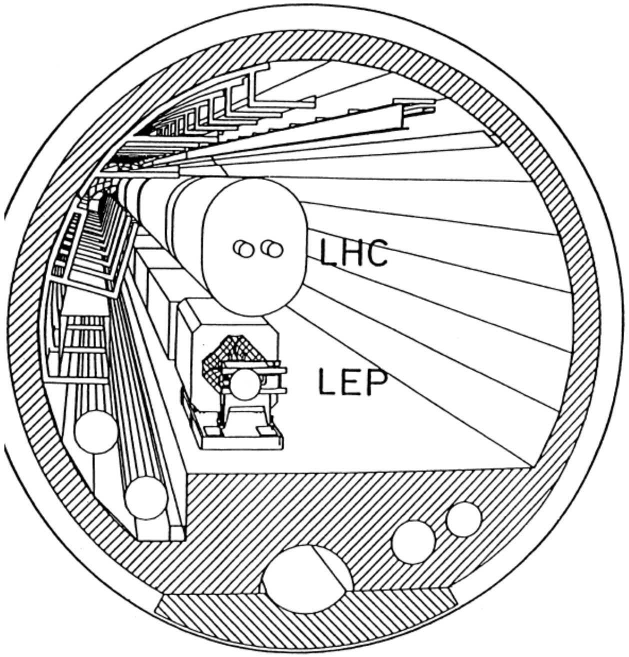
The challenges of LHC commissioning past and future

Experiences with LHC commissioning for Run 1 and Run 2, and plans for the HiLumi LHC, including the injector upgrades.

Mike Lamont



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

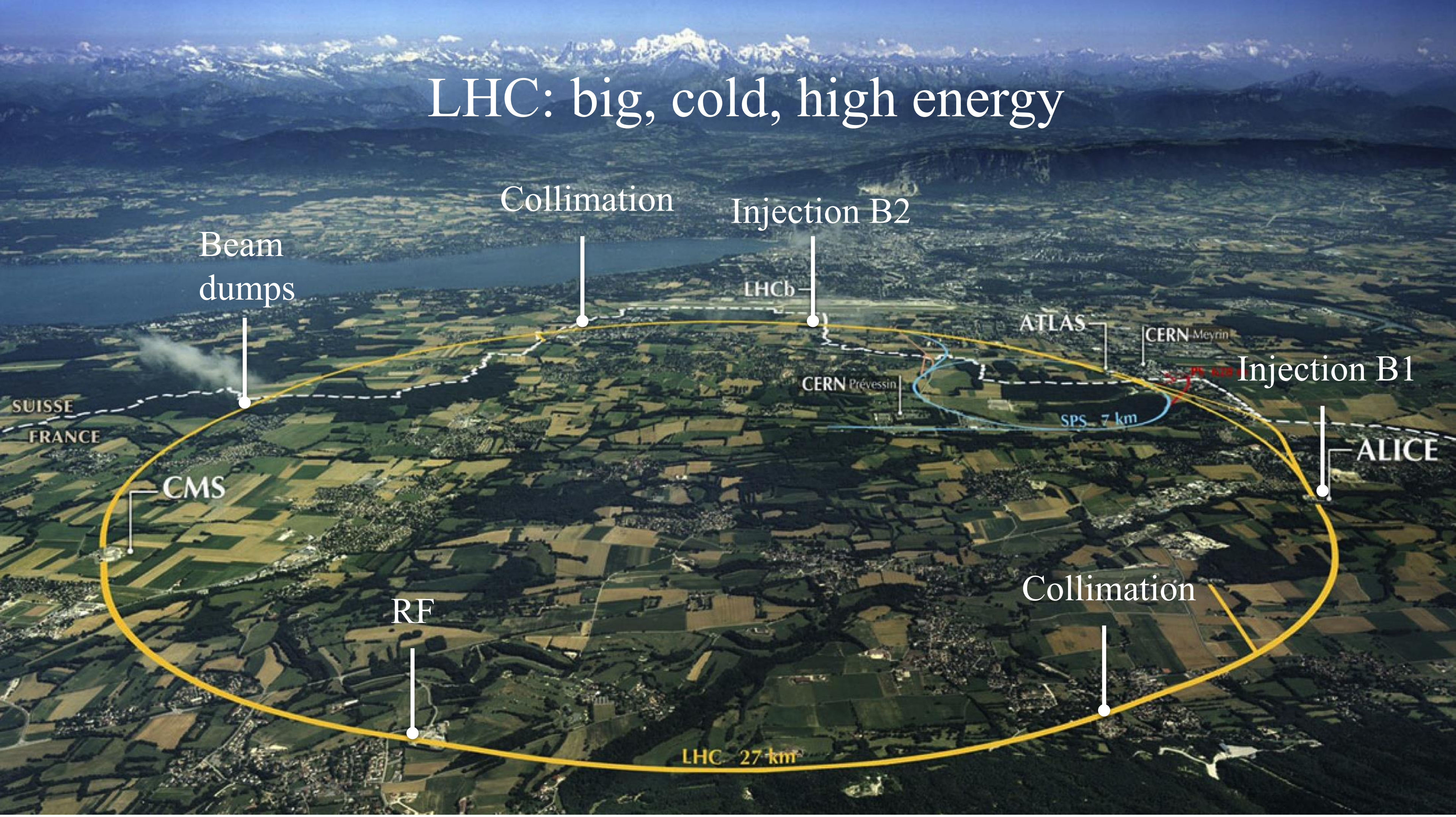
PROCEEDINGS OF THE ECFA–CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

These Proceedings are dedicated to the memory of Sir John Adams

Even before the drawing-board stage, the farsighted John Adams noted in 1977 that the tunnel for a future large electron–positron (LEP) collider should also be big enough to accommodate another ring of magnets.

LHC: big, cold, high energy



1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes helium, ~90 tonnes at 1.9 K
280 MJ stored beam energy in 2016
1.2 GJ magnetic energy per sector at 6.5 TeV


ATTENTION
HAUTE
HIGH
TENSION
DANGER
TE/ABT/FPS
ATTENTION
HAUTE
HIGH
TENSION
DANGER
COUPURE D'URGENCE
EXTRACTION KICKER
MKD
EMERGENCY SWITCHING

And some things that should not have been forgotten were lost. History became legend, legend became myth.

Myth

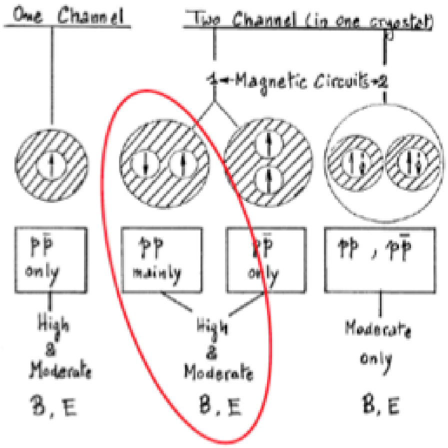
A traditional story, esp. one that involves gods and heroes and explains a cultural practice or natural phenomenon.

- Conception
- Birth
- Initiation
- Descent into the underworld
- Trial and Quest with the possibility of Hubris followed by Nemesis
- Withdrawal from community for meditation and preparation
- Resurrection and rebirth
- Ascension, apotheosis, and atonement

Repeat as required

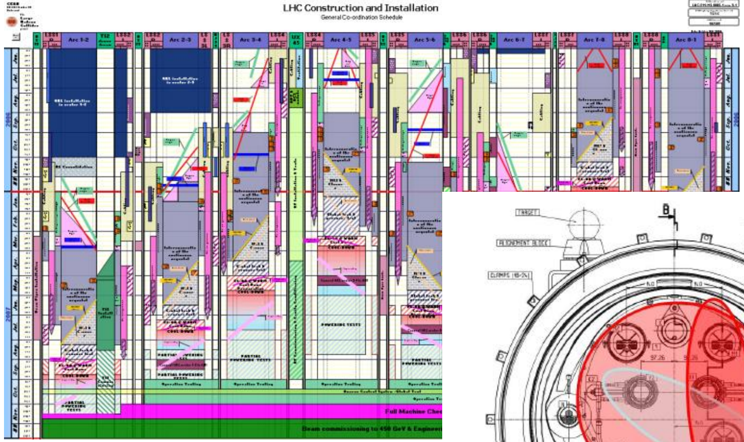
And they often involve rings

Conception

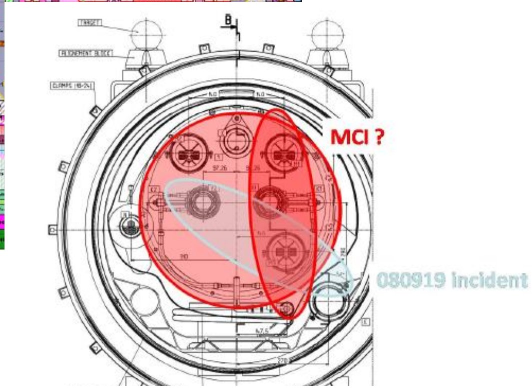


Initiation

LHC approved by the Elders



Birth – overdue



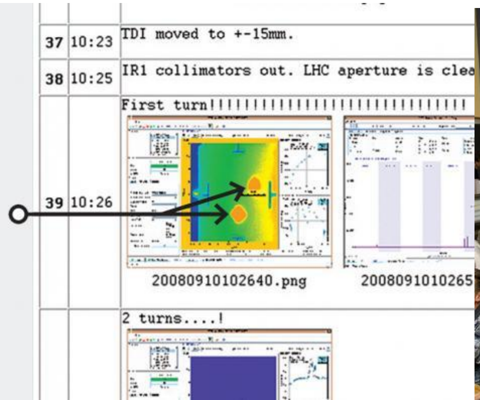
Withdrawal from community for mediation and preparation

Rival stumbles

SSC cancelled

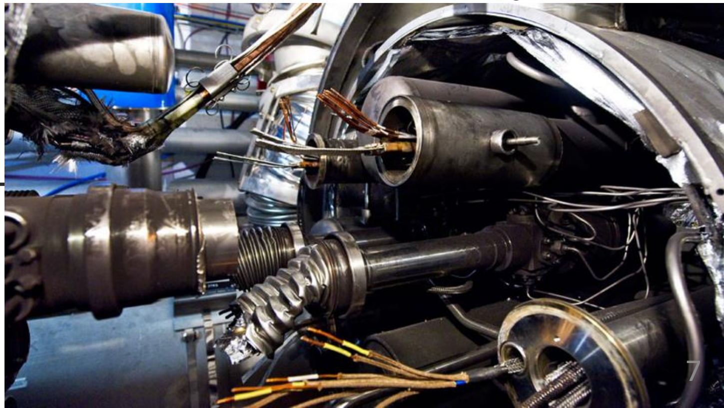
1984	//	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10

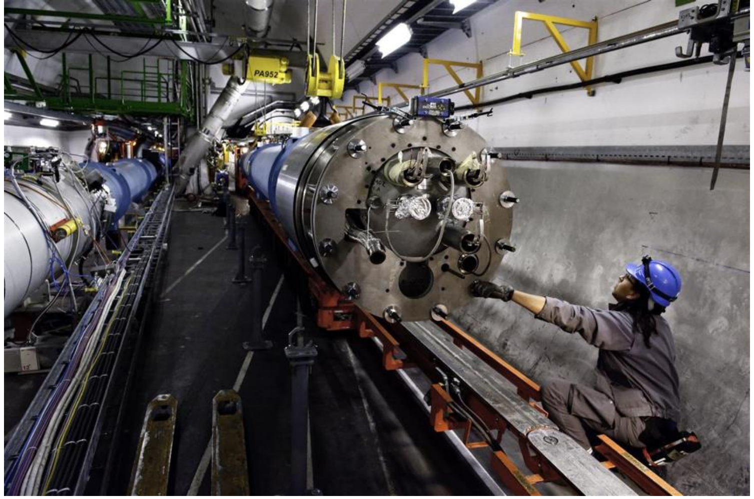
Hubris (?) September 10, 2008



37	10:23	TDI moved to +-15mm.
38	10:25	IR1 collimators out. LHC aperture is clea
39	10:26	First turn!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! 20080910102640.png 2008091010265
		2 turns....!

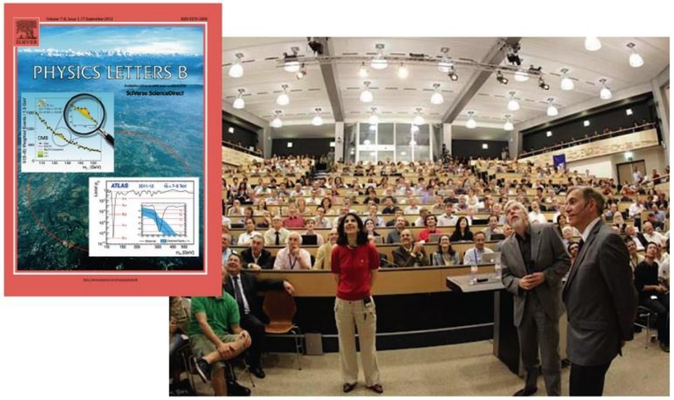
Nemesis September 19, 2008





Trial/descent in the underworld

Apotheosis and atonement



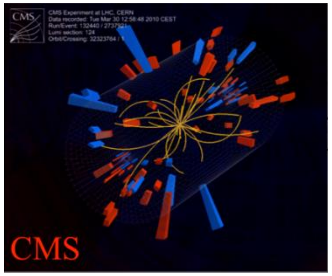
4 July, 2012

November 29, 2009

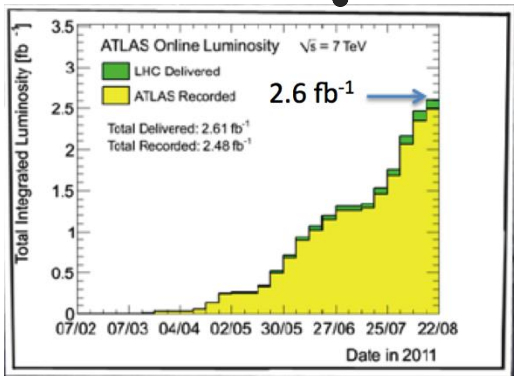
Resurrection and rebirth

2009	2010	2011	2012	2013

March 30, 2010
First collisions at 3.5 TeV



Ascension

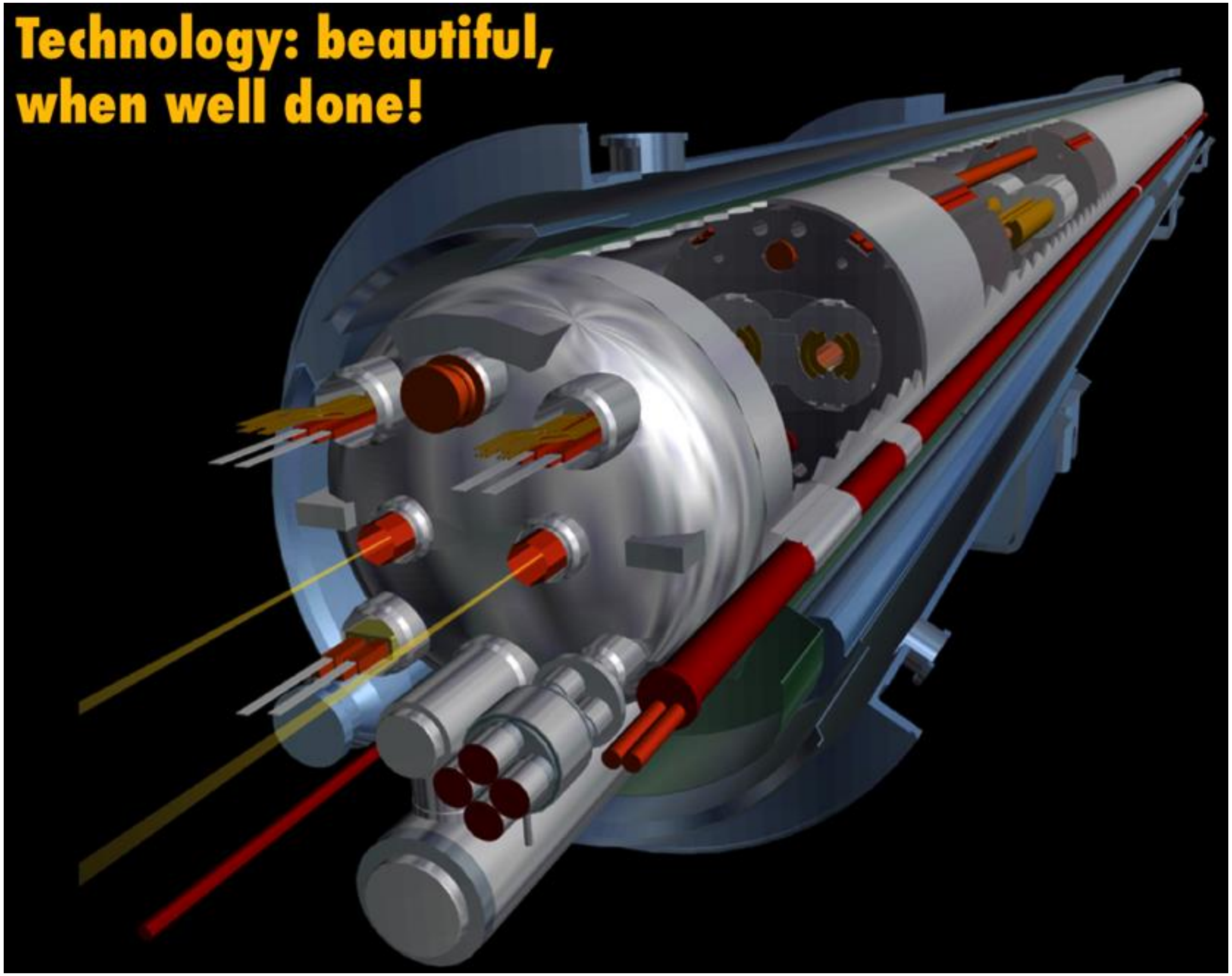


Heroic subplot

Let us not forget Fortuna

- Late
- Over budget
- Blew it up after 9 days
- Costly, lengthy repair
- Rival coming up fast on the outside
- Had to run at half energy
- And yet…

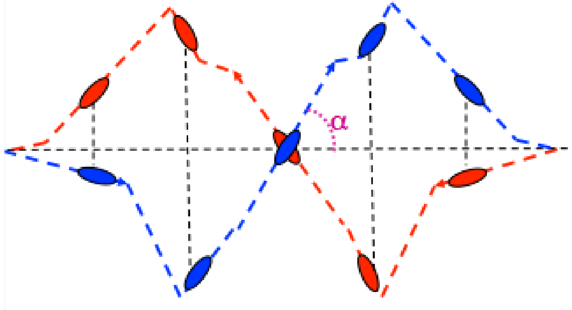
WE FOUND A NEW PARTICLE



FOUNDATIONS

Foreseen limitations circa 1995

- At low energy the main limitation for the beam lifetime comes from the machine non-linearities, i.e. the magnetic field errors
- At collision energy the limiting effects are caused by the beam-beam interaction
  - **Head-on** – conservative approach based on previous experience
  - **Long range** interactions - limiting factor for performance.
- Electron cloud
  - only identified as a problem for the LHC in the late 90ies
  - Pioneering work by Francesco Ruggiero & Frank Zimmermann



Magnets

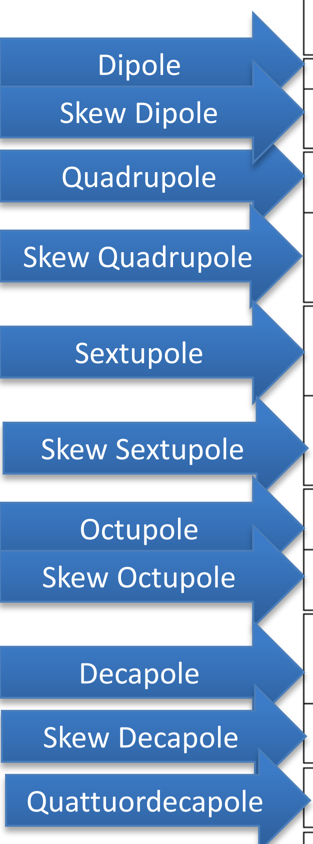
- **Field quality tracking and adjustment**
  - Field quality vitally important for beam stability - good after adjustments and faithful to the tight specifications
- **Magnetic measurement and modelling**
  - Characterize the important dynamic effects in anticipation of correction
  - Important magnetic strength versus current calibration

Field Quality Specification for the LHC Main Dipole Magnets

Stéphane Fartoukh and Oliver Brüning

Abstract

Based on criteria of different nature such as the control of the mechanical aperture or the preservation of the dynamic aperture, hard limits are given for the normal and skew harmonics a_n and b_n, $1 \leq n \leq 5$, and for the systematic b_7 component of the LHC main dipole magnets.

