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

Introduction to accelerator physics and technology: The Large Hadron Collider

Rüdiger Schmidt

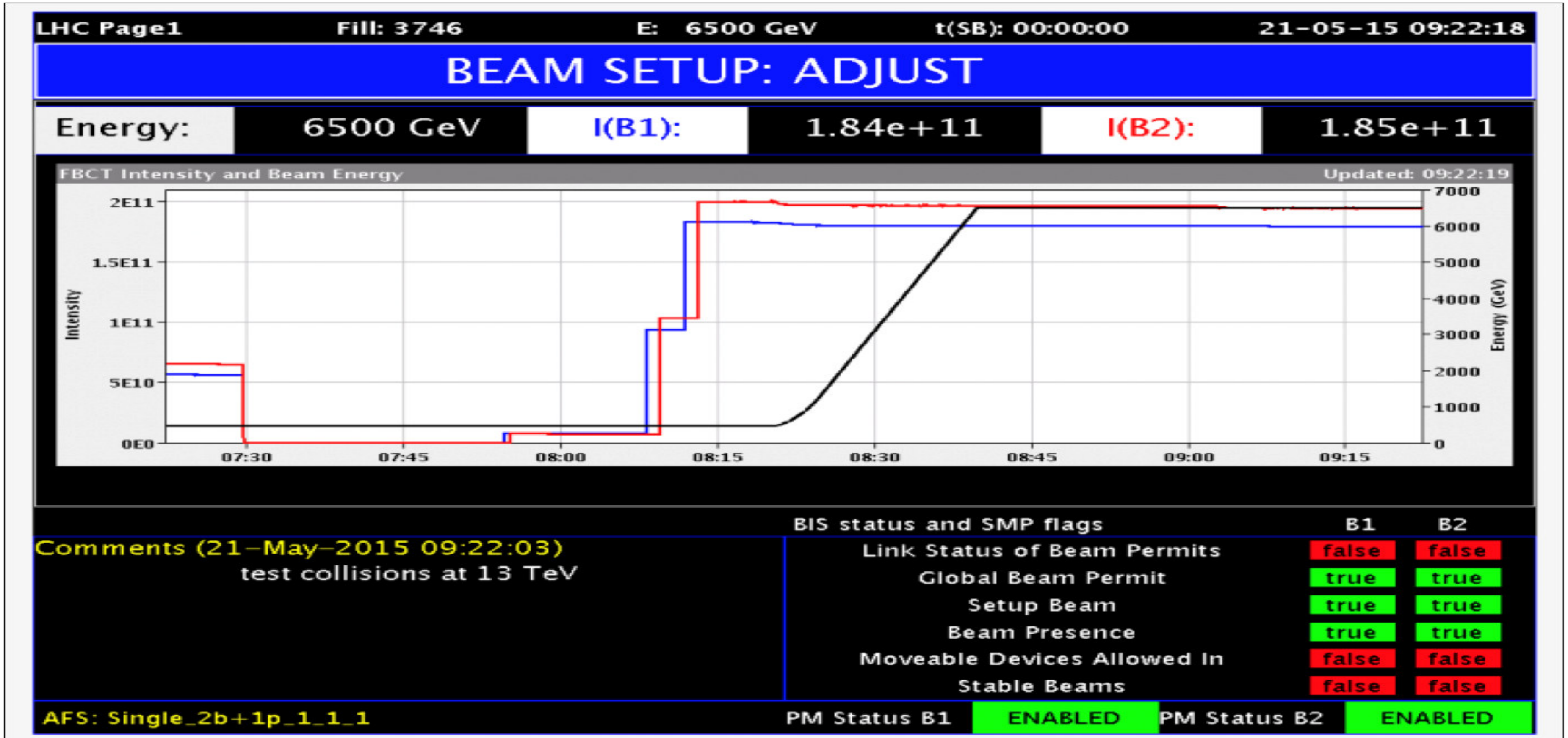
KIT Workshop Freudenstadt 2015

To accelerate a particle to very very high energy …

Particle energy about $2*10^{10}$ TeV

First images of collisions at 13 TeV

by Cian O'Luanaigh

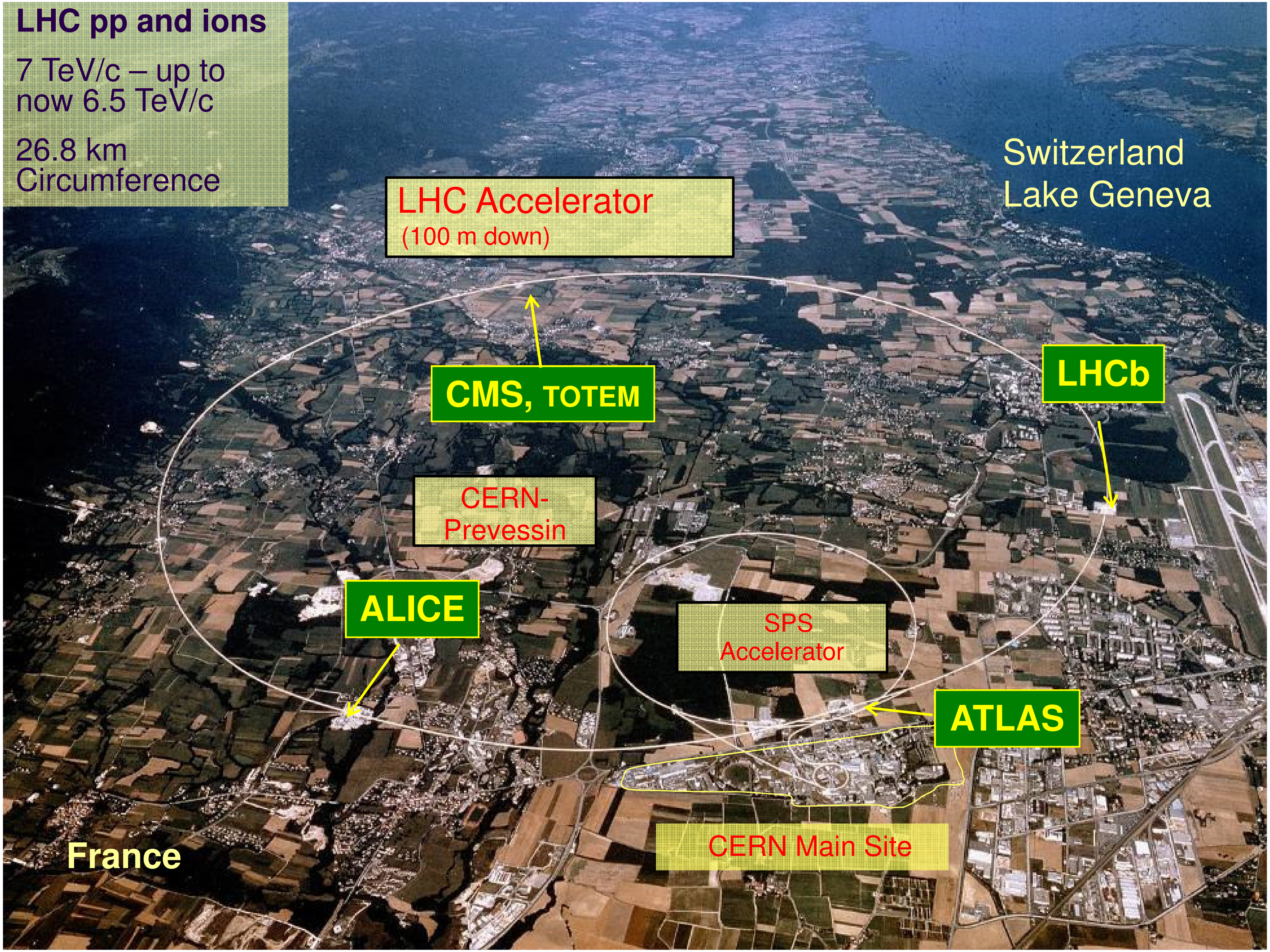


Test collisions continue today at 13 TeV in the Large Hadron Collider (LHC) to prepare the detectors ALICE, ATLAS, CMS, LHCb, LHCf, MOEDAL and TOTEM for data-taking, planned for early June (Image: LHC page 1)

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

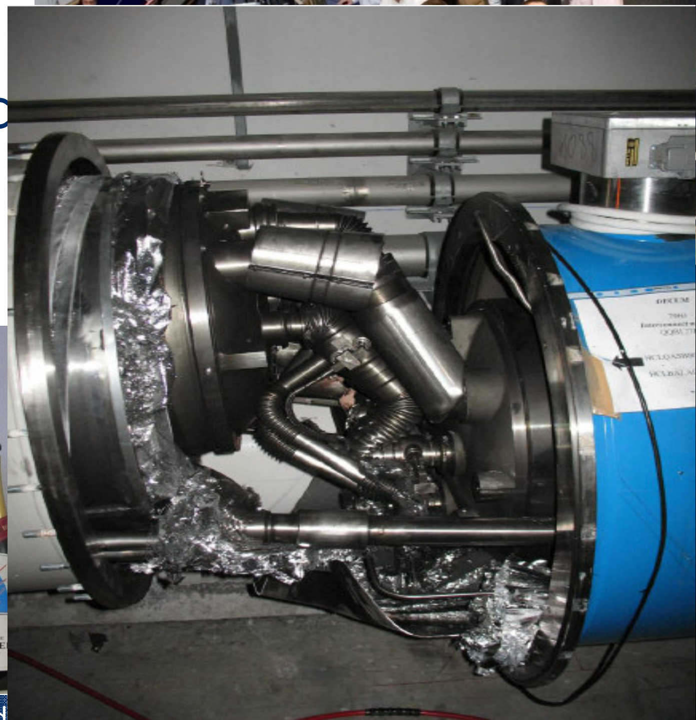


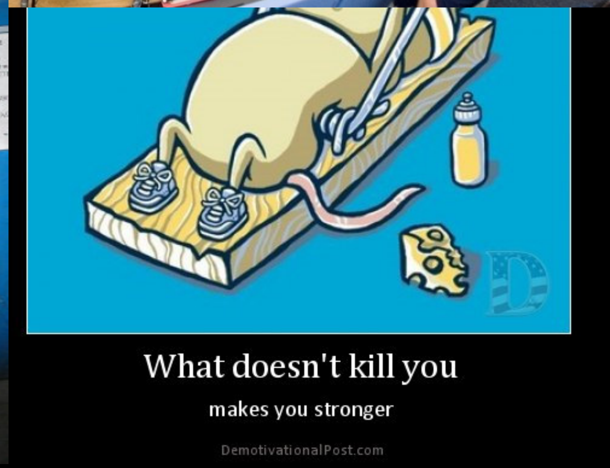
LHC pp and ions
7 TeV/c – up to now 6.5 TeV/c
26.8 km Circumference
LHC Accelerator (100 m down)
Switzerland
Lake Geneva
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
CERN Main Site
France

LHC: A long story starting in the distant past

- First ideas to first p
- Tears of joy…. firs
- Tears of despair (a

- The story of the c





Overview

- Accelerator physics and LHC crash course - DONE
- Energy and Luminosity
- What is accelerator physics?
- Acceleration and deflection of charged particles
- Energy and Luminosity Challenges
- Short Accelerator Physics 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: FCC study…..

Energy and Luminosity

Energy and (integrated) Luminosity

- Particle physics requires an accelerator colliding beams with a centre-of-mass energy as high as possible
- The event rate is determined by cross-section and luminosity

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

- In order to observe events with low cross-section, the luminosity should exceed 10^{34} [$cm^{-2}s^{-1}$]
- The time available for data-taking with high luminosity is important

Integrated Luminosity and Availability

- The total number events is proportional to the **Integrated Luminosity**:

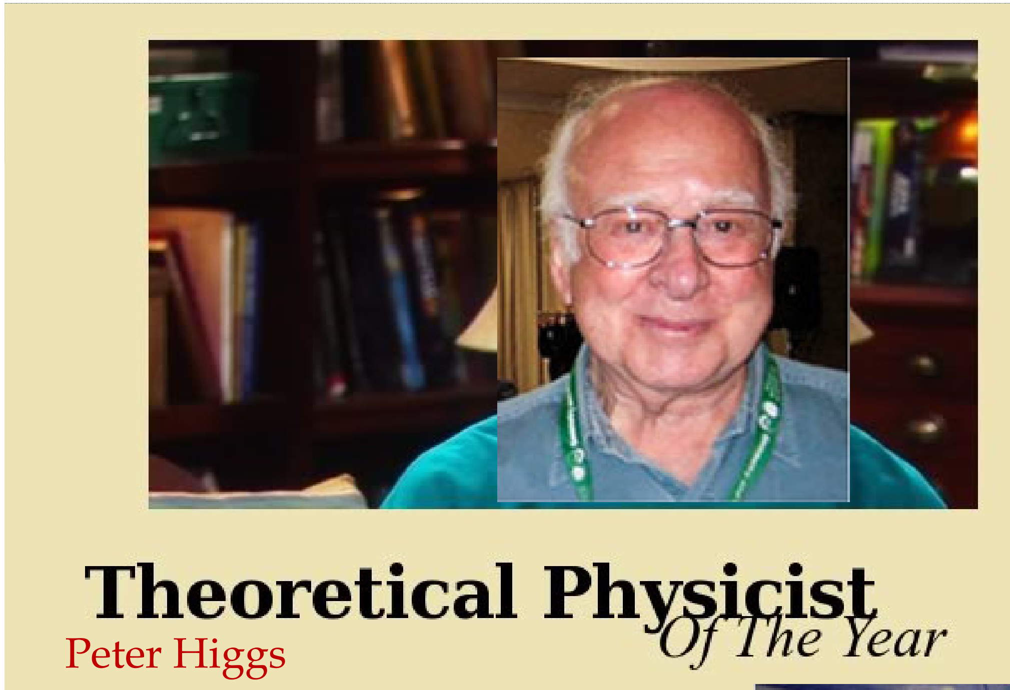
$$\int L(t) \times dt$$

- 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

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 7.7× 10^{33}	**362** now 180
Factor			7	4	2	**50**	**100**

What is Accelerator Physics ?



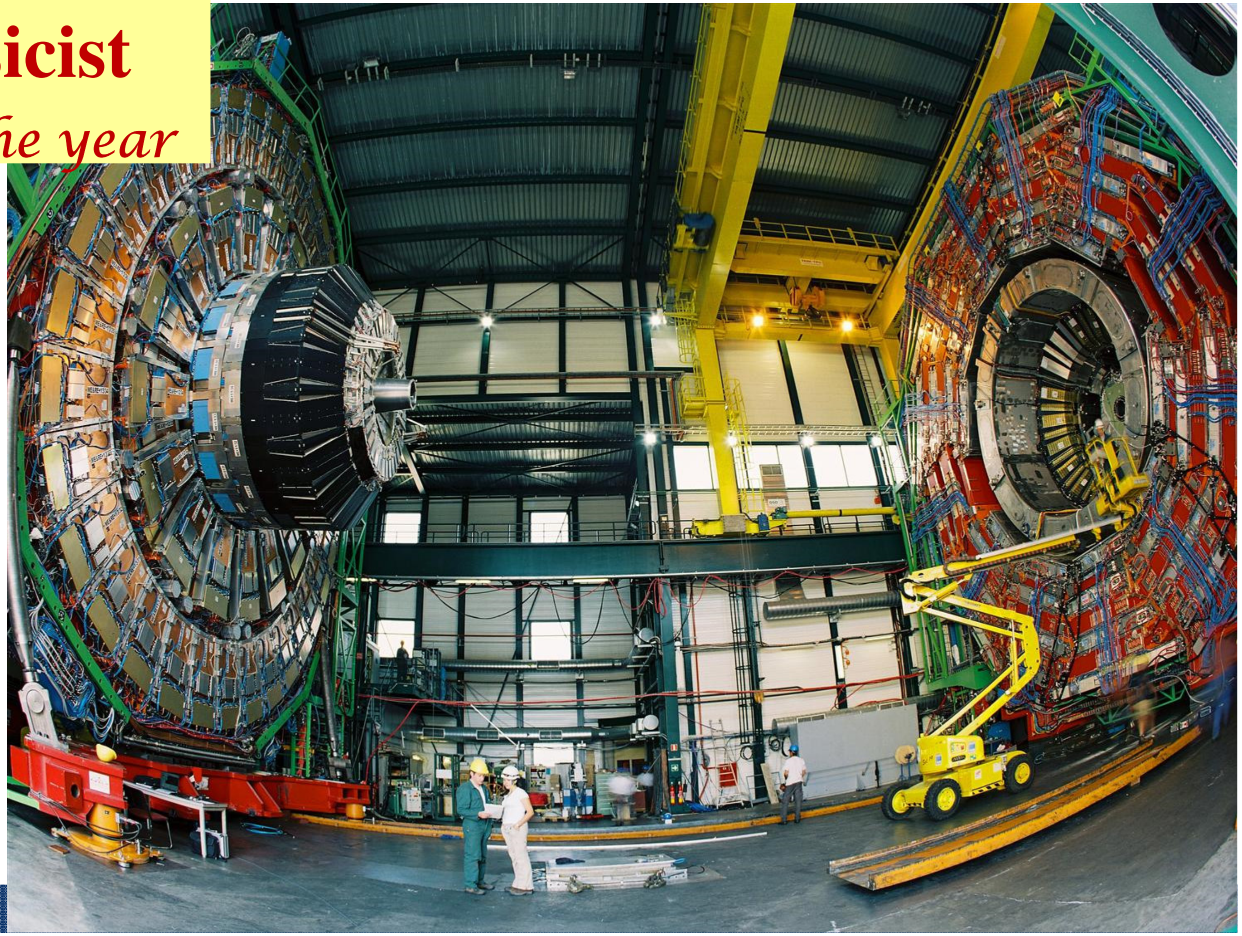
thinking, thinking, thinking ….
and predicting the results

….sometimes correctly!

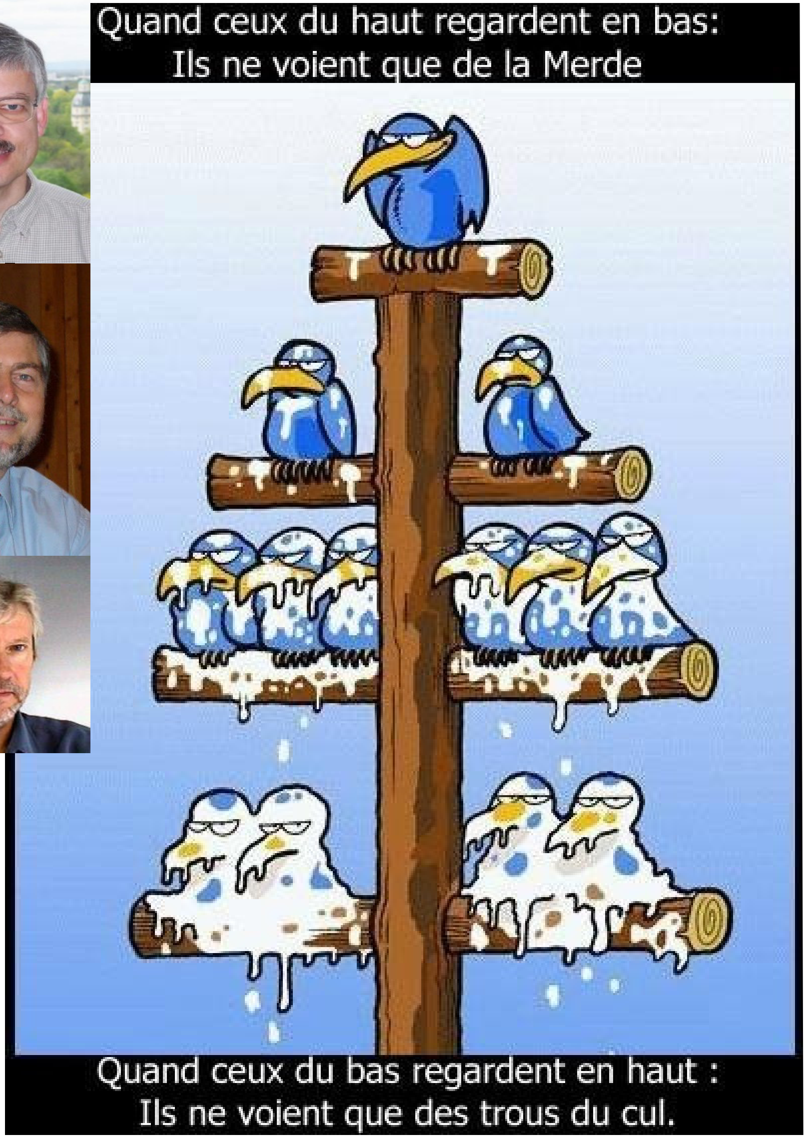
…building the detectors and
analysing the results

Experimental Physicist

F.Gianotti *Person of the year*



The hierarchy in physics



DIE ZEIT 19/7/2012

citing Mike Lamont (Head of CERN accelerator operation):

Among physicists there is a hierarchy: » On top are the theorists, then the experimental physicist, then us, the machine people.«

German original: Und unter den Physikern gebe es eine Hierarchie: »Ganz oben stehen die Theoretiker, dann kommen die Experimentalphysiker und dann wir, die Maschinenleute.«

Accelerator Physicist

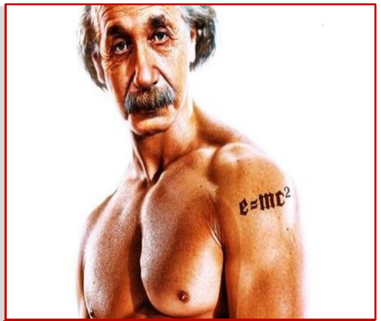
Plumber of the year

…building very long, exceptionally cold and extremely complex machines …

What is accelerator physics … and technology?

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 fairly clever plummer is needed

Plus: mechanical engineering, electrical engineering, computing science, metrology, civil engineering

Plus: 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)?

Lorentz Force

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:

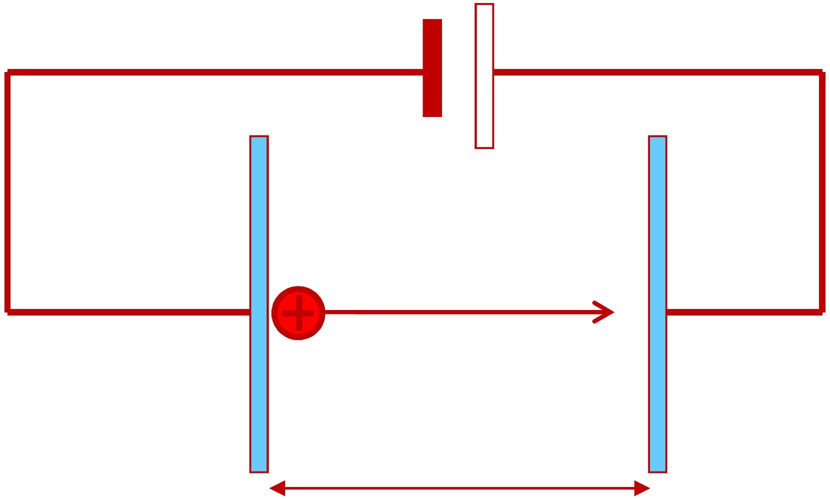
$$\Delta E = \int_{s1}^{s2} \vec{\mathbf{F}} \cdot \mathbf{d}\vec{\mathbf{s}}$$

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

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

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

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



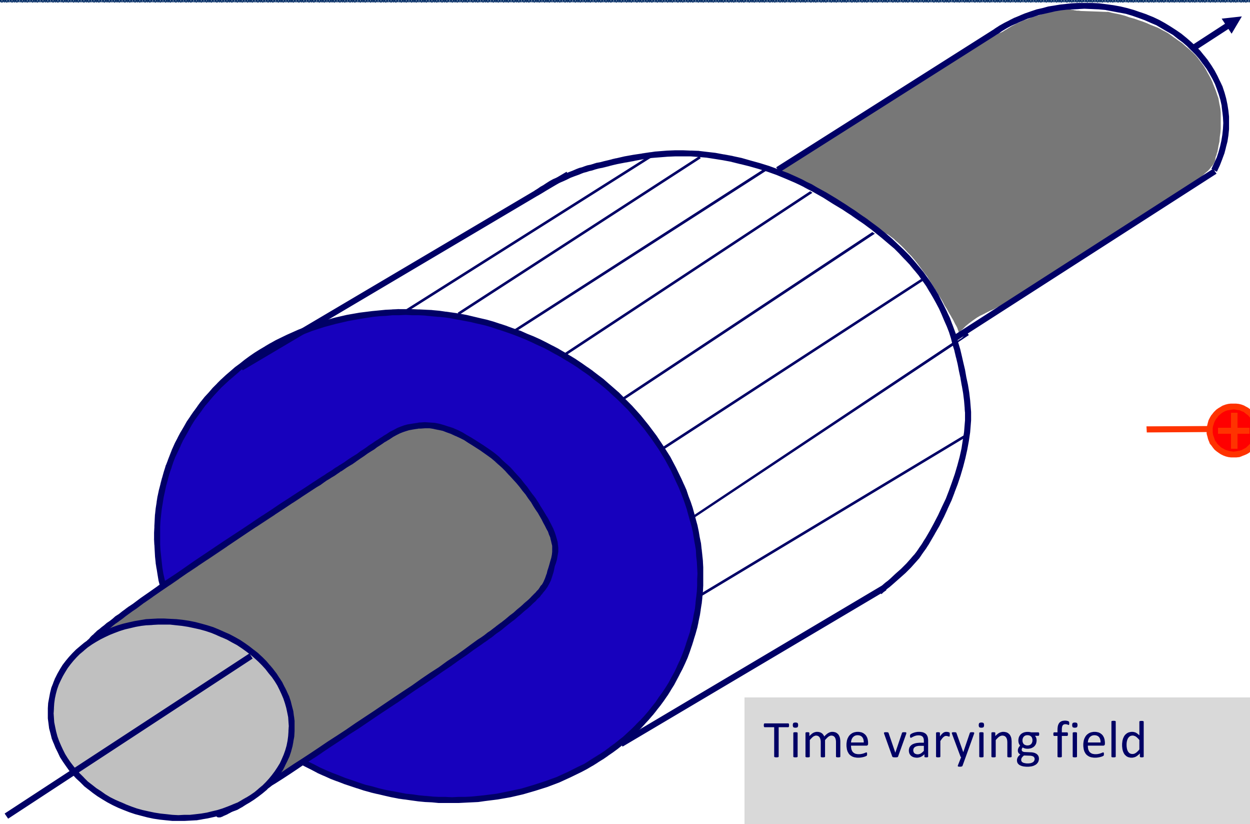
1 MeV requires
U = 1 MV

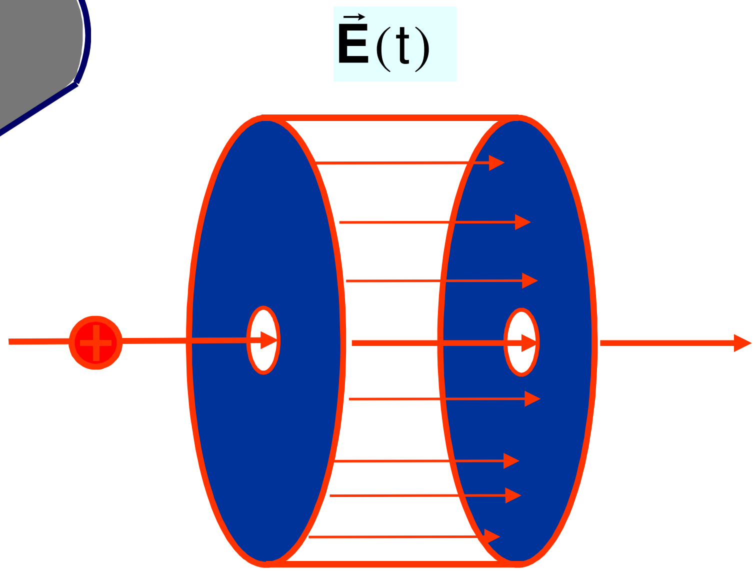
Acceleration of elementary particles to high energy in an electrical field,
e.g. 1 GeV => 1 GV

- 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)

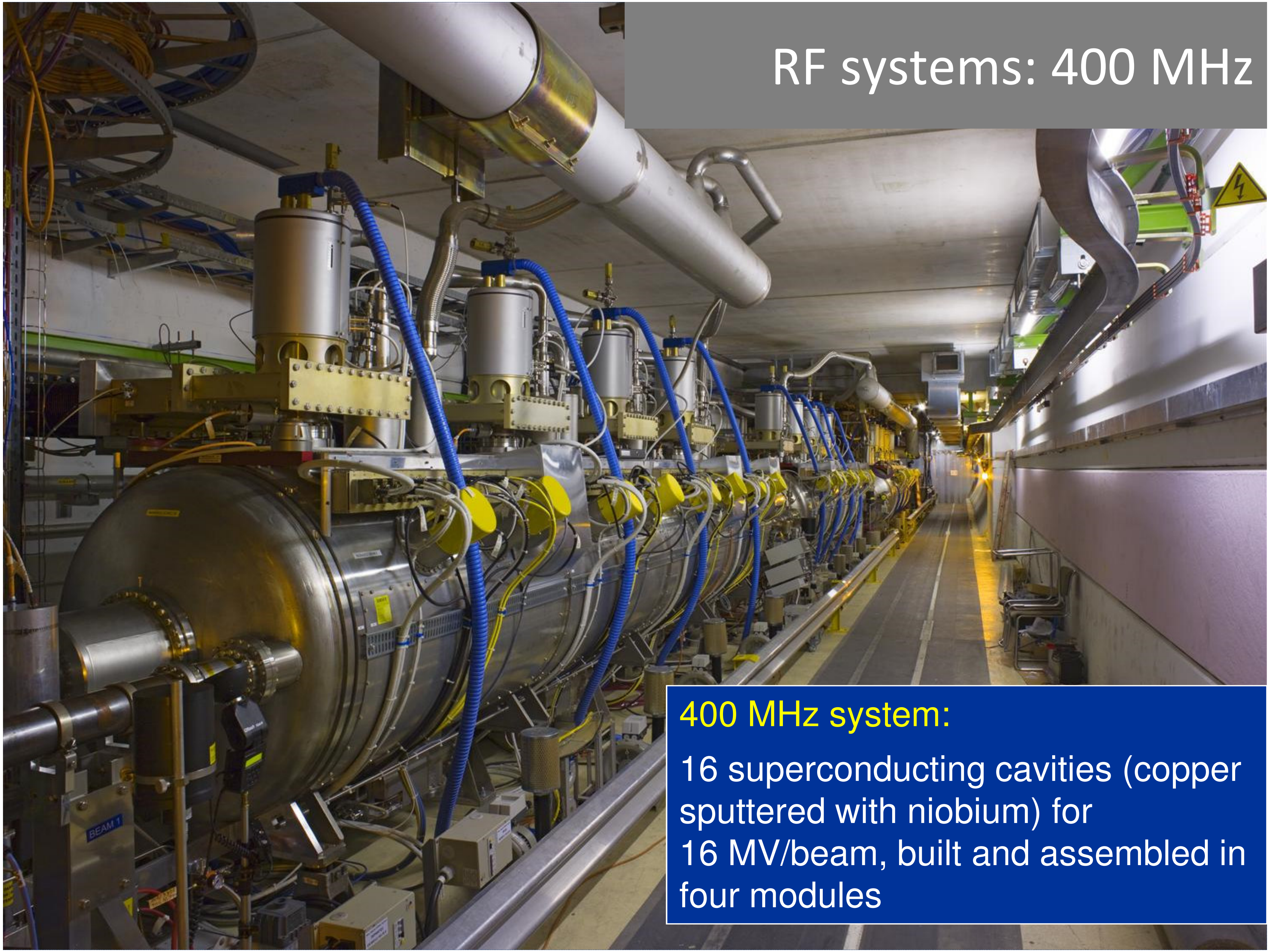
Time varying field

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

Maximum field about 30-40 MV/m

Beams are accelerated in bunches (no continuous beam)

RF systems: 400 MHz

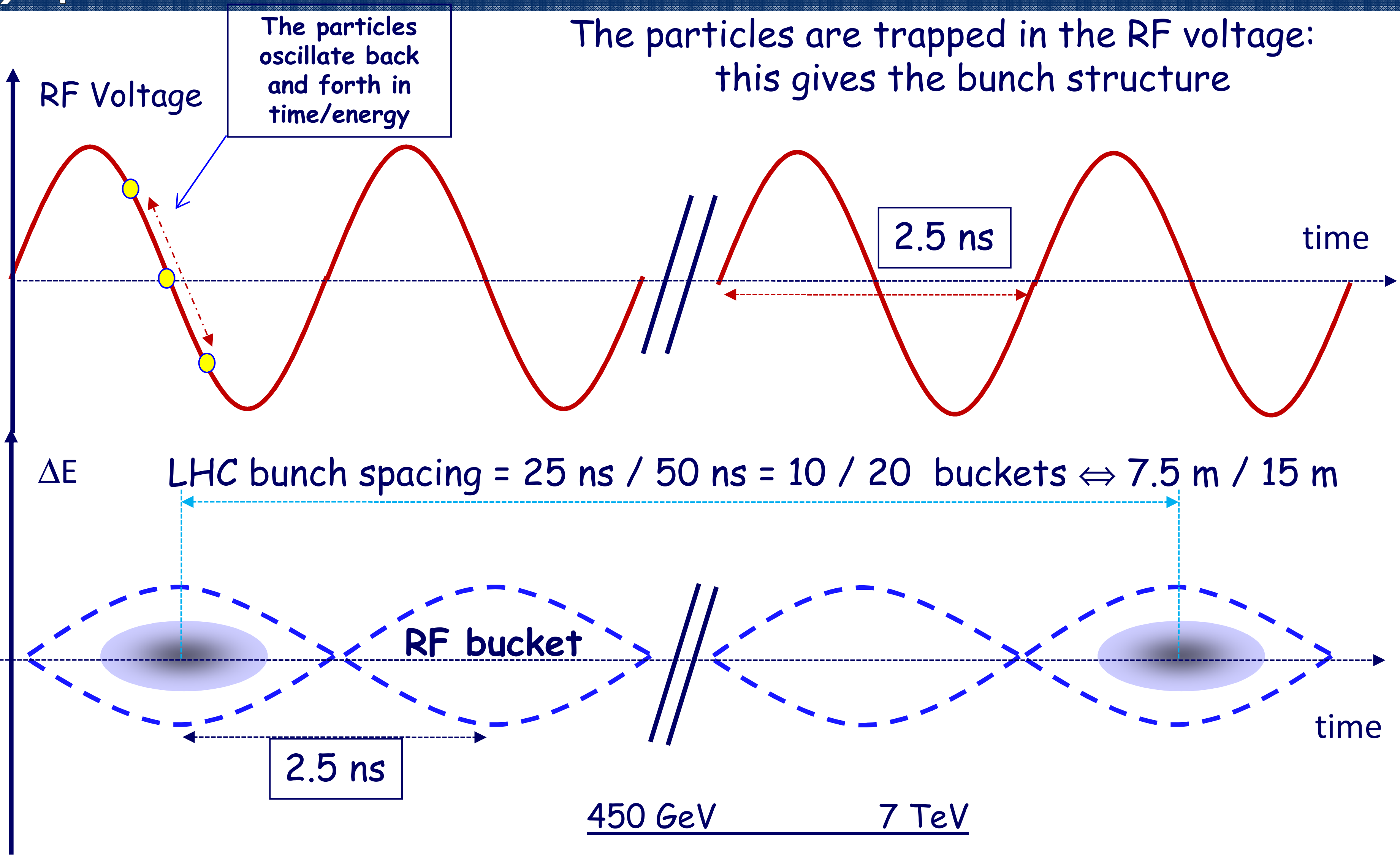


400 MHz system:

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

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%

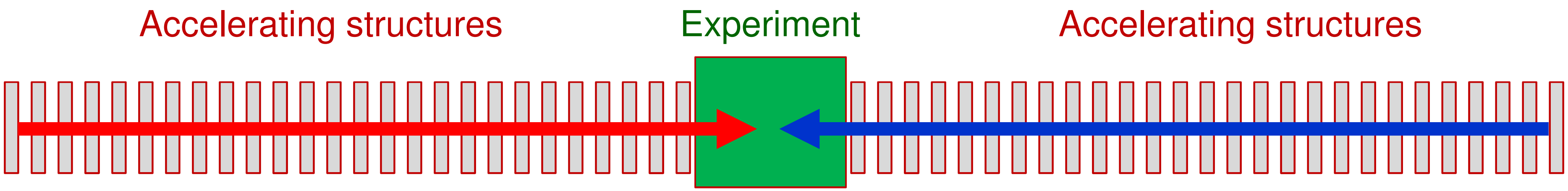
To collide particles at very high energy

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 perticles are colliding only once at the center of the experiment



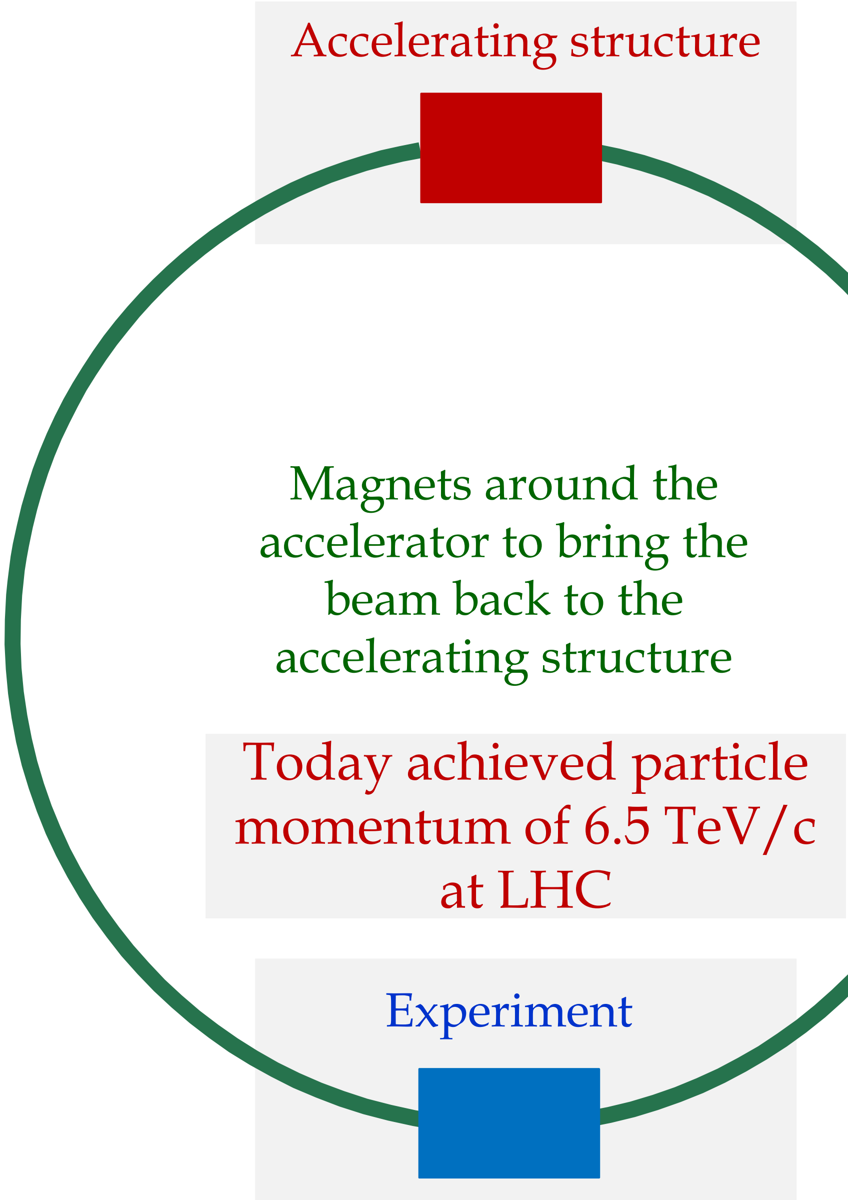
Acceleration of particles with time-varying electrical field

