# LHC: High Luminosity, Higgs Bosons and some surprises

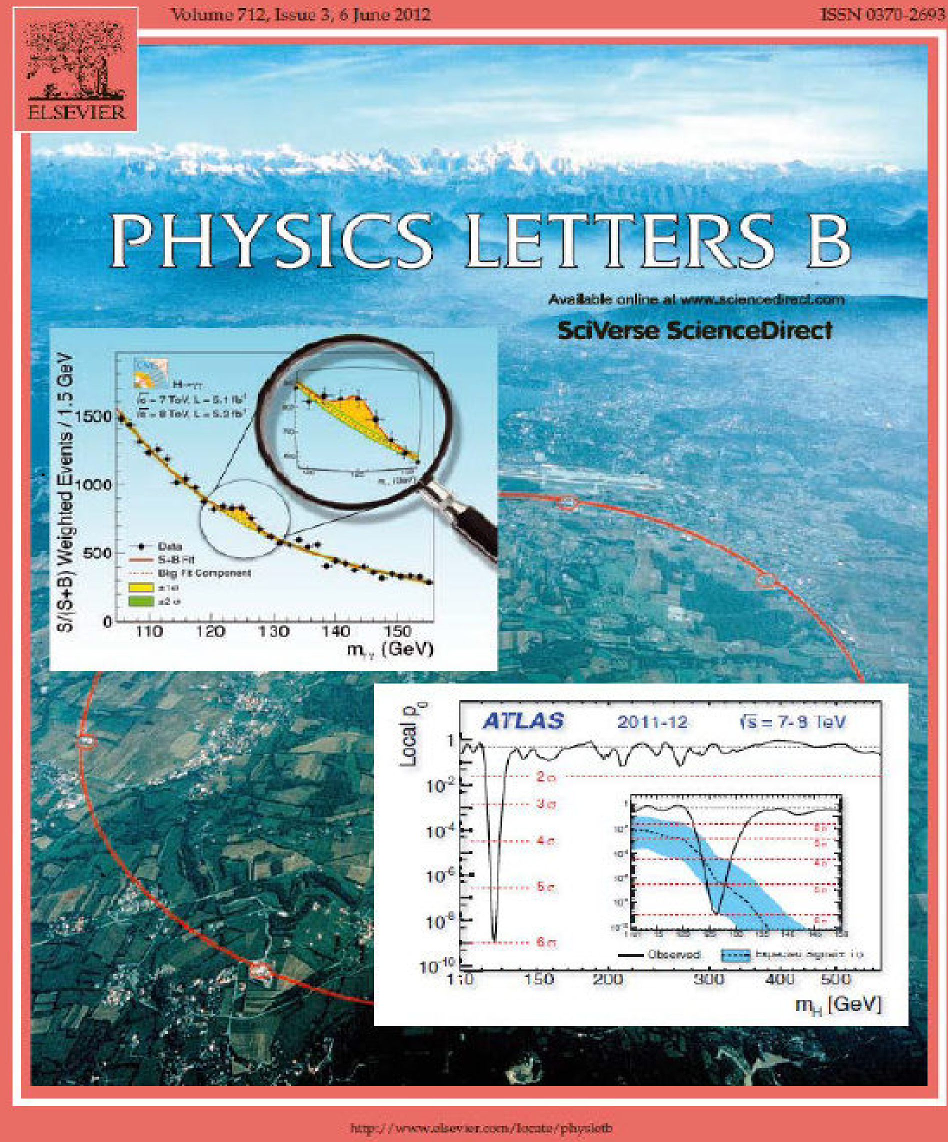
ATLAS Collaboration,
***Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,*** Phys.Lett.B (2012)

CMS Collaboration,
***Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,*** Phys.Lett.B (2012)


Rüdiger Schmidt, CERN


9 July 2013

Hadron Collider Summer School



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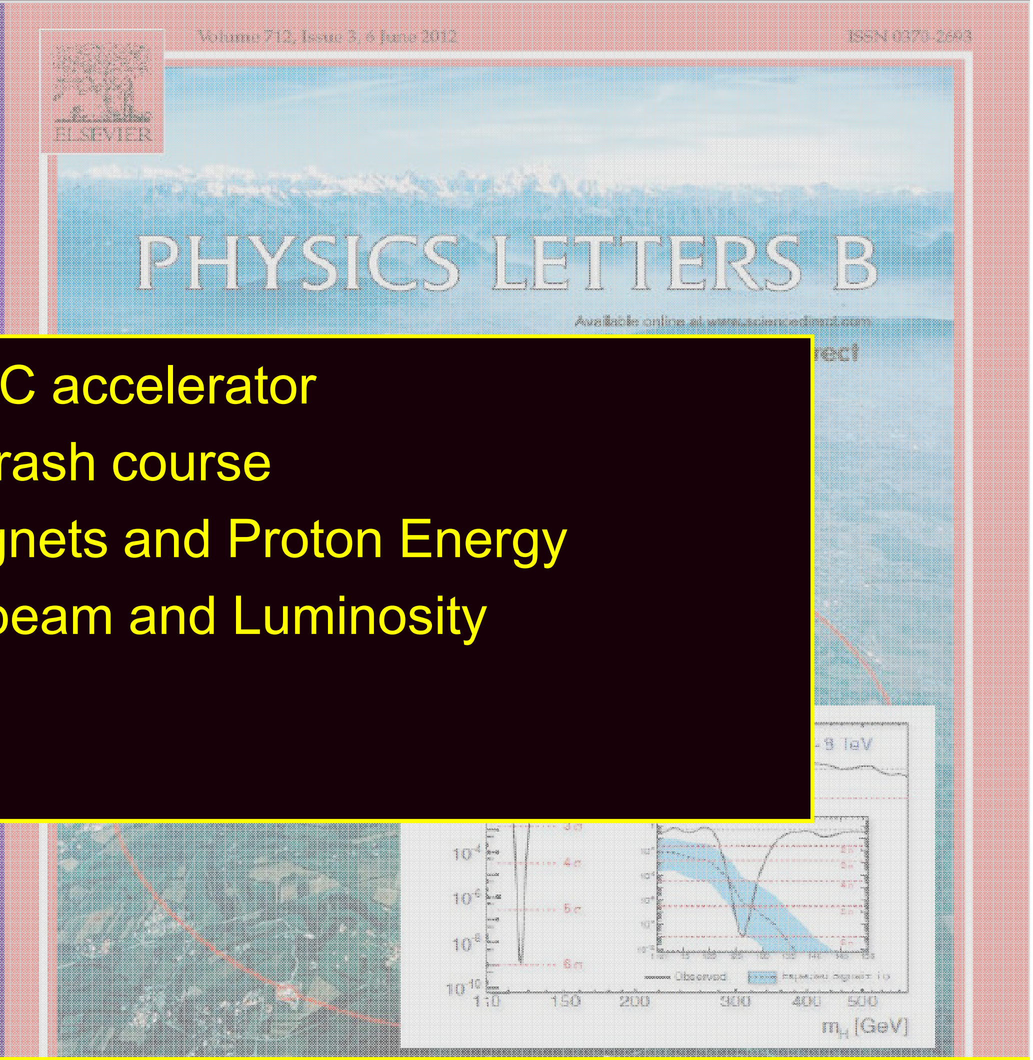



- Introduction to the LHC accelerator
- Accelerator physics crash course
- Superconducting magnets and Proton Energy
- Energy stored in the beam and Luminosity
- Highlights LHC Run 1
- Outlook LHC Run 2


Rüdiger Schmidt, CERN
23 July 2013
Hadron Collider Summ

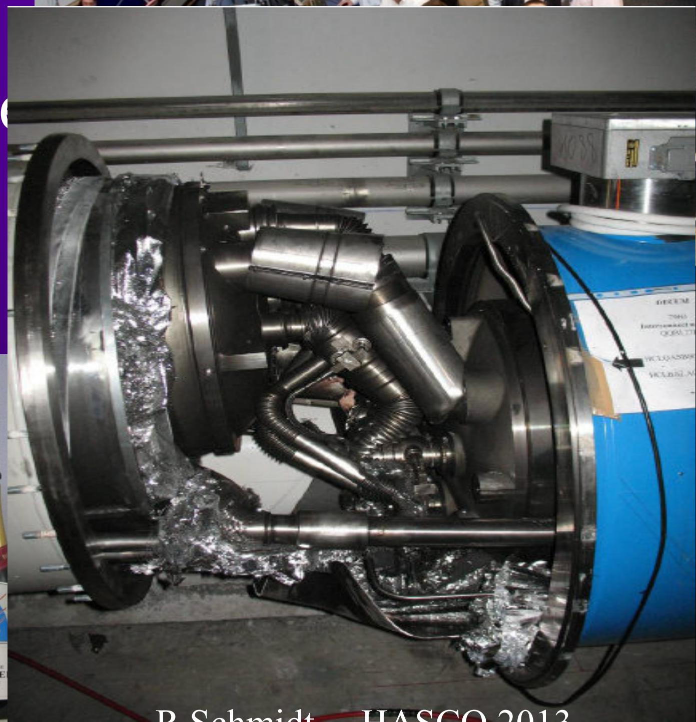


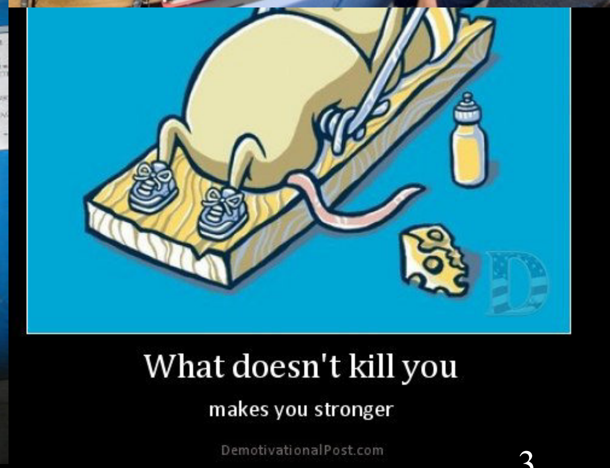
Thanks a lot for slides from several colleagues, in particular Mike Lamont and Jorg Wenninger

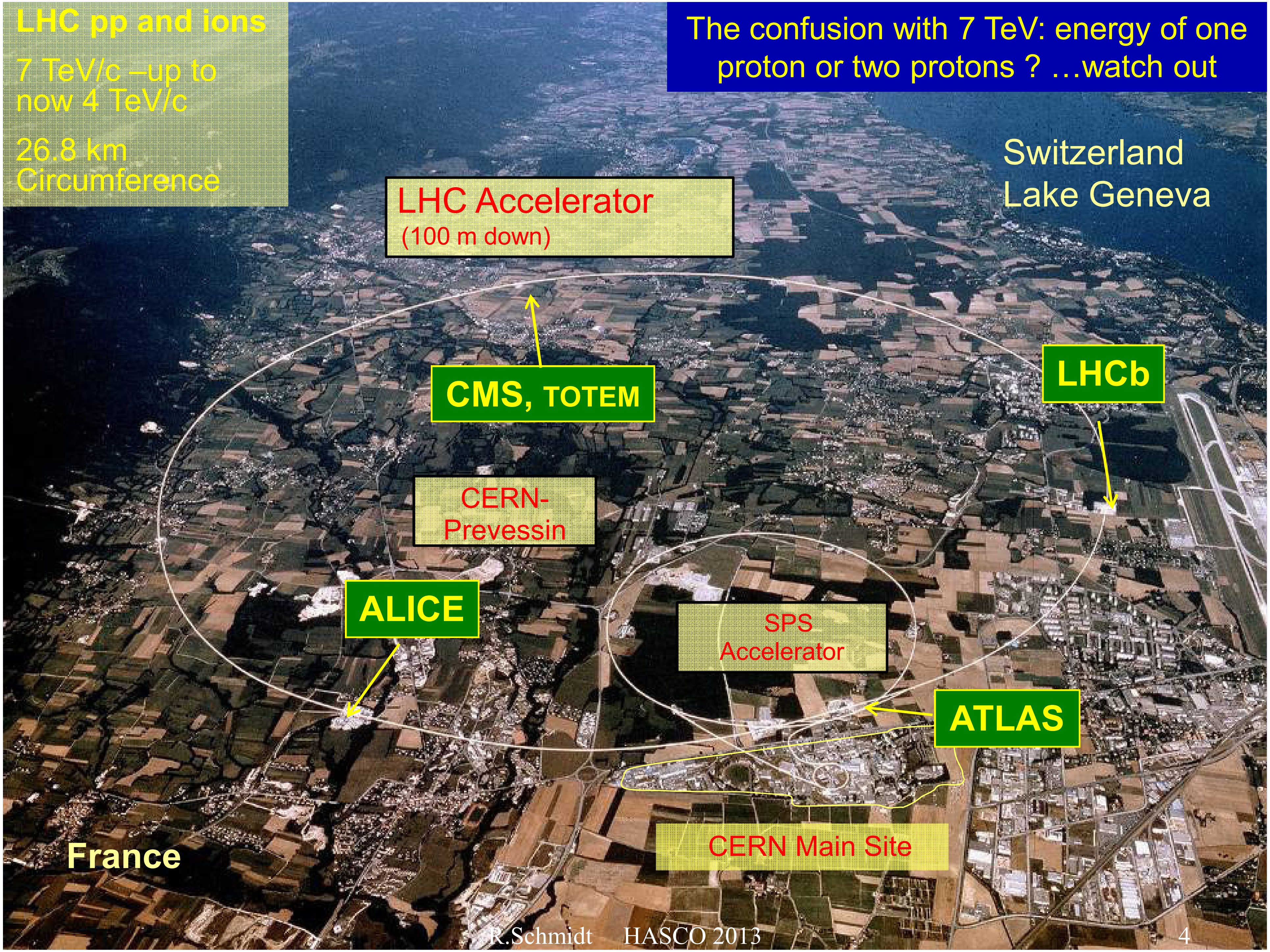
# LHC: A long story starting in the distant past

- First ideas to fir
- Tears of joy….
- Tears of despai

- The story of the







LHC pp and ions
7 TeV/c –up to now 4 TeV/c
26.8 km Circumference
The confusion with 7 TeV: energy of one proton or two protons ? …watch out
Switzerland
Lake Geneva
LHC Accelerator
(100 m down)
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
CERN Main Site
France

# 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

- The total number of particles created at an accelerator (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

- Example: https://lhc-statistics.web.cern.ch/LHC-Statistics/

# 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 4000 | 26800 | 8.3 | $10^{34}$ Now $7.7\times 10^{33}$ | **362 per beam** |
| Factor | | | 7 | 4 | 2 | **50** | **100** |

# Accelerator Physics Crash Course

what is accelerator physics?

theoretical physicists, experimental physicists and accelerator physicists

# What is accelerator physics … and technology?

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

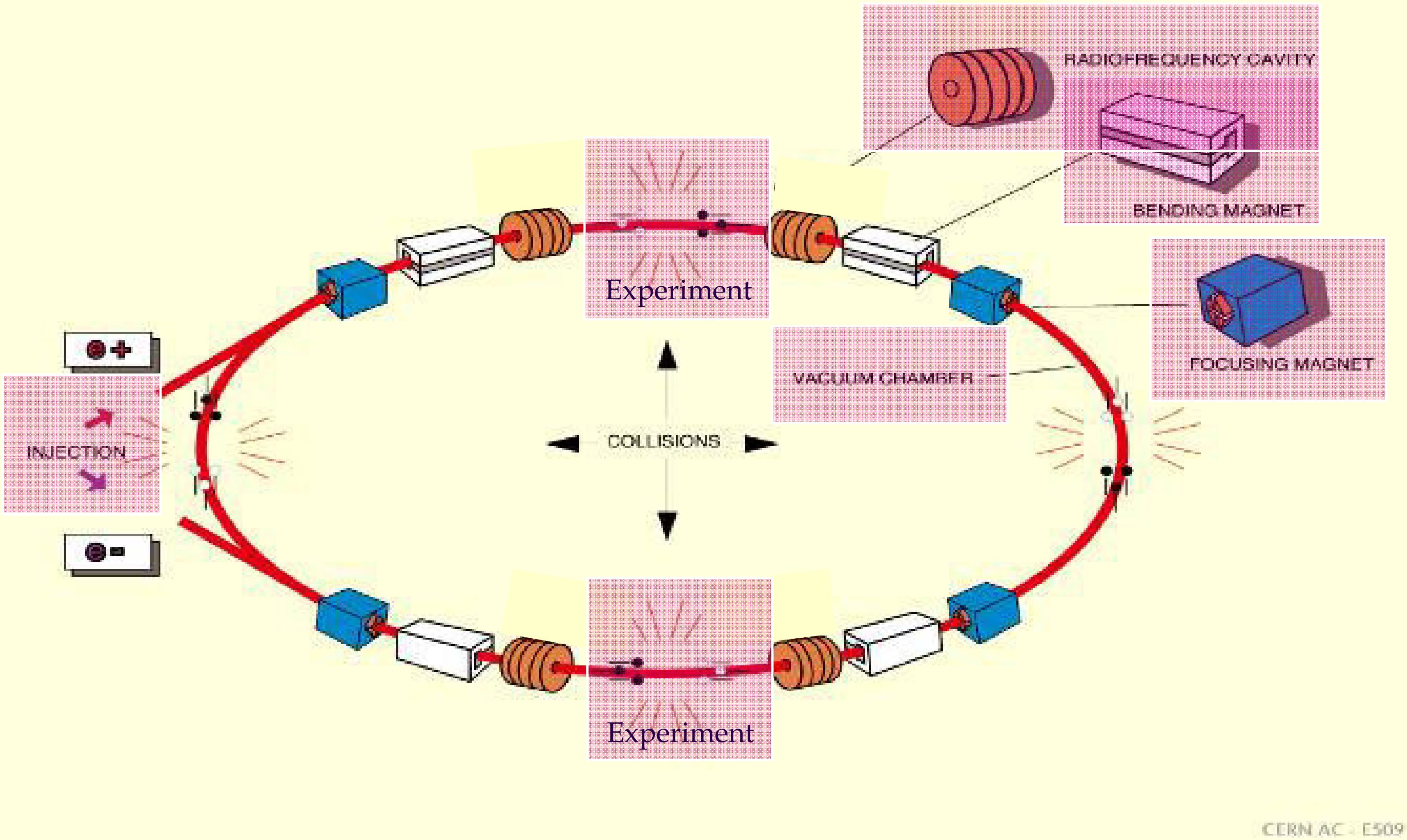
- Electrodynamics
- Relativity
- Particle physics, nuclear physics and radiation physics
- Thermodynamics
- Mechanics
- Quantum Mechanics
- Physics of nonlinear systems
- Material science, solid state physics and surface physics
- Vacuum physics
- Plasma physics and laser physics

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

Plus: Management, reliability engineering and system engineering

# To get to 7 TeV: Synchrotron – circular accelerator and many passages in RF cavities

LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV will take about 20 minutes



# 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:

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

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

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

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

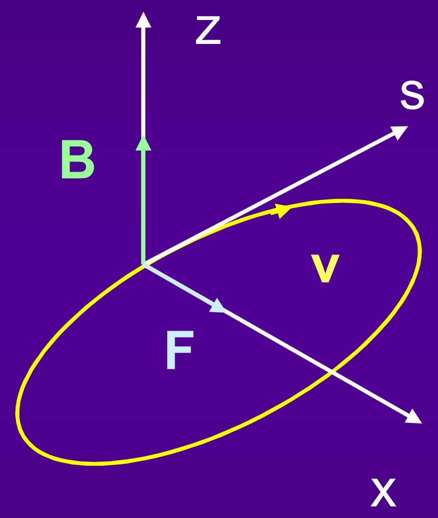
$$\frac{dE}{dt} = q \cdot (\vec{\mathbf{v}} \cdot \vec{\mathbf{E}} + \vec{\mathbf{v}} \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}})) = q \cdot \vec{\mathbf{v}} \cdot \vec{\mathbf{E}}$$

# Particle deflection: superconducting magnets

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:

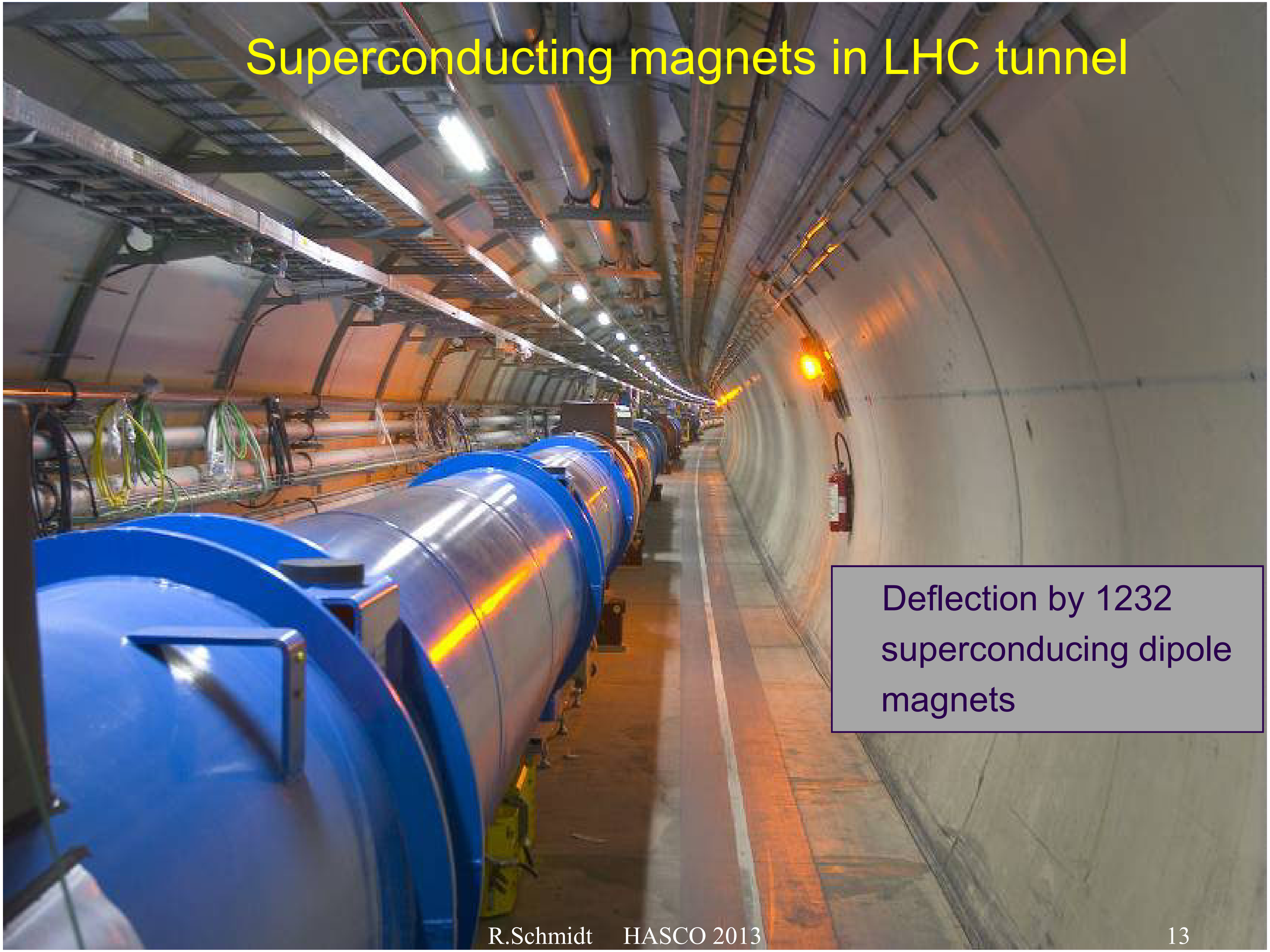
$$\vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$

$$B = \frac{p}{e_0 \cdot R}$$




- Maximum momentum 7000 GeV/c
- Radius 2805 m fixed by LEP tunnel
- **Magnetic field B = 8.33 Tesla**
- Iron magnets limited to 2 Tesla, therefore superconducting magnets are required
- Deflecting magnetic fields for two beams in opposite directions

