CERN Summer School 2015
Introduction to Accelerator Physics

Part V

by
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What's next?


Installed in 26.7 km LEP tunnel
Depth of 70-140 m
Lake of Geneva
The LHC

LHC Design Goals as Proton-Proton Collider

Basically....

As high an energy as possible

$p = 7 \text{ TeV/c}$ in existing LEP tunnel with 27 km circumference

$$\frac{p}{e} = B\rho \qquad \rightarrow B = 8.3 \text{ T}$$

➔ Superconducting magnets

As high a collision rate as possible in the experiments

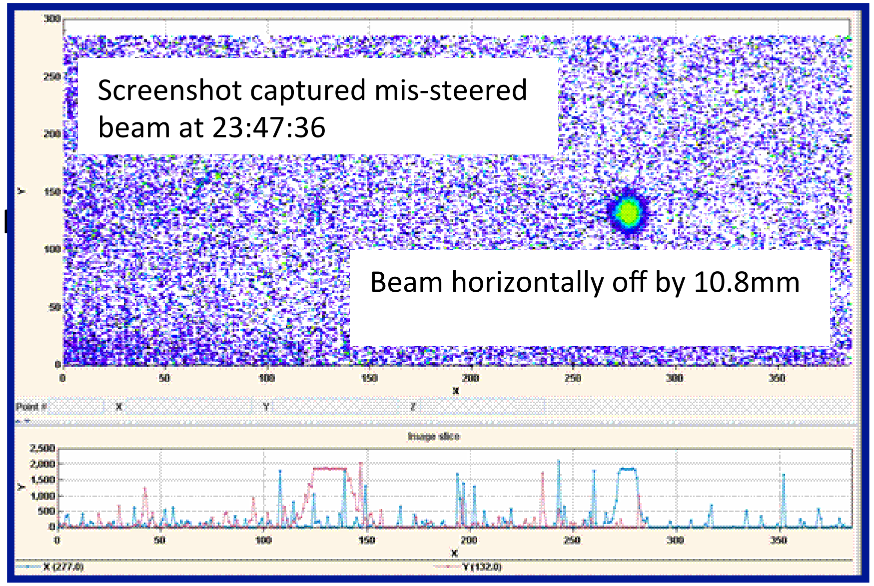
2808 proton bunches with 1.15×10^{11} p^+ per bunch
spaced by 25 ns

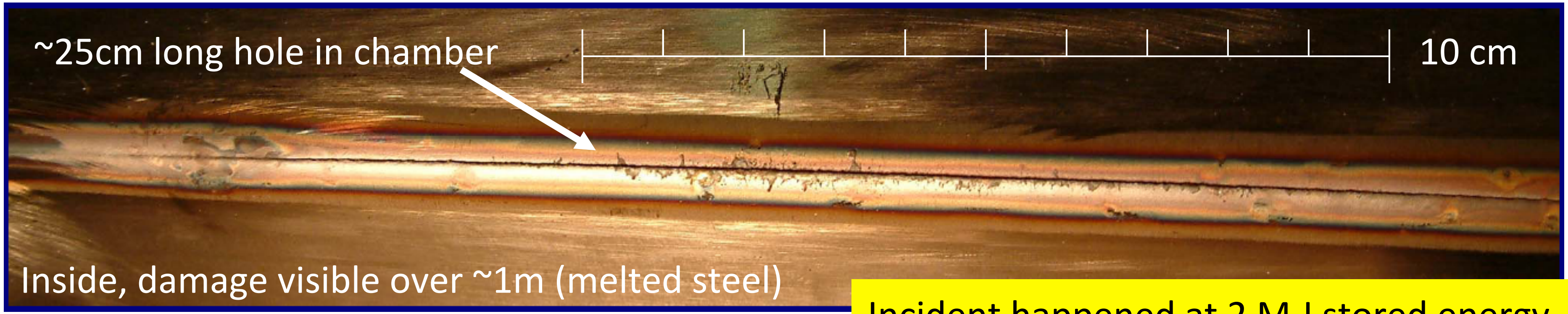
$$\rightarrow 360 \text{ MJ}$$

stored in beam at 7 TeV

Already at injection energy beam loss can damage

- Failure in SPS during setting-up of LHC beam (25/10/04)
- Extraction septum supply tripped due to EMC from the beam
- In 11ms the field dropped 5%
- 3.4×10^{13} p+ @ 450GeV were wrongly extracted onto aperture
- Chamber and quadrupole magnet were damaged and had to be replaced

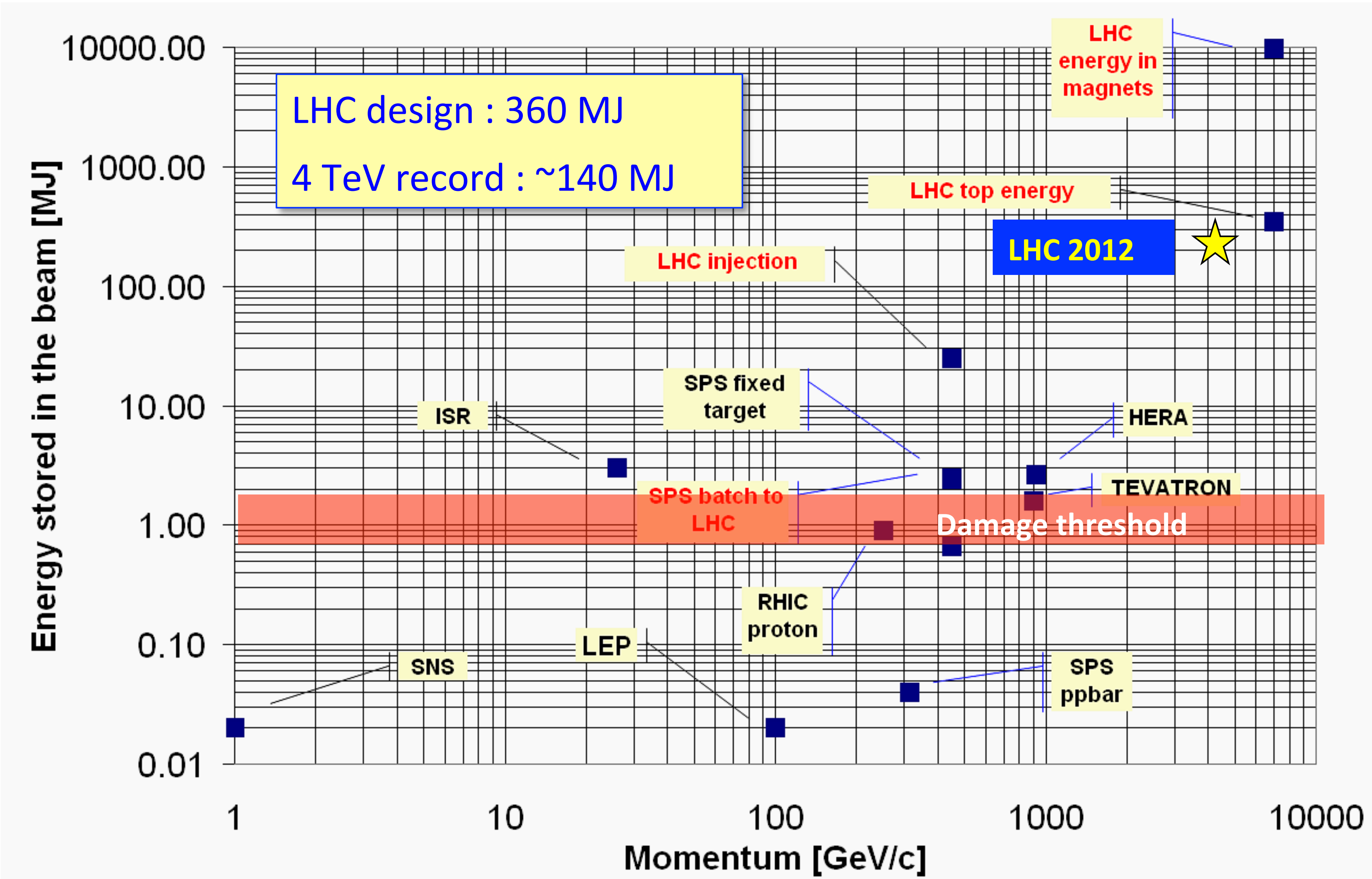




Incident happened at 2 M J stored energy

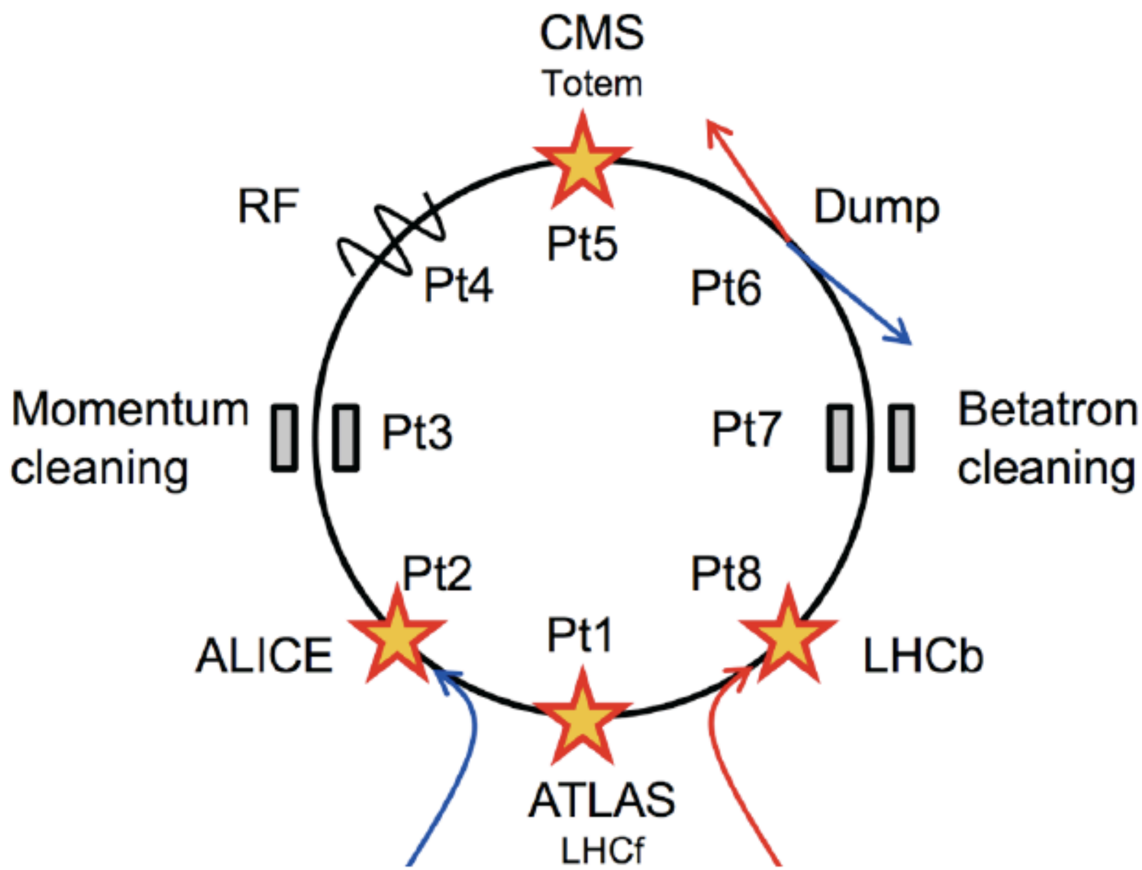
Stored Energy

The stored energy in beam and magnets is orders of magnitude above damage threshold: LHC key system ➔ **Machine Protection System**



The Large Hadron Collider

- Total length 26.66 km, in the former LEP tunnel.
- 8 arcs (sectors), ~3 km each with FODO lattice
- 8 straight sections
- beams cross in 4 points.

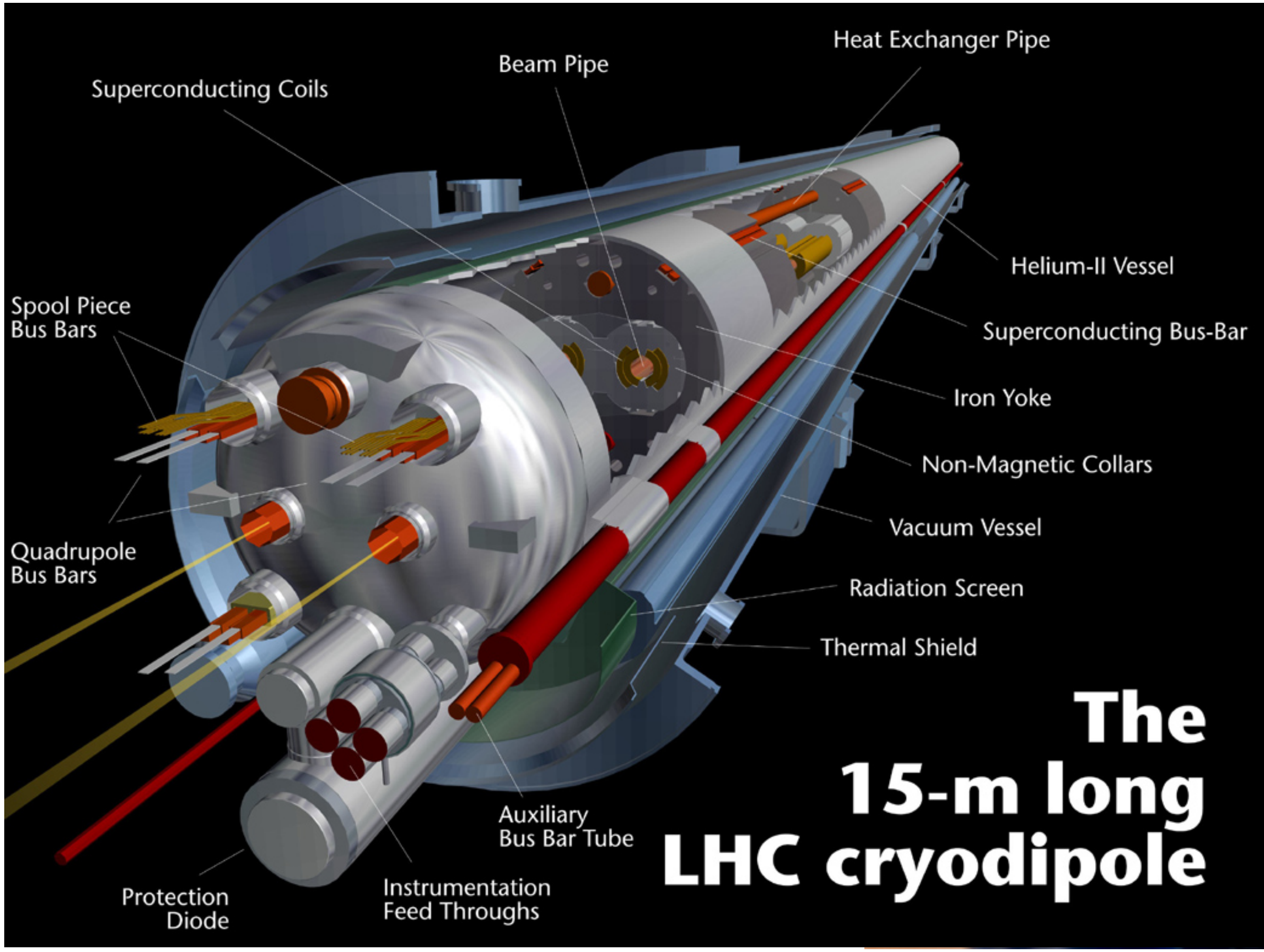


- 2-in-1 magnet design with separate vacuum chambers.
- Designed for acceleration to 7 TeV/c beam

The LHC can be operated with protons and ions (so far Pb_{208}).