- 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

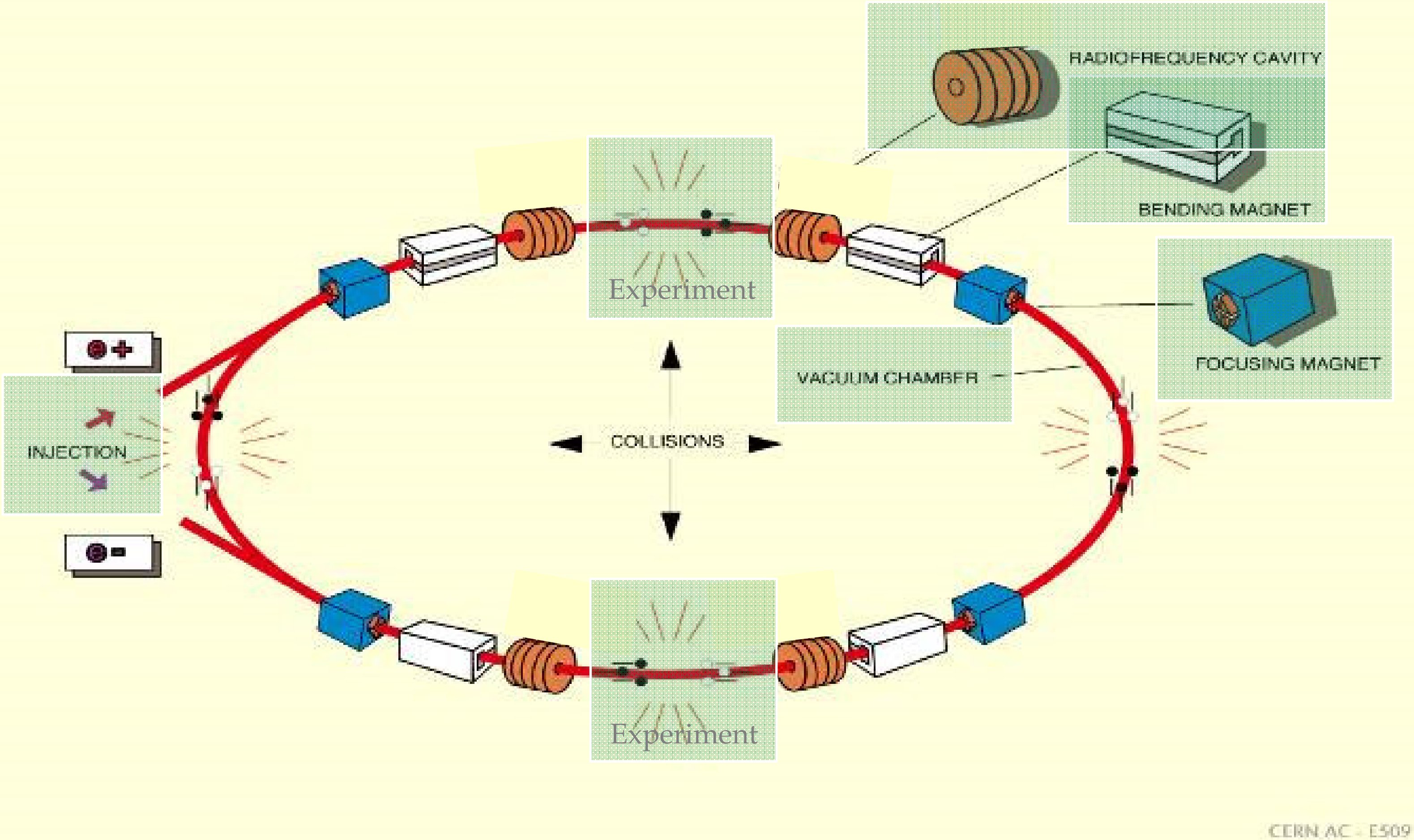
Circular accelerator: re-use accelerating structure

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**

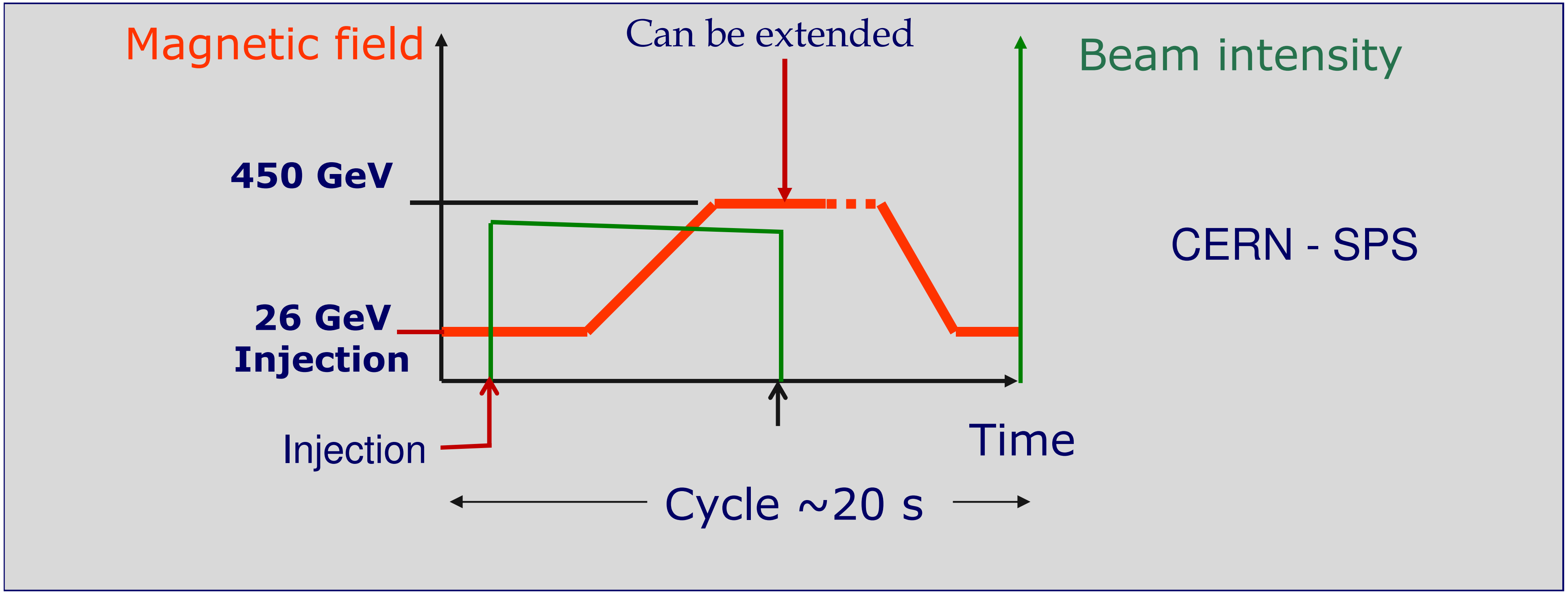


LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 6.5 TeV takes about 20 minutes



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

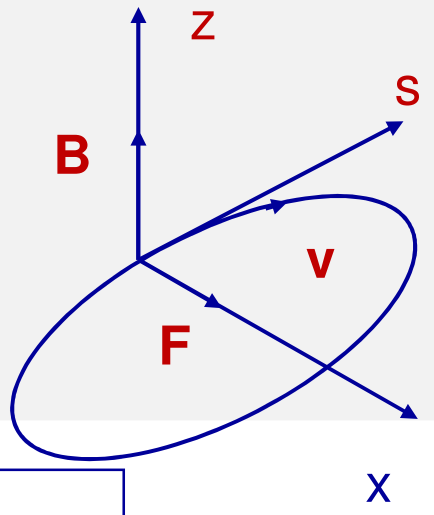
  and about 100 times more particles: 2.2 kW

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:

$$\boldsymbol{p} = \boldsymbol{B} \cdot \boldsymbol{\rho} \cdot \boldsymbol{e_0}$$



Example for LHC

- Radius $\boldsymbol{\rho}$ = 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	0.000	222.00

Protons with synchrotron radiation loss GeV/turn as electrons in LEP: magnetic field more than one order of magnitude above what is possible today (14 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]
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p	14000.00	1.02E-04	0.00	0.00	16.60
p	187232.00	3.22	0.00	0.000	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

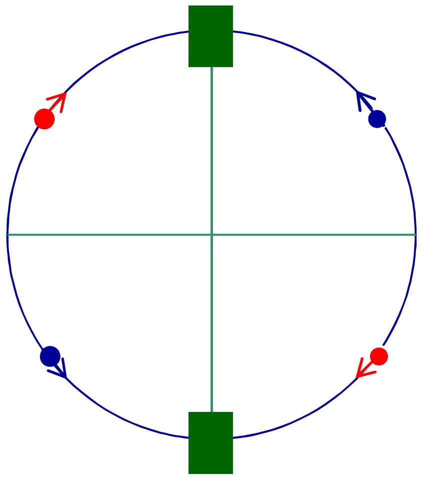
Head-on crossing: $$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y}$$

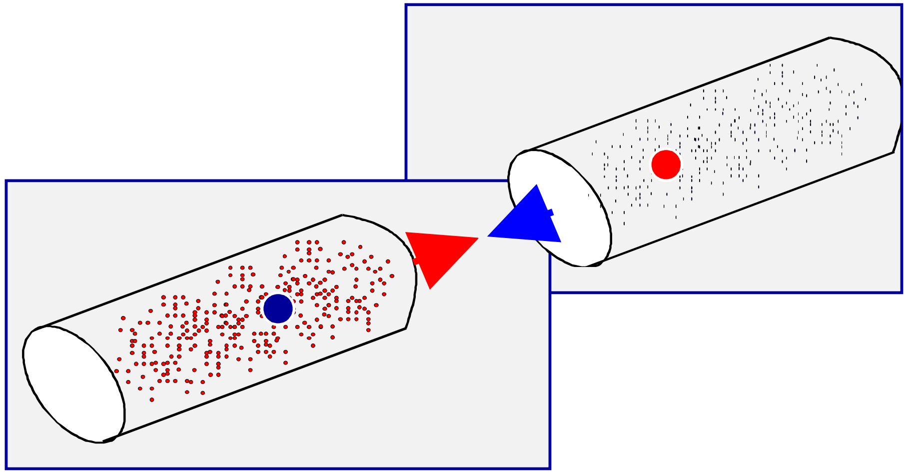
N … number of protons per bunch

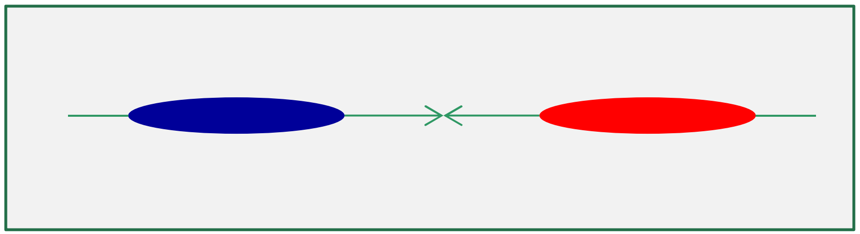
f … revolution frequency

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**

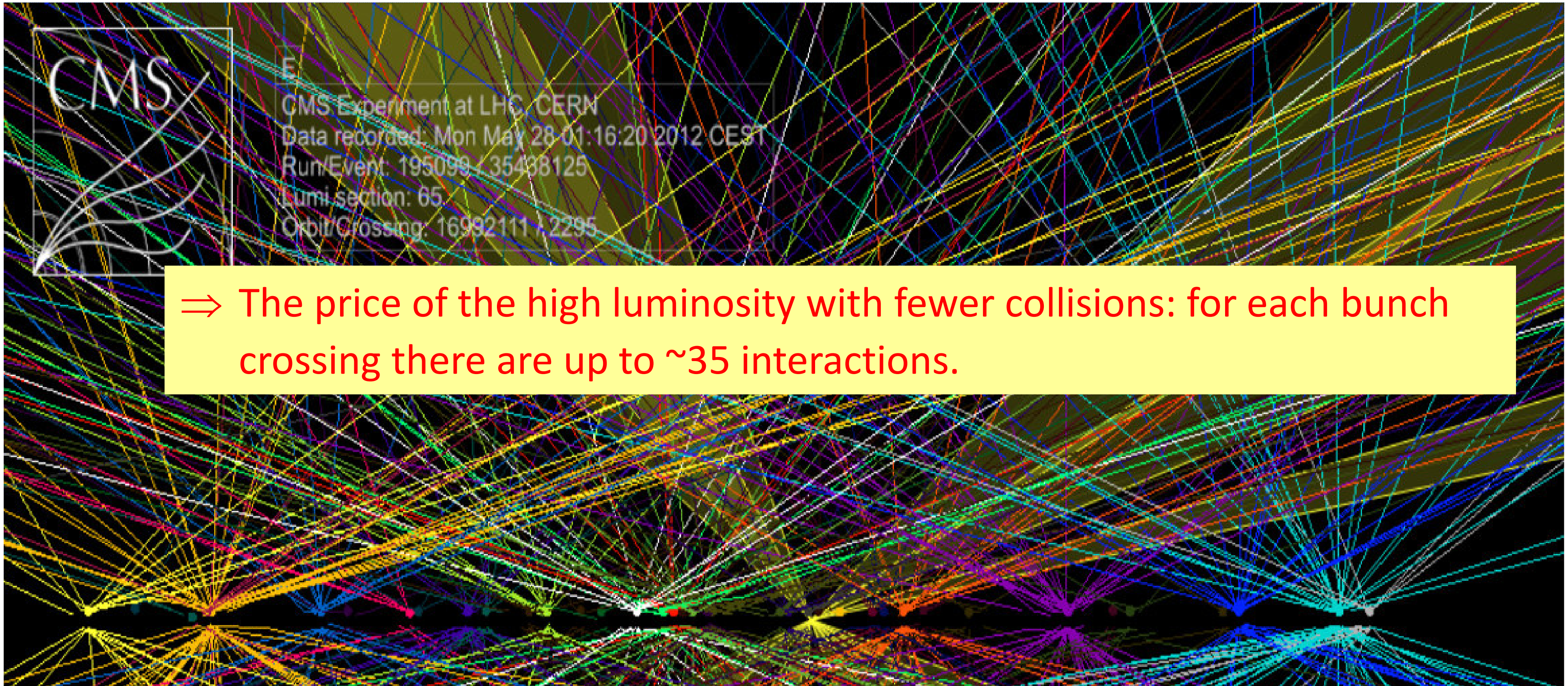
Beam size given by injectors and by space in vacuum chamber

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

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

~**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

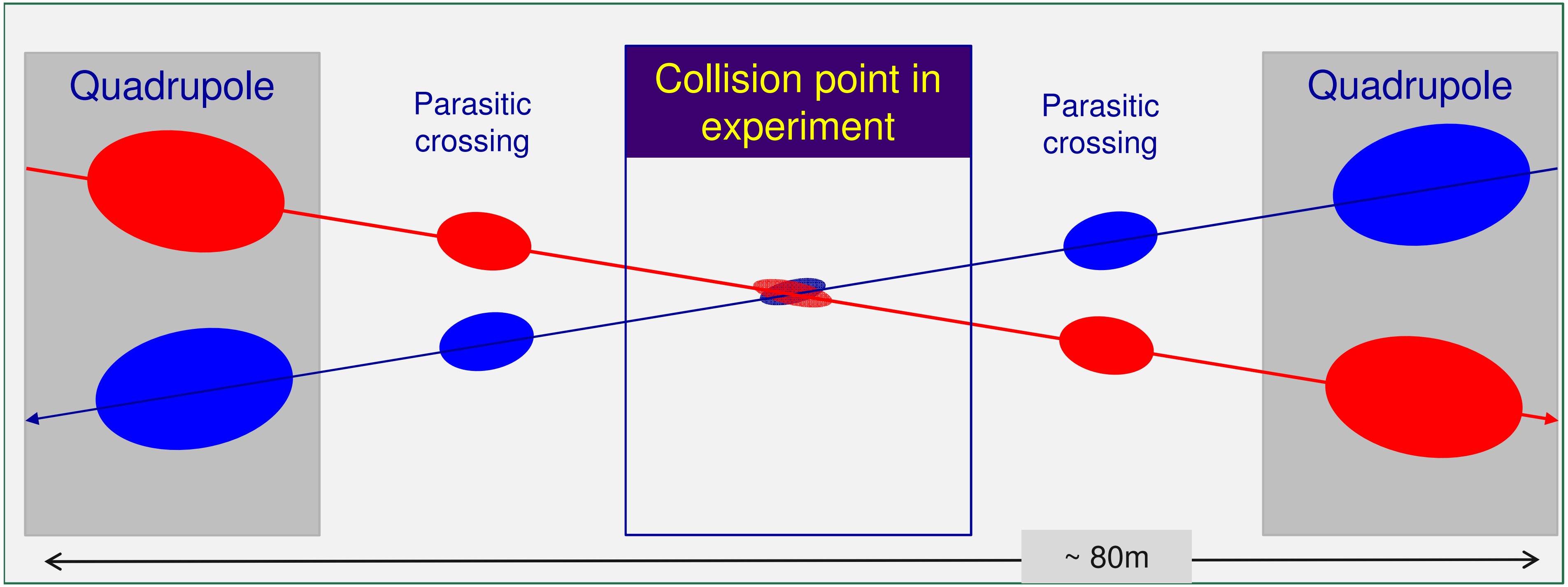
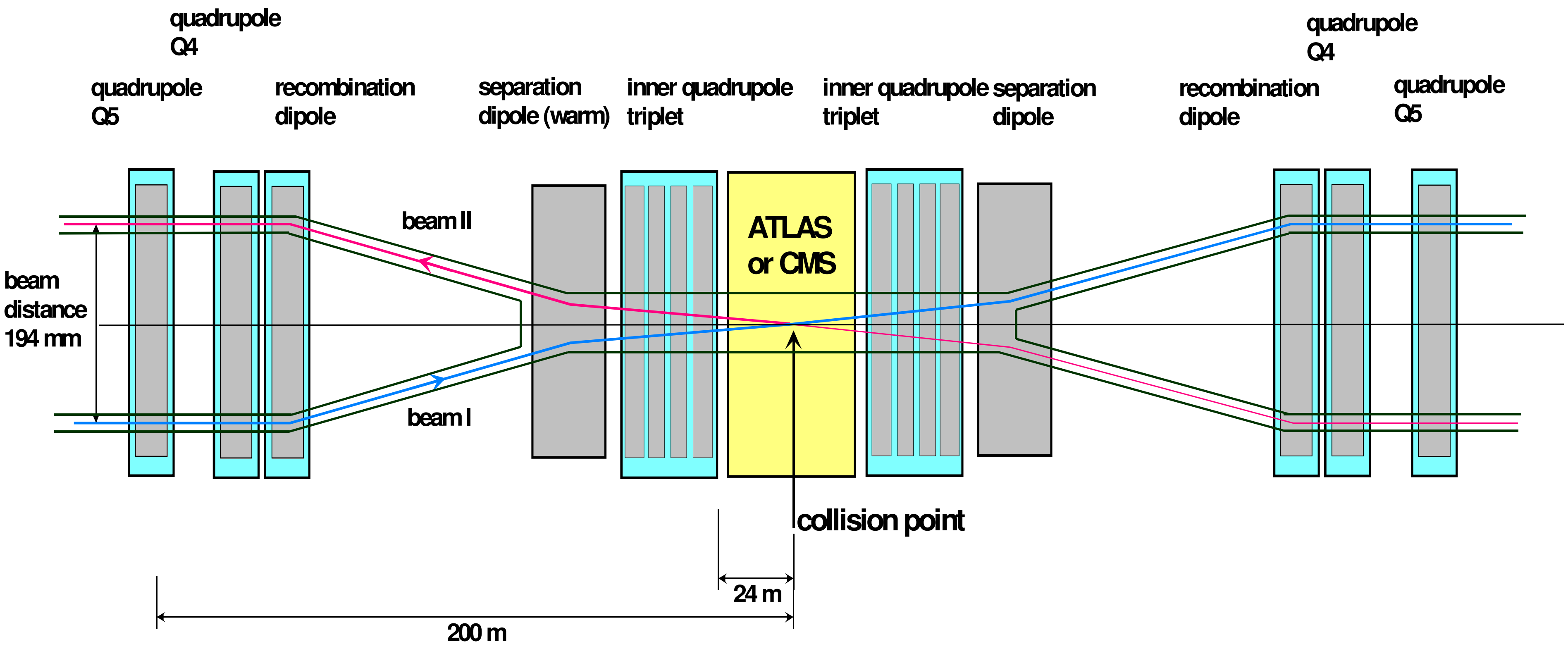


Illustration drawing

- 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:

Event pile up for one bunch crossing:

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

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

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

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

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

$frev_{lhc} = 1.1246 \times 10^{4}\,\frac{1}{\text{s}}$ 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)

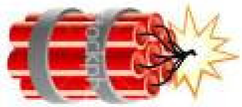
Beam dynamics

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

Energy stored in the beam

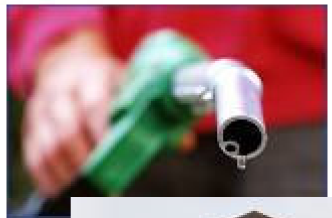
For LHC at 7 TeV/c the energy stored in the beam is equal to 362 MJ

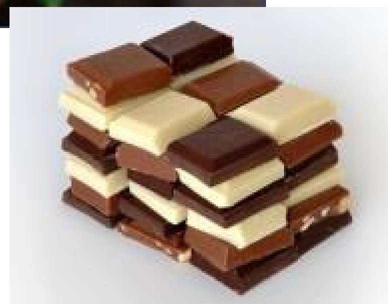
The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 362 MJoule stored in one LHC beam



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

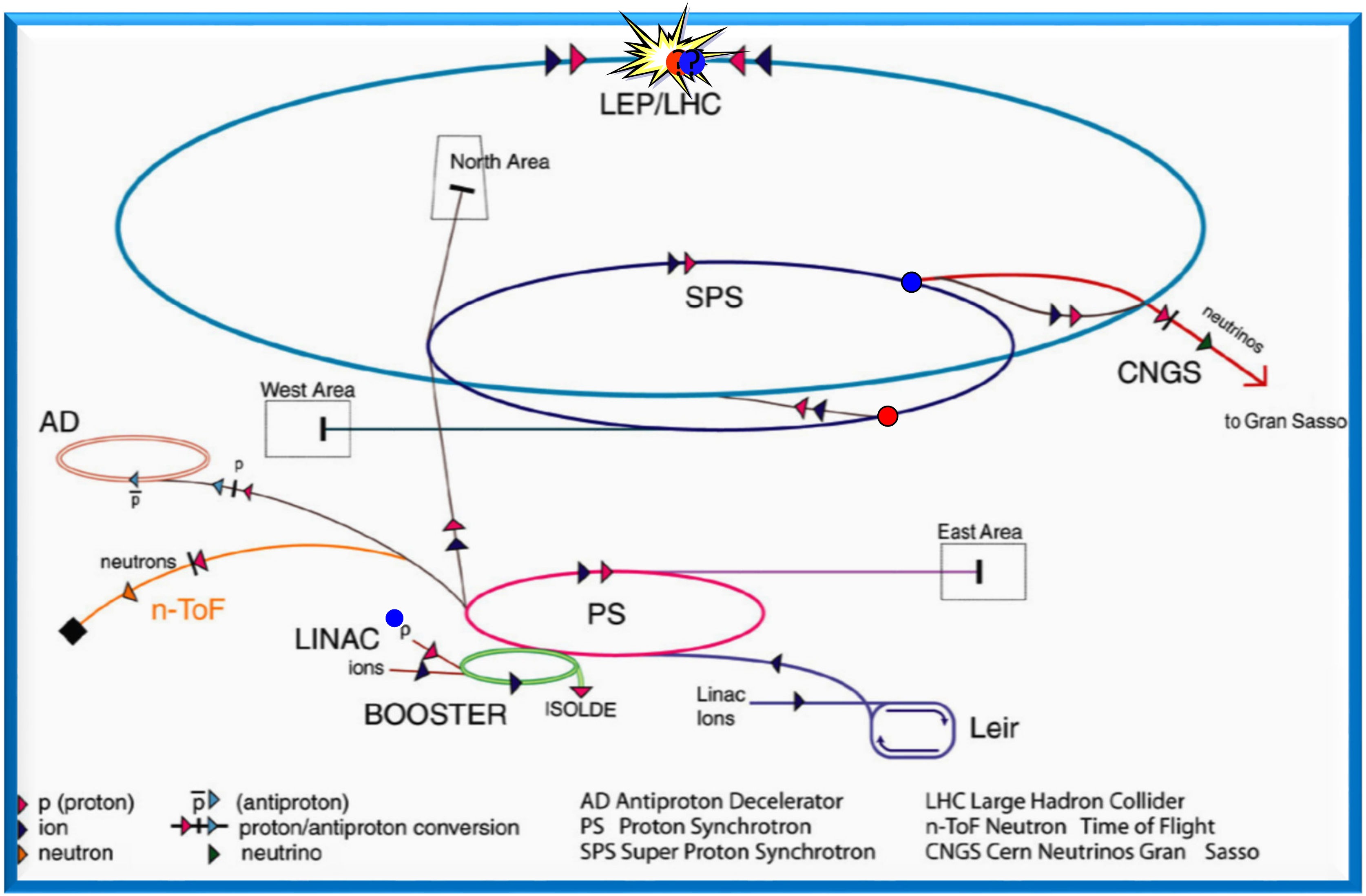
$$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y}$$

- Betatron oscillations
- Betatron tune (Q value)

Short Accelerator Physics Course

How to transport particles in an accelerator?

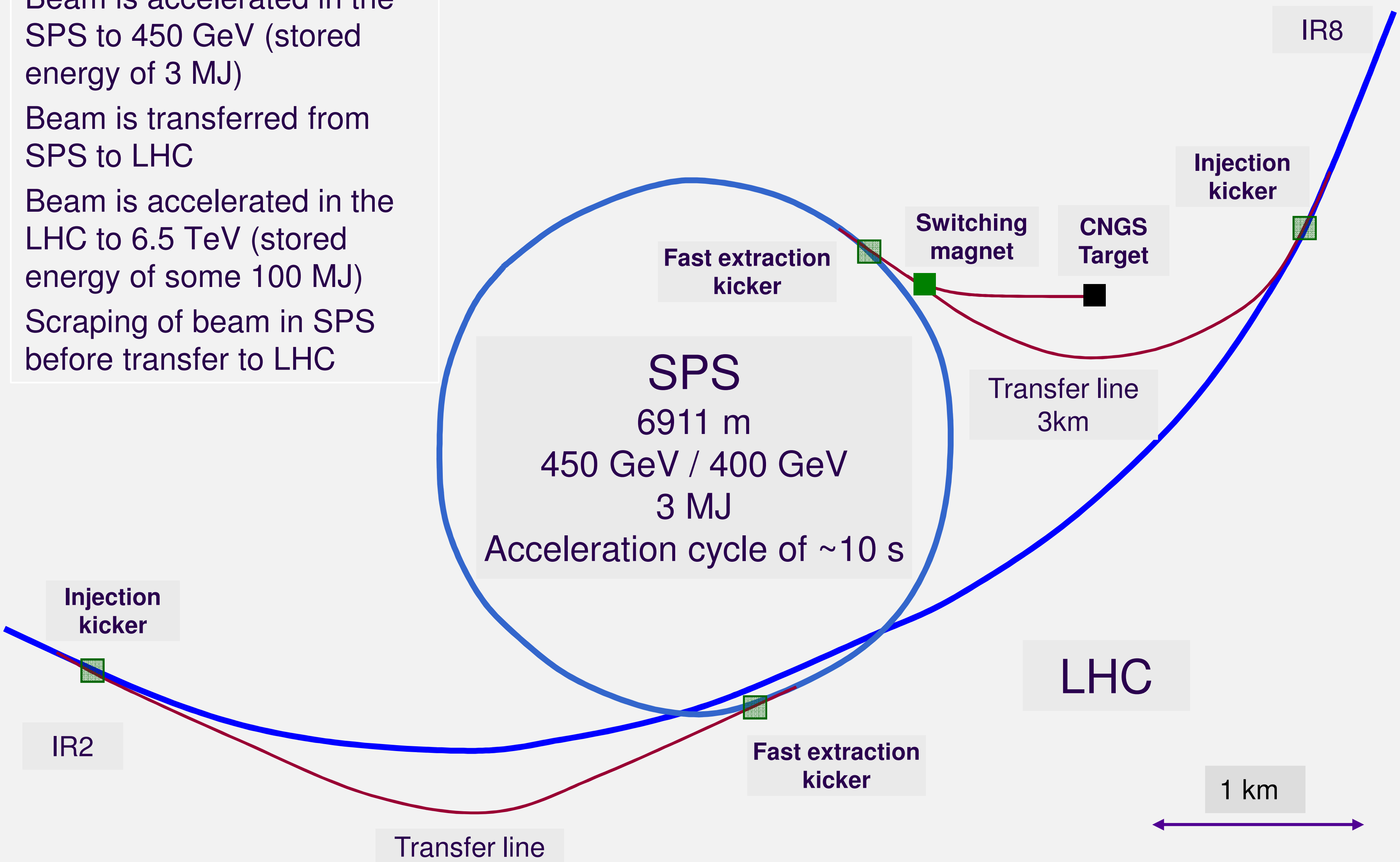
CERN accelerator complex



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:

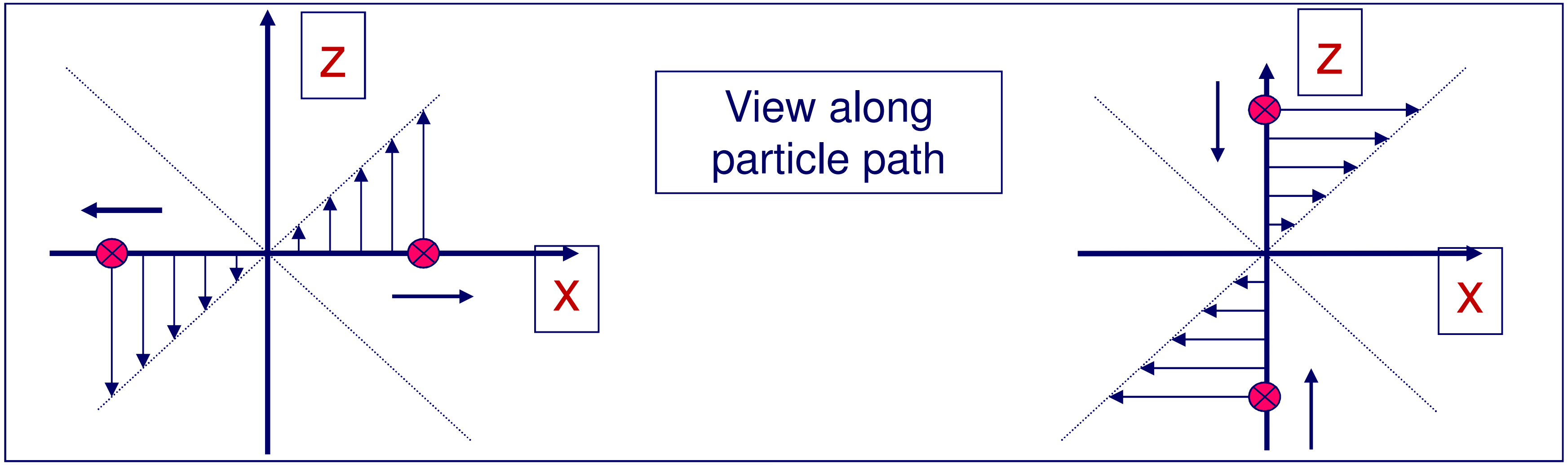
- Particles with different injection parameters (angle, position) separate with time
  - Assuming an angle difference of 10^{-6} rad, two particles would separate by 1 m after 10^{6} m. At the LHC, with a length of 26860 m, this would be the case after 50 turns (5 ms !)
- Particles would „drop“ due to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

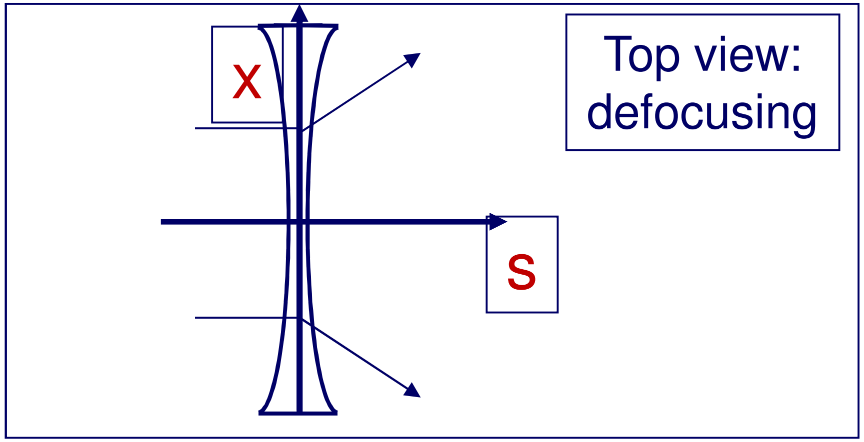
Force by quadrupole magnets

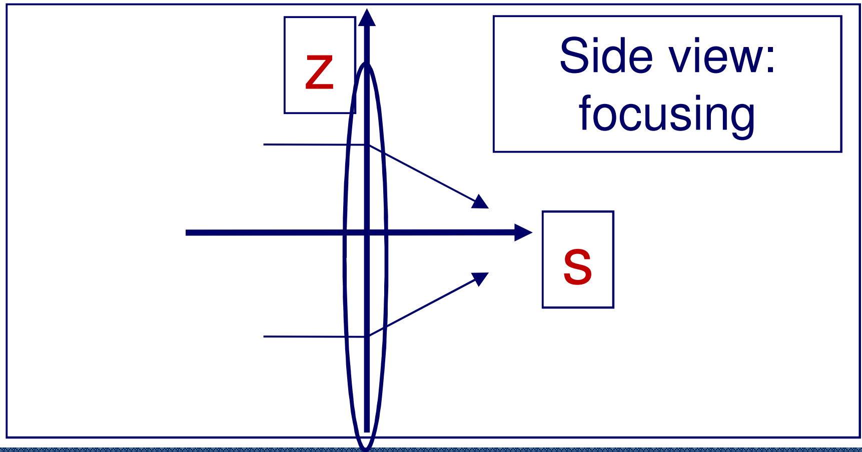
$$B_z(x) = const \times x$$
$$B_{x}(z) = const \times z$$

From Maxwell's equations

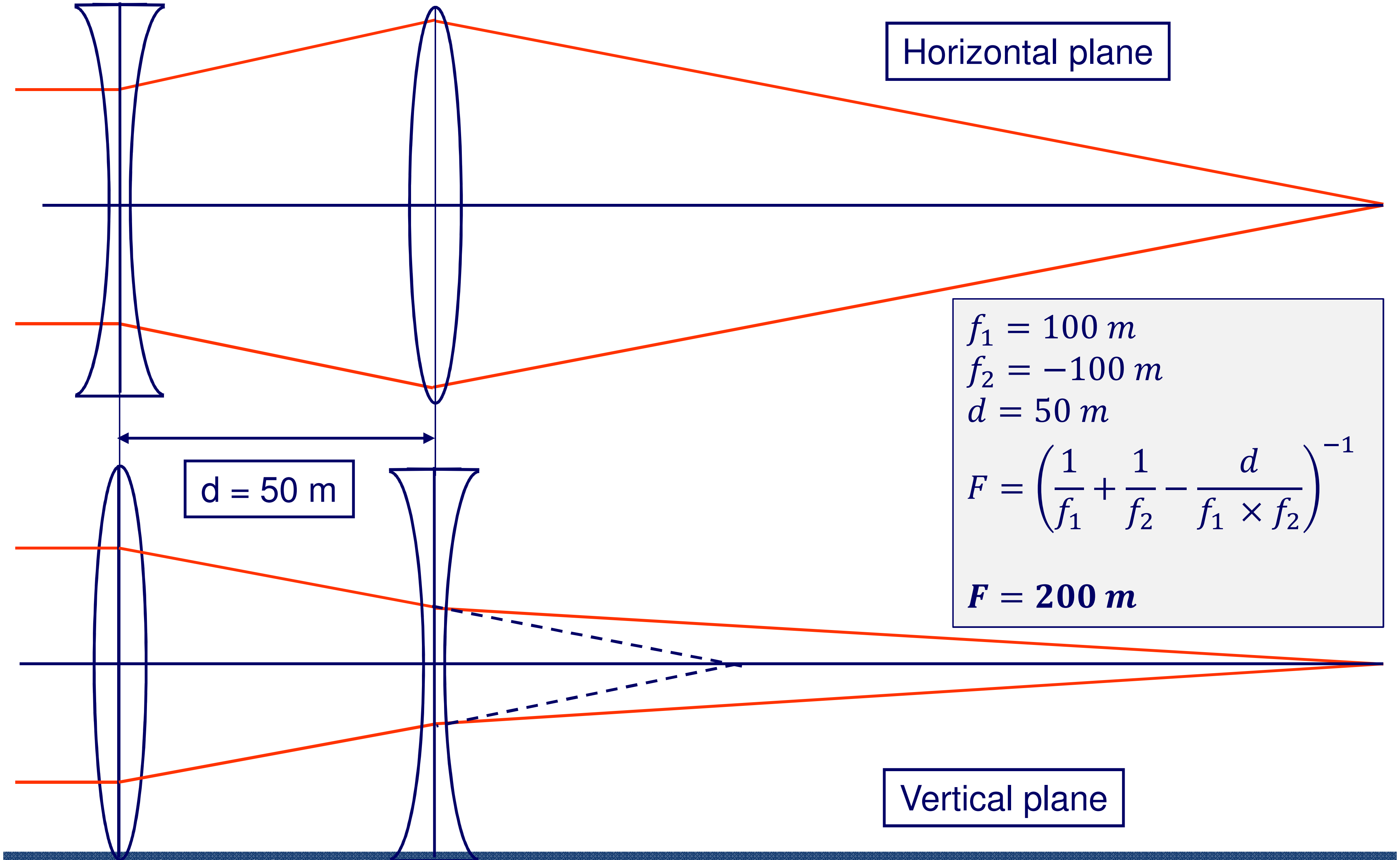
Here: a particle with positive charge travels in s-direction, into the table