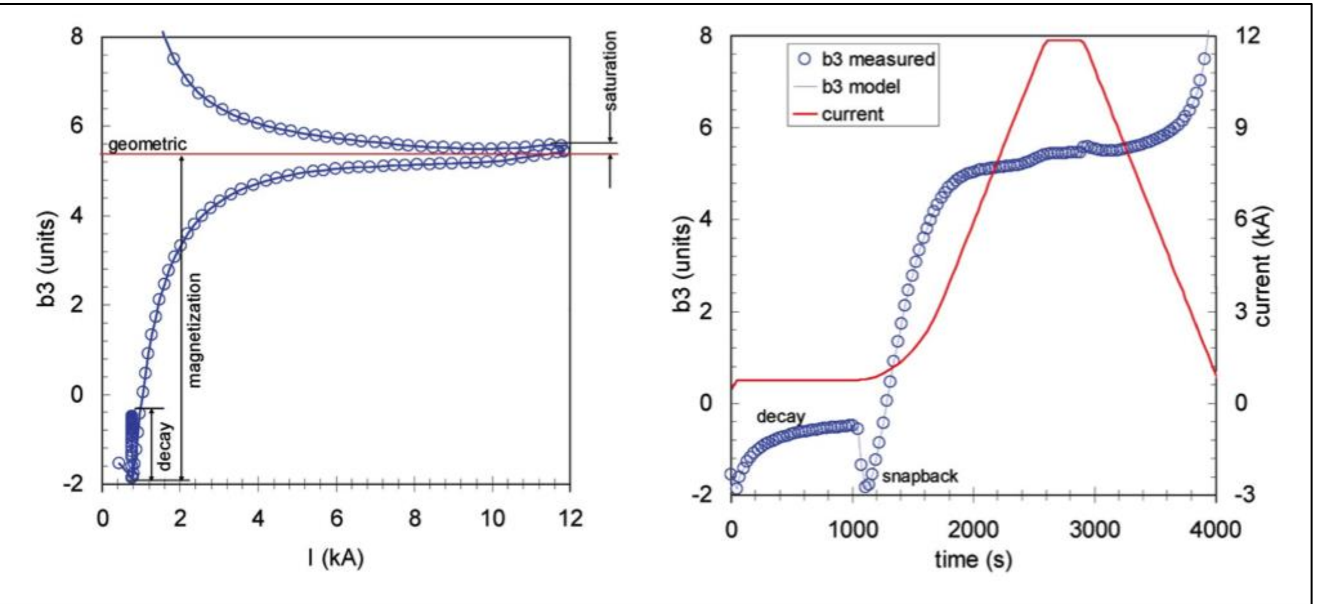


Harmonics a_n & b_n	Injection optics (450 GeV)	Injection optics (end of ramp)	Collision optics (7 TeV)	Systematic (max. value)	Uncertainty (max. value)	Random (r.m.s)	Criteria used
b_1	×	×	×	None	6.5	8.0	Closed orbit and MCB strength at 7 TeV
a_1 (including dipole roll)	×	×	×	6.5 (averaged per arc cell)		8.0	
b_2	×		×	1.4	0.8	0.7 0.8	β-beating and IP phasing
a_2	×	×	×		0.9	1.9 2.3 1.6	Vertical dispersion, linear coupling and MQS strength at 7 TeV
b_3	×		×	10.7 3.0 (including the bias due to uncertainty)		1.4 1.8	b_2 feed-down at injection, off-momentum β-beating, MCS strength at 7 TeV
a_3	×		×		1.5	0.7	Chromatic coupling inducing Q'' and MSS strength at 7 TeV
b_4	×		×	±0.2 (from Table 9901)	0.4	0.5	DA and Q'' at injection, MCO strength at 7 TeV
a_4	×				0.2	0.5 (from Table 9901)	DA at injection
b_5	×		×	1.1 0.8 (including the bias due to uncertainty)		0.5 0.4	DA and Q''' at injection, MCD strength at 7 TeV
a_5	×				0.4	0.4 (from Table 9901)	Off-momentum DA at injection
b_7	×			$-0.3 < \langle b_7 \rangle < 0.1$		0.2 (from Table 9901)	DA at injection
a_6, b_6, a_7 and higher order multipoles	×			OK with the Error Table 9901			DA at injection

Table 15: *Specifications for the dipole field quality at injection, end of ramp and in collision (a_n and b_n given in units of 10^{-4} relative field error at a reference radius $R_{ref} = 17$ mm).*

Magnet measurements and modeling

- … 10 years of measurements, dedicated instrumentation R&D, 4.5 million coil rotations, 50 GB of magnetic field data, 3 Ph.D.s and a few Masters Theses on the subject, 2 years of data pruning and modeling , collaborations and participation in runs in Tevatron and RHIC…
- **… today we have the most complex and comprehensive forecast system ever implemented in a superconducting accelerator**



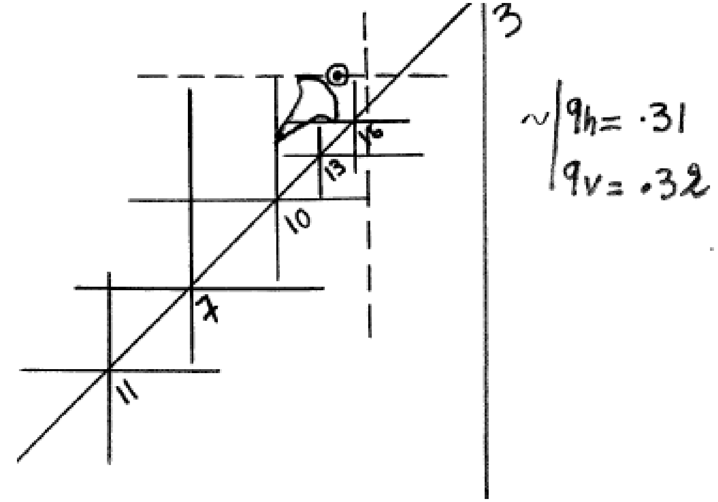
Luca Bottura 2008 for the FIDEL team

Beam-beam related effects for the LHC

(Relevant for LHC performance)

Jacques Gareyte

- Long range and head-on interactions
- Beam-beam induced synchrobetatron resonances
- Coherent beam-beam effects
- Beam-beam induced orbit effects

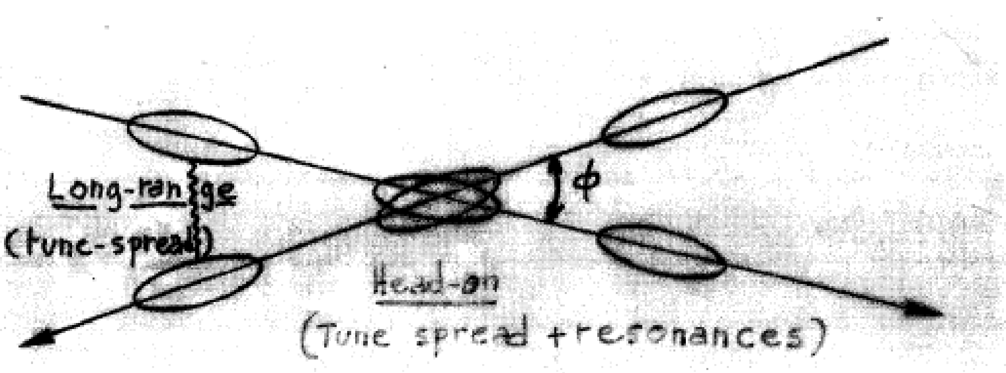


Quiet space to accomodate b. b. tune footprint

- Influence of triplet errors
- Long-range interactions

→ specify Xing angle □
triplet quality □

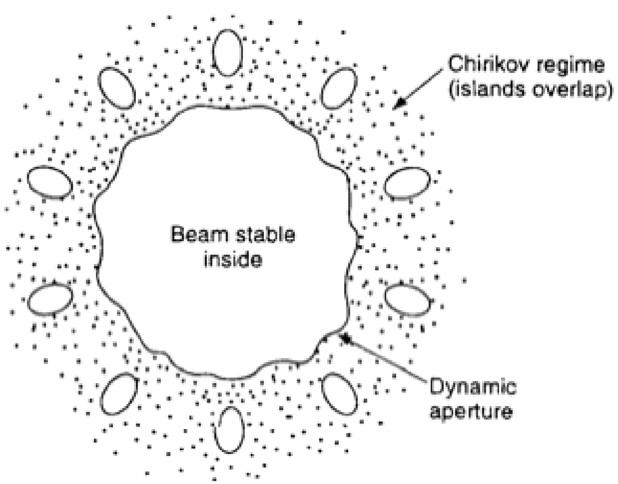
1) Avoid resonances $N \leq 12$

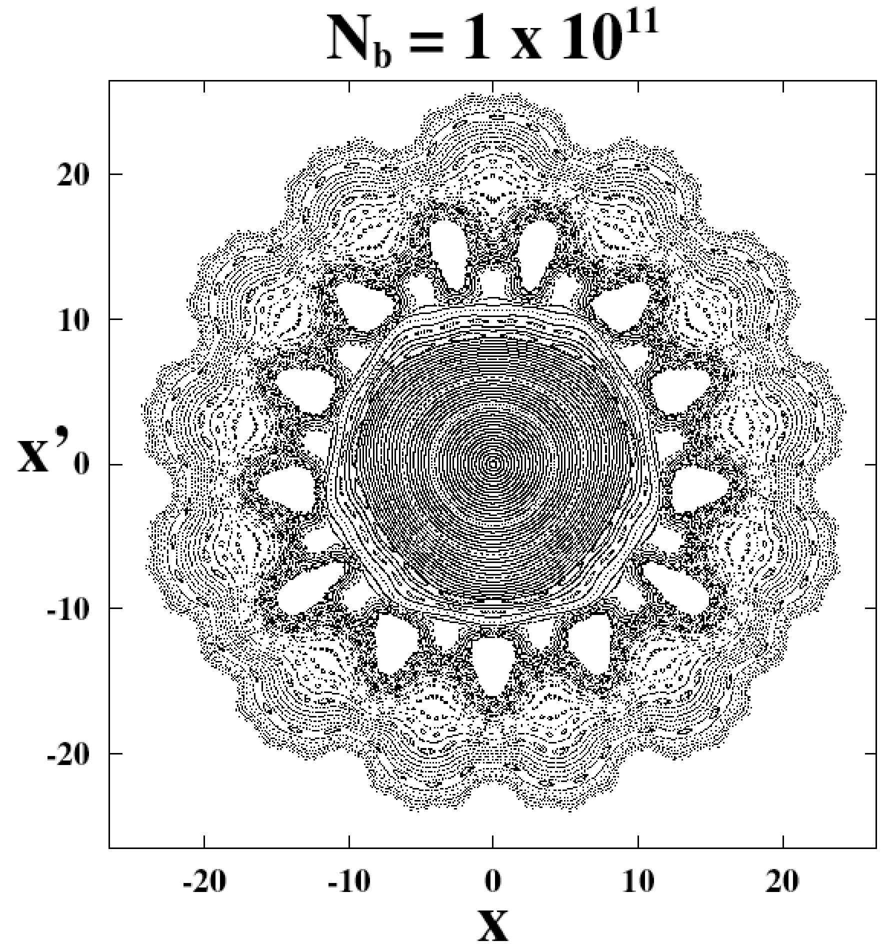


Beam dynamics

Major simulation effort to study:

- Particle stability (dynamic aperture), beam instabilities
- Effect of triplet errors, head-on beam-beam, long-range beam-beam

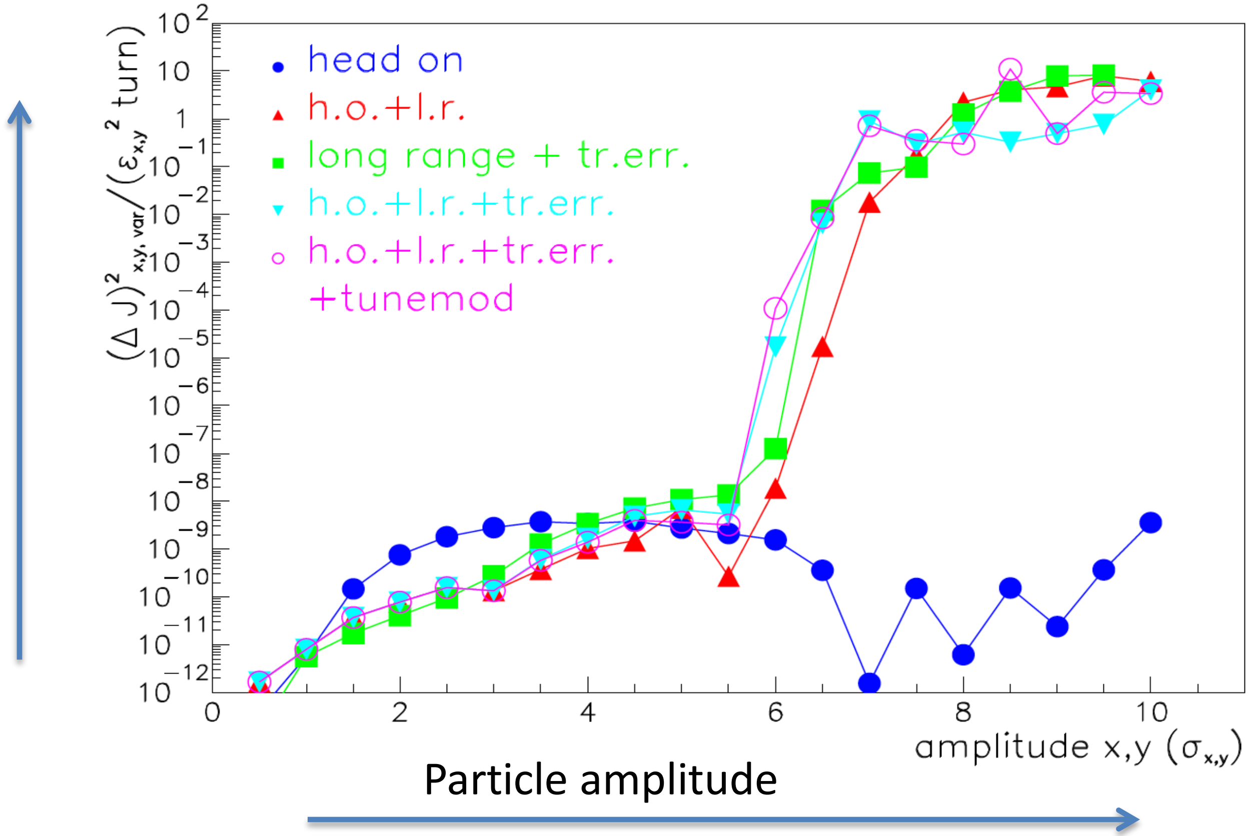




Phase-space plot simulated using a 2-dimensional model of the long-range beam-beam force
Y. Papaphilippou & F. Zimmermann

Long range encounters give rise to a well defined border of stability at the “diffusive aperture”

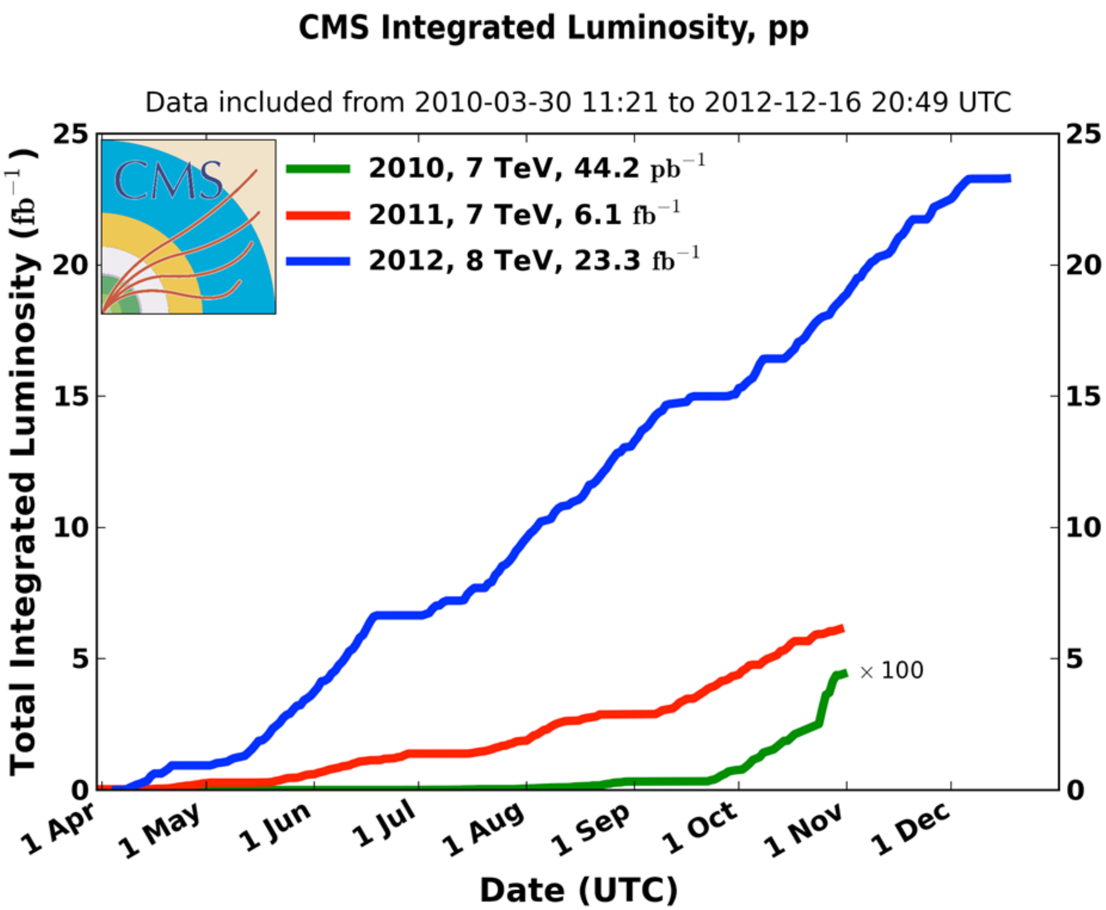
Diffusion rate



Particle amplitude

Y. Papaphilippou & F. Zimmermann

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

Restart 2009

First collisions at 3.5 TeV

That was close!!!

