LHC operations past and future:
part 3

- Overview of performance and limitations
- LS1, Run II and the next 10 years

Mike Lamont
with acknowledgements to all the people whose material I've used
(including Roderik Bruce, Stefano Redaelli, Tobias Baer, Giovanni Iadarola…)

Luminosity

$$L = F \frac{N_{b1} N_{b2} f_{rev} k_b}{2\pi \sqrt{\left(\sigma_{x1}^2 + \sigma_{x2}^2\right)\left(\sigma_{y1}^2 + \sigma_{y2}^2\right)}} . \exp\left\{ - \frac{\left(\bar{x}_1 - \bar{x}_2\right)^2}{2\left(\sigma_{x1}^2 + \sigma_{x2}^2\right)} - \frac{\left(\bar{y}_1 - \bar{y}_2\right)^2}{2\left(\sigma_{y1}^2 + \sigma_{y2}^2\right)} \right\}$$

$$F = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}}$$

Geometrical reduction factor due to the crossing angle

N_1, N_2 number of particles per bunch

k – number bunches per beam

f – revolution frequency

σ^* – beam size at IP

θ_c – crossing angle

σ_z – bunch length

Make some simplifying assumptions:

- **beam 1 = beam 2**
- **round beams at interaction point**
- **collide head-on**

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**

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

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

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

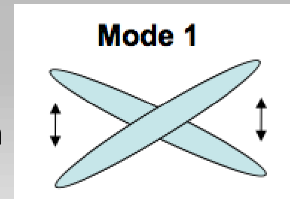
$$\sigma^* = 11.6 \times 10^{-6} \text{ m}$$

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

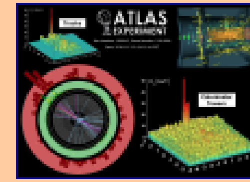
Feb 27
Beam back

March 30
First collisions
3.5 TeV

June
Commission
nominal bunch
intensity



November: jet
"quenching" in HI

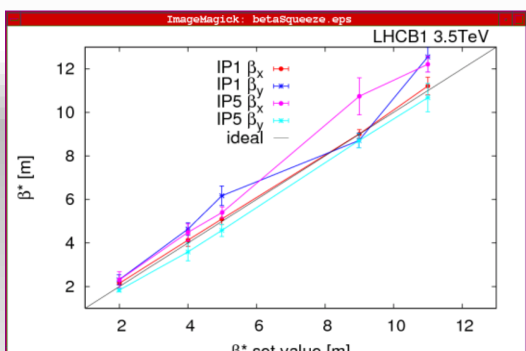


November 4
Switch to lead
ions

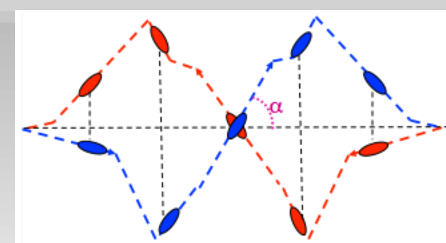
QUALIFICATION

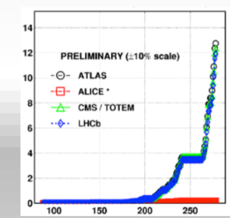
February	March	April	May	June	July	August	September	October	November

April
Commission
squeeze



September
Crossing angles on





October 14 2010
1e32
248 bunches

2010

Total for year: 50 pb^{-1}

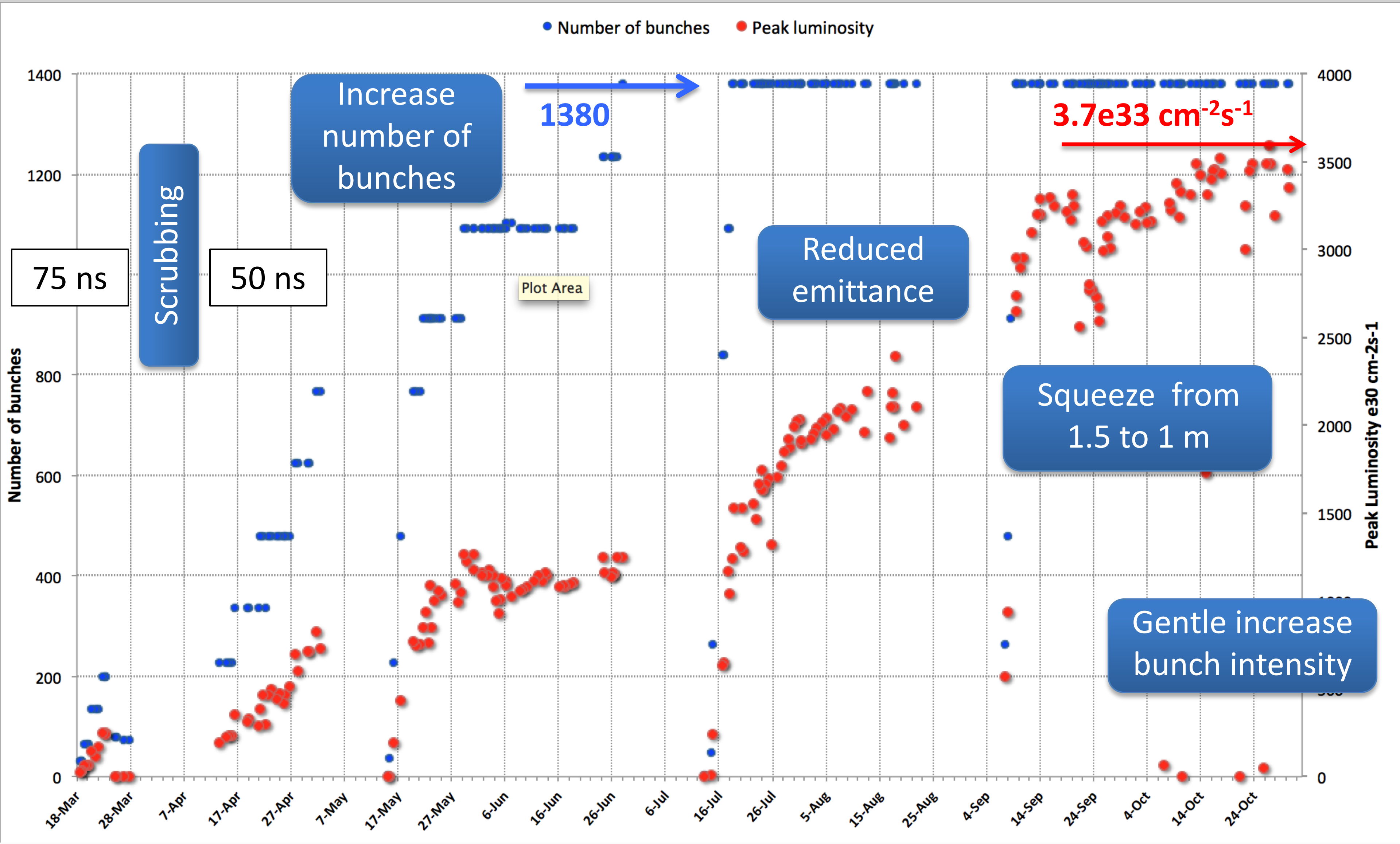
First 7 TeV collisions – that was close

You lucky, lucky buggers!!!


30-Mar-2010 12:28:46 Fill #: 1005 Energy: 2982.0 GeV I(B1): 2.00e+10 I(B2): 2.01e+10
ATLAS ALICE CMS LHCb
Experiment Status STANDBY PHYSICS STANDBY STANDBY
Instantaneous Luminosity
BRAN Count Rate
BKGD 1
BKGD 2
BKGD 3
LHCf
LHCb VELO Position
TOTEM:
CALIBRATION
Monitoring set: S34-A34-RB
30 March, 2010, 12:28:49
RB.A34 [5023 A] [2.97 TeV]
Time of Day
LHC Page1
Fill: 1005
E: 2986 GeV
30-03-2010 12:28:49
BEAM SETUP: RAMP
Energy: 2986 GeV
I(B1): 1.82e+10
I(B2): 1.85e+10
Comments 30-03-2010 11:52:19 :
Ramping again
BIS status and SMP flags
Link Status of Beam Permits
Global Beam Permit
Setup Beam
Beam Presence
Moveable Devices Allowed In
Stable Beams
PM Status B1 ENABLED
PM Status B2 ENABLED
LHC Operation in CCC : 77600, 70480
IP1-ATLAS (Horizontal)
IP2-ALICE (Horizontal)
IP5-CMS (Vertical)
IP8-LHCb (Vertical)
Position (mm)
BPM Position (m)

2011

3.5 TeV
Beta* = 1.5 m



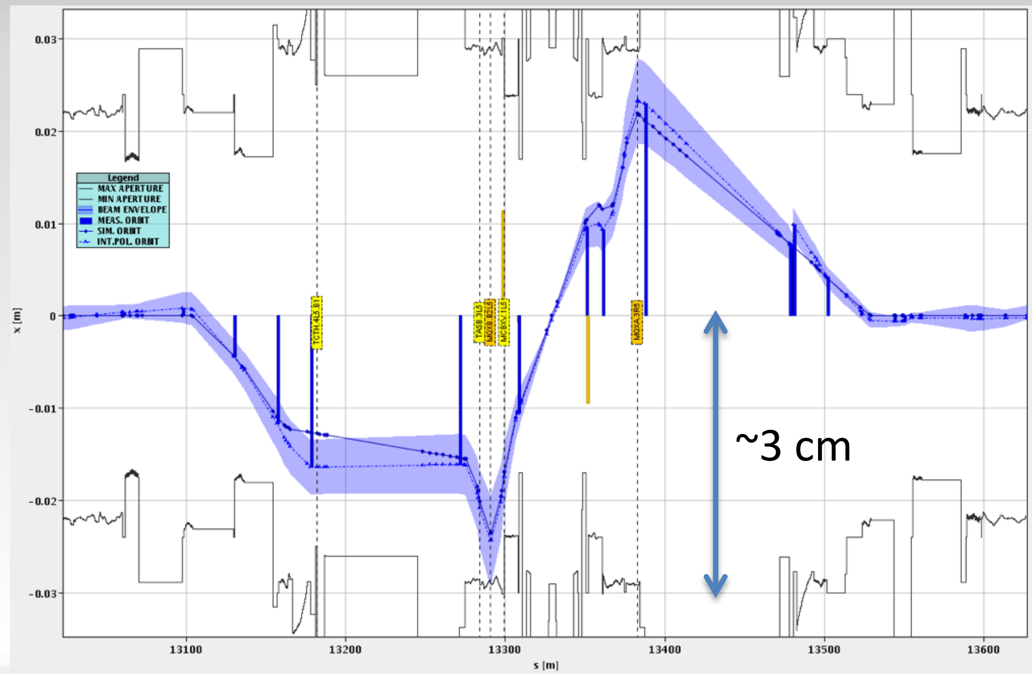
IR1 and IR5 aperture at 3.5 TeV

2011's "platinum mine"

