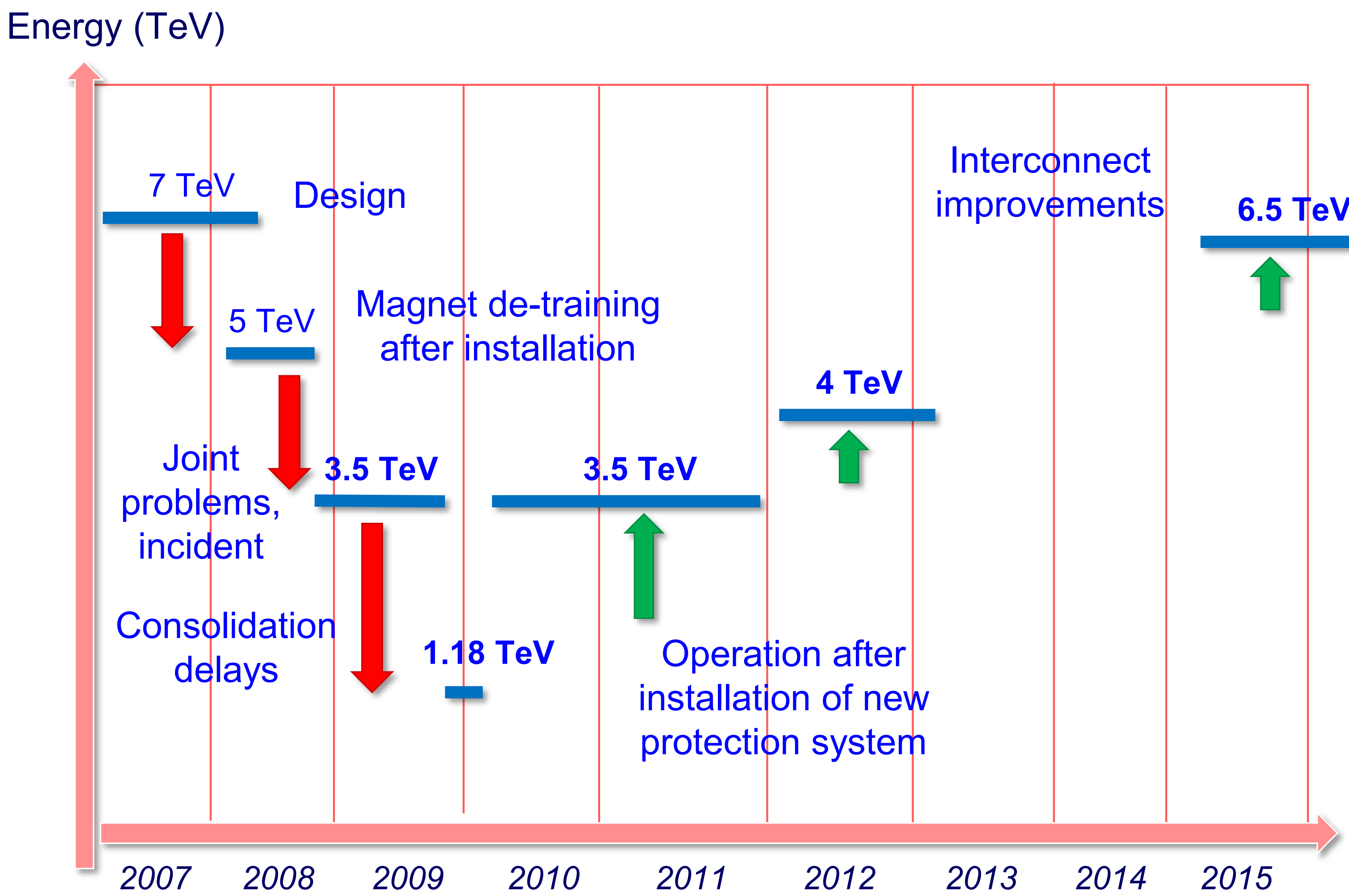
LHC energy evolution



20th November 2009: after 14 months of repair



LHC energy evolution



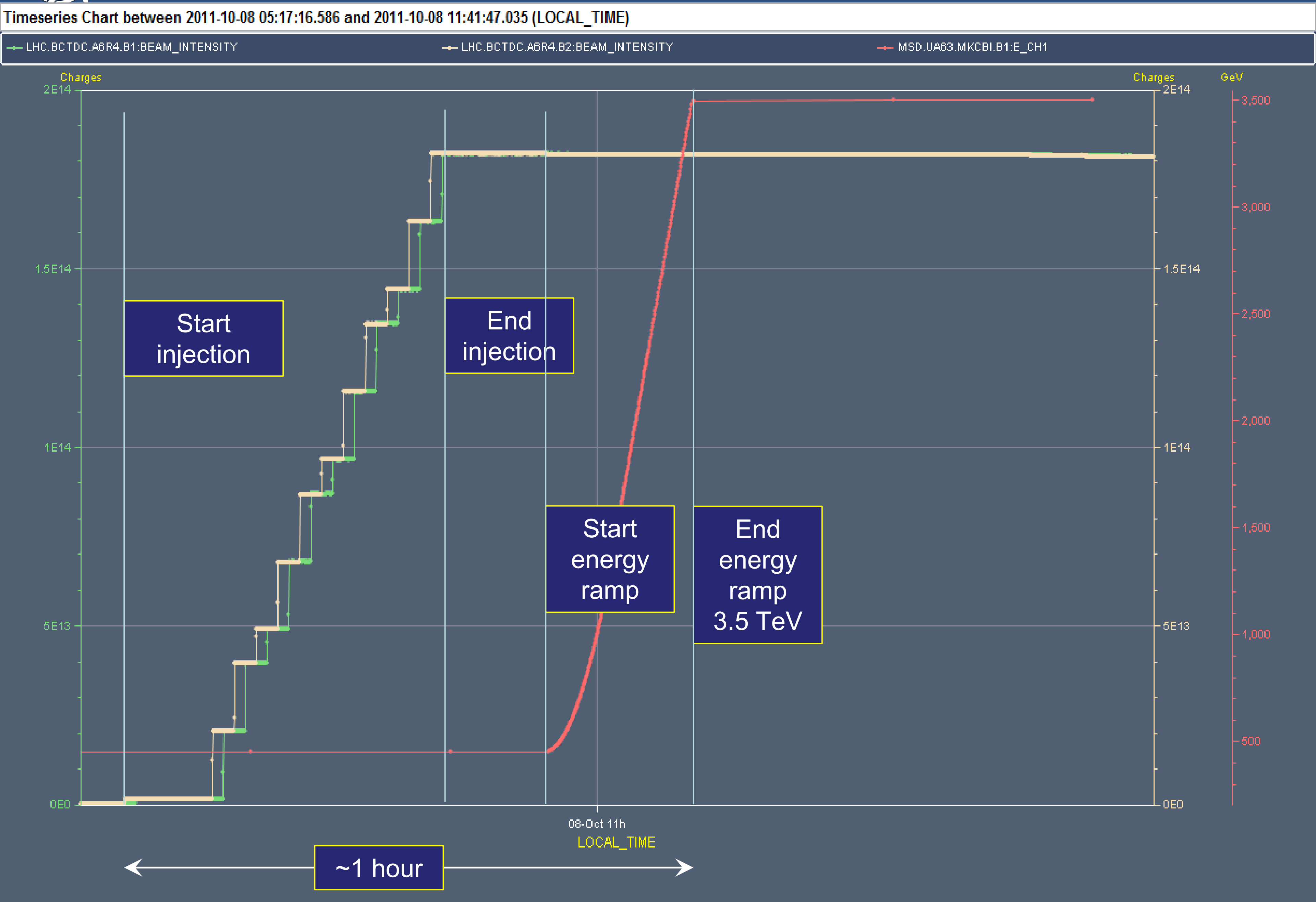
Overview

- Accelerator physics crash course - DONE
- Energy and Luminosity - DONE
- Accelerator physics crash course part II - DONE
- Acceleration and deflection of charged particles - DONE
- Energy and Luminosity Challenges - DONE
- Short Beam Dynamics course - DONE
- Particle Energy and Superconducting Magnets - DONE
- Understanding LHC operation
- Challenges for high intensity beams operation
- Preparing for the next 20 years: HL-LHC, LHC full energy….
- Preparing for the next 50 years: HE-LHC, FCC study…..

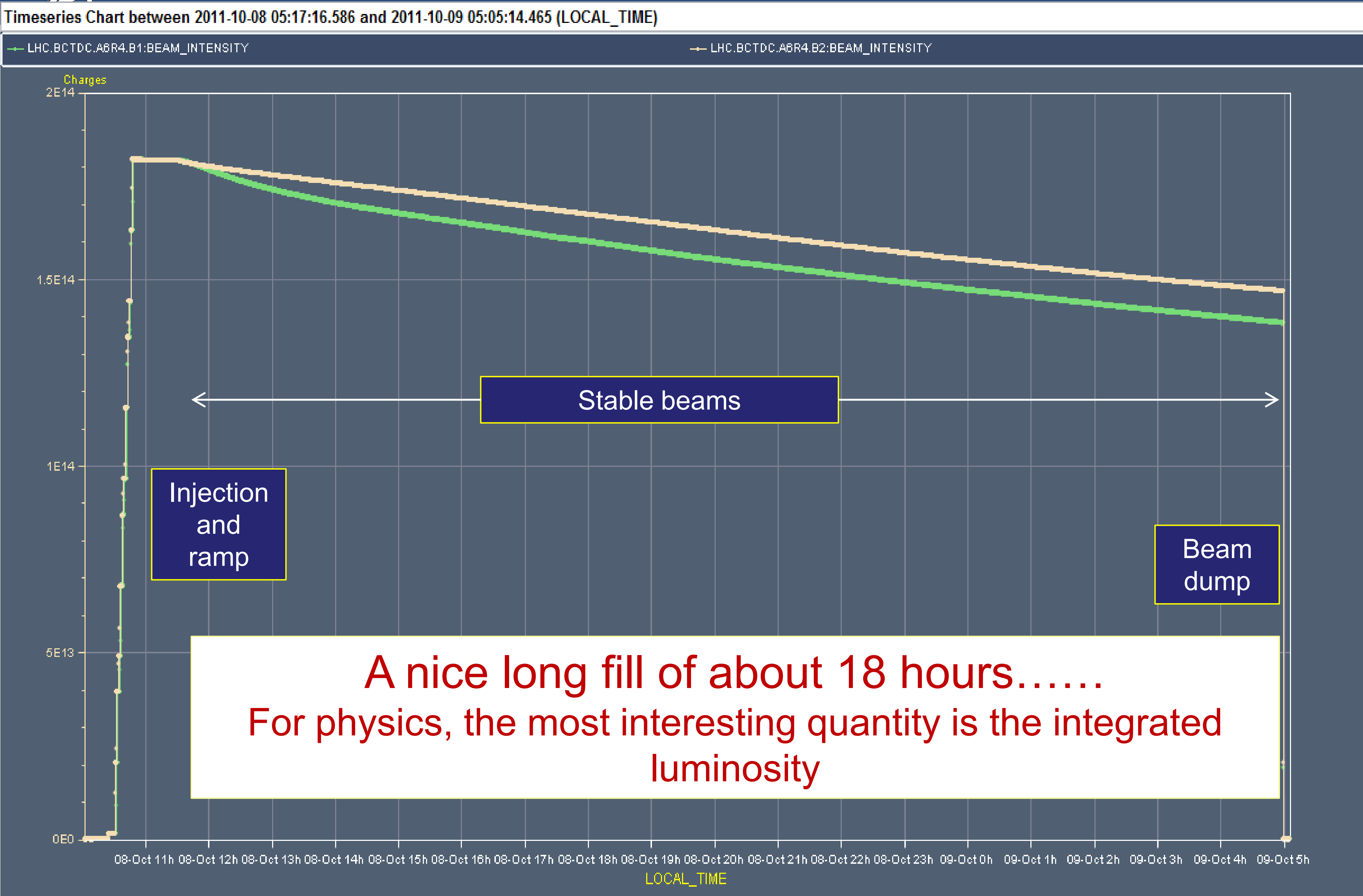
Understanding LHC operation

- Filling
- Ramp
- Squeeze
- Adjust
- Stable beams
- Pilot beam
- Batches
- Closed orbit
- Beta function
- Betatron tunes
- Emittance
- Impedance

Fill 2195 - start of the fill about 1 h (2011)



Excellent fill (2011)



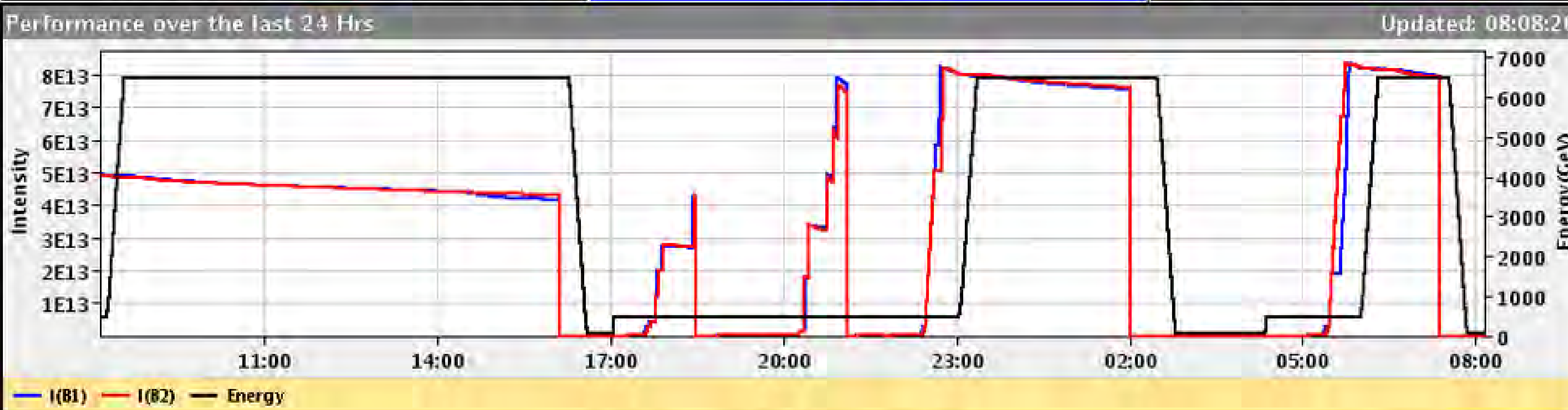
A nice long fill of about 18 hours……

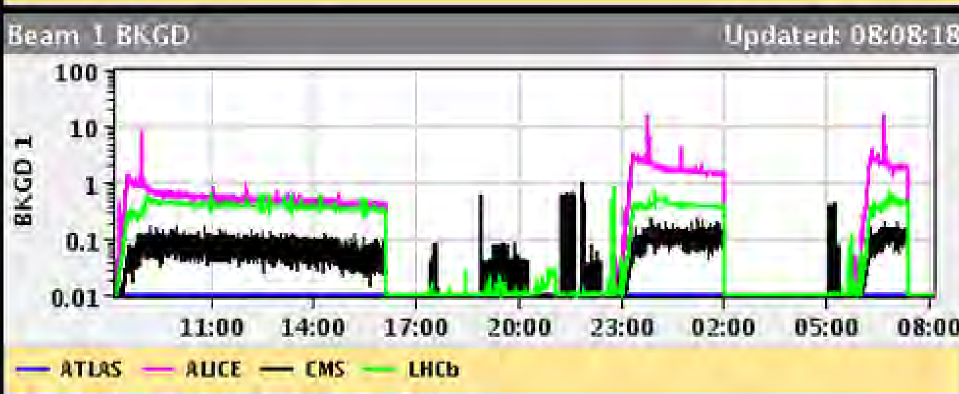
For physics, the most interesting quantity is the integrated luminosity

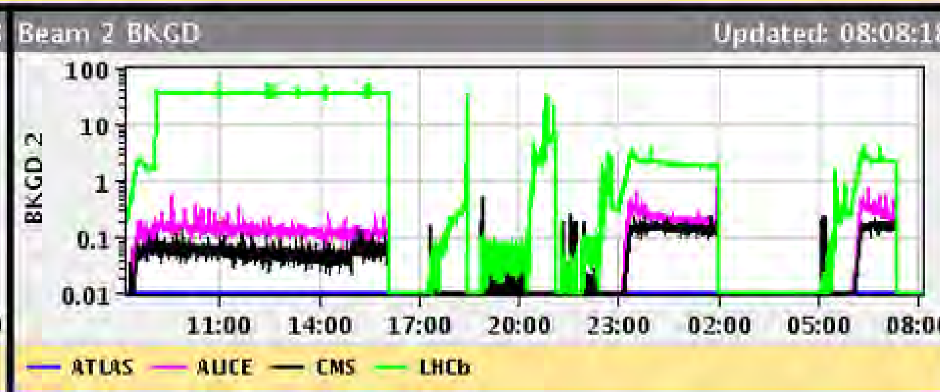
10-Sep-2015 08:08:20 | Fill #: 4343 | Energy: 59 GeV | I(B1): 0.00e+00 | I(B2): 0.00e+00

	ATLAS	ALICE	CMS	LHCb
Experiment Status	CALIBRATION	STANDBY	PHYSICS	CALIBRATION
Instantaneous Lumi [(ub.s)^-1]	0.000	0.000	0.000	0.000
BRAN Luminosity [(ub.s)^-1]	2.8	0.0	0.0	0.0
Fill Luminosity (nb)^-1	0.000	0.000	0.000	0.000
Beam 1 BKGD	0.000	0.000	0.000	0.000
Beam 2 BKGD	0.000	0.000	0.000	0.000

LHCb VELO Position OUT Gap: 58.0 mm | RAMP DOWN | TOTEM: STANDBY







Challenges for high beam intensity operation

Machine Protection and Collimation

Electron clouds

Instabilities

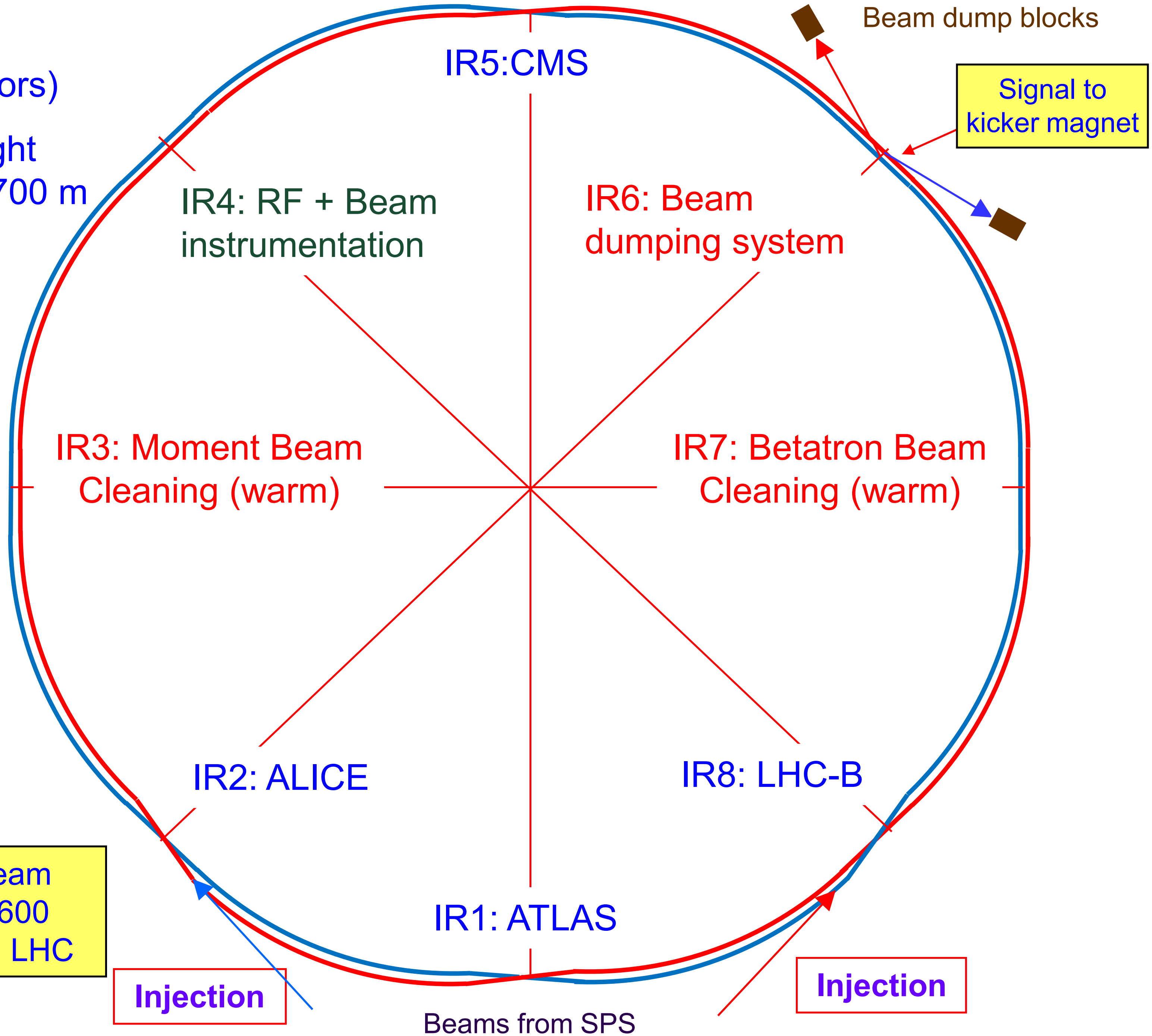
UFOs

Damage of components by em fields from beam

LHC Layout

eight arcs (sectors)

eight long straight section (about 700 m long)



Detection of beam losses with >3600 monitors around LHC

Hydrodynamic tunnelling

In case that the beam is accidentally deflected into a magnet, each bunch will heat the material.

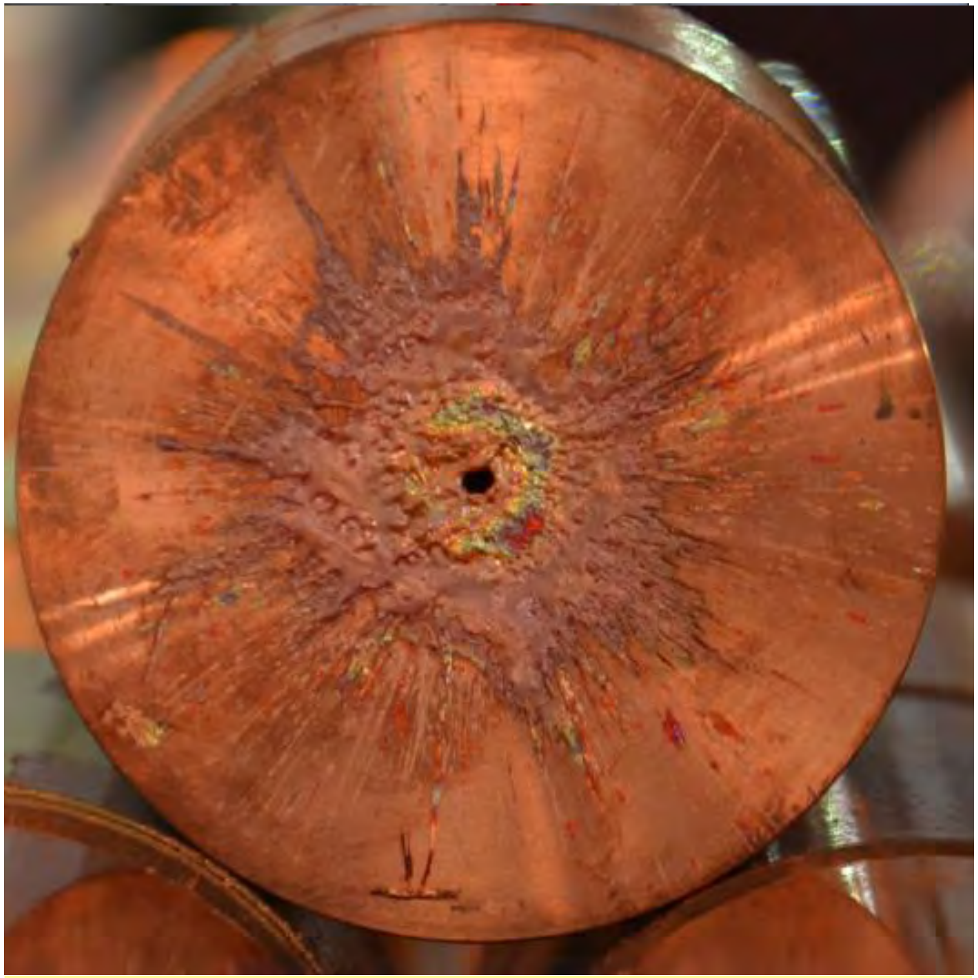
The pressure will build up and the density is reduced.

The following bunches will penetrate deeper into the material.

A controlled experiment was performed at the SPS with a 1 MJ beam, demonstrating hydrodynamic tunnelling.

The penetration for the full beam at LHC is expected to be around 30 m, at FCC (see later) **more than 1000 m**

A single bunch at LHC top energy could drill a hole in the vacuum chamber.