Focusing by two quadrupole magnets, thin lenses

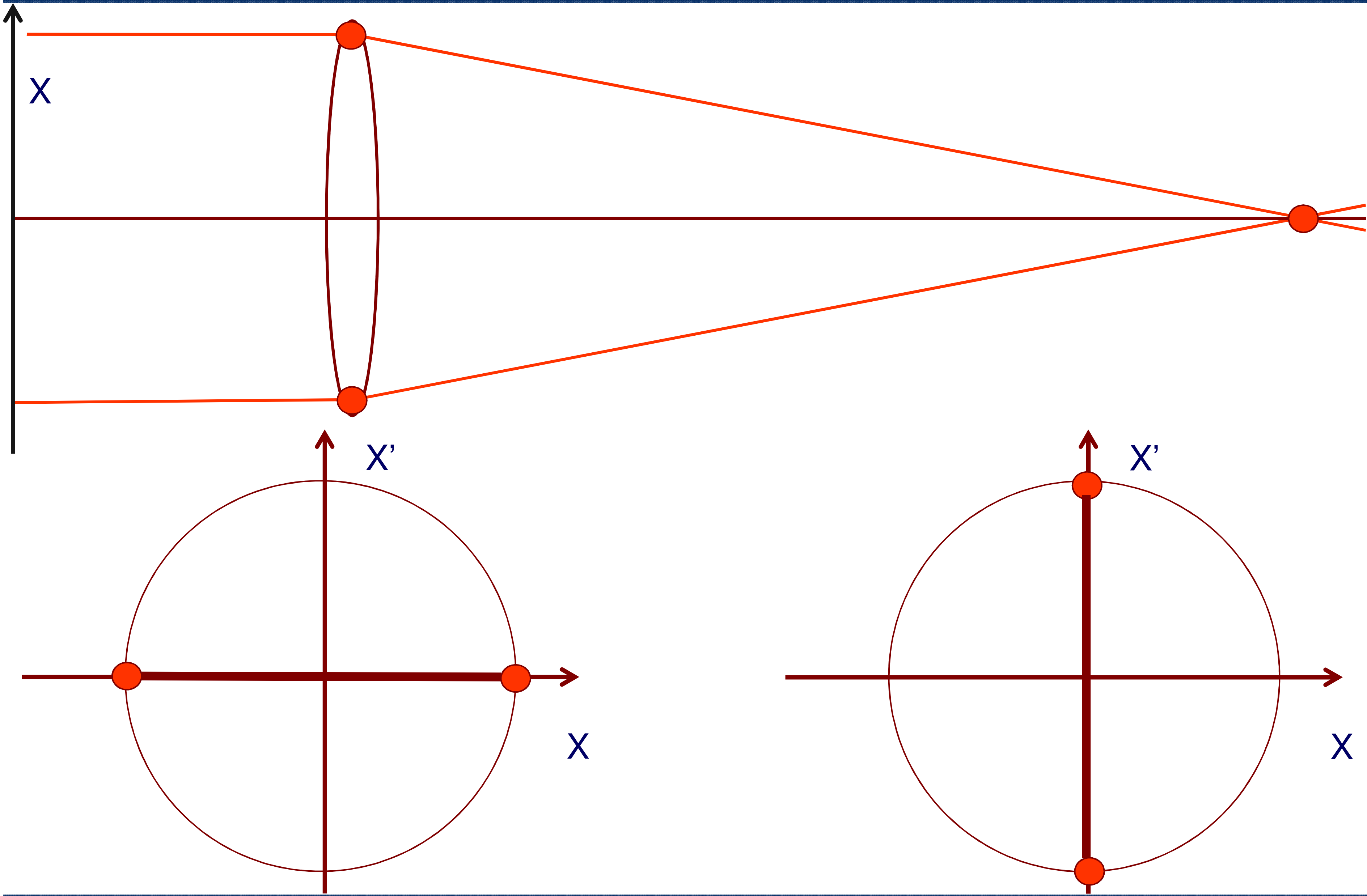


$f_1 = 100\ m$
$f_2 = -100\ m$
$d = 50\ m$

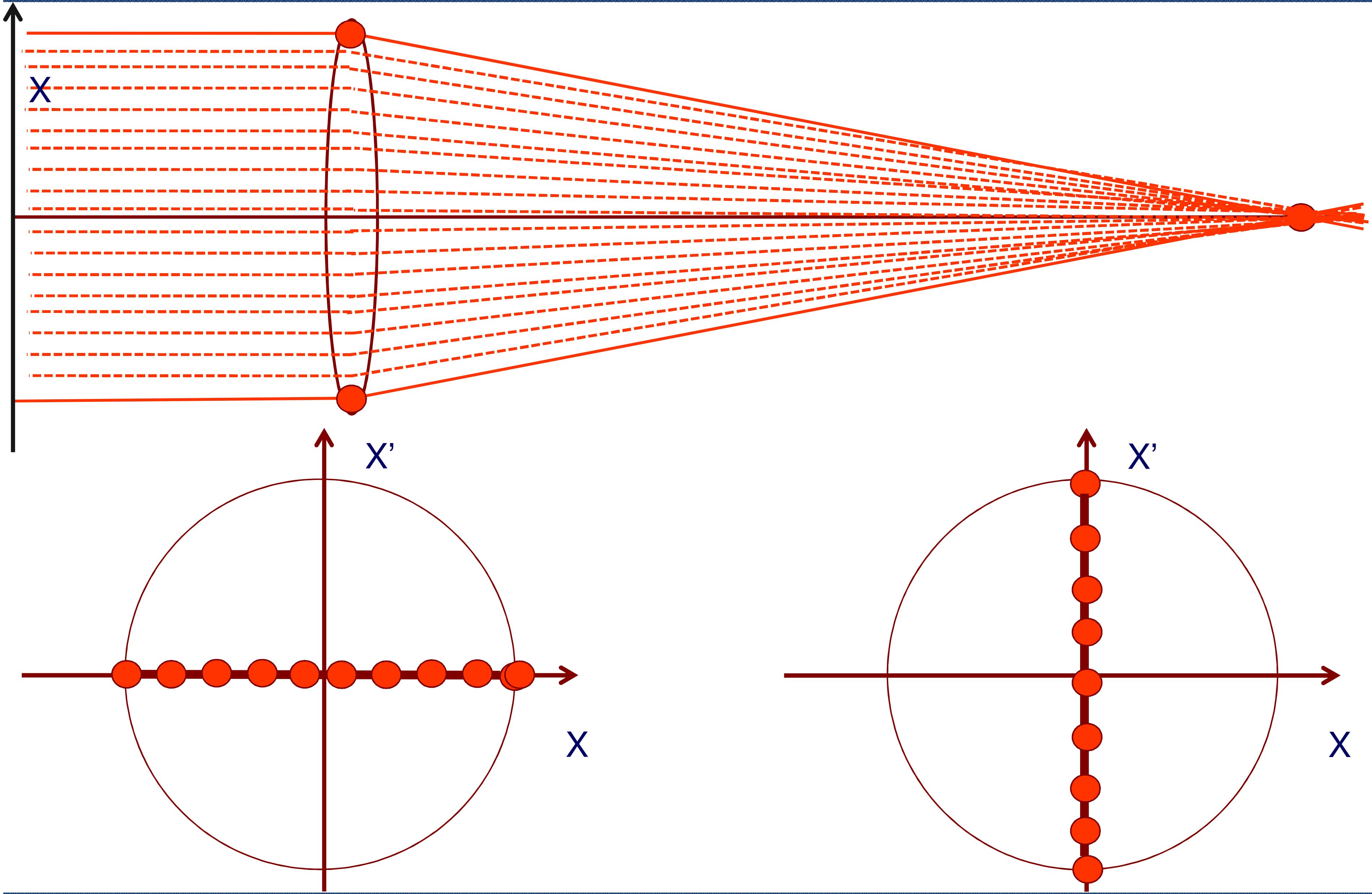
$$F = \left(\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \times f_2}\right)^{-1}$$

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

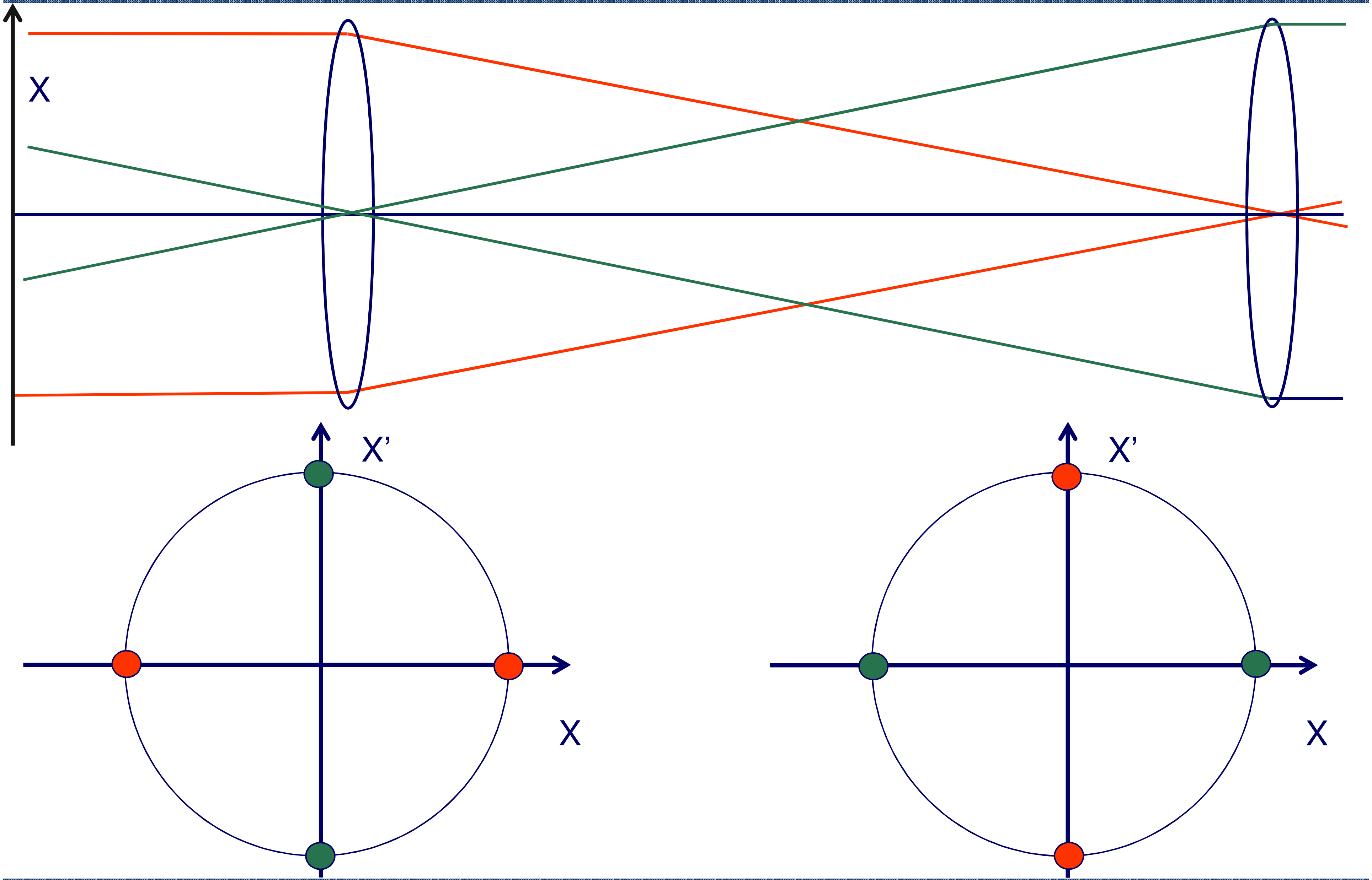
Phase Space of an ensemble of particles



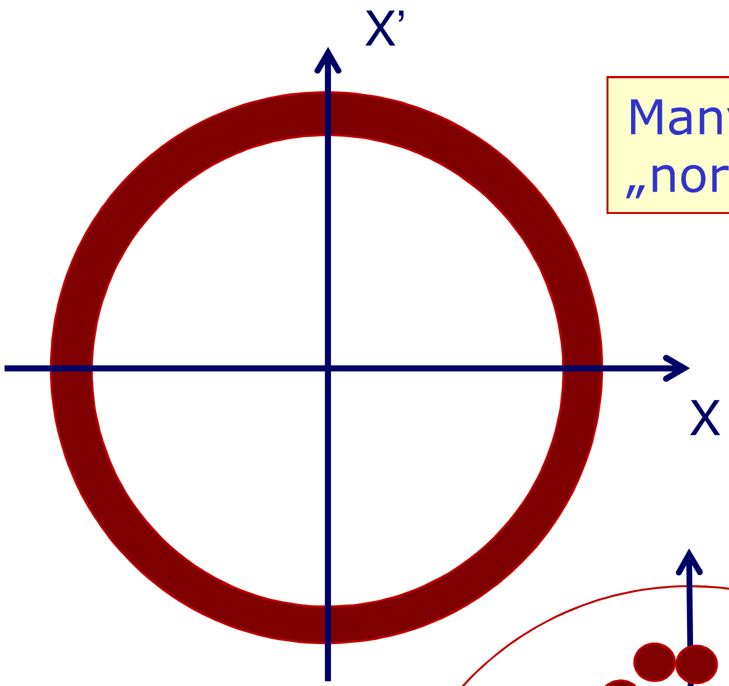
Phase Space of an ensemble of particles



Phase Space of an ensemble of particles

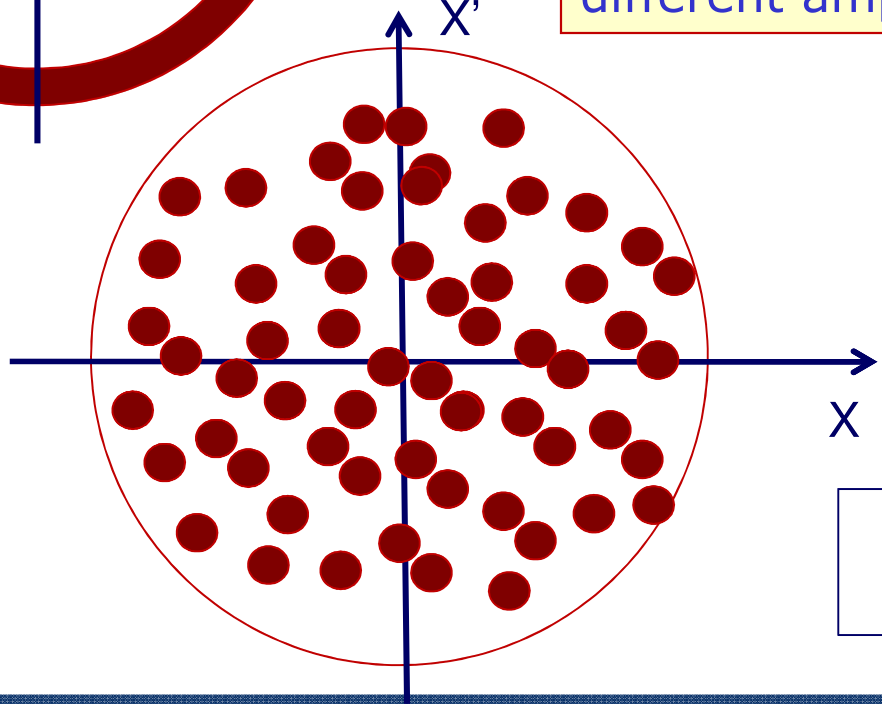


Phase Space of an ensemble of particles



Many particles, same „normalised" amplitude

Real beam: many particles, different amplitudes

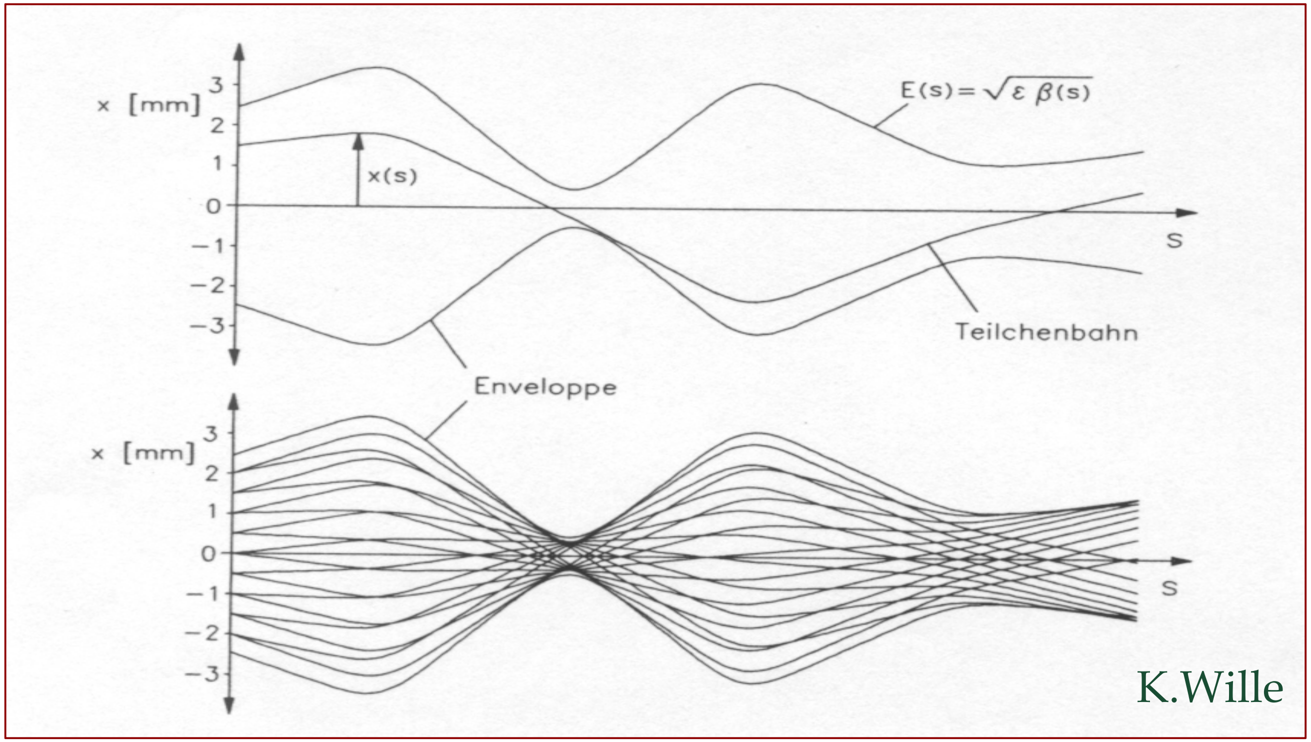


This conservation law: phase space volume occupied by a collection of systems evolving according to Hamilton's equations of motion is preserved in time

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

Betatron oscillations for many particles

Beam size at longitudinal position s

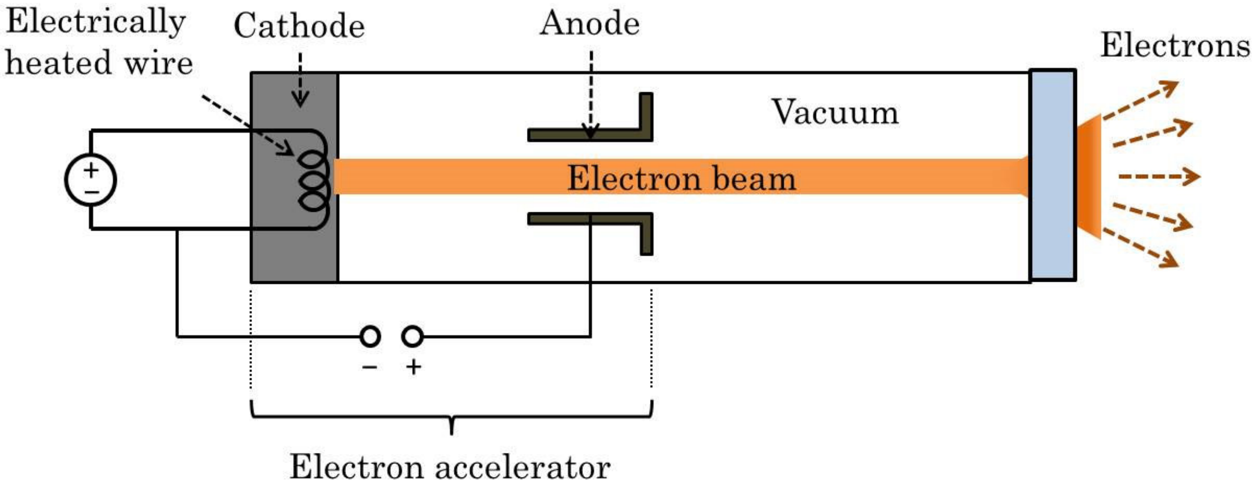


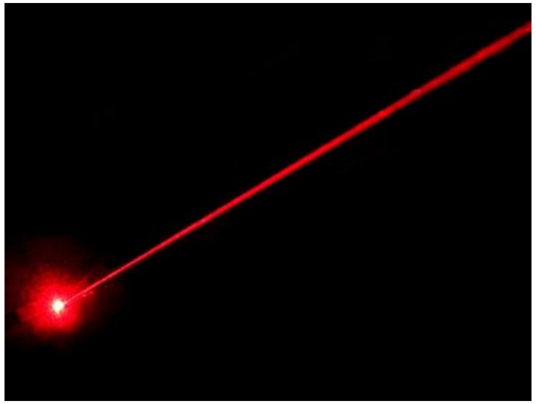
$$\sigma(s) = \sqrt{\epsilon \times \beta(s)} \text{ for each plane x and z}$$

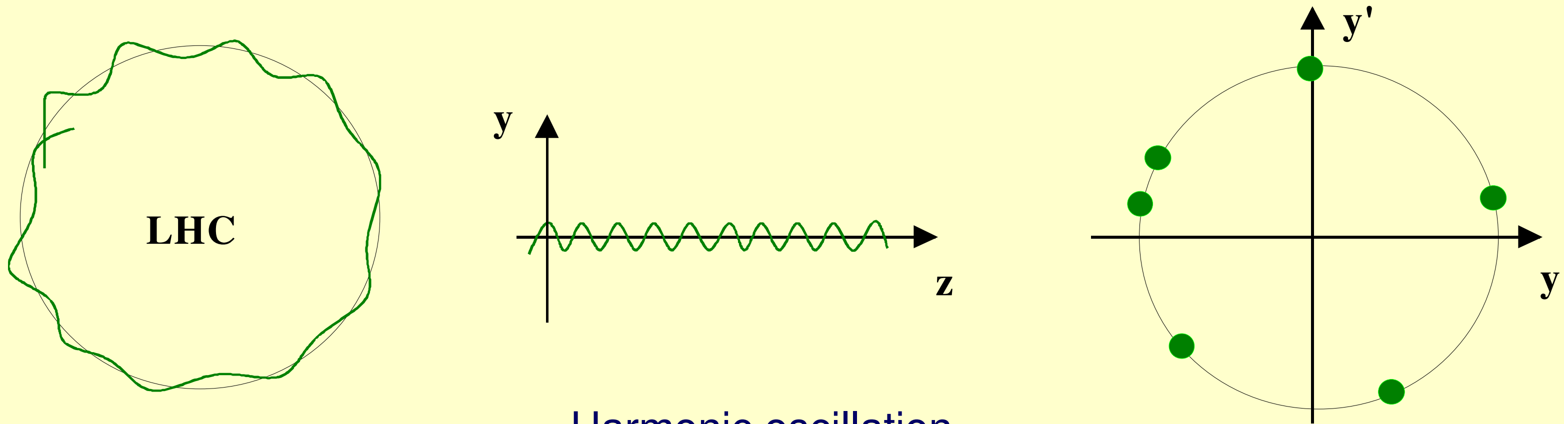
The emittances ϵ_x and ϵ_z are statistical values.

The emittance ϵ decreases proportional to the particle energy during acceleration (adiabatic damping).

Light and particle sources







Particle oscillations in quadrupole field (small amplitude)

Harmonic oscillation after coordinate transformation

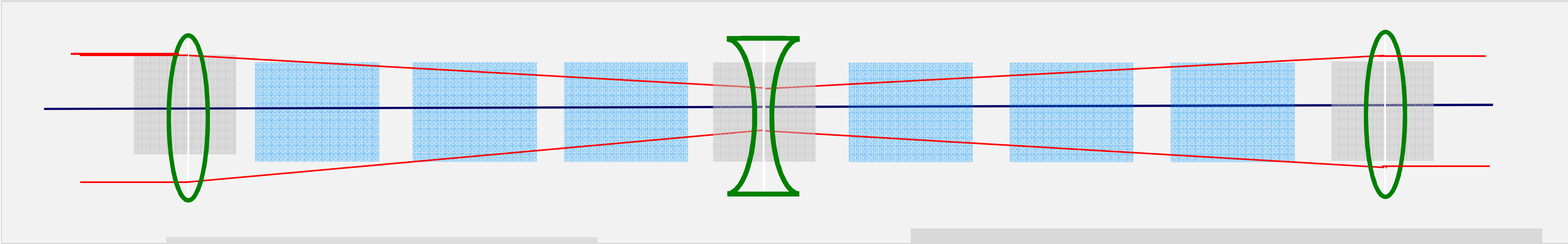
Circular movement in phase space

- 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

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)

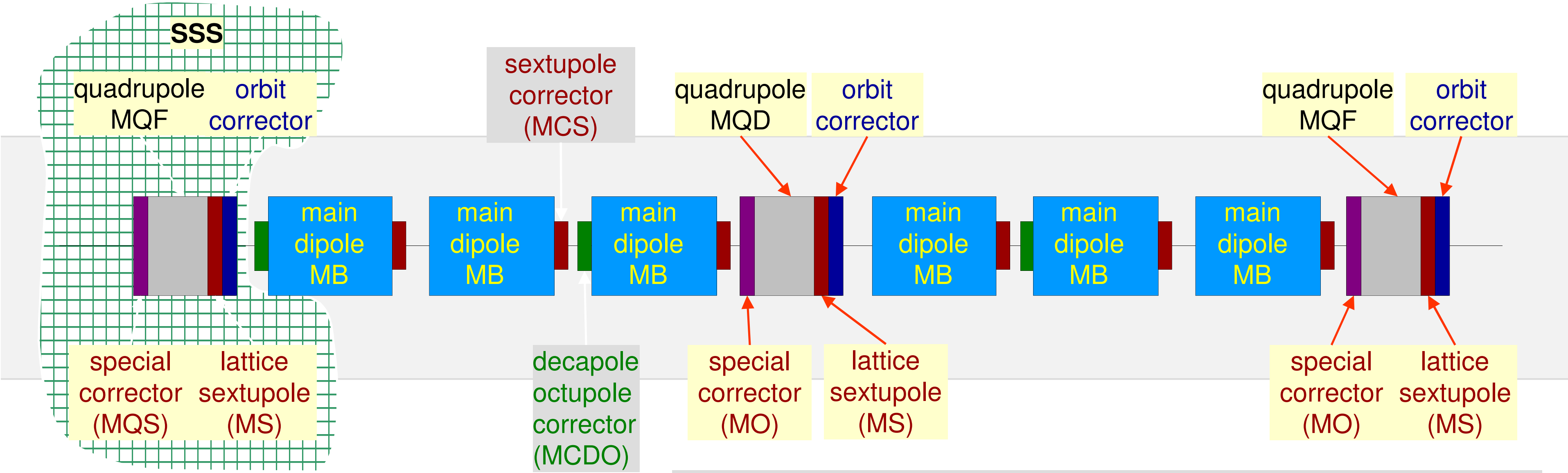
A (F0D0) cell in the LHC arcs



Vertical / Horizontal plane
(QF / QD)

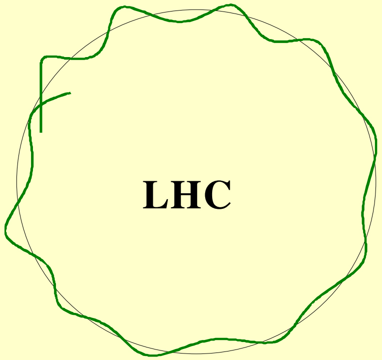
Quadrupole magnets controlling the beam size „to keep protons together" (similar to optical lenses)

LHC Cell - Length about 110 m (schematic layout)

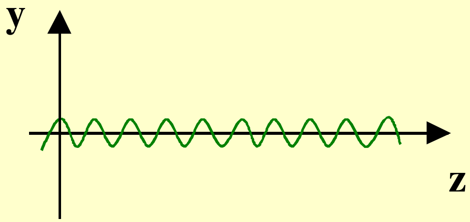


10000 magnets powered in 1700 electrical circuits

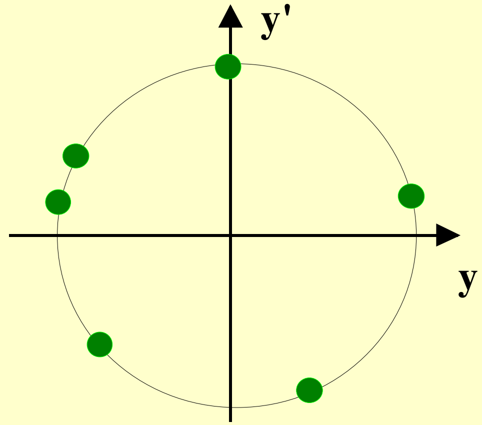
Particle stability and magnets



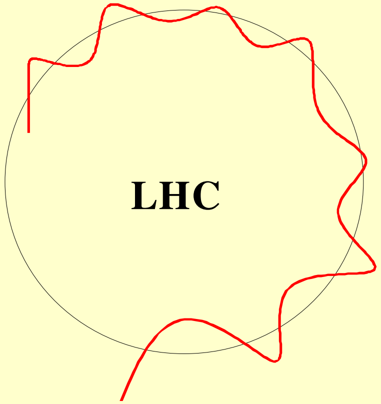
Particle oscillations in quadrupole field (small amplitude)



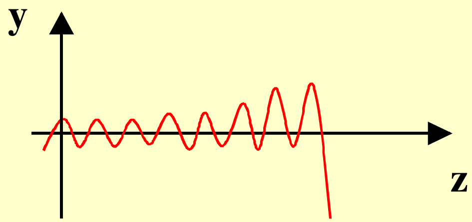
Harmonic oscillation after coordinate transformation



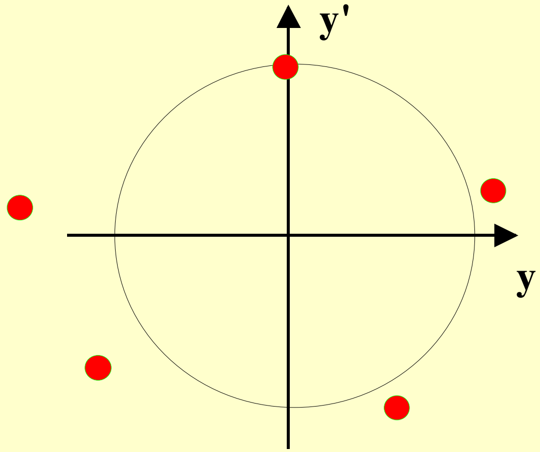
Circular movement in phase space



Particle oscillation assuming non-linear fields, large amplitude

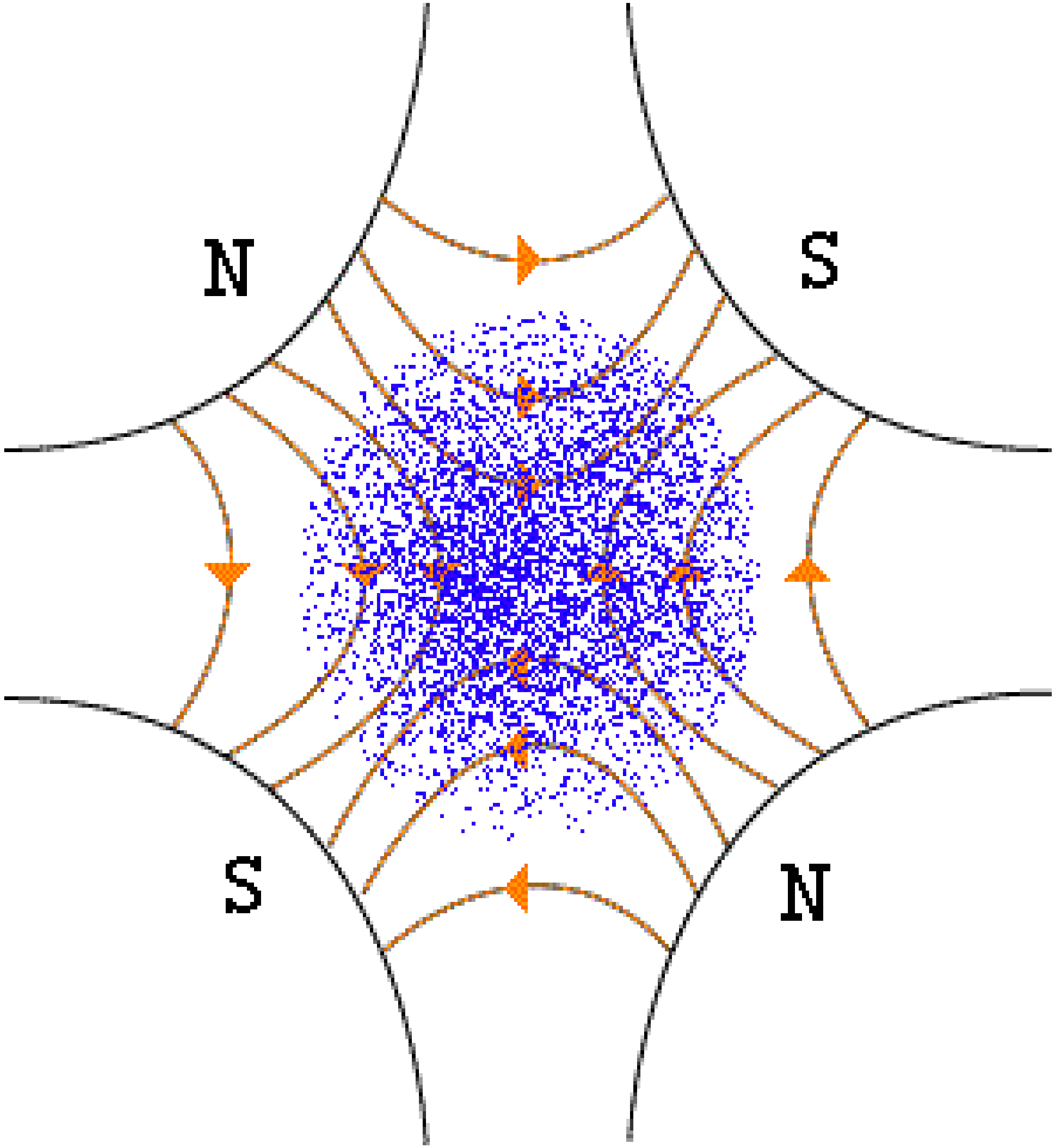


Amplitude grows until particle is lost (touches aperture)



No circular movement in phasespace

Visualising bunch oscillation in accelerator



Particle energy and superconducting magnets

…….the magnetic field strength determines the beam energy

Superconducting magnets in LHC tunnel

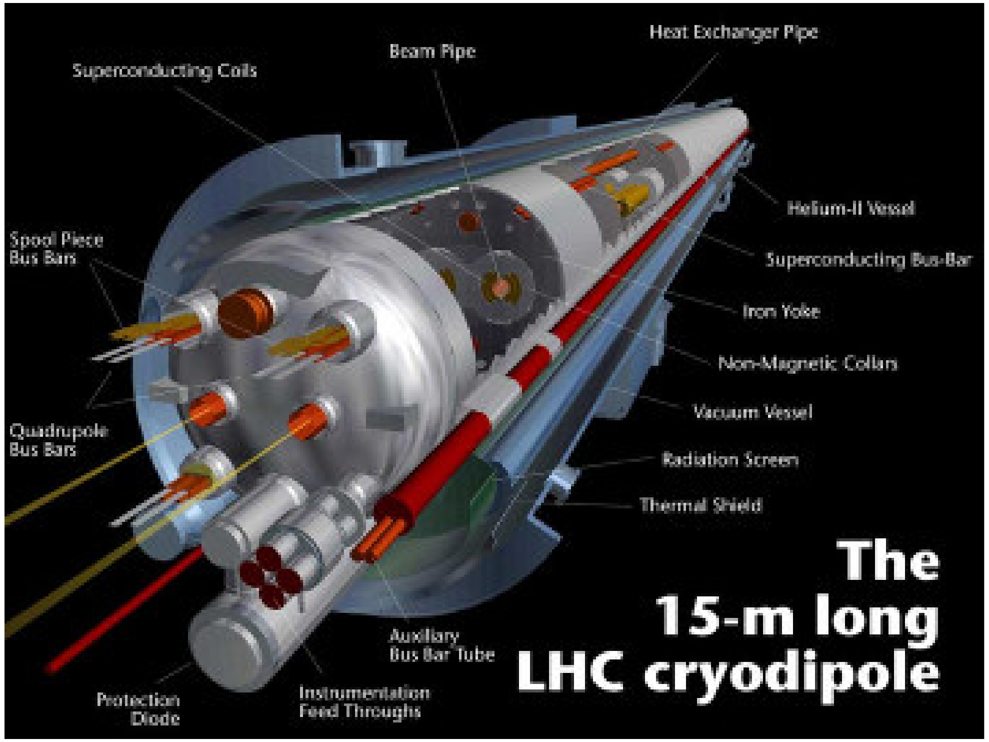
Deflection by 1232
superconducing dipole magnets

Dipole magnets for the LHC

1232 Dipole magnets
Length about 15 m

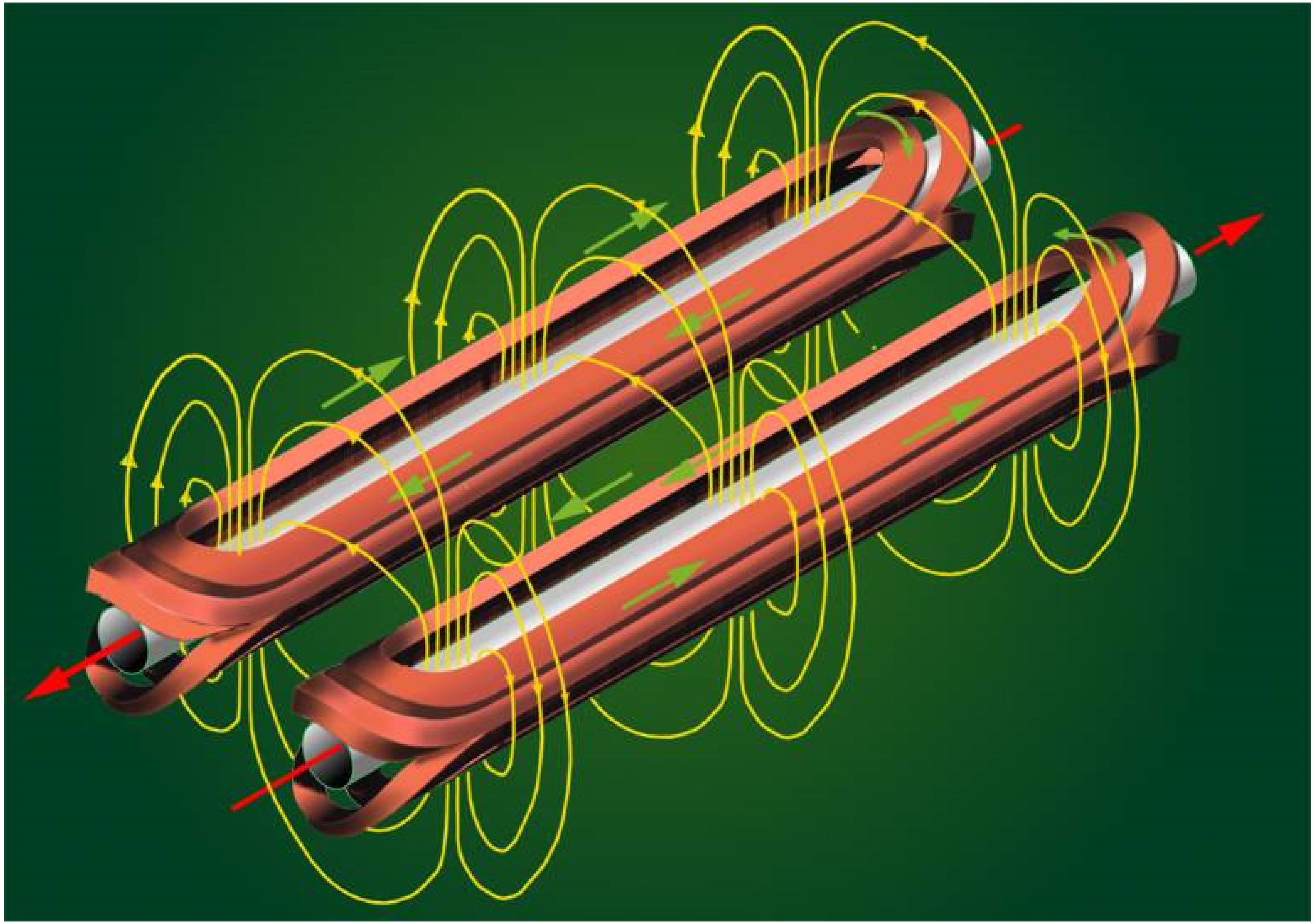
Magnetic Field 8.3 T for 7 TeV

Two beam tubes with an opening of 56 mm

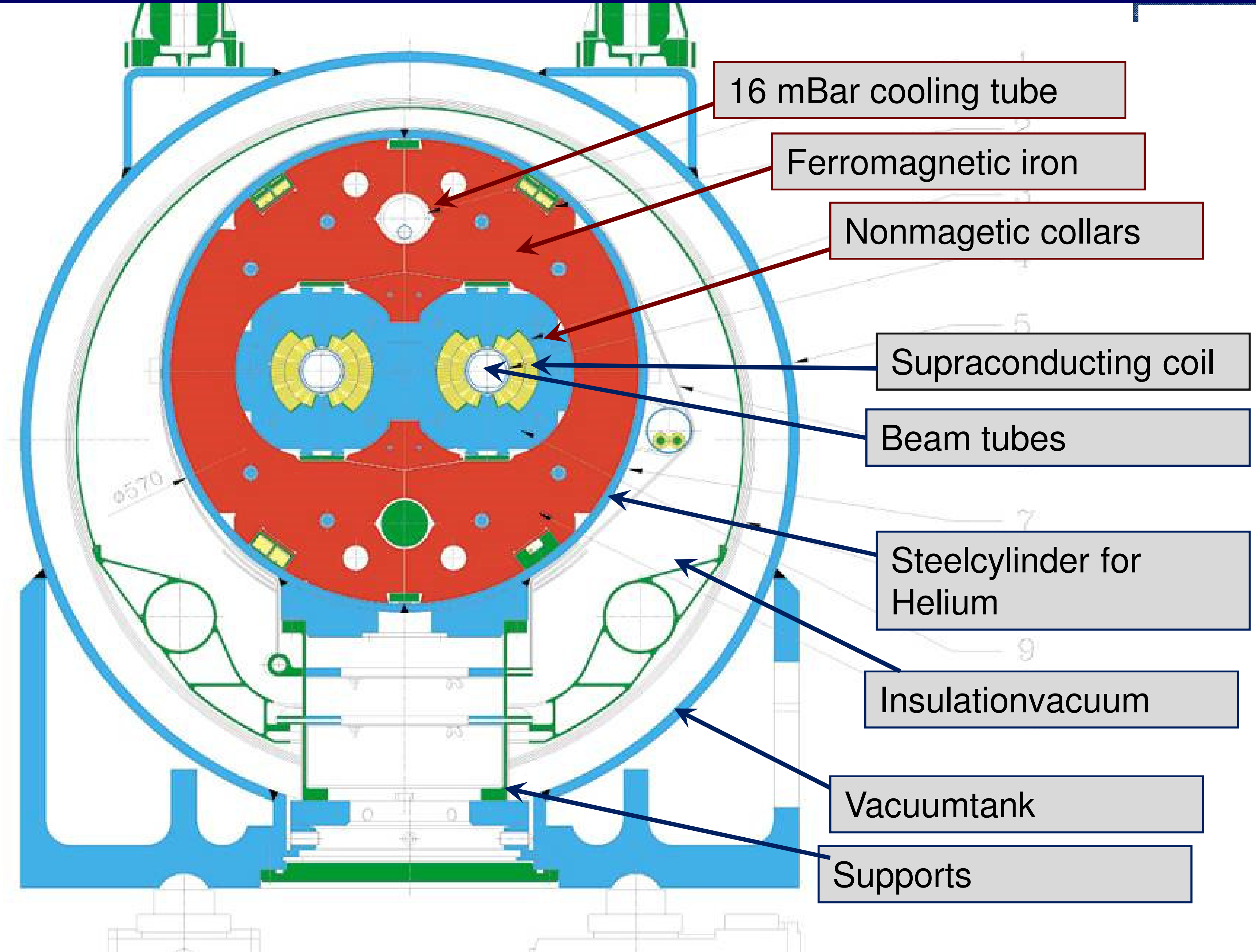


plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets)