*We got **4-6 sigmas** more than the expected 14 sigma*

Triplet aperture compatible with a well-aligned machine, a well centred orbit and a ~ design mechanical aperture

CMS



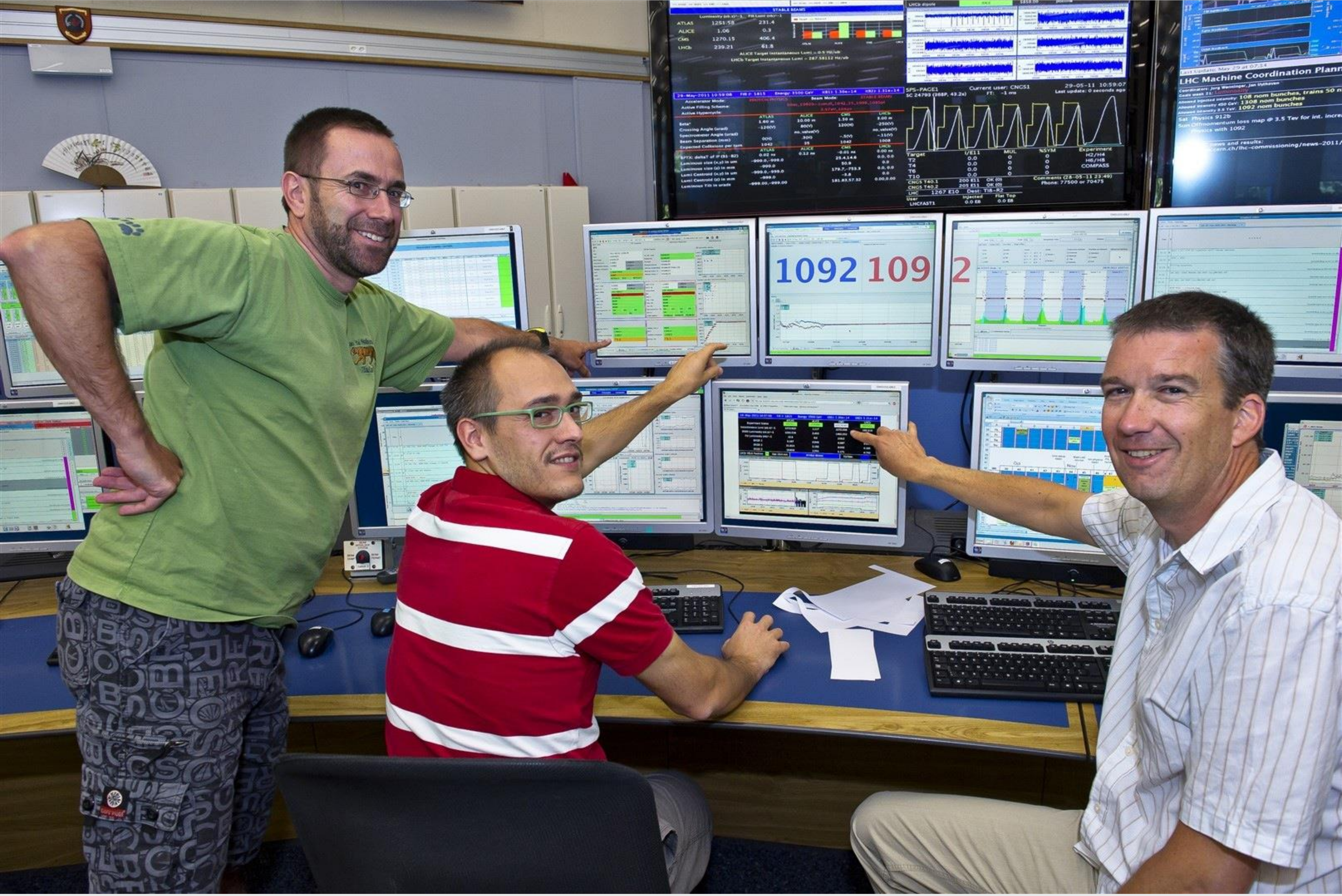
Stefano Redaelli

~600 m

Addition margin allowed squeeze to beta* = 1 m

– big success – luminosity up to 3.3e33 $cm^{-2}s^{-1}$

Stefano Redaelli



Sunday 29 May 2011:
2 x 1092 bunches colliding, luminosity above 1.2 x 10^33, and a beam energy of 73 MJ.

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

4 TeV
50 ns
Beta* = 60 cm
Tight collimator settings

18 April
1380 bunches
5.5e33 $cm^{-2}s^{-1}$

March 15
Beam back

4 July

13-14 September
Proton-lead test

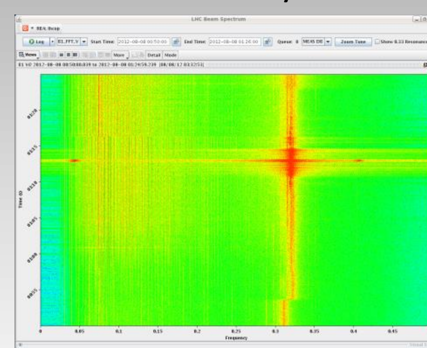
March	April	May	June	July	August	September	October	November	December

March 18
Squeezed to 60 cm

6 June
6.8e33 $cm^{-2}s^{-1}$

7 August
Flip octupole polarity
Raise chromaticity

ICHEP2012
Melbourne



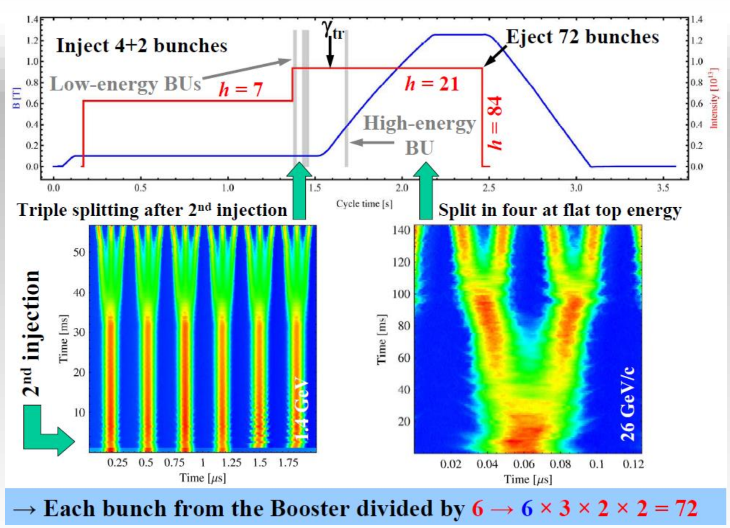
December
25 ns scrubbing run

2012

18 June: end running period ~6.7 fb^{-1} for summer conferences

Performance from injectors 2012

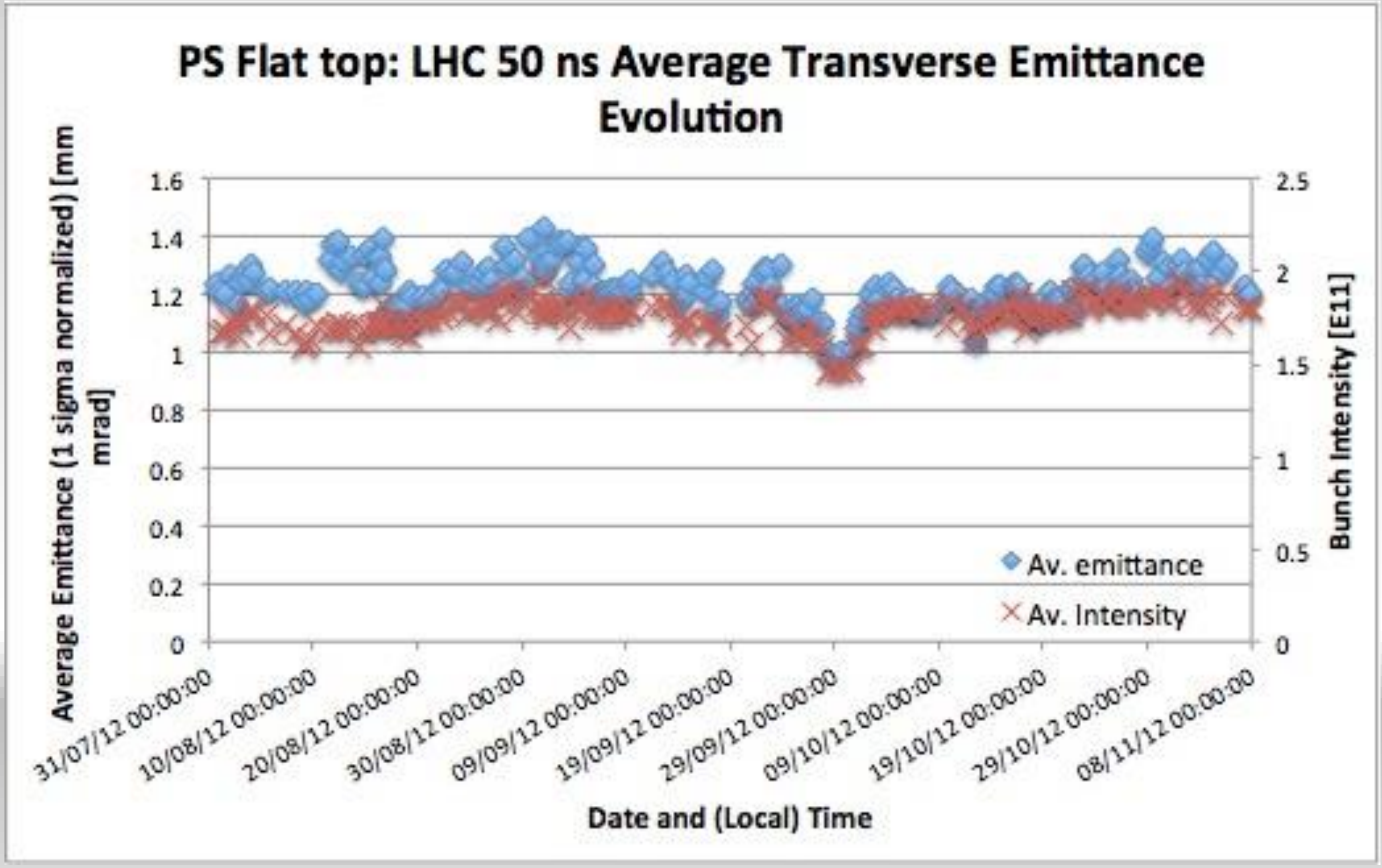
Bunch spacing [ns]	Protons per bunch [ppb]	Norm. emittance H&V [μm] Exit SPS
50	1.7×10^{11}	1.8
25	1.2×10^{11}	2.7
25 (design report)	1.15×10^{11}	3.75