Target damaged by the SPS beam, after penetrating 60 cm of solid copper (~0.5% LHC beam energy)

F.Burkart, N.Tahir et al

Beam losses, machine protection and collimation

Accidental beam losses

"Machine Protection" protects equipment from damage, activation and downtime

Machine protection includes a large variety of systems

Failures are detected, and a extraction kicker deflects the beam into a beam dump block

Continuous beam losses

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

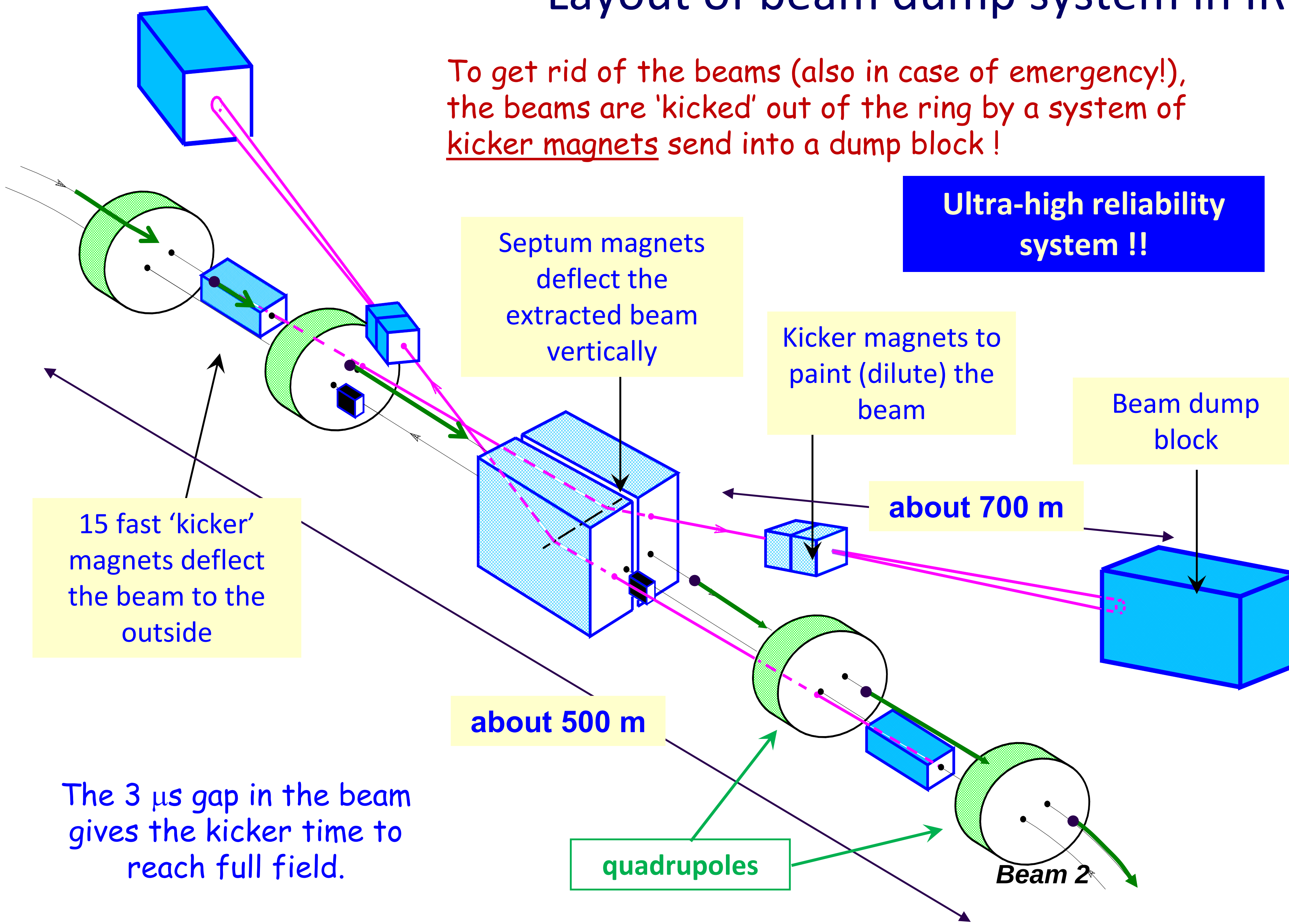
A collimation system is a (very complex) system installed in the LHC to capture mostly halo particles

Such system is also called (beam) Cleaning System

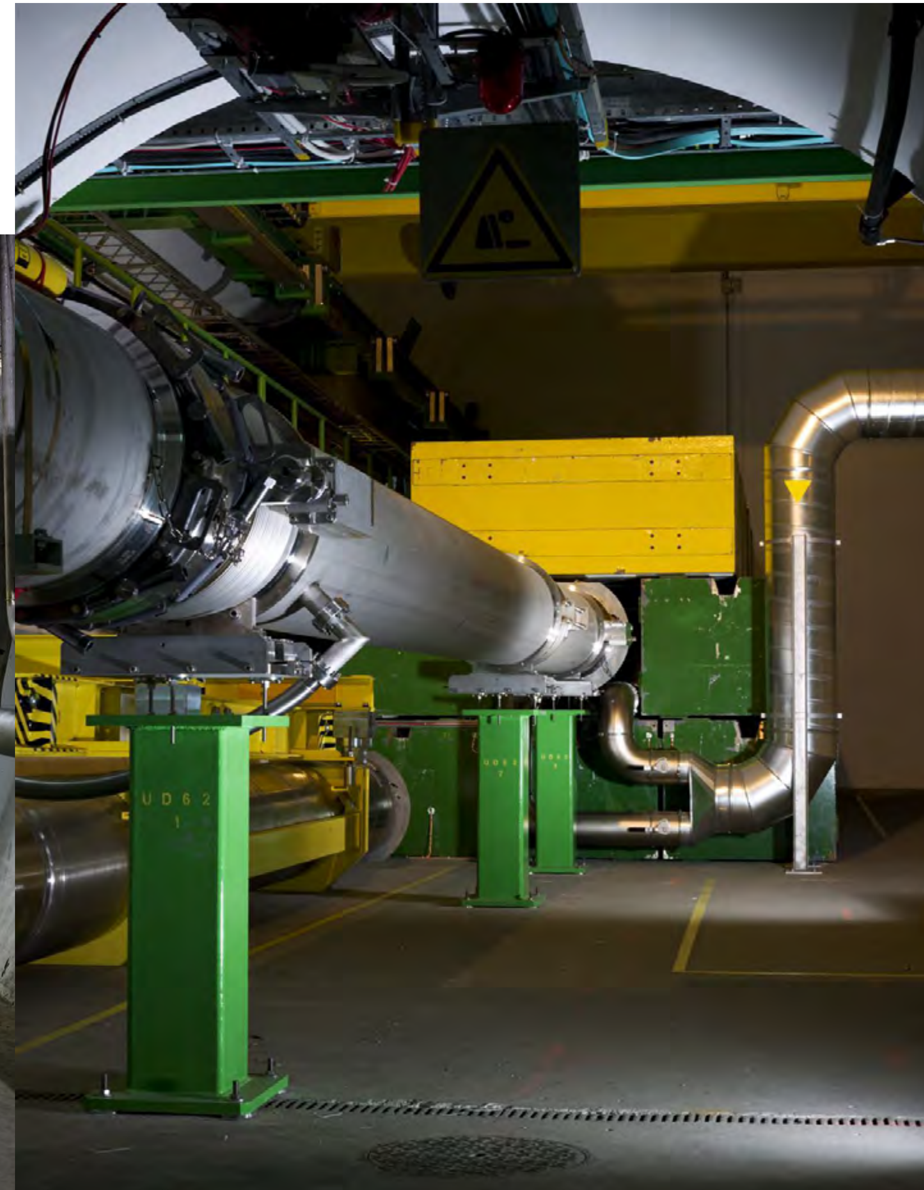
Layout of beam dump system in IR6

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

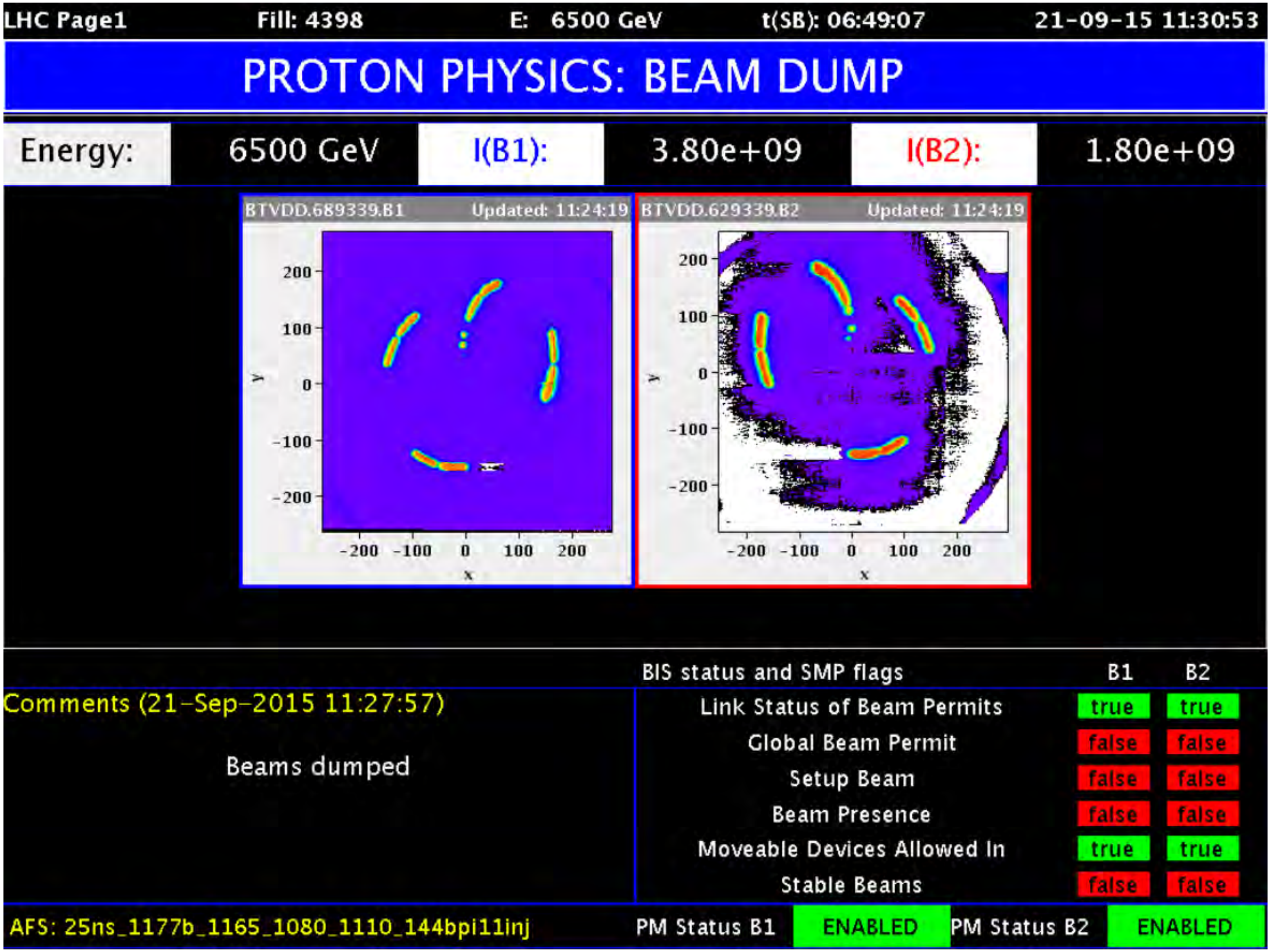
Ultra-high reliability system !!



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

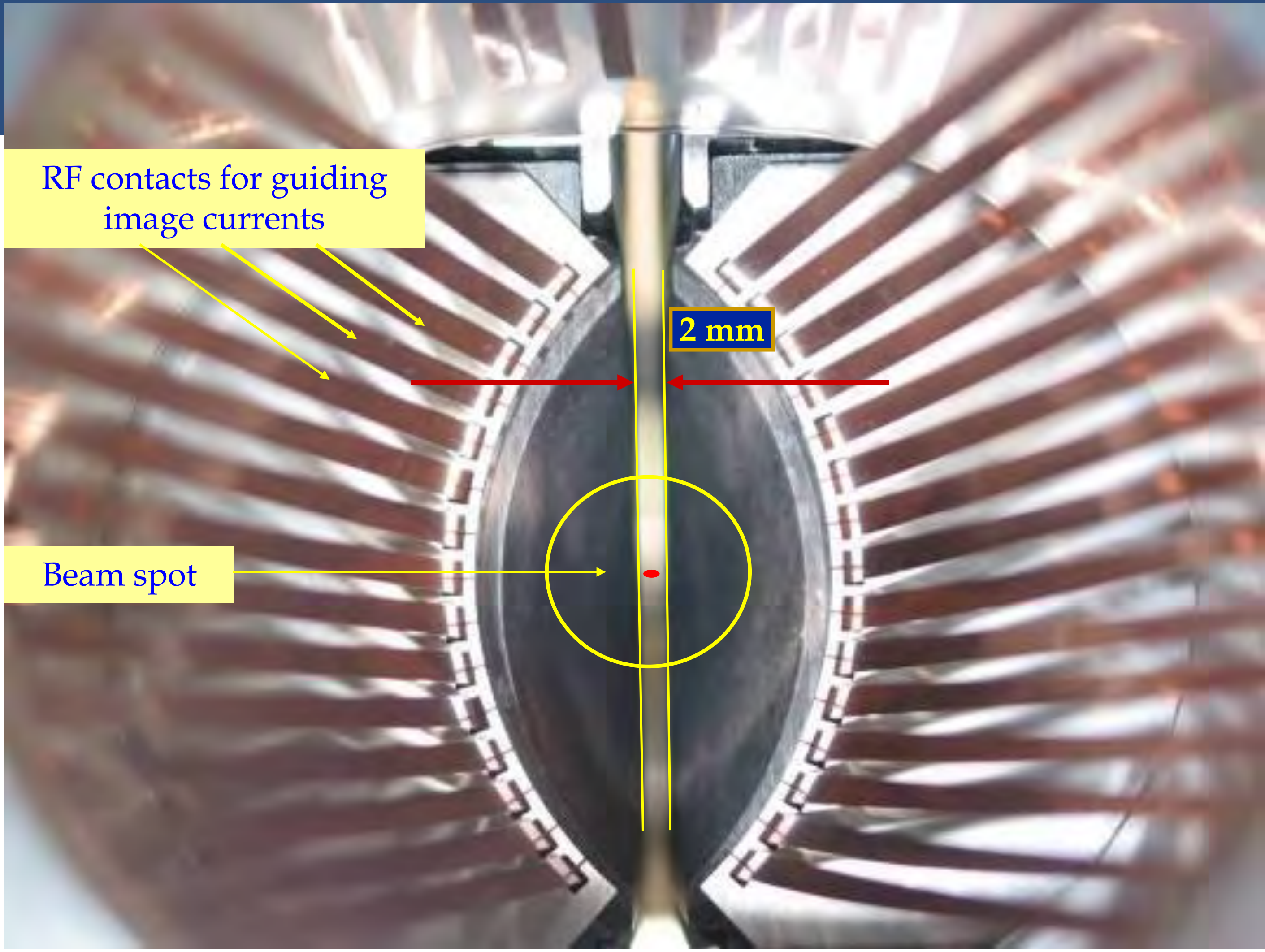

U D 6 2

Beam dump with 1380 bunches



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

View of a two sided collimator



about 100 collimators are installed in LHC

Betatron beam cleaning

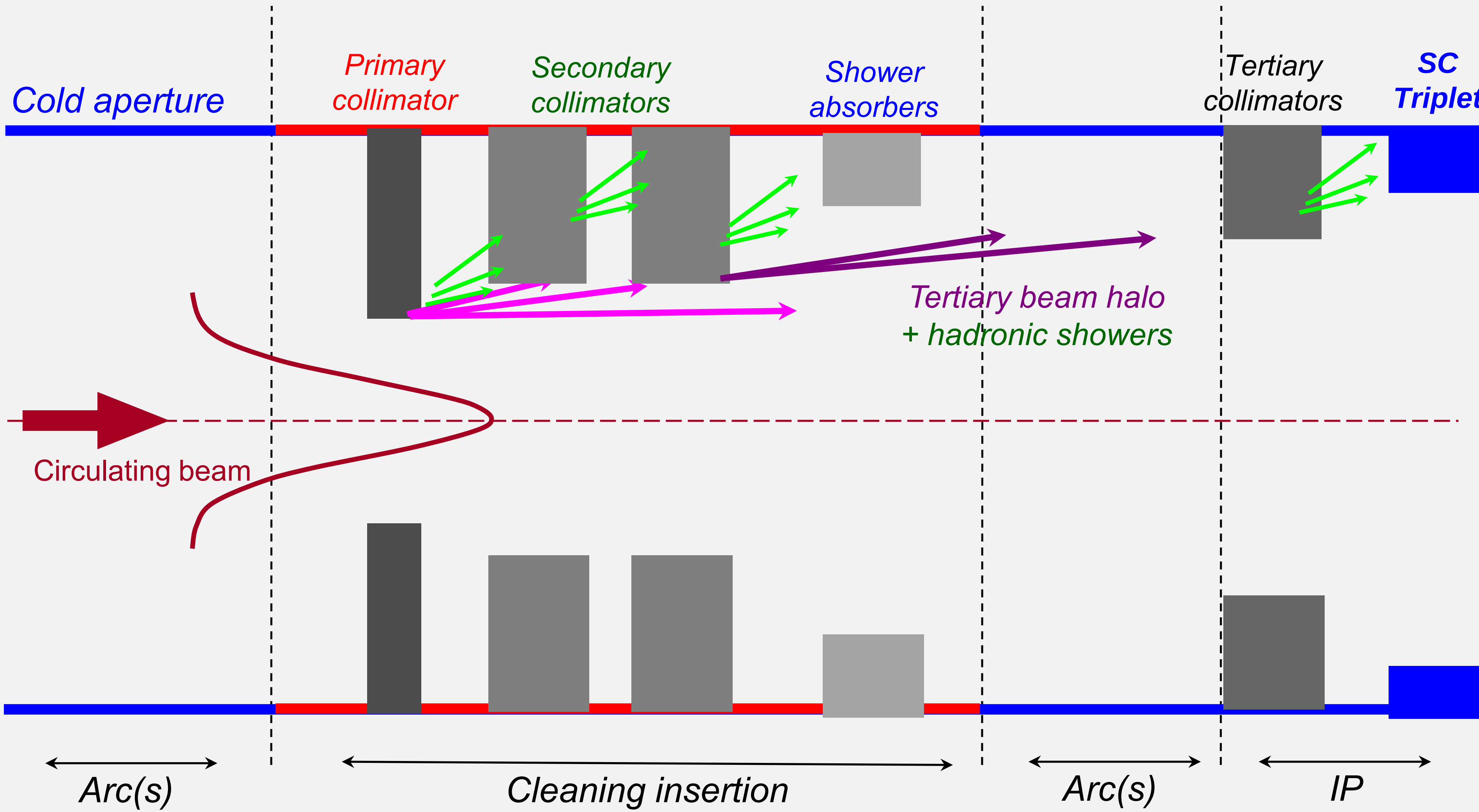
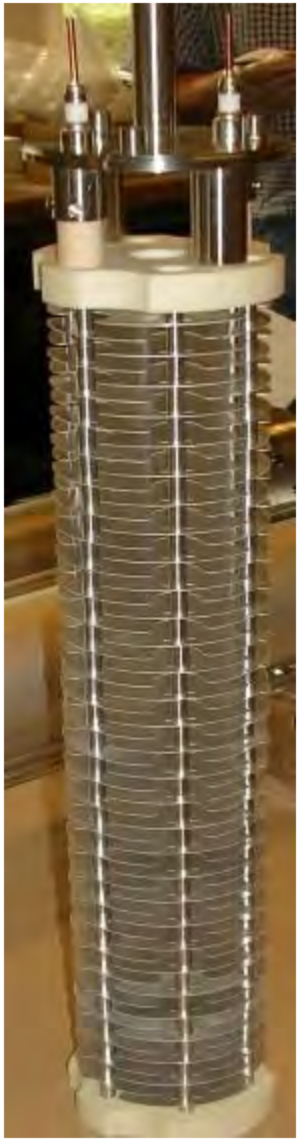
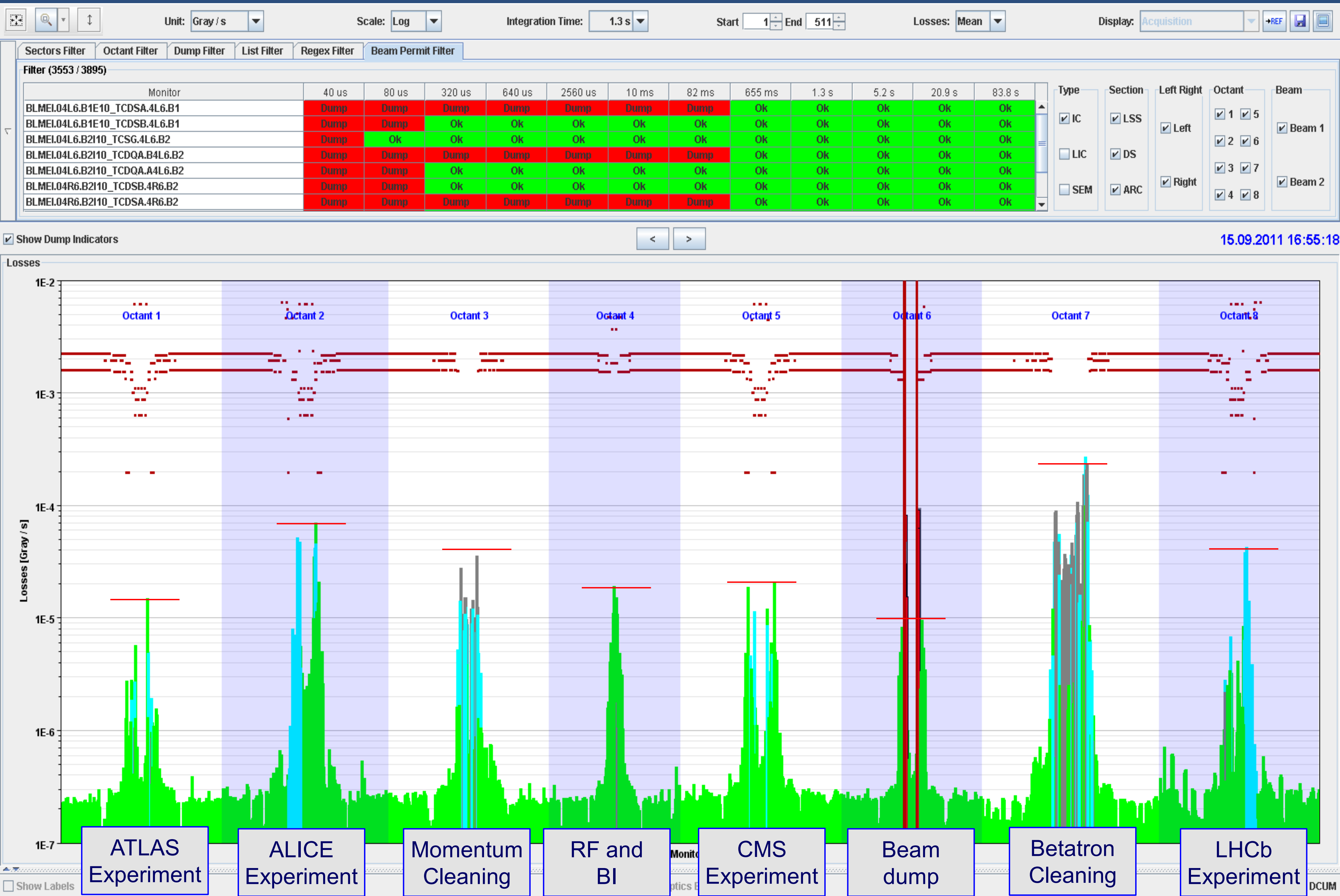


Illustration drawing

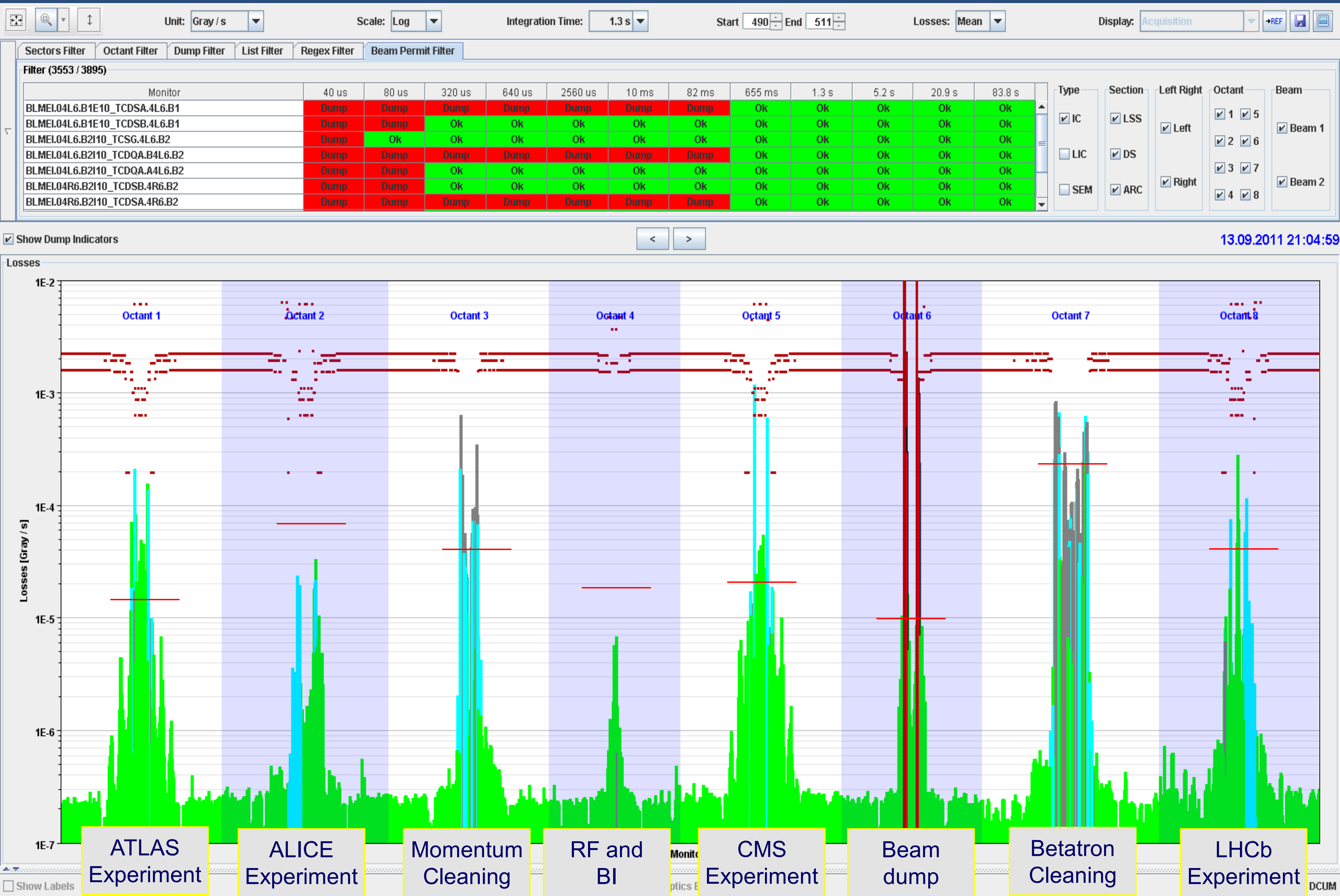
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!



BLM system: beam losses before collisions



Continuous beam losses during collisions



Accidental beam losses during collisions

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

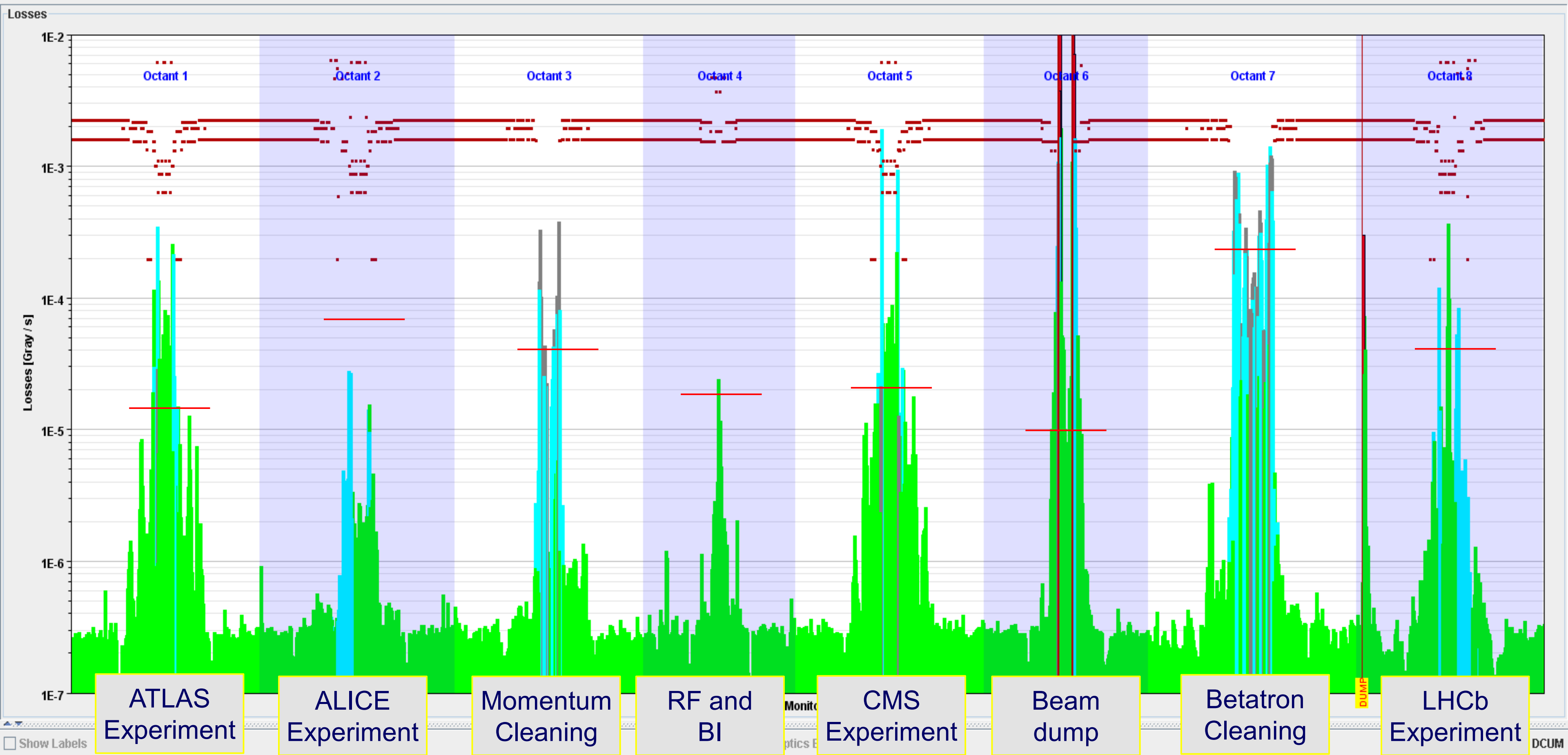
Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

Filter (3550 / 3892)

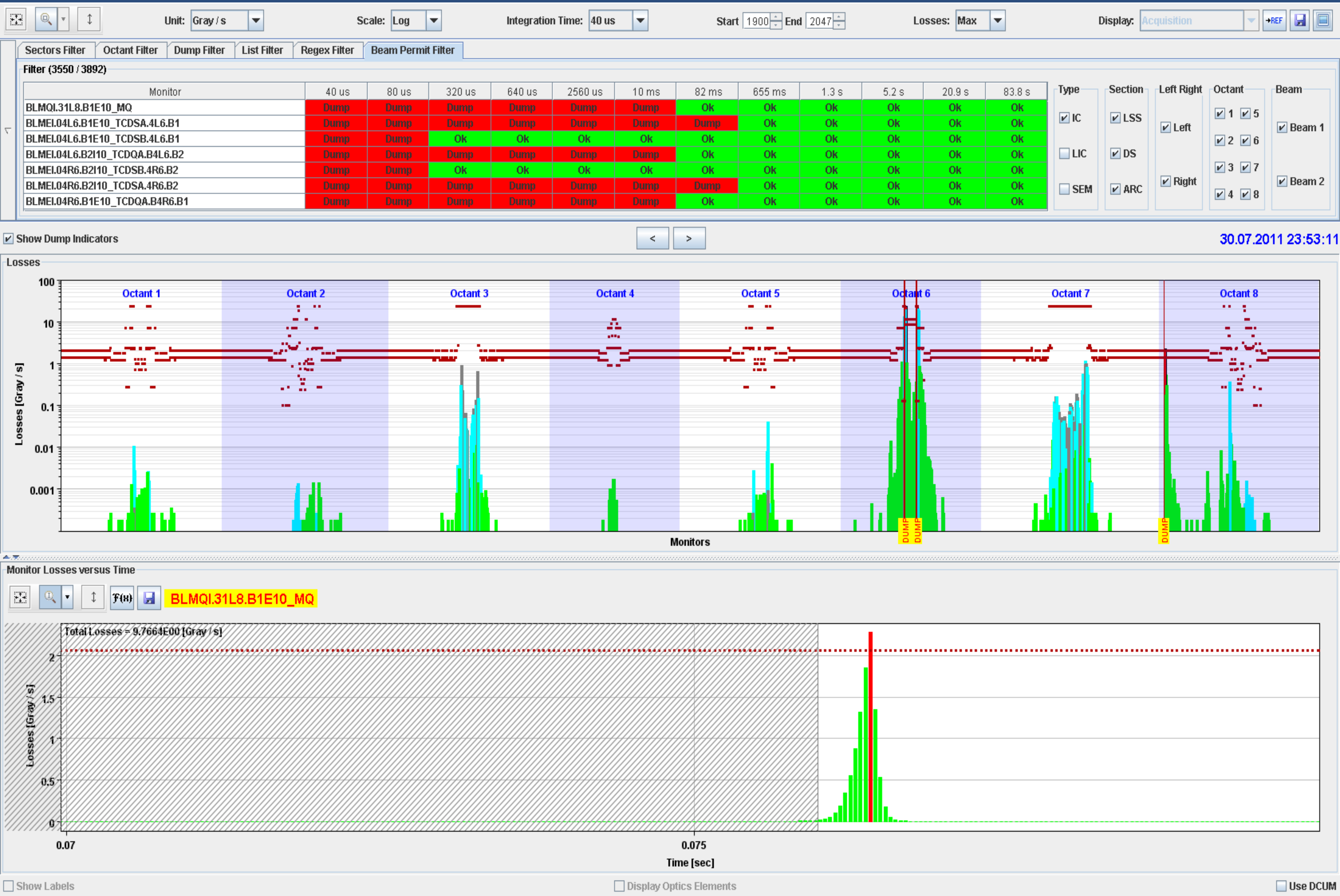
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	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, 2, 3, 4, 5, 6, 7, 8 | Beam: Beam 1, Beam 2

Show Dump Indicators | 30.07.2011 23:53:11



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

UFOs at LHC

Surprising 'Unidentified Falling Objects'

Very fast localized beam losses are observed when the LHC beam intensity is increased.

