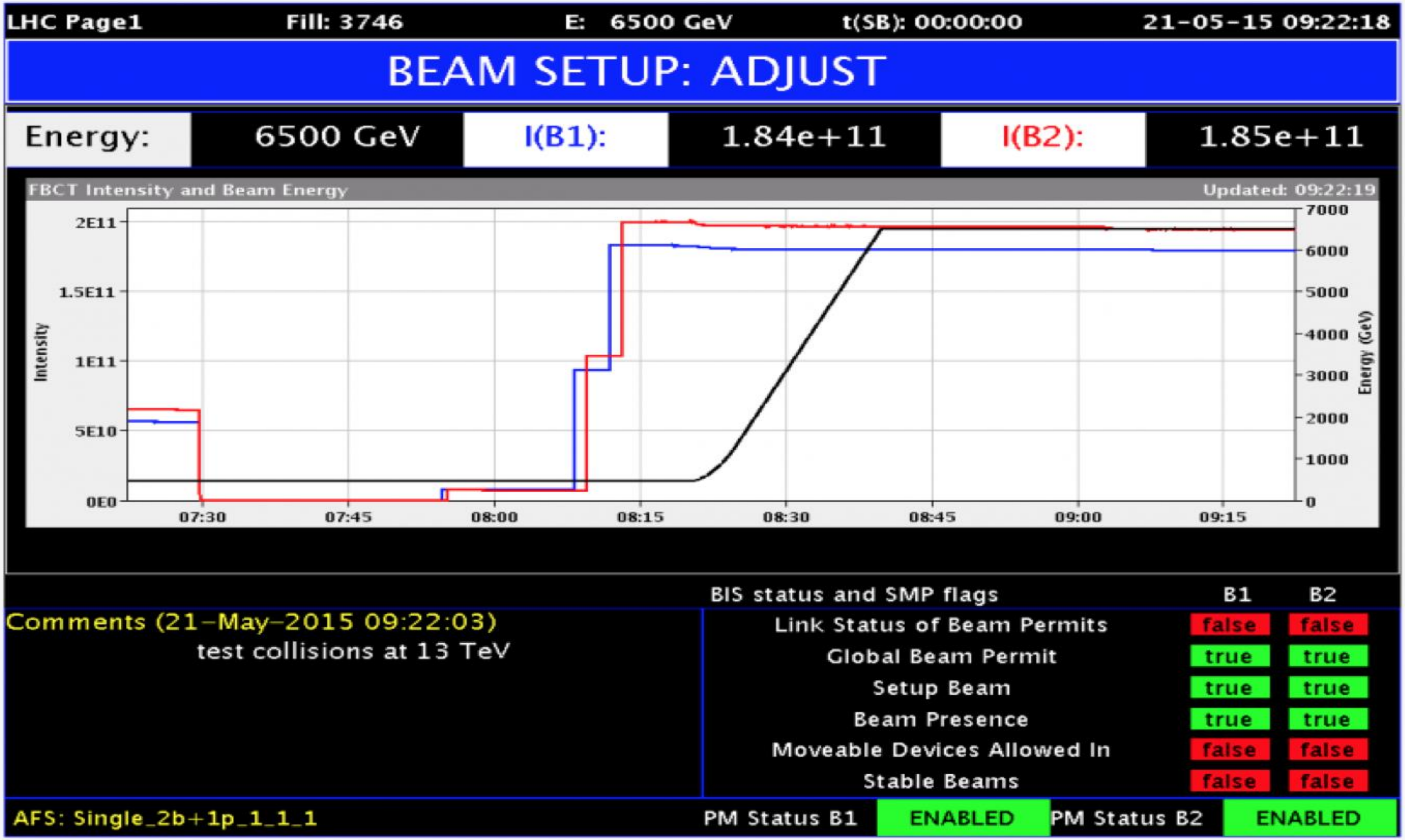
To accelerate a particle to very very high energy …

Particle energy about $6*10^{10}$ TeV

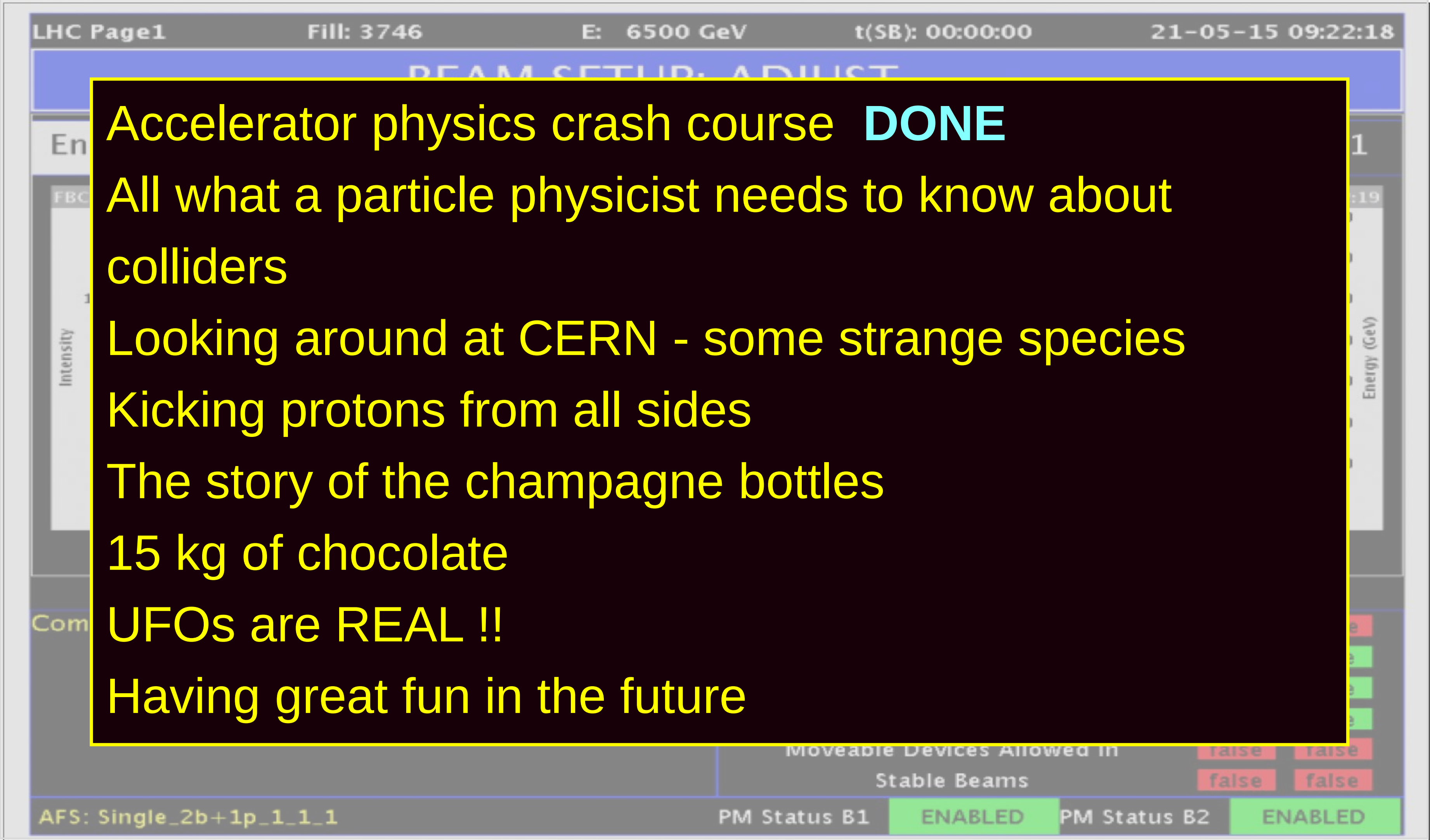
To accelerate particles to much lower energy …



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

First images of collisions at 13 TeV at LHC

by Cian O'Luanaigh

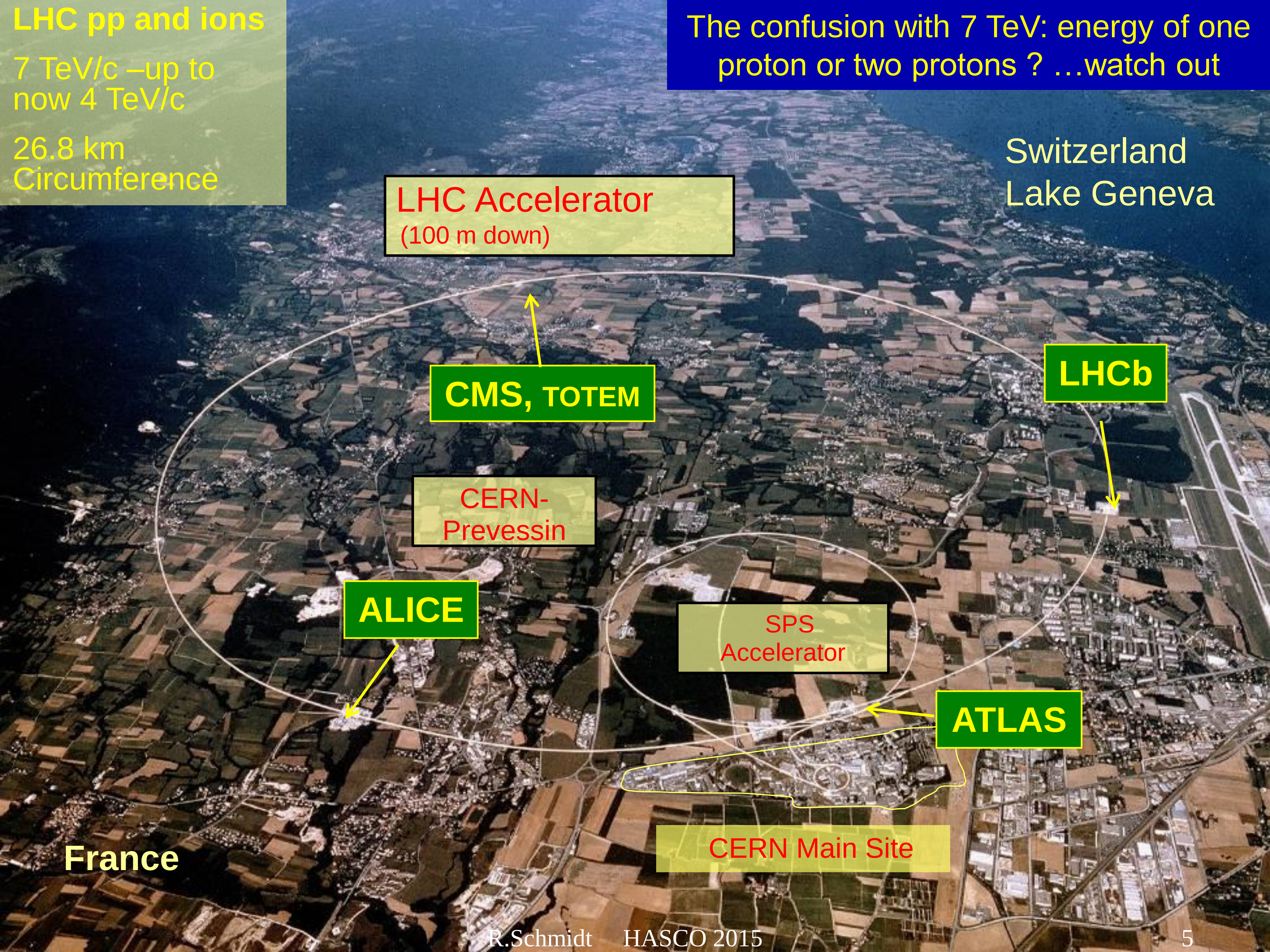


- Accelerator physics crash course **DONE**
- All what a particle physicist needs to know about colliders
- Looking around at CERN - some strange species
- Kicking protons from all sides
- The story of the champagne bottles
- 15 kg of chocolate
- UFOs are REAL !!
- Having great fun in the future

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

LHC: A long story starting in the distant past

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


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
LHC Accelerator
(100 m down)
Switzerland
Lake Geneva
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/

Accelerator Physics Crash Course

what is accelerator physics?

what strange species are accelerator physicists?

What is accelerator physics … and technology?

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

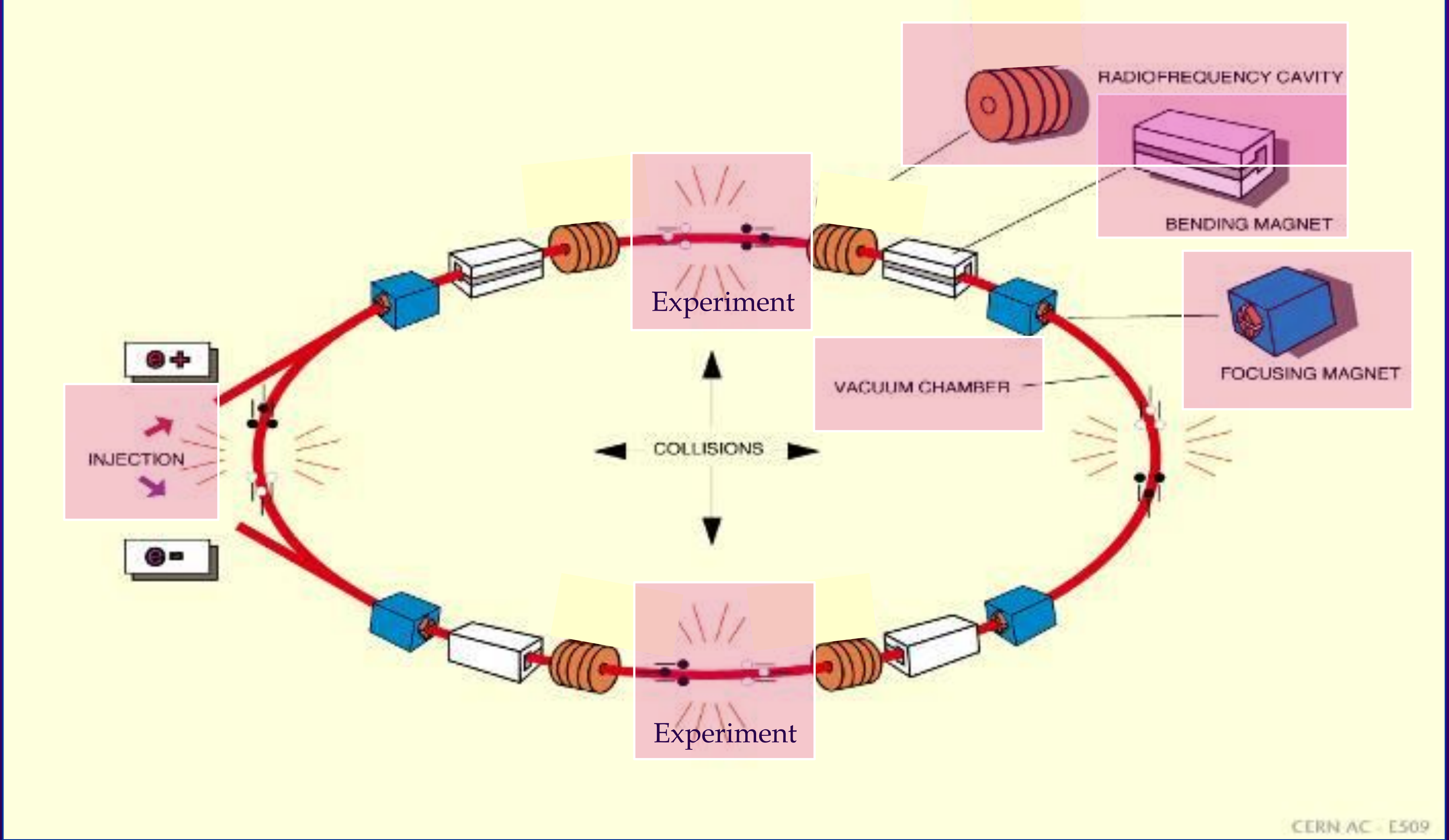
- Electrodynamics
- Relativity
- Particle physics, nuclear physics and radiation physics
- Thermodynamics
- Mechanics
- Quantum Mechanics
- Physics of nonlinear systems
- Material science, solid state physics and surface physics
- Vacuum physics
- Plasma physics and laser physics

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 takes 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:

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

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

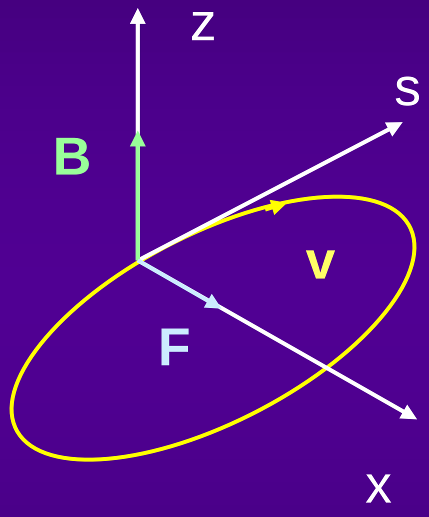
$$\frac{dE}{dt} = q \cdot (\vec{\mathbf{v}} \cdot \vec{\mathbf{E}} + \vec{\mathbf{v}} \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}})) = q \cdot \vec{\mathbf{v}} \cdot \vec{\mathbf{E}}$$

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:

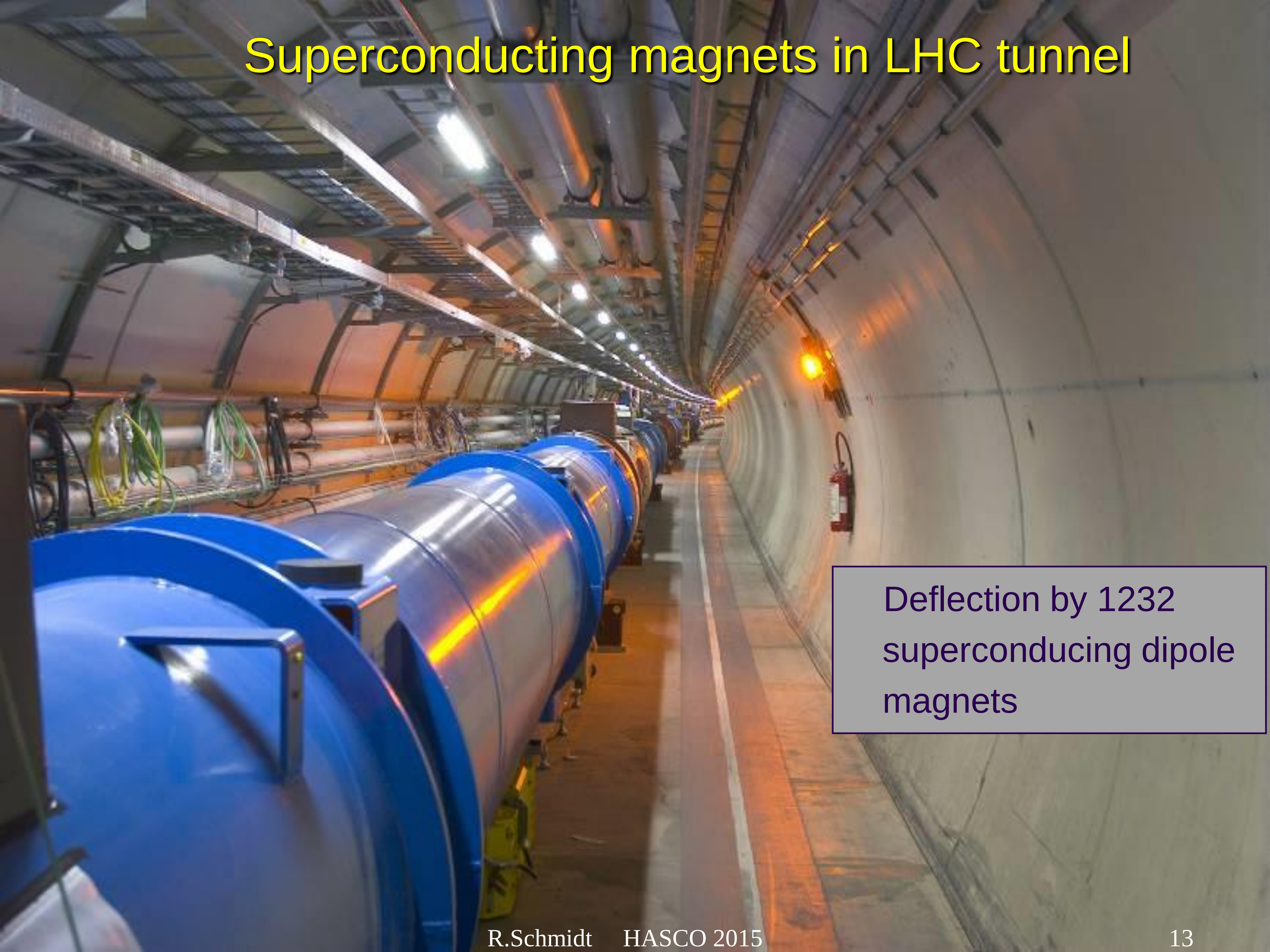
$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