Chose to stay with 50 ns:

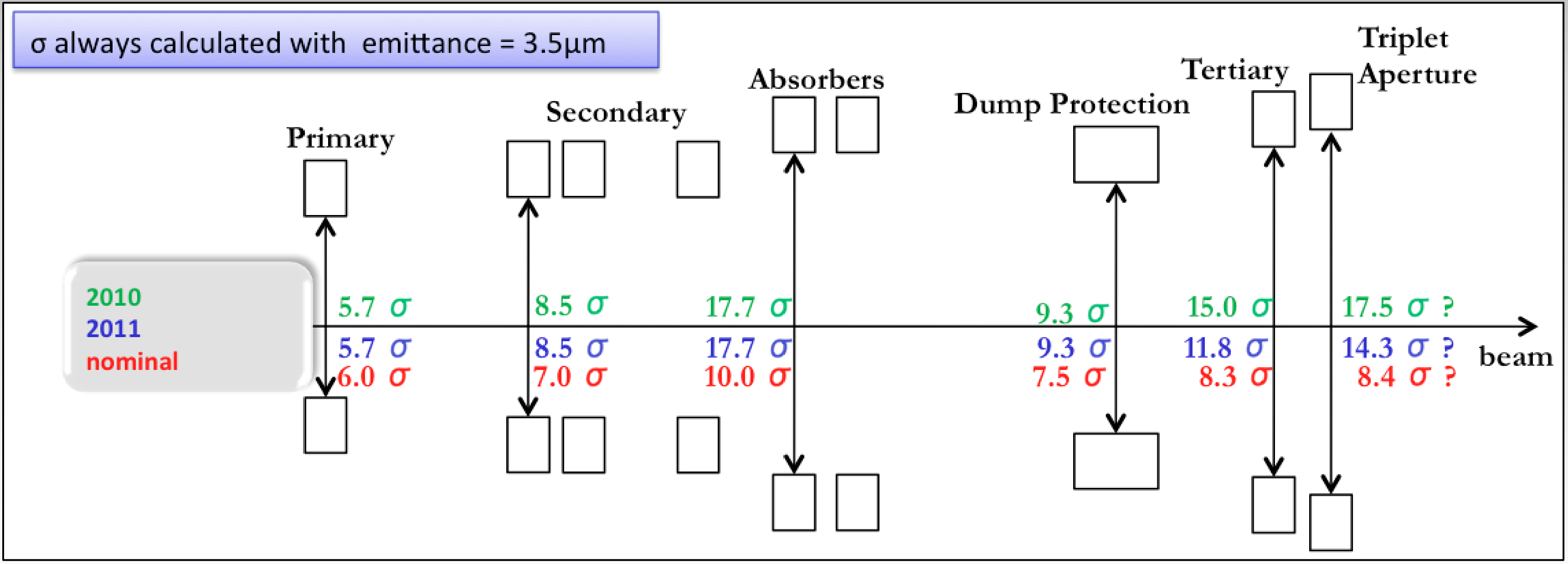
- I_b^2
- lower total intensity
- less of an electron cloud challenge

Performance from injectors 2012



The very good performance does not come without constant monitoring and optimization.

Collimator settings 2012



Collimation hierarchy has to be respected in order to achieve satisfactory protection and cleaning.

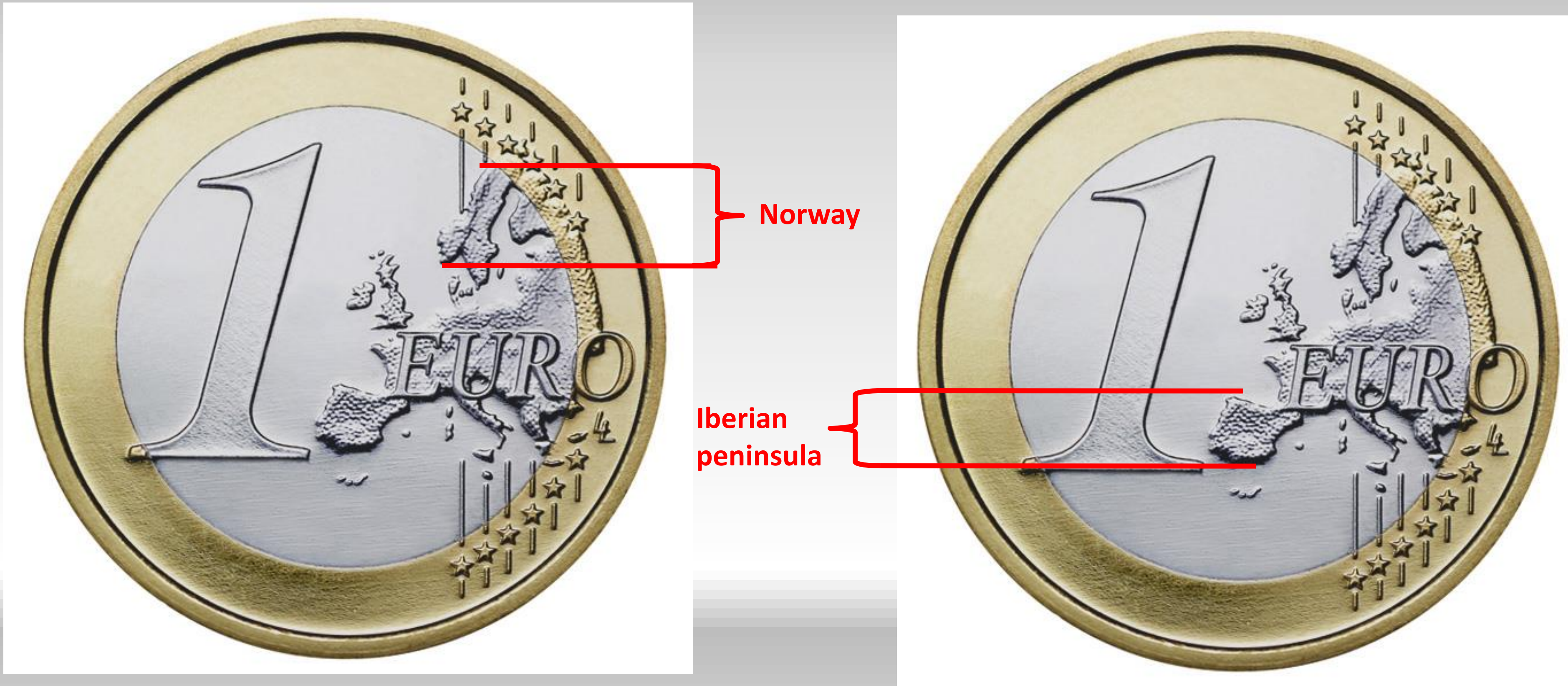
Aperture plus tight settings allowed us to squeeze to 60 cm.