# Superconducting magnets in LHC tunnel

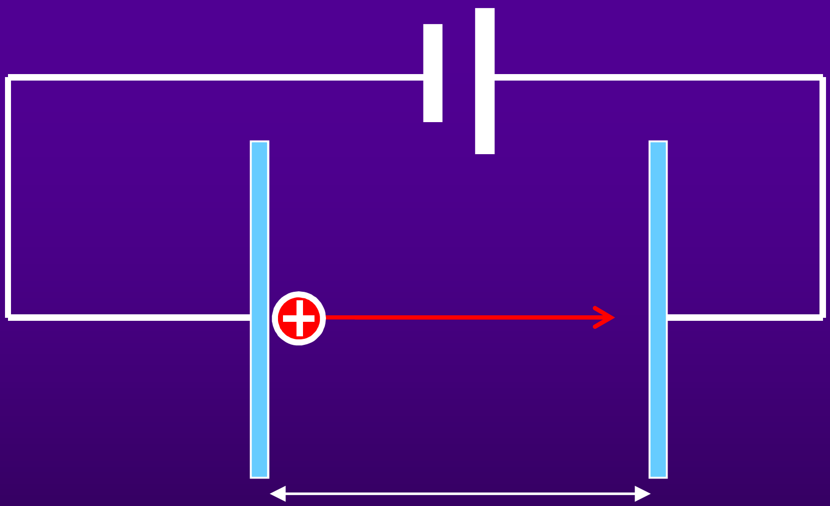


Deflection by 1232 superconducing dipole magnets

# Particle acceleration: accelerating protons to 7 TeV

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

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

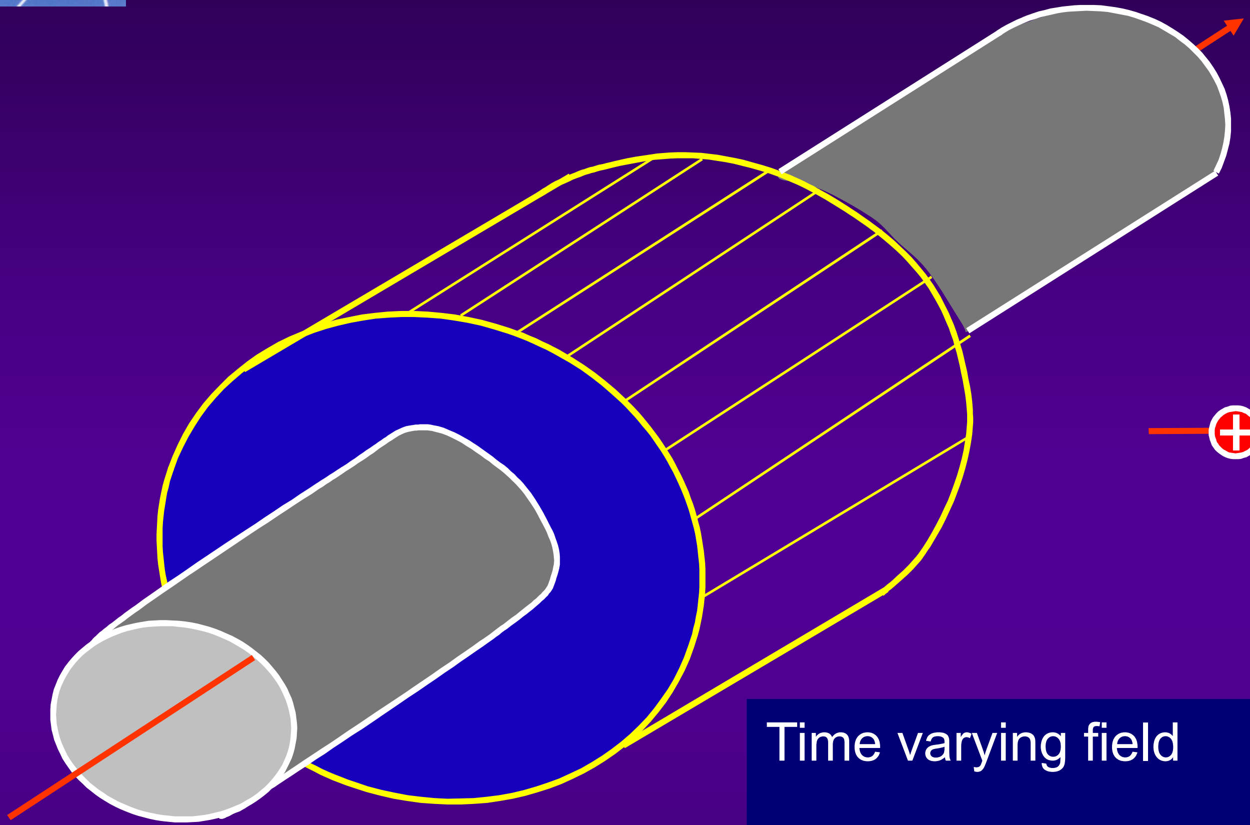


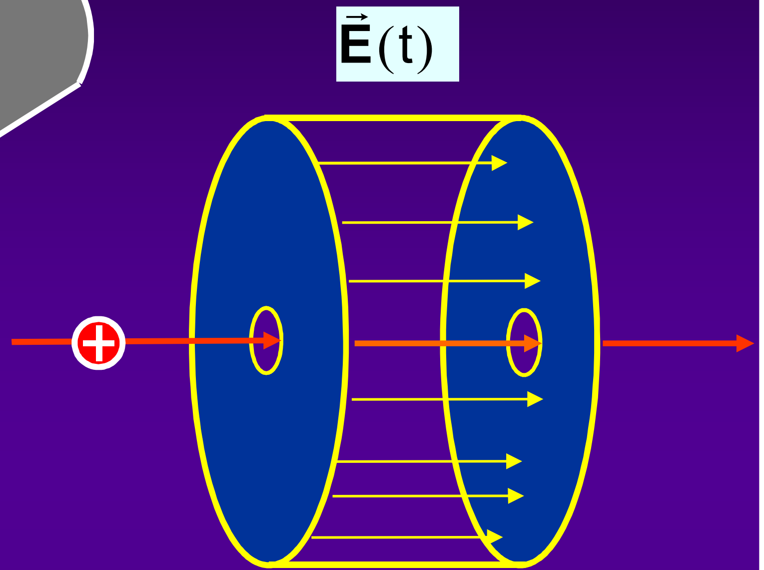
1 MeV requires
U = 1 MV

Acceleration of the protons in an electrical field with 7 TV

- no constant electrical field above some Million Volt (break down)
- no time dependent electrical field above some 10 Million Volt (about 30 MV/m)

# Particle acceleration with RF cavity






Time varying field

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

Maximum field about 20 MV/m

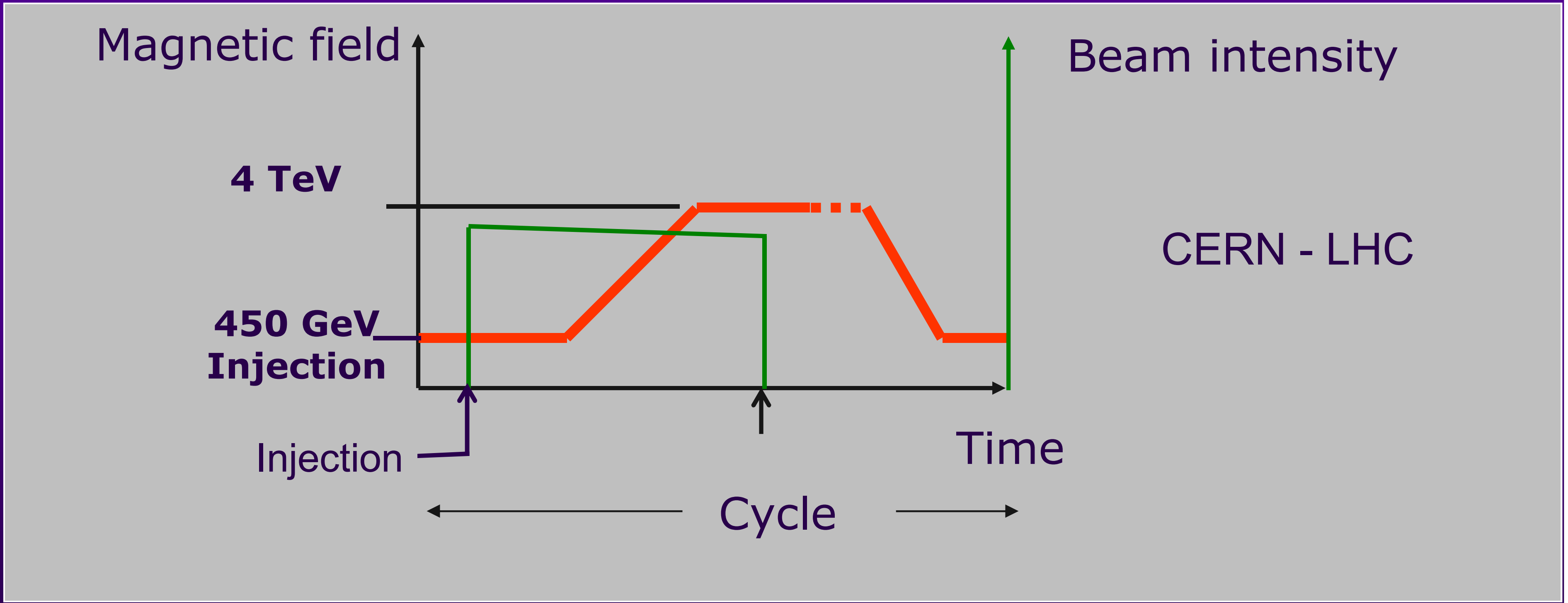
Beams are accelerated in bunches (no continuous beam)

LHC RF frequency
400 MHz

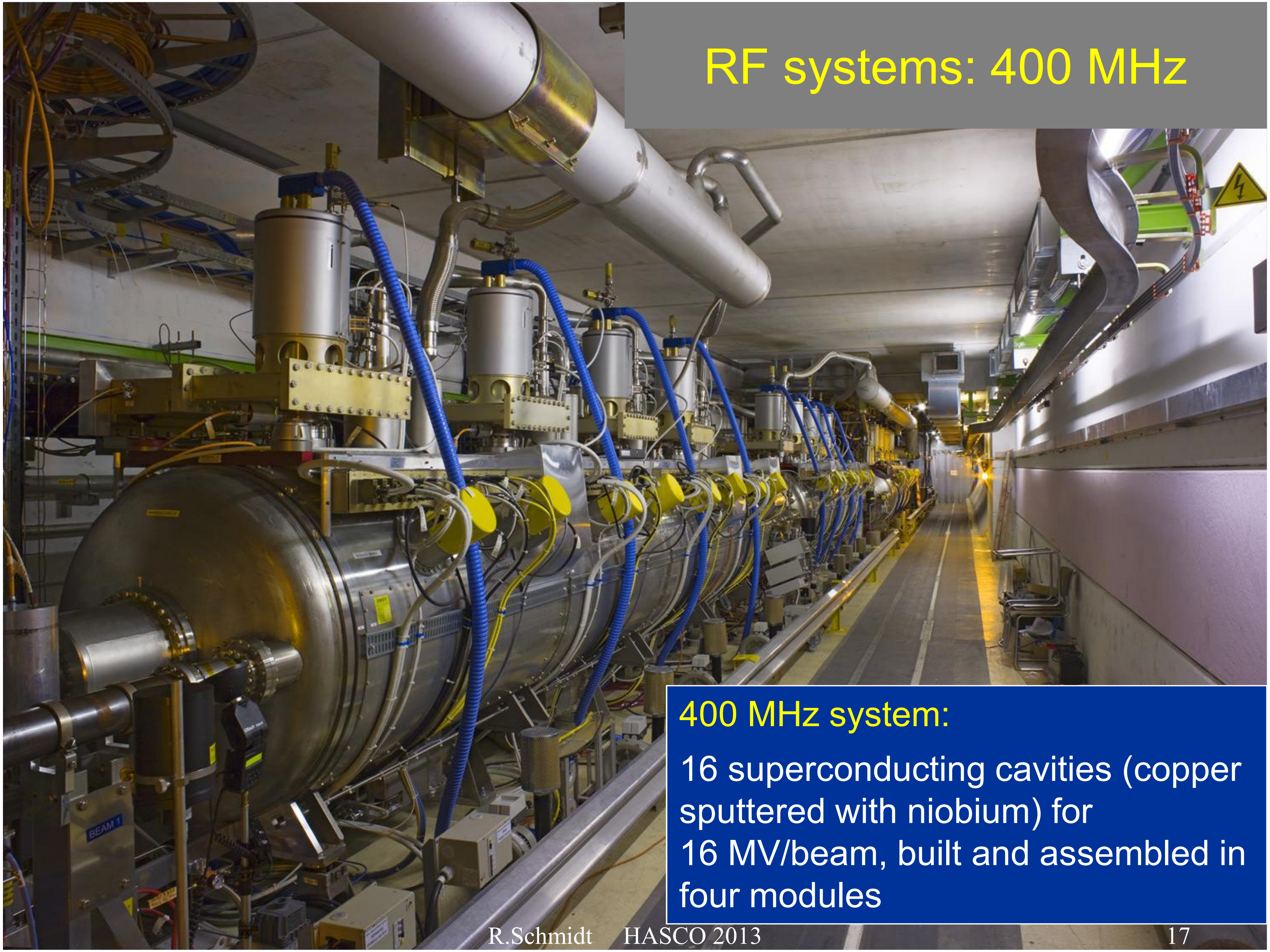
Revolution frequency
11246 Hz

# Principle of a synchrotron

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



# RF systems: 400 MHz

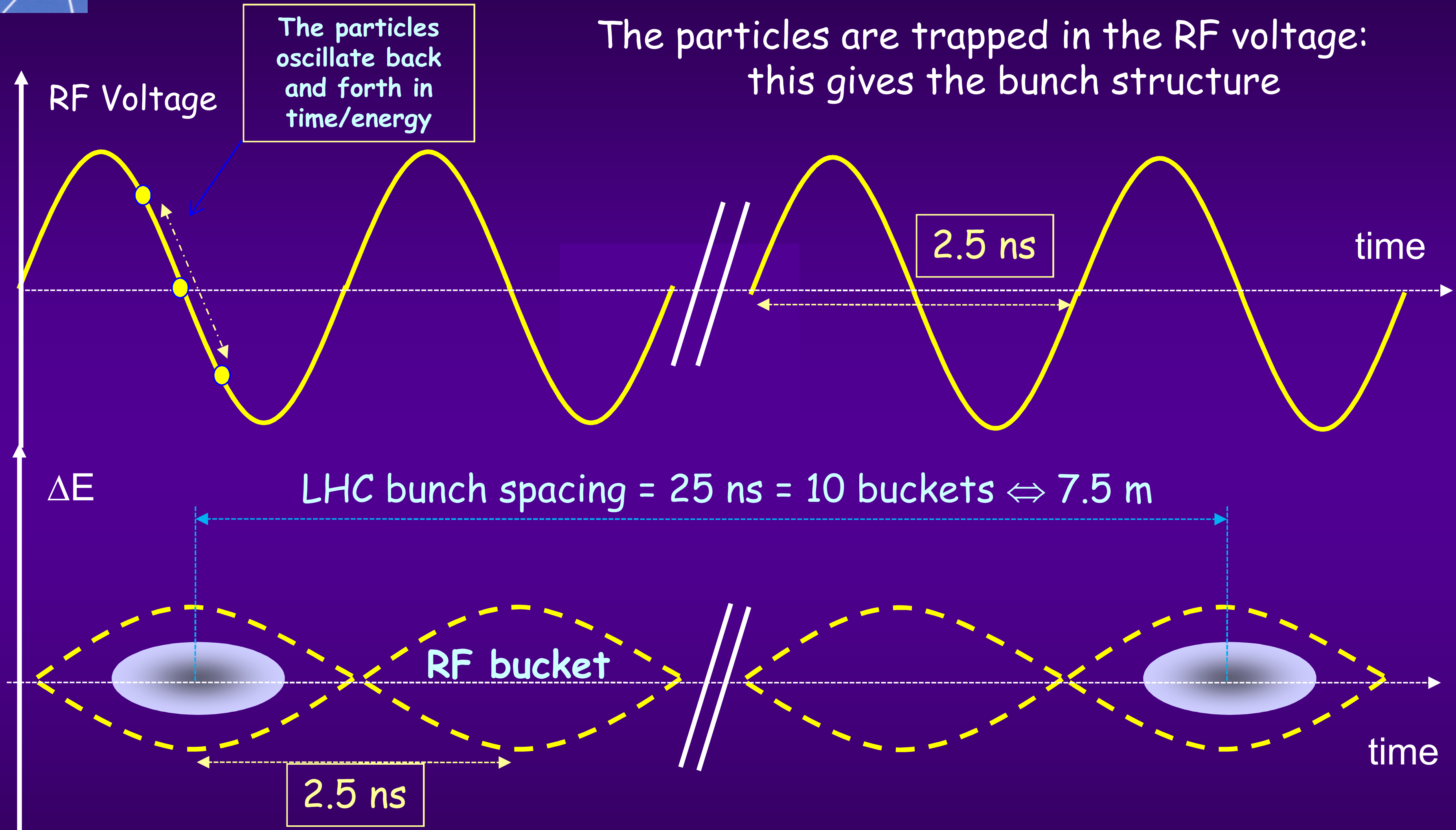


400 MHz system:

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



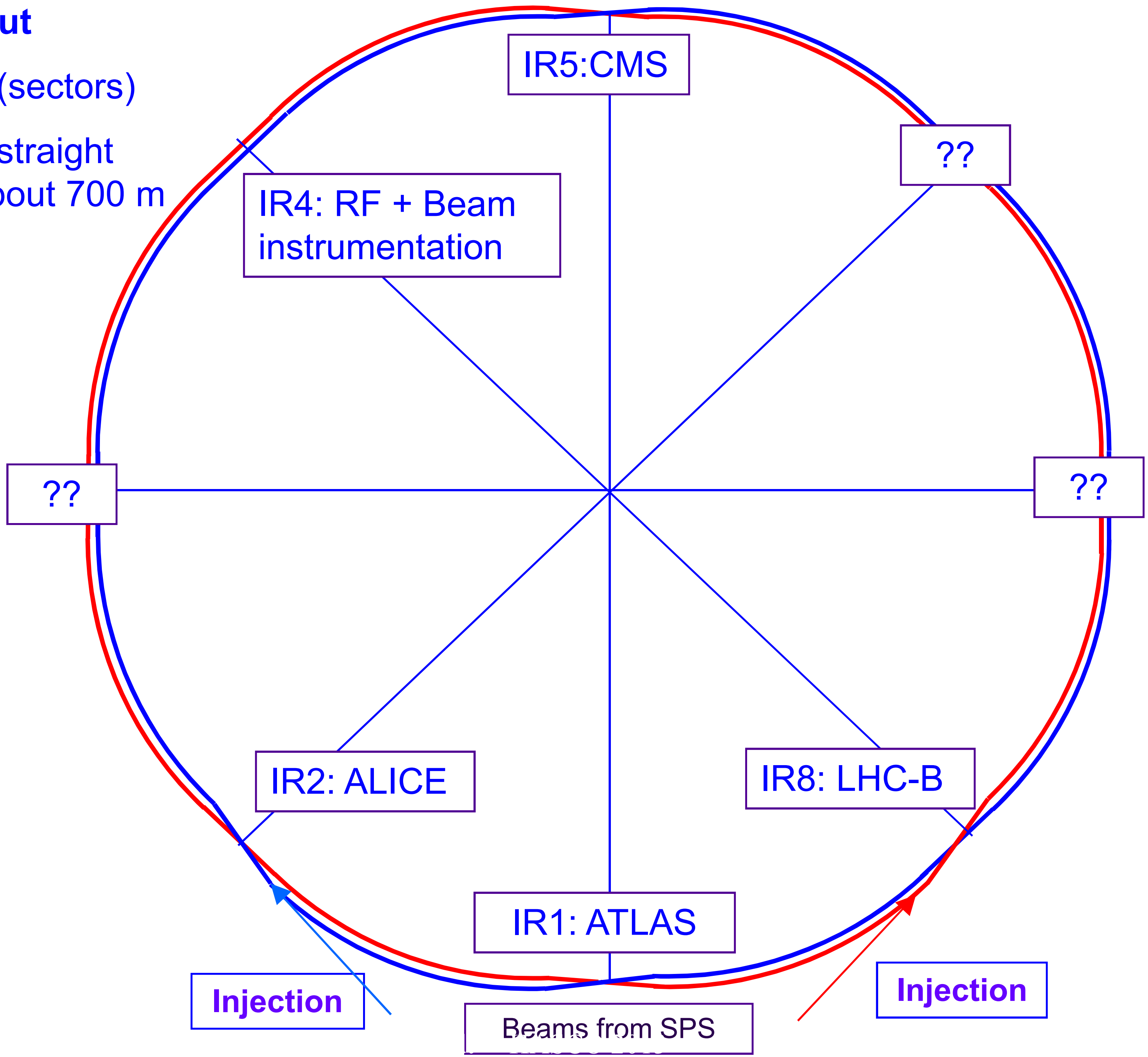

| | 450 GeV | 7 TeV |
|---|---|---|
| RMS bunch length | 11.2 cm | 7.6 cm |
| RMS energy spread | 0.031% | 0.011% |

# LHC layout and beam transport

**LHC Layout**

eight arcs (sectors)

eight long straight section (about 700 m long)



# Beam transport

Need for getting protons on a circle: dipole magnets

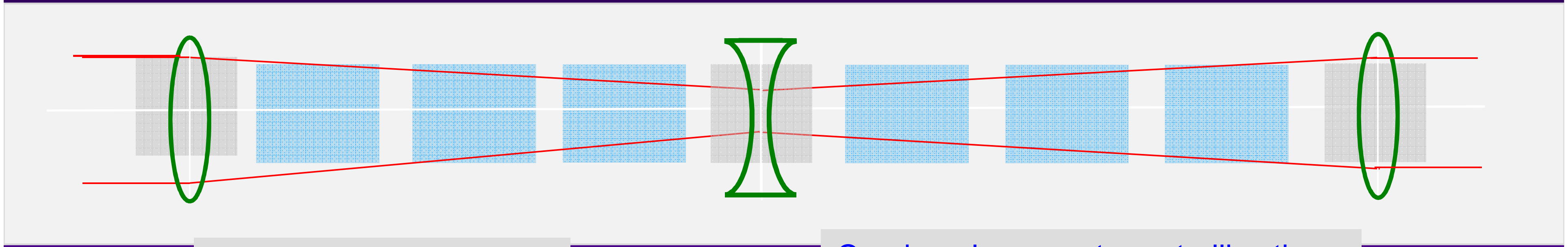
Need for focusing the beams:

- 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

# Magnets and beam stability

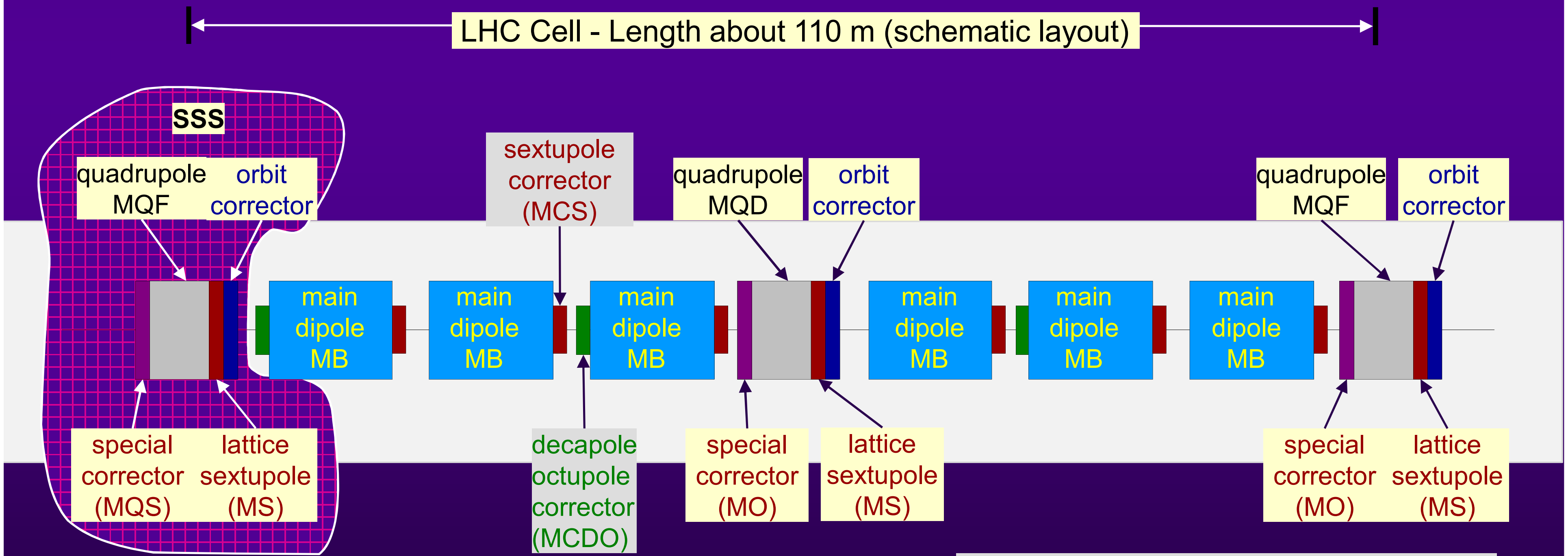
- Dipole magnets
  - To make a circle around LHC
- Quadrupole magnets
  - To keep beam particles together
  - Particle trajectory stable for particles with nominal momentum
- Sextupole magnets
  - To correct the trajectories for off momentum particles
  - Particle trajectories stable for small amplitudes (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



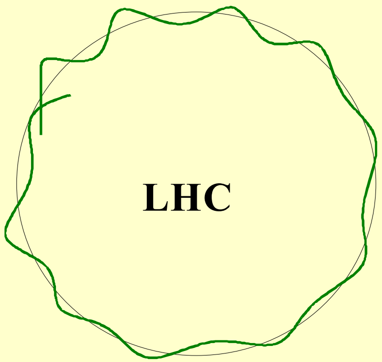
Vertical / Horizontal plane
(QF / QD)

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

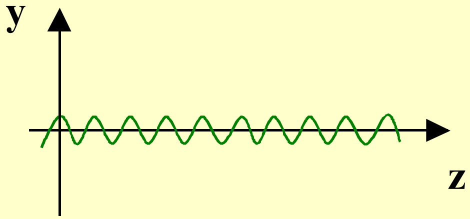



10000 magnets powered in 1700 electrical circuits

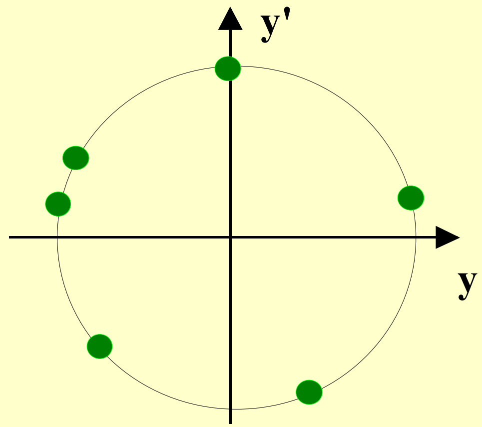
# Particle stability and superconducting magnets - Quadrupolar- and multipolar fields



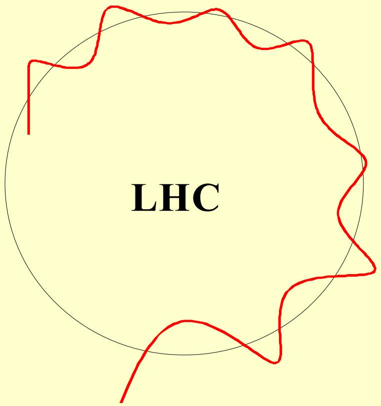

Particle oscillations in quadrupole field (small amplitude)