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



- 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

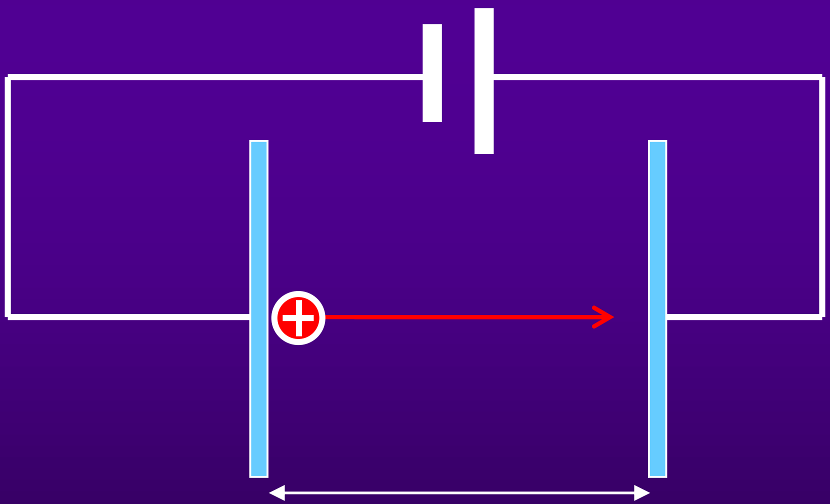


Deflection by 1232 superconducing dipole magnets

Particle acceleration: accelerating protons to 7 TeV

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

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

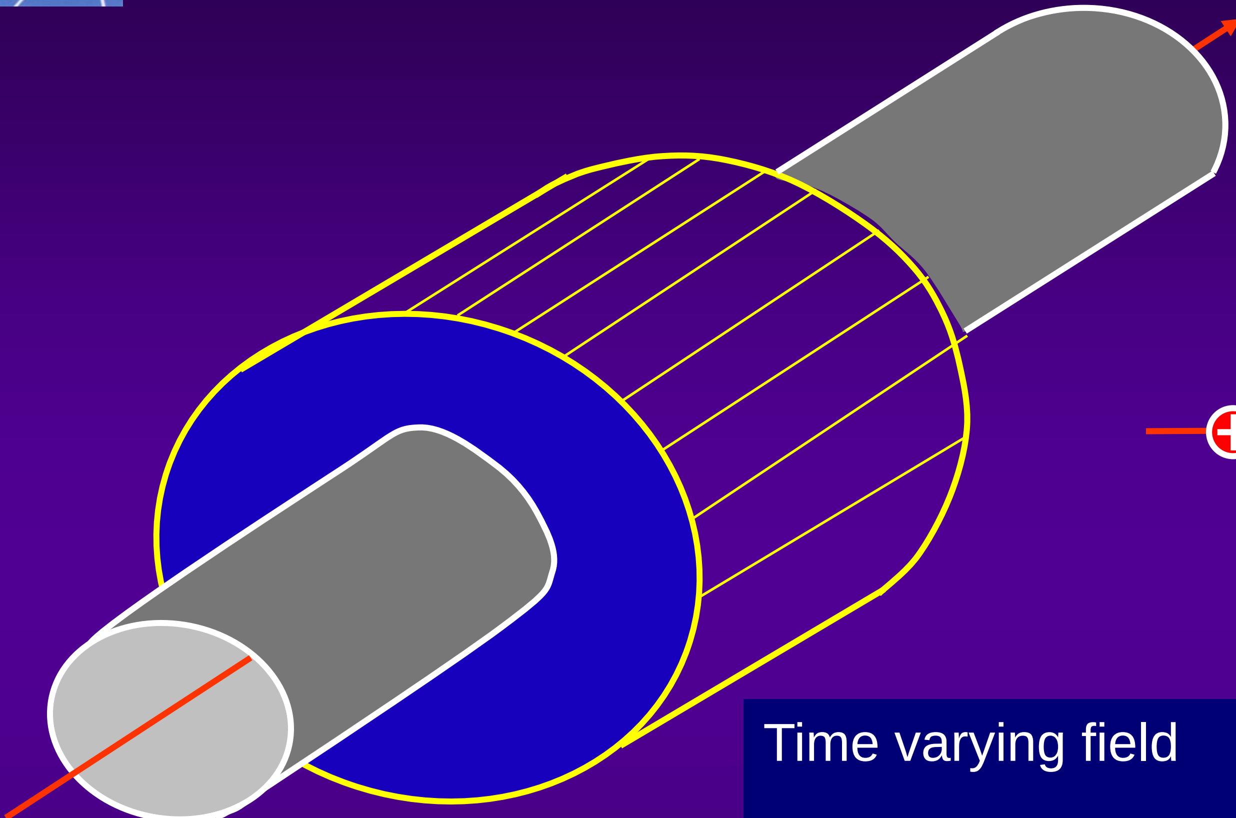


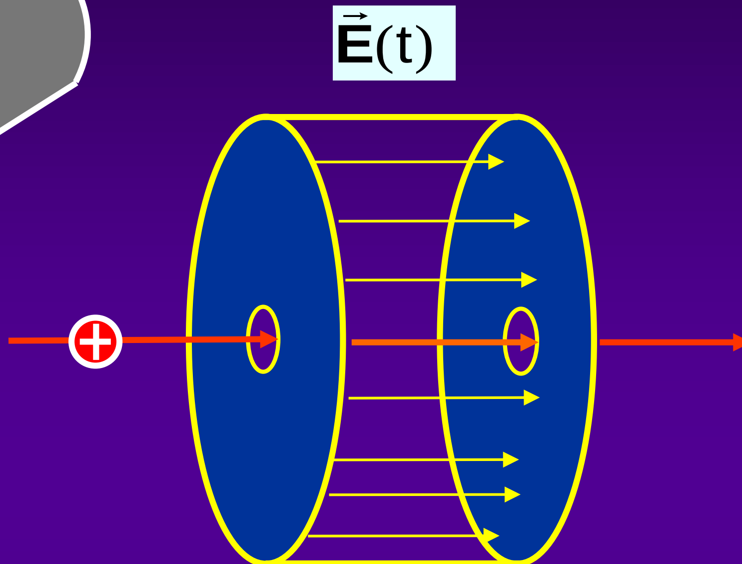
1 MeV requires
U = 1 MV

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)

Particle acceleration with RF cavity





LHC RF frequency
400 MHz

Revolution frequency
11246 Hz

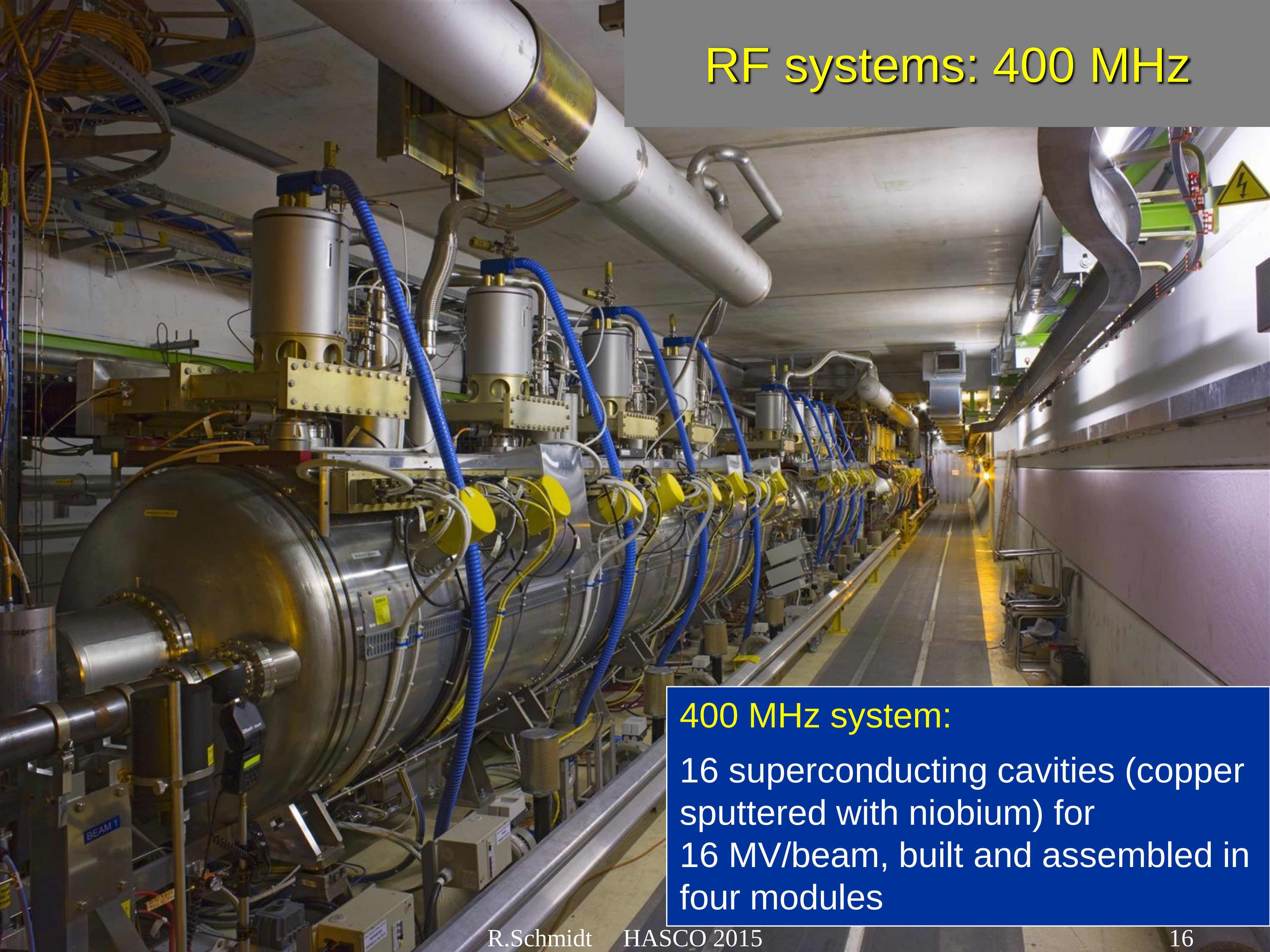
Time varying field

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

Maximum field about 20 MV/m

Beams are accelerated in bunches (no continuous beam)

RF systems: 400 MHz



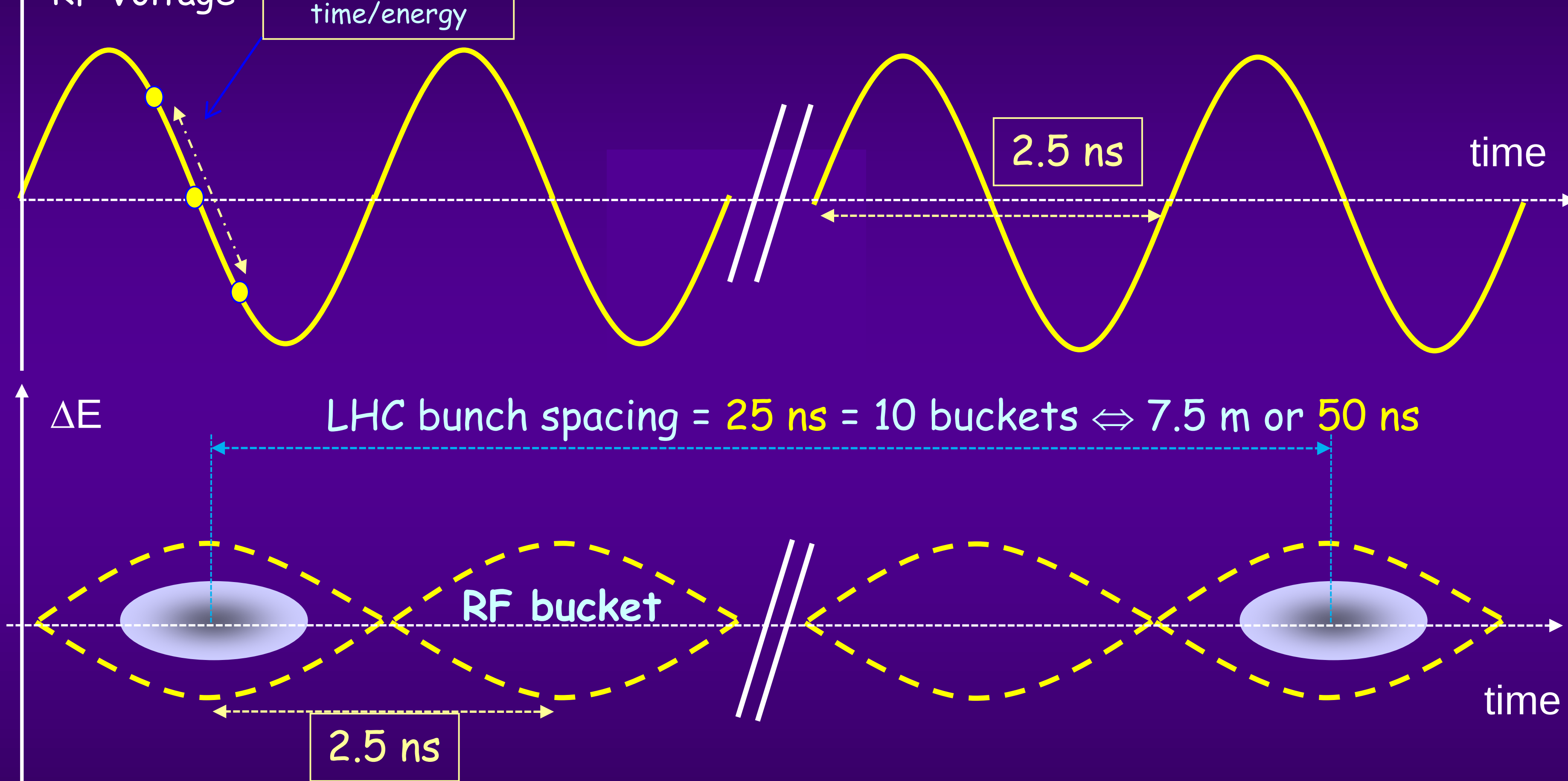
400 MHz system:

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

Capture of Surfers by a water wave for acceleration

400 MHz RF buckets and bunches

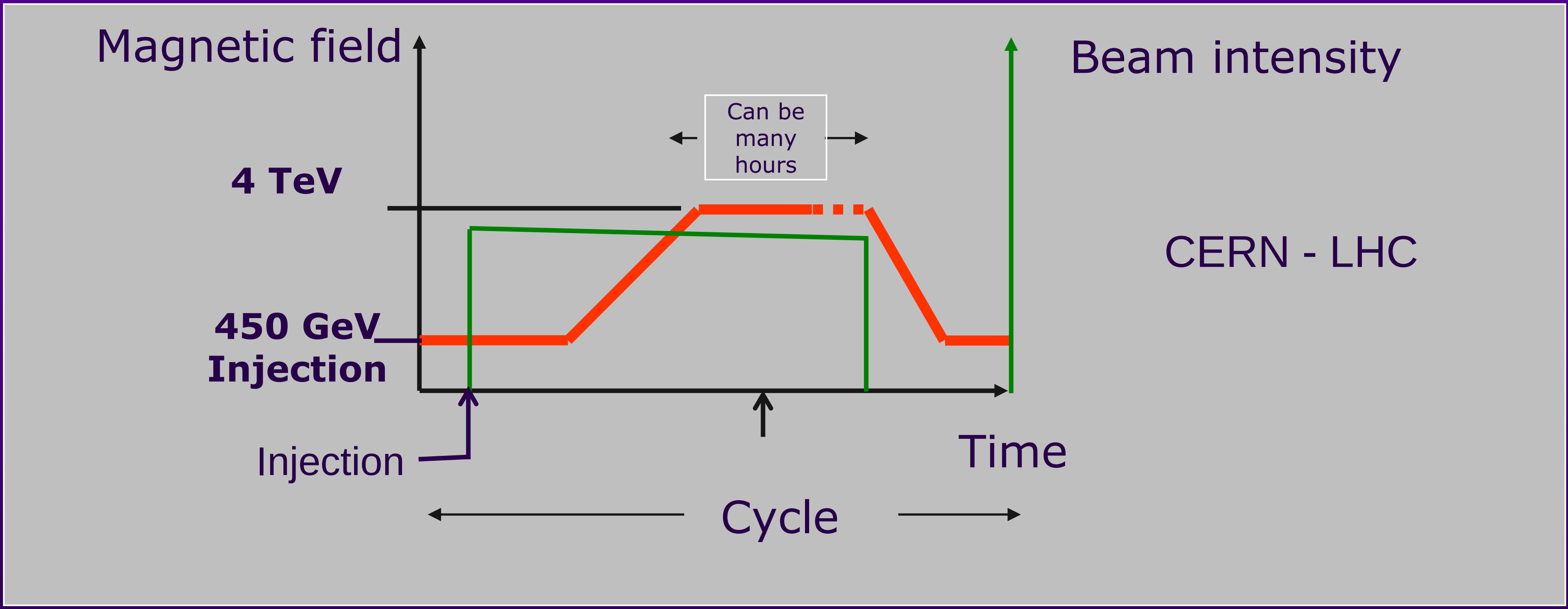
The particles are trapped in the RF voltage: this gives the bunch structure



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

Principle of a synchrotron

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

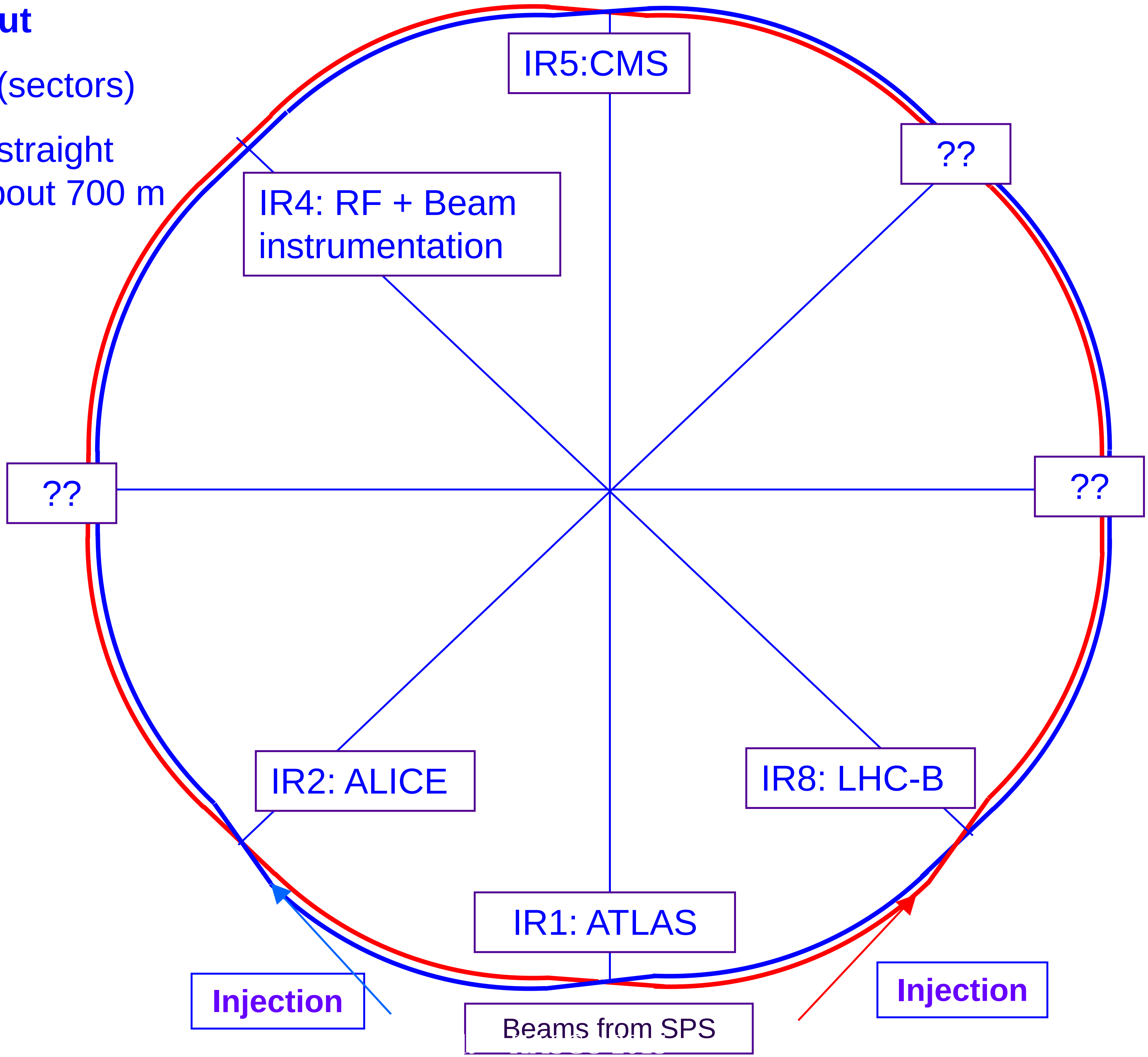


LHC layout, injection and beam transport

LHC Layout

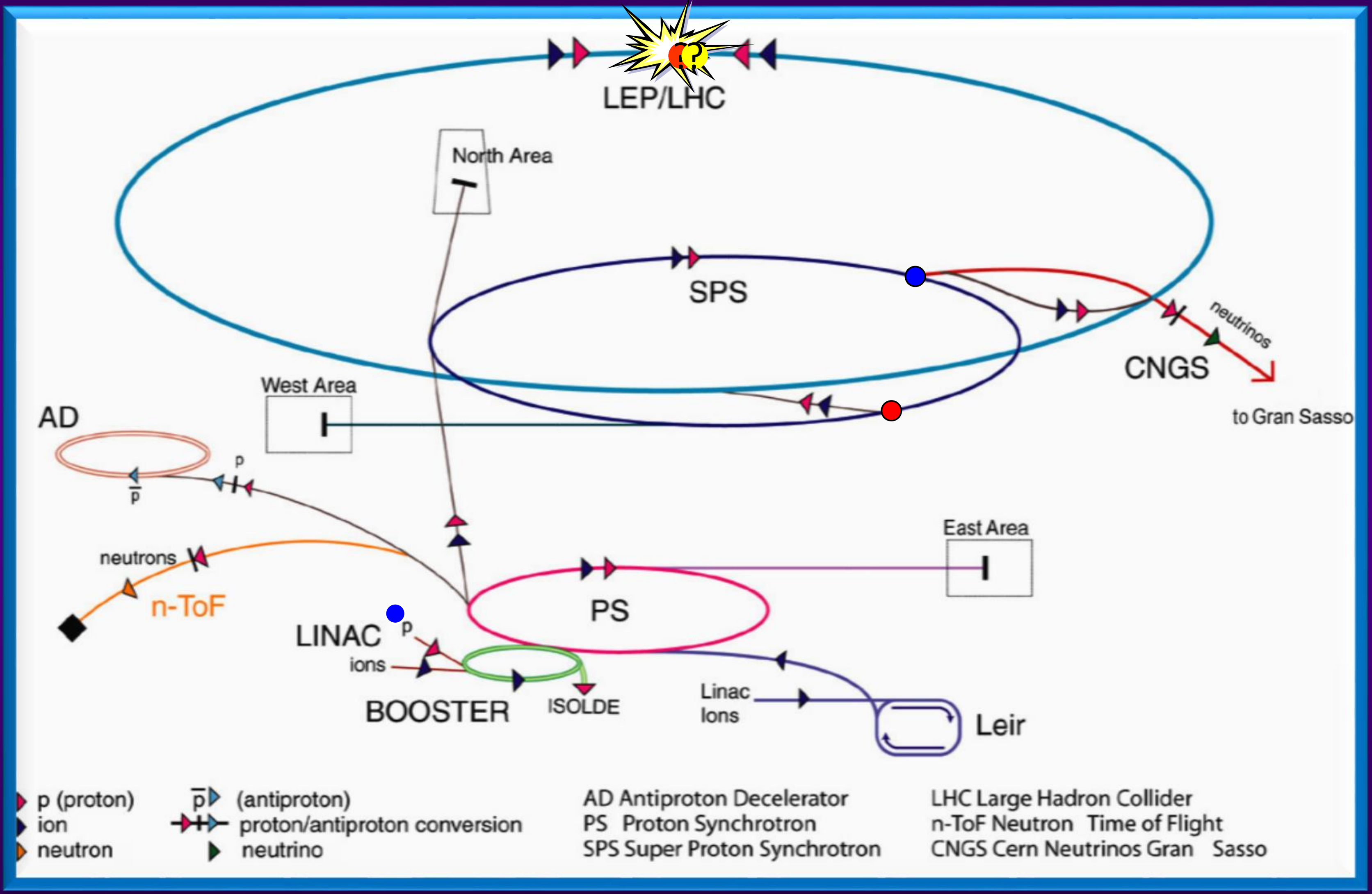
eight arcs (sectors)

eight long straight section (about 700 m long)