2012: tight settings

	σ
TCP 7	4.3
TCSG 7	6.3
TCLA 7	8.3
TCSG 6	7.1
TCDQ 6	7.6
TCT	9.0
Aperture	10.5

Roderik Bruce

Tight collimator settings

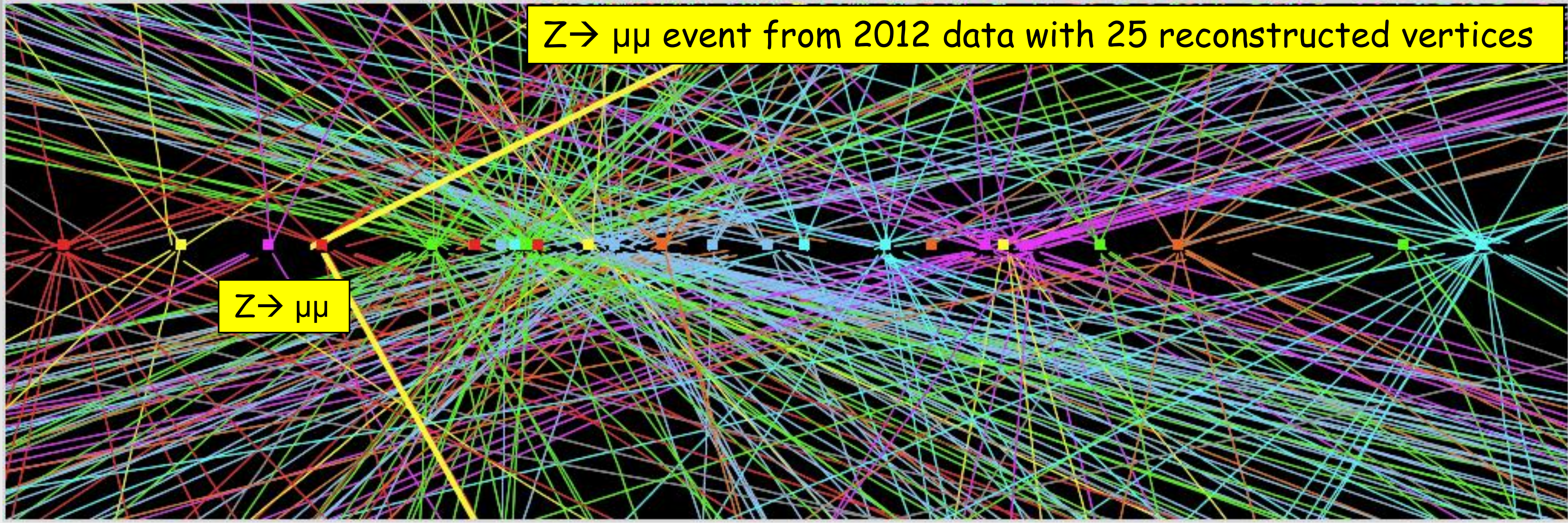


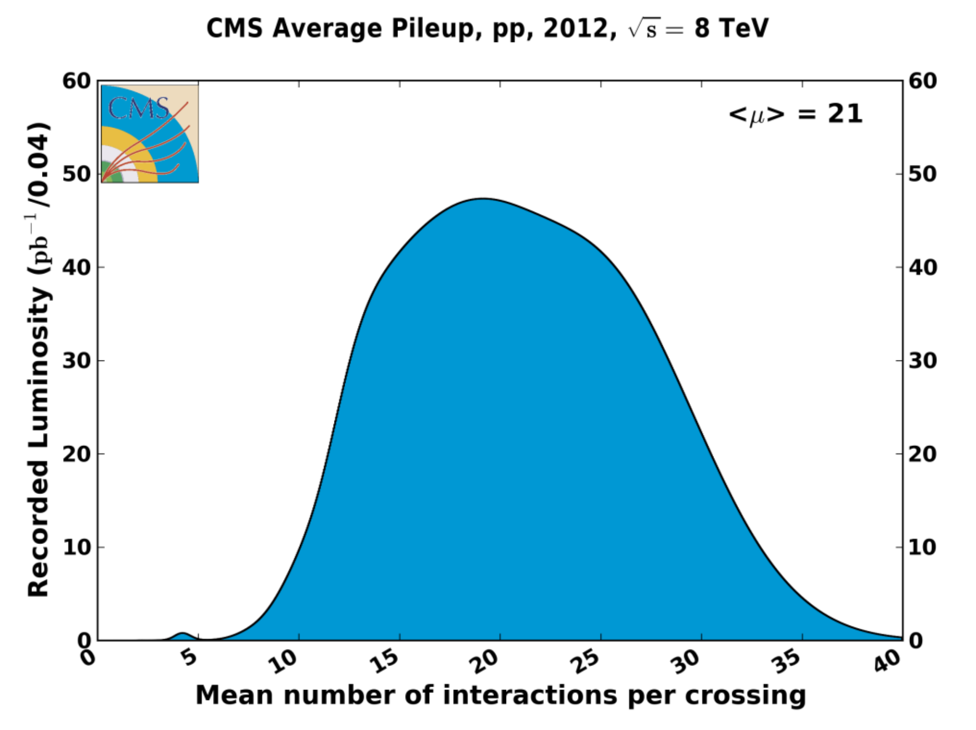
Intermediate settings (2011):
~3.1 mm gap at
primary collimator

Tight settings (2012):
~2.2 mm gap at
primary collimator

Peak performance through the years

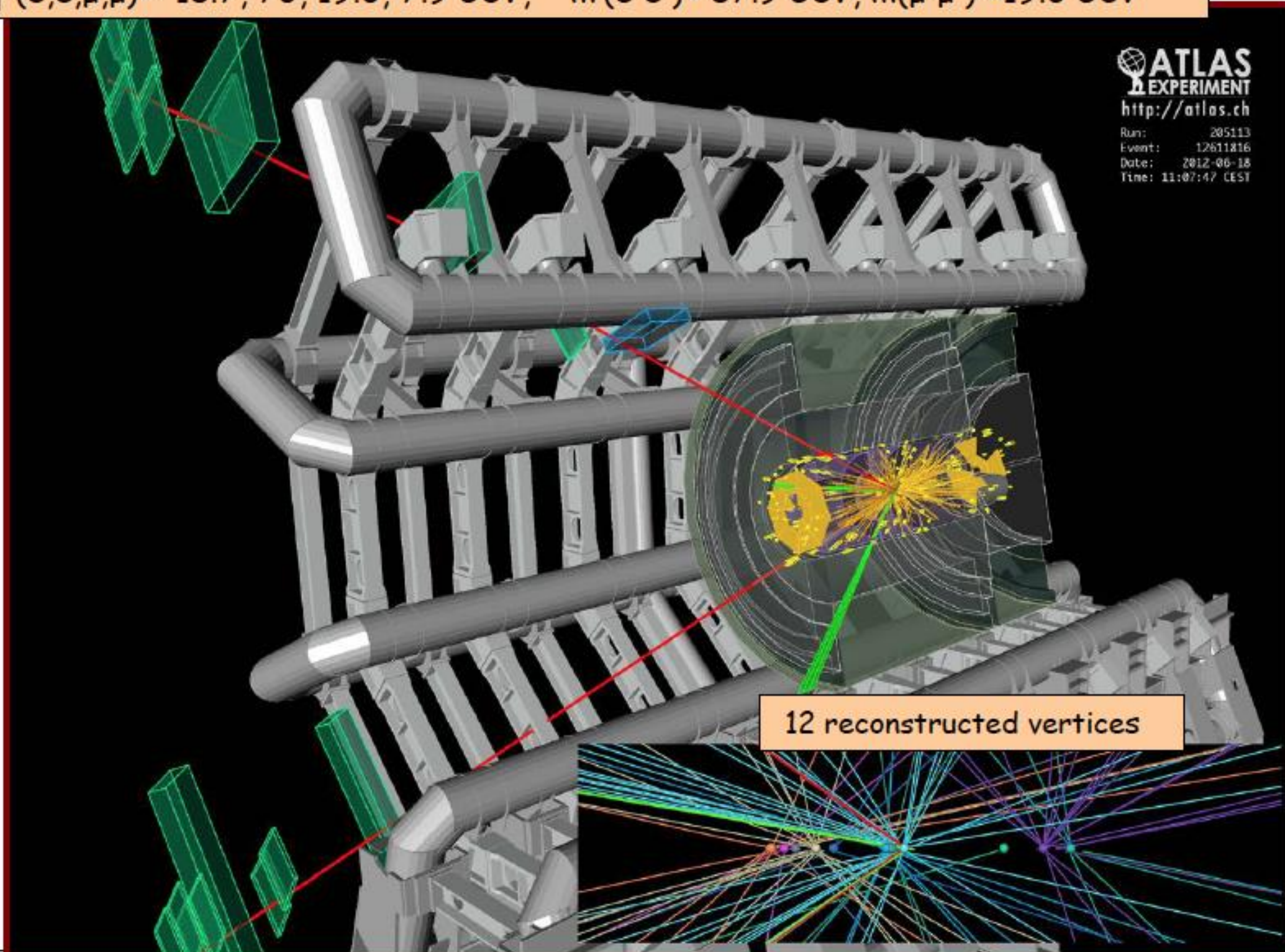
	2010	2011	2012	Nominal
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