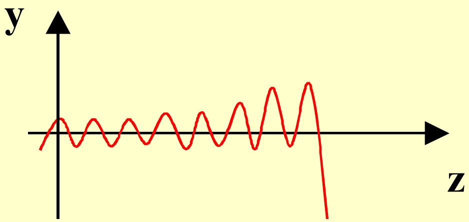

Harmonic oscillation after coordinate transformation



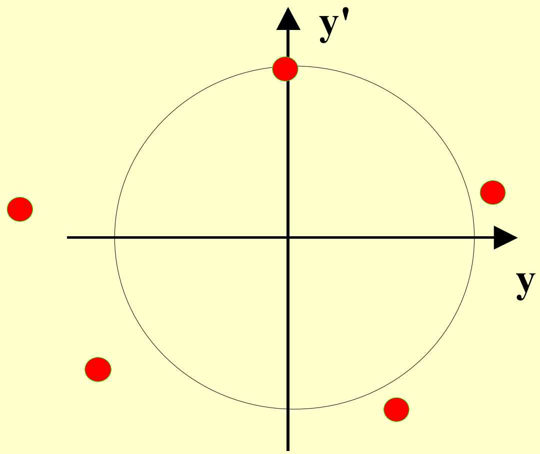

Circular movement in phase space




Particle oscillation assuming non-linear fields, large amplitude




Amplitude grows until particle is lost (touches aperture)




No circular movement in phasespace

# LHC superconducting magnets

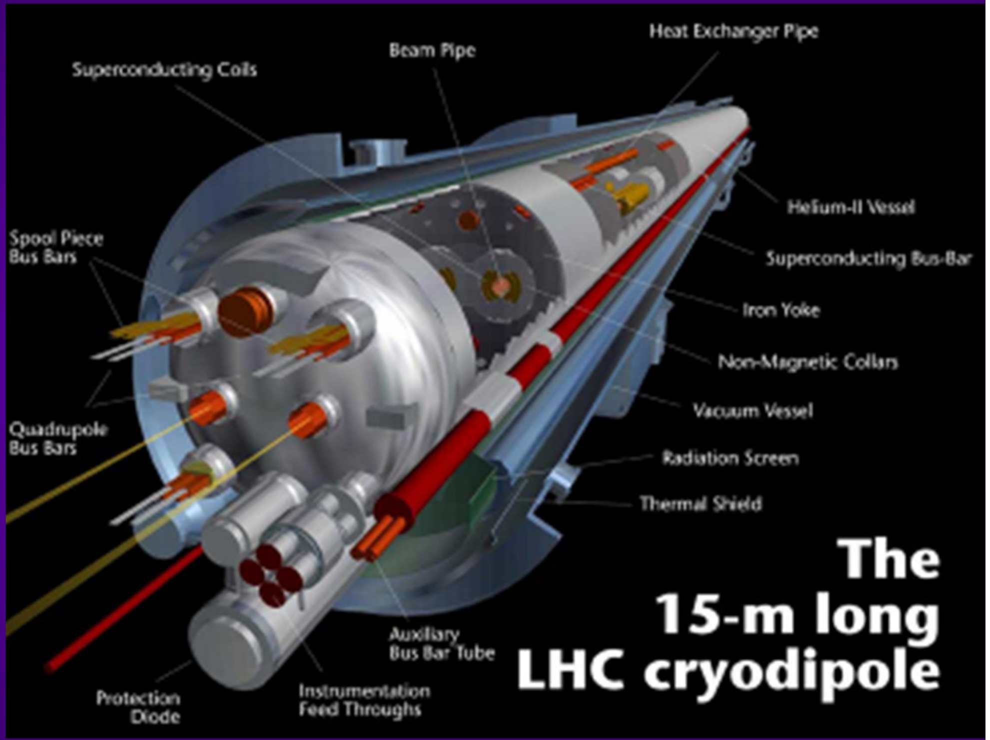
…….determine the beam energy

# Dipole magnets for the LHC

1232 Dipole magnets
Length about 15 m

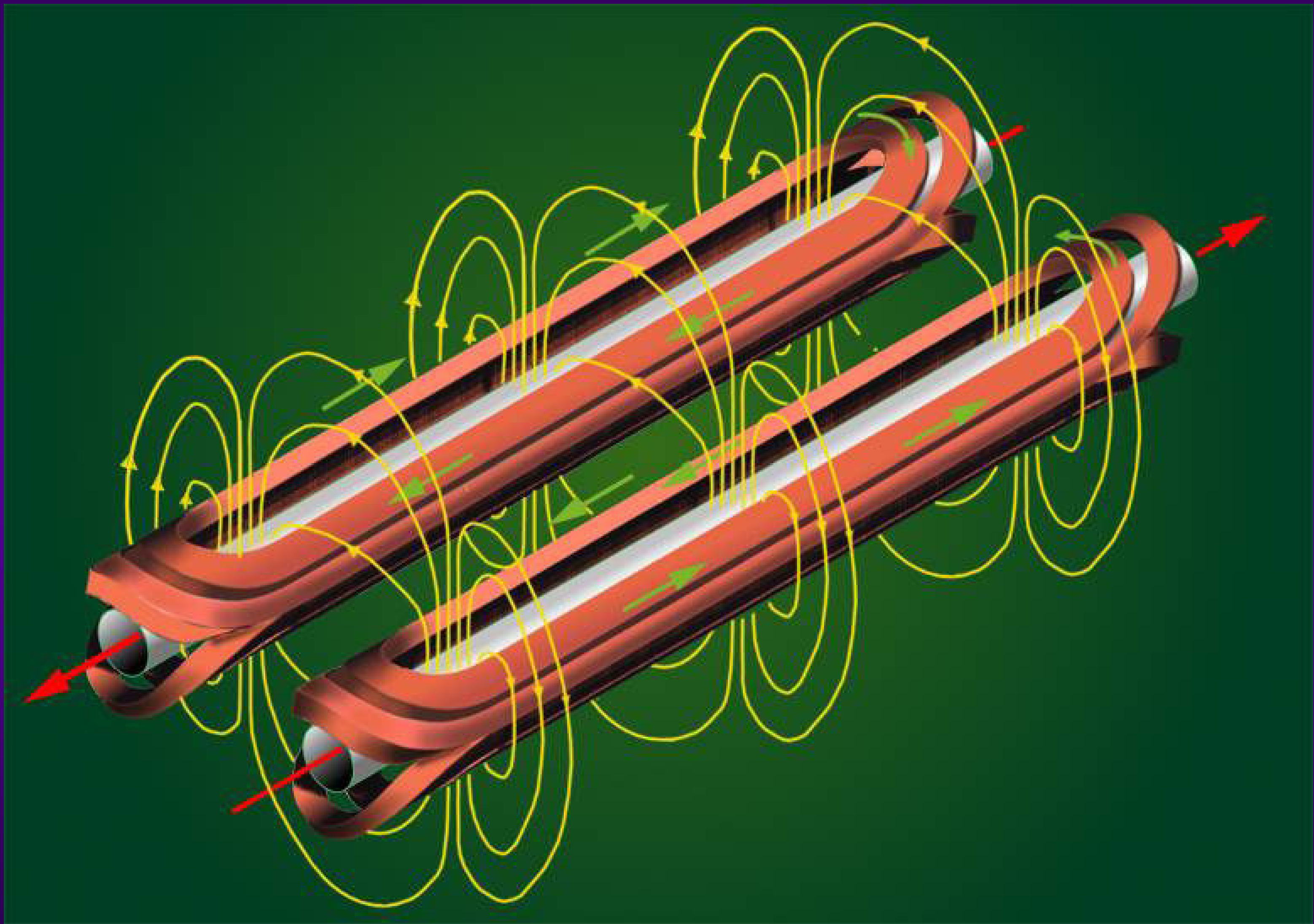
Magnetic Field 8.3 T for 7 TeV

Two beam tubes with an opening of 56 mm

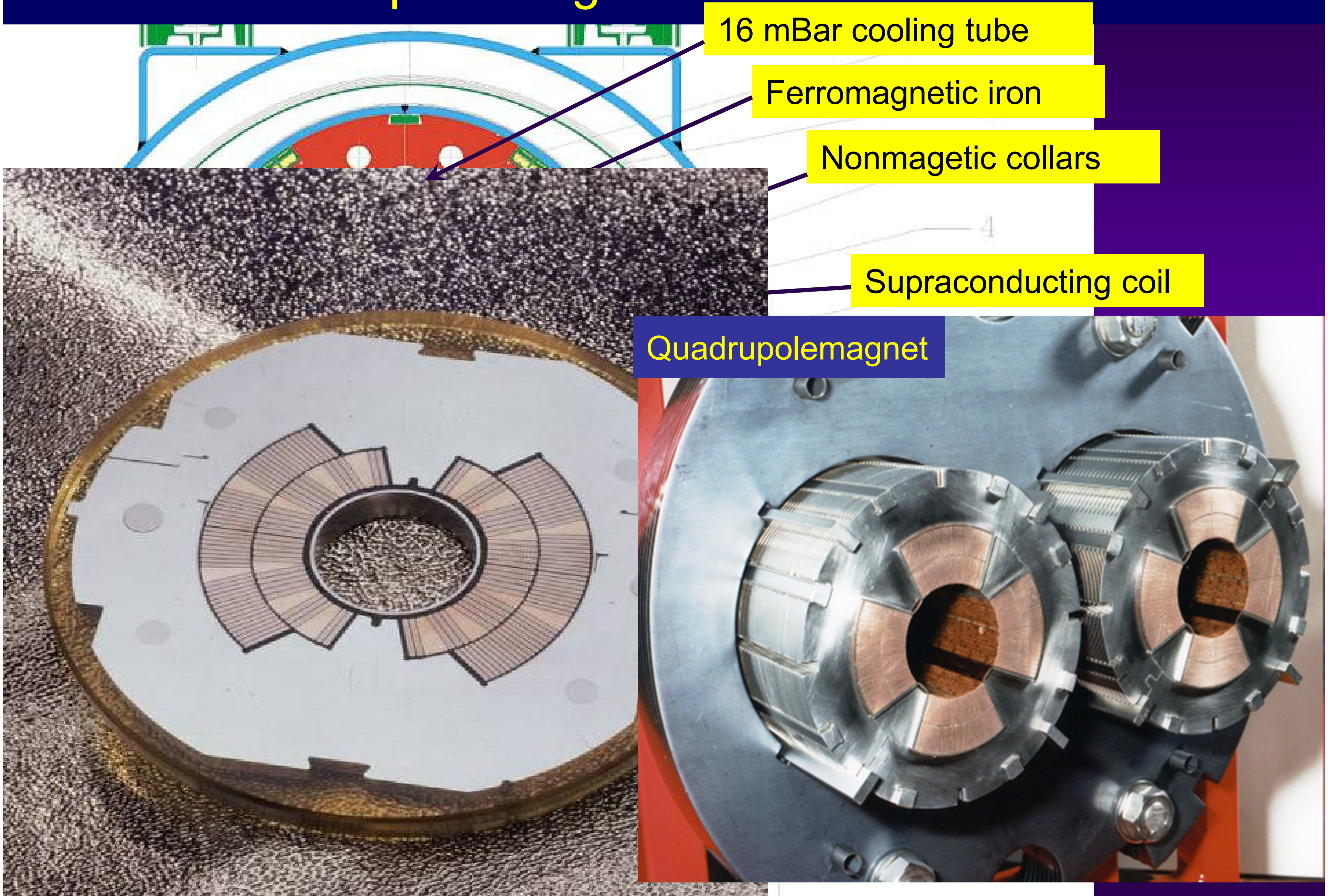



plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets)

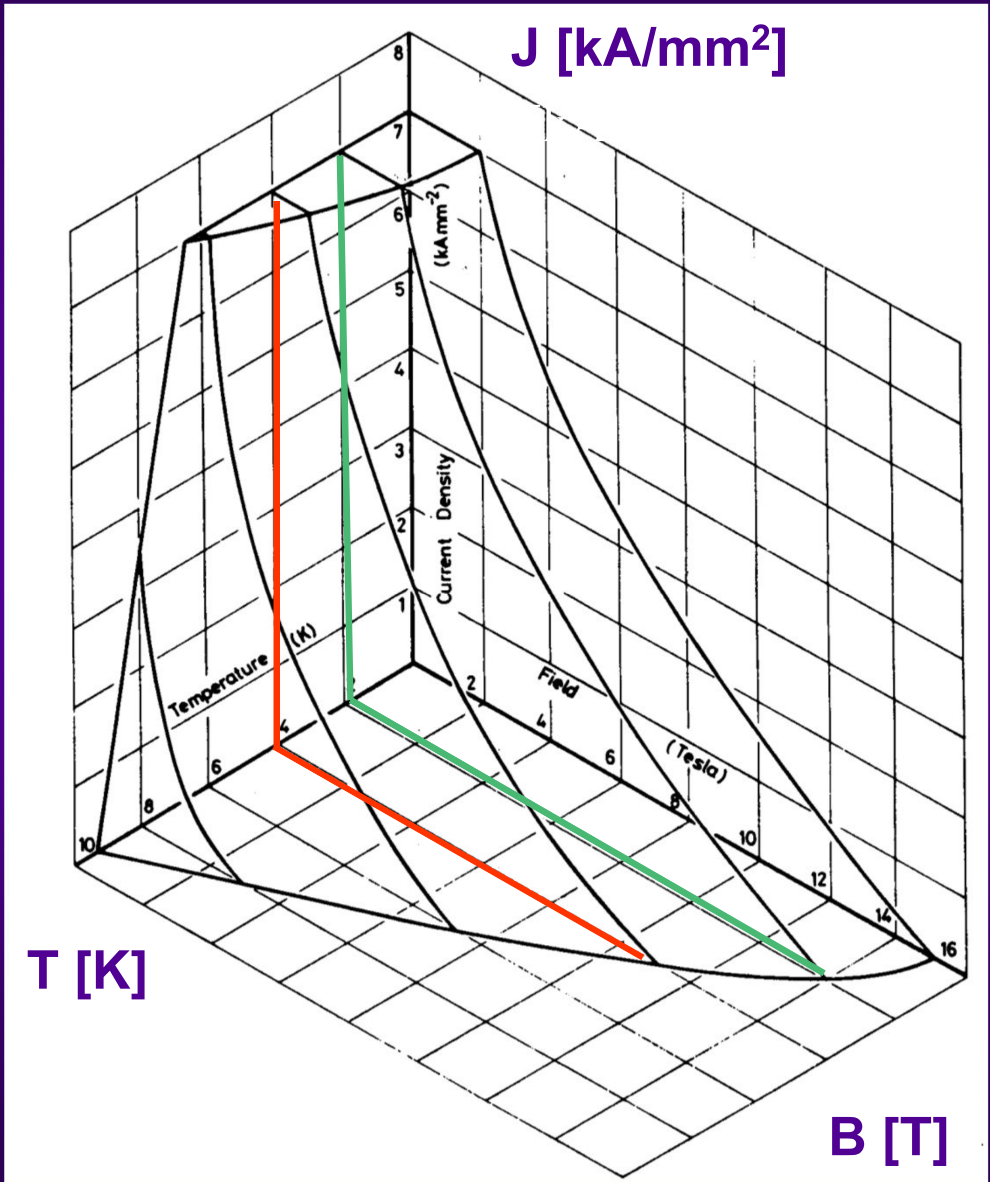
# Coils for Dipolmagnets



# Dipole magnet cross section



# Operating temperature of superconductors (NbTi)

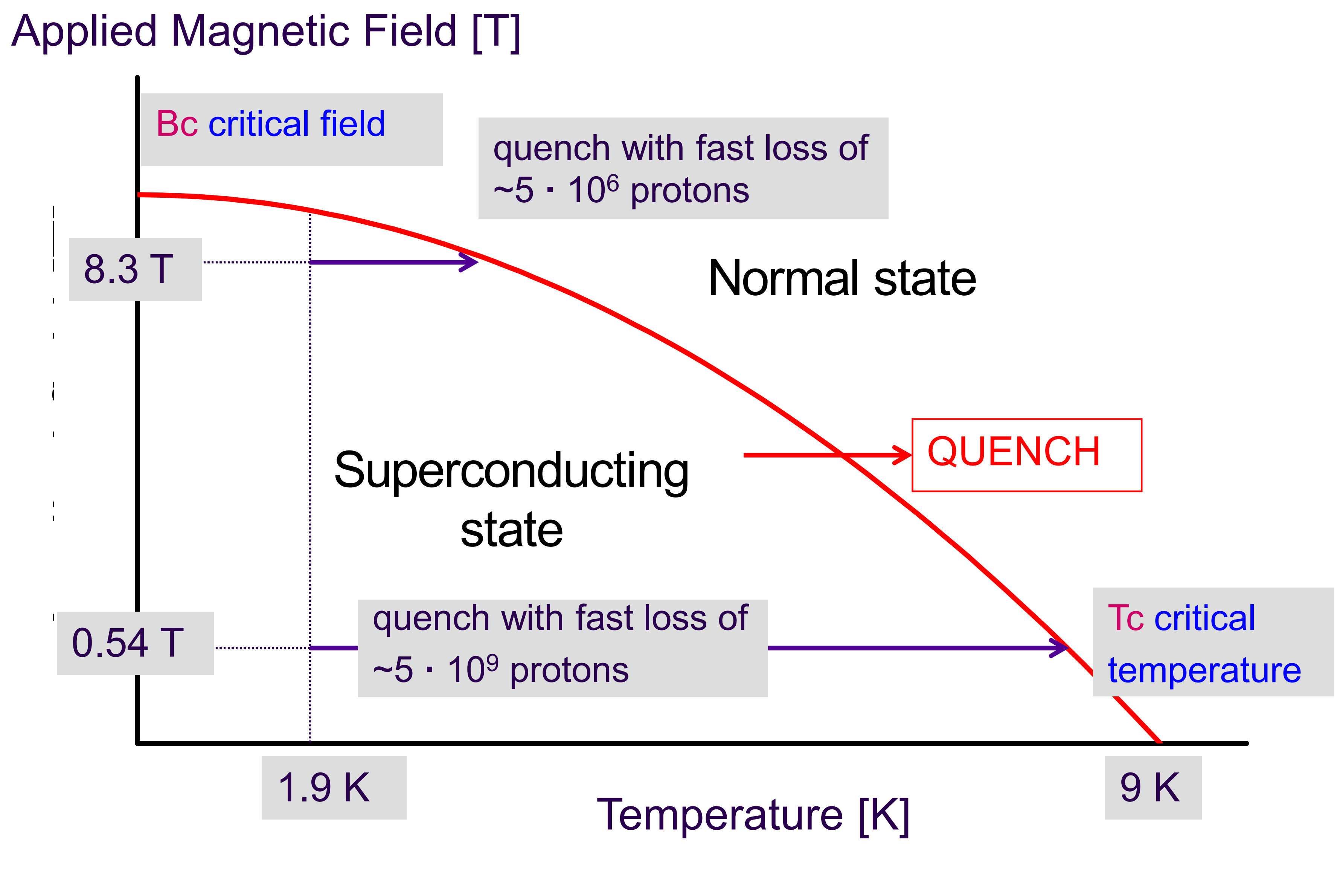



The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

Superconducting magnets produce high field with high current density

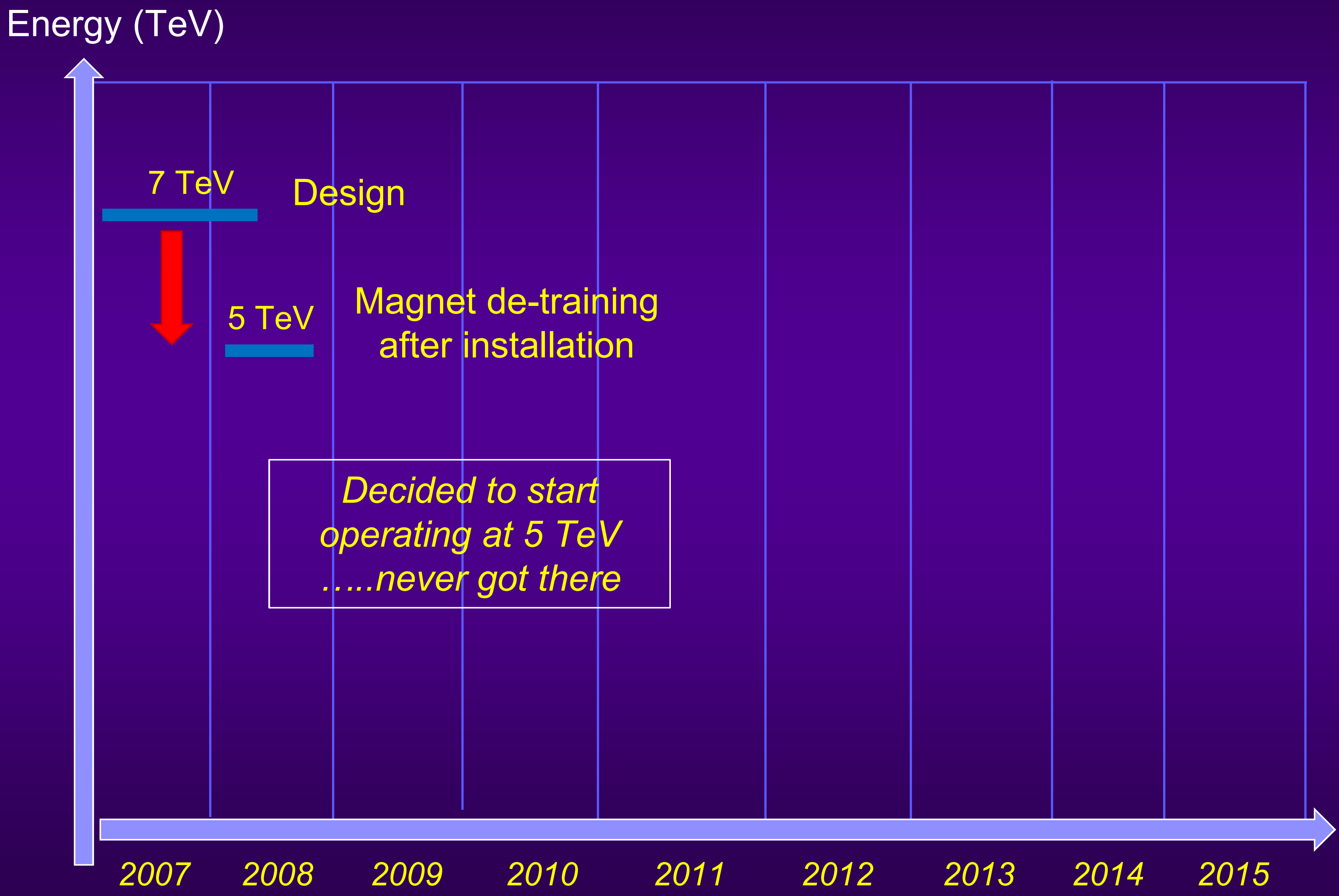
Lowering the temperature enables better usage of the superconductor, by broadening its working range

# Operational margin of a superconducting magnet



# Energy and superconducting magnets

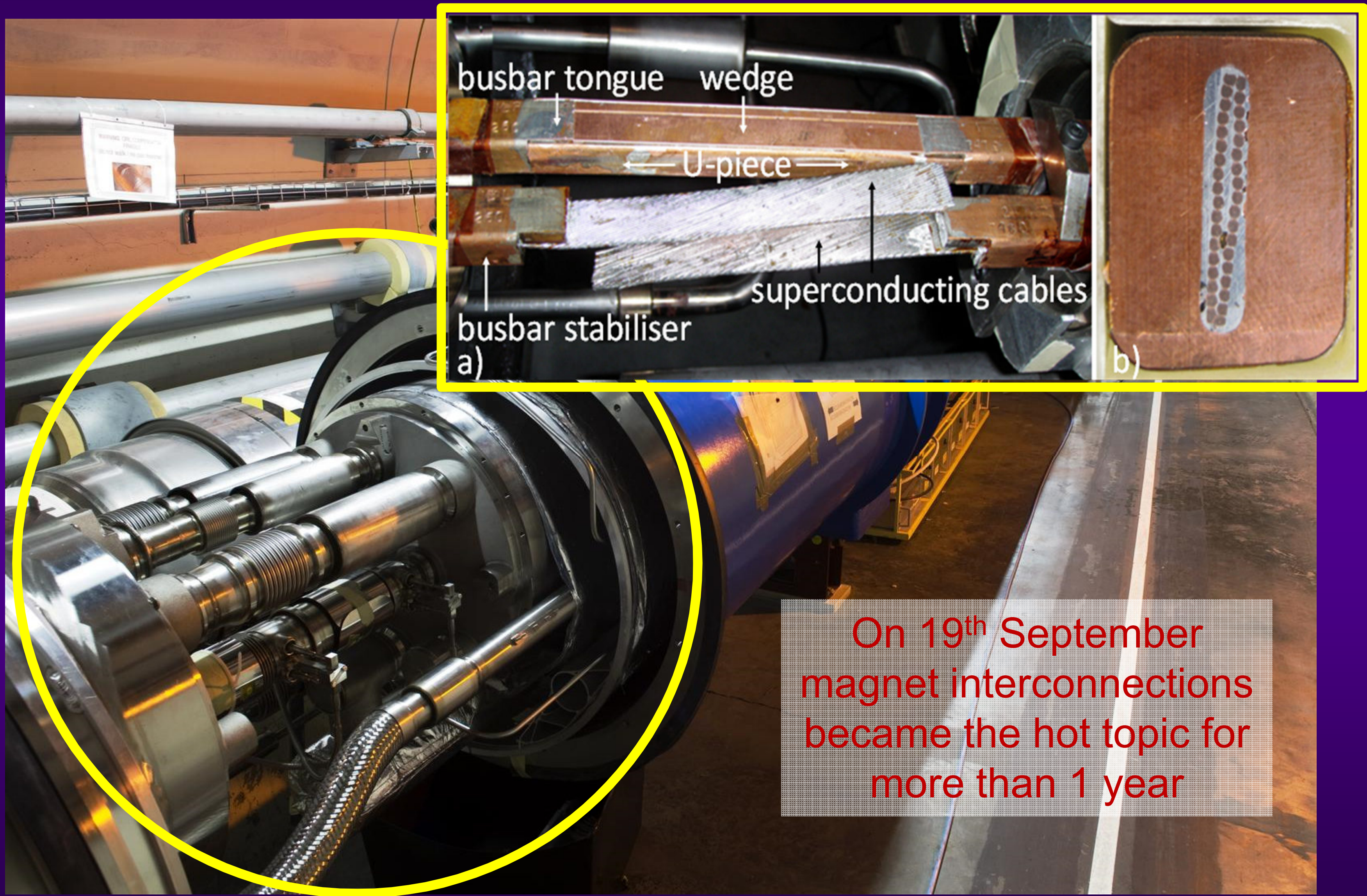
# LHC energy evolution



# September 10$^{th}$ 2008

## A brief moment of glory

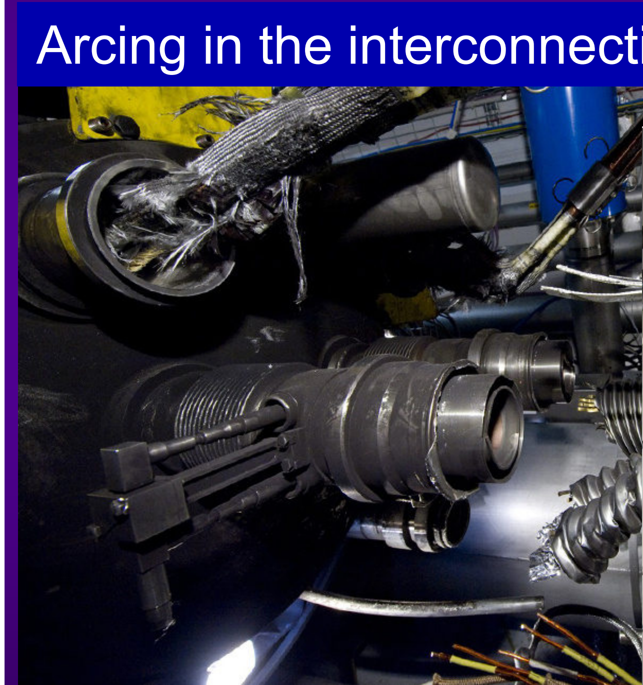
# September 19$^{th}$ 2008




On 19$^{th}$ September magnet interconnections became the hot topic for more than 1 year