CERN accelerator complex

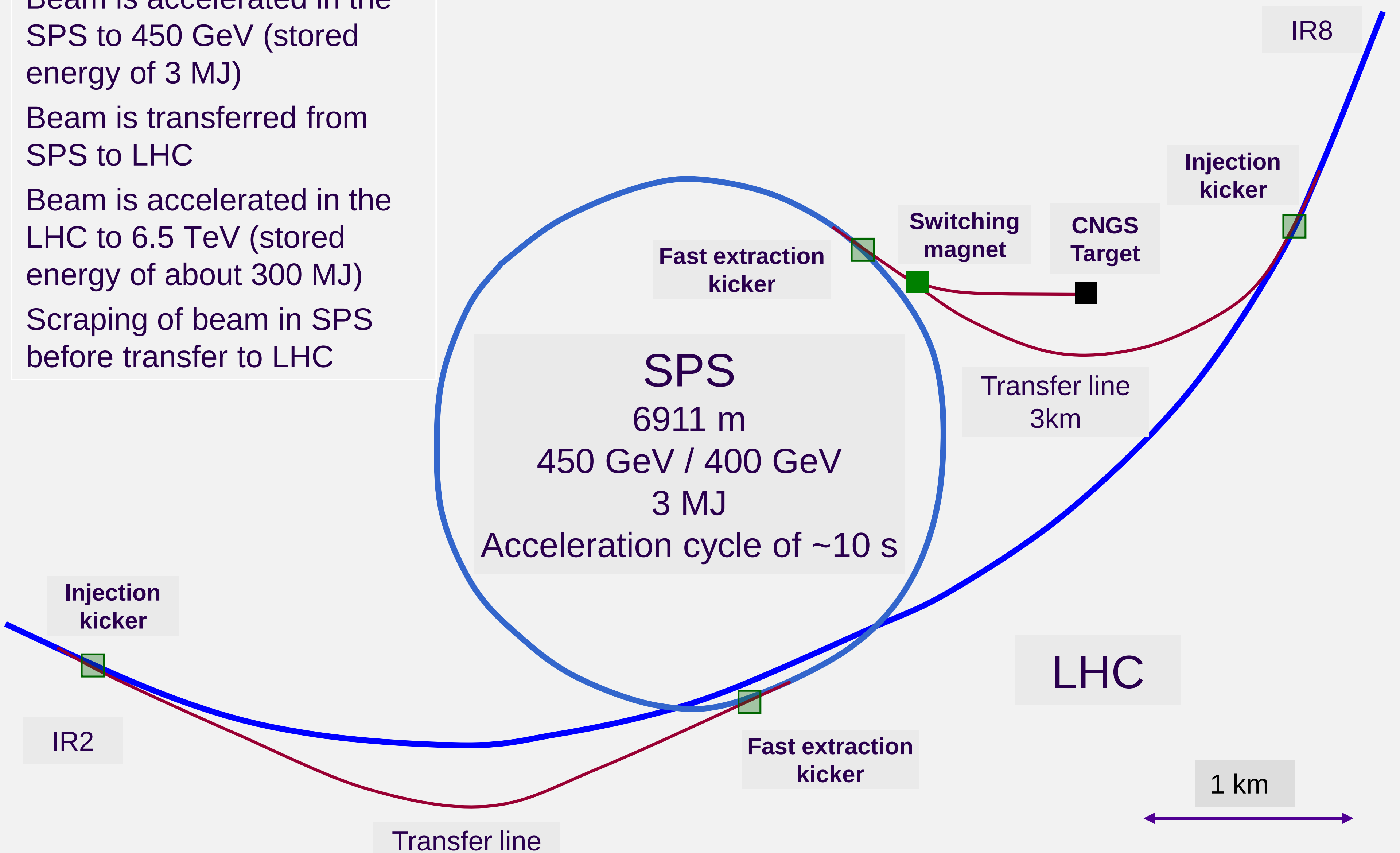
Click for Movie



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 6.5 TeV (stored energy of about 300 MJ)
- Scraping of beam in SPS before transfer to LHC



LHC energy and superconducting magnets

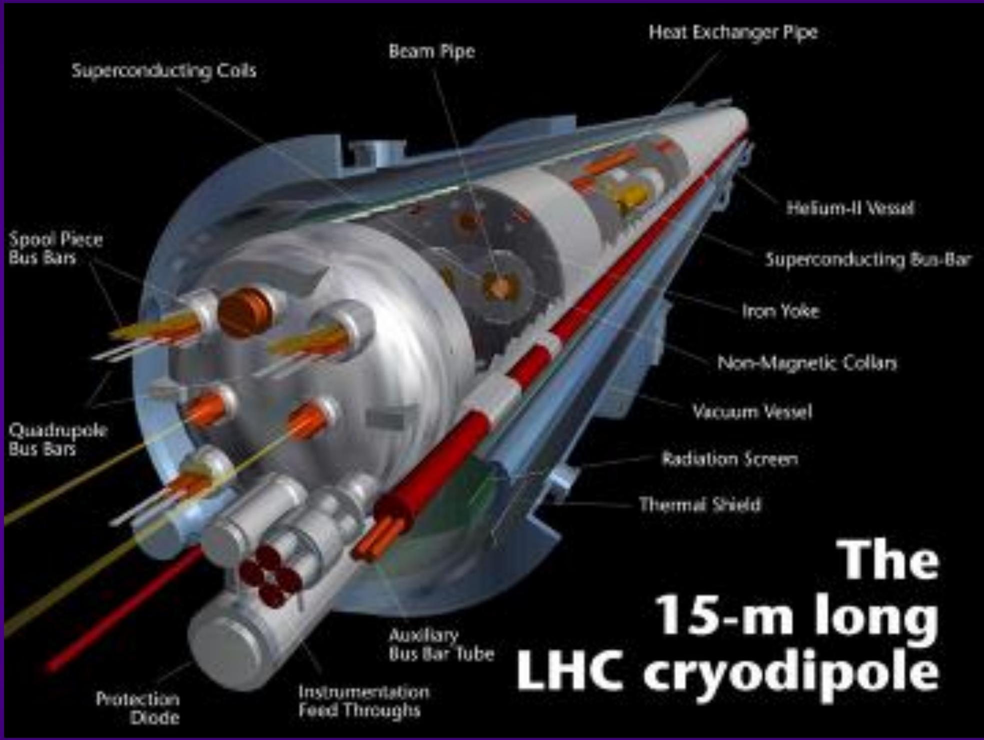
…….the field strength determines the beam energy

Dipole magnets for the LHC

1232 Dipole magnets
Length about 15 m

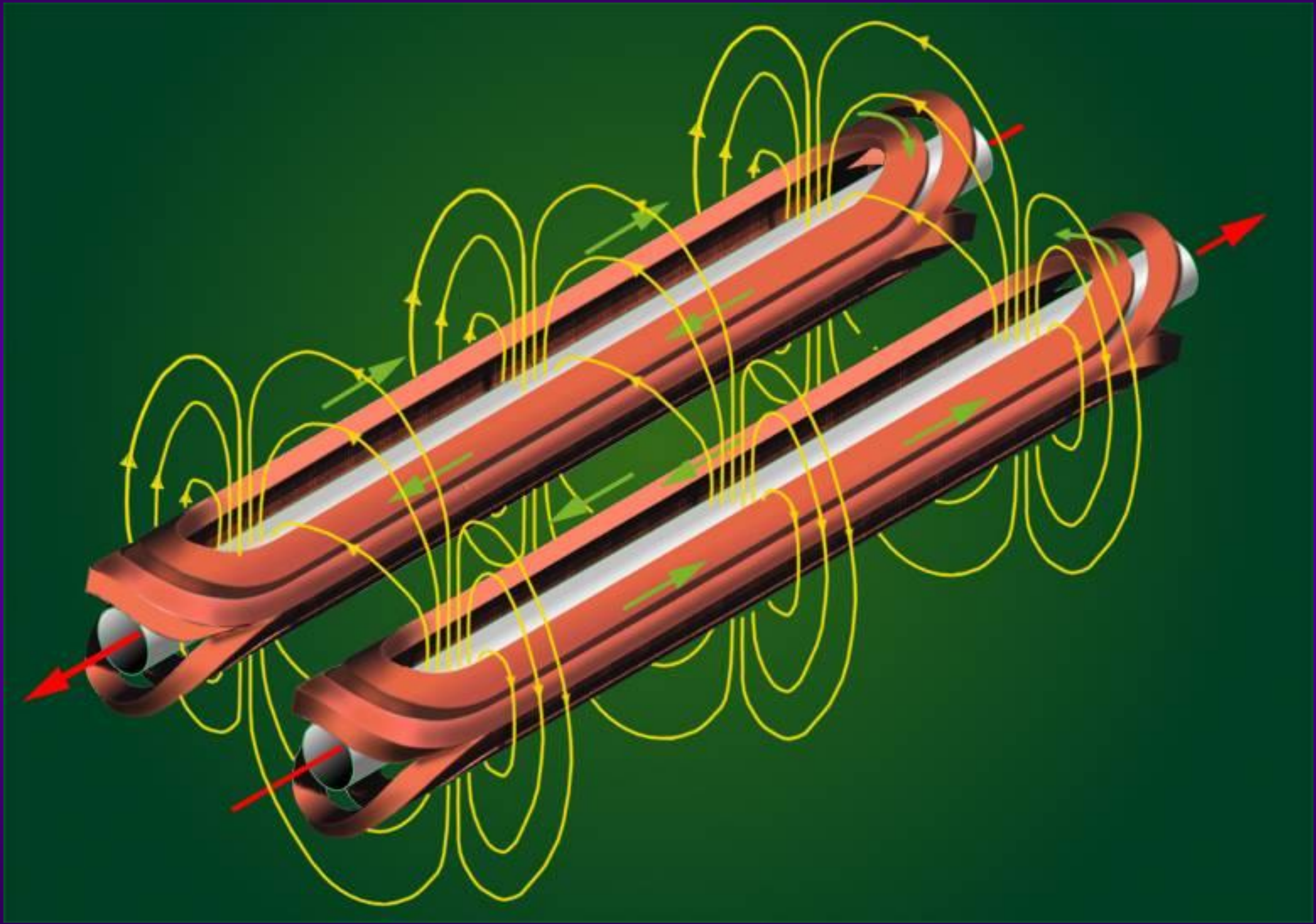
Magnetic Field 8.3 T for
7 TeV

Two beam tubes with an
opening of 56 mm

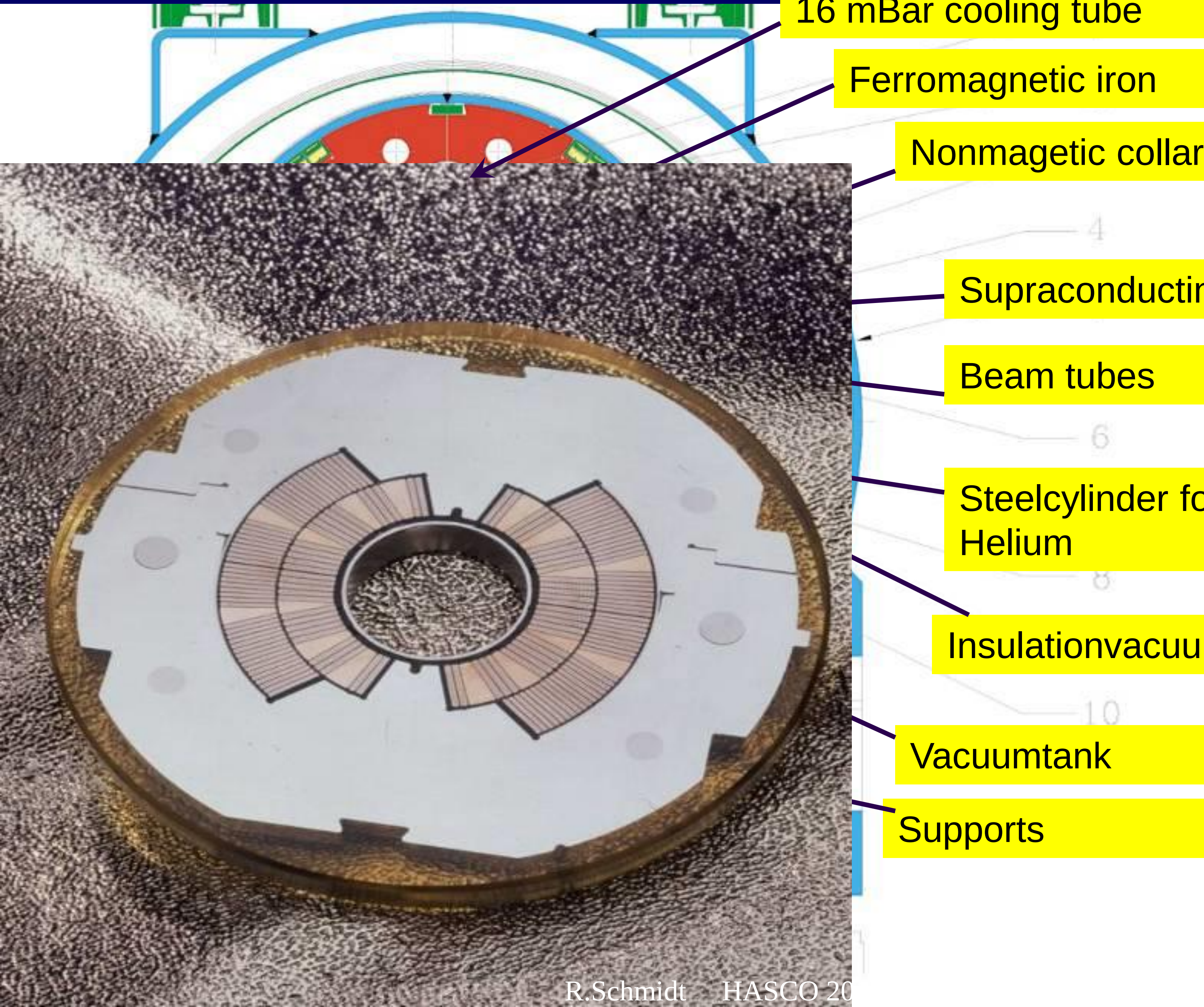


plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets)

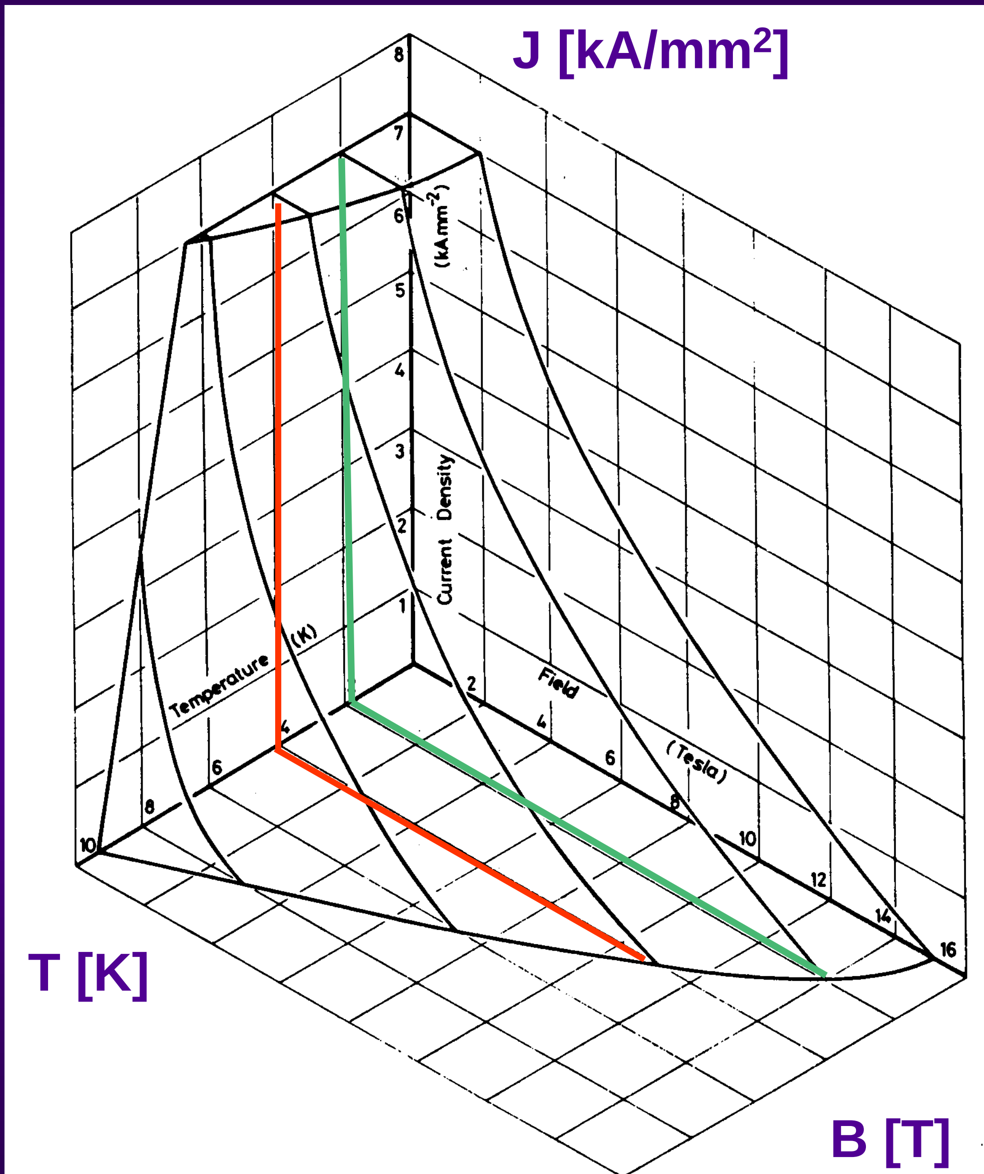
Coils for Dipolmagnets



Dipole magnet cross section



Operating temperature of superconductors (NbTi)