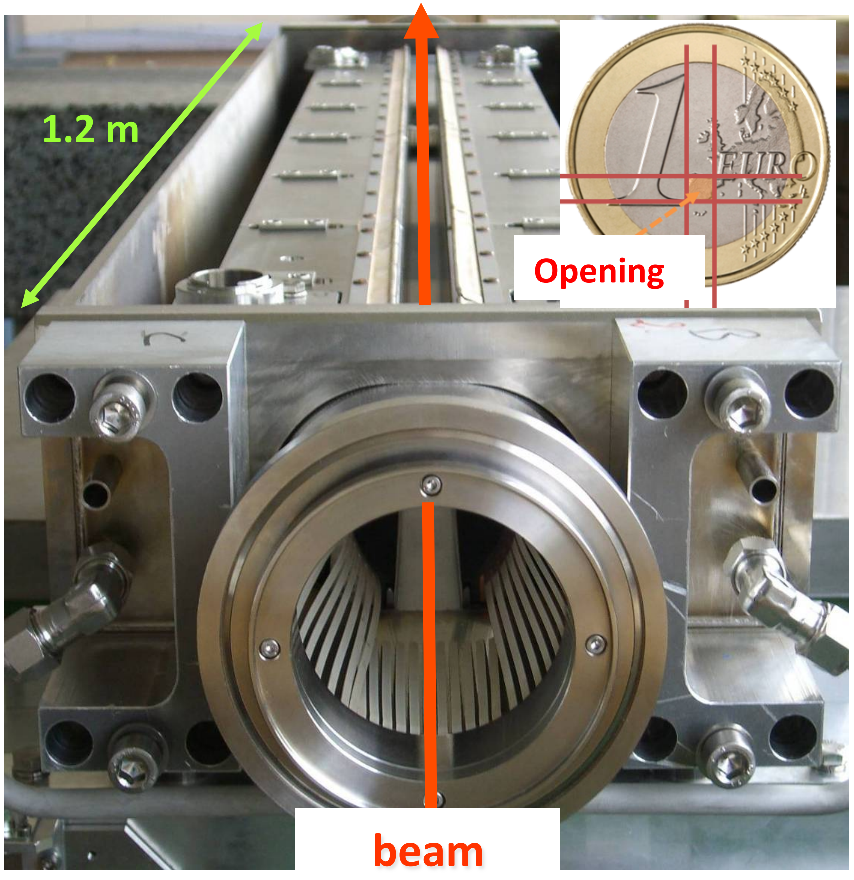
The LHC 2-in-1 Main Dipoles

- **1232** NbTi superconducting dipole magnets – each 15 m long
- Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium).
    - *But they do not like beam loss – quench with few mJ/cm³.*



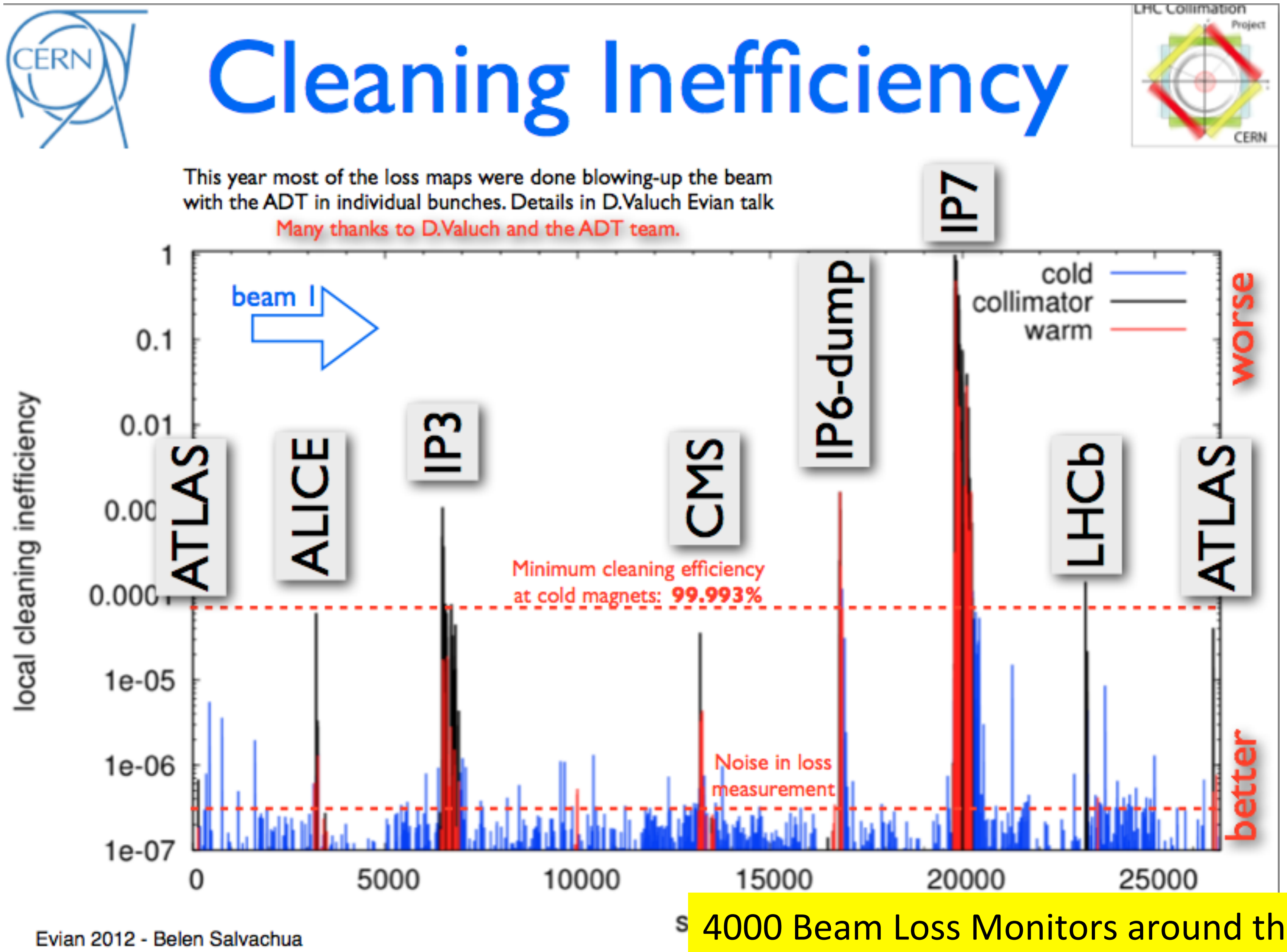
Beam Collimation

- 2 dedicated beam collimation insertions in the LHC. “All” particles should be lost on the beam cleaning collimators and not on the superconducting magnets.
- The different collimators have to be aligned with beam, 1-by-1. Their settings have to follow the collimation hierarchy and the energy ramp.



- Almost ***100 collimators*** *and* ***absorbers***, with a typical length of ~1 m.
- LHC run 1: The system managed to intercept ~99.99% of the protons that were lost from the beam.
  - ***No magnet was quenched with beam at 3.5 / 4 TeV .***

Collimator beam loss cleaning inefficiency



4000 Beam Loss Monitors around the ring

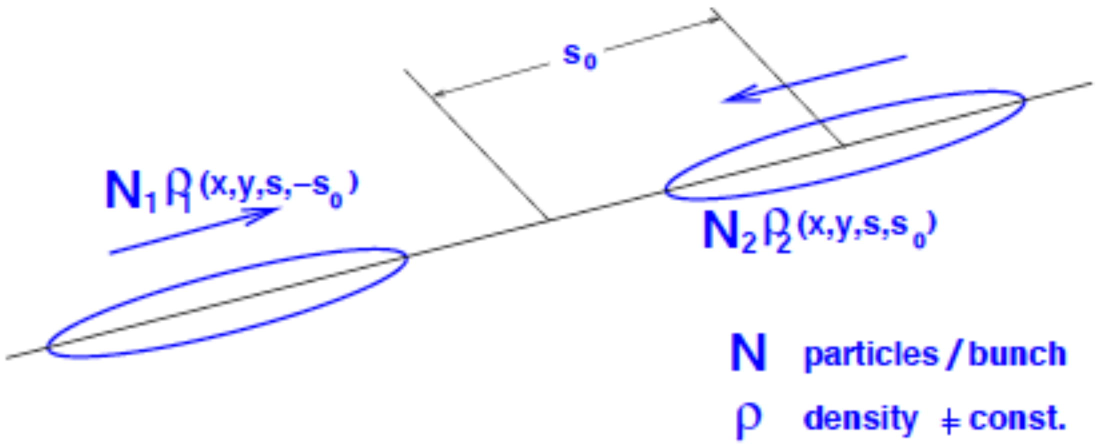
COLLISION RATE - LUMINOSITY

Collider Luminosity

Experiments are interested in maximum number of interactions per second dR/dt:

Luminosity is the proportionality factor between cross section and number of interactions per second:

$$\frac{dR}{dt} = \mathcal{L} \times \sigma_p$$



$$\mathcal{L} \propto K \cdot N_1 \cdot N_2 \int \int \int \int_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)dx,dy,ds,ds_0$$

$$s_0 = c \cdot t \qquad K = \sqrt{[(\vec{v}_1 - \vec{v}_2)^2 - (\vec{v}_1 \times \vec{v}_2)]/c^2}$$

Collider Luminosity

Assume Gaussian particle distributions

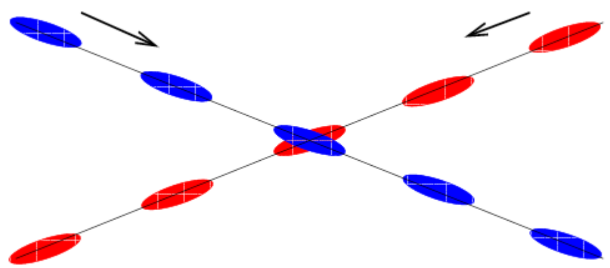
$$\rho(x) = \frac{1}{\sigma_x\sqrt{2\pi}}\exp(-\frac{x^2}{2\sigma_x^2})$$

And assume: $\sigma_{1x} = \sigma_{2x}, \sigma_{1y} = \sigma_{2y}, \sigma_{1s} = \sigma_{2s}$

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}\cdot S \cdot H$$

Correction factors S and H.

If colliding with many bunches, need collision with crossing angle to avoid unwanted collisions.



The larger the crossing angle, the smaller S.

Collider Luminosity

Correction factor H: Hour glass effect

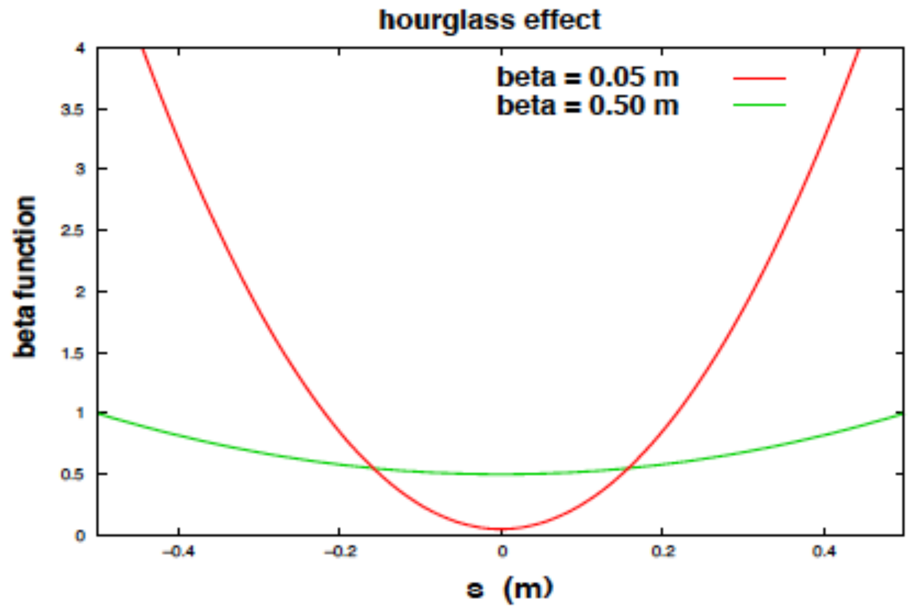
$$\sigma_{x,y} = \sqrt{\beta^*_{x,y} \cdot \varepsilon}$$

Here β* comes in

β depends on s

$$\beta(s) = \beta^* \cdot (1 + (\frac{s}{\beta^*})^2)$$

Beam size depends on s. The longer the bunch the larger the effect.



LHC Design Luminosity

Design parameters for 7 TeV/c per beam operation:

- $N_1 = N_2 = 1.15 \times 10^{11}$ protons per bunch
- $n_b = 2808$ bunches per beam ➔ bunch spacing = 25 ns
- $f_{rev} = 11.2455$ kHz
- crossing angle $\phi = 285\ \mu$rad
- $\beta^*_x = \beta^*_y = 0.55$ m
- $\sigma^*_x = \sigma^*_y = 16.6\ \mu$m (3.5 μm normalized emittance), $\sigma_s = 7.7$ cm

LHC Design Luminosity

Without crossing angle and hour glass effect:

$$\mathcal{L} = 1.2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Effect of crossing angle:

$$\mathcal{L} = 0.973 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Effect of crossing angle & hour glass:

$$\mathcal{L} = 0.969 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Integrated luminosity

What counts is not peak performance but total accumulated number of events

$$\underbrace{\sigma_p}\cdot\underbrace{\mathcal{L}_{int}} = \sigma_p \cdot \int_0^T \mathcal{L} dt$$

unit “barn” = 10^{-24} cm^2

unit “ inverse barn” = 10^{24} cm^{-2}

1 fbarn^{-1} = 10^{39} cm^{-2}

For example:

For 1 fbarn^{-1}: requires 10^7 s at $\mathcal{L} = 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

One year has 3.1536 × 10^7 s.

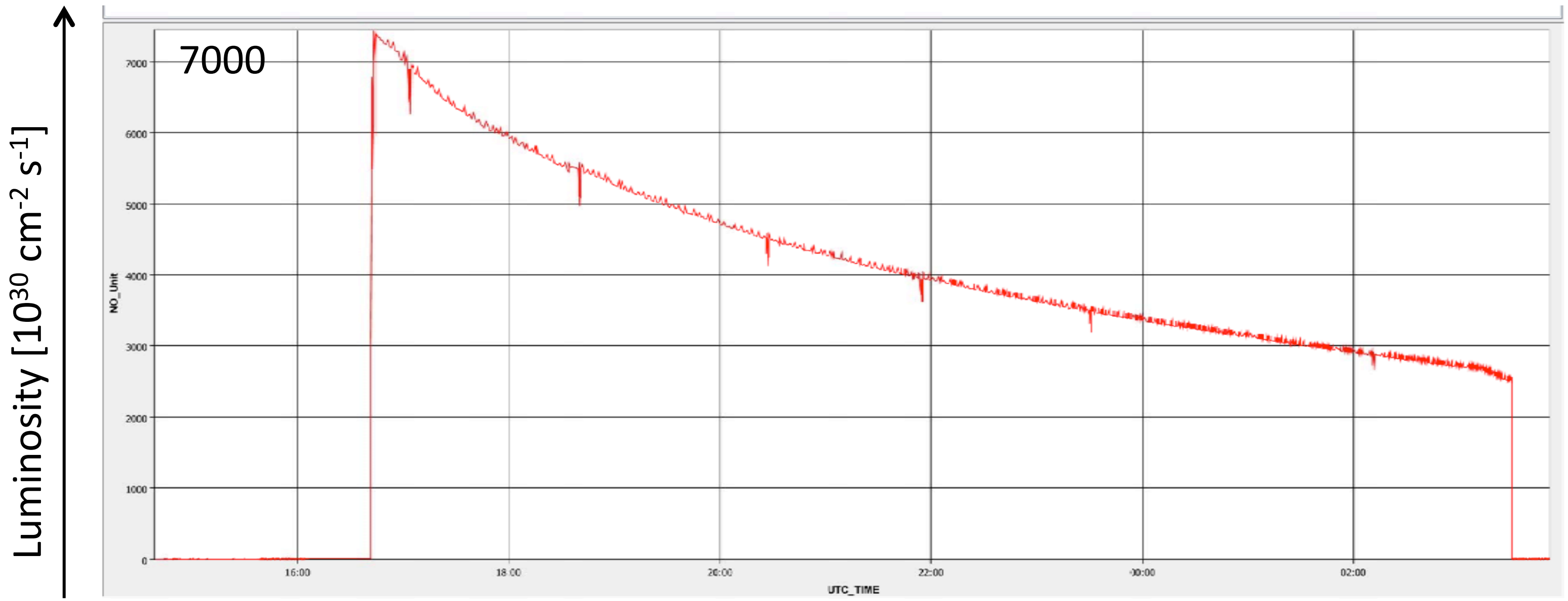
Luminosity during Fill

LHC fill = one full operational cycle: injection + energy ramp ... collision + data taking + beam abort

Luminosity decays during fill after beams have been put into collision:

- intensity burn-off (for nominal parameters about 20 interactions per crossing)
- Emittance growth

$$\mathcal{L}(t) = \mathcal{L}_0 \exp(-\frac{t}{\tau})$$



Optimizing Luminosity

Luminosity is higher for

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma^2} = \frac{N_1 N_2 f n_b}{4\pi\beta^* \varepsilon}$$

- High number of bunches
- High number of particles per bunch $\propto N^2$
- Small emittance
- Small β*
- Small crossing angle, short bunches

Unfortunately cannot arbitrarily play with these parameters:
"Collective effects" cause beam instabilities for too high bunch intensities, too small bunch spacing, too "bright" beams

β* together with crossing angle are linked to the available aperture in the triplet quadrupole magnets.

