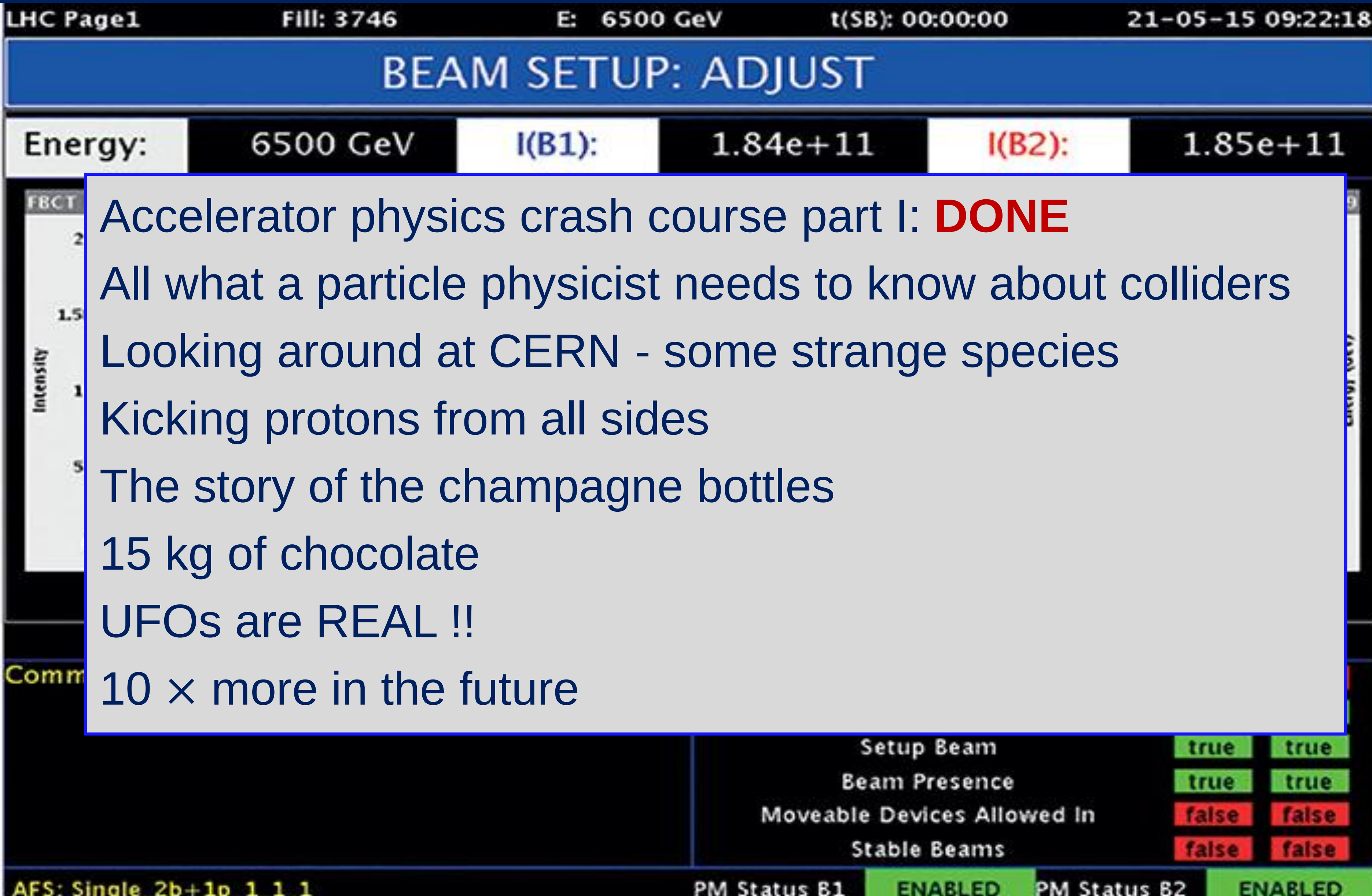
Accelerator Physics

To accelerate particles to much lower energy …



Accelerator physics crash course part I: **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 !!

10 × more in the future

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/

LHC pp and ions
7 TeV/c –up to now 6.5 TeV/c
26.8 km Circumference
The confusion with 7 TeV: energy of one proton or two protons ? …watch out
Switzerland
Lake Geneva
LHC Accelerator
(100 m down)
CMS, TOTEM
LHCb
CERN-Prevessin
ALICE
SPS Accelerator
ATLAS
CERN Main Site
France

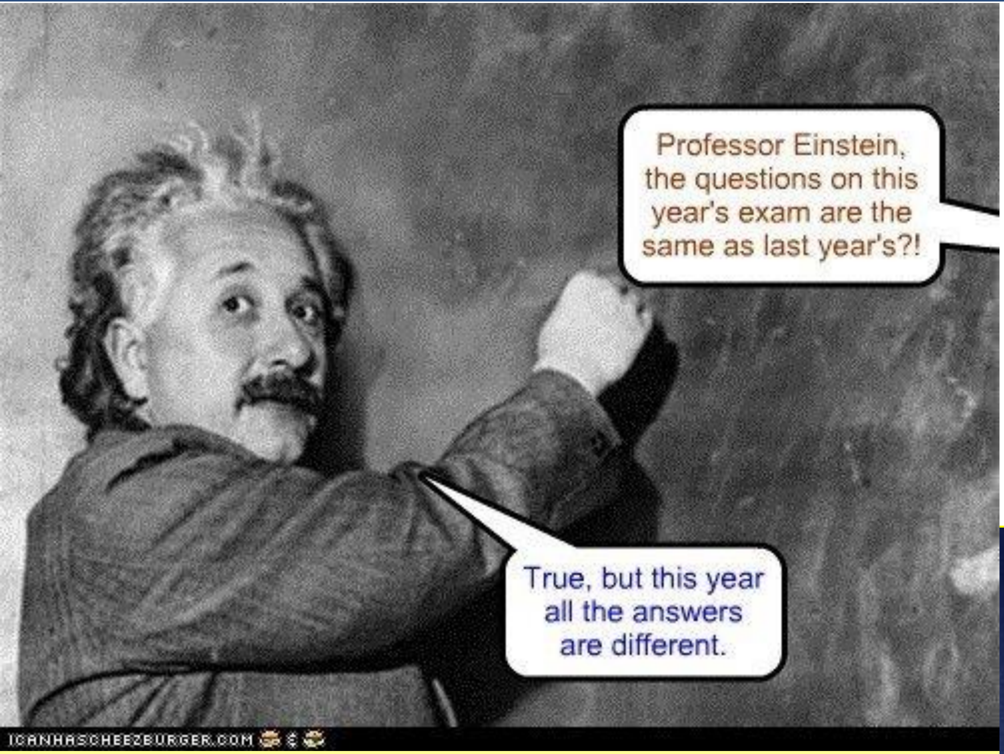
LHC: A long story starting in the distant past

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

Accelerator Physics Crash Course Part II

what is accelerator physics?

what species are accelerator physicists?

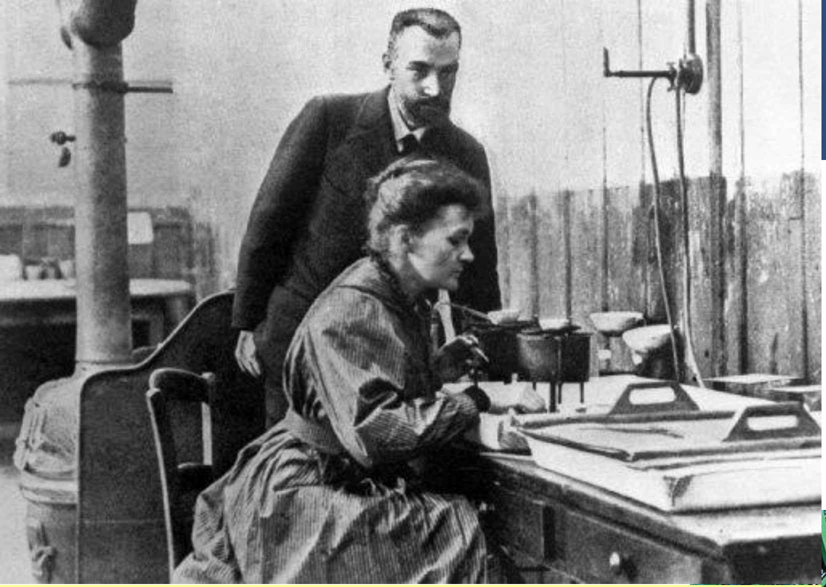


thinking, thinking, thinking ….
and predicting the future

….sometimes correctly!

Theoretical Physicist

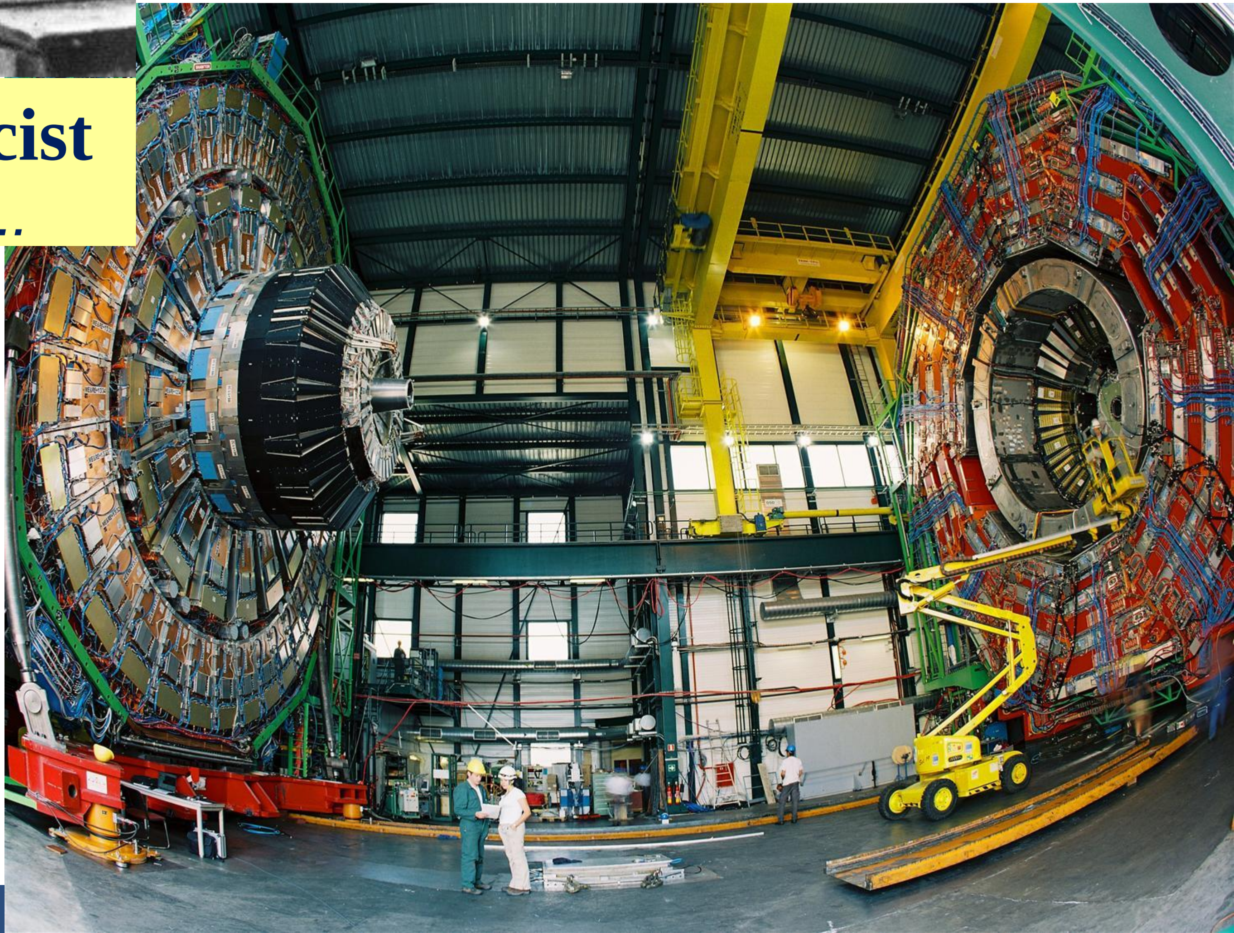
some time ago…



Experimental Physicist

some time ago…

…building the detectors, taking data and analysing the results



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

Also important: Management, reliability engineering and system engineering

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:

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

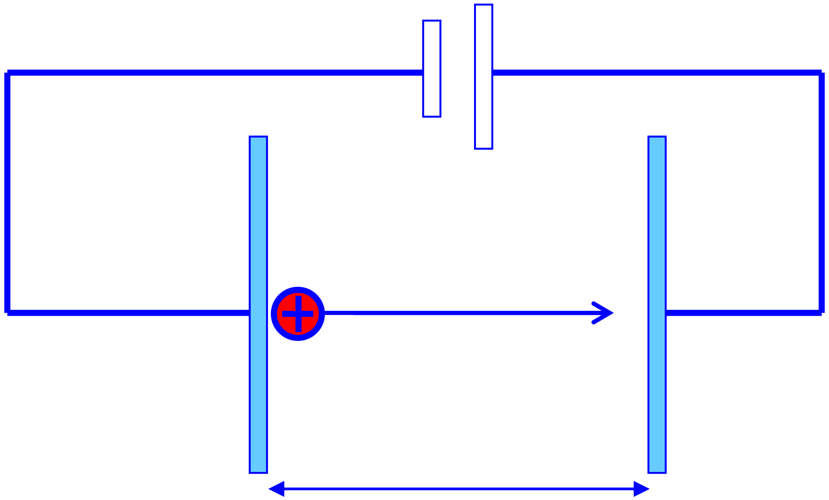
$$\frac{dE}{dt} = \vec{\mathbf{v}} \cdot \vec{\mathbf{F}}$$

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

Particle acceleration: accelerating protons to 7 TeV

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

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



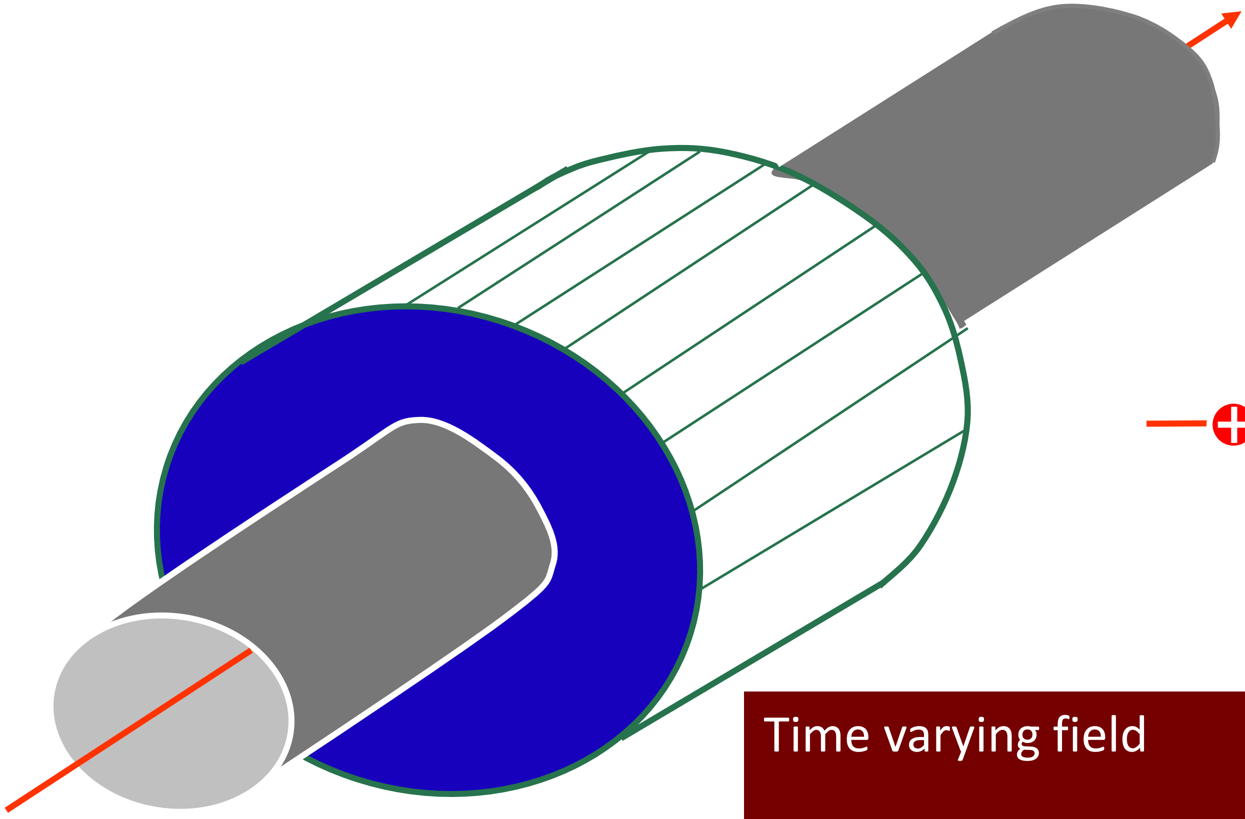
1 MeV requires
U = 1 MV

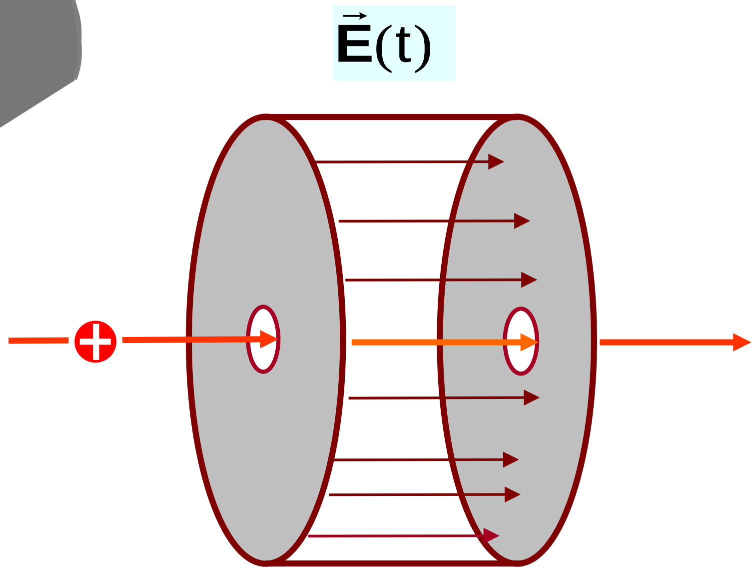
Acceleration of the protons in an electrical field with 7 TV

LHC: very simple, build a potential of 7000000000000 V and accelerate the protons

Does this work??

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

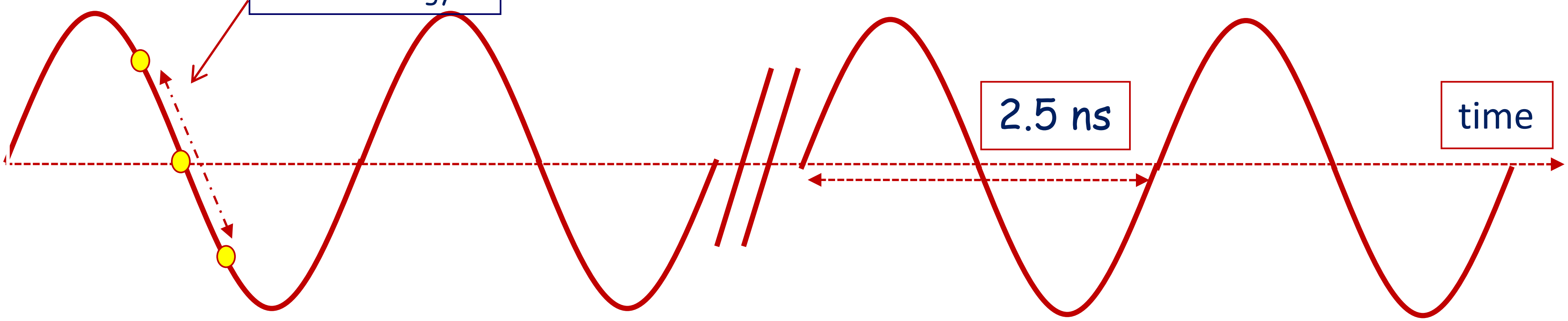
Beams are accelerated in bunches (no continuous beam)

Capture of Surfers by a water wave for acceleration

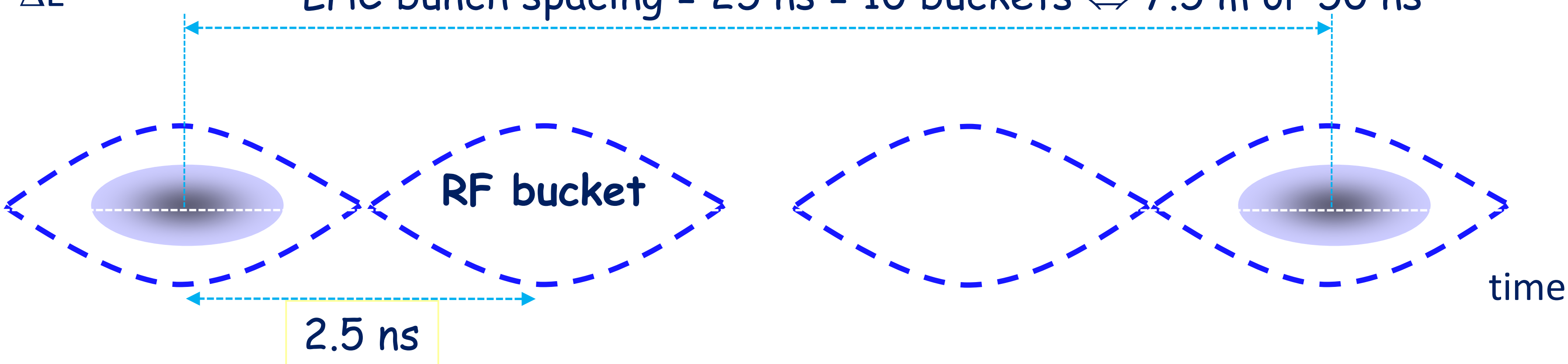
400 MHz RF buckets and bunches

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

The particles oscillate back and forth in time/energy



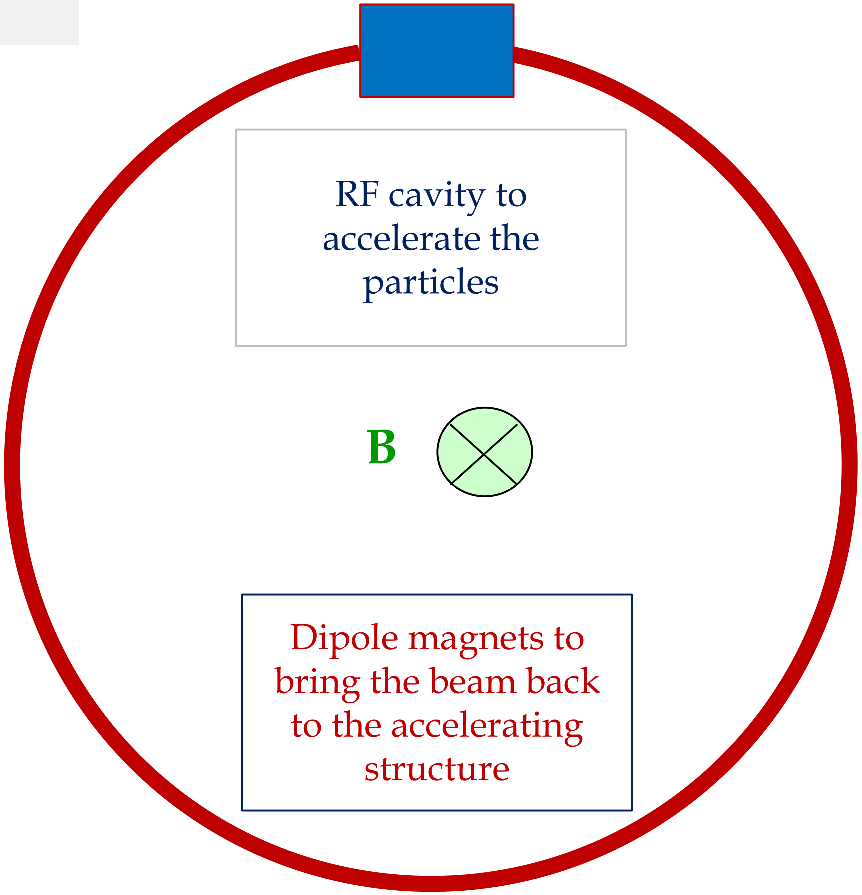
LHC bunch spacing = 25 ns = 10 buckets ⇔ 7.5 m or 50 ns