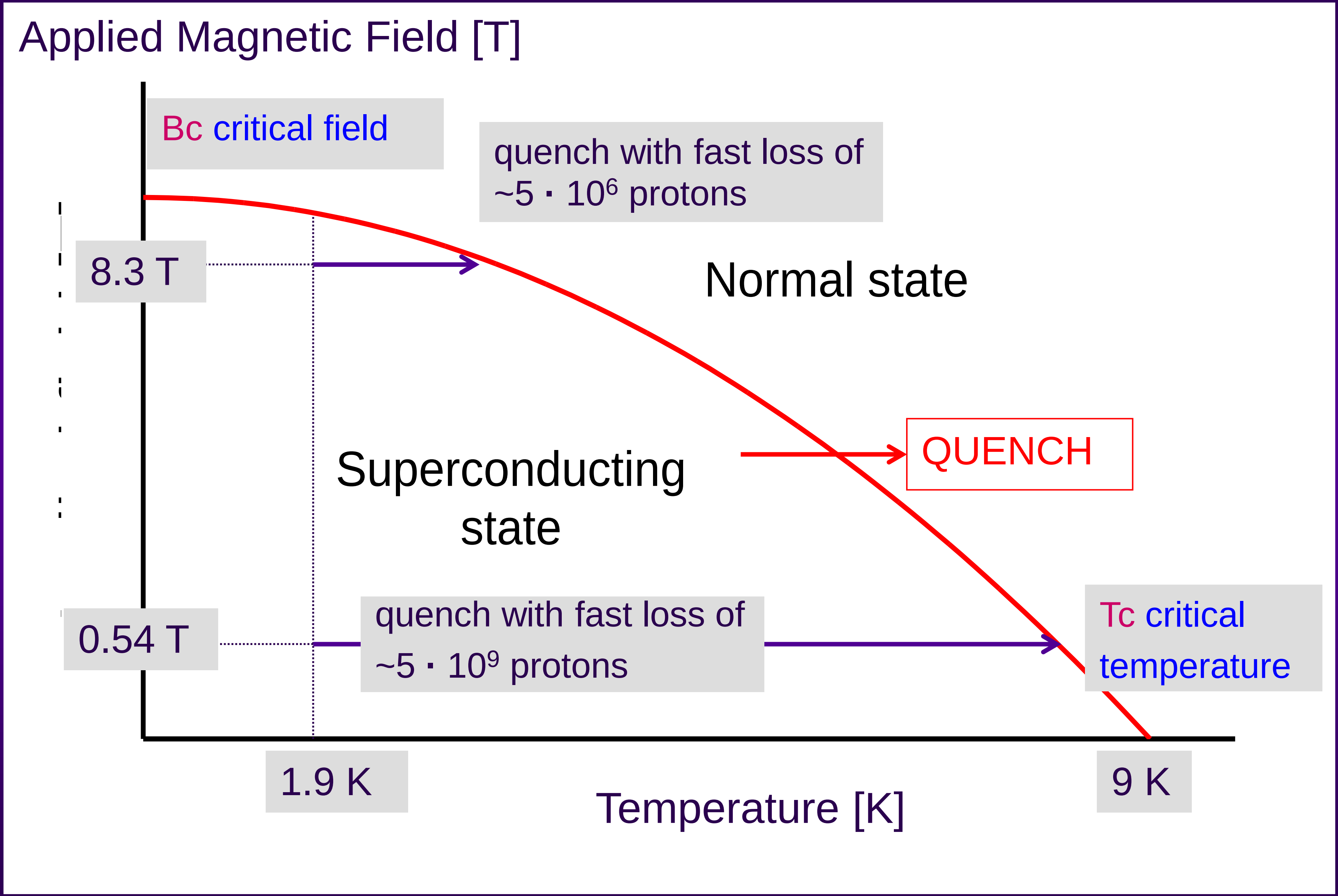


The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

Superconducting magnets produce high field with high current density

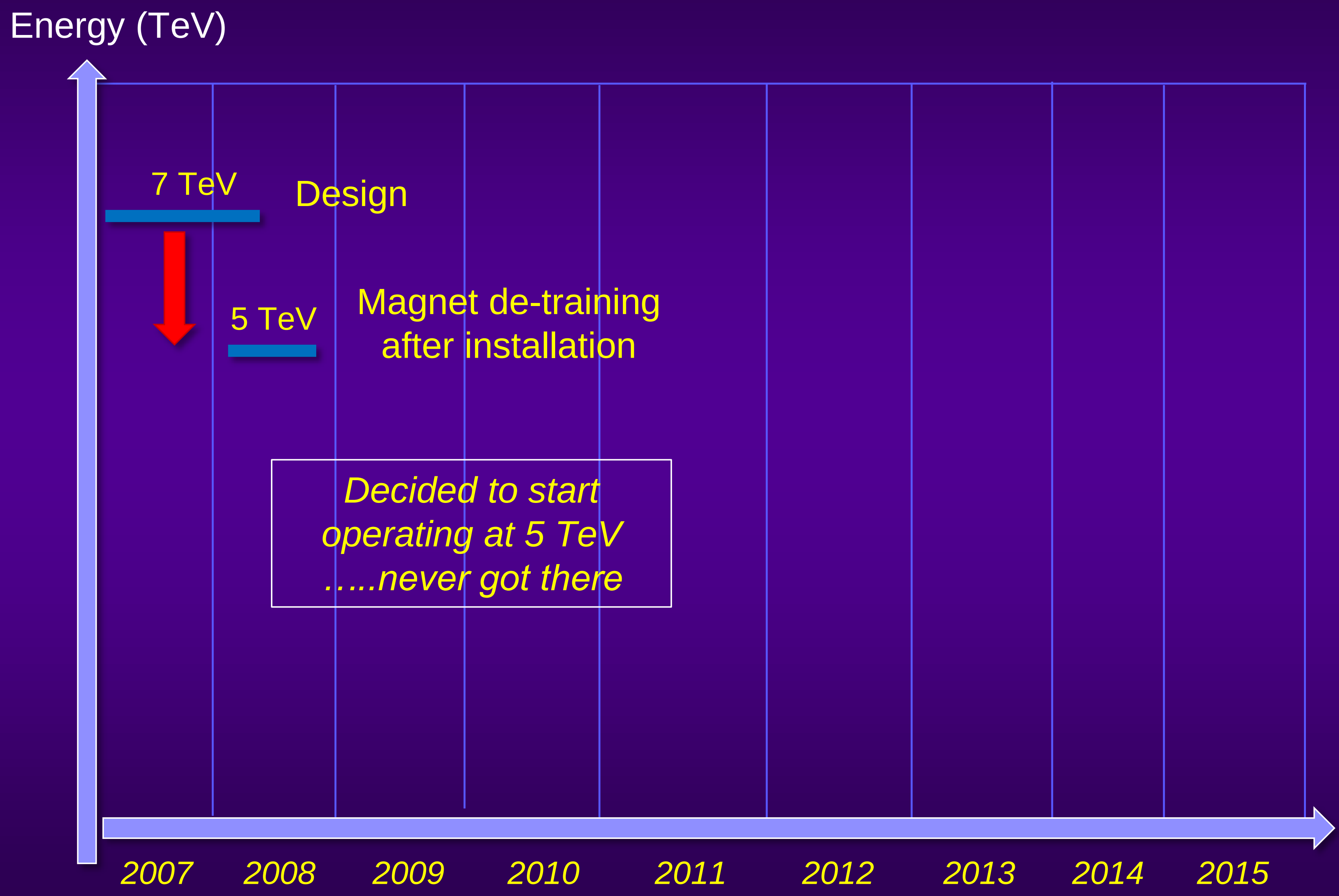
Lowering the temperature enables better usage of the superconductor, by broadening its working range

Operational margin of a superconducting magnet



Dipole magnets from surface to tunnel

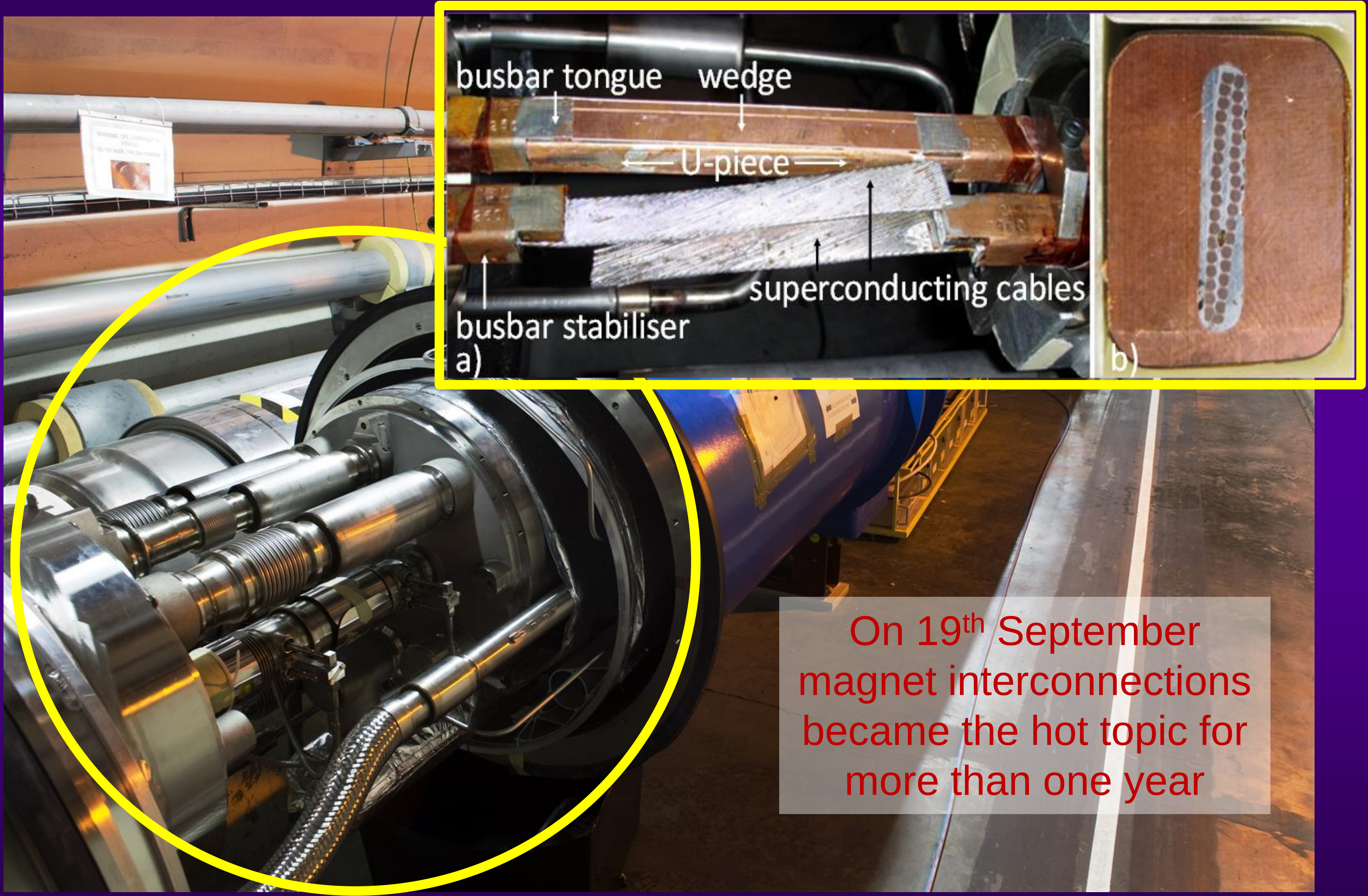
LHC energy evolution



September 10th 2008

A brief moment of glory

September 19th 2008



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

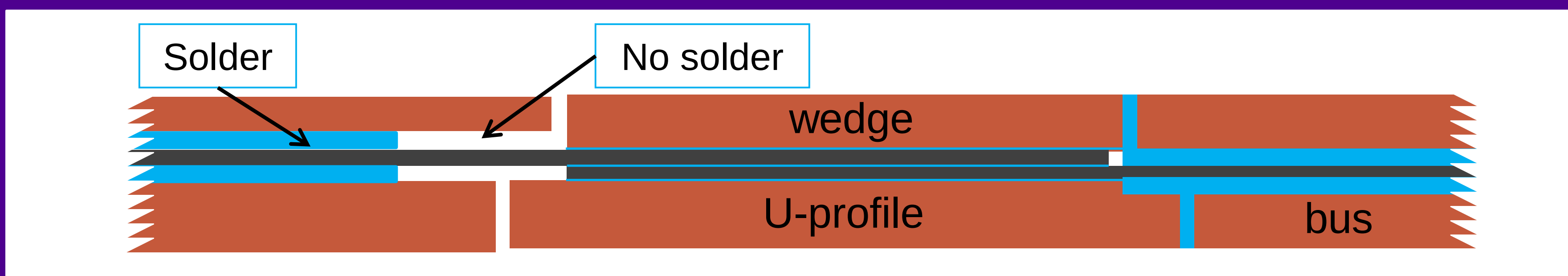
Incident September 19th 2008

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

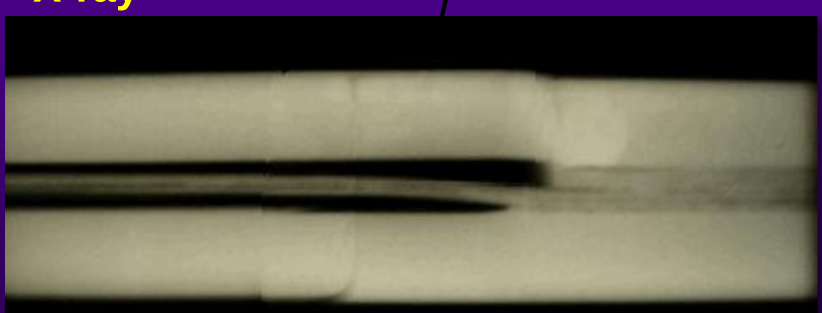
53 magnets had to be repaired

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.



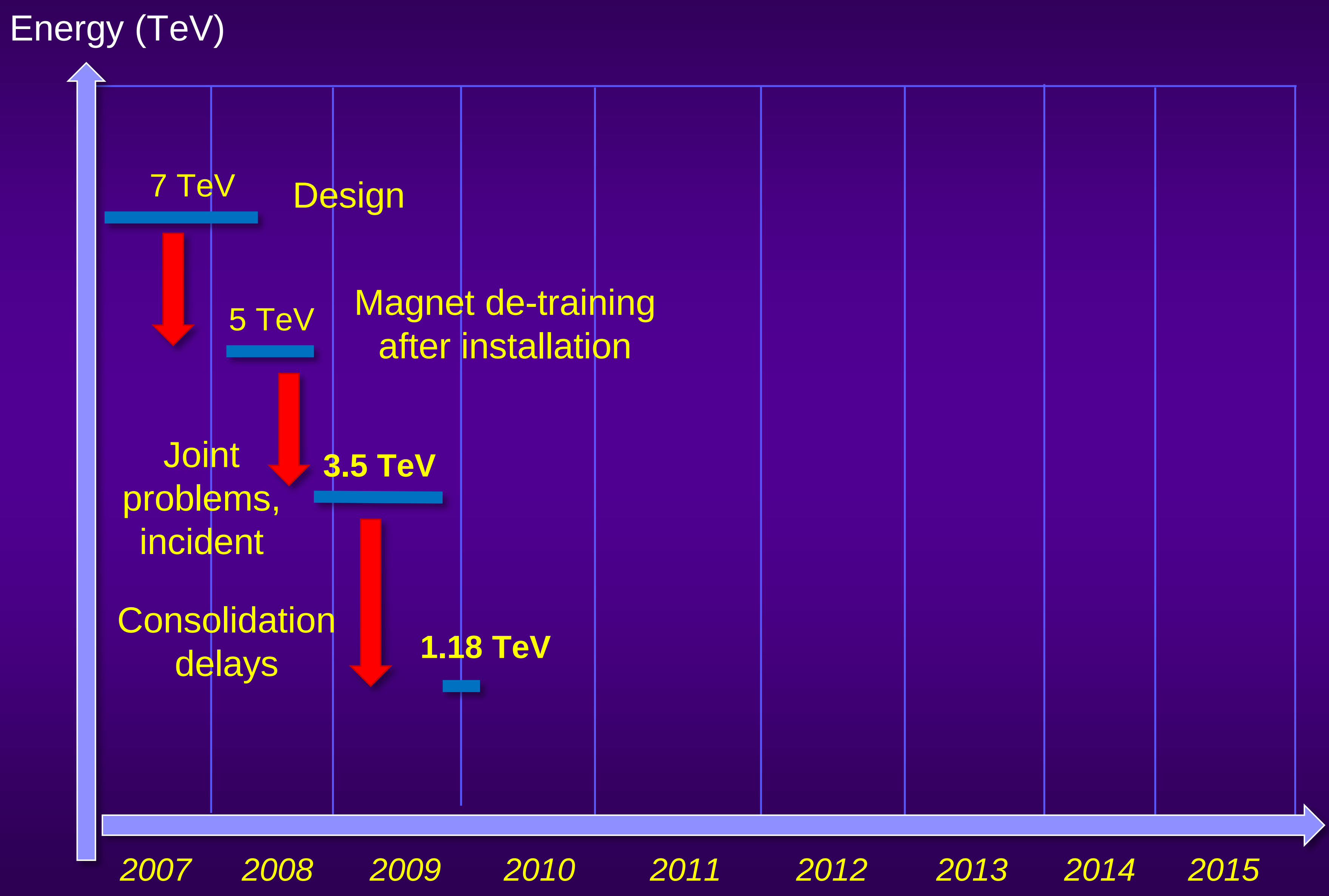
X-ray



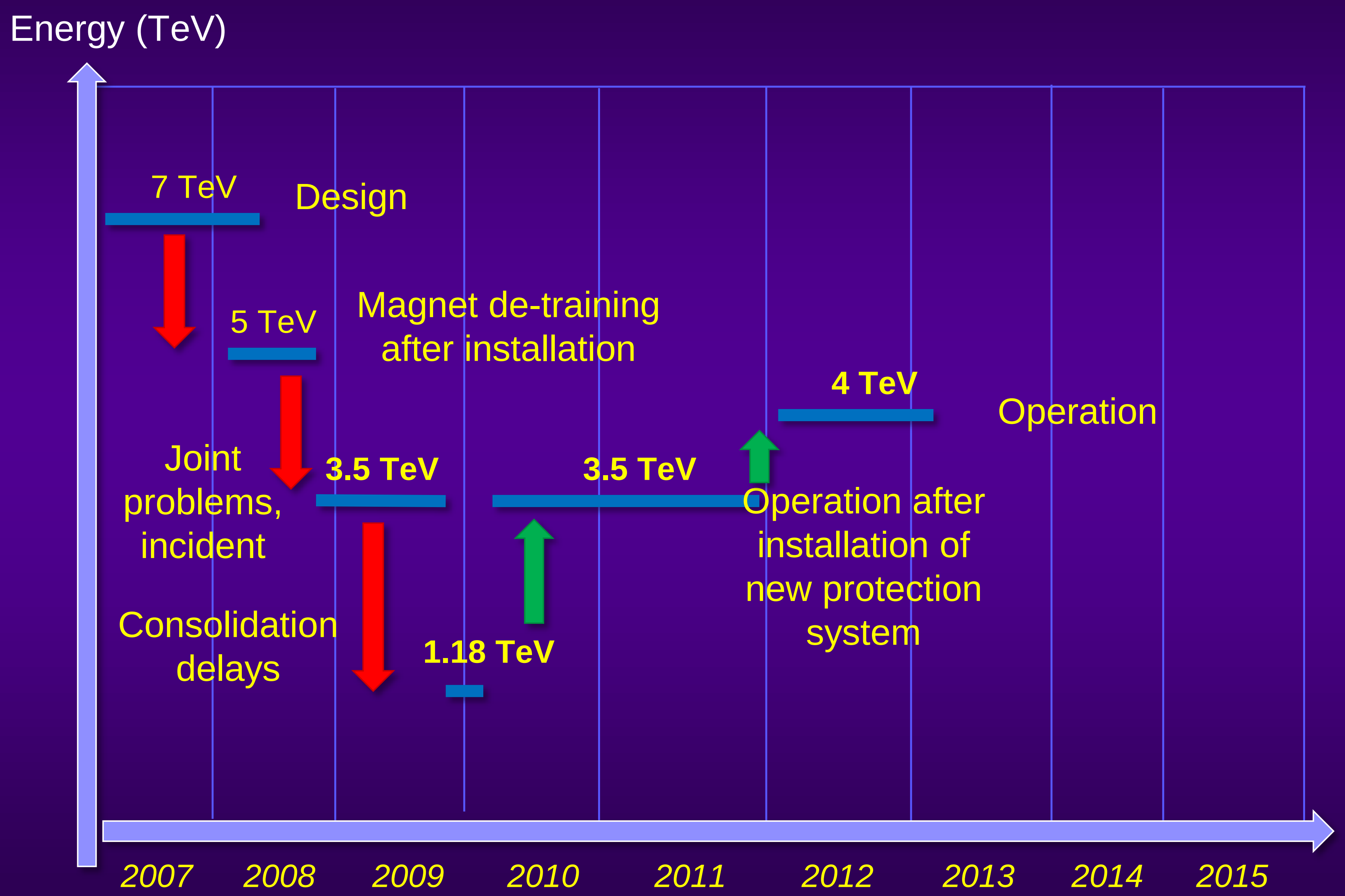
During repair work, inspection of the joints revealed systematic voids caused by the welding procedure.

→ Energy limitation for run 1 !!

LHC energy evolution



LHC energy evolution



High luminosity and consequences

High luminosity by colliding trains of bunches

Number of „New Particles“ per unit of time:

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

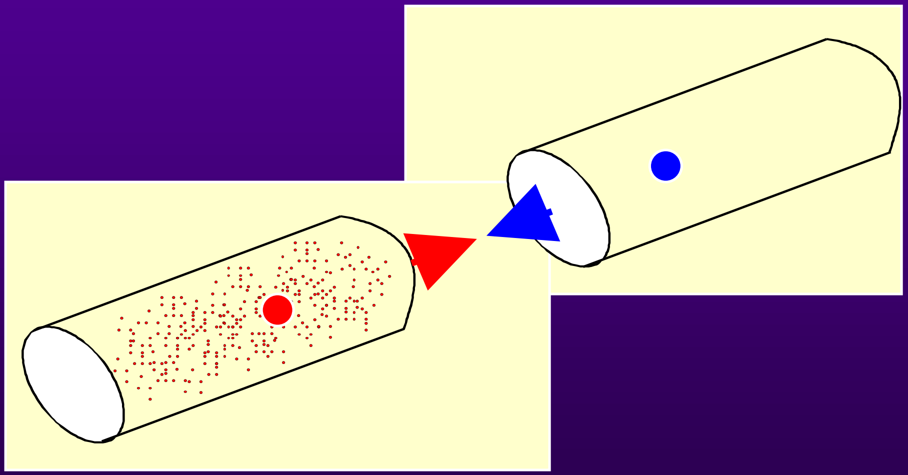
The objective for the LHC as proton – proton collider is a luminosity of about 10^{34} [$cm^{-2}s^{-1}$]

- 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 **1-3×10¹¹** due to the beam-beam interaction and beam instabilities

Beam size given by injectors and by space in vacuum chamber

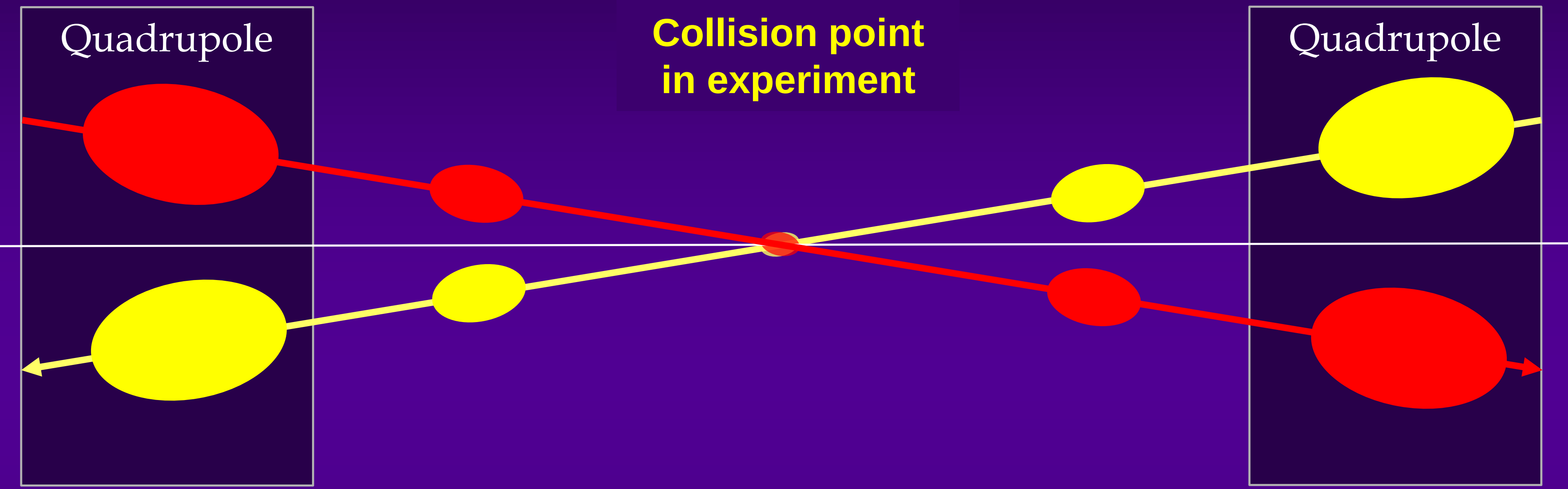
f = **11246 Hz**

Beam size **16 μm**

for β = 0.5 m (β is a function of the lattice)