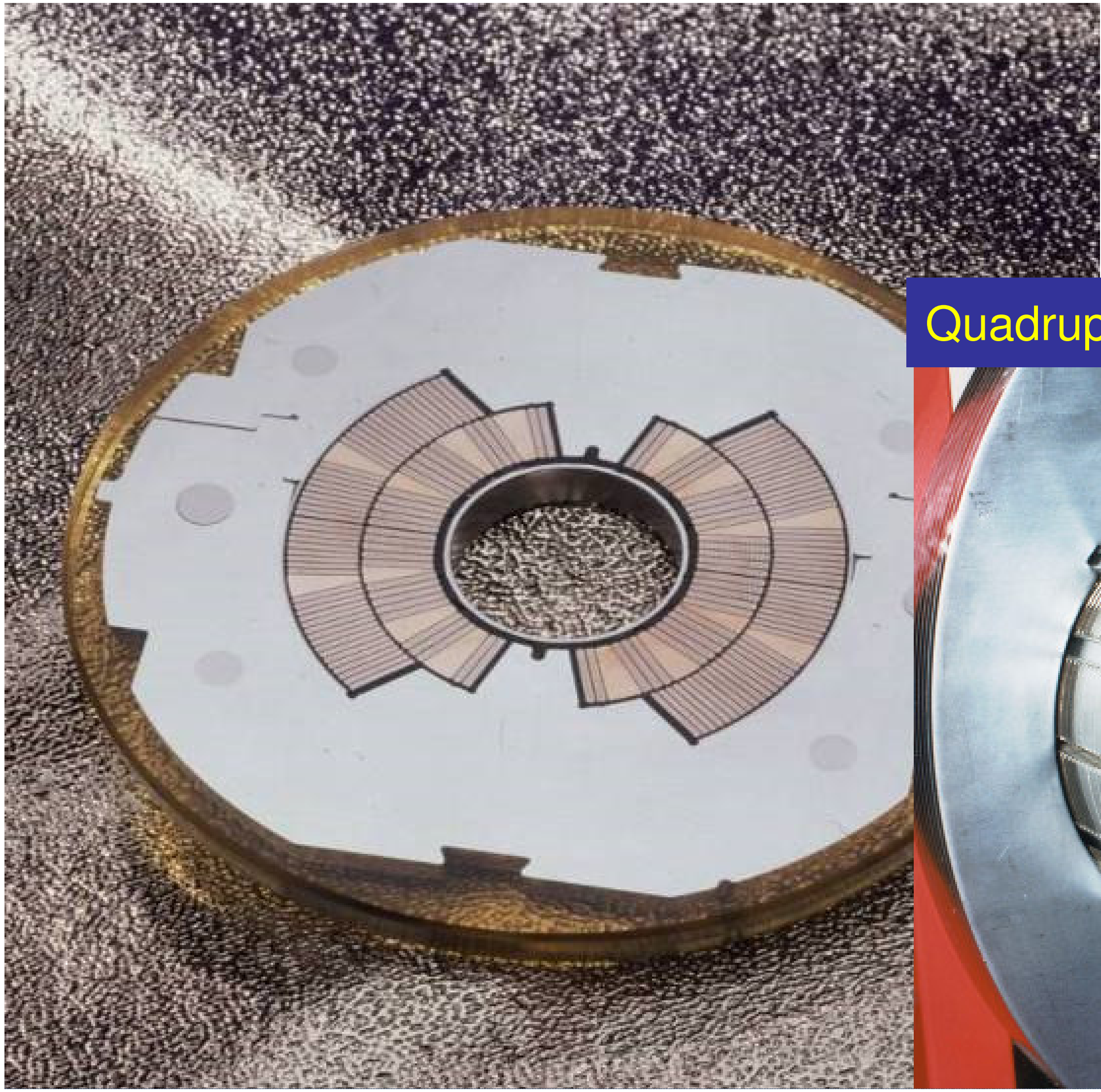
Coils for Dipolmagnets

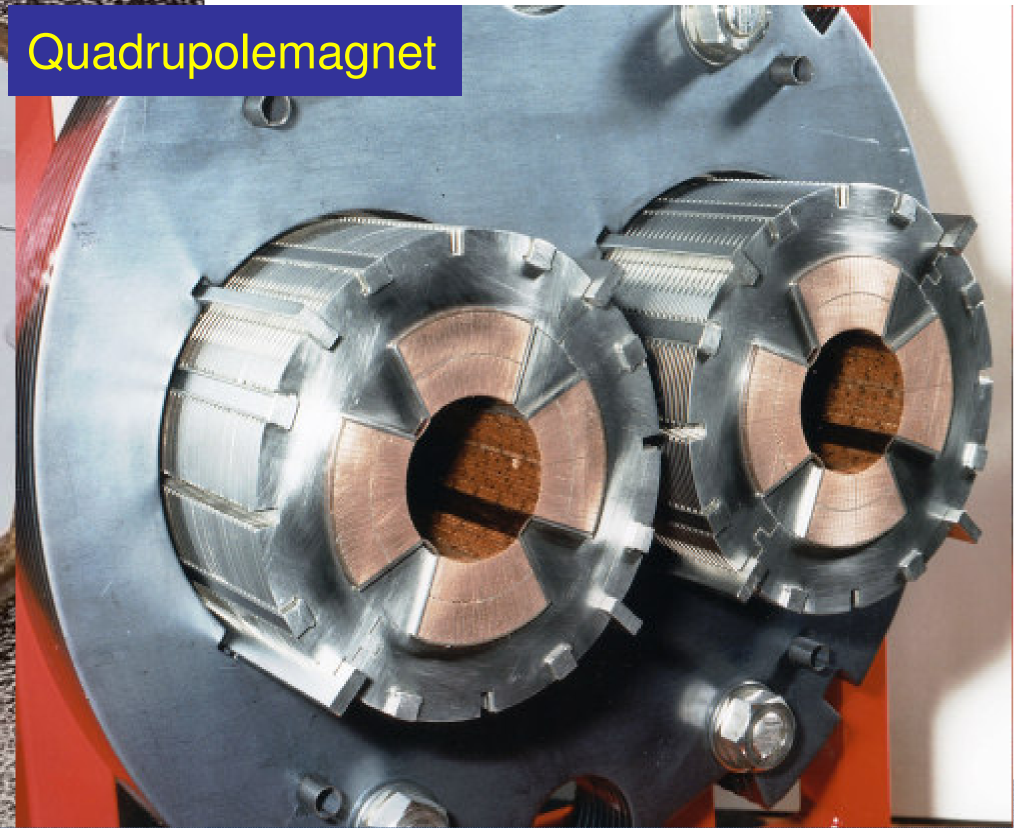


Dipole magnet cross section

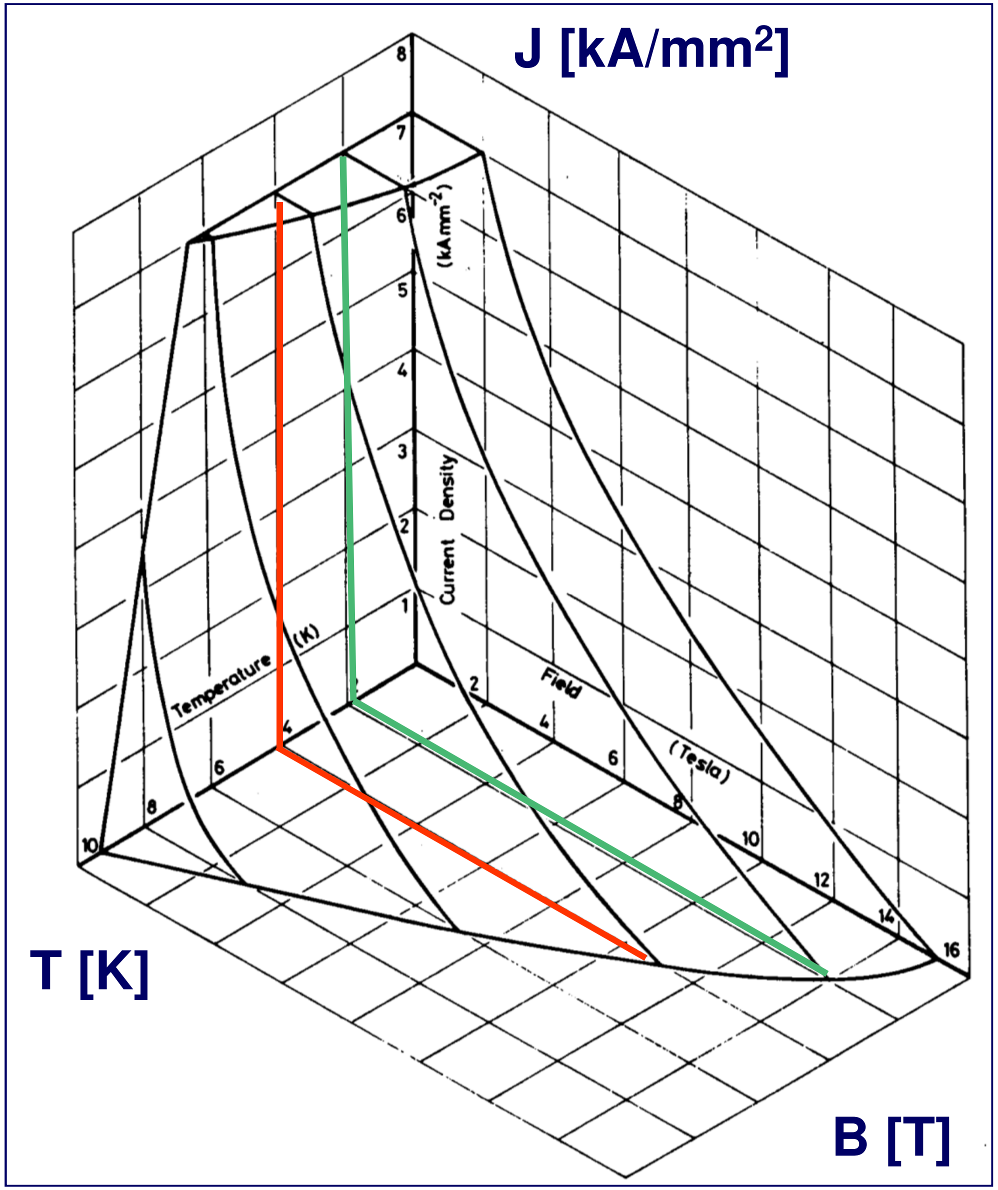


Coils: dipole and quadrupole magnets





Operating temperature of superconductors (NbTi)

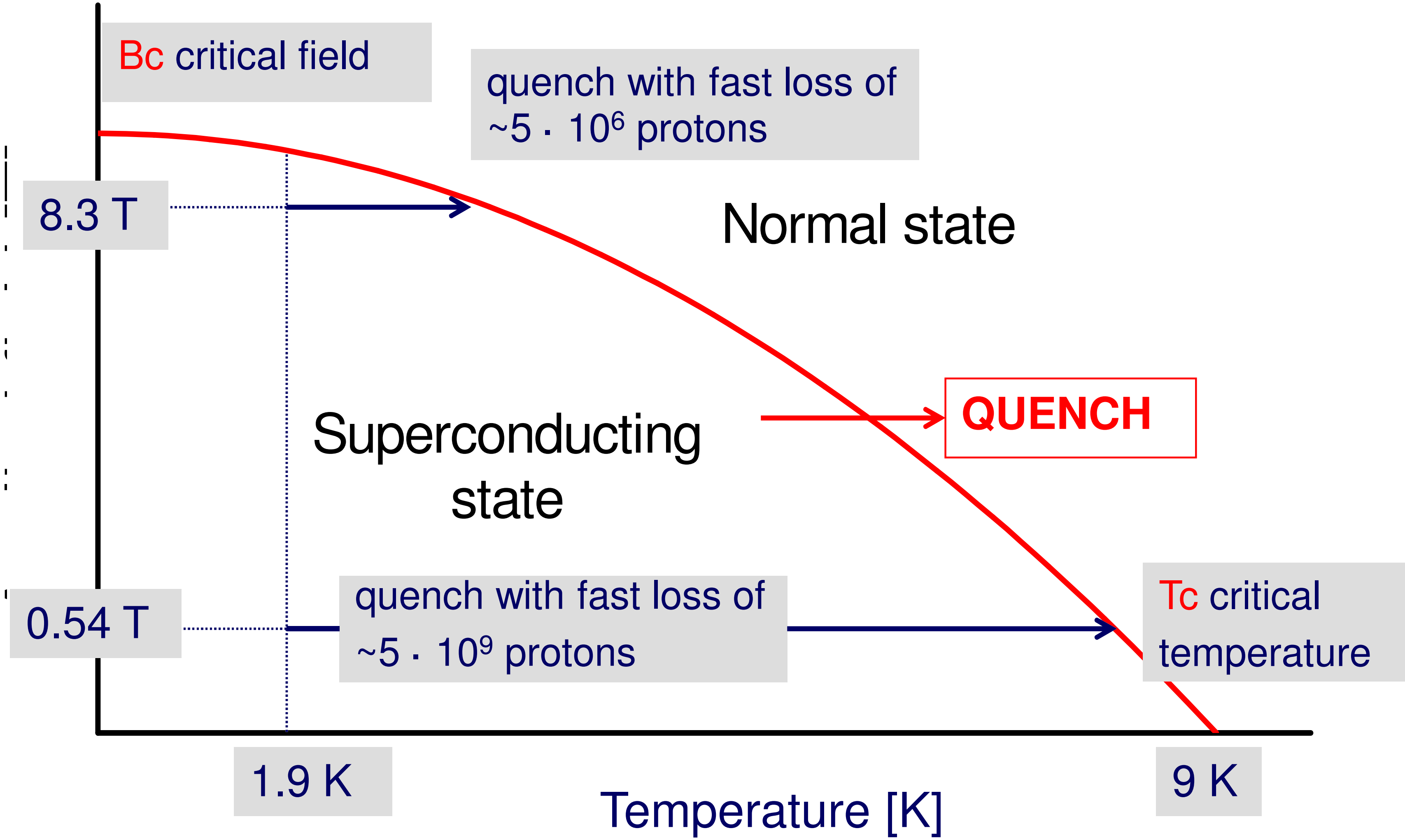


The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

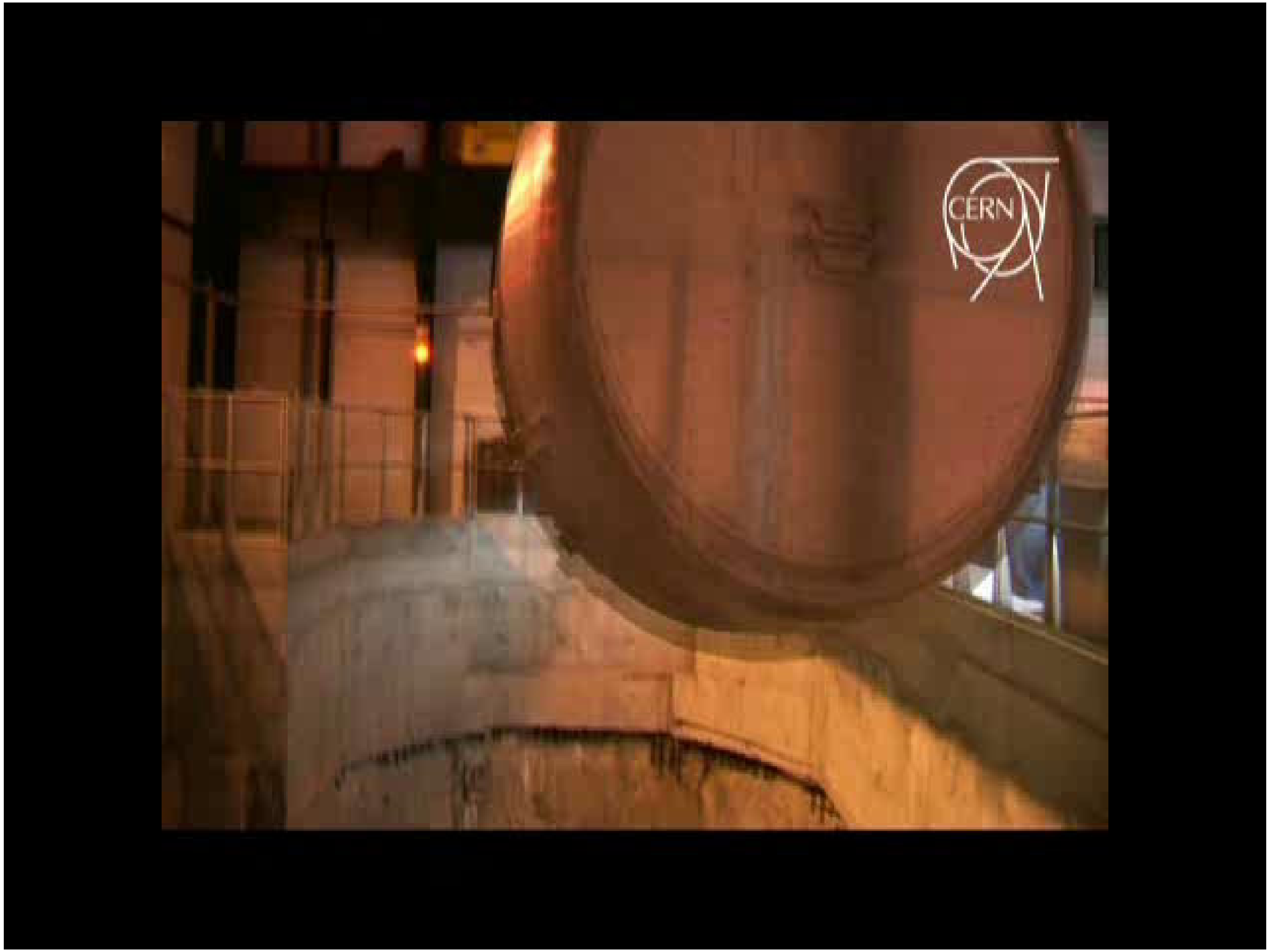
Superconducting magnets produce high field with high current density

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

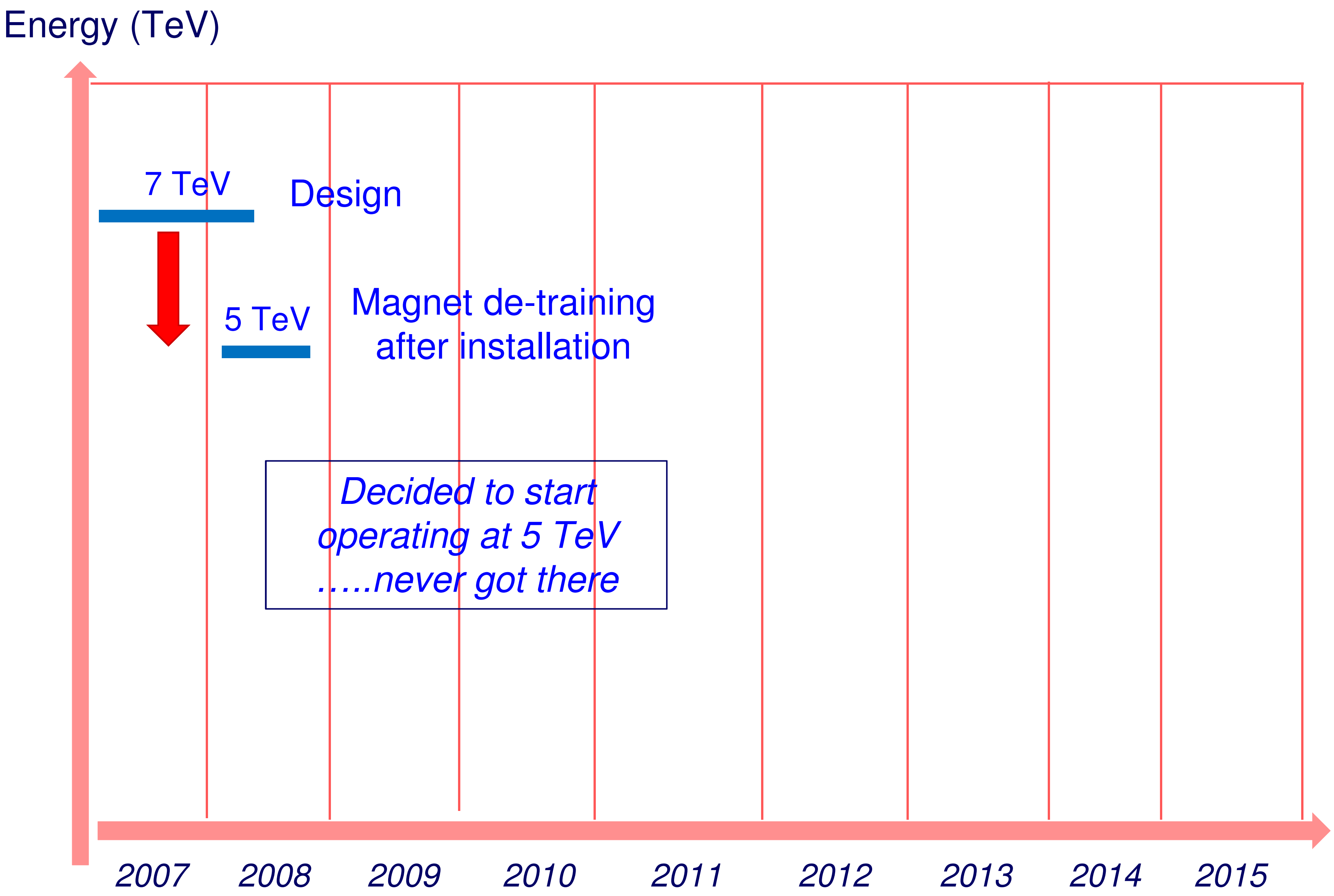
Operational margin of a superconducting magnet



Dipole magnets from surface to tunnel



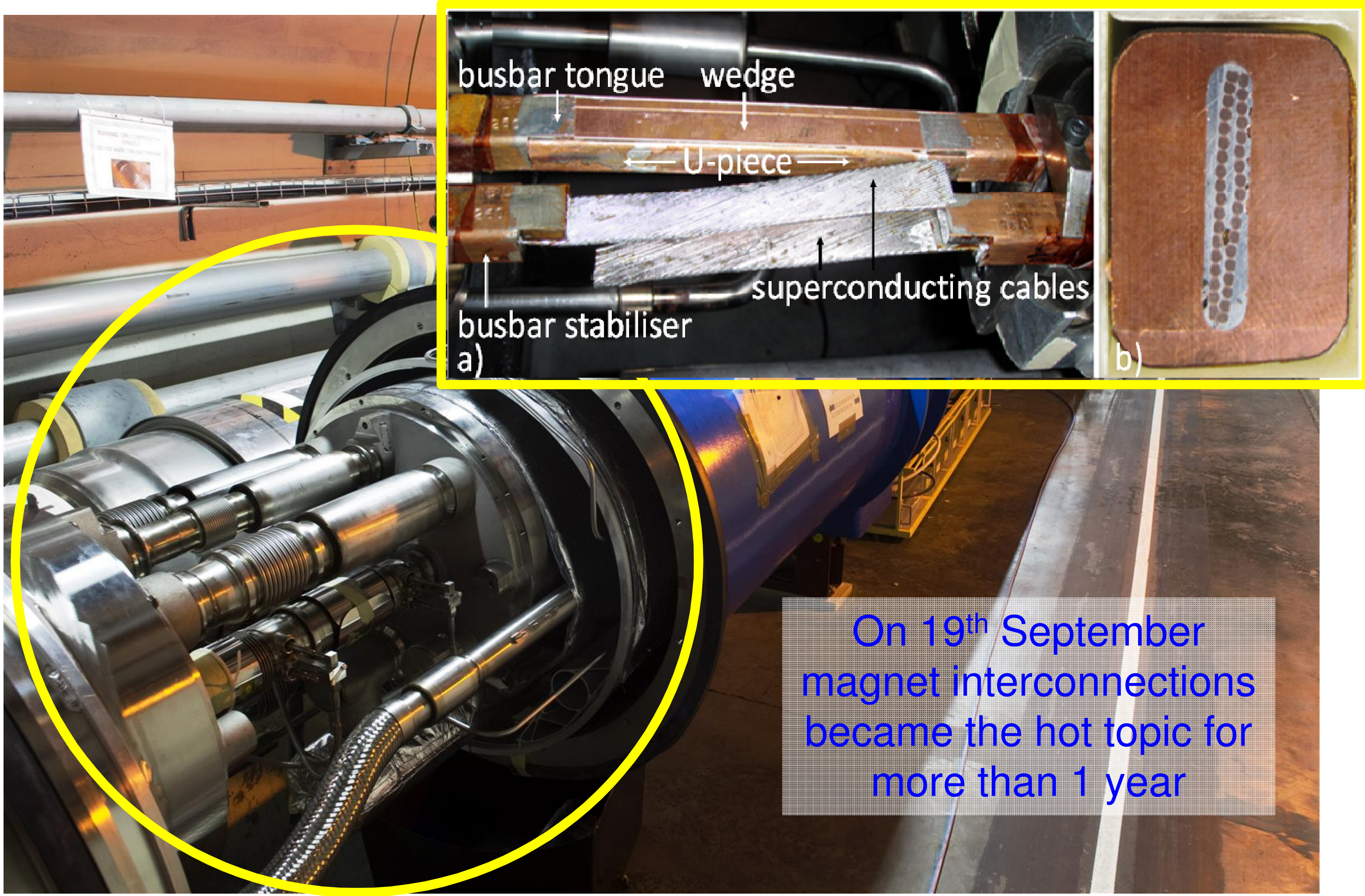
LHC energy evolution



September 10th 2008

A brief moment of glory

September 19th 2008



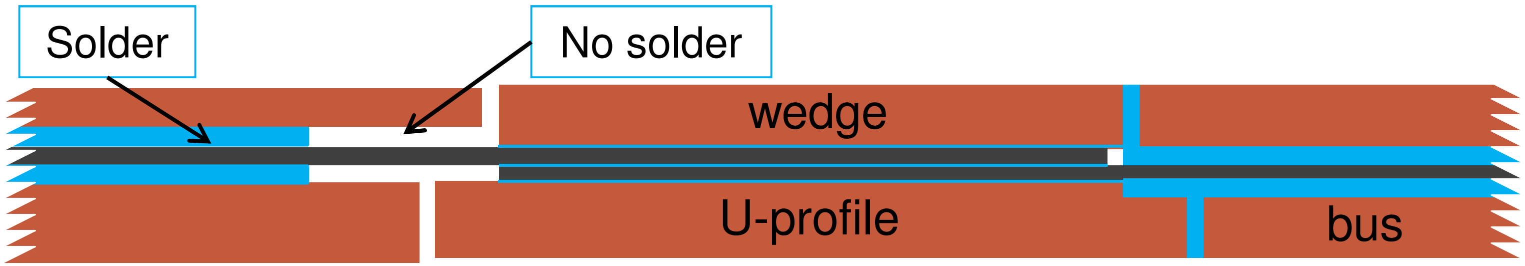
On 19th September magnet interconnections became the hot topic for more than 1 year

Incident September 19^{th} 2008

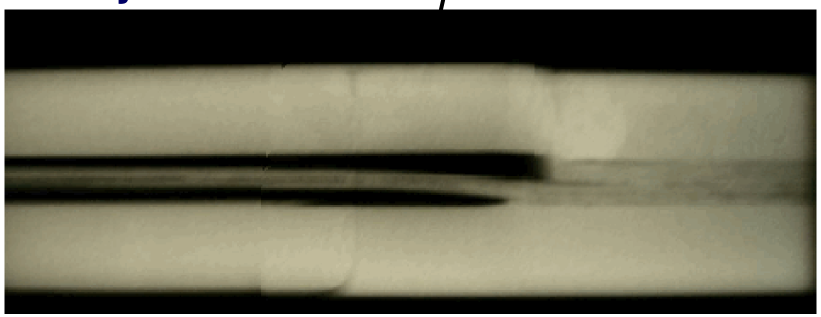
53 magnets had to be repaired

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.



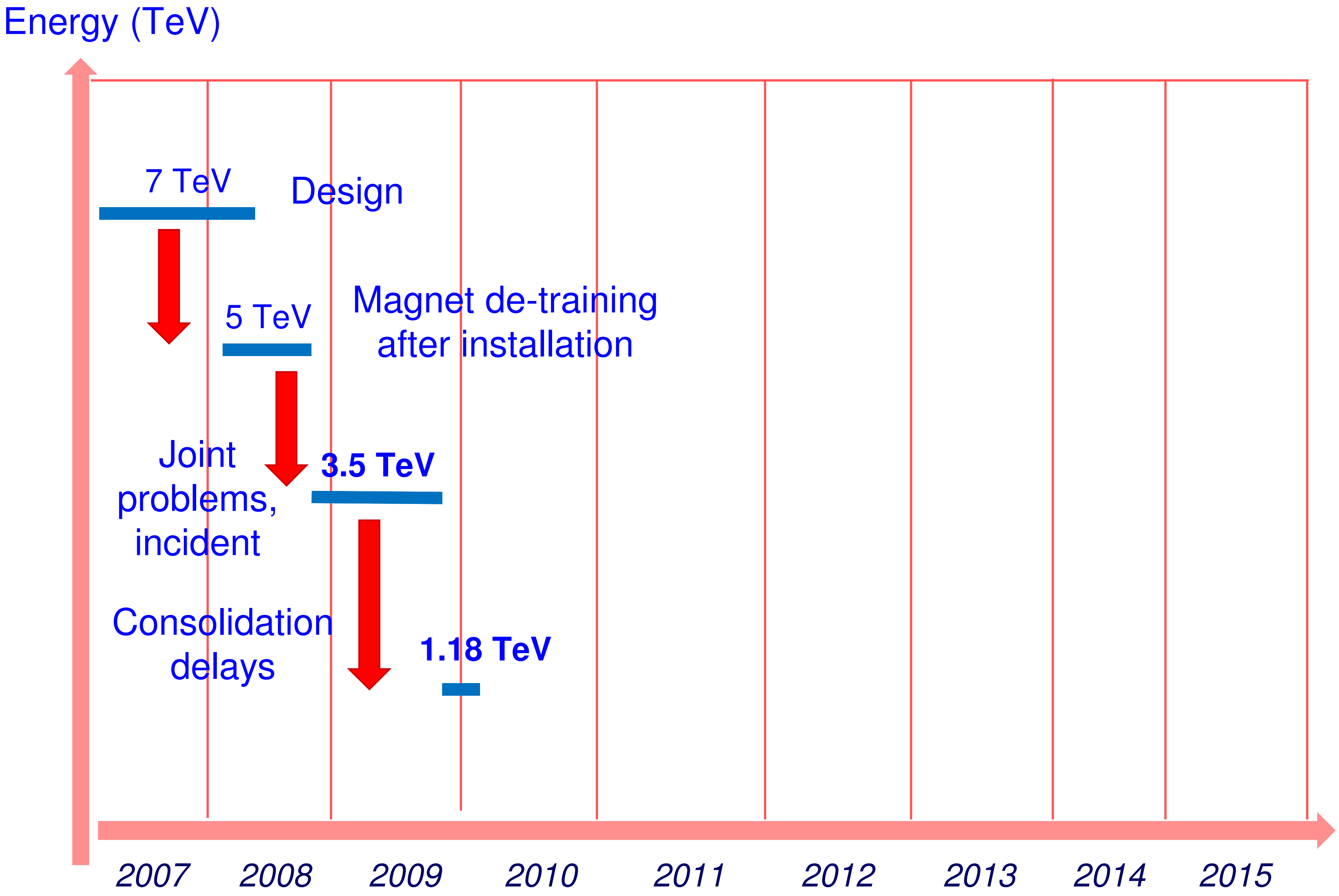
X-ray



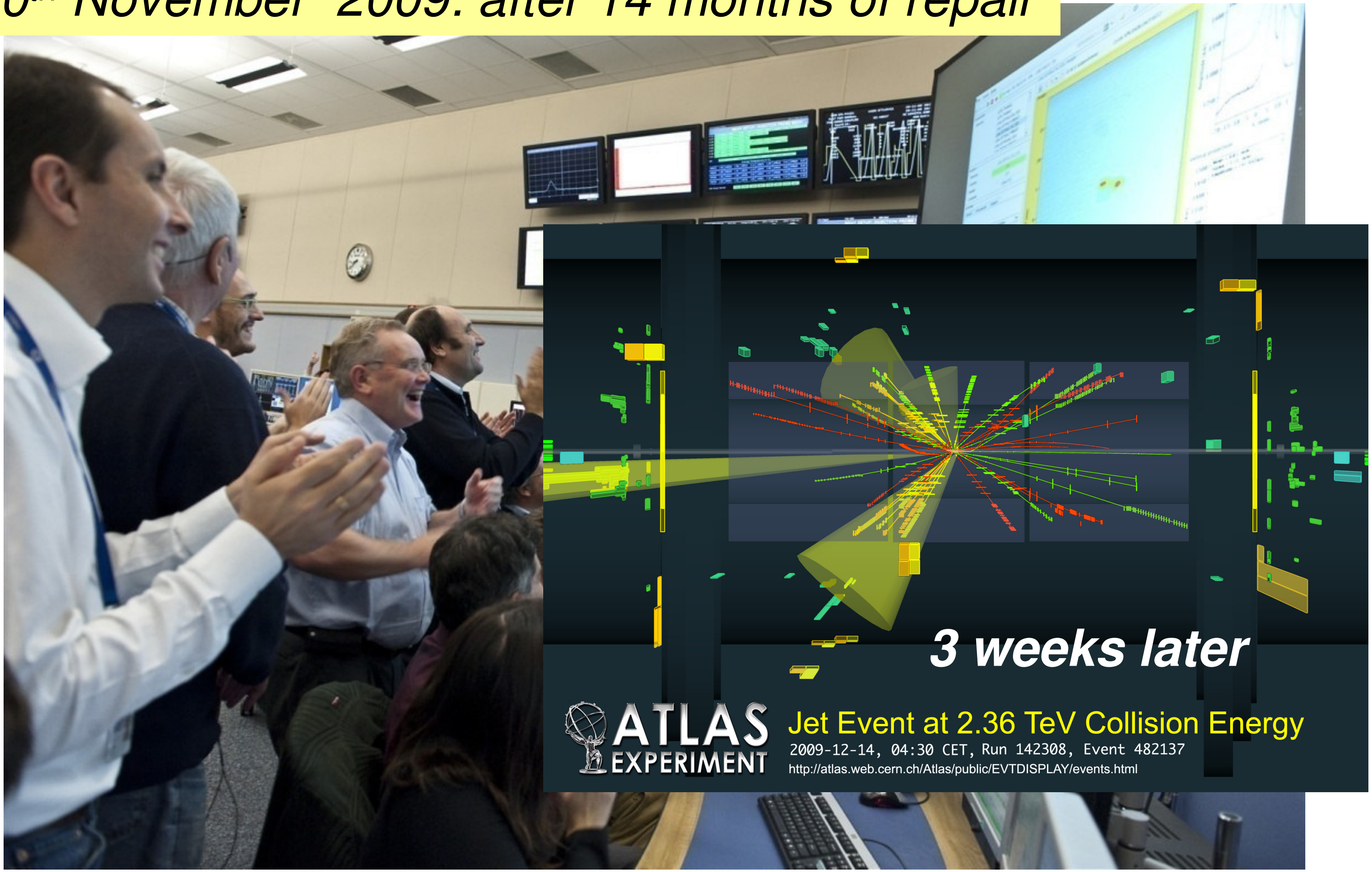
During repair work, inspection of the joints revealed systematic voids caused by the welding procedure.

➡ Energy limitation for Run 1 !!