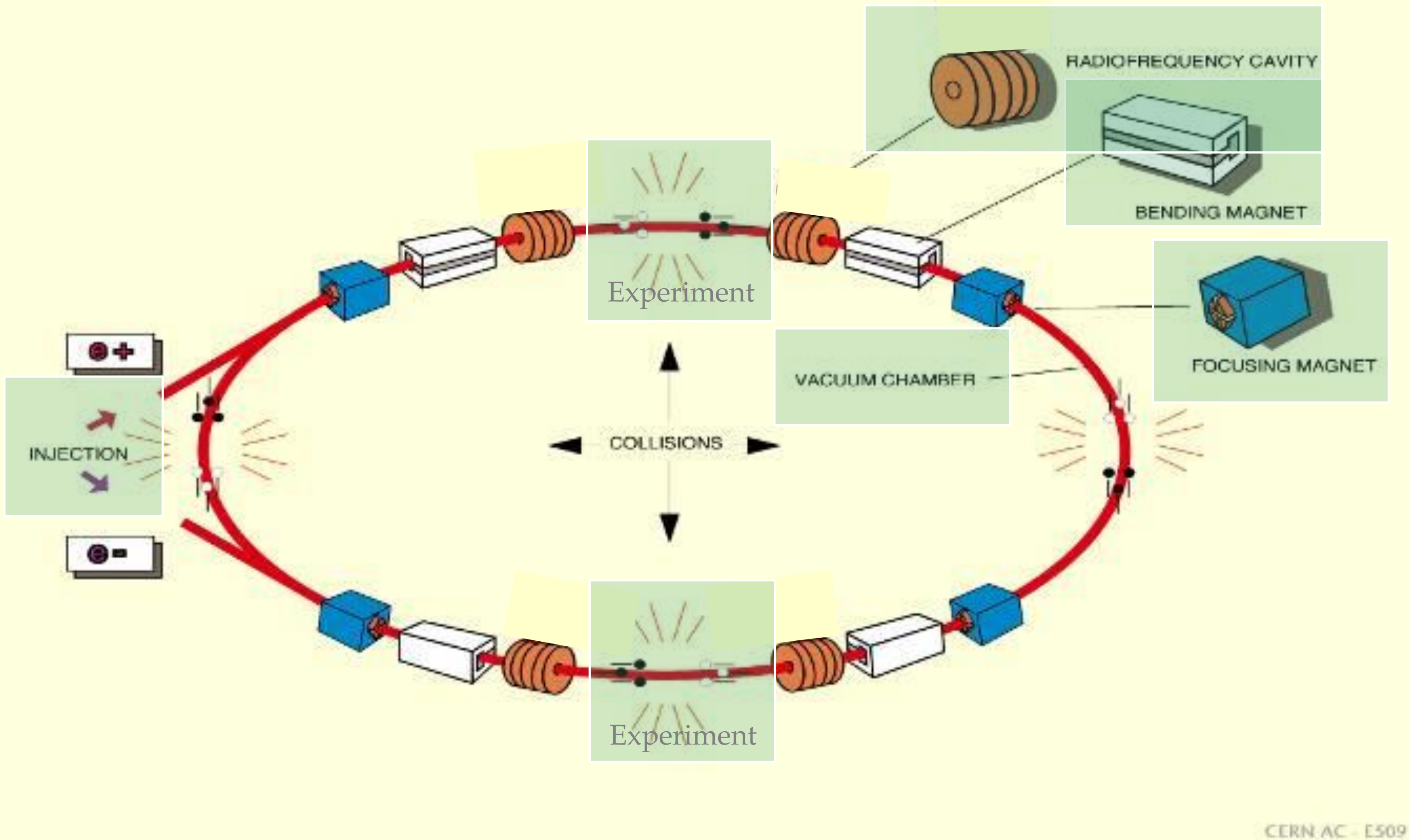
	450 GeV	7 TeV
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

Circular accelerator: re-use of accelerating structure

- To accelerate to high energy, synchrotrons were developed
- Synchrotrons are the most widespread type of accelerators
- A synchrotron is a circular accelerator, the particles make many turns
- The magnetic field is increased, and at the same time the particles are accelerated
- The particle trajectory is (roughly) constant



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

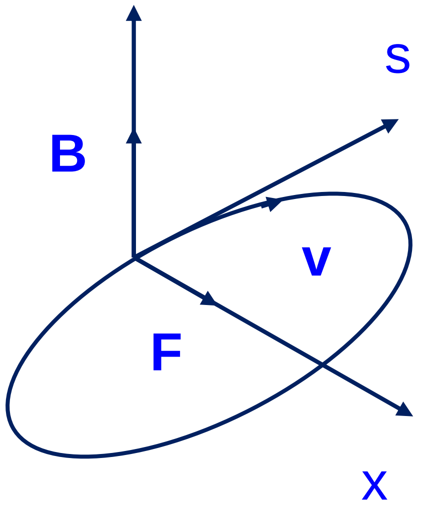


Particle deflection: superconducting magnets

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

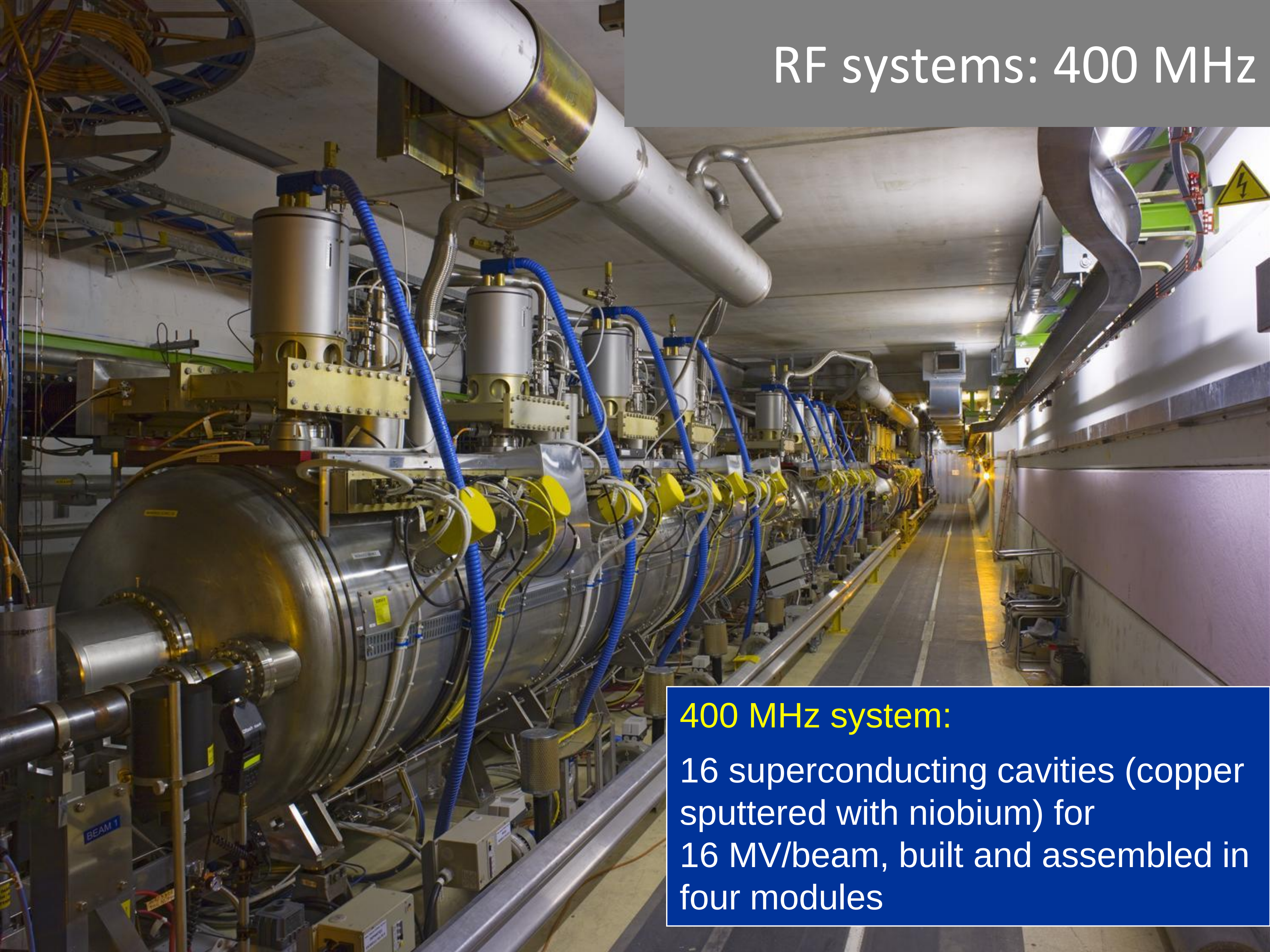
Iron magnets limited to 2 Tesla, therefore superconducting magnets are required

Deflecting magnetic fields for two beams in opposite directions

Superconducting magnets in LHC tunnel

Deflection by 1232 superconducting dipole magnets

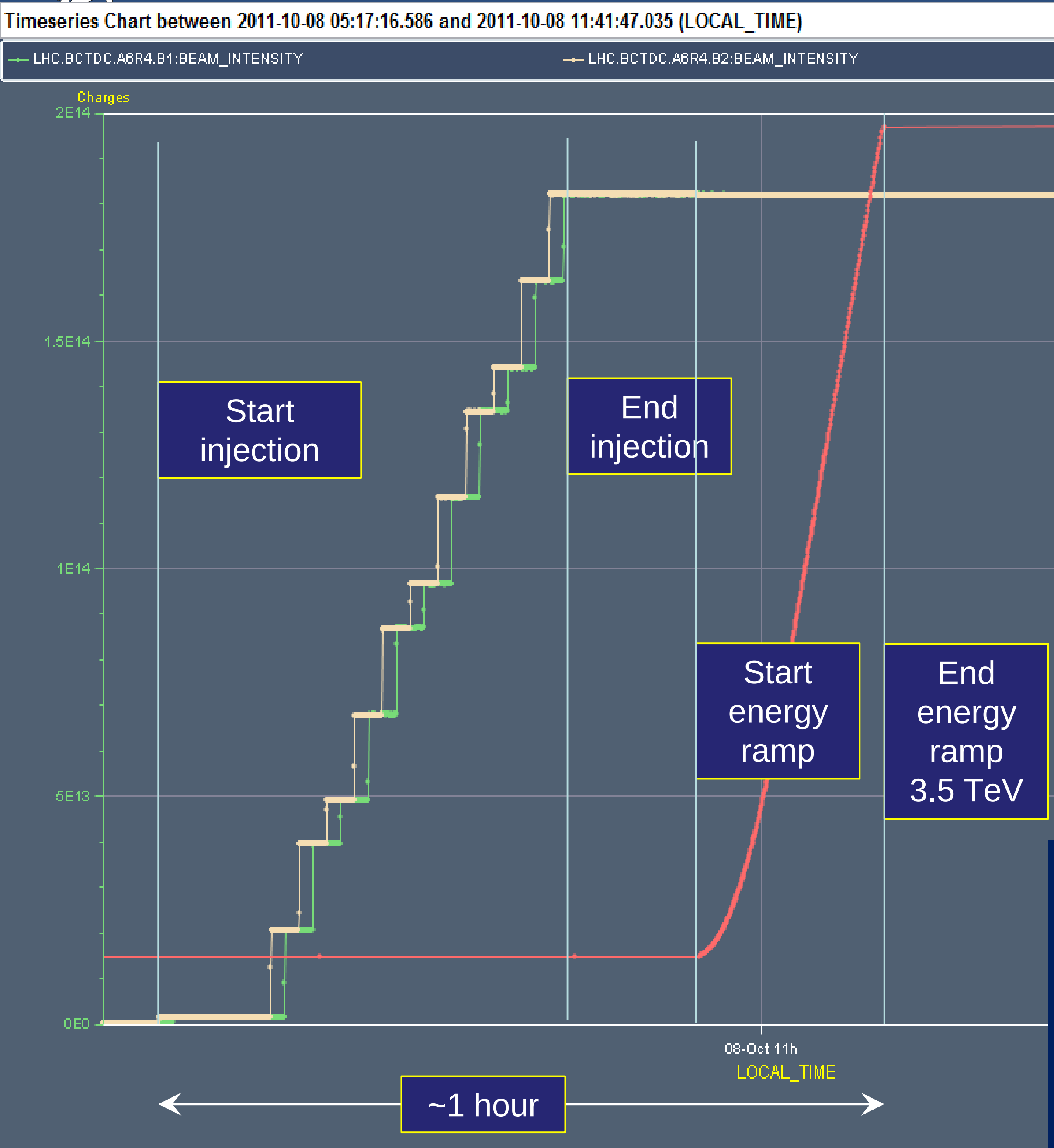
RF systems: 400 MHz



400 MHz system:

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

Synchrotron principle: LHC Fill 2195 - (2011)



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

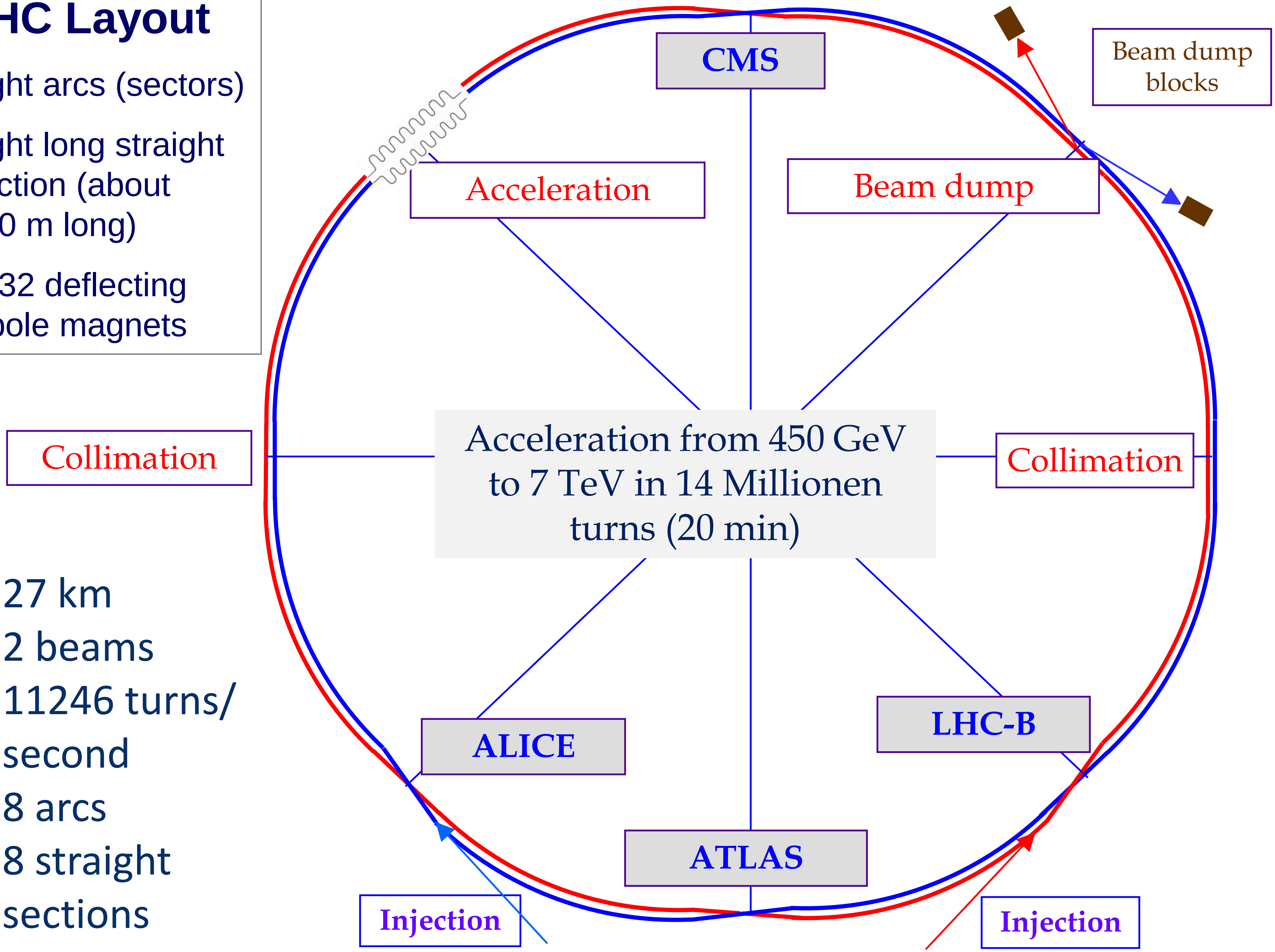
LHC layout, injection and beam transport

LHC Layout

eight arcs (sectors)

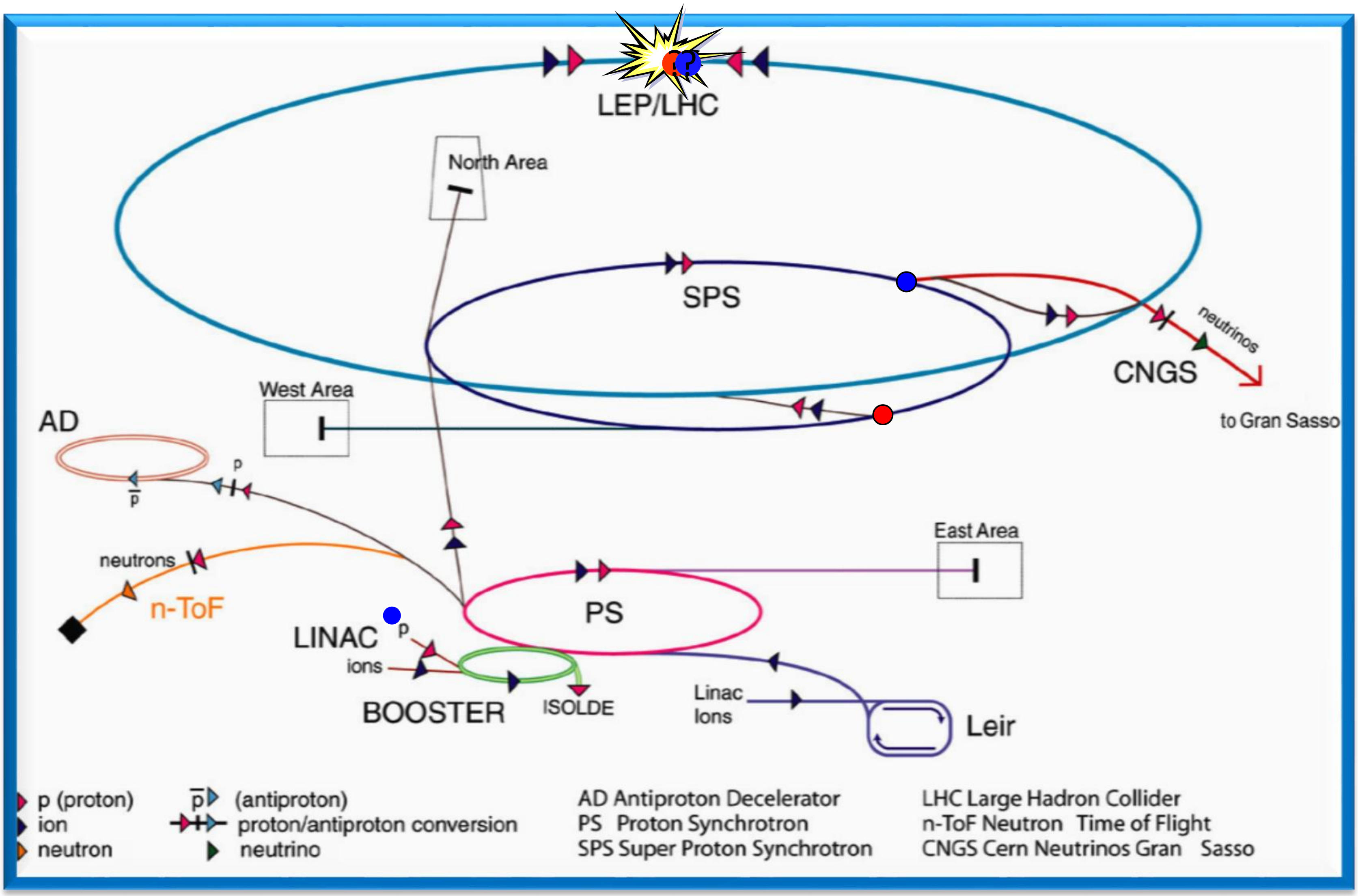
eight long straight section (about 700 m long)

1232 deflecting dipole magnets



- 27 km
- 2 beams
- 11246 turns/ second
- 8 arcs
- 8 straight sections

CERN accelerator complex



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

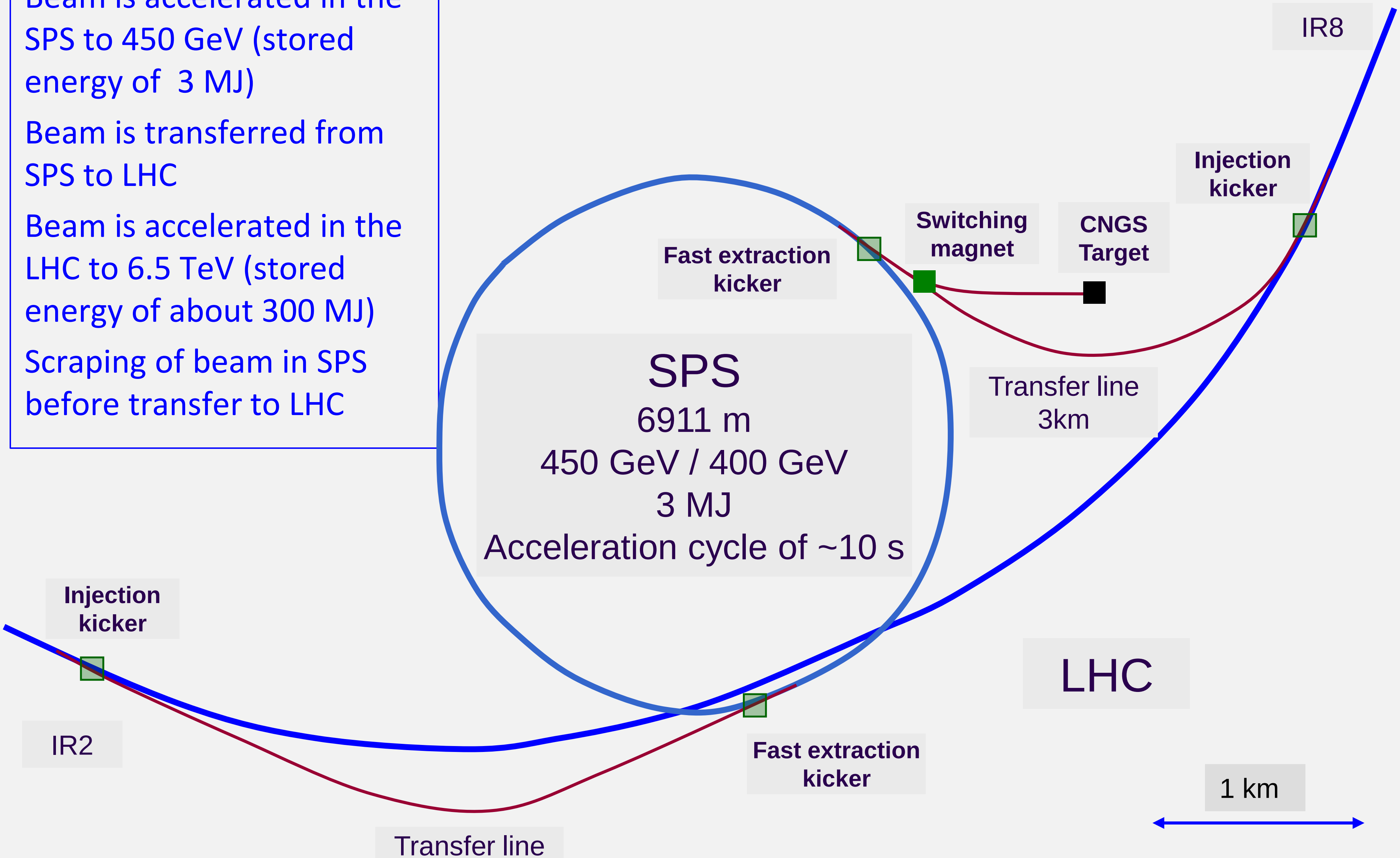
SPS, transfer line and LHC

Beam is accelerated in the SPS to 450 GeV (stored energy of 3 MJ)