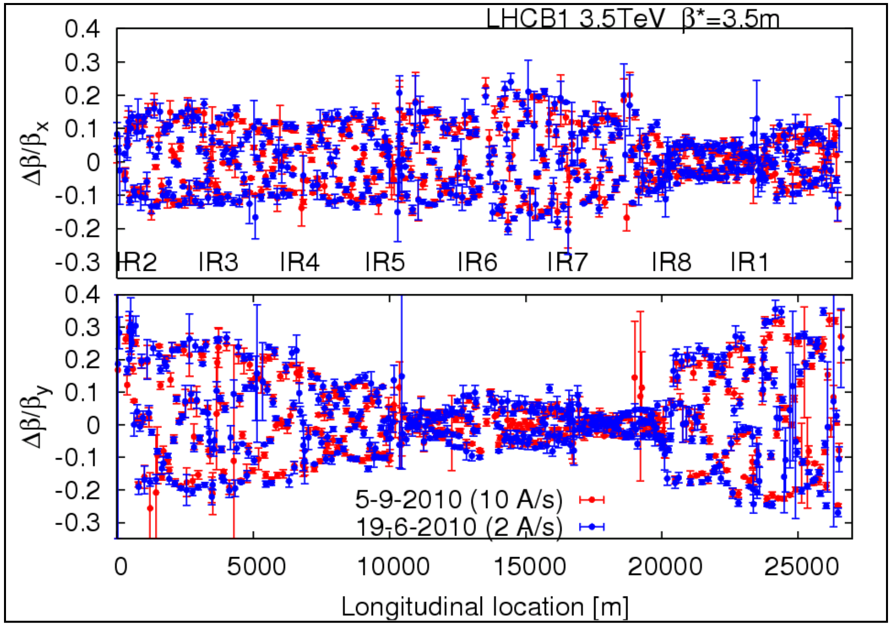
We delivered 5.6 fb^{-1} to Atlas in 2011 and all we got was a blooming tee shirt

0.5 and 0.25 million dollar babies

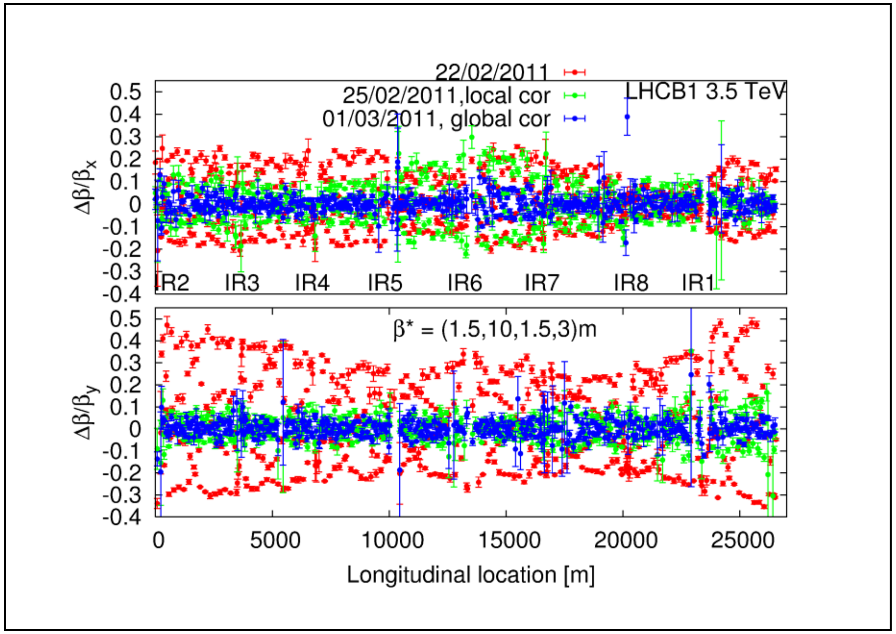
Optics

Optics stunningly stable

and well corrected



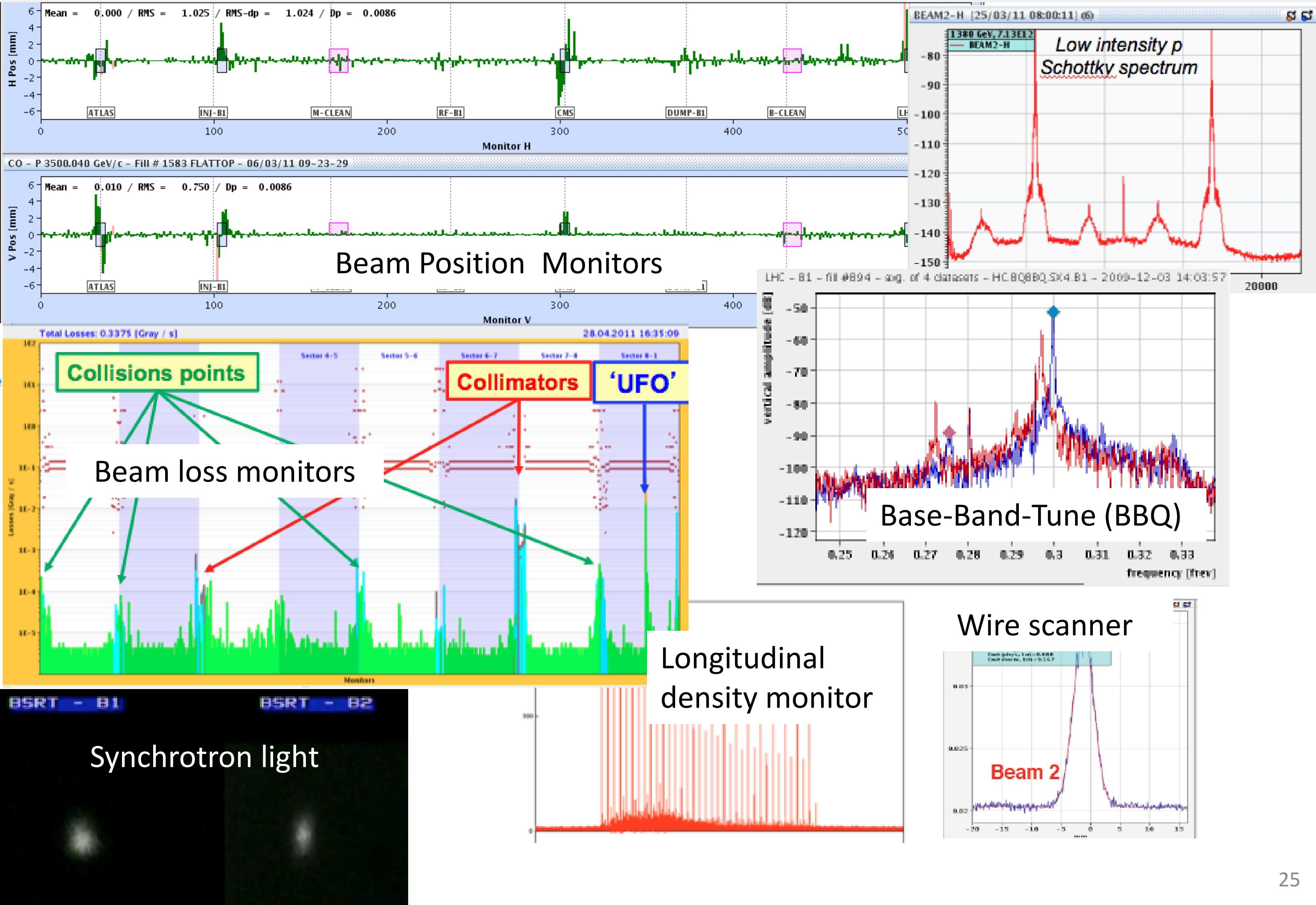
Two measurements of beating at 3.5 m
3 months apart



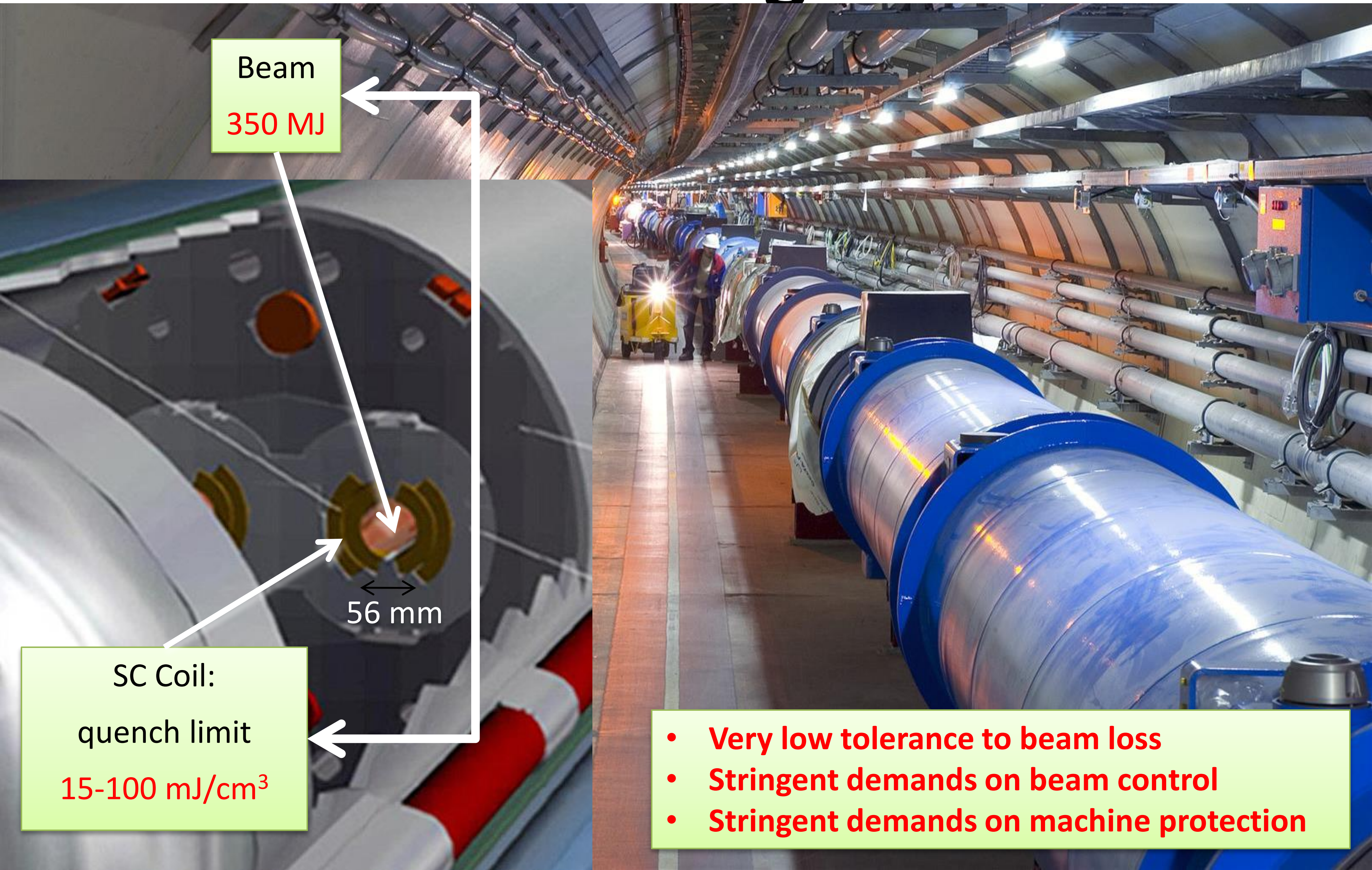
Local and global correction at 1.5 m

R. Tomas, G. Vanbavinckhove, M. Aiba, R. Calaga, R. Miyamoto

Beam Instrumentation: brilliant – the enabler

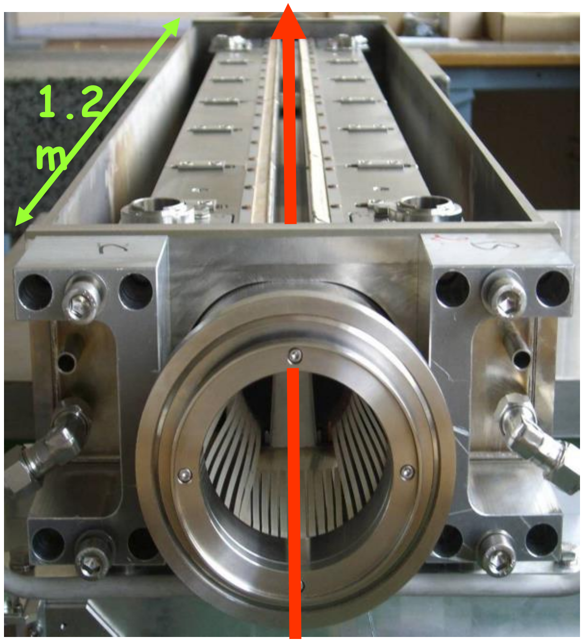


Machine protection – the big challenge



- **Very low tolerance to beam loss**
- **Stringent demands on beam control**
- **Stringent demands on machine protection**

Collimation system



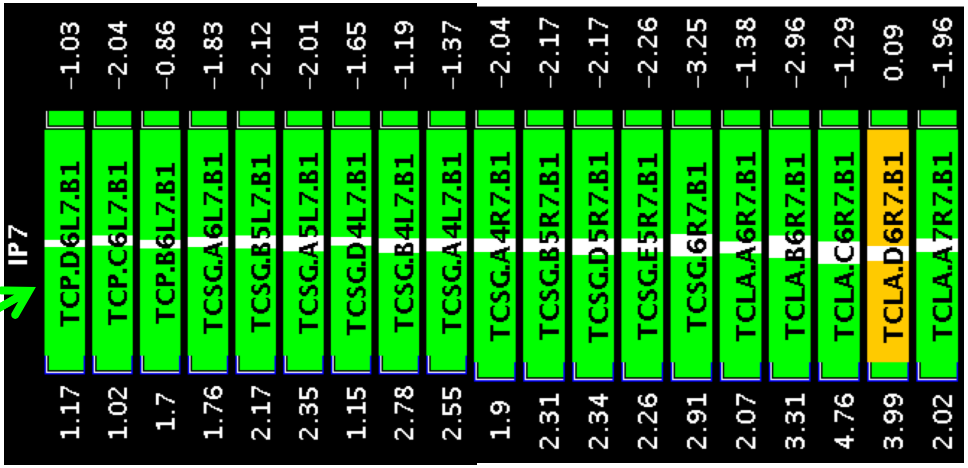
beam

Total = 108 collimators

About 500 degrees of freedom.