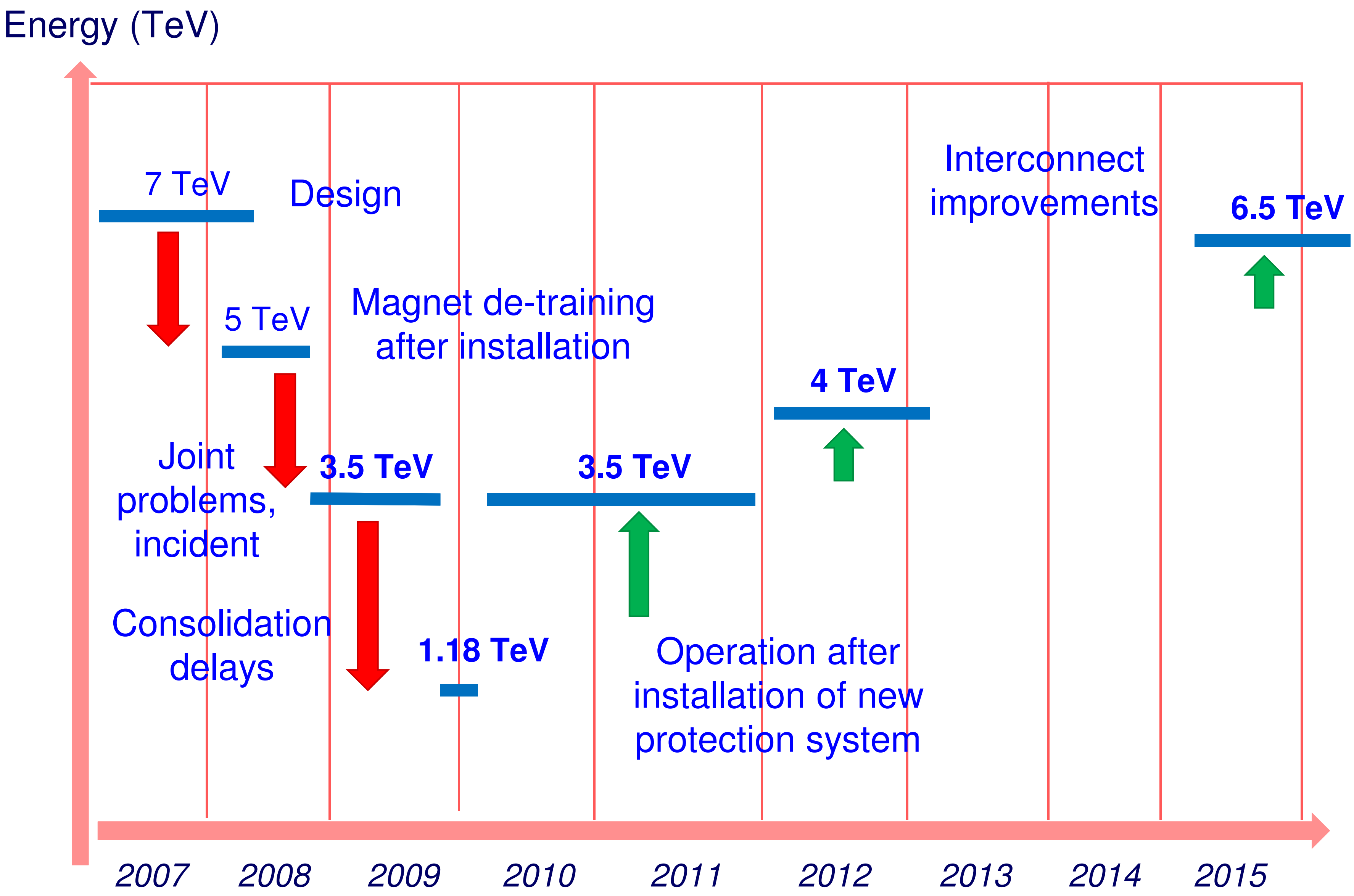
LHC energy evolution



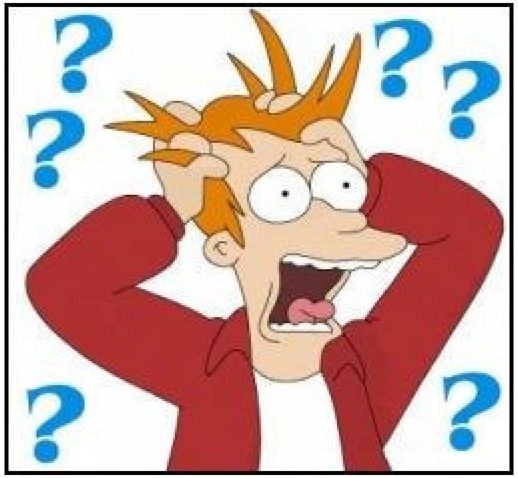
20th November 2009: after 14 months of repair



LHC energy evolution



Understanding LHC operation



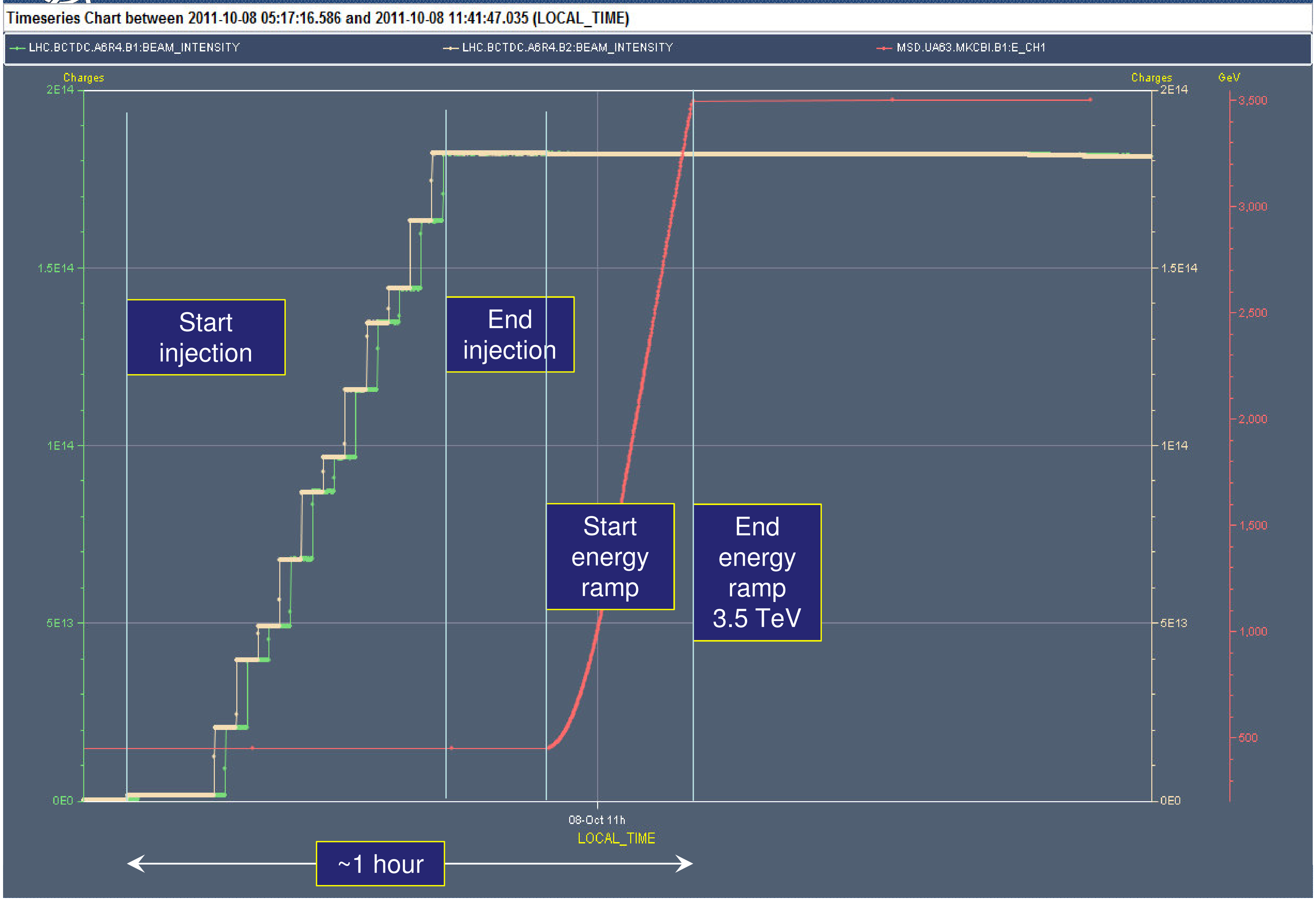
- Filling
- Ramp
- Squeeze
- Adjust
- Stable beams
- Pilot beam
- Batches
- Closed orbit
- Beta function
- Betatron tunes
- Emittance
- Impedance

From first year to first fb-1

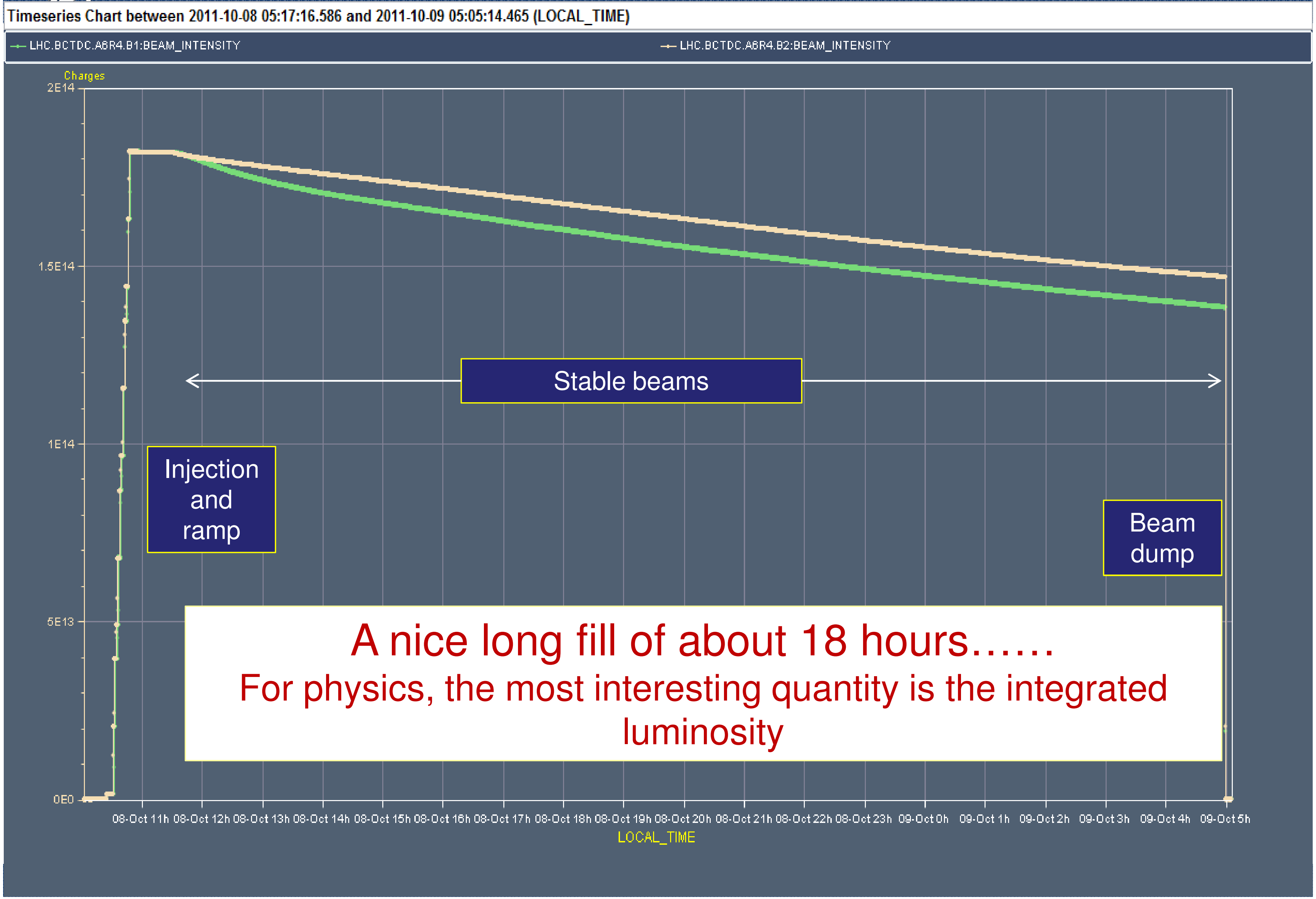
Champagne
DELAMOTTE
Pb-Pb 1.5x
Nov 2011
La Demoiselle
BRUT
THANKS
Back in 2012 !
β*=90m run - ALFA/ATLAS community
DE SAINT GALL
1 fb-1
Thanks LHC !
LHCb Collaboration
Charles de Cazanove
CMS cuvée 2012
Summer Solstice 2012
6 fb-1
LHCb
0.5 fb
June 2012

2015: arriving at 13 TeV cm energy

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

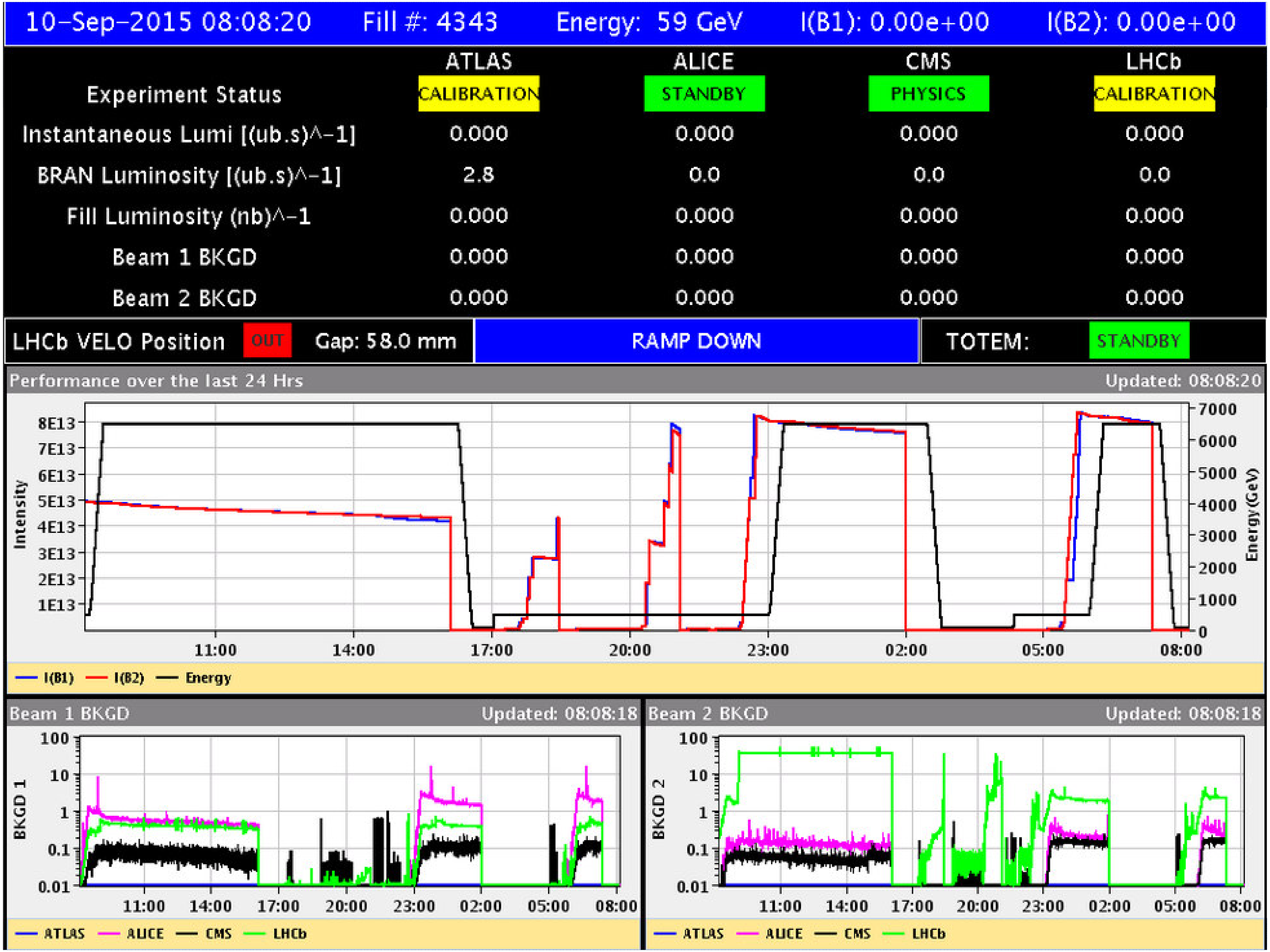


Excellent fill (2011)



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
Performance over the last 24 Hrs
Updated: 08:08:20
Intensity
Energy (GeV)
I(B1)
I(B2)
Energy
Beam 1 BKGD
Updated: 08:08:18
BKGD 1
ATLAS
ALICE
CMS
LHCb
Beam 2 BKGD
Updated: 08:08:18
BKGD 2
ATLAS
ALICE
CMS
LHCb

Challenges for high beam intensity operation

Machine Protection and Collimation

Electron clouds

Instabilities

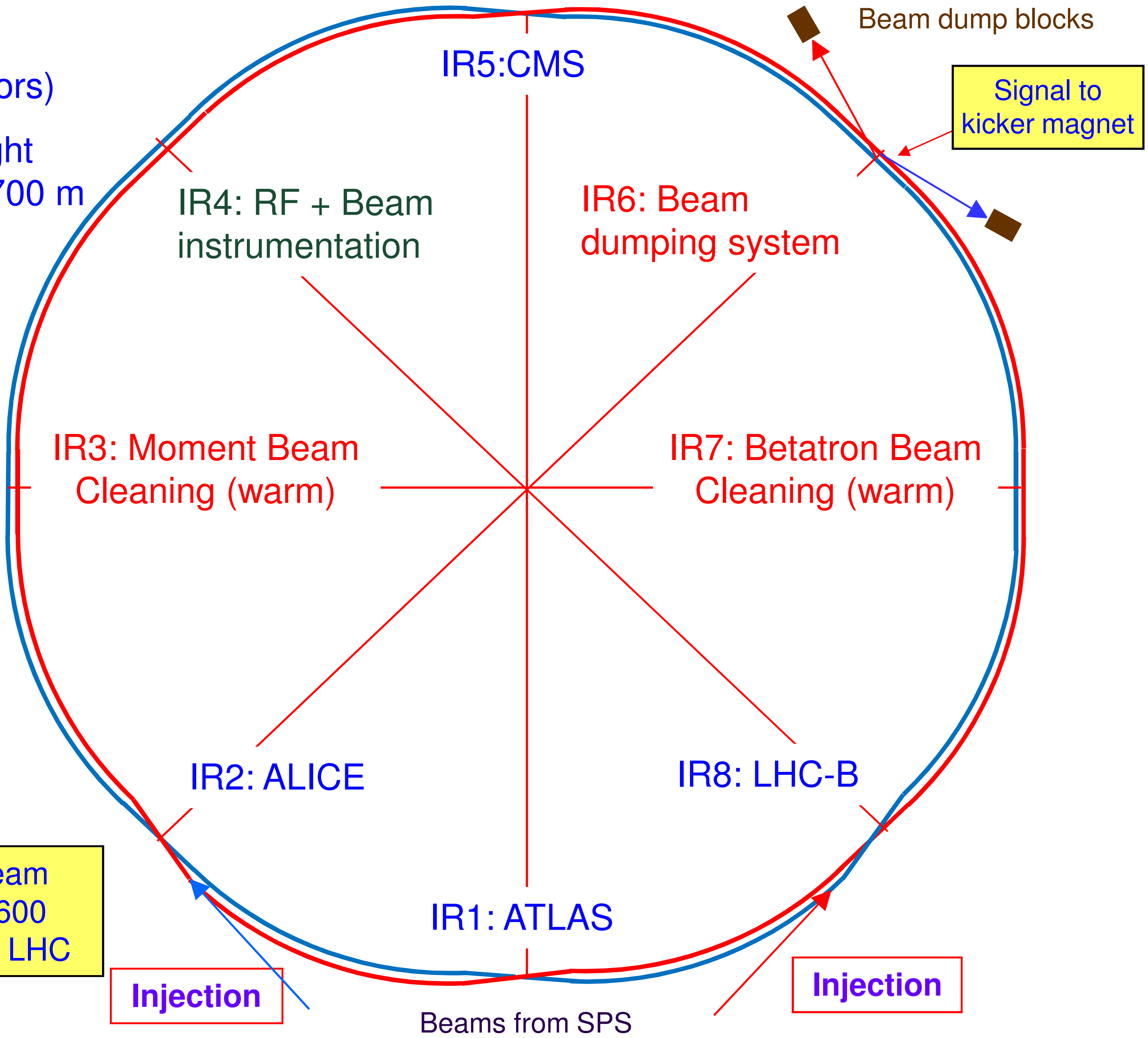
UFOs

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.

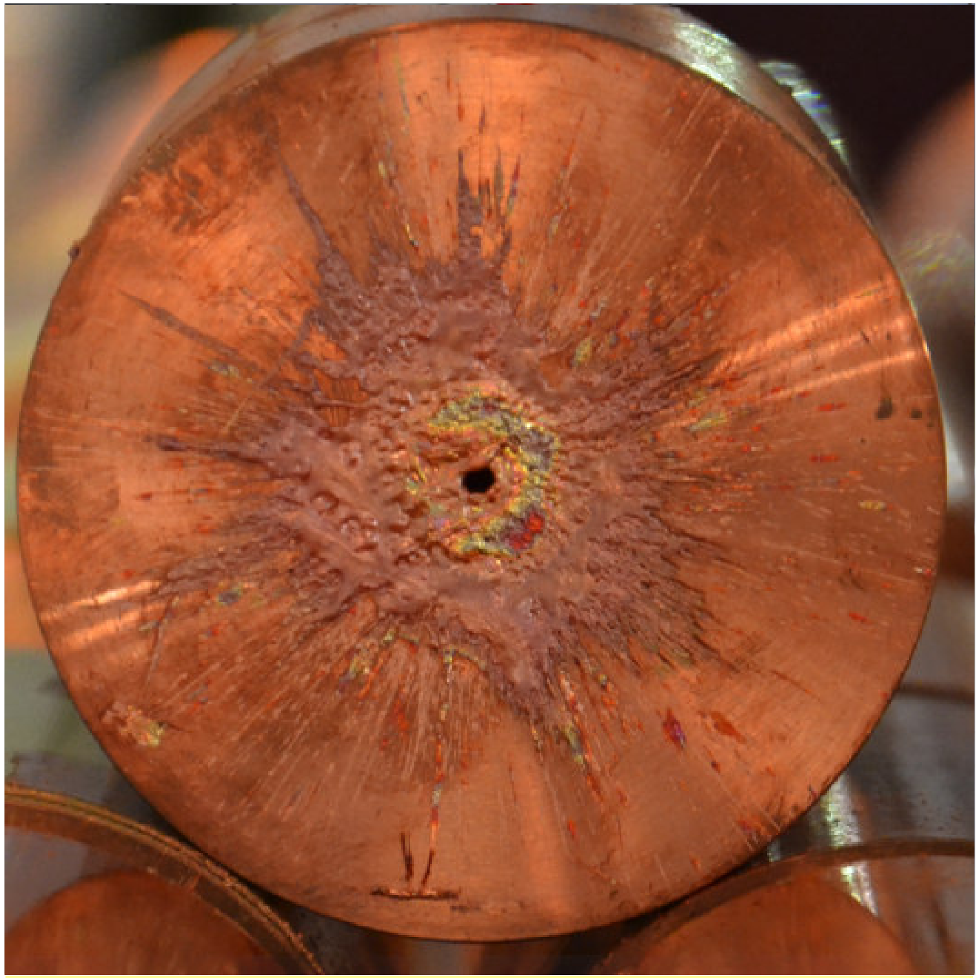
The pressure will build up and the density is reduced.

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 the LHC is expected to be around 30 m.

A single bunch at 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

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

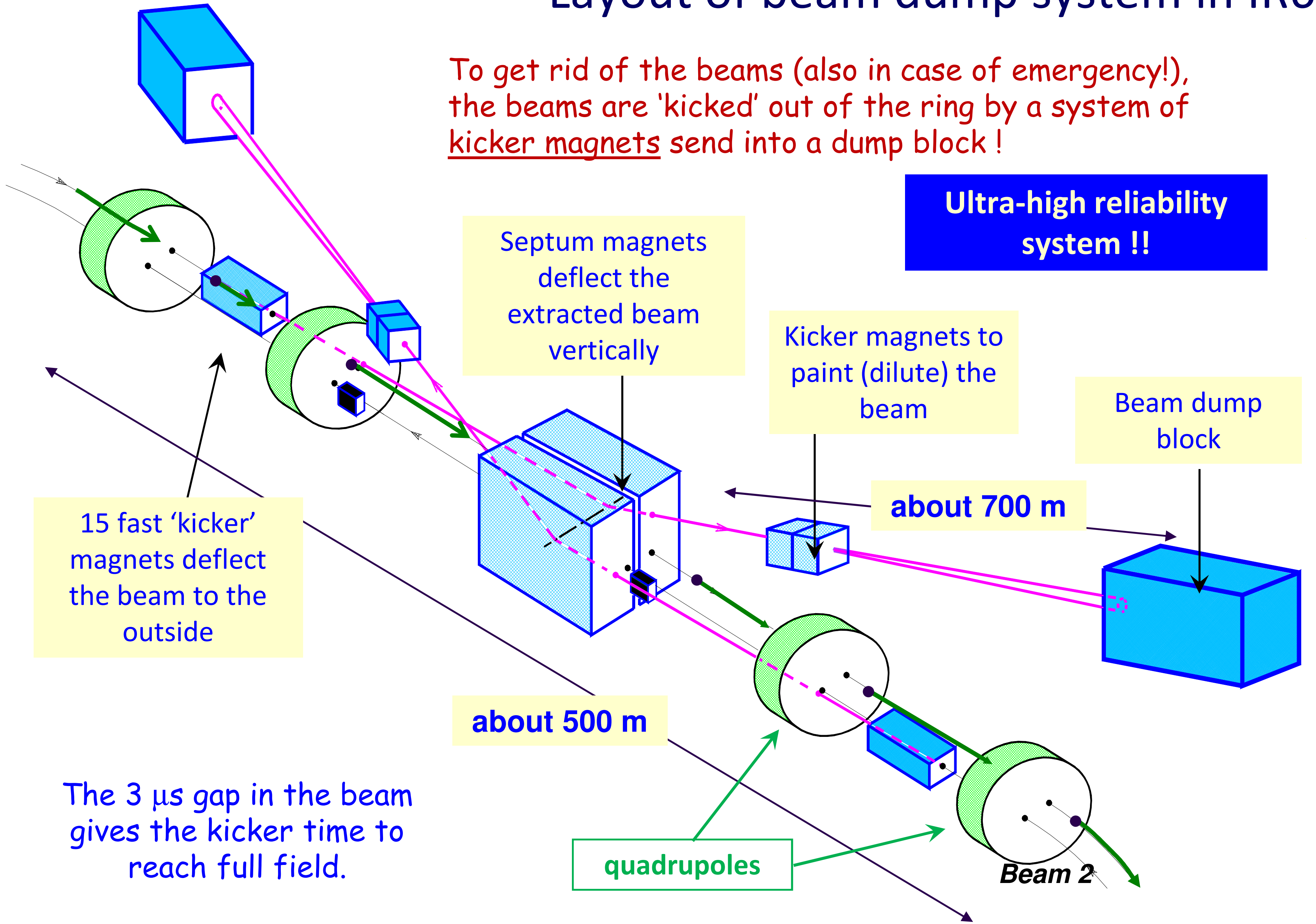
Accidental beam losses

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

Machine protection includes a large variety of systems

Layout of beam dump system in IR6

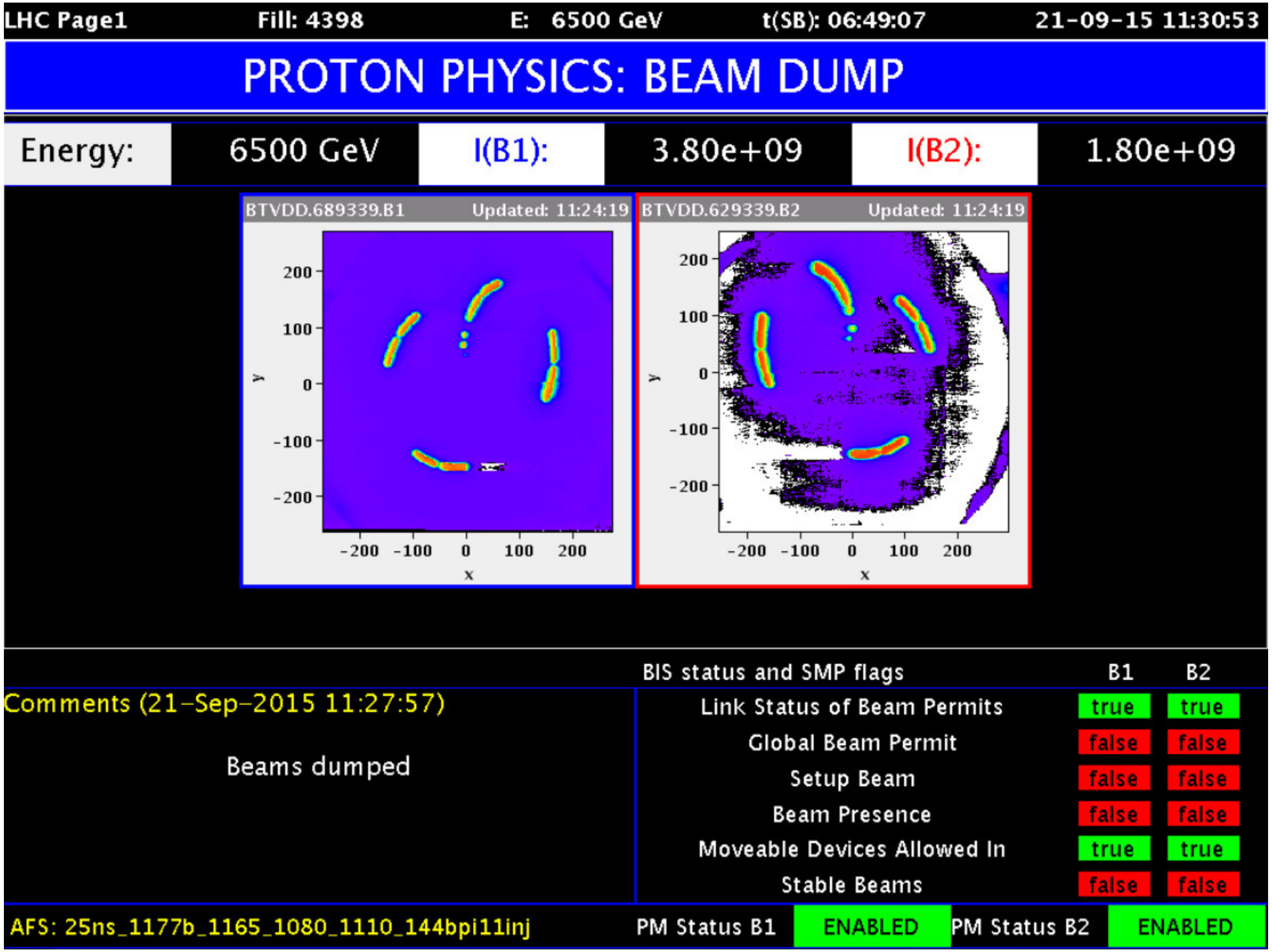
To get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of <u>kicker magnets</u> send into a dump block !



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

Beam dump line

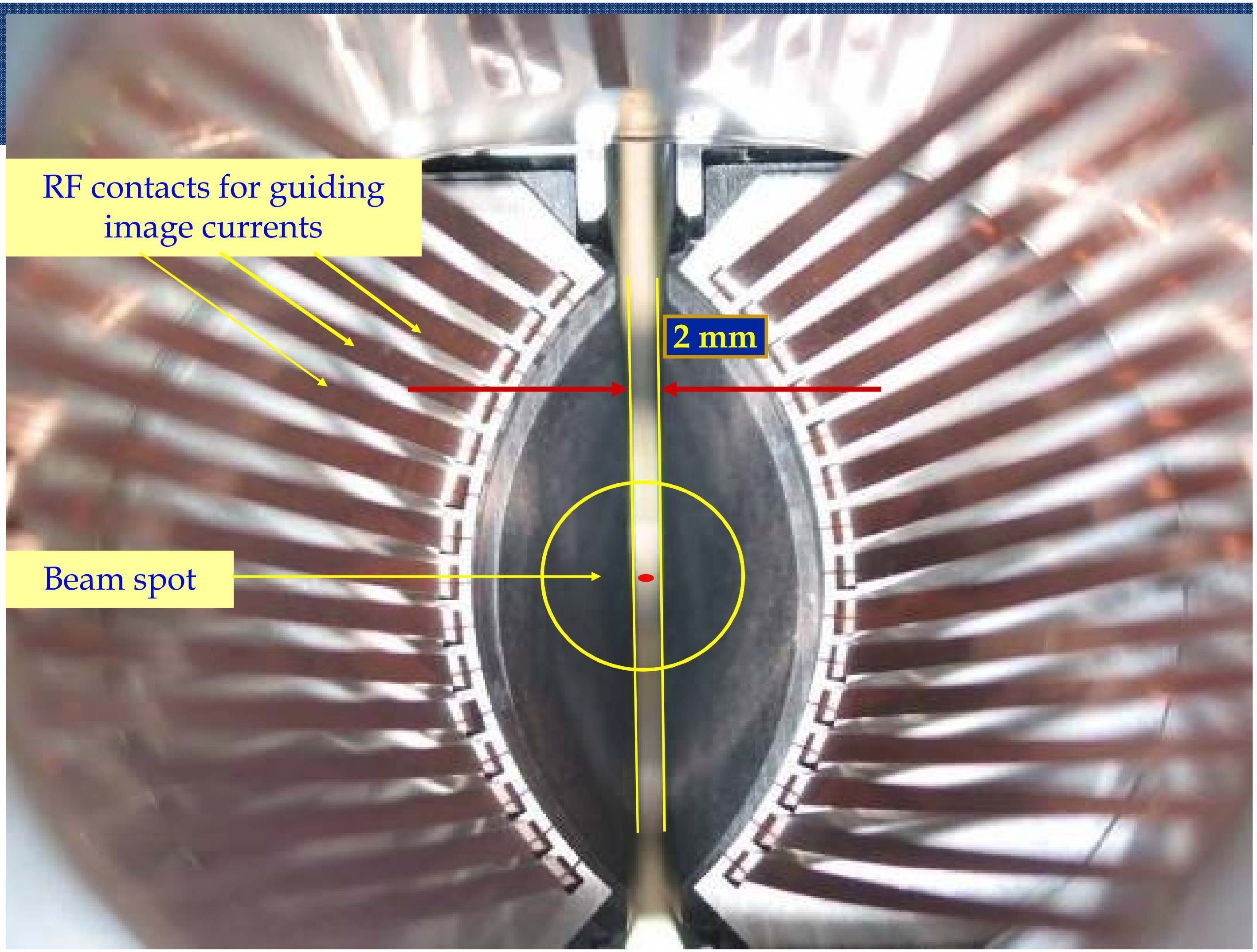
Beam dump with 1380 bunches



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

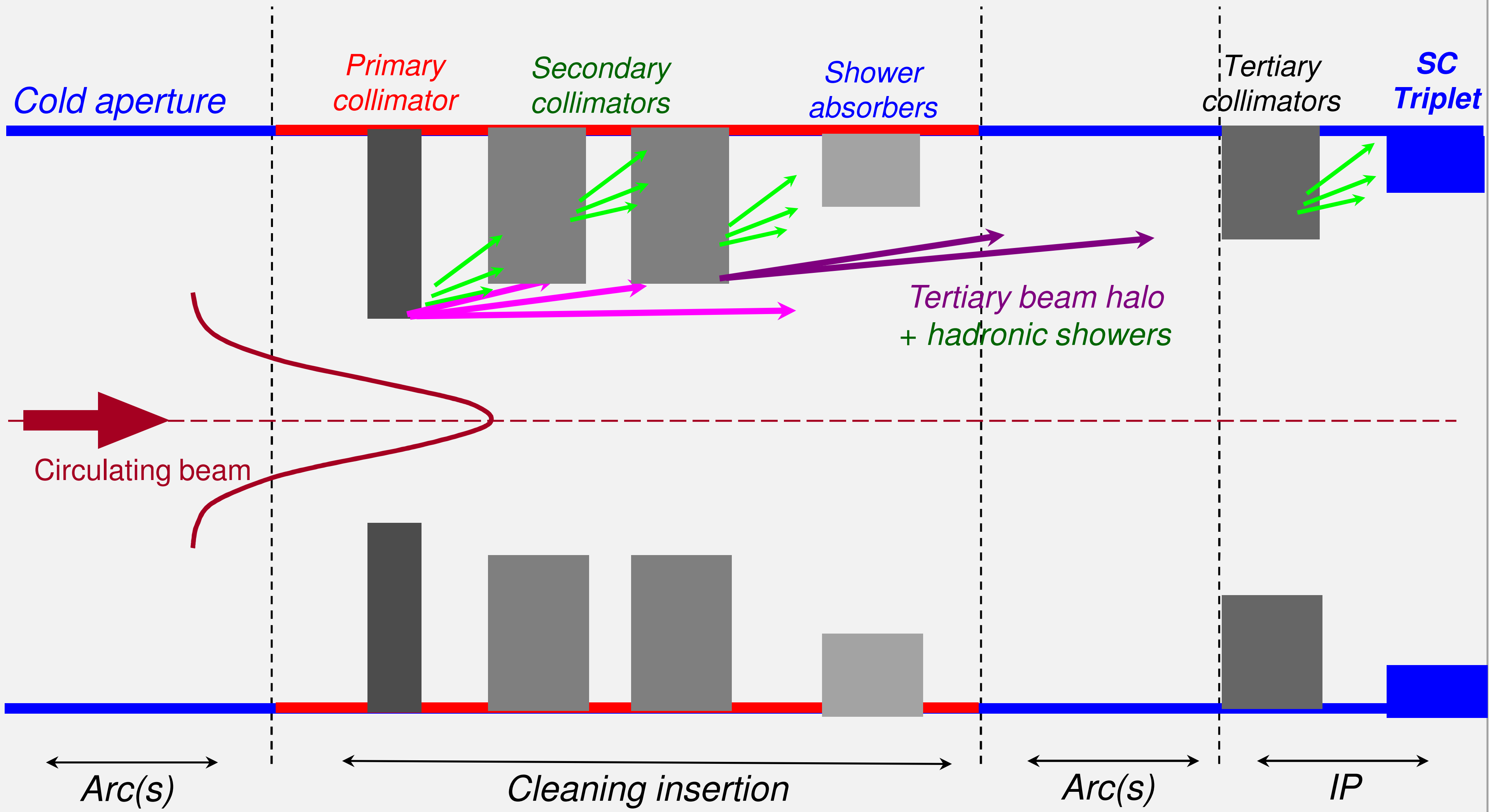
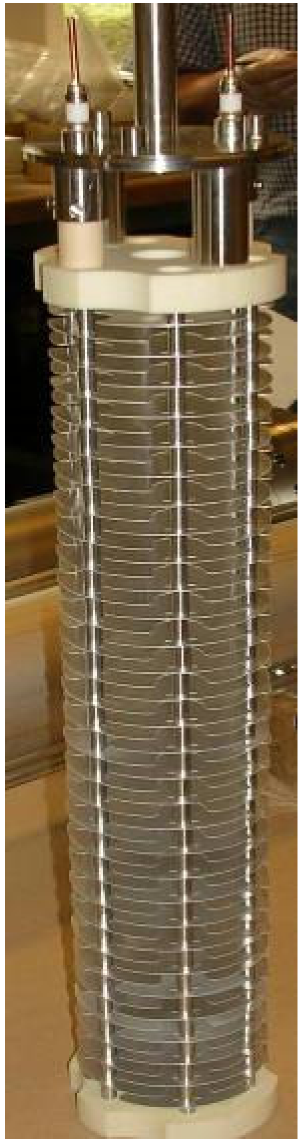
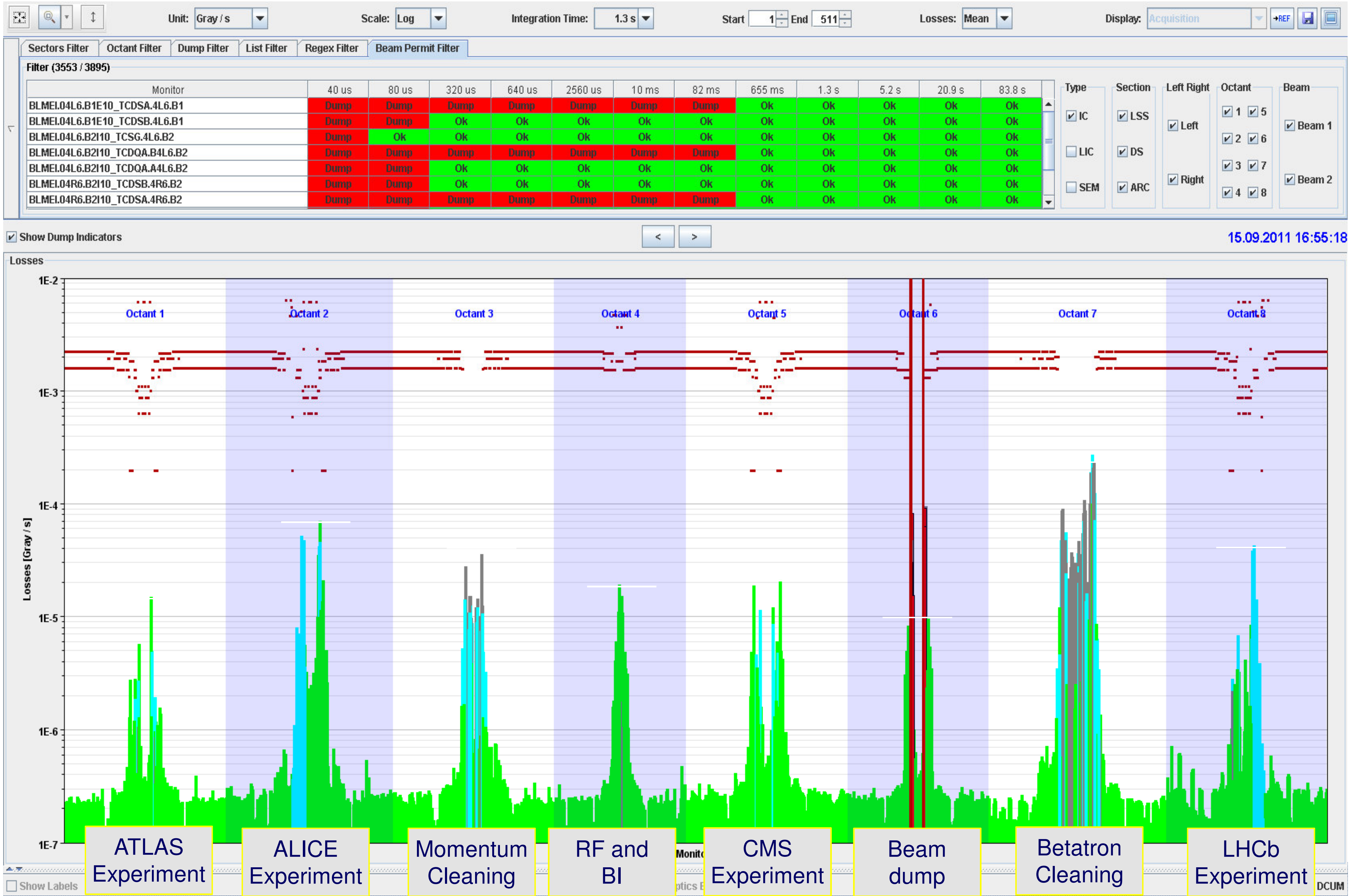


Illustration drawing

- 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!