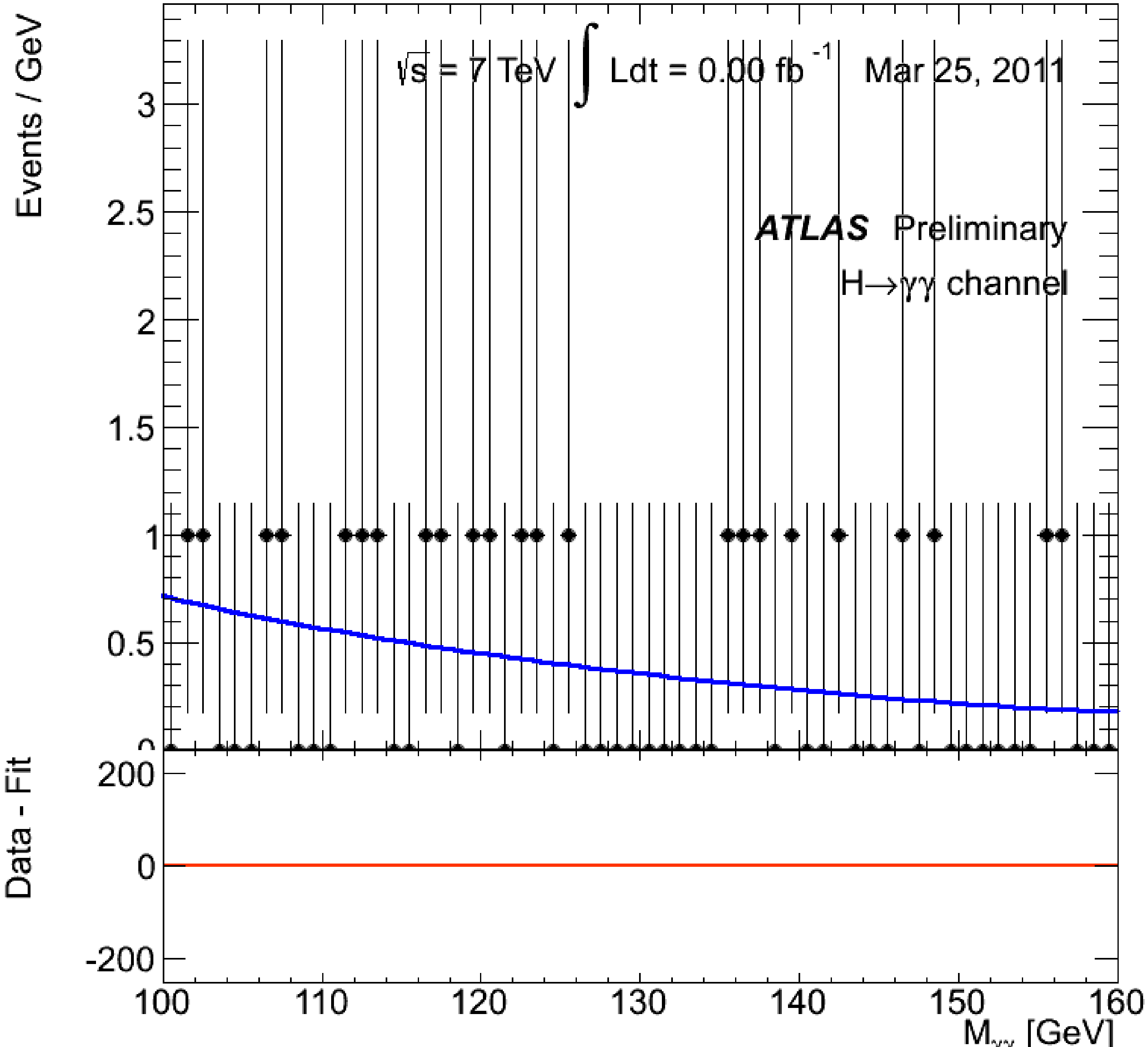

Z→ μμ event from 2012 data with 25 reconstructed vertices
Z→ μμ


CMS Average Pileup, pp, 2012, $\sqrt{s} = 8$ TeV
<μ> = 21
Recorded Luminosity (pb^{-1}/0.04)
Mean number of interactions per crossing
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40

2e2μ candidate with $m_{2e2\mu}$= 123.9 GeV

p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV





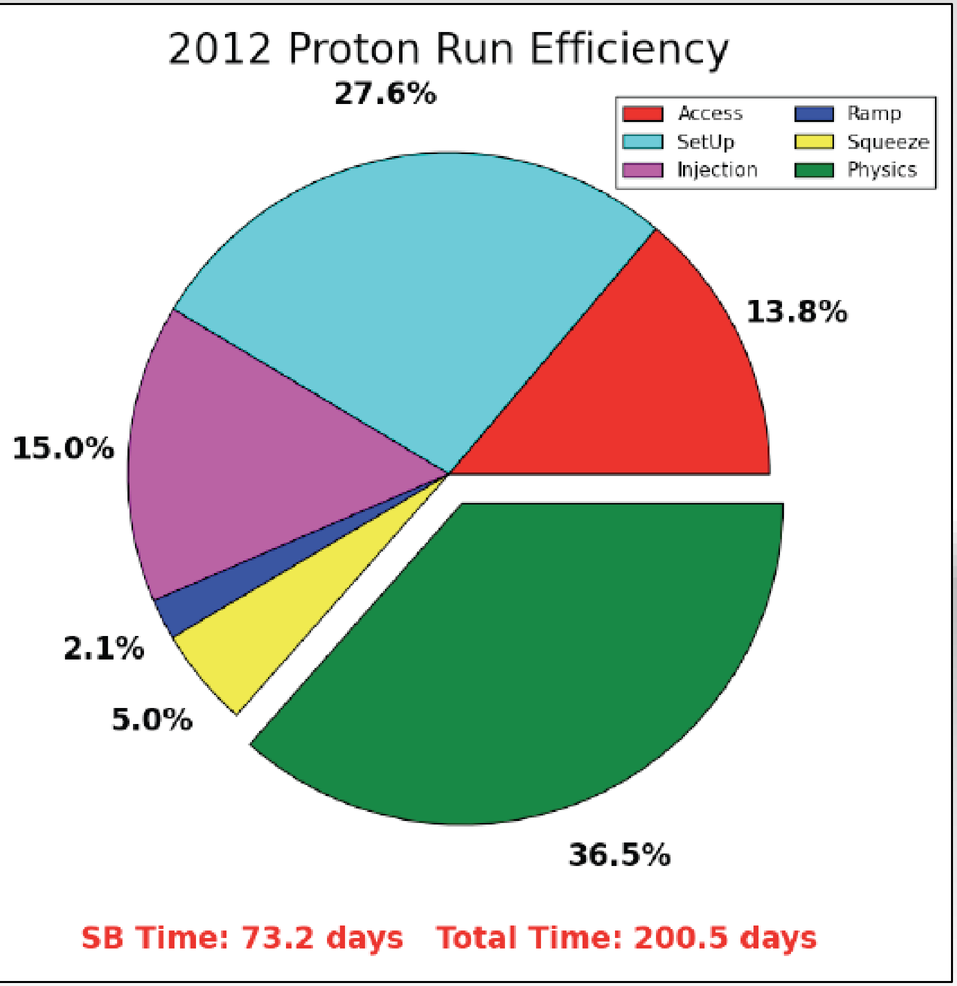
√s = 7 TeV ∫ Ldt = 0.00 fb -1 Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
Data - Fit
M γγ [GeV]

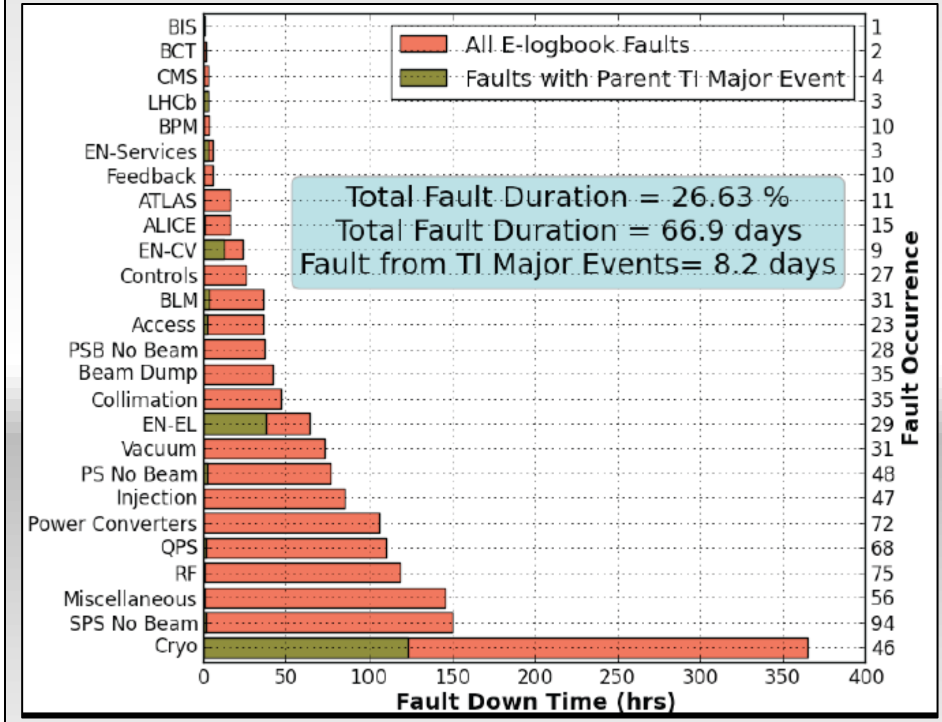
Operational efficiency has, at least occasionally, been not so bad

	2010	2011	2012
Max. luminosity in one fill [pb^{-1}]	6	122	237
Max. luminosity delivered in 7 days [pb^{-1}]	25	584	1350
Longest time in stable beams for 7 days	69.9 hours (41.6%)	107.1 hours (63.7%)	91.8 hours (54.6%)