B1 collimators IP7

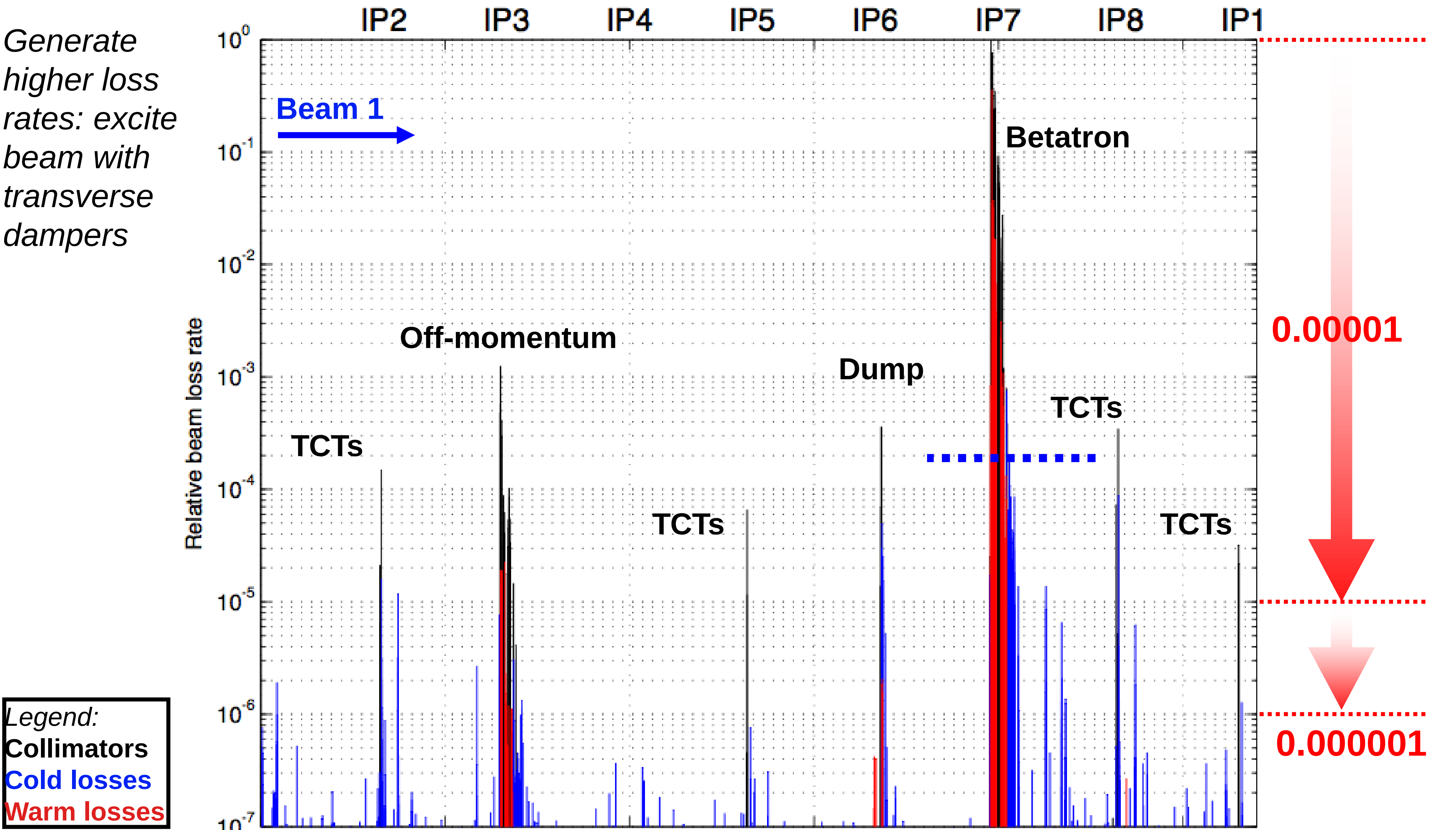
Beam 1



2.2 mm gap

Collimation

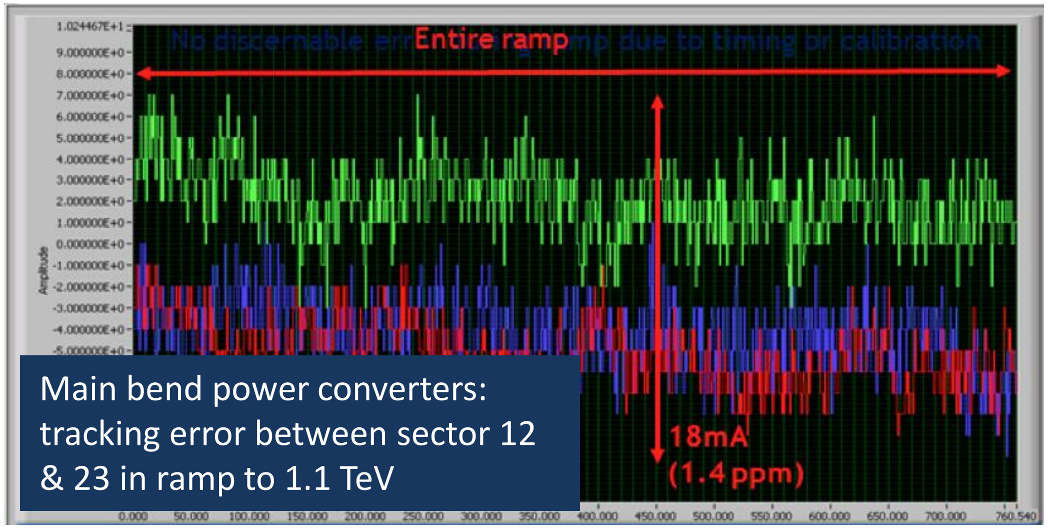
Generate higher loss rates: excite beam with transverse dampers



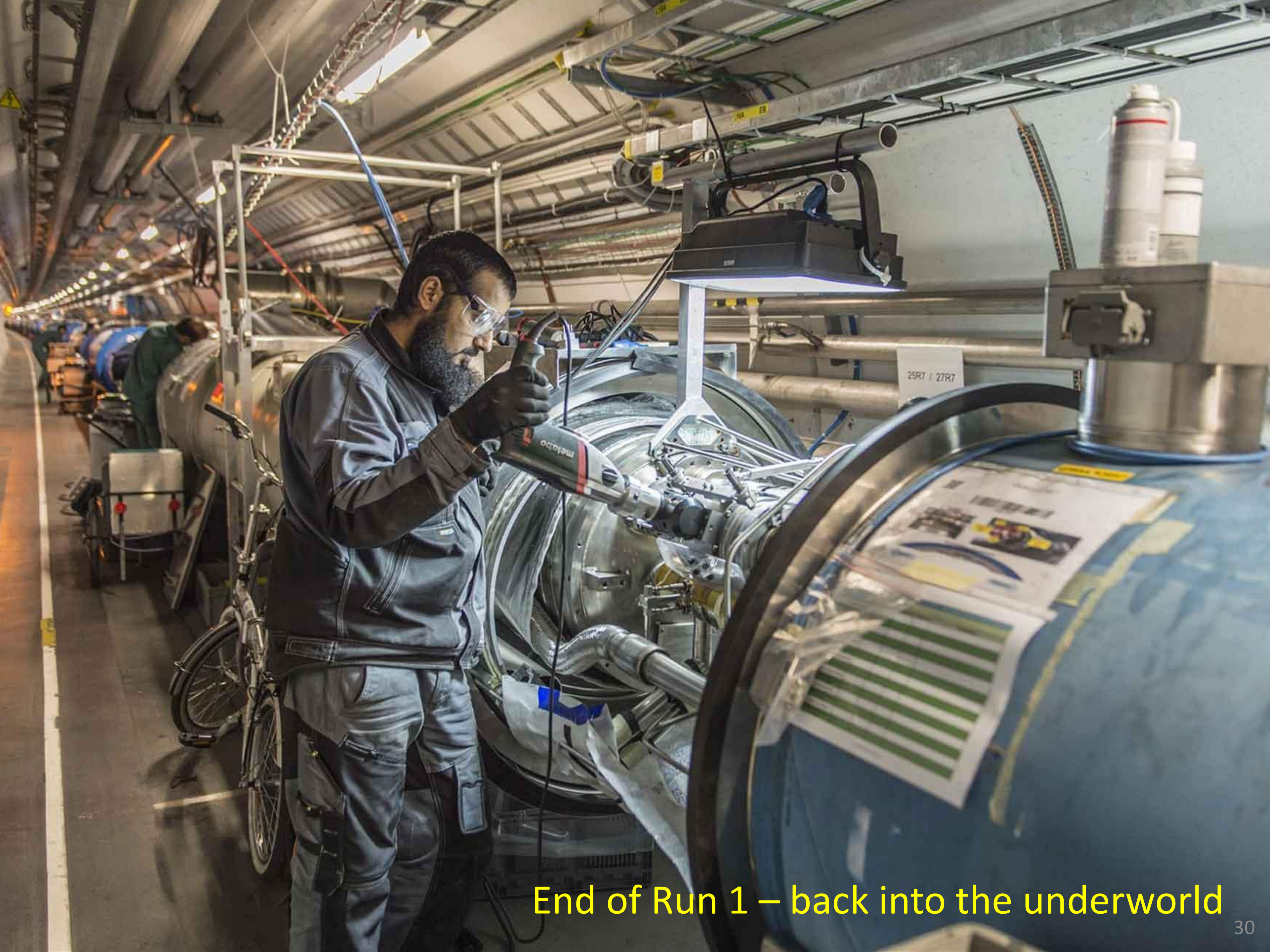
Routine collimation of 250 MJ beams without a single quench from stored beam

Exit Run 1(2010 – 2012)

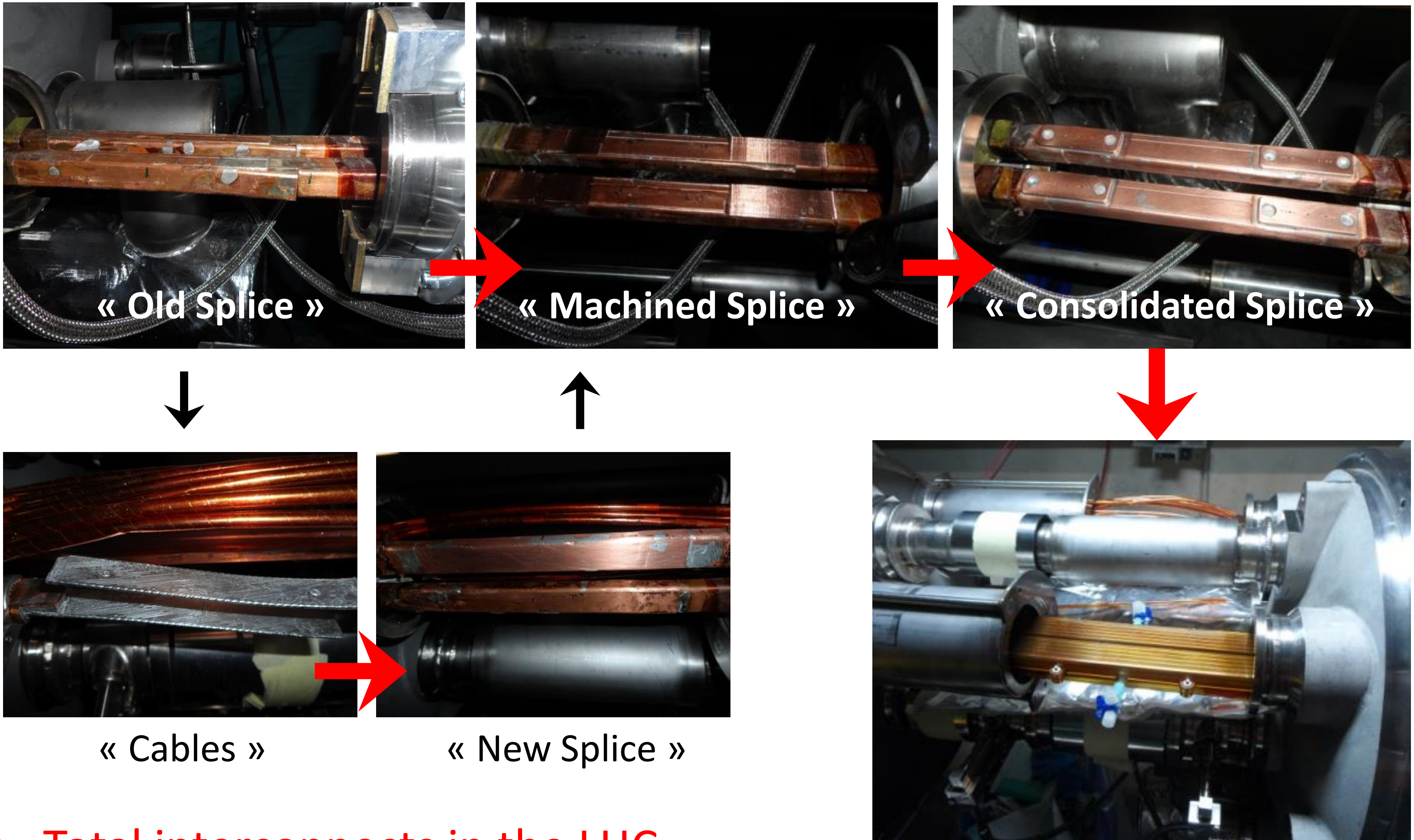
- Foundations well proven at 4 TeV
  - Magnets, vacuum, cryogenics, RF, powering, instrumentation, collimation, beam dumps etc.
- Huge amount of experience gained
  - Operations, optics, collimation…
- Healthy respect for machine protection



Main bend power converters: tracking error between sector 12 & 23 in ramp to 1.1 TeV



End of Run 1 – back into the underworld

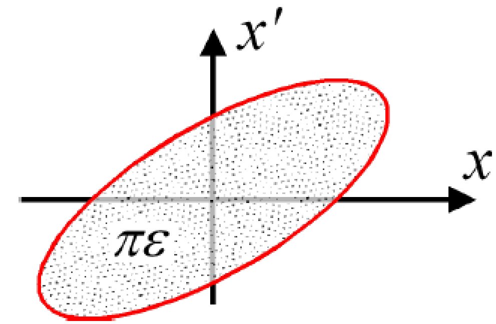


« Insulation box »

- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~ 30%)
- Number of shunts applied: > 27,000

Luminosity

$$L = \frac{N^2 k_b f}{4\pi \sigma_x^* \sigma_y^*} F = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$



N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
ε_n	**Normalized emittance**
β*	**Beta function at IP**

Round beams, beam 1 = beam 2

$$\varepsilon_n = \beta\gamma\varepsilon$$

$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

$$\varepsilon_N = 2.5 \times 10^{-6} \text{ m.rad}$$

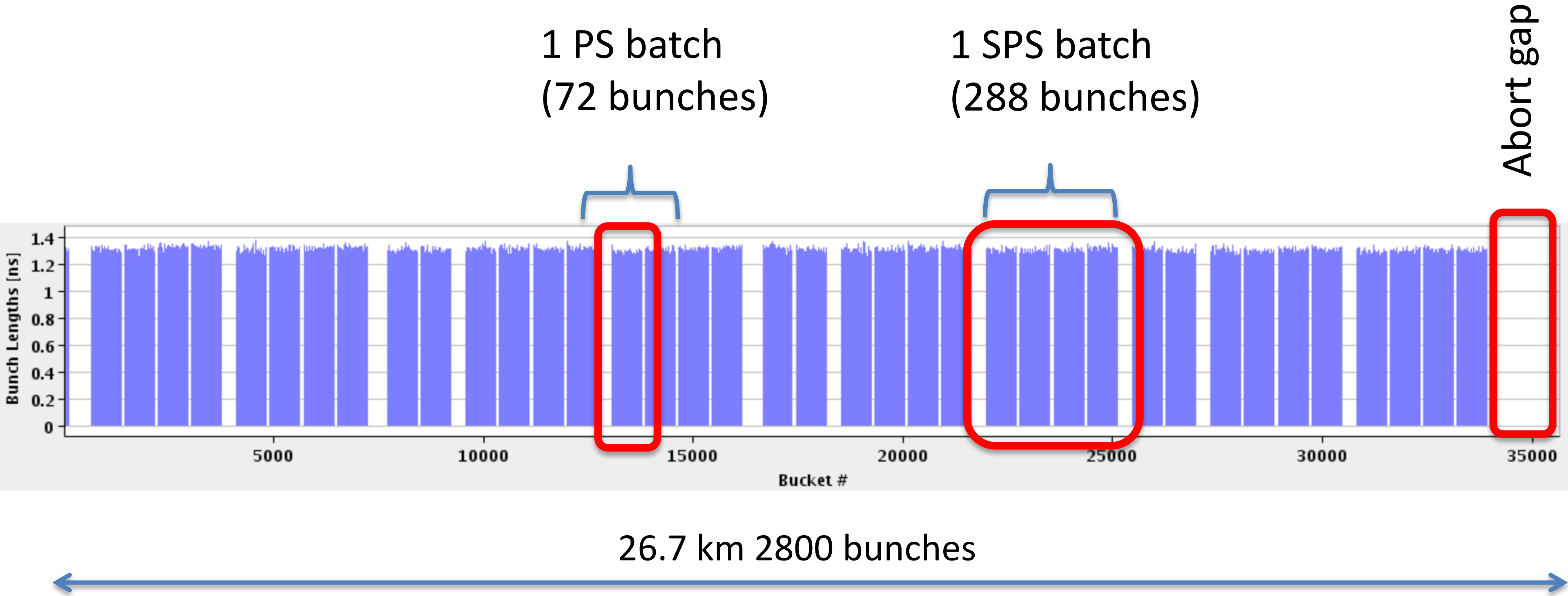
$$\varepsilon = 3.35 \times 10^{-10} \text{ m.rad}$$

$$\sigma^* = 11.6 \times 10^{-6} \text{ m}$$

$$\left(p = 7 \text{ TeV}, \ \beta^* = 0.4 \text{ m}\right)$$

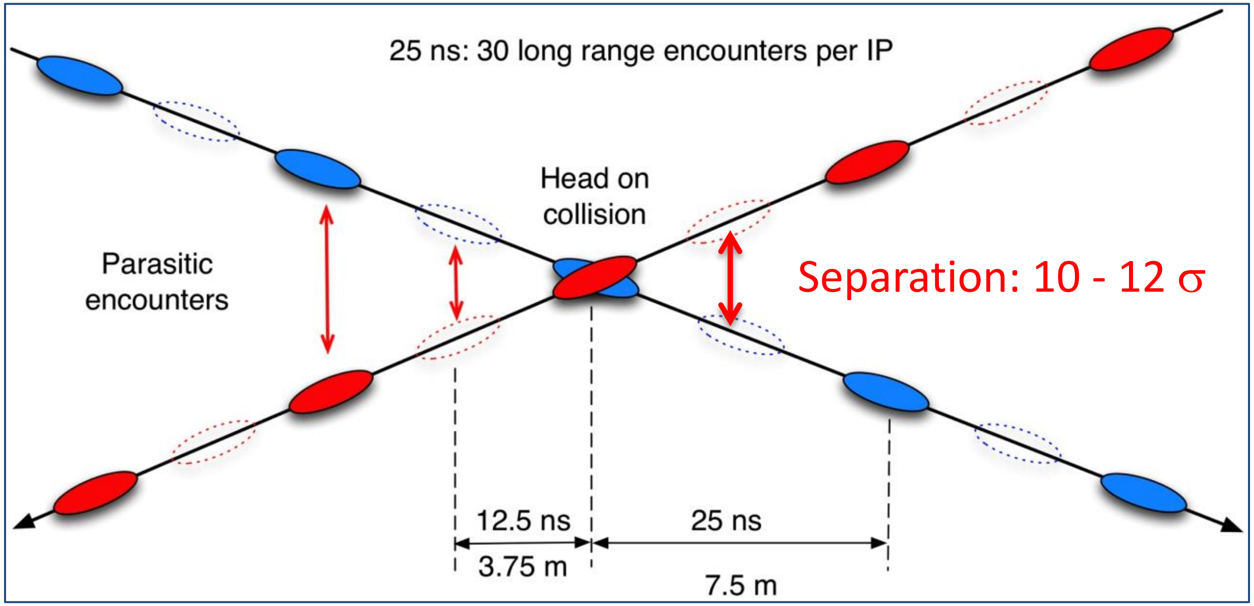
Nominal LHC bunch structure

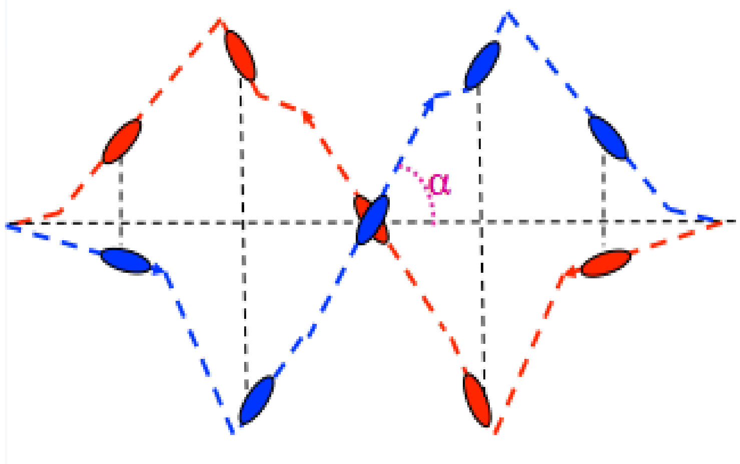
- 25 ns bunch spacing
- ~2800 bunches
- Nominal bunch intensity 1.15 x 10^{11} protons per bunch



Crossing angle

work with a crossing angle to avoid parasitic collisions.