The beam losses were traced to **dust particles entering into the beam** – '**UFO**'.

Losses too high => beams dumped to avoid a quench, but sometimes magnets quench

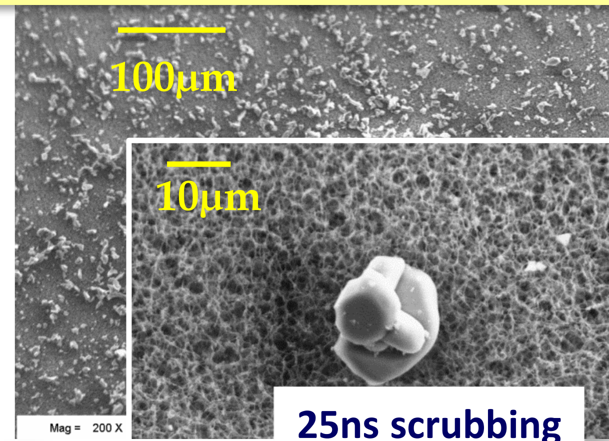
2015: **2 UFO quenches** (vs. **>10 beam dumps** due to UFOs in the arc + 2 in LSS).

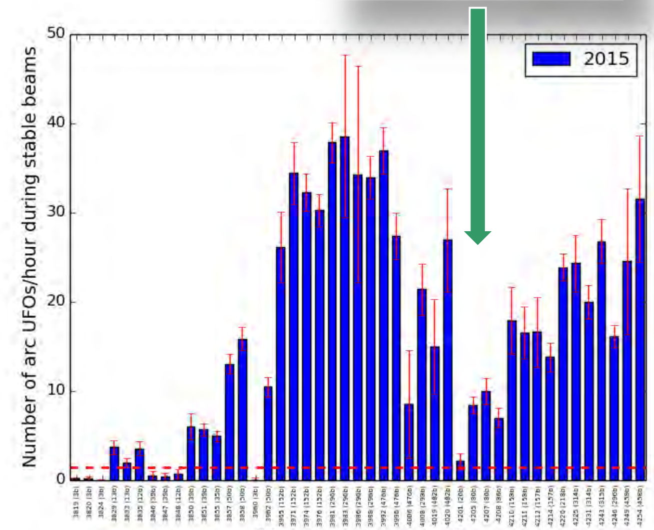
2017: **2 UFO quenches** and **17 UFOs induced beams dumps**.

Loss monitor thresholds were adjusted to balance the risk of spurious dumps and the need for quench prevention in 2015 and 2016 – still ongoing.

A clear conditioning has been observed along the year

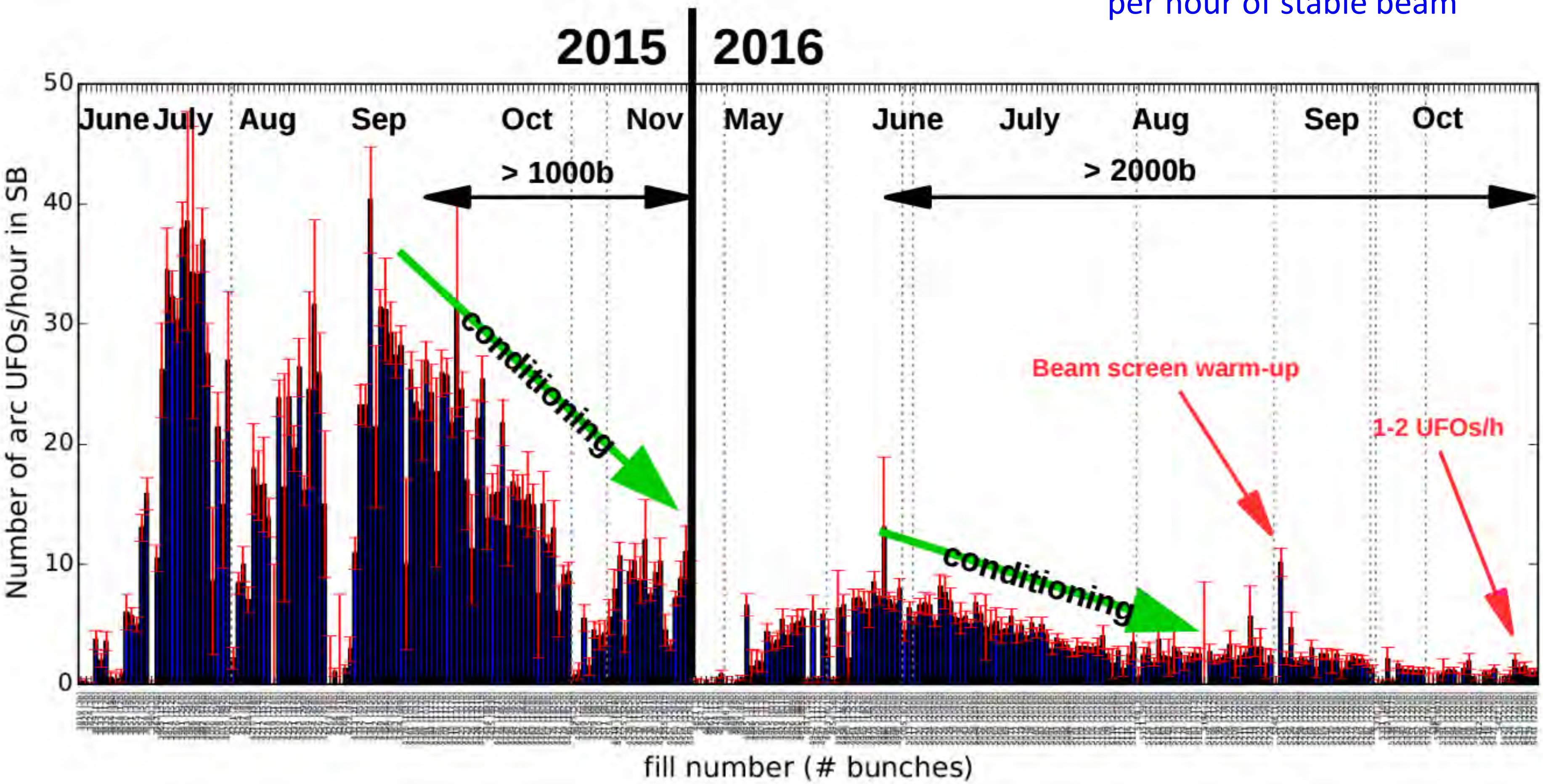
In one accelerator component UFOs were traced to Aluminum oxide particles.





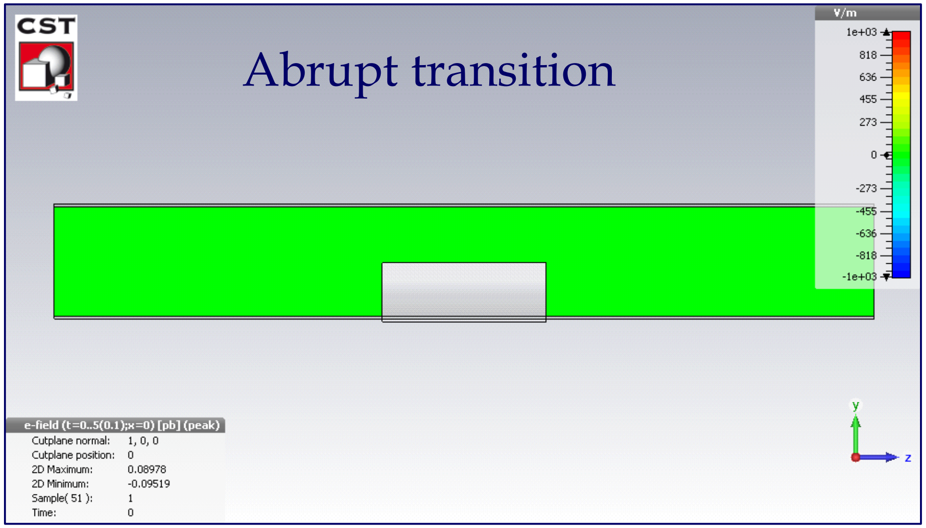
A steady conditioning is observed on the UFO rate.

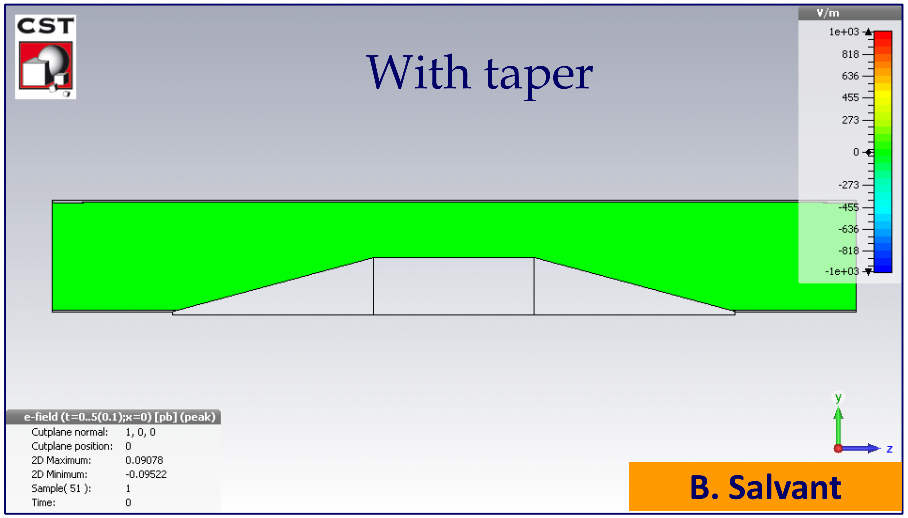
Number of arc UFOs (cells ≥ 12) per hour of stable beam



Wake fields and Impedances Challenge

- Intense bunches generate electromagnetic fields when passing inside a structure (in particular Carbon collimators – opening of ~1 mm!!!)
- → results in an EM force, called wake field in time domain coupling with the beam

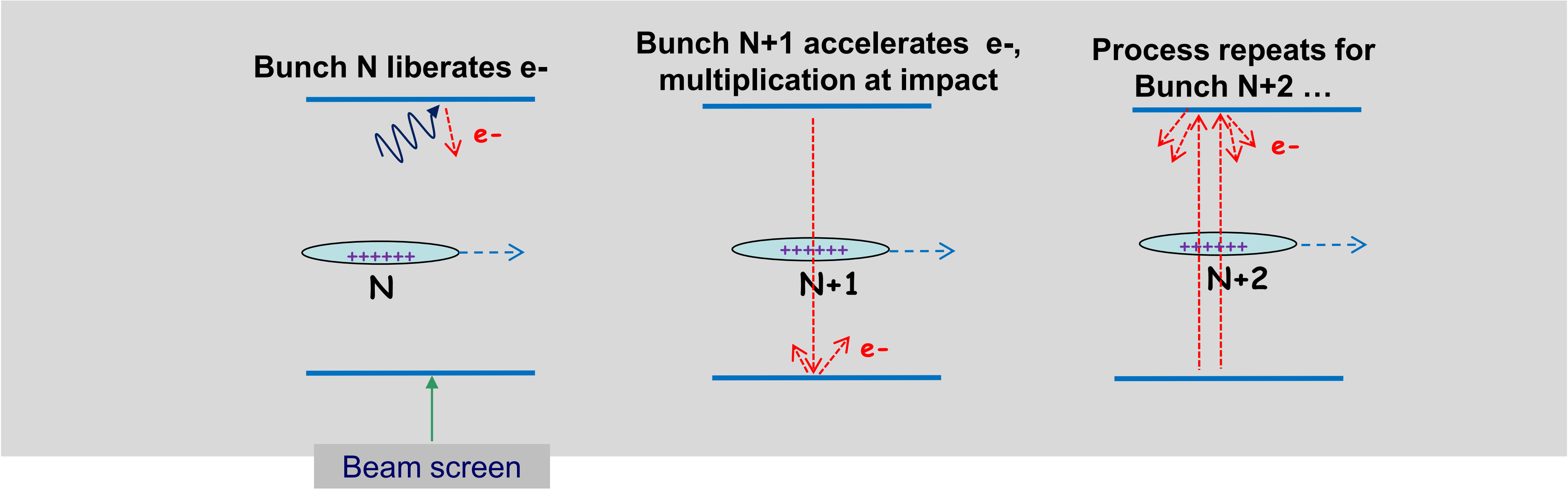




- Avoid the abrupt transition for the beam fields at the location of the beam passage (taper)
- Reduce the resistivity of the material

Electron cloud challenge

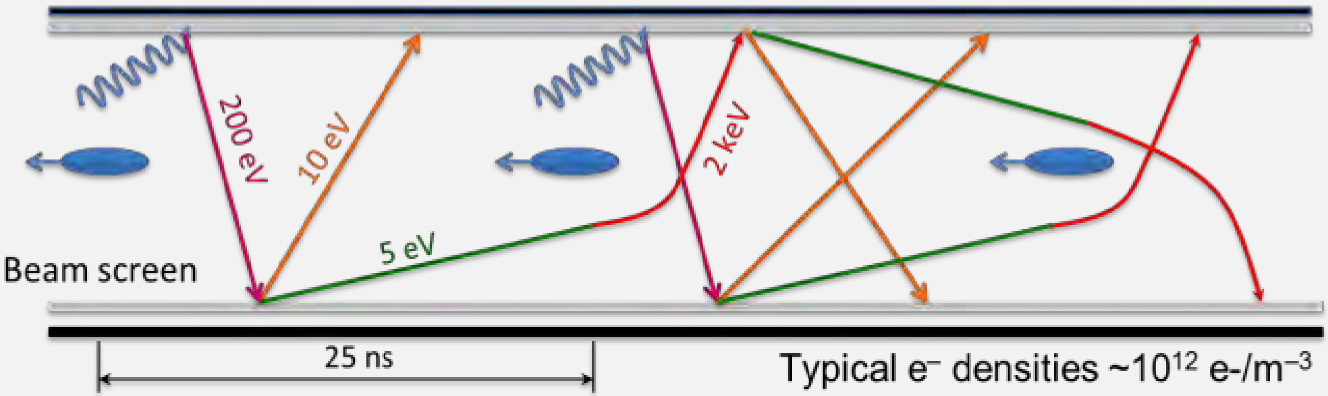
In high intensity accelerators with positively charged beams and closely spaced bunches, electrons liberated on vacuum chamber surface can multiply and build up a cloud of electrons.



The cloud triggers vacuum pressure increases and beam instabilities!

Electron energies are in the 10 to few 100 eV range.

Electron cloud effects



Secondary emission yield [SEY]

- SEY>SEY_{th} ➔ avalanche effect (multipacting)
- SEY_{th} depends on bunch spacing and population

Possible consequences:

- instabilities, emittance growth, desorption, vacuum degradation, background
- excessive energy deposition in the cold sectors – cooling limit

Electron bombardment of a surface has been proven to reduce **secondary electron yield (SEY)** of a material as a function of the delivered electron dose. This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up.

Electron cloud mitigation

Strong reduction of e-clouds with larger bunch spacing:

With **50 ns spacing** e-clouds are **much weaker** than **with 25 ns** !

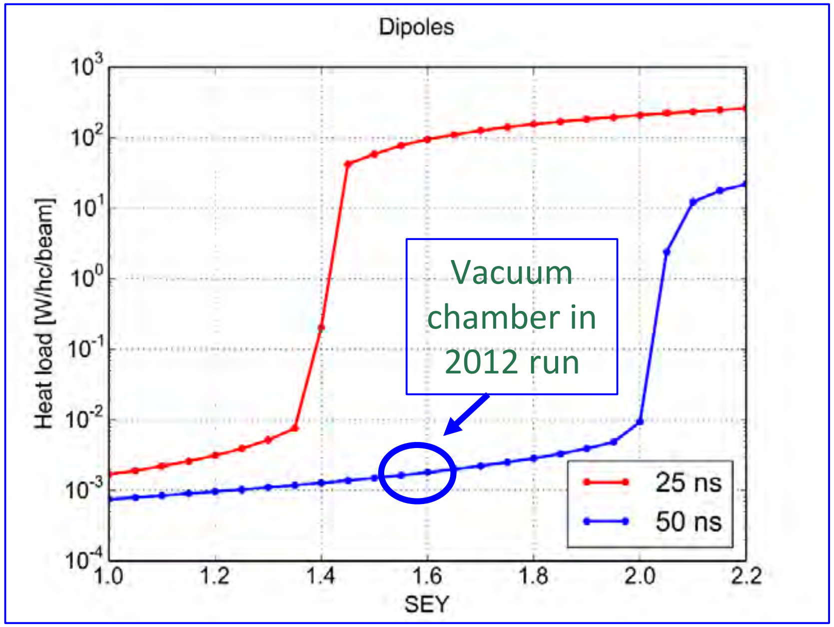
→ One of the main reason to operate in 2012 with 50 ns spacing

Remedy: conditioning by beam-induced electron bombardment ("scrubbing") leading to a progressive reduction of the SEY (Secondary Electron Yield).

- Done at 450 GeV where fresh beams can be injected easily.
- Now, after some years of operation, operation with 25 ns bunch spacing is possible

Electron cloud mitigation

- Strong dependence of e-clouds on bunch spacing.



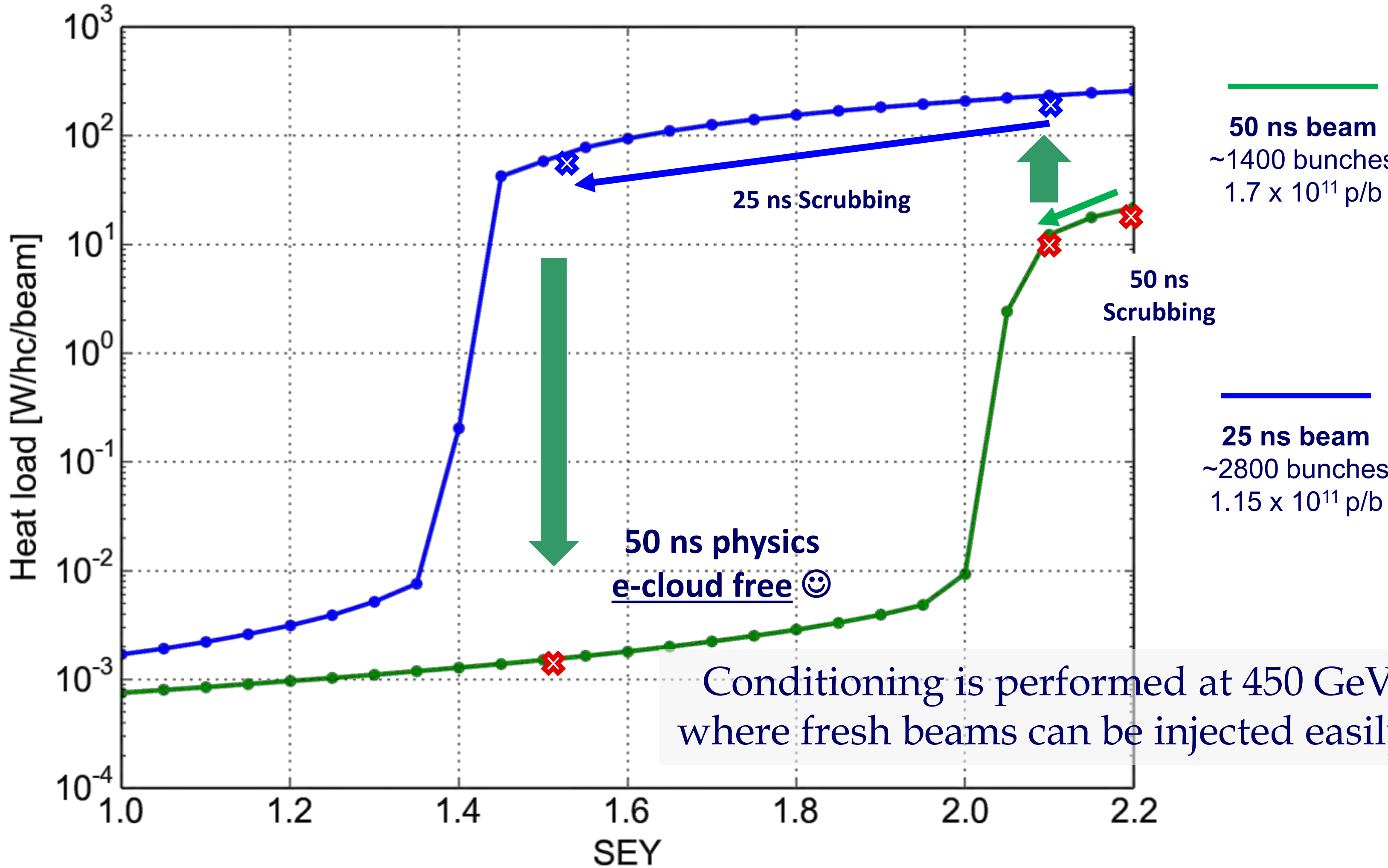
With 50 ns spacing e-clouds are much weaker than for 25 ns spacing !

→ To ease life during Run 1, bunch spacing was reduced to 50 ns

- Conditioning of the vacuum chamber by beam-induced electron bombardment (“scrubbing”): progressive reduction of the SEY

Scrubbing for 50 ns operation

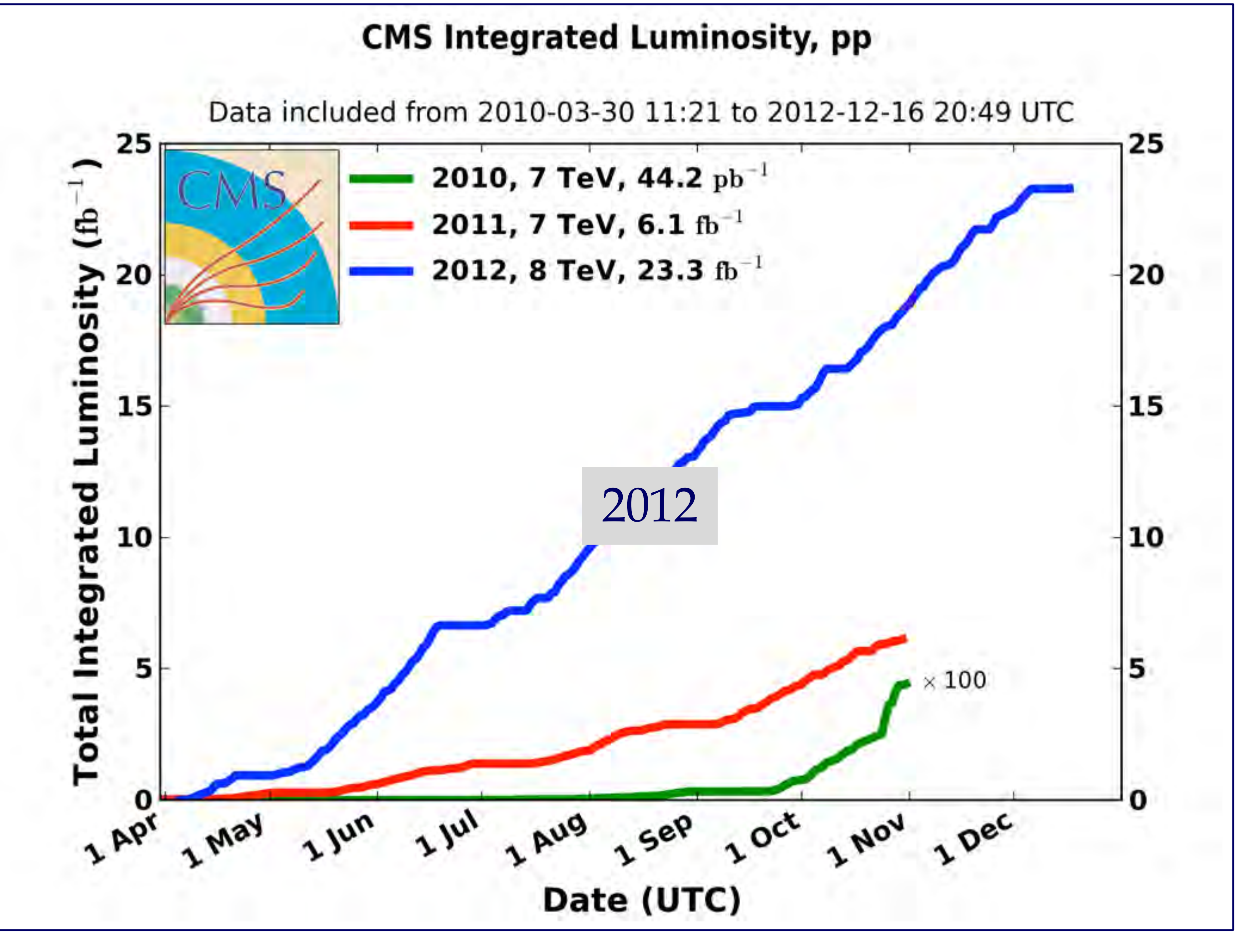
During the first scrubbing run for 50 ns operation, a 25 ns beam is used to condition the vacuum chamber.



Conditioning is performed at 450 GeV where fresh beams can be injected easily.

Overall performance during Run 1 (2010-2012).....