β* and the Squeeze

Remember: mini-beta insertions

Beta around the waist:

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

Unfortunately the detectors are large

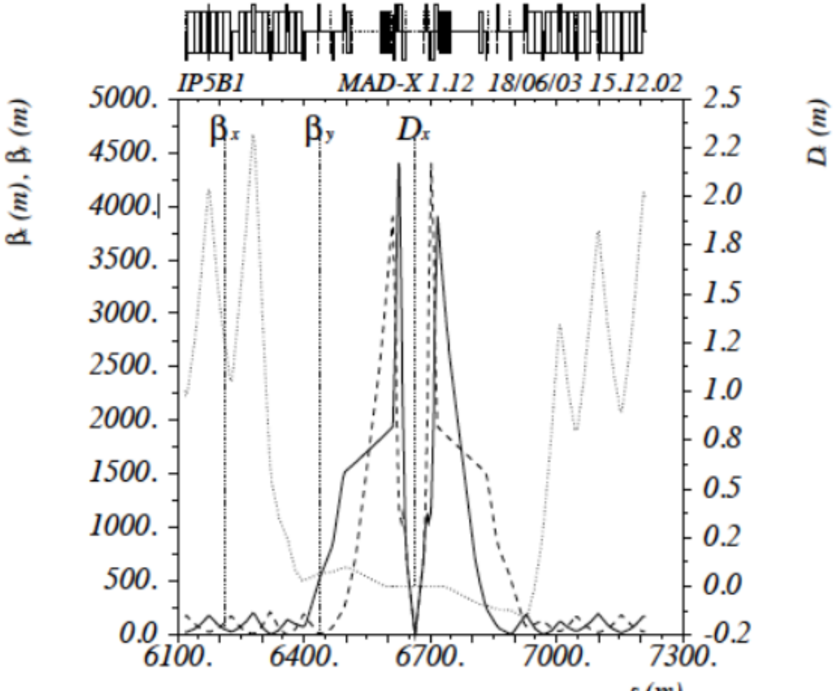
$$\beta_{max} = 4.5\text{km} \qquad \sigma = 1.5\text{mm}$$

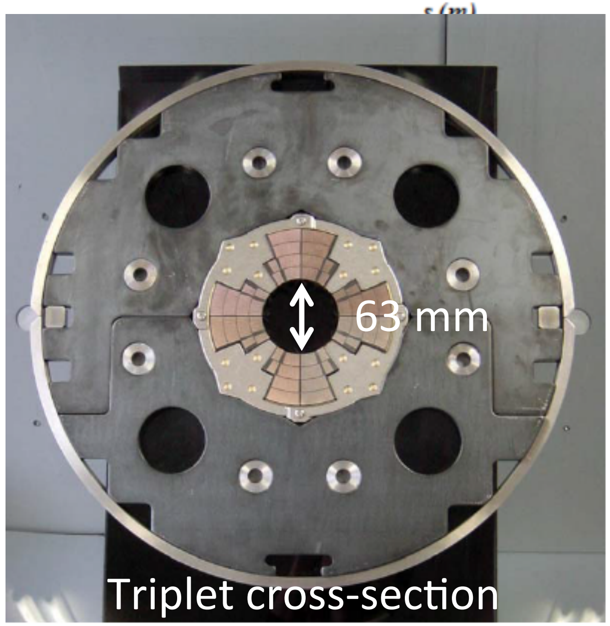
... @ 7 TeV

@ 450 GeV: 5.7 mm!!!

➔ Can only go to small β* at top energy.

➔ Inject with β* = 11 m. Max $\beta_{triplet}$ ~ 240 m





Triplet cross-section

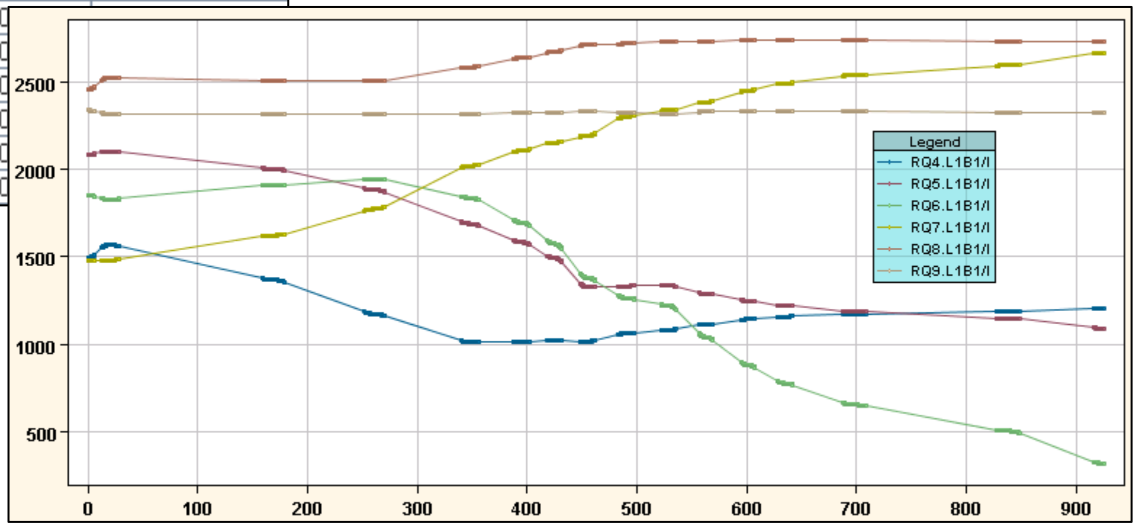
The Squeeze

During the squeeze the optics is changed locally. Everywhere else the beta functions are kept constant.

Go through a set of different optics. Can stop at each point and correct.

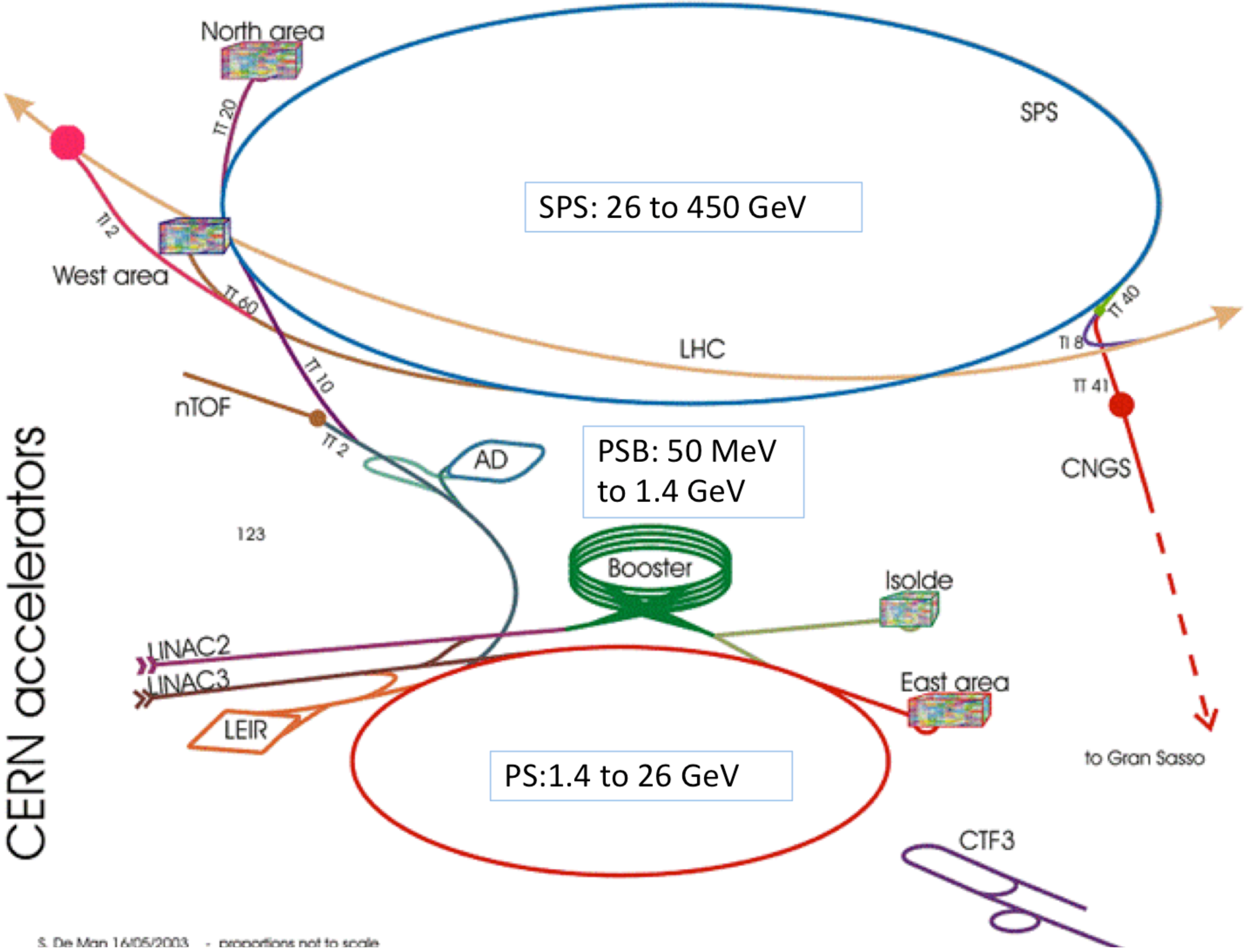
Optic Name	Energy	Time
A1100C1100A1000L1000_INJ_2012	4000.0	0
A1100C1100A1000L1000_2012	4000.0	19
A900C900A900_0.00915L750_0.00932_2012	4000.0	169
A700C700A750_0.00897L600_0.00909_2012	4000.0	262
A400C400A600_0.00889L500_0.00900_2012	4000.0	348
A300C300A500_0.00889L375_0.00888_2012	4000.0	396
A250C250A450_0.00889L350_0.00882_2012	4000.0	425
A200C200A400_0.00889L325_0.00878_2012	4000.0	455
A160C160A350_0.00889L300_0.00875_2012	4000.0	491
A150C150A300_0.00889L300_0.00875_2012	4000.0	529
A120C120A300_0.00889L300_0.00875_2012	400	
A100C100A300_0.00889L300_0.00875_2012	400	
A90C90A300_0.00889L300_0.00875_2012	400	
A80C80A300_0.00889L300_0.00875_2012	400	
A70C70A300_0.00889L300_0.00875_2012	400	
A60C60A300_0.00889L300_0.00875_2012	400	

The different optics played during the 2012 squeeze.



The current functions of some of the involved quadrupoles in point 1.

LHC Filling from the LHC Injector Chain



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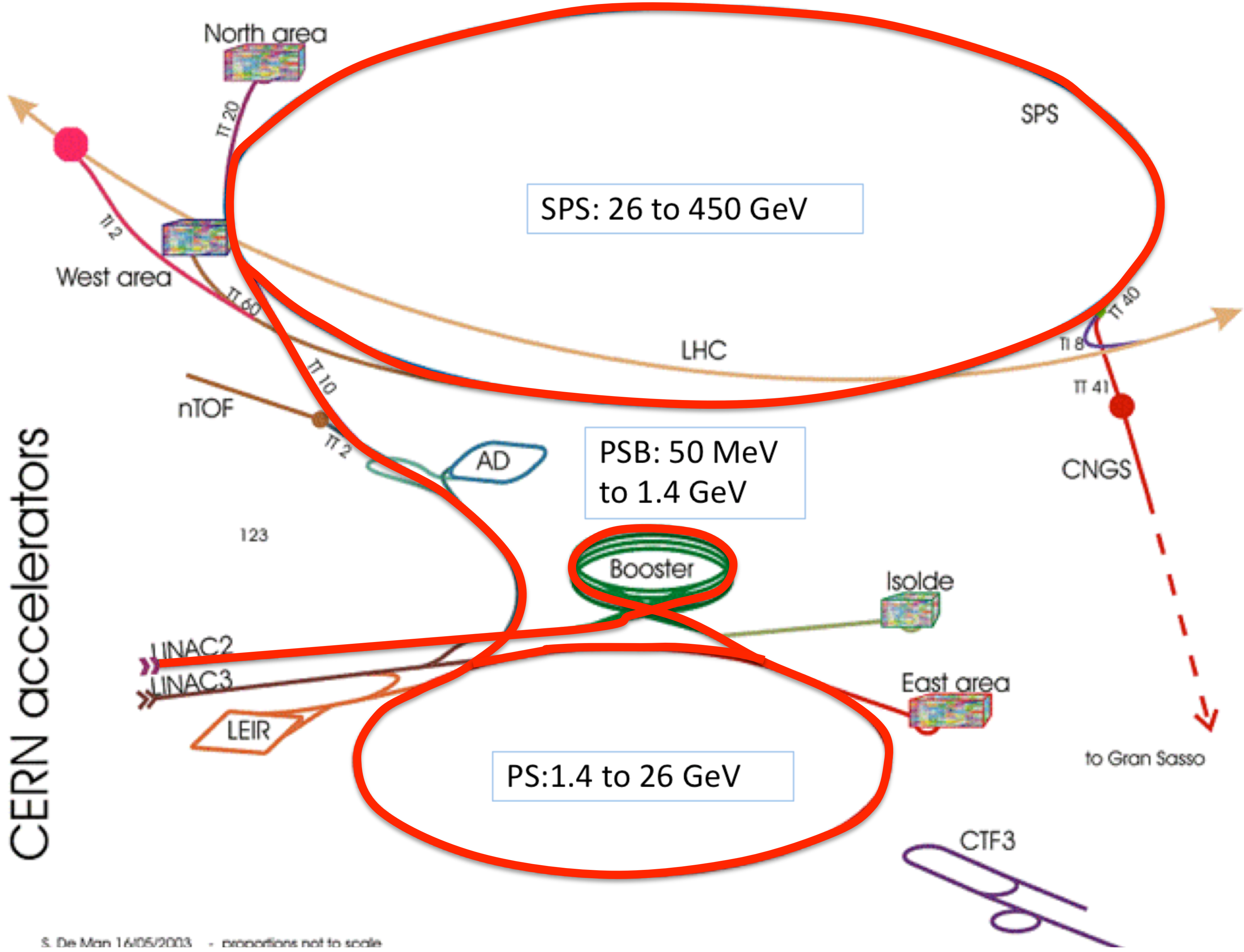

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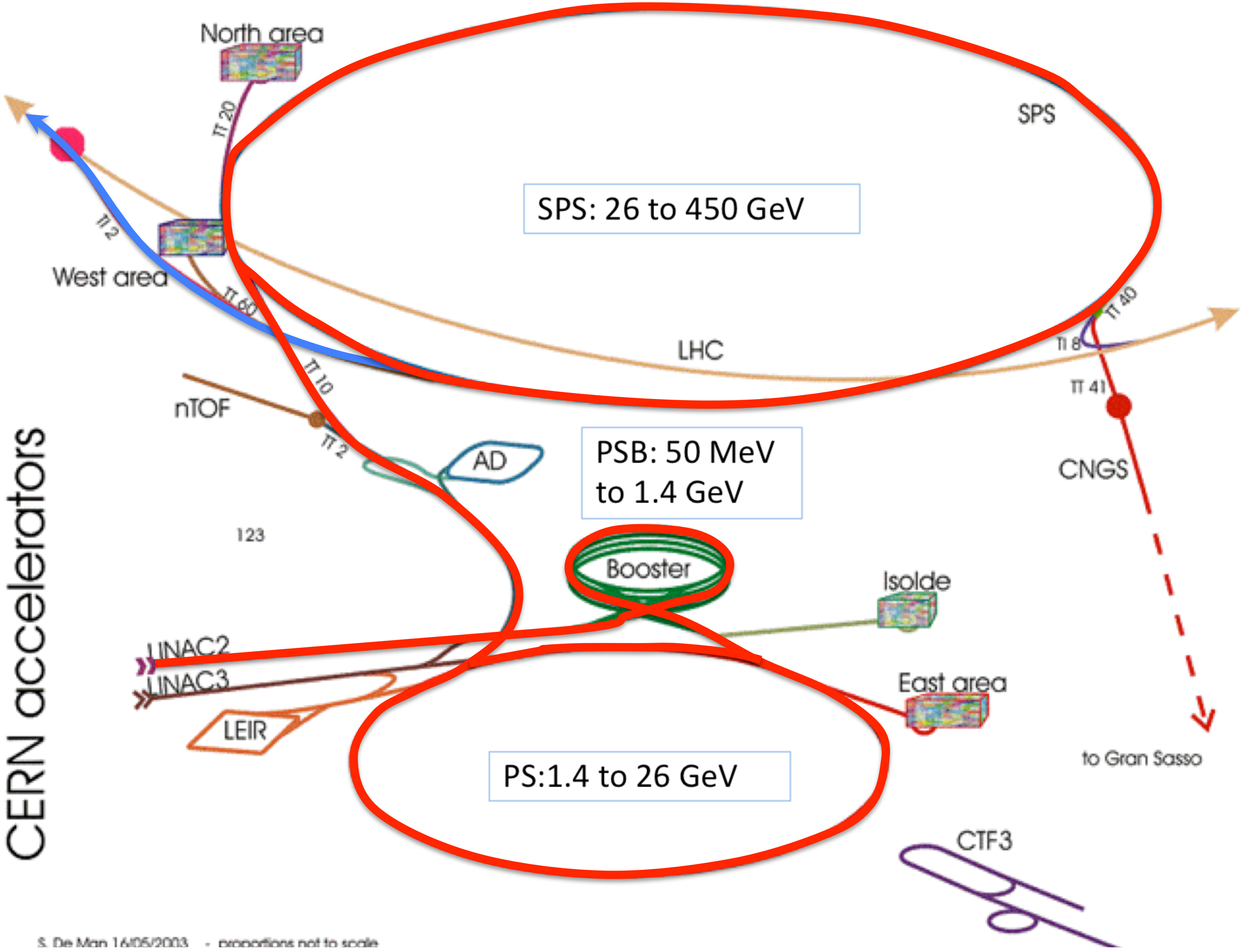