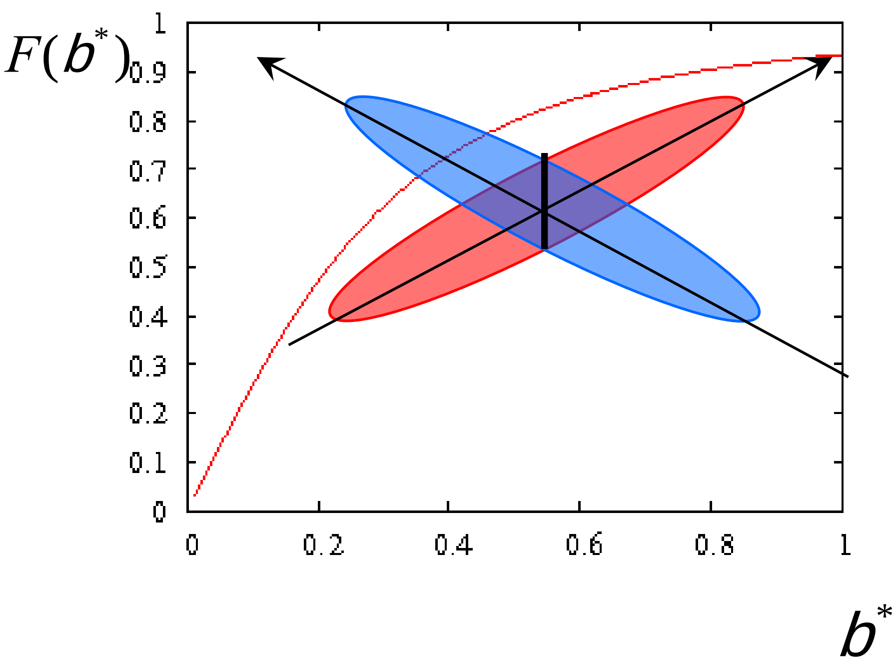


Crossing angle

→ reduction of long range beam-beam interactions
→ reduction of beam-beam tune spread and

nces

→ reduction of the mechanical aperture
→ reduction of luminous region
→ reduction of overlap & instantaneous luminosity



geometric luminosity reduction factor:

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

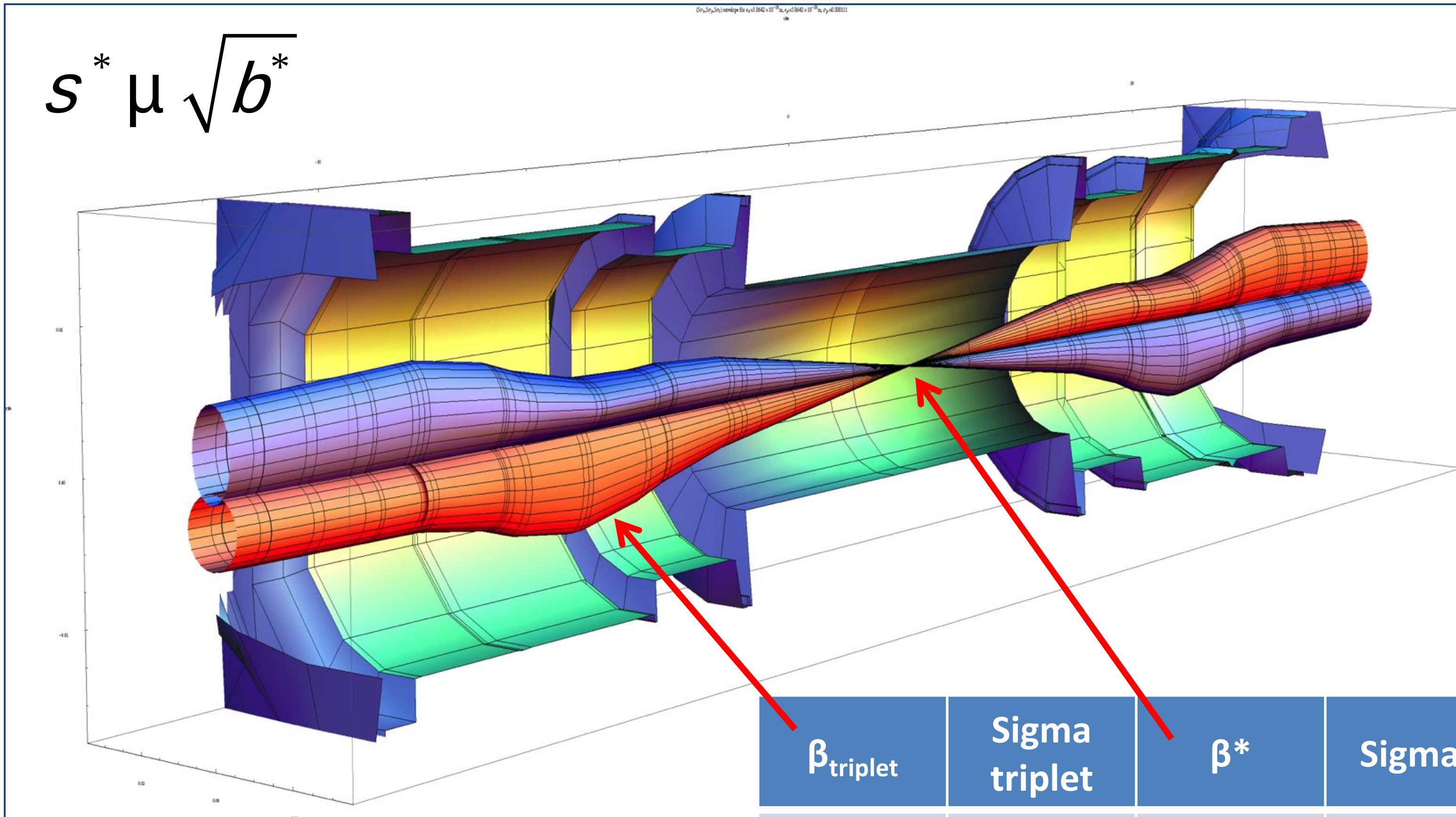
Crossing angle reduced about 6 weeks ago

X-angle [urad]	F
370	0.59
280	0.7

Squeeze in ATLAS/CMS

- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution – experience counts

$$s^{*} \mu \sqrt{b^{*}}$$



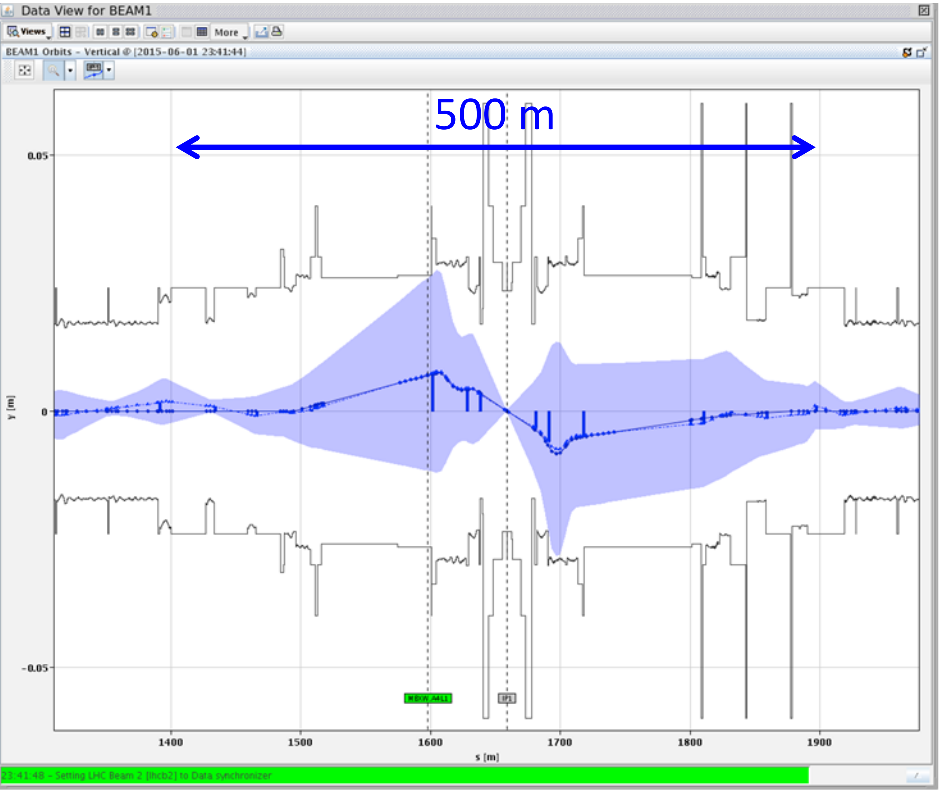
$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	40 cm	13 um

Image courtesy John Jowett

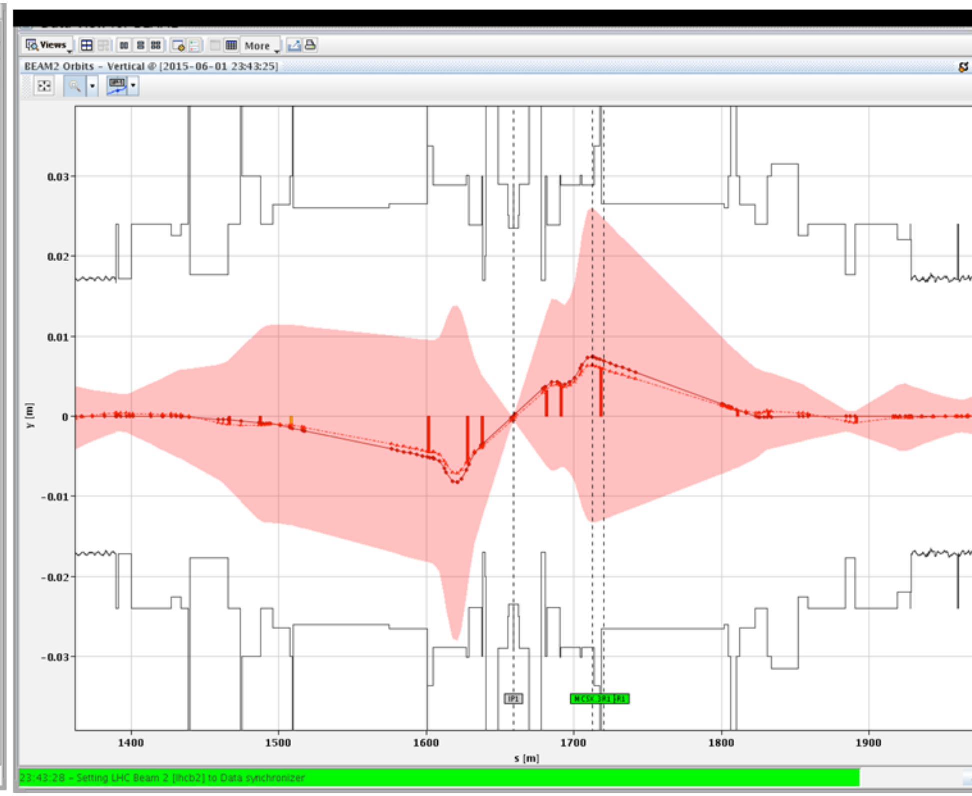
Triplets

Aperture

Carefully checked with beam



IP1 – B1



IP1 – B2

Run 2

LHC - 2015

- Target energy: 6.5 TeV
  - looking good after a major effort
- Bunch spacing: 25 ns
  - strongly favored by experiments – pile-up
- Beta* in ATLAS and CMS: 80 cm

Energy

- Lower quench margins
- Lower tolerance to beam loss
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

- Electron-cloud
- UFOs
- More long range collisions
- Larger crossing angle, higher beta*
- Higher total beam current
- Higher intensity per injection

2013 - 2015

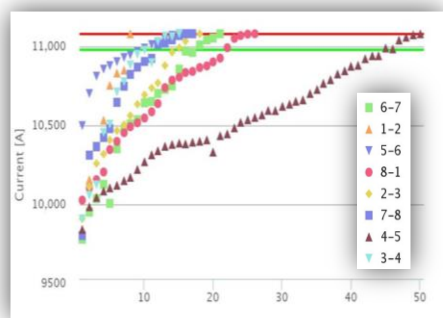
28th October
Physics with record number of bunches
Peak luminosity 5 x 10^{33} $cm^{-2}s^{-1}$

April ‘13 to Sep. ‘14

3rd June
First Stable Beams

5th April

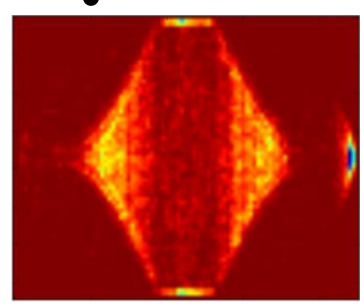
13-14 | Aug 14-Apr 15 | 2015



Dipole training campaign

10th April
Beam at 6.5 TeV

Struggle



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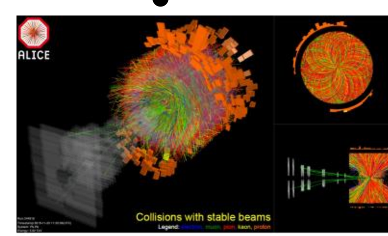
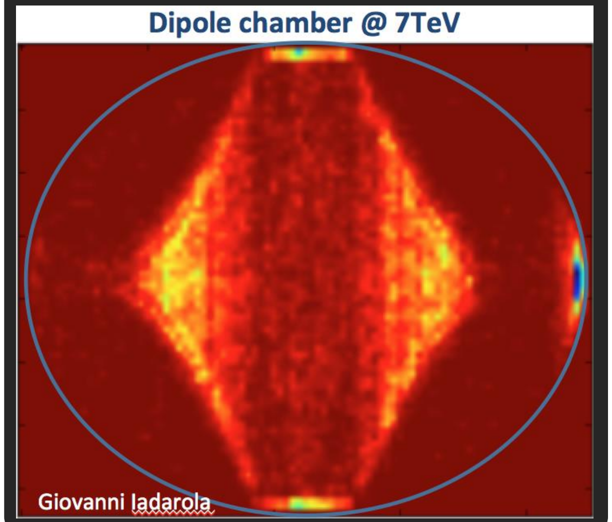


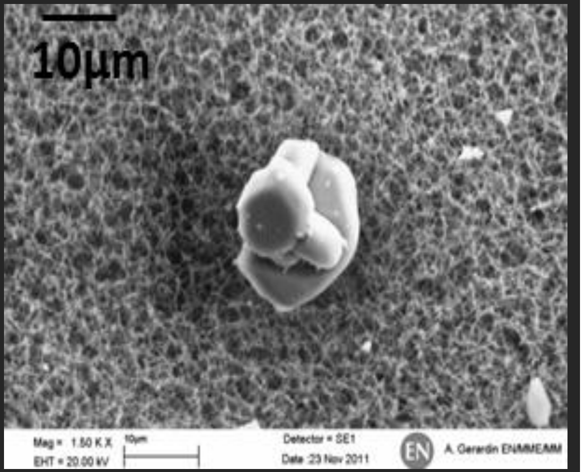
Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

2015: re-commissioning year, relaxed parameters, some issues…

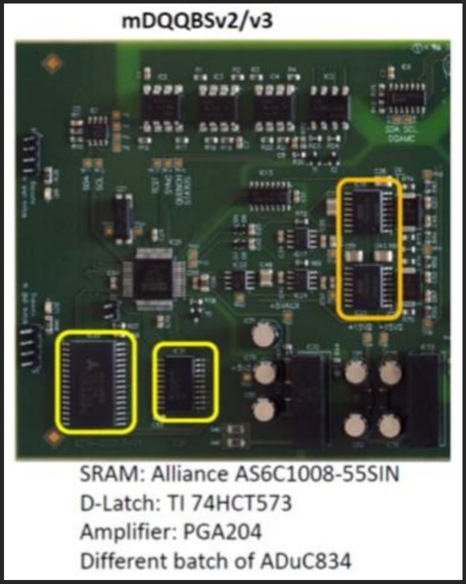
Electron cloud
- Anticipated
- Significant head load to cryogenics