# Incident September 19th 2008

An interconnect was not ok and opened. An electrical arc provoked a He pressure wave damaging ~700 m of LHC, polluting the beam vacuum over more than 2 km



Arcing in the interconnection

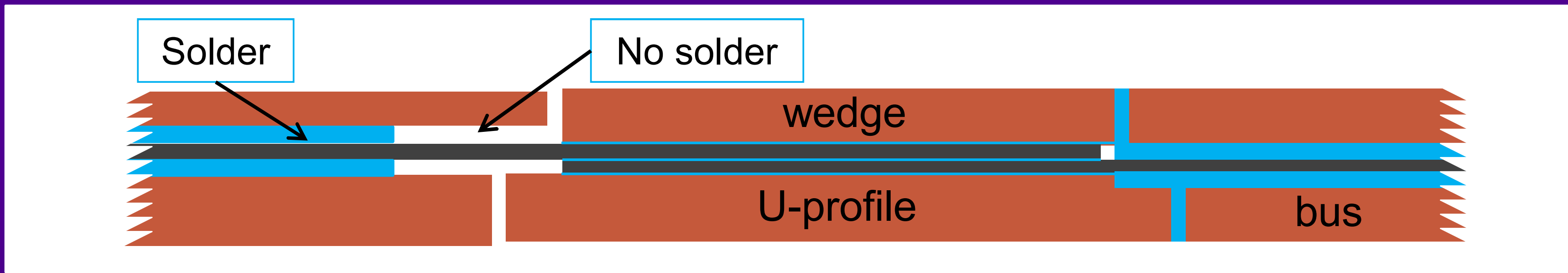
Over-pressure

Magnet displacement

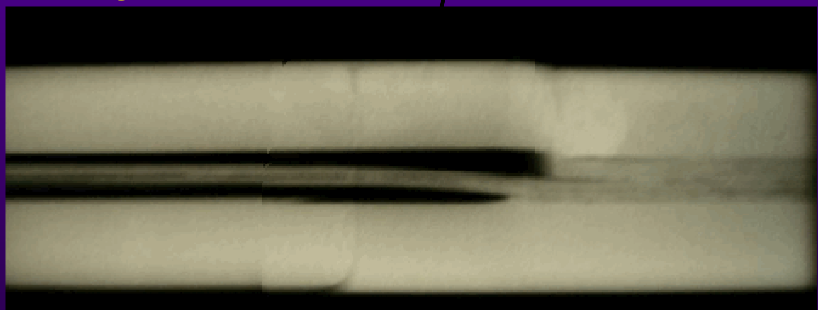
53 magnets had to be repaired

# 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.



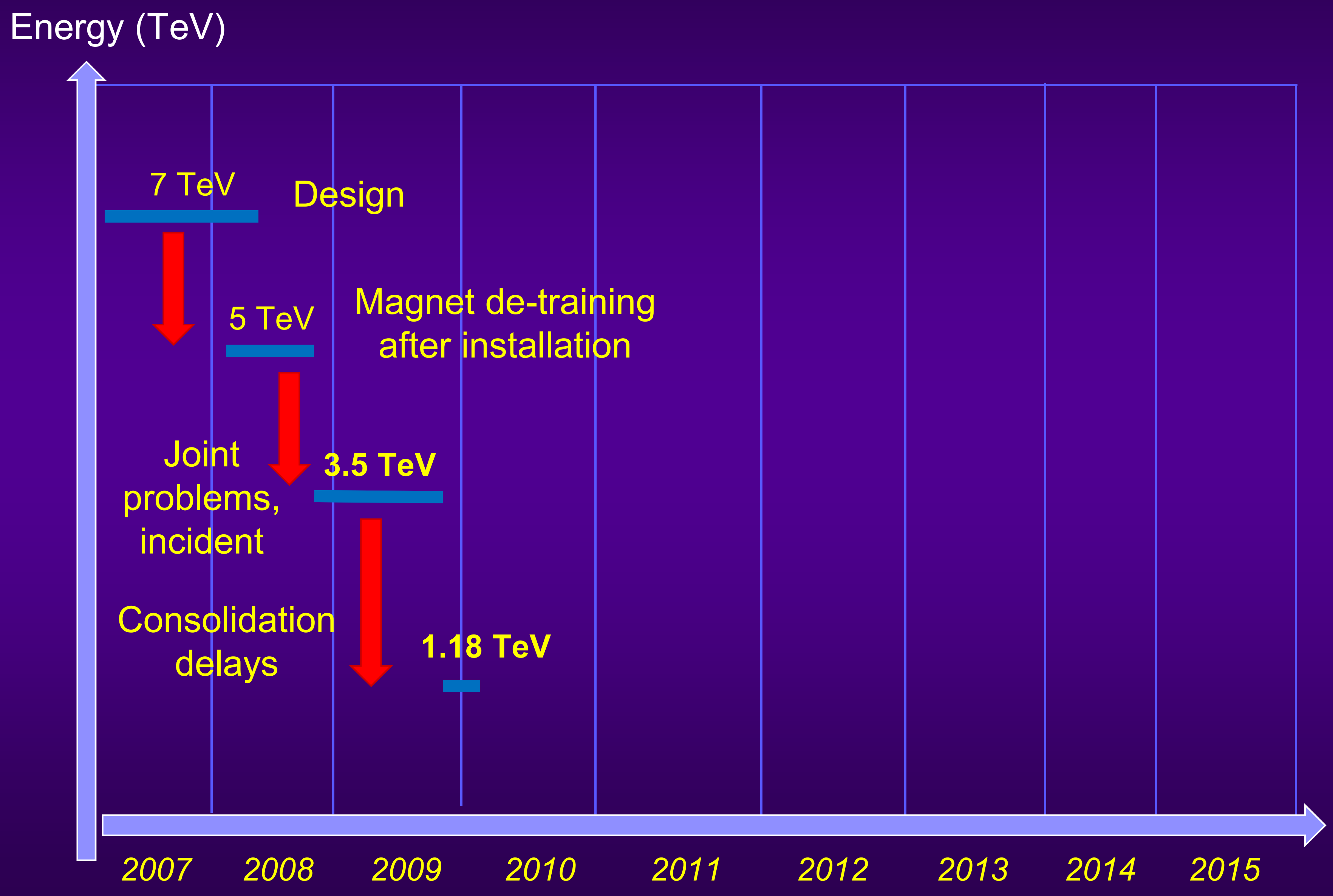

X-ray



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

→ Energy limitation for run 1 !!

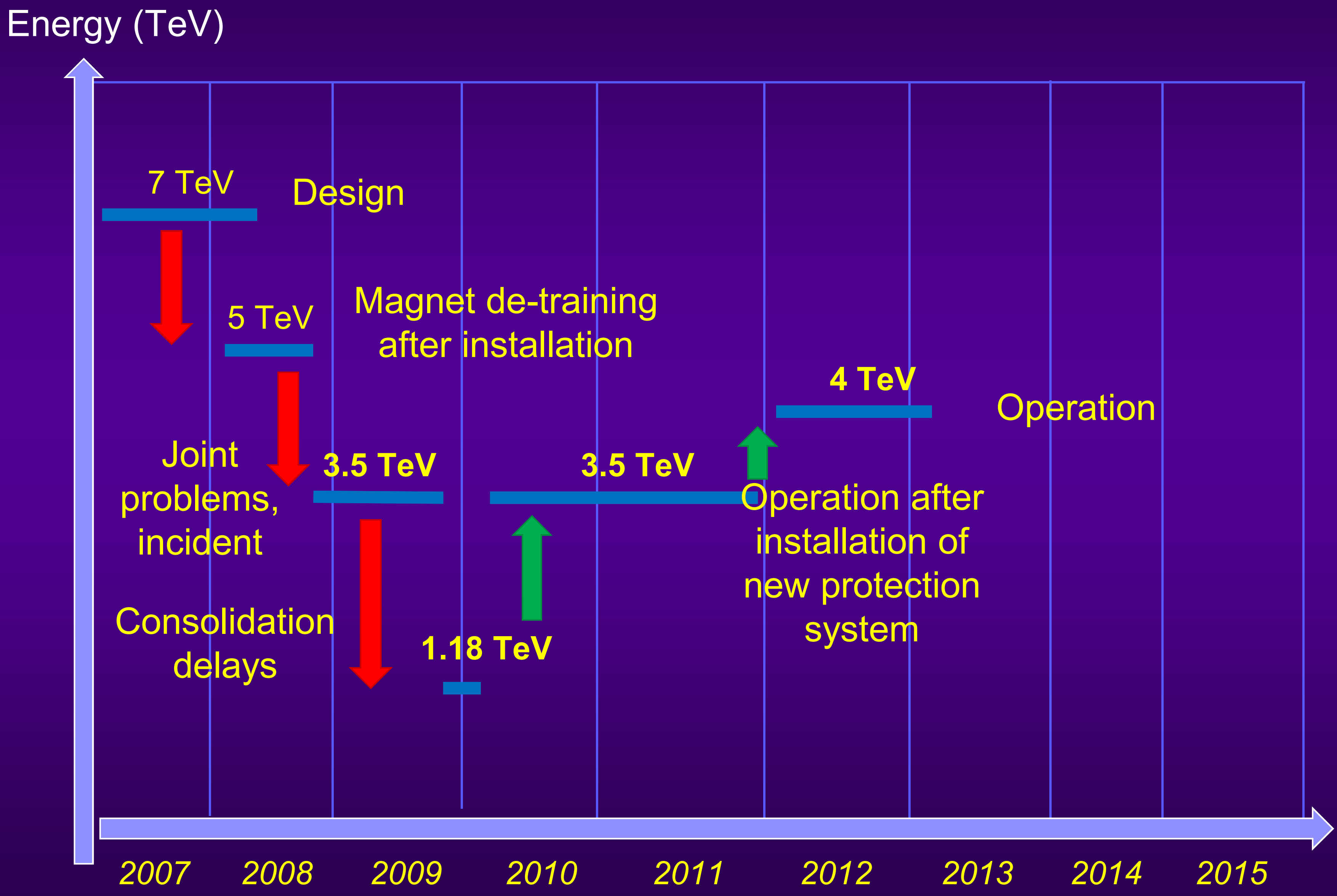
# LHC energy evolution



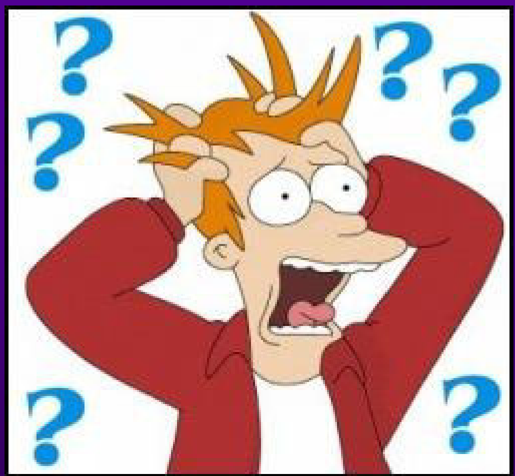
# LHC is back !

*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

# From 2010….

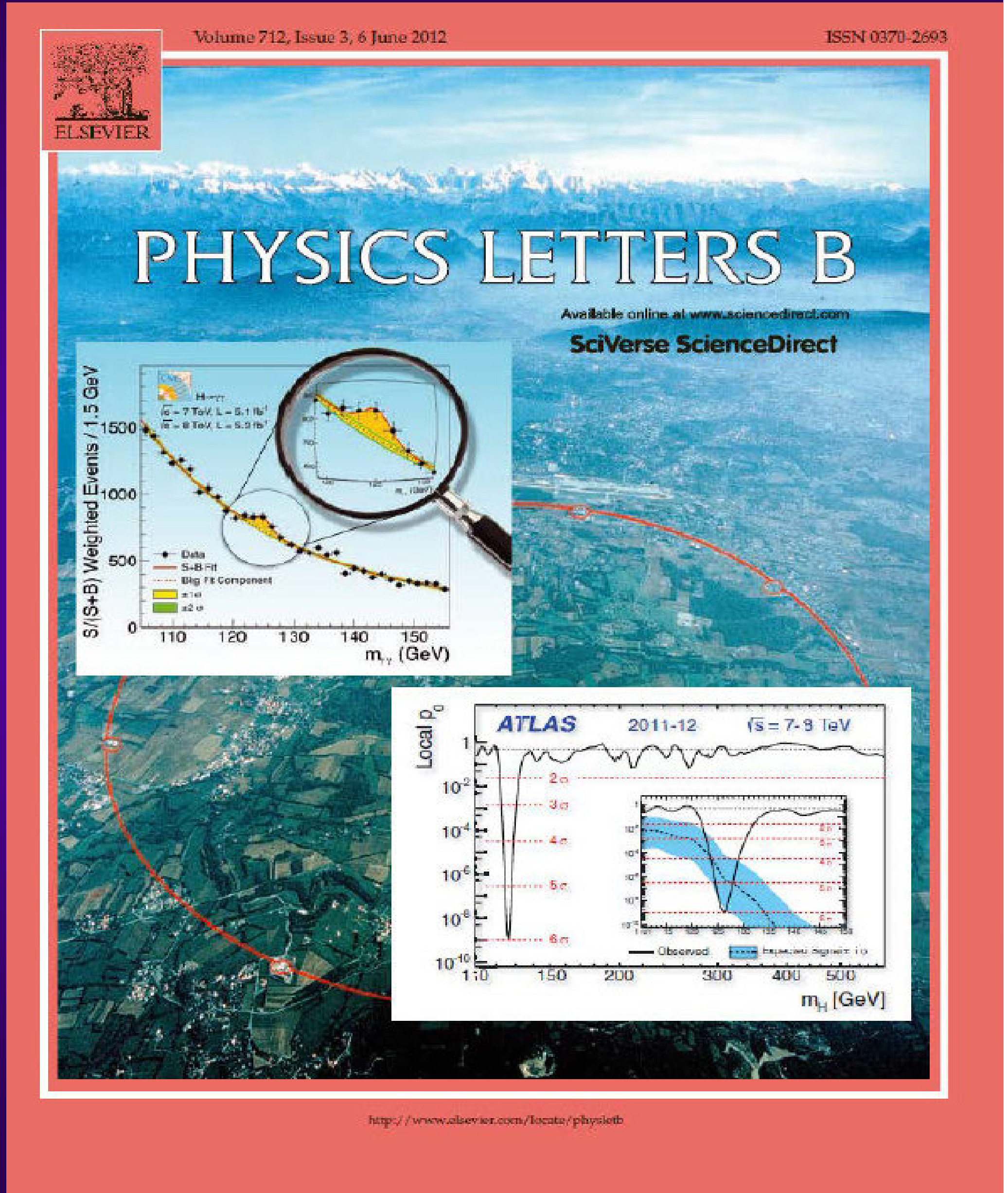
1.35×10^32
IN THE
BOX
POMMERY
MOËT
10^33
Congratulation from ATLAS !!
First W
ATLAS EXPERIMENT
DE SAINT GALL
Compact Muon Solenoid Experiment
First top candidate
ATLAS
2010
LHC on target!
Thanks from CMS Technical Coordination
for the excellent performance and collaboration
Laurent-Perrier

# …..to 2012


1 fb-1 6 fb-1

# ……….late in 2012

BRUT IMPERIAL
Champagne

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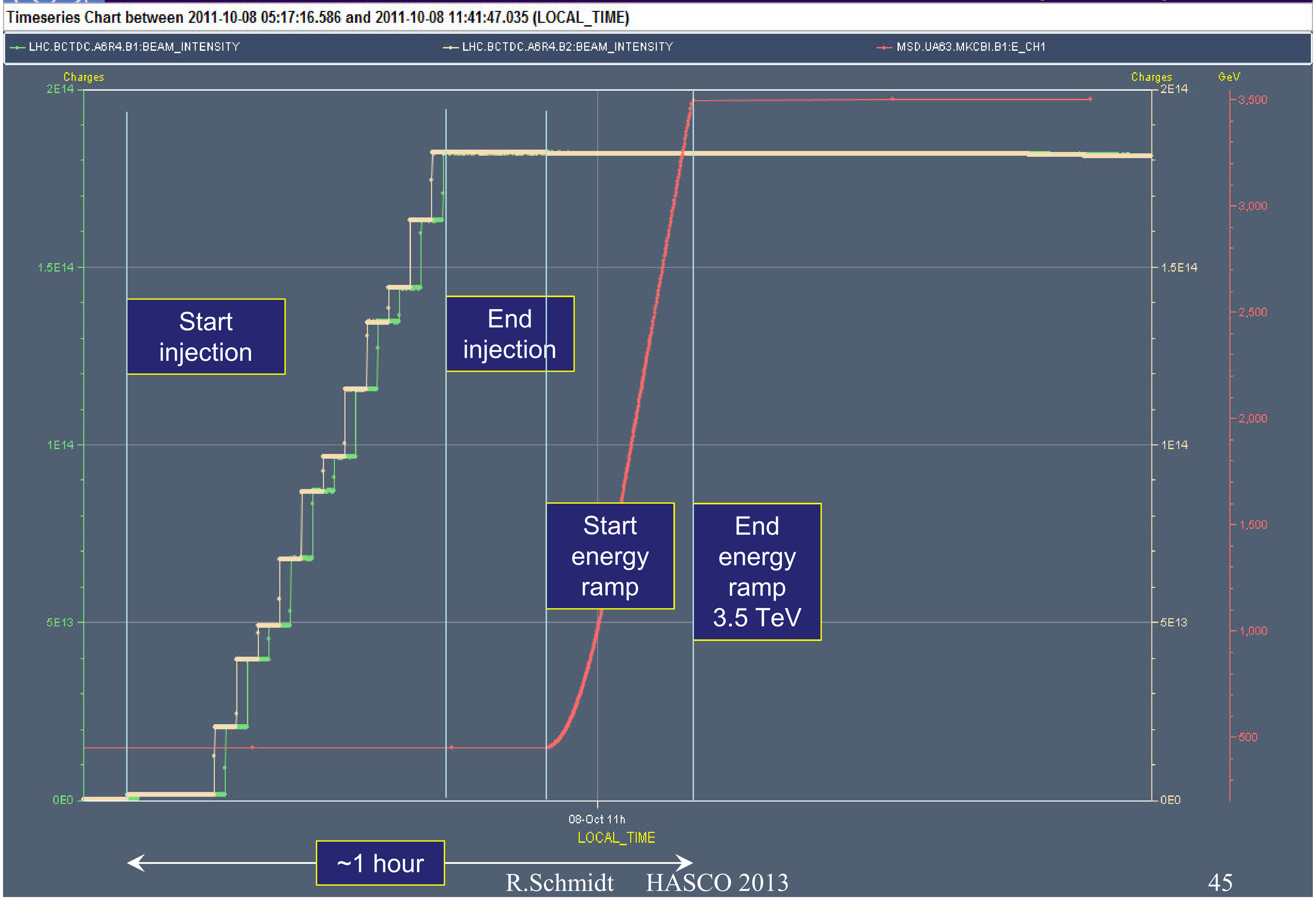
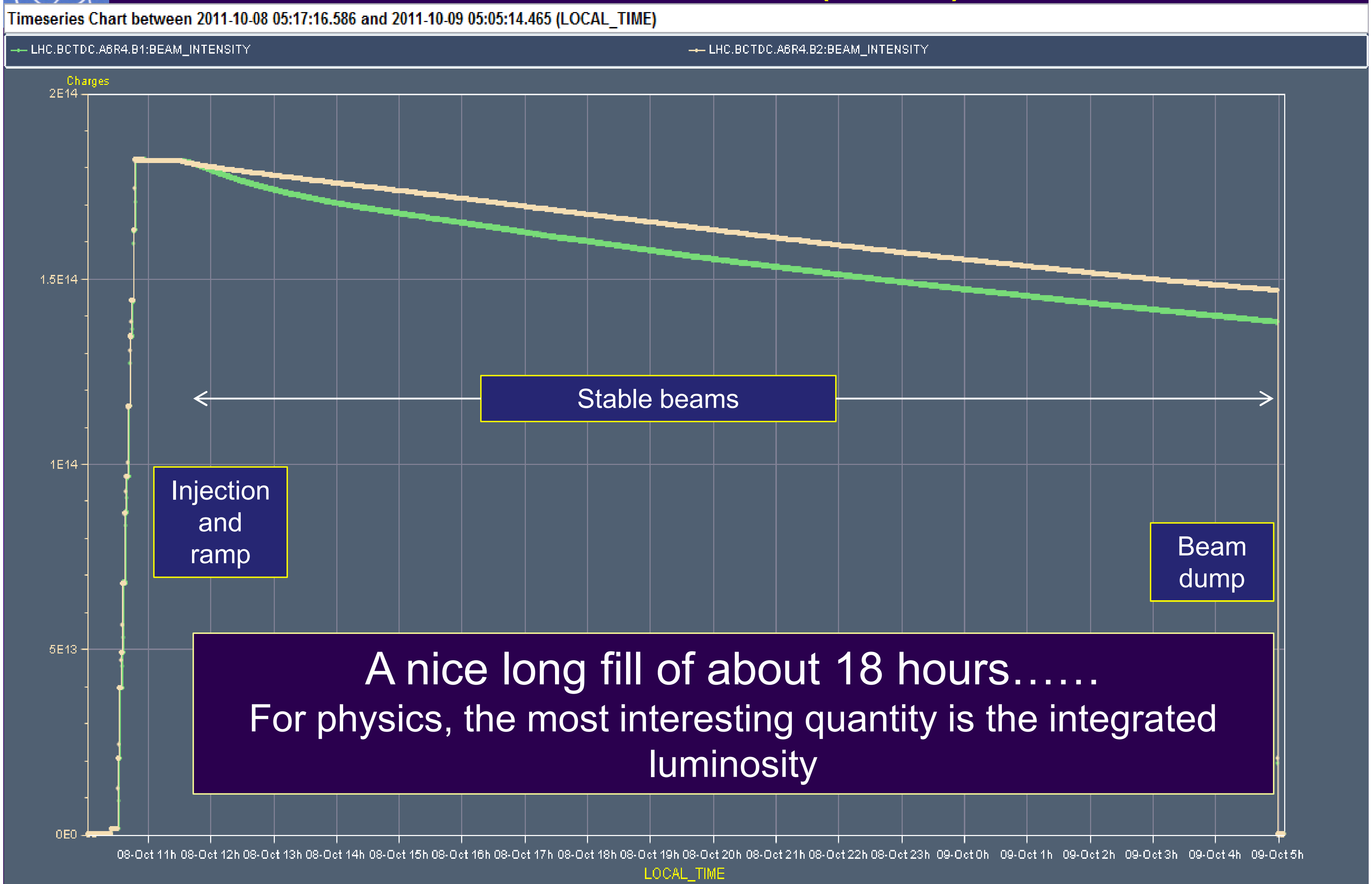
ELSEVIER
PHYSICS LETTERS B
Available online at www.sciencedirect.com
SciVerse ScienceDirect
S/(S+B) Weighted Events / 1.5 GeV
Data
S+B Fit
Bkg Fit Component
$m_{\gamma\gamma}$ (GeV)
Local $p_0$
ATLAS
2011-12
$\sqrt{s}$ = 7-8 TeV
Observed
$m_H$ [GeV]
http://www.elsevier.com/locate/physletb