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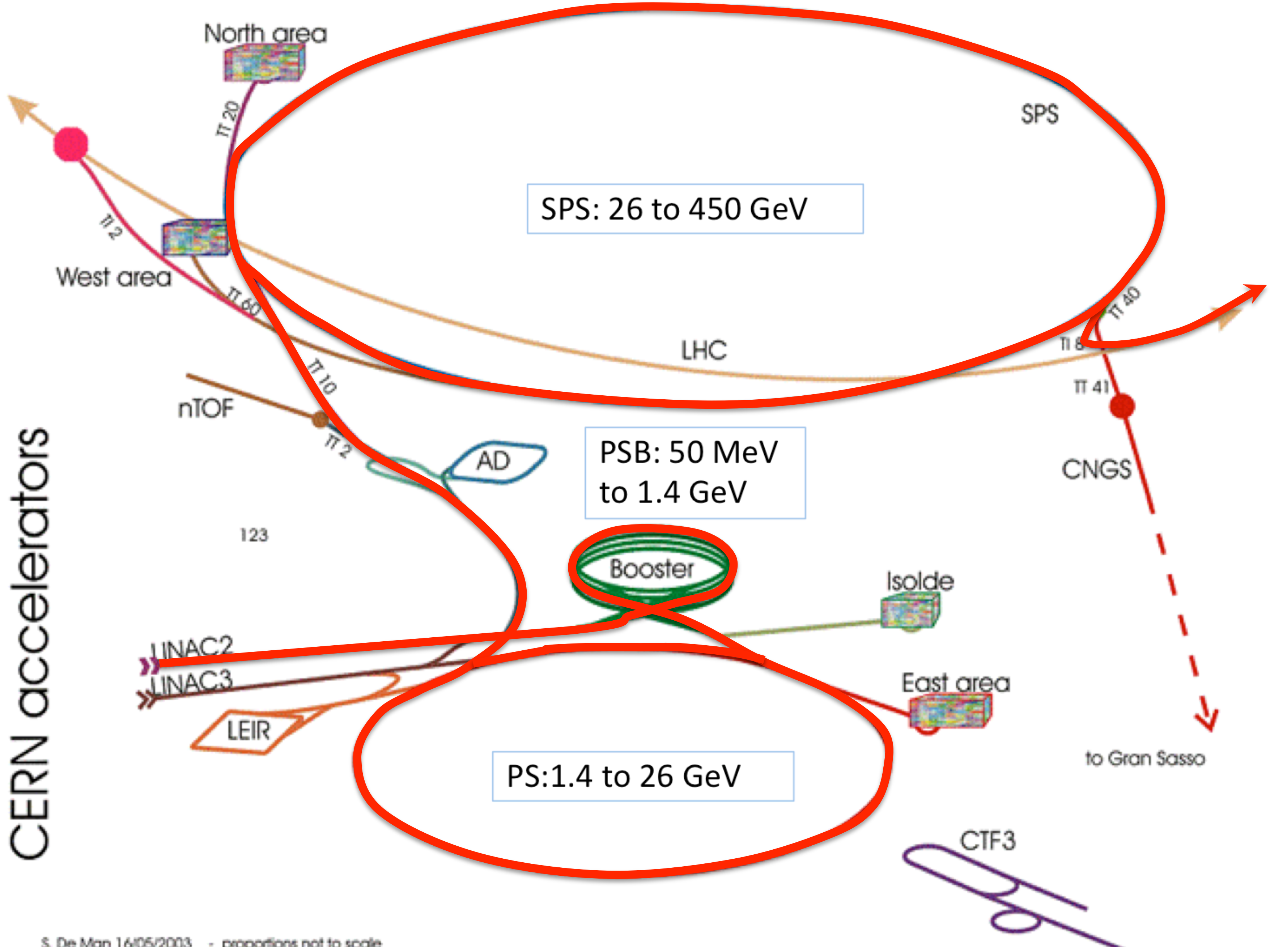
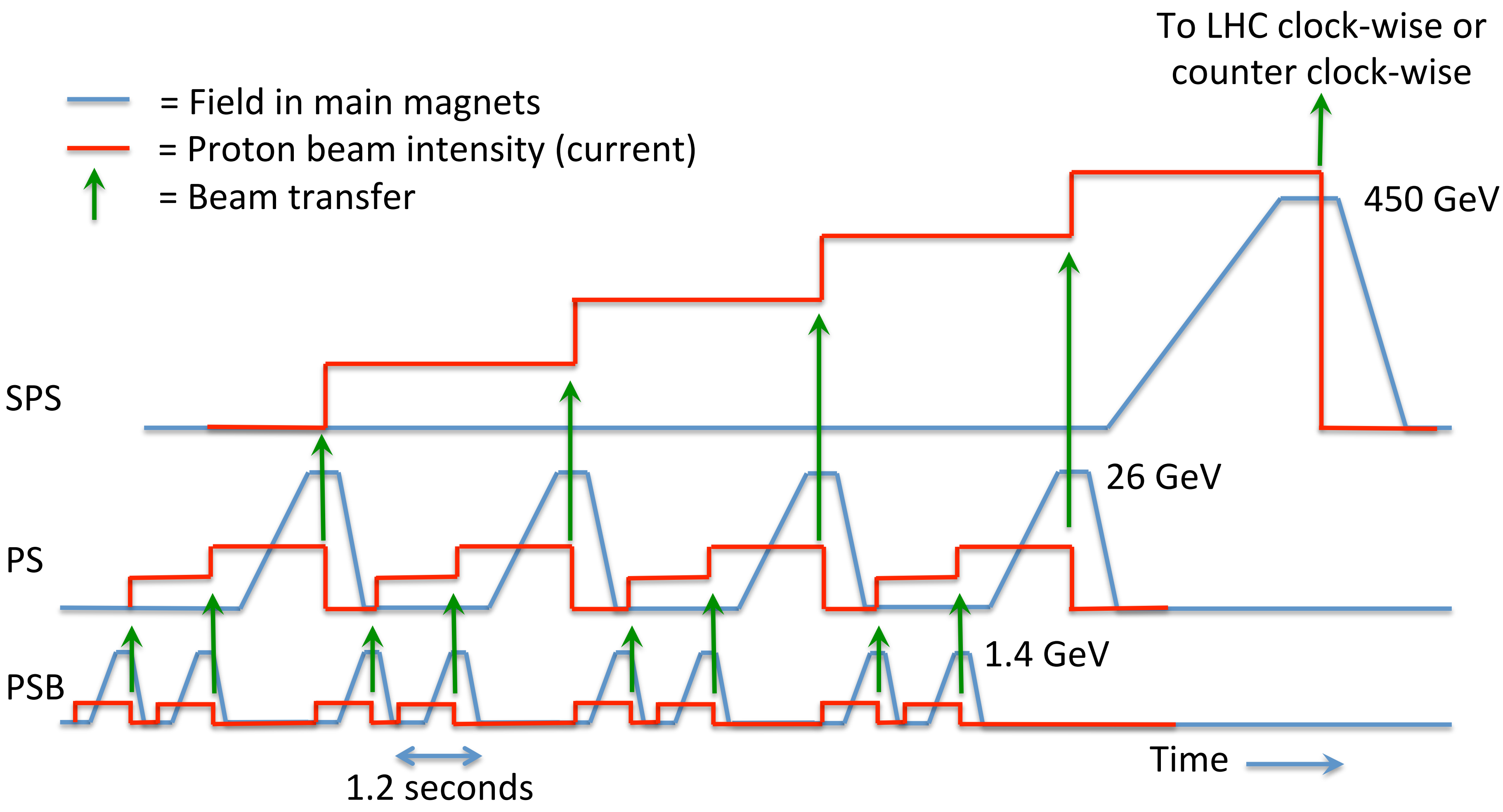
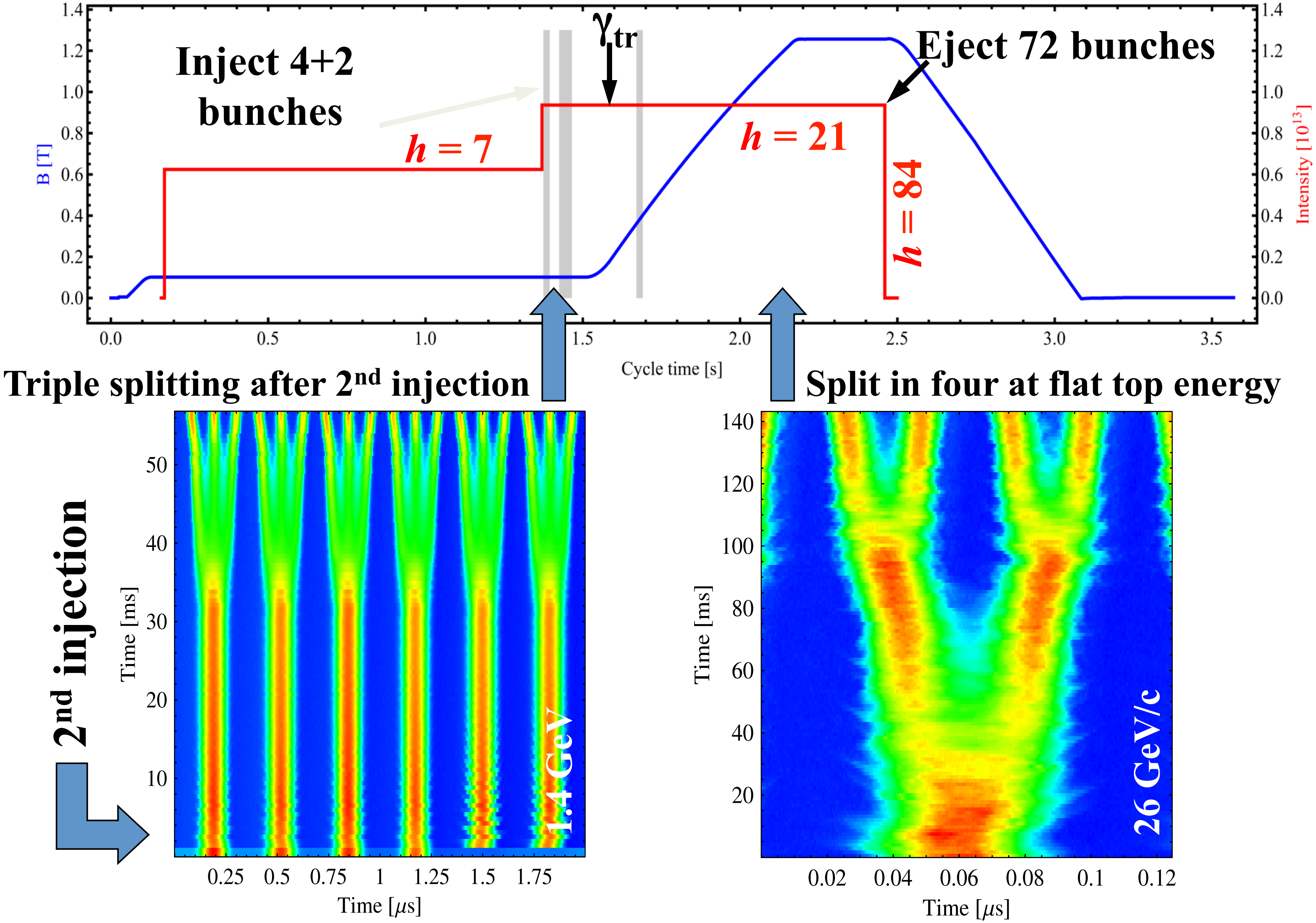


The LHC Injector Cycling



The 25 ns cycle in the PS

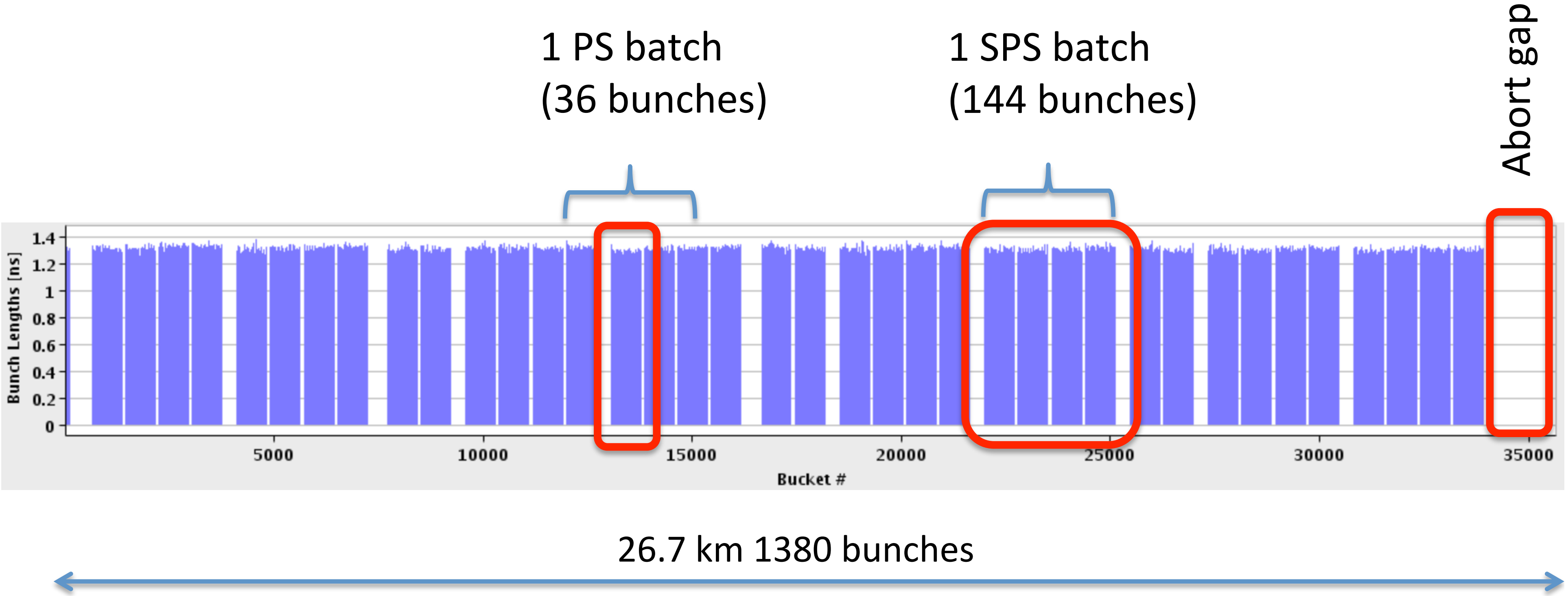


→ **Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72**

In the LHC…2012: 50 ns

Due to “electron cloud” could not run with 25 ns ➔ 50 ns bunch spacing.

