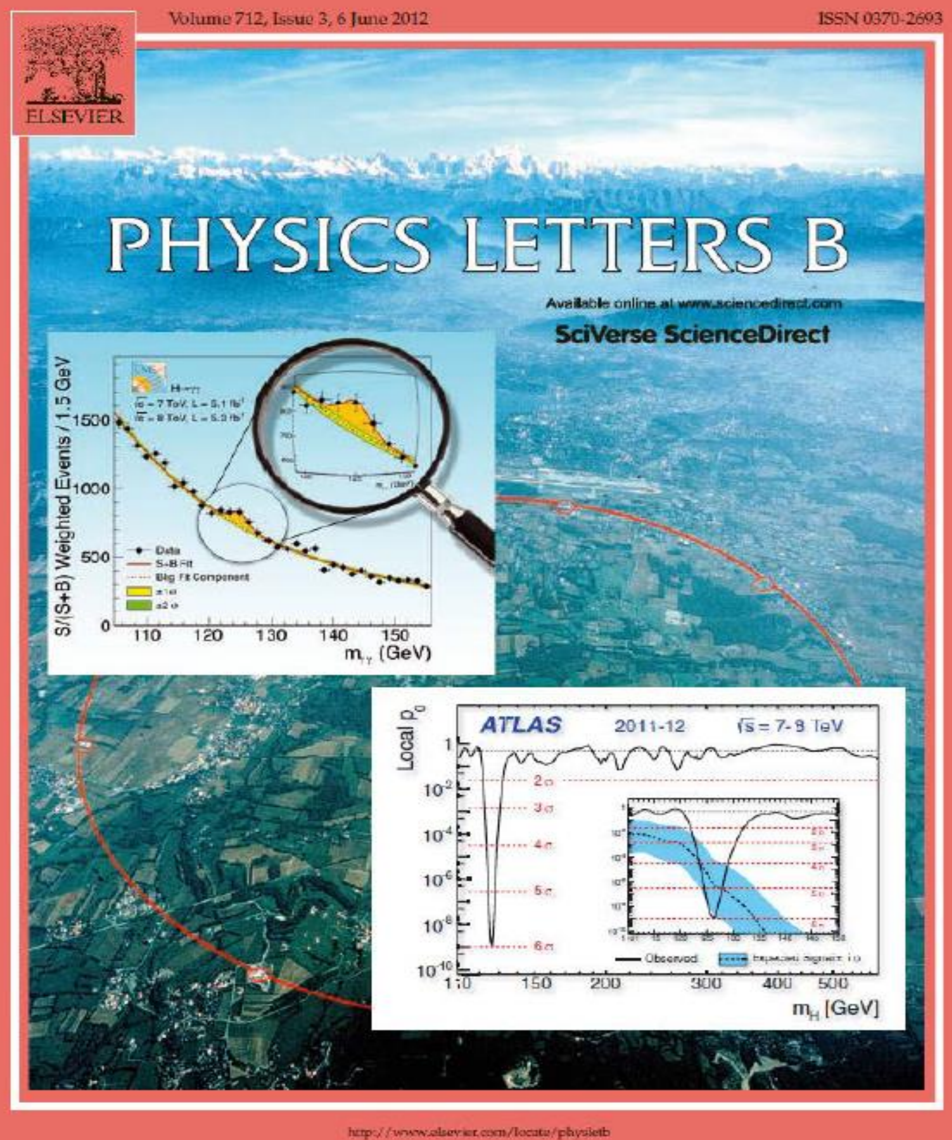
LHC: High Luminosity, Higgs Bosons and some surprises

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

22 July 2014

Hadron Collider Summer School

LHC: High Luminosity, Higgs Bosons and some surprises

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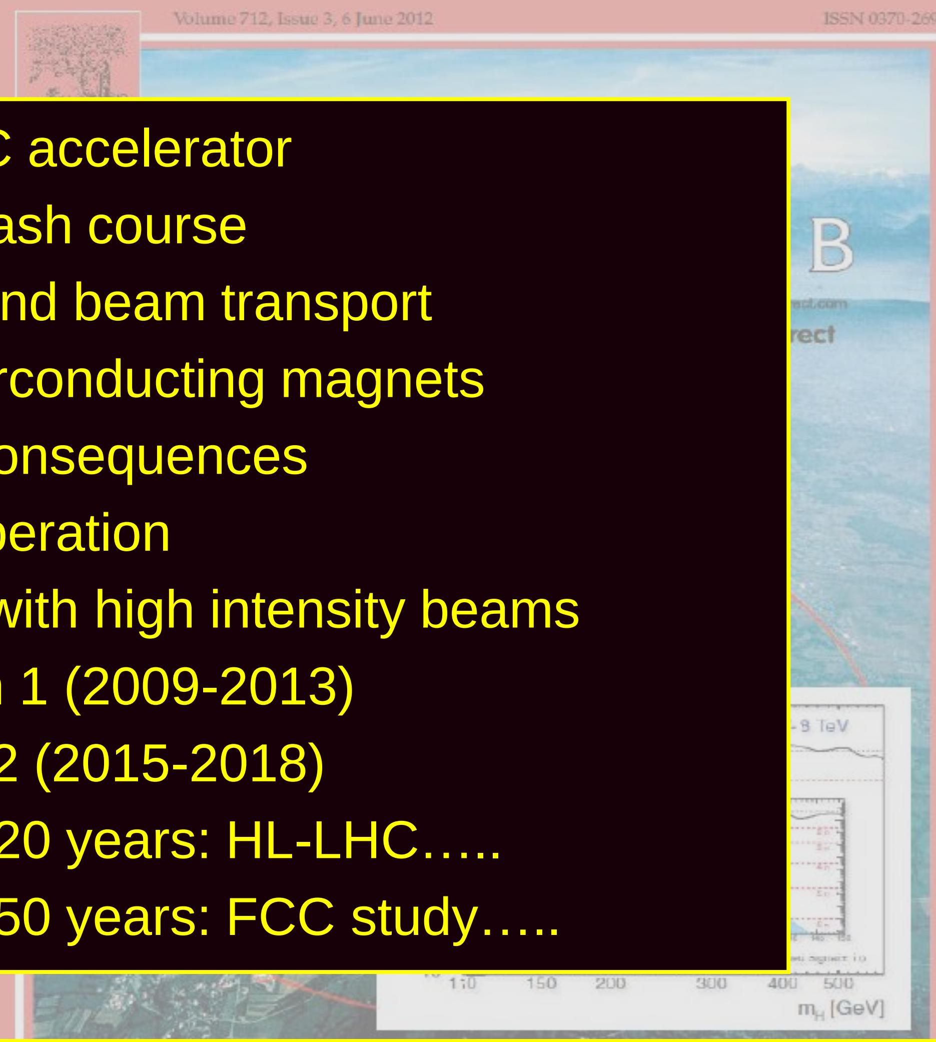


- Introduction to the LHC accelerator
- Accelerator physics crash course
- LHC layout, injection and beam transport
- LHC Energy and superconducting magnets
- High Luminosity and consequences
- Understanding LHC operation
- Challenges operating with high intensity beams
- Performance LHC Run 1 (2009-2013)
- Lessons for LHC Run 2 (2015-2018)
- Preparing for the next 20 years: HL-LHC…..
- Preparing for the next 50 years: FCC study…..

Rüdiger Schmidt, CERN

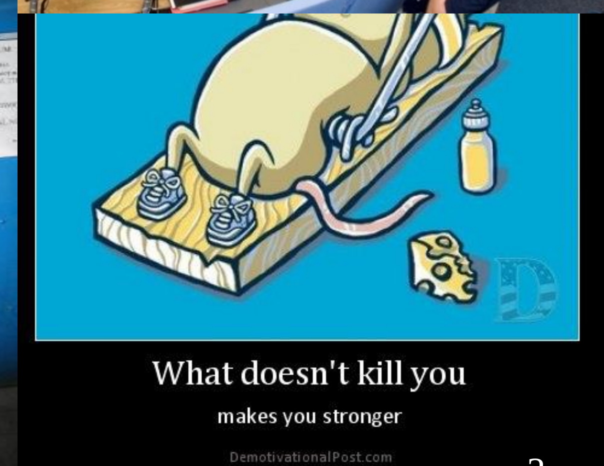
23 July 2013
Hadron Collider Summ

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

LHC: A long story starting in the distant past

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

- The story of the

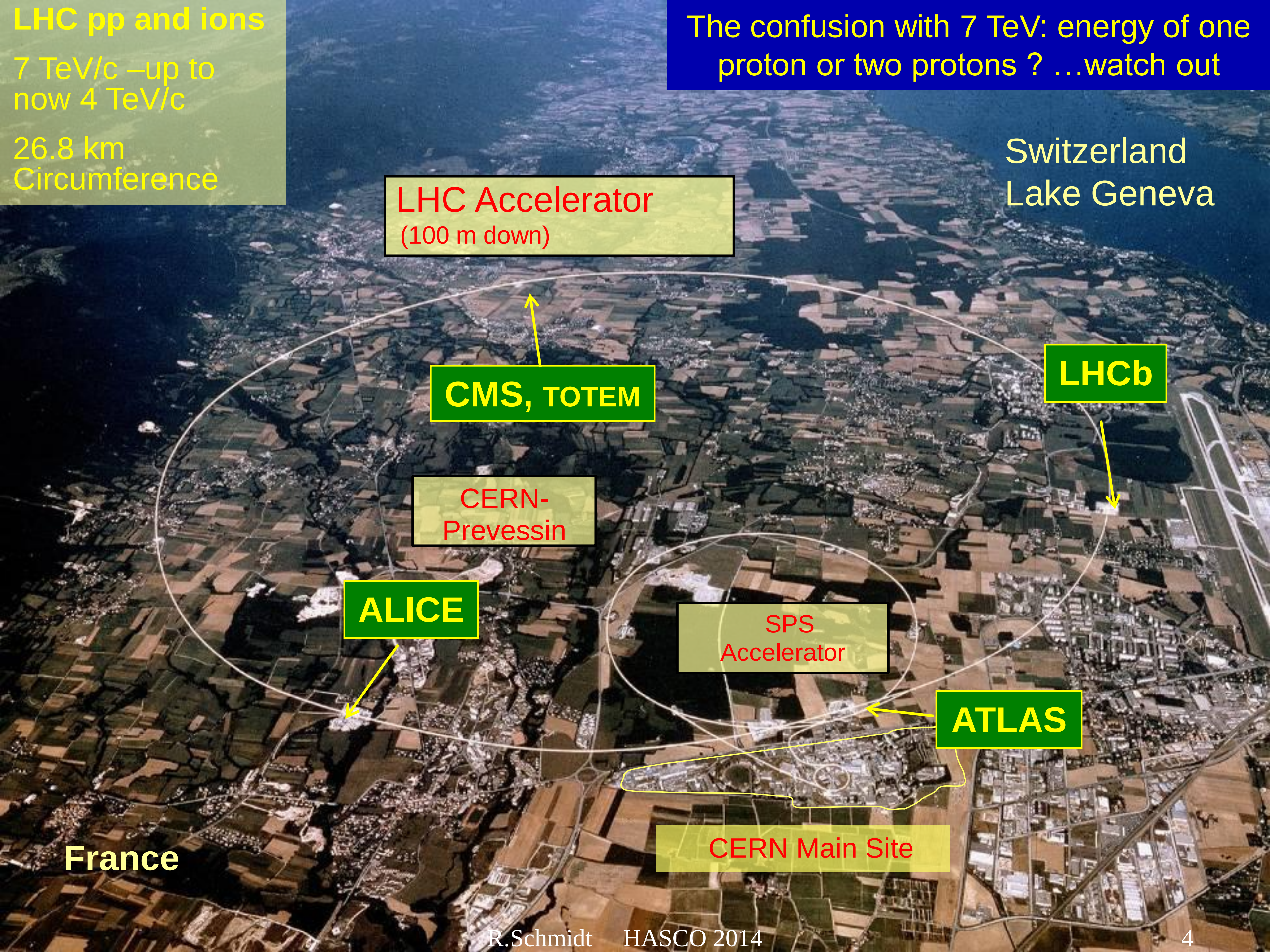


The confusion with 7 TeV: energy of one proton or two protons ? …watch out

LHC pp and ions

7 TeV/c –up to now 4 TeV/c

26.8 km Circumference



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× 10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**

Accelerator Physics Crash Course

what is accelerator physics?

what strange species are accelerator physicists?

Theoretical Physicist *Of The Year*

Big bang theory

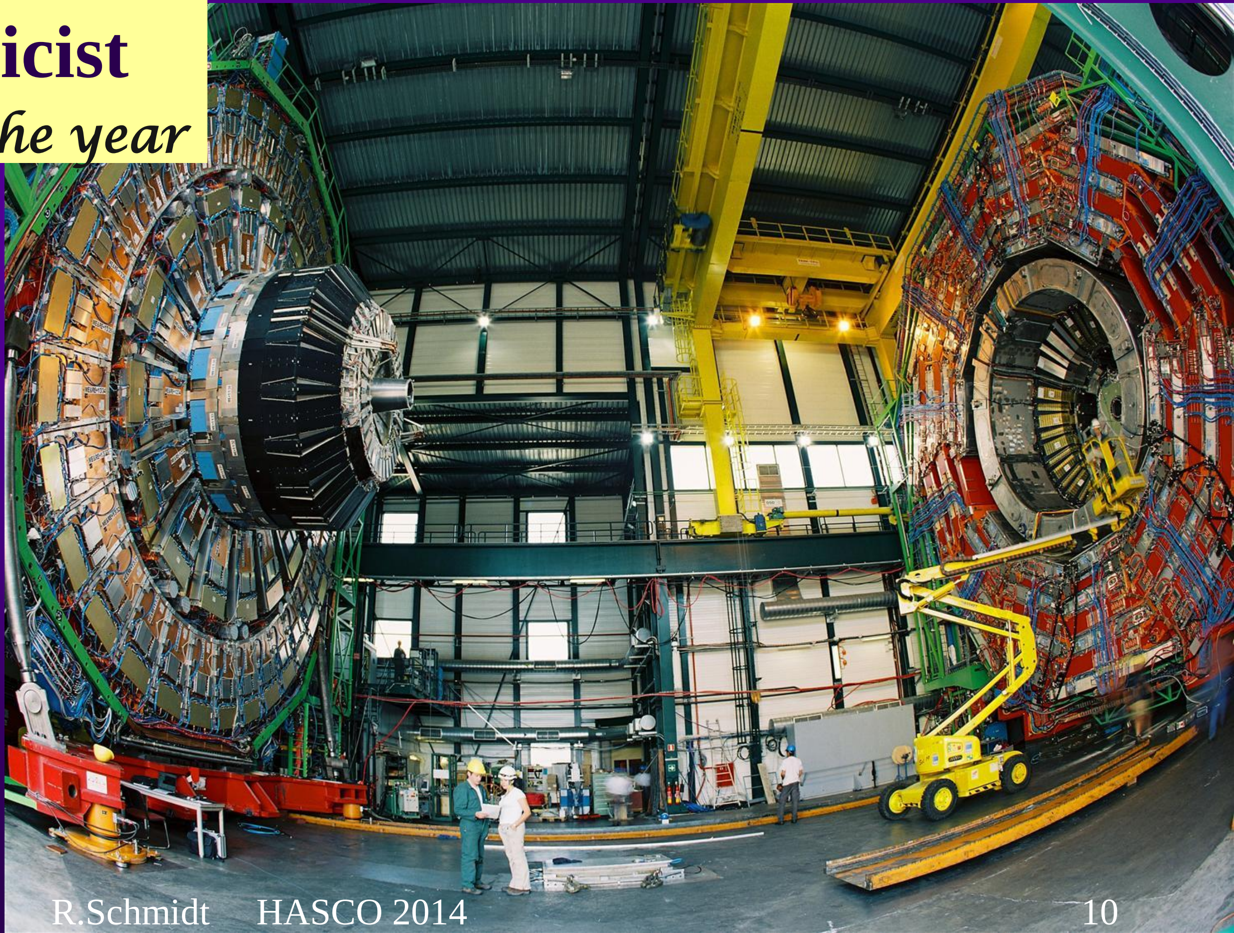
thinking, thinking, thinking ….
and predicting the results

....sometimes correctly!

…building the detectors and analysing the results

Experimental Physicist

Person of the year



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

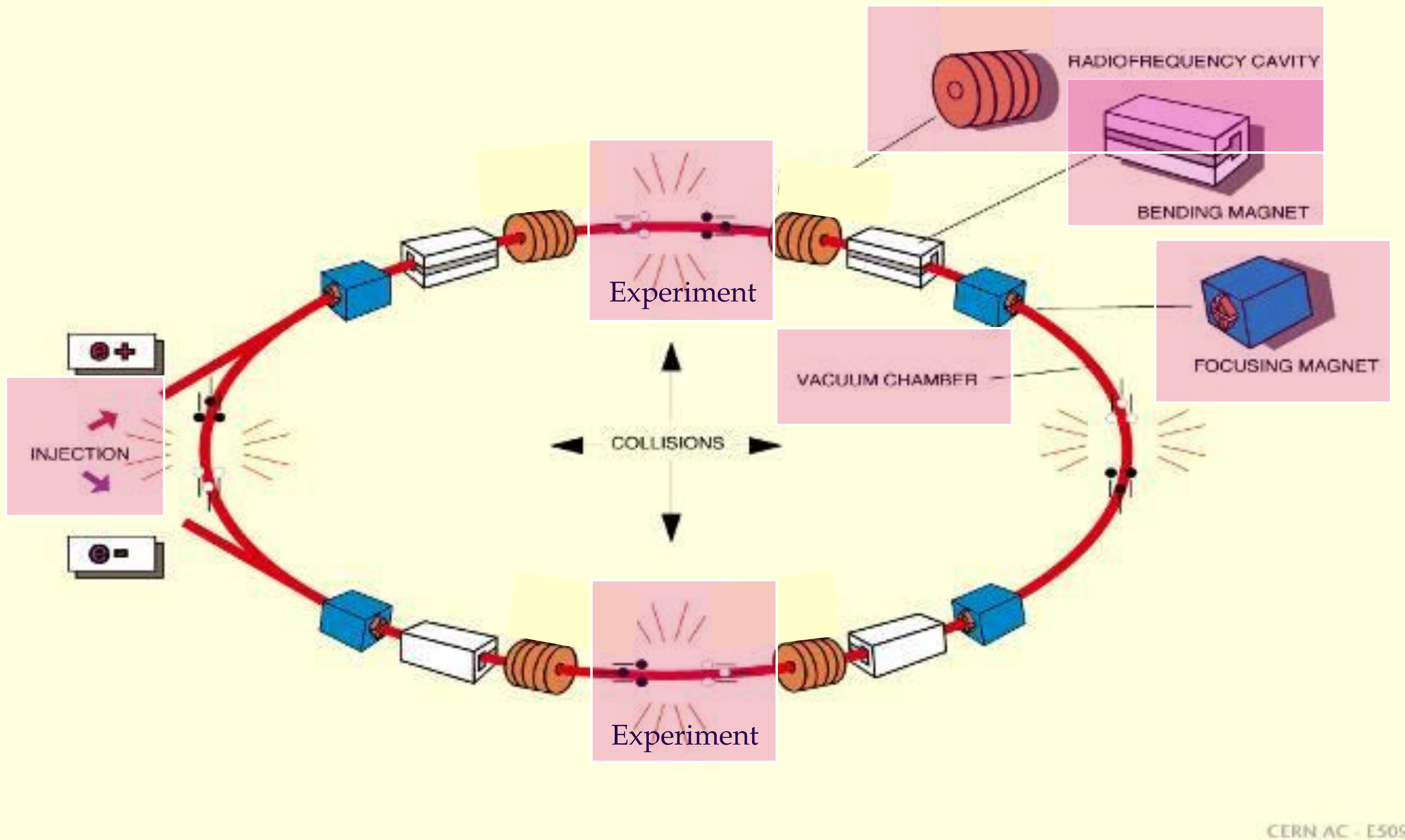
What does he need to know?

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:

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

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

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

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

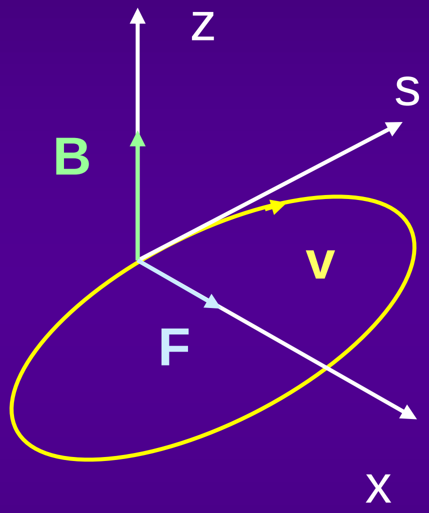
$$\frac{dE}{dt} = q \cdot (\vec{\mathbf{v}} \cdot \vec{\mathbf{E}} + \vec{\mathbf{v}} \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}})) = q \cdot \vec{\mathbf{v}} \cdot \vec{\mathbf{E}}$$

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:

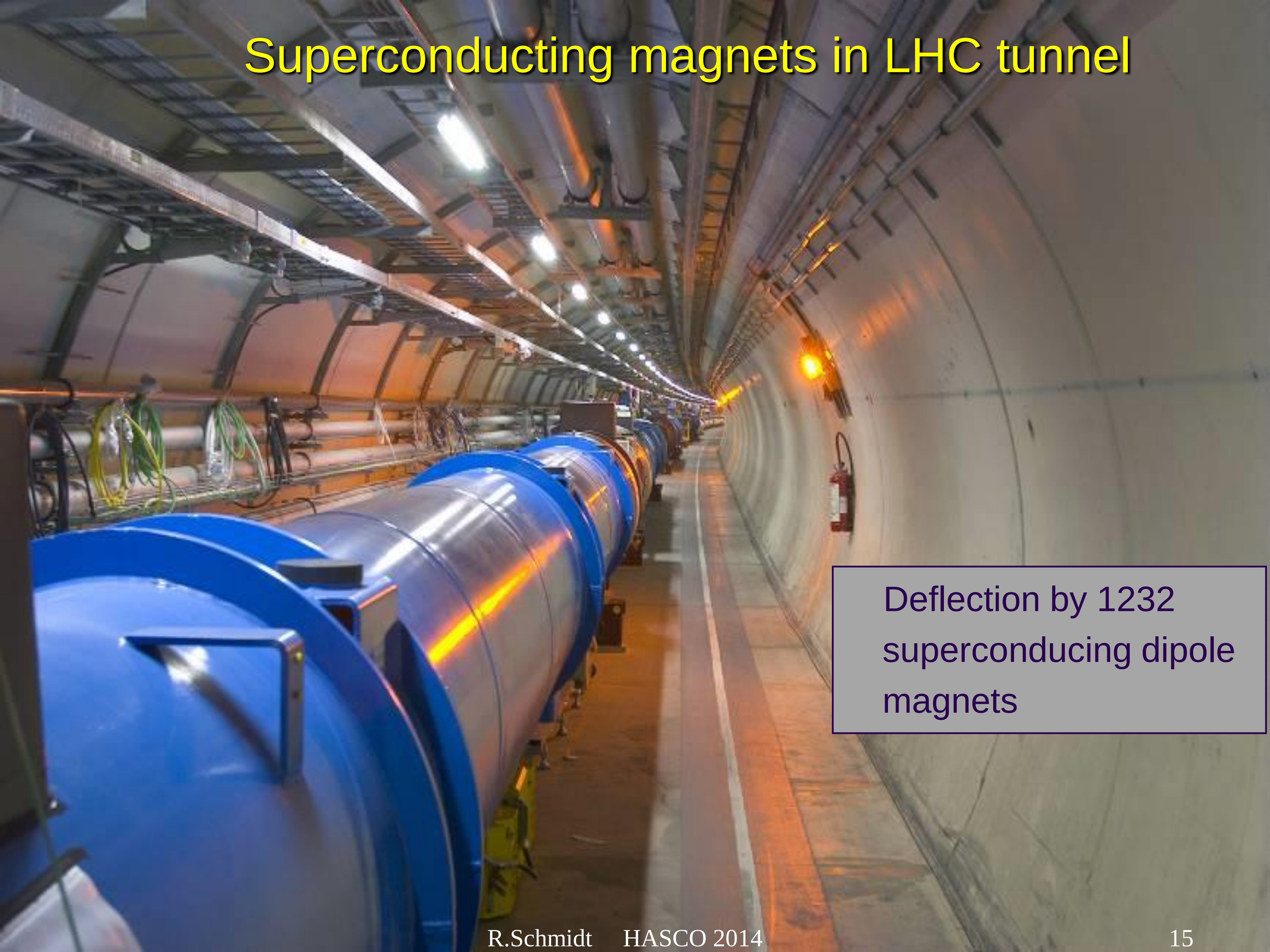
$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

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



- 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

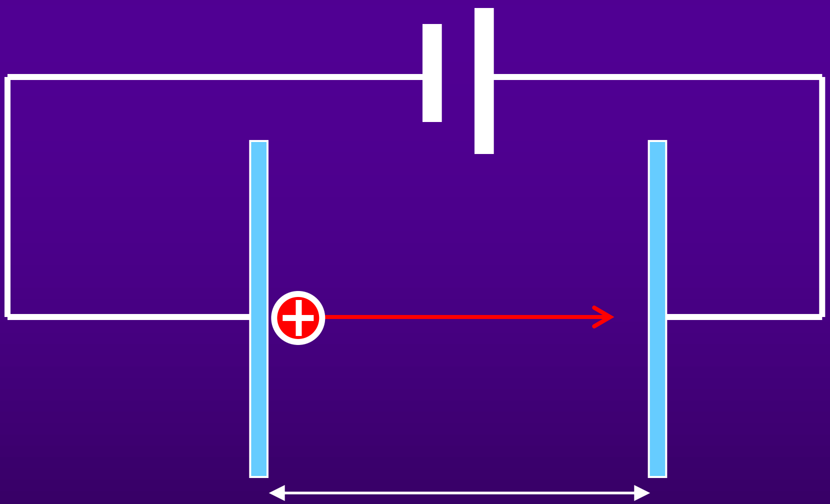


Deflection by 1232 superconducing dipole magnets

Particle acceleration: accelerating protons to 7 TeV

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

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



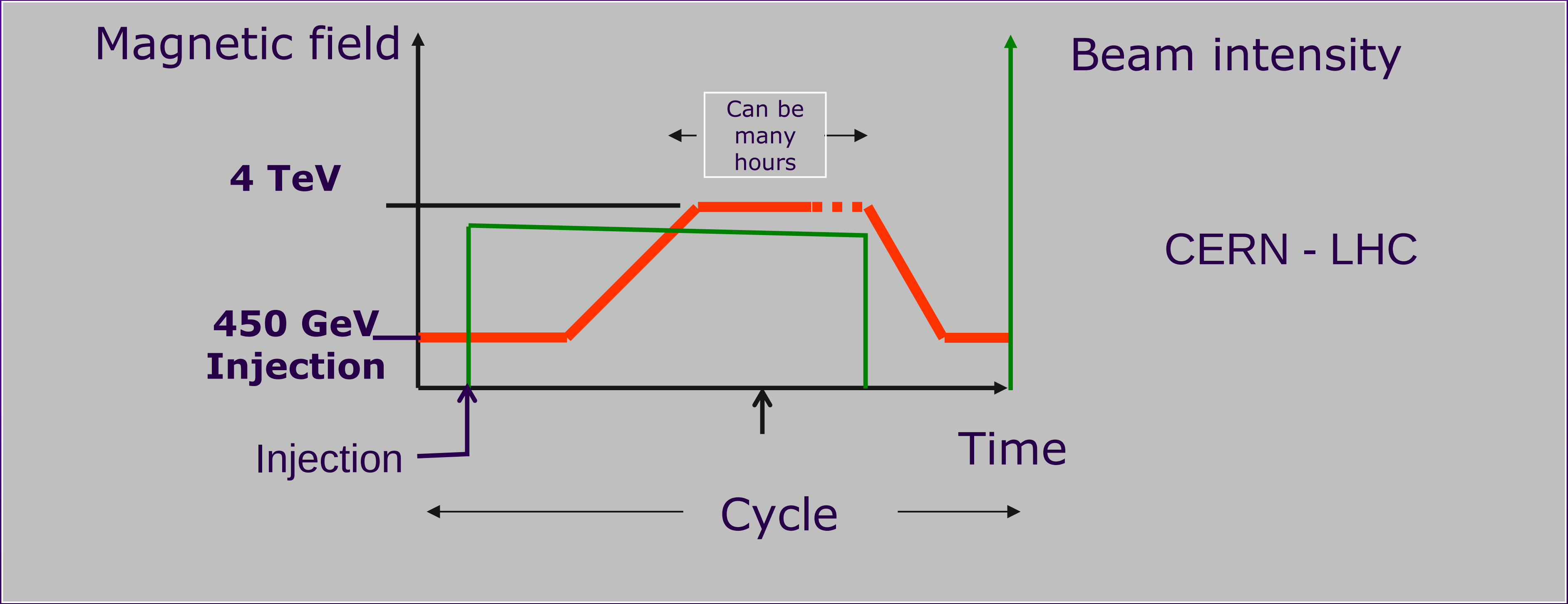
1 MeV requires
U = 1 MV

Acceleration of the protons in an electrical field with 7 TV

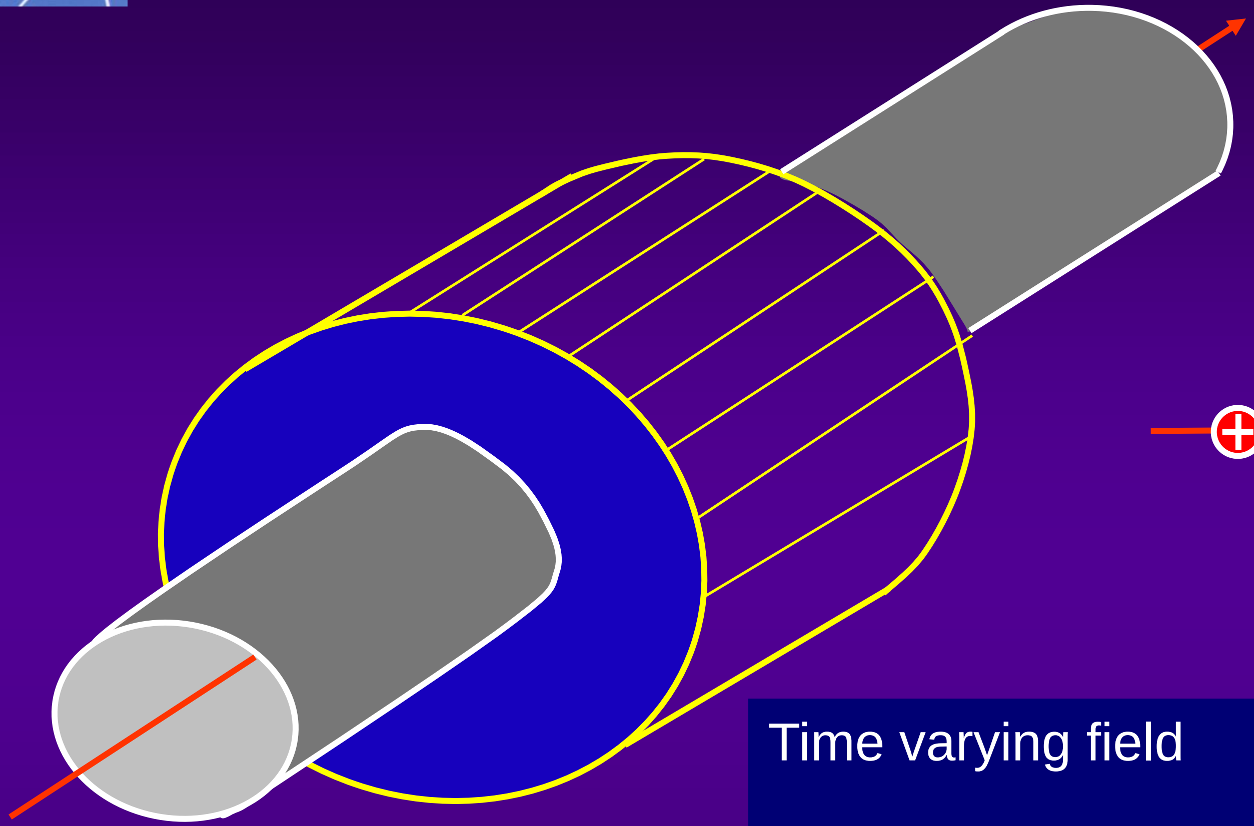
- no constant electrical field above some Million Volt (break down)
- no time dependent electrical field above some 10 Million Volt (about 30 MV/m)