Beam is transferred from SPS to LHC

Beam is accelerated in the LHC to 6.5 TeV (stored energy of about 300 MJ)

Scraping of beam in SPS before transfer to LHC



High energy and consequences

superconducting magnets

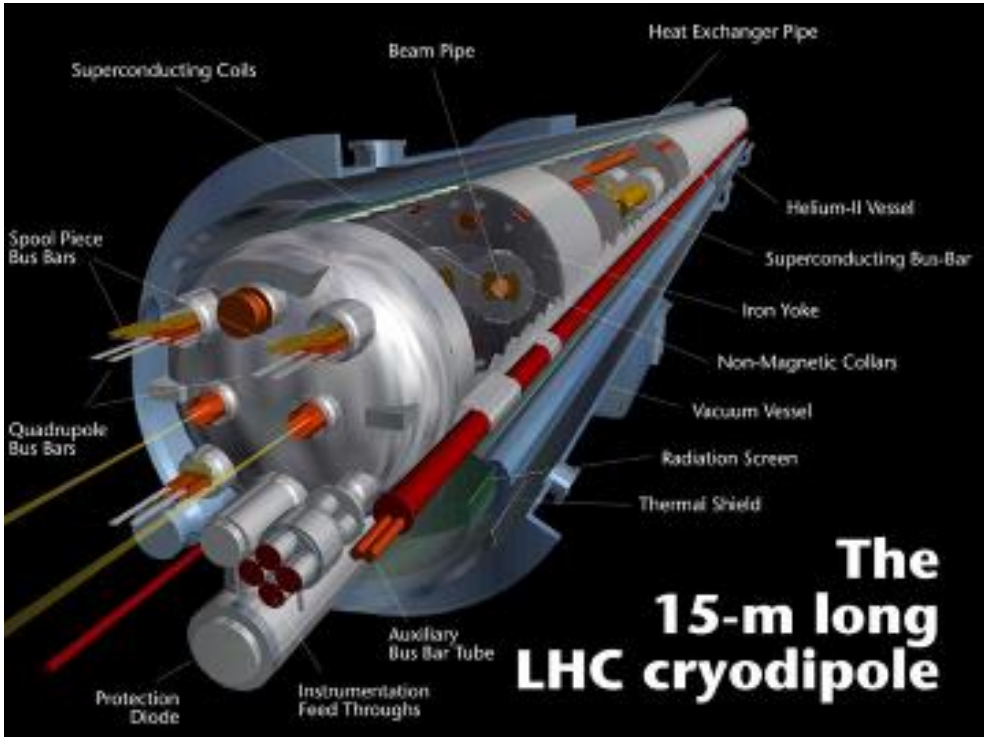
…….the field strength determines the beam energy

Dipole magnets for the LHC

1232 Dipole magnets
Length about 15 m

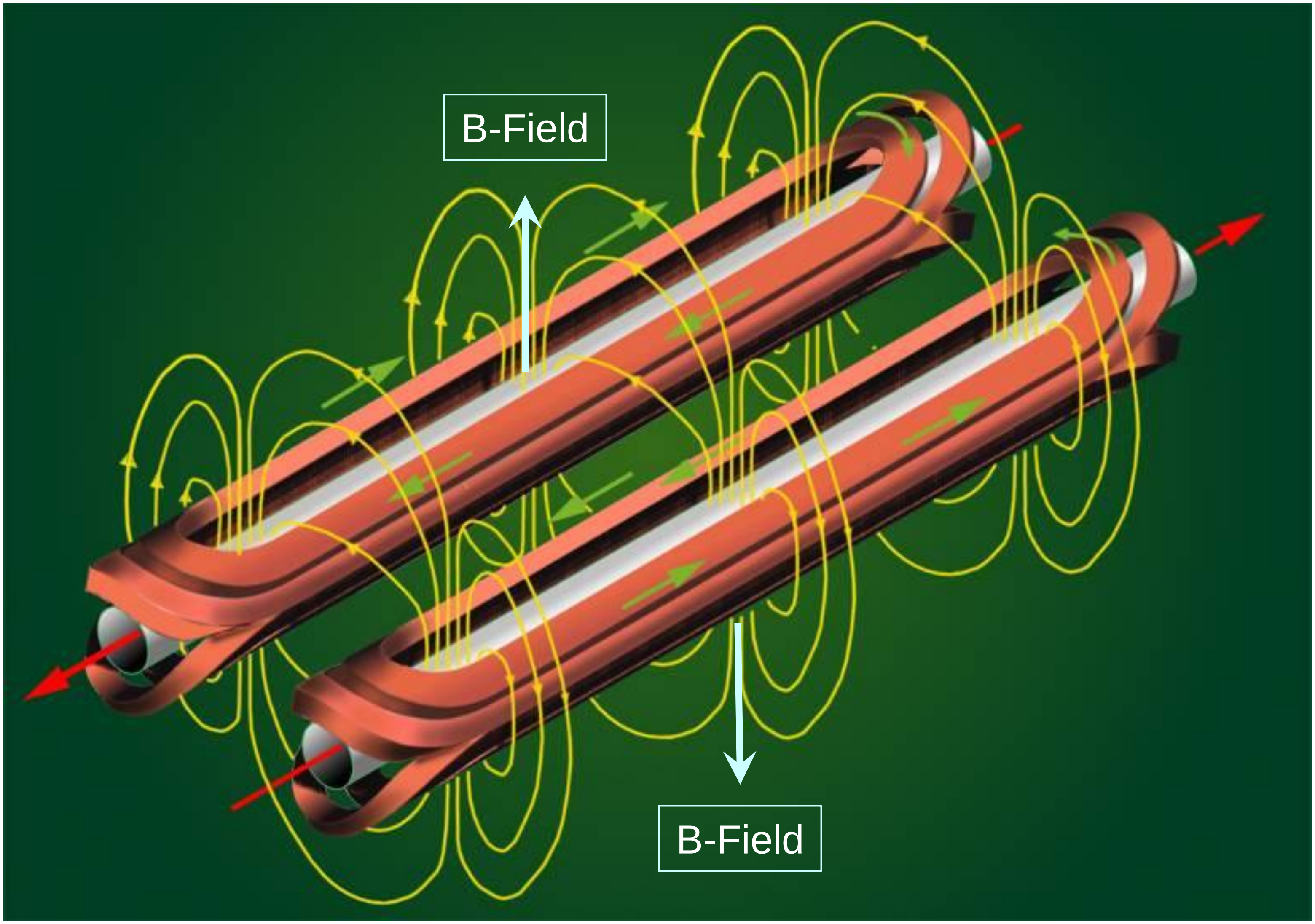
Magnetic Field 8.3 T for
7 TeV

Two beam tubes with an
opening of 56 mm

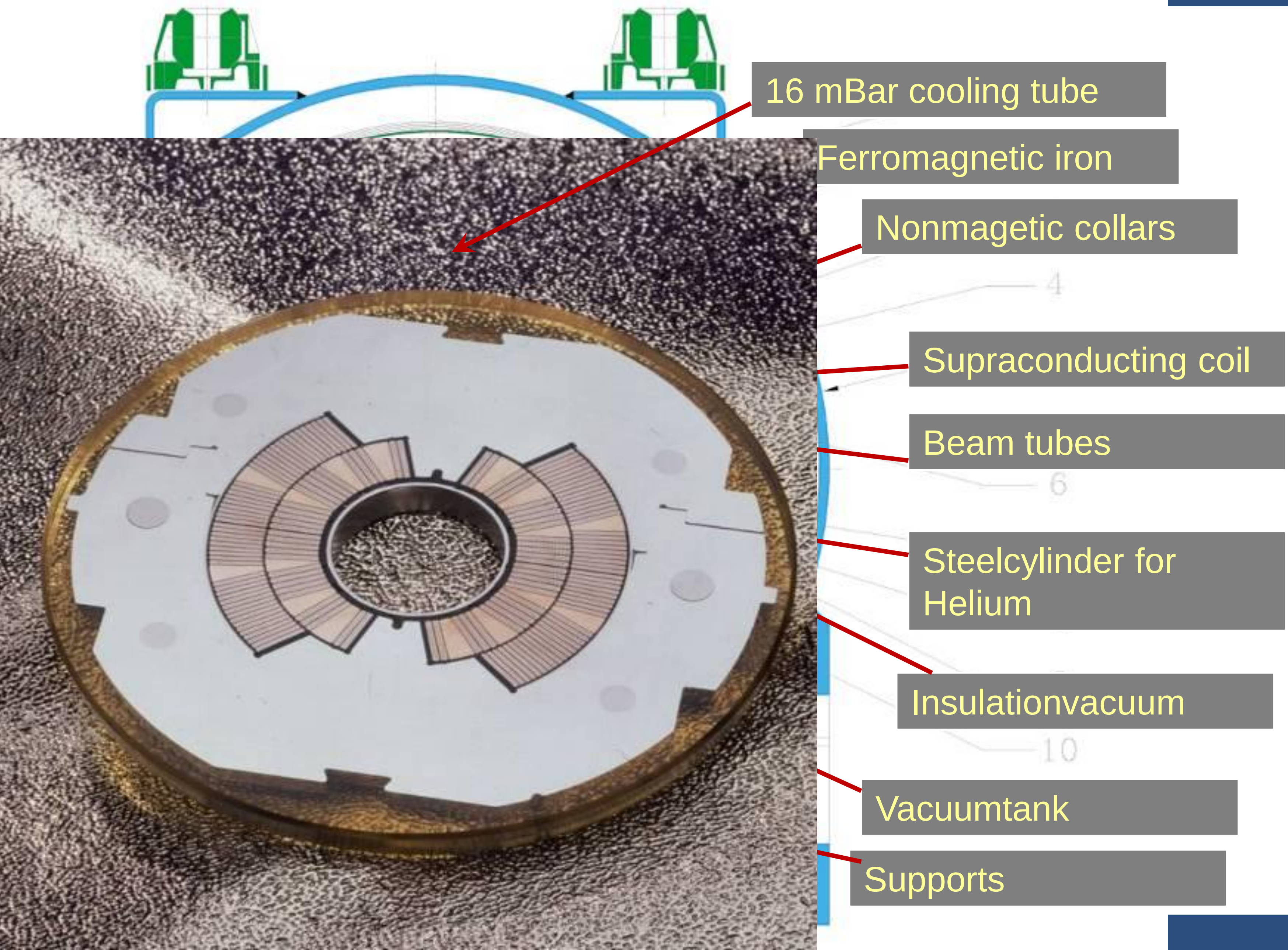


plus many other magnets, to ensure beam stability (1700 main magnets and about 8000 corrector magnets)

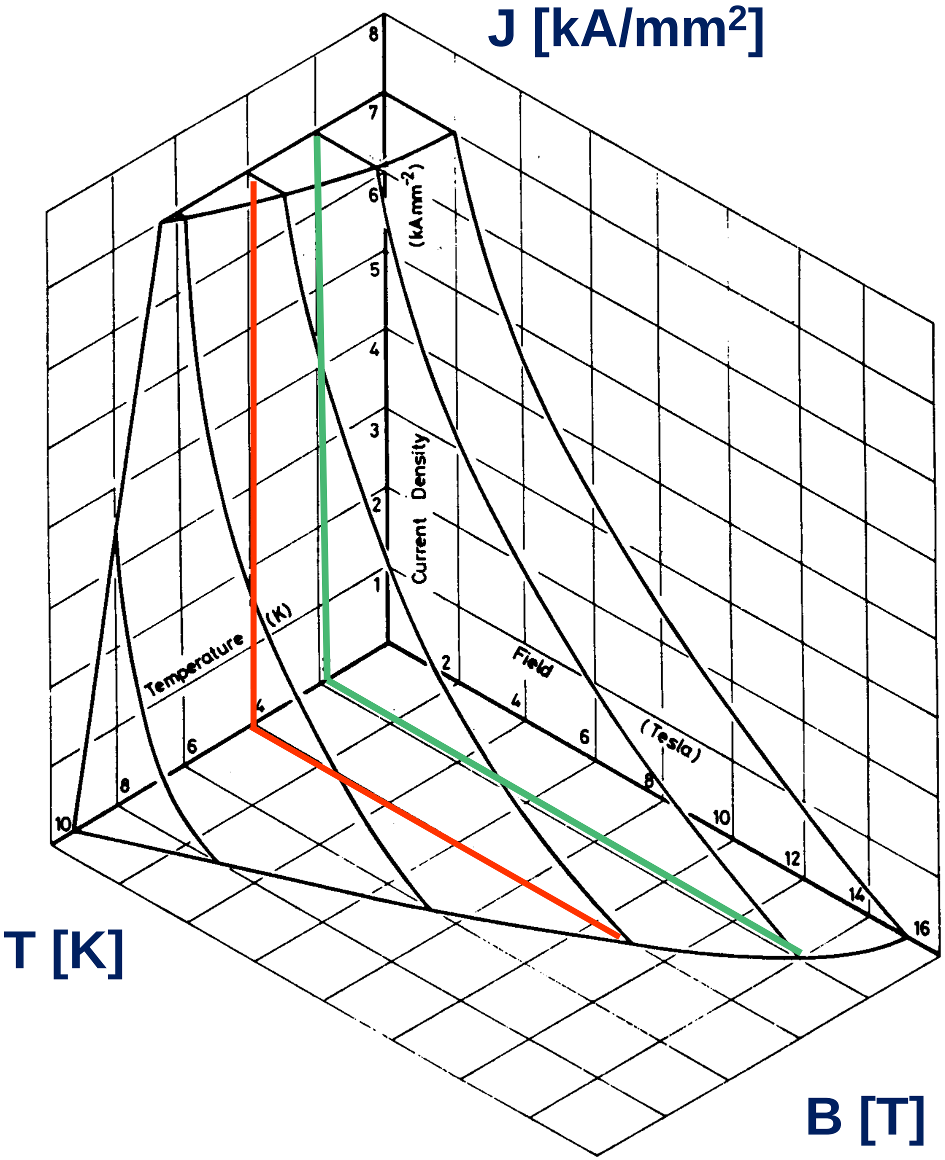
Coils for Dipolmagnets



Dipole magnet cross section



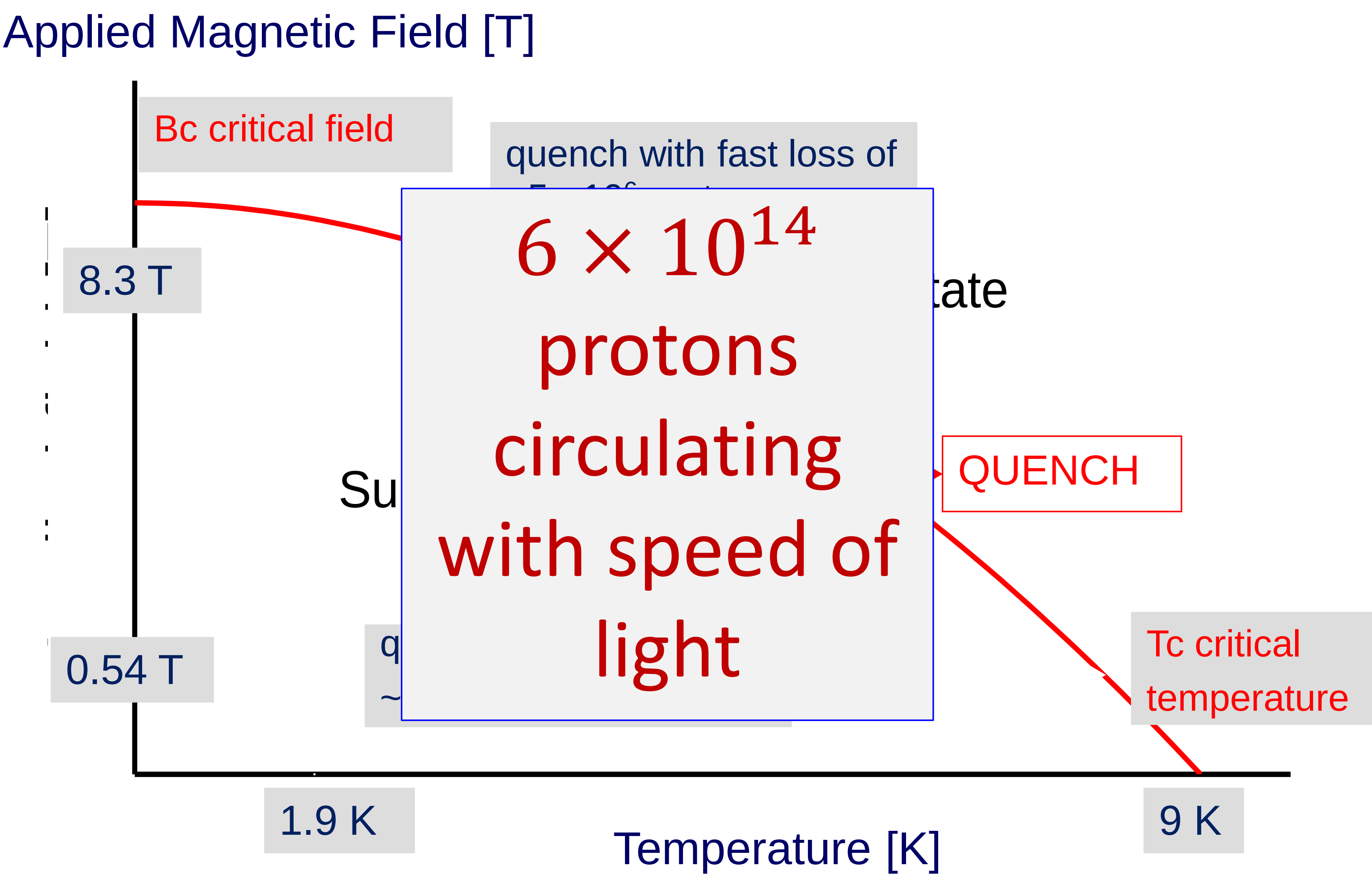
Operating temperature of superconductors (NbTi)



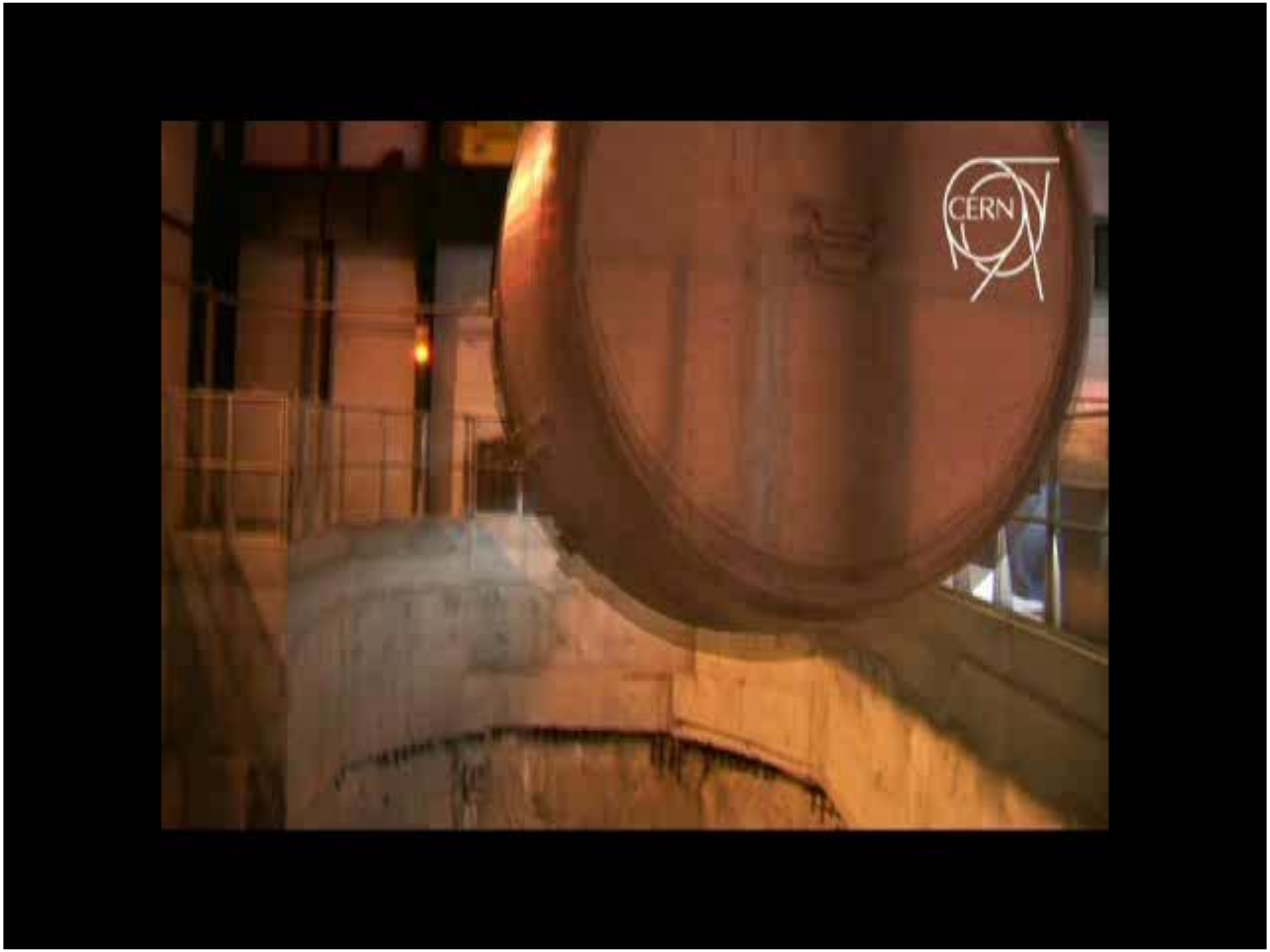
The superconducting state only occurs in a limited domain of temperature, magnetic field and transport current density