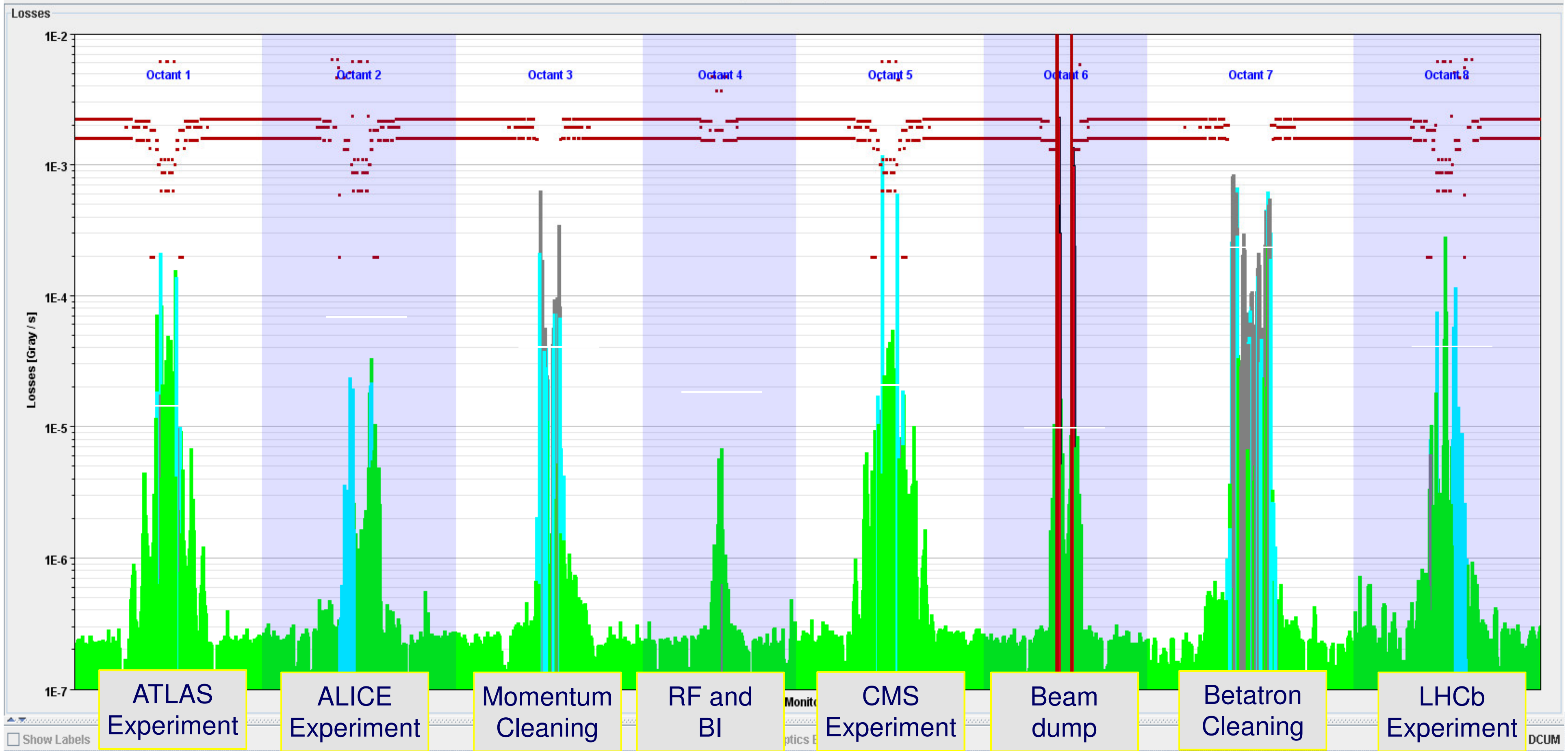
BLM system: beam losses before collisions



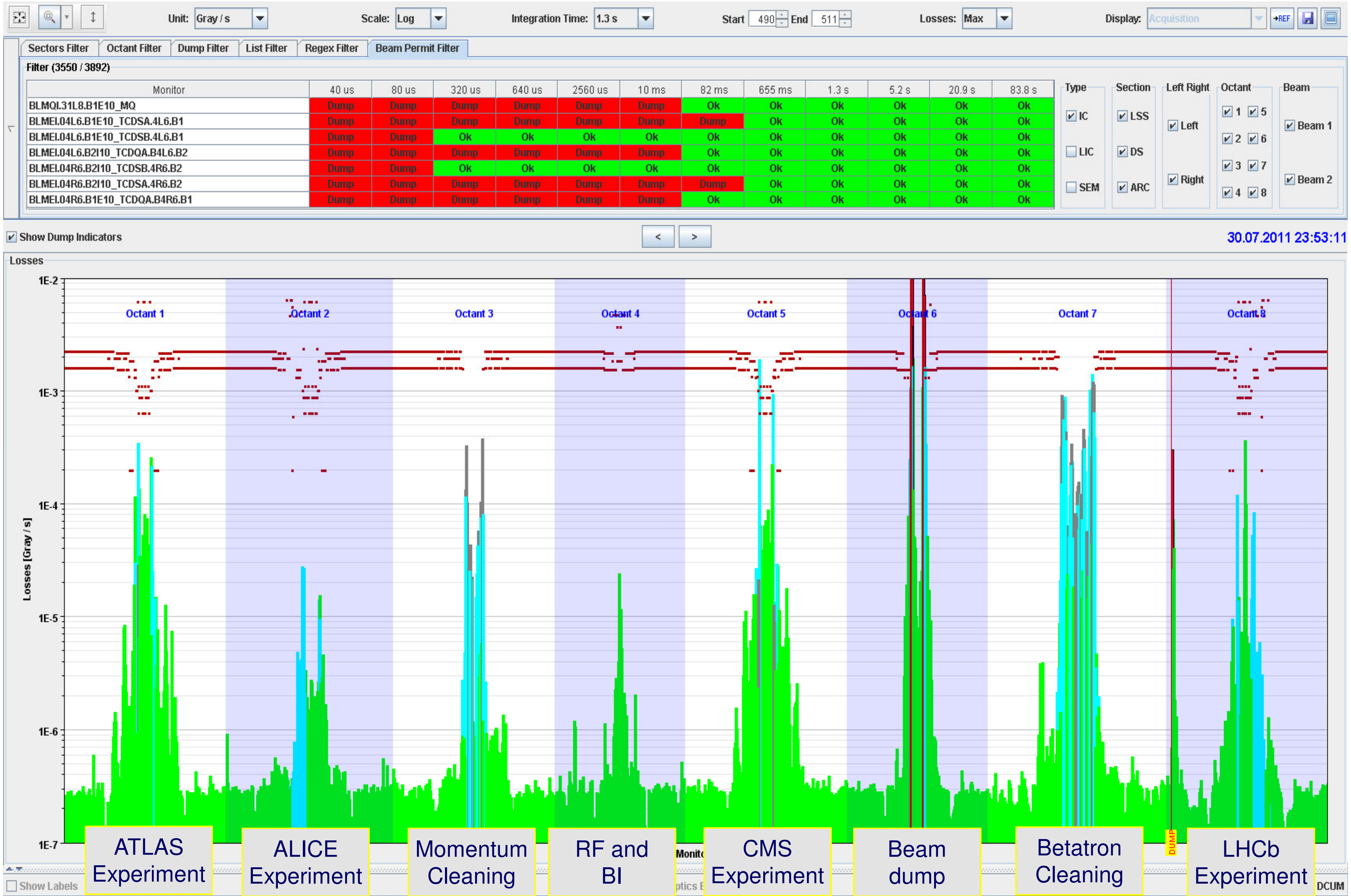
Continuous beam losses during collisions

Filter (3553 / 3895)

Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCSG.4L6.B2	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.A4L6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok

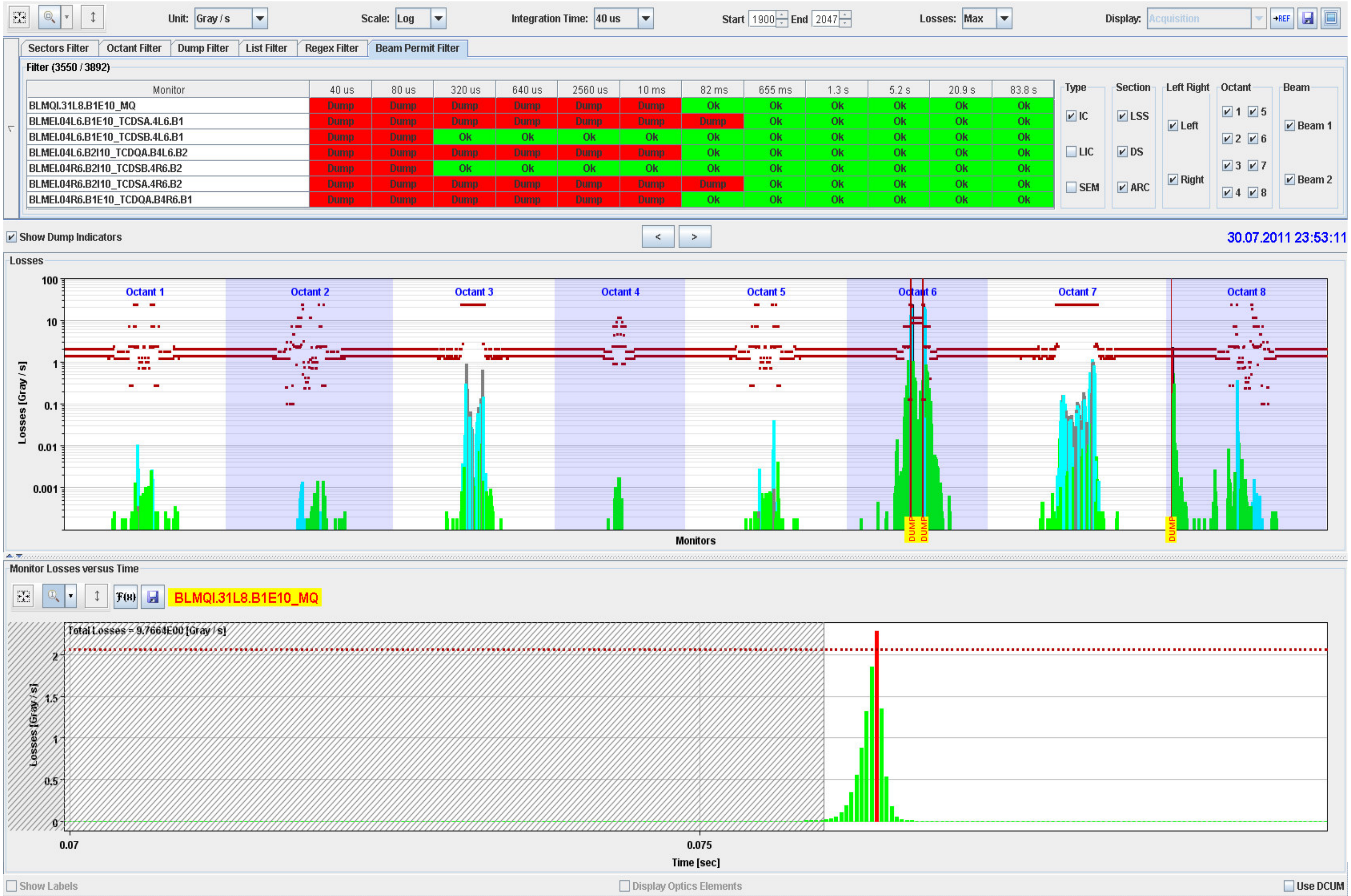


Accidental beam losses during collisions



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

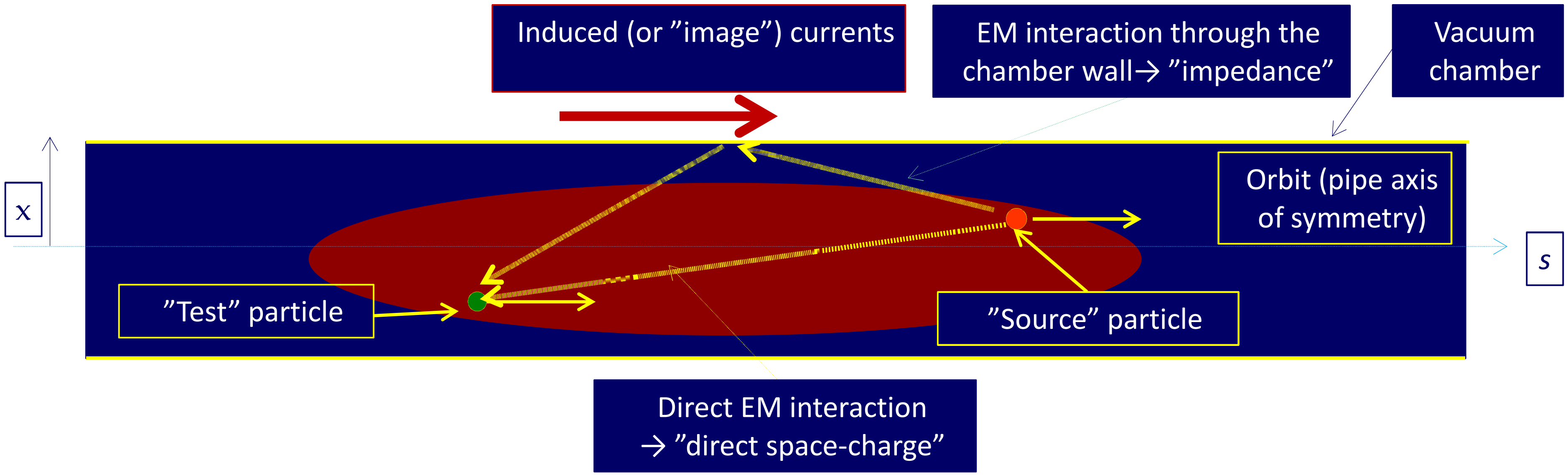
Accidental beam losses during collisions

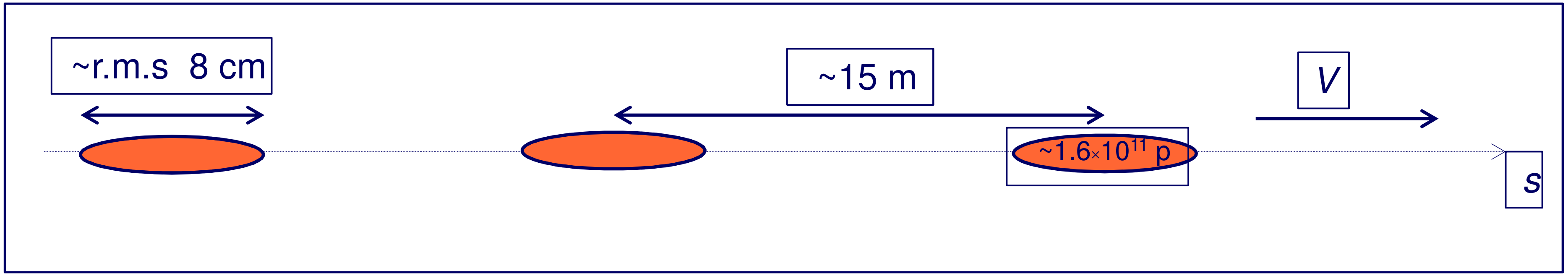


Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok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

Limits to the bunch population

- High bunch population and tight bunch spacing make the beams prone to instabilities related to impedances i.e. to **self-generated fields**





Limits to the bunch population

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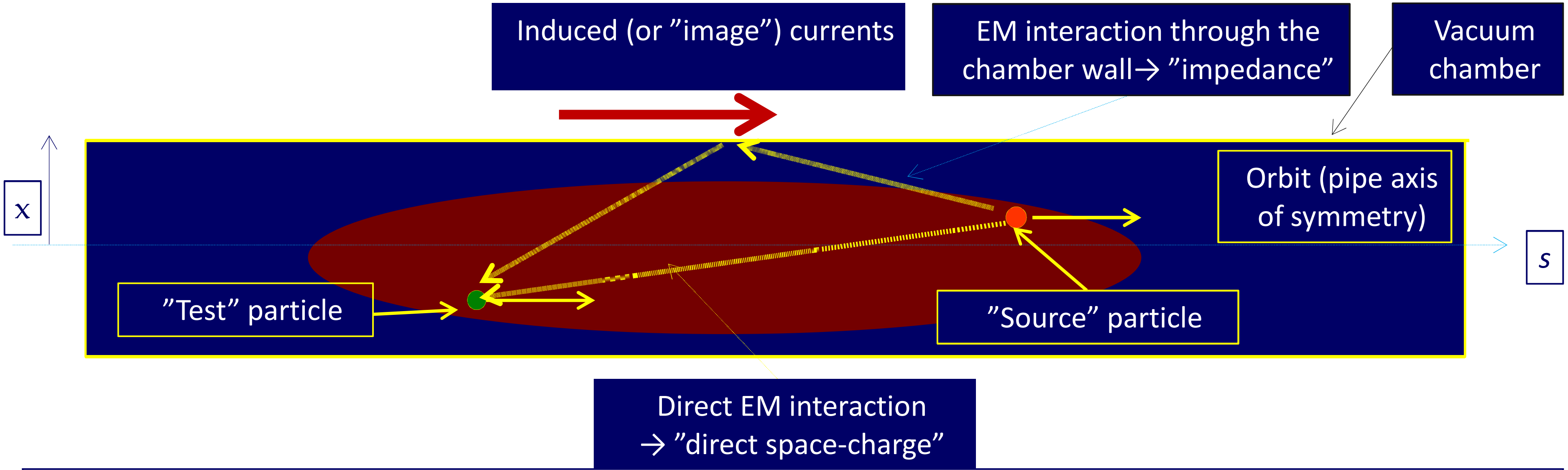
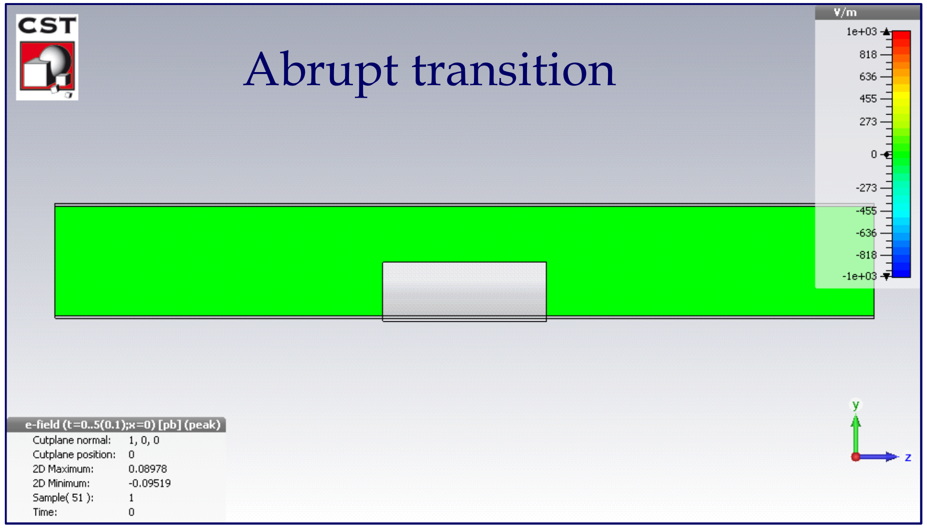
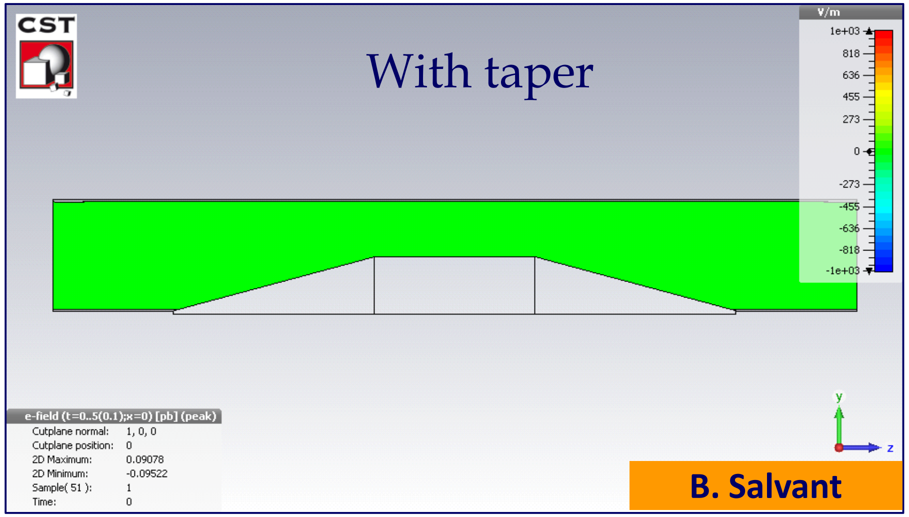


- In 2012 instabilities have become critical due to higher bunch intensity and tighter collimators settings → larger impedance. Cures:
  - Transverse feedback
  - Non-linear magnetic fields (sextupoles, octupoles, beam-beam) that produce a frequency spread among particles – kill coherent motion
- We are far away from a full understanding!

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

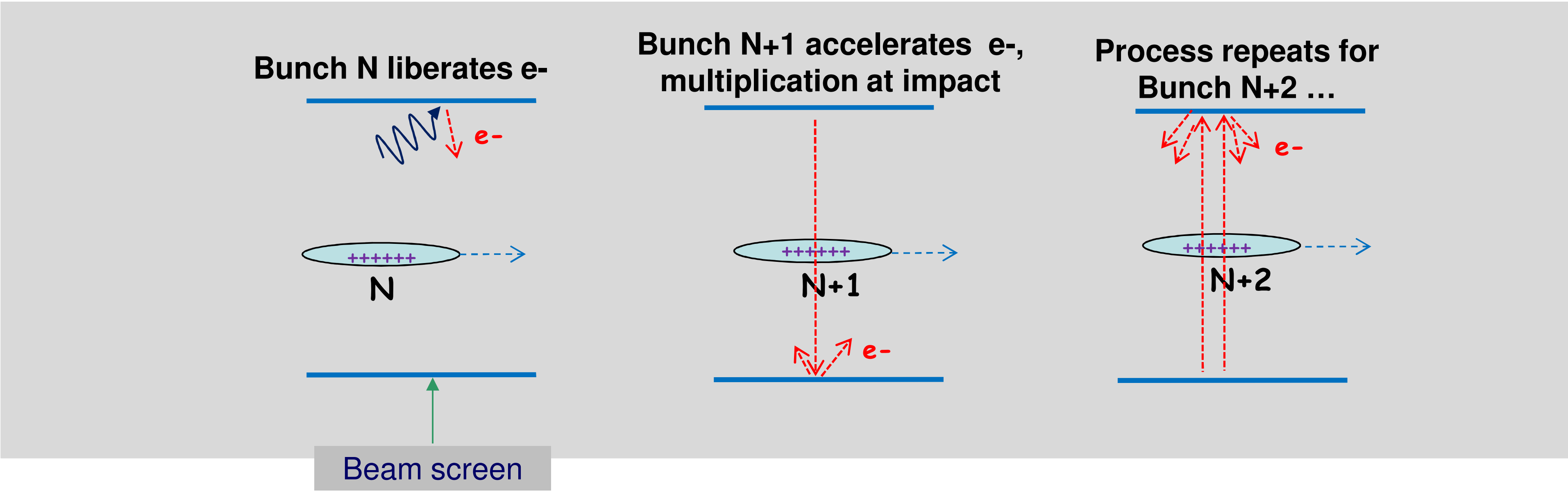




- Avoid the abrupt transition for the beam fields at the location of the beam passage (taper)
- Reduce the resistivity of the material

Electron cloud challenge

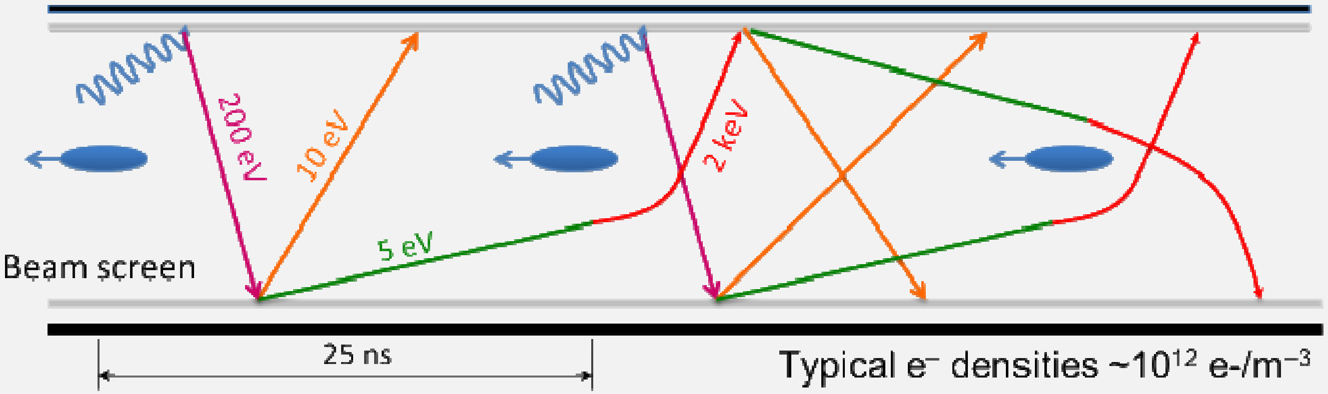
In high intensity accelerators with positively charged beams and closely spaced bunches, electrons liberated on vacuum chamber surface can multiply and build up a cloud of electrons.



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

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.

G. Iadarola, G. Rumolo

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.

From 2012 to 2015 …and beyond

2012: high intensity proton operation at 4 TeV

2013: few weeks for ion operation

2013-2015: consolidation (interconnects, others)

2015…..2017: proton and ion operation at 6.5 TeV

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

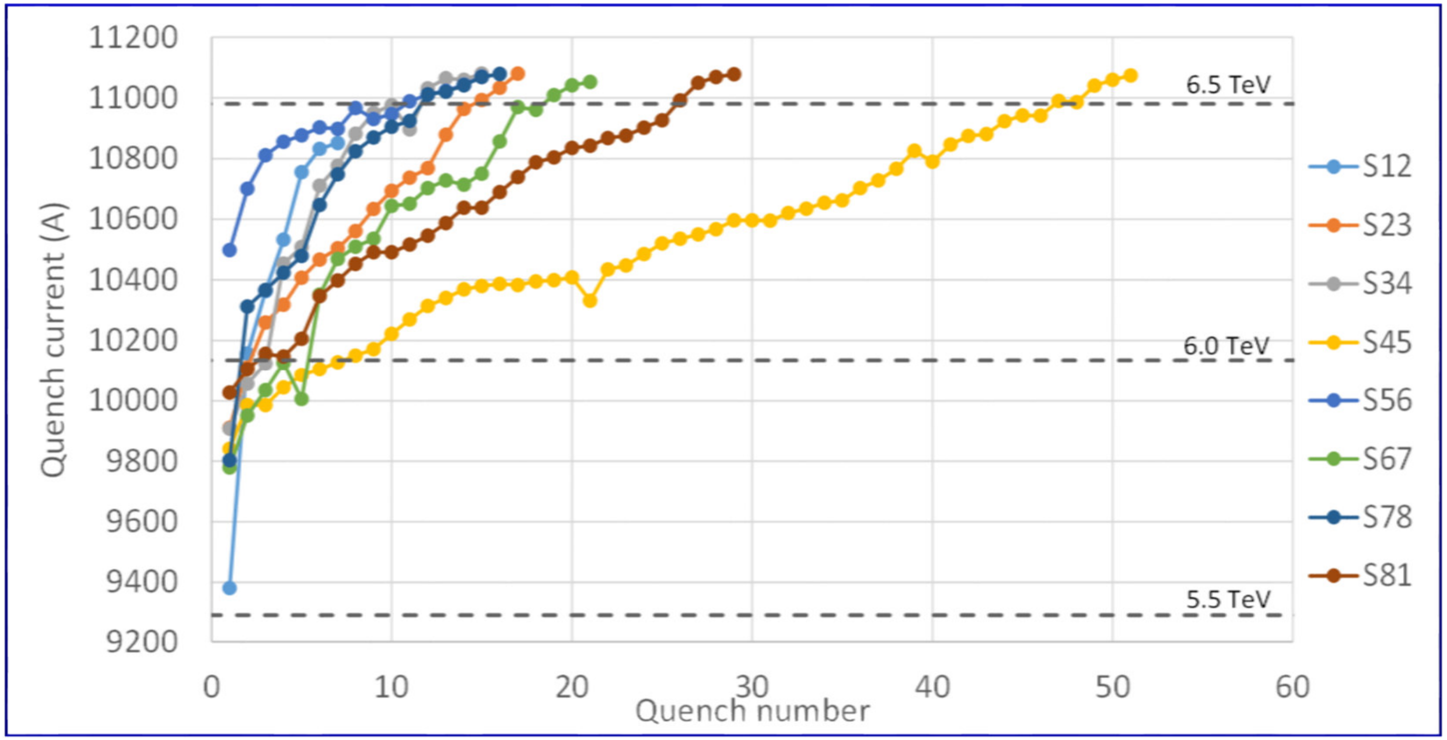
Maximize the integrated luminosity

Small focusing – β* as small as possible

Highest possible efficiency

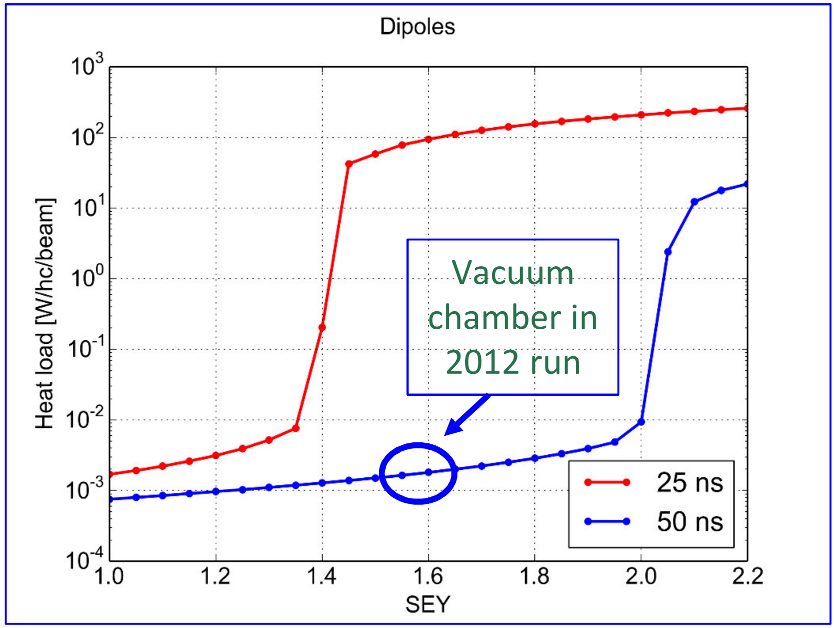
Dipole training campaign

- 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.



Electron cloud mitigation

- Strong dependence of e-clouds on bunch spacing.

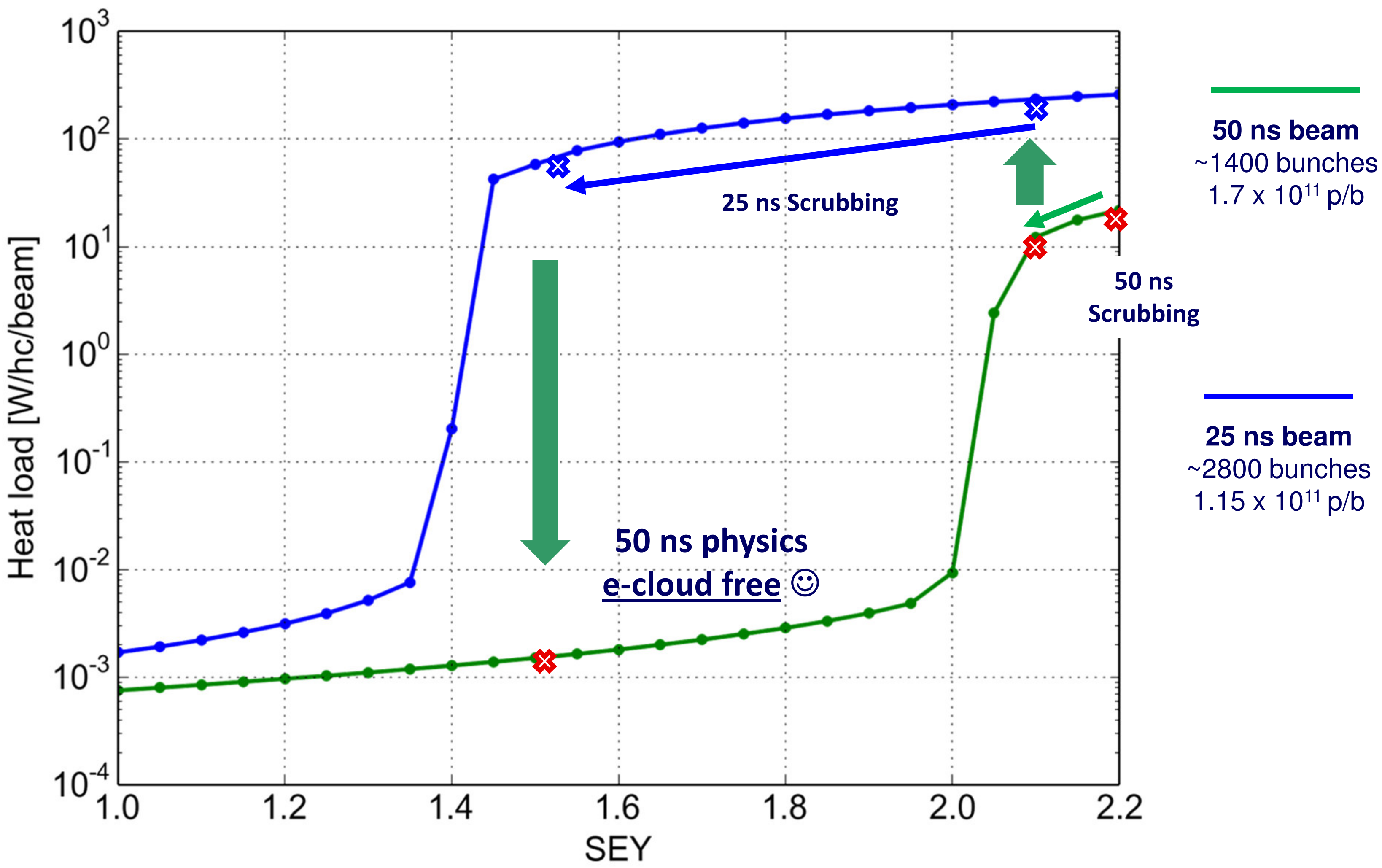


With 50 ns spacing e-clouds are much weaker than for 25 ns spacing !

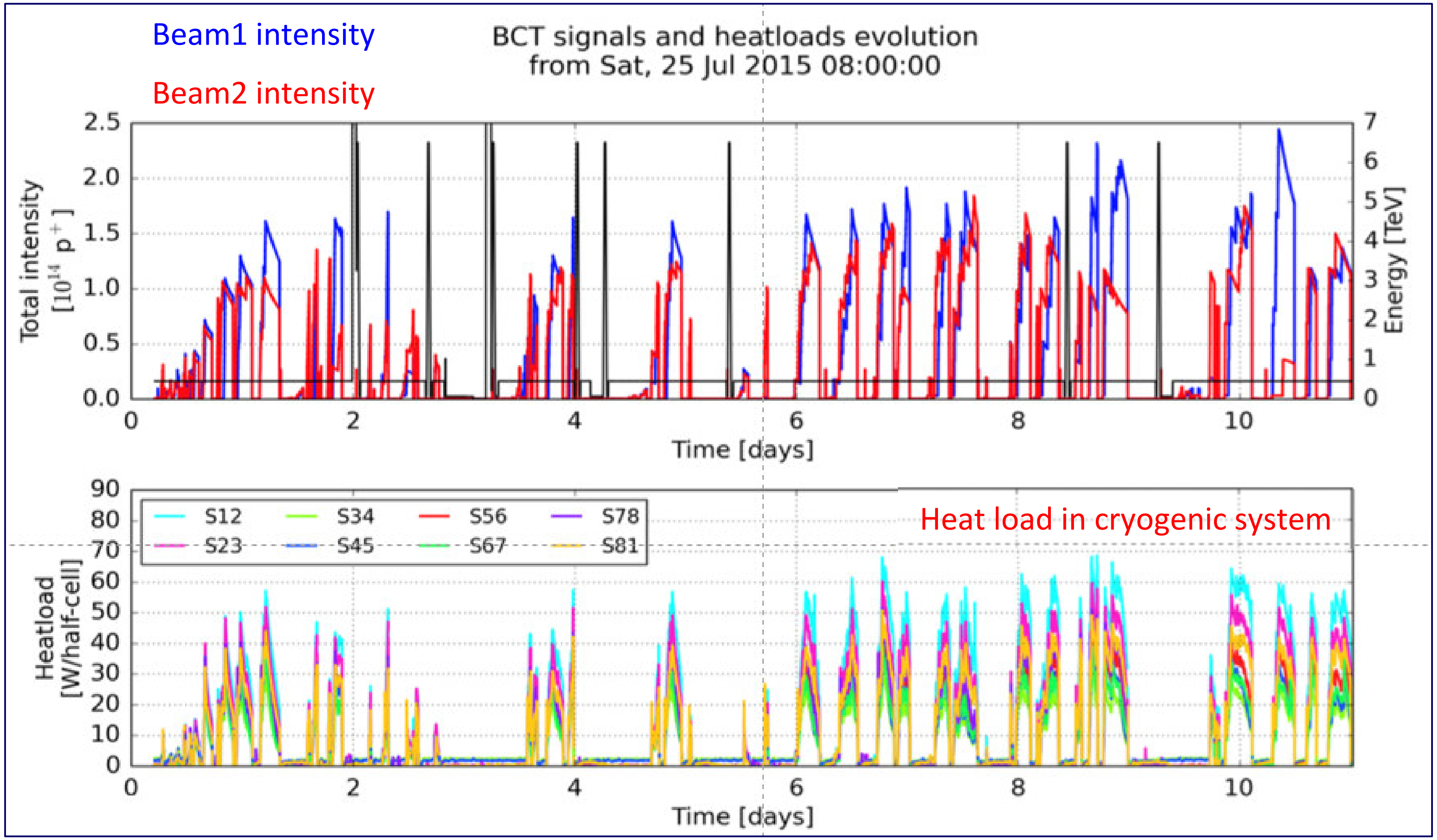
→ To ease life during Run 1, bunch spacing was reduced to 50 ns

- Conditioning of the vacuum chamber by beam-induced electron bombardment ("scrubbing"): progressive reduction of the SEY
- Conditioning is performed at 450 GeV where fresh beams can be injected easily.
- One must condition with a beam that is more powerful (⍰ more electron could generation) that the beam one plans to use for operation.

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



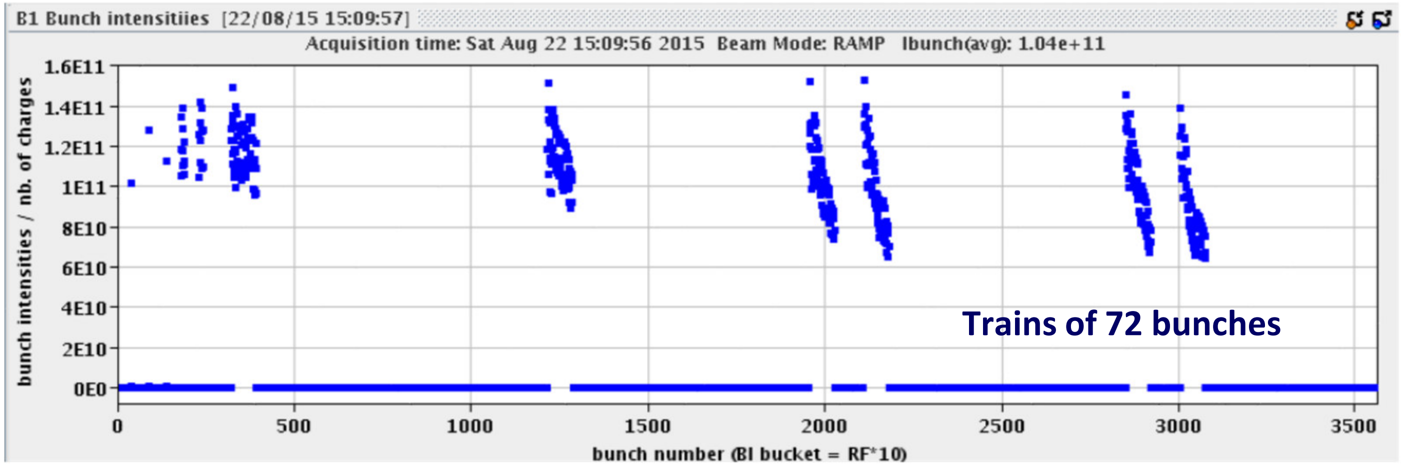
(Second) 2015 scrubbing run



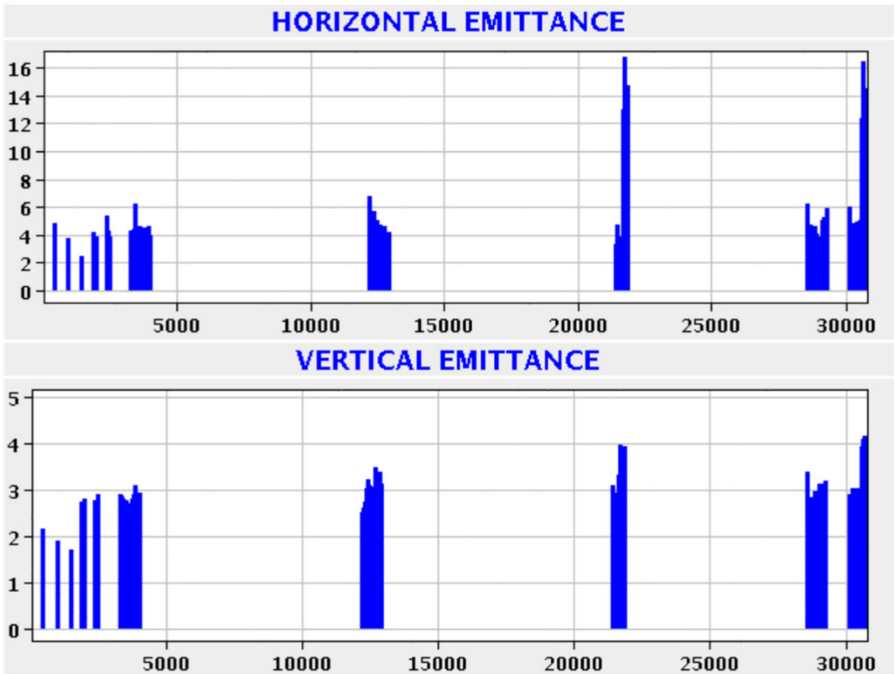
- Scrubbing with 25 ns beams
- At the end, machine conditions were reasonable for ~1200 bunches operation (max. possible 2800). Number of bunches limited by high vacuum pressures at injection on some absorbers and cryogenic heat load

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 has to continue in parallel to physics operation.