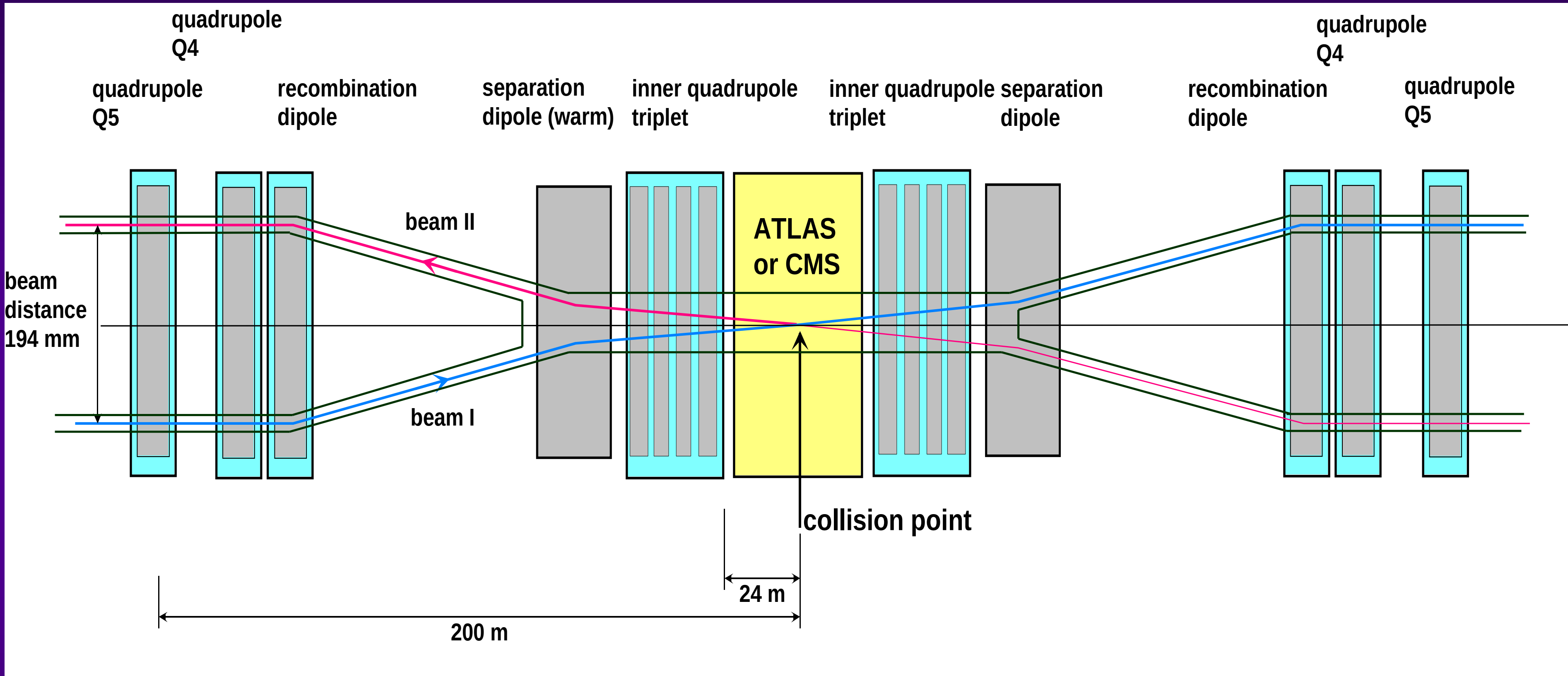
$$L = \frac{N^2 \times f \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y} = 10^{34}\ [cm^{-2}s^{-1}] \quad \text{for 2808 bunches}$$

…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

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: $\sigma_{tot} := 100\ \text{mBarn}$

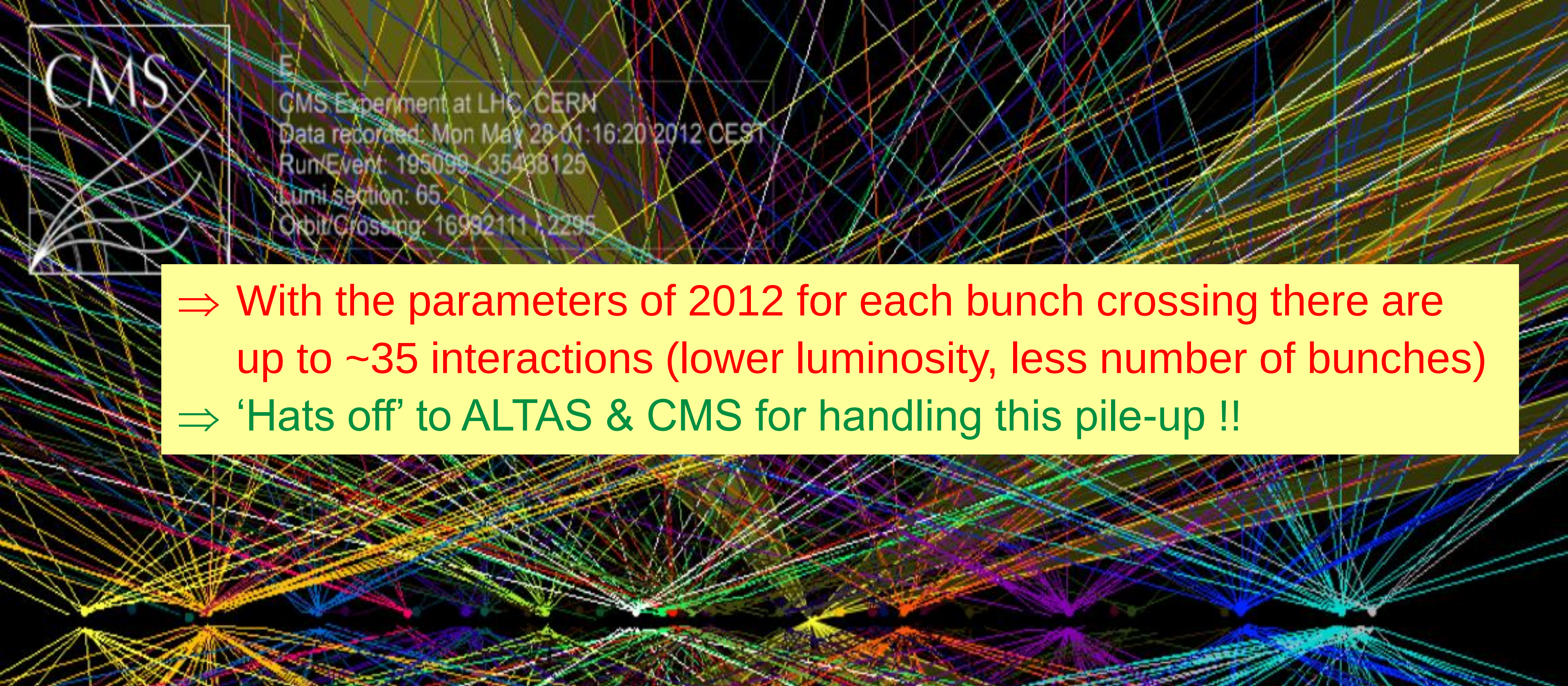
$\sigma_{tot} = 1 \times 10^{-25}\ \text{cm}^2$

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

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

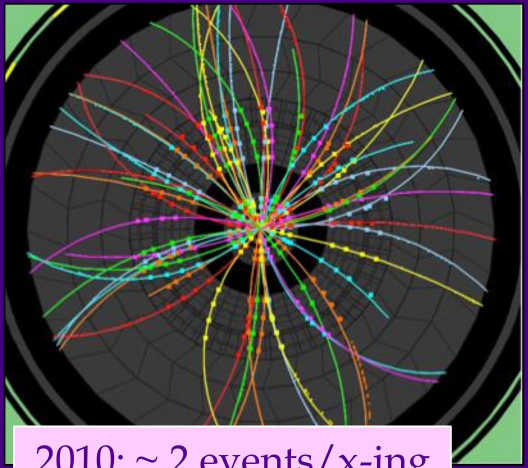
$frev_{lhc} = 1.1246 \times 10^{4}\ \frac{1}{\text{s}}$ and $N_{bunches\_1beam} = 2808$

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



⇒ 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

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

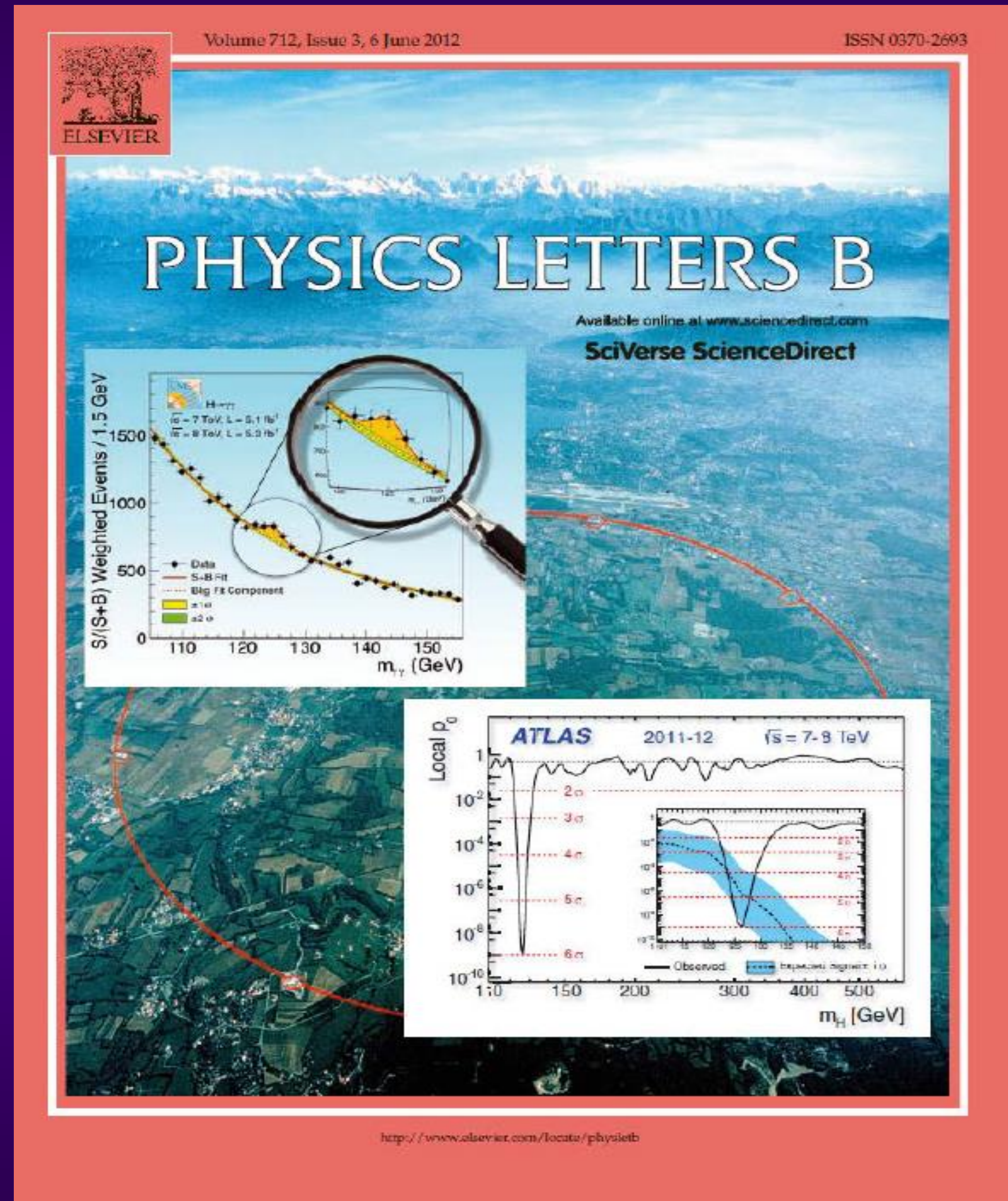
From 2010….


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 EXPERIMENT
2010
LHC on target!
Thanks from CMS Technical Coordination
for the excellent performance and collaboration

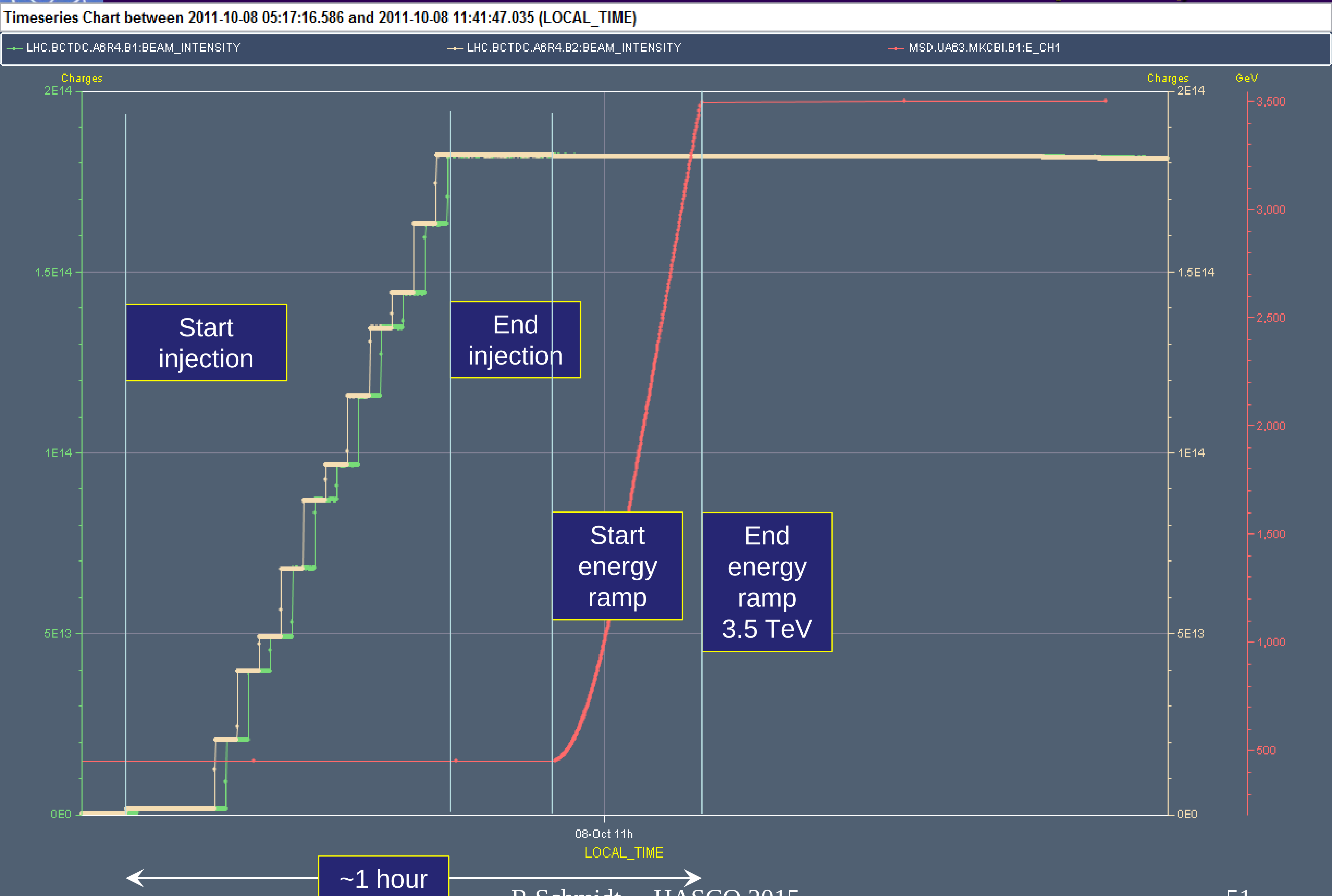
…..to 2012

1 fb-1 6 fb-1

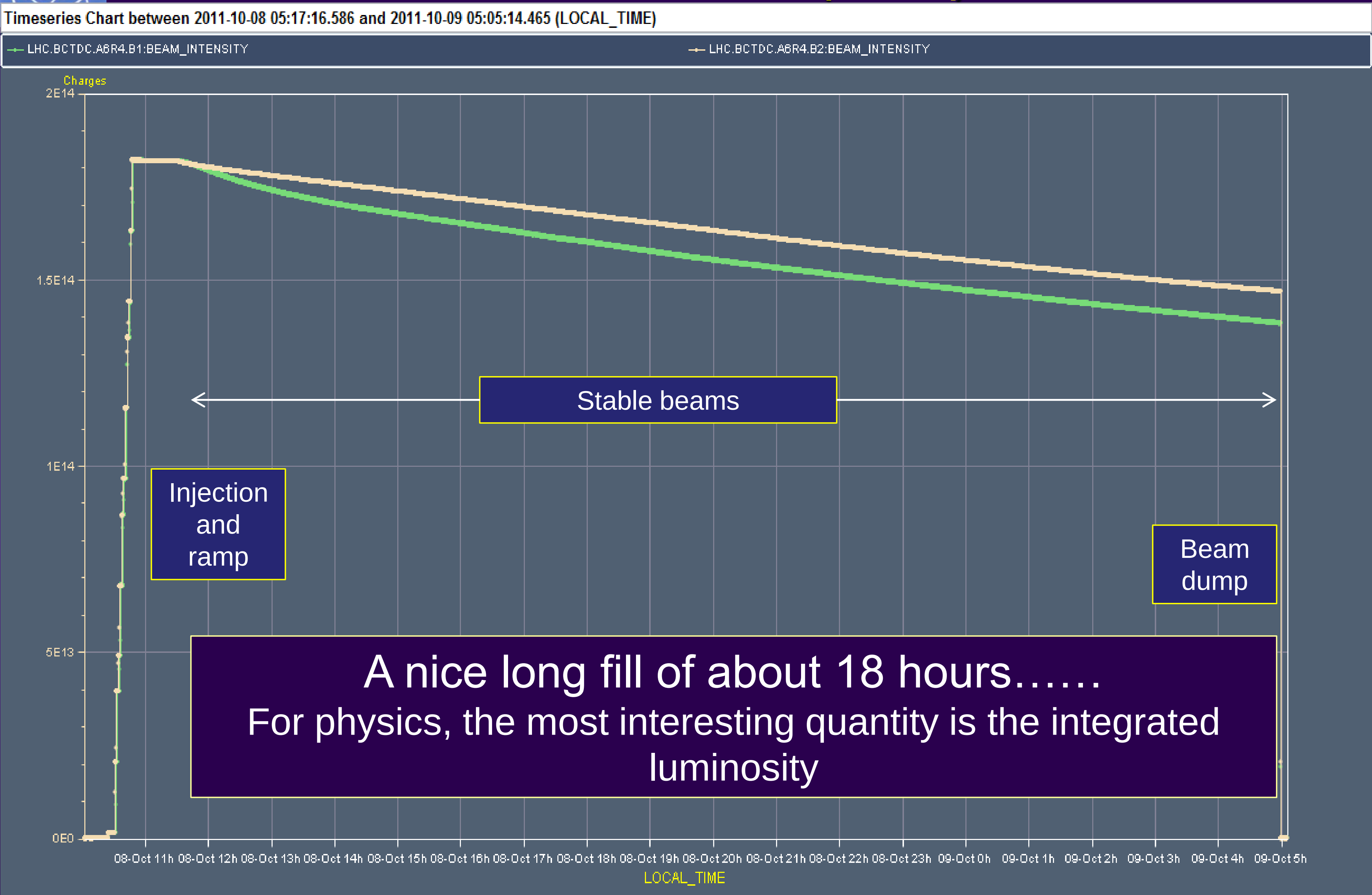
………late in 2012 celebrating the Higgs…



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



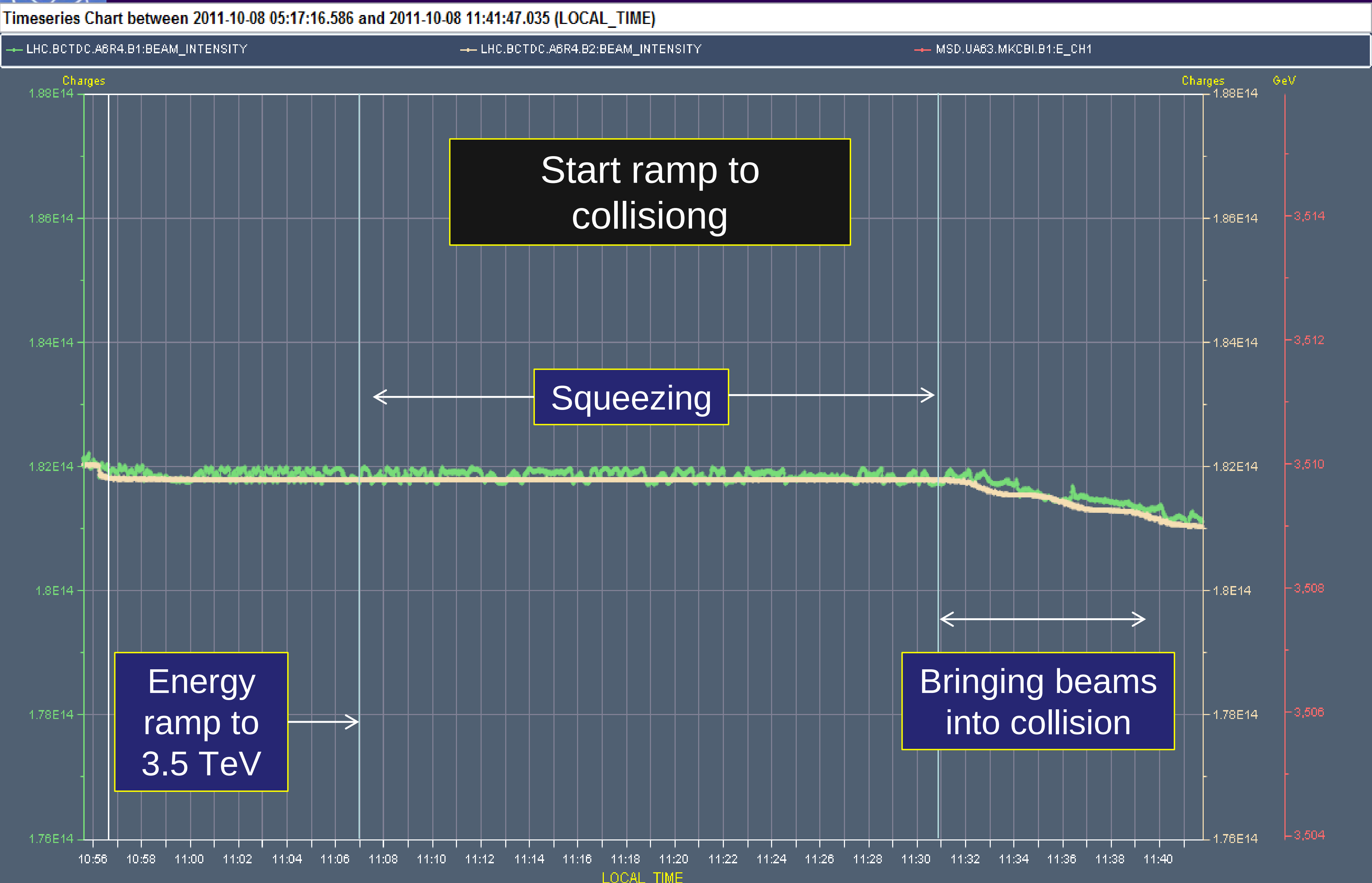
Excellent fill (2011)