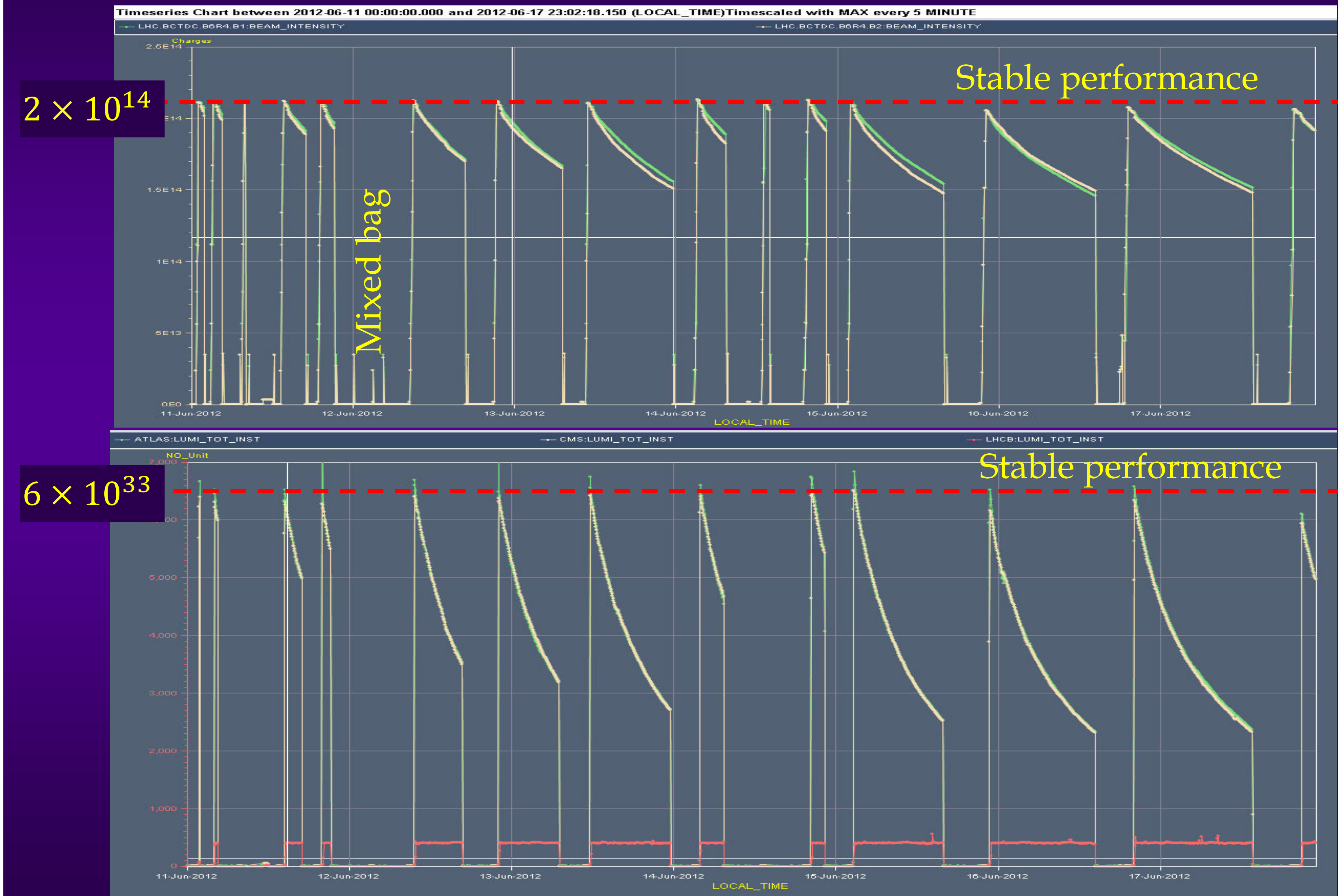
# Fill 2195 - start of the fill about 1 h (2011)



# Excellent fill (2011)



# Beam Intensities and Luminosity 11-18/6/2012

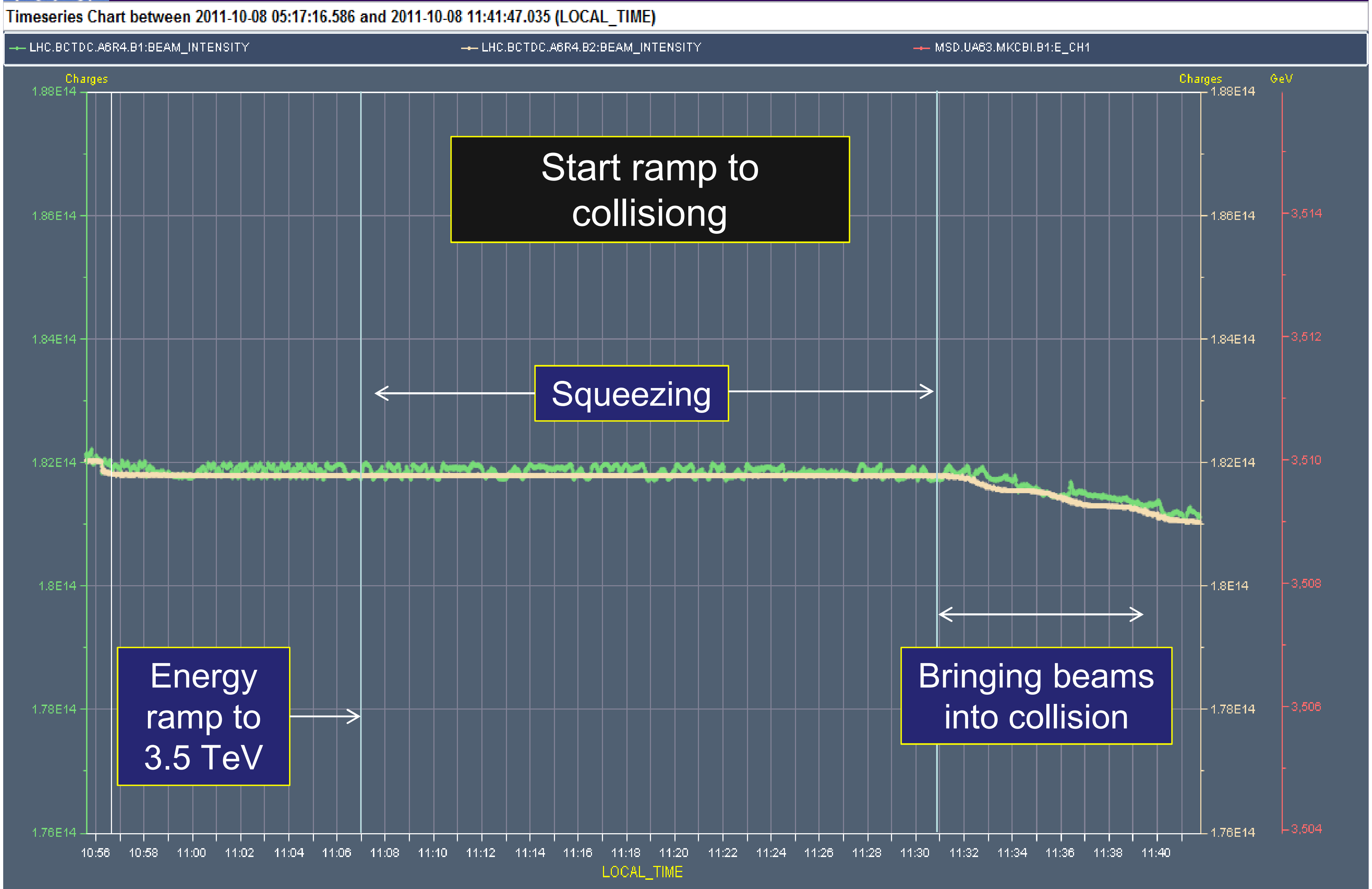


# Overview of fills

| Fill | Duration | Ibeam | Lpeak [e30 cm-2s-1] | Lint [pb-1] | Dump |
|---|---|---|---|---|---|
| 2723 | 2:26 | 2.03E+14 | 6406 | 46.06 | Trip of ROD.A81B1, SEU? |
| 2724 | 1:13 | 2.03E+14 | 6329 | 25.905 | Electrical perturbation |
| 2725 | 7:04 | 2.05E+14 | 6520 | 115.5 | Trip of S81 |
| 2726 | 8:58 | 2.05E+14 | 6499 | 142.5 | Elecitrical perturbation, FMCM |
| 2728 | 11:41 | 2.06E+14 | 6525 | 171.5 | **Operator dump** |
| 2729 | 3:28 | 2.06E+14 | 6502 | 67.7 | BLM self trigger |
| 2732 | 1:52 | 2.06E+14 | 6592.5 | 40 | QPS trigger RQX.R1, SEU? |
| 2733 | 12:34 | 2.06E+14 | 6674 | 183 | Triplet RQX.L2 tripped. |
| 2734 | 15:33 | 2.01E+14 | 6257.5 | 203.5 | **Operator dump** |
| 2736 | 17:29 | 2.02E+14 | 6465.5 | 233 | **Operator dump** |
| 2737 | 3:36 | 1.99E+14 | 6021 | 66.1 | RF Trip 2B2 |
| Total | 51.1% | | | 1301 | |

51 % of time in stable beams !

# Reference fill 2195 in 2011 – at 3.5 TeV



# Luminosity and energy stored in the beam

# High luminosity by colliding trains of bunches

Number of „New Particles“ per unit of time:

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

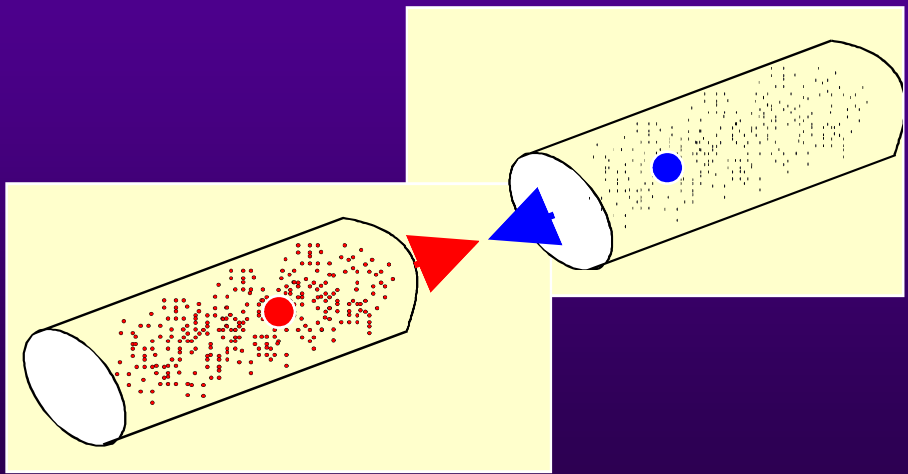
The objective for the LHC as proton – proton collider is a luminosity of about $10^{34}$ [$cm^{-2}s^{-1}$]

- LEP (e+e-) : 3-4 $10^{31}$ [$cm^{-2}s^{-1}$]
- Tevatron (p-pbar) : some $10^{32}$ [$cm^{-2}s^{-1}$]
- B-Factories : > $10^{34}$ [$cm^{-2}s^{-1}$]

# Luminosity parameters

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

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



# Beam-beam interaction and beam instabilities determine parameters

Number of protons per bunch limited to about **1-3×10¹¹** due to the beam-beam interaction and beam instabilities

Beam size given by injectors and by space in vacuum chamber

f = **11246 Hz**

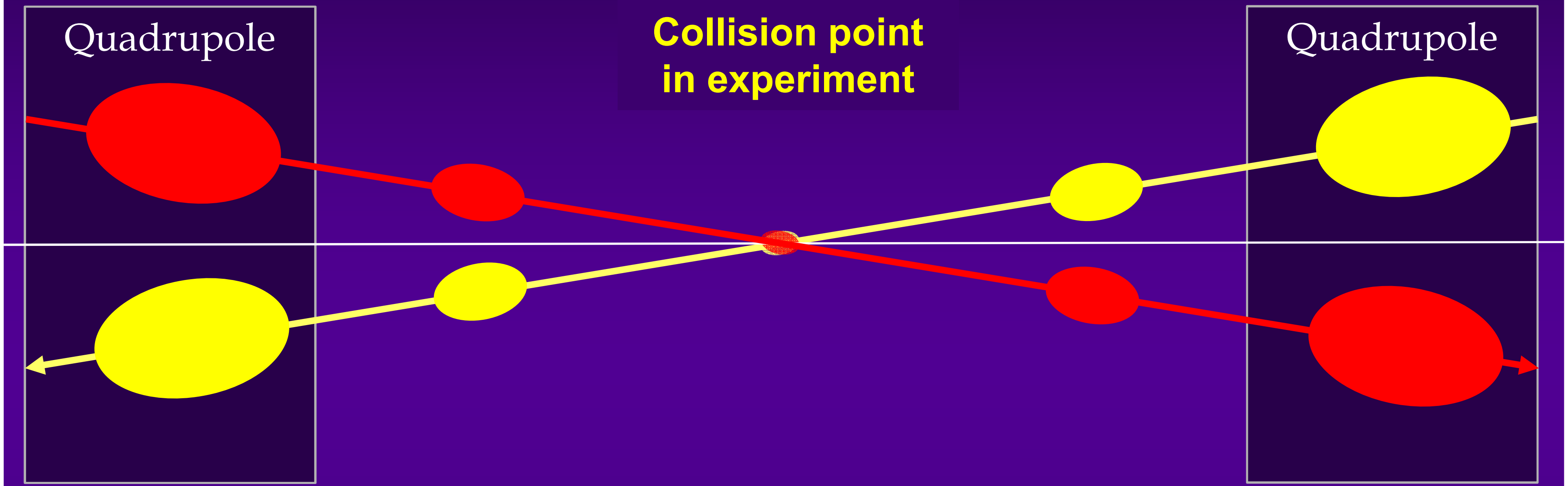
Beam size **16 μm**, for β = 0.5 m (β is a function of the lattice)

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

with **2808** bunches (every 25 ns one bunch)

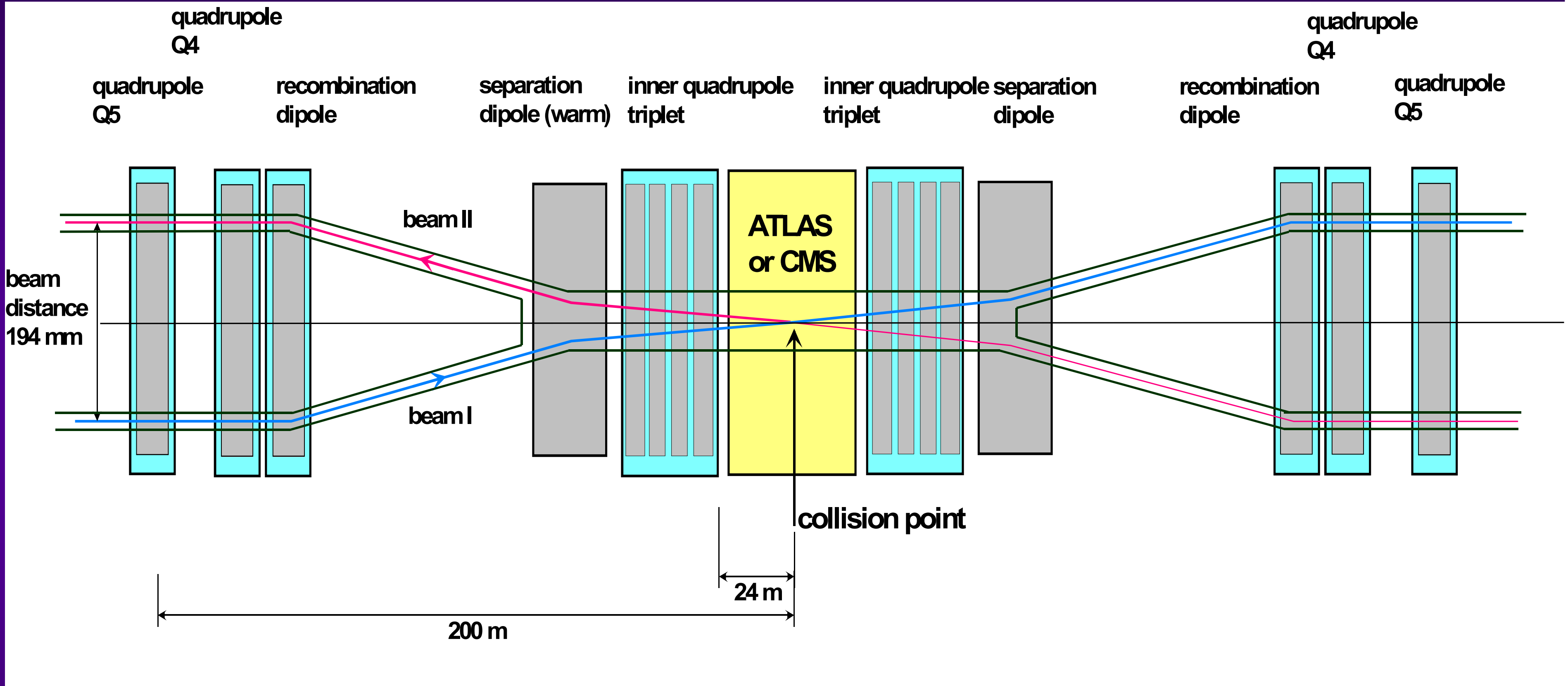
**$L = 10^{34}\ [cm^{-2}s^{-1}]$**

# …smallest beam size at experiments




- Large beam size in adjacent quadrupole magnets
- Separation between beams needed, about 10 $\sigma$
- Limitation with aperture in quadrupoles
- Limitation of $\beta$ function at IP to 1 m (2011) and 0.6 m (2012)

# Experimental long straight sections

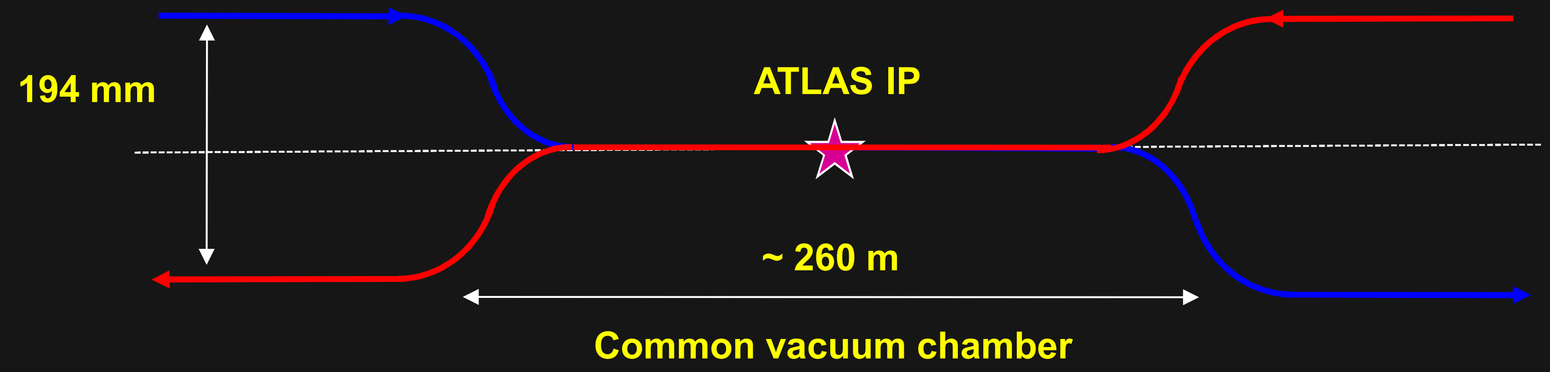



Example for an LHC insertion with ATLAS or CMS

- 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

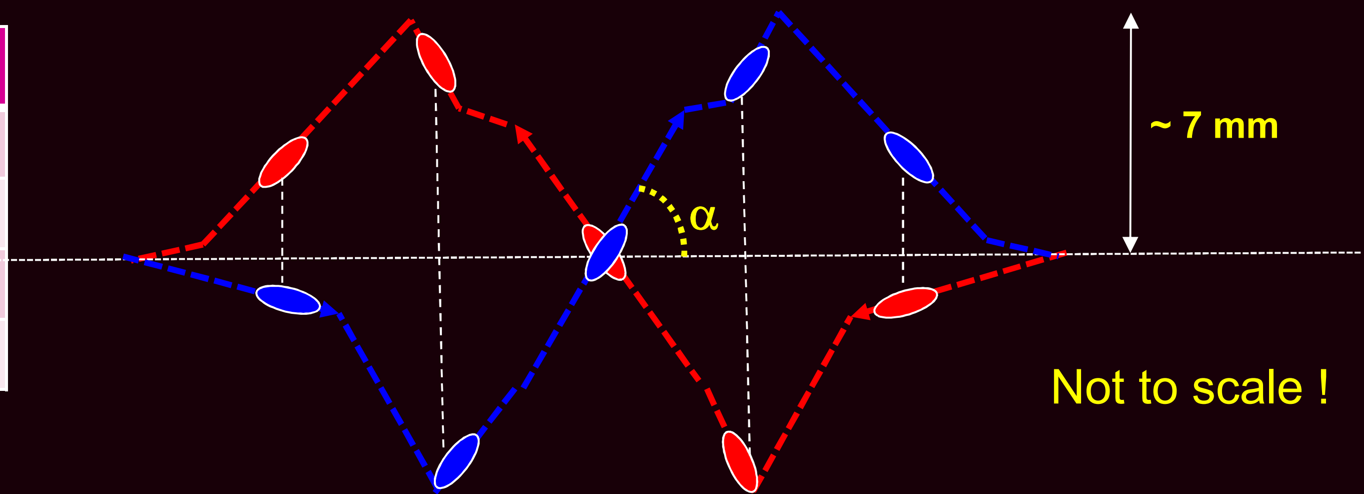
# Separation and crossing: example of ATLAS

Horizontal plane: the beams are combined and then separated




Vertical plane: the beams are deflected to produce a crossing angle at the IP to avoid undesired encounters in the region of the common vacuum chamber

| | α (μrad) |
|---|---|
| ATLAS | -145 / ver. |
| ALICE | 90 / ver. |
| CMS | 120 / hor |
| LHCb | -220 /hor |



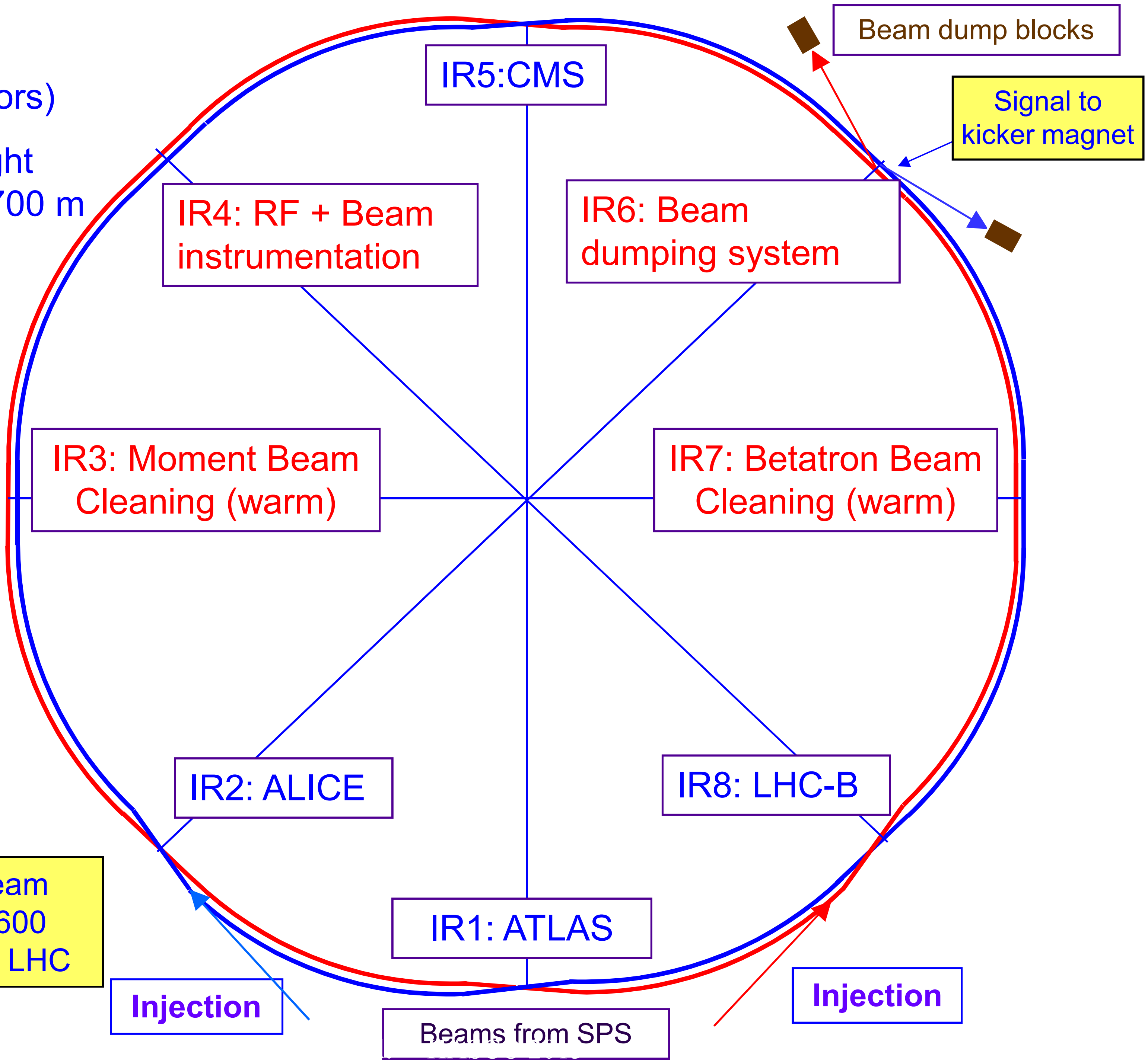
# Very high luminosity: consequences

- High energy stored in the beams
- Dumping the beam in a safe way
- Avoiding beam losses, in particular in the superconducting magnets
  - Beam induced magnet quenching (when $10^{-8}$-$10^{-7}$ of beam hits magnet at 7 TeV)
  - Beam cleaning (Betatron and momentum cleaning)
- Radiation, in particular in experimental areas from beam collisions (beam lifetime is dominated by this effect)
  - Single event upsets in the tunnel electronics
- Beam instabilities due to impedance and beam–beam effects
- Photo electrons, generated by beam losses - accelerated by the following bunches – lead to instabilities