UFOs
- 8 UFO dumps within 2 weeks (Sep 20 to Oct 5)
- Conditioning observed

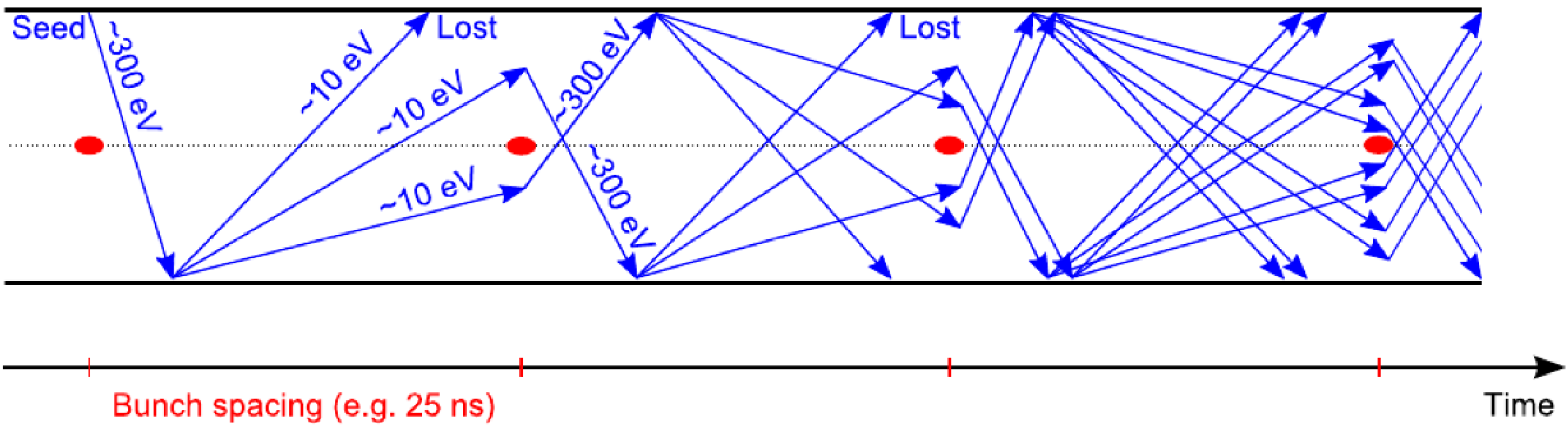


Radiation to electronics
- Mitigation measures (shielding, relocation…)
- Non-rad hard components used in LS1 upgrade



Exit 2015 with reasonable performance & hope for production in 2016

25 ns & electron cloud



Possible consequences:

- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

Electron bombardment of a surface has been proven to reduce drastically the **secondary electron yield (SEY)** of a material.

This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up.

LHC 2016

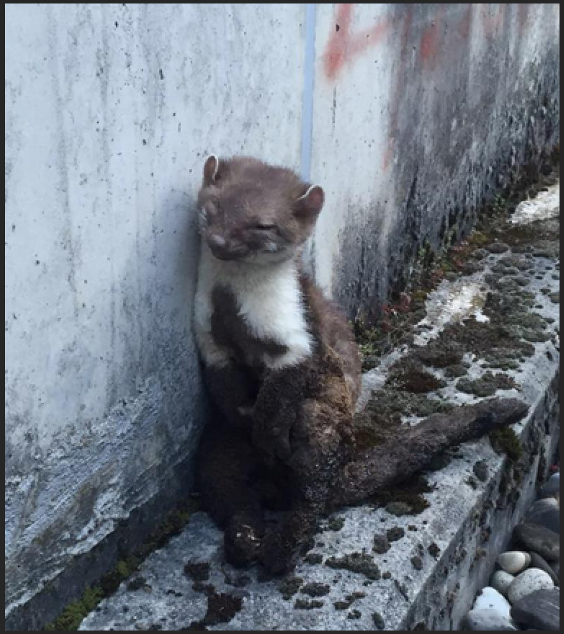
Choose a relatively bold set of operational parameters based on past experience

- Energy: 6.5 TeV
- 25 ns beam - nominal bunch population (~1.2e11)
- Low emittance from injectors – variations possible
- Squeeze harder in ATLAS and CMS
  - beta* = 40 cm
  - cf. 80 cm in 2015, 55 cm design

$$\mathcal{L} \propto \frac{1}{\beta^*}$$

Overcome a few problems

WEASEL



PS MAIN POWER SUPPLY

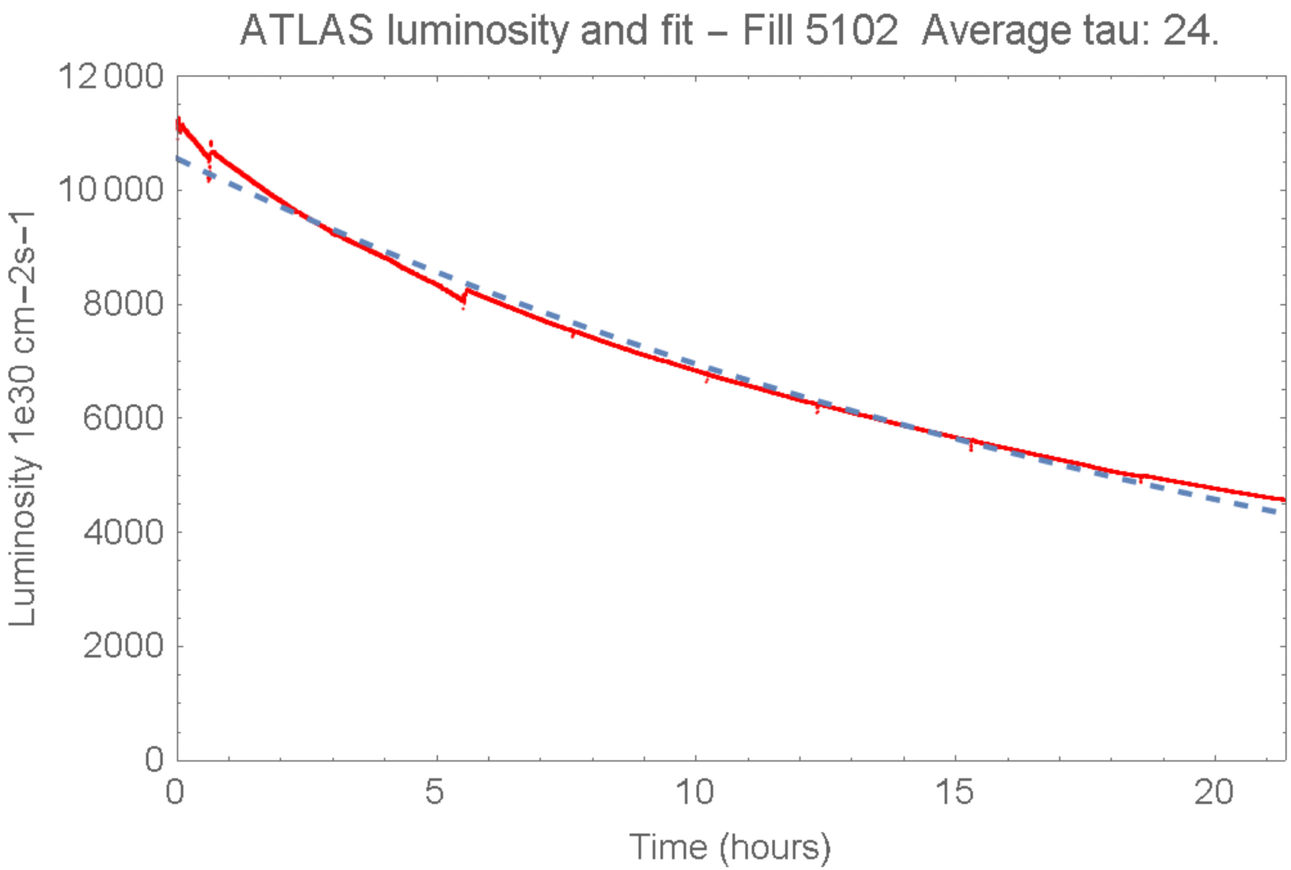
SPS BEAM DUMP

- **Limited to 96 bunches per injection**
- **2220 bunches per beam cf. 2750**

Design luminosity reached

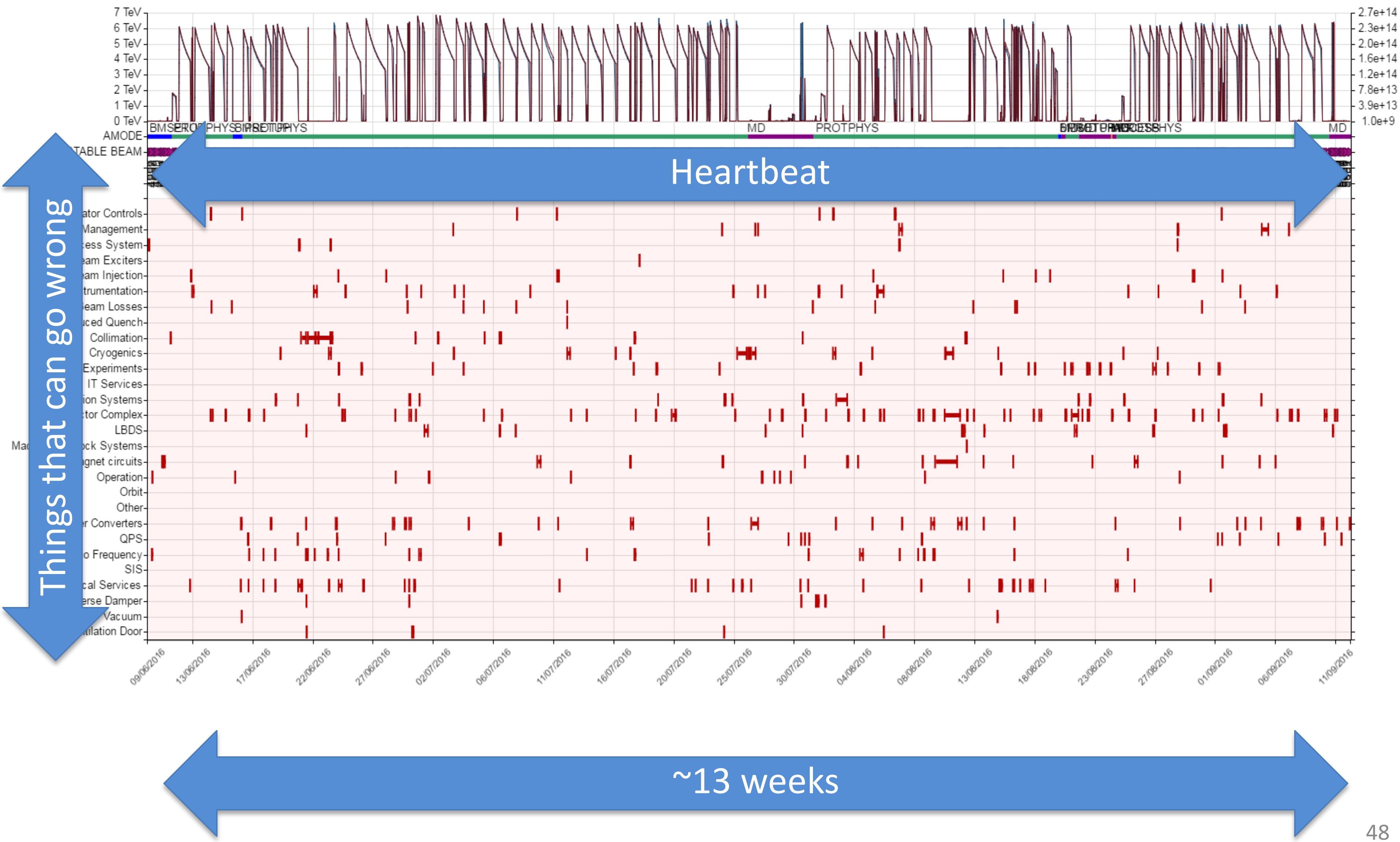
Reduced beta* and lower transverse beam sizes from the injectors compensating the lower number of bunches

Luminosity lifetime



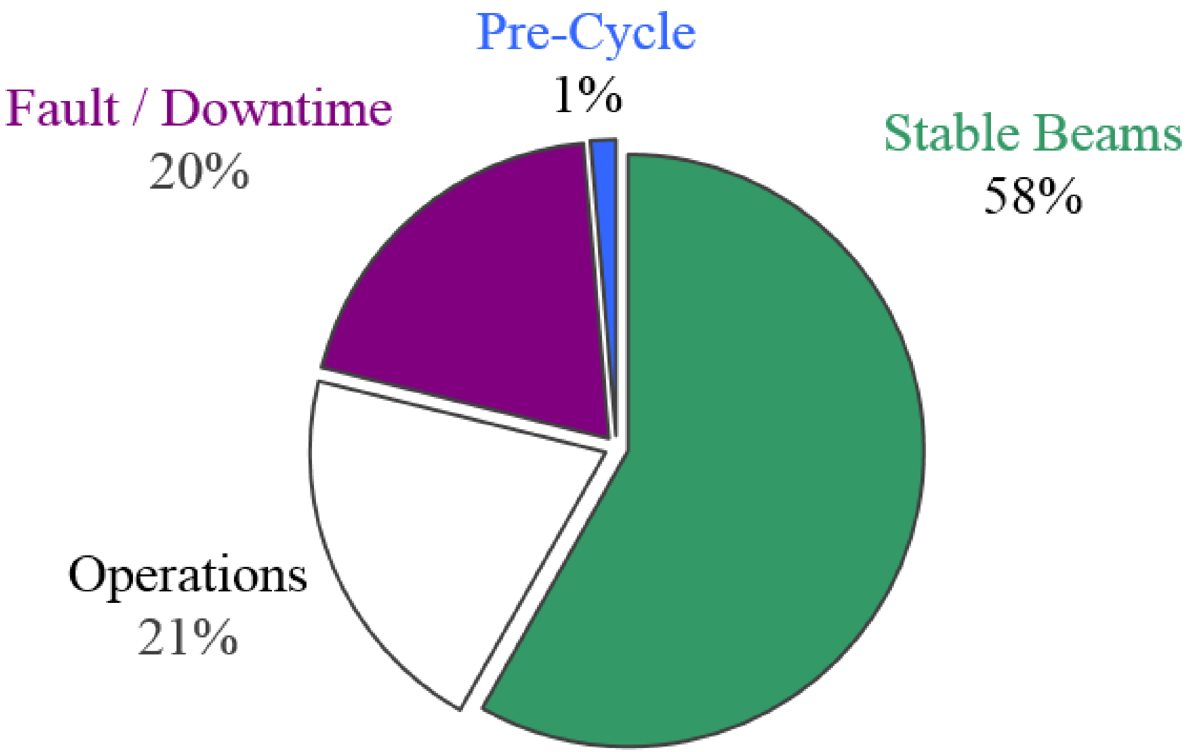
- Excellent luminosity lifetime – main component - proton loss to inelastic collisions in ATLAS, CMS and LHCb
- Sufficient dynamic aperture!