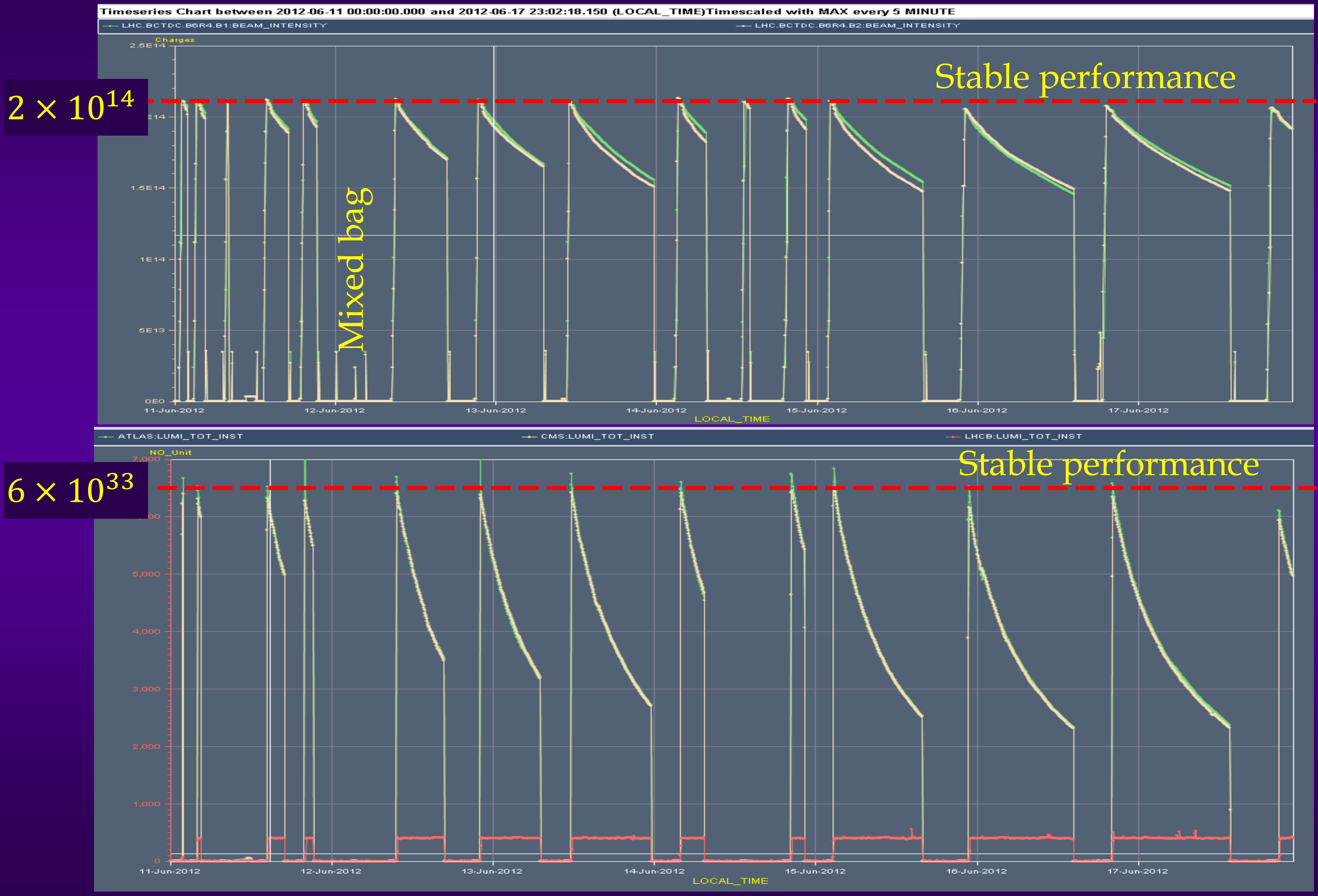
A nice long fill of about 18 hours……

For physics, the most interesting quantity is the integrated luminosity

Reference fill 2195 in 2011 – at 3.5 TeV



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 !

Challenges operating with high intensity beams

Machine Protection and Collimation

Electron clouds

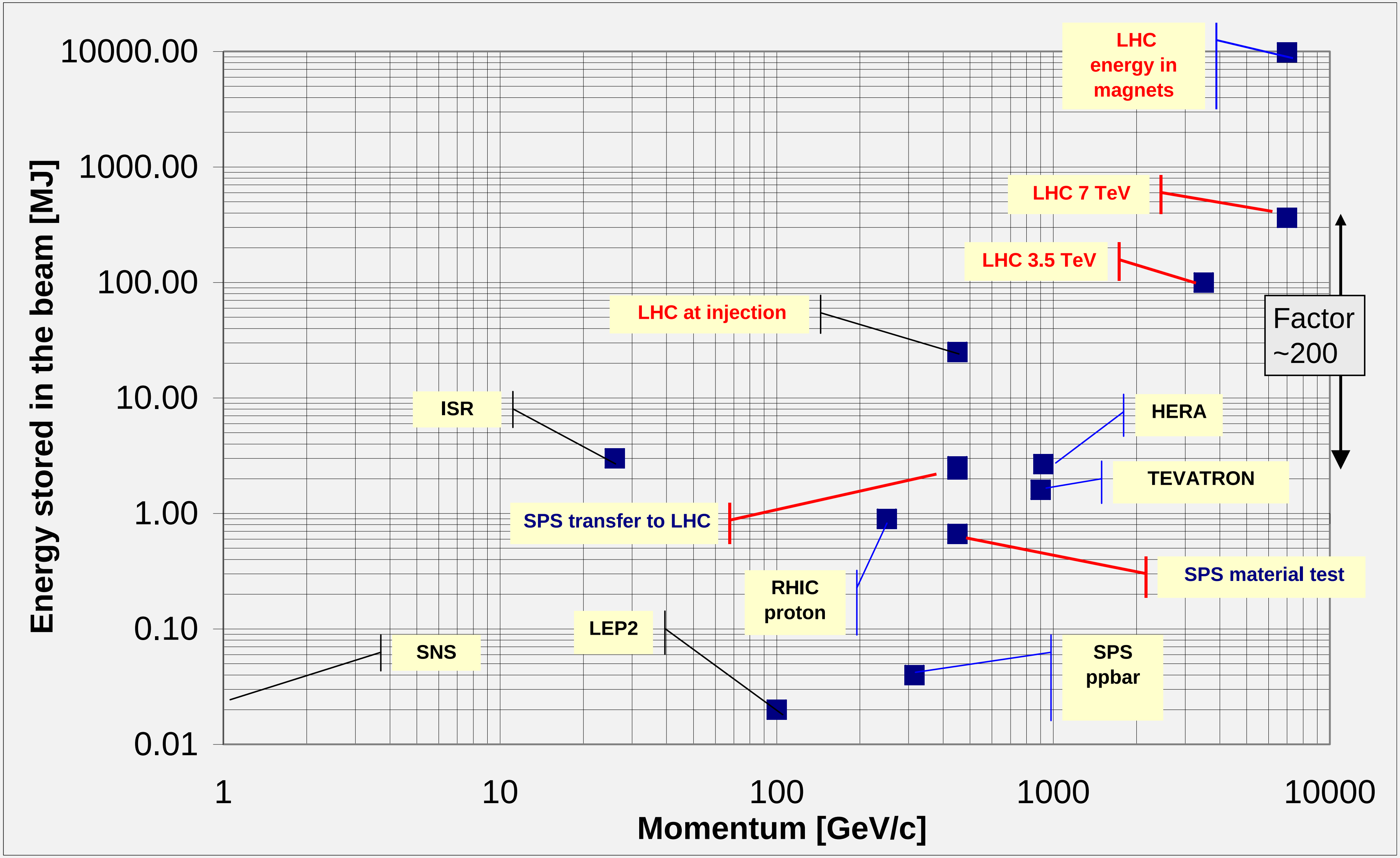
Instabilities

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

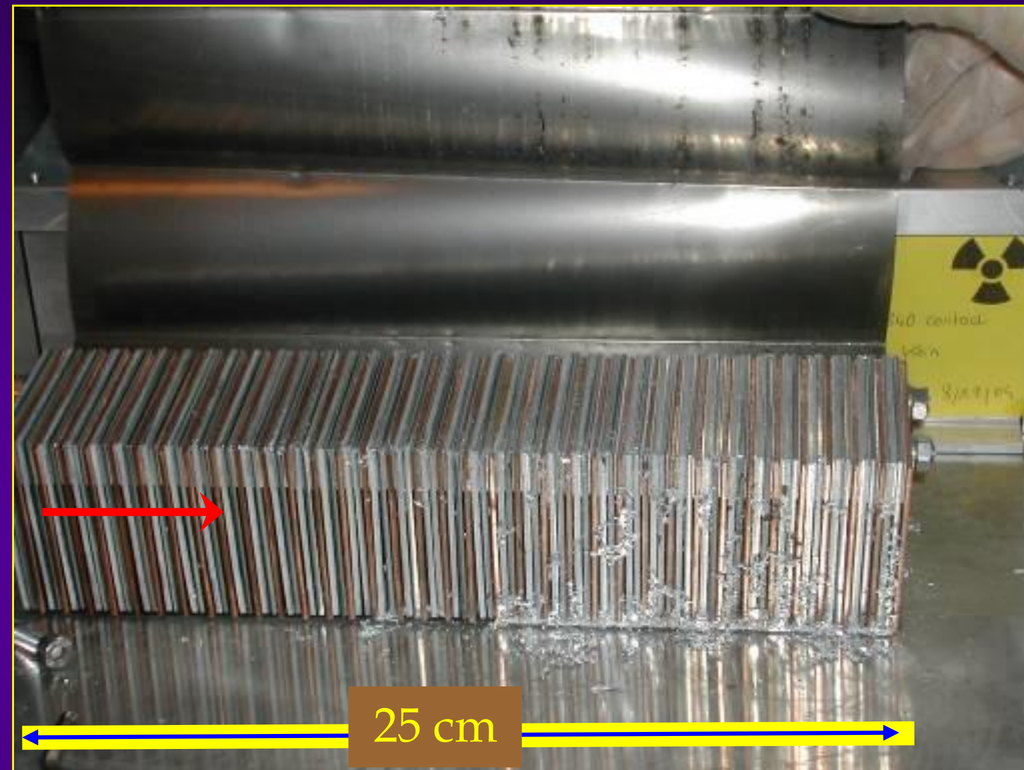
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

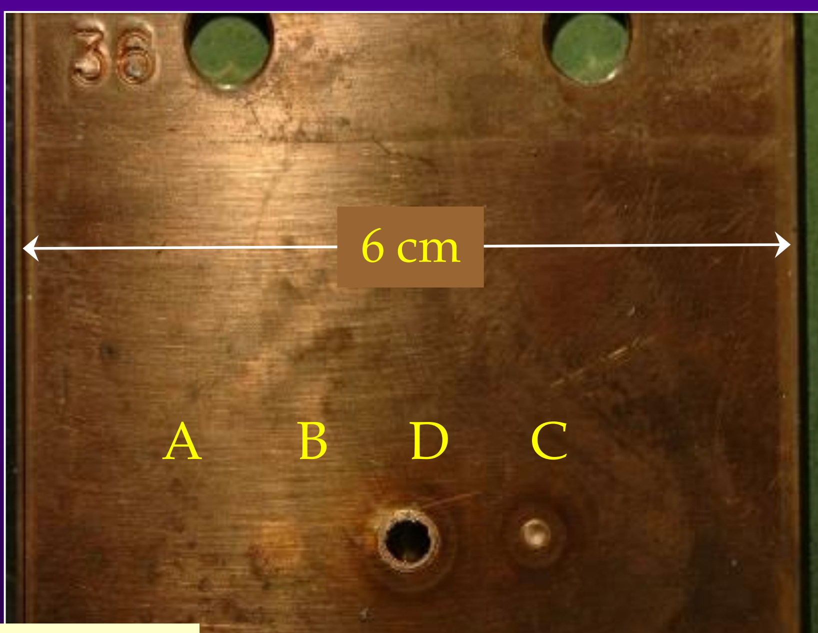
above damage limit for copper

stainless steel no damage

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

below damage limit for copper





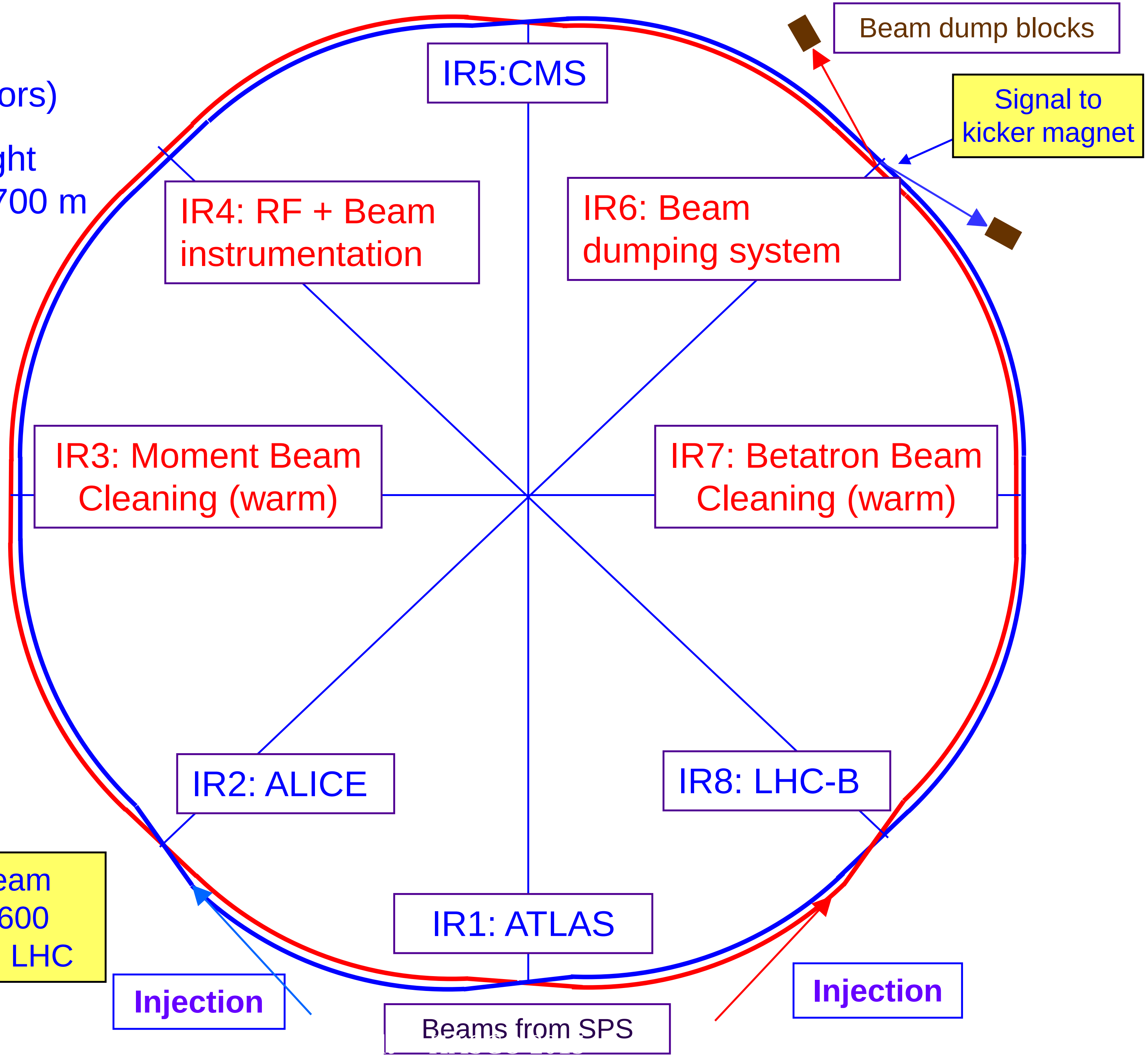
- Damage limit ~200 kJoule
- 0.1 % of the full LHC 7 TeV beams
- factor of ~10 below the energy in a bunch train injected into LHC

V.Kain et al

LHC Layout

eight arcs (sectors)

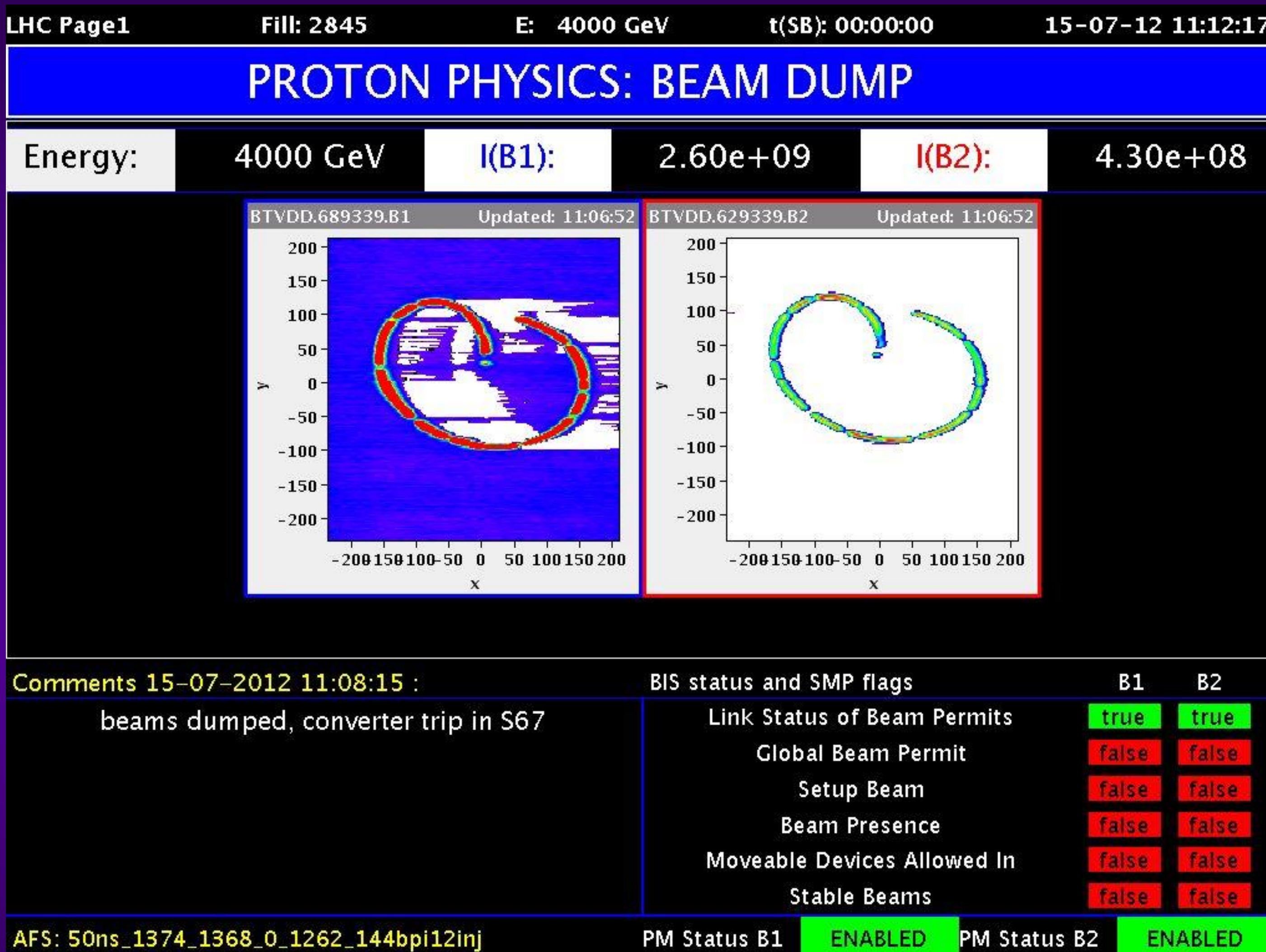
eight long straight section (about 700 m long)



Detection of beam losses with >3600 monitors around LHC

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

BLM system: beam losses before collisions

Unit: Gray / s Scale: Log Integration Time: 1.3 s Start 1 End 511 Losses: Mean Display: Acquisition