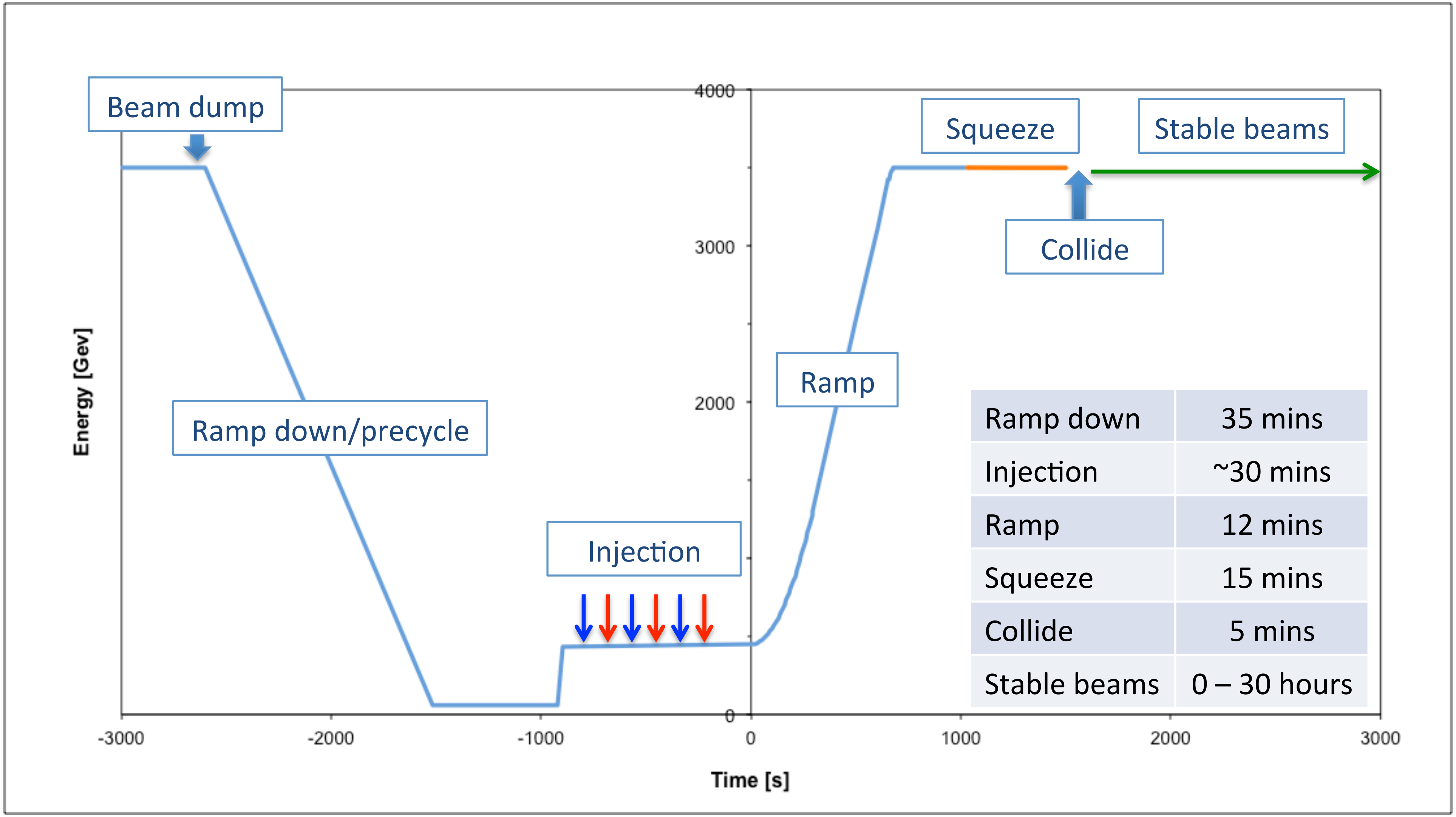
With up to 1.7 x 10^{11} protons per bunch



LHC Operational Cycle 2012

Injection energy: 450 GeV

Top energy: 4 TeV



Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

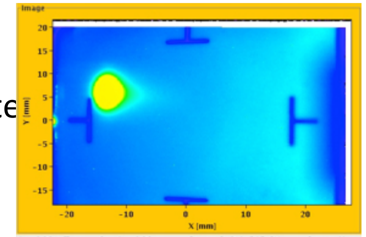
LHC Run I Timeline

2008	2009	2010	2011	2012

Courtesy M. Lamont

LHC Run I Timeline

August 2008
First Injection te



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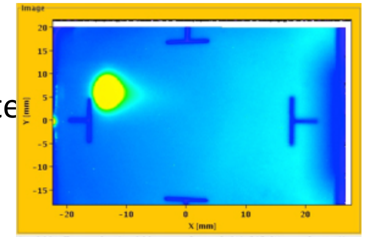

September 10, 2008
Circulating beams

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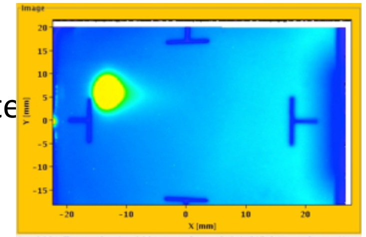

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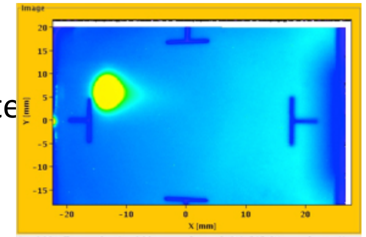

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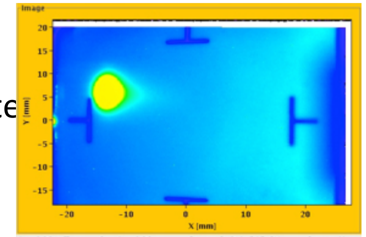

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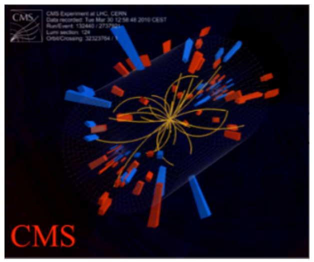
March 30, 2010
First collisions at 7 TeV CM



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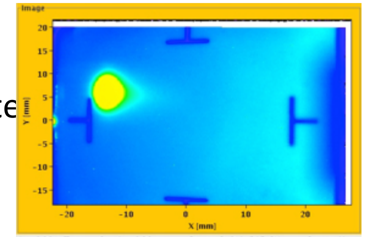

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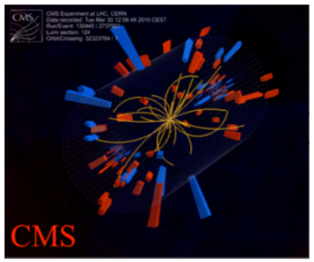
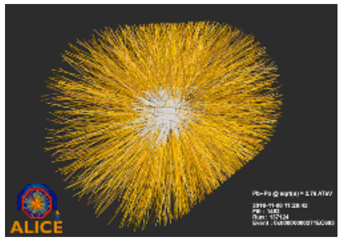


November 2010
First Lead ion run



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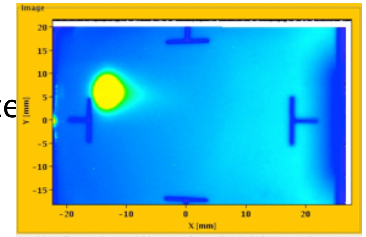

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Beams back

June 28, 2011
1380 bunches

1380

2008 | 2009 | 2010 | 2011 | 2012

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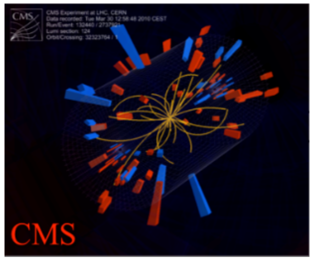

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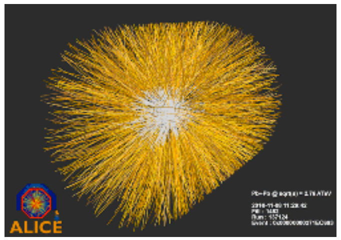

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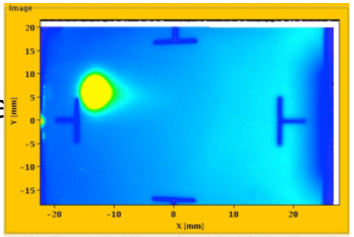

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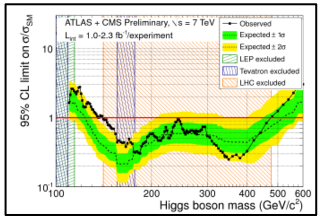

December 2011
5.6 fb^{-1}

June 28, 2011
1380 bunches

1380

2008 | 2009 | 2010 | 2011 | 2012

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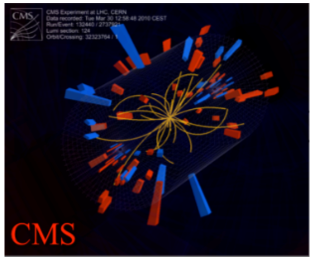
First collisions at 7 TeV CM



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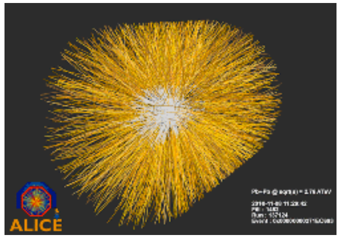

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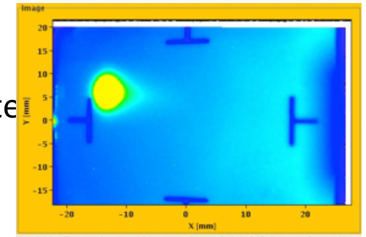

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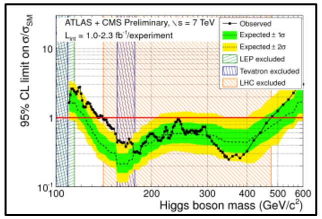

December 2011
5.6 fb^{-1}

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1380 bunches

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Energy: 4 TeV

March 2012
4 TeV

2008 | 2009 | 2010 | 2011 | 2012

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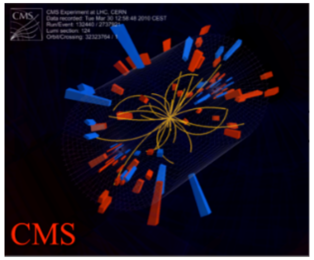

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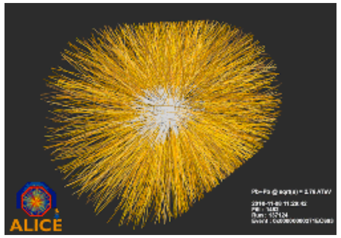

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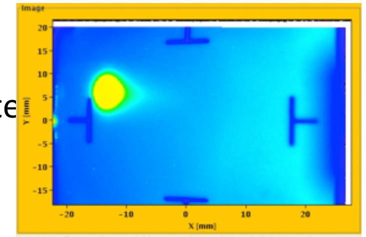

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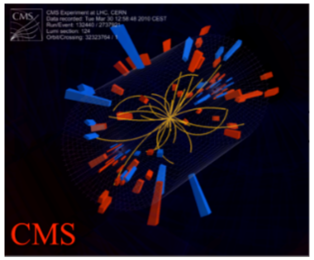
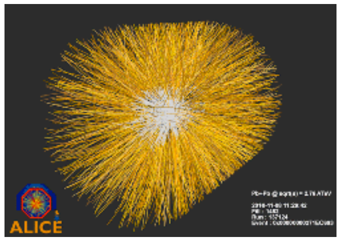
March 30, 2010
First collisions at 7 TeV CM