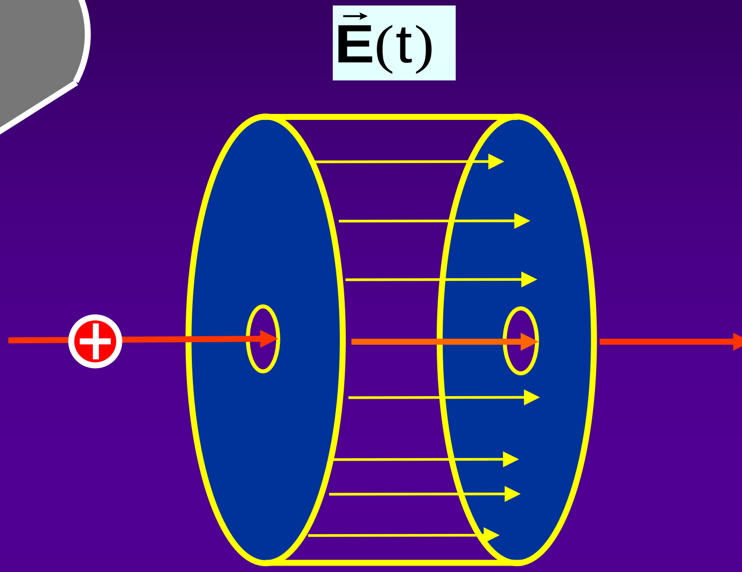
Principle of a synchrotron

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



Particle acceleration with RF cavity





Time varying field

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

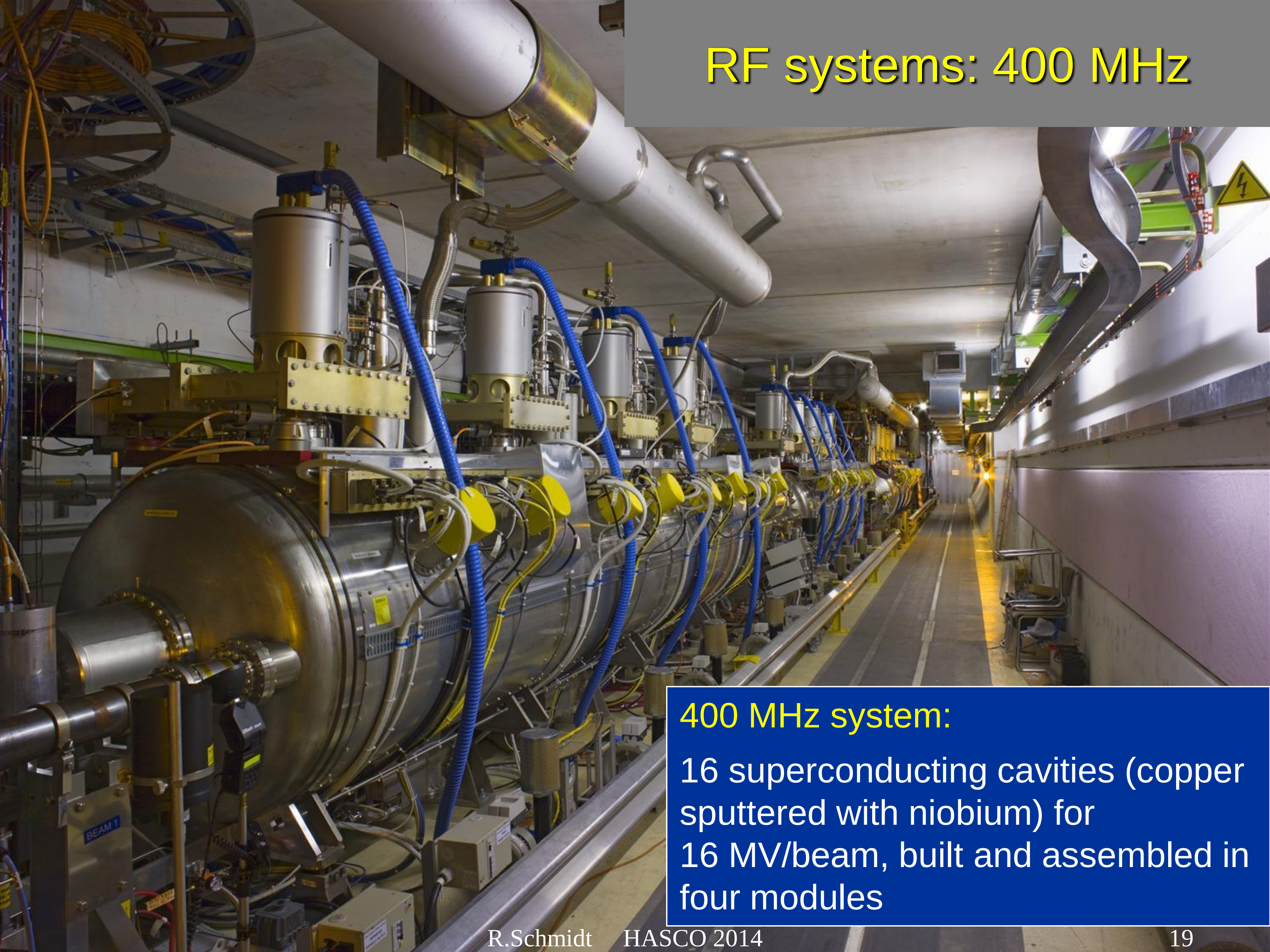
Maximum field about 20 MV/m

Beams are accelerated in bunches (no continuous beam)

LHC RF frequency
400 MHz

Revolution frequency
11246 Hz

RF systems: 400 MHz

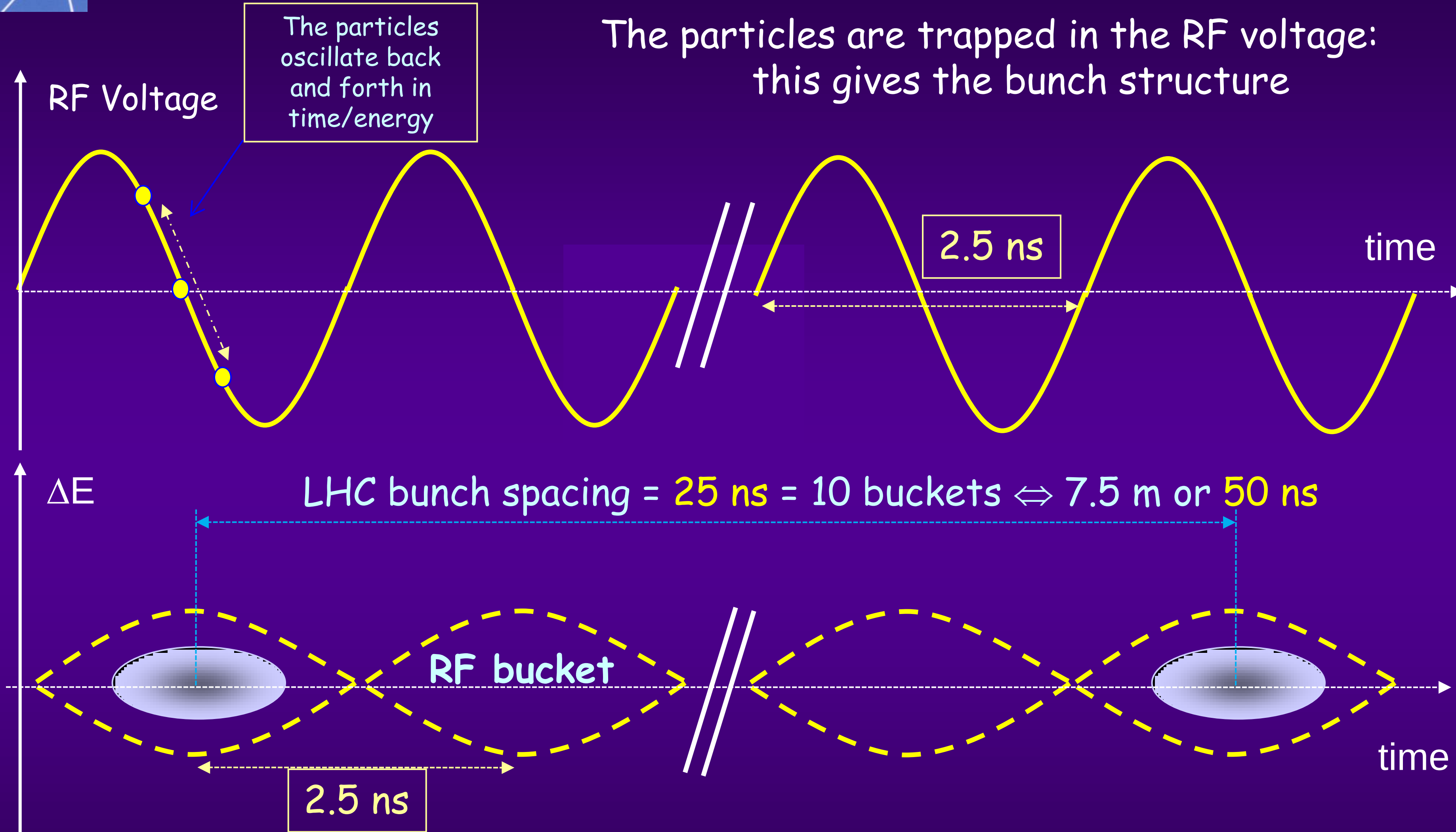


400 MHz system:

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



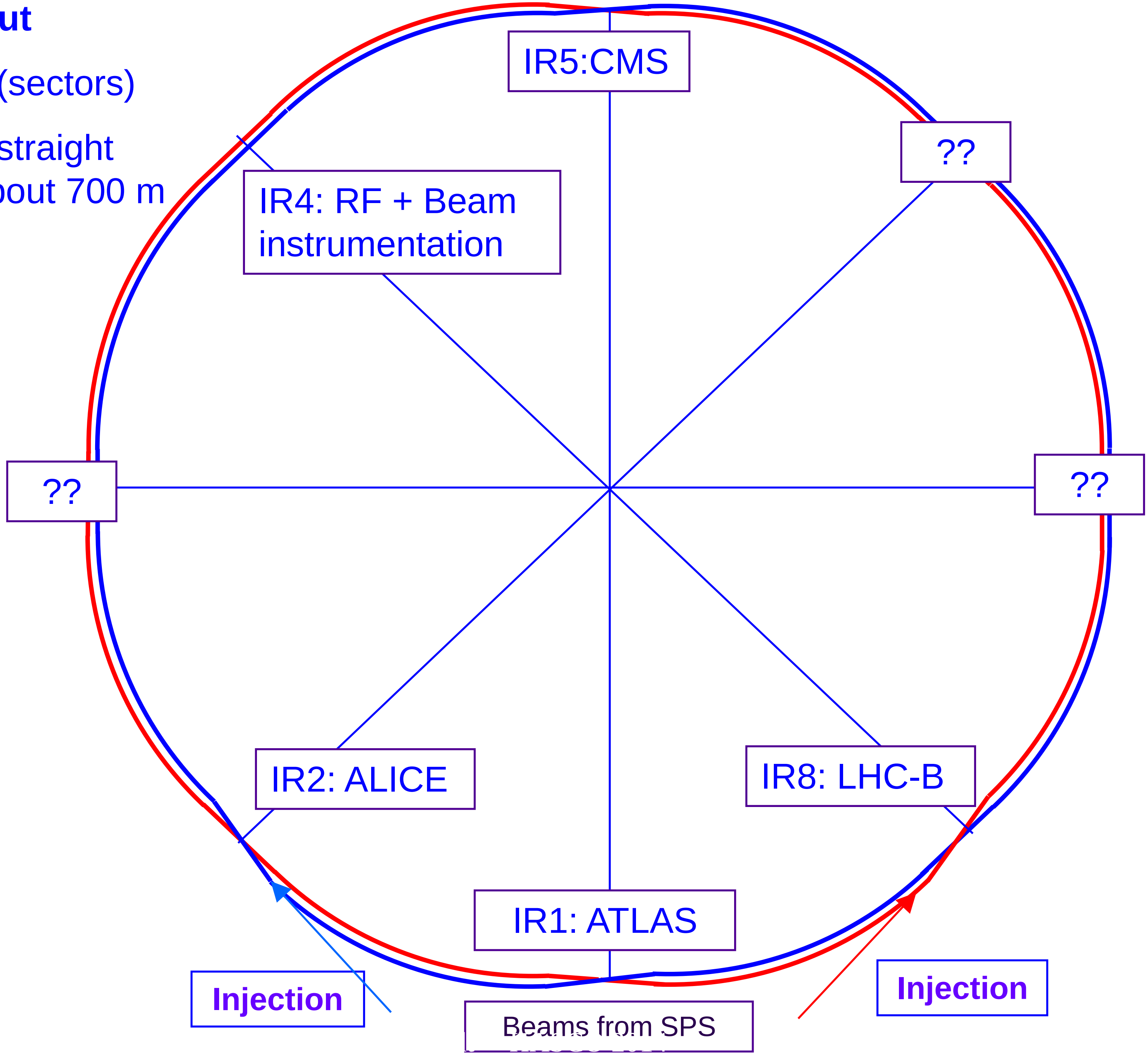
	450 GeV	7 TeV
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

LHC layout, injection and beam transport

LHC Layout

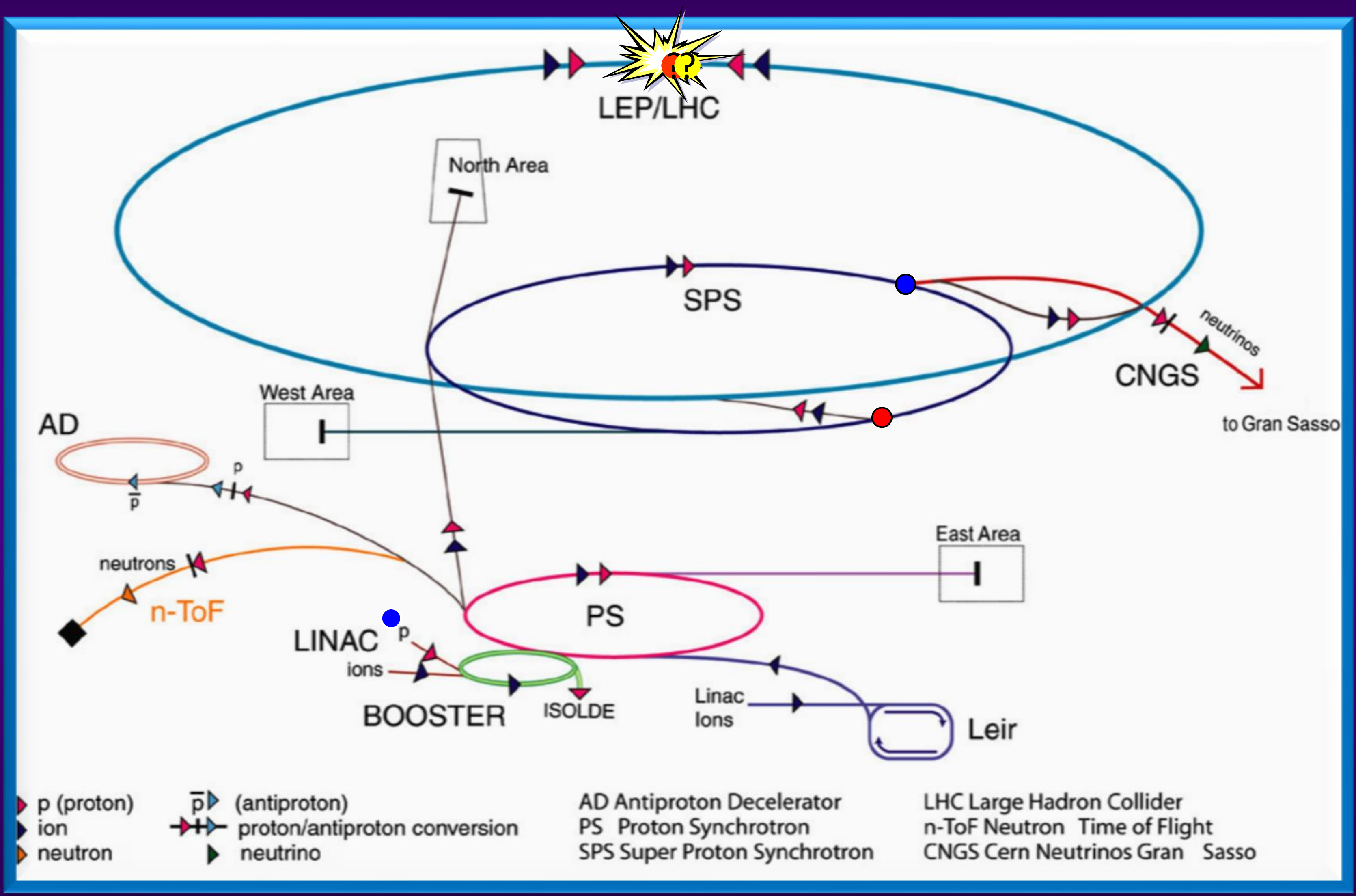
eight arcs (sectors)

eight long straight section (about 700 m long)



CERN accelerator complex

Click for Movie



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

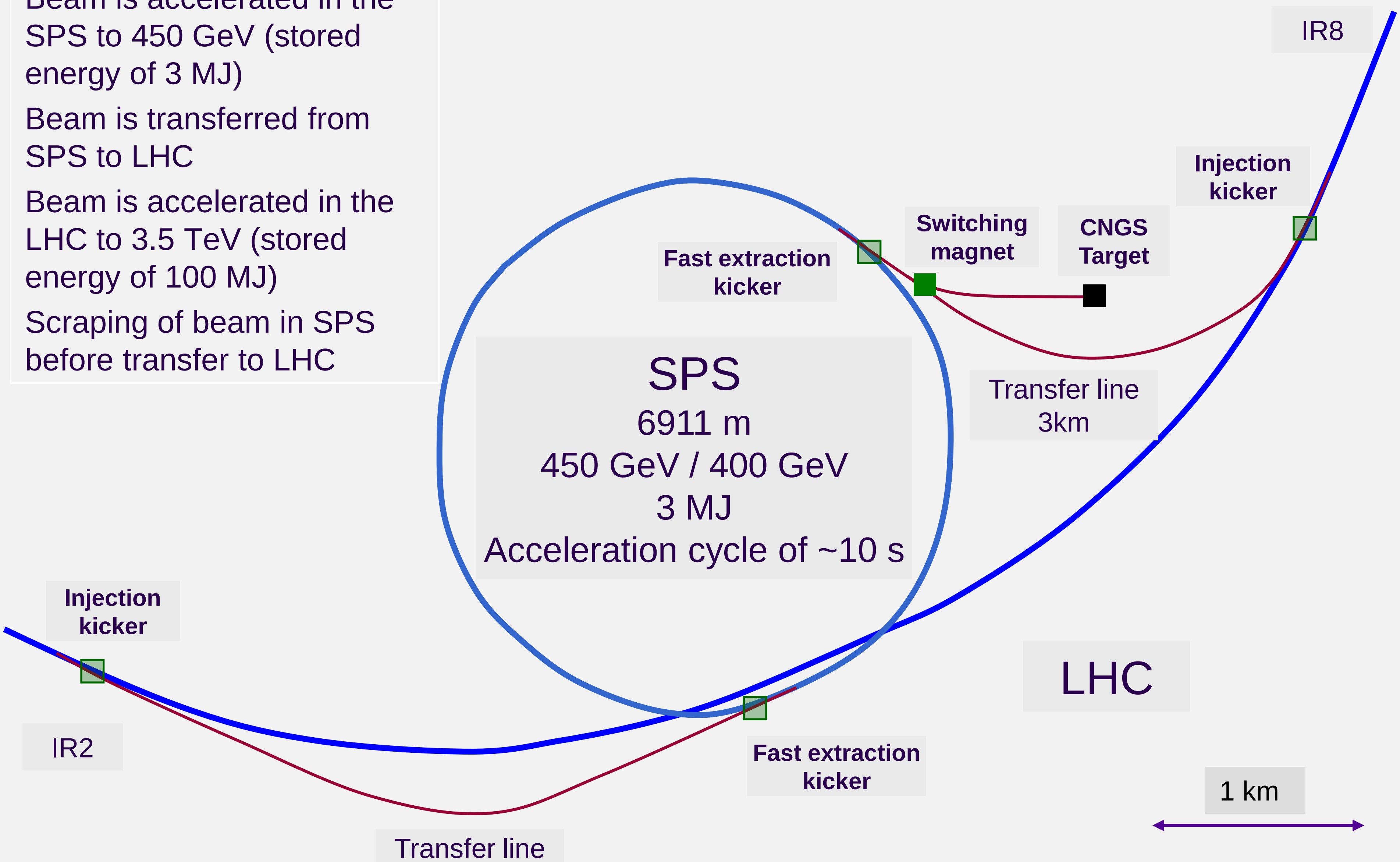
SPS, transfer line and LHC

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 3.5 TeV (stored energy of 100 MJ)

Scraping of beam in SPS before transfer to LHC



Beam transport

Need for getting protons on a circle: dipole magnets

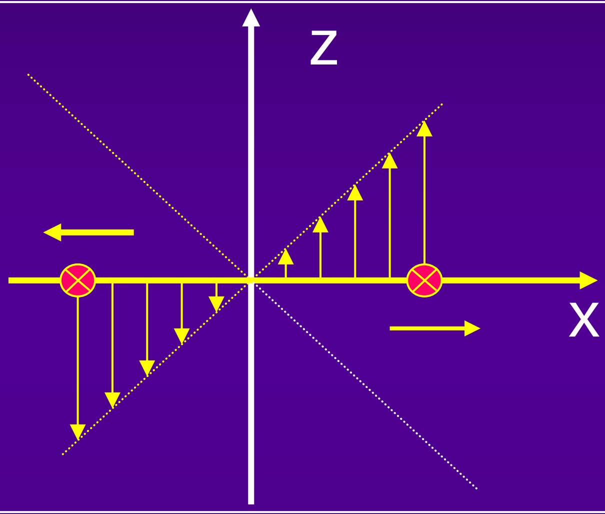
Need for focusing the beams:

- 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

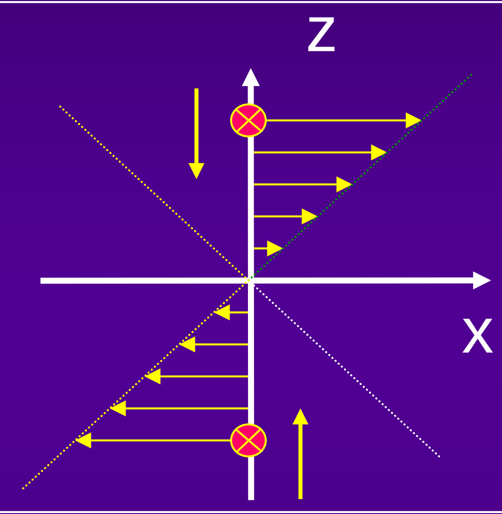
Force by quadrupole magnets

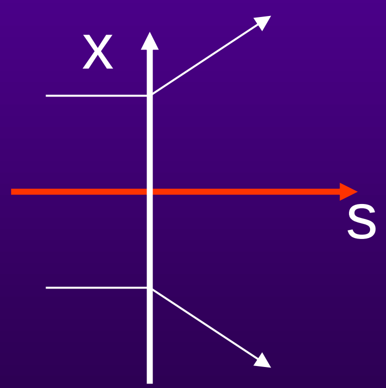
$$B_z(x) = const \times x$$
$$B_x(z) = const \times z$$

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

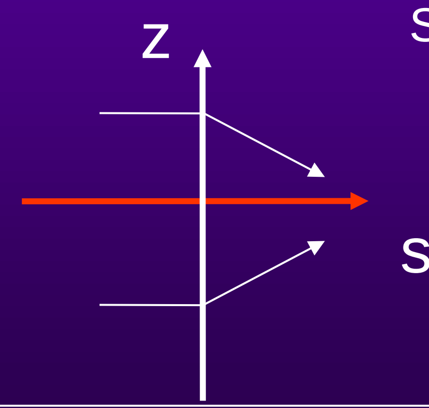


View along particle path



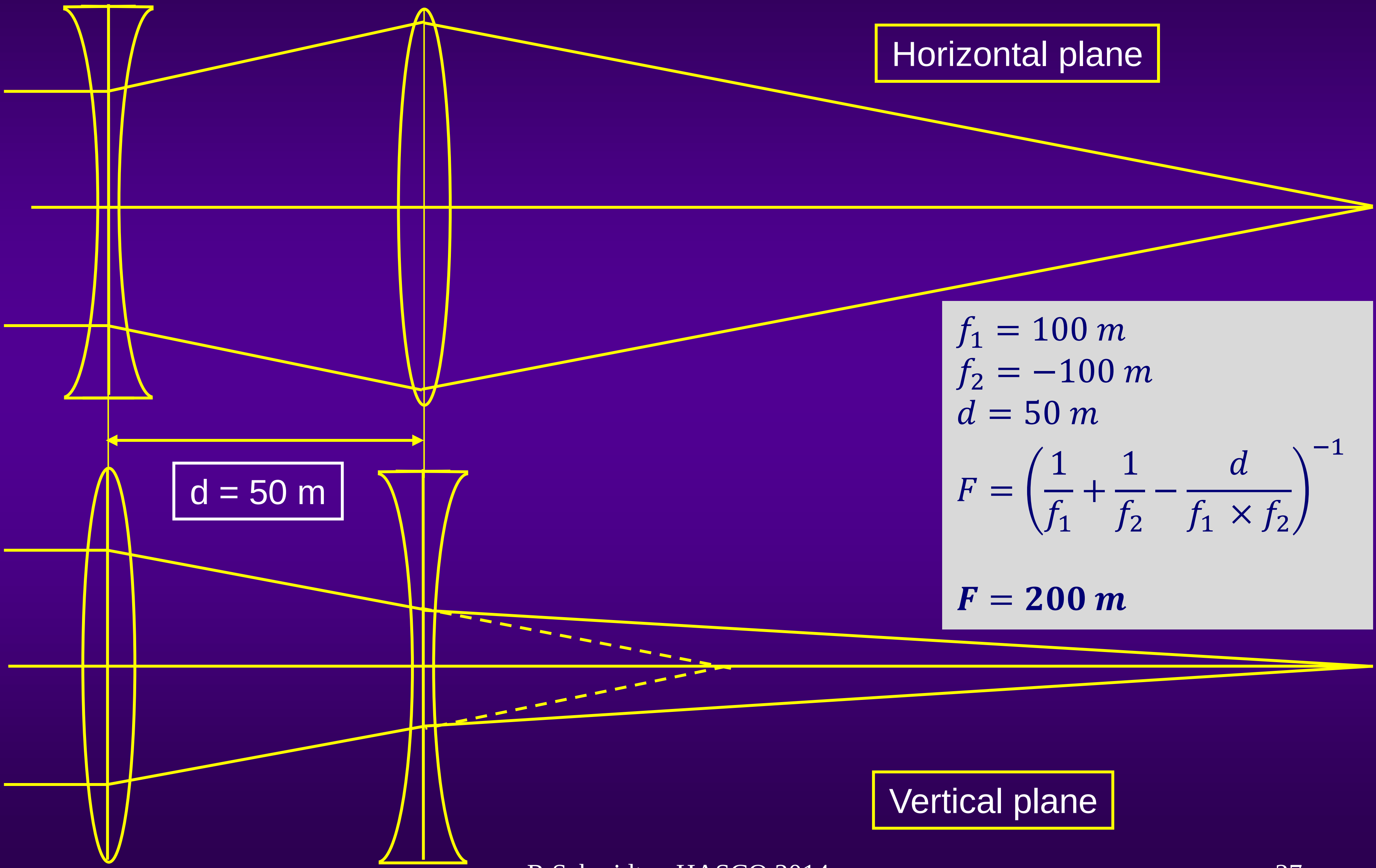


Top view: defocusing



Side view: focusing

Focusing by two quadrupole magnets, thin lens approximation



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

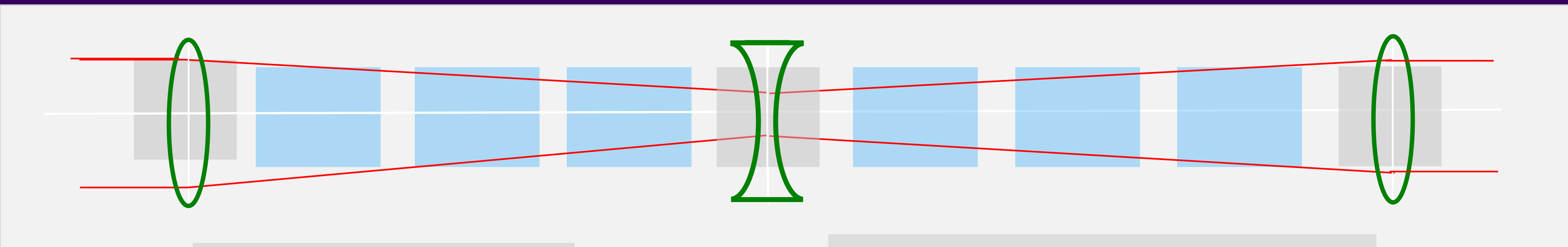
$$F = \left(\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \times f_2}\right)^{-1}$$

$\boldsymbol{F = 200\ m}$

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)

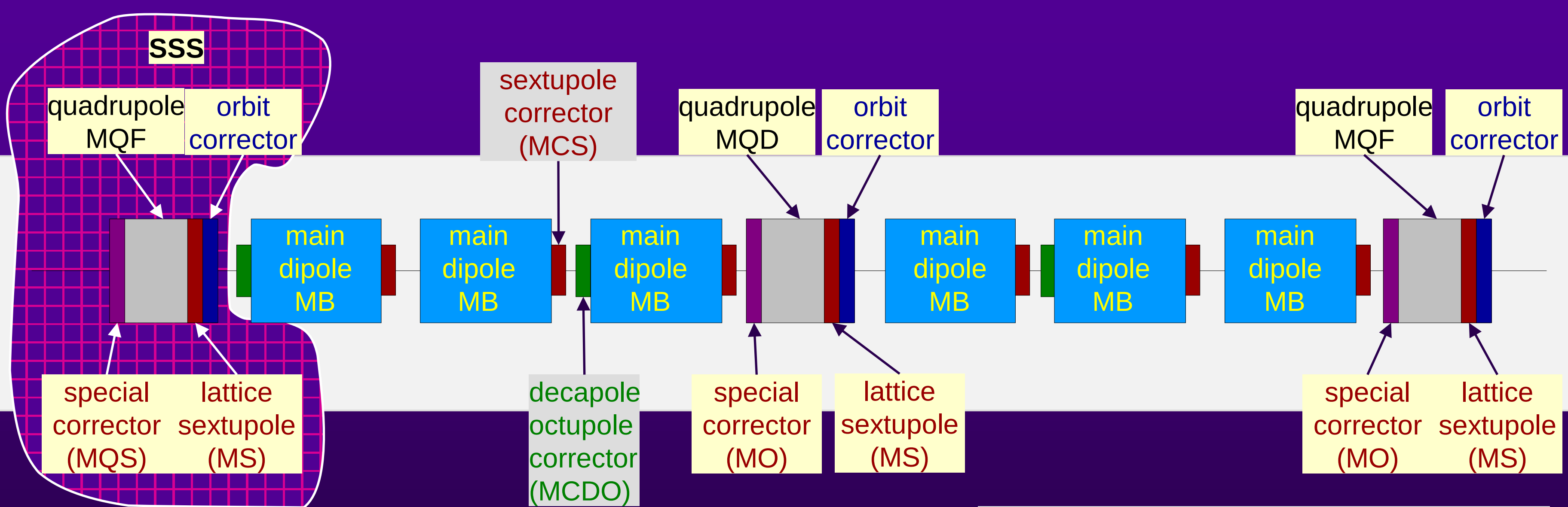
A (F0D0) cell in the LHC arcs



Vertical / Horizontal plane (QF / QD)

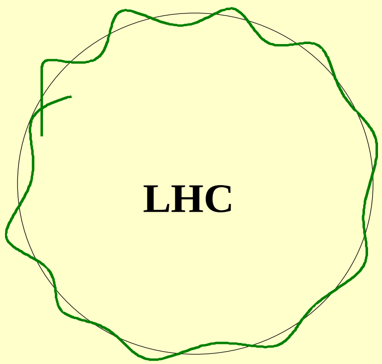
Quadrupole magnets controlling the beam size „to keep protons together“ (similar to optical lenses)

LHC Cell - Length about 110 m (schematic layout)

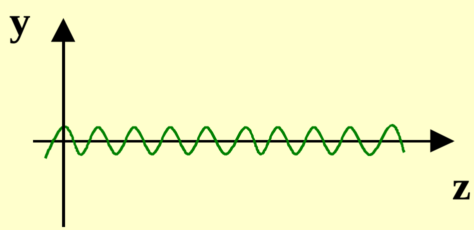


10000 magnets powered in 1700 electrical circuits

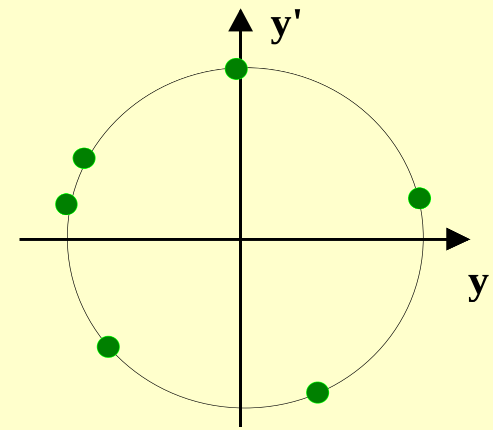
Particle stability and superconducting magnets - Quadrupole- and multipole fields



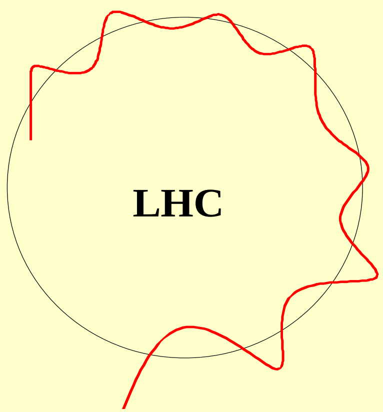
Particle oscillations in quadrupole field (small amplitude)