**LHC Layout**

eight arcs (sectors)

eight long straight section (about 700 m long)




Detection of beam losses with >3600 monitors around LHC

# Challenges for high intensity

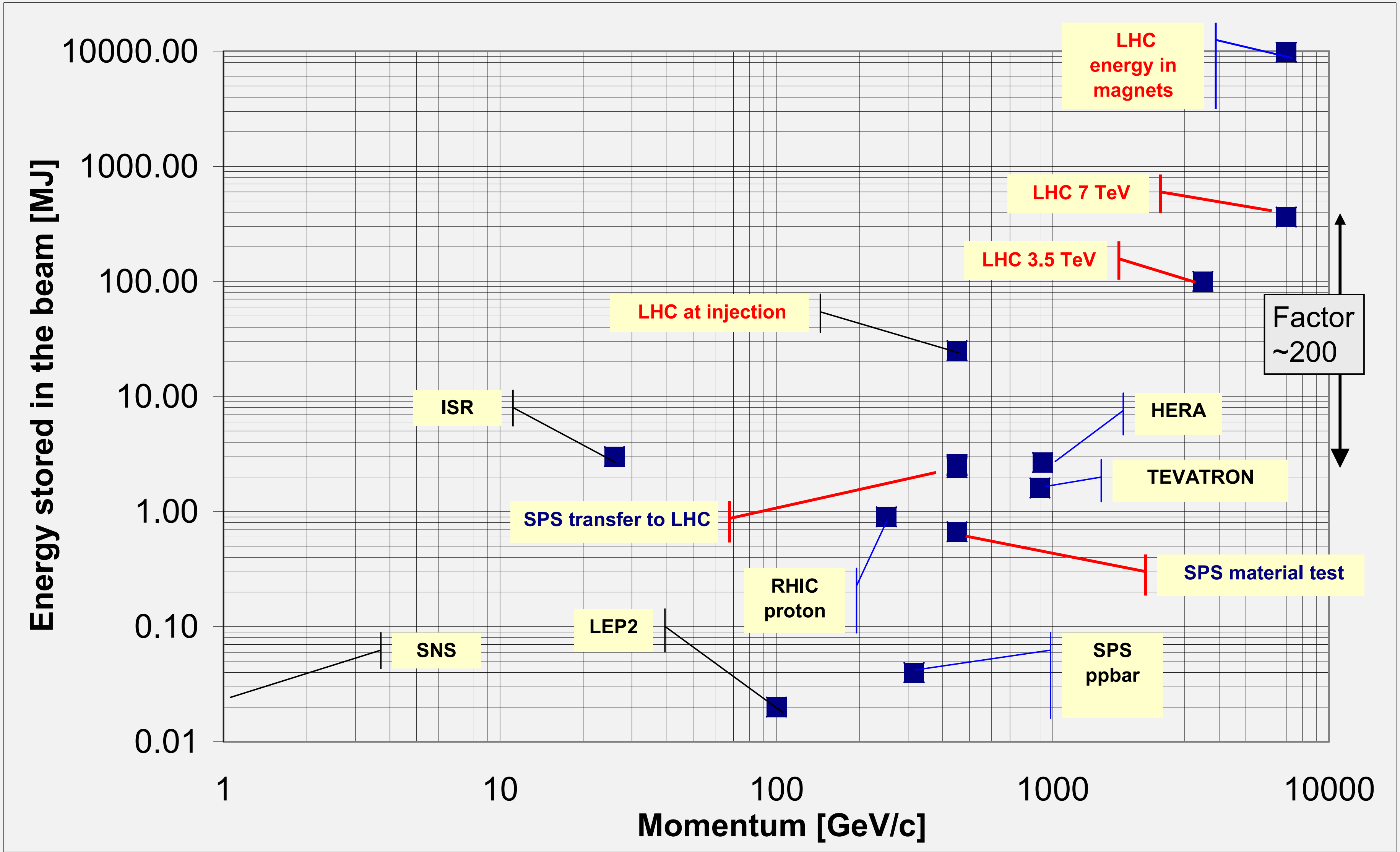
*Machine Protection and Collimation*

*Electron clouds*

*Instabilities*

*Damage of components*

# Energy stored magnets and beam

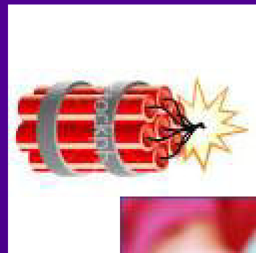


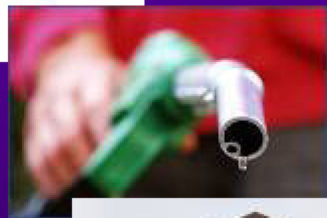
# What does this mean?


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

**360 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 !!

# SPS experiment: Beam damage with 450 GeV proton beam

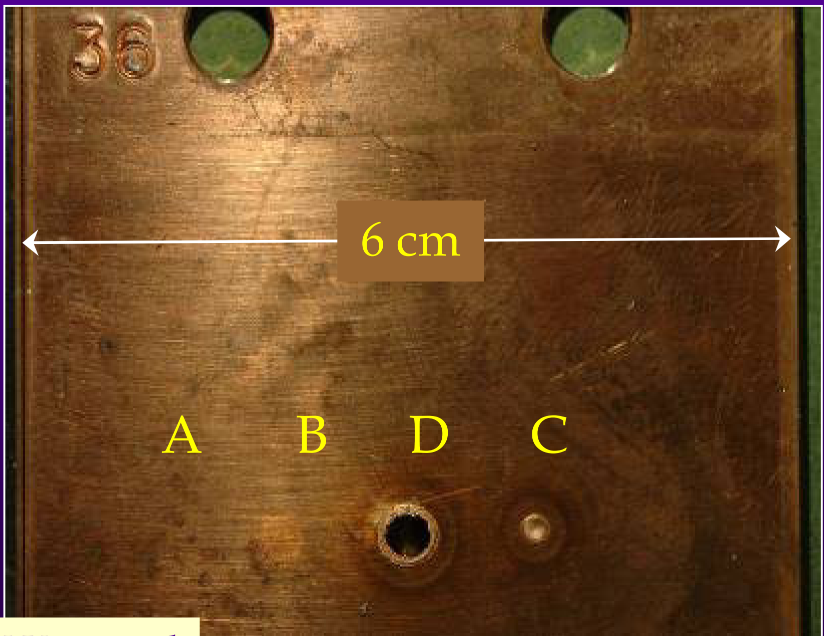
Controlled SPS experiment

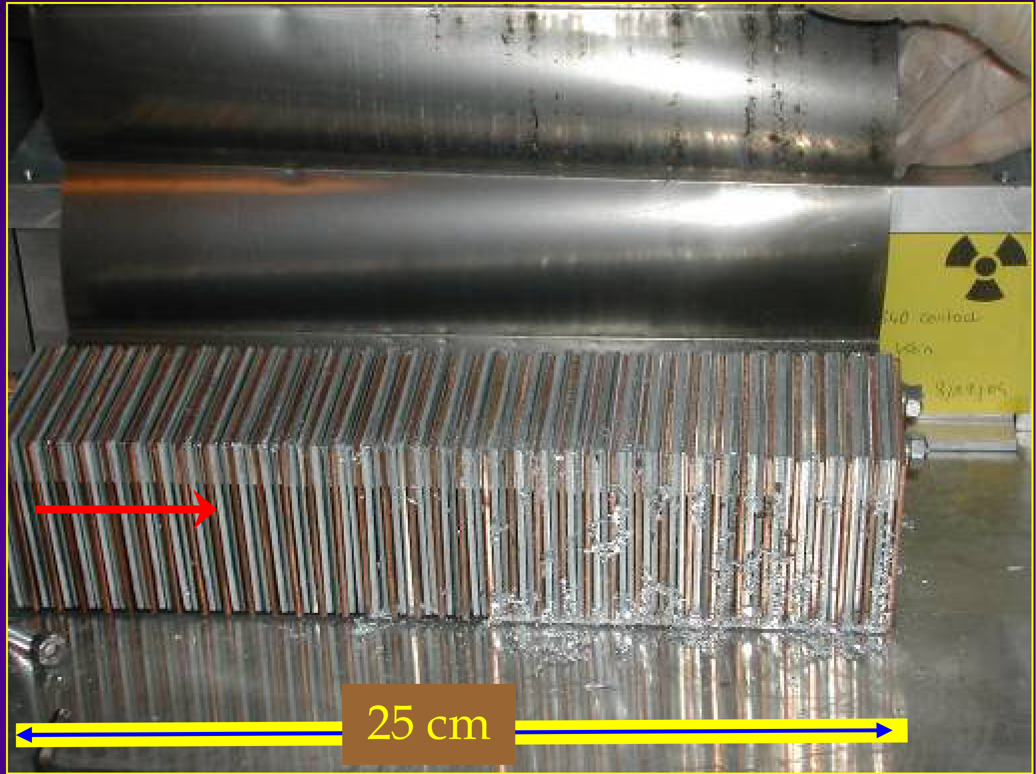
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

above damage limit for copper
stainless steel no damage

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

below damage limit for copper




- Damage limit ~200 kJoule
- 0.1 % of the full LHC 7 TeV beams
- factor of ~10 below the energy in a bunch train injected into LHC

V.Kain 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**

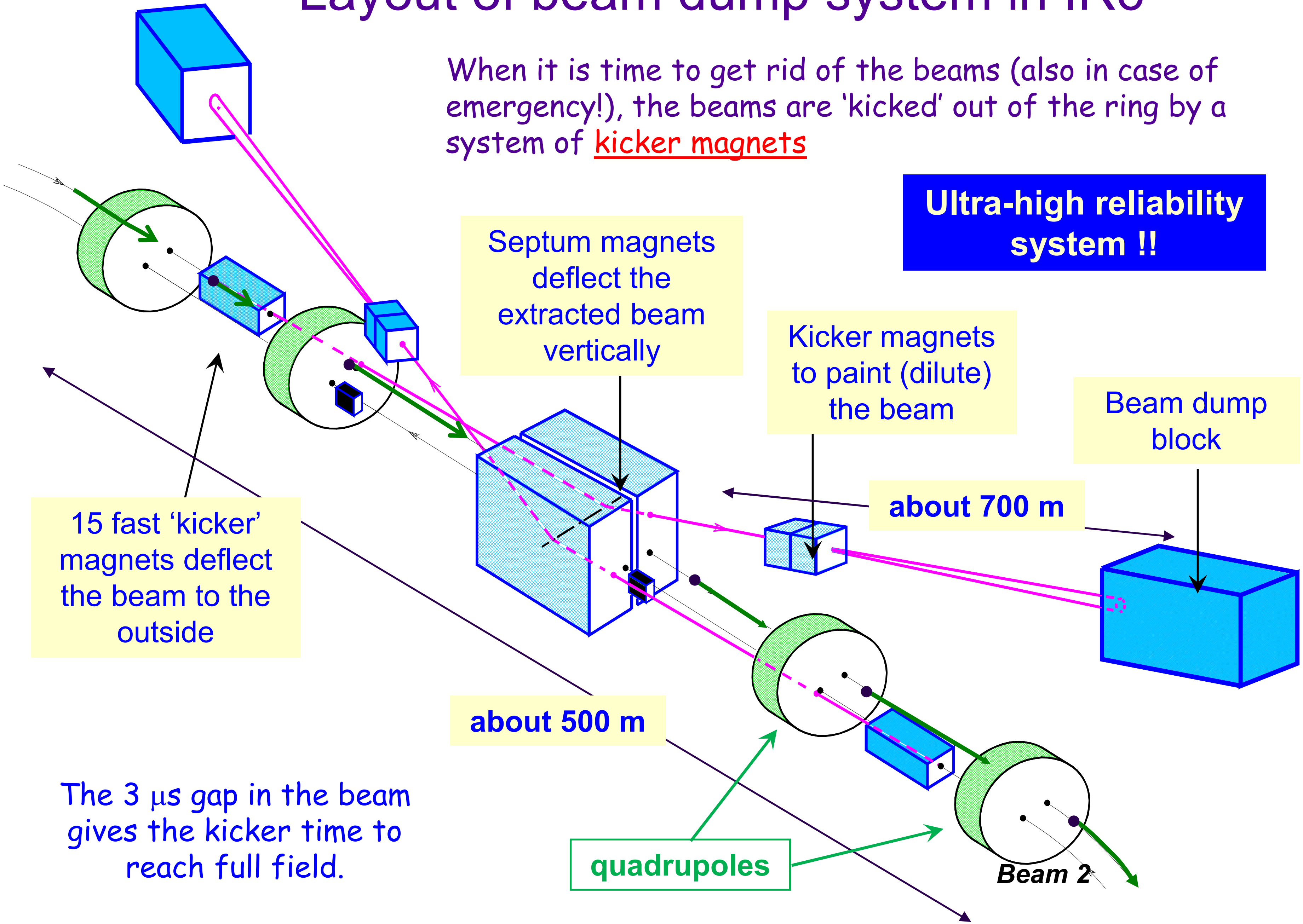
**"Machine Protection"** protects equipment from damage, activation and downtime

Machine protection includes a large variety of systems

# Layout of beam dump system in IR6

When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets

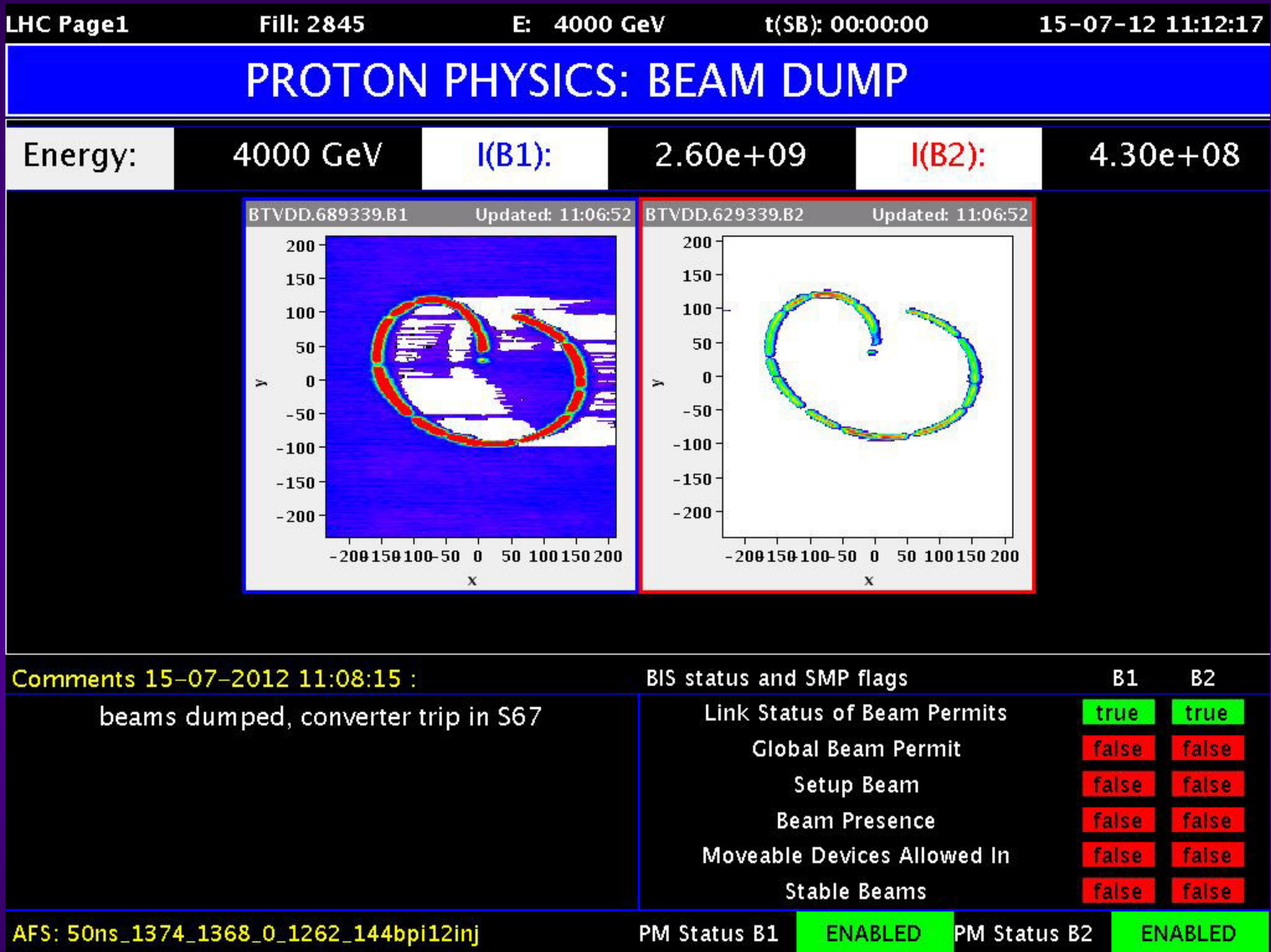
**Ultra-high reliability system !!**




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

# Dump line

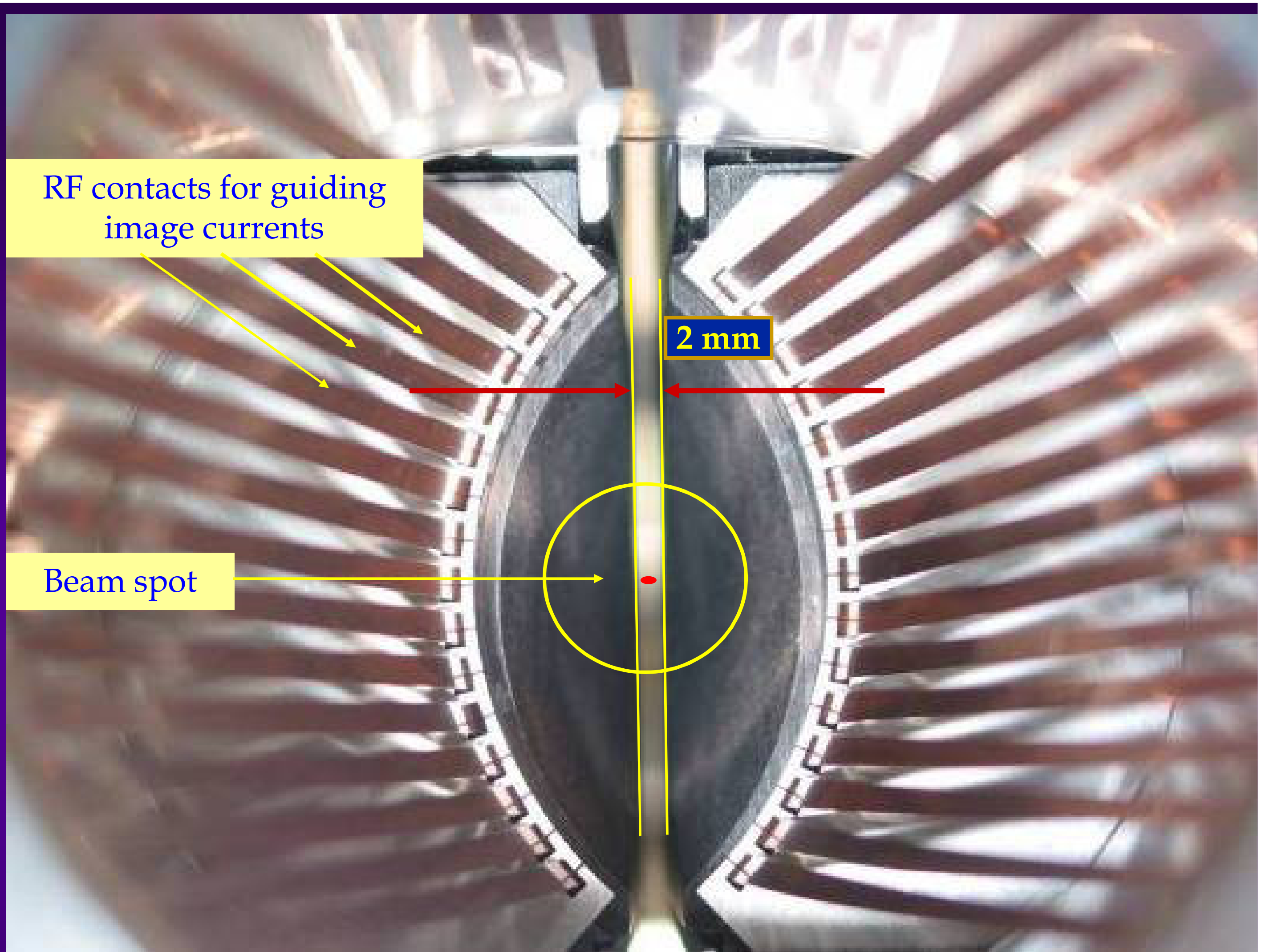
# Beam dump with 1380 bunches




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

View of a two sided collimator

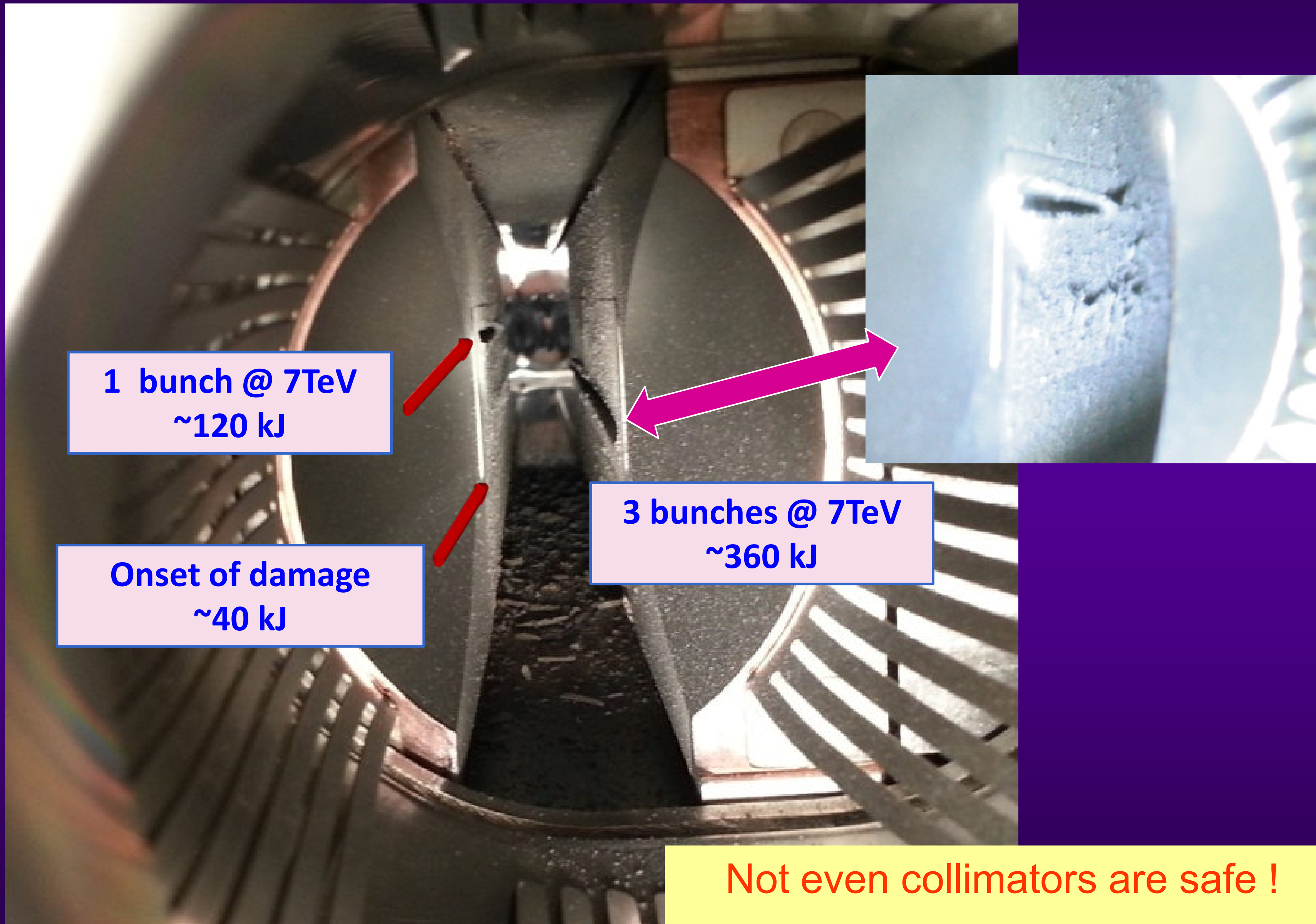
about 100 collimators are installed in LHC





Ralph Assmann, CERN

# Beam impact on a Tungsten collimator (experiment at SPS)




Not even collimators are safe !