Integrated luminosity 2010-2012

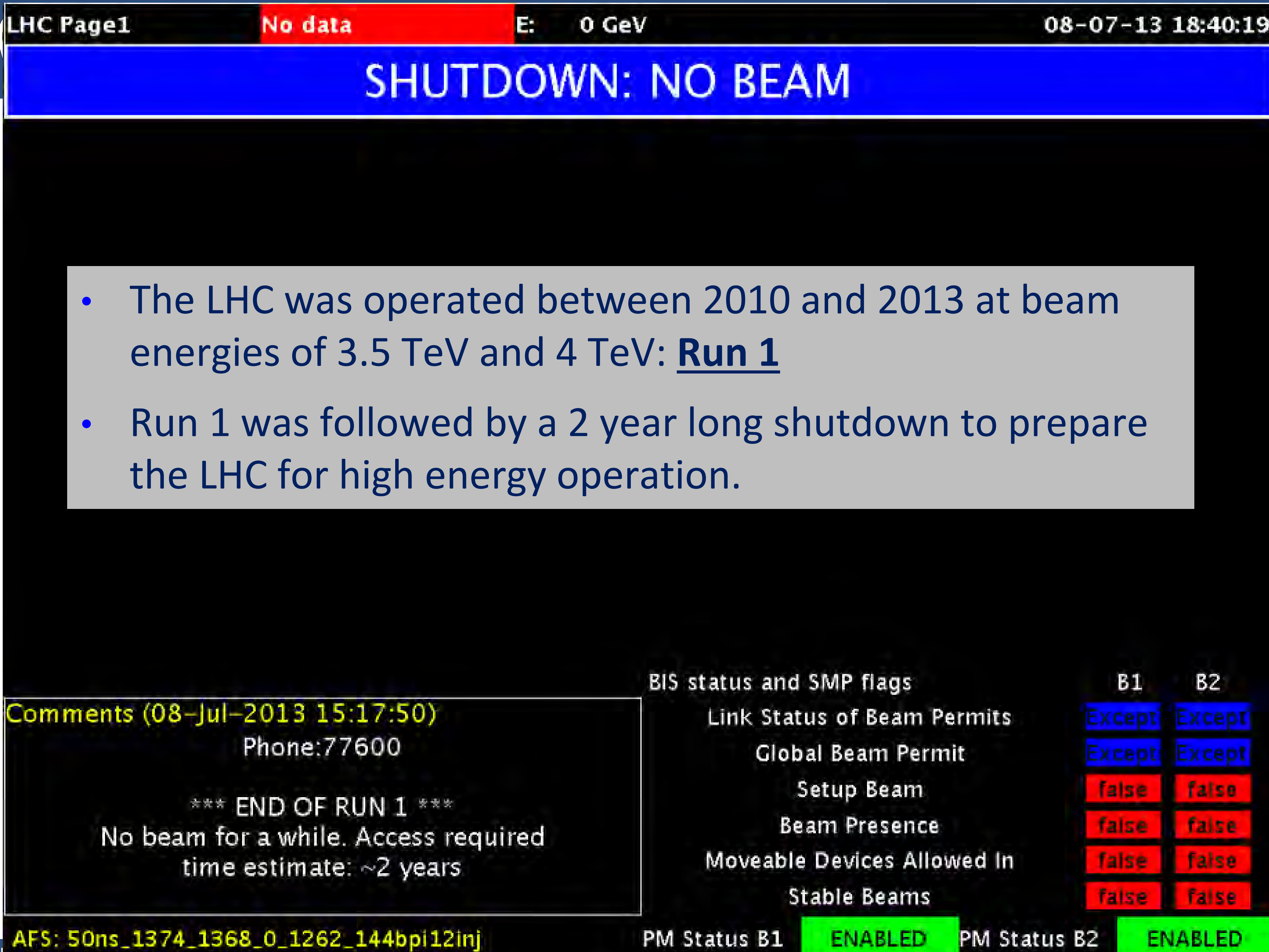


- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

What we learned during LHC Run 1.....

- It was required to limit the maximum energy
- Very high luminosity can be achieved
- Instabilities were observed and are not fully understood
- High-intensity operation close to beam instability limits
- UFOs and electron cloud effects need to be watched
- Availability was ok, but need to be further considered

- The LHC was operated between 2010 and 2013 at beam energies of 3.5 TeV and 4 TeV: **Run 1**
- Run 1 was followed by a 2 year long shutdown to prepare the LHC for high energy operation.



From 2013 to 2015 …and beyond

2013-2015: consolidation (interconnects, others)

2015…..2018: proton and ion operation at 6.5 TeV

Operate with 25 ns bunch spacing (50 ns spacing not favoured due to event pile-up)

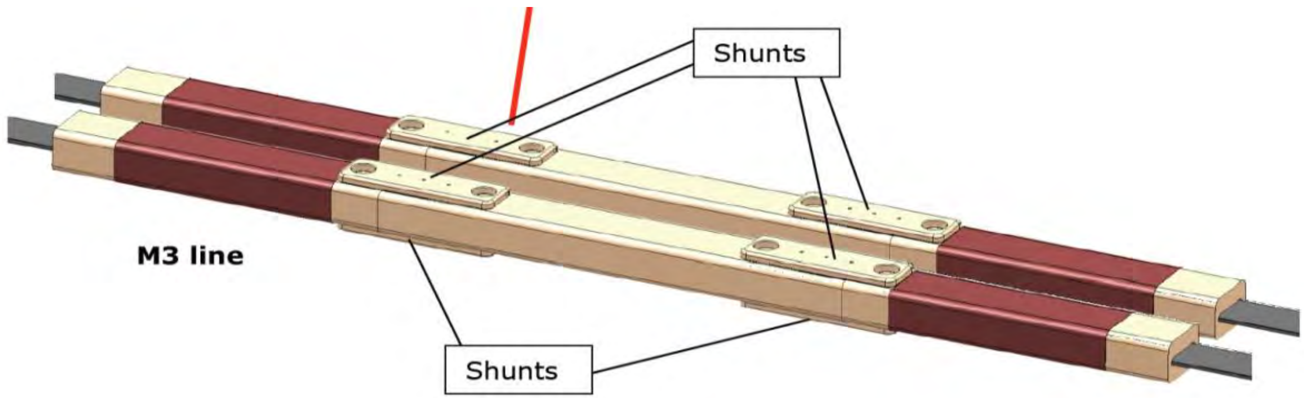
Maximize the integrated luminosity

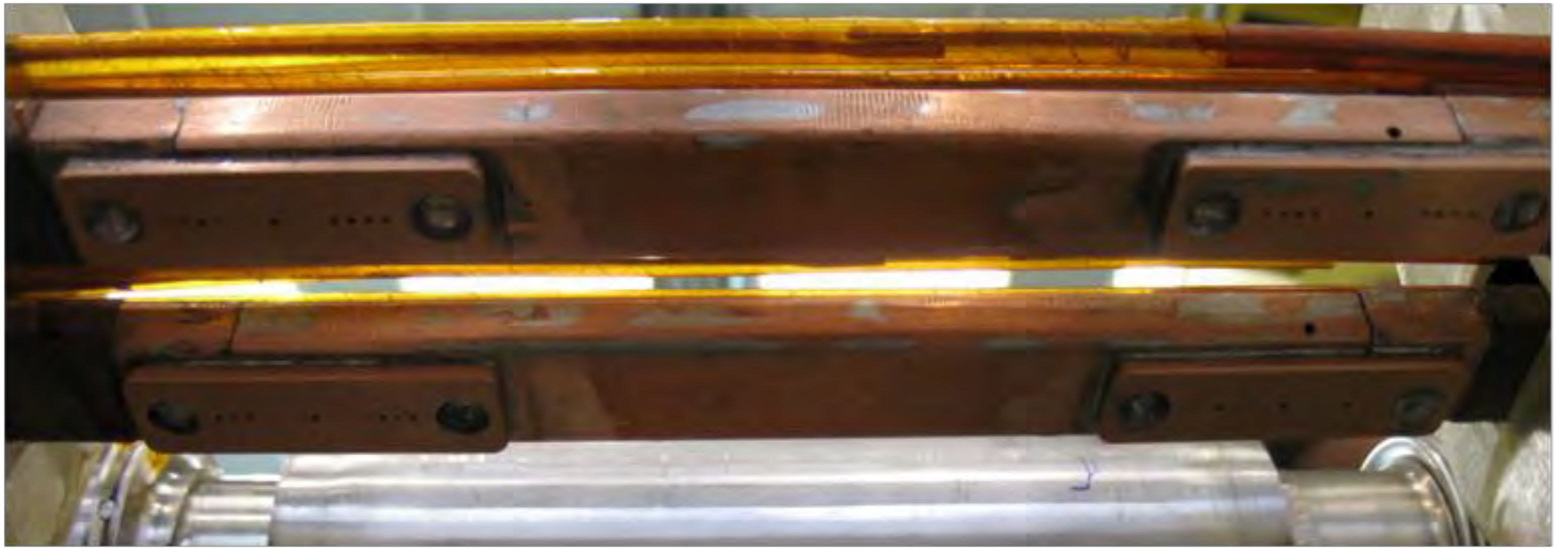
Small focusing – β* as small as possible

Highest possible efficiency

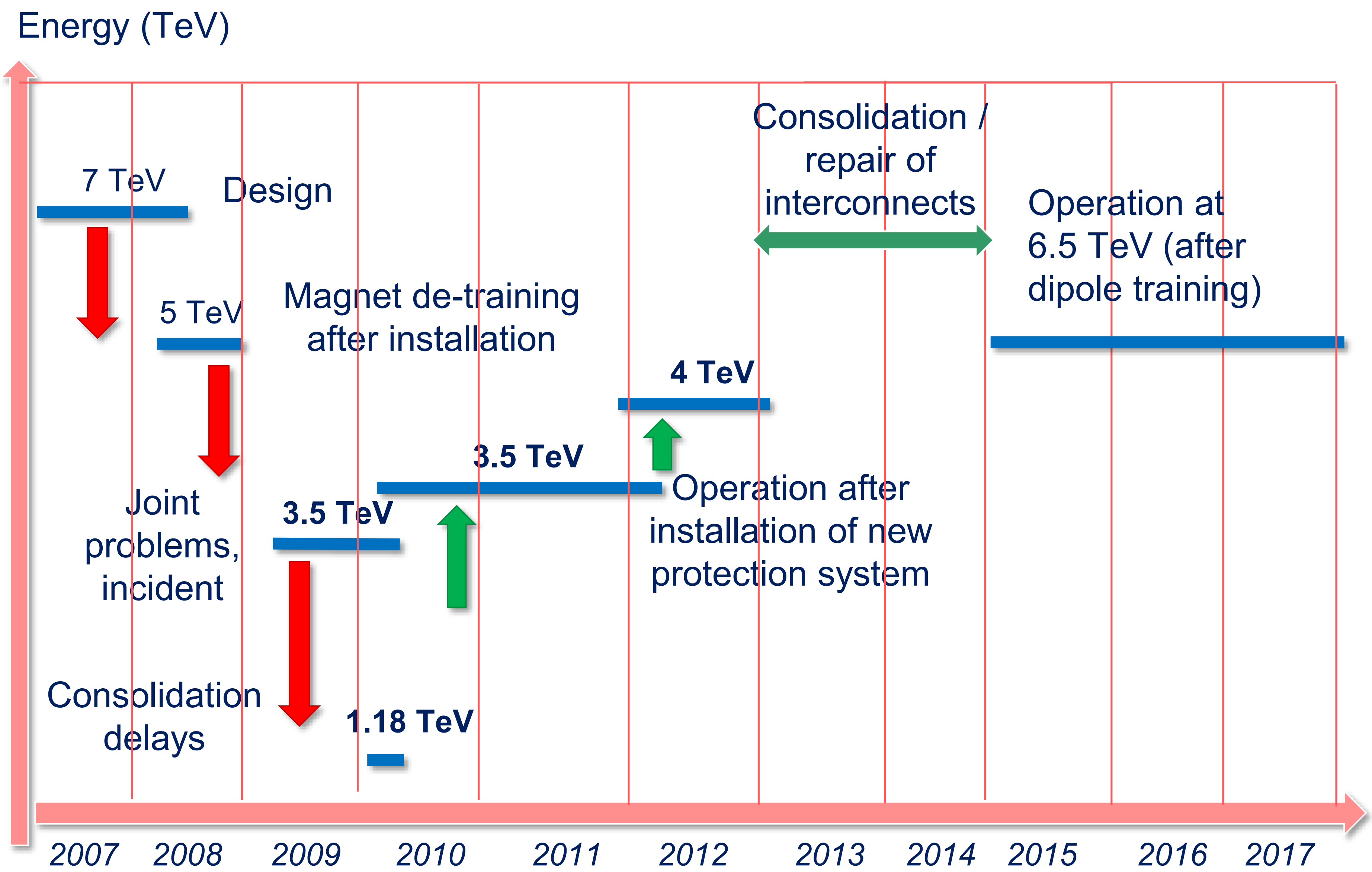
Preparing for nominal energy

Around 10000 high current magnet interconnections were checked and partially redone.



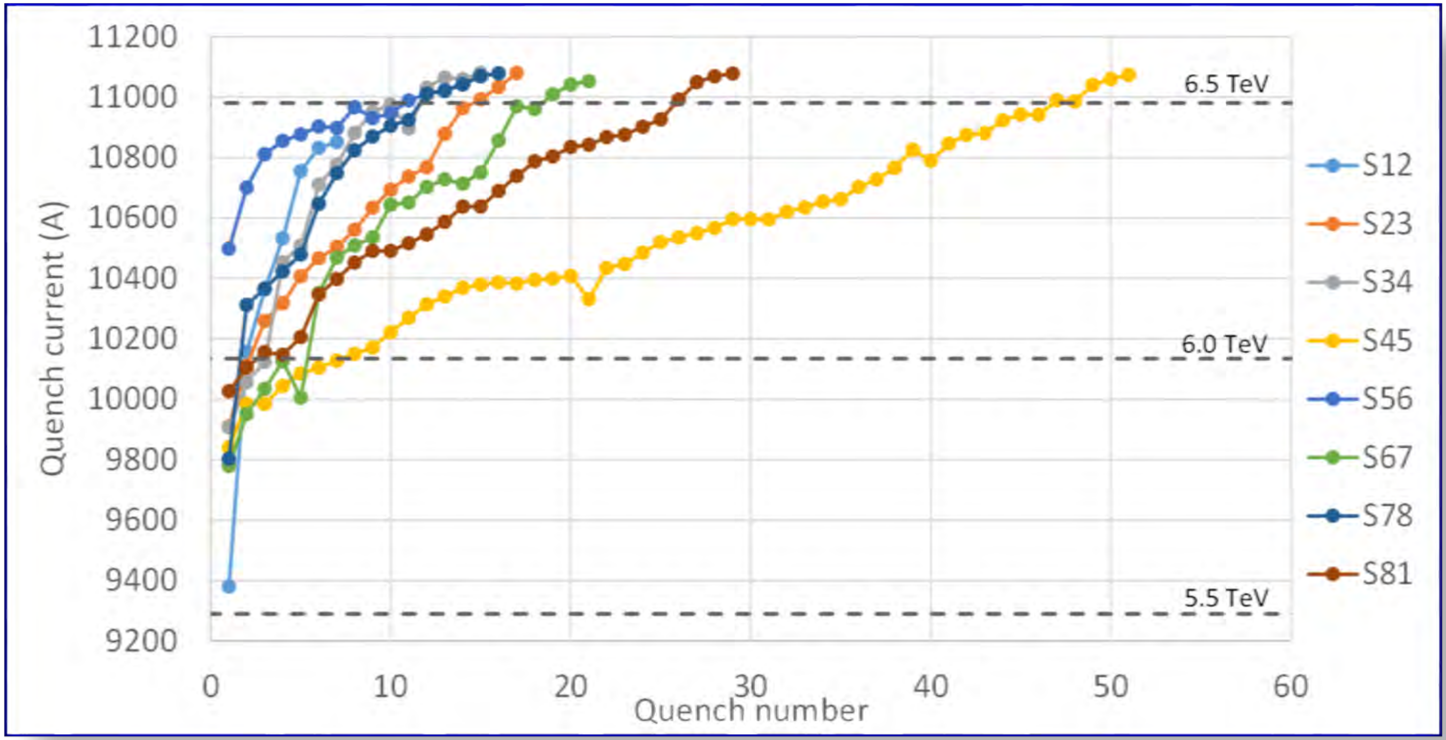


LHC energy evolution



Dipole training campaign

- The 1232 main dipole magnets had to be trained for 6.5 TeV operation.
  - 2-3 training quenches could be performed for each sector in 24 hours, limited by the recovery time of the cryogenic system.
  - About 150 training quenches were required.
- The large spread in number of quenches between the eight sectors (arcs) is due to the mixture of magnets from the 3 producers.
- Training quenches are due to frictional energy from coil movements.



8 LHC sectors (~ arcs)

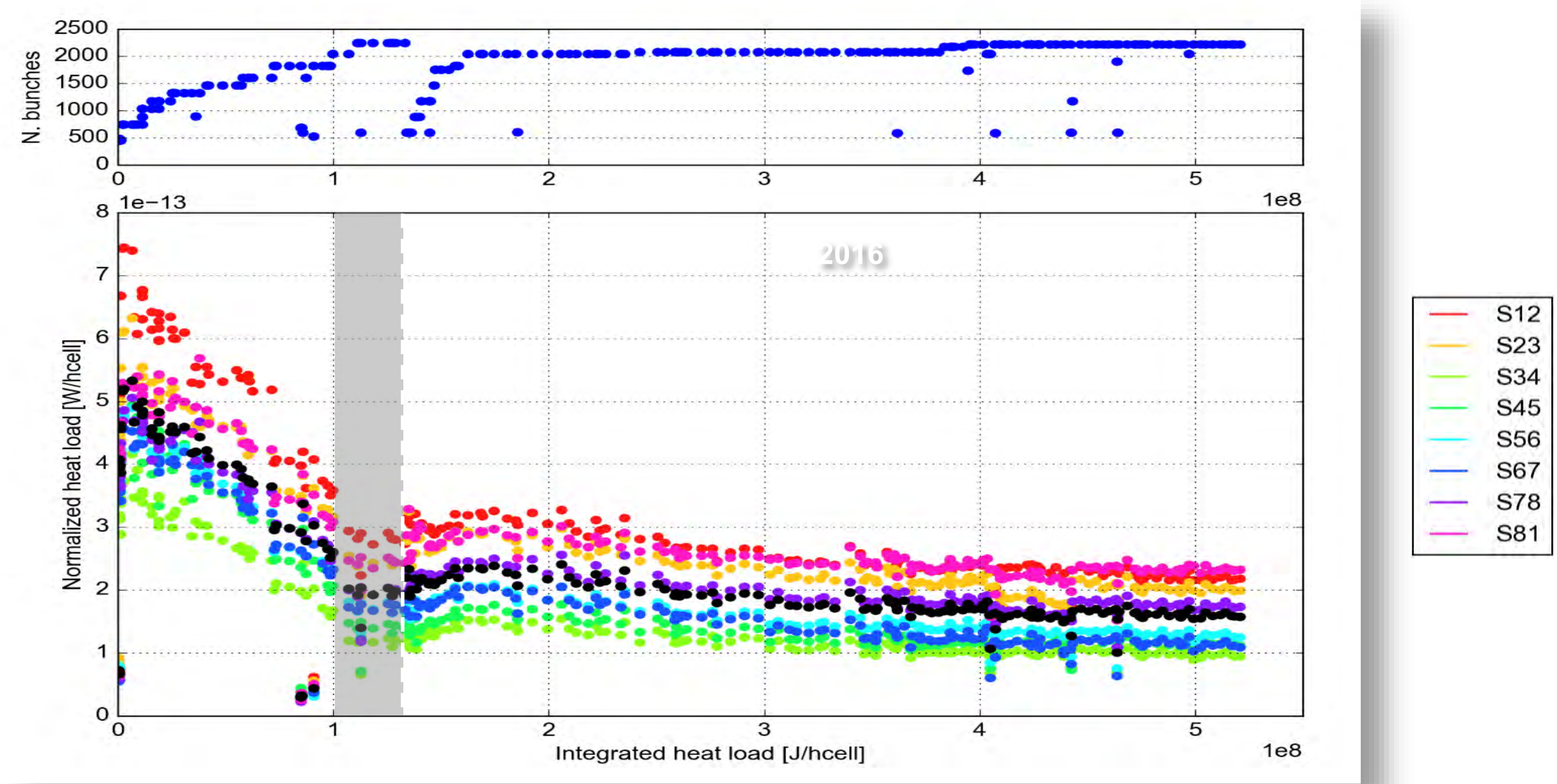
Run 2

2015 to 2017

Goals of the 4 year long Run 2 from 2015 to 2018:

- ✓ Operate the LHC at 6.5 TeV.
- ✓ Operate with a bunch spacing of 25 ns.
  - *During Run 1 LHC was operated with 50 ns spacing (e-cloud).*
- ✓ Deliver ≥ 100 fb^{-1} of integrated luminosity.

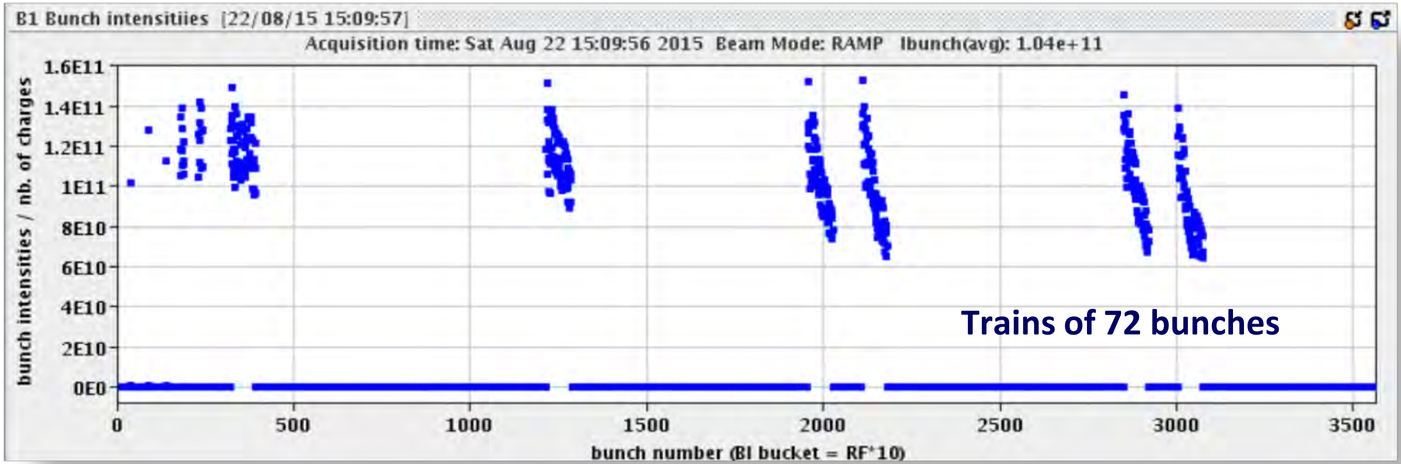
Scrubbing in 2015 and 2016



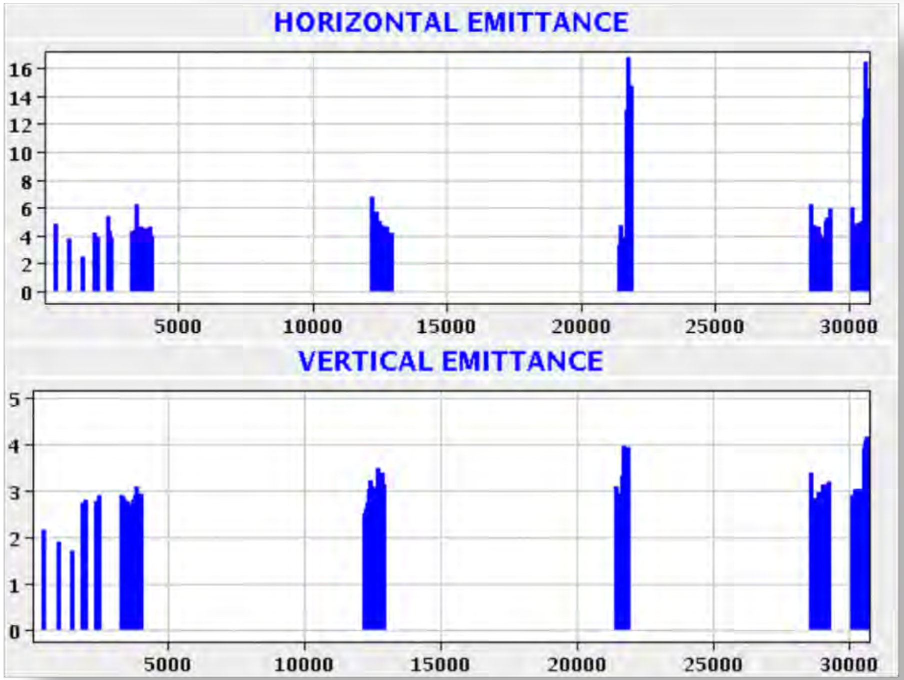
- Evolution from the heat load normalized to the total beam intensity
- Conditioning observed in 2015 continued over the first two months of 2016
- Very little change in the following months
- No correlation of this evolution with changes of settings and beam configuration

25 ns beam quality

Bunch intensity



Bunch emittance (μm)



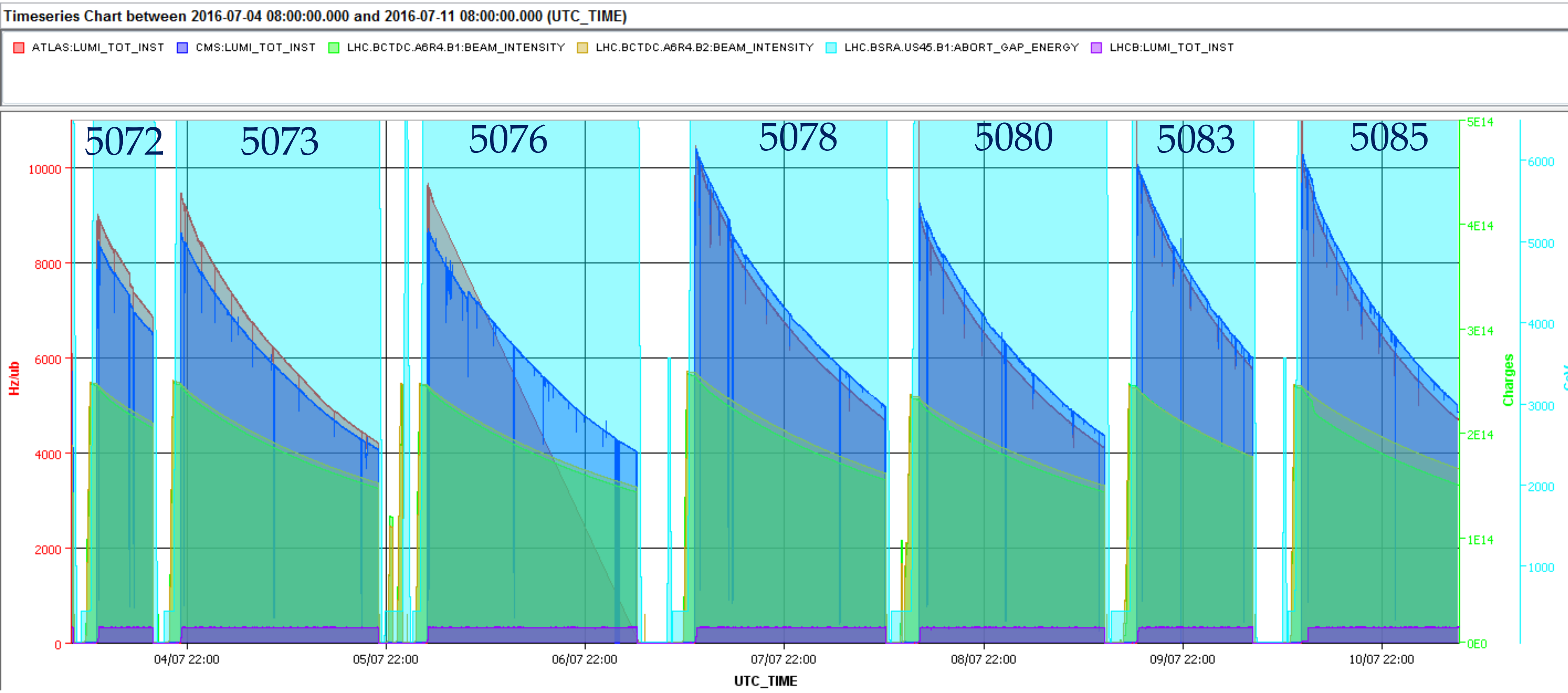
The 25 ns beams are operated with trains of 48, 72 or 144 bunches (nominal 288), the signature of electron clouds is visible:

- *Intensity along the trains.*
- *Blown up bunches.*

Scrubbing has not completely removed e-clouds. The conditioning continues in parallel to physics operation.