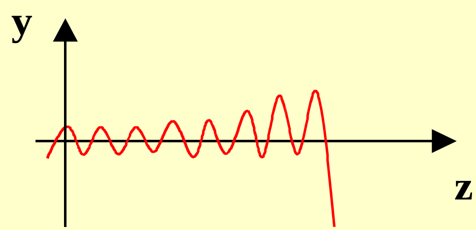
Harmonic oscillation after coordinate transformation



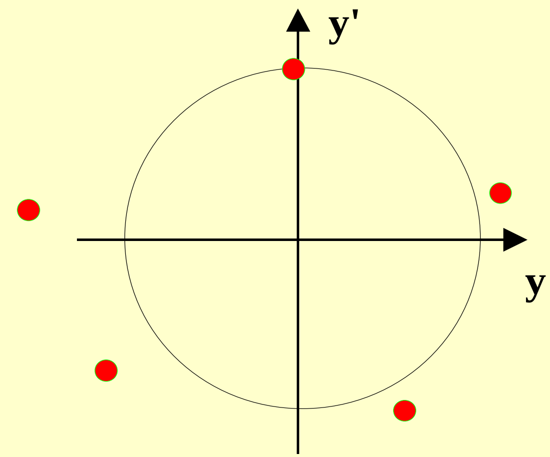
Circular movement in phase space



Particle oscillation assuming non-linear fields, large amplitude

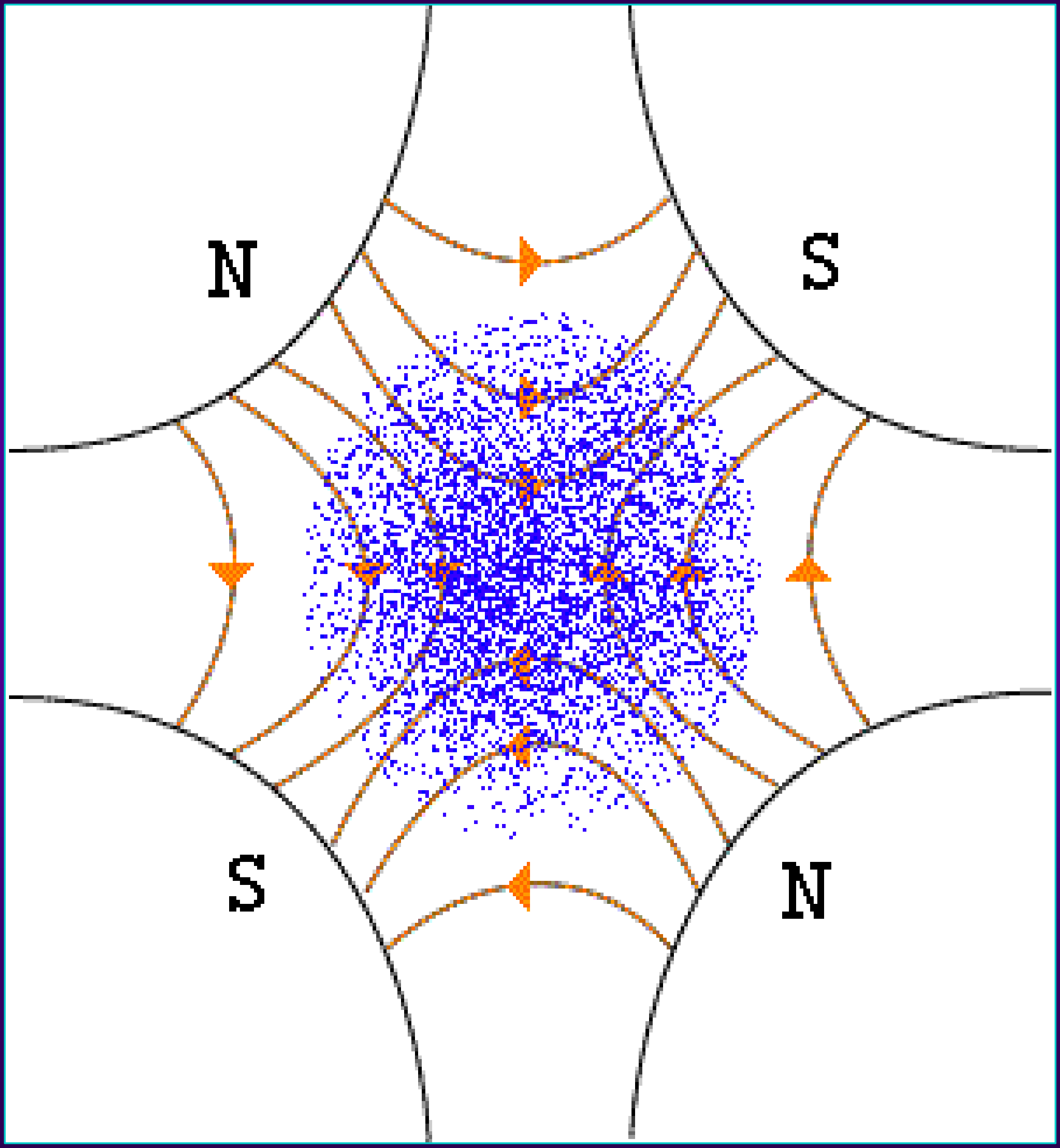


Amplitude grows until particle is lost (touches aperture)



No circular movement in phasespace

Visualising bunch oscillation in accelerator



LHC energy and superconducting magnets

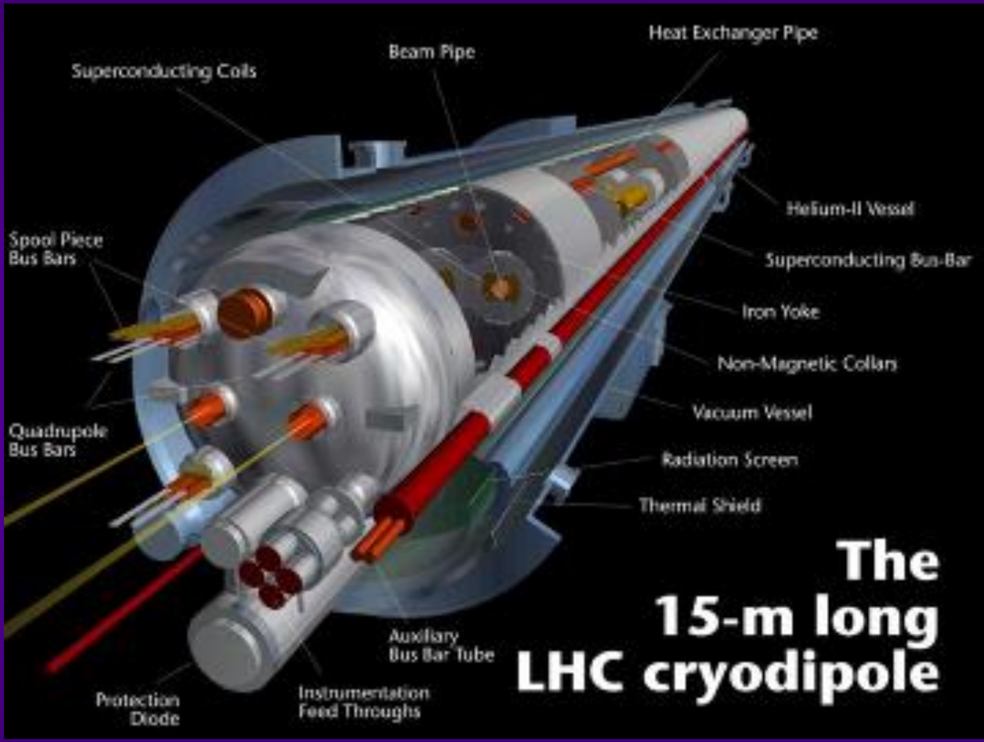
…….the field strength determines the beam energy

Dipole magnets for the LHC

1232 Dipole magnets
Length about 15 m

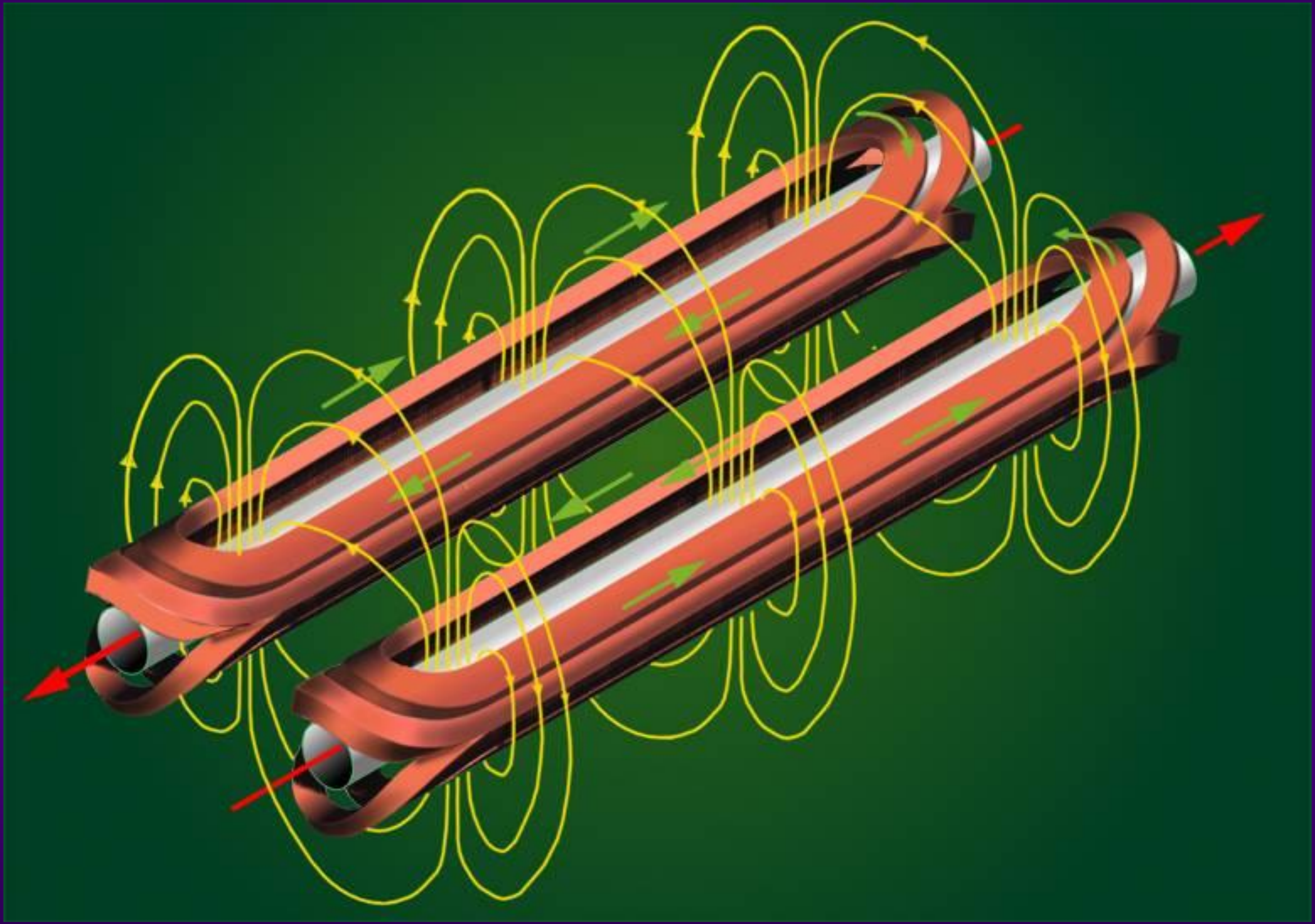
Magnetic Field 8.3 T for
7 TeV

Two beam tubes with an
opening of 56 mm

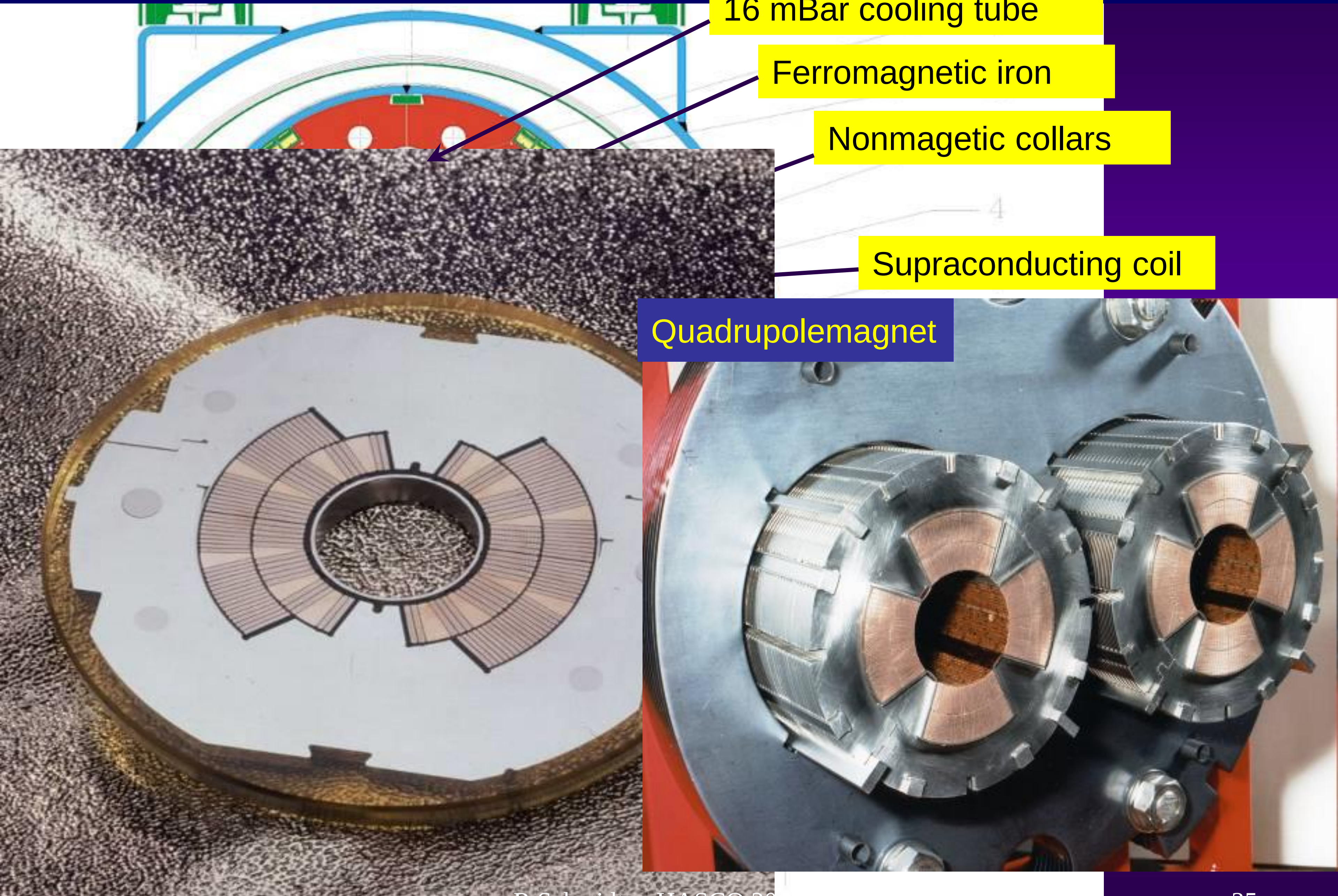


plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets)

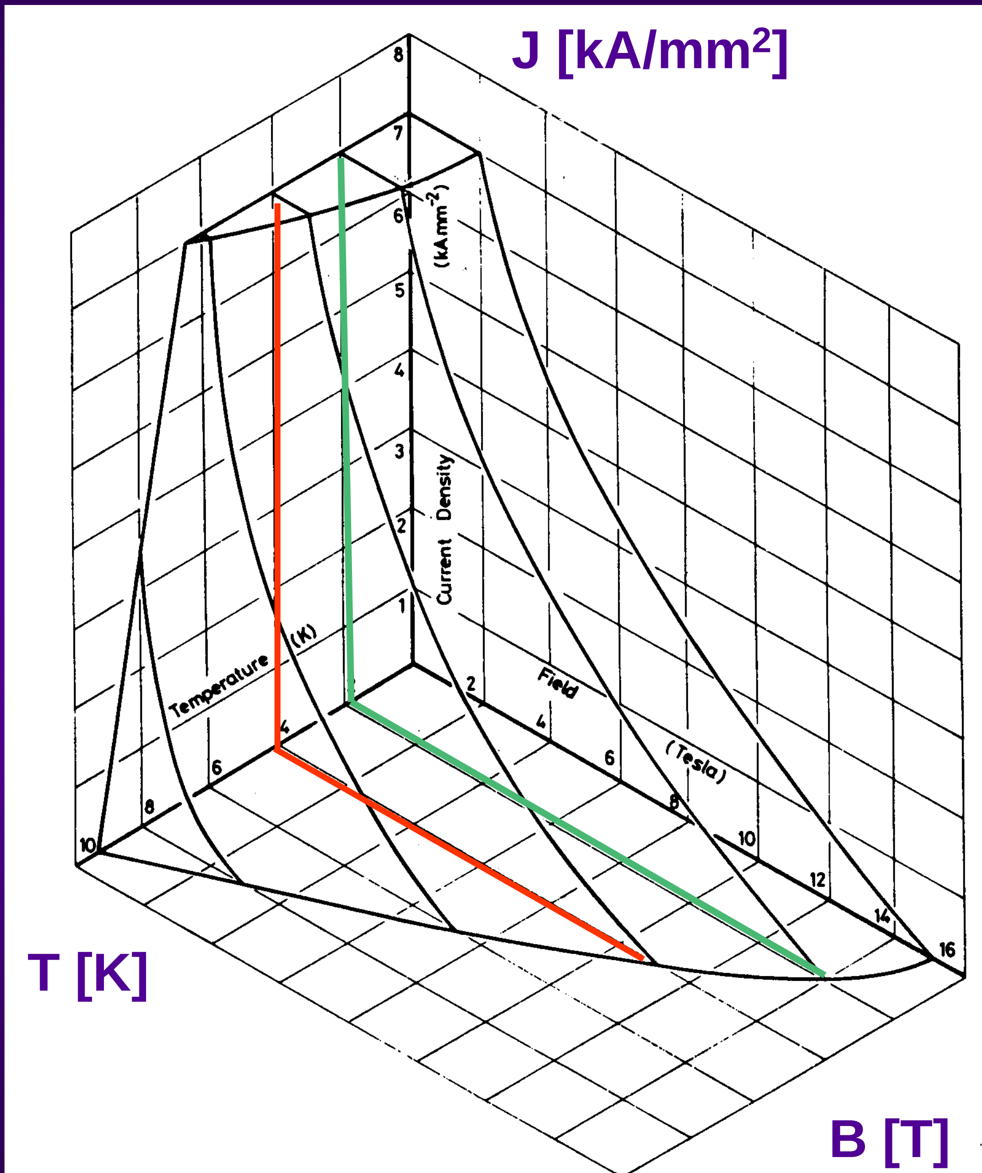
Coils for Dipolmagnets



Dipole magnet cross section



Operating temperature of superconductors (NbTi)

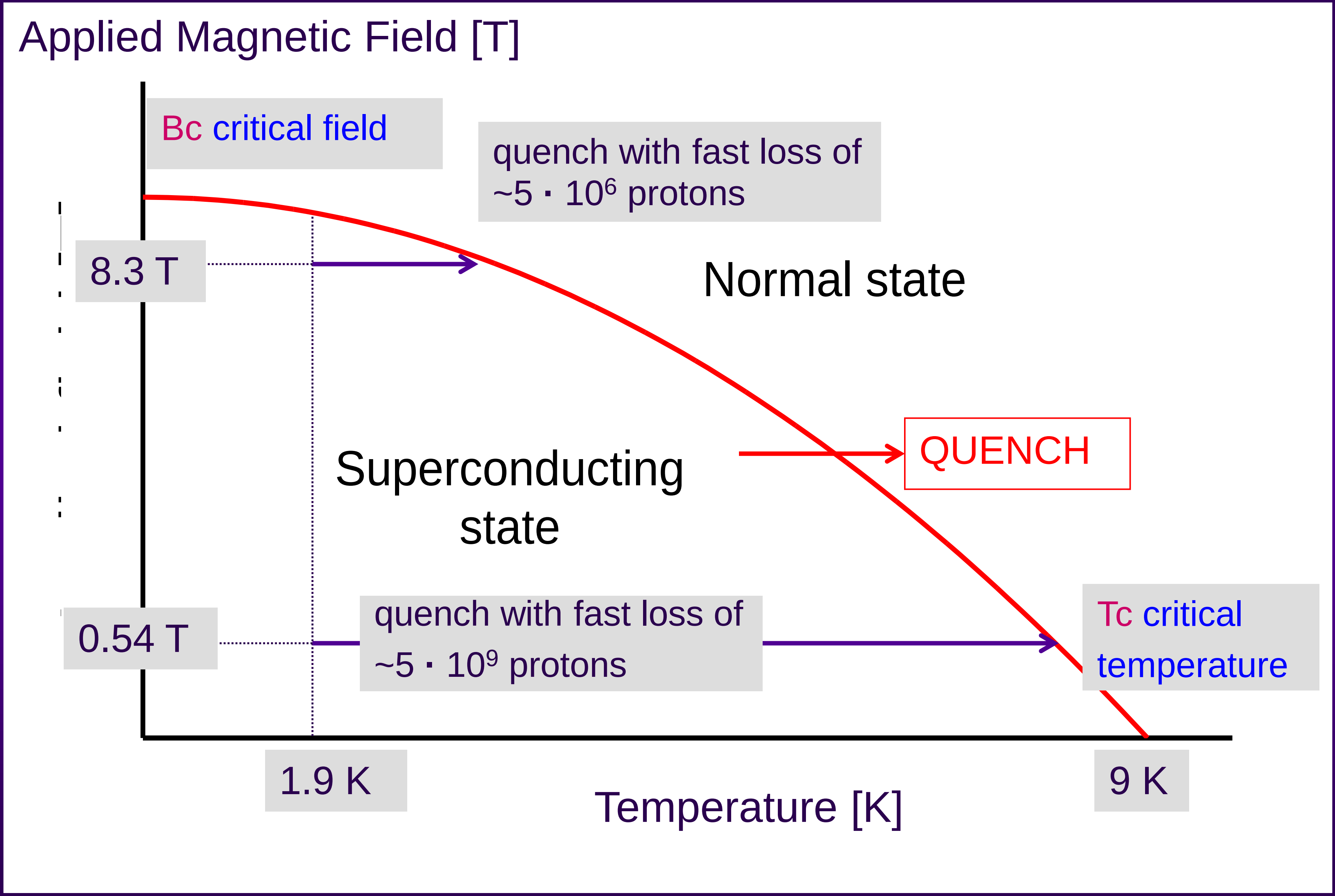


The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

Superconducting magnets produce high field with high current density

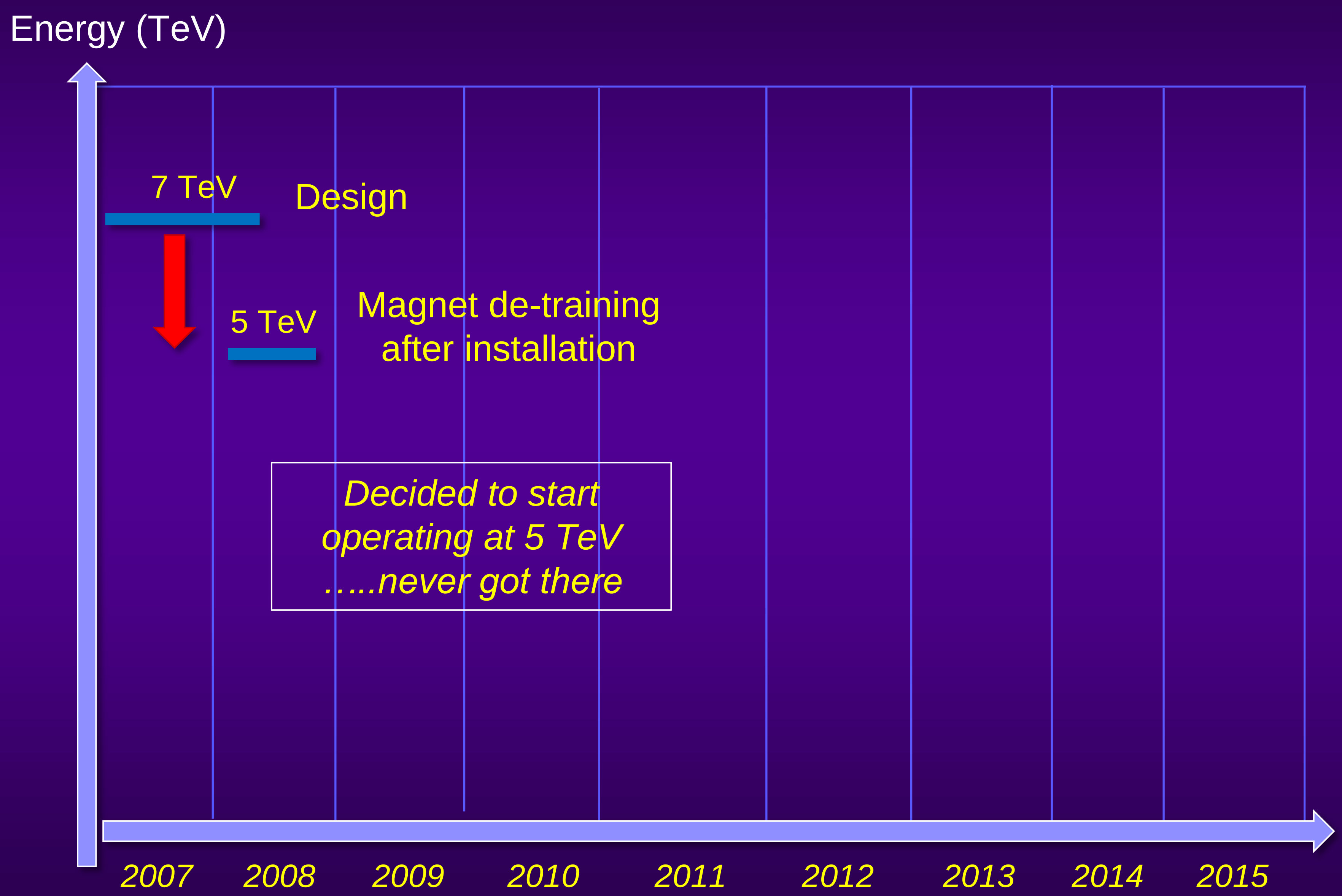
Lowering the temperature enables better usage of the superconductor, by broadening its working range

Operational margin of a superconducting magnet



Dipole magnets from surface to tunnel

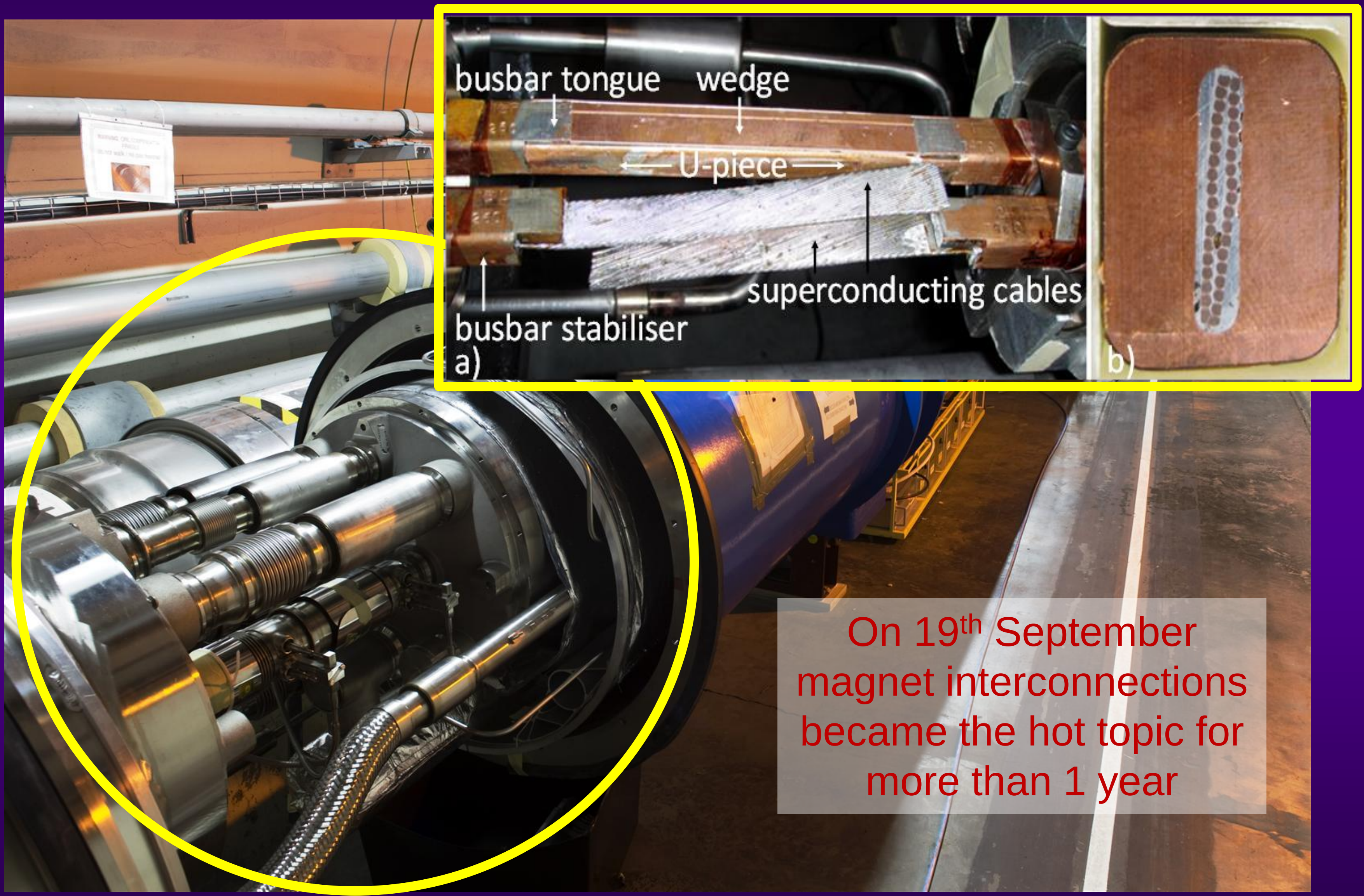
LHC energy evolution



September 10th 2008

A brief moment of glory

September 19th 2008



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

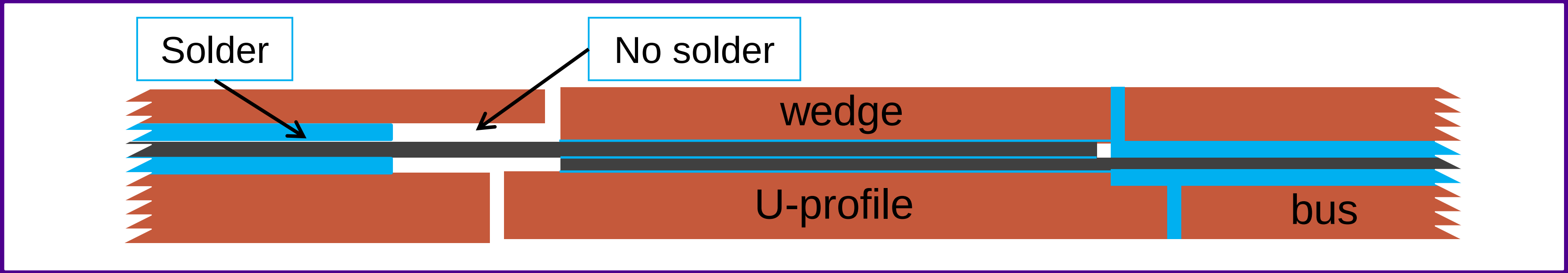
Incident September 19th 2008

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

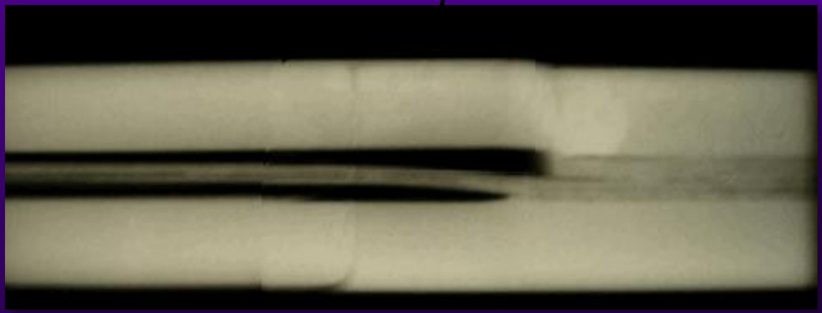
53 magnets had to be repaired

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.