Then enjoy some remarkable availability



Availability: 11th June – 8th September

79 days proton physics

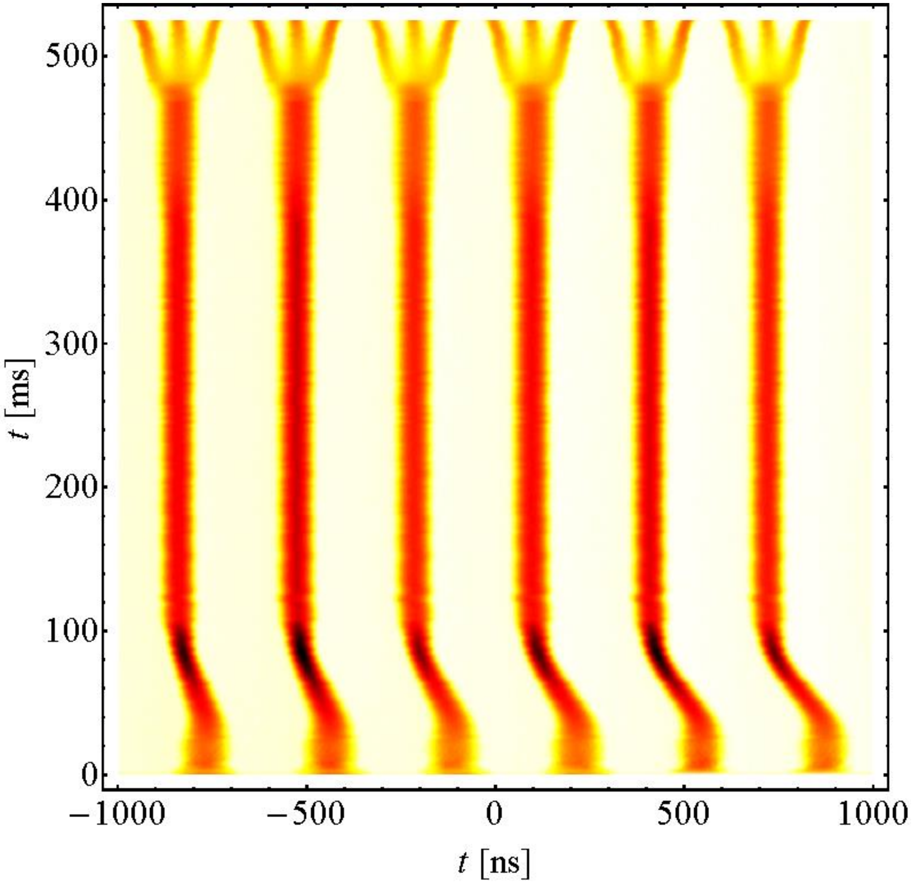


Stable Beams 58%

Beam from injectors

Lower than nominal emittance taken a step further

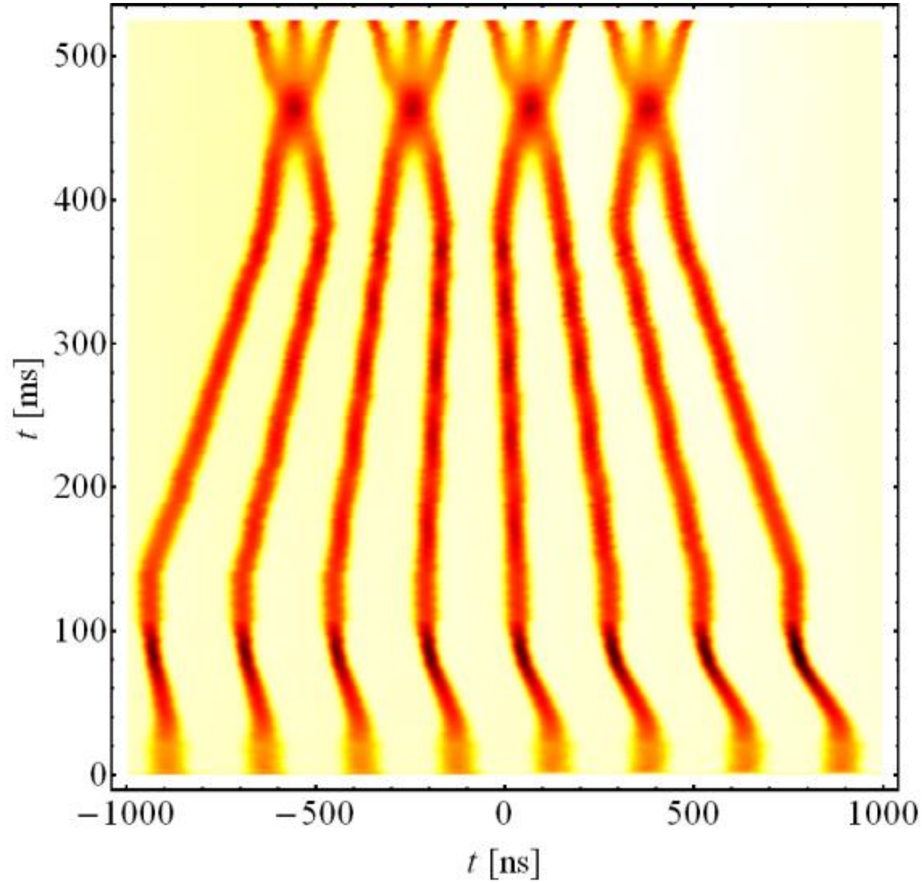
Standard 25 ns scheme



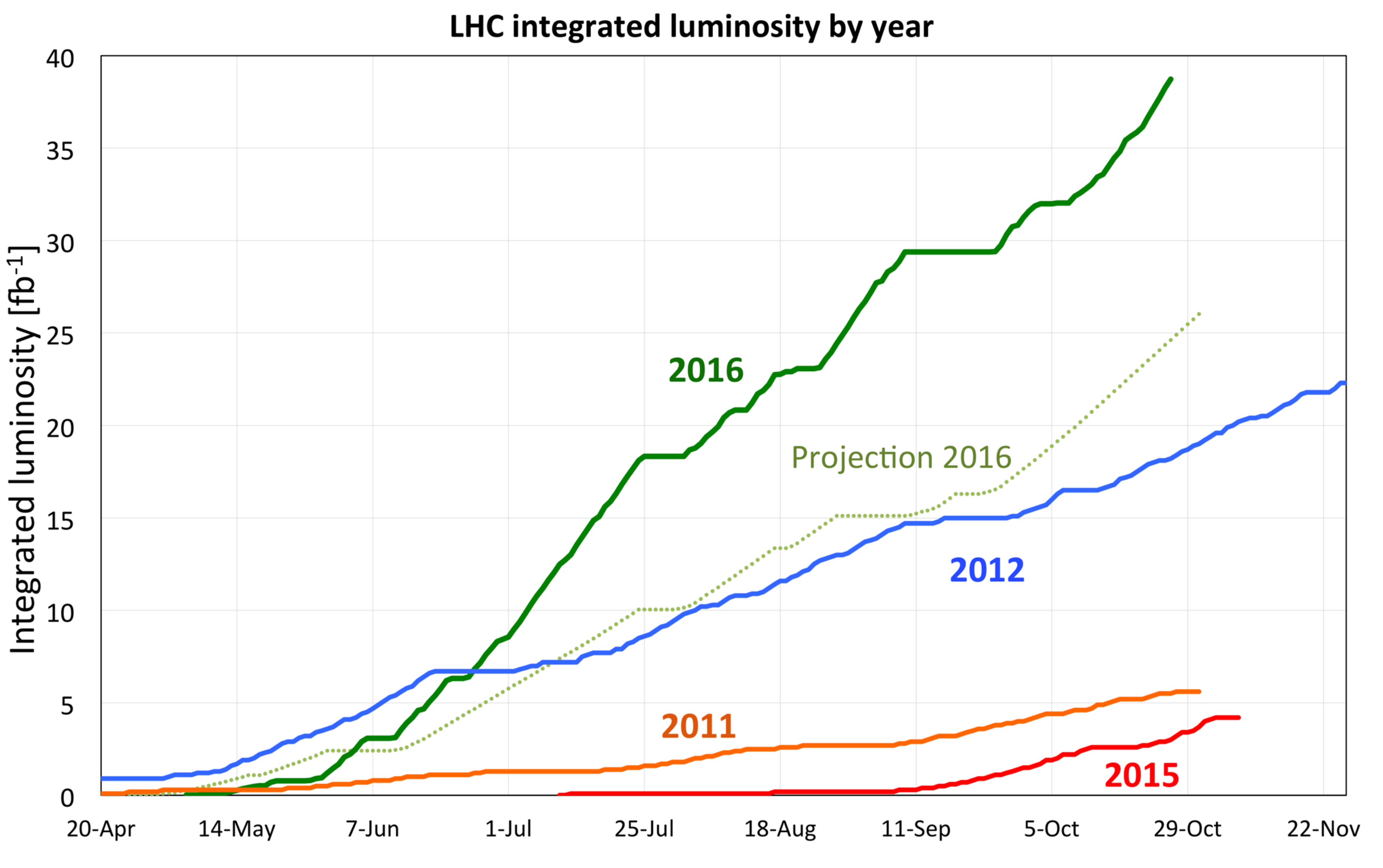
PS circumference

BCMS

(**B**atch **C**ompression, **M**erging & **S**plitting)



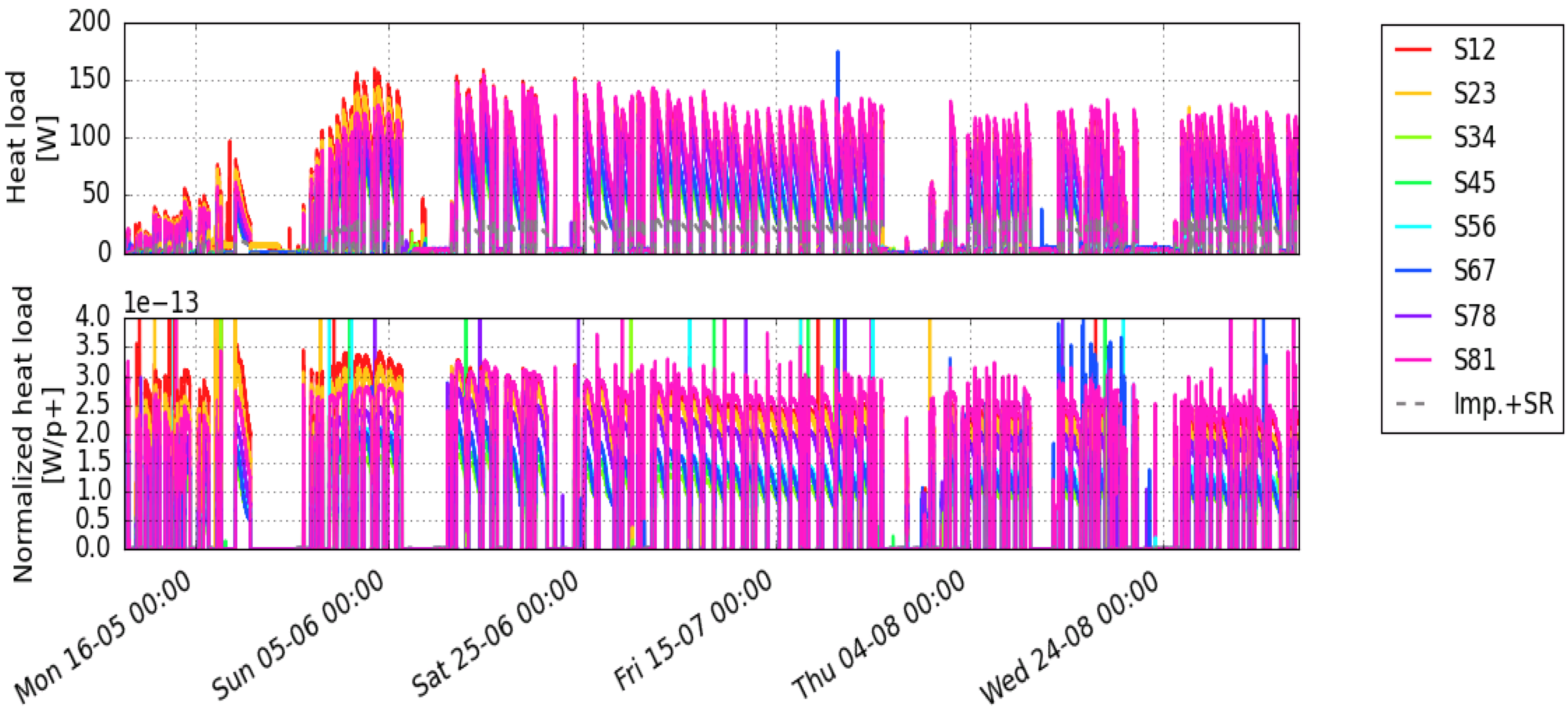
Lower intensity, **smaller** bunches from PSB


LHC integrated luminosity by year
Integrated luminosity [fb-1]
40
35
30
25
20
15
10
5
0
20-Apr
14-May
7-Jun
1-Jul
25-Jul
18-Aug
11-Sep
5-Oct
29-Oct
22-Nov
2016
Projection 2016
2012
2011
2015

2016
No one is more surprised than we are

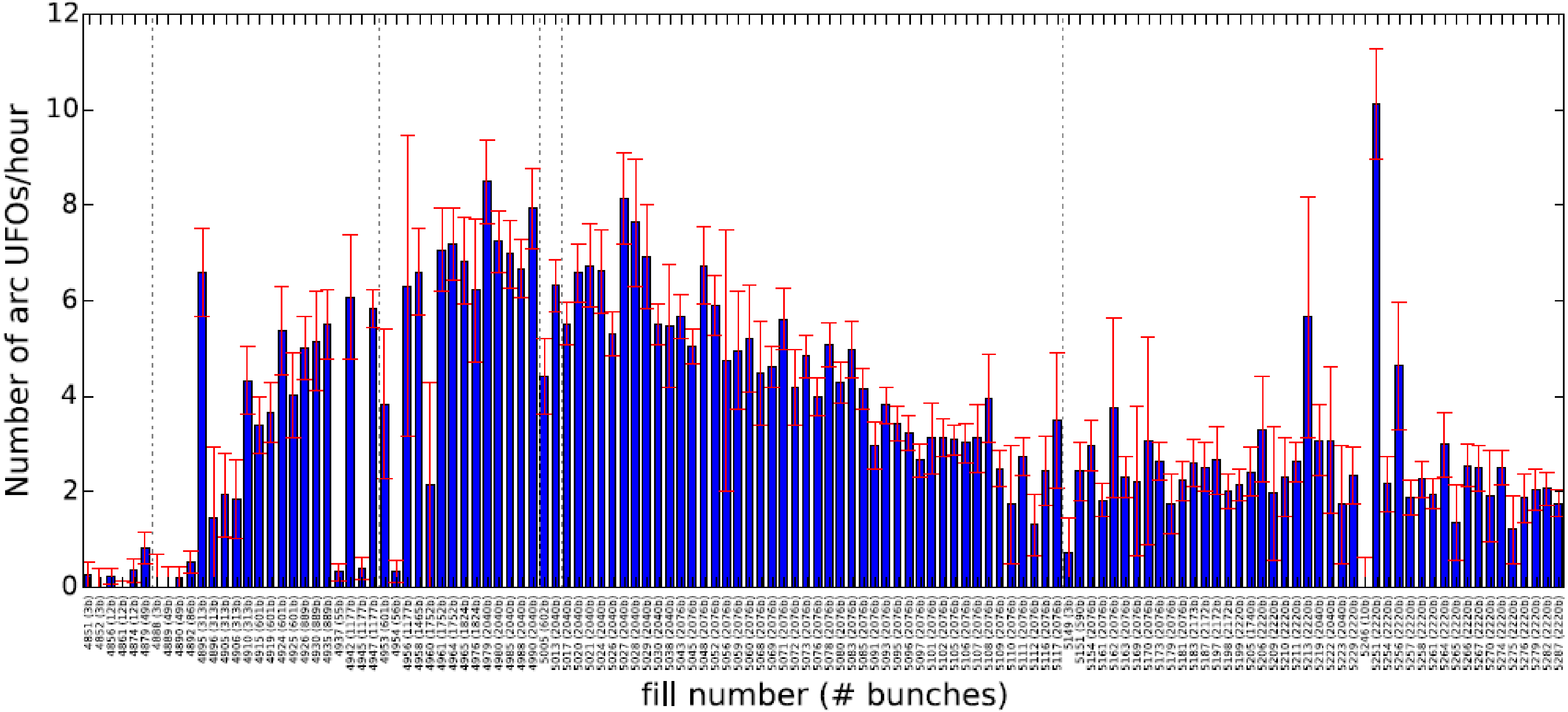
- Good peak luminosity, excellent luminosity lifetime
- Stunning availability
  - Sustained effort from hardware groups
- Few premature dumps – long fills
  - UFO rate down, radiation to electronics mitigated

Electron cloud – heat loads



Very slow electron cloud reduction despite significant doses

UFOs 2016

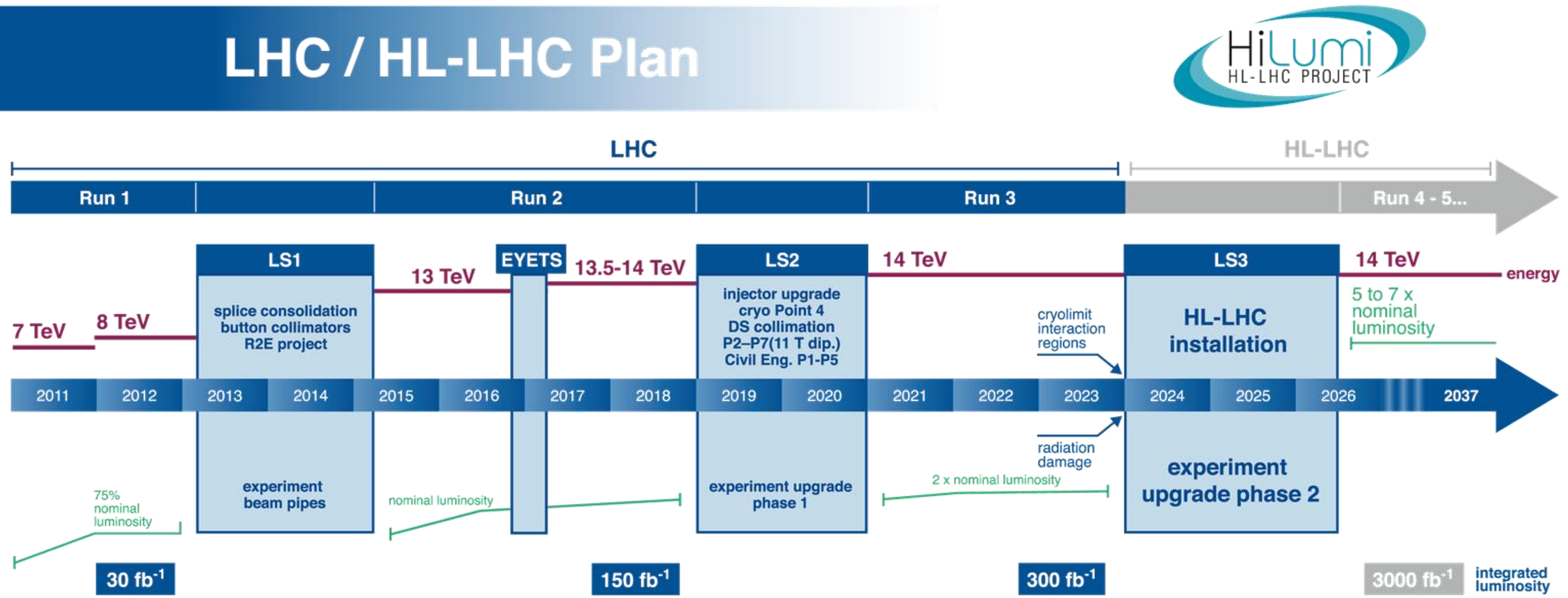


Machine status - summary

- Excellent and improved system performance
- Magnets behaving well at 6.5 TeV
- Good beam lifetime through the cycle
- Operationally things well under control
- Magnetically reproducible as ever
- Optically good, corrected to excellent
- Aperture is fine and compatible with the collimation hierarchy.

HL-LHC - goals

- Prepare machine for operation beyond 2025 and up to ~2035
- Operation scenarios for:
  - total integrated luminosity of 3000 fb^{-1} in around 10-12 years
  - an integrated luminosity of ~250 fb^{-1} per year
  - mu ≤ 140 (peak luminosity of $5x10^{34}$ $cm^{-2}s^{-1}$)



HL-LHC: key 25 ns parameters

Protons per bunch	2.2×10^{11}
Number of bunches	2748
Normalized emittance	2.5 micron
Beta*	20 cm
Crossing angle	510 microrad
Geometric reduction factor	0.39
Virtual luminosity	1.3×10^{35} $cm^{-2}s^{-1}$
Levelled luminosity	5×10^{34} $cm^{-2}s^{-1}$
Levelled <pile-up>	132

HL-LHC How?