Fill 5083

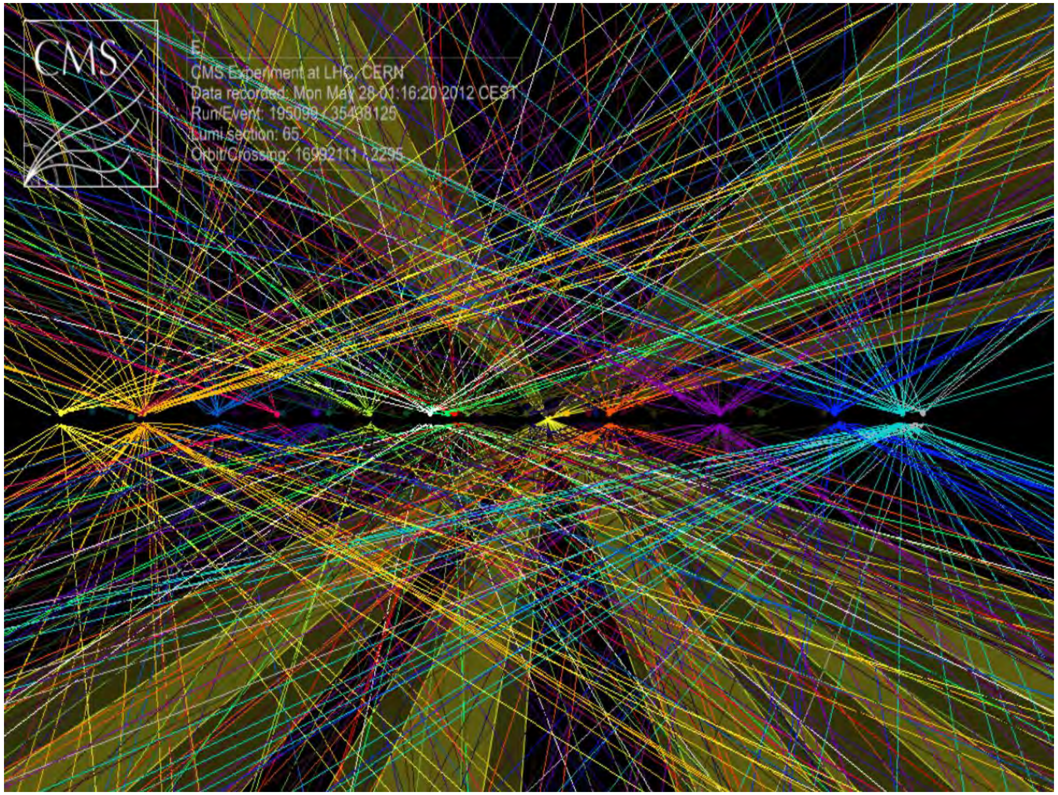
Luminosity > $1x10^{34}$ $cm^{-2}s^{-1}$



Design Luminosity achieved !!!!

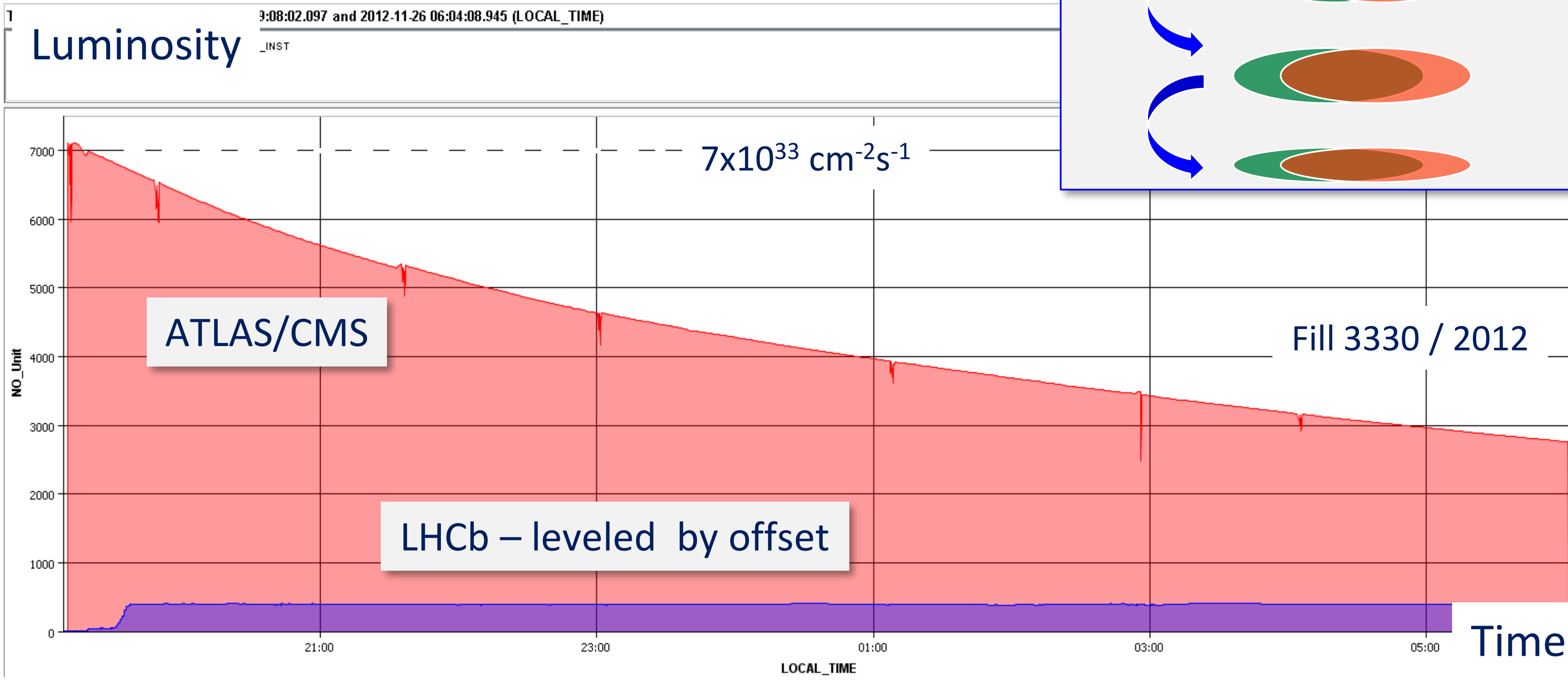
Question

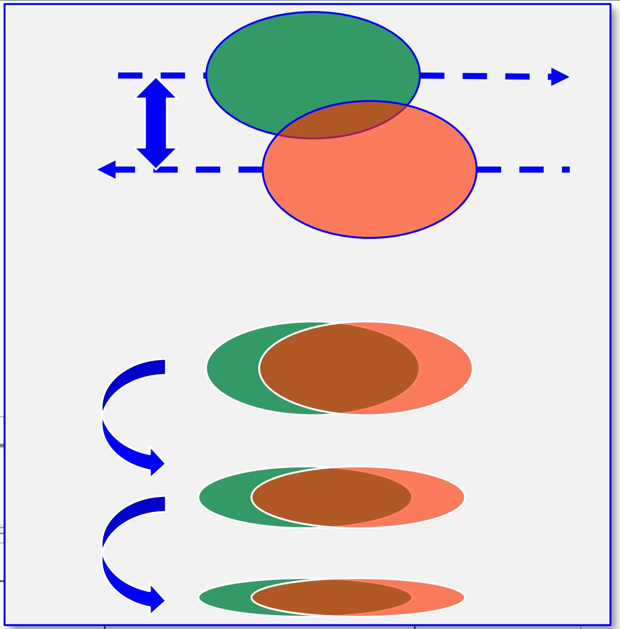
How to reduce (level) the luminosity if pile-up cannot be accepted?



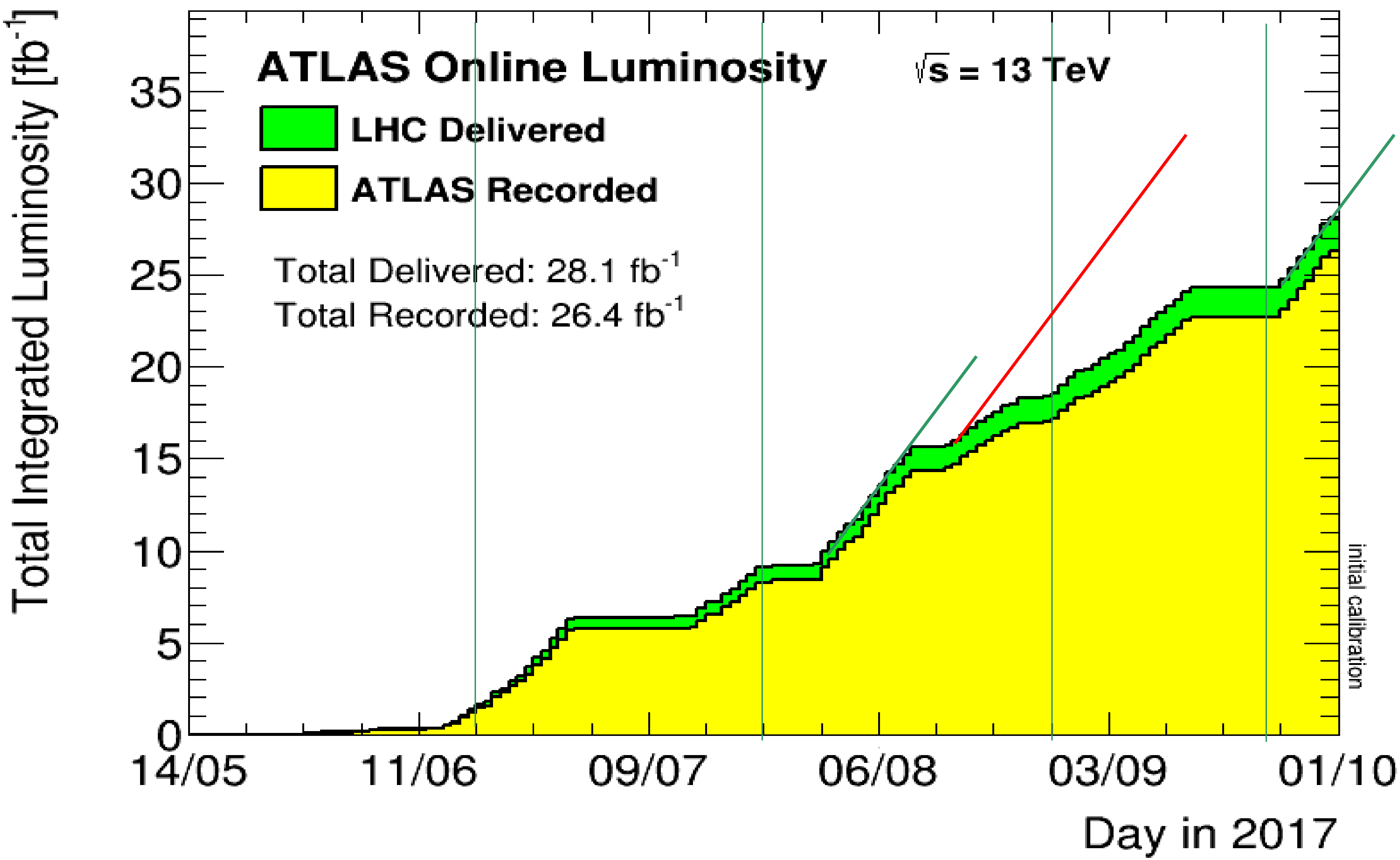
Leveling luminosities

- We have levelled the luminosity of LHCb by adjusting the offsets between the beams.
- We are considering to level luminosities by adjusting the beam size at IP.
- Better / mandatory for beam stability.

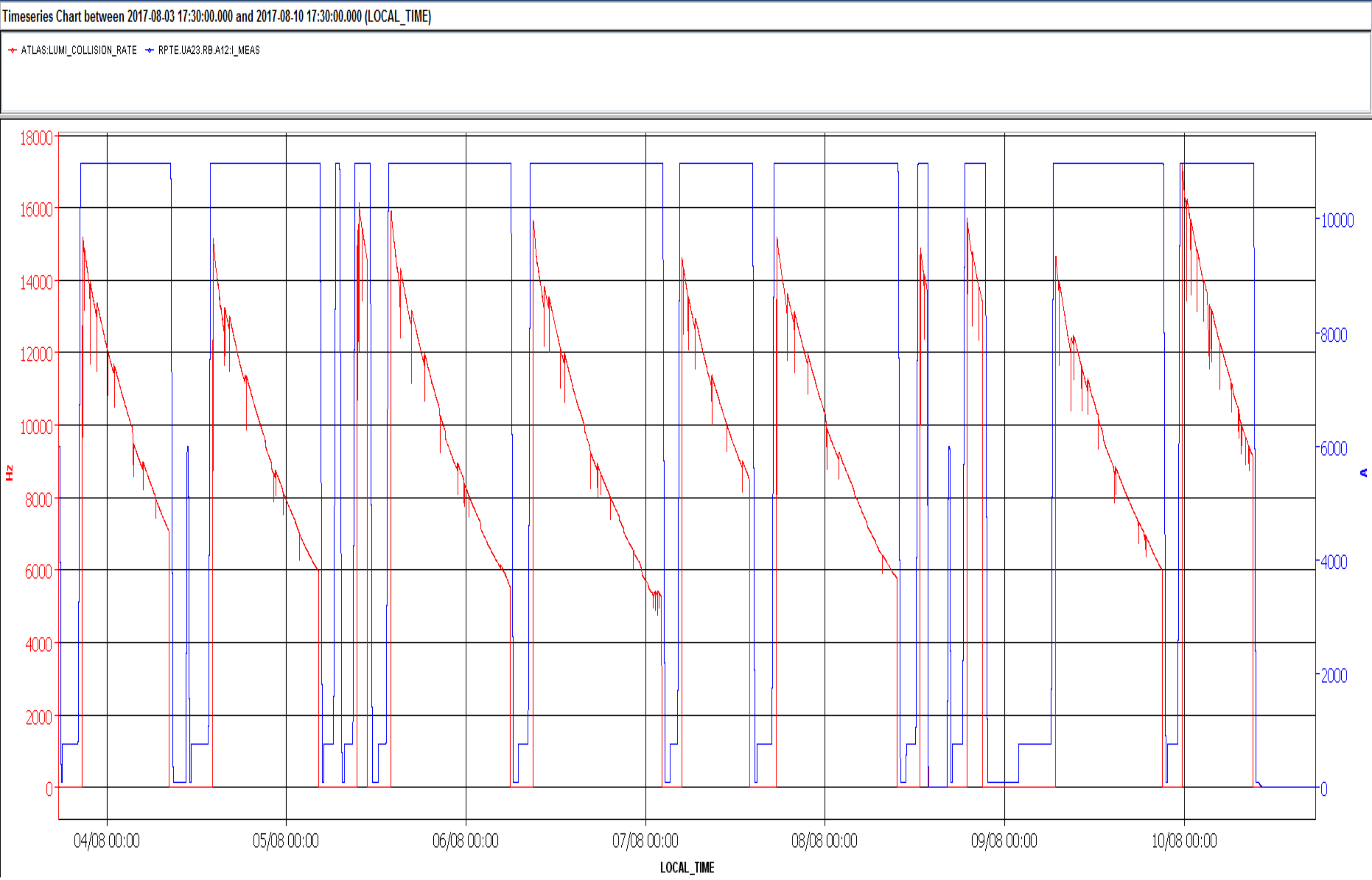




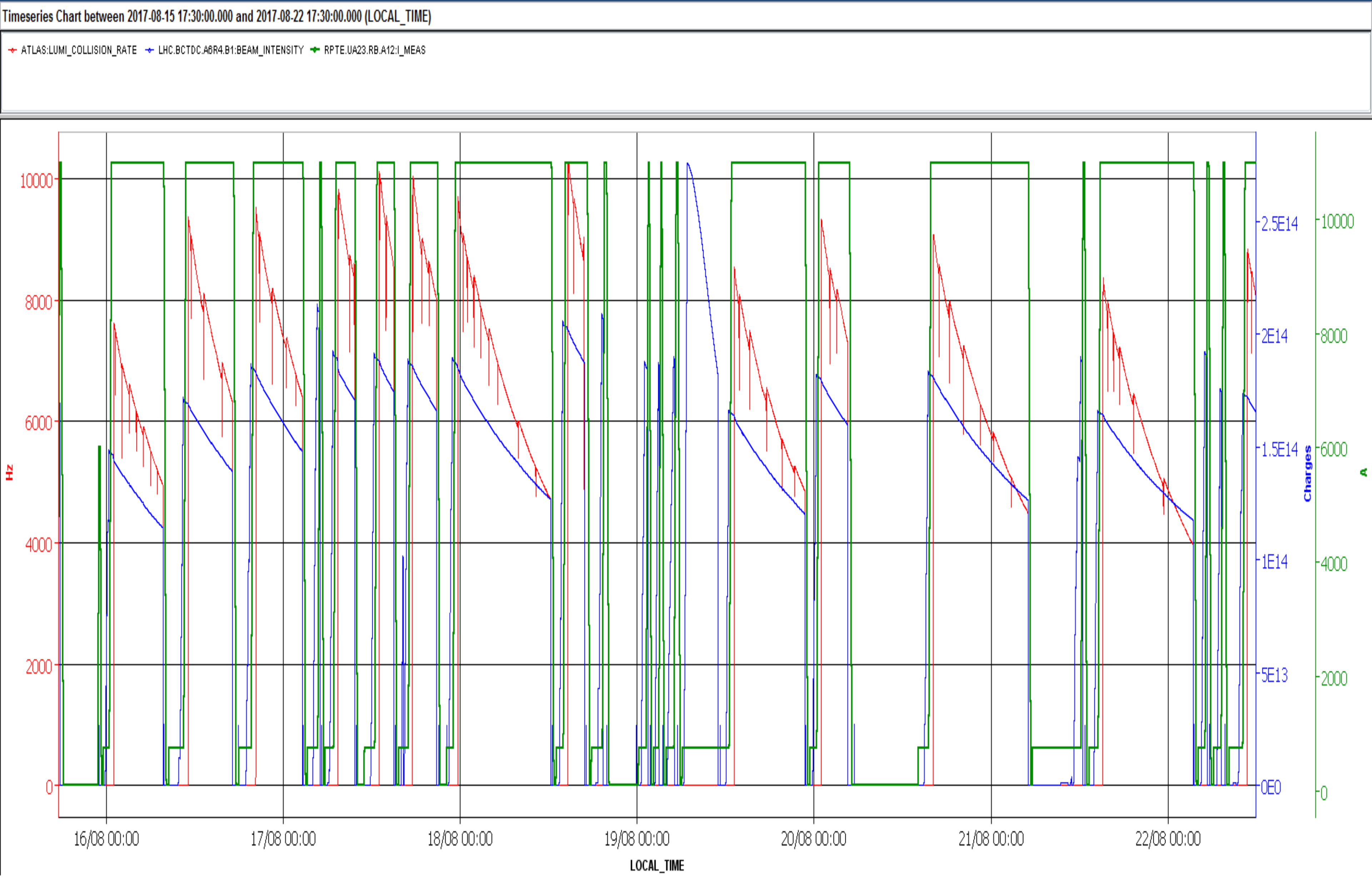
Luminosity in 2017



Great week

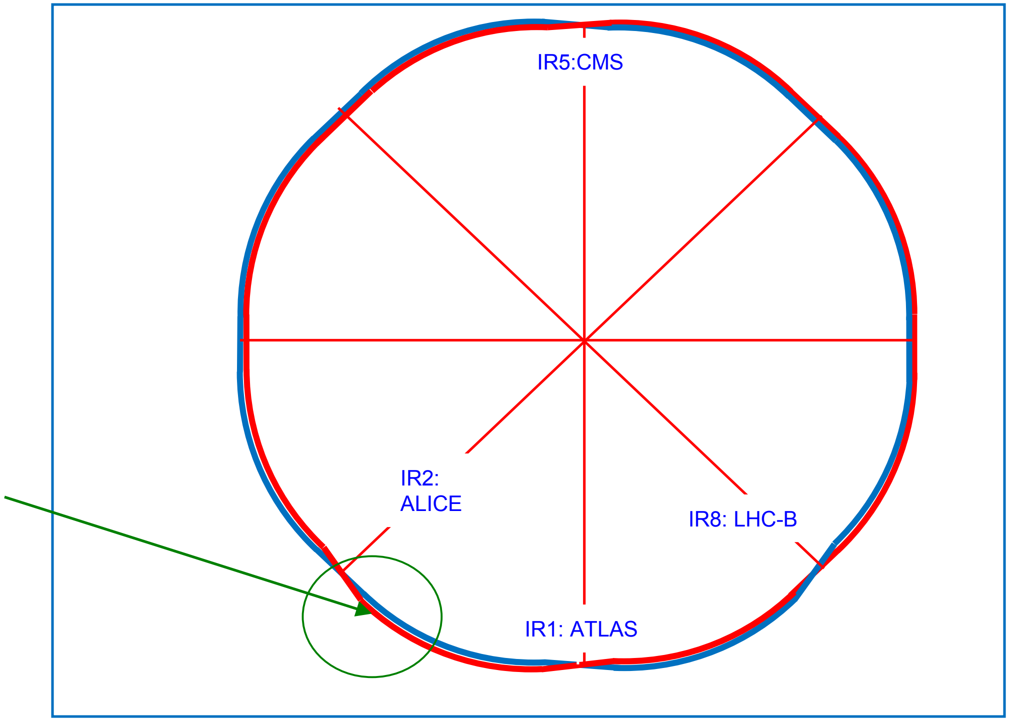

Timeseries Chart between 2017-08-03 17:30:00.000 and 2017-08-10 17:30:00.000 (LOCAL_TIME)
ATLAS:LUMI_COLLISION_RATE
RPTE.UA23.RB.A12:I_MEAS
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Hz
10000
8000
6000
4000
2000
0
A
04/08 00:00
05/08 00:00
06/08 00:00
07/08 00:00
08/08 00:00
09/08 00:00
10/08 00:00
LOCAL_TIME

Less great …

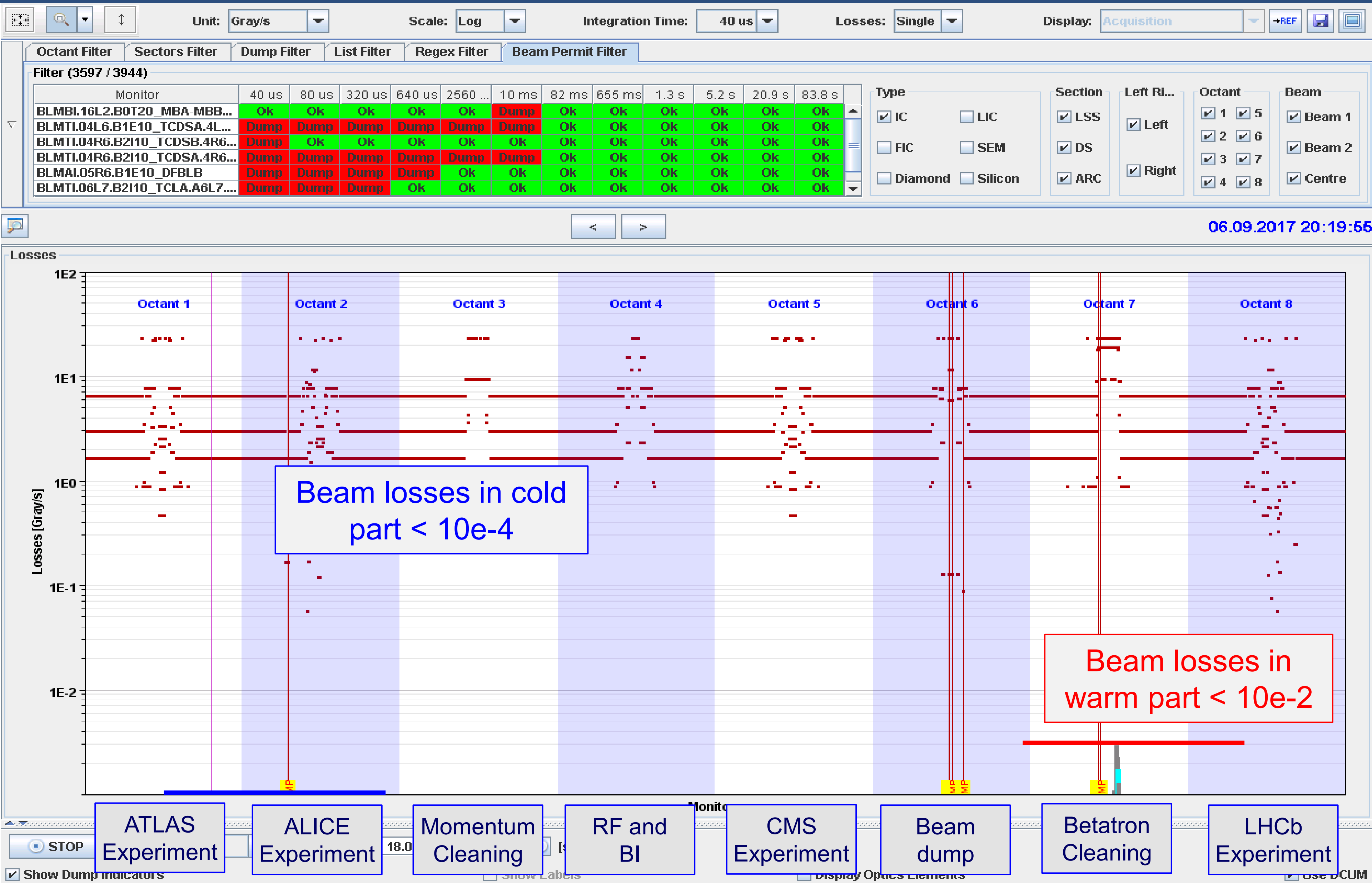

Timeseries Chart between 2017-08-15 17:30:00.000 and 2017-08-22 17:30:00.000 (LOCAL_TIME)
ATLAS:LUMI_COLLISION_RATE
LHC.BCTDC.A6R4.B1:BEAM_INTENSITY
RPTE.UA23.RB.A12:I_MEAS
Hz
10000
8000
6000
4000
2000
0
Charges
2.5E14
2E14
1.5E14
1E14
5E13
0E0
A
10000
8000
6000
4000
2000
0
16/08 00:00
17/08 00:00
18/08 00:00
19/08 00:00
20/08 00:00
21/08 00:00
22/08 00:00
LOCAL_TIME

The LHC accelerator is always good for surprises…..