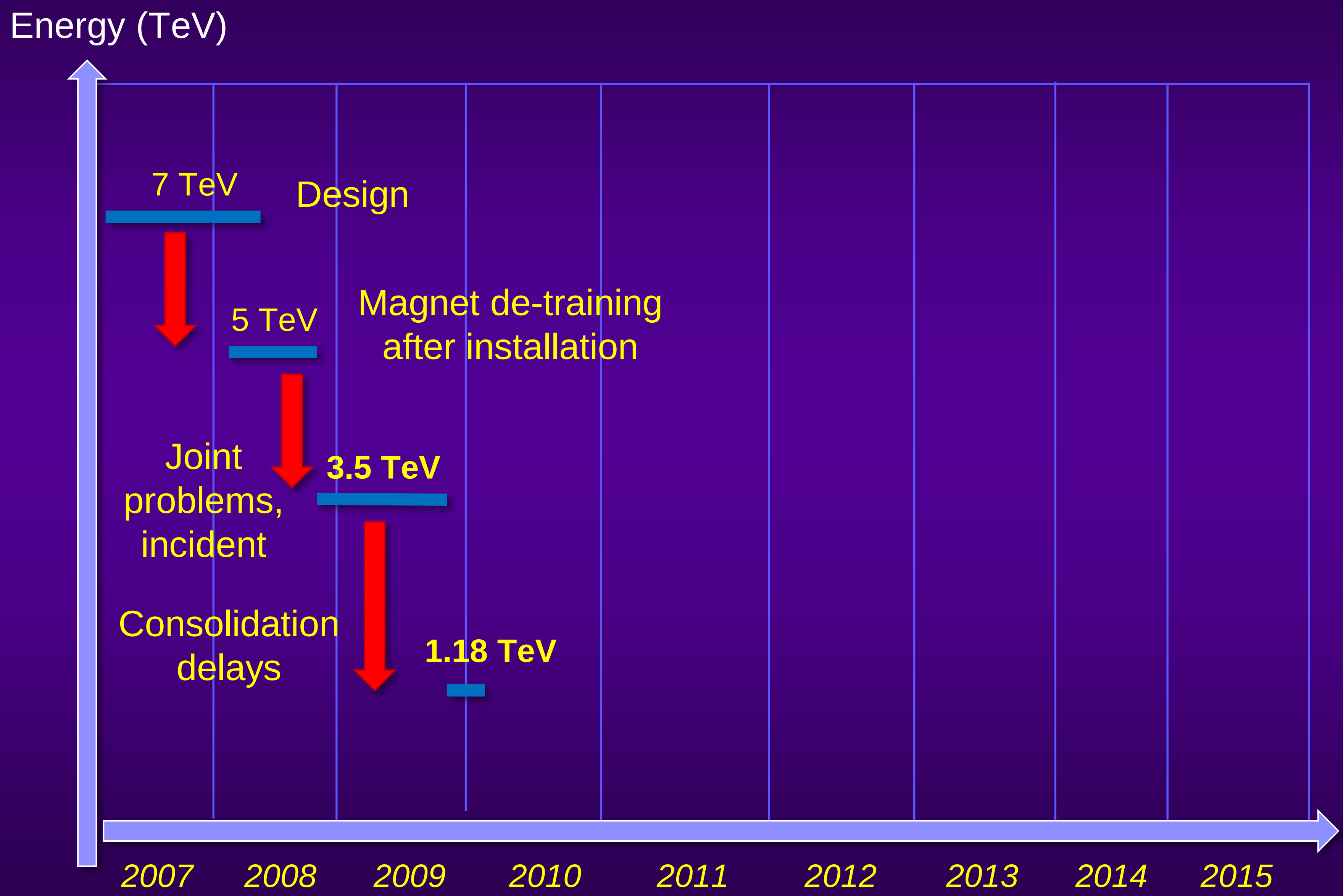
X-ray



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

Energy limitation for run 1 !!

LHC energy evolution

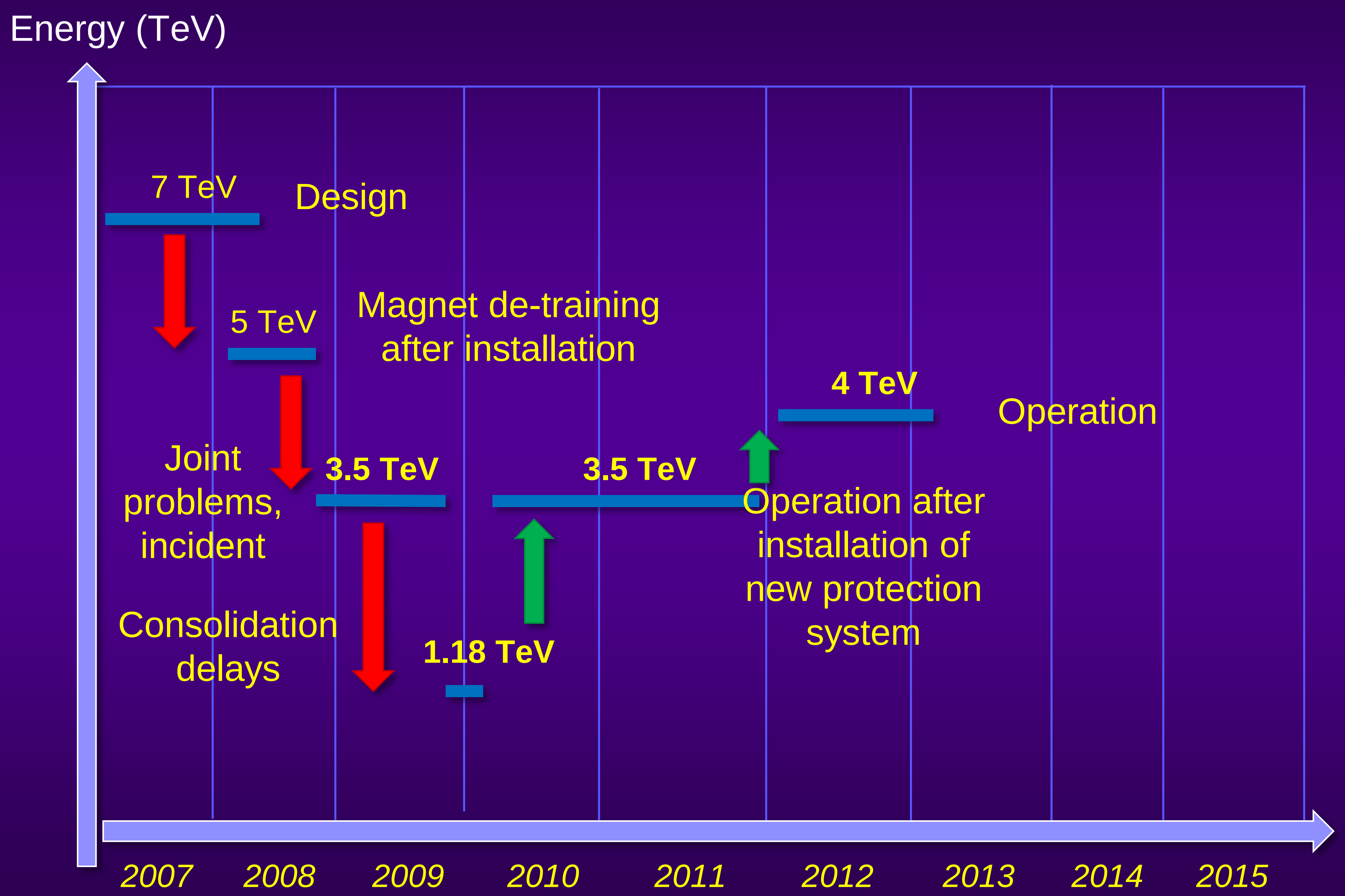


LHC is back !

20th November 2009: after 14 months of repair

3 weeks later

LHC energy evolution



High luminosity and consequences

High luminosity by colliding trains of bunches

Number of „New Particles“ per unit of time:

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

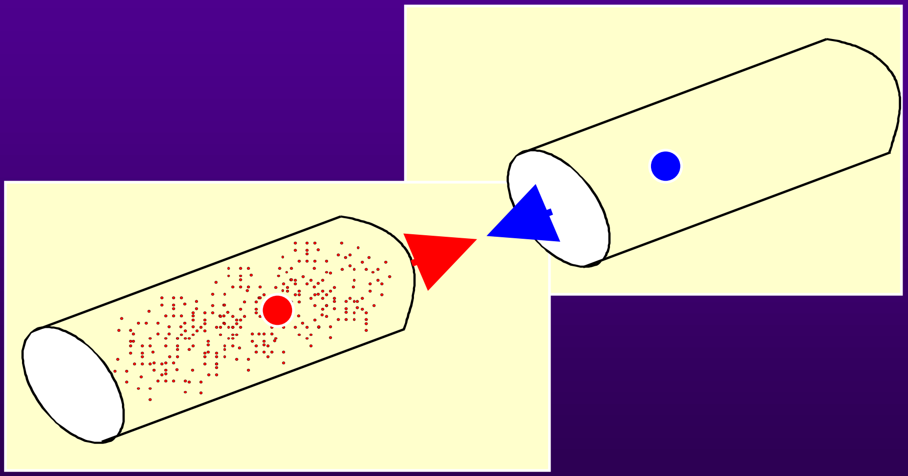
The objective for the LHC as proton – proton collider is a luminosity of about 10^{34} [$cm^{-2}s^{-1}$]

- 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$\times$10^{11}** due to the beam-beam interaction and beam instabilities

Beam size given by injectors and by space in vacuum chamber

f = **11246 Hz**

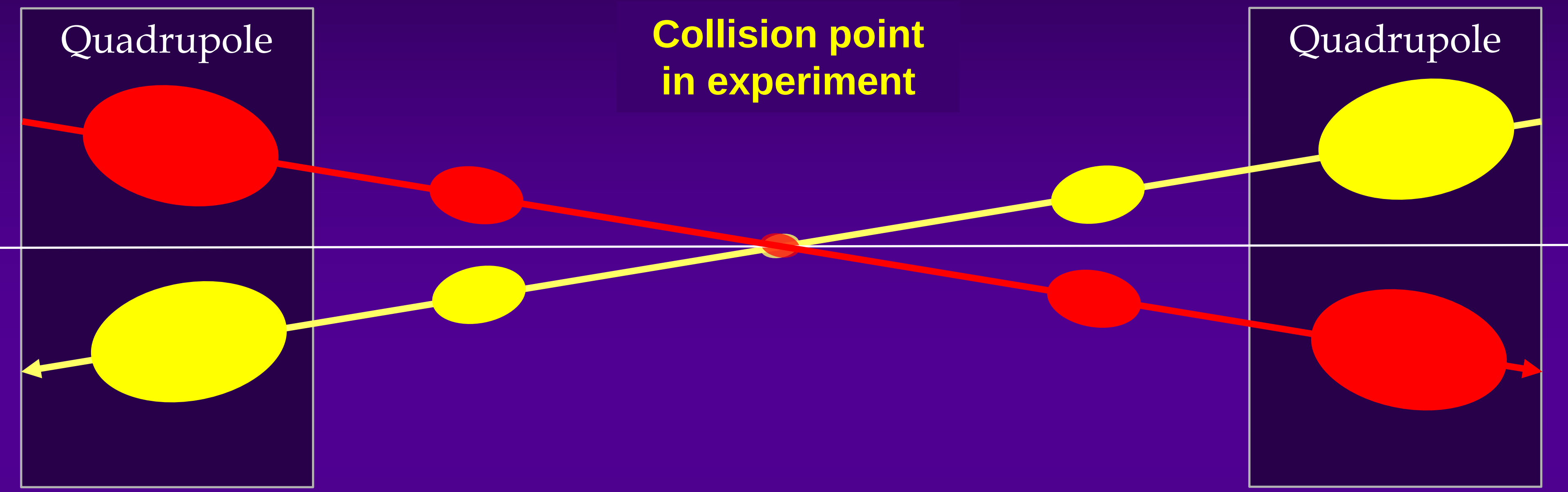
Beam size **16 μm**, for β = 0.5 m (β is a function of the lattice)

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

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

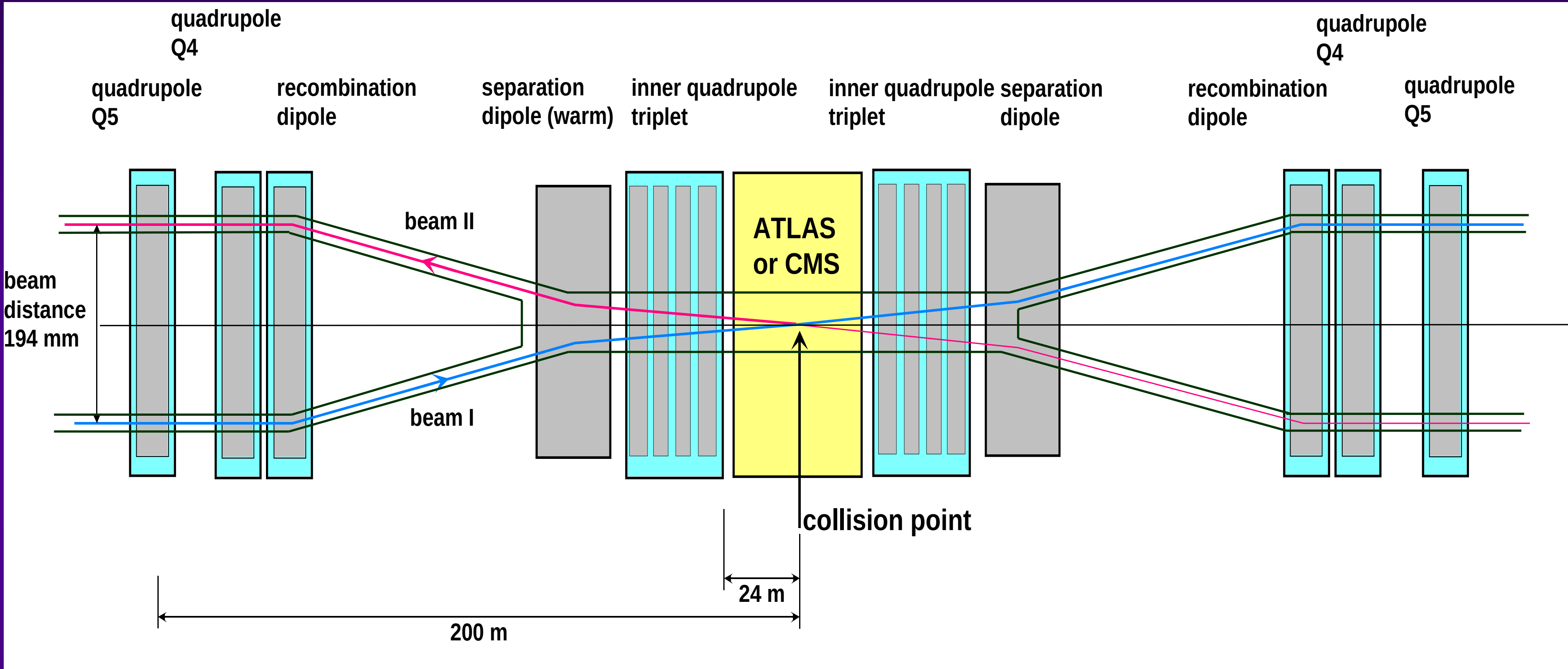
L = 10^{34} [cm^{-2}s^{-1}]

…smallest beam size at experiments



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

Experimental long straight sections

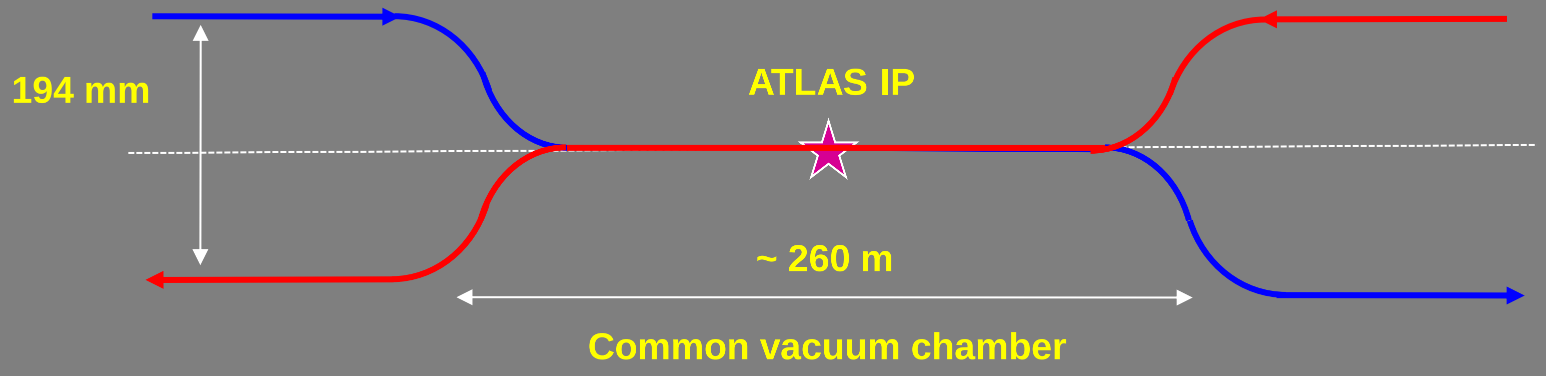


Example for an LHC insertion with ATLAS or CMS

- 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

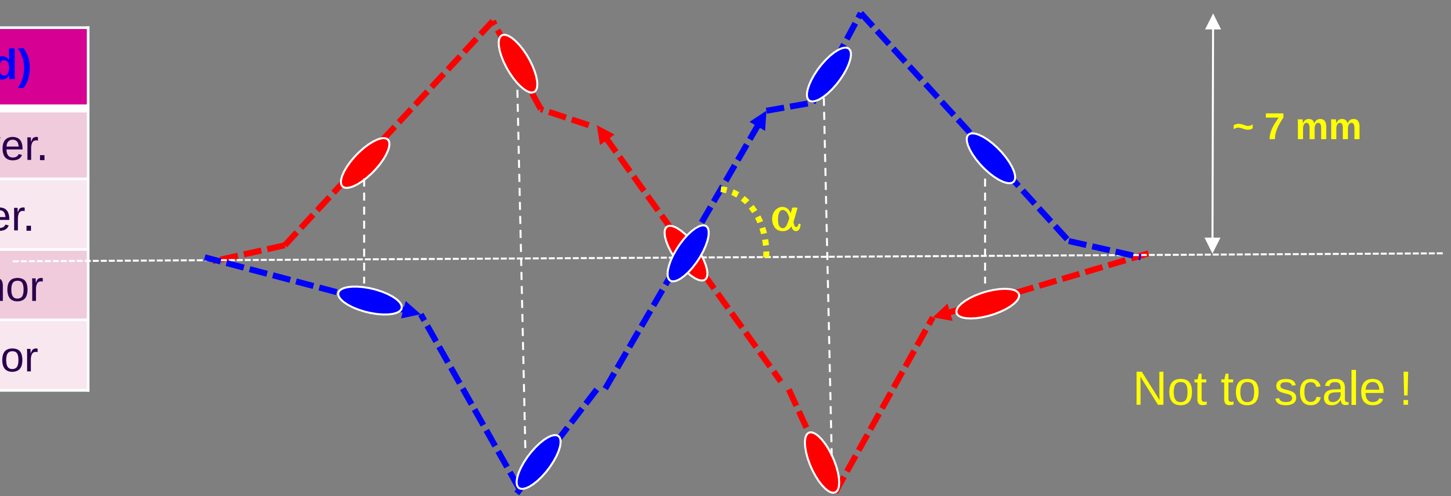
Separation and crossing: example of ATLAS

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



Event pile up in LHC experiments

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

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

Event pile up for one bunch crossing:

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

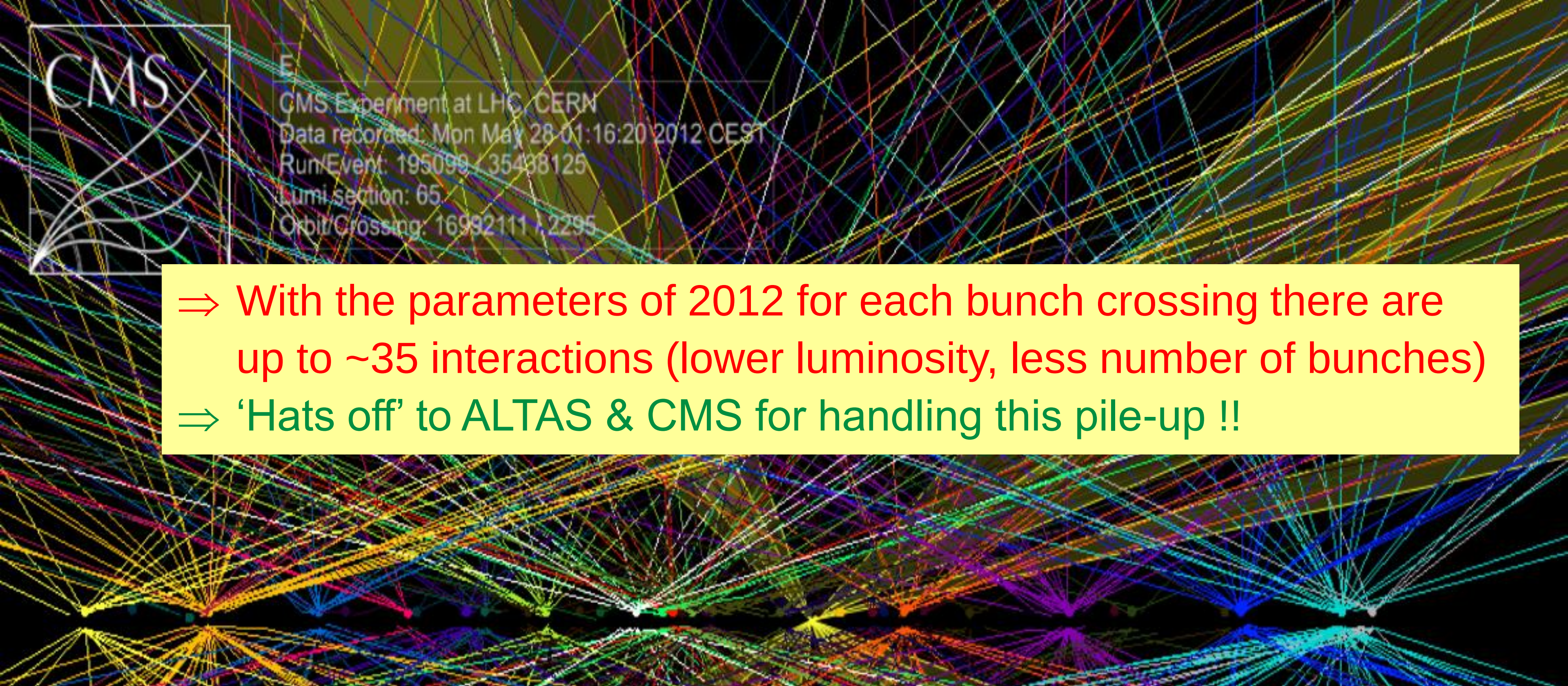
$\sigma_{tot} = 1 \times 10^{-25}\ \text{cm}^2$

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

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

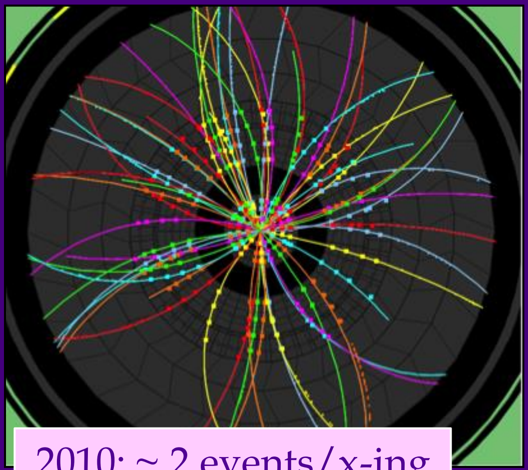
$frev_{lhc} = 1.1246 \times 10^{4}\ \frac{1}{s}$ and $N_{bunches\_1beam} = 2808$

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



⇒ With the parameters of 2012 for each bunch crossing there are up to ~35 interactions (lower luminosity, less number of bunches)

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

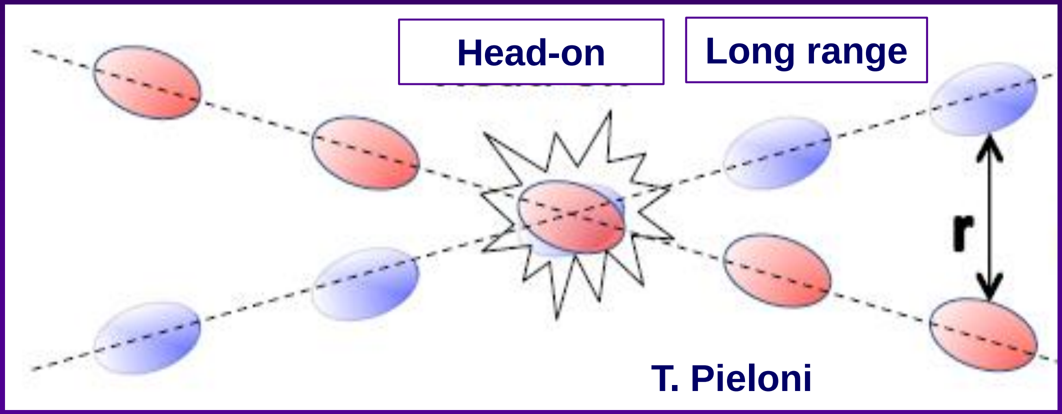


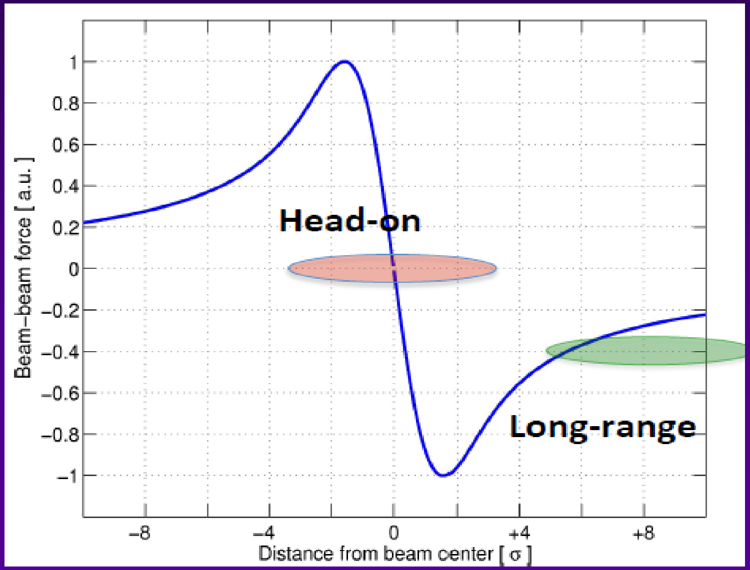
2010: ~ 2 events/x-ing

2011: ~ 10 events/x-ing

2012: ~ 20 events/x-ing

Beam-Beam Effects





Strong non linear fields when counter-rotating beams share vacuum chamber.

- Spread in betatron frequencies
- Risk of overlapping resonances driven by magnetic errors
- Spread in frequencies and strength of resonances expressed as tune shift for head-on collisions: $\Delta Q_{bb} \propto \frac{N_b}{\varepsilon_n}$
- Limitation of number of protons in one bunch

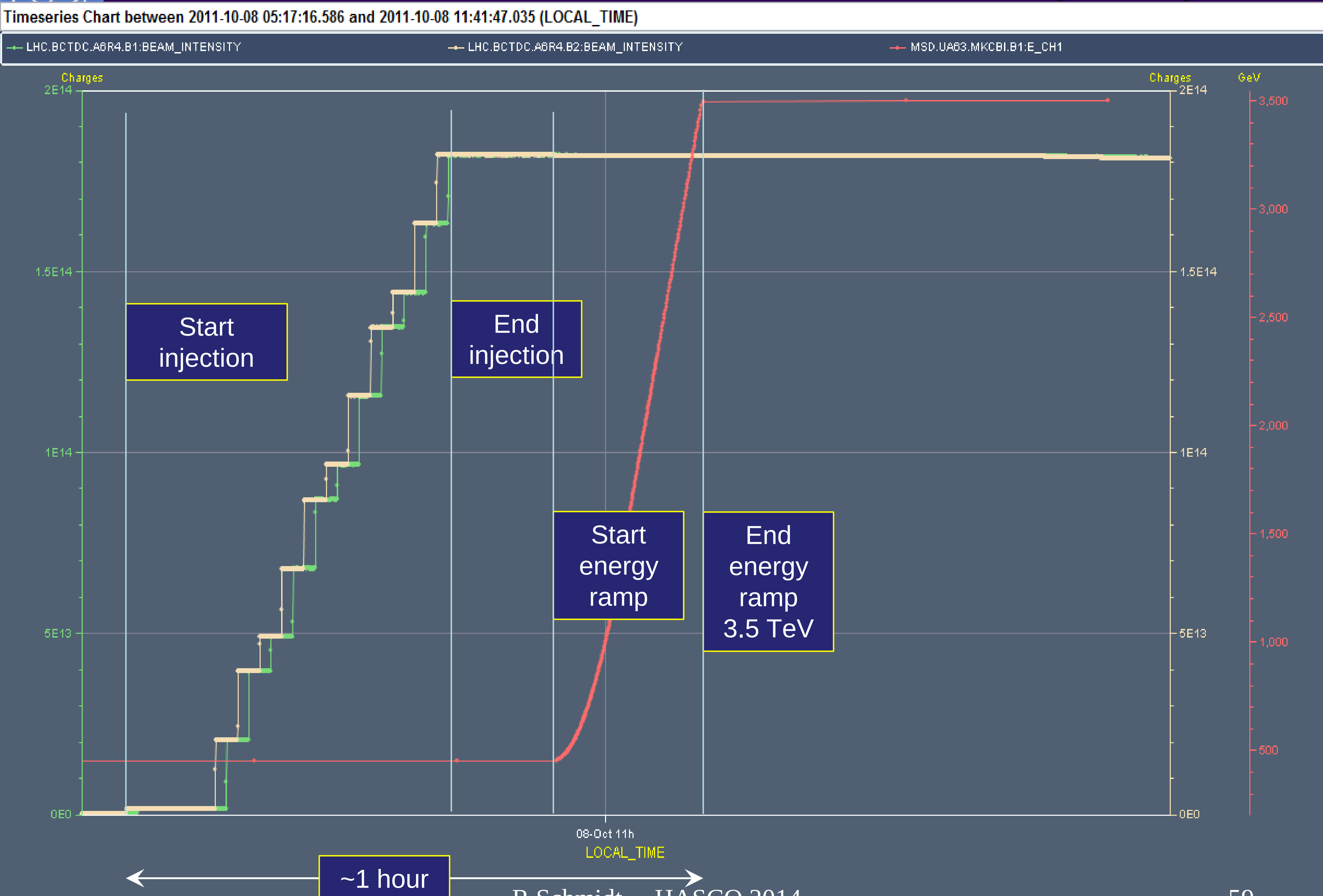
High luminosity: consequences

- High energy stored in the beams: Machine Protection
  - Dumping the beam in a safe way in case of failure
  - 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
- UFOs – see later
- Beam instabilities due to impedance and beam–beam effects
- Photo electrons, generated by beam losses - accelerated by the following bunches – lead to instabilities