We are looking for new materials…

Courtesy A. Bertarelli (CERN-EN)

# Betatron beam cleaning

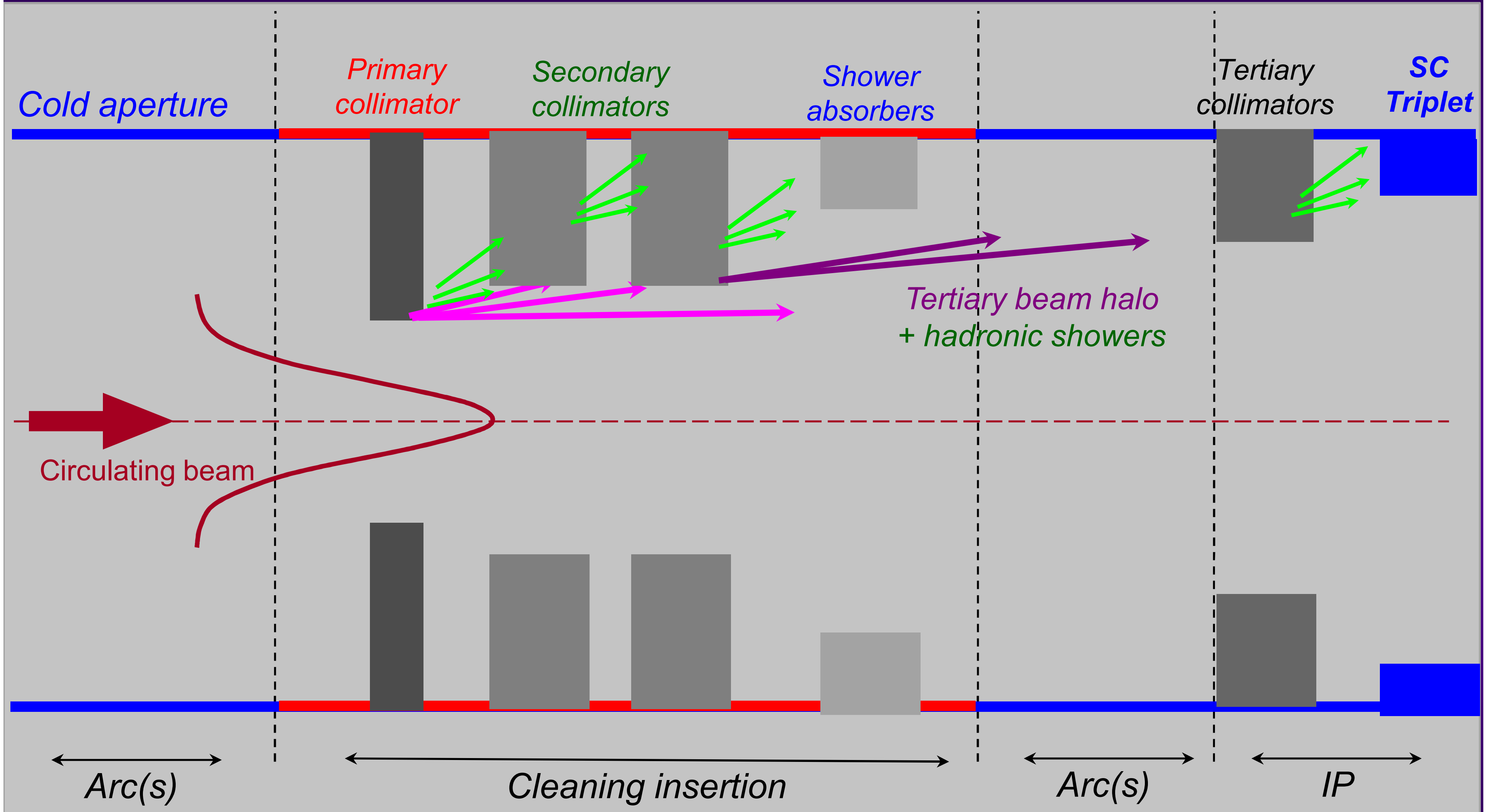
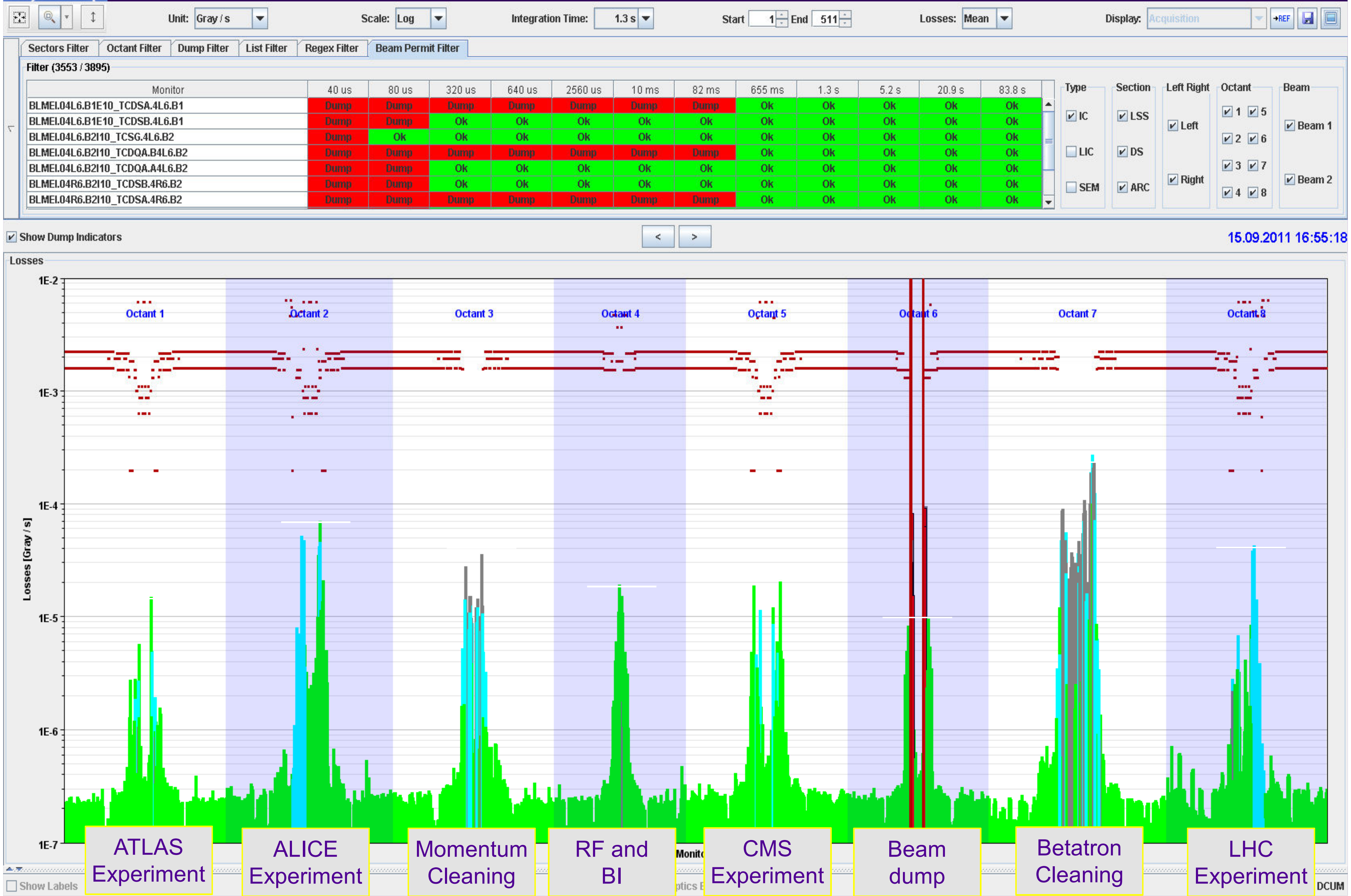



Illustration drawing

# Beam Loss Monitors

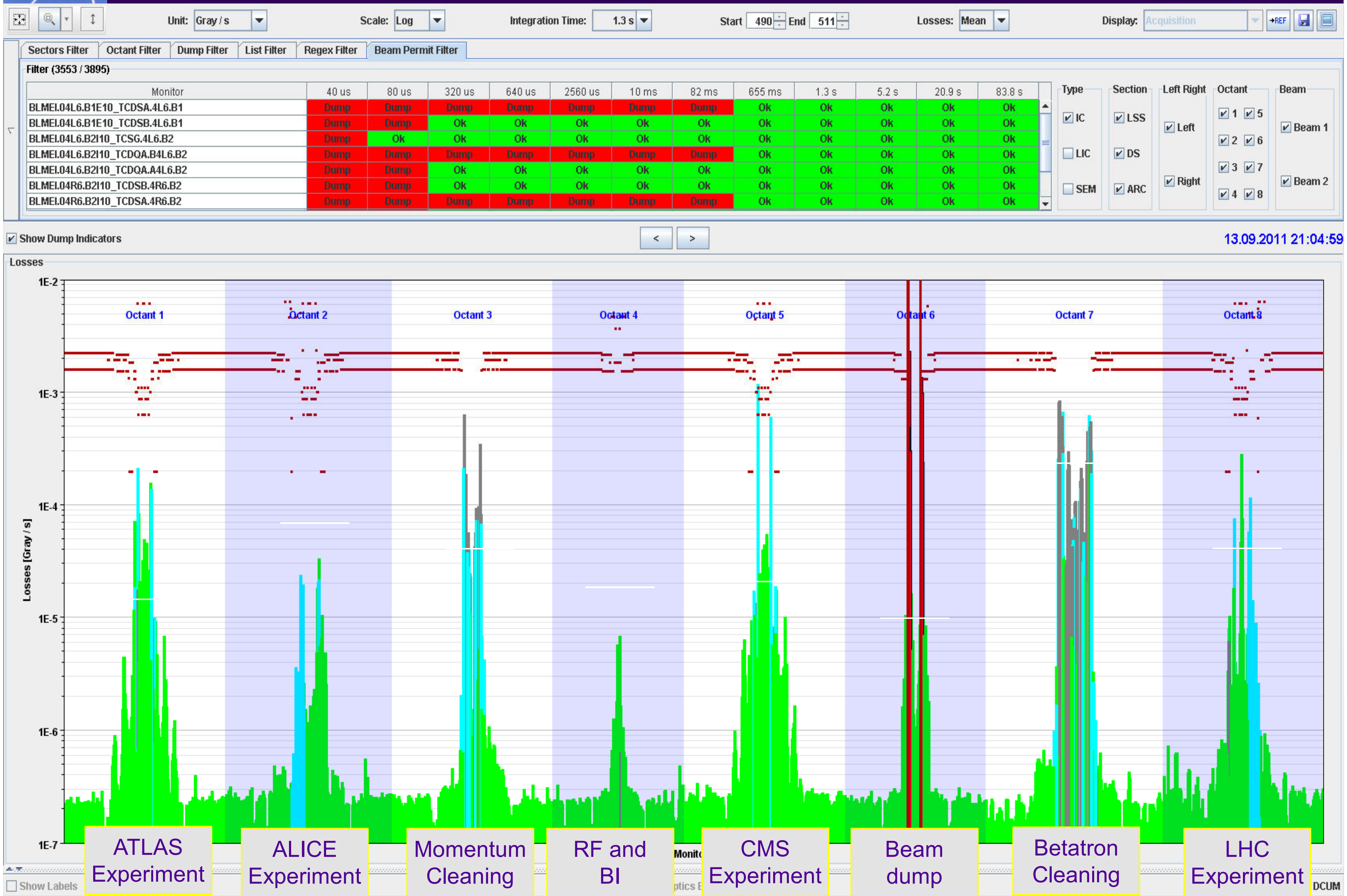
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> $10^6$)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!

# BLM system: beam losses before collisions




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

# Continuous beam losses during collisions



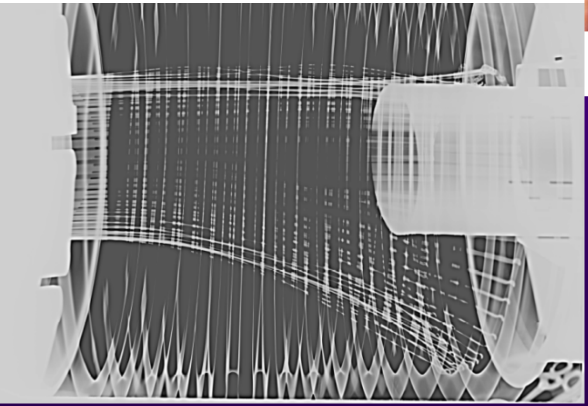
# Damage from heating by the beam

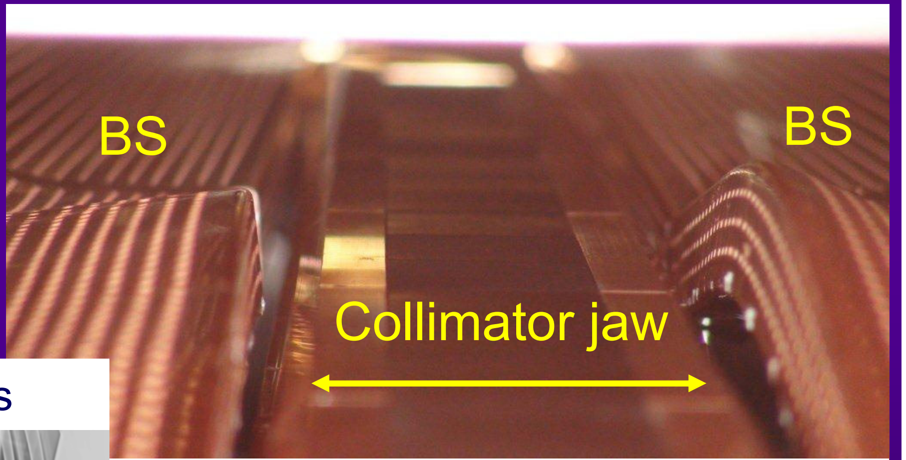
High intensity beams may deposit large amounts of power in incorrectly shielded components around the beam

- Design, manufacturing or installation errors may lead to partial or total damage of accelerator components.
- So far they have not limited the LHC, fixed or mitigated.

Damaged mirror of the synchrotron light telescope

Damaged RF fingers



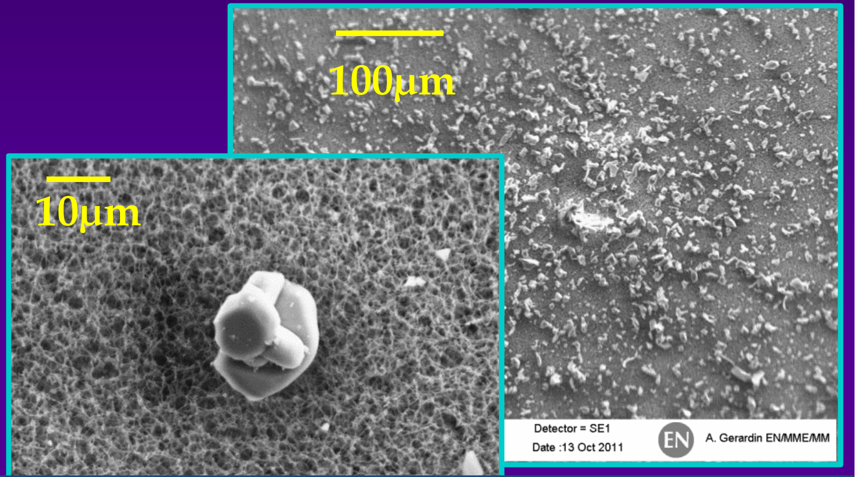


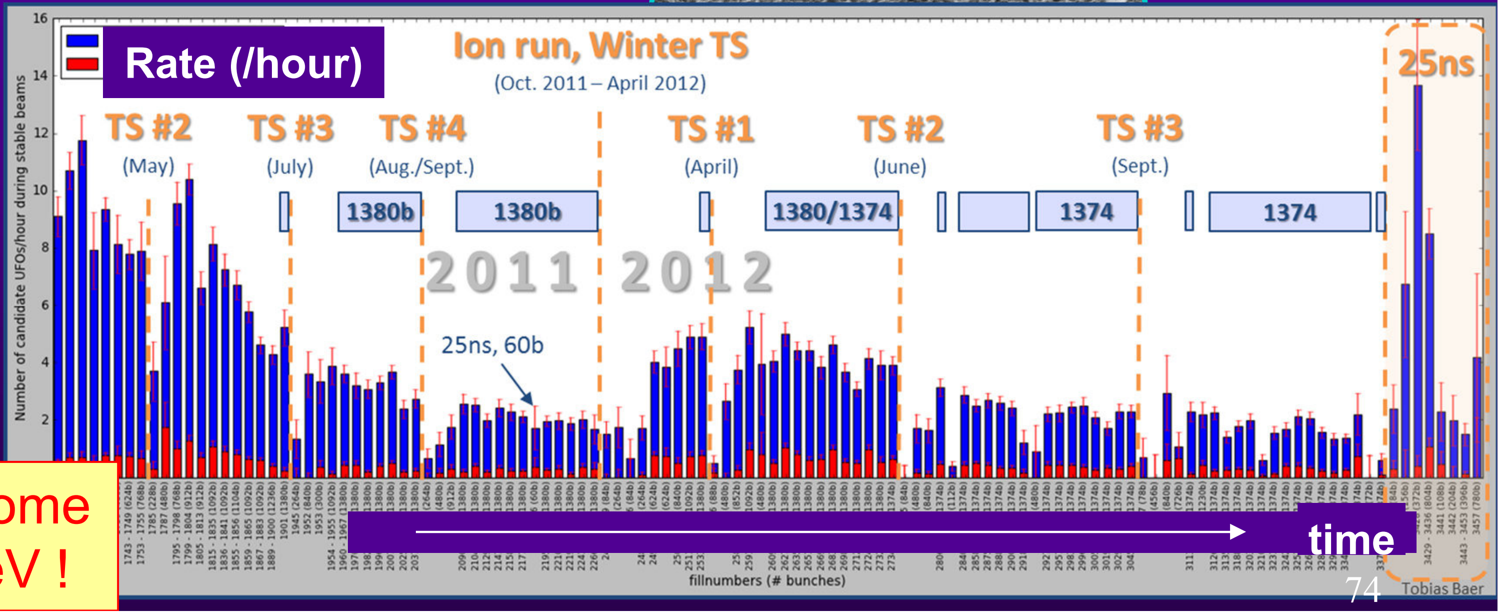

Damaged beam screen (BS) in a collimator

# Surprising 'Unidentified Falling Objects'

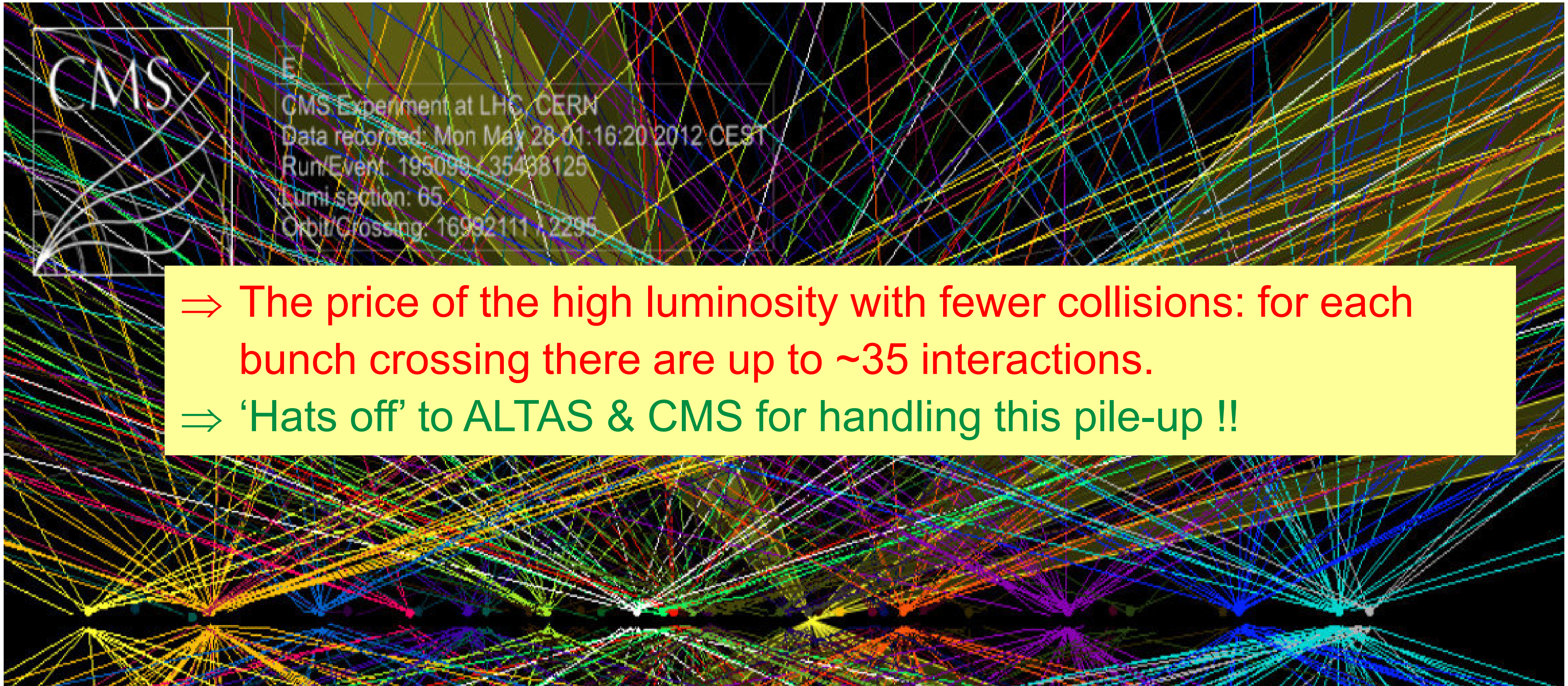
- Very fast and localized beam losses were observed as soon as the LHC intensity was increased in 2010.
- The beam losses were traced to **dust particles falling into the beam – 'UFO'**.
- If the **losses are too high**, the beams are dumped to avoid a magnet quench.
  - ~20 beams dumped /year
  - Some conditioning of the UFO-rate from ~10/hour to ~2/hour.

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



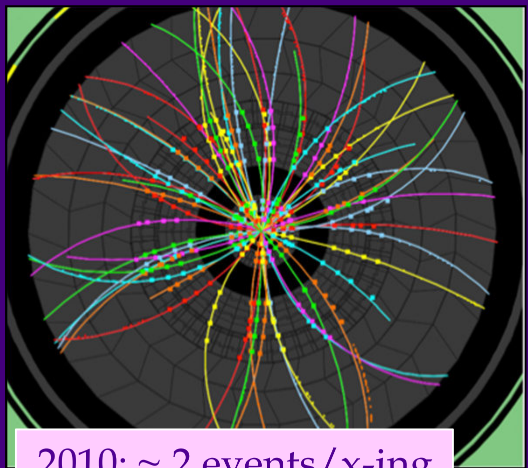




UFOs could become an issue at 7 TeV !




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

⇒ ‘Hats off’ to ALTAS & CMS for handling this pile-up !!

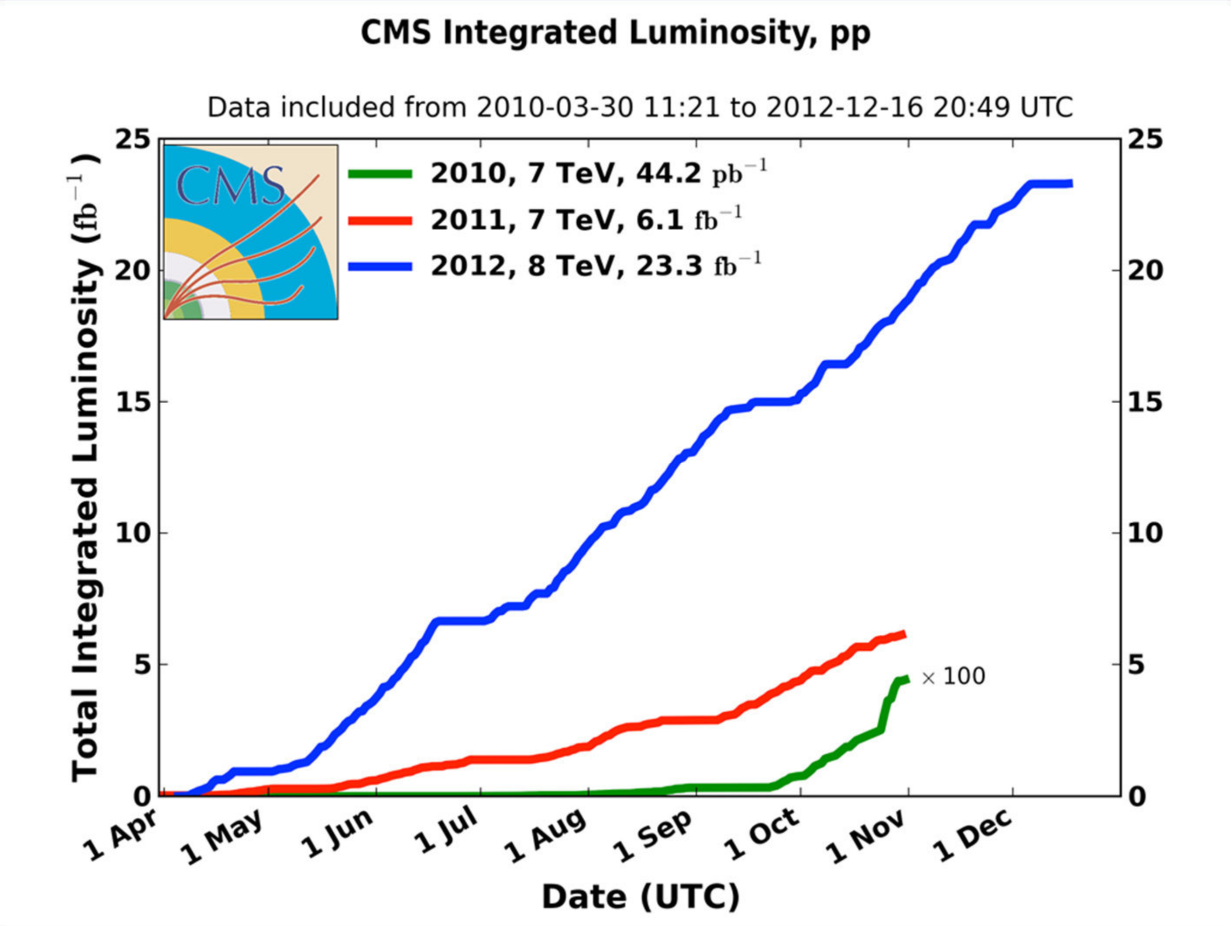


2010: ~ 2 events/x-ing

2011: ~ 10 events/x-ing

2012: ~ 20 events/x-ing

# Integrated luminosity 2010-2012

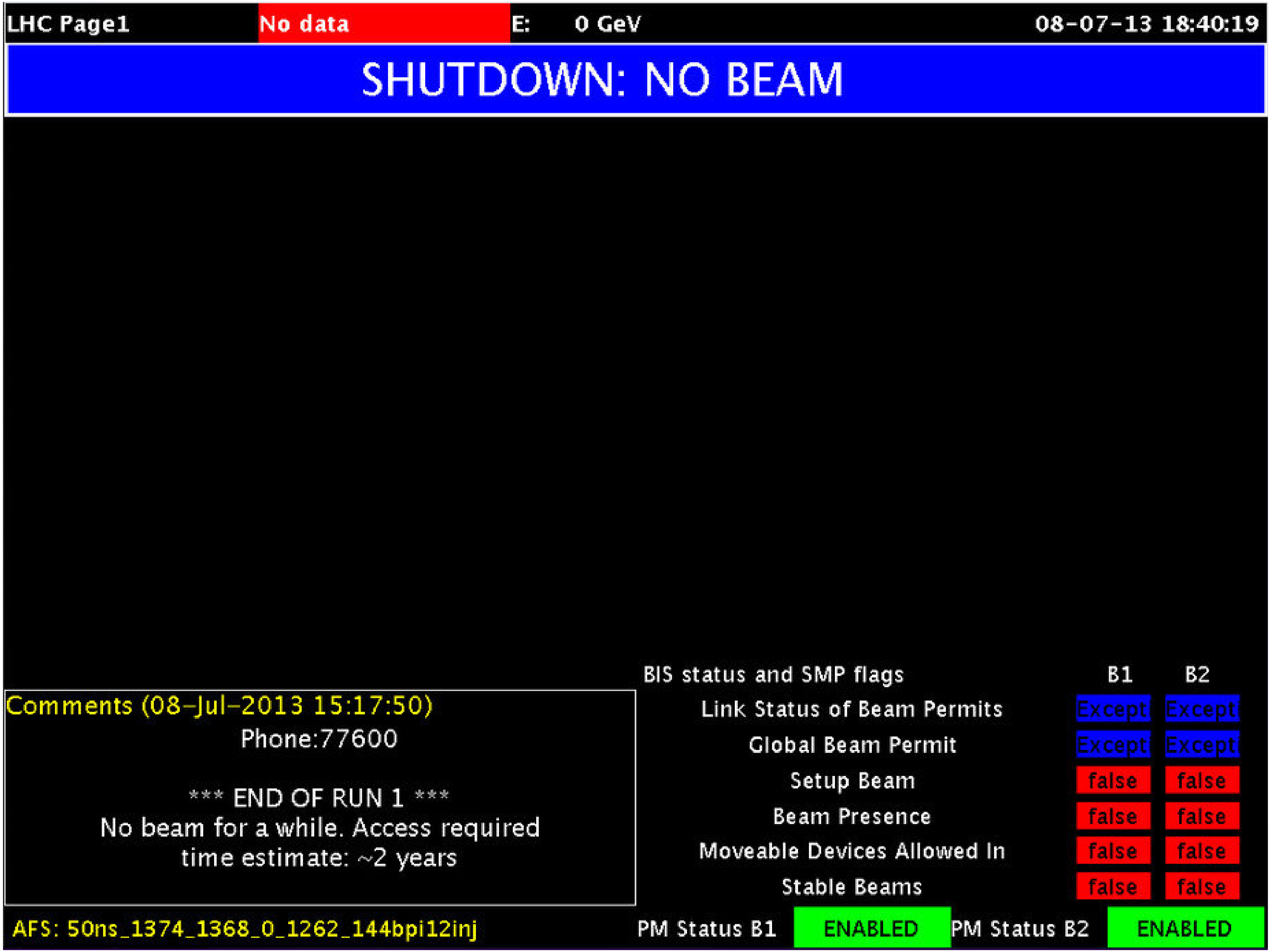



- 2010: **0.04 fb$^{-1}$**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb$^{-1}$**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb$^{-1}$**
  - 8 TeV CoM
  - Production