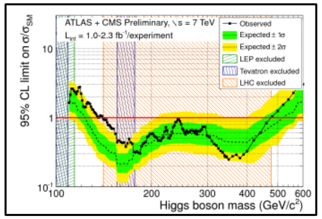
November 2010
First Lead ion run



June 28, 2011
1380 bunches

1380

December 2011
5.6 fb^{-1}

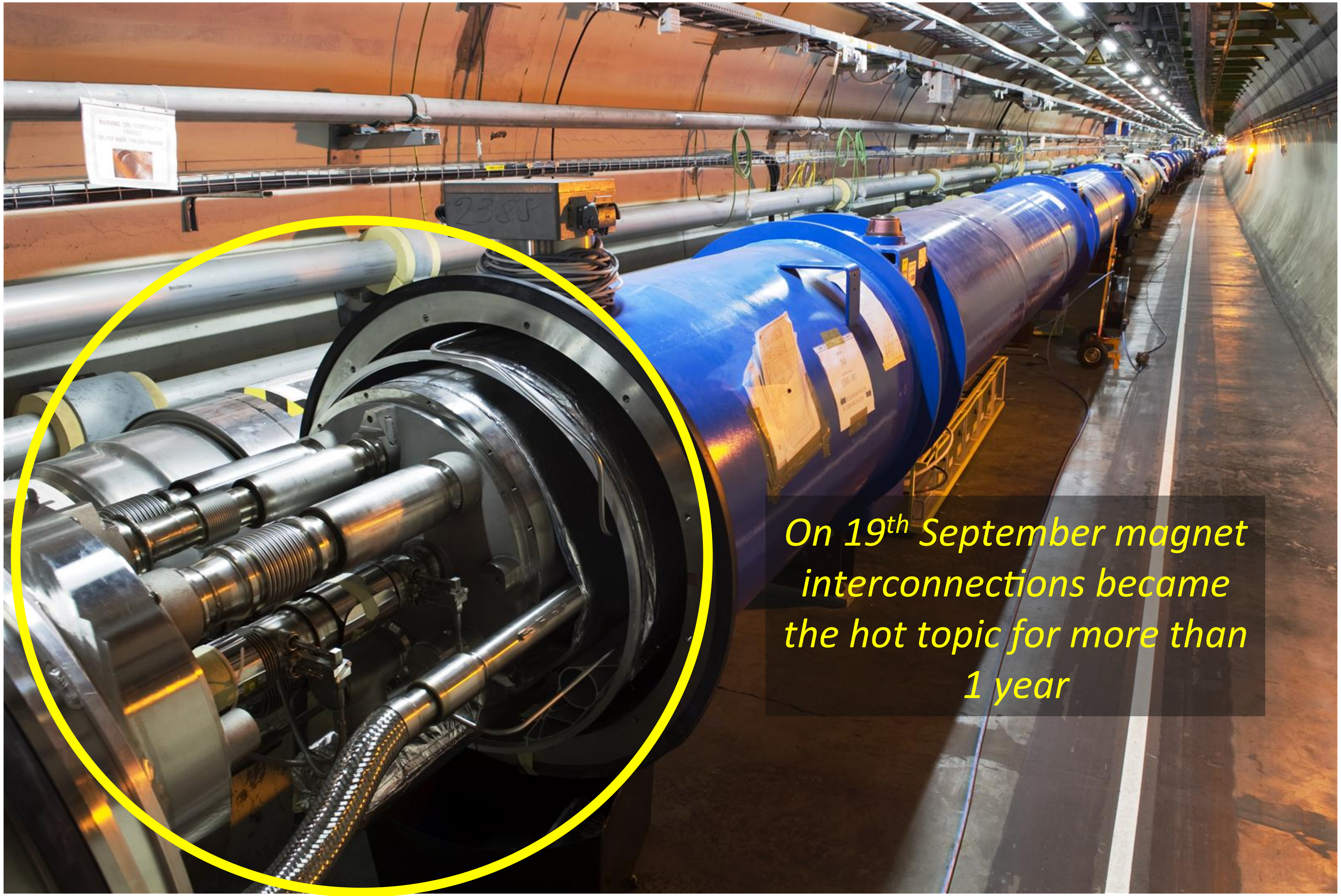


March 2012
4 TeV

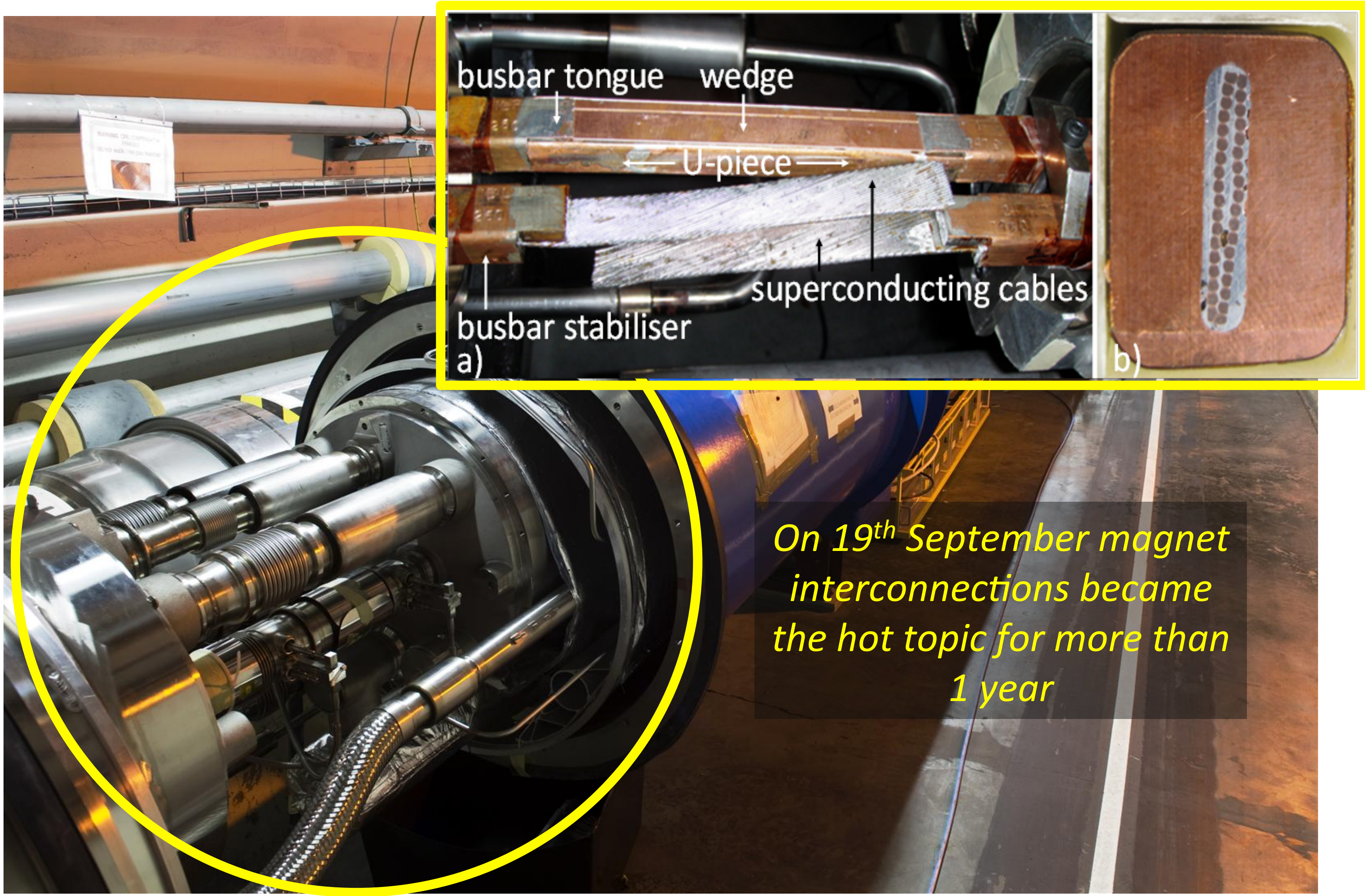
July 4, 2012
Higgs Seminar

2008 | 2009 | 2010 | 2011 | 2012

LHC Magnet Interconnect



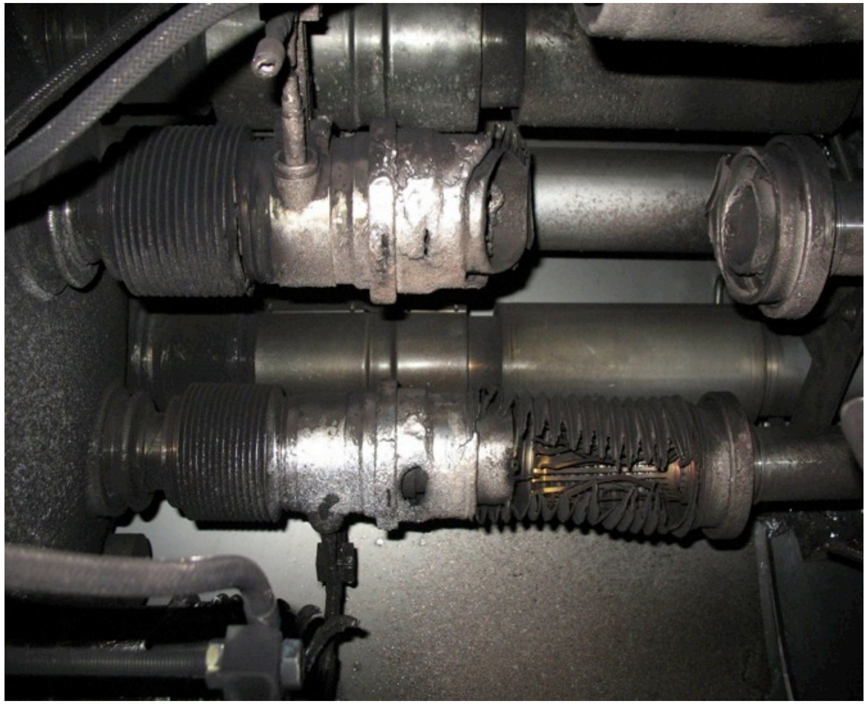
LHC Magnet Interconnect



Incident September 19th 2008

An electrical arc in a defect interconnection provoked a He pressure wave that damaged ~700 m of the LHC and polluted the beam vacuum over more than 2 km…

Arcing in the interconnection



Incident September 19th 2008

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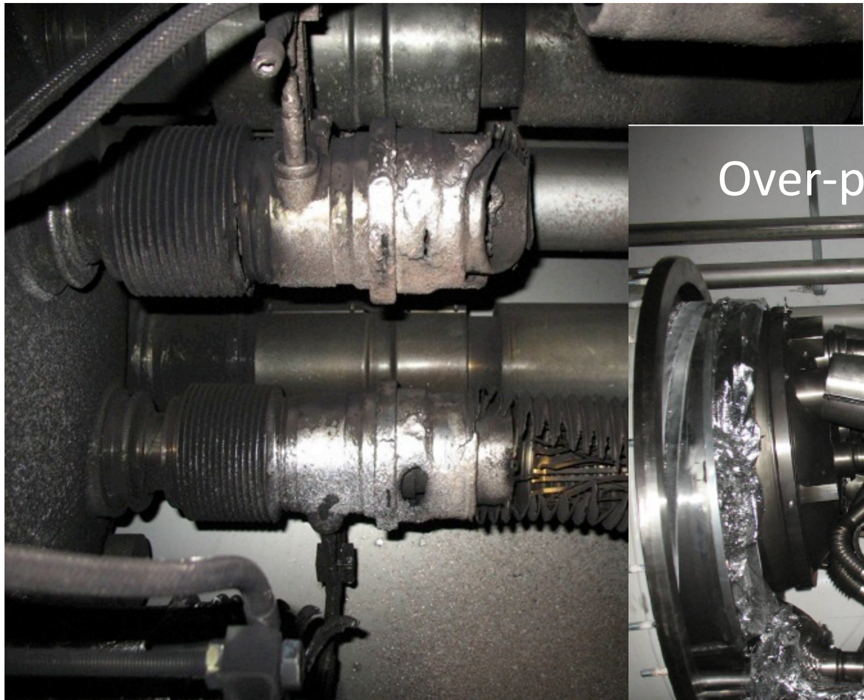
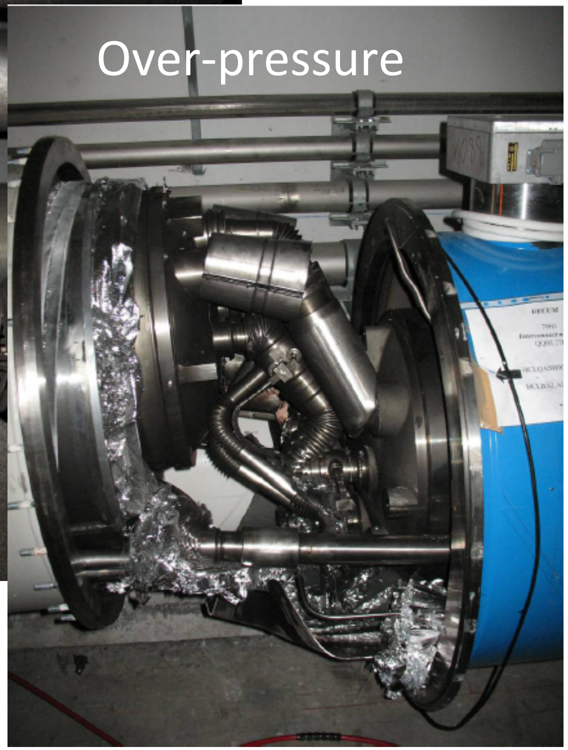
Arcing in the interconnection



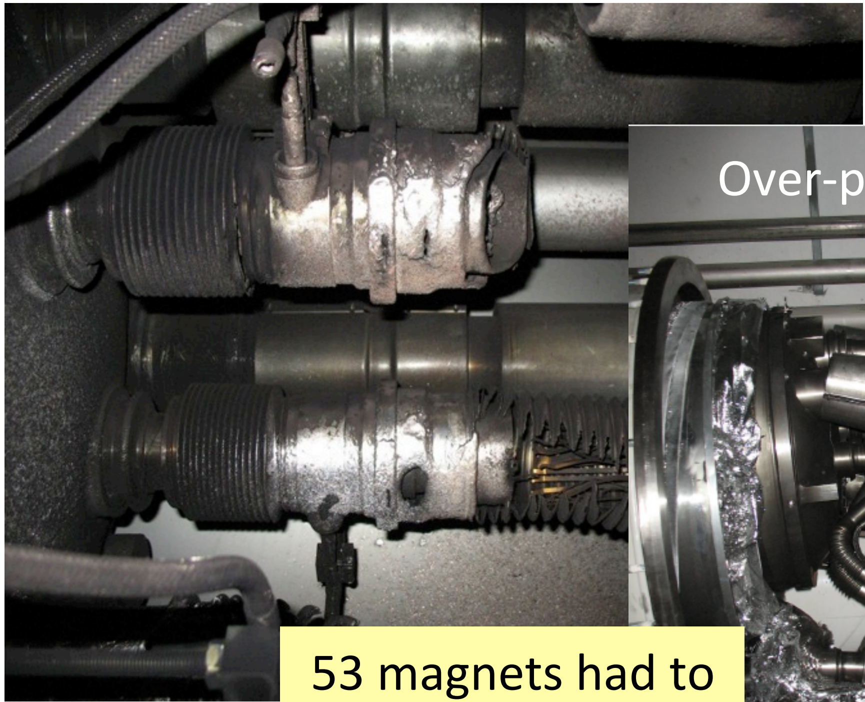


Over-pressure

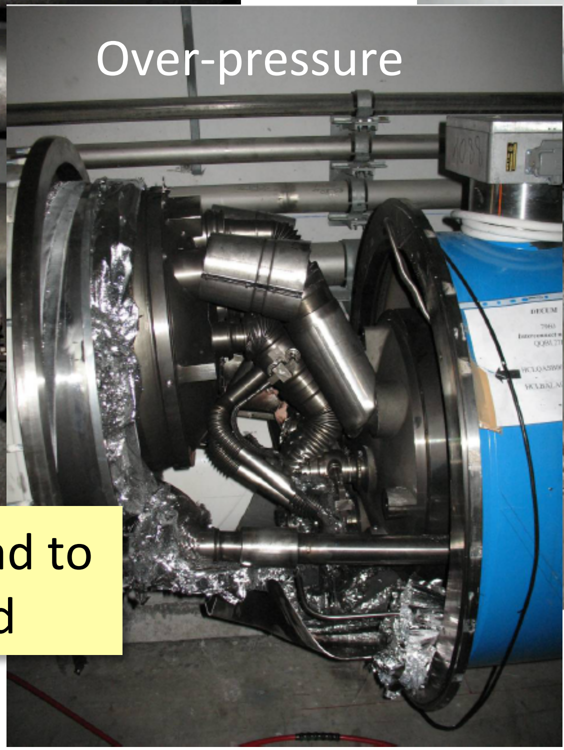
Incident September 19th 2008

An electrical arc in a defect interconnection provoked a He pressure wave that damaged ~700 m of the LHC and polluted the beam vacuum over more than 2 km…

Arcing in the interconnection



Over-pressure

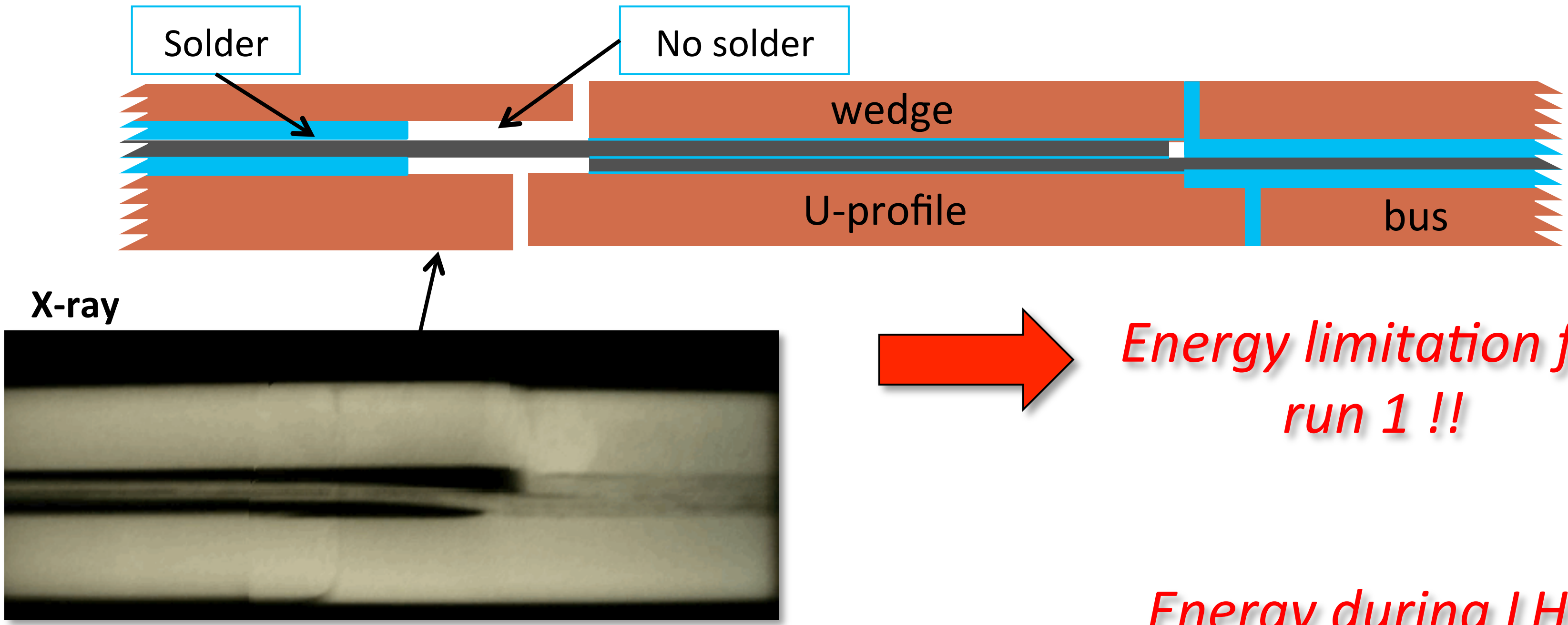


53 magnets had to be repaired

Magnet displacement

Inspection during consolidation → 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.



Energy limitation for run 1 !!

All LHC joints were consolidated during more than 2 years of shutdown.
Start-up 2015: energy = 6.5 TeV

Energy during LHC run 1:

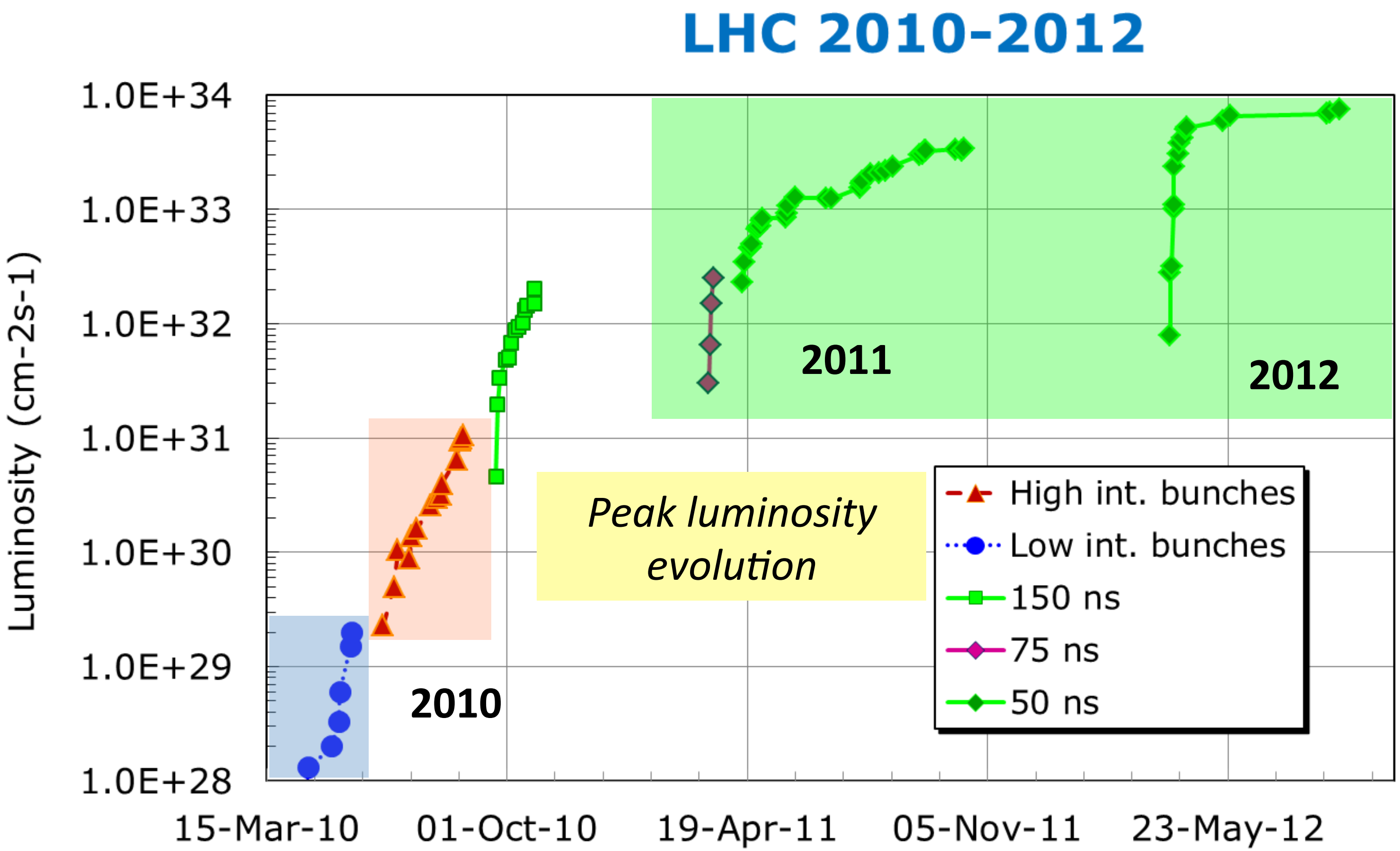
3.5 – 4 TeV

LHC Performance 2010-2012

Low bunch intensity operation, first operational exp. with Machine Protection

Ramping to 1 MJ stored energy, stability run at 1-2 MJ

Towards Higgs…



Courtesy J. Wenninger

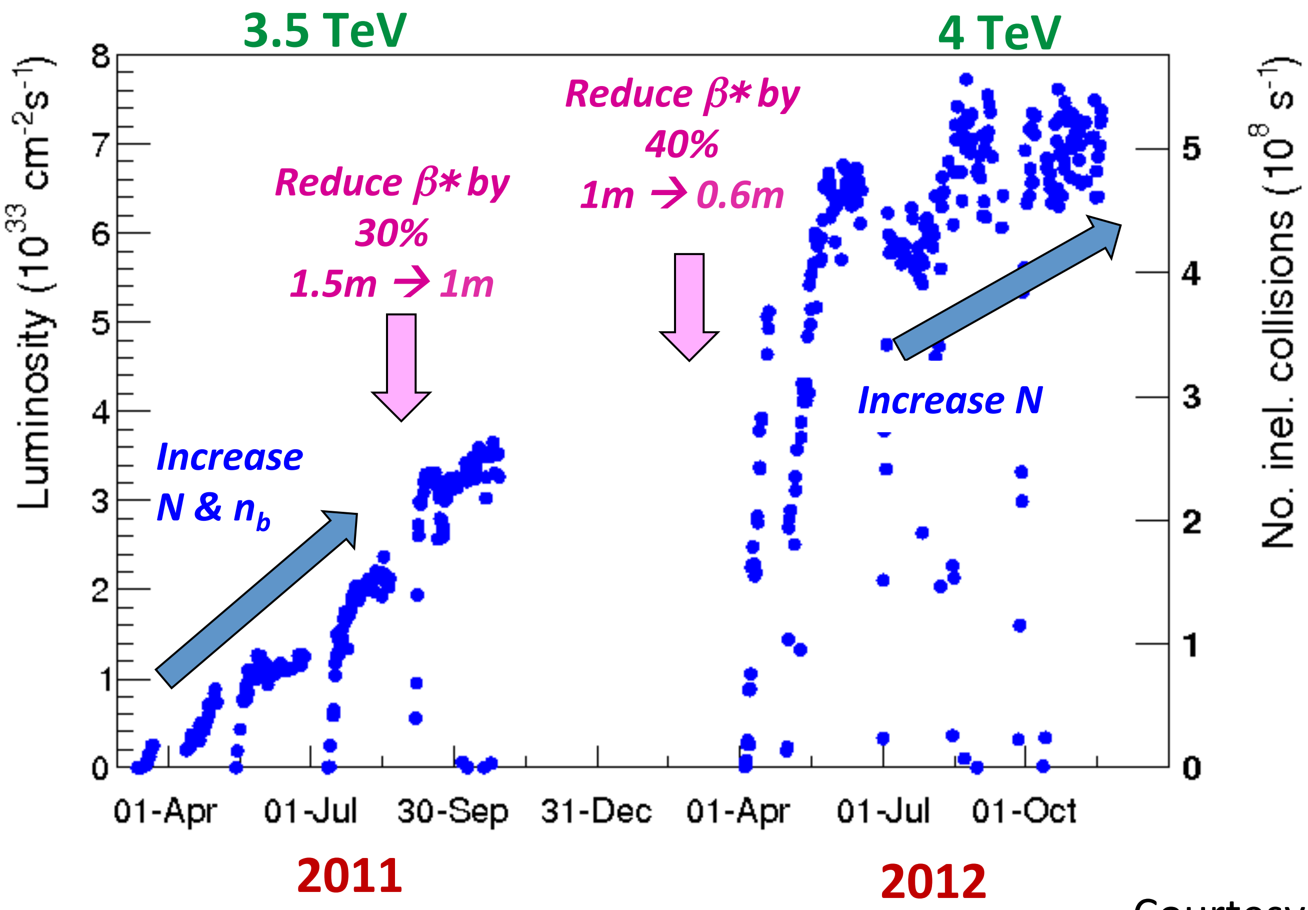
High Luminosity 2011-2012

Optimizing parameters to push peak performance.

Record luminosity: 7.7 x 10^{33} cm^{-2} s^{-1}

ATLAS and CMS have collected ~ 28 $fbarn^{-1}$

Limited by beam stability



Courtesy J. Wenninger

LHC Run II

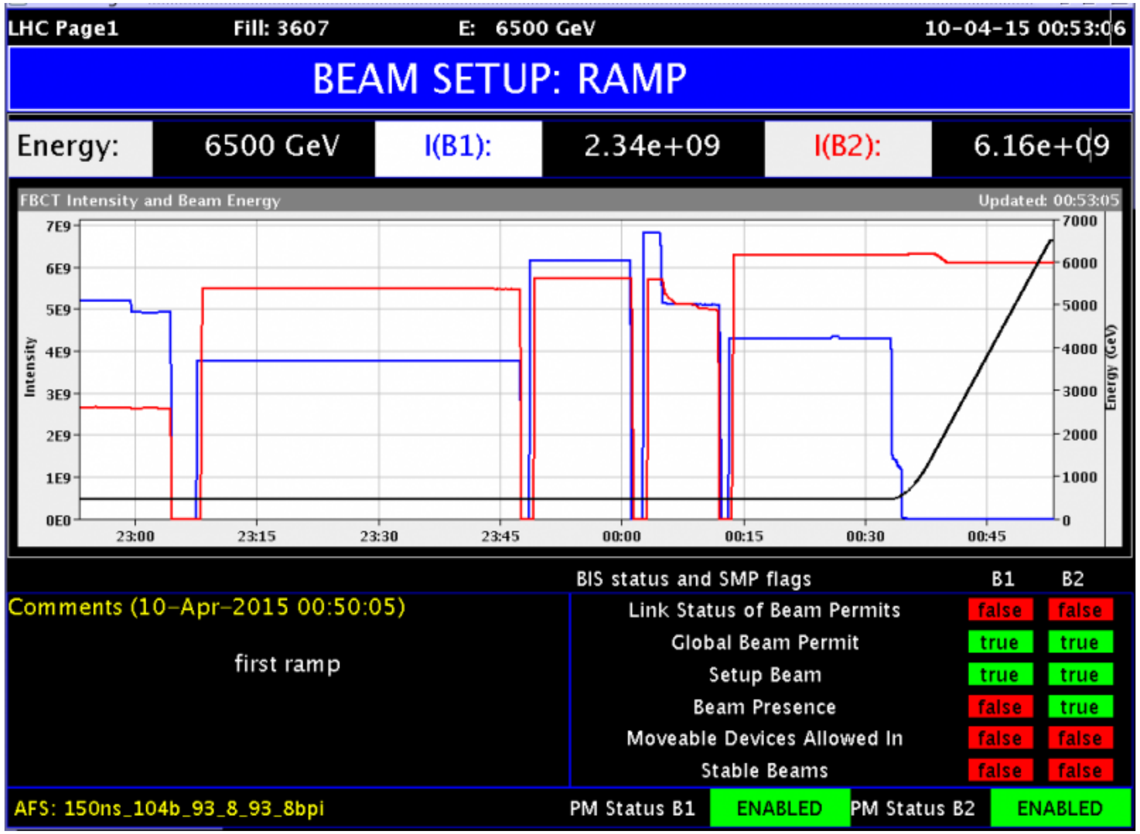
LHC started up in April 2015 (Easter).

Top Energy: 6.5 TeV

β^* = 80 cm

Crossing angle: 290 μrad

Bunch spacing? 25 ns?



The possible bunch spacing can only be decided after the final scrubbing.

50 ns versus 25 ns

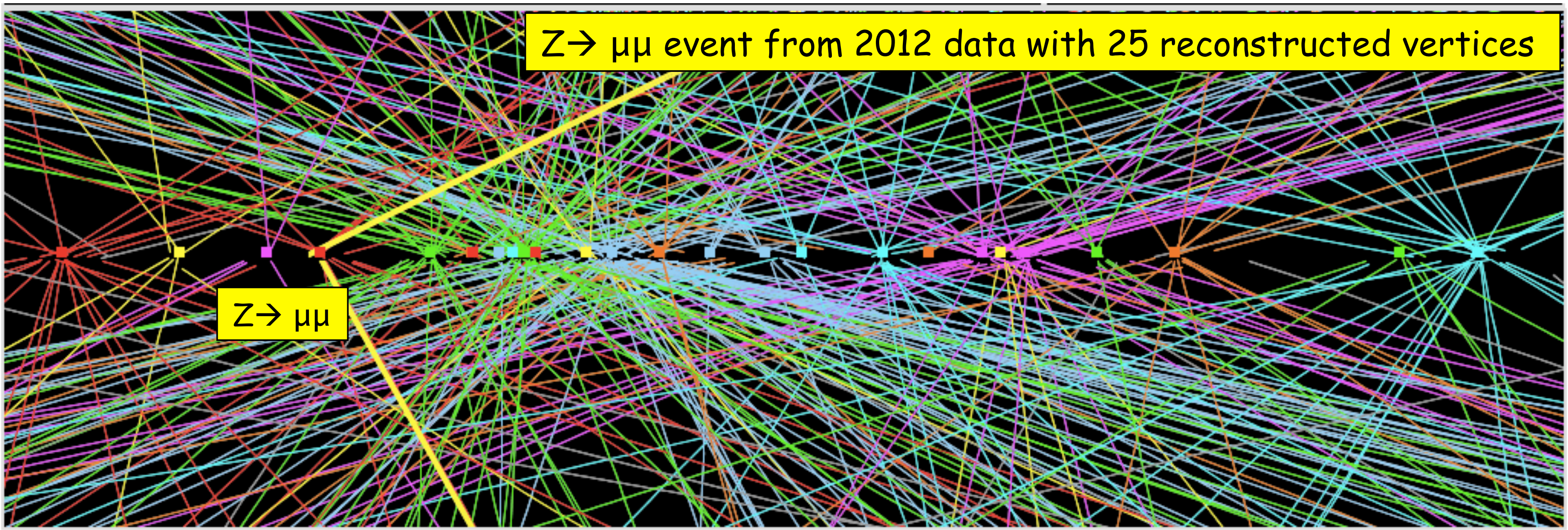
Excellent performance during LHC run I due to very “bright” 50 ns beams from injectors.

Brightness: $\dfrac{N}{\varepsilon}$

50 ns 2012: 1.7×10^{11} p+/bunch,
1.5 μm normalized emittance

The price to pay (apart from instabilities):

High luminosity with fewer collisions: high pile-up. 2012 up to 35 events per crossing



The Event Pile-up μ Issue

➔ Run 2 energy ≥ 6.5 TeV

Scaling $\mathcal{L}$ = 7.7 × 10^{33} cm^{-2} s^{-1} to 7 TeV: ~ 2 × 10^{34} cm^{-2} s^{-1} with 50 ns

➔ Pile-up of ~ 100

The pile-up limit for the experiments in 2015: $\mu \sim 50$

2 options:

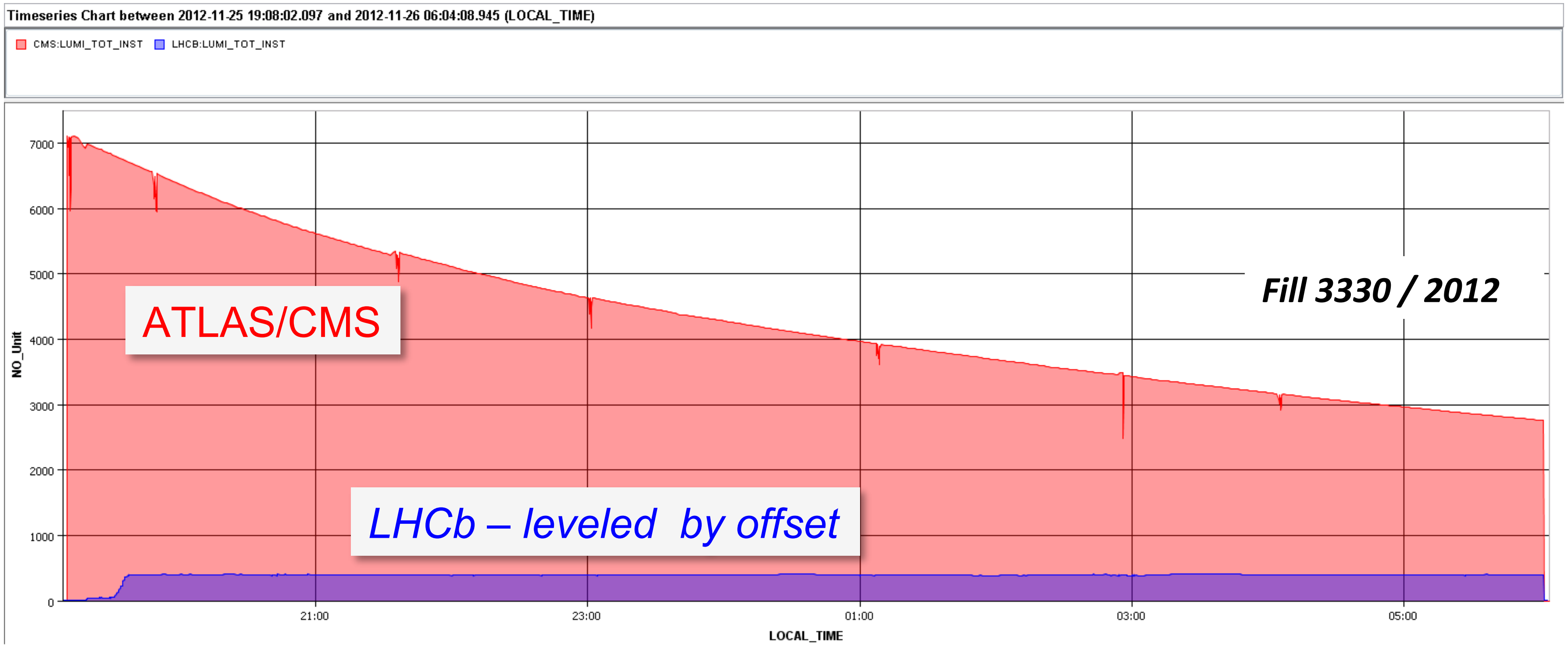
- Luminosity leveling

- Make 25 ns bunch spacing work:
    - For the same total luminosity: less luminosity per bunch