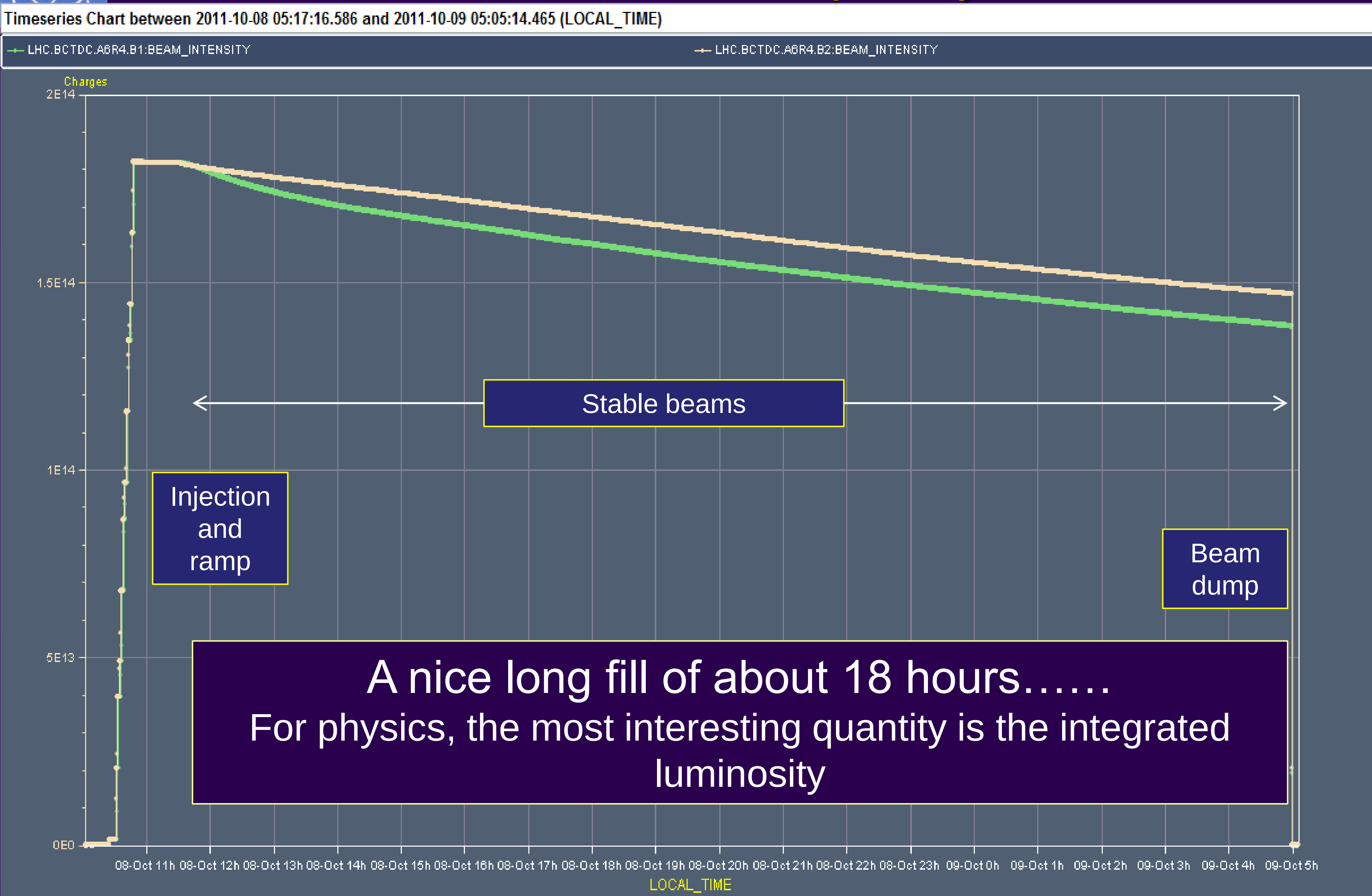
Understanding LHC operation

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

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



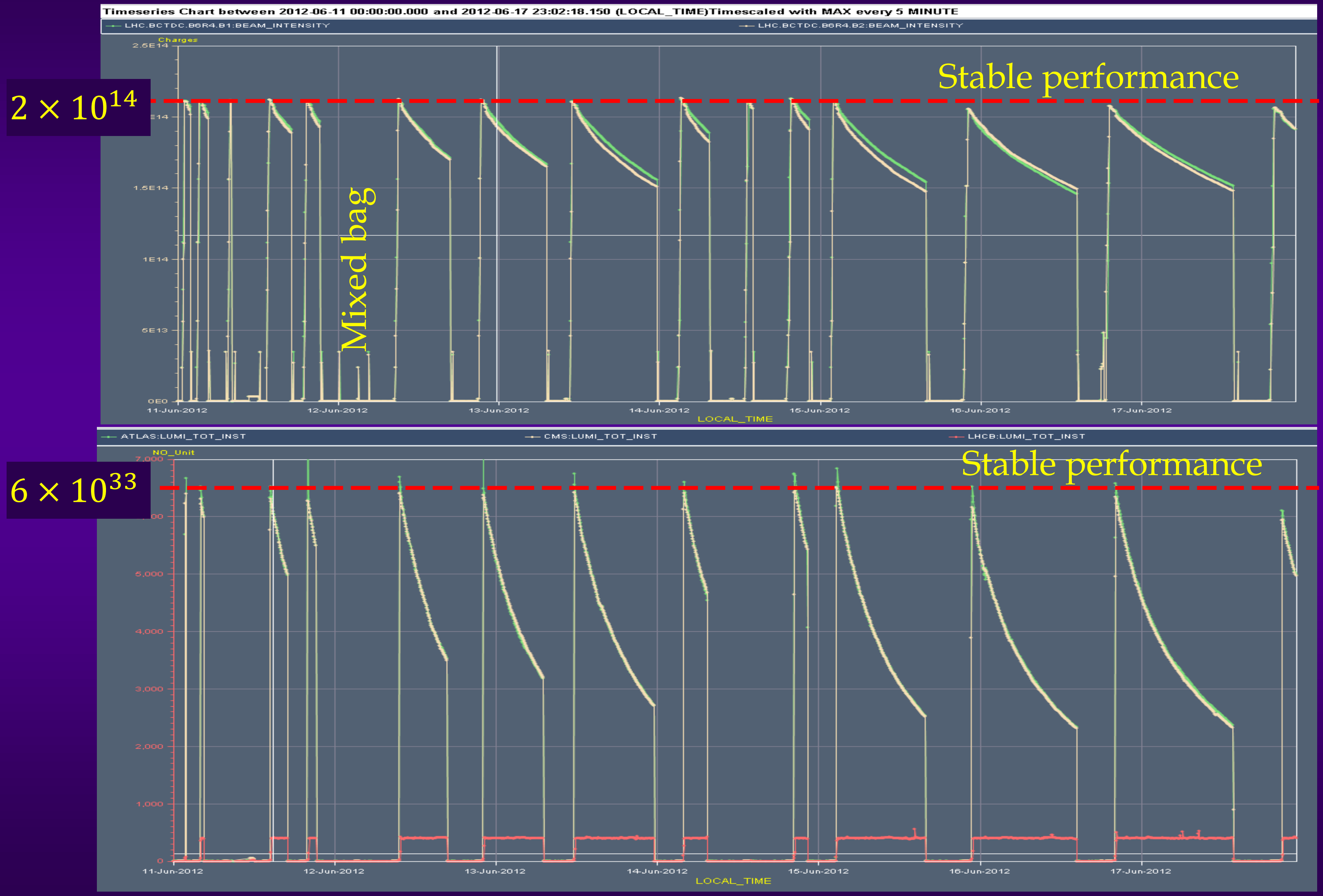
Excellent fill (2011)



A nice long fill of about 18 hours……

For physics, the most interesting quantity is the integrated luminosity

Beam Intensities and Luminosity 11-18/6/2012

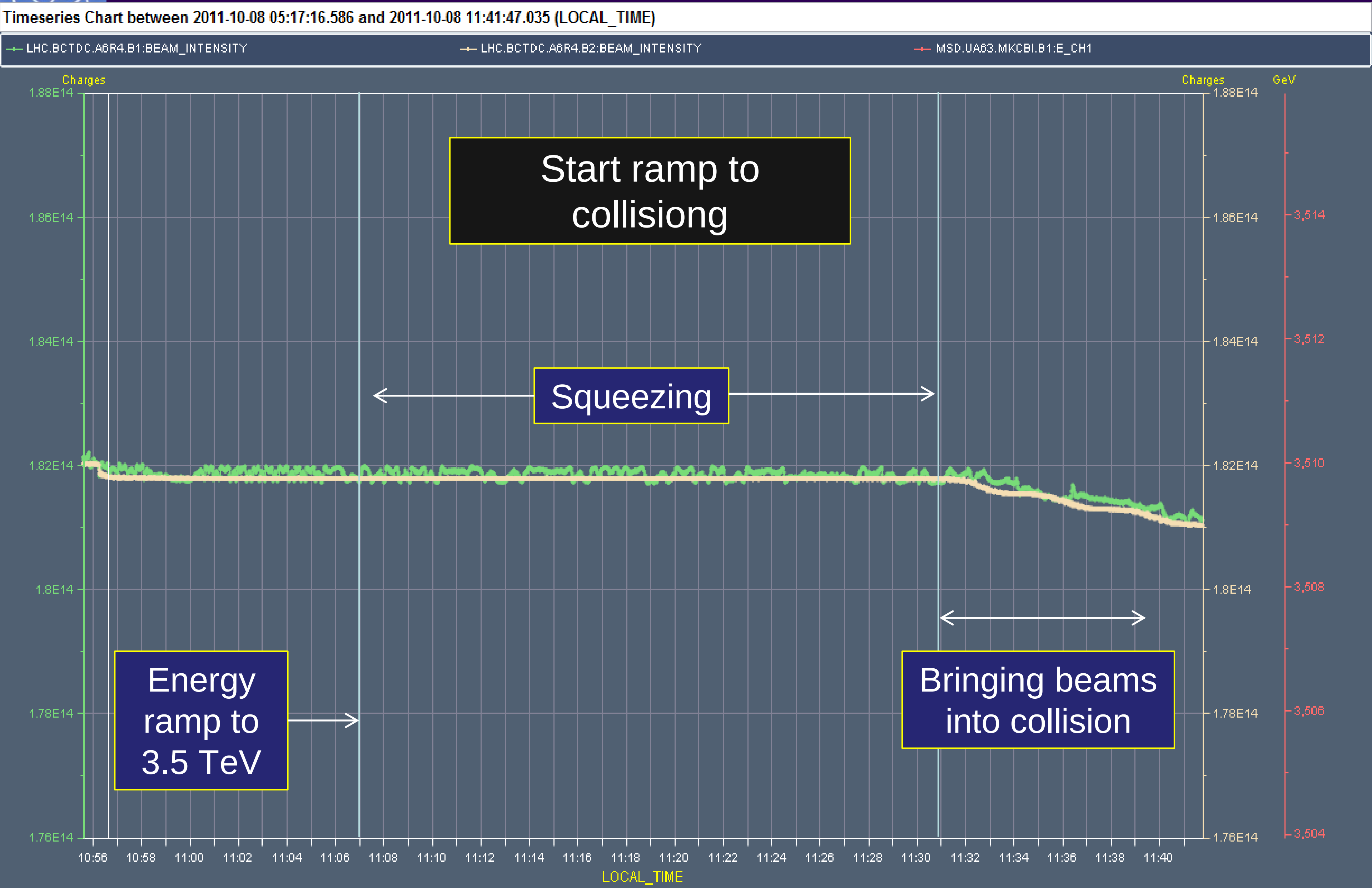


Overview of fills

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



Challenges operating with high intensity beams

Machine Protection and Collimation

Electron clouds

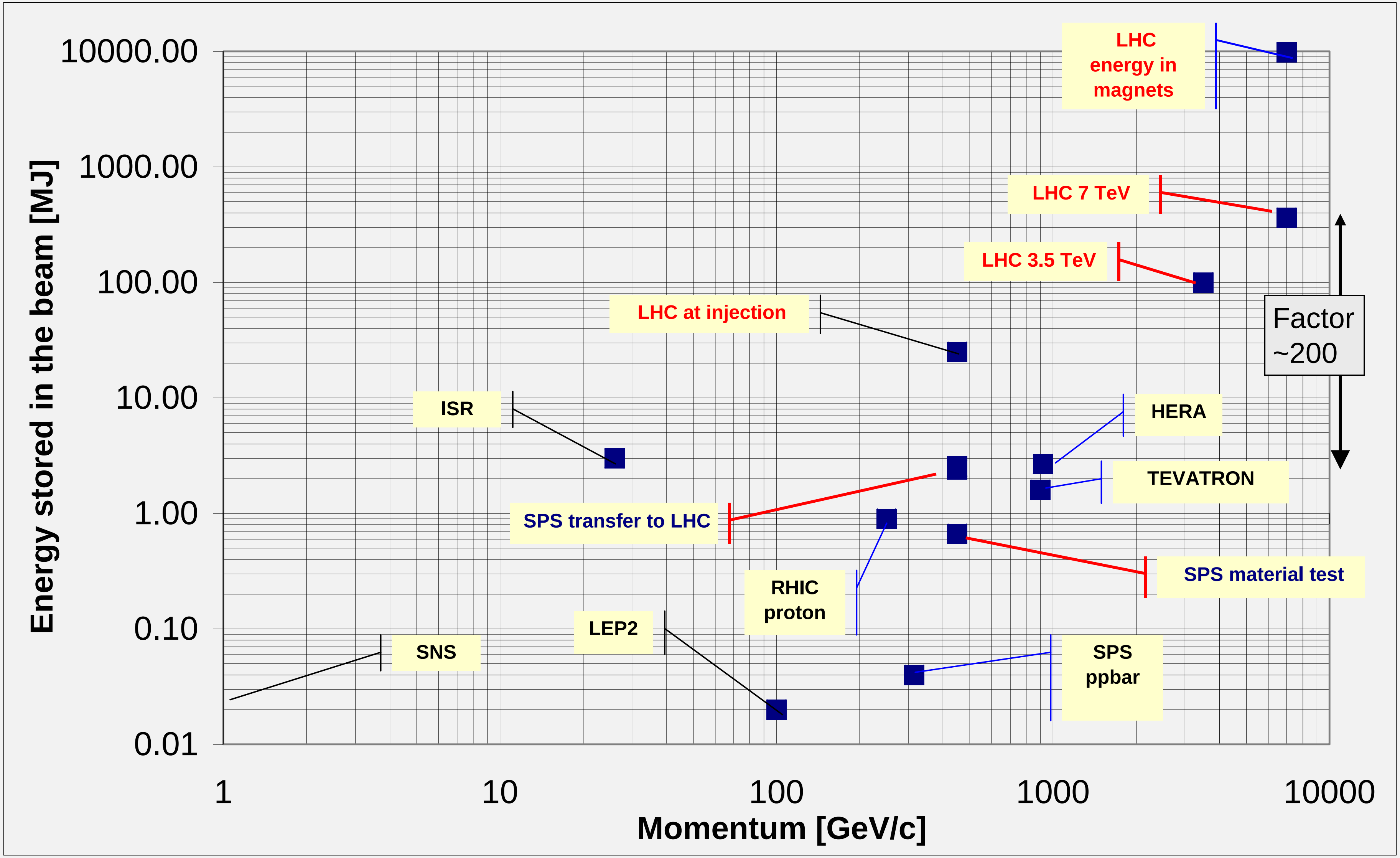
Instabilities

Damage of components

Ufos

Pile-up in the LHC experiments

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

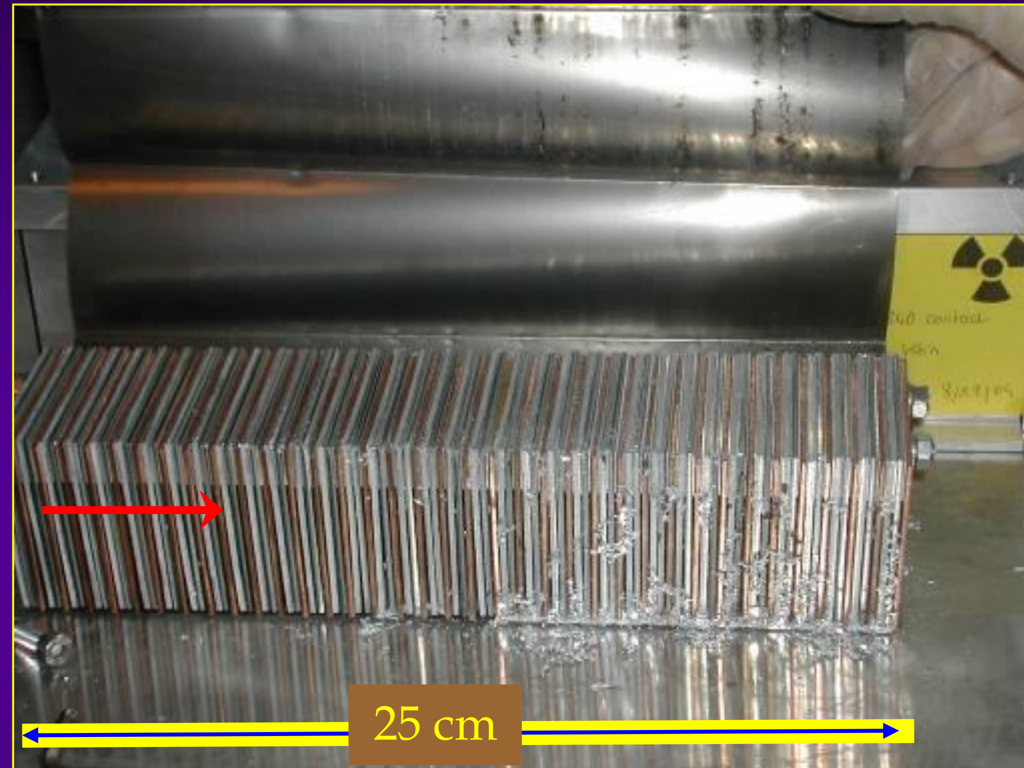
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

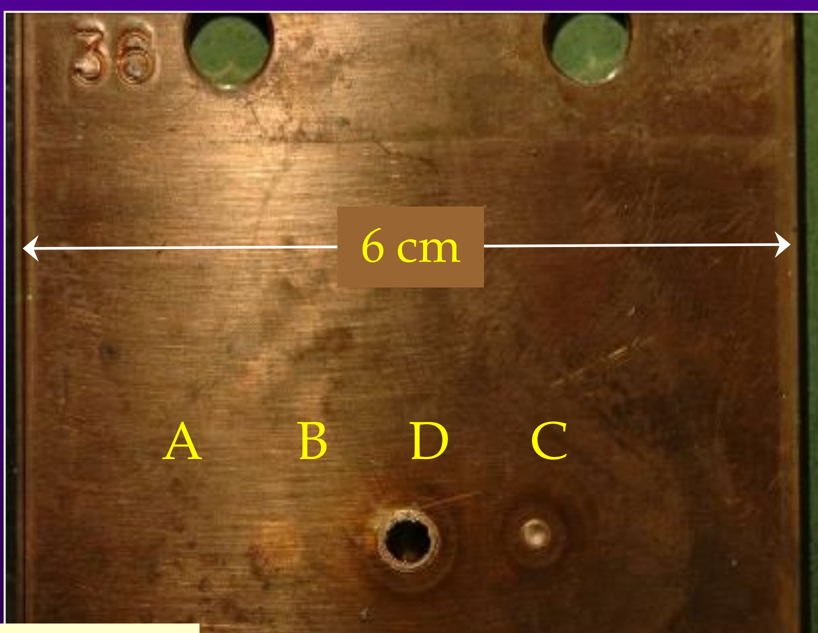
above damage limit for copper

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

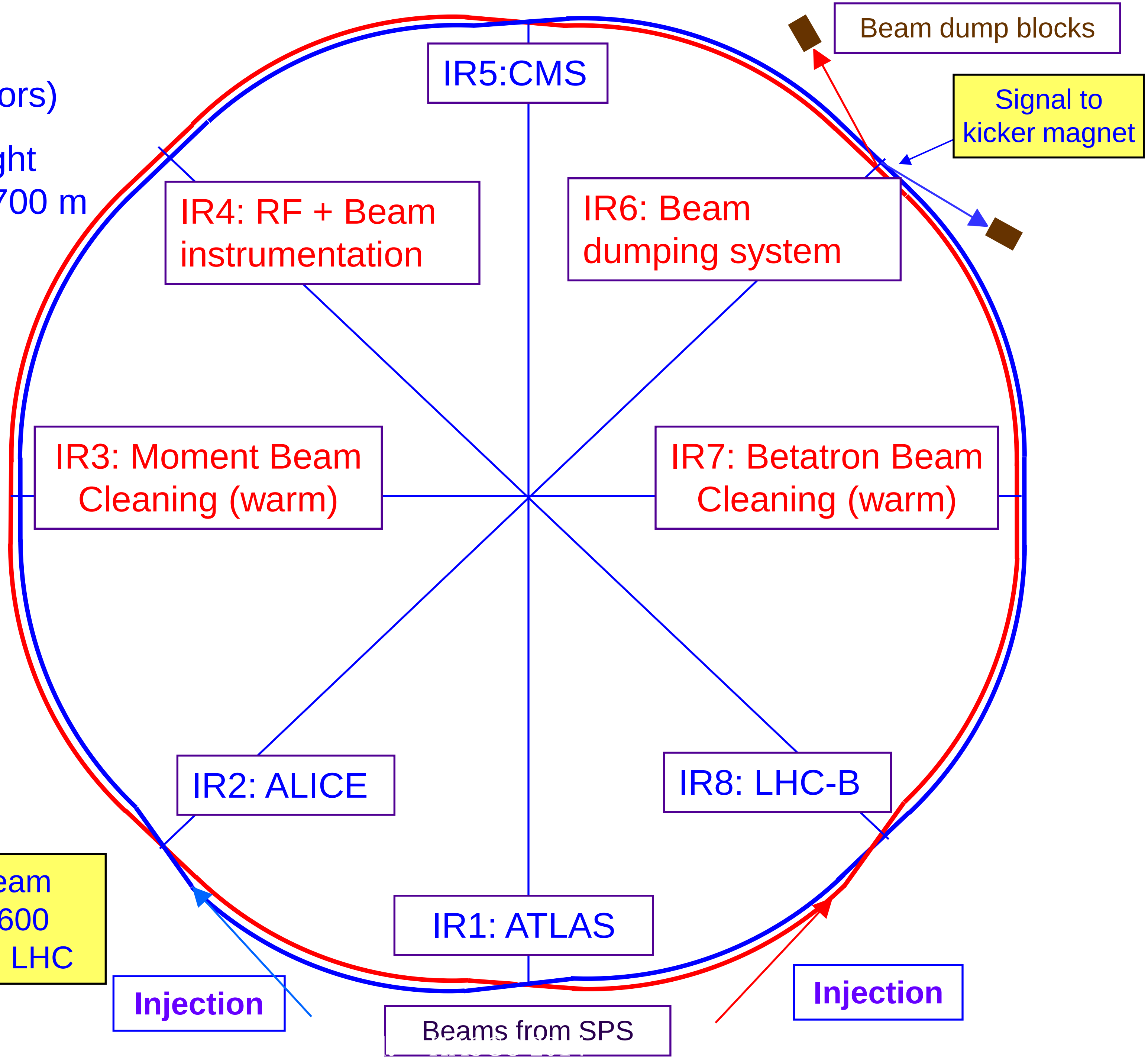
Strategy for protection and related systems

- Capture beam losses with collimators to reduce losses in the cold machine
- Detect failure at hardware level and stop beam operation
- Detect initial consequences of failure with beam instrumentation ….before it is too late…
- Stop beam operation
  - inhibit injection
  - extract beam into beam dump block
  - stop beam by beam absorber / collimator
- Some elements in the protection systems
  - beam dump (fast kicker magnet and absorber block)
  - collimators and beam absorbers
  - beam loss monitors

LHC Layout

eight arcs (sectors)

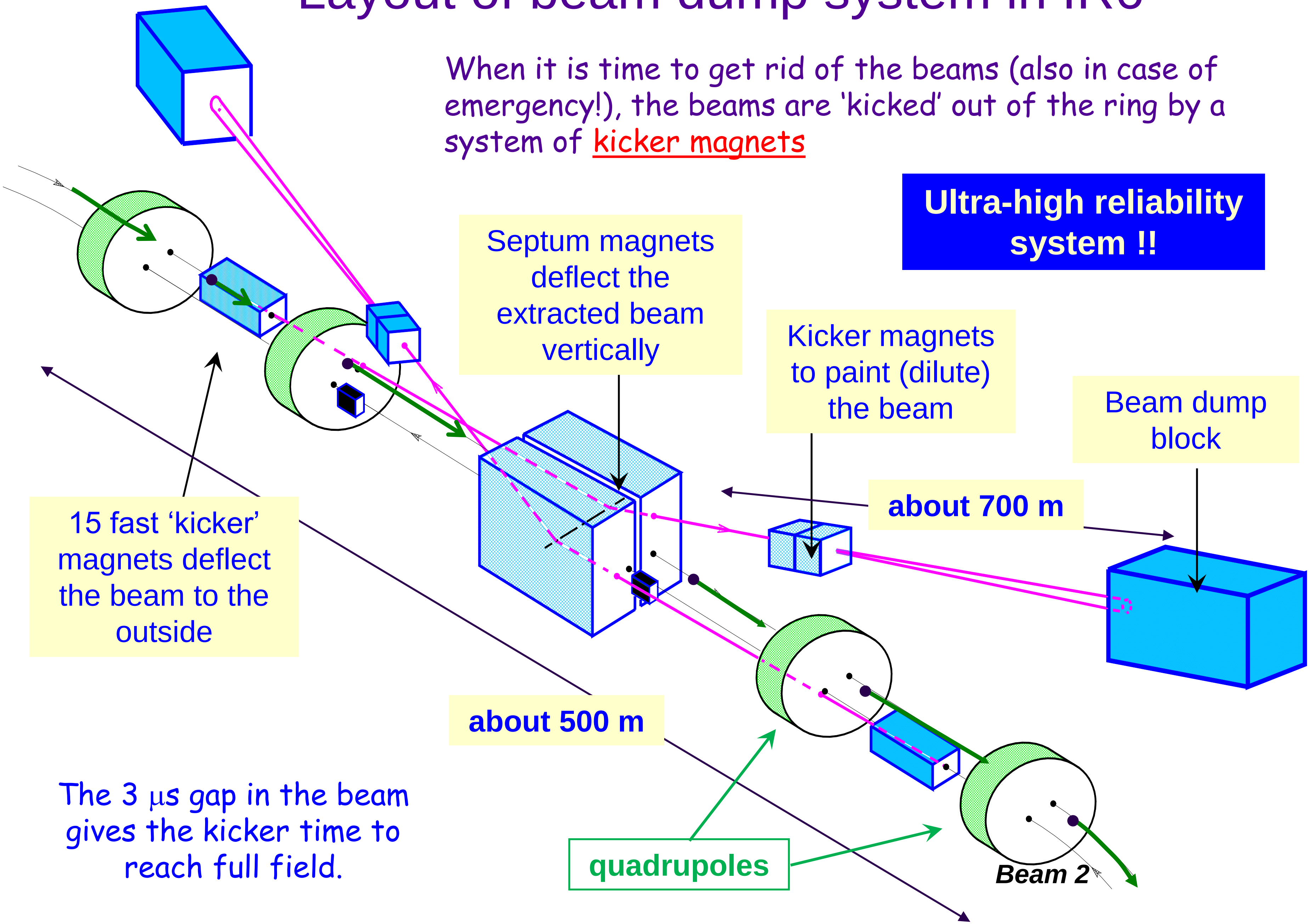
eight long straight section (about 700 m long)



Detection of beam losses with >3600 monitors around LHC

Layout of beam dump system in IR6

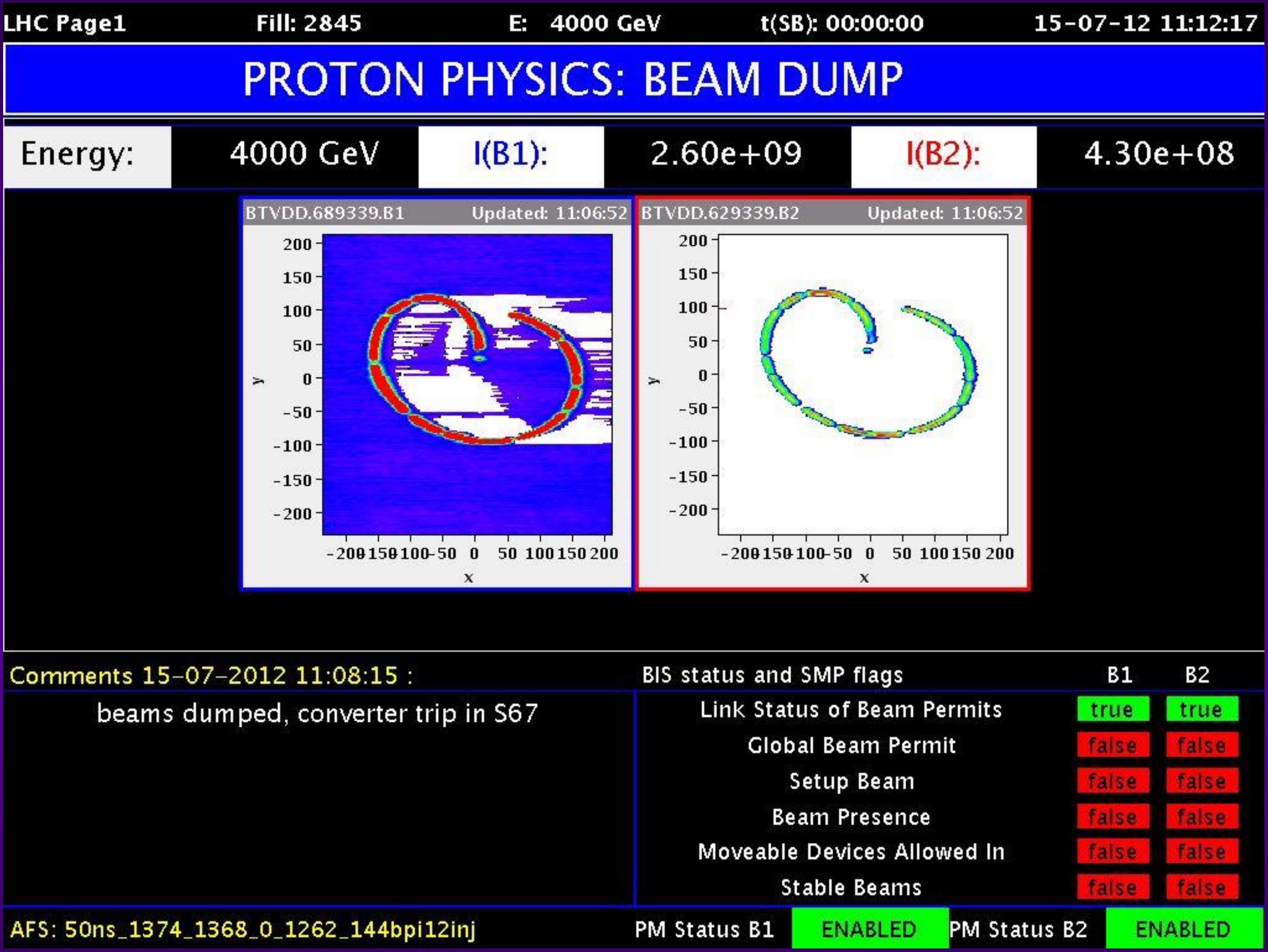
When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets



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

Dump line

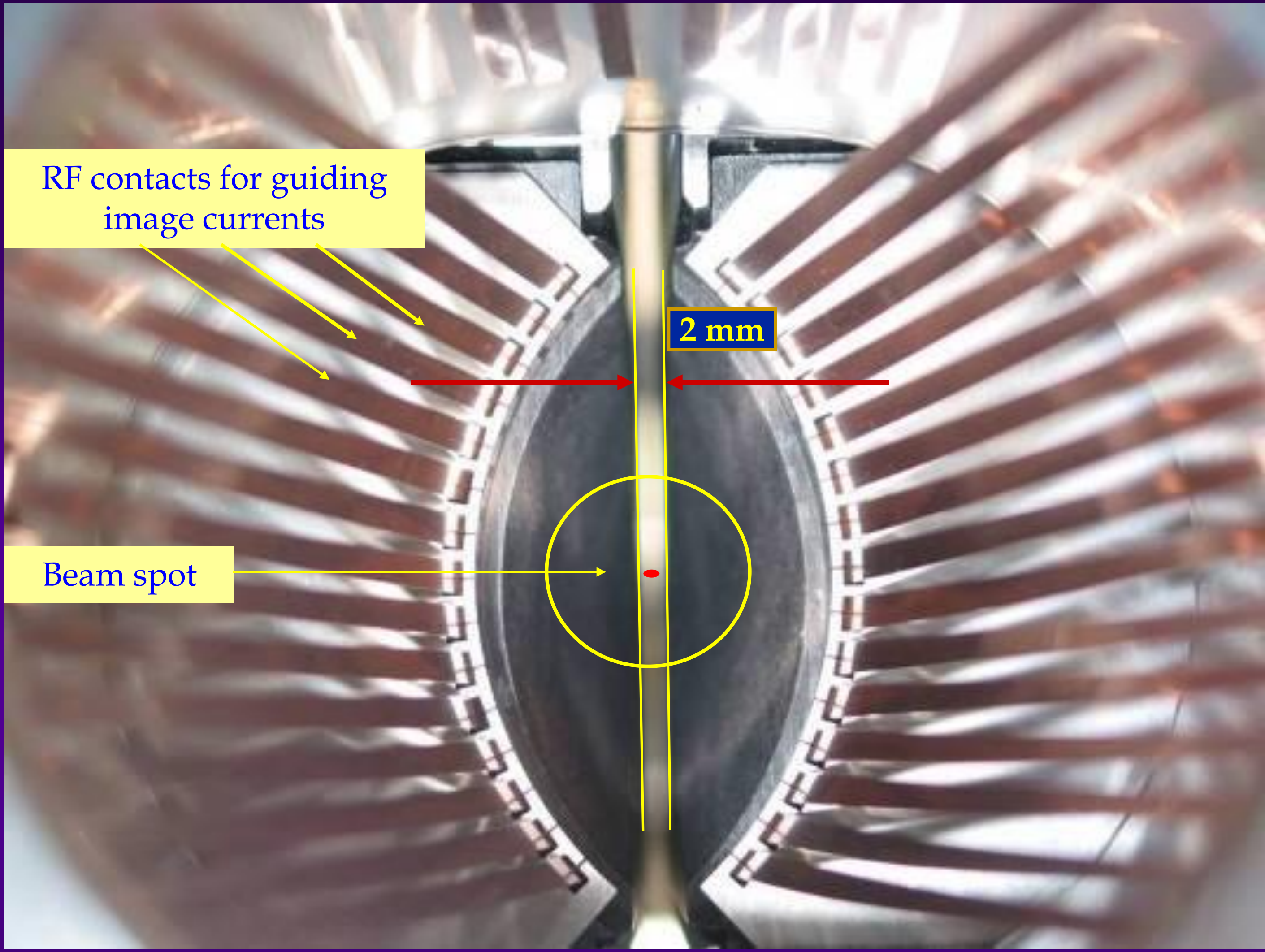
Beam dump with 1380 bunches



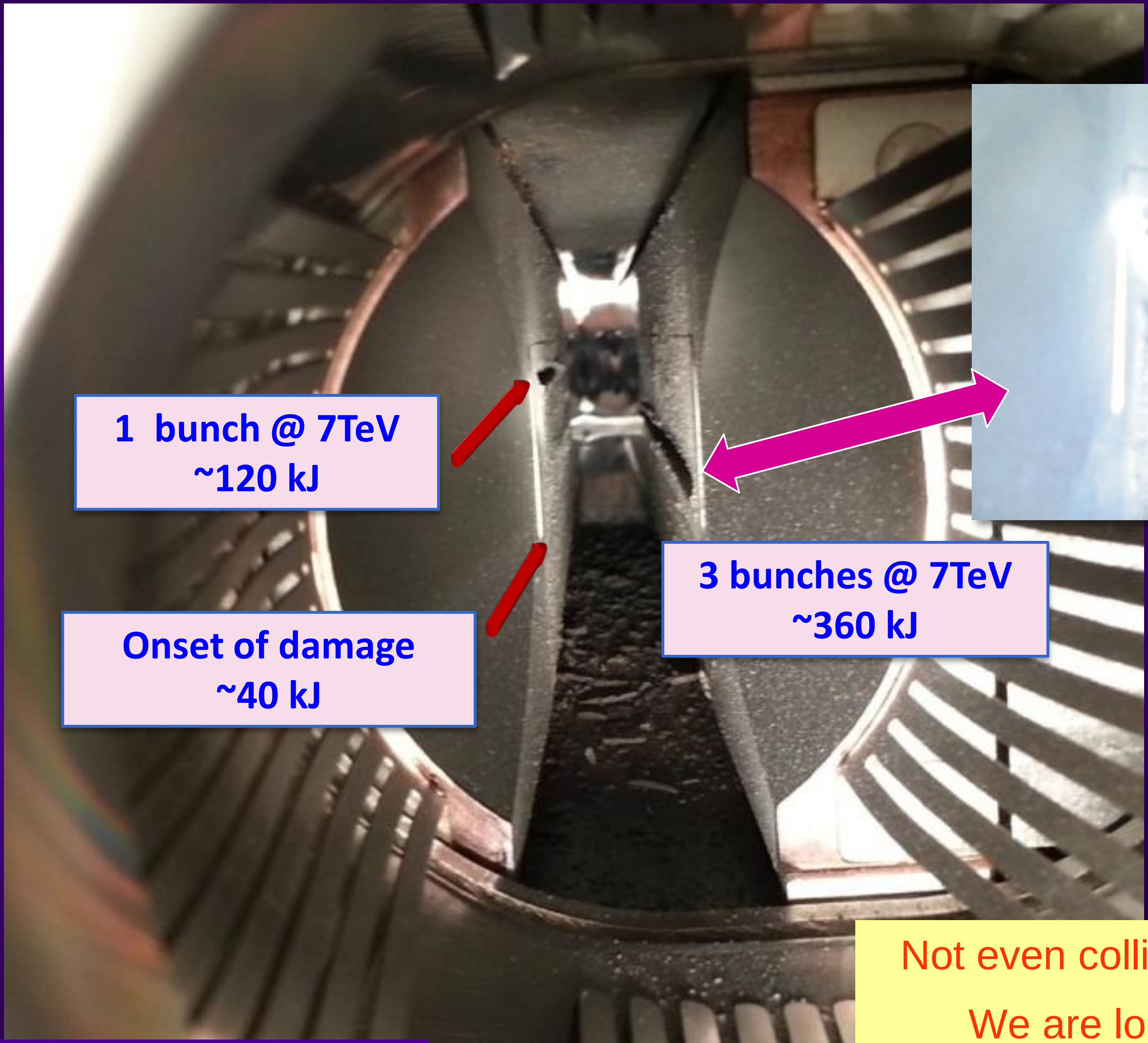
Beam spot at the end of the beam dumping line, just in front of the beam dump block

View of a two sided collimator

about 100 collimators are installed in LHC



Beam impact on a Tungsten collimator (experiment at SPS)



Courtesy A. Bertarelli (CERN-EN)

Not even collimators are safe !