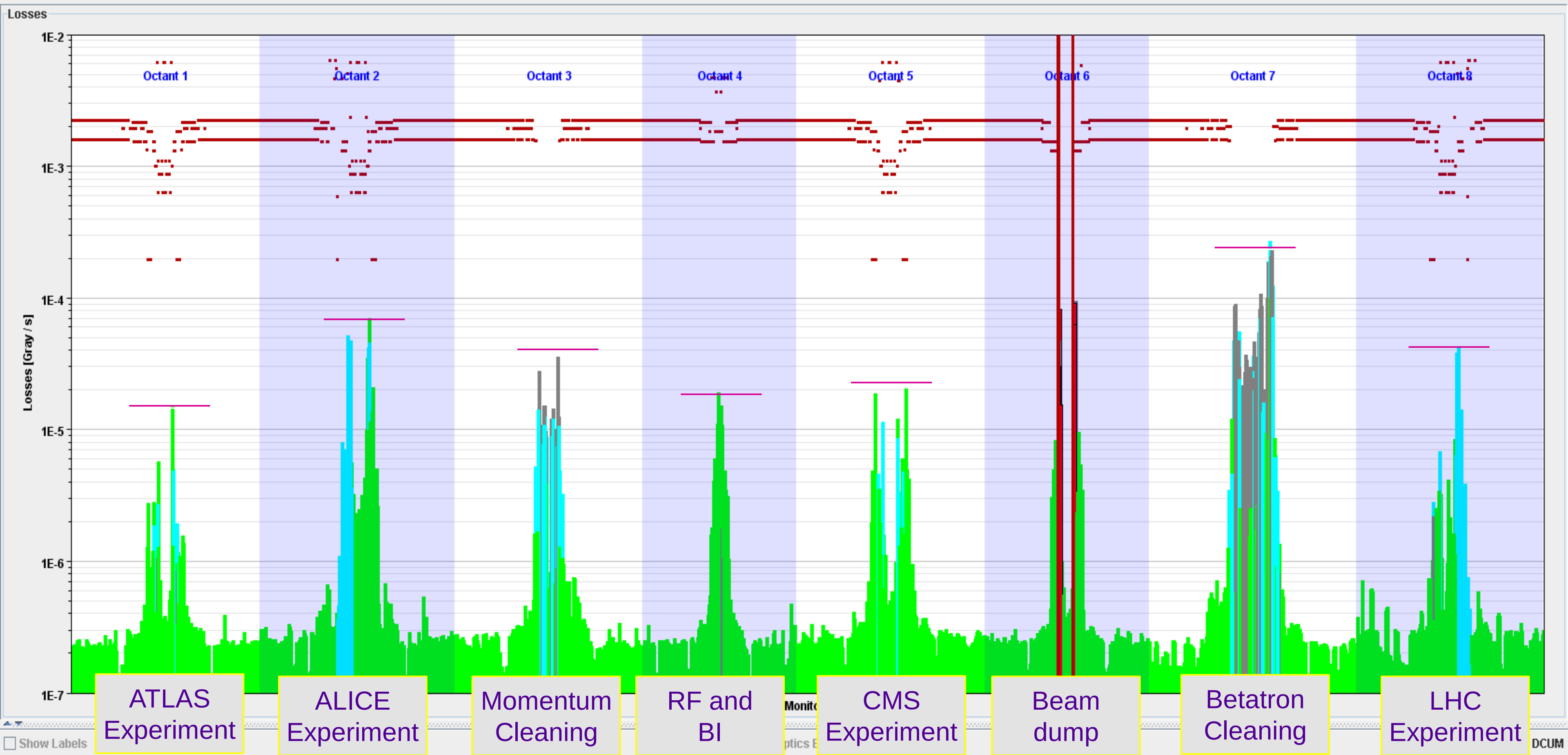
Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

Filter (3553 / 3895)

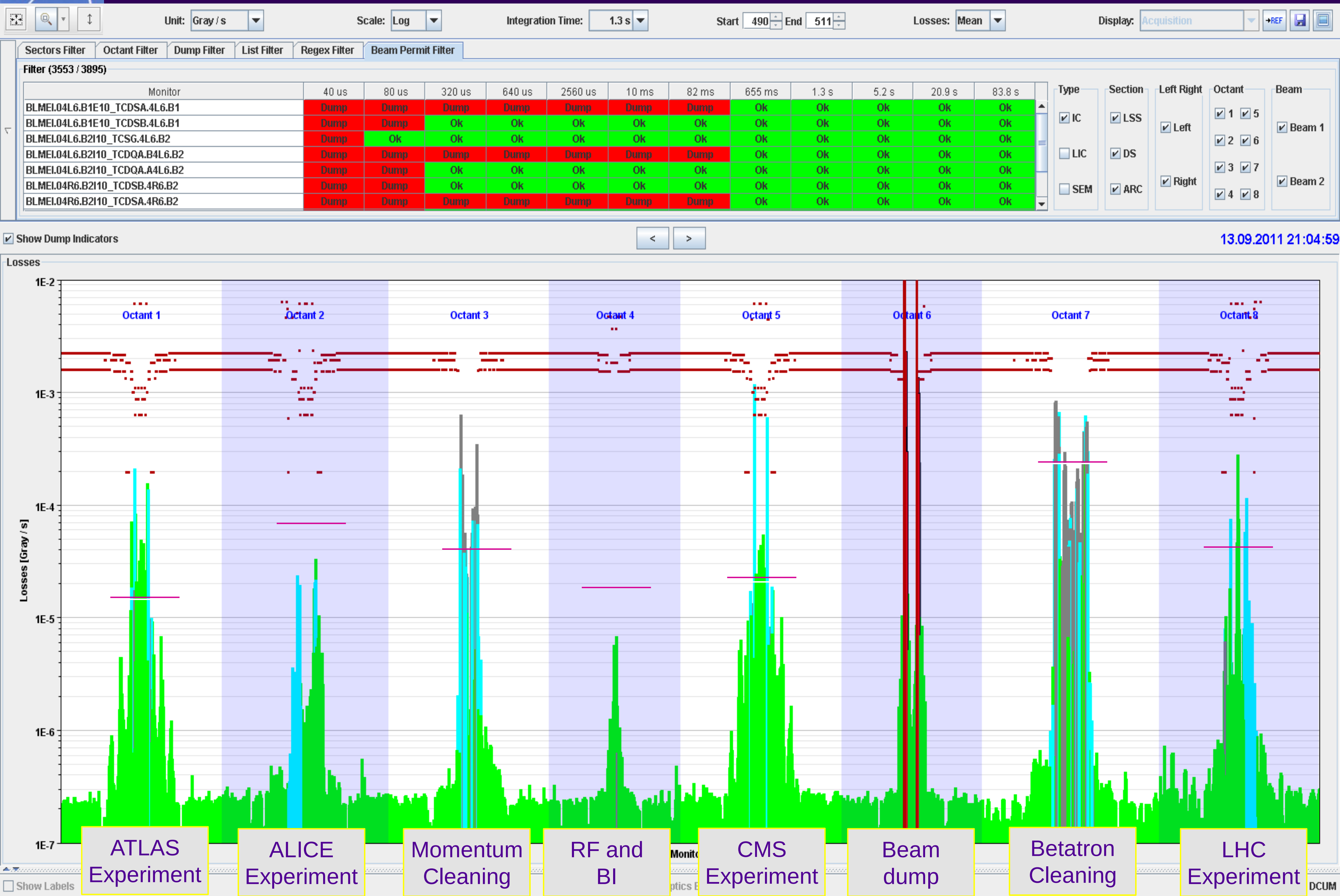
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCSG.4L6.B2	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok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

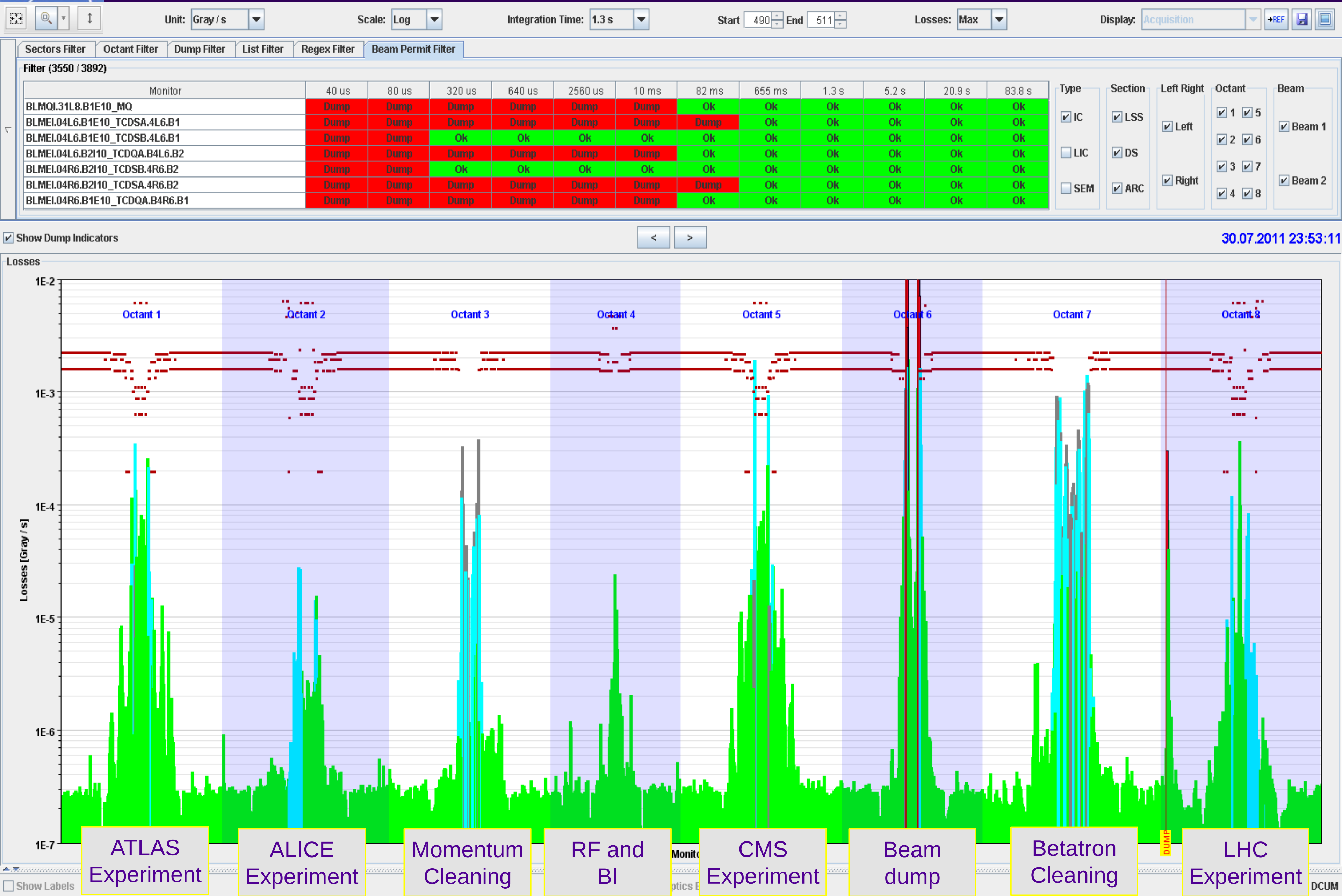
Show Dump Indicators — 15.09.2011 16:55:18



Continuous beam losses during collisions

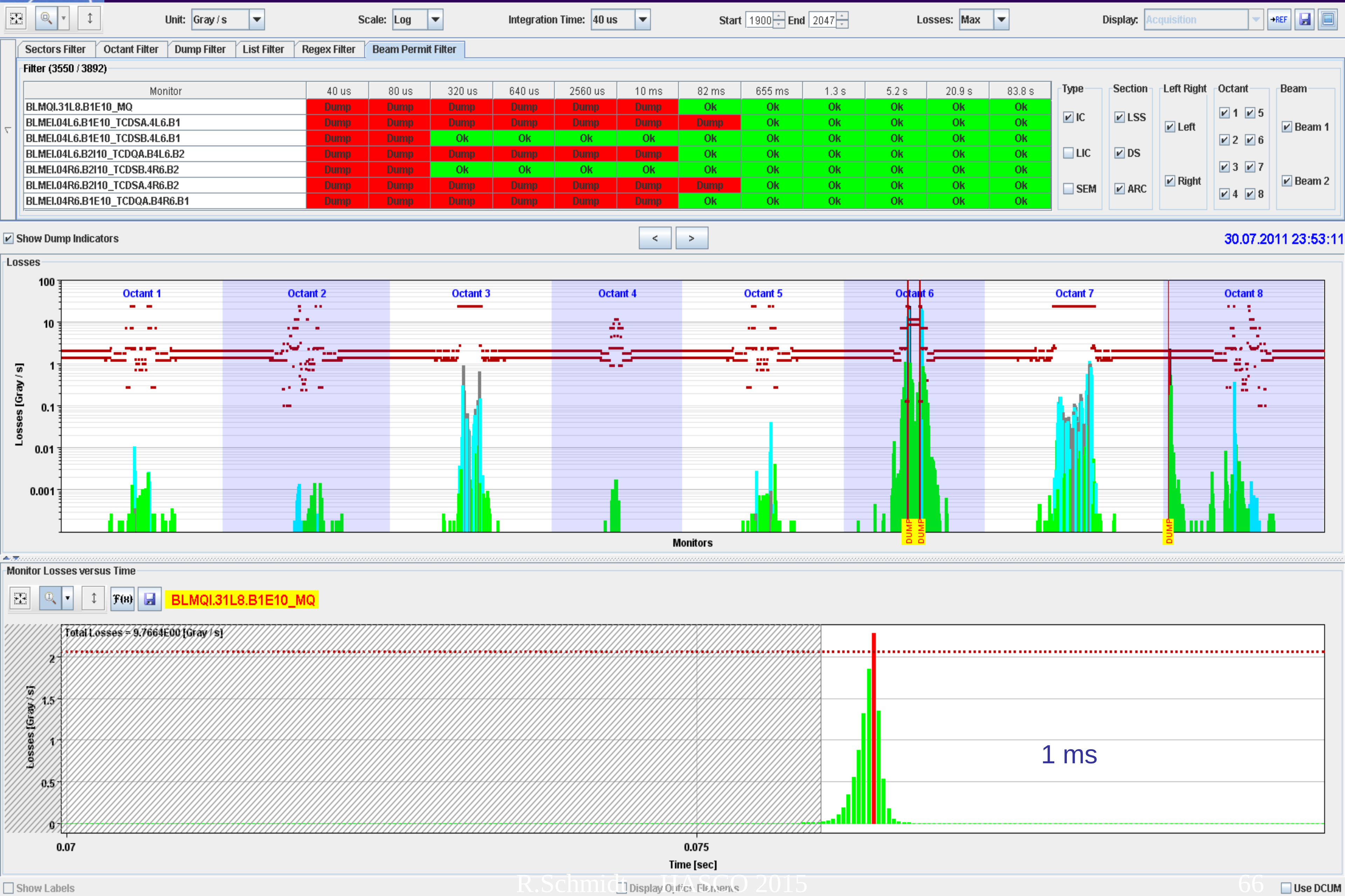


Accidental beam losses during collisions



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

Zoom one monitor: beam loss as a function of time

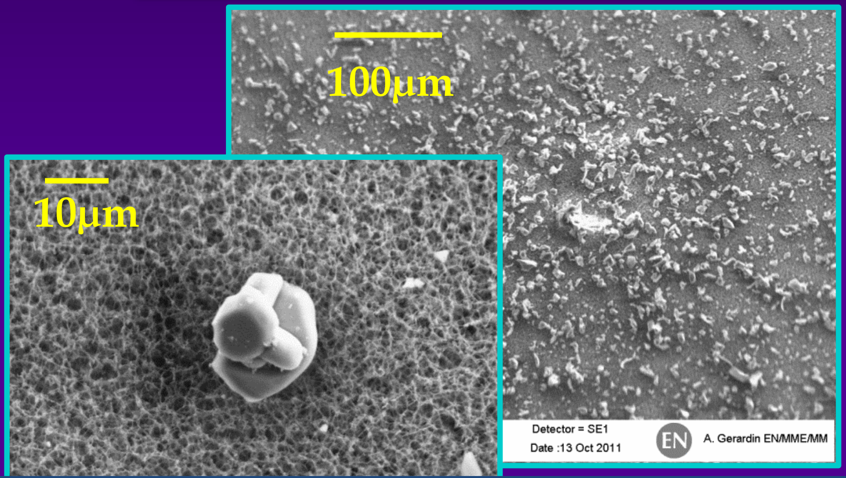


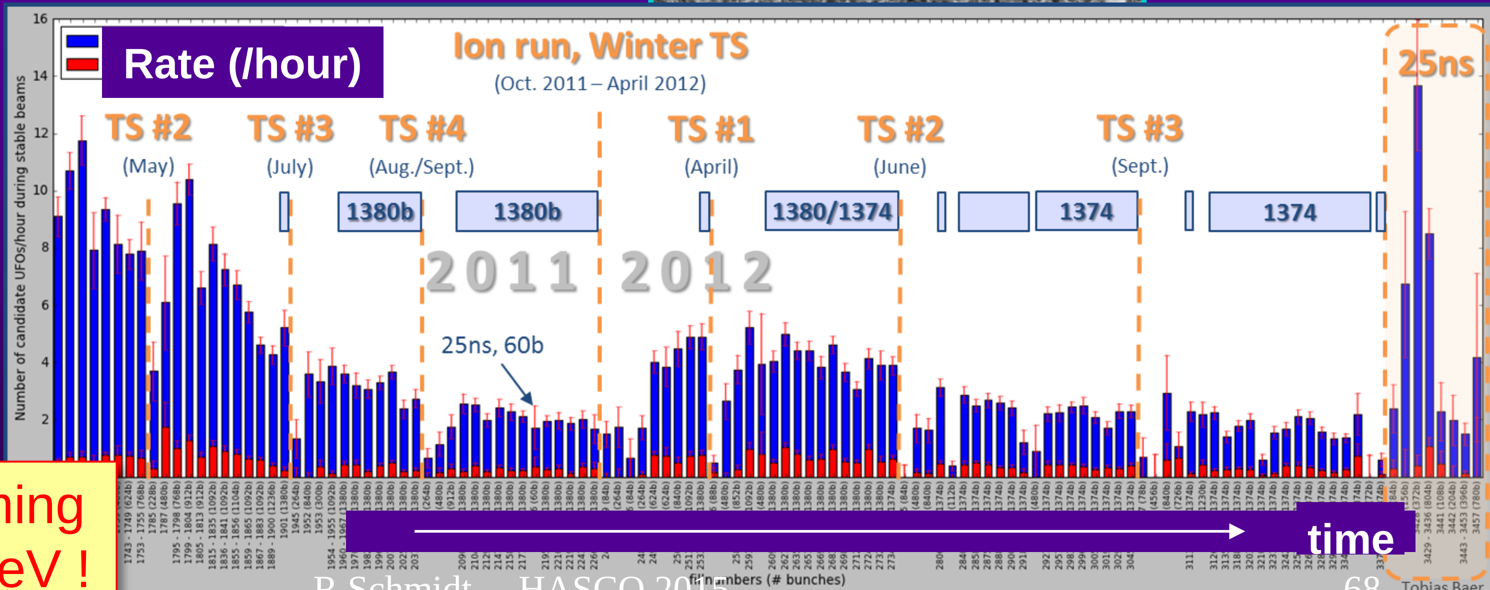
UFOs at LHC

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.

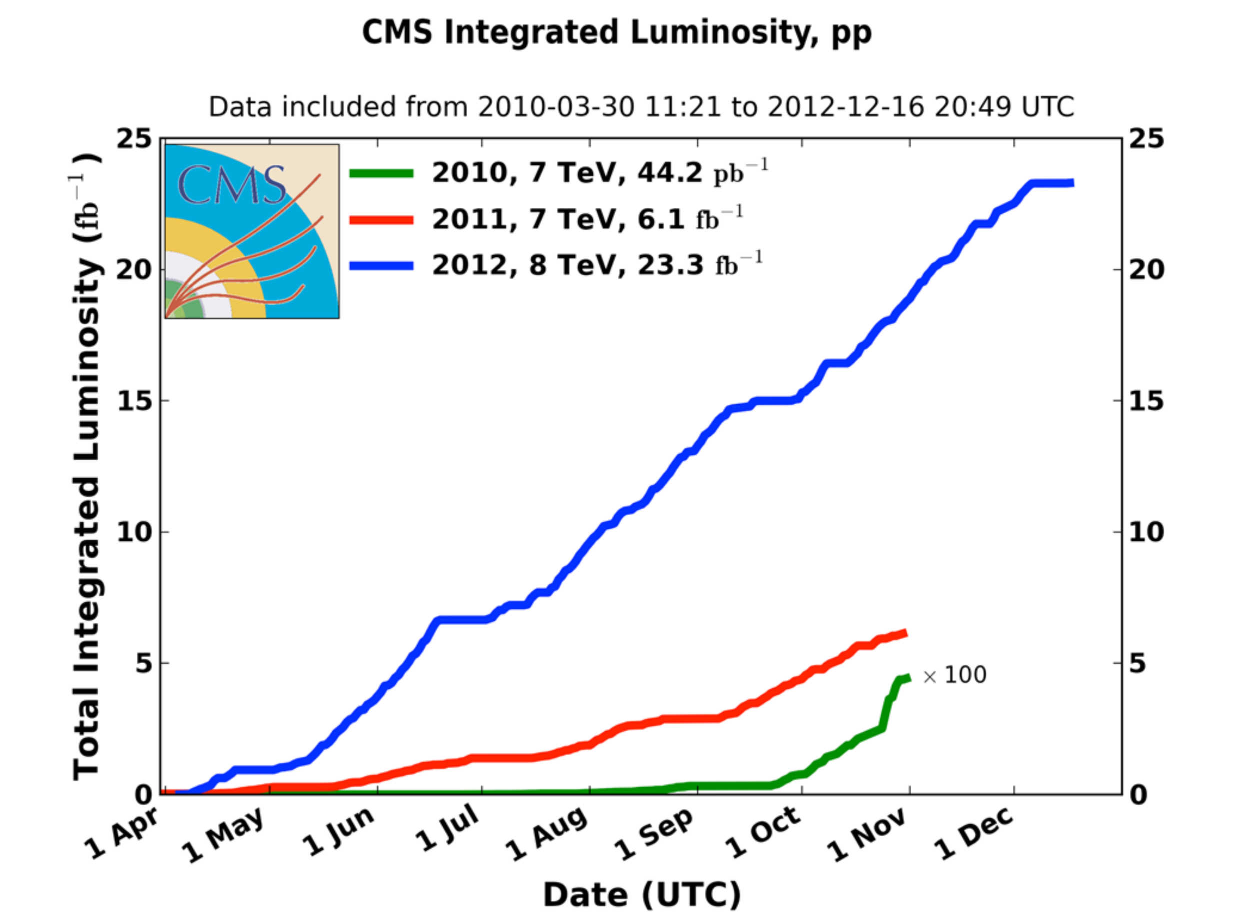




UFOs are becoming an issue at 6.5 TeV !