Luminosity Leveling

Reduce the peak luminosity on purpose by

- Offset leveling
- β* leveling



Luminosity Leveling

Reduce the peak luminosity on purpose by

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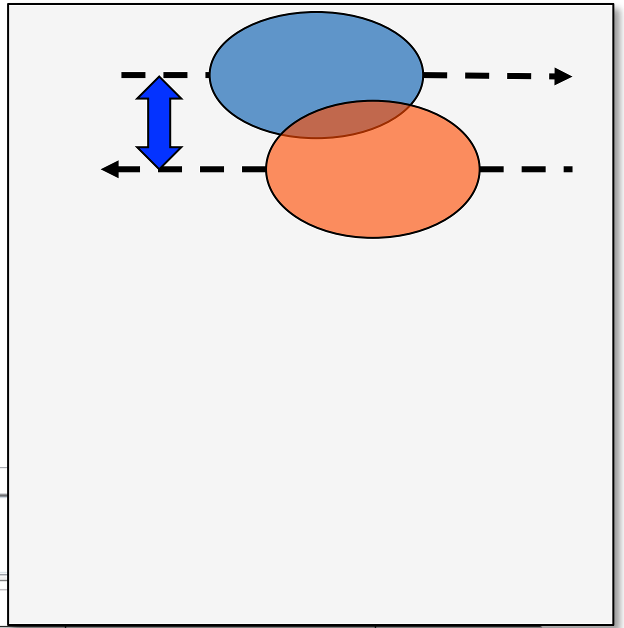
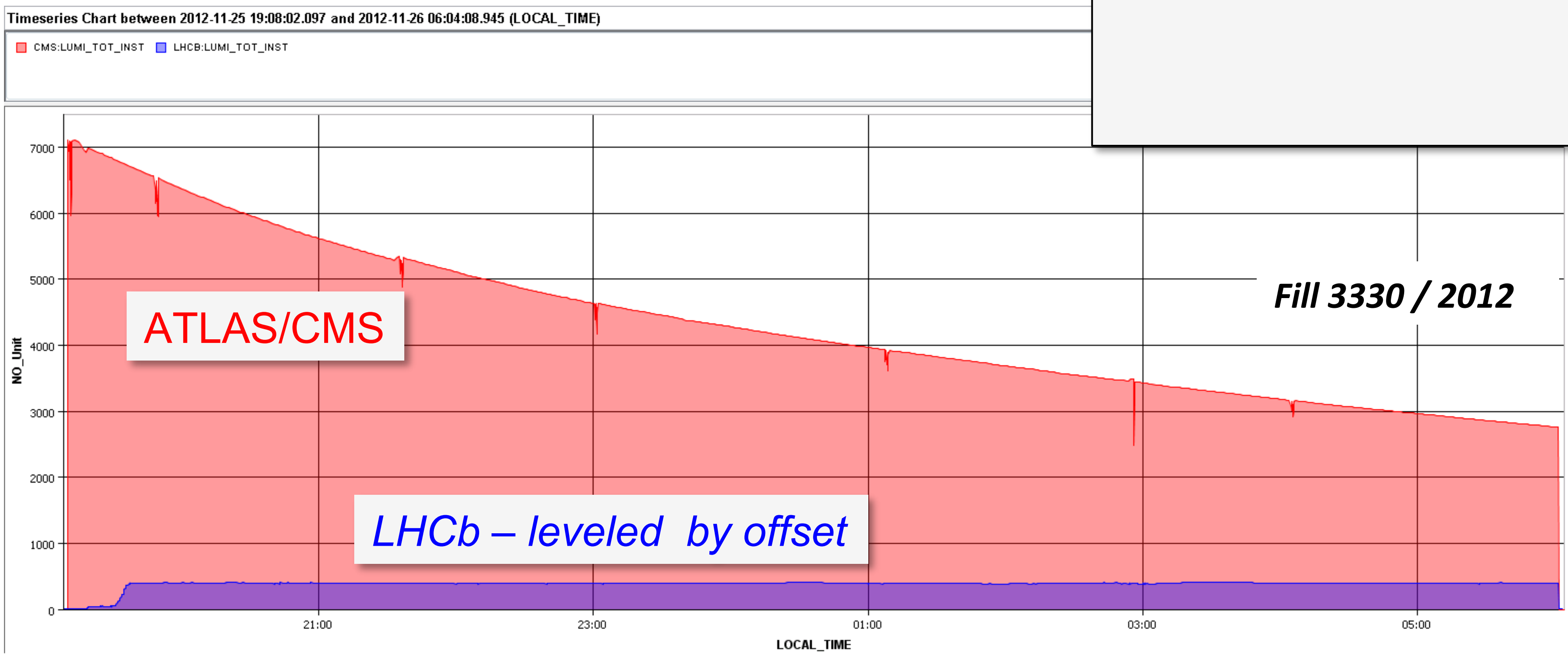
- β^* leveling

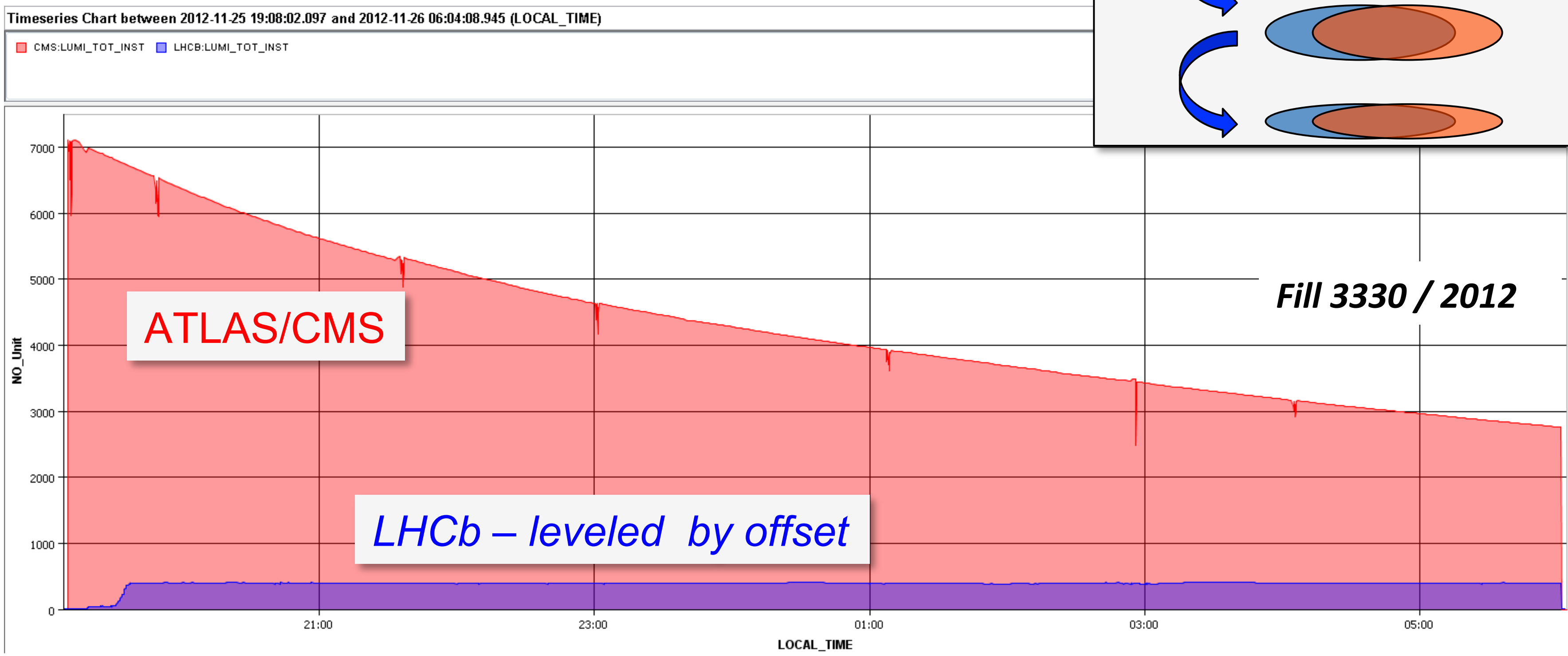


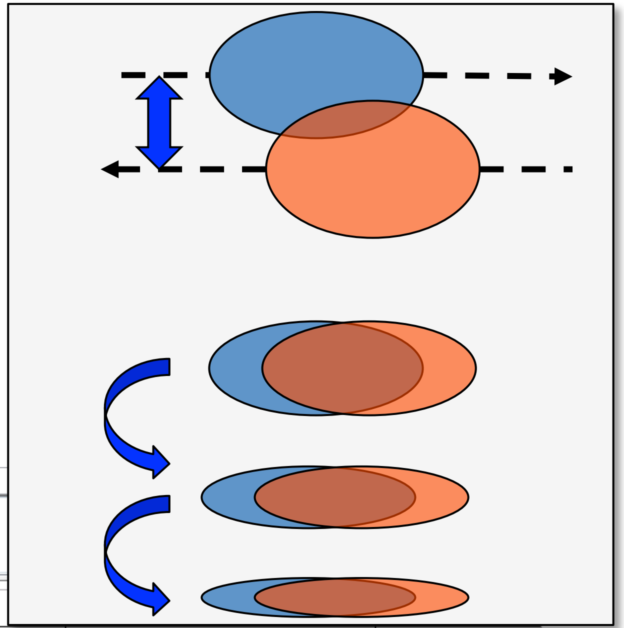


Luminosity Leveling

Reduce the peak luminosity on purpose by

- ➢ Offset leveling
- ➢ β* leveling





LHC Run II - 2015

Higher energy, new bunch spacing, "new" machine.

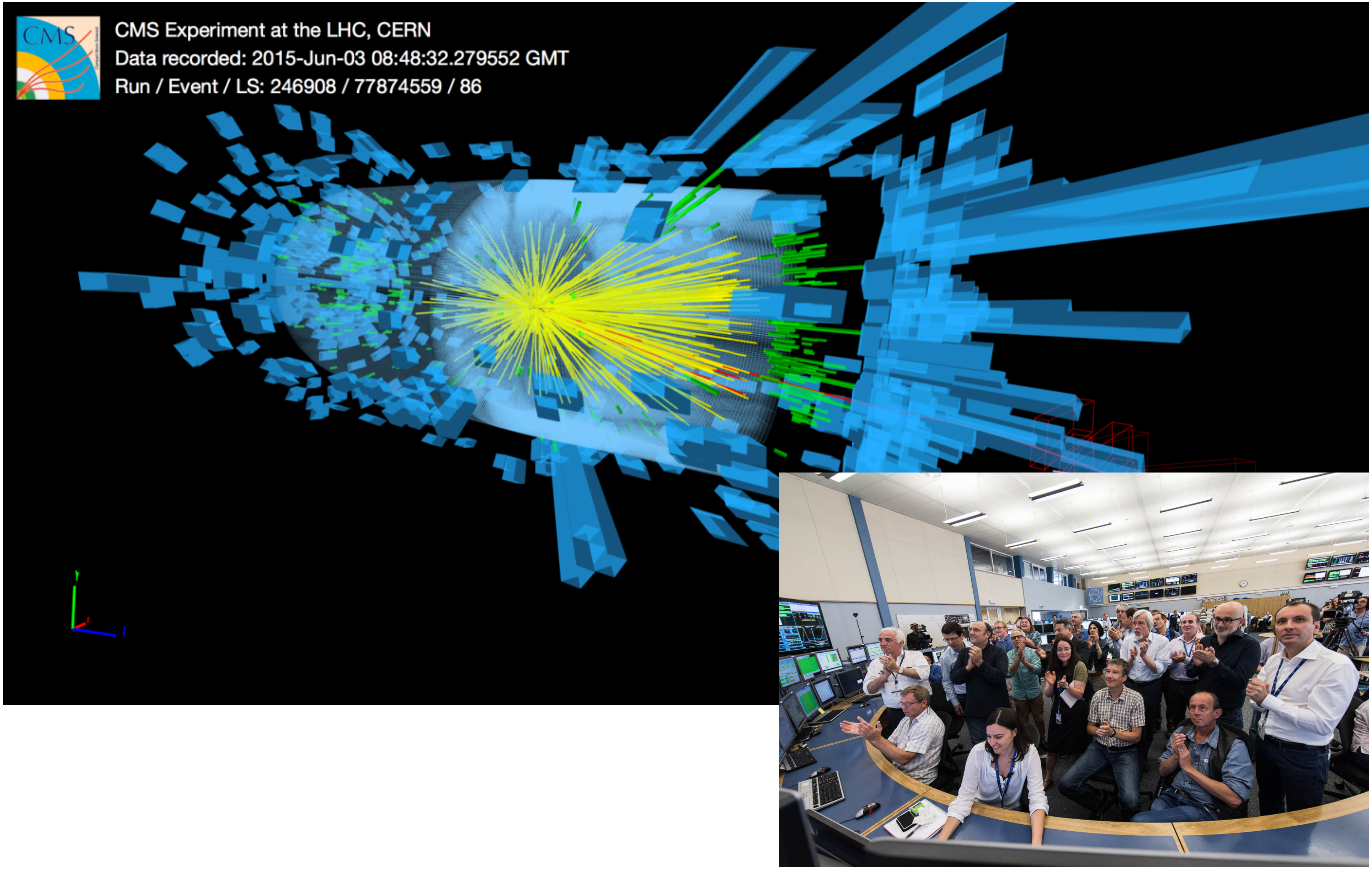
The plan:

- We have foreseen a longer than usual time to re-commission the LHC and all its systems with beam
  - **2 months** (April and May 2015) of low intensity commissioning of the LHC cycle. Maximum number of bunches: 3 × 3
  - Establish circulating orbit at 450 GeV, establish acceleartion, commission squeeze, correct optics, establish collisions, set up collimators, qualify all machine protection systems.

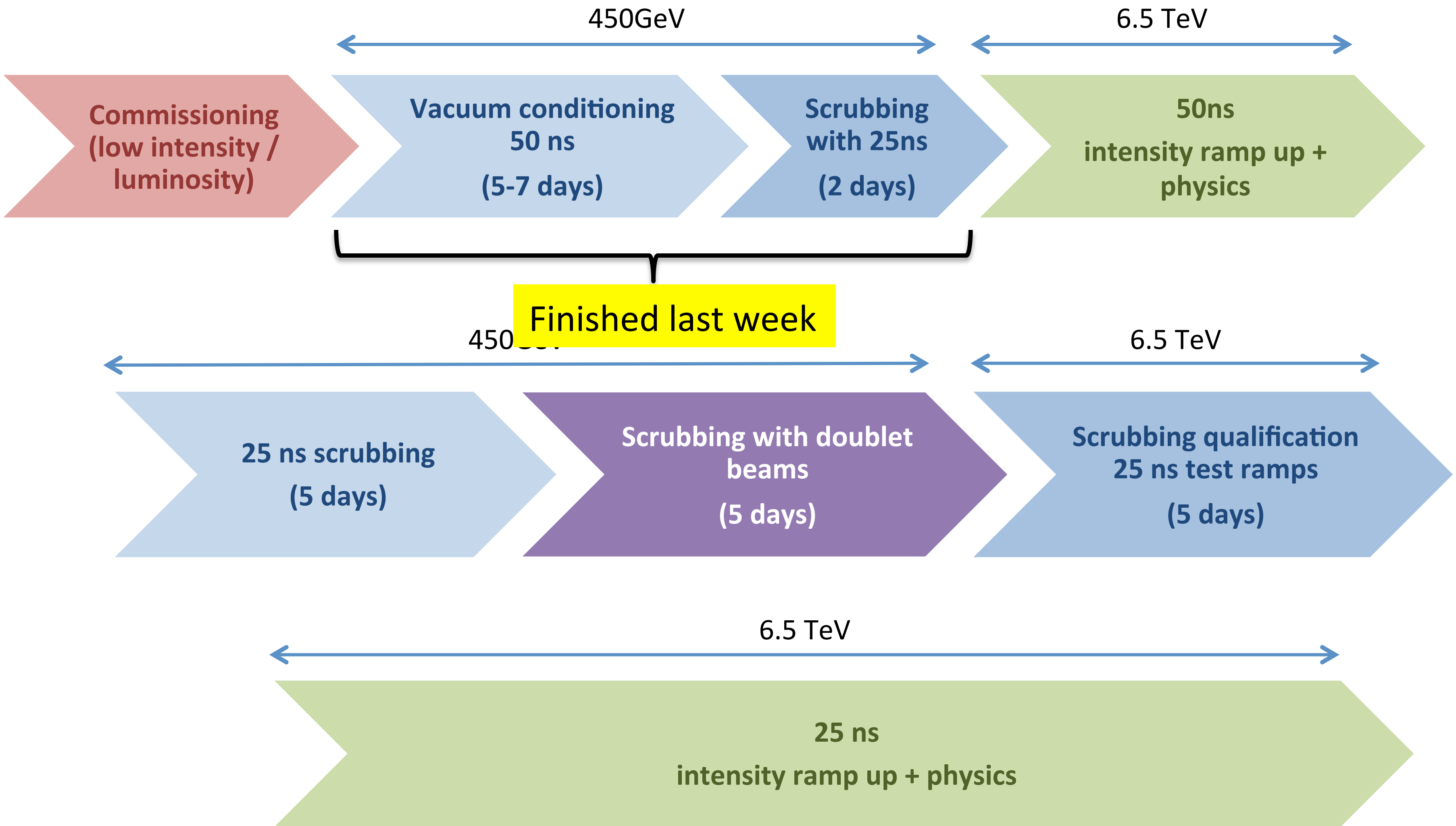
We are here now

  - Scrubbing & Intensity ramp-up

Physics start-up at 6.5 TeV 3rd of June 2015



Commissioning in 2015



Courtesy G. Iadarola and G. Rumolo

> 2015

The goal for the coming years:

collect 300 fb^{-1} at ≥ 6.5 TeV until Long Shutdown 3 (2023).

- 2019: 18 months of Long Shutdown 2

After Long Shutdown 3 the LHC will be prepared for High Luminosity LHC (HL-LHC).

THE END