We are looking for new materials…

Betatron beam cleaning

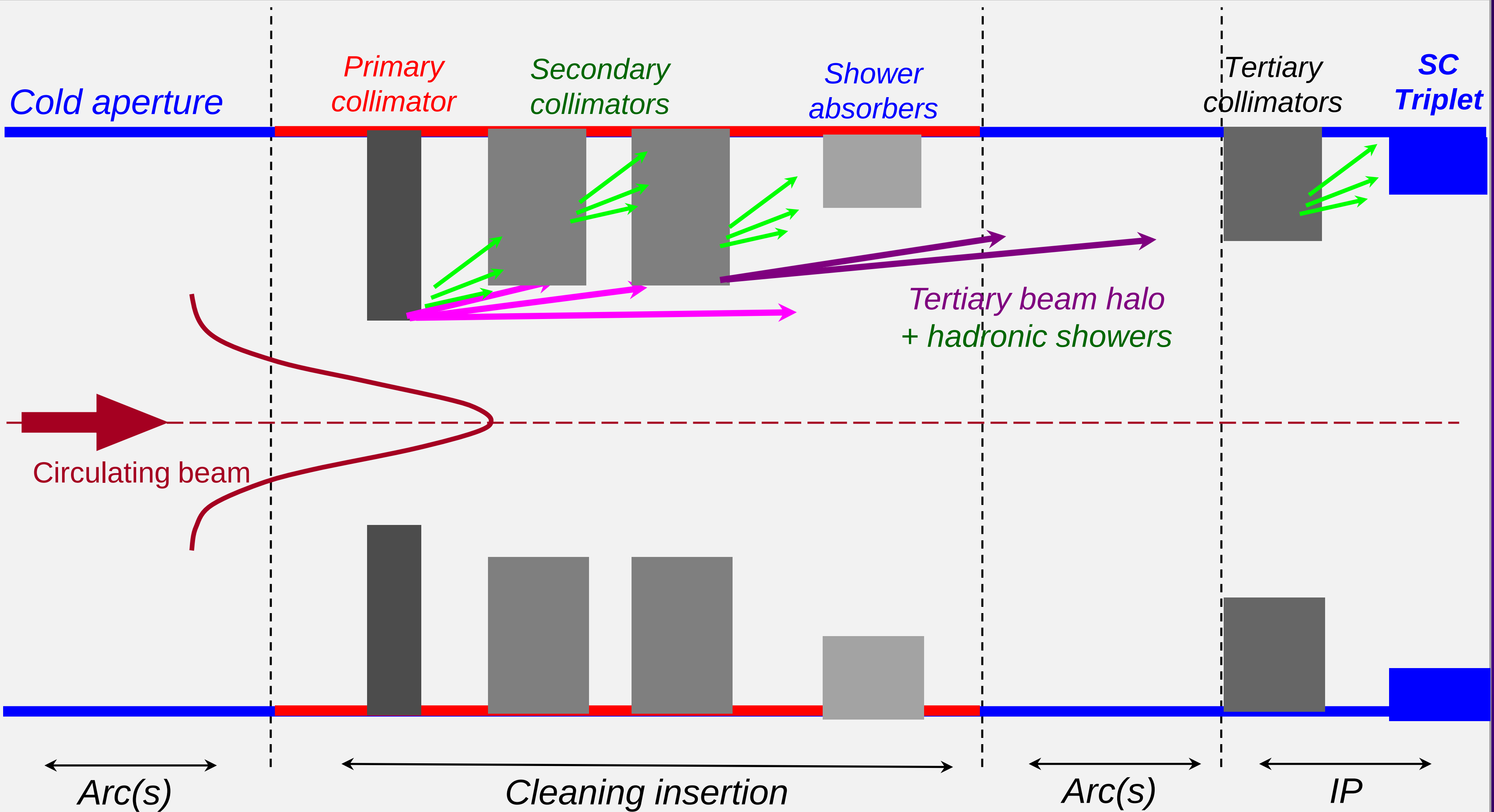
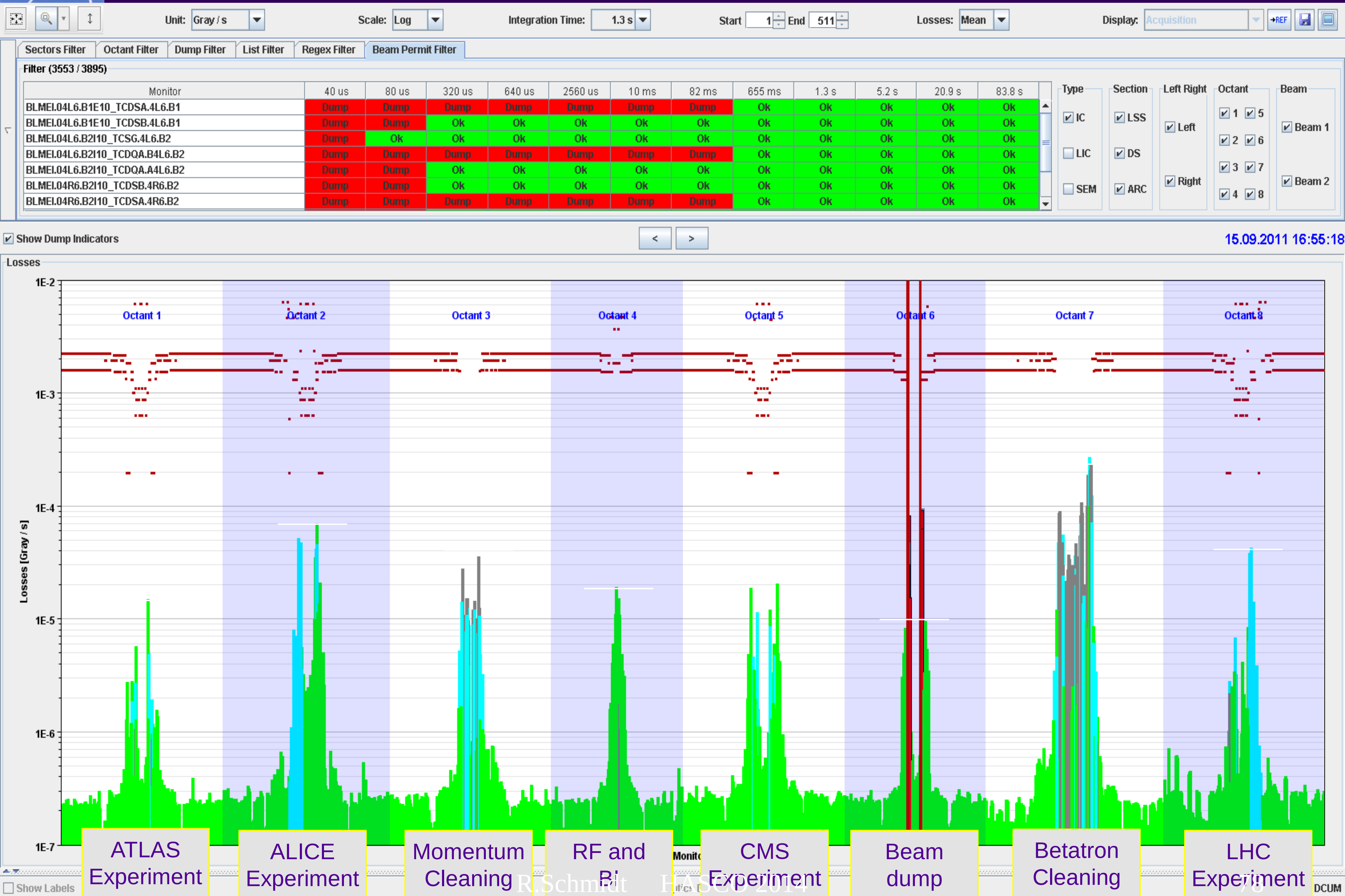


Illustration drawing

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

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

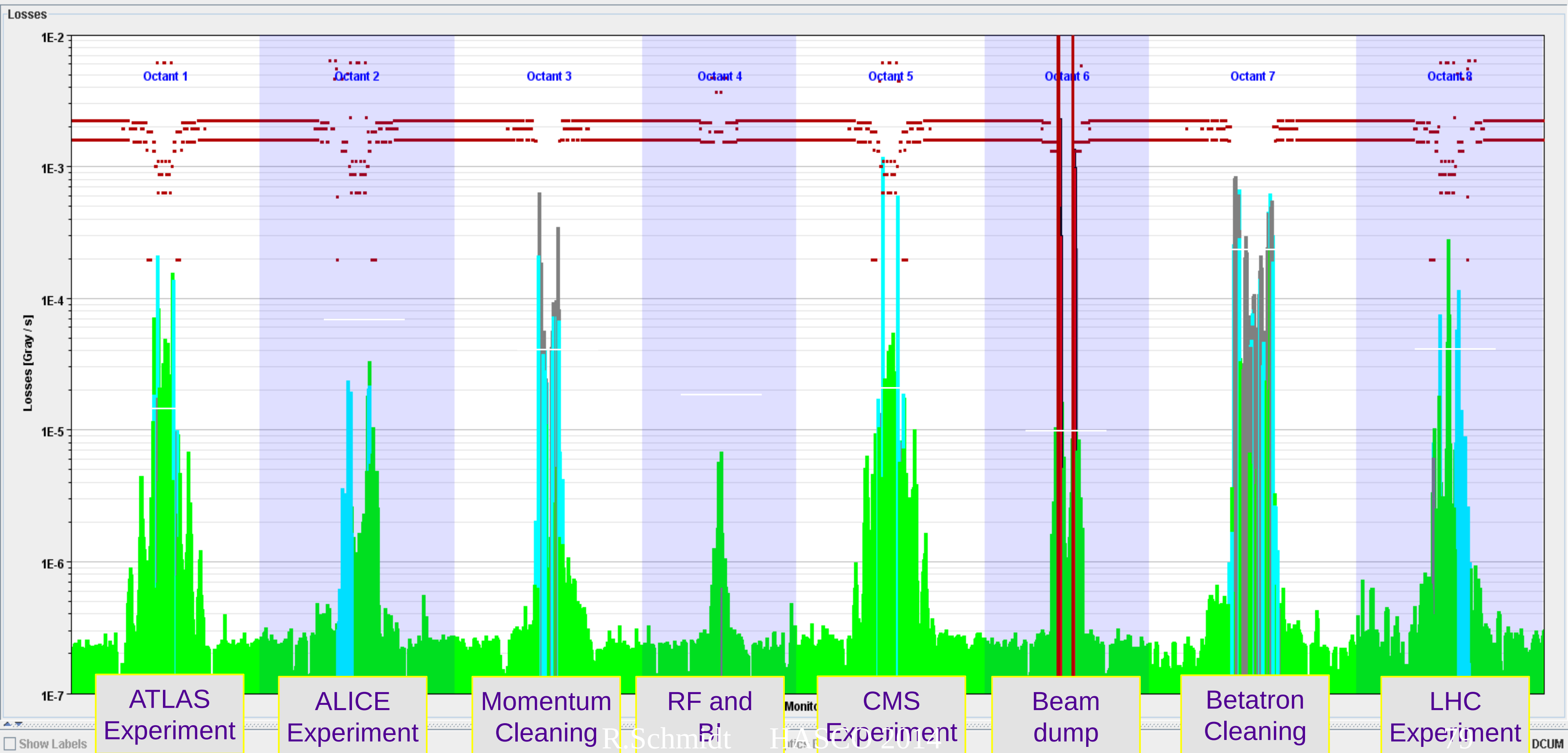
Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

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

Type: IC, LIC, SEM — Section: LSS, DS, ARC — Left Right: Left, Right — Octant: 1, 2, 3, 4, 5, 6, 7, 8 — Beam: Beam 1, Beam 2

Show Dump Indicators 13.09.2011 21:04:59



Accidental beam losses during collisions

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

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

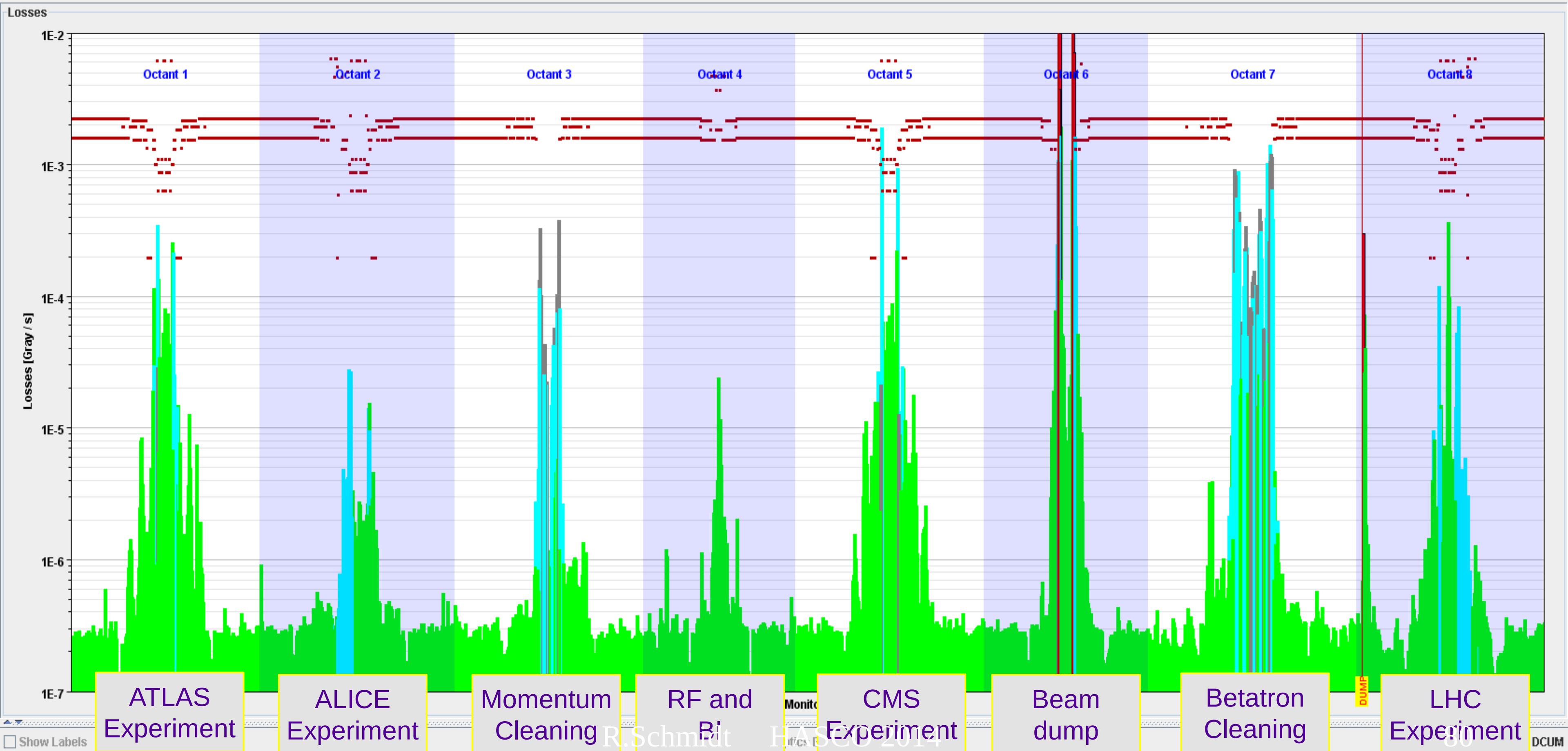
Filter (3550 / 3892)

Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B1E10_TCDQA.B4R6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok

Type: IC, LIC, SEM | Section: LSS, DS, ARC | Left Right: Left, Right | Octant: 1, 2, 3, 4, 5, 6, 7, 8 | Beam: Beam 1, Beam 2

Show Dump Indicators

30.07.2011 23:53:11



Zoom one monitor: beam loss as a function of time

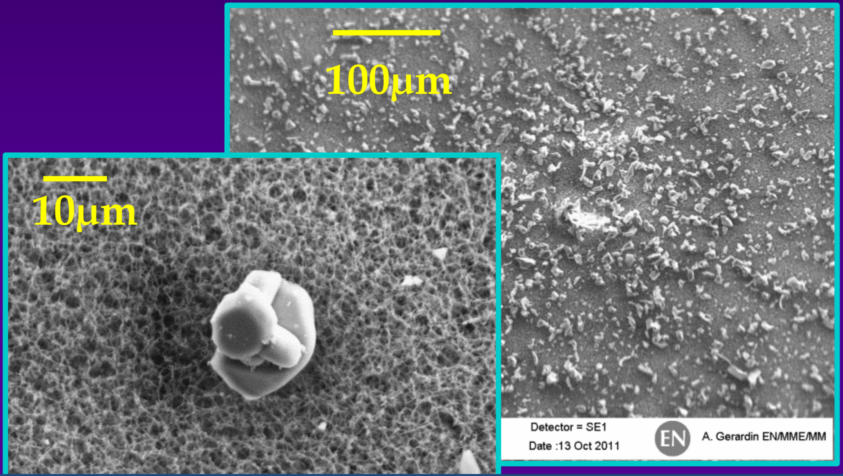
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B1E10_TCDQA.B4R6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok

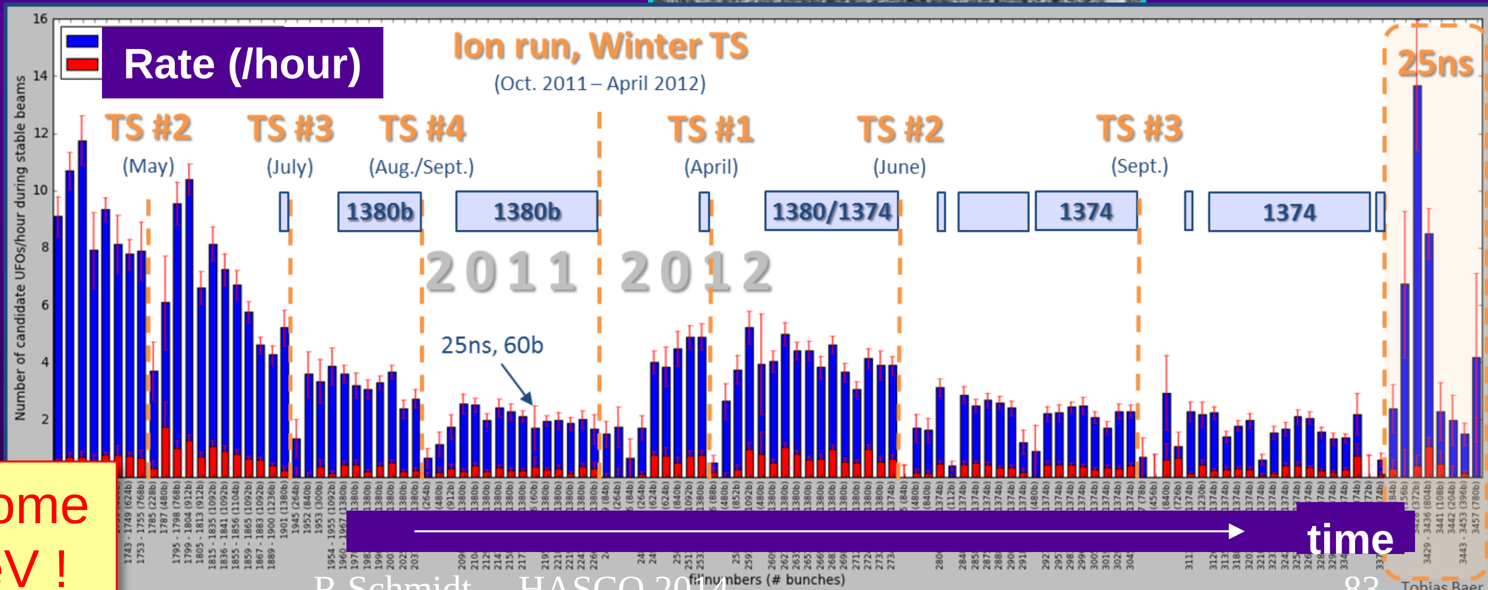
UFOs at LHC

Surprising ‘Unidentified Falling Objects’

- Very fast 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.

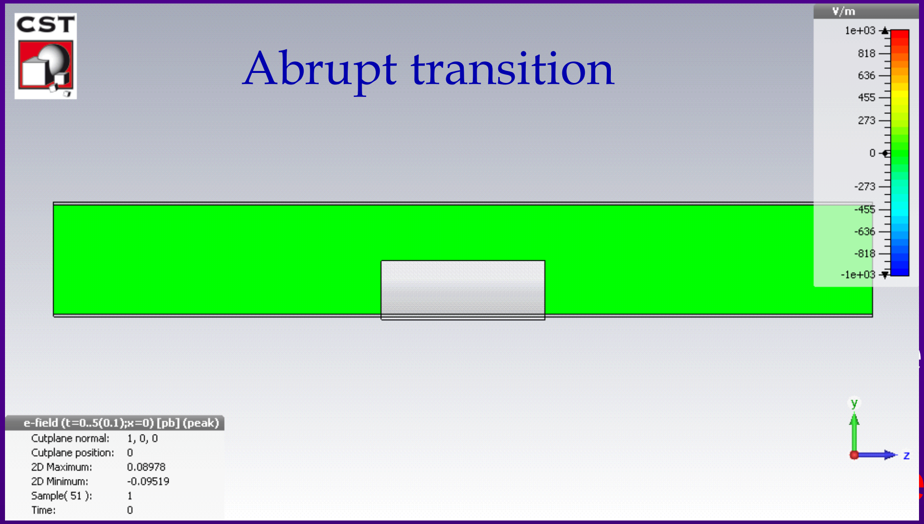


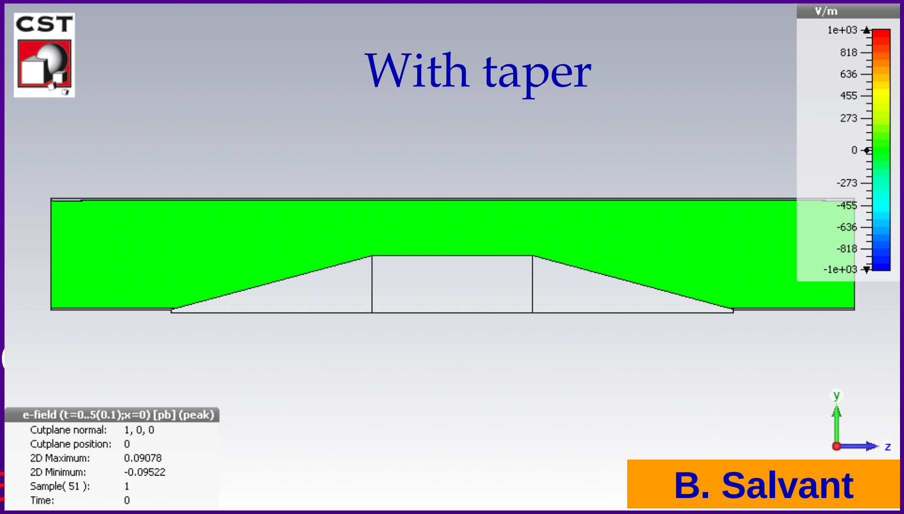


UFOs could become an issue at 7 TeV !

Wake fields and Impedances Challenge

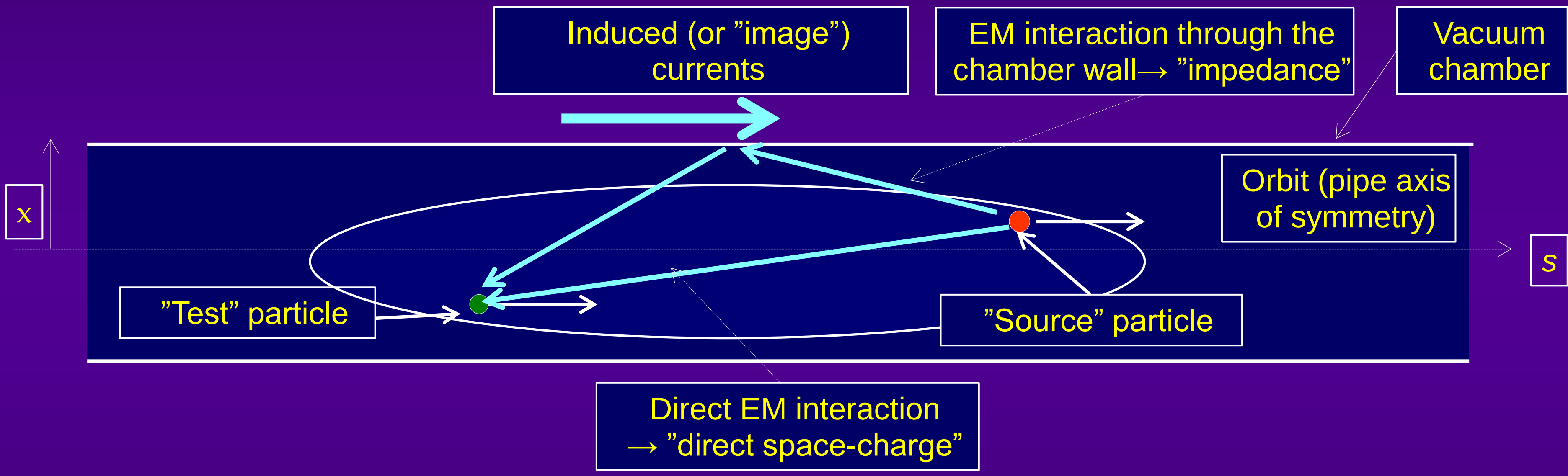
- Intense bunches generate electromagnetic fields when passing inside a structure (in particular Carbon collimators – opening of ~1 mm!!!)
- → results in an EM force, called wake field in time domain coupling with the beam

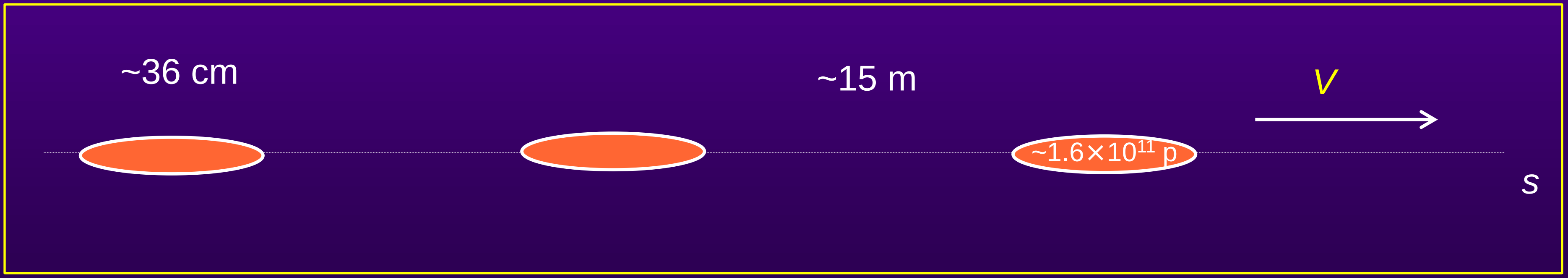




Limits to the bunch population

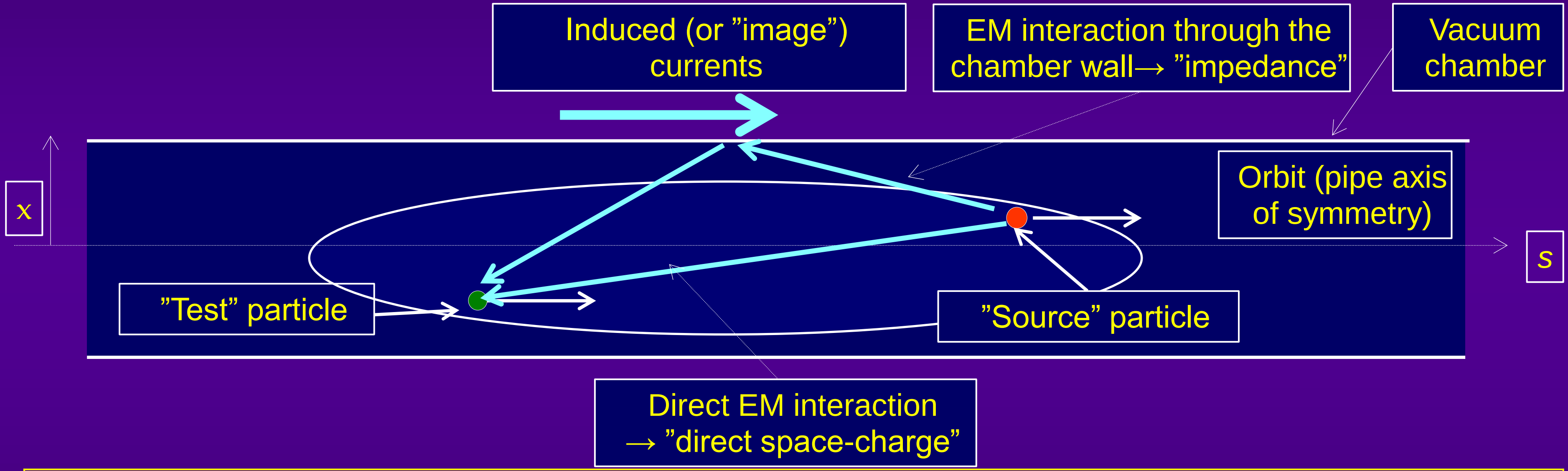
- High bunch population and tight bunch spacing make the beams prone to instabilities related to impedances i.e. to **self-generated fields**





Limits to the bunch population

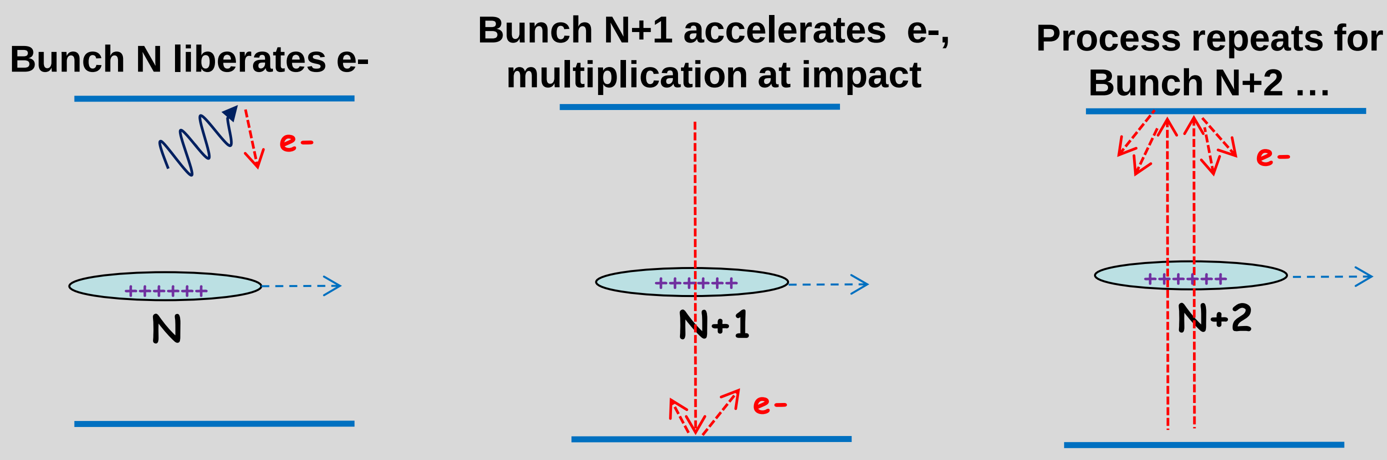
- High bunch population and tight bunch spacing make the beams prone to instabilities related to impedances i.e. to **self-generated fields**



- 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!