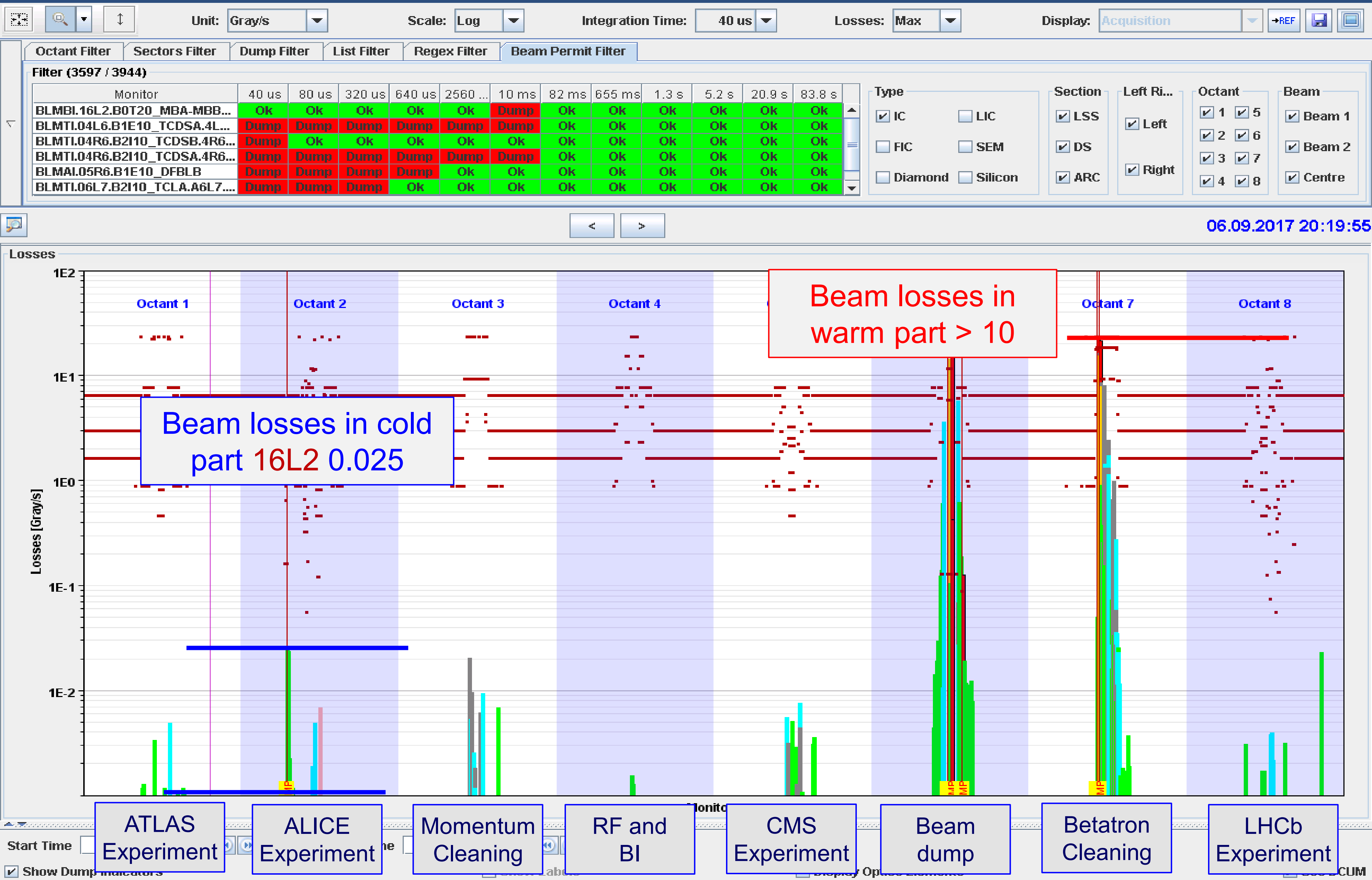
16 L2



Normal operation

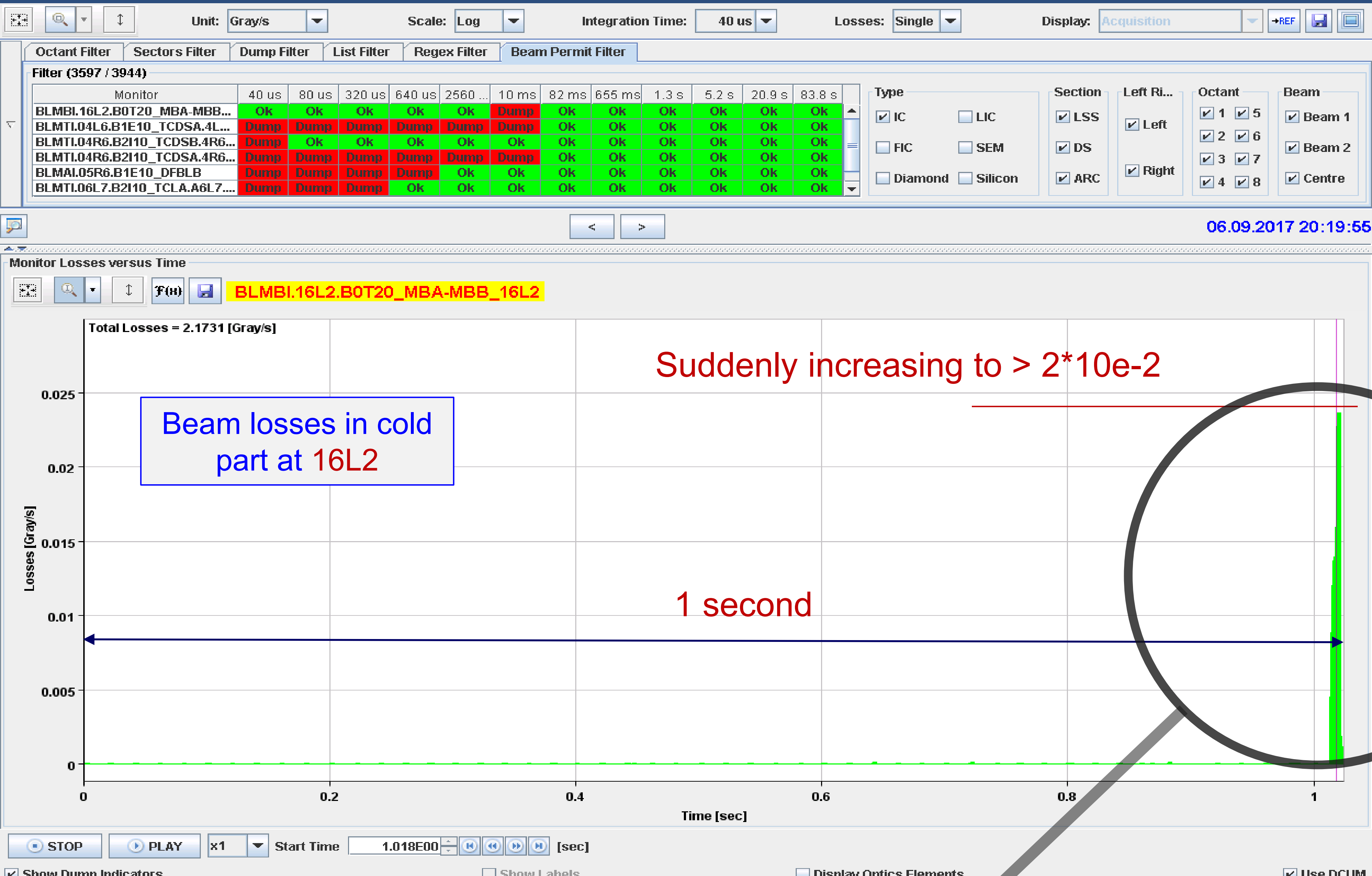


High losses – beam dump

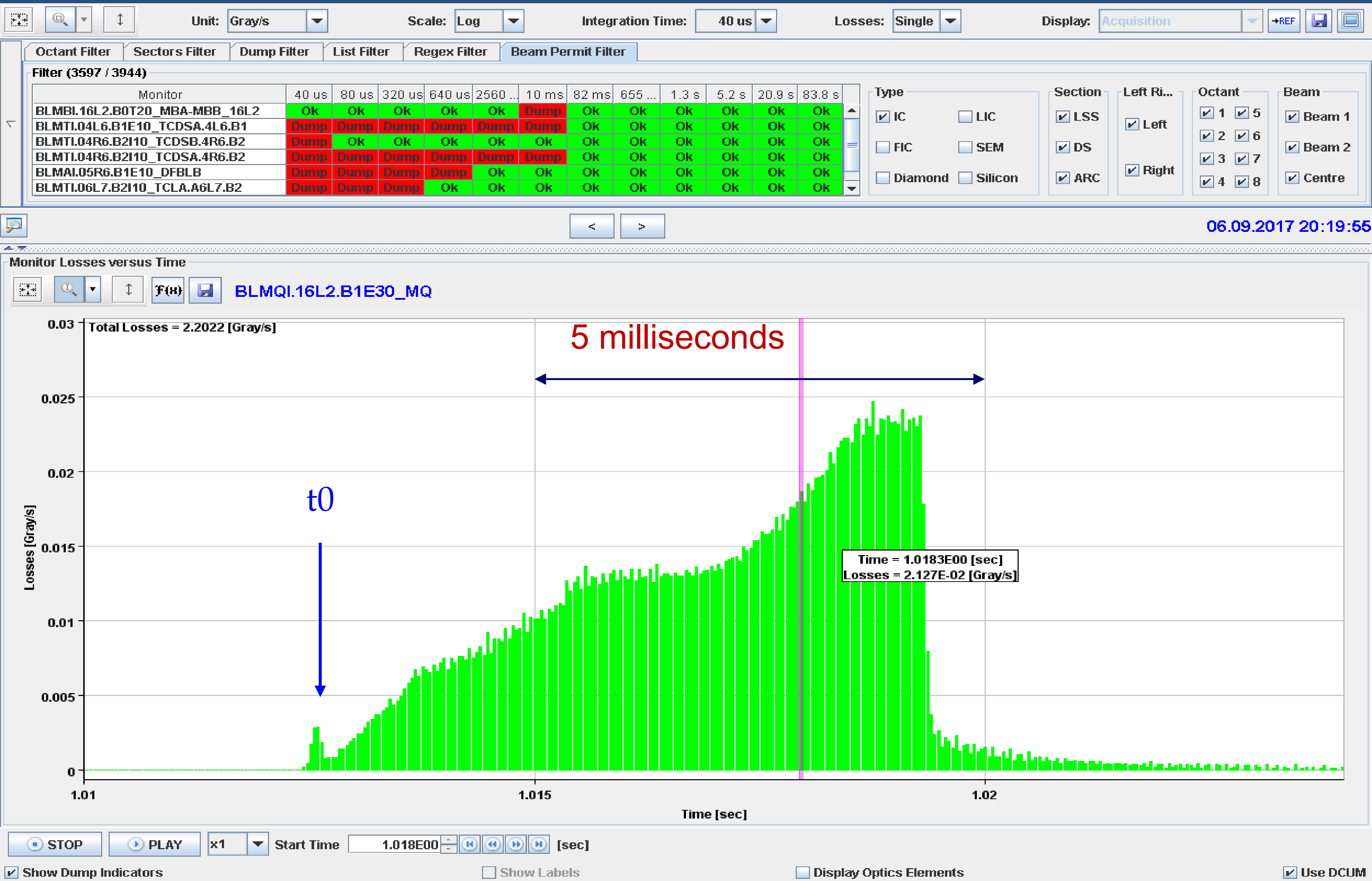


Monitor	40 us	80 us	320 us	640 us	2560 ...	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMBI.16L2.B0T20_MBA-MBB...	Ok	Ok	Ok	Ok	Ok	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMTI.04L6.B1E10_TCDSA.4L...	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMTI.04R6.B2I10_TCDSB.4R6...	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMTI.04R6.B2I10_TCDSA.4R6...	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMAI.05R6.B1E10_DFBLB	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMTI.06L7.B2I10_TCLA.A6L7....	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok

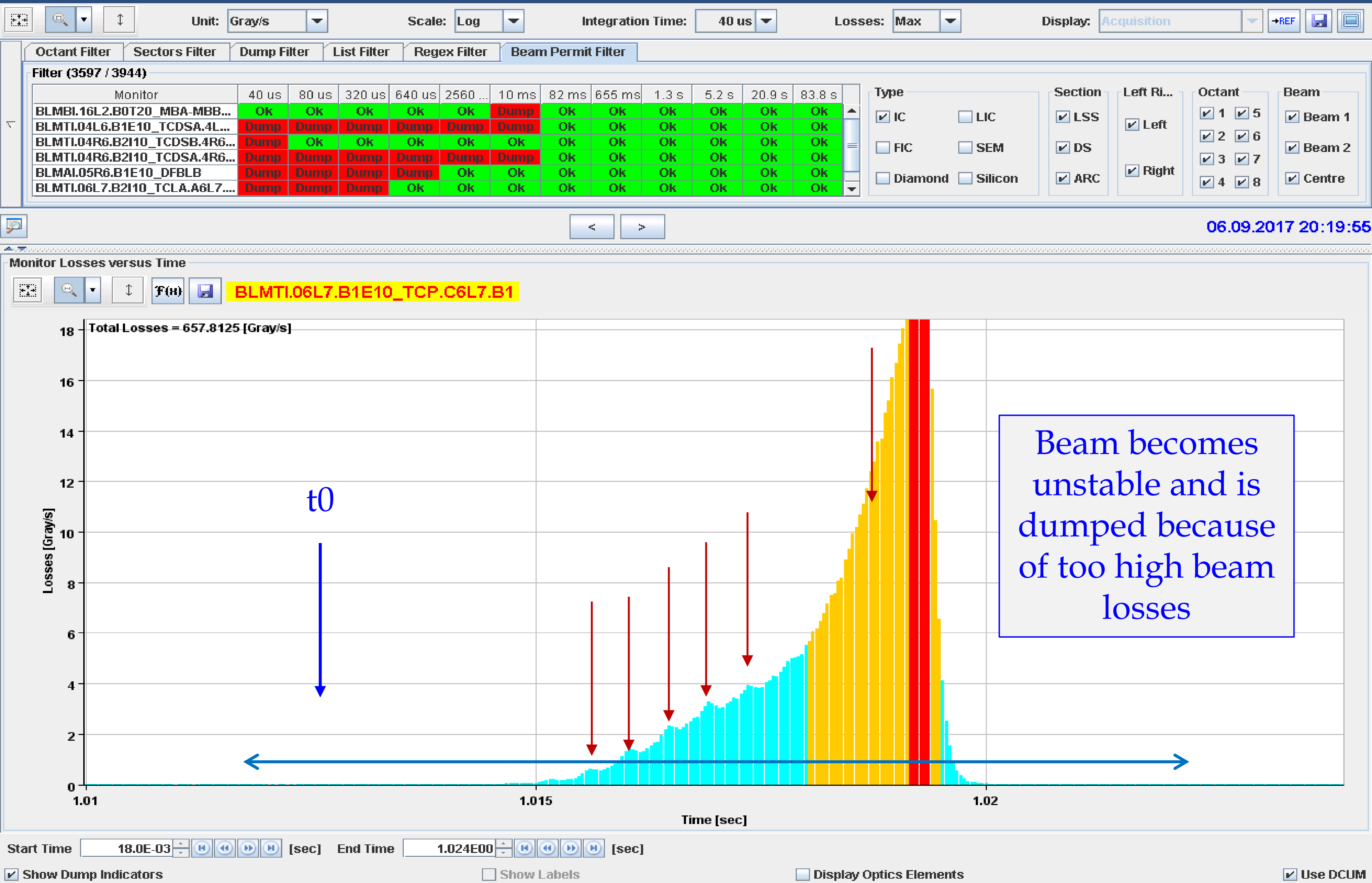
UFO "Type 2"


Unit: Gray/s
Scale: Log
Integration Time: 40 us
Losses: Single
Display: Acquisition
Octant Filter
Sectors Filter
Dump Filter
List Filter
Regex Filter
Beam Permit Filter
Filter (3597 / 3944)
Monitor | 40 us | 80 us | 320 us | 640 us | 2560 ... | 10 ms | 82 ms | 655 ms | 1.3 s | 5.2 s | 20.9 s | 83.8 s
BLMBI.16L2.B0T20_MBA-MBB... | Ok | Ok | Ok | Ok | Ok | Dump | Ok | Ok | Ok | Ok | Ok | Ok
BLMTI.04L6.B1E10_TCDSA.4L... | Dump | Dump | Dump | Dump | Dump | Dump | Ok | Ok | Ok | Ok | Ok | Ok
BLMTI.04R6.B2I10_TCDSB.4R6... | Dump | Ok | Ok | Ok | Ok | Ok | Ok | Ok | Ok | Ok | Ok | Ok
BLMTI.04R6.B2I10_TCDSA.4R6... | Dump | Dump | Dump | Dump | Dump | Dump | Ok | Ok | Ok | Ok | Ok | Ok
BLMAI.05R6.B1E10_DFBLB | Dump | Dump | Dump | Dump | Ok | Ok | Ok | Ok | Ok | Ok | Ok | Ok
BLMTI.06L7.B2I10_TCLA.A6L7.... | Dump | Dump | Dump | Ok | Ok | Ok | Ok | Ok | Ok | Ok | Ok | Ok
Type: IC, LIC, FIC, SEM, Diamond, Silicon
Section: LSS, DS, ARC
Left Ri...: Left, Right
Octant: 1, 2, 3, 4, 5, 6, 7, 8
Beam: Beam 1, Beam 2, Centre
06.09.2017 20:19:55
Monitor Losses versus Time
BLMBI.16L2.B0T20_MBA-MBB_16L2
Total Losses = 2.1731 [Gray/s]
Suddenly increasing to > 2*10e-2
Beam losses in cold part at 16L2
1 second
Losses [Gray/s]
Time [sec]
0.025
0.02
0.015
0.01
0.005
0
0.2
0.4
0.6
0.8
1
STOP
PLAY
x1
Start Time 1.018E00 [sec]
Show Dump Indicators
Show Labels
Display Optics Elements
Use DCUM

Zoom on UFO Type 2



Beam losses at collimators



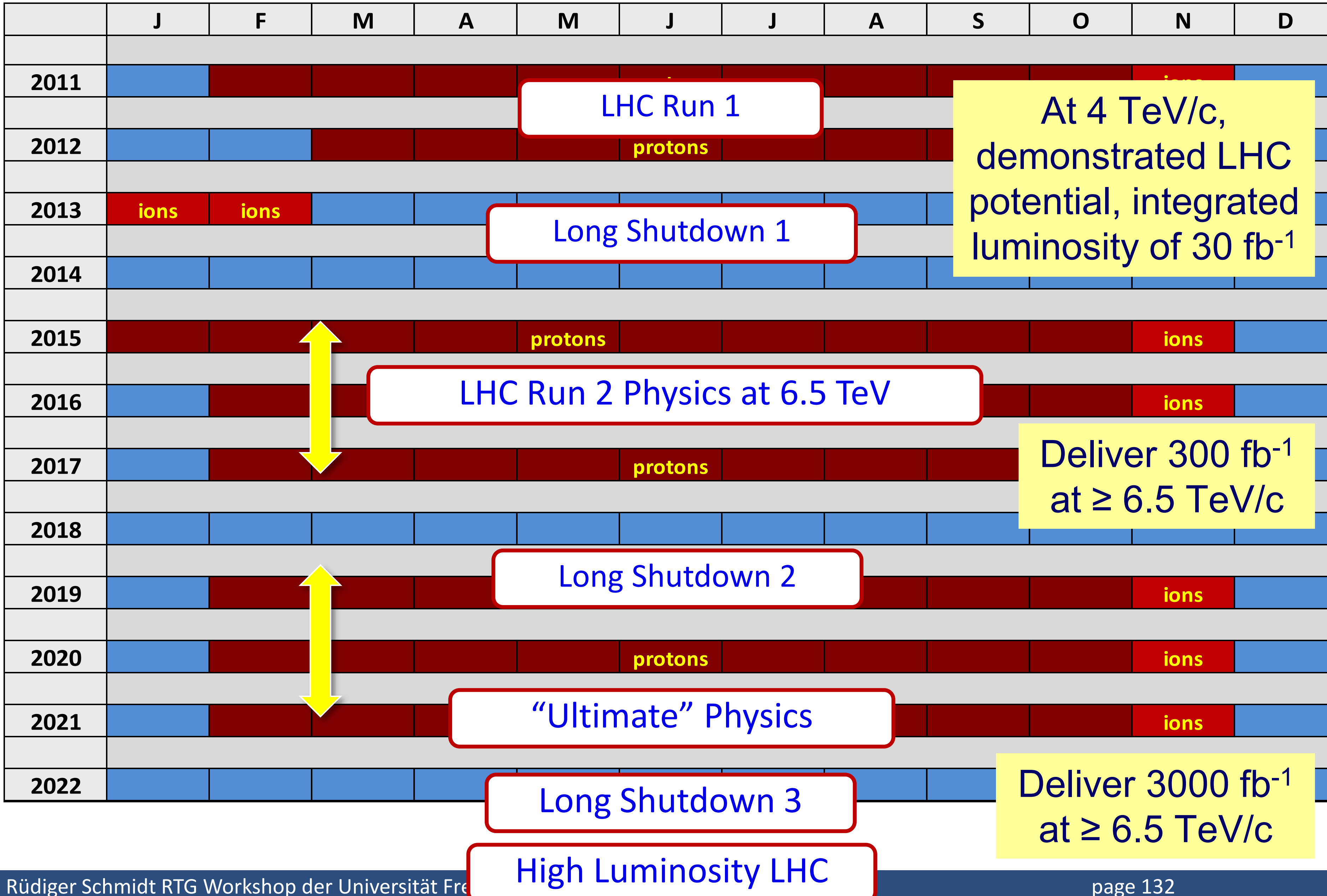
The next 20 years

LHC

and

High Luminosity-LHC (HL-LHC)

The next years



Horizon 2025: LHC High Luminosity Upgrade

Motivation

- Very **ambitious target** for $\int L(t) \times dt$: 200 – 300 fb^{-1}/y (×10 today)
- Radiation damage limit of existing sc quadrupoles close to experiments

Past experience from 2010-2012 operating with 50 ns bunch spacing

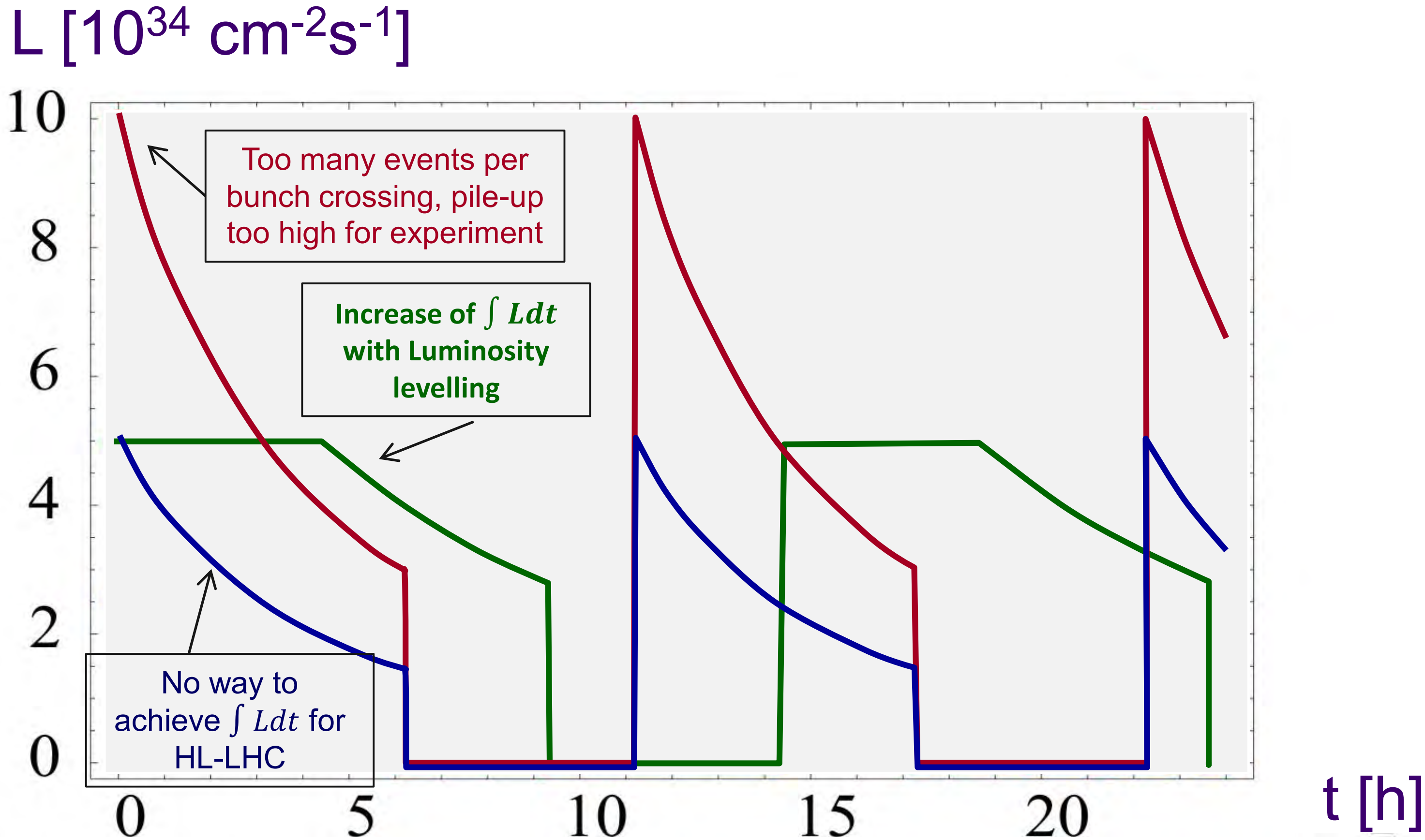
- **Operation with large bunch** intensity possible (no serious limitation)
- Single bunch with > $3x10^{11}$ protons per bunch with 2.5 um emittance provided by injector complex
- **Operation with very small beams** (low β* optics) successfully tested in injector complex

Pile-up/pile-up density HL-LHC beam physics constraint ➔ bunch spacing of 25 ns and luminosity leveling

- Total current: collimation efficiency, upper limits from: beam dump, vacuum, machine protection, radiation protection, …
- Electron cloud

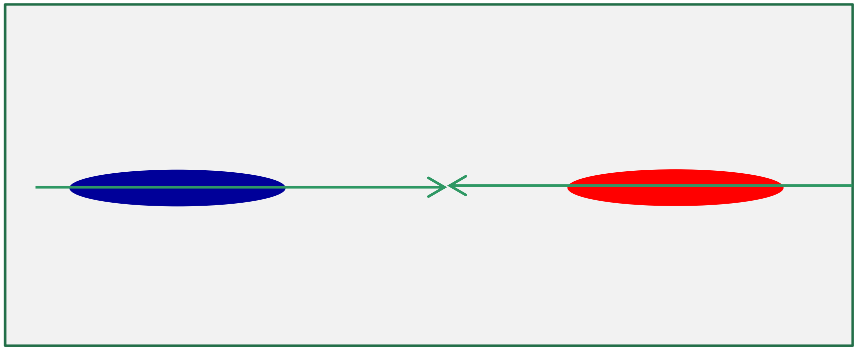
Integrated Luminosity increase by levelling

- $\int Ldt$ increase by increasing L_max not feasible (pile up too high): **Luminosity levelling** can increase $\int Ldt$
- **High availability** is required **(optimise length of fills)**



Luminosity parameters with crossing angle

Head-on collision…..
…..not an option for HL-LHC



Luminosity parameters with crossing angle

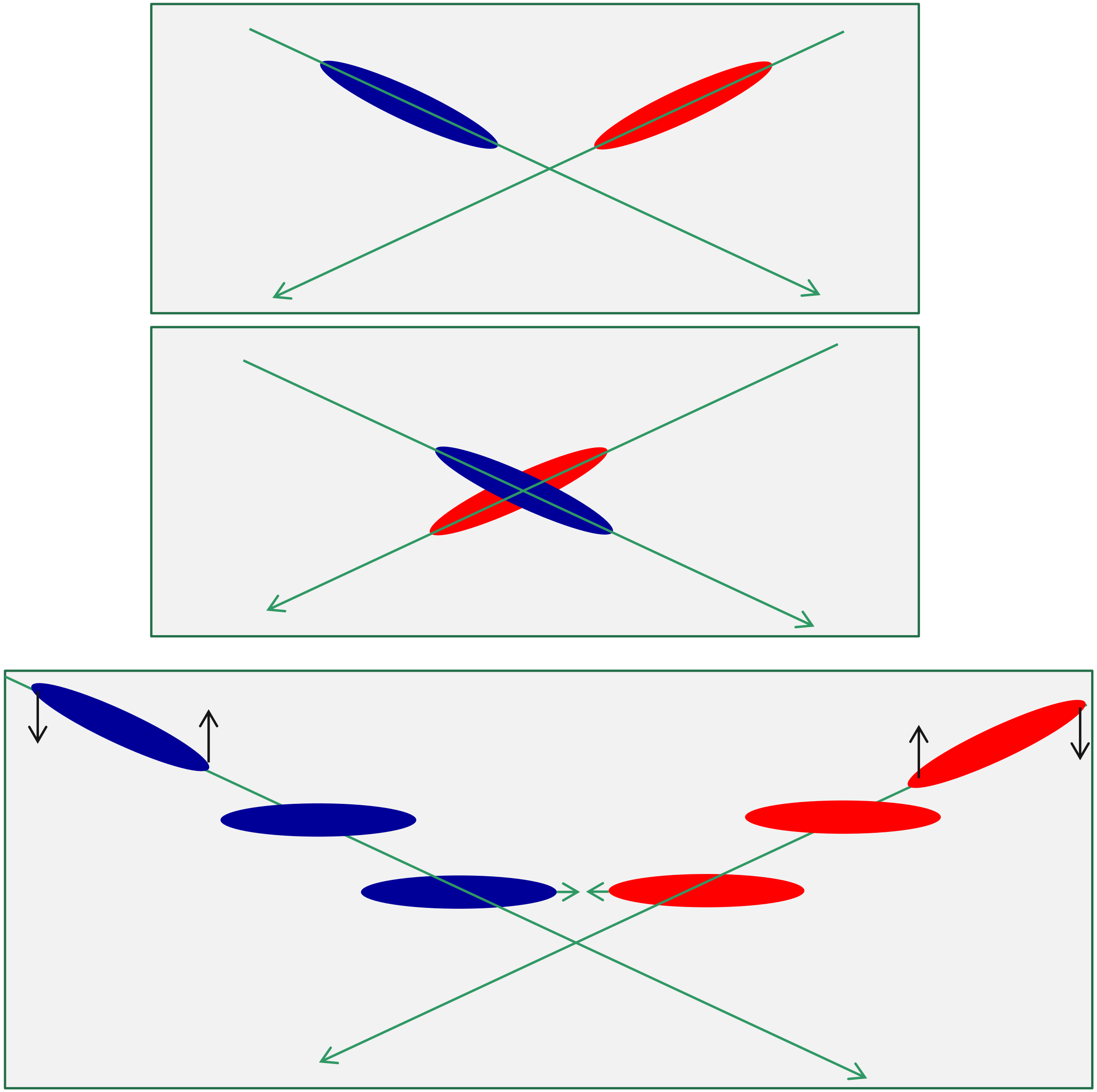
HL-LHC: Bunches collide with smaller beams and a larger crossing angle as in LHC: reduction of luminosity