Availability

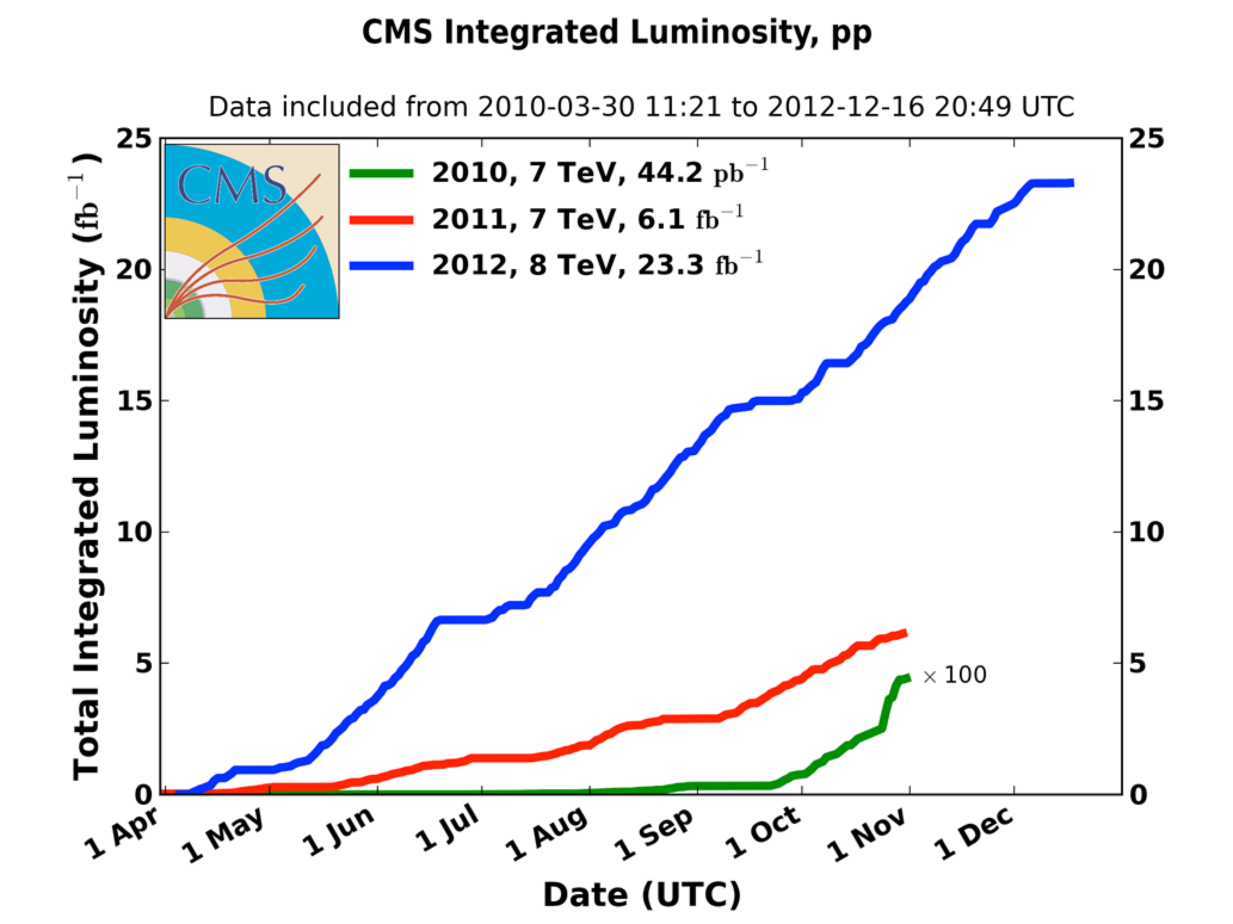
- There are a lot of things that can go wrong – it's always a battle
- But pretty good considering the complexity and principles of operation





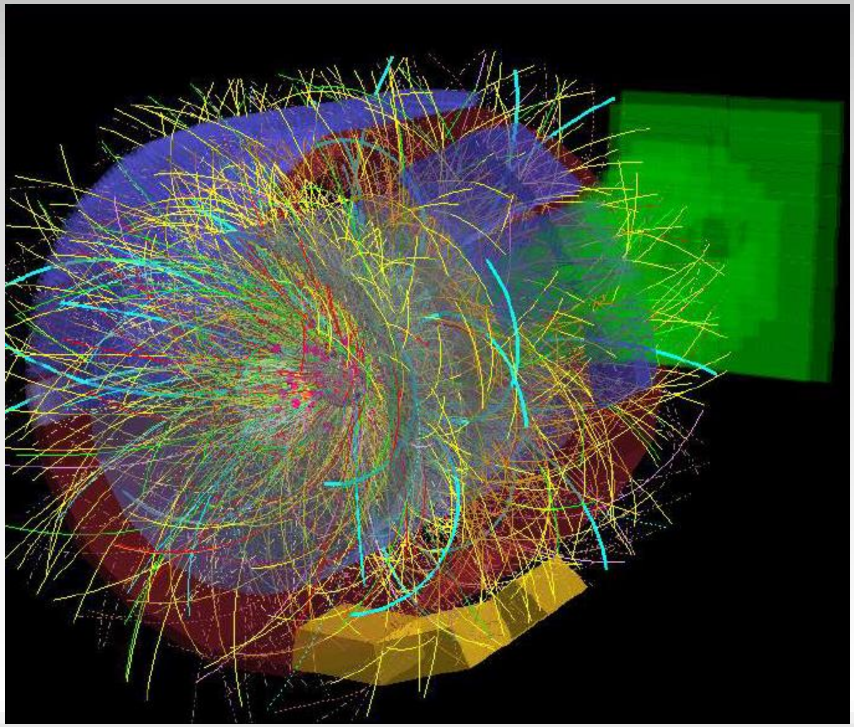
Cryogenics availability in 2012: 93.7%

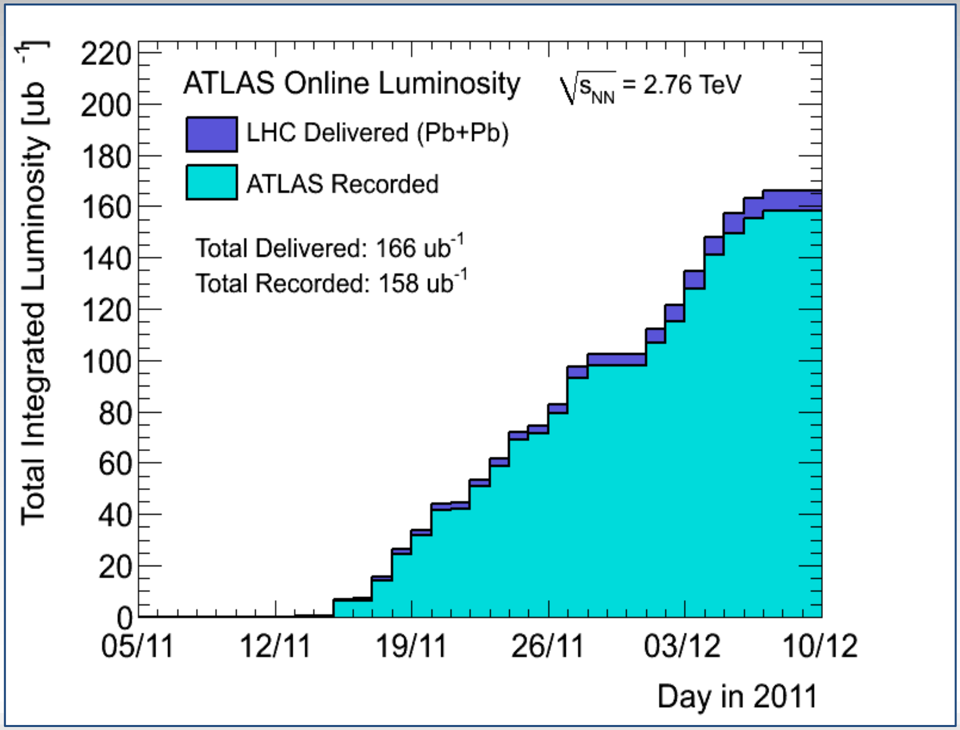
Integrated luminosity 2010-2012



- 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

Pb-Pb

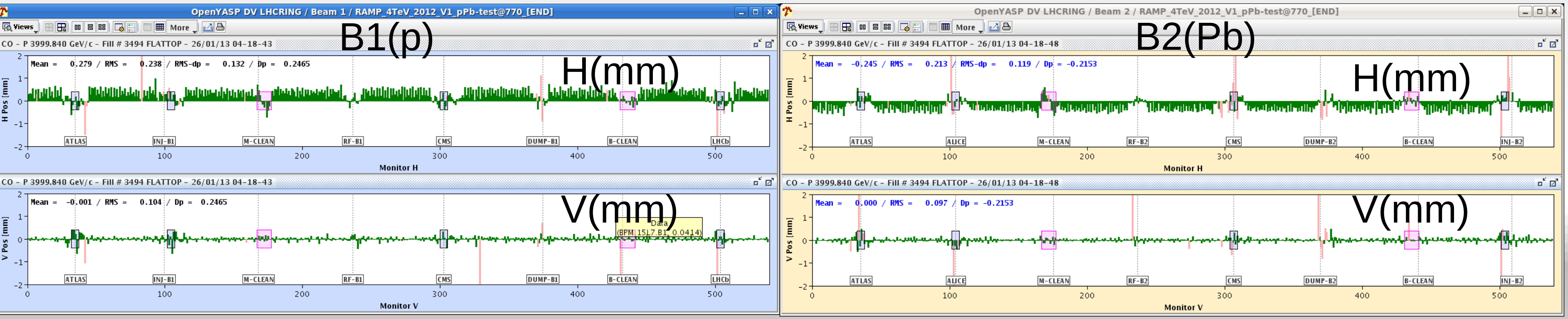




- Good performance from the injectors - bunch intensity and emittance
- Preparation, Lorentz's law: impressively quick switch from protons to ions
- Peak luminosity around 5 x 10^{26} $cm^{-2}s^{-1}$ at 3.5Z TeV – nearly twice design when scaled to 6.5Z TeV

Proton-lead

- Beautiful result
- Final integrated luminosity above experiments' request of 30 nb^{-1}
- Injectors: average number of ions per bunch was ~$1.4x10^8$ at start of stable beams, i.e. around twice the nominal intensity



Beam orbits at top energy with RF frequencies locked to B1

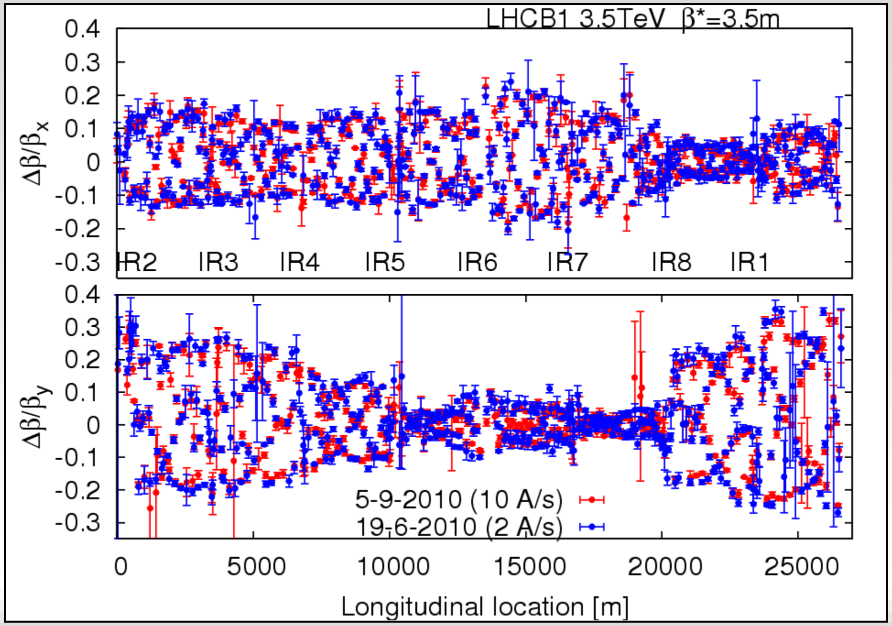
WHAT WE KNOW

In general – optics etc.