Superconducting magnets produce high field with high current density

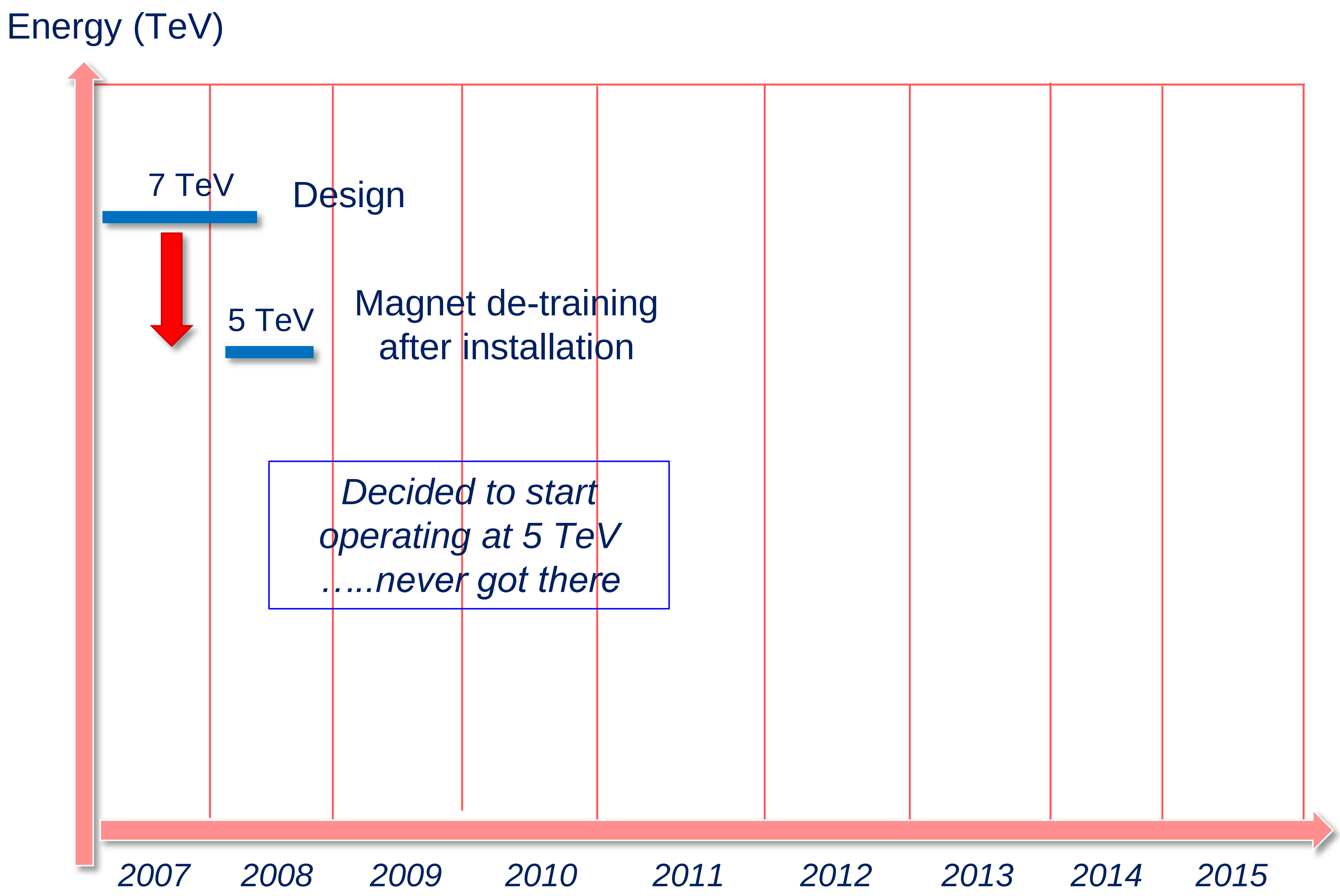
Lowering the temperature from 9 K to 1.9 K enables better usage of the superconductor by broadening its working range and increasing the maximum field


Applied Magnetic Field [T]
Bc critical field
quench with fast loss of
8.3 T
0.54 T
6×10^{14} protons circulating with speed of light
QUENCH
Tc critical temperature
1.9 K
9 K
Temperature [K]

Dipole magnet transport from surface to tunnel



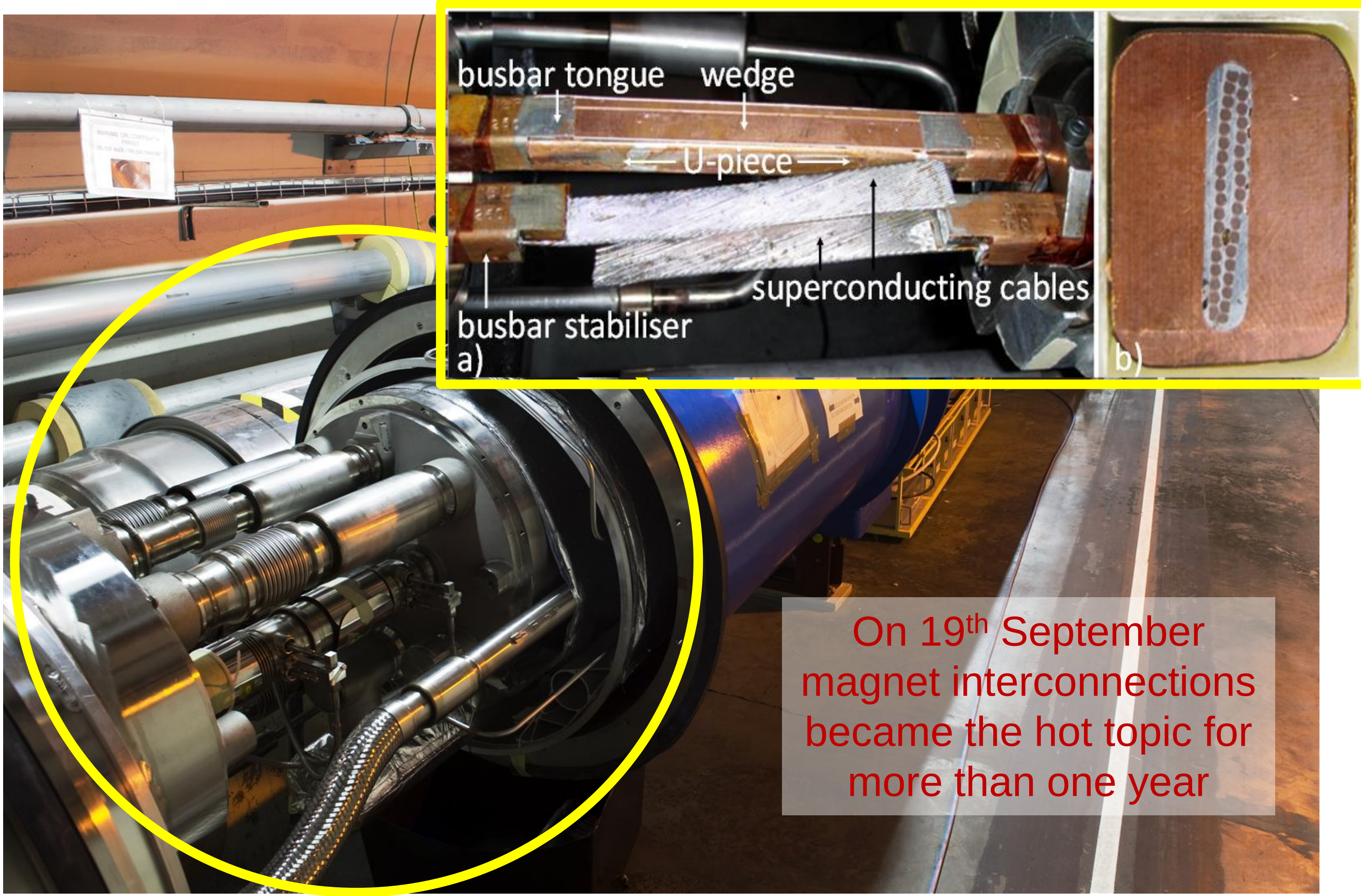
LHC energy evolution



September 10th 2008

A brief moment of glory

September 19th 2008

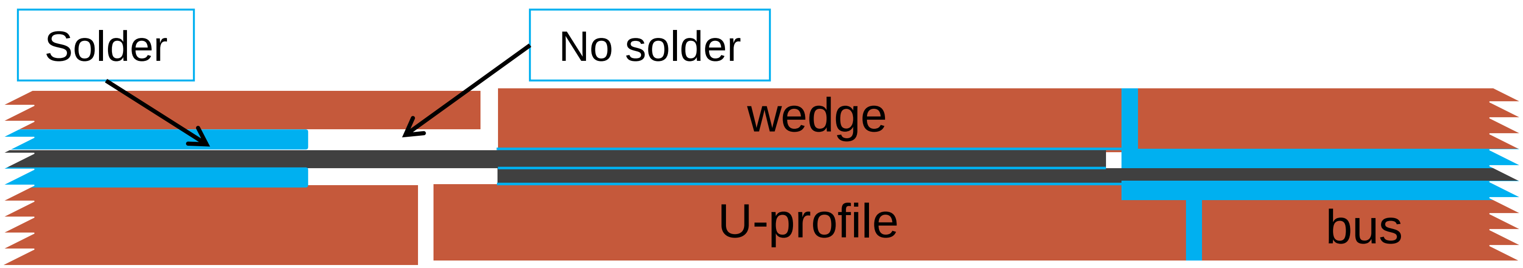


On 19th September magnet interconnections became the hot topic for more than one year

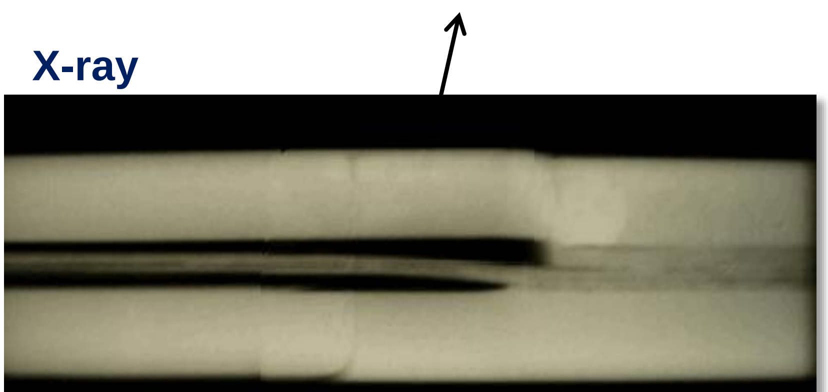
53 magnets had to be repaired

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.

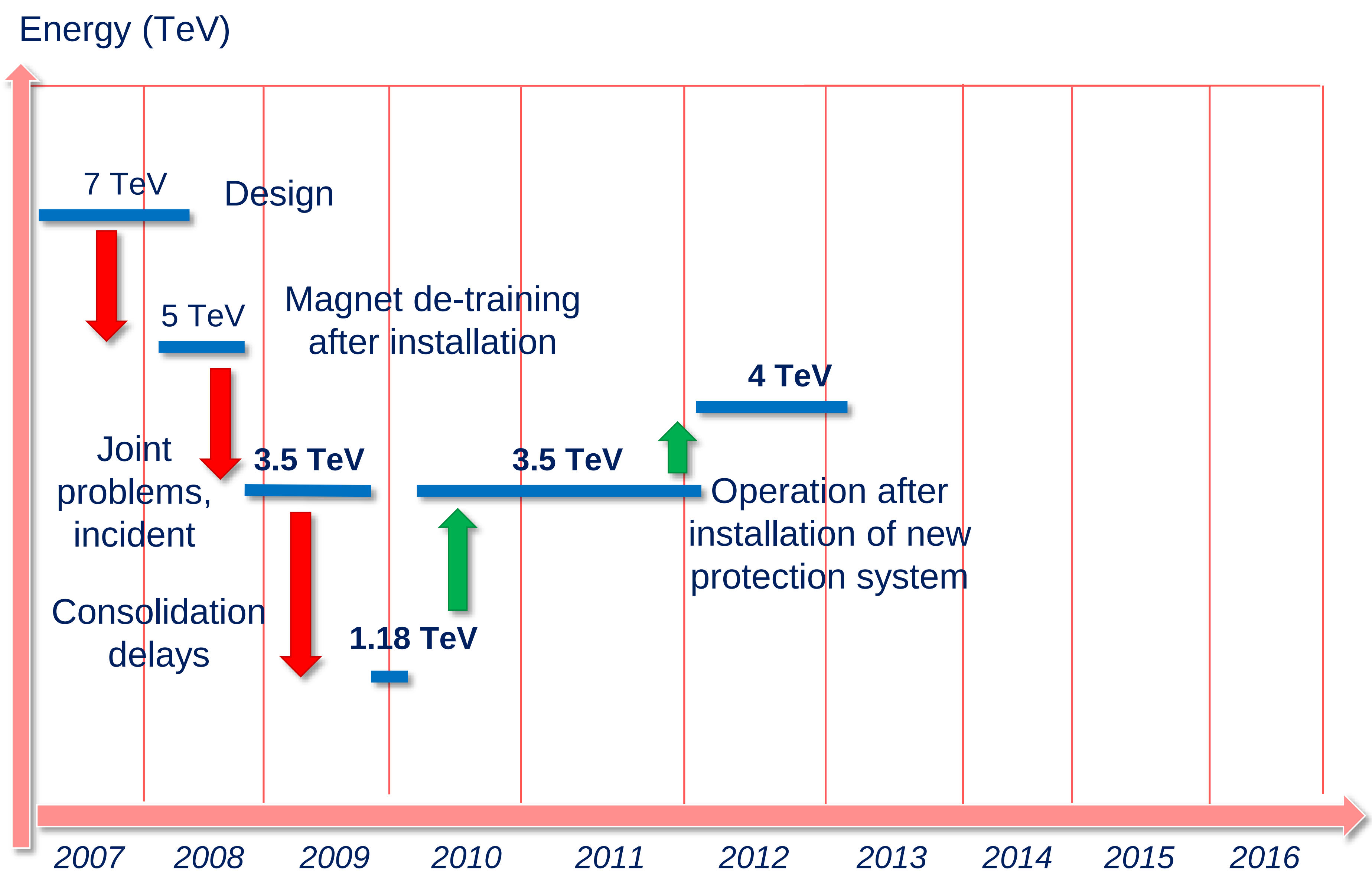


X-ray



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

→ **Energy limitation for run 1 !!**


Energy (TeV)
7 TeV
Design
5 TeV
Magnet de-training after installation
4 TeV
Joint problems, incident
3.5 TeV
3.5 TeV
Operation after installation of new protection system
Consolidation delays
1.18 TeV
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016

High luminosity and consequences

High luminosity by colliding trains of bunches

Number of „New Particles“
per unit of time:

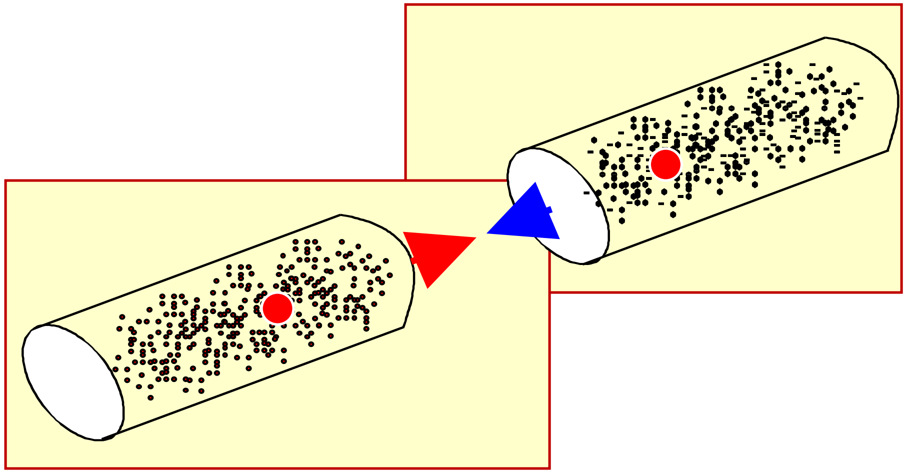
$$\frac{N}{\Delta T} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma[cm^2]$$

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} [$cm^{-2}s^{-1}$]

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

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 **1-3×10^{11}** due to the beam-beam interaction and beam instabilities

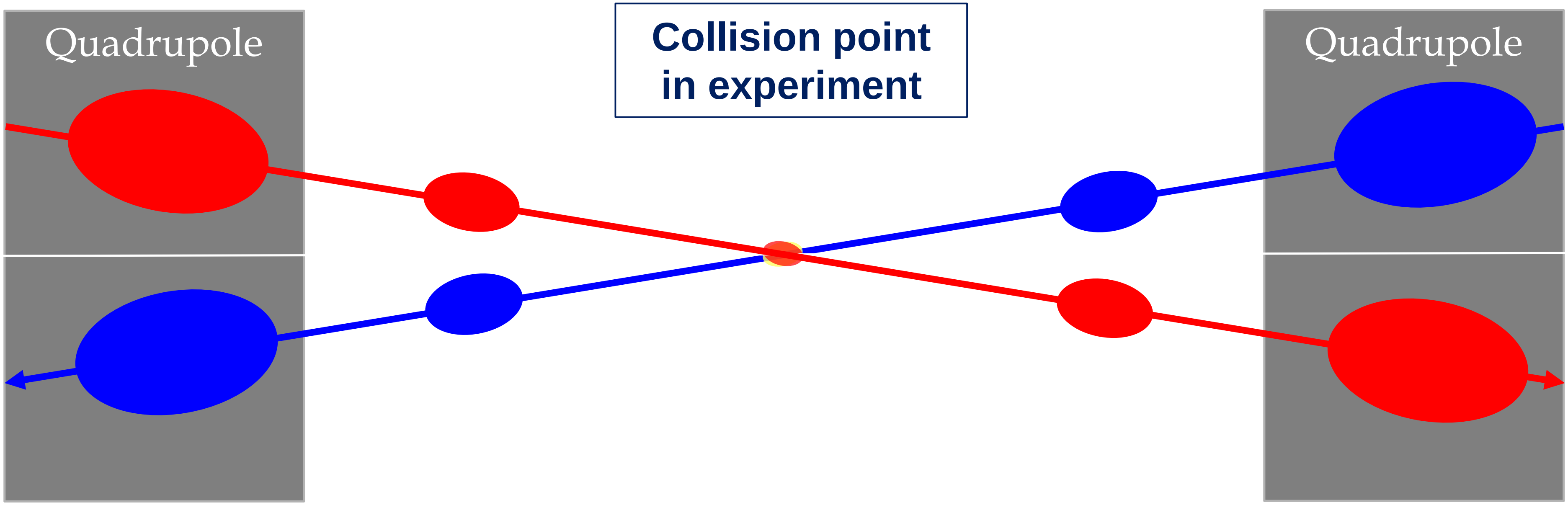
Beam size given by injectors and by space in vacuum chamber

f = **11246 Hz**

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

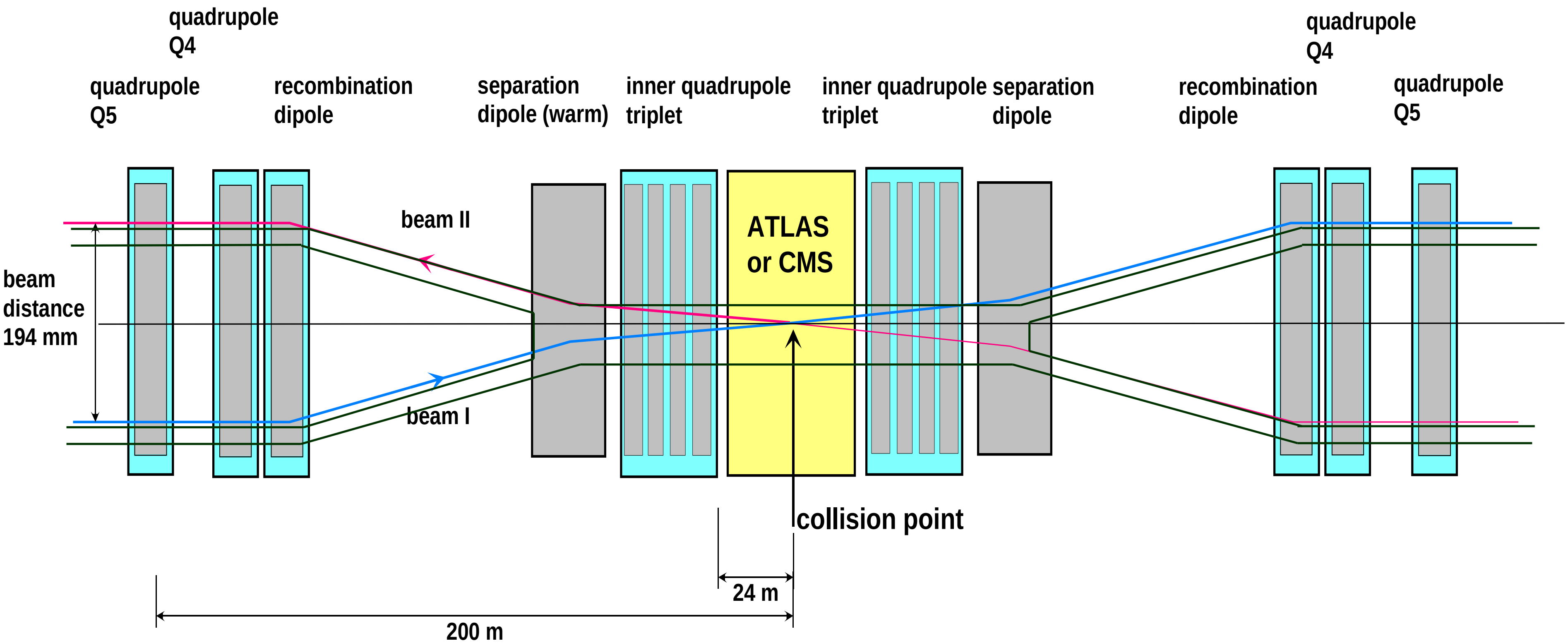
$$L = \frac{N^2 \cdot f \cdot n_b}{4 \cdot \pi \cdot \sigma_x \cdot \sigma_y} = 10^{34}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$ for 2808 bunches

…smallest beam size at experiments



- Large beam size in adjacent quadrupole magnets
- Separation between beams needed, about 10 σ
- Limitation is the aperture in quadrupoles
- Limitation of β function at IP to 0.4 m (2017)

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 250 μrad

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

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

Event pile up for one bunch crossing:

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

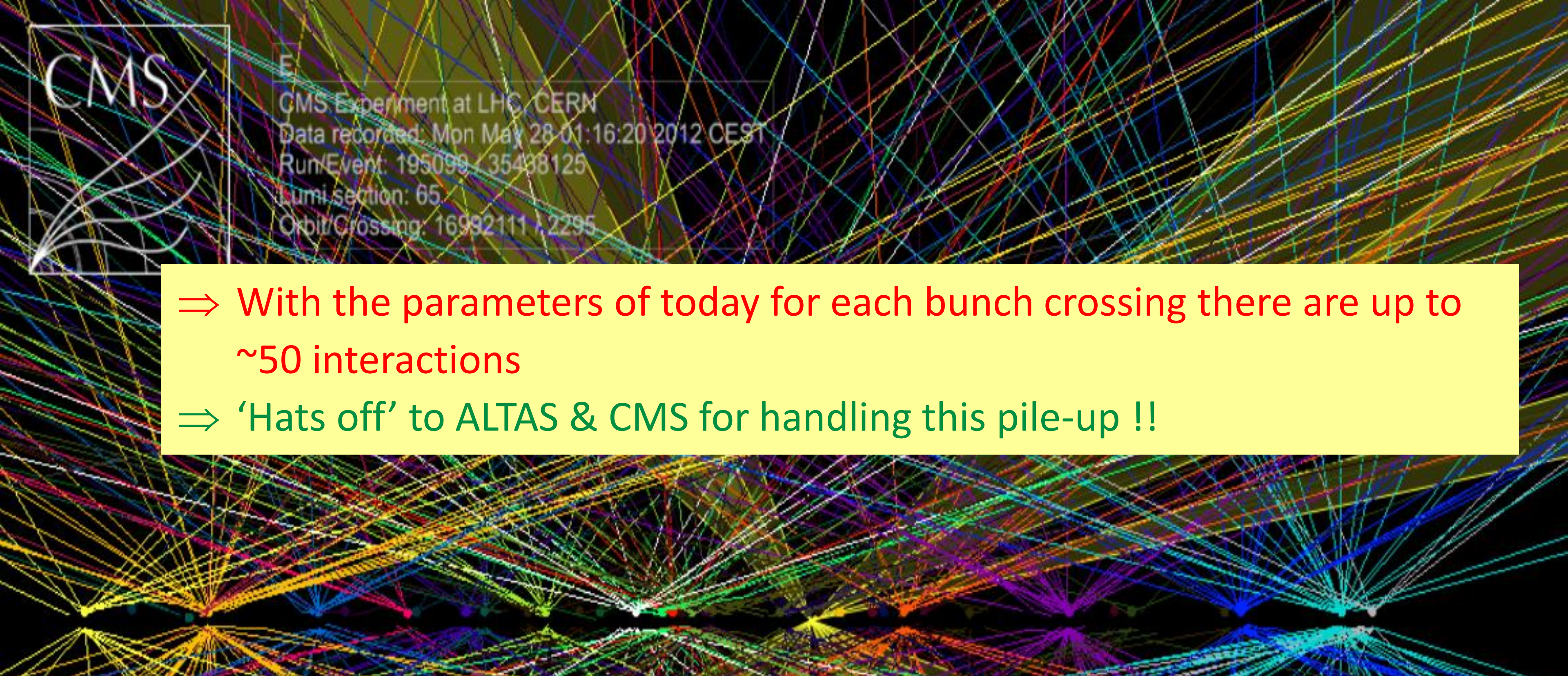
$\sigma_{tot} = 1 \times 10^{-25}\,\mathrm{cm}^2$

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

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

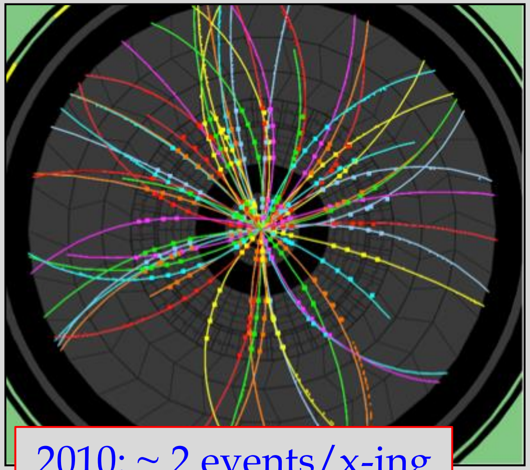
$frev_{lhc} = 1.1246 \times 10^{4}\,\frac{1}{\mathrm{s}}$ and $N_{bunches\_1beam} = 2808$

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



⇒ With the parameters of today for each bunch crossing there are up to ~50 interactions

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



2010: ~ 2 events/x-ing

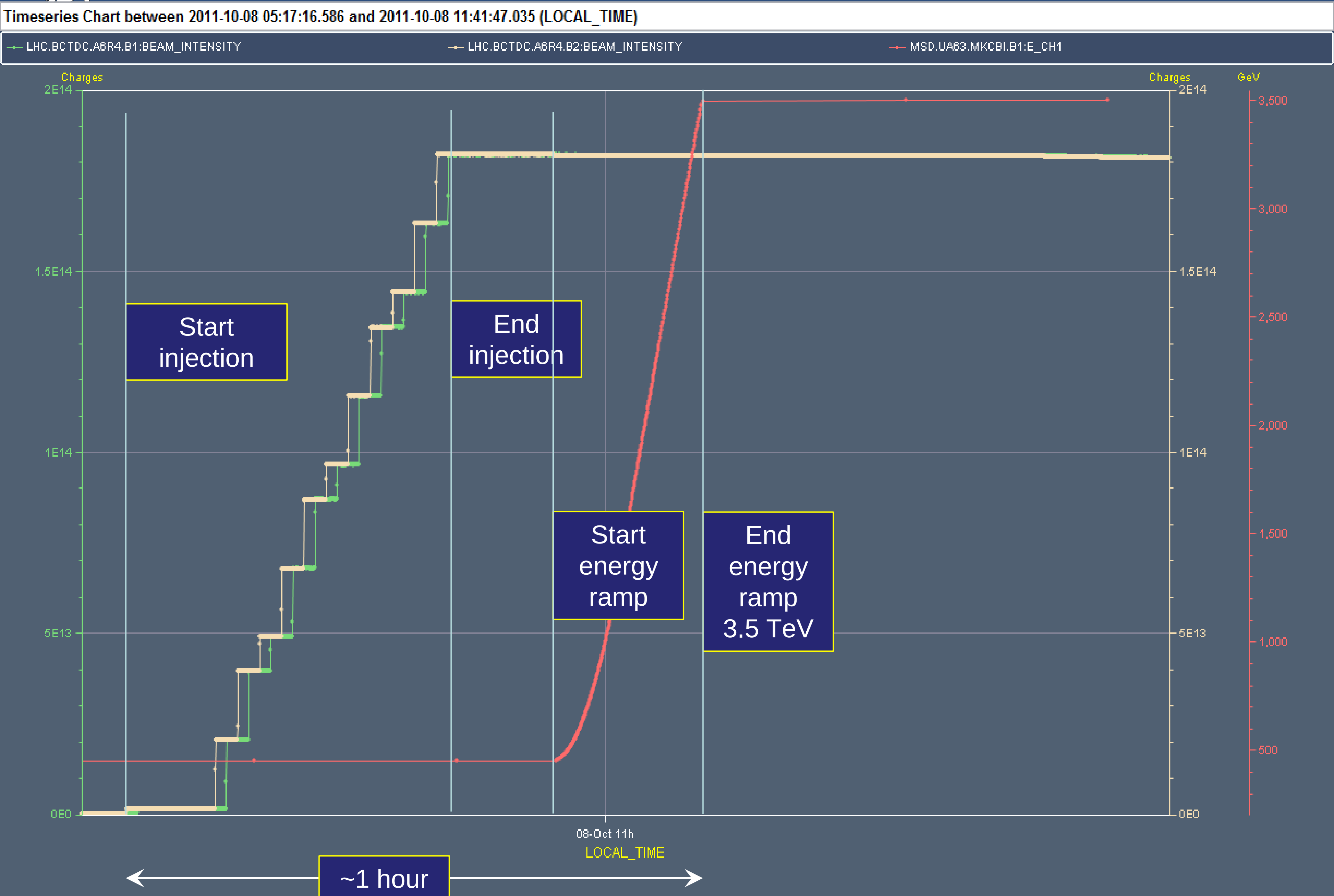
2011: ~ 10 events/x-ing

2012: ~ 20 events/x-ing

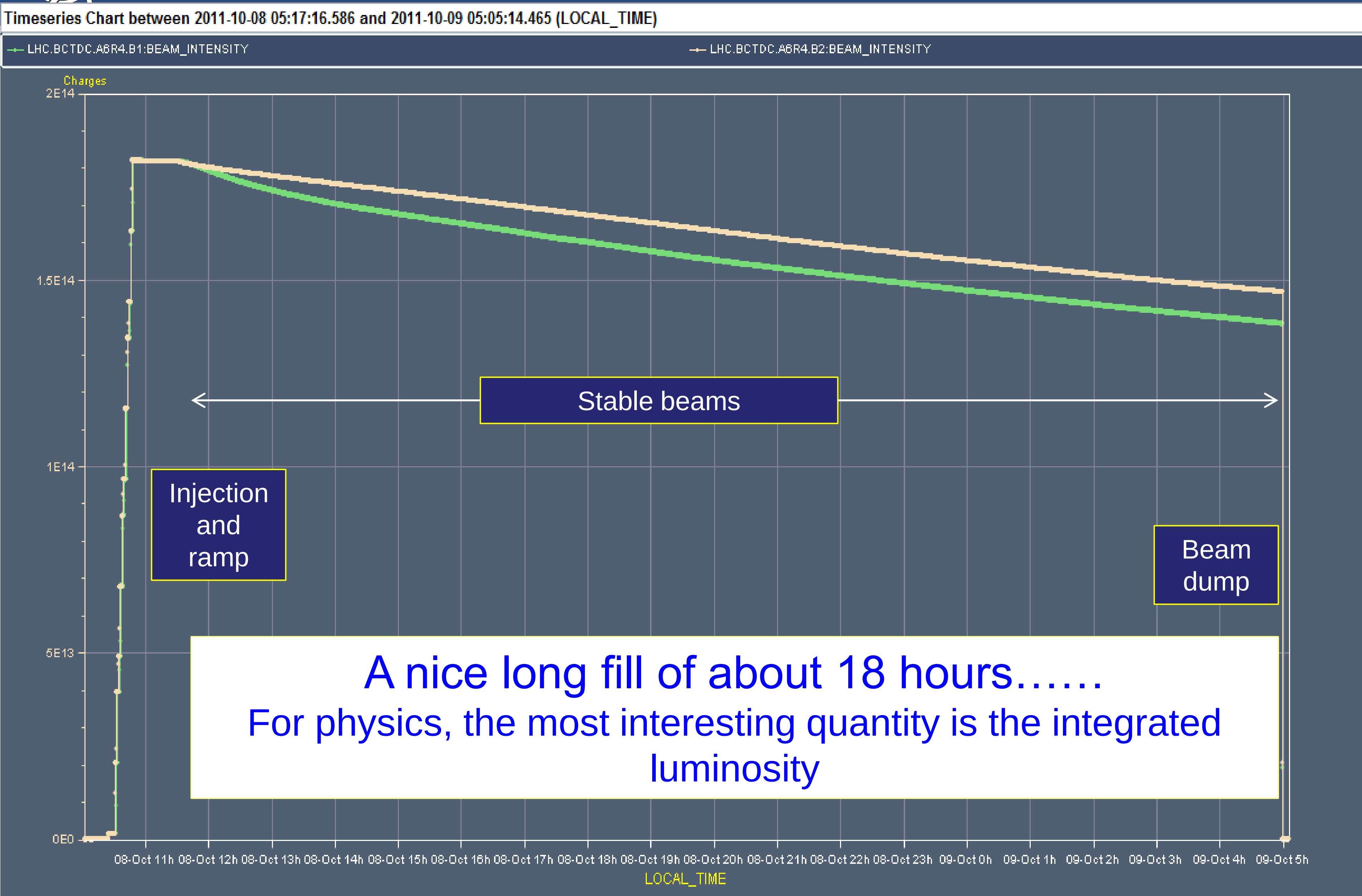
Understanding LHC operation

- 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)



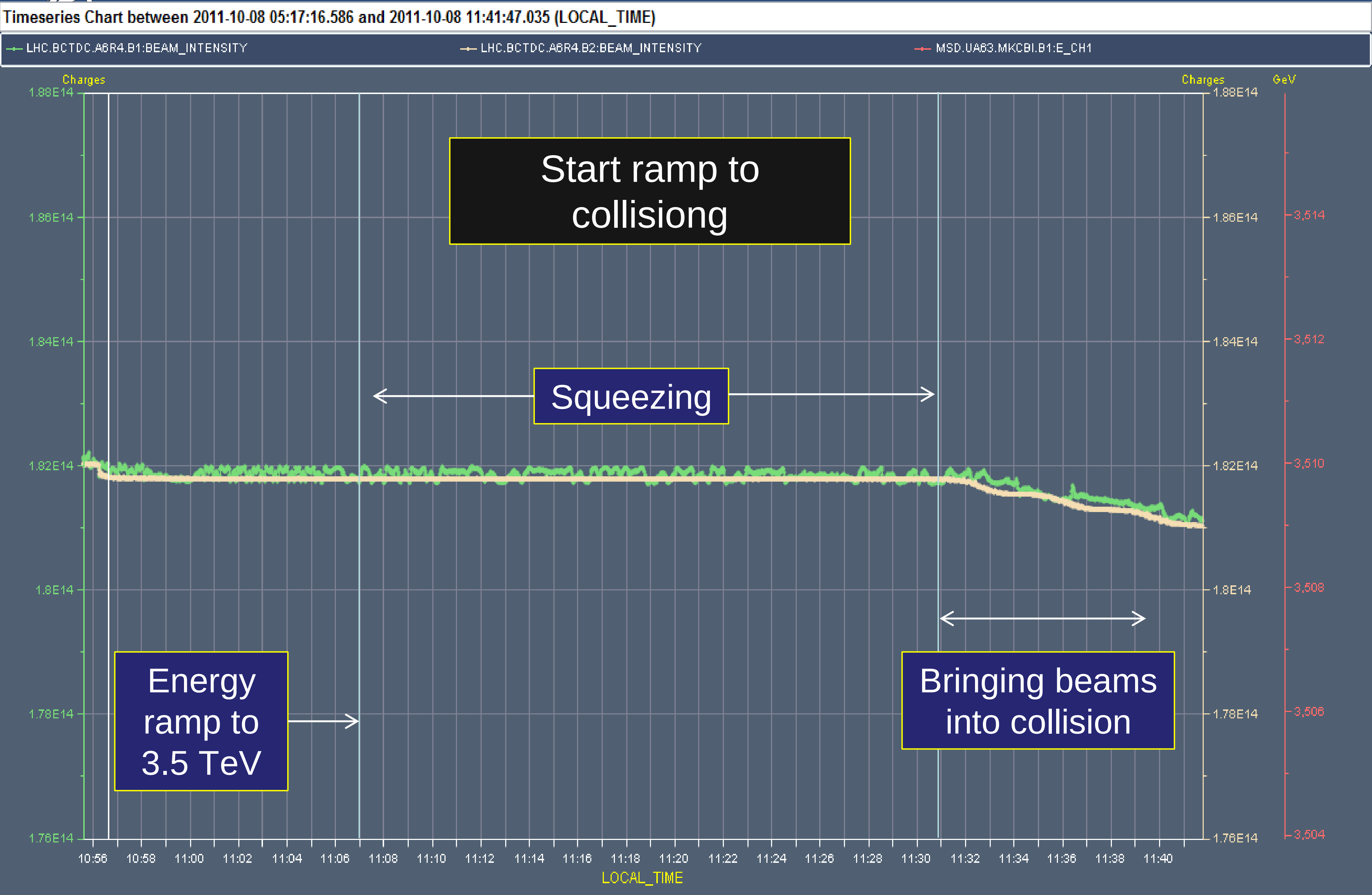
Excellent fill (2011)



A nice long fill of about 18 hours……

For physics, the most interesting quantity is the integrated luminosity

Reference fill 2195 in 2011 – at 3.5 TeV



Challenges operating with high intensity beams

Machine Protection and Collimation

Electron clouds

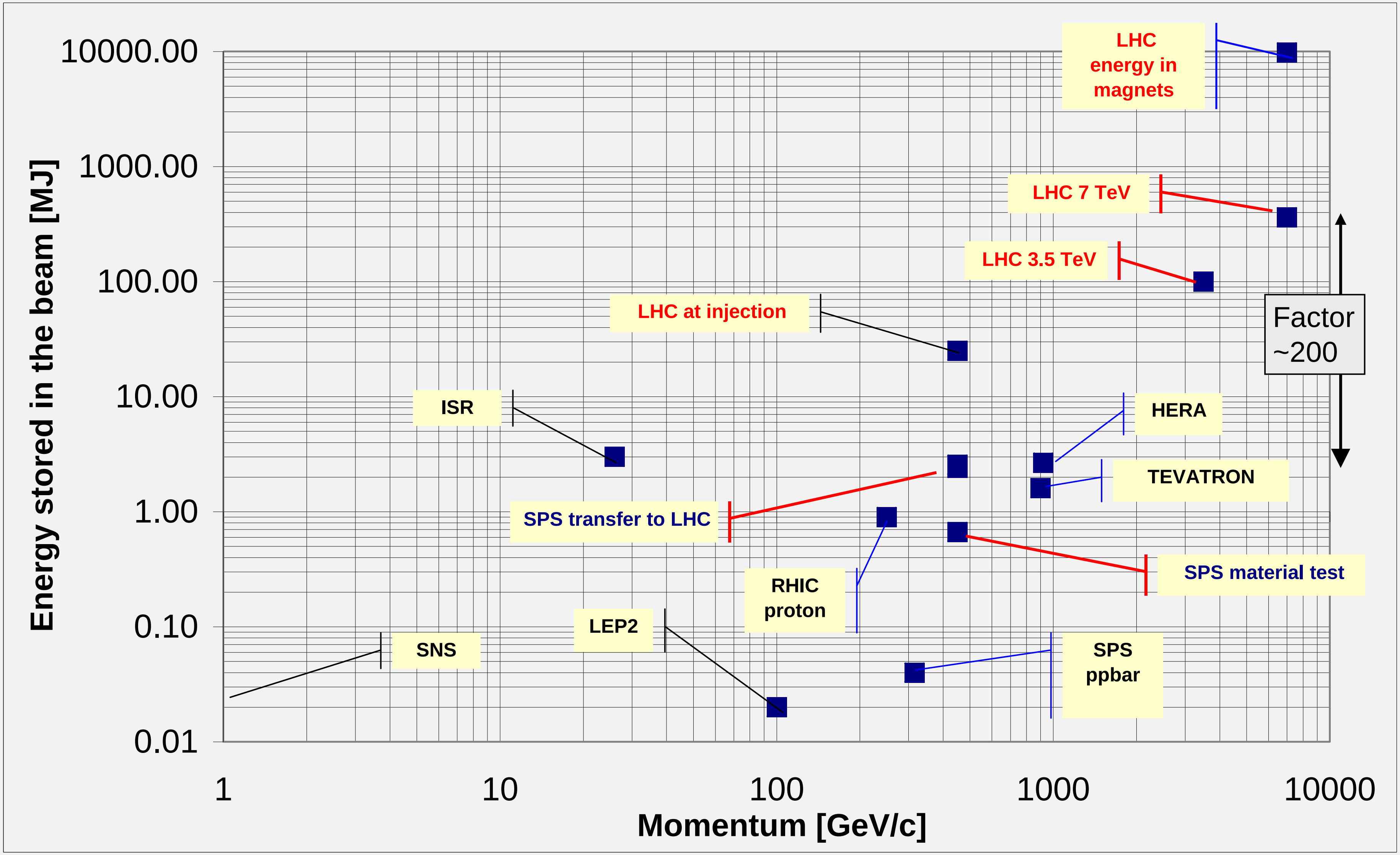
Instabilities

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 !!

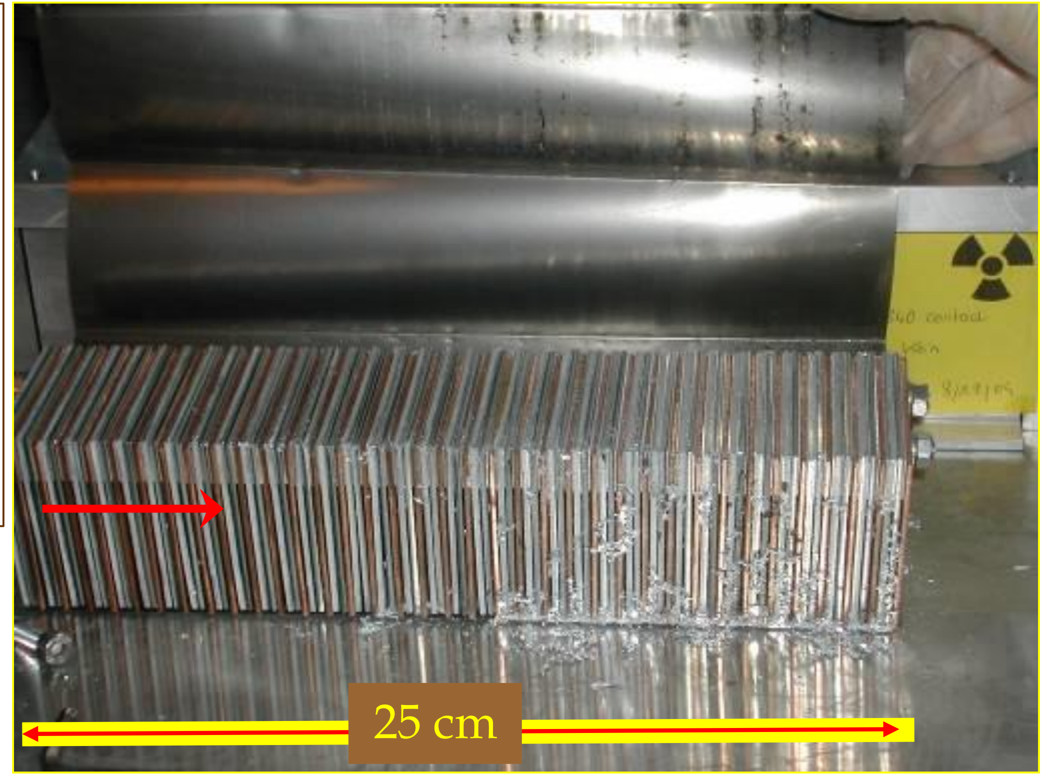
SPS experiment: Beam damage with 450 GeV protons