Angle crossing (ineffective overlap):

$$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y} \cdot R$$

R ... reduction factor

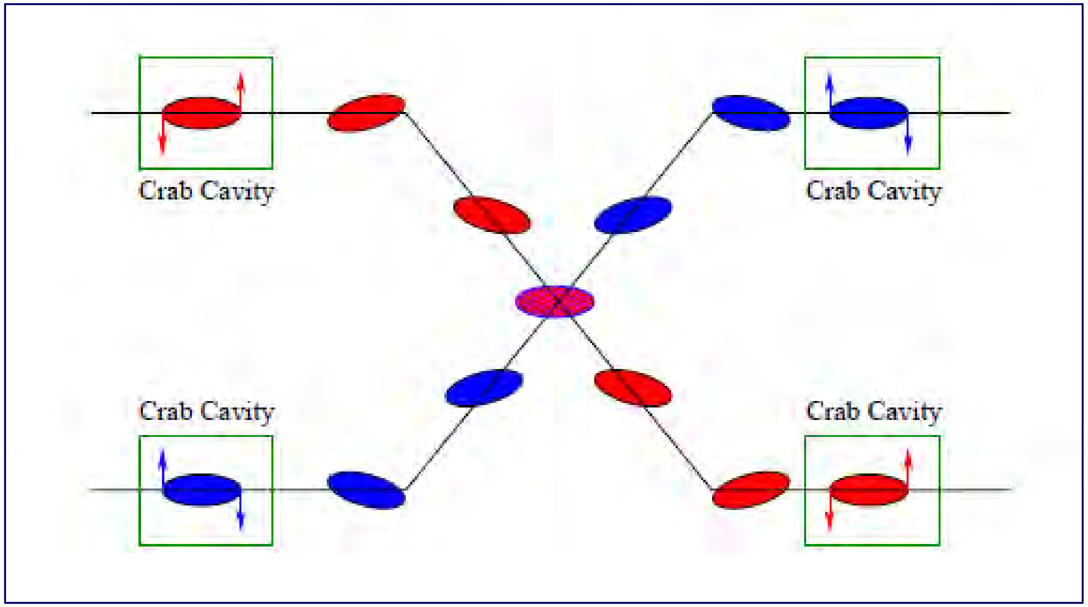
Tilt bunches before collisions with **crab cavities:** recovering luminosity => R ~1



Operation at pile-up limit

- Choose parameters that allow higher than design pile-up
- Low β*, Low Emittance, high bunch population
- Crab Cavities as tool to maximize overlap among colliding bunches (i.e. virtual luminosity) and minimize pile-up density

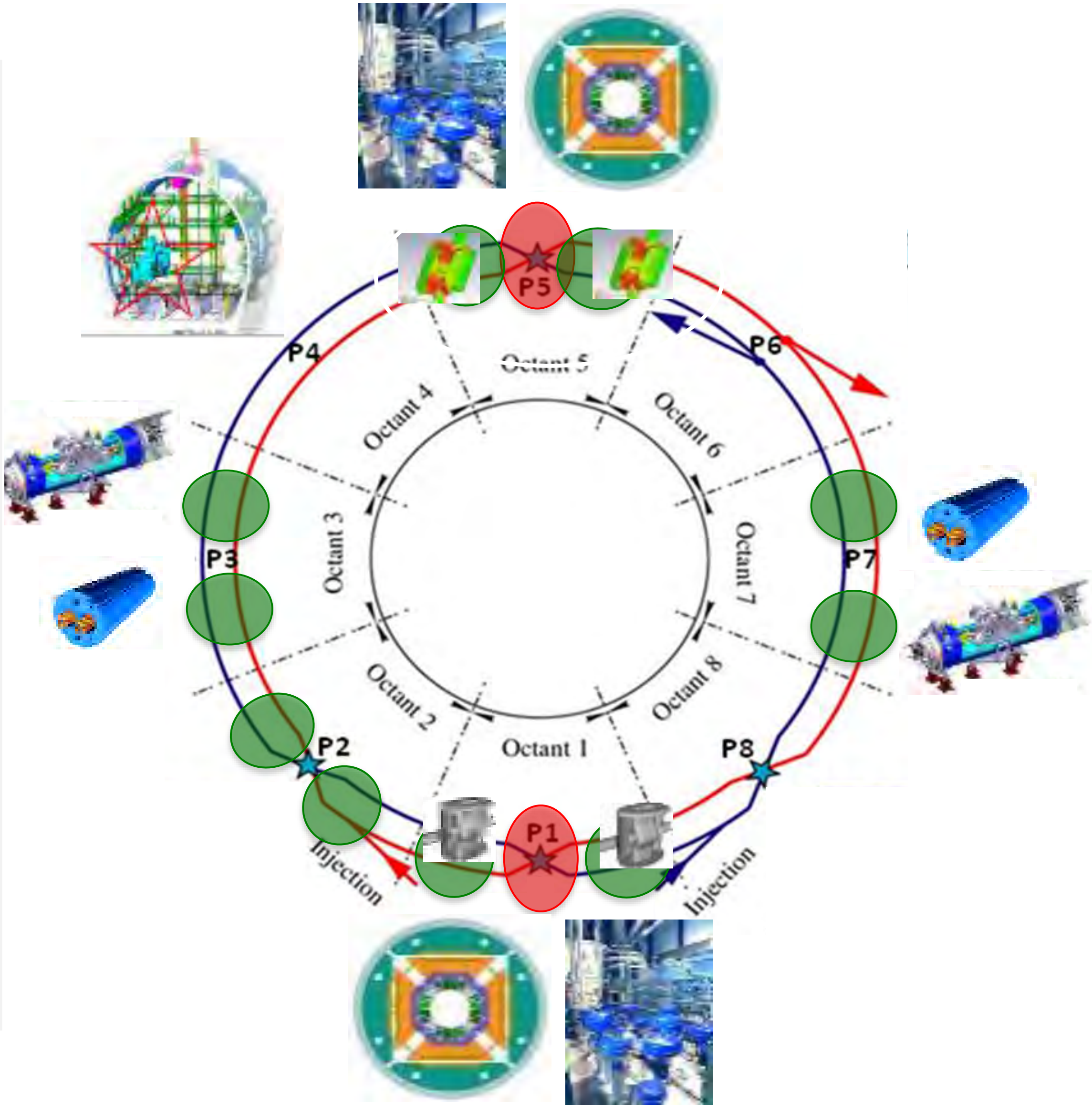
$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$



- Levelling mechanisms for controlling performance during run, e.g. with dynamic β* squeeze

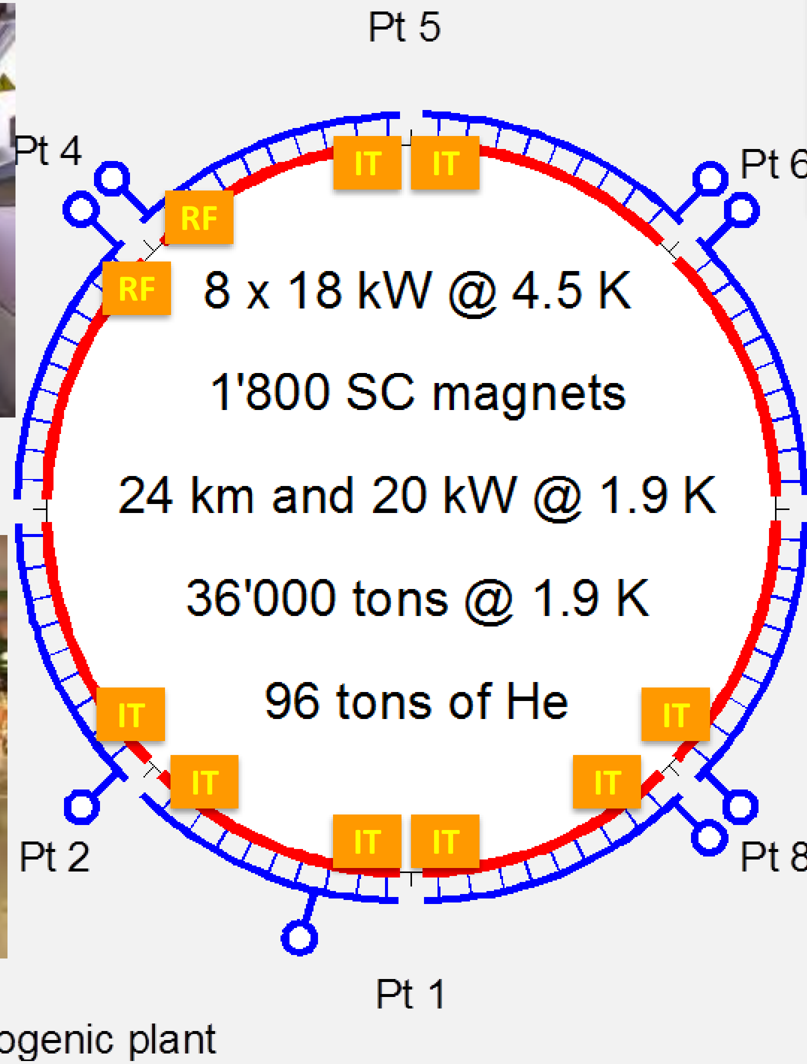
Main modifications of LHC

- New **high field/larger aperture** interaction region **sc magnets**
- **Crab Cavities** to take advantage of the small β*
- **New collimators** (lower impedance)
- **Cryo-collimators** and **high field 11 T dipoles** in cold part of LHC
- Additional **cryo plants** for magnets and RF (P1, P4, P5)
- **HTS Superconducting links** to allow power converters to be moved to protected areas (availability)

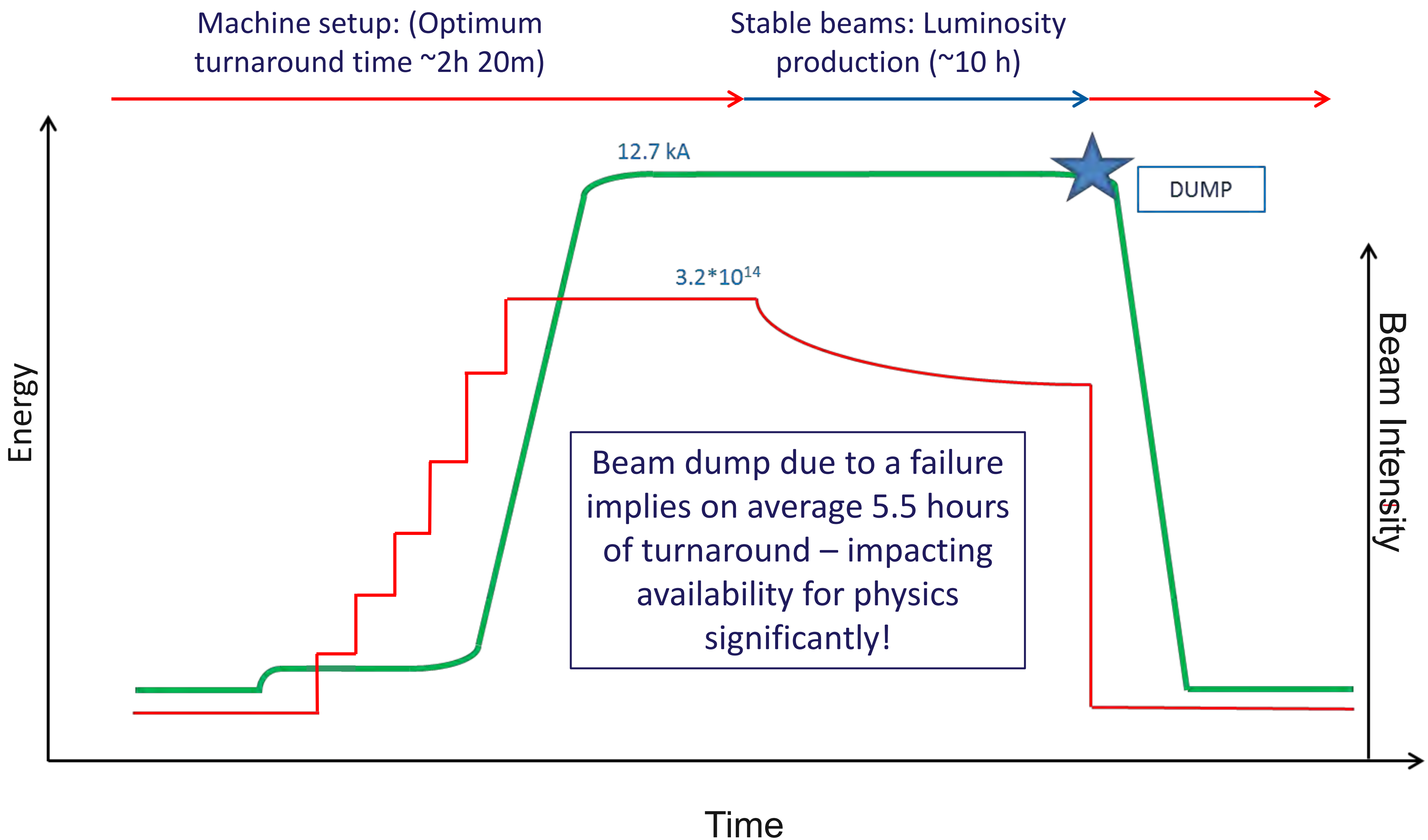


Technical bottlenecks: Cryogenics

Cryo power limitation in Pt 4, interdependency of different systems with different cool-down time, reduced flexibility and no/little redundancy

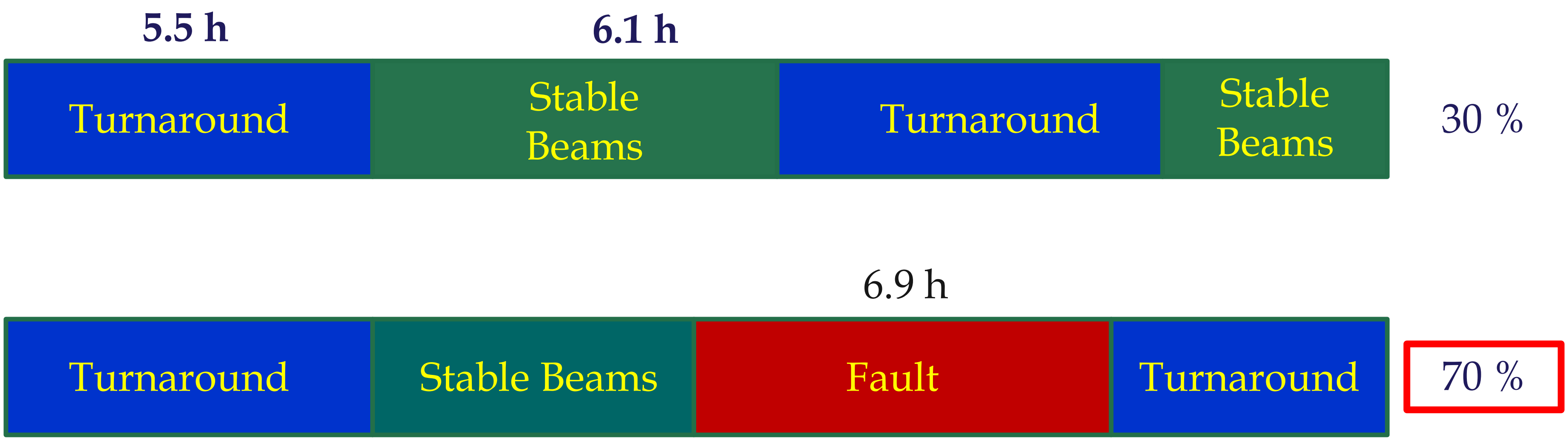


LHC operational cycle



Beam dump due to a failure implies on average 5.5 hours of turnaround – impacting availability for physics significantly!

Integrated Luminosity and Availability

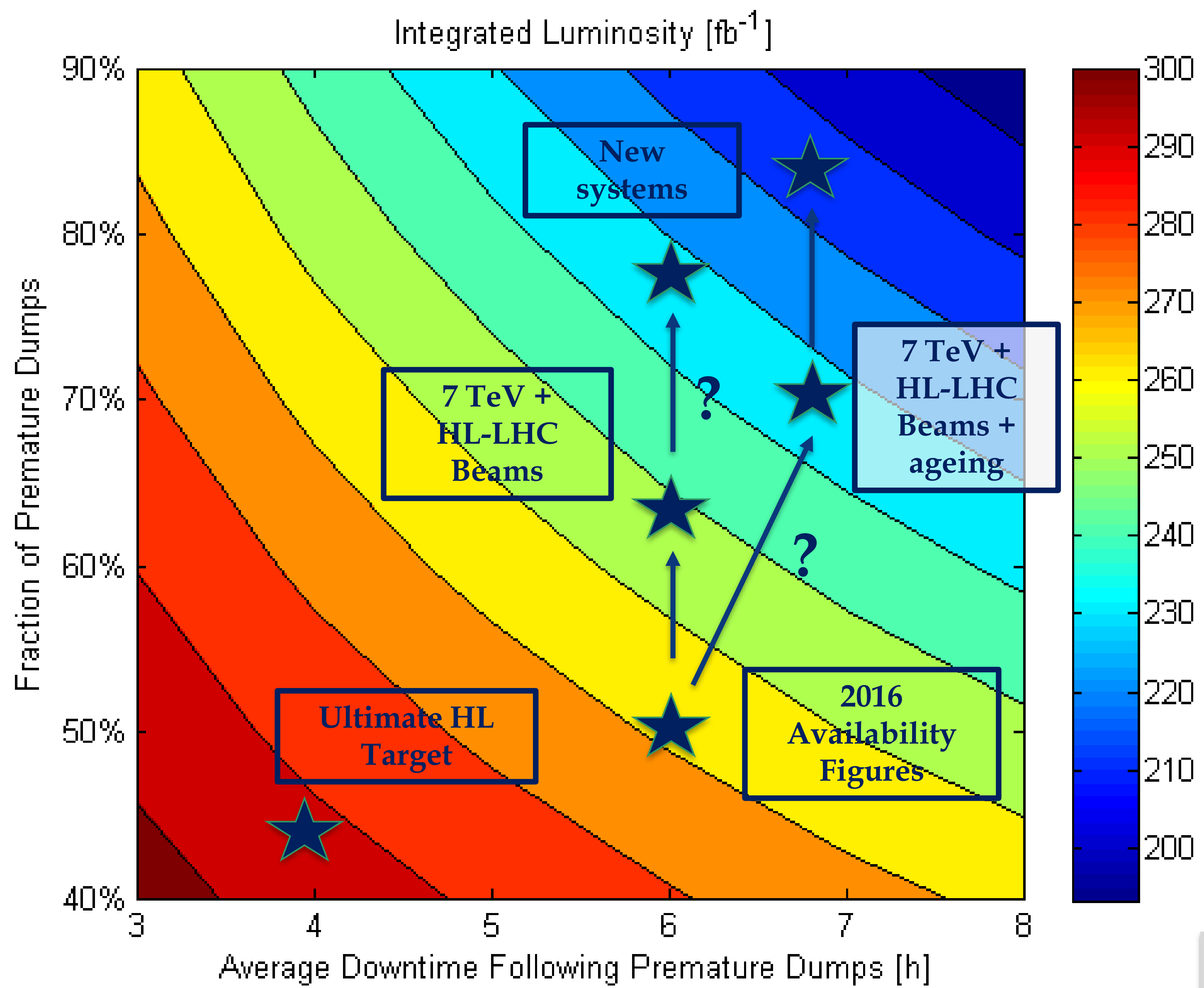


- **Machine Failure Rate** (MFR) = fraction of premature beam dumps due to a failure = 70 %

- **Monte Carlo model** for integrated luminosity:
  - Based on observed failure distributions
  - The model accurately reproduces 2012 operation
  - **Extrapolated distributions** for future LHC runs and HL-LHC

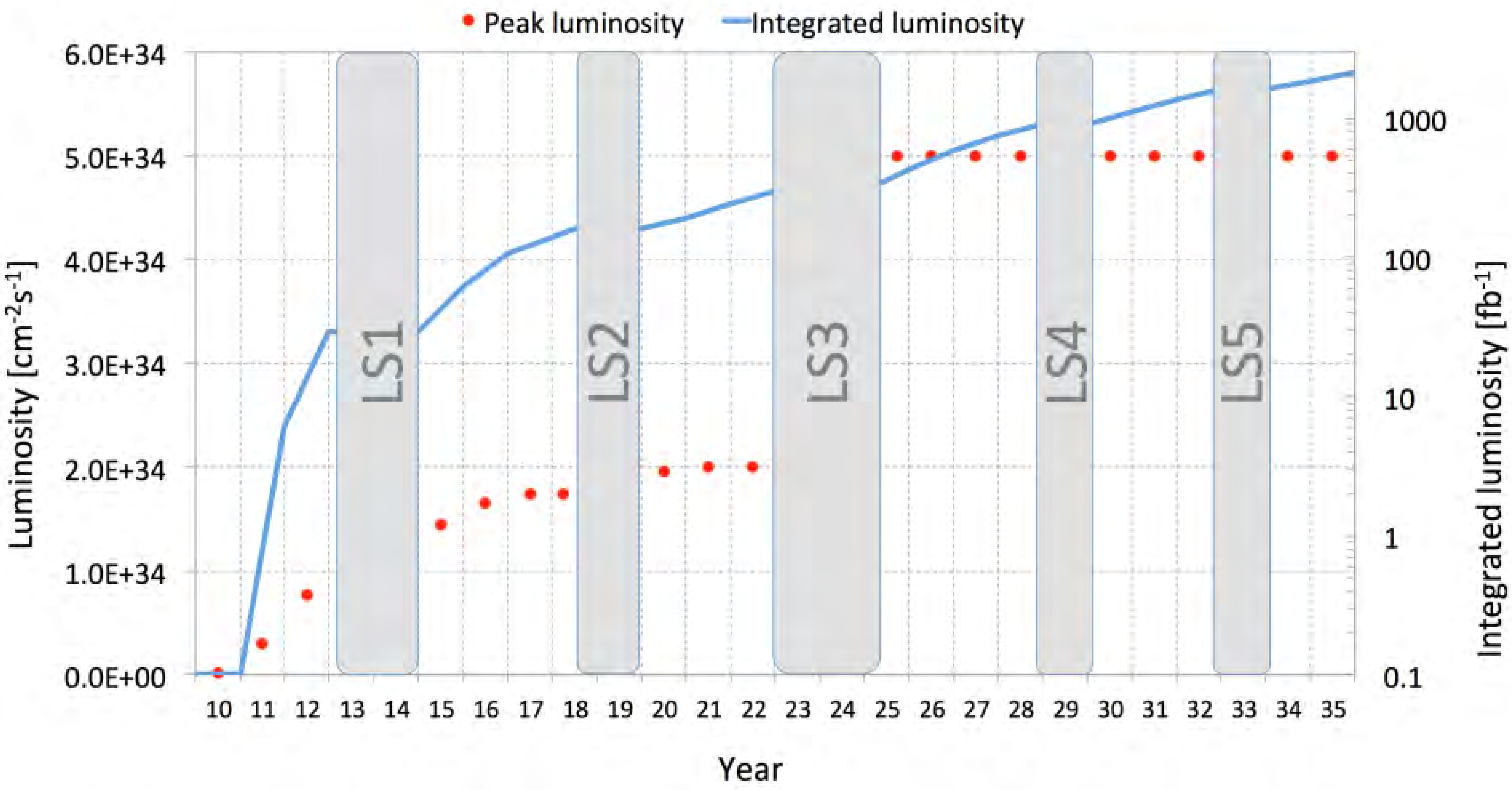
A. Apollonio

Availability for HL-LHC



A. Apollonio

LHC High Luminosity Upgrade



M. Lamont

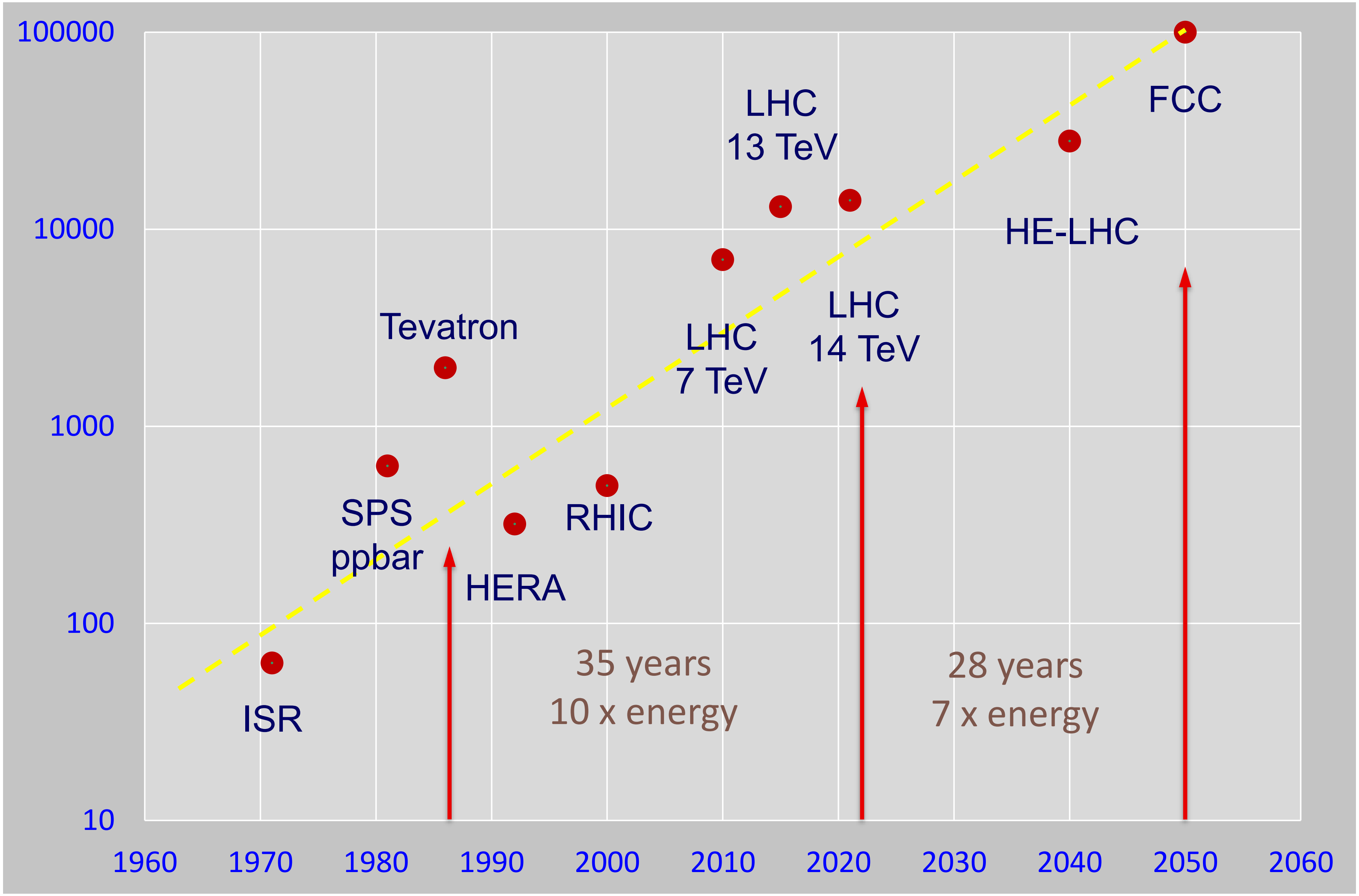
First ideas for LHC presented in 1984

Physics operation started 25 years later

Preparing for the next 50 years

- Full exploitation of LHC
- HE - LHC
- FCC Study – Proton collisions at a c.m. energy of 100 TeV

Center of Mass Energy of Hadron Colliders [GeV]



Full exploitation of LHC c.m. energy of 15 TeV (now 13 TeV) ?

LHC Design and full LHC exploitation

Initial design

- LHC design energy: 7 TeV for a dipole magnet field of 8.3 T
- The magnets were designed for operating at 9 T
- With a field of 9 T, an ultimate beam energy of 7.56 TeV could be reached

Issues

- Already for the operation at 6.5 TeV, an extensive magnet training campaign is required
- The number of training quenches will increase for operation at 7 TeV, and even more at 7.56 TeV
- It is expected that part of the magnets will not reach this field
- Quench margin very small (beam loss risk to quench magnets)
- Being discussed and studied in detail….