# What we learned during LHC Run 1…..

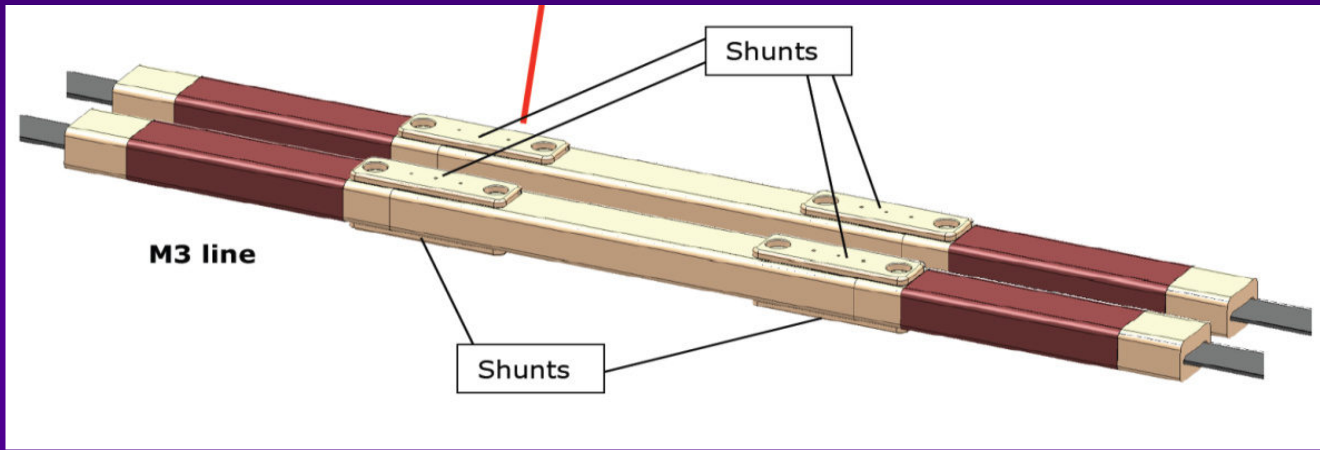
- Head-on beam-beam effect is not a limitation
- Long range beam-beam effect has to be taken seriously
  - Need separation of 10 -12 σ (otherwise bad lifetime and beam loss)
- Small as possible emittances are good
- Established β* reach (aperture, collimation, optics)
- Luminosity levelling via offset tested – works fine in LHCb!
- High-intensity operation close to beam instability limits
- Instabilities were observed and are not fully understood
  - For small IP beam offsets while going into collisions, ….
  - Impedances (kicker, collimator heating), collective effects, ...
- Availability
  - Single Event Upsets, vacuum pressure increase, UFOs, cryogenics, magnet protection system, .….) – require follow-up and consolidation

# Preparing for future runs

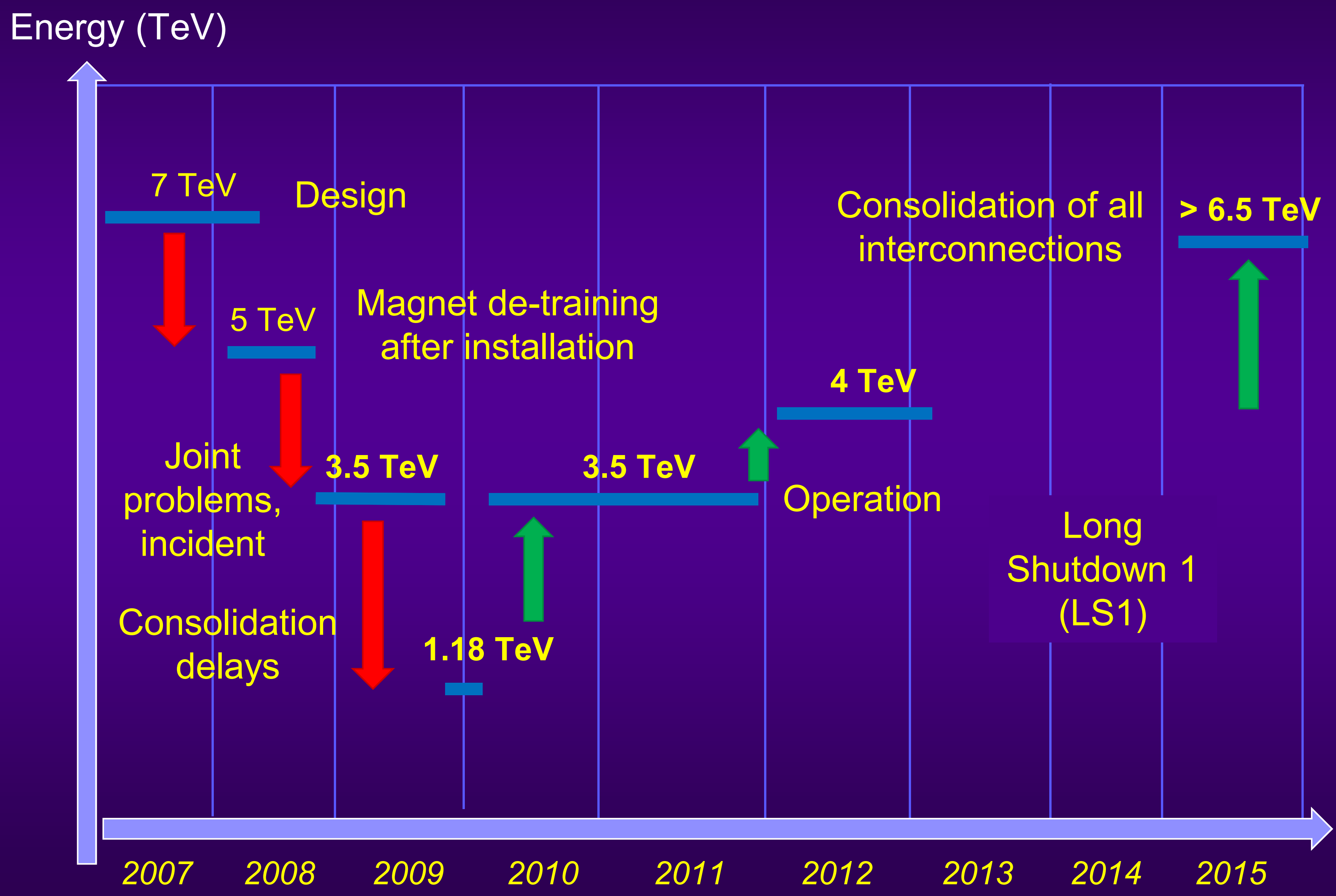

LHC Page1
No data
E: 0 GeV
08-07-13 18:40:19
SHUTDOWN: NO BEAM
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
Except
Except
Global Beam Permit
Except
Except
Setup Beam
false
false
Beam Presence
false
false
Moveable Devices Allowed In
false
false
Stable Beams
false
false
Comments (08-Jul-2013 15:17:50)
Phone:77600
*** END OF RUN 1 ***
No beam for a while. Access required
time estimate: ~2 years
AFS: 50ns_1374_1368_0_1262_144bpi12inj
PM Status B1
ENABLED
PM Status B2
ENABLED

# Preparing for nominal energy

Around 10000 high current magnet interconnections will be checked and re-done if needed. All of them will consolidated – 12 months of work.




# LHC energy evolution



# Luminosity projections

Two out of many possible scenarios @ 6.5 TeV

| Beam | k | $N_b$ [$10^{11}$ p] | Emit. [mm] | b* [m] | Luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | Event pile-up | Int. L [$fb^{-1}$] |
|---|---|---|---|---|---|---|---|
| 50 ns | 1260 | 1.70 | 1.6 | 0.4 | 2.0 | 110* | ~30 |
| 25 ns low emittance | 2520 | 1.15 | 1.9 | 0.4 | 1.5 | 42* | ~50 |
| 25 ns standard | 2760 | 1.15 | 3.7 | 0.5 | 0.85 | 23 | ~30 |

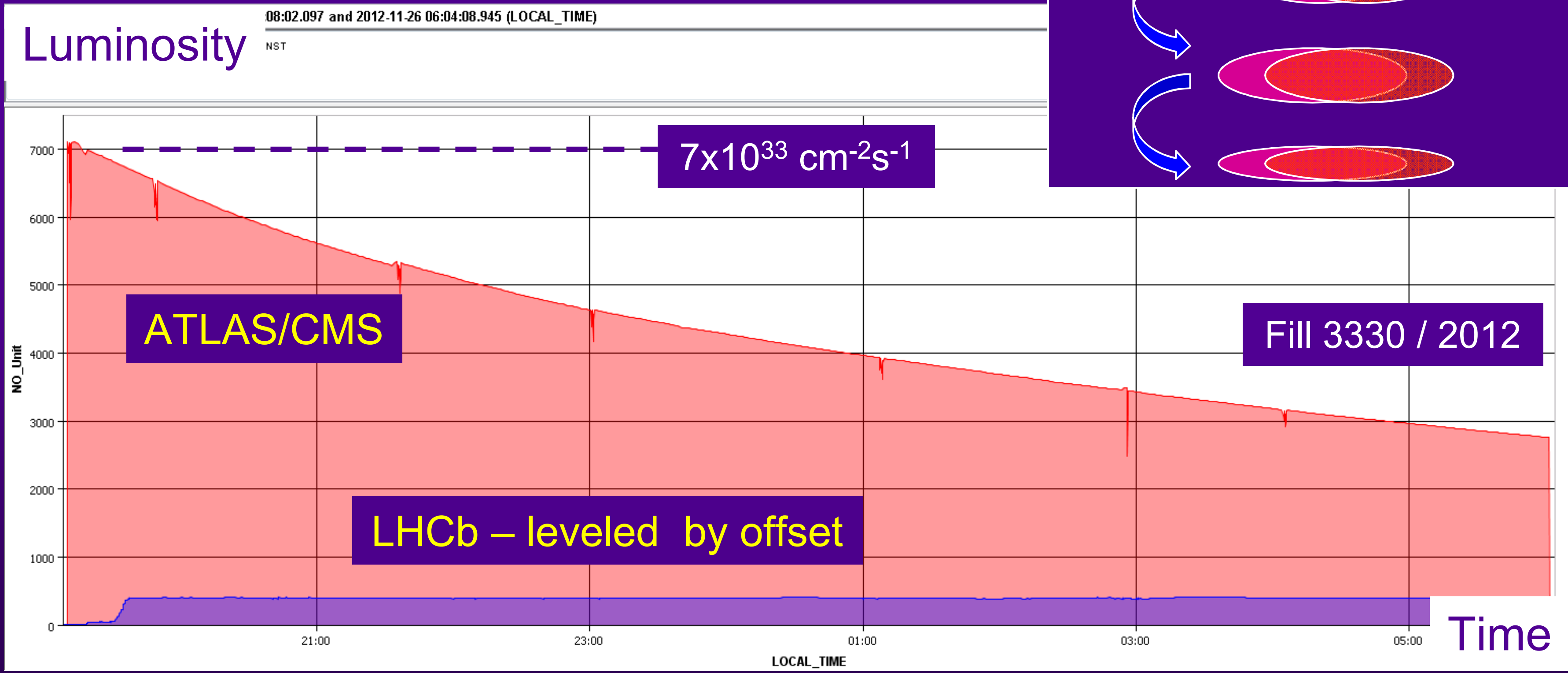
- The cryogenic limit to the luminosity is expected ~ $1.75\times10^{34}$ $cm^{-2}s^{-1}$ !
  - Cooling limit of the triplet quadrupole magnets (collision debris).
- Many scenarios imply luminosity leveling to control pile-up
  - Discussion & optimization between machine & experiments.

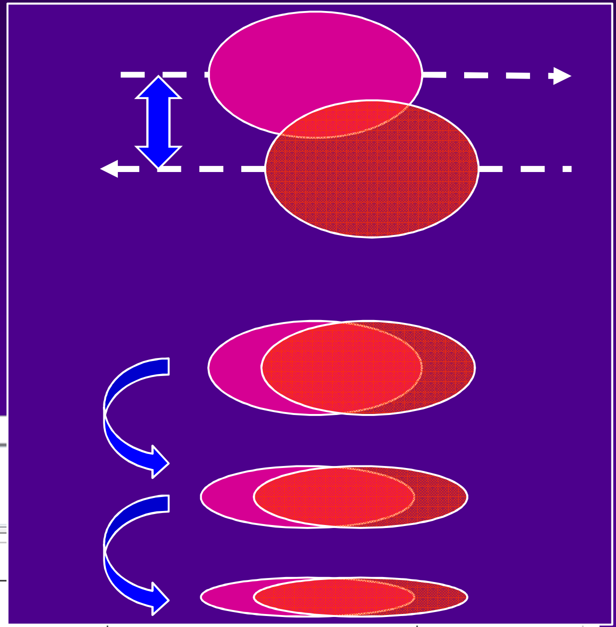
(*) leveled down to a pile-up of ~40.

Integrated Luminosity based on 120 days of production/year, 35% efficiency.

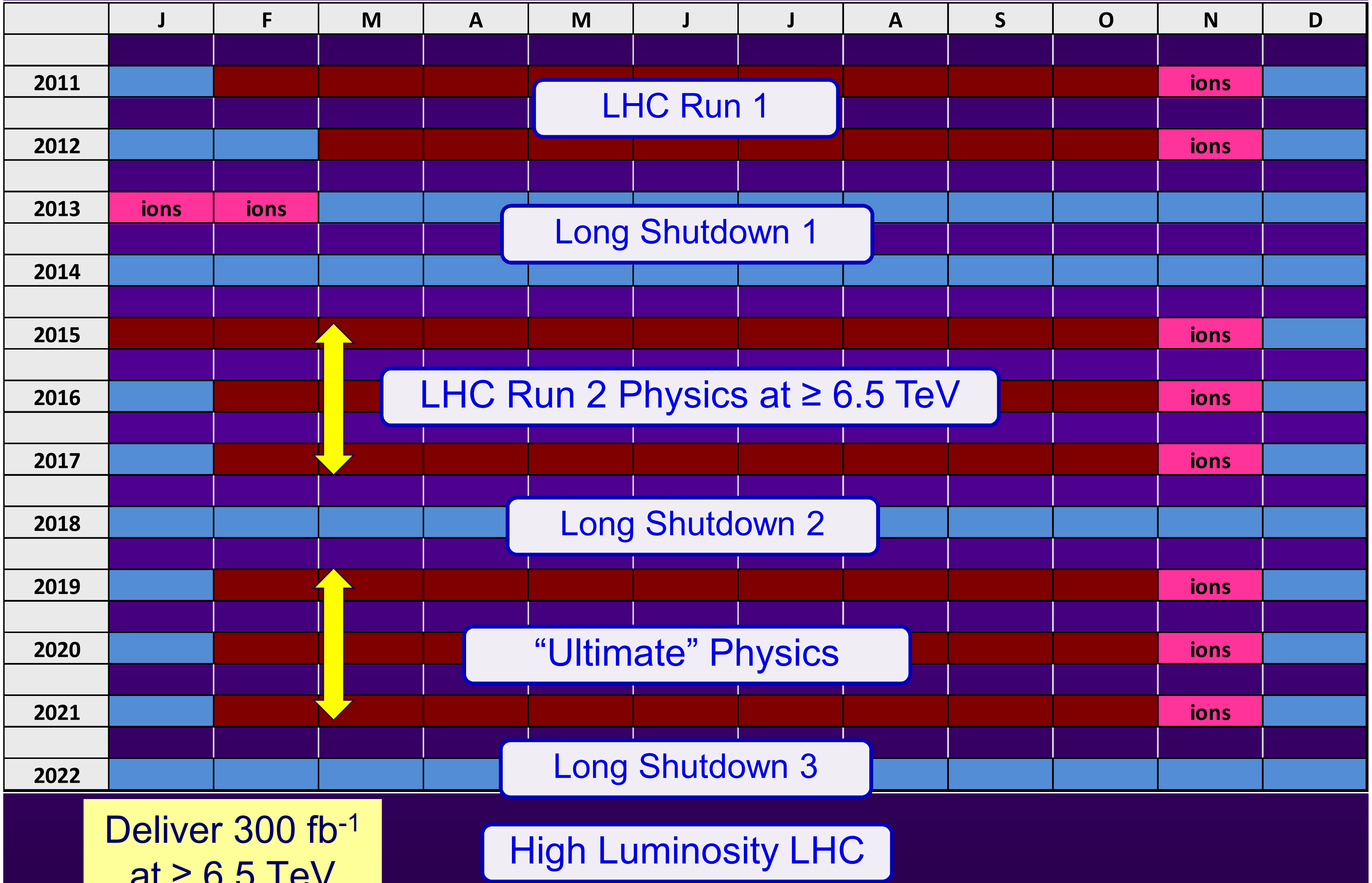
# Leveling luminosities

- 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.

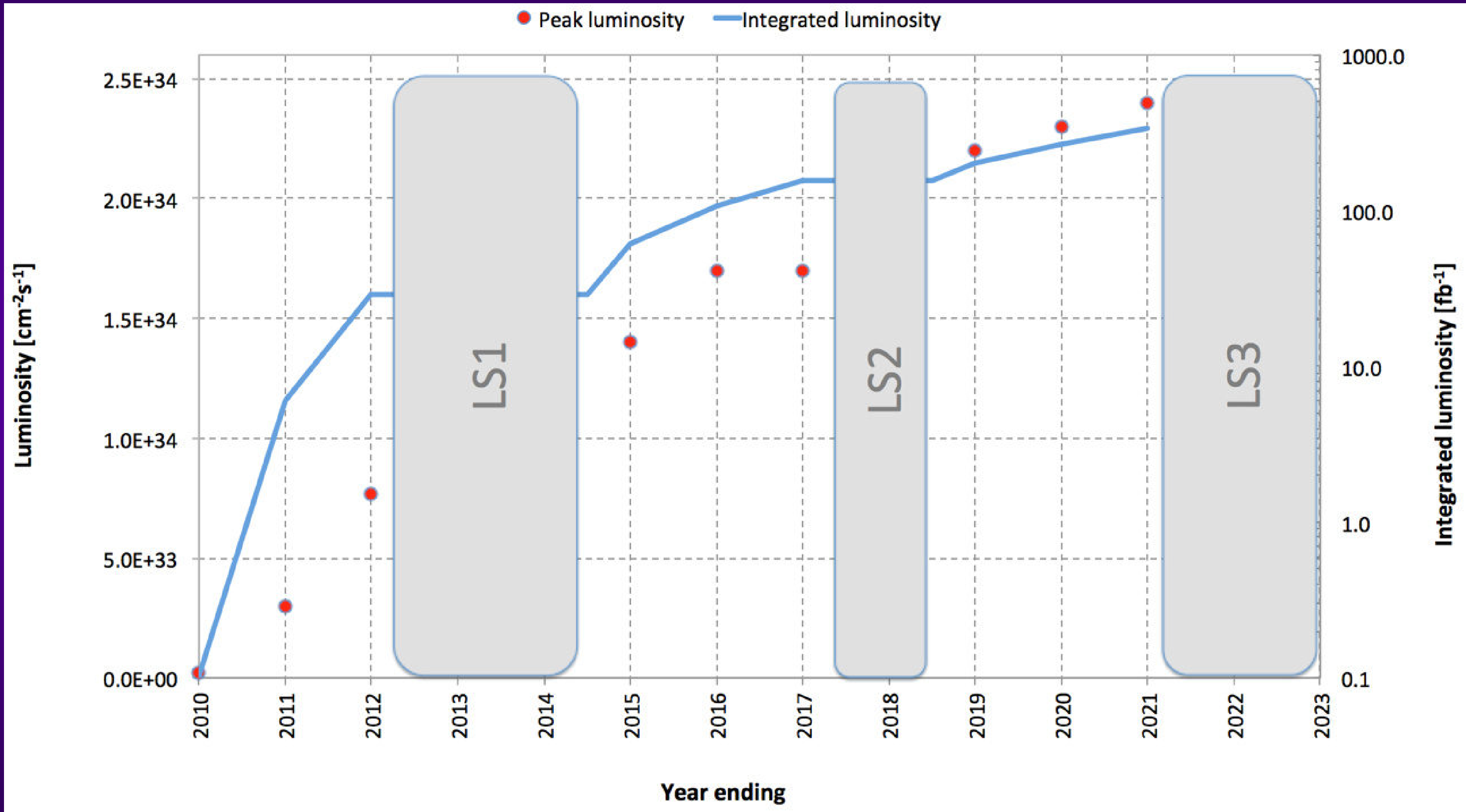


# The next years



# Timeline towards HL-LHC



# Outlook: LHC operation in 2015

- Magnet re-commissioning starts in the summer of 2014.
  - During magnet re-commissioning in 2014 we will define the target energy for the run : ≥ 6.5 TeV.
  - Experience of 2008: 6.5 TeV OK, 7 TeV lot of magnet training.
- Early in 2015 explore LHC at 6.5+ TeV with low intensity.
  - Full system commissioning up to first collisions ~ 2 months.
- The first serious luminosity operation and some intensity ramp up will be made with 50 ns spacing.
  - We think that we know how to do that!
- Then preparation of the LHC for 25 ns operation – electron cloud reduction at injection – 2-3 weeks.

…and finally intensity ramp up and production at 25 ns.

It should be possible to achieve nominal luminosity of $10^{34}$ [$cm^{-2}s^{-1}$] or more

# However…..

- Performance could be impacted by
  - UFOs at higher energy and with 25 ns buch spacing
  - Radiation to electronics – SEU's
  - Electron cloud & high energy & at 25 ns
  - Long-range beam-beam & smaller crossing angle & at 25 ns
  - Single- and bunch-by-bunch beam instabilities (impedances...)

# Final remarks

- The progress in LHC performance has been great.
- Luminosity of close to nominal at 4 TeV – this was more than we expected!
- The LHC is performing better than expected - thanks to the quality of the design, the construction, the operation and the injectors.
- The interconnections between the magnets was the only weak spot…
- Expectations for 2015 are very high – the work to meet them is in full swing.

Fabiola Gianotti + Peter Higgs

# Acknowledgements

- LHC enjoying benefits of decades long international design, construction, installation effort.
- Progress with beam represents phenomenal effort by all teams involved.
- Many colleagues at CERN contributed to the LHC success story, in particular from the injector chain.

Thanks to all who were involved !

Thanks for your attention