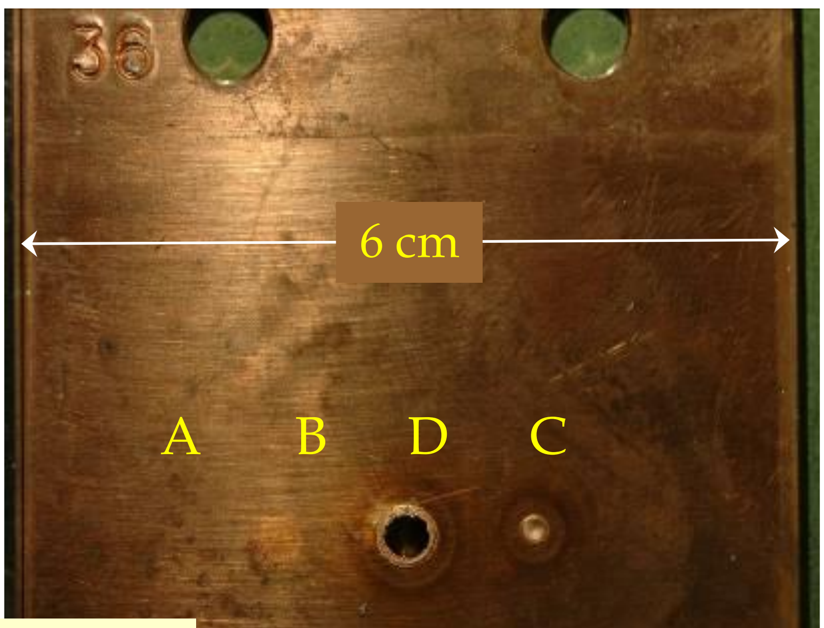
Controlled SPS experiment

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

stainless steel no damage

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





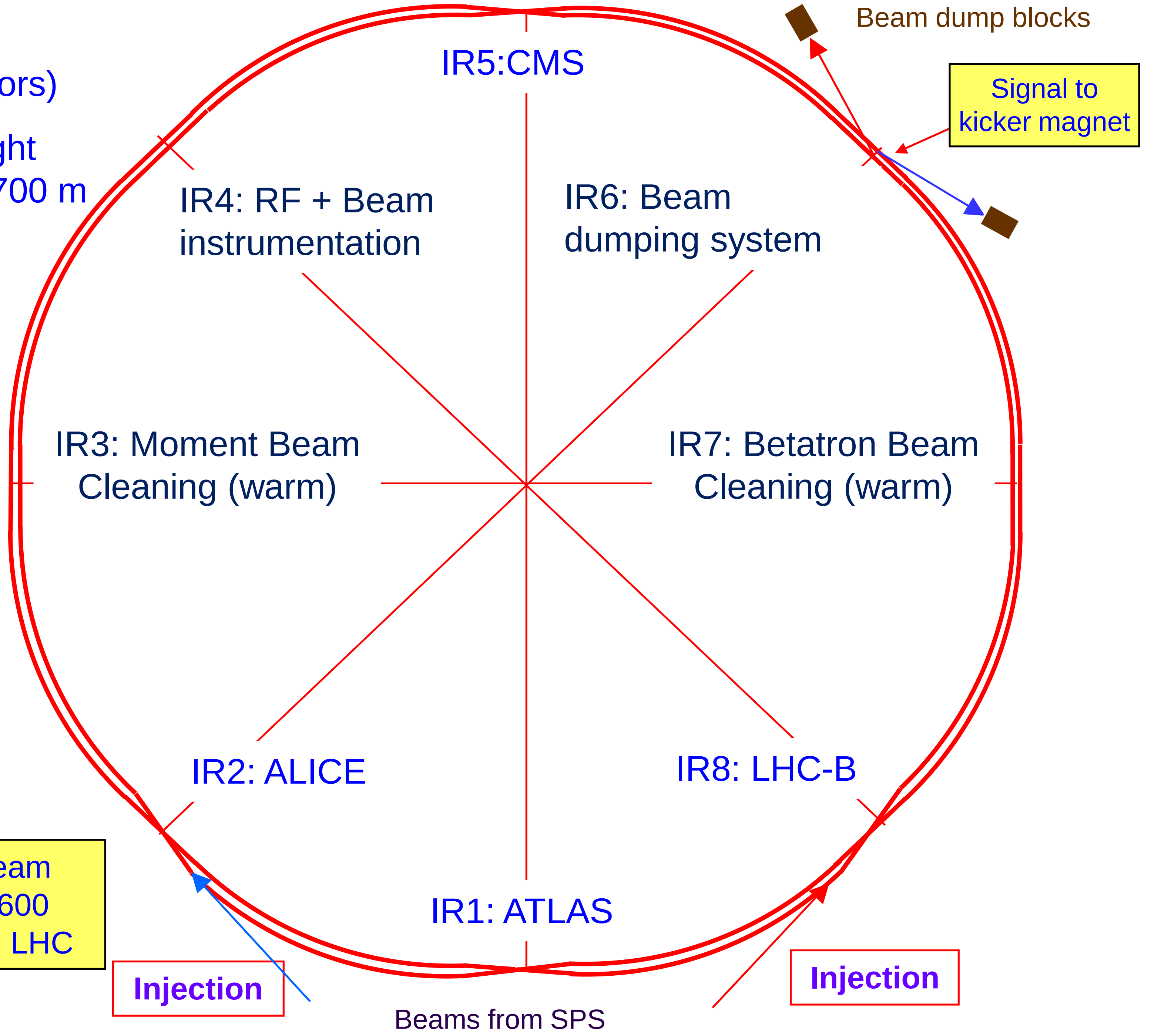
- 0.1 % of the full LHC 7 TeV beams
- factor of three below the energy in a bunch train injected into LHC
- damage limit ~200 kJoule

V.Kain et al

LHC Layout

eight arcs (sectors)

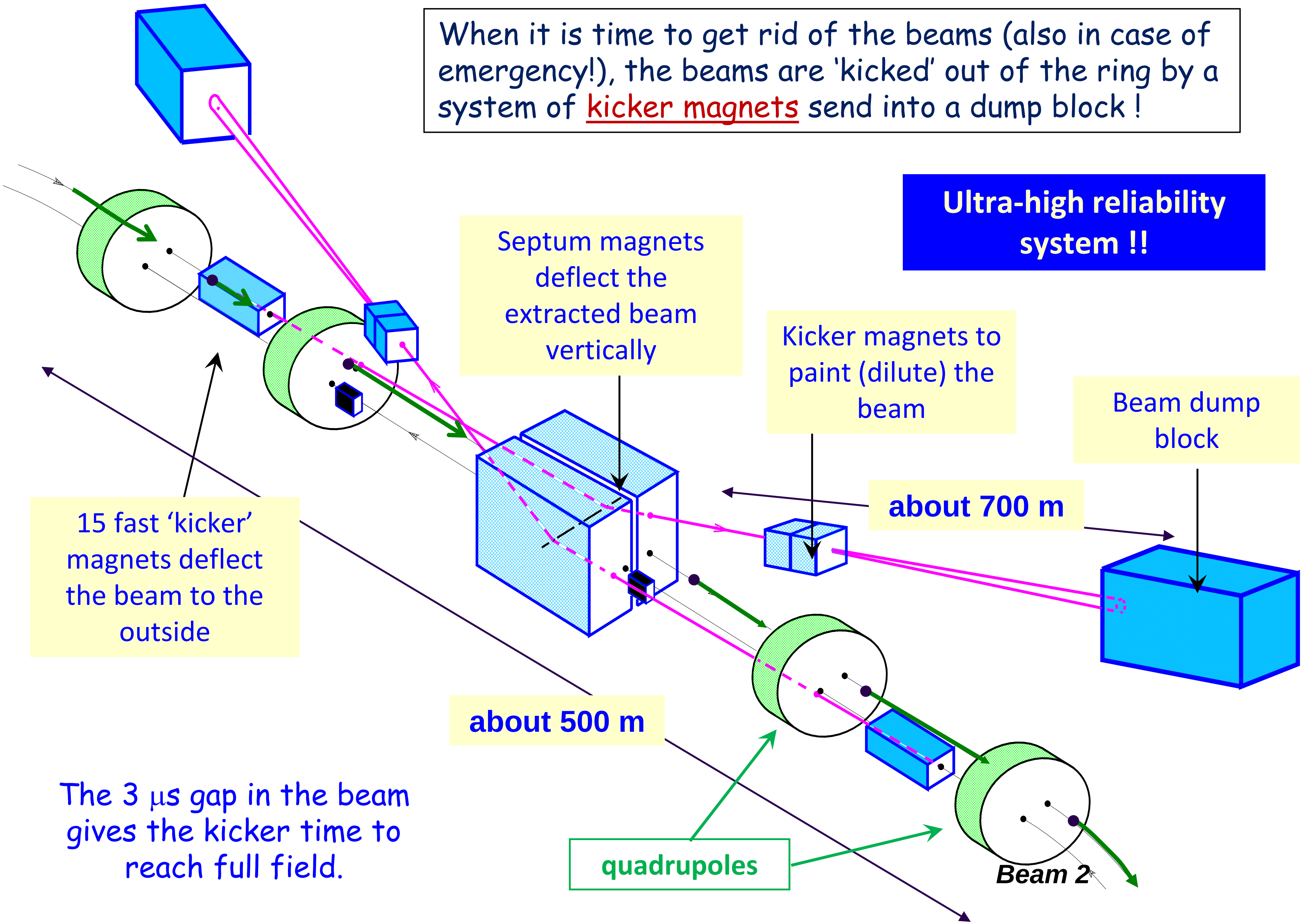
eight long straight section (about 700 m long)



Detection of beam losses with >3600 monitors around LHC

Layout of beam dump system in IR6

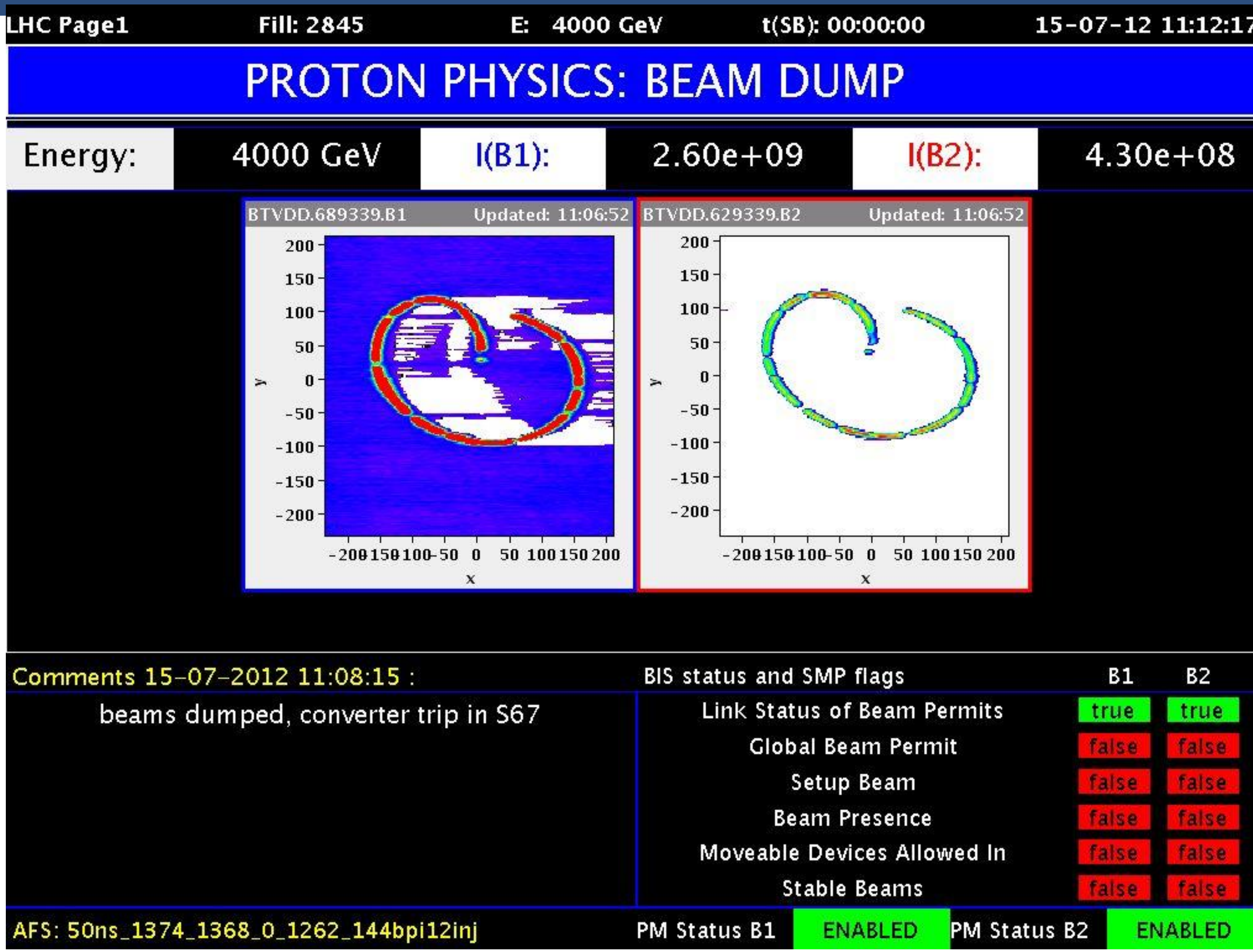
When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets send into a dump block !



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

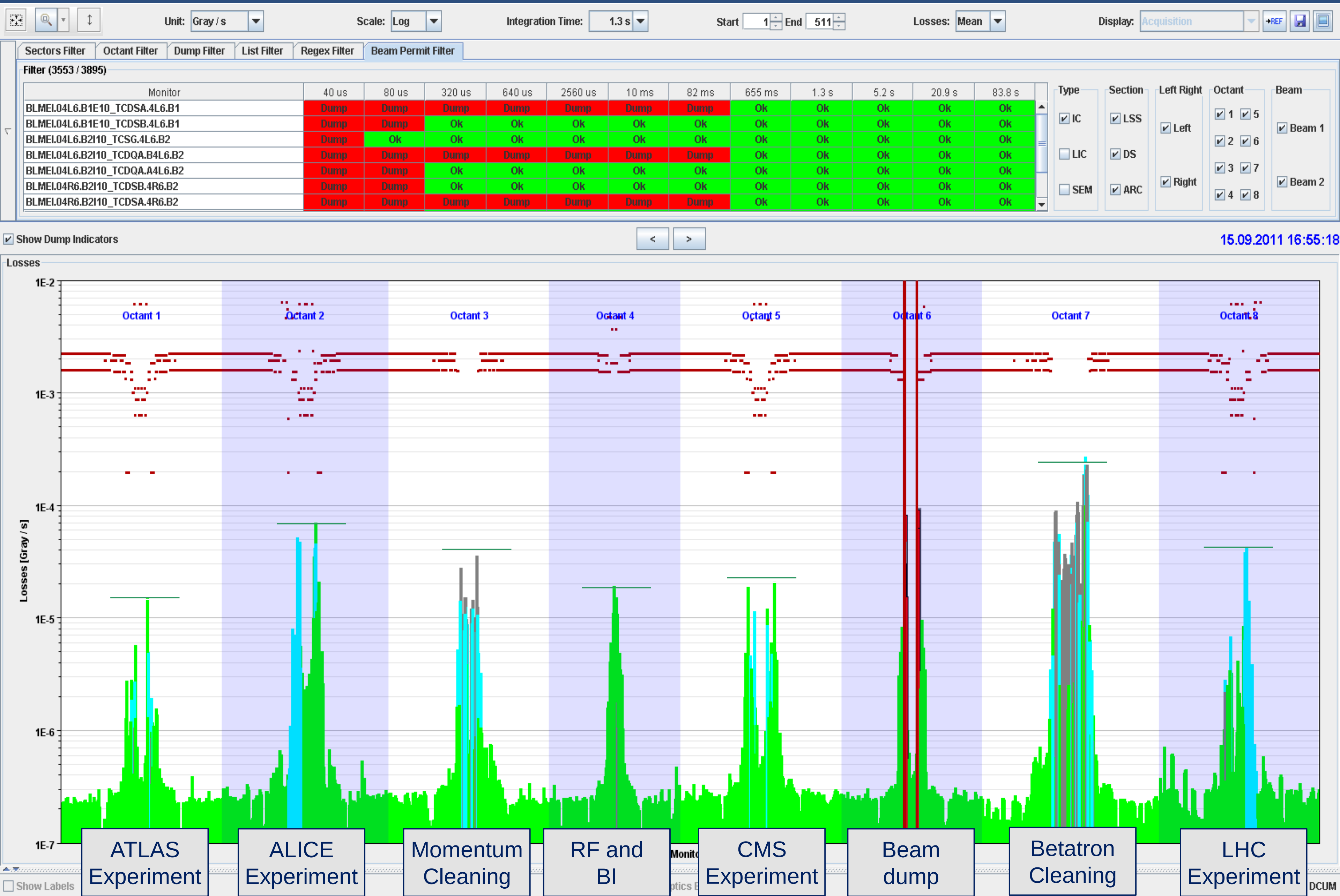
Dump line

Beam dump with 1380 bunches



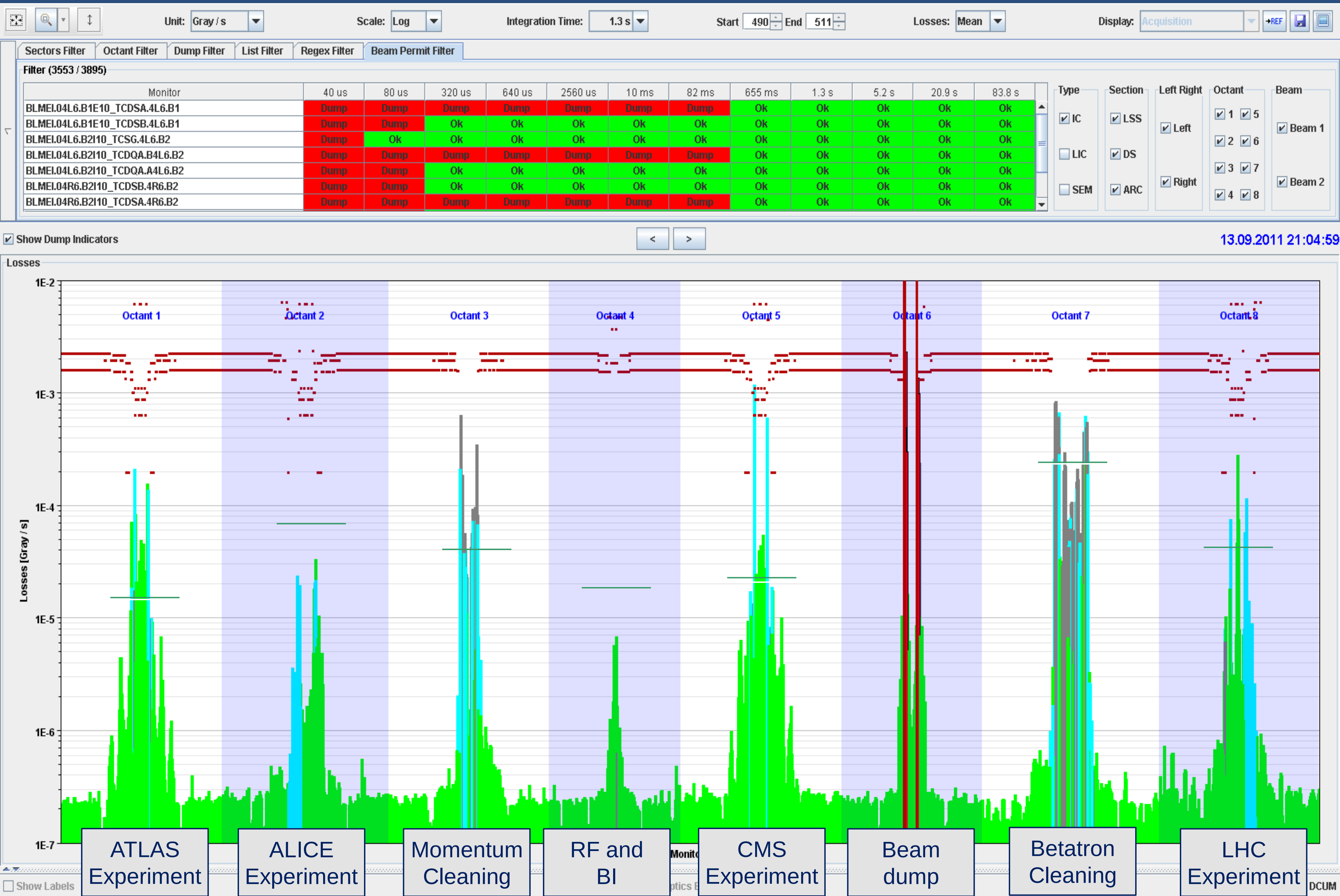
Beam spot at the end of the beam dumping line, just in front of the beam dump block

BLM system: beam losses before collisions



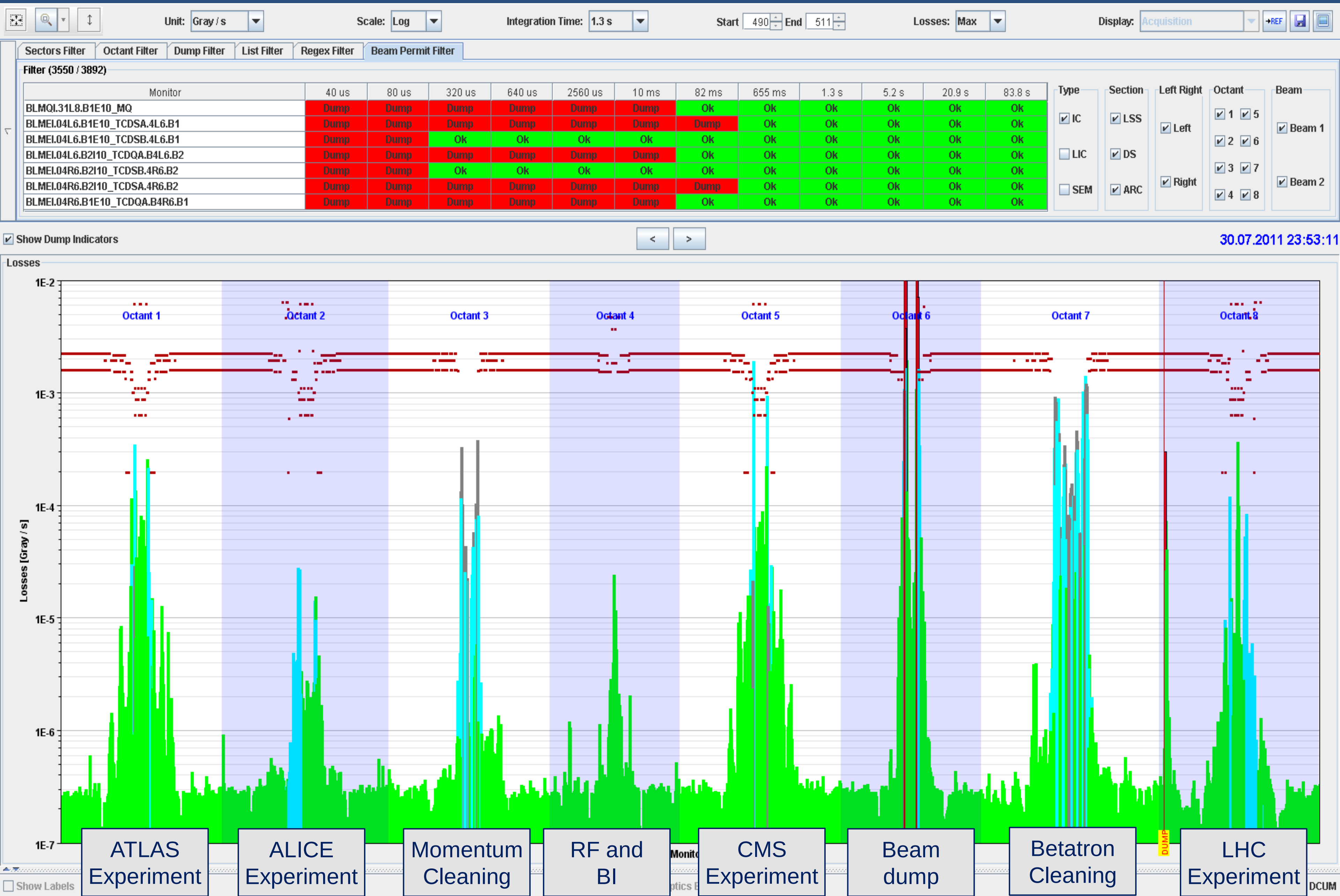
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCSG.4L6.B2	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok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



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

Accidental beam losses during collisions



Zoom one monitor: beam loss as a function of time

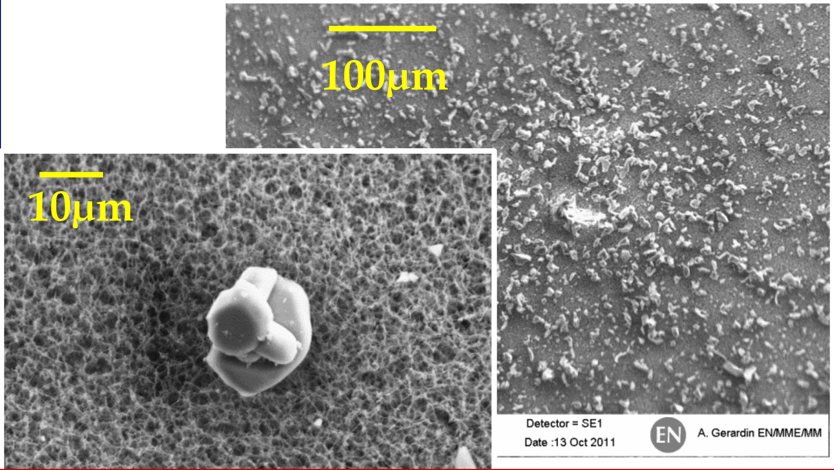
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok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

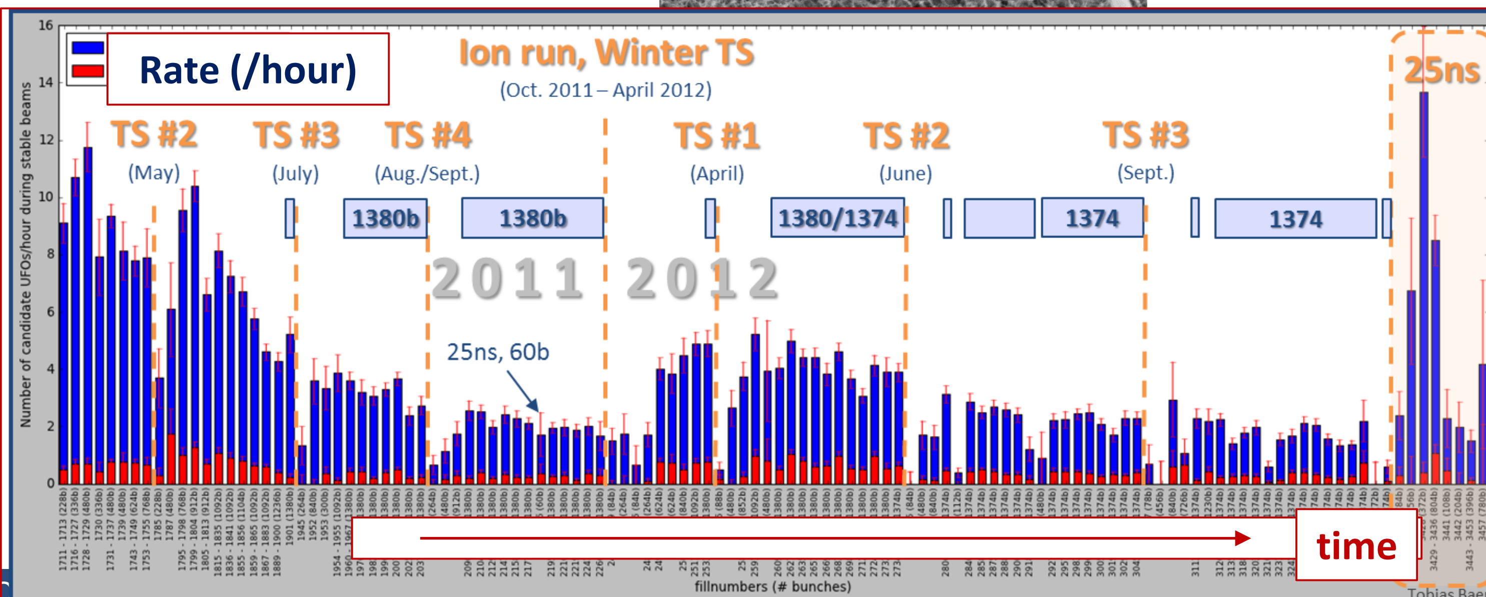
UFOs at LHC

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.
  - Some 10 beams dumped / year
  - Some conditioning of the UFO-rate from ~10/hour to ~2/hour.