UFOs at LHC

Surprising ‘Unidentified Falling Objects’

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

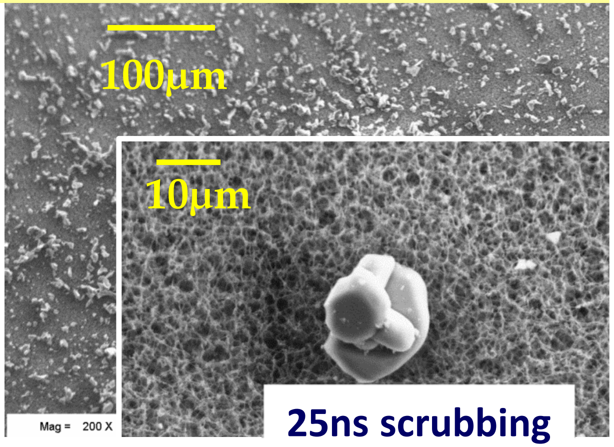
The beam losses were traced to **dust particles entering into the beam** – ‘**UFO**’.

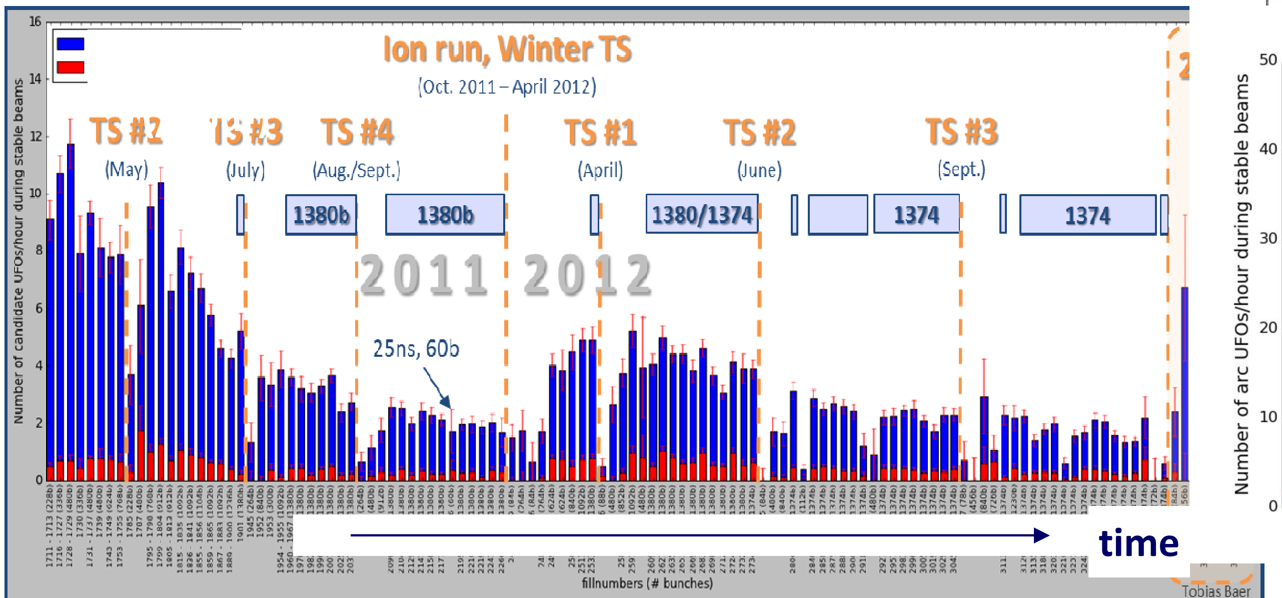
Losses too high => beams dumped to avoid a quench, but sometimes magnets quench

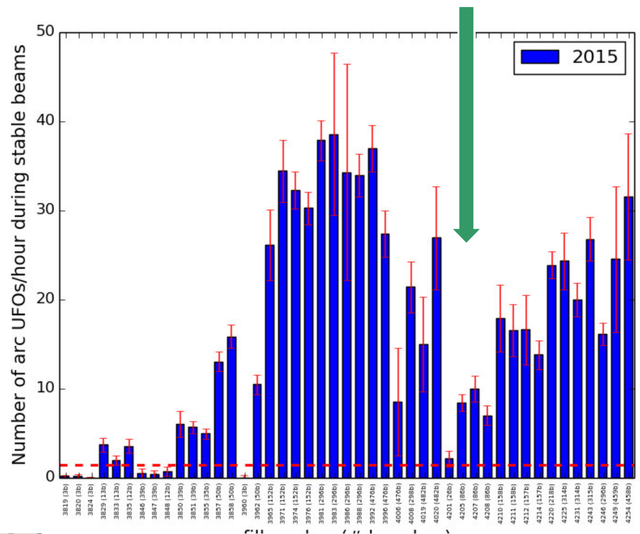
2015: **2 UFO quenches** (vs. **>10 beam dumps** due to UFOs in the arc + 2 in LSS)

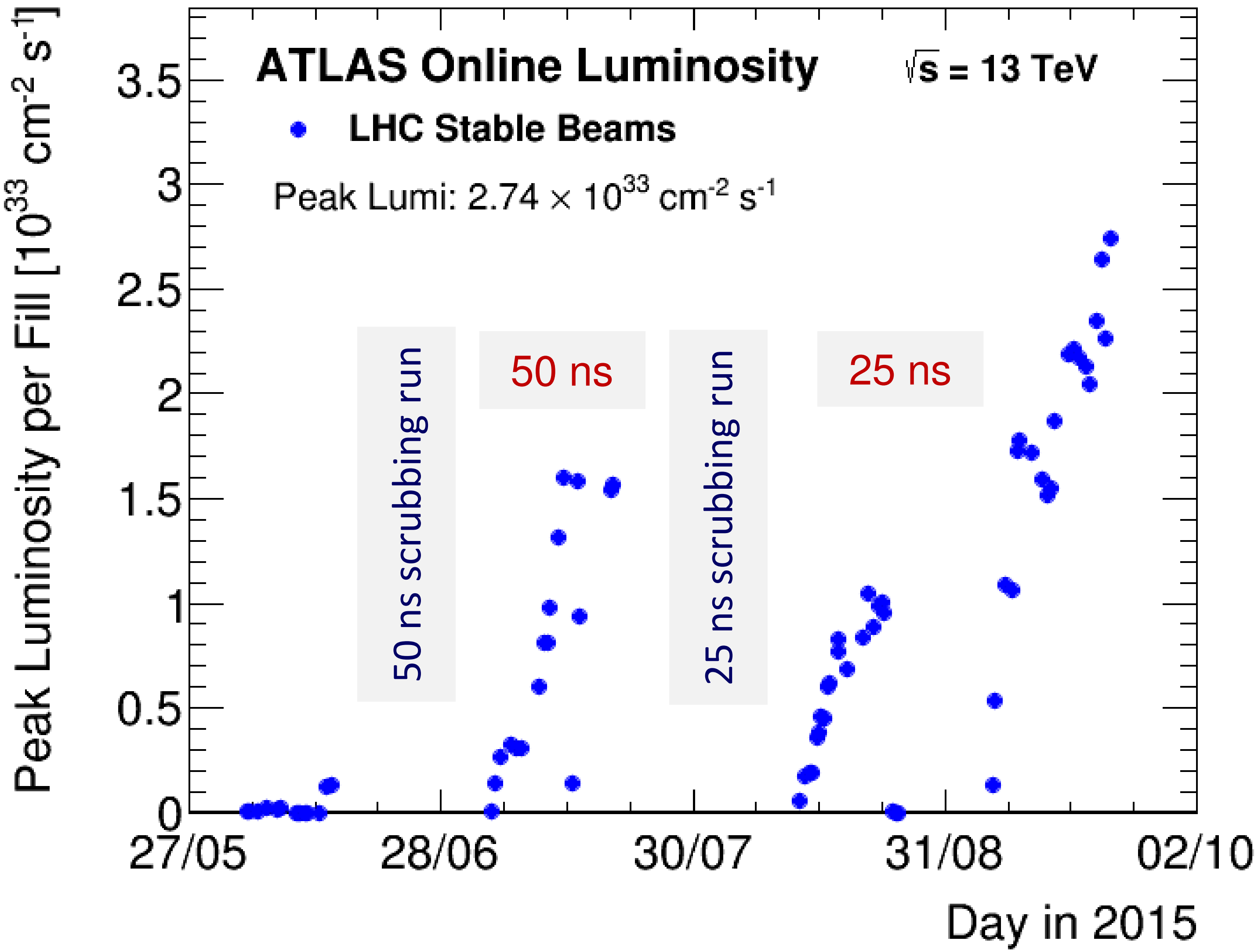
Conditioning of the UFO-rate expected

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

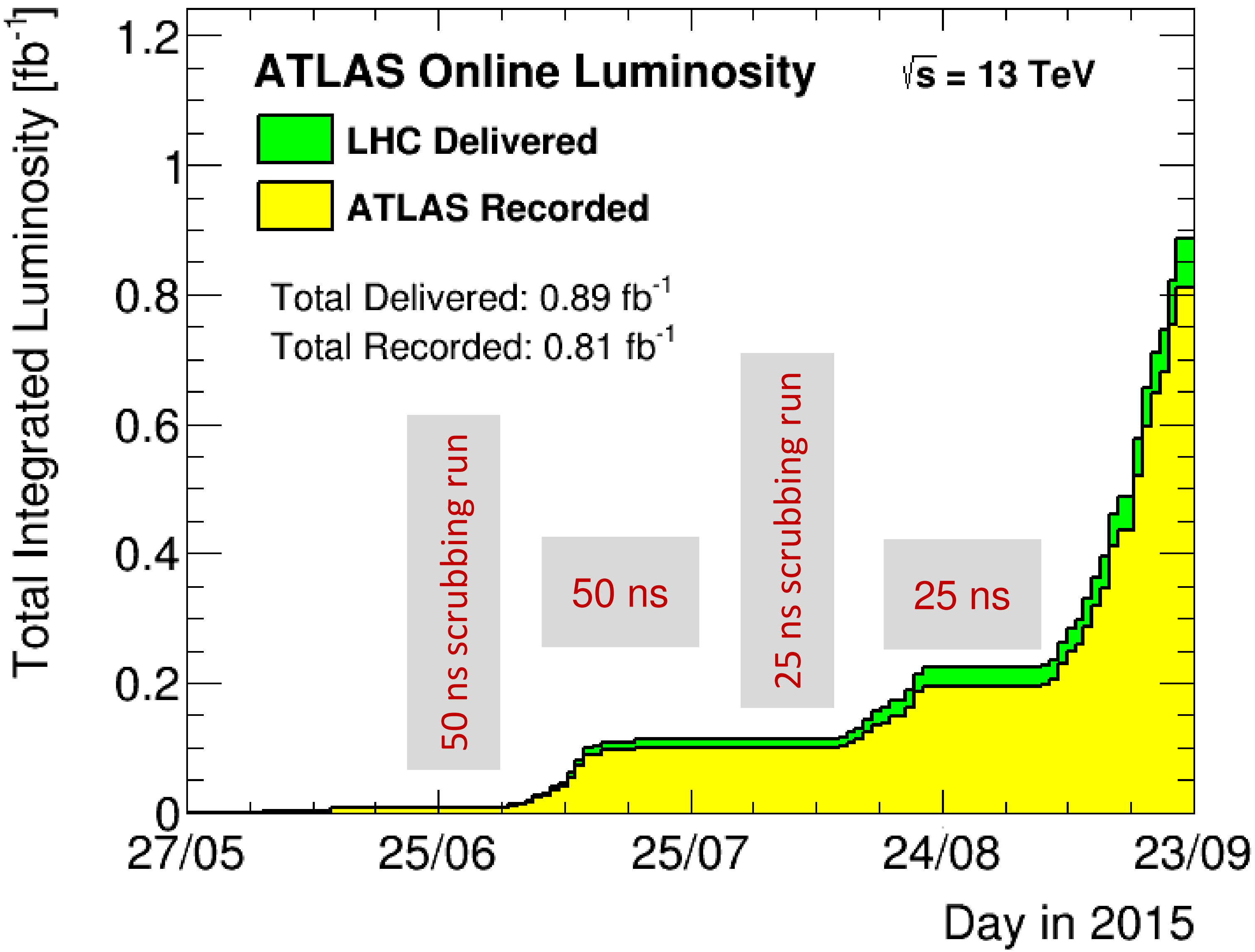






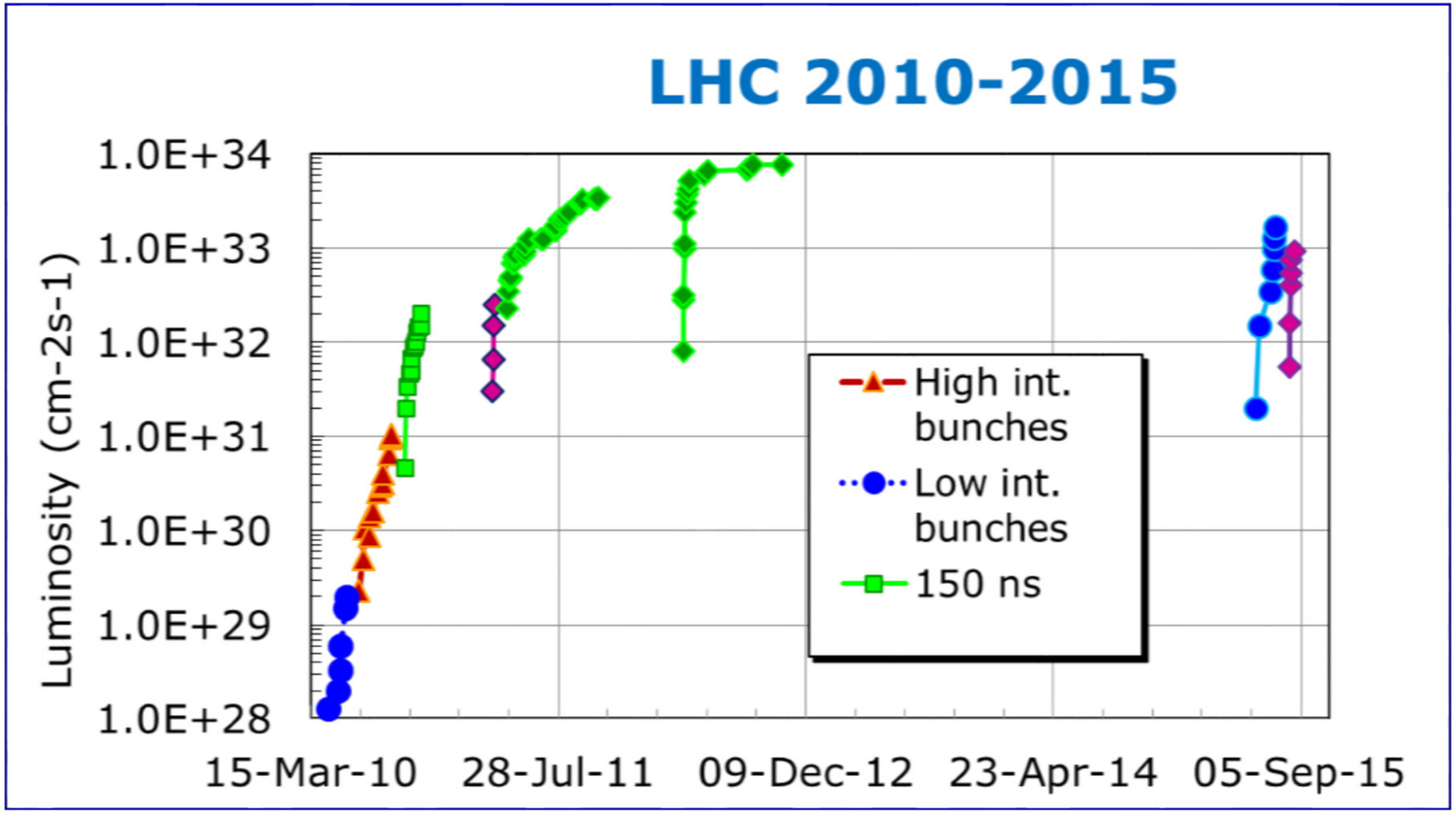

ATLAS Online Luminosity
√s = 13 TeV
LHC Stable Beams
Peak Lumi: 2.74 × 10^33 cm^-2 s^-1
Peak Luminosity per Fill [10^33 cm^-2 s^-1]
3.5
3
2.5
2
1.5
1
0.5
0
27/05
28/06
30/07
31/08
02/10
Day in 2015
50 ns scrubbing run
50 ns
25 ns scrubbing run
25 ns

2015 Overview



The start-up of Run 2 was faster then for Run 1, but we are still far from the Run 1 performance. We are still in the learning phase for 25 ns.

Operation with 50 ns beams is easier !



Some scenarios @ 6.5 TeV

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

Beam	k	N_b [10^{11} p]	ε [μm]	β* [m]	Peak L [10^{34} $cm^{-2}s^{-1}$]	Event pile-up	Int. L(*) [fb^{-1}]
25 ns – 2015	~1500	1.1	3.5	**0.8**	**0.31**	14	~2
25 ns – standard	~2700	1.2	3.0	**0.8**	**0.78**	21	~20
25 ns – pushed	~2500	1.2	2.0	**0.4**	**1.7**	51	~40-50
50 ns	1360	1.6	2.2	**0.4**	**1.65**	90	~30

(*): per year

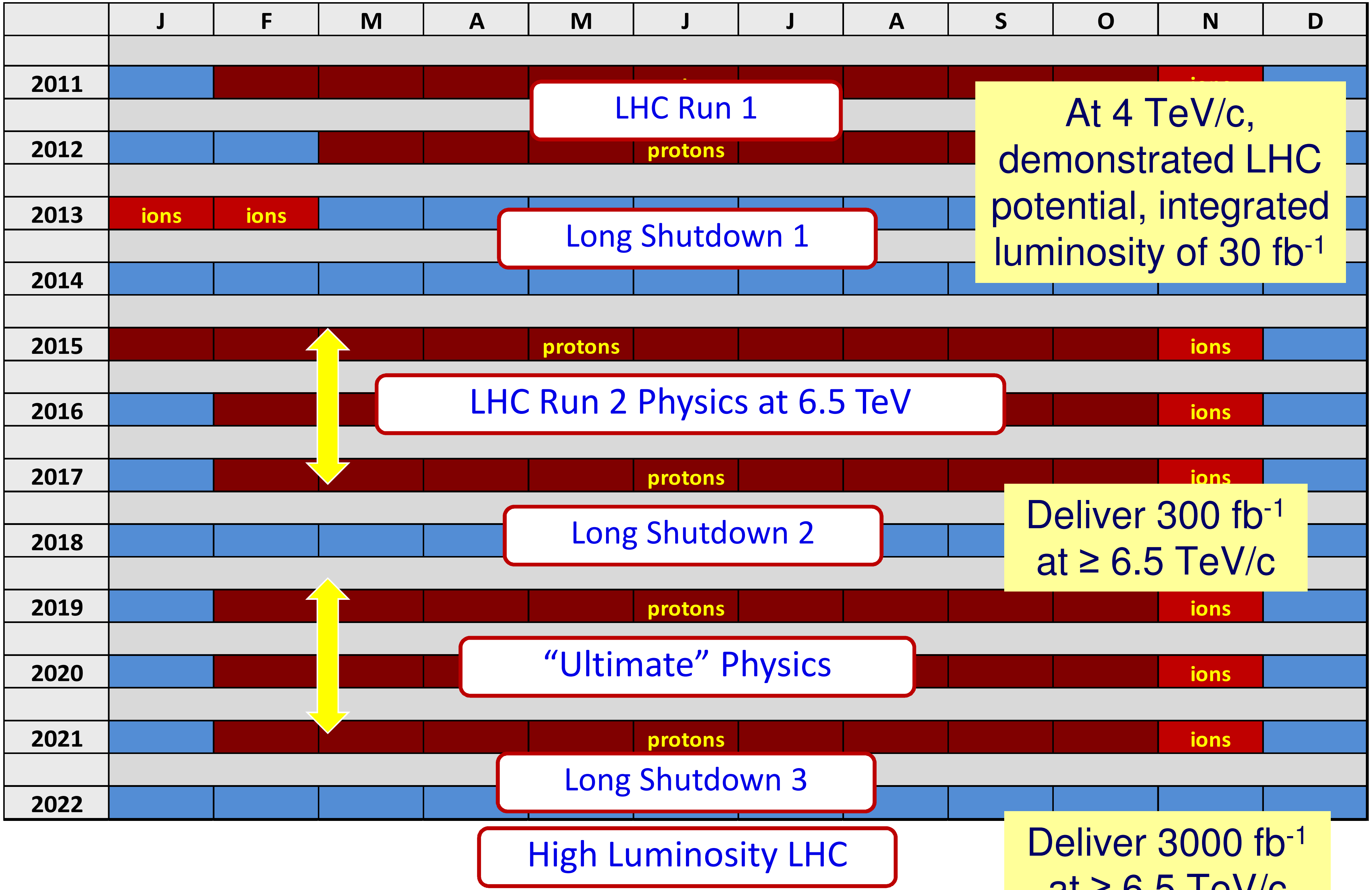
The next 20 years

LHC

and

High Luminosity-LHC (HL-LHC)

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

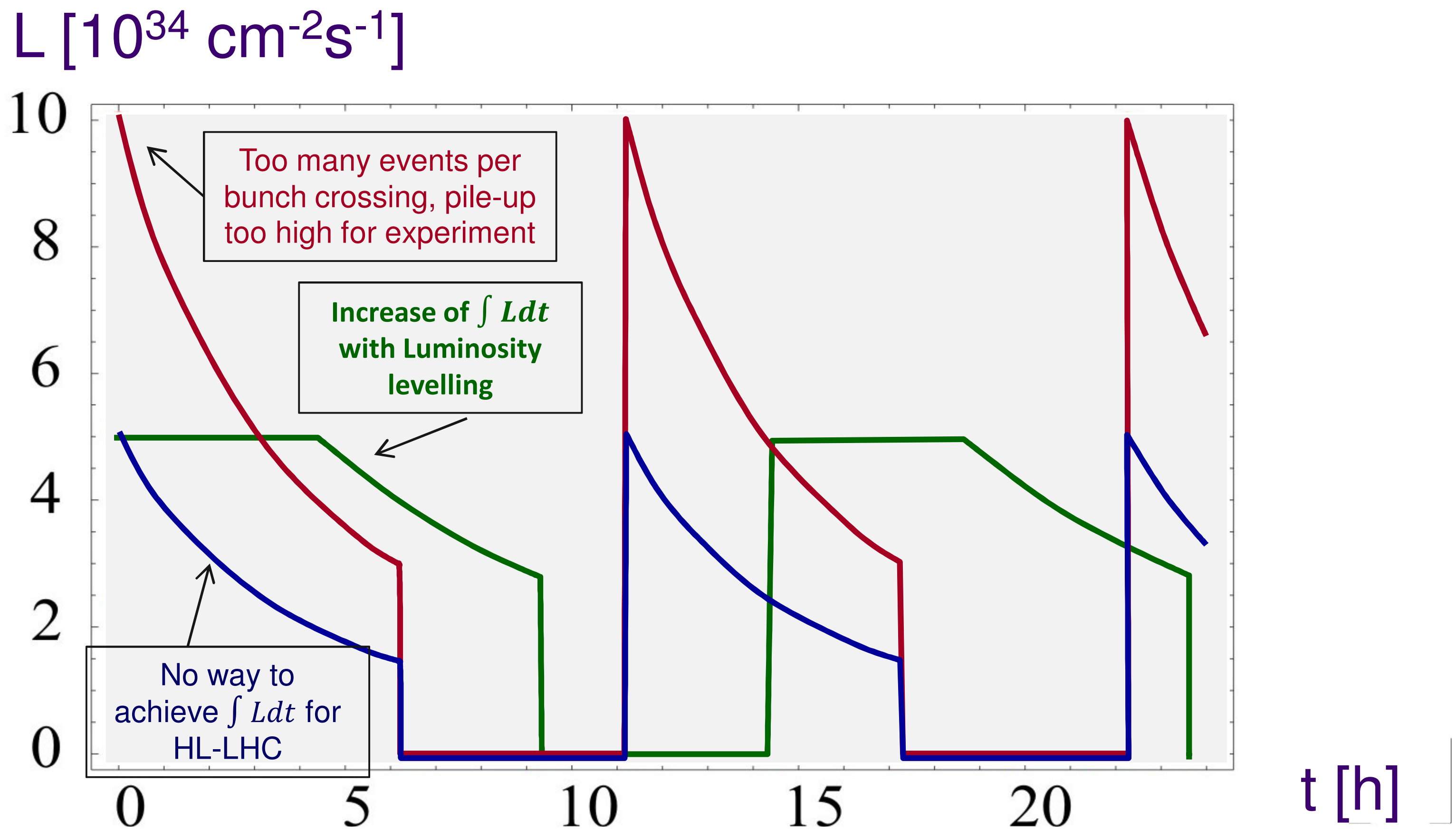
- **Operation with large bunch** intensity possible (no serious limitation)
- Single bunch with > $3x10^{11}$ protons per bunch with 2.5 um emittance provided by injector complex
- **Operation with very small beams** (low β* optics) successfully tested in injector complex

Pile-up/pile-up density HL-LHC beam physics constraint ➔ bunch spacing of 25 ns and luminosity leveling required for 2015 and later

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

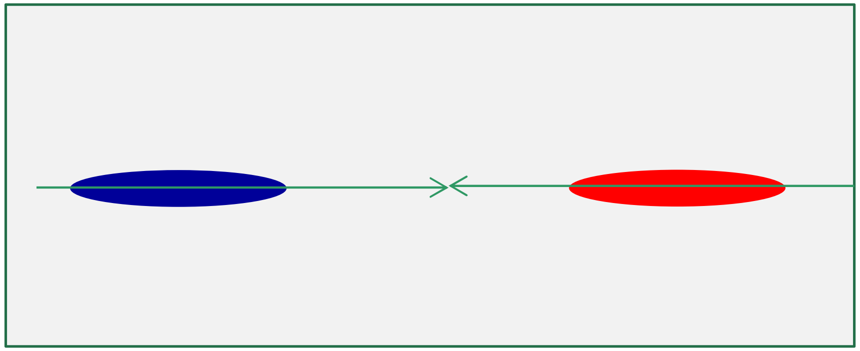
Integrated Luminosity increase by levelling

- $\int Ldt$ 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)**



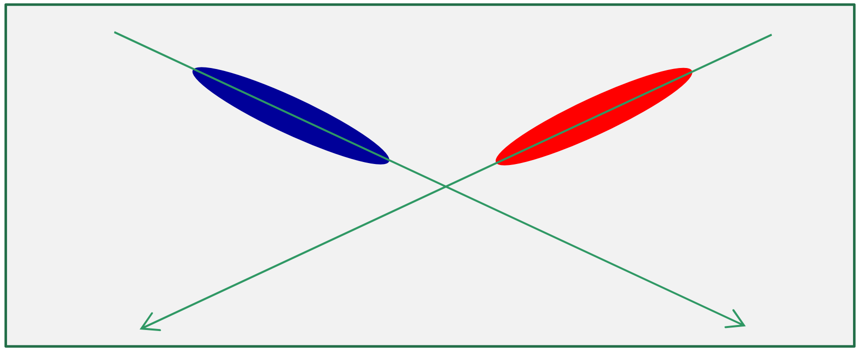
Luminosity parameters with crossing angle

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



Luminosity parameters with crossing angle

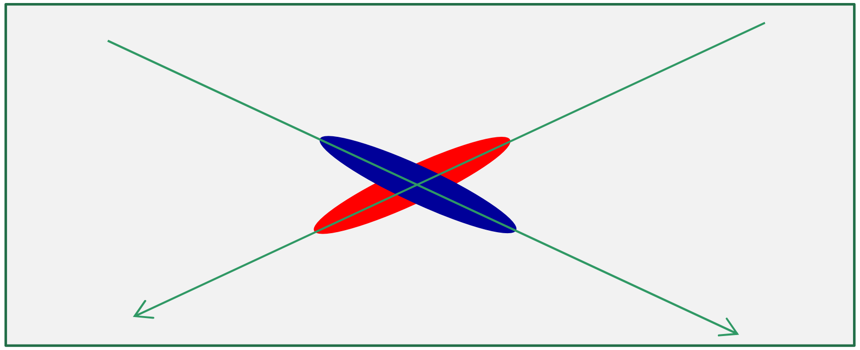
HL-LHC: Bunches collide with smaller beams and a larger crossing angle as in LHC: reduction of luminosity



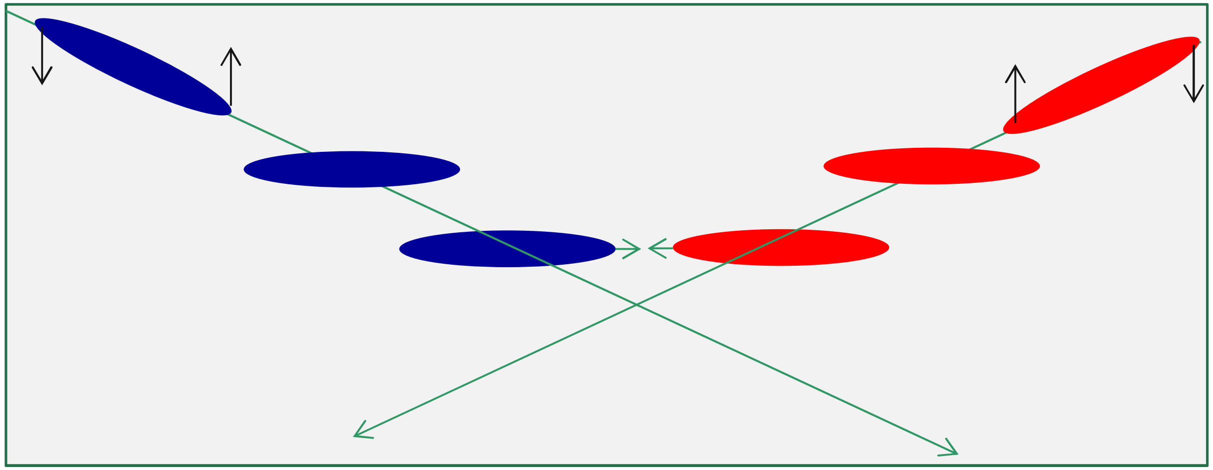
Angle crossing (ineffective overlap):

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

R ... reduction factor



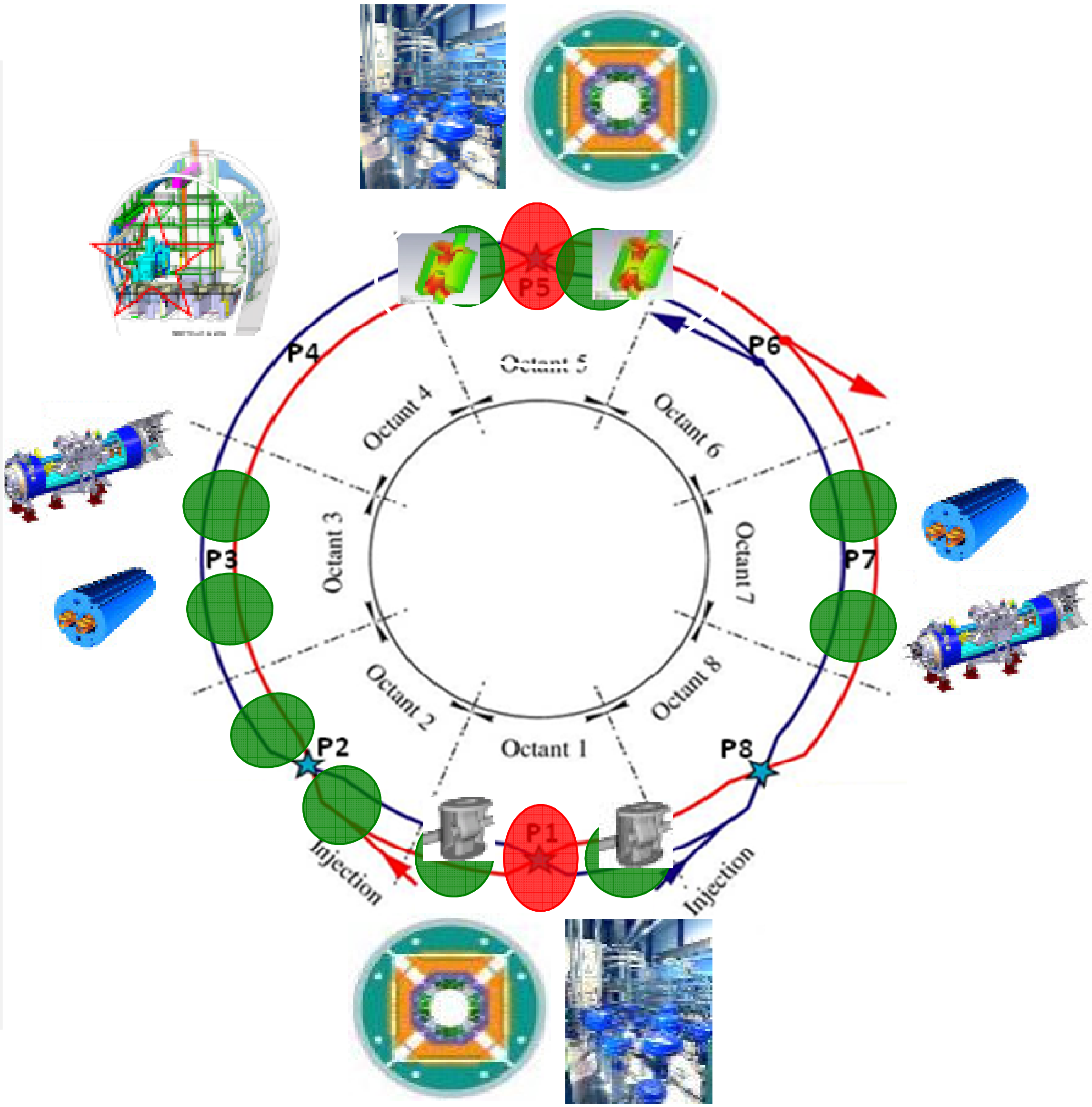
Tilt bunches before collisions with **crab cavities:** recovering luminosity => R ~1



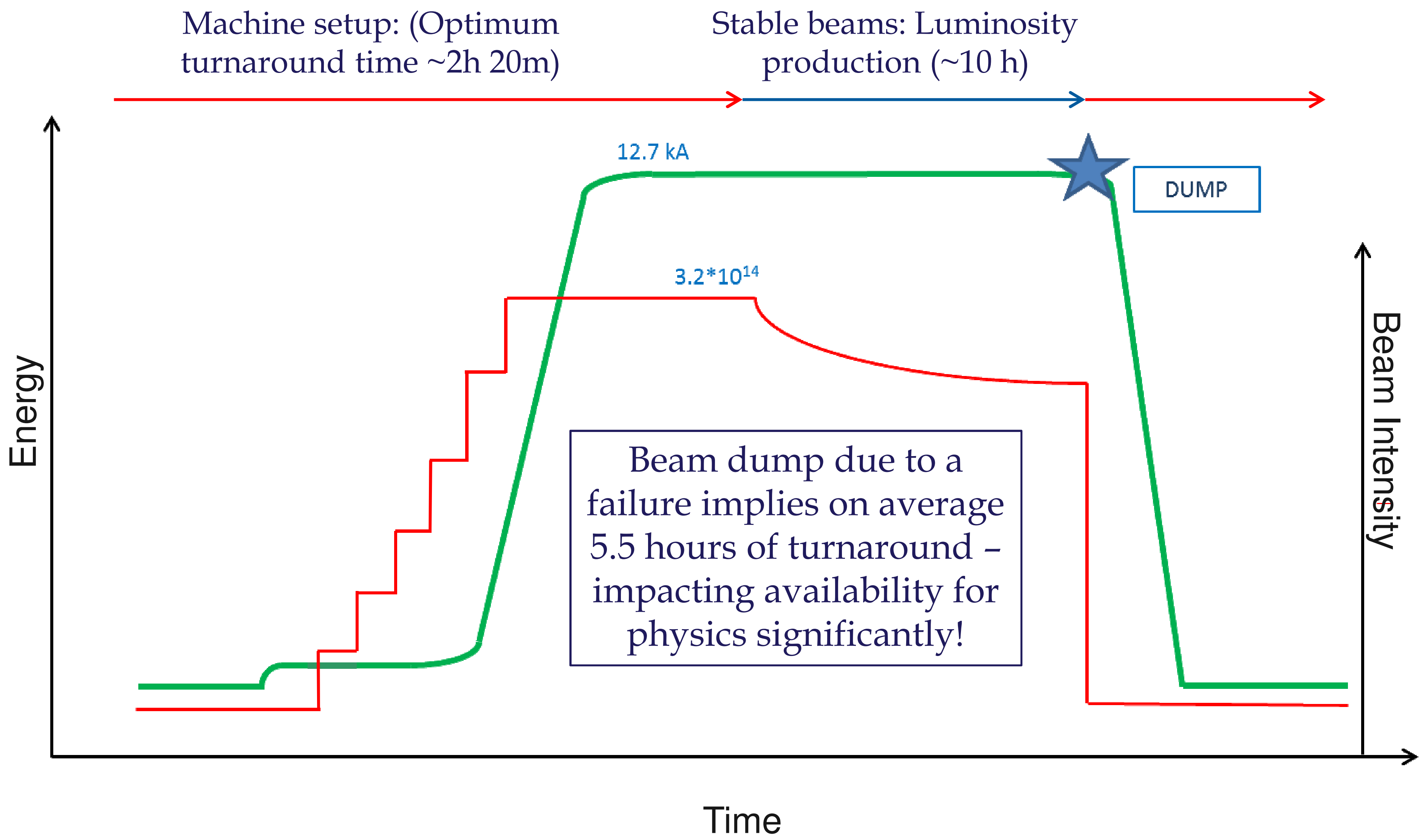
Hardware for the Upgrade

Main modifications of LHC

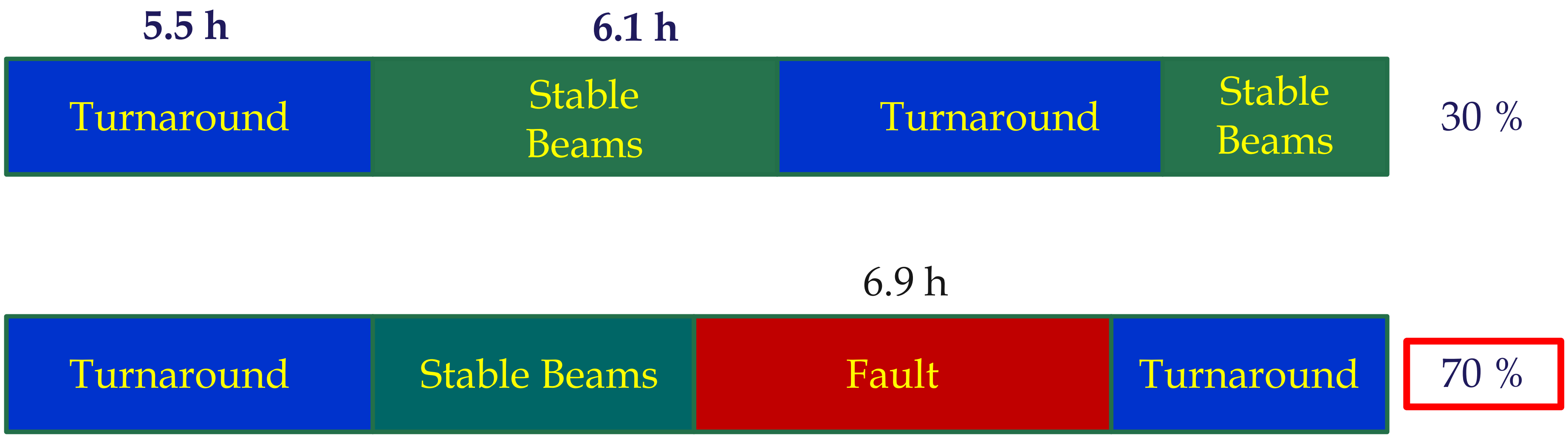
- New **high field/larger aperture** interaction region **sc magnets**
- **Crab Cavities** to take advantage of the small β^*
- **New collimators** (lower impedance)
- **Cryo-collimators** and **high field 11 T dipoles** in cold part of LHC
- Additional **cryo plants** for magnets and RF (P1, P4, P5)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