- **Lower beta* (~20 cm)**
  - New inner triplet magnets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - High bunch population, low emittance, 25 ns beam

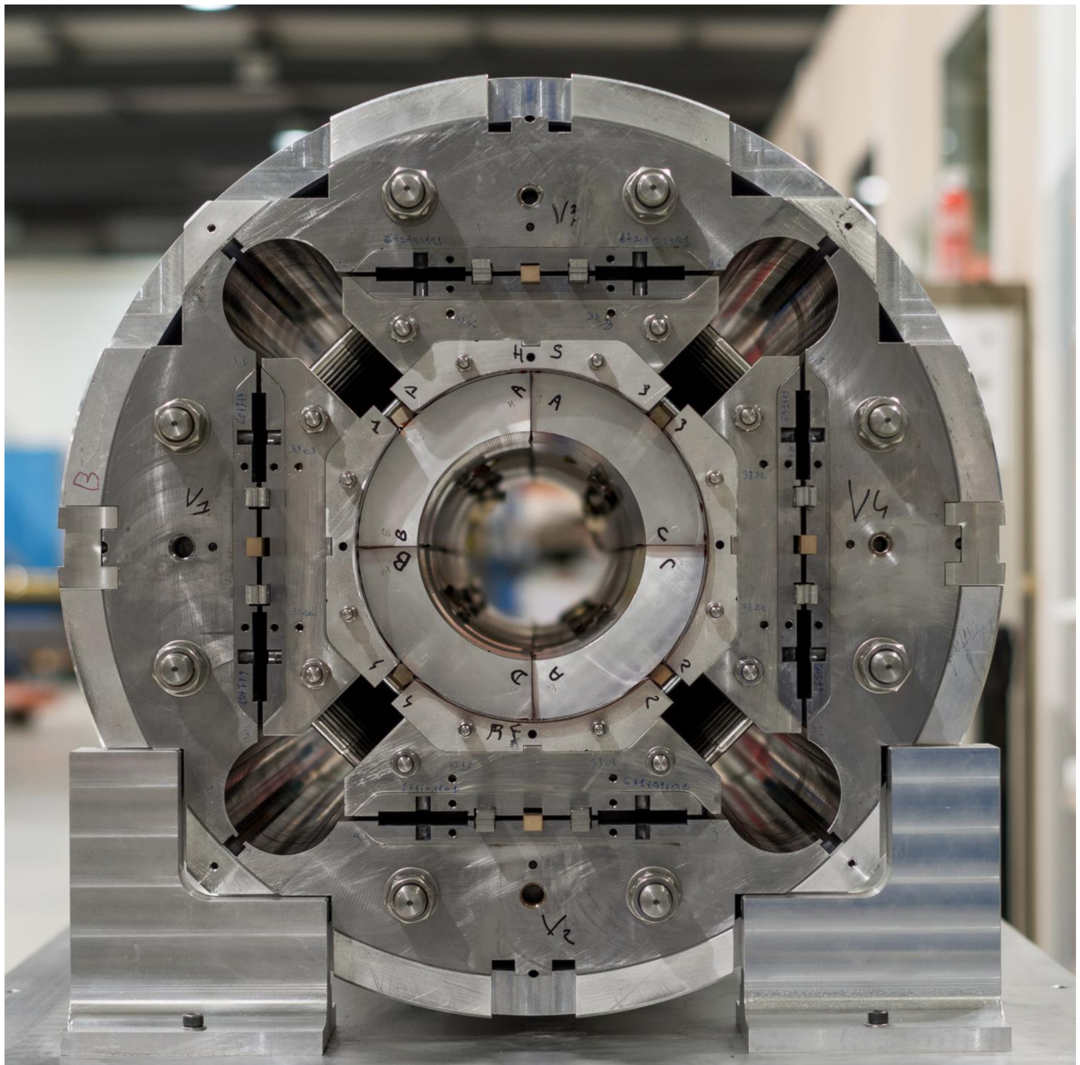
1. Squeeze harder

	2016	HL-LHC
β*	40 cm	20 cm
Beam size at IP (sigma)	17 um	8 um
β at triplet	~4.5 km	~20 km
Beam size at triplet	1.5 mm	2.6 mm
Crossing angle	370 urad	510 urad

The reduction in beam size buys luminosity but:

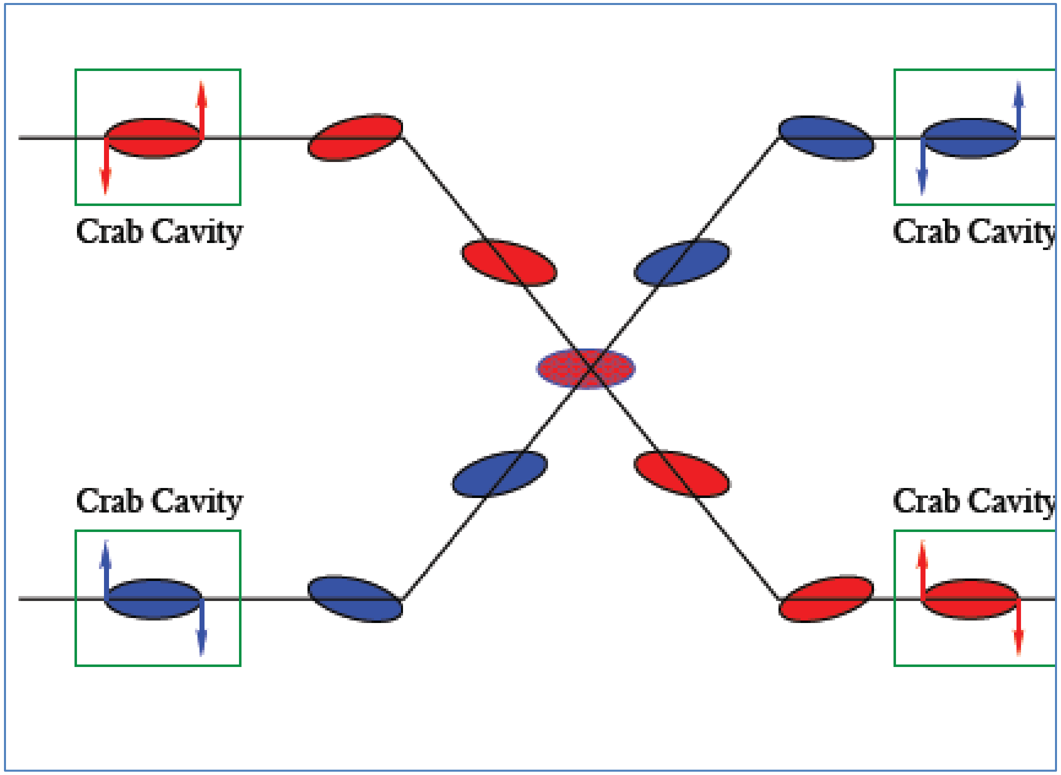
- Bigger beams in inner triplets and so
- Larger crossing angle
- And thus larger aperture in inner triplets is required.

Challenge:
build a wide aperture quadrupole



2. Crossing angle compensation

Attempt to claw back the very significant reduction in luminosity from the large crossing angle



Crab Cavity

- Create a oscillating transverse electric field
- Kick head and tail of the bunch in opposite directions

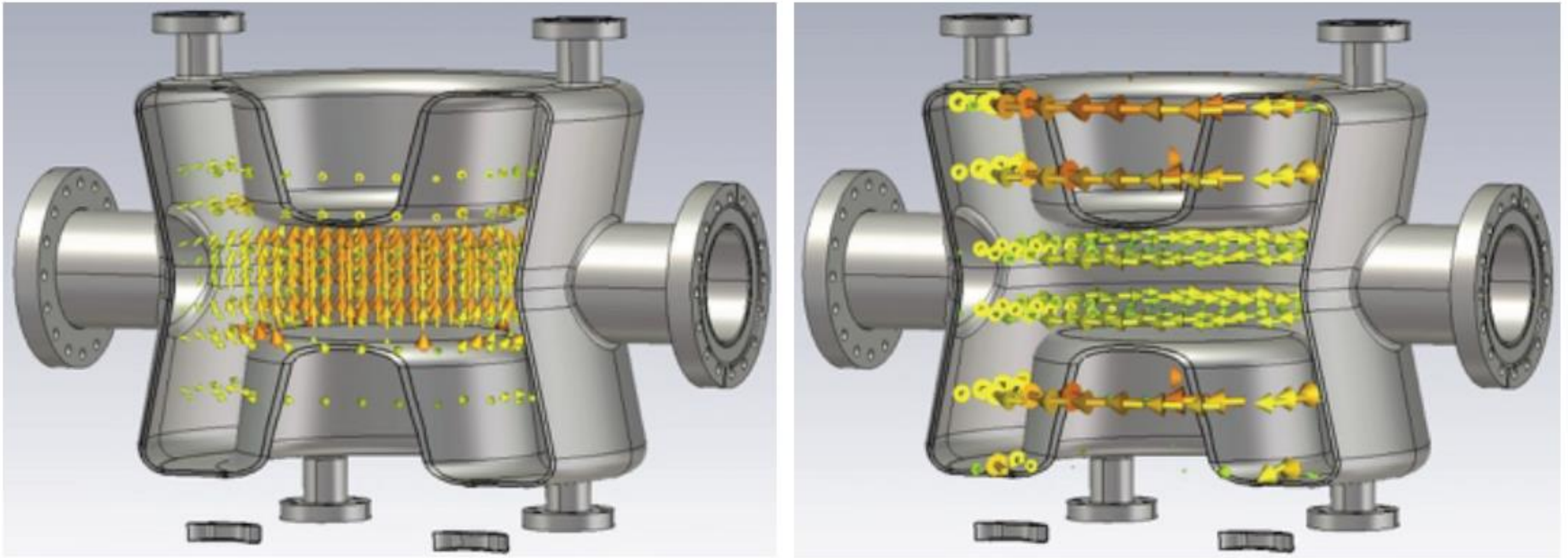


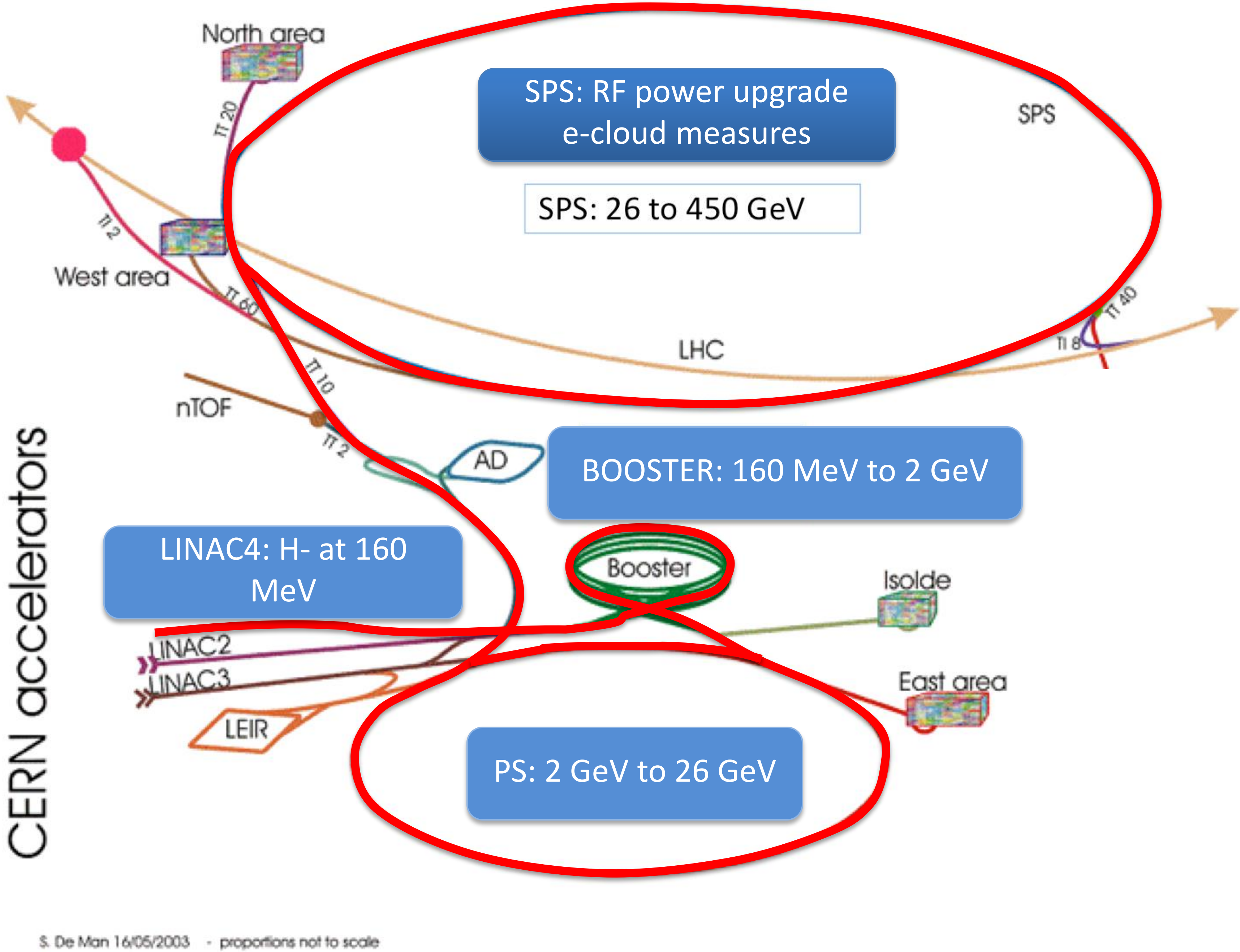
Figure 4. Electric (left) and magnetic (right) field distributions inside the DQWCC.

3. High brightness beams from injectors

25 ns	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)	B_l (ns)
2012	1.2	2.6	1.5
HL-LHC	**2.3**	**2.1**	**1.7**

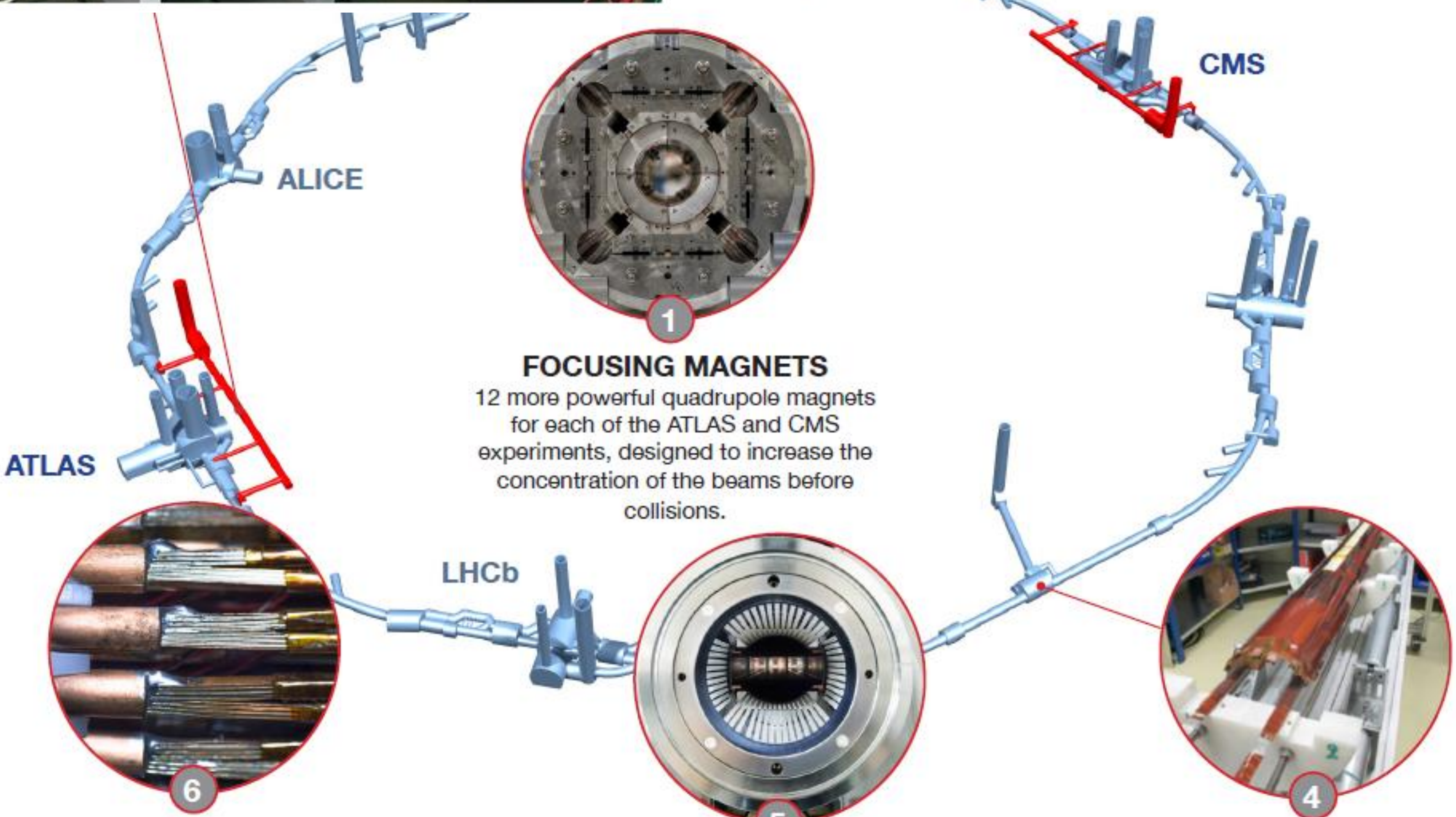
Injectors must produce 25 ns proton beams with about double intensity and higher brightness

A cascade of improvements is needed across the whole injector chain to reach this target



SPS: RF power upgrade
e-cloud measures
SPS: 26 to 450 GeV
SPS
North area
TT 20
West area
TT 2
TT 60
LHC
TT 40
TI 8
TT 10
nTOF
TT 2
AD
BOOSTER: 160 MeV to 2 GeV
LINAC4: H- at 160 MeV
Booster
Isolde
LINAC2
LINAC3
LEIR
East area
PS: 2 GeV to 26 GeV
CERN accelerators
S. De Man 16/05/2003 - proportions not to scale

March 2016: Nb_3Sn quadrupole model (1.5 m long, aperture =150 mm) reached current of 18 kA (nominal: 16.5 kA) at FNAL. 2 coils from CERN + 2 coils from US.



FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

CERN Novembre 2015

HL-LHC out to 2035+

Project now approved