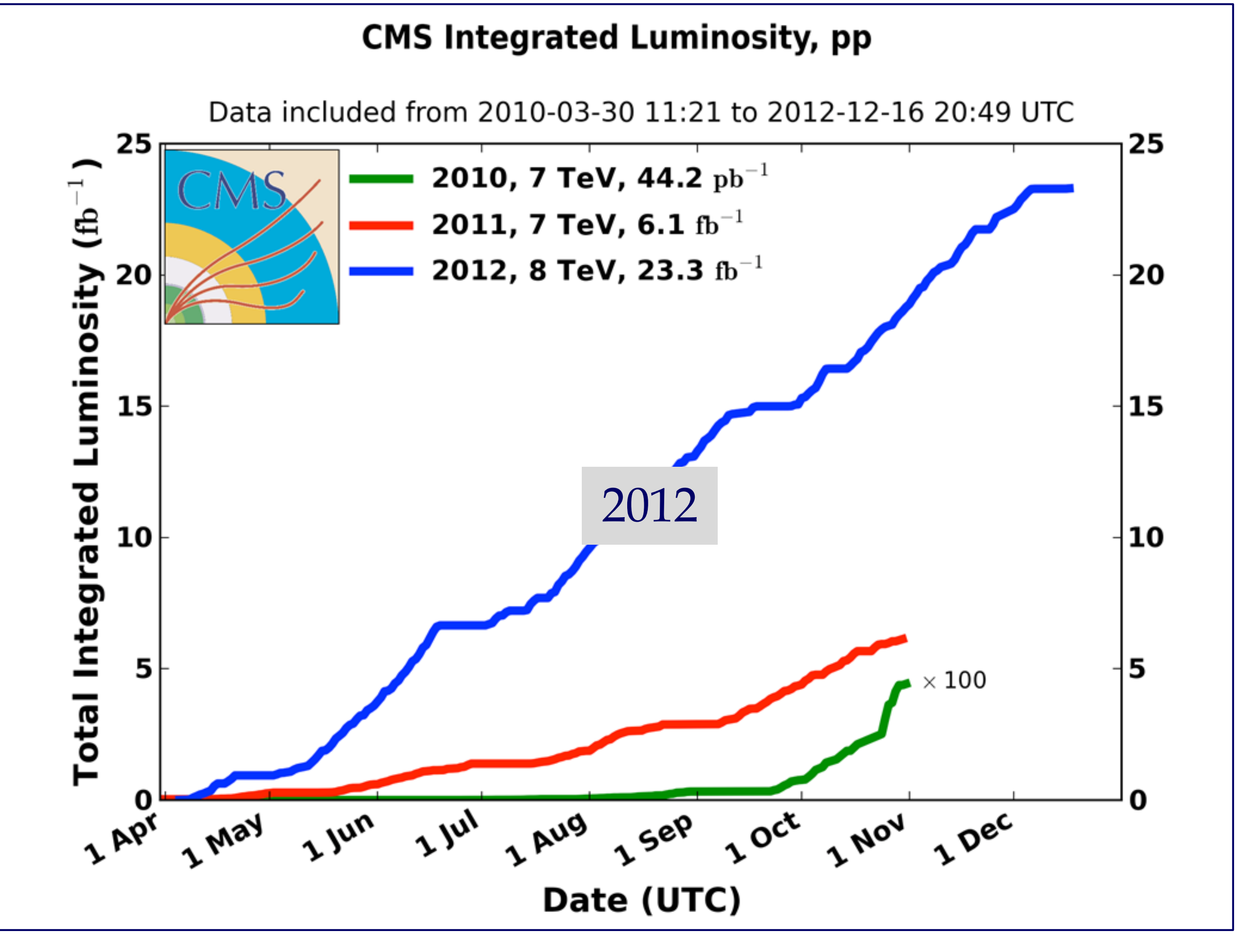
In one accelerator component UFOs were traced to Aluminum oxide particles.





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

Run 2

2015 to 2017

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

SHUTDOWN: NO BEAM

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

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

Phone:77600

*** END OF RUN 1 ***

No beam for a while. Access required

time estimate: ~2 years

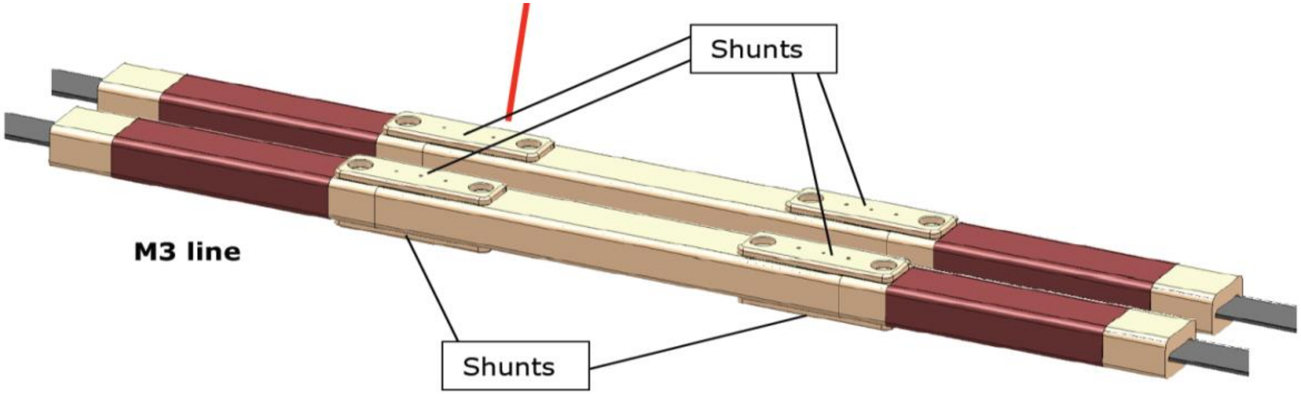
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	Except	Except
Global Beam Permit	Except	Except
Setup Beam	false	false
Beam Presence	false	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

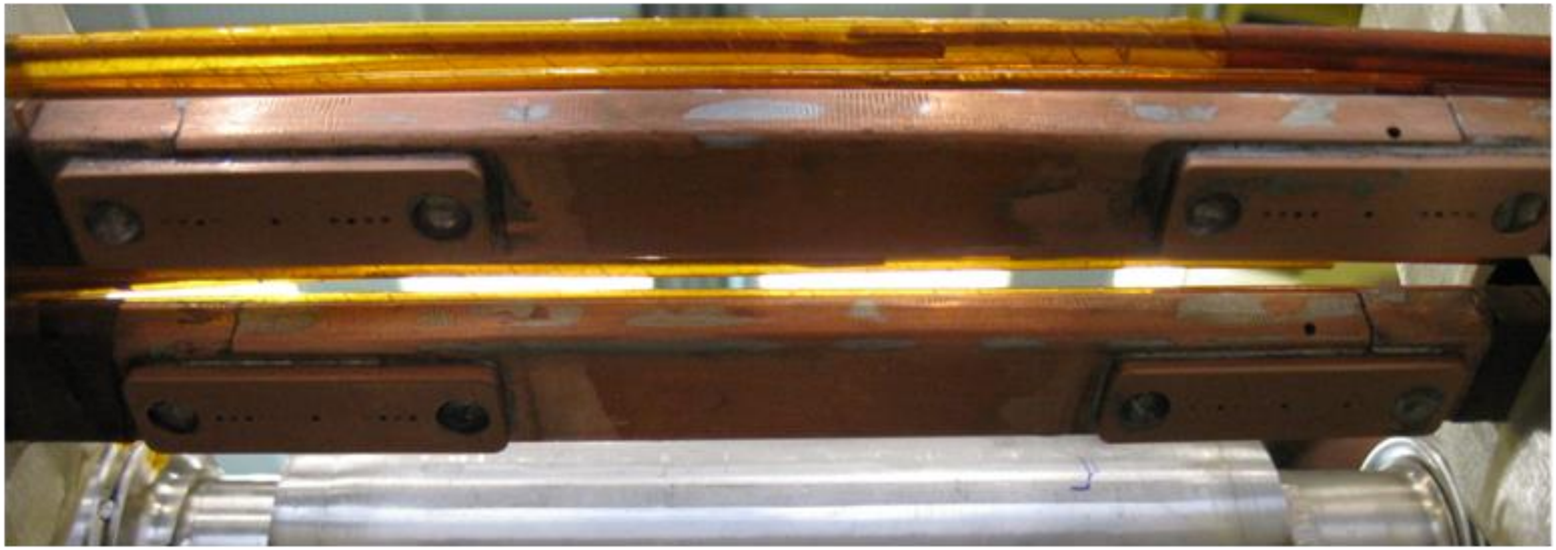
AFS: 50ns_1374_1368_0_1262_144bpi12inj

PM Status B1 ENABLED PM Status B2 ENABLED

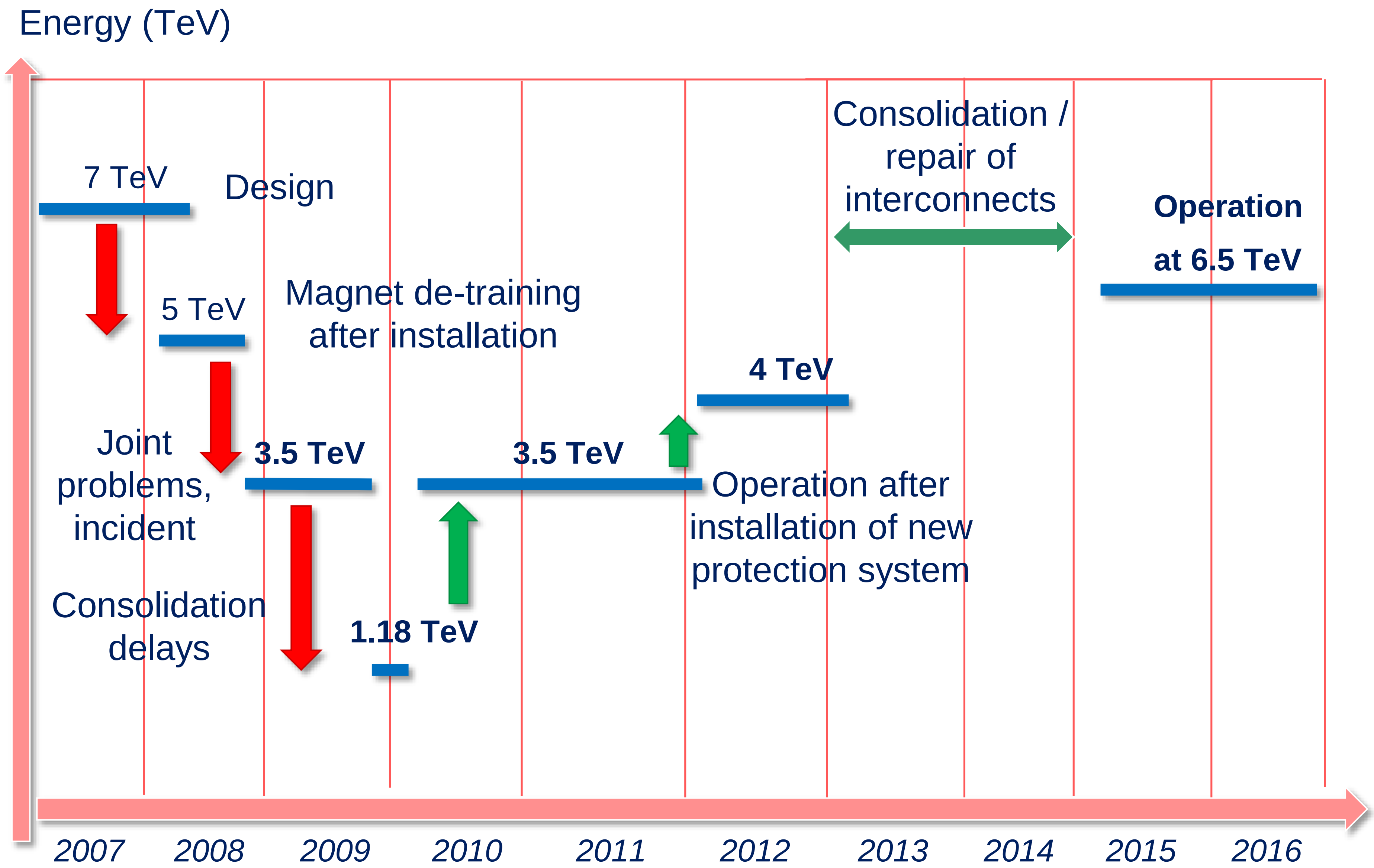
Preparing for nominal energy

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

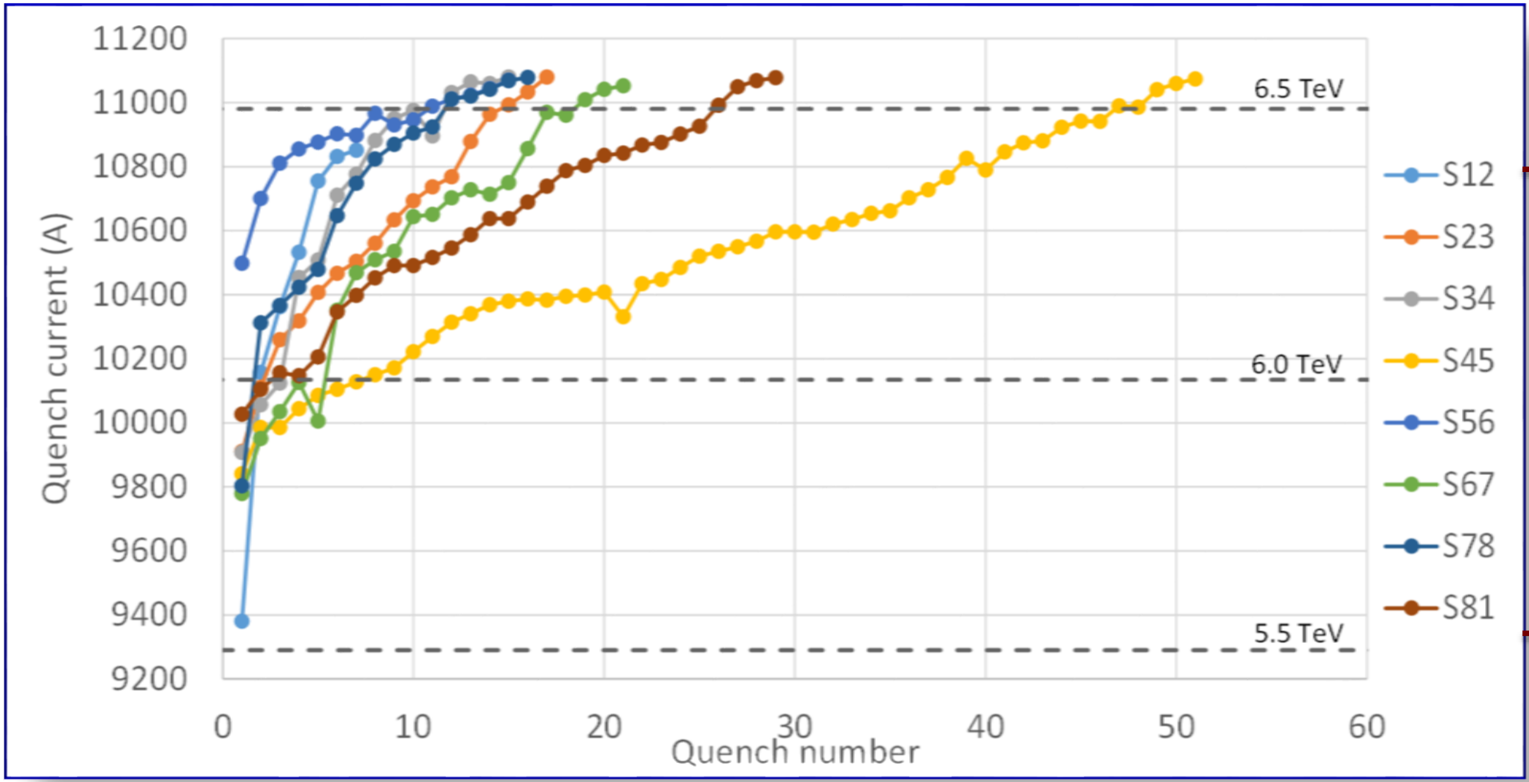


Goals of the 4 year long Run 2 from 2015 to 2018:

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

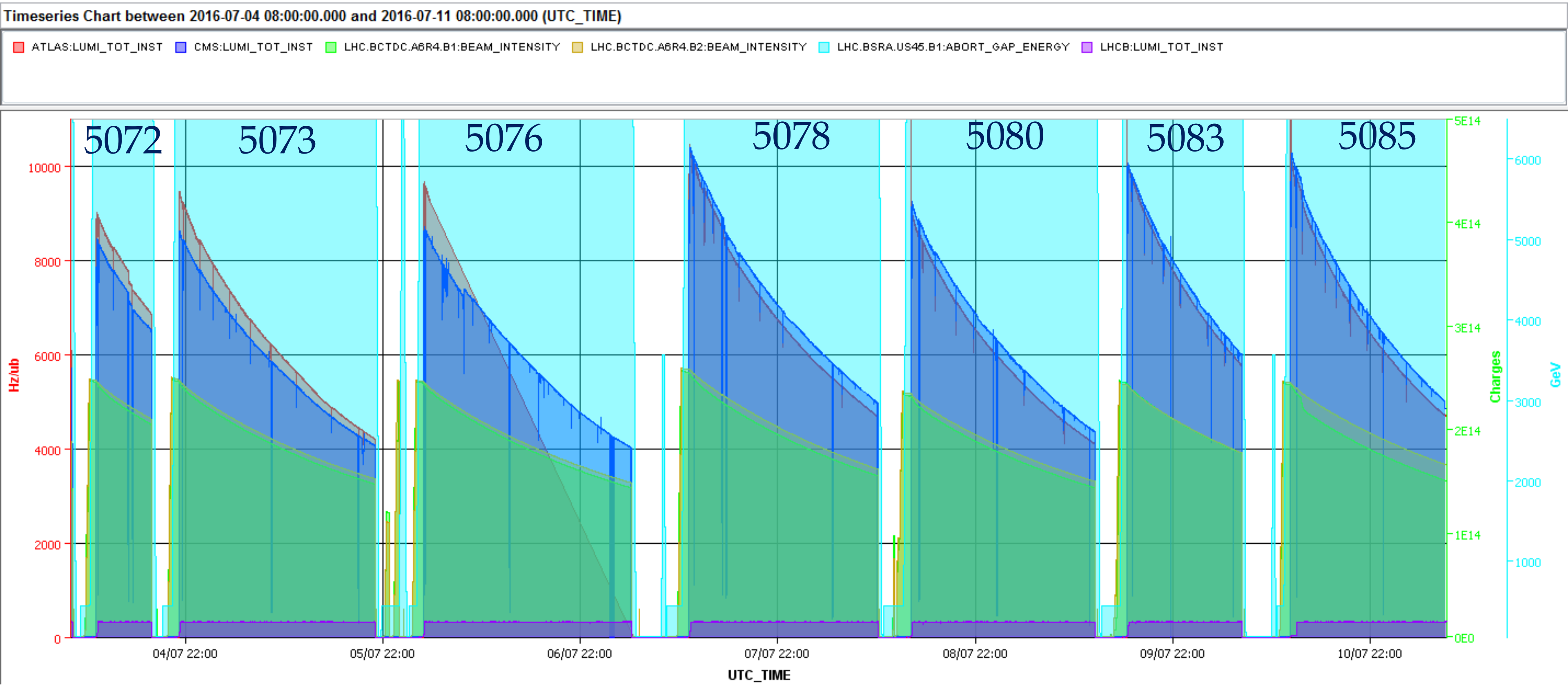
Dipole training and energy

- The 1232 main dipole magnets were trained for 6.5 TeV operation in 2015
- More than 150 training quenches were required to reach the 6.5 TeV level
  - The spread in number of quenches between the sectors (arcs) is due to the mixture of magnets from the 3 producers.