- Linear optics: remarkably close to model, beating good and corrected to excellent
- Very good magnetic model
  - including dynamic effects
- Better than expected aperture
  - tolerances, alignment
- Beta* reach established and exploited
  - aperture, collimation, optics

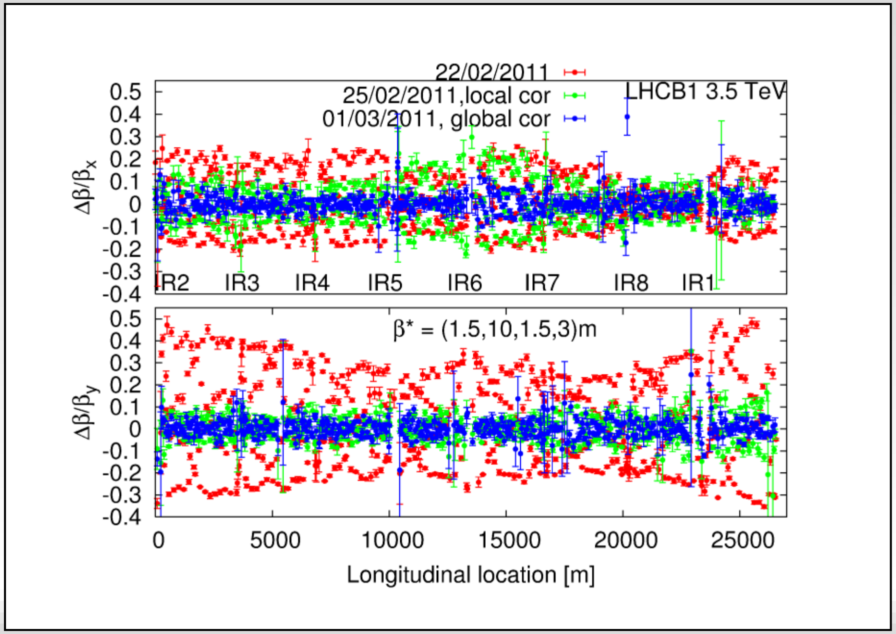
Optics

Optics stunningly stable



Two measurements of beating at 3.5 m 3 months apart

and well corrected



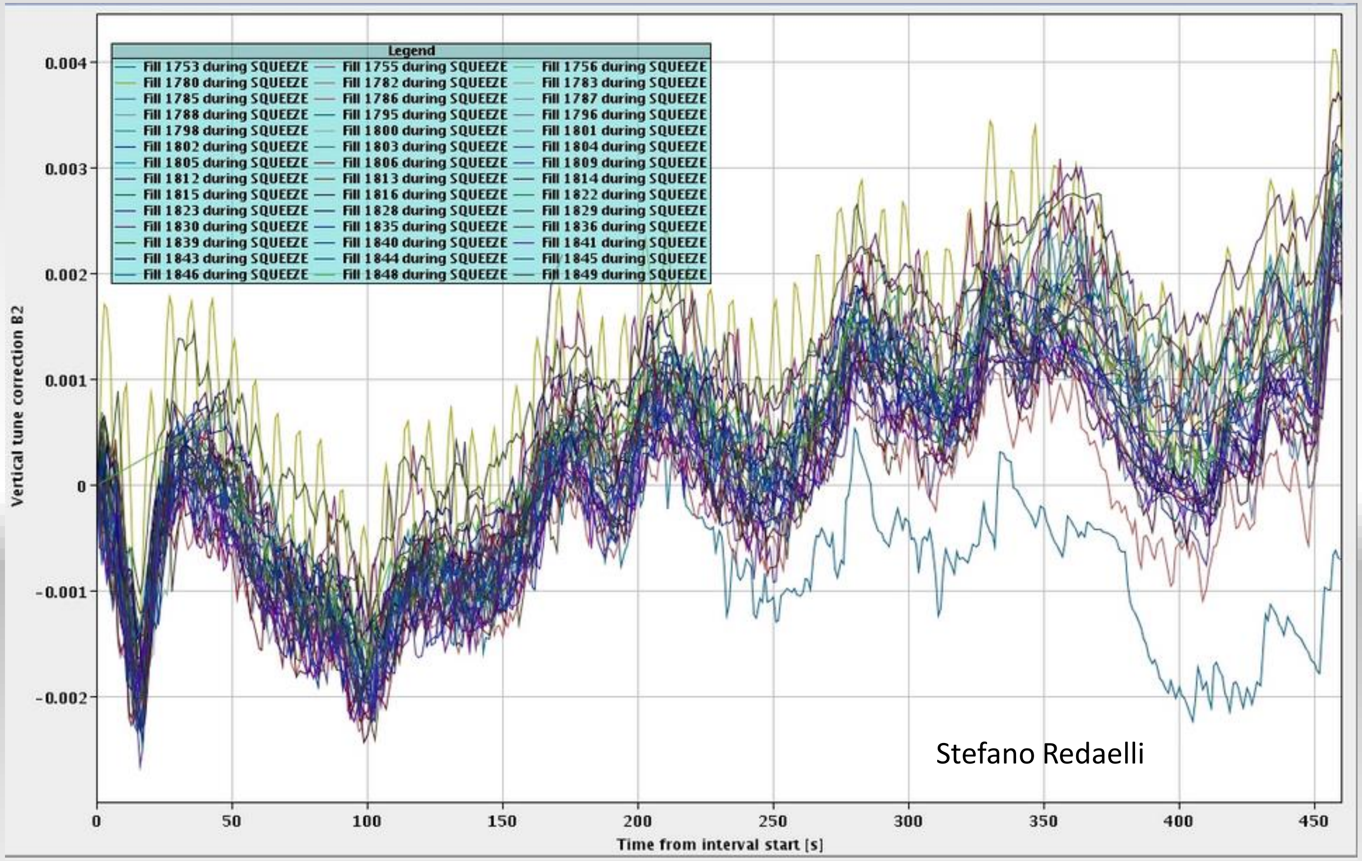
Local and global correction at 1.5 m

Rogelio Tomas Garcia and team

Reproducibility

LHC magnetically reproducible with rigorous pre-cycling:
optics, orbit, collimator set-up, tune, chromaticity…