FCC Study – Proton collisions c.m. energy of 100 TeV

FCC Study Scope

Conceptual Design Report (CDR) and cost review for the next European Strategy Update in 2018:

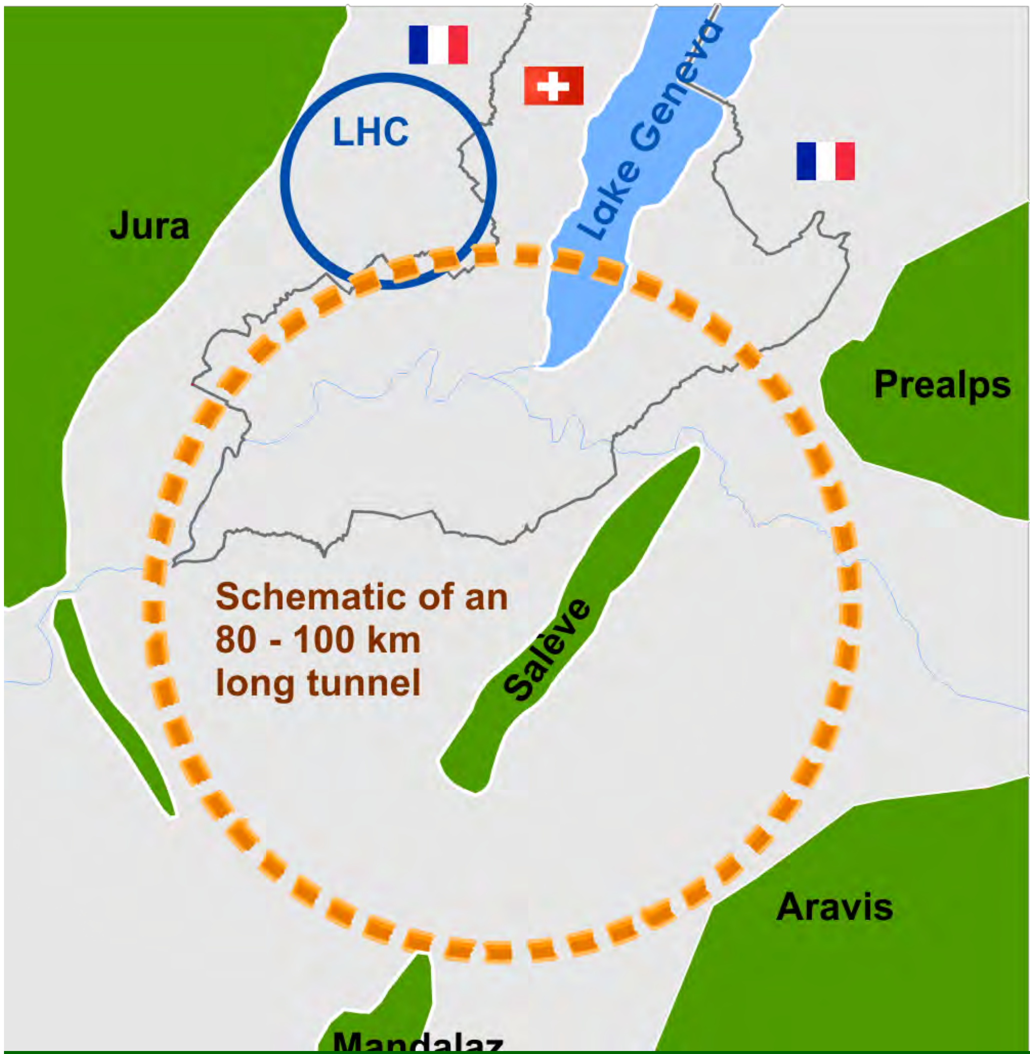
pp-collider (FCC-hh)

~**16 T**-> 100 TeV c.m. pp in 100 km

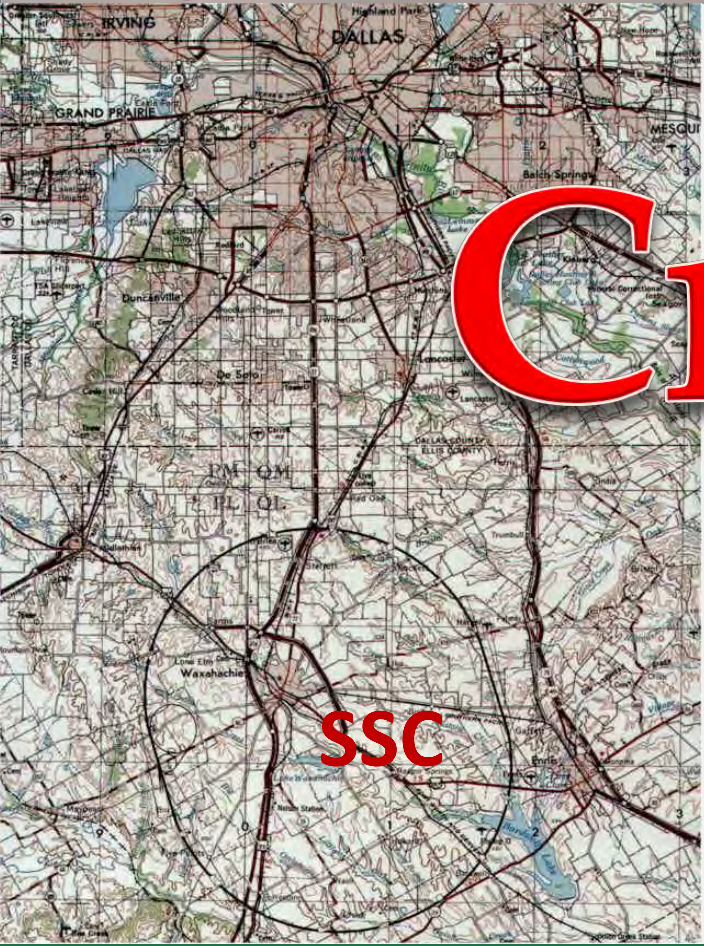
~**20 T**-> 100 TeV c.m. pp in 80 km

e^+e^- collider (FCC-ee) as potential intermediate step

p-e collider (FCC-he) option



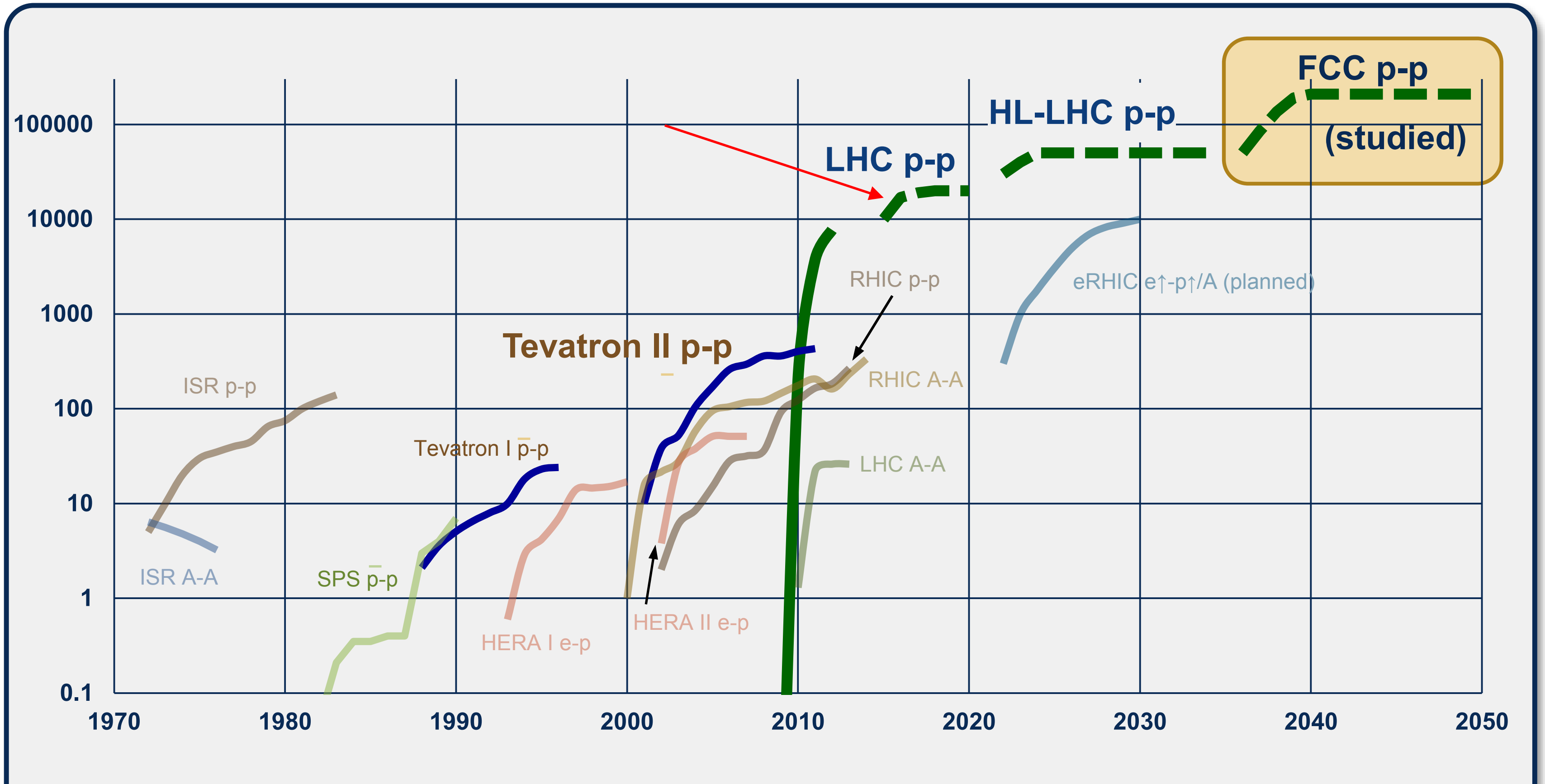
Requires a 80-100 km infrastructure in Geneva area



- SSC (Superconducting Super Collider): particle accelerator complex under construction in the vicinity of Waxahachie, Texas, to be the world's largest and most energetic Hadron Collider (87.1 km) and an c.m. energy of 40 TeV.
- When the project was cancelled in 1993, 22.5 km of tunnel and 17 shafts to the surface were already dug, nearly two billion dollars had already been spent on this facility.
- **Green field: no lab, no injectors, area moderately attractive….. and no working LHC**

Crazy ?

Luminosity evolution



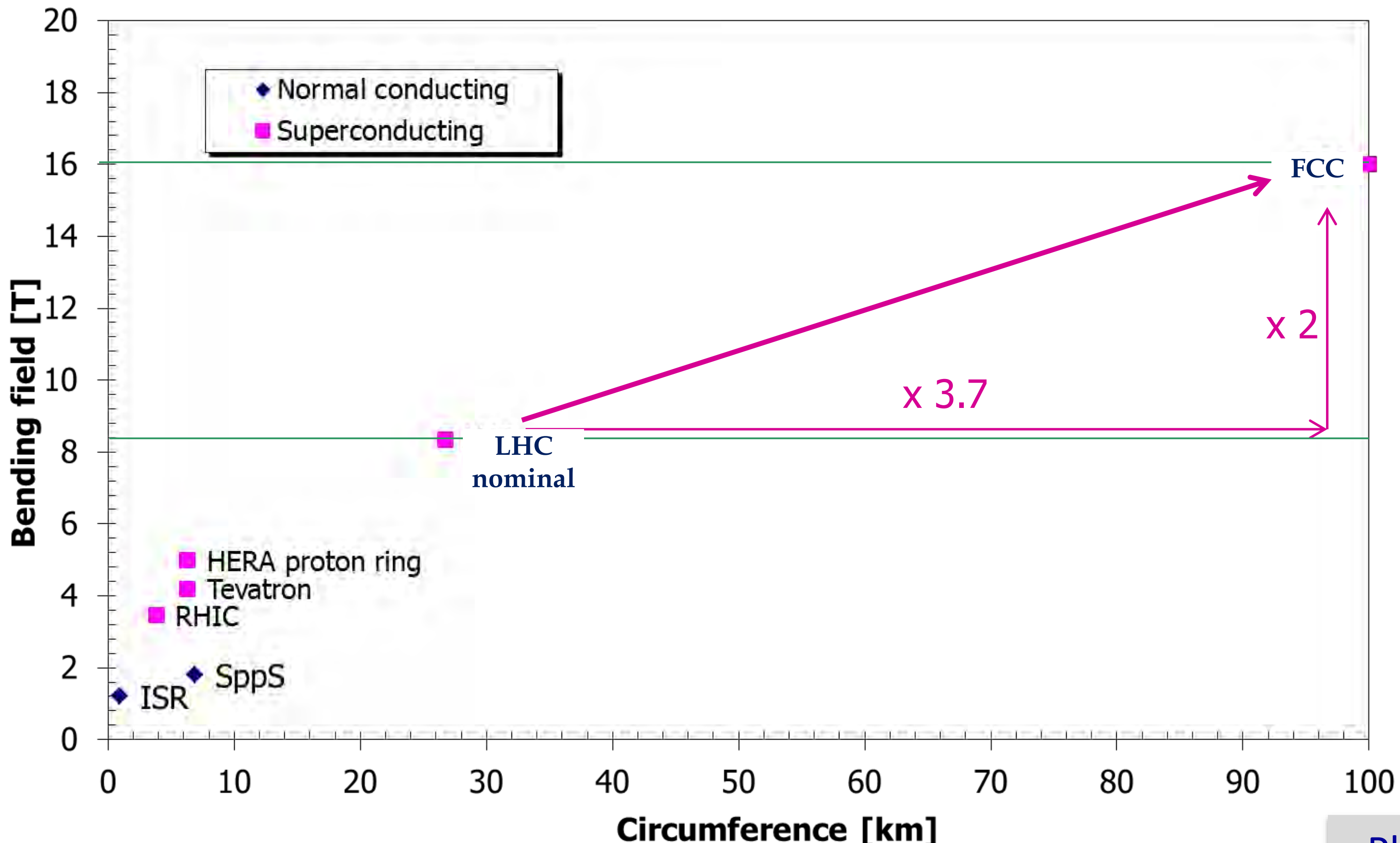
Hadron collider peak luminosity evolution per Interaction Point [x 10^{30} $cm^{-2}s^{-1}$]

FCC-hh parameter (other parameter sets exist)

parameter	FCC-hh	LHC nominal
Energy	**100 TeV c.m.**	14 TeV c.m.
Dipole field	**16 T**	8.33 T
Number of IP	2 main + 2	4
Normalized emittance	2.2 μm	3.75 μm
Luminosity / IP_{main}	$5 \times 10^{34}\ cm^{-2}s^{-1}$	$1 \times 10^{34}\ cm^{-2}s^{-1}$
Energy stored in each beam	**8.4 GJ**	0.36 GJ
Synchrotron radiation	**28.4 W/m/aperture**	0.17 W/m/aperture
Bunch spacing	25 ns (5 ns)	25 ns

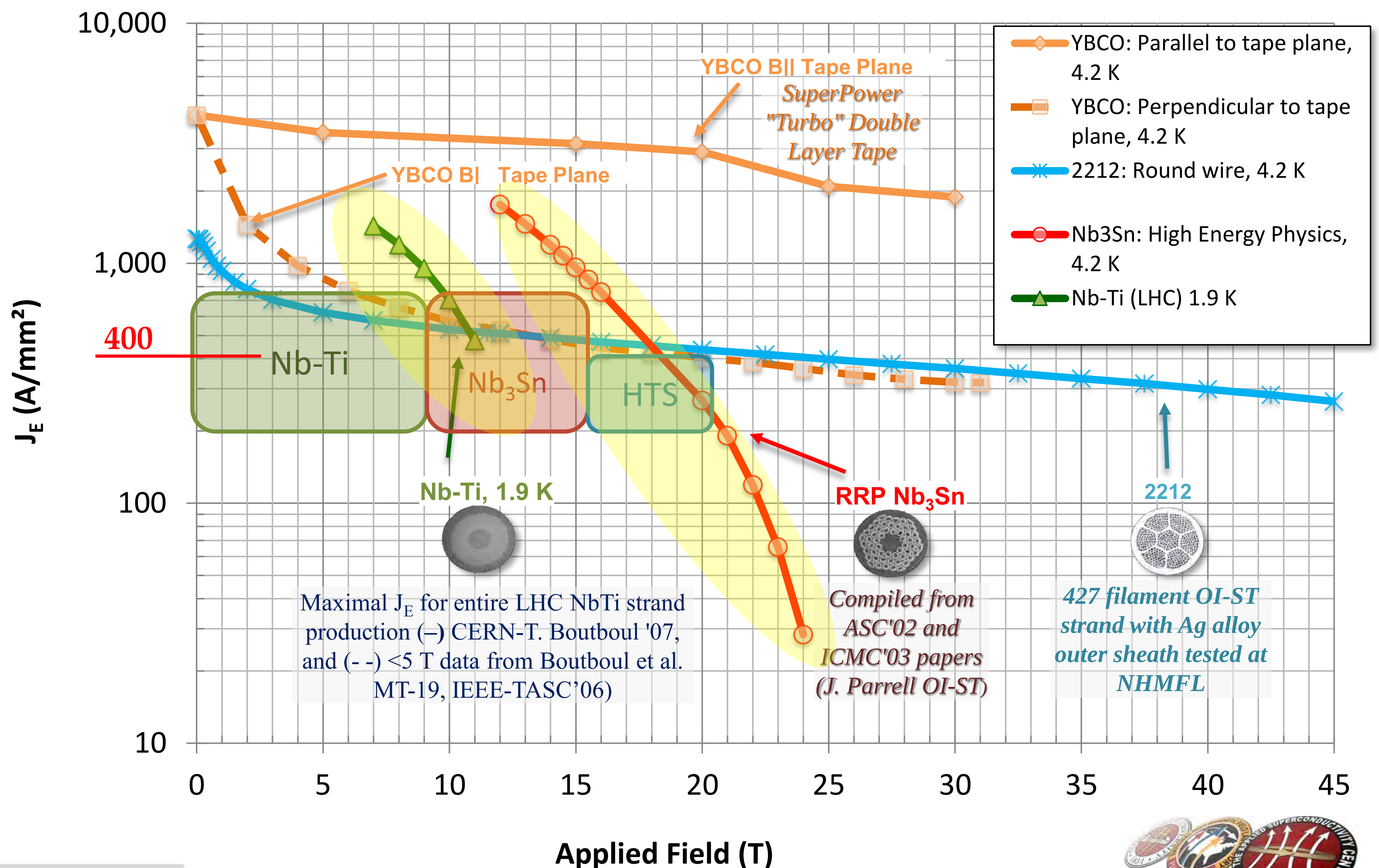
FCC-hh design targets

- Pushing the energy frontier by **maximizing the energy reach**
- **Hadron collider only option for** exploring energy scale at **tens of TeV**



Ph. Lebrun

Advanced superconductors to reach high fields



Ph. Lebrun

FCC-hh Challenges: Magnets

FCC-hh baseline: 16 T Nb3Sn technology for 100 TeV in 100 km

- **Develop Nb3Sn-based 16 T dipole technology**
  - With sufficient aperture of ~40 mm (LHC = 56 mm) and accelerator features (field quality, ability to protect, cycling operation)
  - Learn from Nb3Sn magnets in the LHC (HL-LHC 11 T dipoles)
  - Technology push to achieve duplication of critical current density of Nb3Sn
  - Possible goal: 16 T short dipole models by 2018 (in collaboration with America, Asia, Europe)

- **In parallel HTS development targeting 20 T**
  - HTS insert, generating 5 T additional field, ~40mm aperture and accelerator features
  - R&D goal: demonstrate HTS/LTS technology for building magnets with a field of 20 T

Stored energy 8 GJ per beam

- 20 times higher than LHC, equivalent to A380 (560 t) at nominal speed (850 km/h)

- Collimation, control of beam losses and radiation effects (shielding) important
- Injection, beam transfer and beam dump very critical

Damage of a beam with an energy of 2 MJ

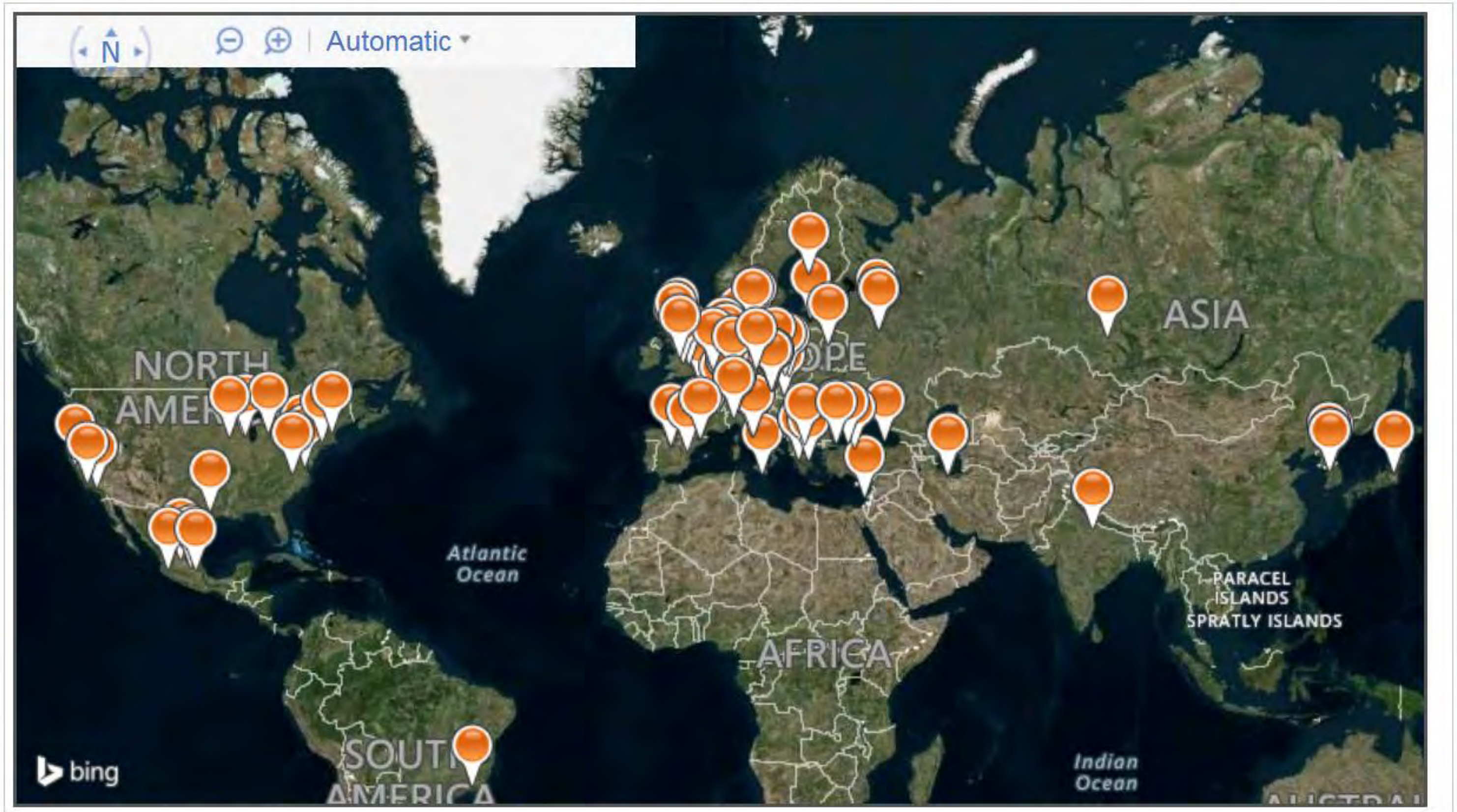
Machine protection issues to be addressed early on!

FCC-hh Accelerator Physics Challenges

- High synchrotron radiation load on beam pipe (up to 26 W/m/aperture in arcs, total of ~5 MW)
  - Heat extraction: photon stop, beam screen design, cryo load, ….
- Synchrotron radiation damping
  - Beams shrinking, controlled blow up, luminosity levelling, etc…
- Impedances, instabilities, feedbacks
  - Beam-beam, e-cloud, resistive wall, feedback systems design
- Optics and beam dynamics
  - IR design, dynamic aperture studies, SC magnet field quality

- Study launched at FCC kick-off meeting in February 2014
- Global collaboration based on general MoUs between CERN and individual partners + specific addenda for each participant, inc
- De ... am ap

Worldwide Collaboration



Scope of FCC study

- Main emphasis of the conceptual design study: long-term goal of a **hadron collider with a centre-of-mass energy** of the order **of 100 TeV** in a new tunnel of **80 - 100 km** circumference.
- Conceptual design study shall also **include a lepton collider** and its detectors, as a **potential intermediate step** towards realization of the hadron facility. Potential synergies with linear collider detector designs should be considered.
- Options for **e-p scenarios** and their impact on the infrastructure shall be examined at conceptual level.
- The study shall include **cost and energy** optimisation, **industrialisation** aspects and provide **implementation** scenarios, including **schedule and cost** profiles

German Members

- DESY, Hamburg
- FZJ, Jülich
- GSI, Darmstadt
- IML, Dortmund
- KIT/ANKA, Eggenstein-Leopoldshagen
- TU Darmstadt, Darmstadt
- TU Dresden, Dresden
- TUBF, Freiberg
- TUDO, Dortmund
- UFRA, Frankfurt am Main
- UROS, Rostock
- USIEGEN, Siegen
- USTUTT, Stuttgart

Parameter for the FCC e+e- collider

	Z	Z	W	H	tt
Circumference [km]	100				
Bending radius [km]	11				
Beam energy [GeV]	45.6		80	120	175
Luminosity/IP for 2IPs [10^{34} $cm^{-2}s^{-1}$]	207	90	19.1	5.1	1.3
Horizontal beam size at IP σ^* [μm] Vertical beam size at IP σ^* [nm]	10 32	9.5 45	16 45	25 49	36 70
Crossing angle at IP [mrad]	30				
Energy spread [%] - Synchrotron radiation - Total (including BS)	 0.04 0.22	 0.04 0.09	 0.07 0.10	 0.10 0.12	 0.14 0.17
Bunch length [mm] - Synchrotron radiation - Total	 1.2 6.7	 1.6 3.8	 2.0 3.1	 2.0 2.4	 2.1 2.5
Energy loss / turn [GeV]	0.03		0.33	1.67	7.55
SR power / beam [MW]	50				

HE – LHC

HE-LHC

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36

HE-LHC

parameter	FCC-hh	HE-LHC	(HL) LHC
beta* [m]	1.1-0.3	0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)	2.5 (0.5)	(2.5) 3.75
rms IP beam size [μm]	6.7 (3) – 3.5 (1.5)	6.6 (3.0)	(8.2) 16.7
half crossing angle [μrad]	37 - 70	131 (60)	(255) 143
Piwinski angle	0.42 – 1.51	1.50 (1.50)	(2.52) 0.65
crab cavities needed	NO - YES	YES (YES)	(YES) NO
synchr. rad. power / ring [kW]	2400	101	(7.3) 3.6
beam-screen half aperture [mm]	13.2	13.2 or 14	17
beam-screen temperature [K]	50	20 or 50	20
SR power / length [W/m/ap.]	28.4	4.6	(0.33) 0.17
ΔE / turn [keV]	4600	93	6.7
long. emit. damping time [h]	0.54	1.8	12.9
total cross section [mbarn]	156	125	112
inelastic cross section [mbarn]	109	91	82

Injection energy

The injection energy usually scaled with the top energy

- LHC has a dynamic range of 16 (from 450 GeV to 7 TeV), which is already challenging
- A higher energy allows to reduce the magnet aperture from 56 mm to 40 mm
    - reduction of cost related to the coil
    - more compact coil in a situation where the tunnel size becomes a hard constraint
    - less stored energy
- This requires an upgrade of the injector complex, with a superconducting SPS as a possible option
- An alternative option to inject at 450 GeV is being investigated

Conclusions

- LHC demonstrated that an ultra-complex accelerator can **operate reliably**, **achieve high luminosity** and **produce excellent physics**
- The next step is HL-LHC – with an **increase of integrated luminosity** by **one order of magnitude**
- **Reaching a luminosity an order of magnitude above 10^{34} [$cm^{-2}s^{-1}$] and operating reliably is a formidable challenge**
- Today, the **only realistic option** to collide particles at a c.m. energy in the range **of 100 TeV** are **circular proton colliders**
- We will **learn from HL-LHC** as a preparation **for FCC**
- **HE-LHC might be a step in between**
- Discussing other options, such as a linear collider or a e-LHC (electron proton collider) – requires input from particle physics

Thanks for your attention

Plumber visiting Breisach

Thanks a lot for slides from several colleagues, in particular A.Apollonio, G.Arduini, M.Lamont, A.Lechner and J.Wenninger