Electron cloud challenge

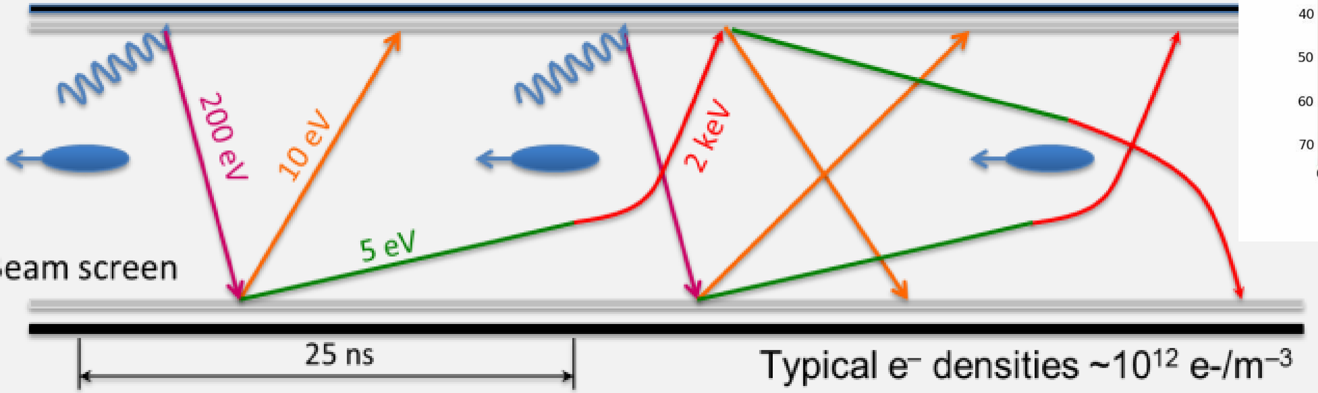
In high intensity accelerators with positively charged beams and closely spaced bunches, electrons liberated on vacuum chamber surface can multiply and build up a cloud of electrons.

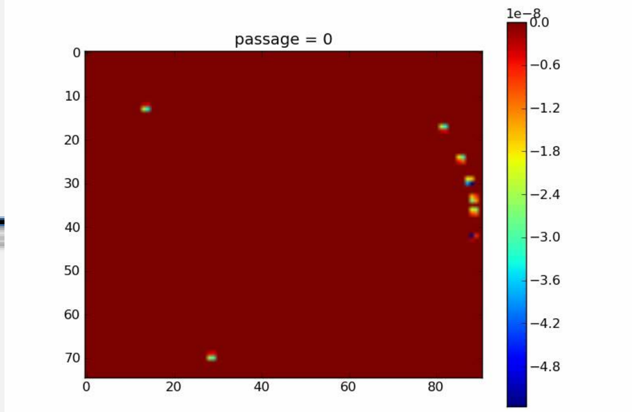


The cloud triggers vacuum pressure increases and beam instabilities!

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

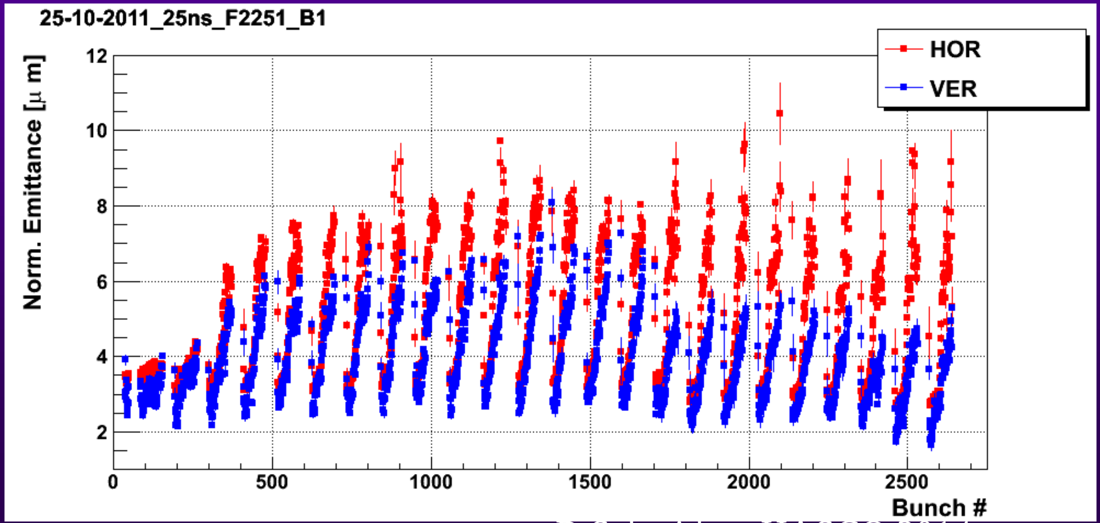
Strong reduction of e-clouds with larger bunch spacing:

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

→ One of the main reason to operate so far with 50 ns spacing

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

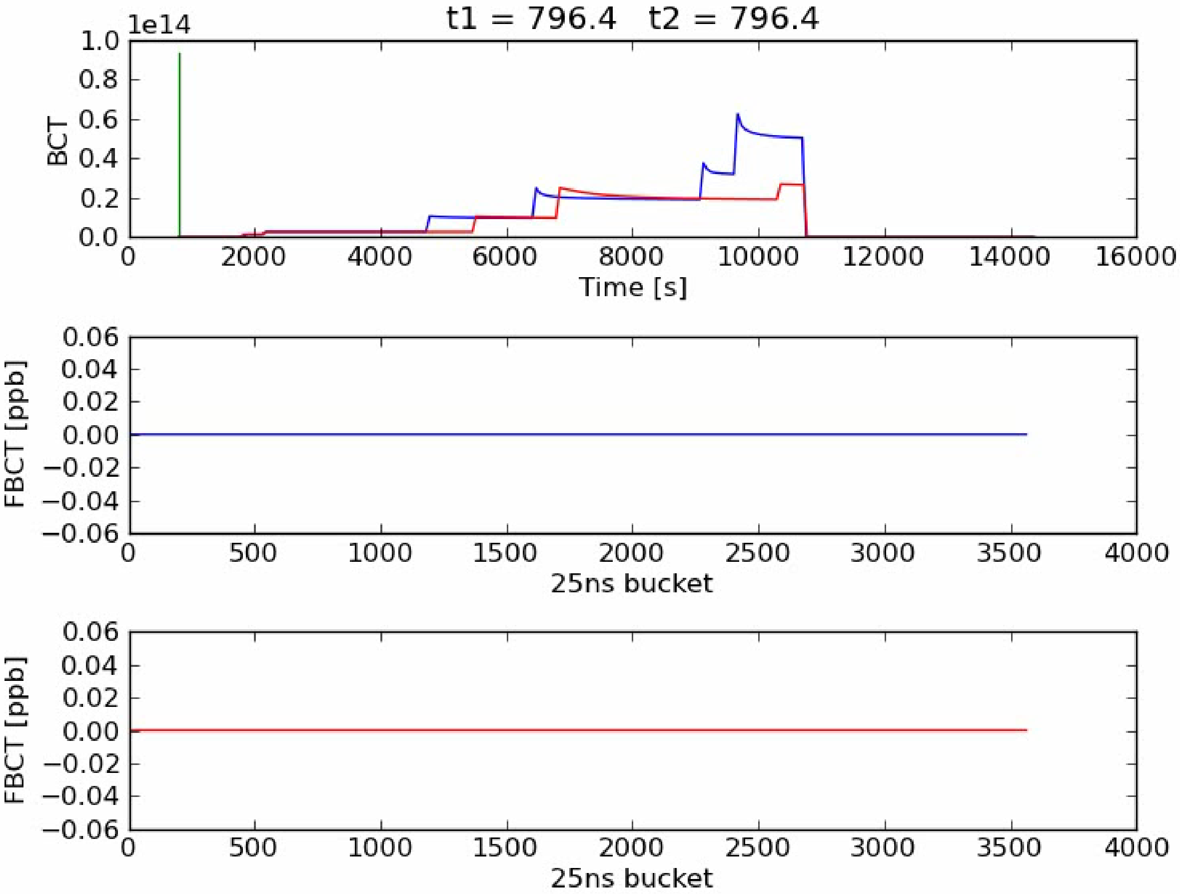
- e-clouds are produced deliberately with the beams to bombard the surface of the chamber to reduce the SEY until the cloud 'disappears'.
- Done at 450 GeV where fresh beams can be injected easily.



Beam emittances ($\propto$ beamsize * beamsize) in the presence of e-clouds

Electron cloud effects

2012 injection tests (10 July 2012)



Beam 1

Beam 2

Bunch-by-bunch population Beam 1

Bunch-by-bunch population Beam 2

G.Rumolo

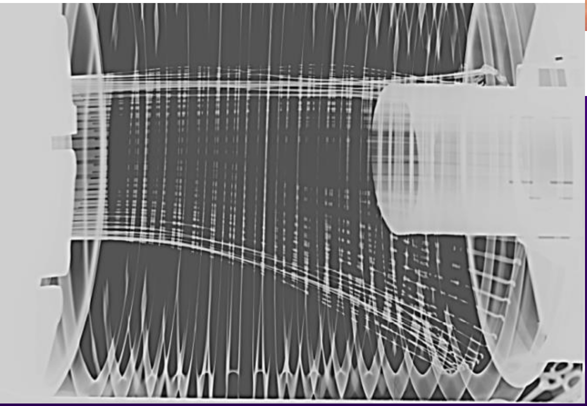
Damage from heating by the beam

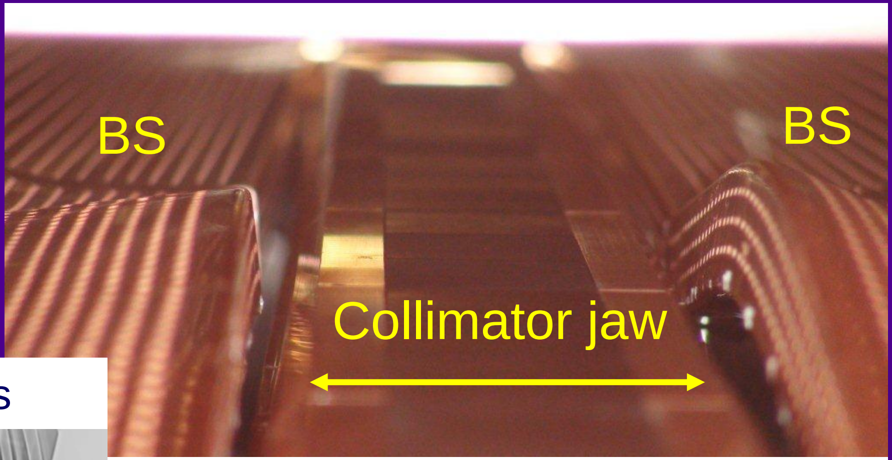
High intensity beams may deposit large amounts of power in incorrectly shielded components around the beam

- 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

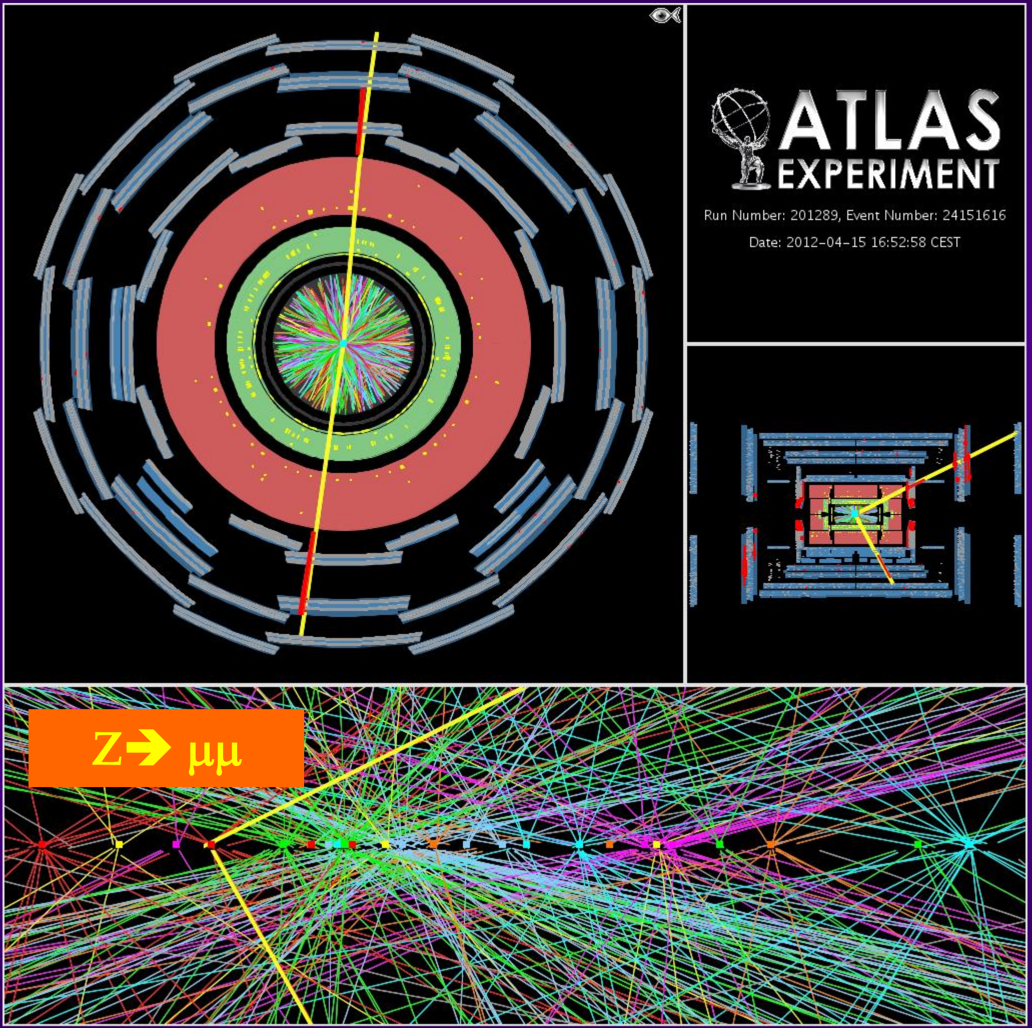
Damaged RF fingers





Damaged beam screen (BS) in a collimator

Pile-up density

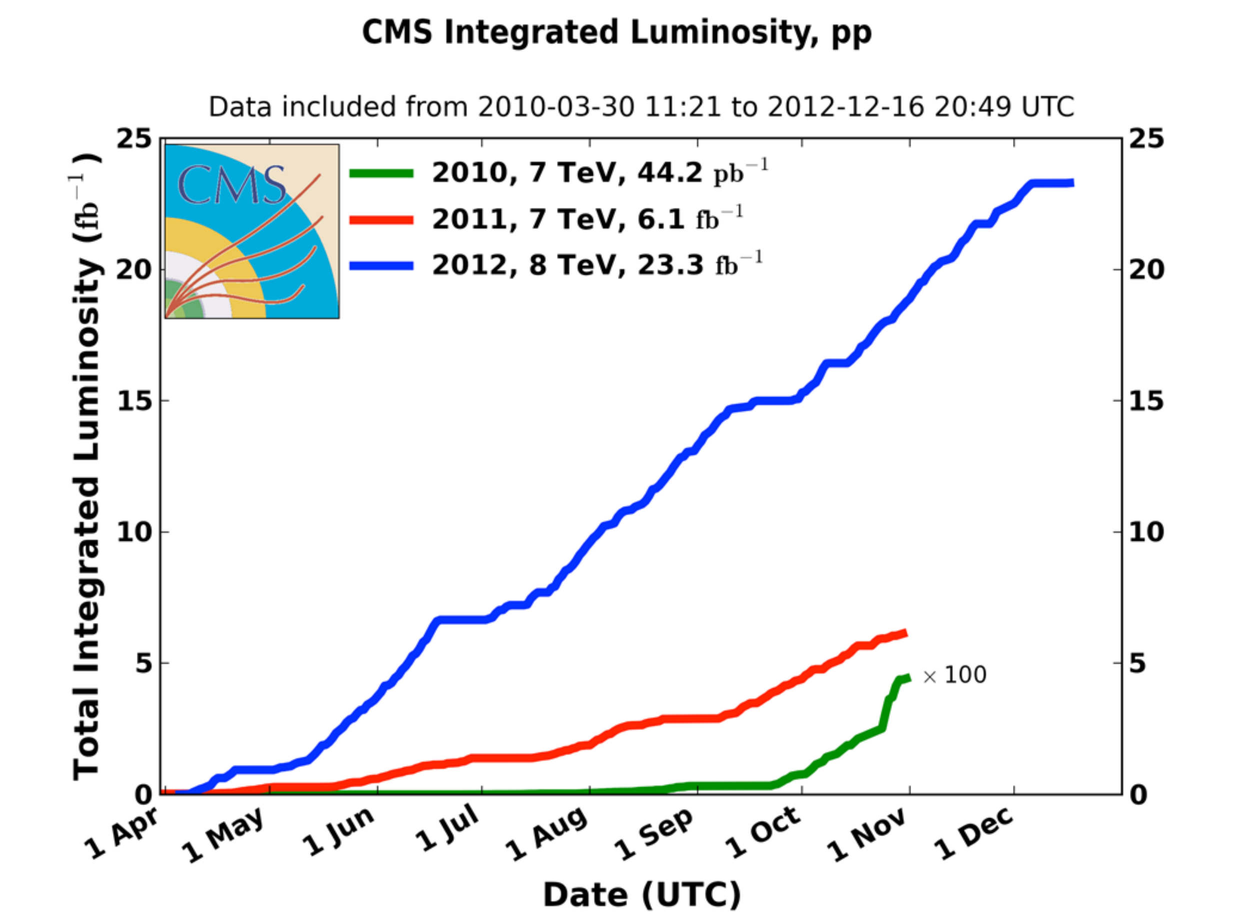


- 25 reconstructed vertices – in a luminous region of 4.3 cm r.m.s. length
- Peaks of >40 events per bunch crossing observed with luminosities in the range of $7x10^{33}$ $cm^{-2}s^{-1}$
- That is why we are here

- Pile-up proportional to luminosity per bunch → more bunches (i.e. 25 ns) is better

Overall performance during Run 1.....

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

Summary: 2010 to 2012

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

Parameter	2010	2011	2012	Nominal
Energy [TeV]	3.5	3.5	**4.0**	7.0
N_b [10^{11} p/bunch]	1.2	1.45	**1.6**	1.15
k (no. bunches)	368	1380	**1380**	2808
Bunch spacing [ns]	150	75 / 50	**50**	25
Stored energy [MJ]	25	112	**140**	362
ε^* [μm]	2.4	2.4	**2.5**	3.75
β^* [m]	3.5	1.5 → 1	**0.6**	0.55
Crossing angle [μrad]	200	240	**290**	285
L [10^{34} cm^{-2}s^{-1}]	0.02	0.35	**0.76**	1.0
Beam-beam parameter/IP (ΔQ_{bb})	-0.0054	-0.0065	**-0.0069**	-0.0033
Average Pile-up @ beg. of fill	8	17	**38**	26

What we learned during LHC Run 1…..

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

…..and lessons for Run 2

preparing for the run (2015 to 2018)

LHC Page1 | No data | E: 0 GeV | 08-07-13 18:40:19

SHUTDOWN: NO BEAM

Comments (08-Jul-2013 15:17:50)

Phone:77600

*** END OF RUN 1 ***

No beam for a while. Access required

time estimate: ~2 years

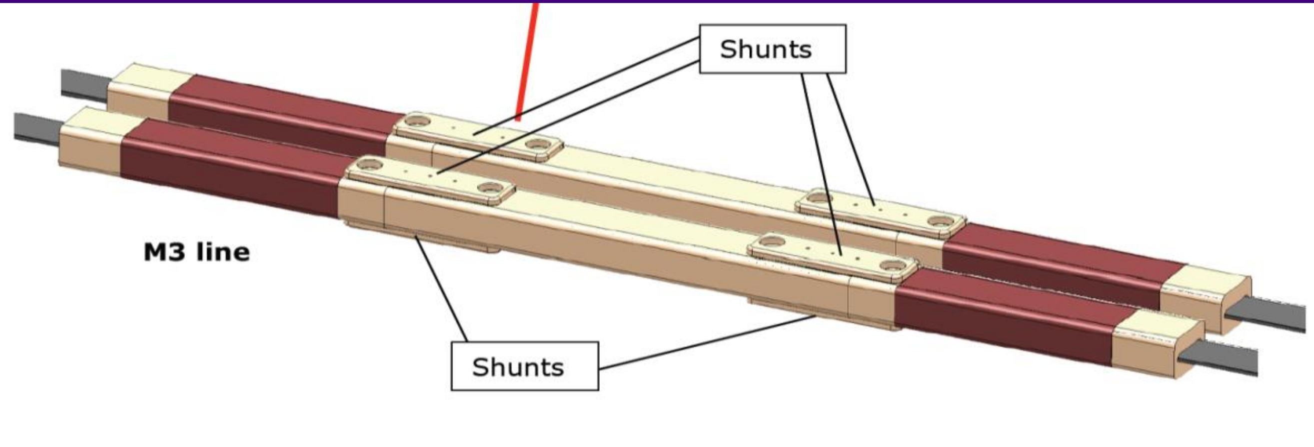
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	Except	Excepti
Global Beam Permit	Except	Excepti
Setup Beam	false	false
Beam Presence	false	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

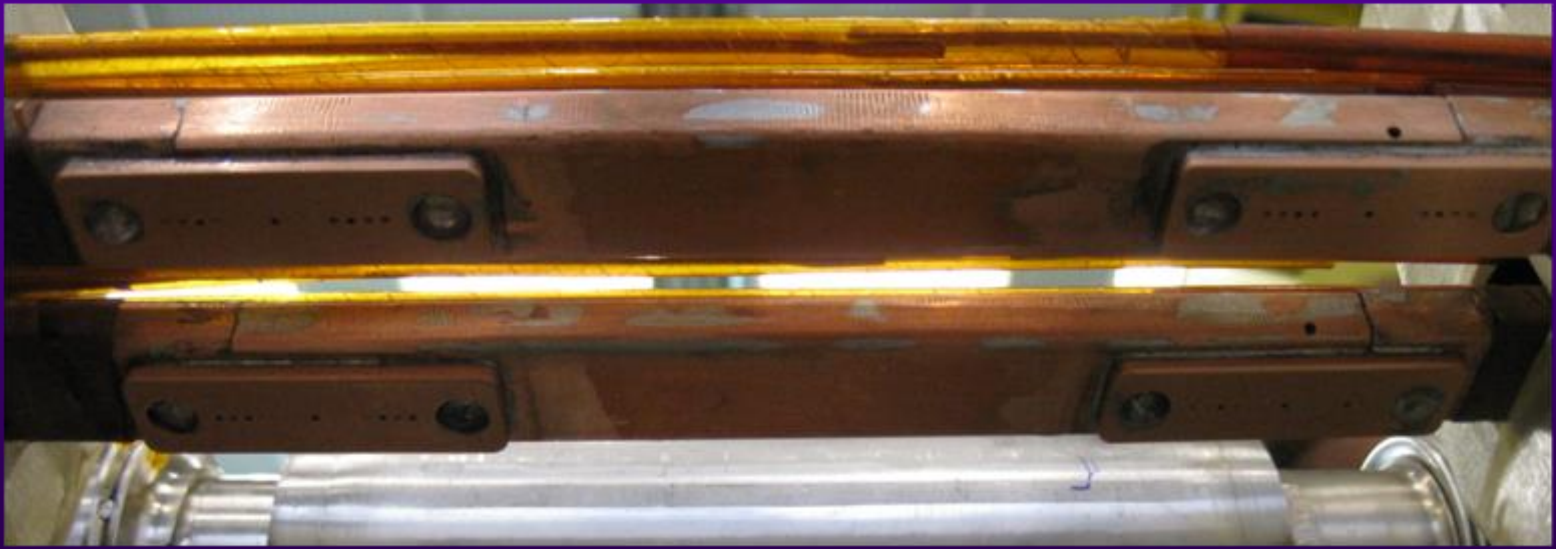
AFS: 50ns_1374_1368_0_1262_144bpi12inj

PM Status B1 ENABLED PM Status B2 ENABLED

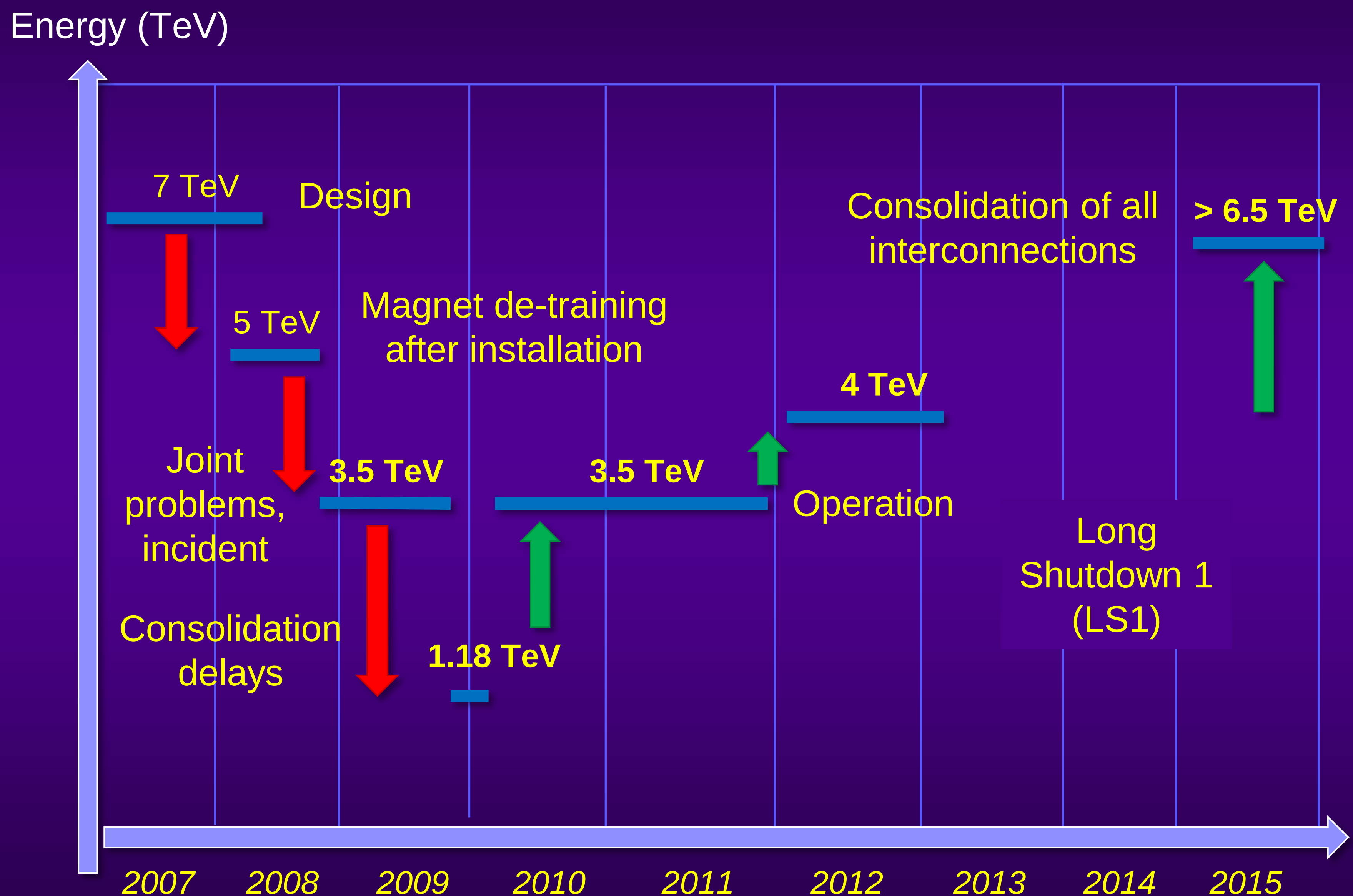
Preparing for nominal energy

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}/y]
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

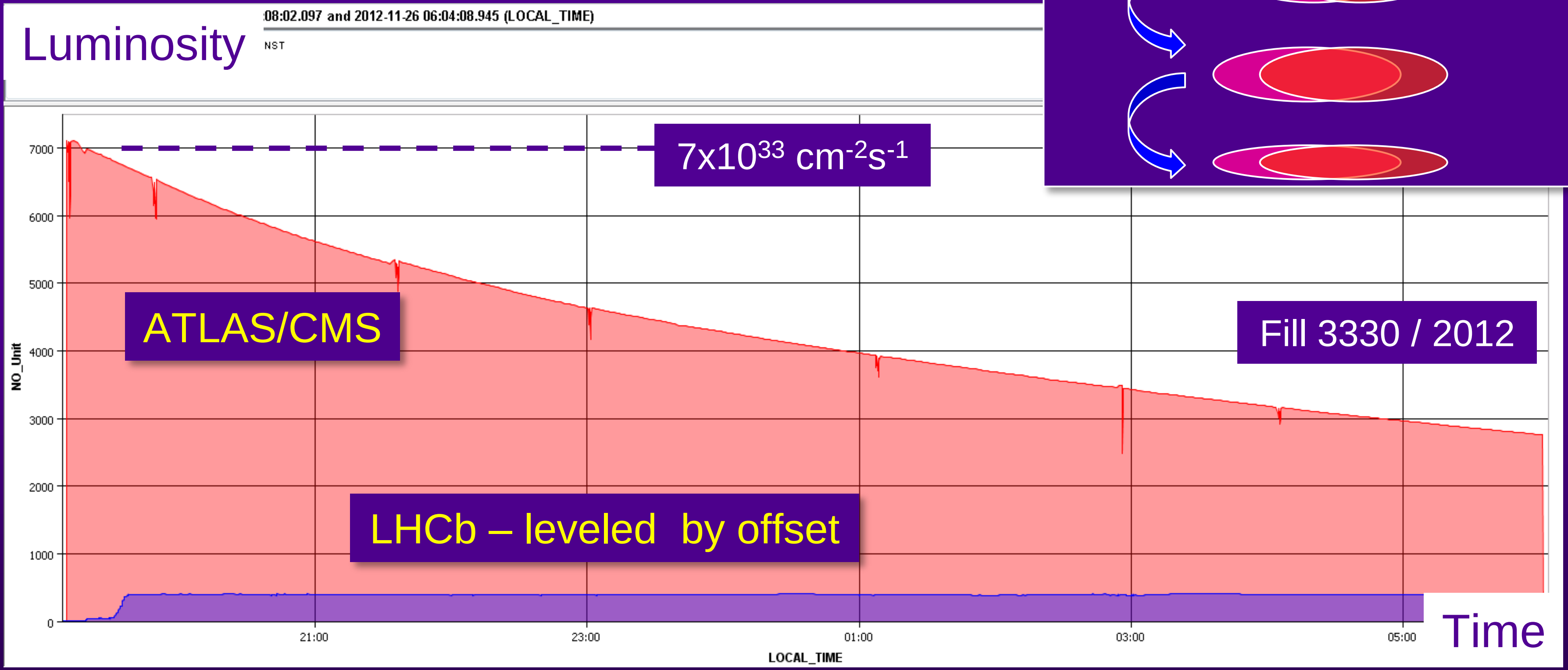
- The cryogenic limit to the luminosity is expected ~ 1.75×10^{34} $cm^{-2}s^{-1}$!
  - Cooling limit of the triplet quadrupole magnets (collision debris).
- Many scenarios imply luminosity leveling to control pile-up
  - Discussion & optimization between machine & experiments.