Overall performance during Run 1.....

Integrated luminosity 2010-2012



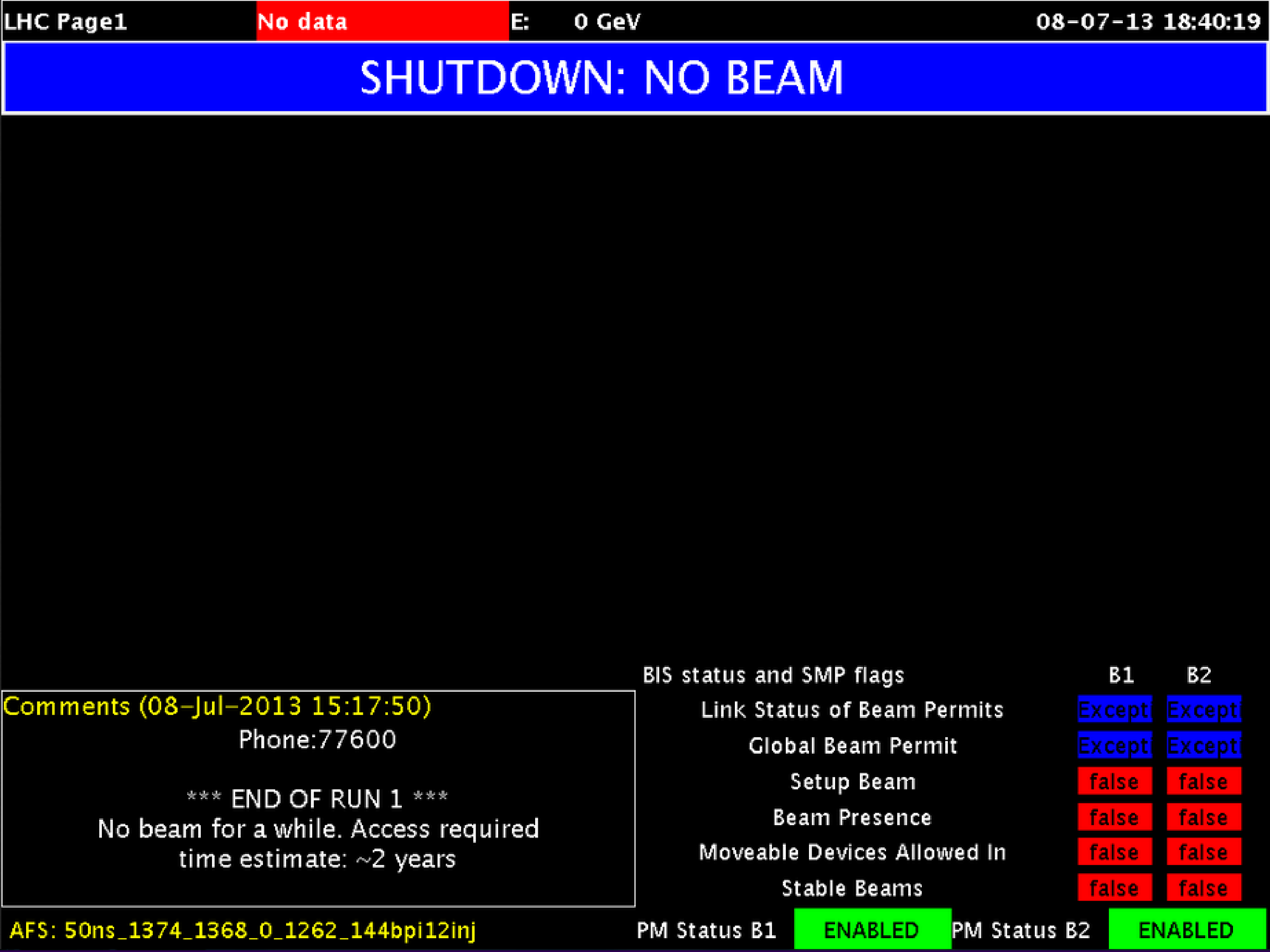
- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

What we learned during LHC Run 1…..

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

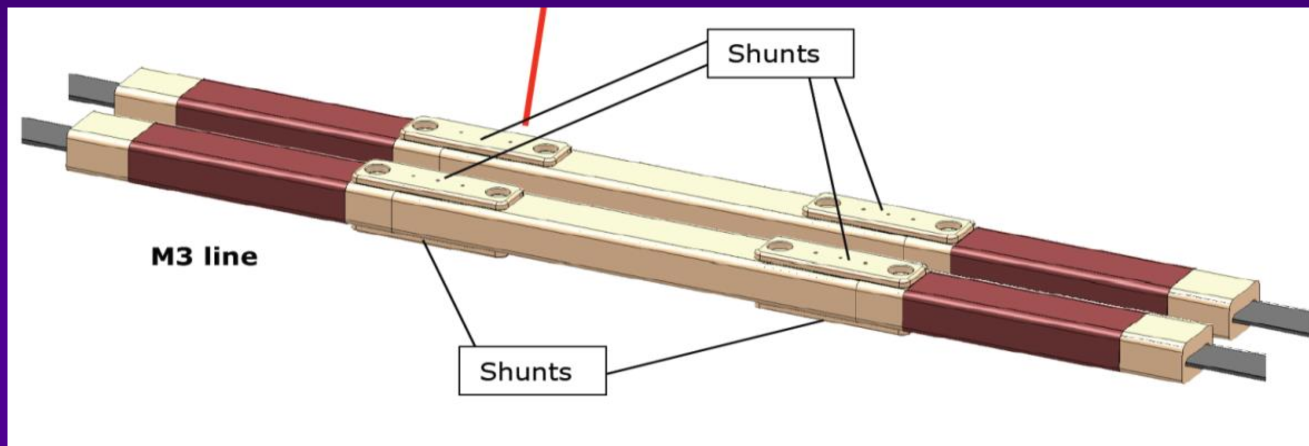
…..first experience of Run 2

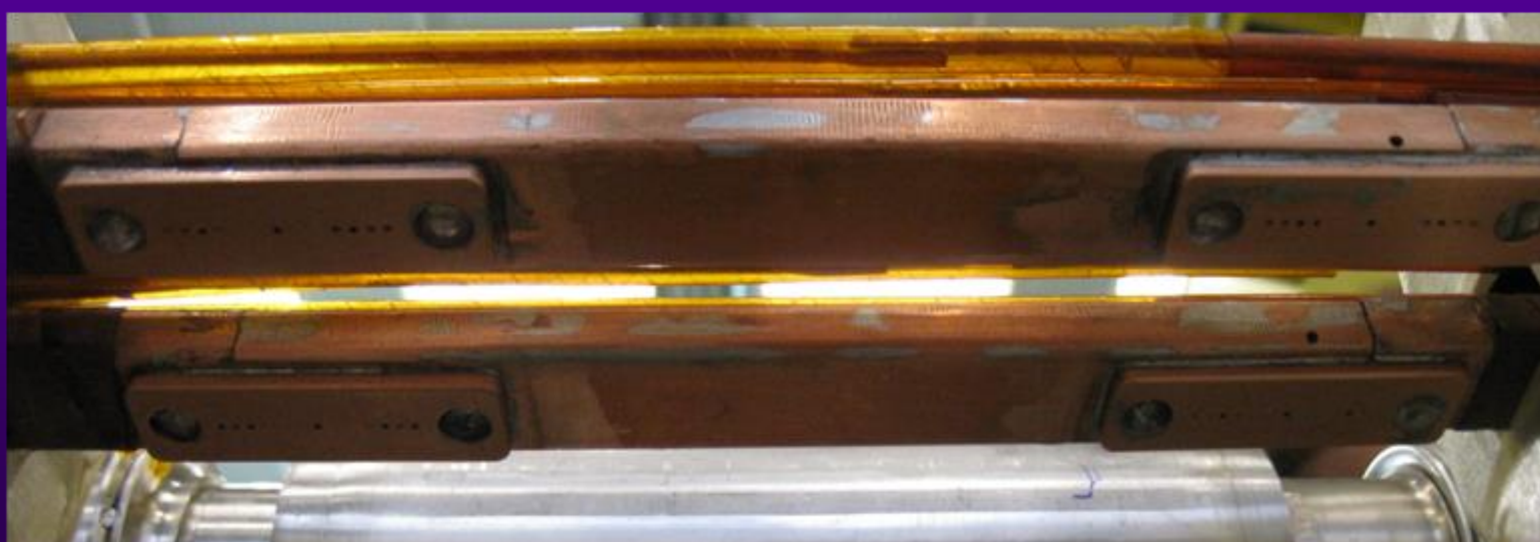
2015 to 2018


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
Except
Global Beam Permit
Except
Except
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

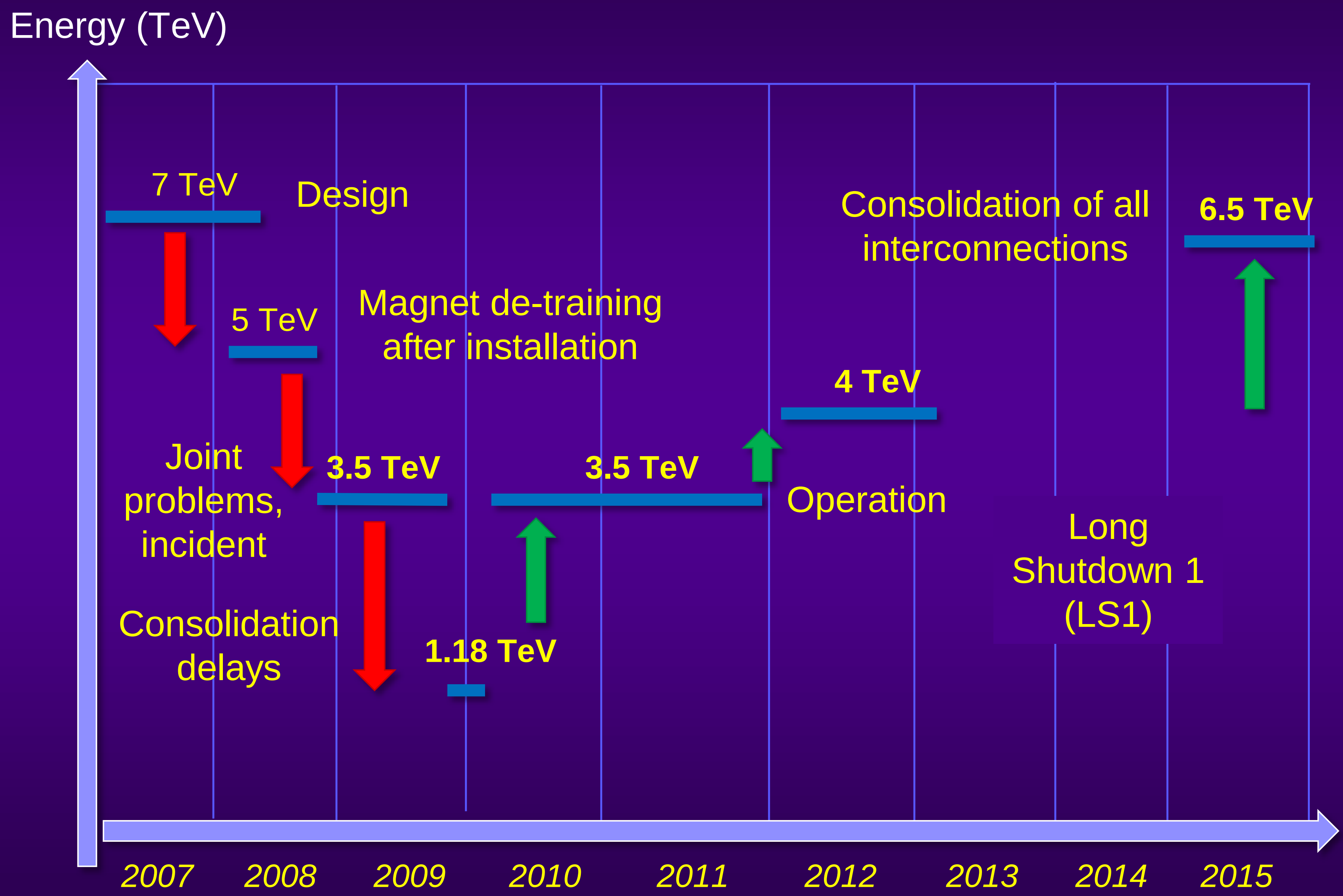
Preparing for nominal energy

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

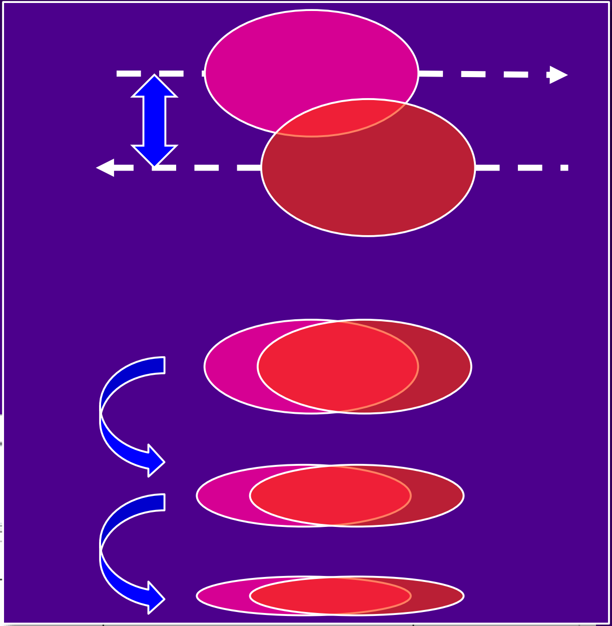
Some out of many possible scenarios @ 6.5 TeV

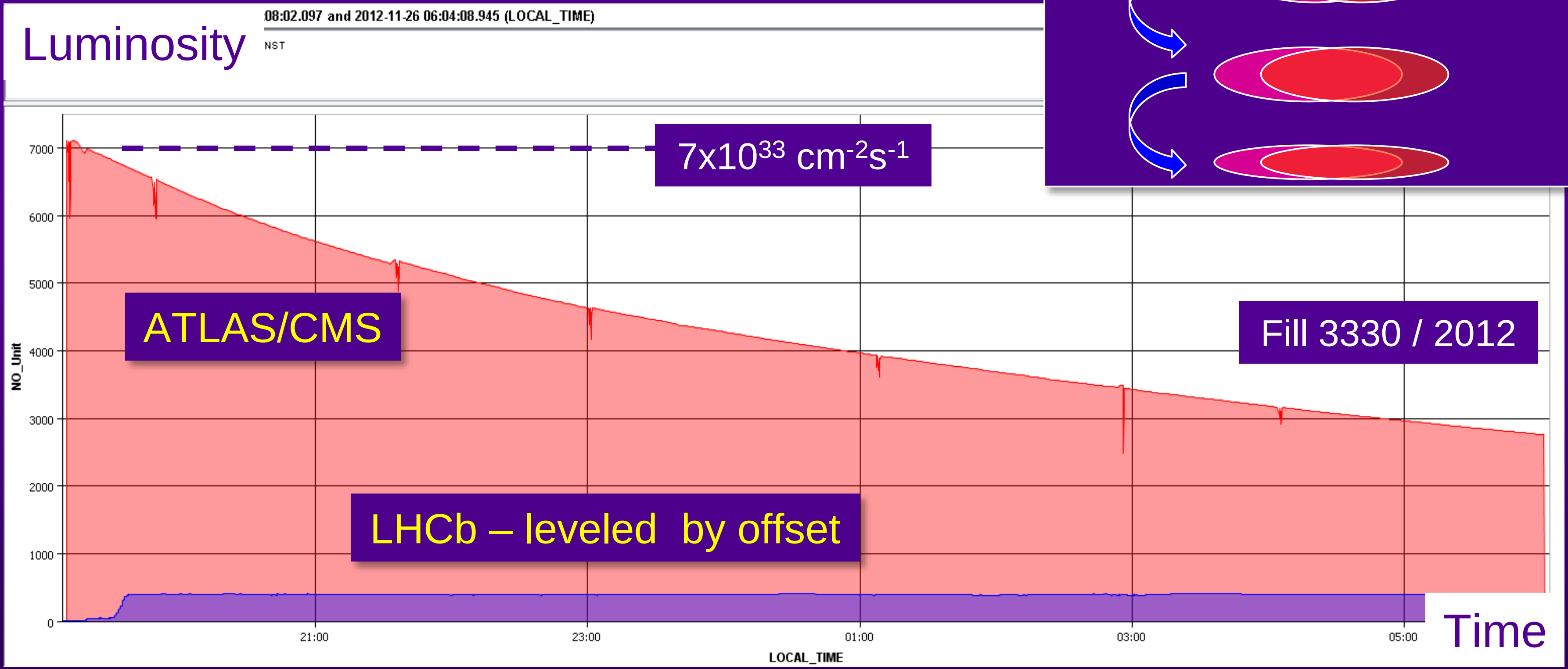
Beam	k	N_b [10^{11} p]	Emit. [mm]	b* [m]	Luminosity [10^{34} $cm^{-2}s^{-1}$]	Event pile-up	Int. L [fb^{-1}/y]
50 ns	1260	1.70	1.6	0.4	2.0	110*	~30
25 ns low emittance	2520	1.15	1.9	0.4	1.5	42*	~50
25 ns standard	2760	1.15	3.7	rted	0.85	23	~30

- Operation with 25 ns beam is preferred
- Operation started with 50 ns beam (up to 480 bunches)
- Preparation for 25 ns operation is ongoing

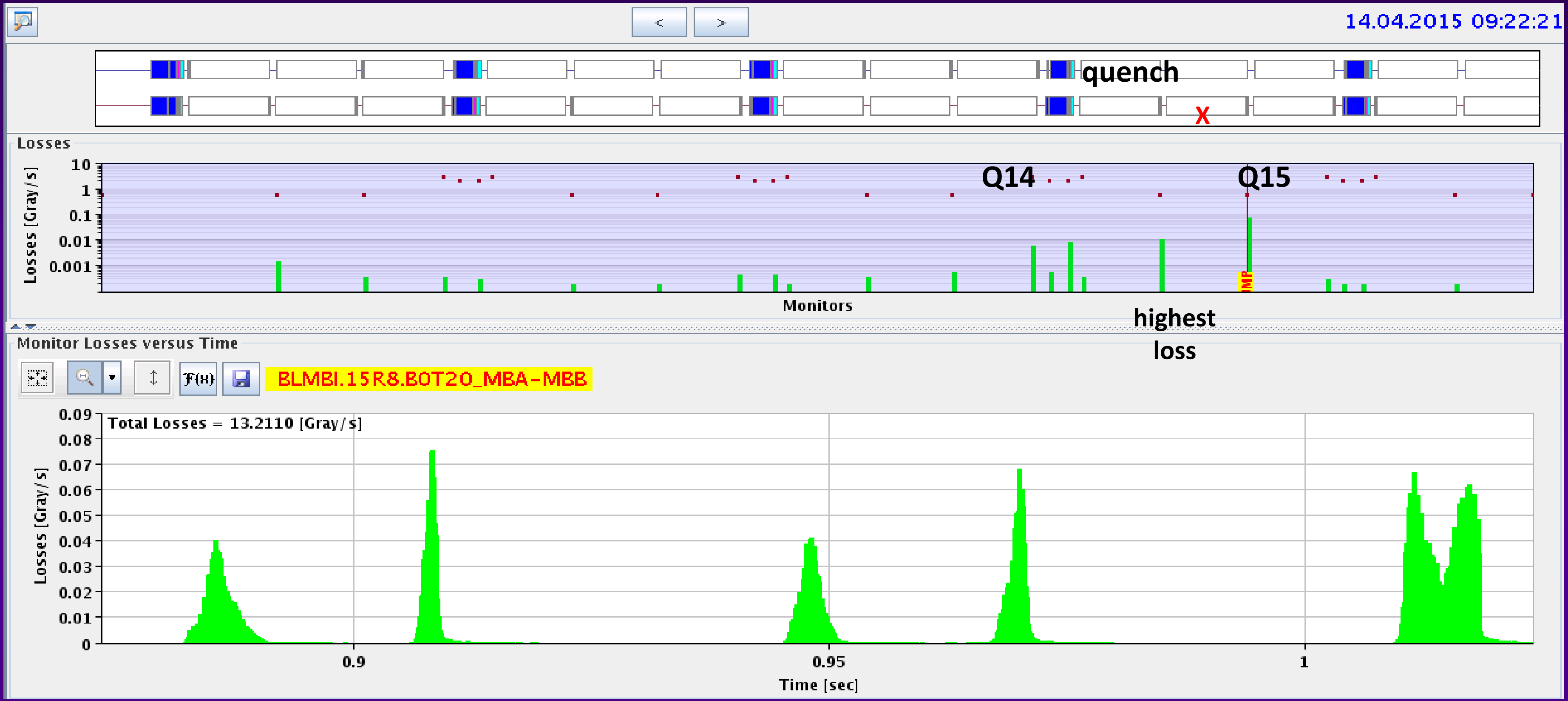
Leveling luminosities

- 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.





M-UFOs (multiple UFOs)



- Multiple loss events after a short time at 6.5 TeV compatible with particles falling into the beam
  - Loss patterns point to a specific position in the middle of a dipole magnet
  - Magnets quenched several times, numerous BLM triggered dumps…

Outlook: LHC operation in 2015

- Major job done in LS1 and during powering tests
- Looking good at 6.5 TeV
- Challenge - high beam intensity operation, e-cloud and UFOs
- Fundamentals look sound, no show stoppers for the moment
- Some problems – resolution cost time
- 2015 will be a short year for proton physics but lay foundations for luminosity production for the rest of Run 2

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

Final remarks

- The progress in LHC performance has been great.
- Luminosity close to nominal at 4 TeV, more than expected, thanks to the quality of the design, the construction, the operation and the injectors.
- Operation at 6.5 TeV comes with new challenges

The LHC remains an exciting accelerators to work on, every day with new surprises…

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 !

That’s why the job market for accelerator physicists is excellent

Thanks for your attention