LHC operational cycle



Integrated Luminosity and Availability



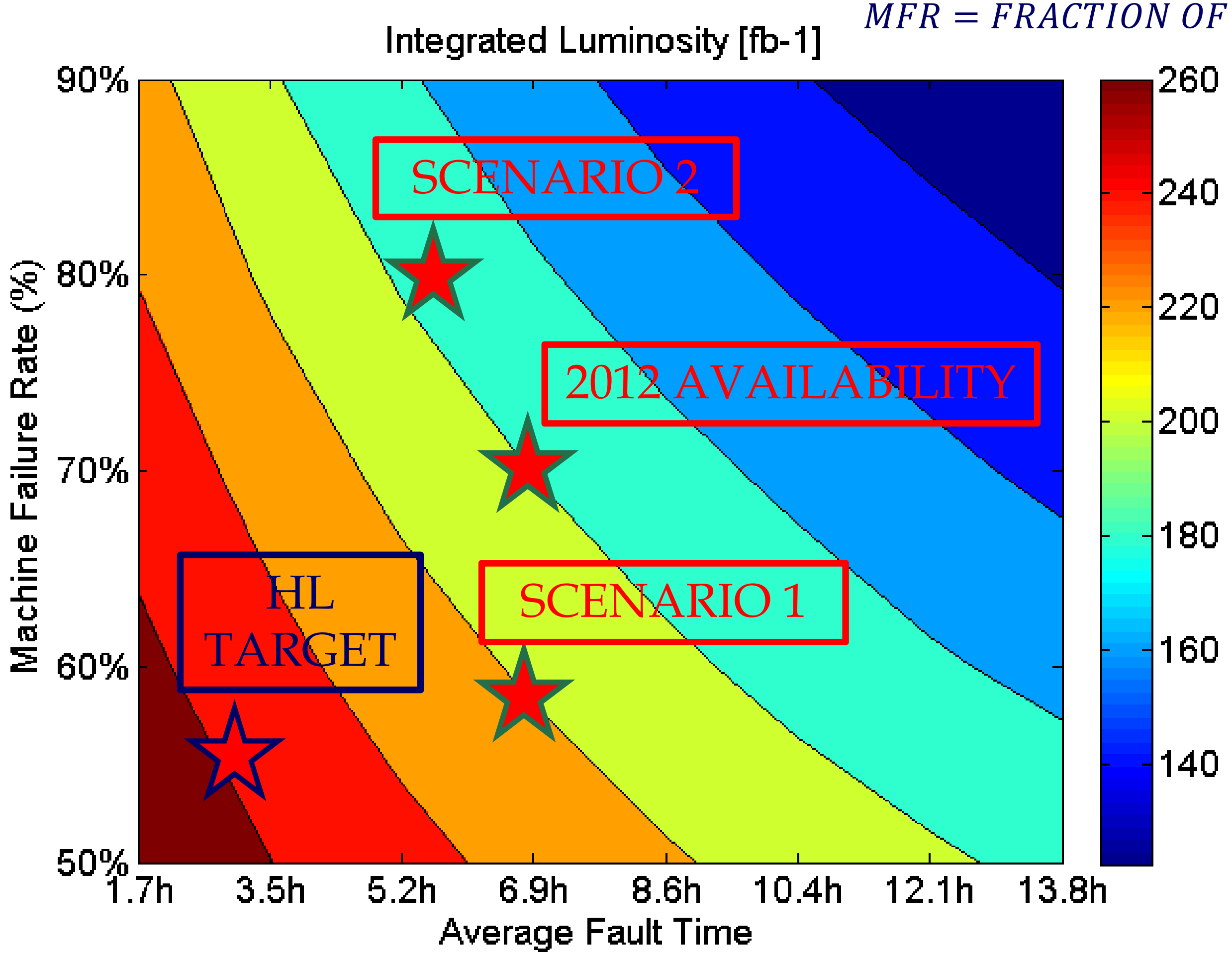
- **Machine Failure Rate** (MFR) = fraction of premature beam dumps due to a failure = 70 %

- **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

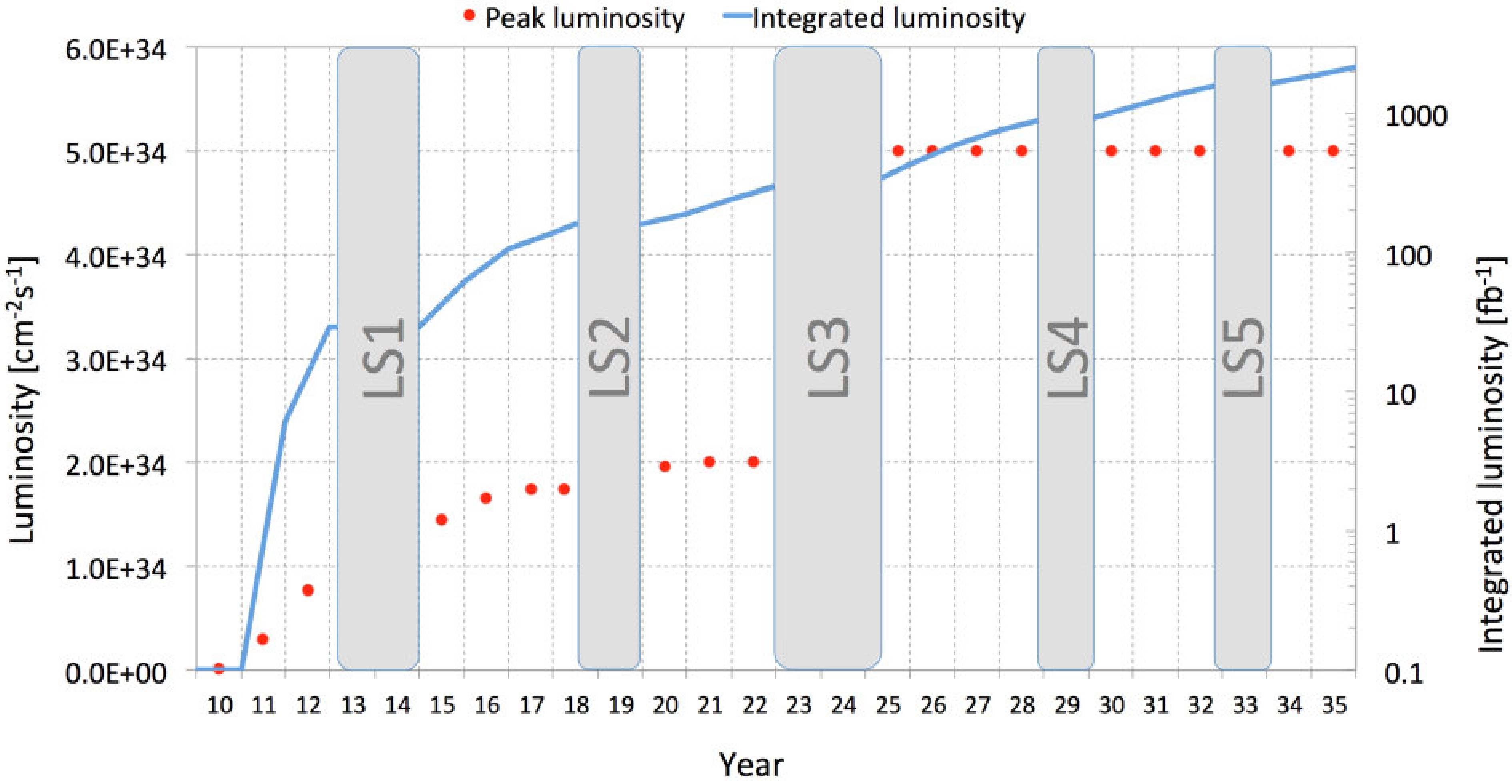
$MFR = FRACTION\ OF\ PREMATURE\ DUMPS$



To achieve HL-LHC parameters, challenging upgrades to achieve availability is required

A. Apollonio

LHC High Luminosity Upgrade



M. Lamont

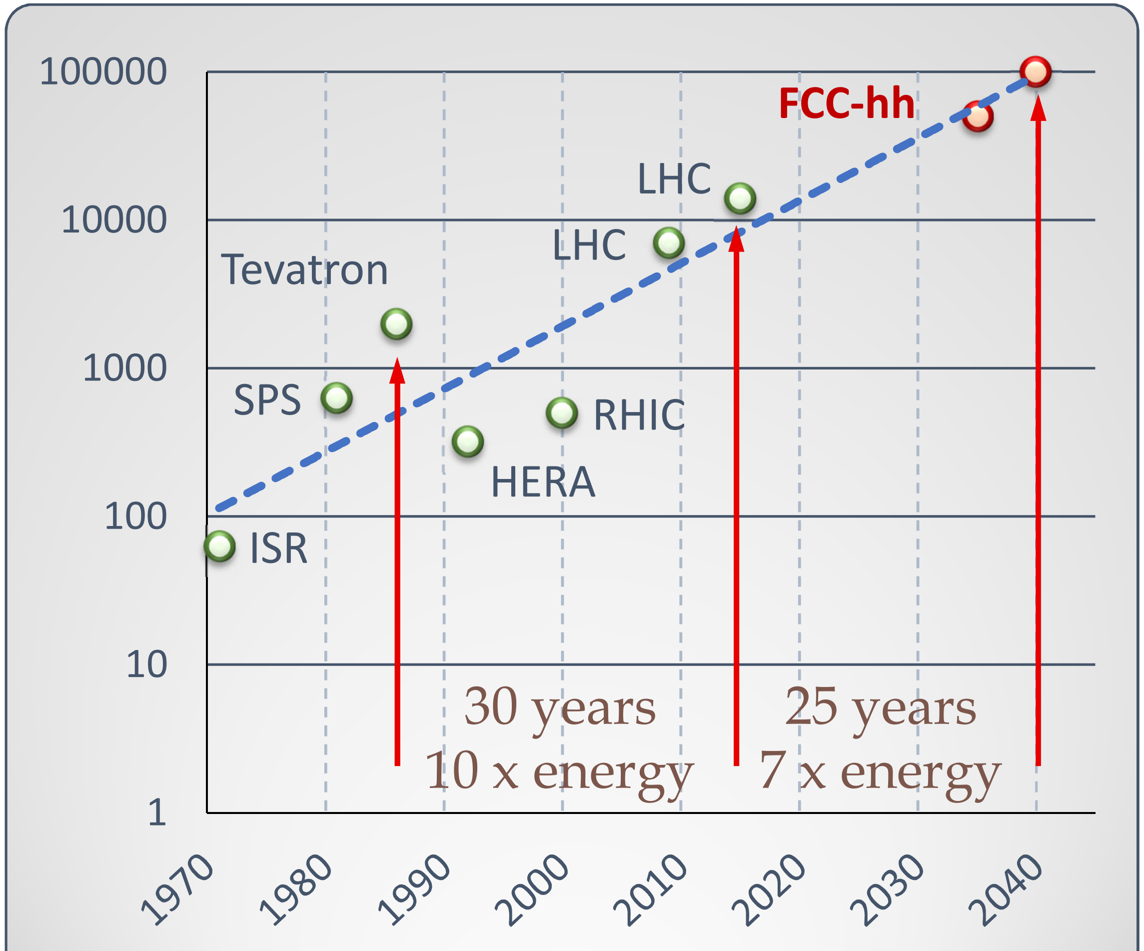
First ideas for LHC presented in 1984

Physics operation started 25 years later

Preparing for the next 50 years

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

C.M. energy evolution



Hadron collider c.m. energy evolution [GeV vs. year]

FCC Study Scope

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

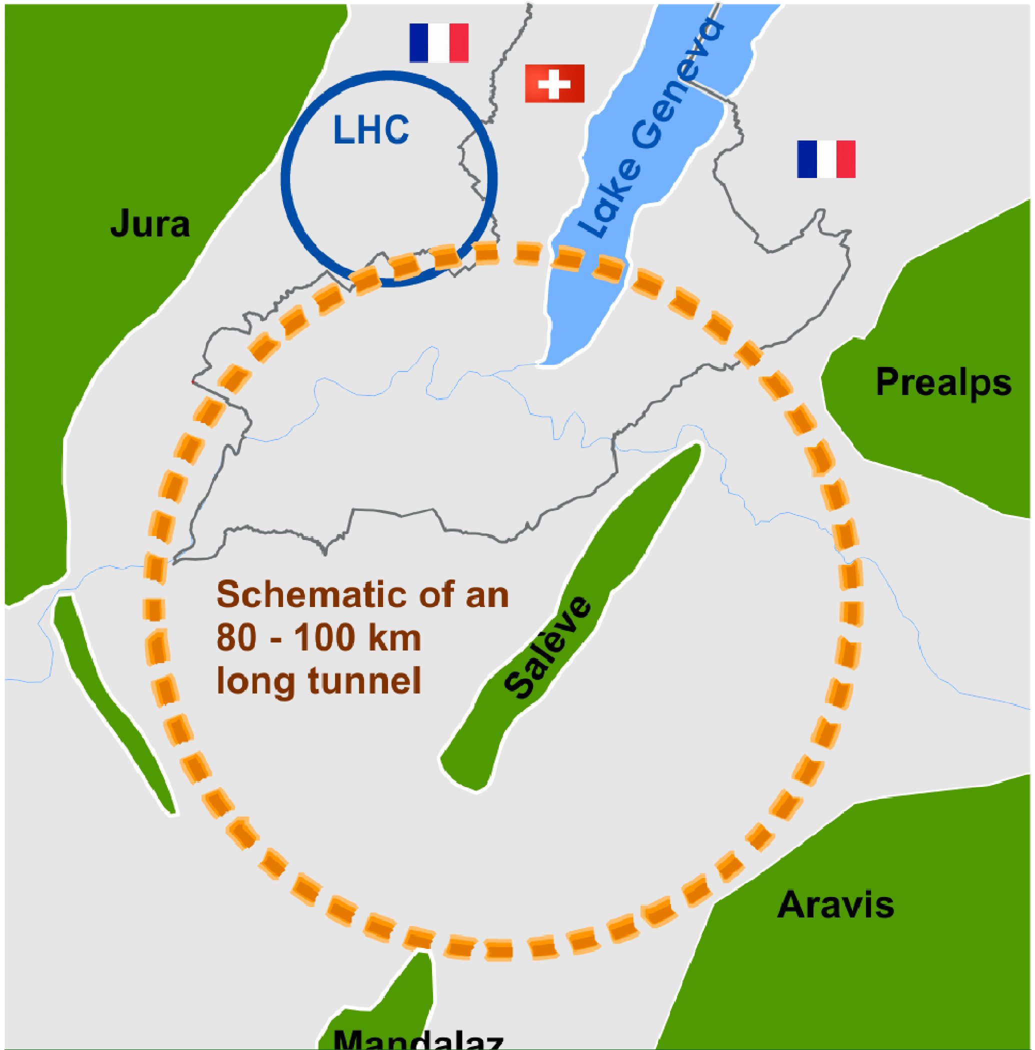
pp-collider (FCC-hh)

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

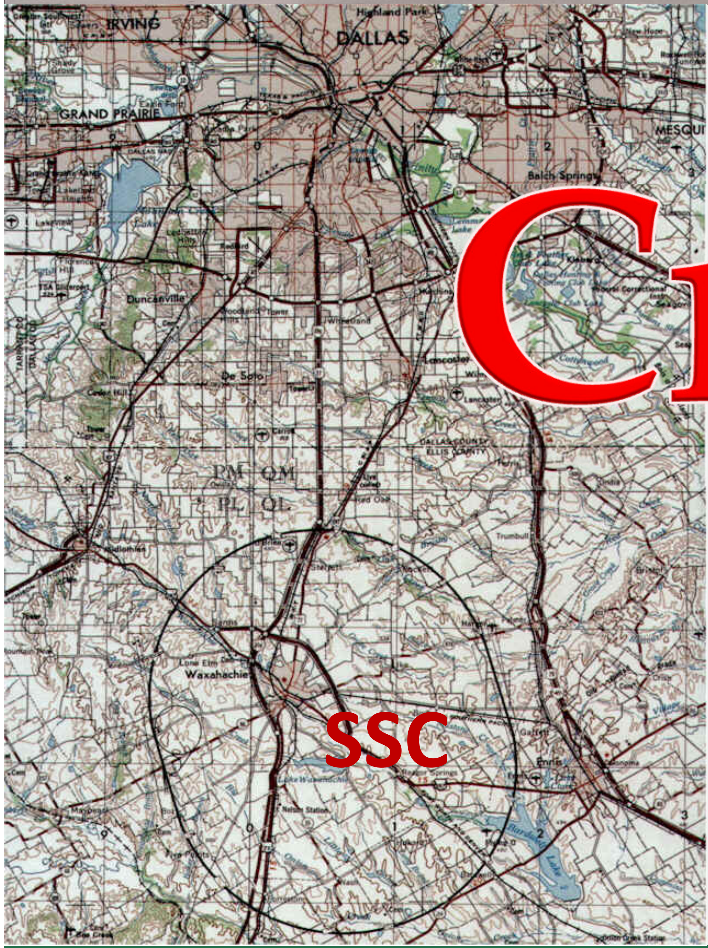
~**20 T**-> 100 TeV c.m. pp in 80 km

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

p-e collider (FCC-he) option



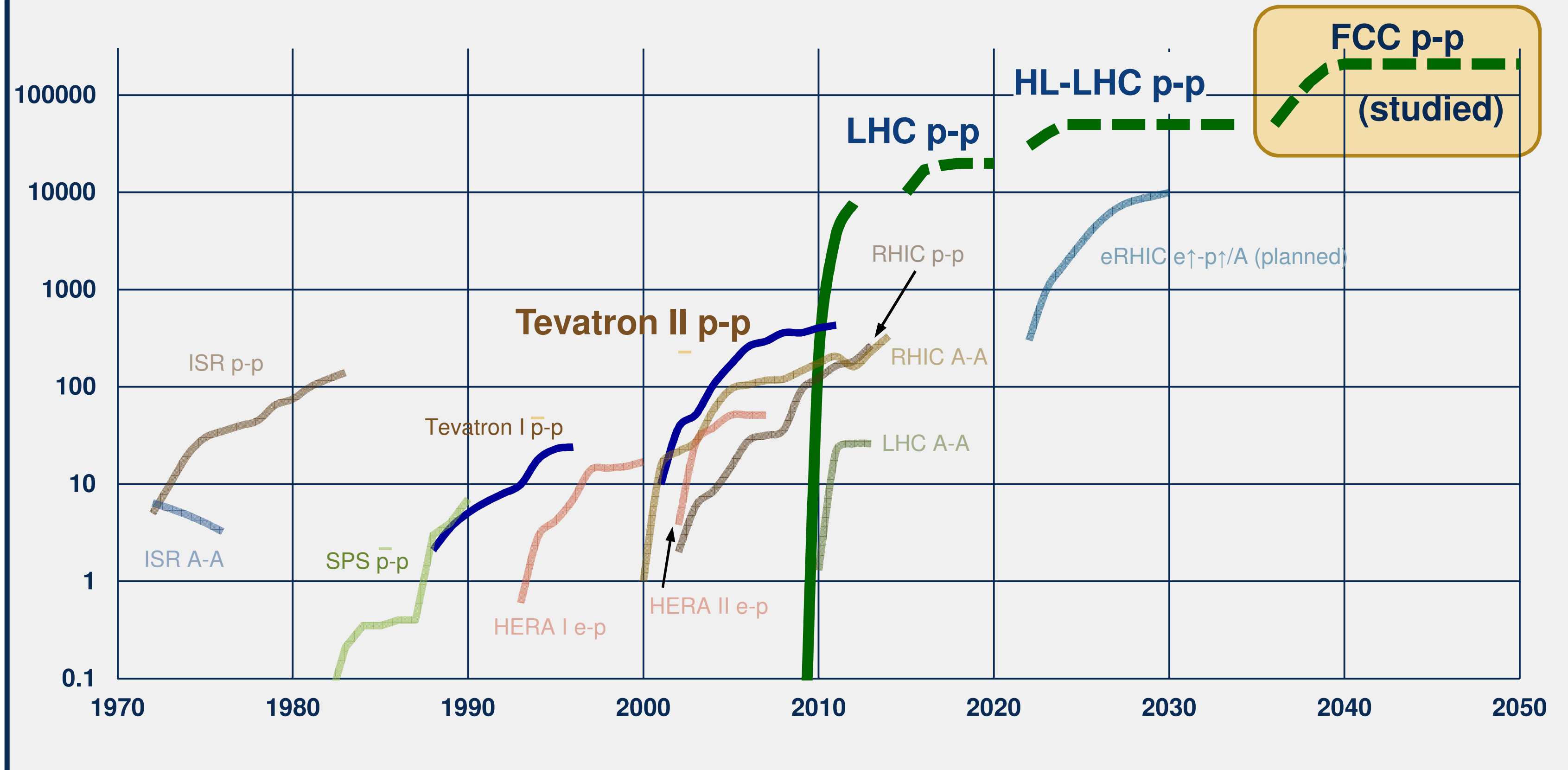
Requires a 80-100 km infrastructure in Geneva area



- 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



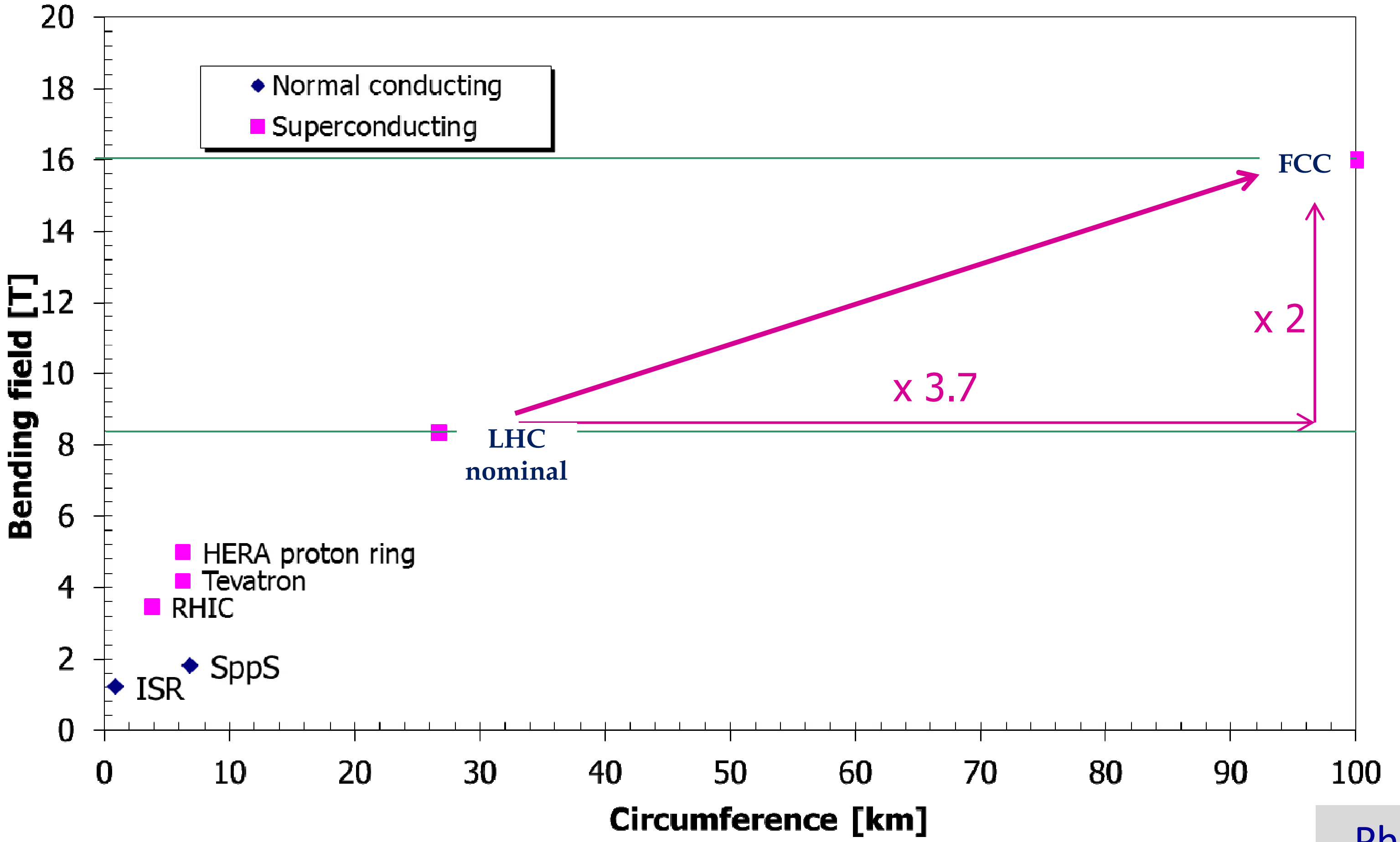
Hadron collider peak luminosity evolution per Interaction Point [x 10^{30} $cm^{-2}s^{-1}$]

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 x 10^{34} $cm^{-2}s^{-1}$	1 x 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

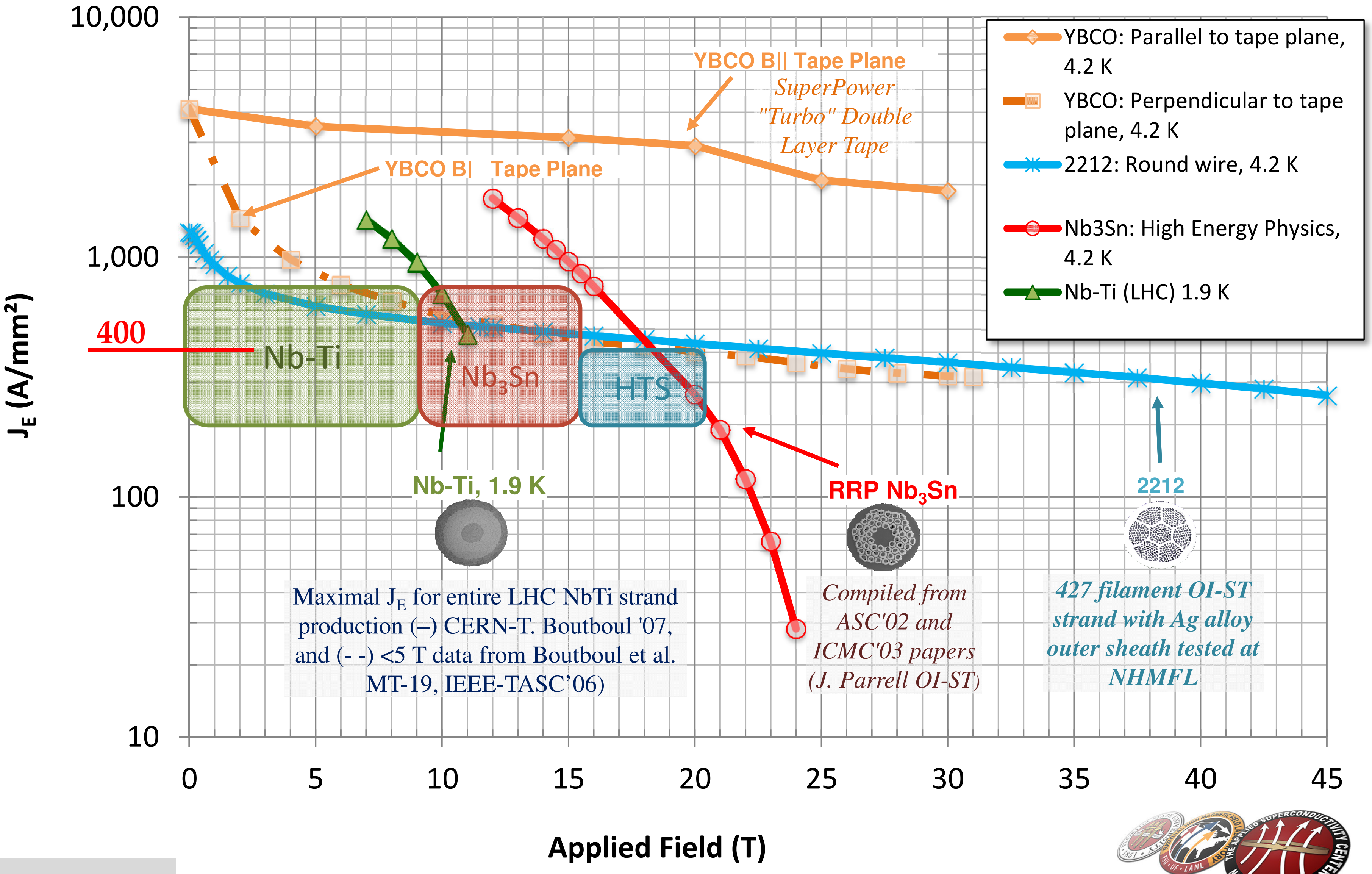
FCC-hh design targets

- 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 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
- Presently forming a global collaboration based on general MoUs between CERN and individual partners + specific addenda for each participant
- First International Collaboration Board meeting on 9-10 September 2014 at CERN, chaired by Prof. L. Rivkin (PSI/EPFL)
- Design study proposal: EU support in the Horizon 2020 program approved

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

FCC study

49 FCC collaboration members, 27 Feb. 2015 (now >60)

ALBA/CELLS, Spain
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland

GWNU, Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI/Oxford, UK
JINR Dubna, Russia
FZ Jülich, Germany

KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany
Korea U Sejong, Korea
MEPhI, Russia
MIT, USA
NBI, Denmark
Northern Illinois U., USA
NC PHEP Minsk, Belarus
U. Liverpool, UK
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland

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**
- There are a **number of very interesting challenges** for the realisation of such collider, and scientists who are interested in such R&D are **very welcome to join**!

Thanks for your attention

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

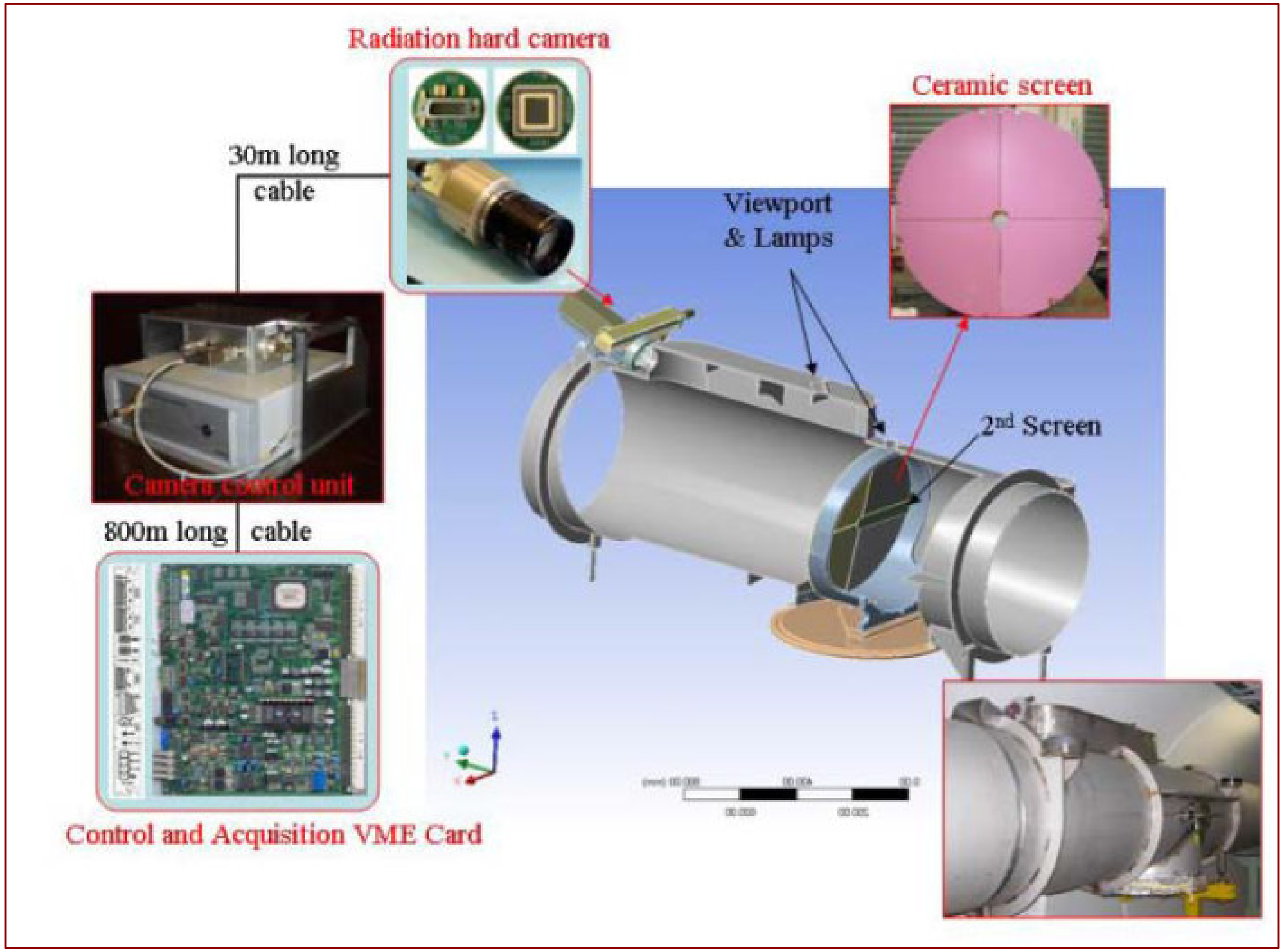
Plumber visiting Freudenstadt

Literature

- The Physics of Particle Accelerators: An Introduction, Klaus Wille, Oxford, 2000
- Proceedings of CERN ACCELERATOR SCHOOL (CAS), Yellow Reports, many topics, General Accelerator Physics, and topical schools on Vacuum, Superconductivity, Synchrotron Radiation, Cyclotrons, and others… http://cas.web.cern.ch/cas/
- 5th General CERN Accelerator School, CERN 94-01, 26 January 1994, 2 Volumes, edited by S.Turner
- A.Wolski, Beam Dynamics in High Energy Particle Accelerators, Imperial College Press
- Superconducting Accelerator Magnets, K.H.Mess et al., WorldScientific 1996
- Handbook of Accelerator Physics and Engineering, A.W.Chao and M.Tigner, World Scientific, 1998
- A.Sessler, E.Wilson: Engines of Discovery, World Scientific, Singapur 2007
- Conferences and Workshops (EPAC, PAC, IPAC, …) – http://www.jacow.org

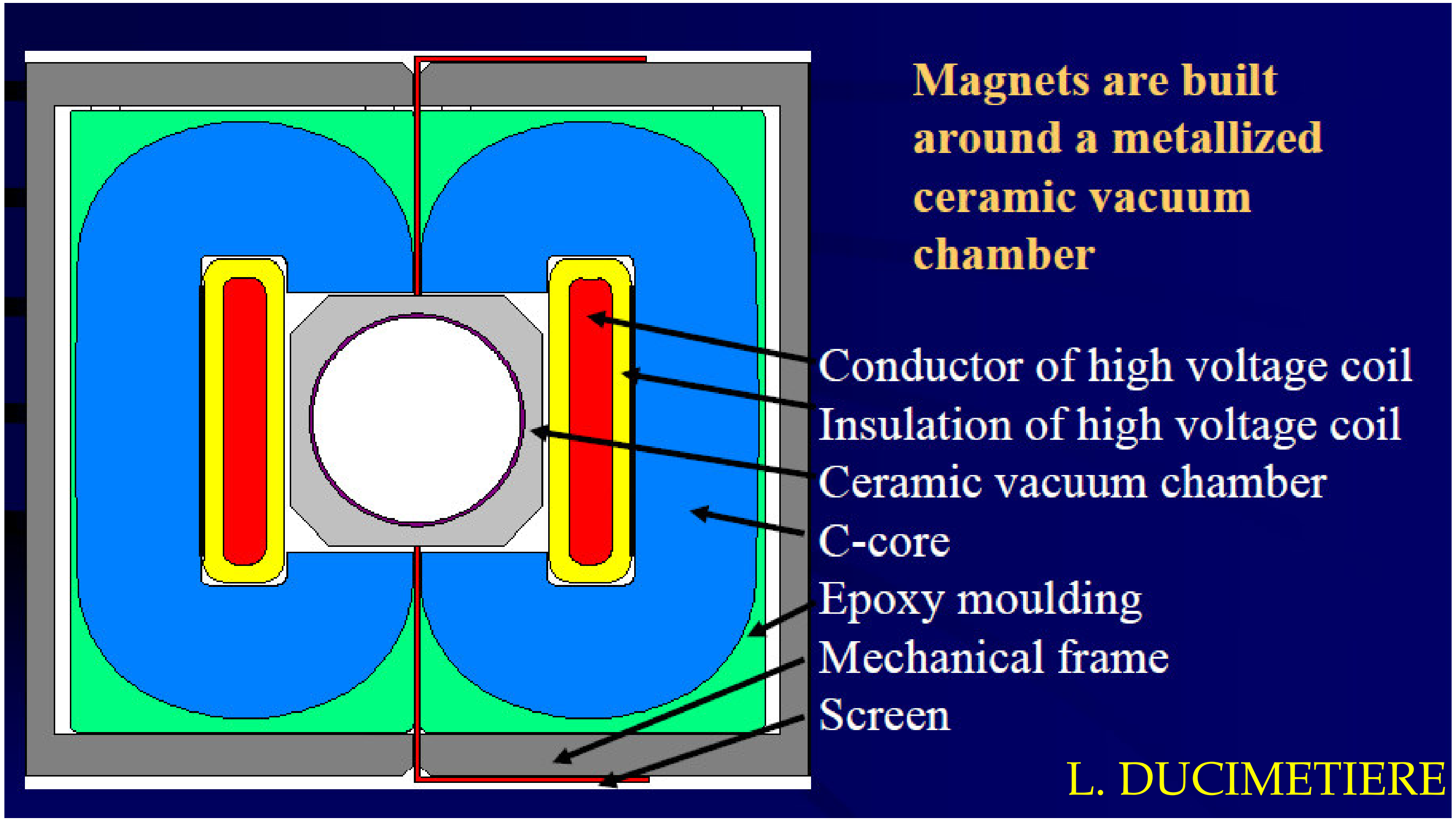
Comment: Screen

- Beam dump scintillating screen: Alumina doped with 0.5% chrome sesquioxide and at room temperature two principal lines of luminescence at 692.9 and 694.3 nm are generated with a decay time of 3.4 ms.



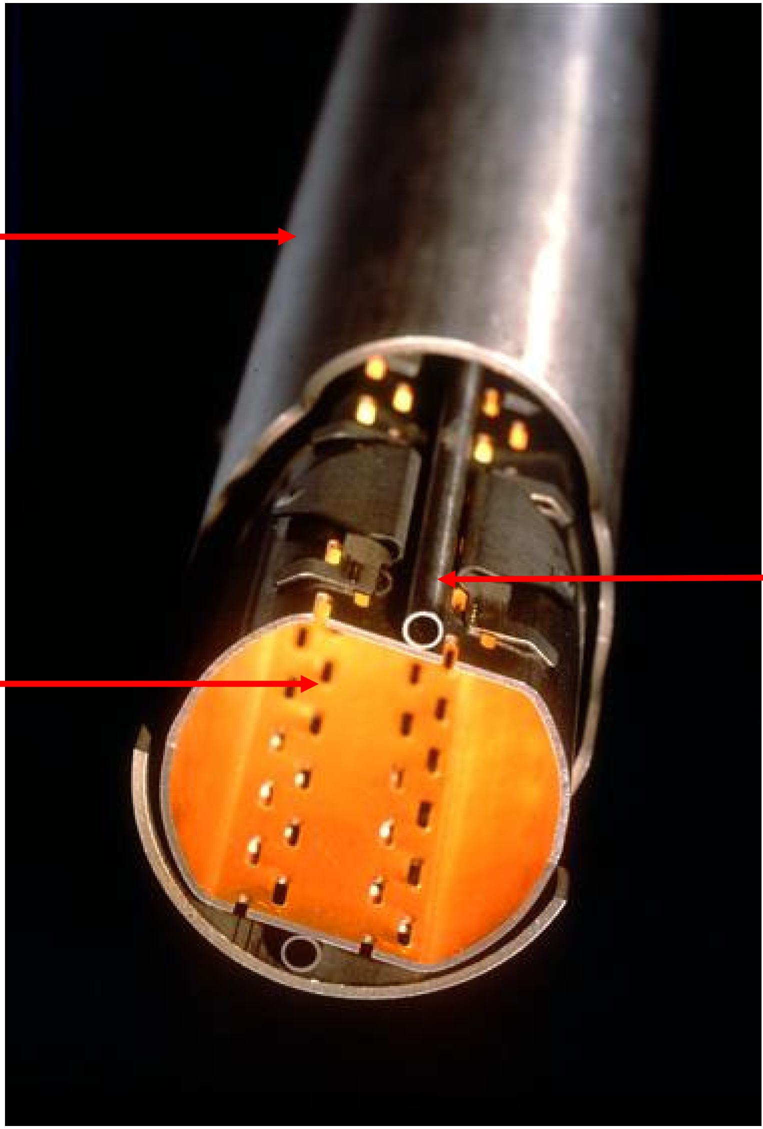
Comment: Extraction kicker magnet

Kicker magnet (LHC) : one turn for the current (low inductance), HV, field, kick strength per magnet 0.428 Tm, length 1.4 m



Comment: LHC Beam Screen

Vacuum chamber 1.9 K (stainless steel)



Beam screen (stainless steel + copper)

Helium tubes 4-40 K