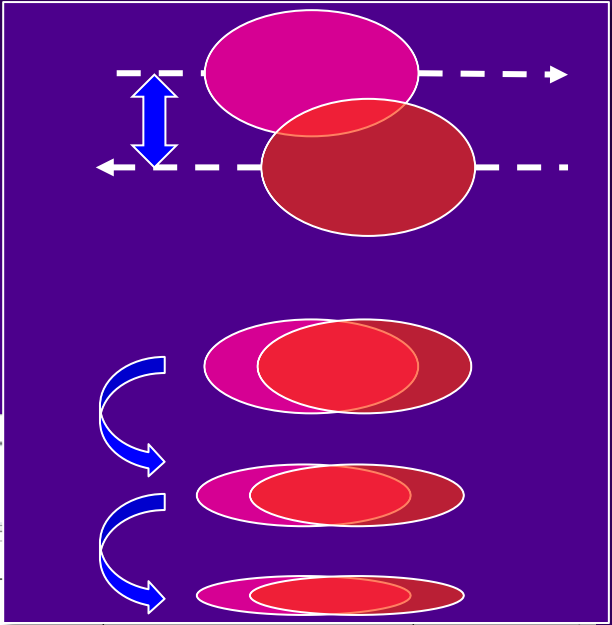
(*) leveled down to a pile-up of ~40.

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.





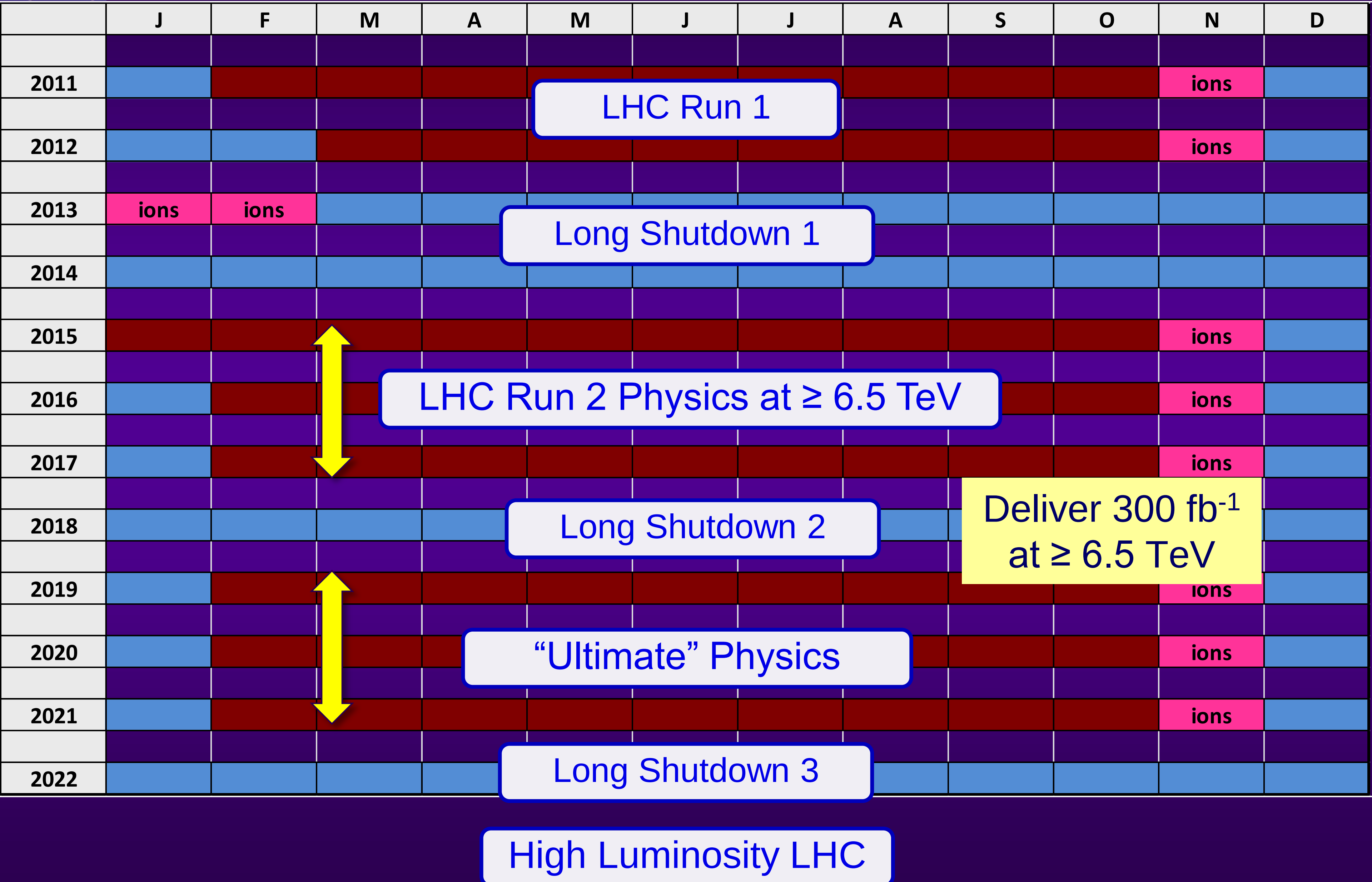
Outlook: LHC operation in 2015

- 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

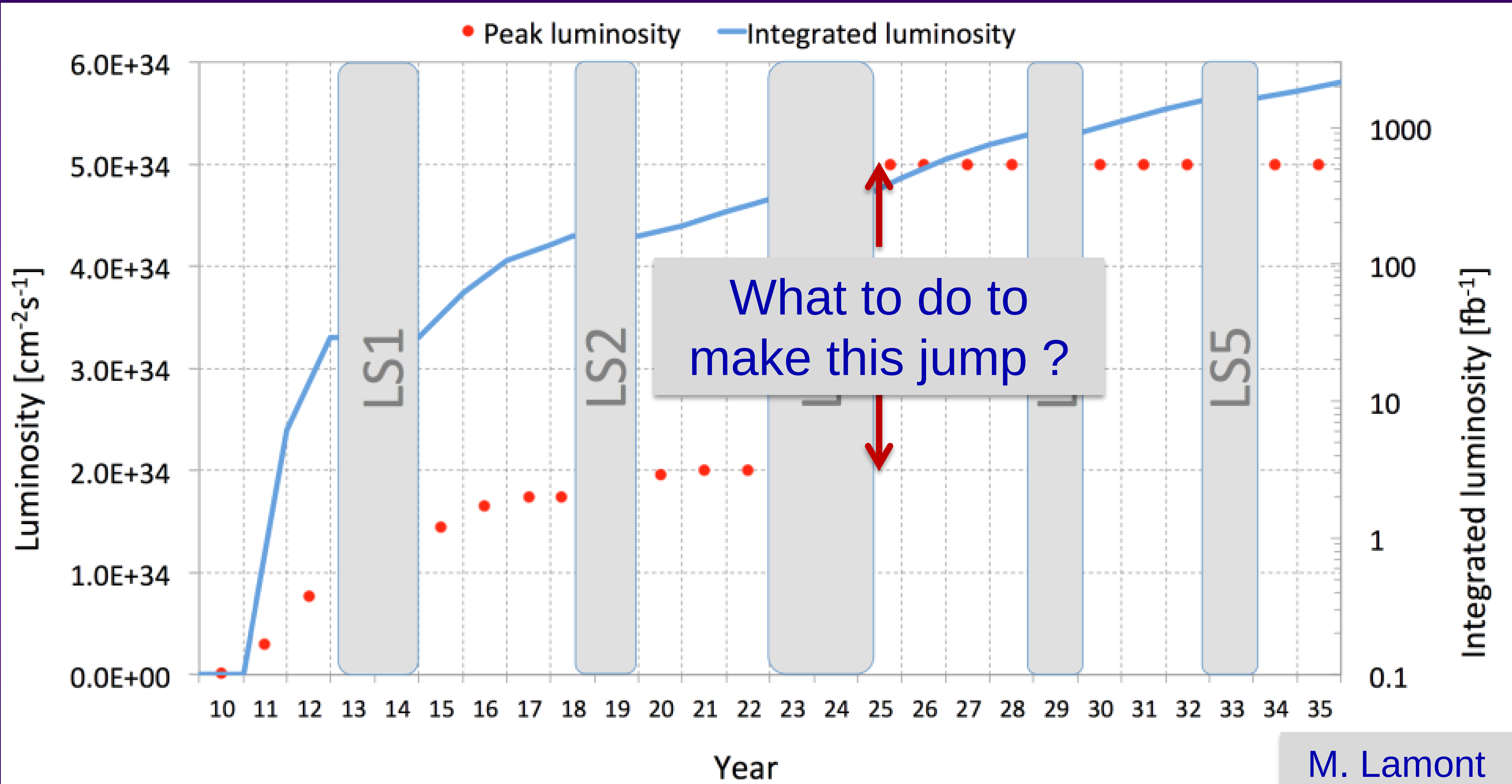
The next years



Preparing for the next 20 years:

High Luminosity LHC (HL-LHC)

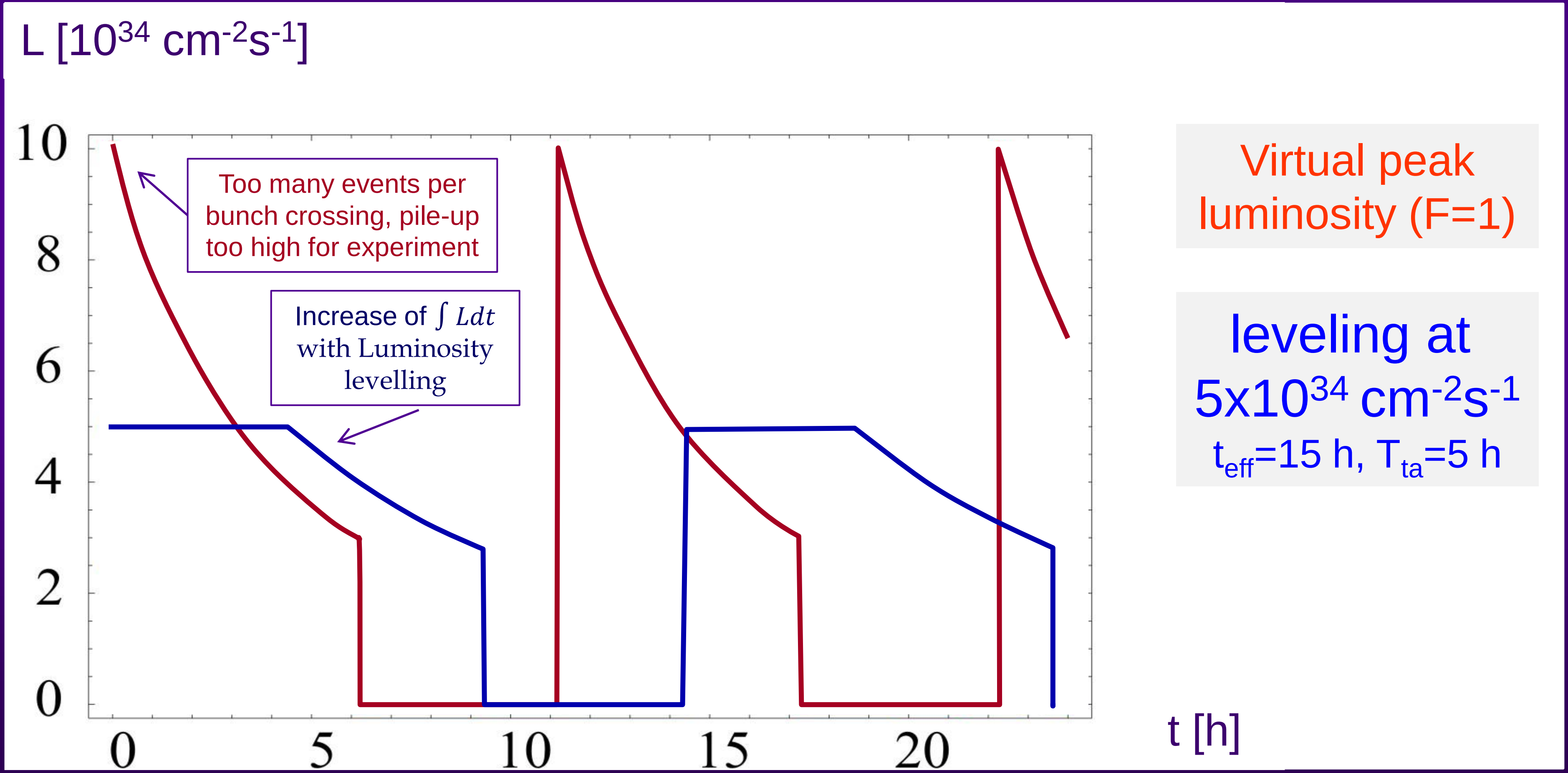
LHC High Luminosity Upgrade



M. Lamont

Integrated luminosity increase by levelling

- Integrated luminosity increase by increasing maximum luminosity not feasible (pile up too high)
- Luminosity levelling can increase integrated luminosity



LHC Upgrade

Motivation

- Target (very ambitious): 200 – 300 fb^{-1}/y (×10 today)
- Radiation damage limit of IR quadrupoles (~400 fb^{-1})
- Improve availability of the systems

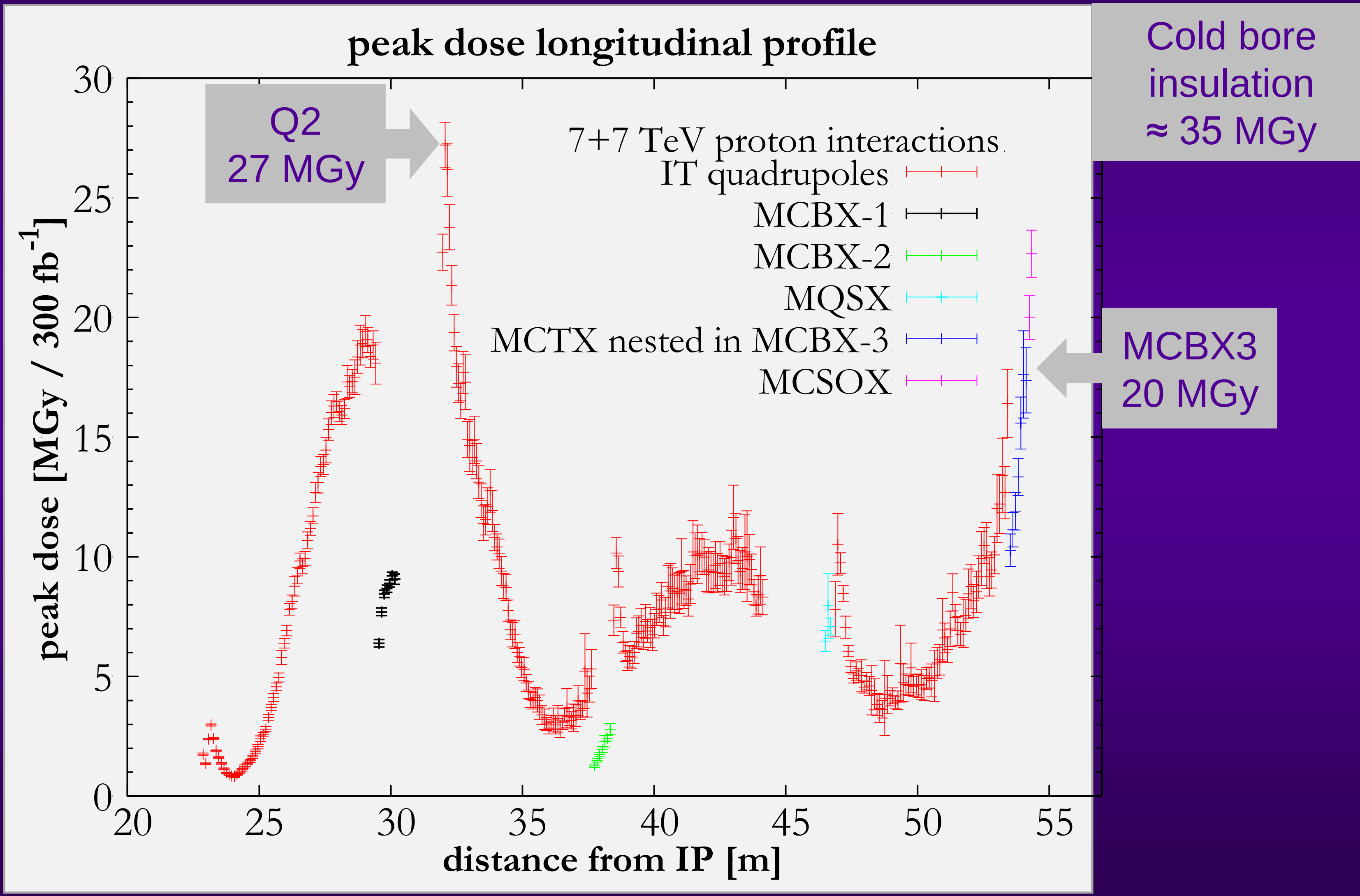
2010-2012 experience

- Head-on beam-beam limit higher than initially expected
- Single bunch with > $3x10^{11}$ ppb with 2.5 mm emittance accelerated in the SPS
- Low β* optics successfully tested during Machine Studies

Pile-up/pile-up density HL-LHC beam physics constraint ➔ 25 ns operation required

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

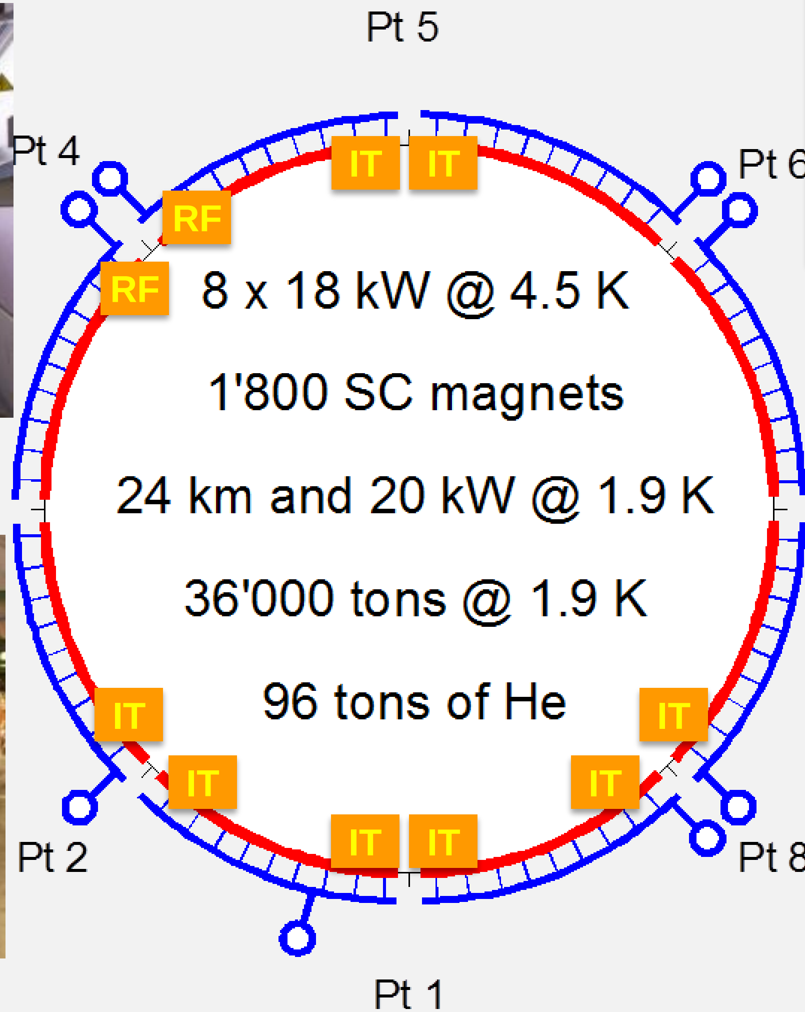
Radiation damage to triplet



F. Cerutti, N. Mokhov, L. Esposito,…

Technical bottlenecks: Cryogenics

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



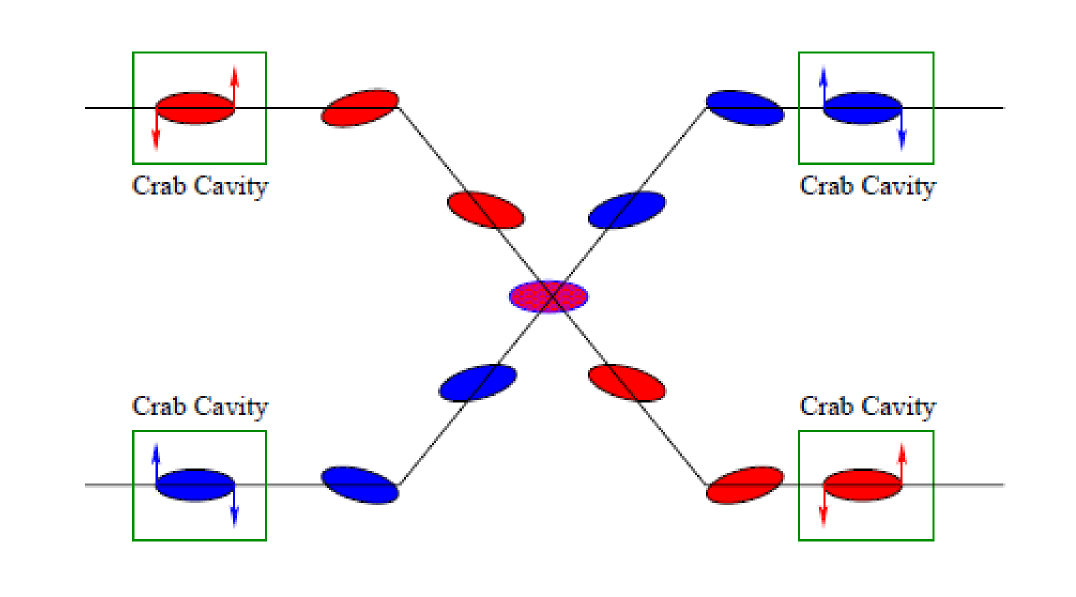
Cryogenic plant

Ingredients for the Upgrade

Operation at pile-up limit

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

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



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

HL-LHC Performance Estimates

Parameter	Nominal	25ns – HL-LHC
Bunch population N_b [10^{11}]	1.15	2.2
Number of bunches	2808	2748
Beam current [A]	0.58	1.12
Crossing angle [μrad]	300	590
Beam separation [σ]	9.9	12.5
β^* [m]	0.55	0.15
Normalized emittance ε_n [μm]	3.75	2.5
ε_L [eVs]	2.51	2.51
Relative energy spread [10^{-4}]	1.20	1.20
r.m.s. bunch length [m]	0.075	0.075
Virtual Luminosity (w/o CC) [10^{34} cm^{-2}s^{-1}]	1.2 (1.2)	21.3 (7.2)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.1
Levelled Pile-up/Pile-up density [evt. / evt./mm]	26/0.2	140/1.25

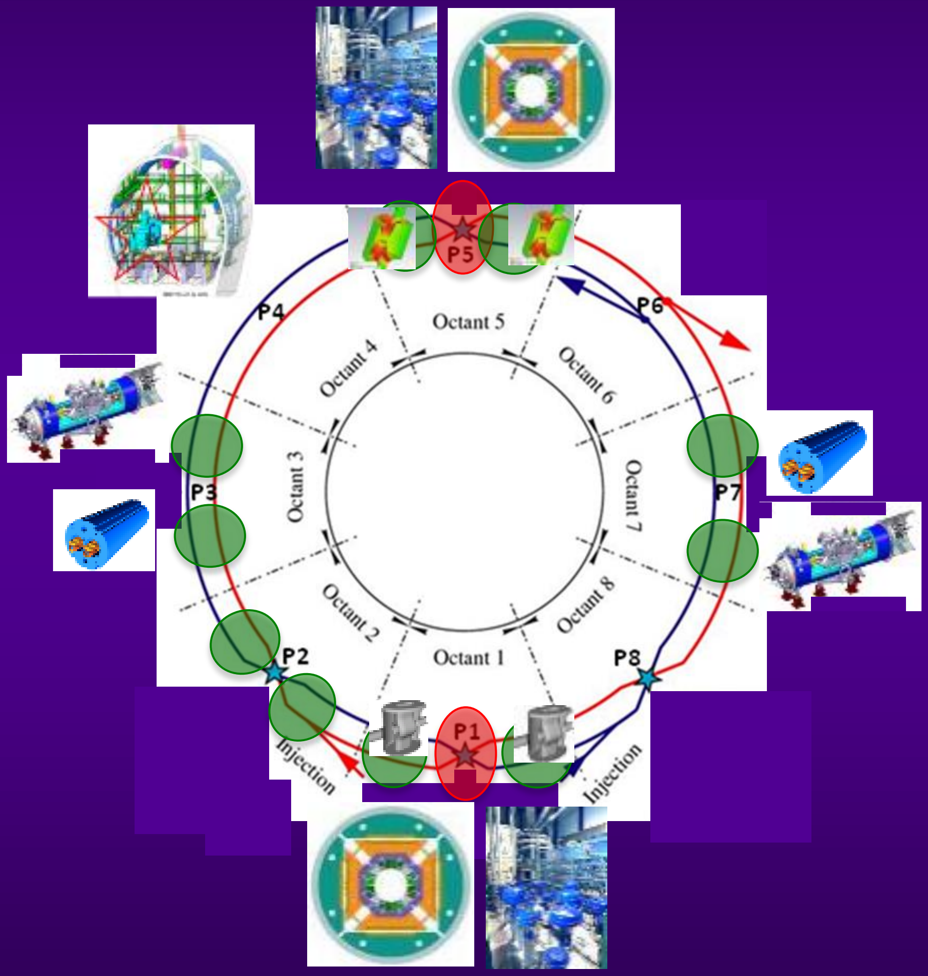
Aim for ~250 fb^{-1}/y

ΔQ_{bb} ~ -0.01

Hardware for the Upgrade

Main modifications

- New high field/larger aperture interaction region magnets
- Cryo-collimators and high field 11 T dipoles in dispersion suppressors
- Crab Cavities to take advantage of the small β^*
- New collimators (lower impedance)
- Additional cryo plants (P1, P4, P5)
- SC links to allow power converters to be moved to surface



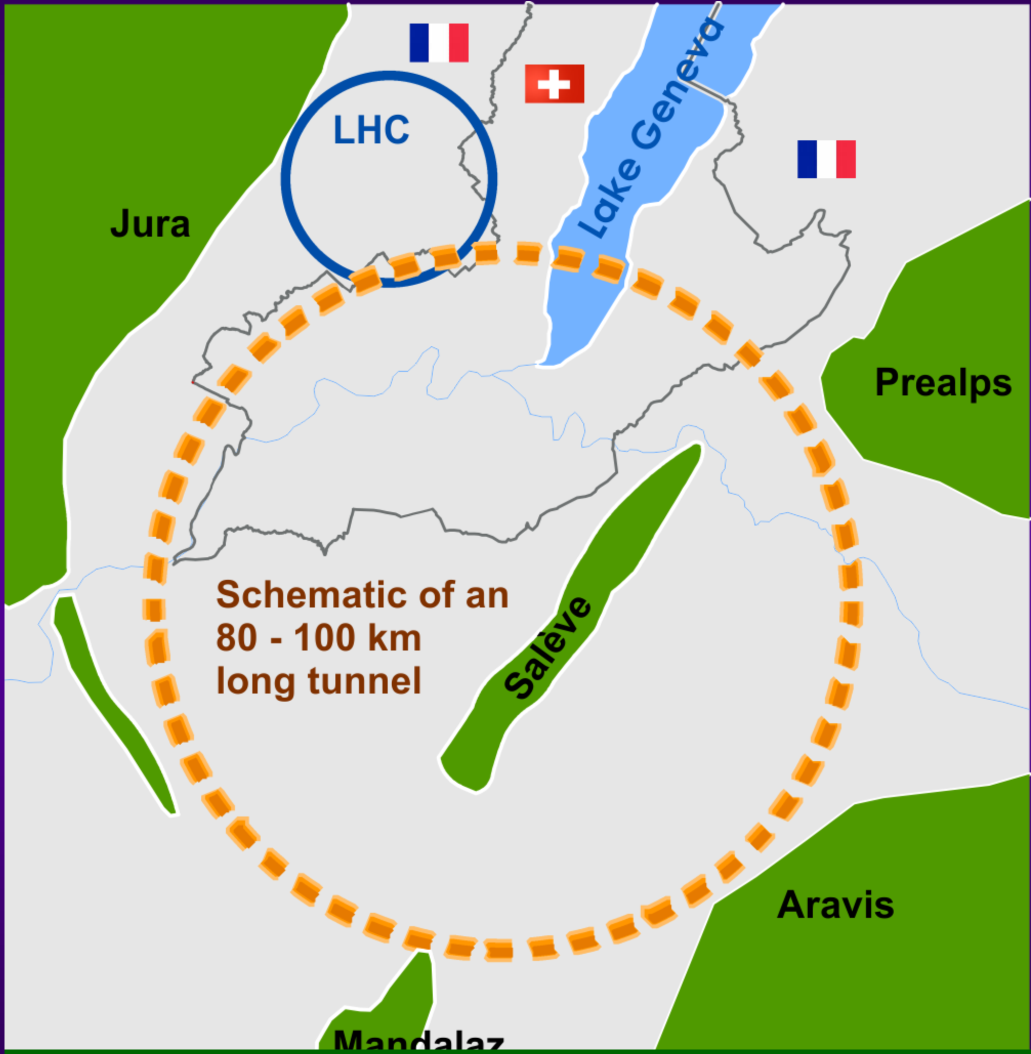
Preparing for the next 50 years:

FCC Study

FCC Study Scope

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

- pp-collider (FCC-hh): defining infrastructure requirements
  - ~16 T ➔ 100 TeV pp in 100 km
  - ~20 T ➔ 100 TeV 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

Crazy?

- The Superconducting Super Collider (SSC) was a particle accelerator complex under construction in the vicinity of Waxahachie, Texas, that was set to be the world's largest and most energetic, Hadron Collider. Its planned ring circumference was 87.1 km with an energy of 20 TeV per proton.

- When the project was cancelled in 1993, 22.5 km of tunnel and 17 shafts to the surface were already dug, and nearly two billion dollars had already been spent on the massive facility

Main FCC-hh parameters

	LHC (Design)	HL-LHC	FCC-hh (100km / 83km)
Main parameters and geometrical aspects			
C.o.M. Energy [TeV]	14		100
Circumference C [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Straight sections	8		12
Number of IPs	2 HL + 2 LL		2 HL + 2 LL
Injection energy [TeV]	0.45		3.3
Physics performance and beam parameters			
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0 (lev.)	5.0
Pile-up (25 ns/5 ns) [evts./crossing]	27	140 (lev.)	171/34

- Two main experiments sharing the beam-beam tune shift
- Two reserve experimental areas not contributing to tune shift
- Currently assume 25 ns bunch distance as baseline

FCC-hh beam parameters

	LHC (Design)	HL-LHC	FCC-hh (100/83)
Beam parameters			
Number of bunches (25 ns / 5 ns)	2808	2748	10600 (8900) / 53000 (44500)
Protons per bunch [10^{11}]	1.15	2.2	1.0/0.2
ε^* (25 ns / 5ns) [μm]	3.75	2.5	2.2/0.44
Maximum total b-b tune shift ΔQ_{bb}/IP	-0.003	-0.01	-0.005
Beam current [A]	0.584	1.12	0.5
RMS bunch length [cm]	7.55		8 (7.55)
β^* [m]	0.55	0.15	1.1
RMS IP spot size (25 ns/5ns) [μm]	16.7	7.1 (min)	6.8/3
Full crossing angle [μrad]	285	590	74 / n/a

Rather conservative parameters as compared to HL-LHC

FCC-hh: Other parameters

	LHC (Design)	HL-LHC	FCC-hh (100km / 83km)
Stored Energy/beam [GJ]	0.36	0.68	**8.4**
Arc SR heat load [W/m/aperture]	0.17	0.33	**28.4 (44.3)**
Energy loss per turn [MeV]	0.0067		4.6 (5.86)
Critical photon energy [keV]	0.044		4.3 (5.5)
Total synchr. Power [MW]	0.0072	0.0146	**4.8 (5.8)**
Long. emittance damping time [h]	12.9		**0.54 (0.32)**
Hor. emittance damping time [h]	25.8		**1.08 (0.64)**
Dipole coil aperture [mm]	56		40

- Huge beam (and magnetic) stored energy!!!!
- Synchrotron radiation!!!
- **Half – way between a hadron and lepton machine**

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 (~40 mm) and accelerator features (field quality, protectability, cycled operation) > learn from Nb3Sn magnets in the LHC (HL-LHC 11 T dipoles). In parallel conductor developments
  - 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 O(5 T) additional field in large aperture O(100 mm, 15 T)
  - Possible goal: demonstrate HTS/LTS 20 T technology in two steps a field record attempt to break the 20 T barrier (no aperture), and a 5 T insert, with sufficient aperture (40 mm) and accelerator features

FCC-hh Challenges

- Energy in beam & magnets => dump, collimation, quench protection (Stored beam energy > 20 x LHC)
- Beam losses, radiation effects => collimation, shielding
- High synchrotron radiation load on beam pipe (up to 26 W/m/aperture in arcs, total of ~5 MW for FCC-hh)
  - Heat extraction: photon stop, beam screen design, cryo load,
- Synchrotron radiation damping
  - 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

Concluding remarks

- To reach 3000 fb-1 by ~2035 we are pushing even further the above challenges…
- Several Technologies/Techniques are being developed to provide margin for the achievement of these challenging parameters

Final remarks

- The progress in LHC performance has been great.
- Luminosity of close to nominal at 4 TeV – 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.
- Luminosity performance and choices for the upgrade are now constrained by the acceptable detector pile-up/pile-up density

- The interconnections between the magnets were the only weak spot…
- Expectations for 2015 are very high – the work to meet them is in full swing.
- With run II we will explore high energies and operation with 25 ns (all but trivial). Aim for 300 fb-1 by the end of Run III.
- We start to look at the future beyond HL-LHC (it is time to do it to be ready…)

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