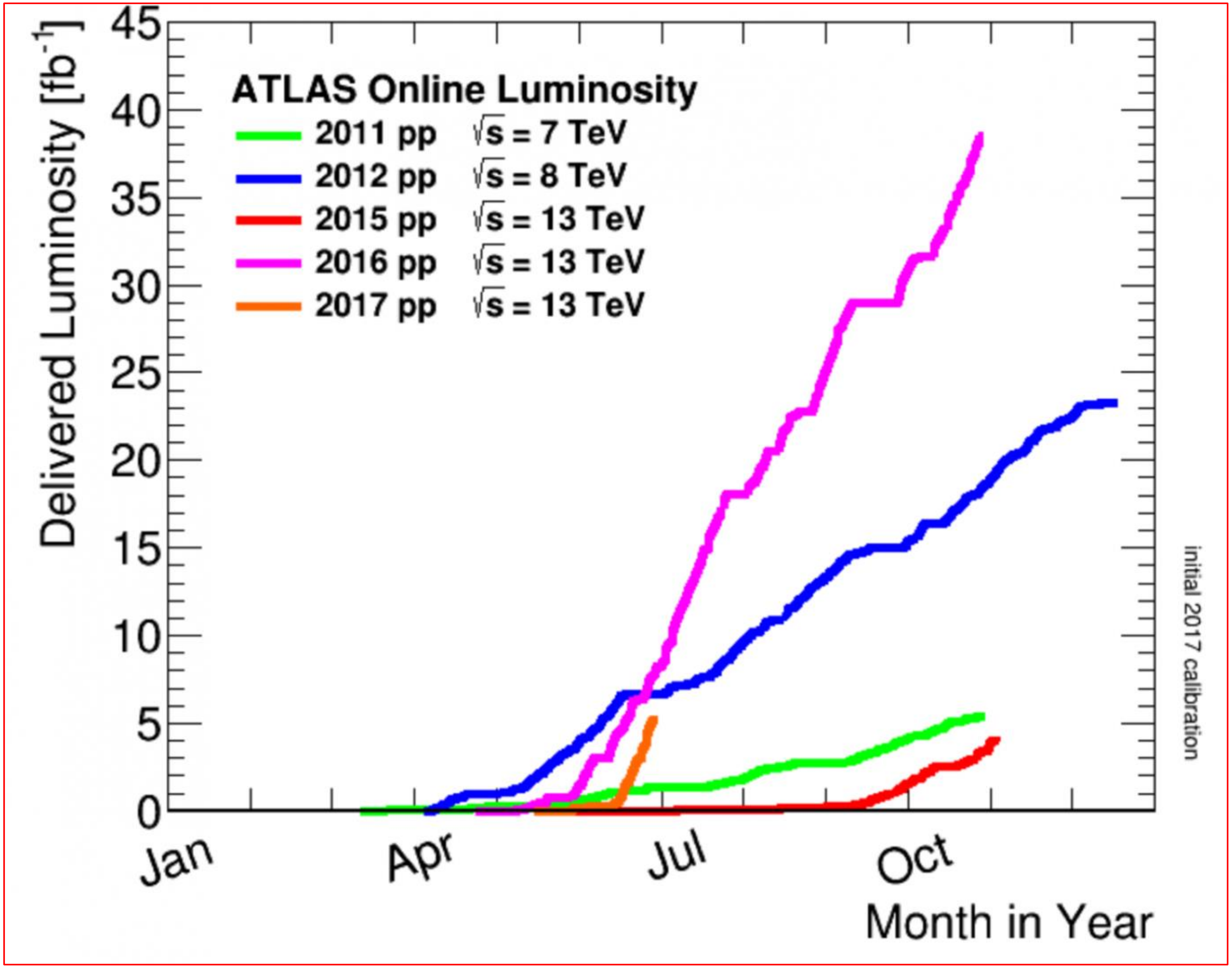
8 LHC sectors (~ arcs)

Fill 5083
Luminosity > $1x10^{34}$ $cm^{-2}s^{-1}$

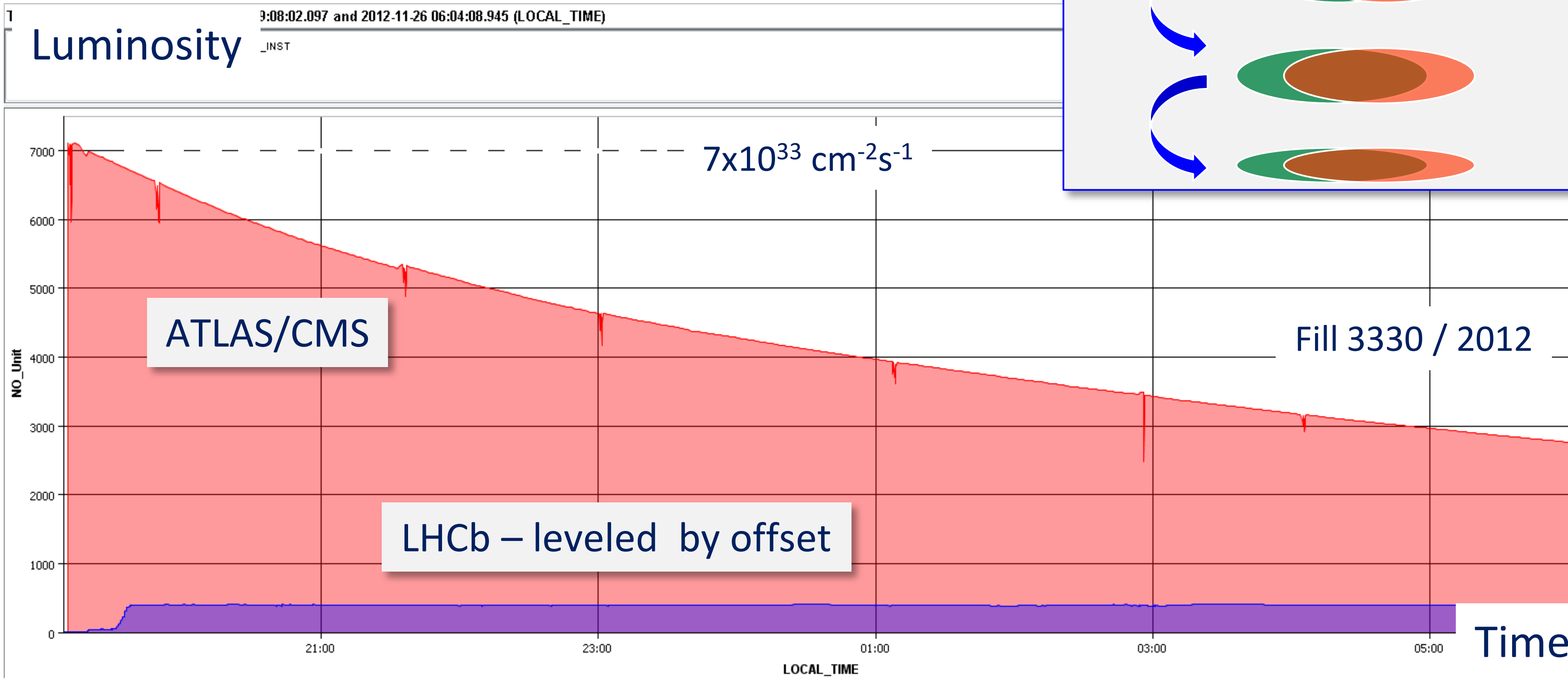


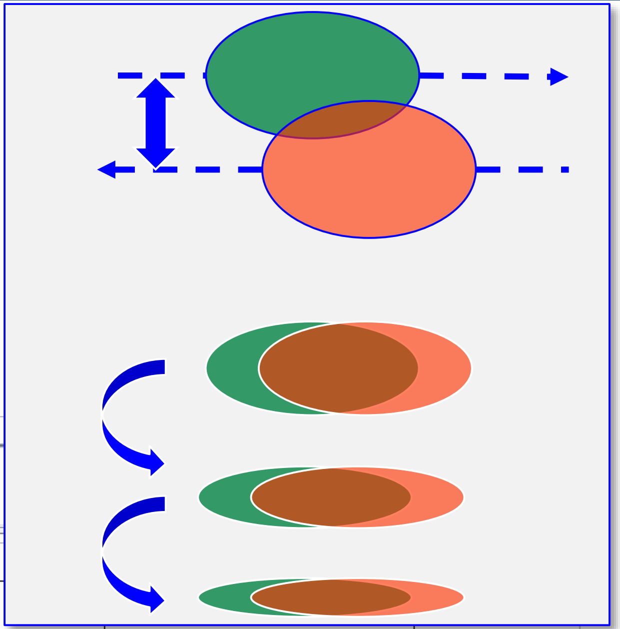
Design Luminosity achieved !!!!

Integrated luminosity for ATLAS

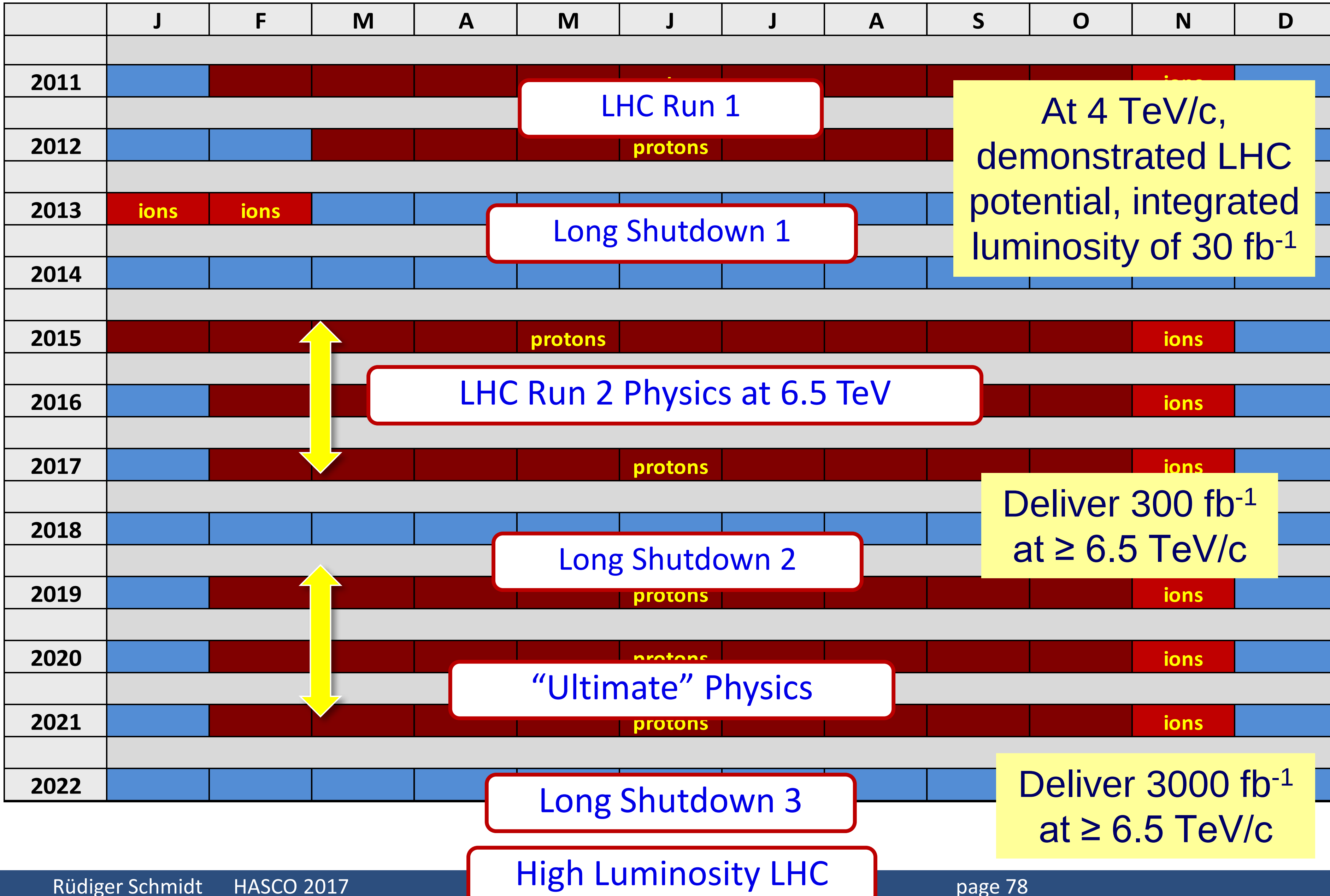


- We have levelled the luminosity of LHCb by adjusting the offsets between the beams.
- We are considering to level luminosities by adjusting the beam size at IP.
- Better / mandatory for beam stability.



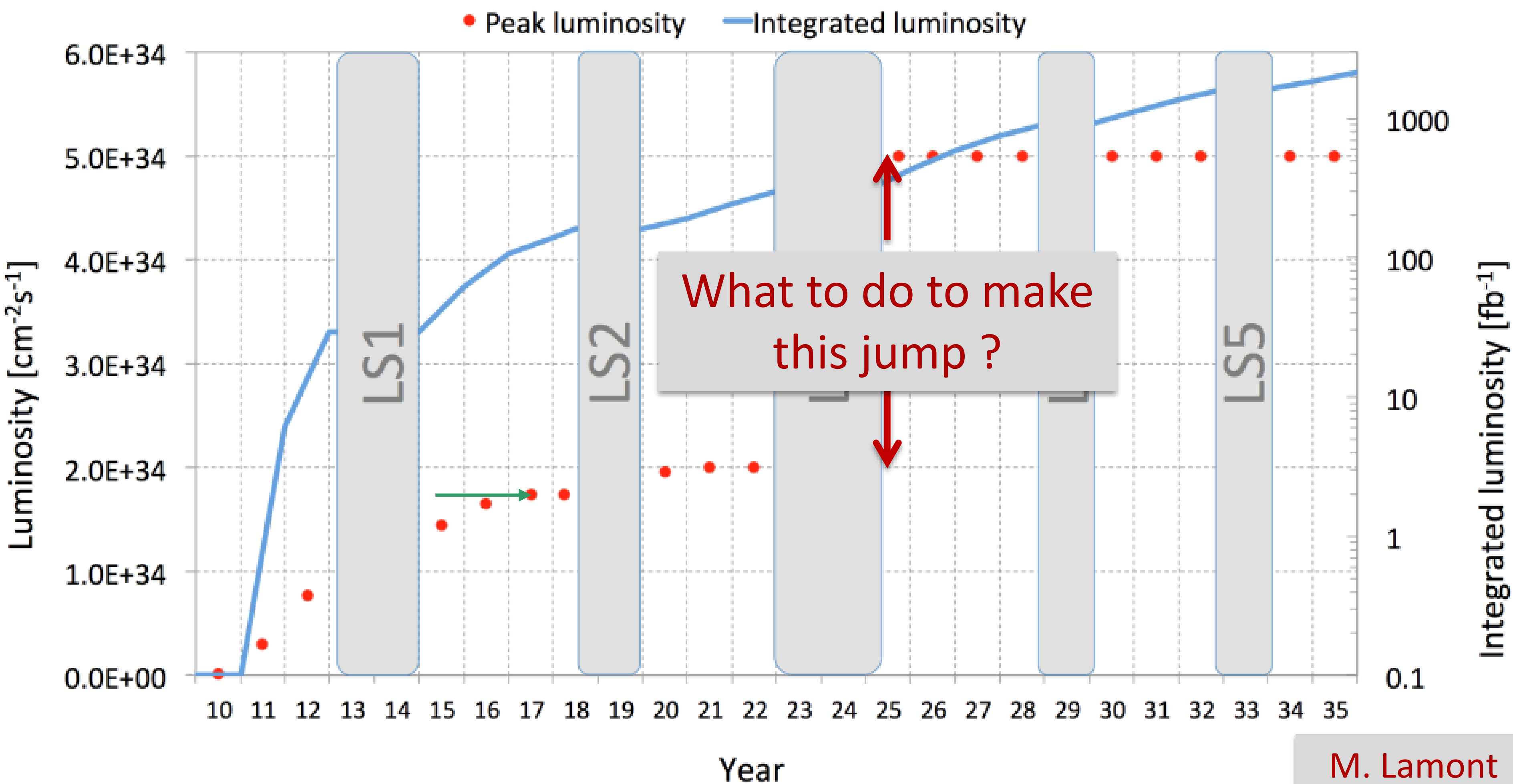


The next years



Preparing for the next 20 years:

High Luminosity LHC (HL-LHC)


Peak luminosity
Integrated luminosity
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
Luminosity [cm^{-2}s^{-1}]
1000
100
10
1
0.1
Integrated luminosity [fb^{-1}]
LS1
LS2
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year
What to do to make this jump ?

M. Lamont

LHC Upgrade

Motivation

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

2010-2012 experience

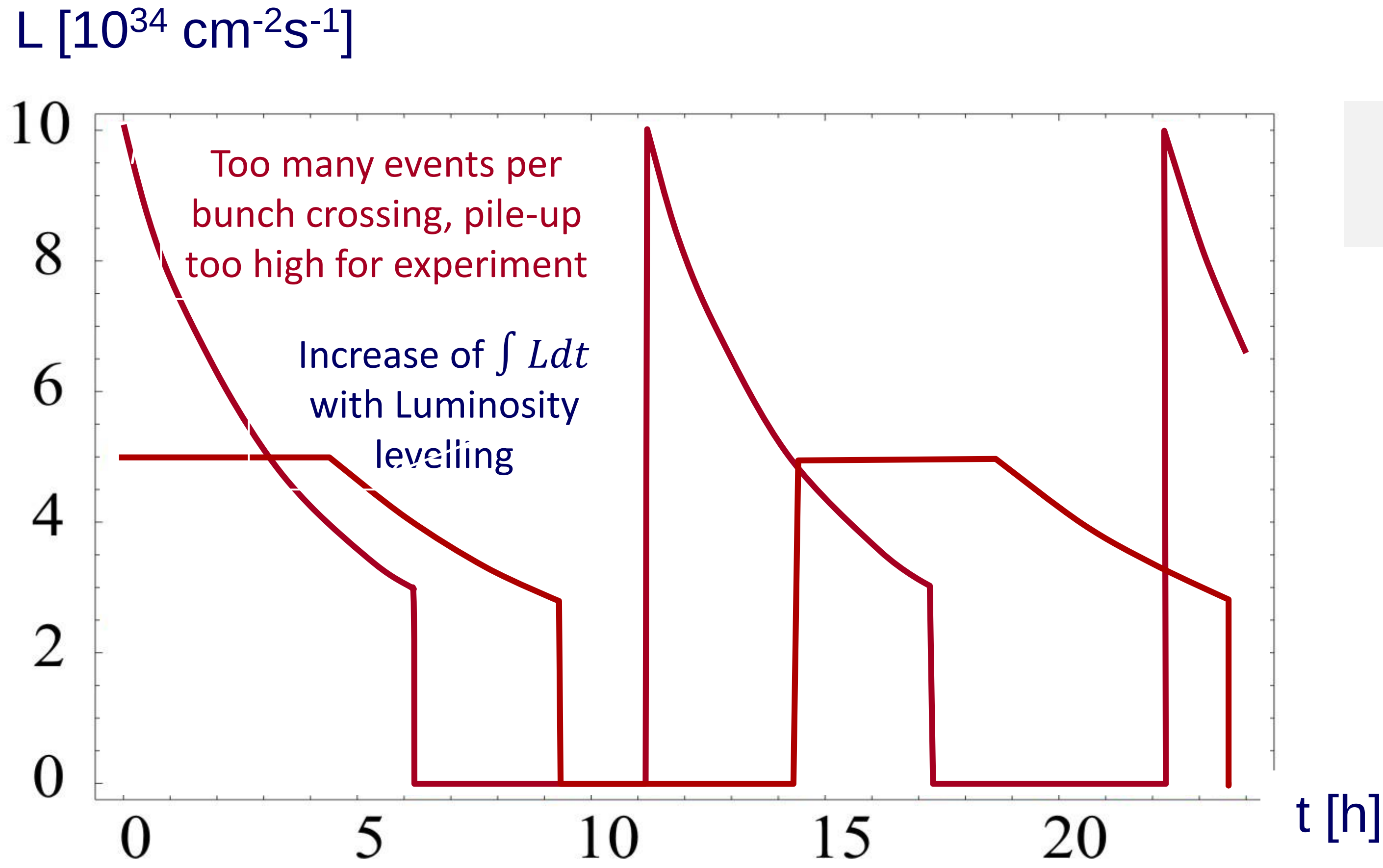
- Head-on beam-beam limit higher than initially expected
- Single bunch with > $3x10^{11}$ ppb with 2.5 mm emittance accelerated in the SPS
- Low β* optics successfully tested during Machine Studies

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, …

Integrated luminosity increase by levelling

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



Virtual peak luminosity (F=1)

leveling at 5×10^{34} cm^{-2}s^{-1}

t_{eff}=15 h, T_{ta}=5 h

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

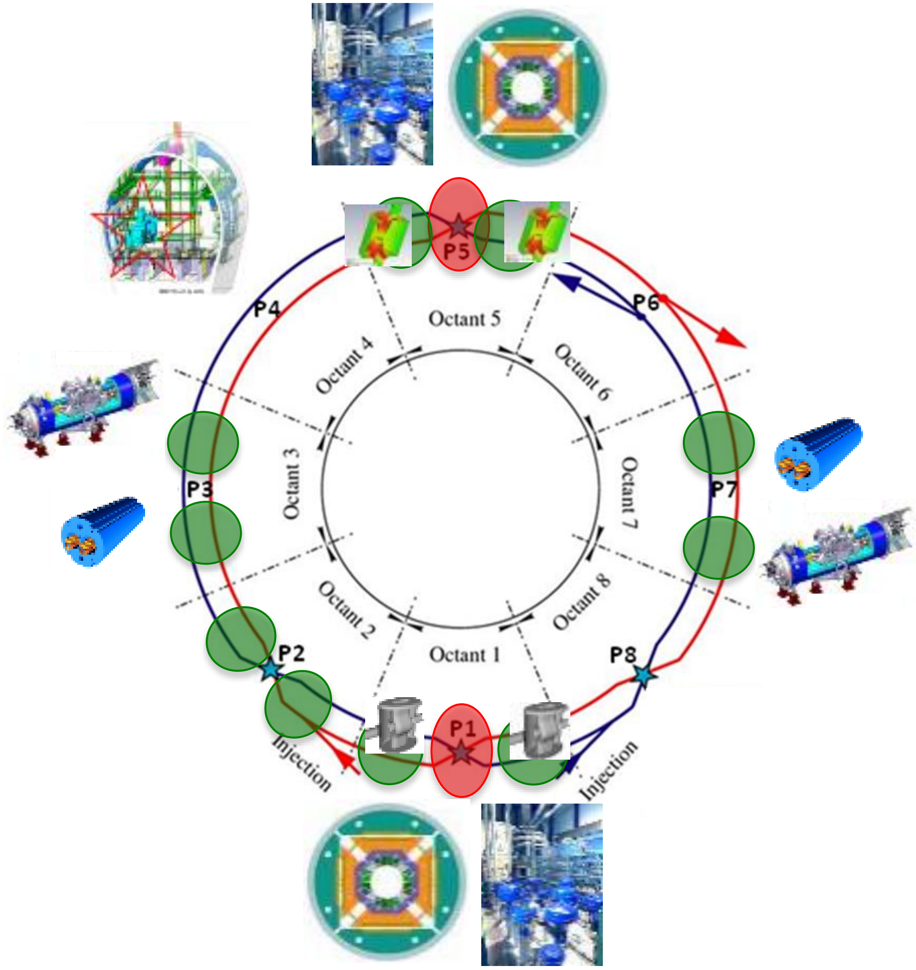
Aim for ~250 fb^{-1}/y

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



Final remarks

- The progress in LHC performance has been great.
- Luminosity above nominal at 6.5 TeV, is already more than 50% above design, thanks to the quality of the design, the construction, the operation and the injectors.
- Operation at 6.5 TeV has been surprisingly efficient

Still, 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 !