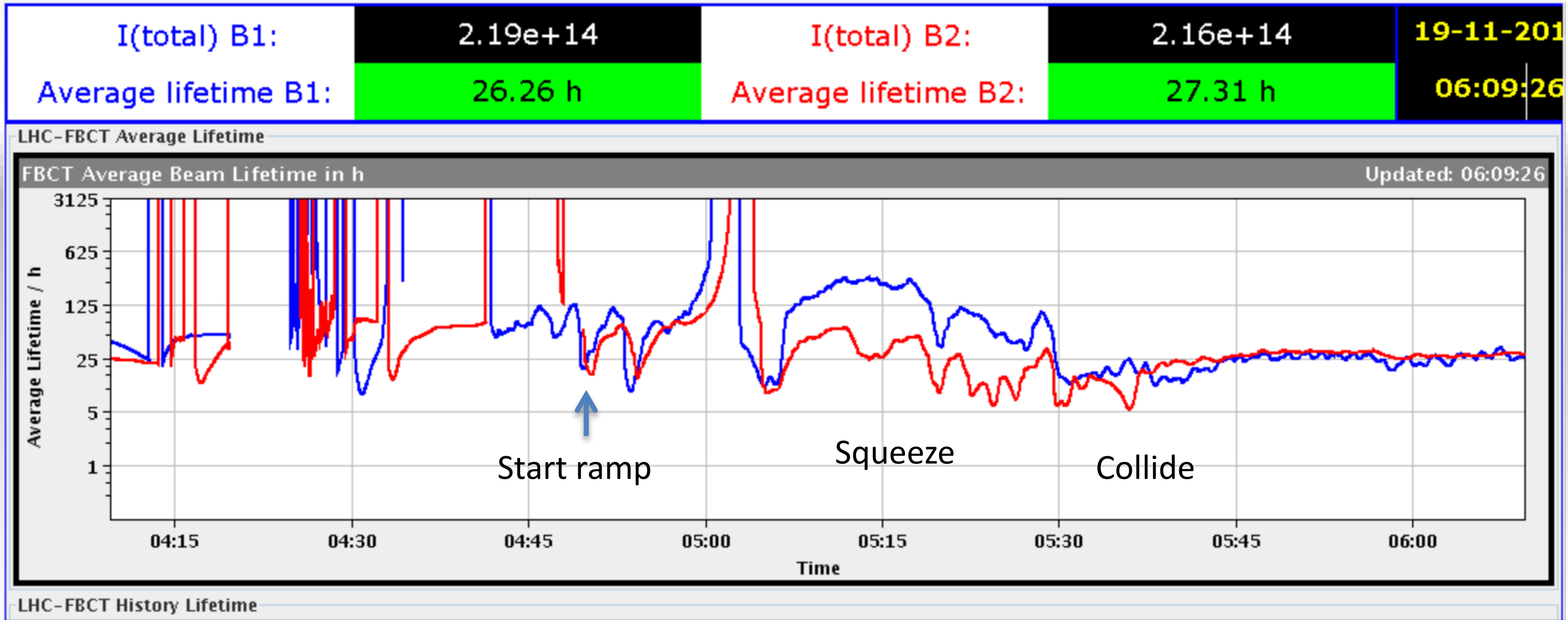
7 e-3

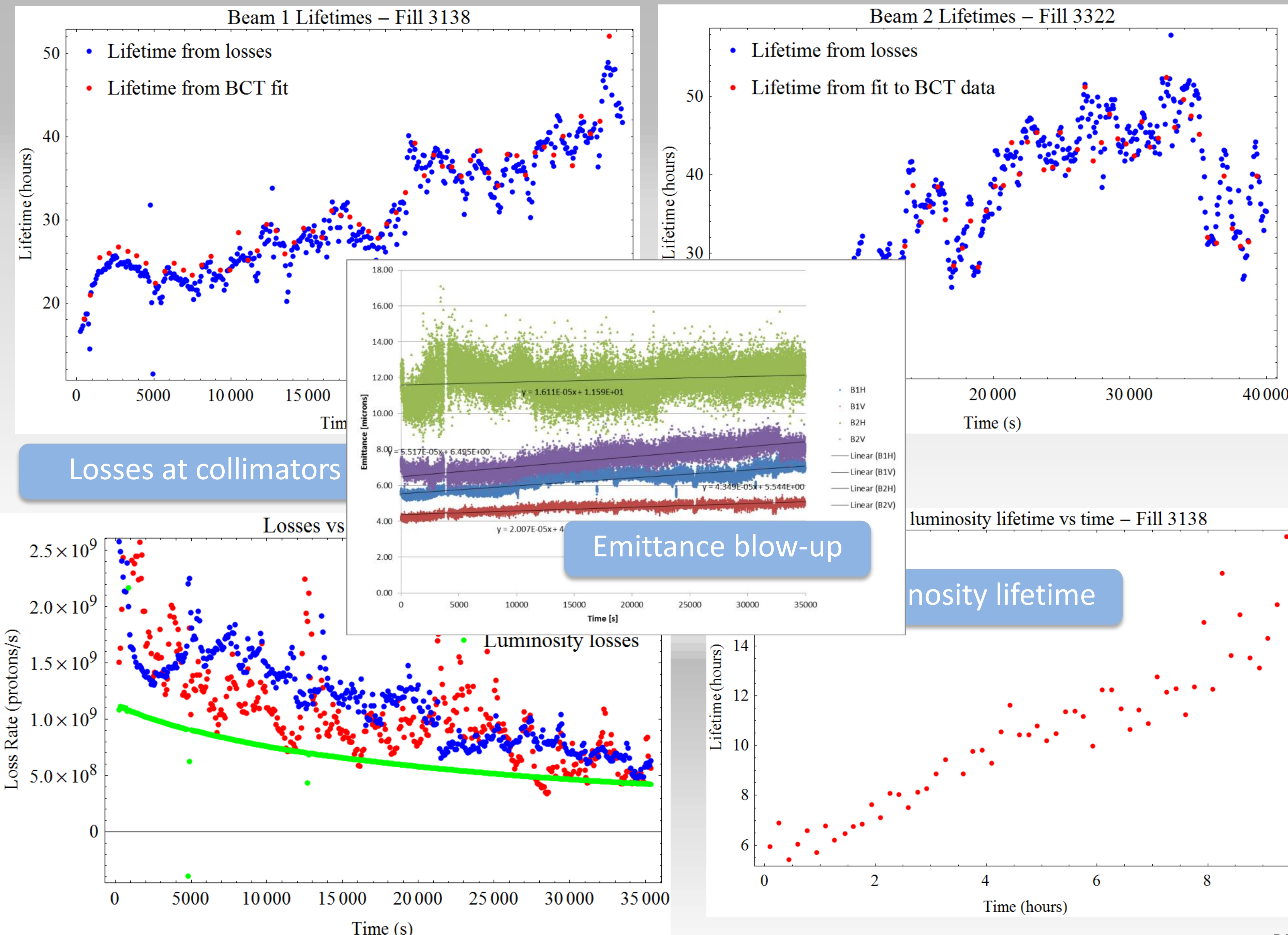


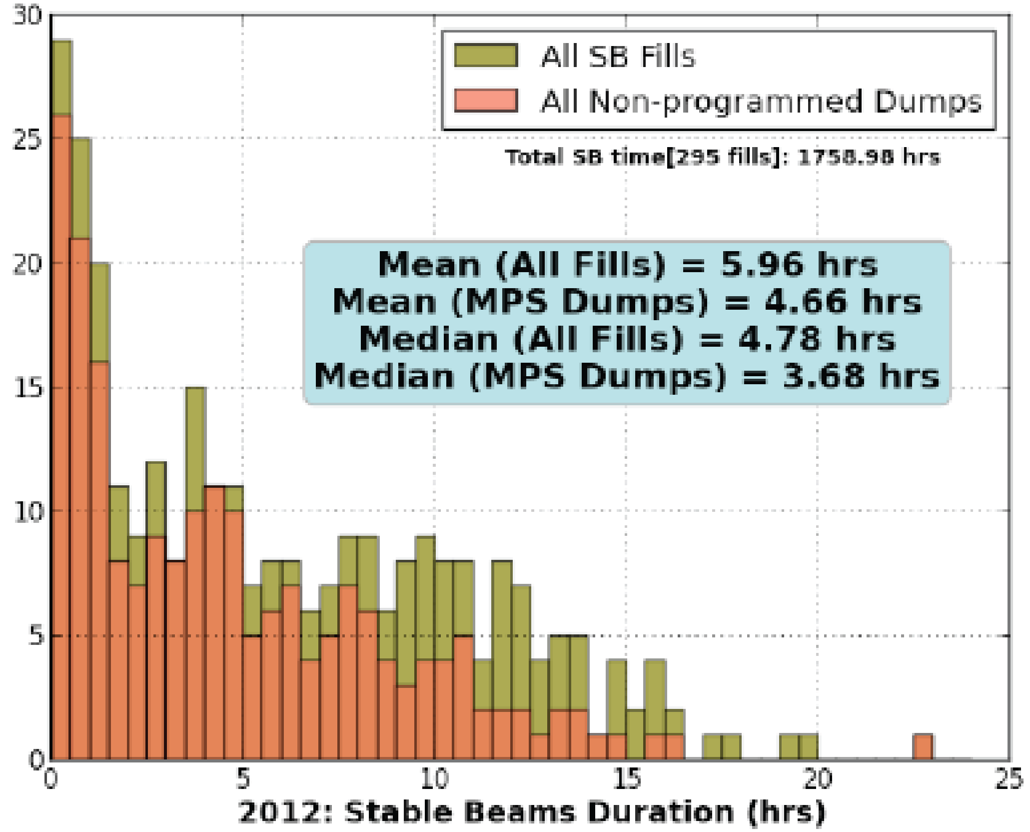
Tune corrections made by feedback during squeeze

Beam lifetime

- Excellent single beam lifetime – good vacuum conditions
- Excellent field quality, good correction of non-linearities
- Low tune modulation, low power converter ripple, low RF noise




Beam 1 Lifetimes – Fill 3138
Lifetime from losses
Lifetime from BCT fit
Lifetime (hours)
Beam 2 Lifetimes – Fill 3322
Lifetime from losses
Lifetime from fit to BCT data
Lifetime (hours)
Time (s)
Losses at collimators
Emittance [microns]
y = 1.611E-05x + 1.159E+01
y = 5.517E-05x + 6.495E+00
y = 4.349E-05x + 5.544E+00
Time [s]
B1H
B1V
B2H
B2V
Linear (B1H)
Linear (B1V)
Linear (B2H)
Linear (B2V)
Emittance blow-up
Loss Rate (protons/s)
Luminosity losses
Time (s)
luminosity lifetime vs time – Fill 3138
Lifetime (hours)
Time (hours)



Optimum fill length?

2012: Mean SB Duration = 5.96 hrs

- Fill Lifetime with non-programmed dumps show a more exponential decay

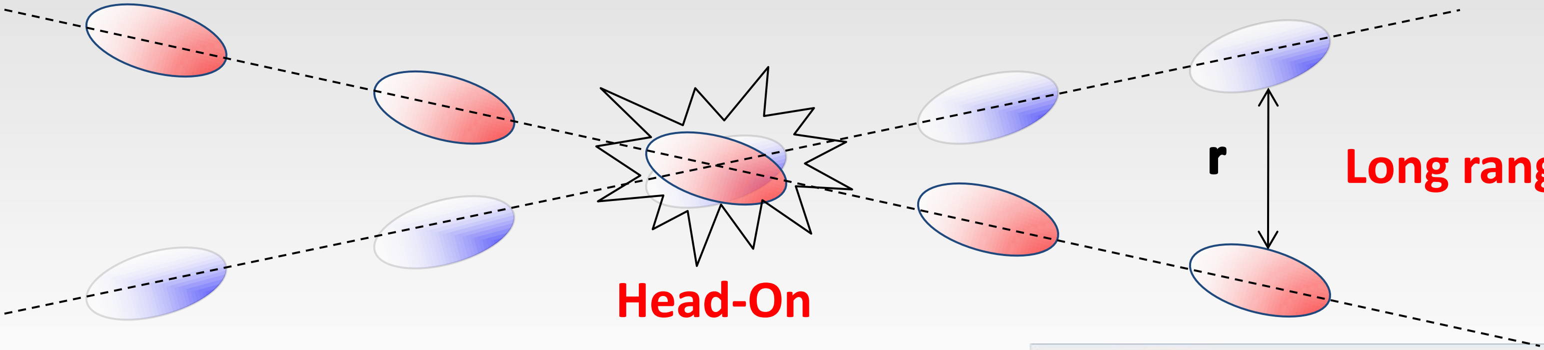
2011: Mean SB Duration = 5.76 hrs

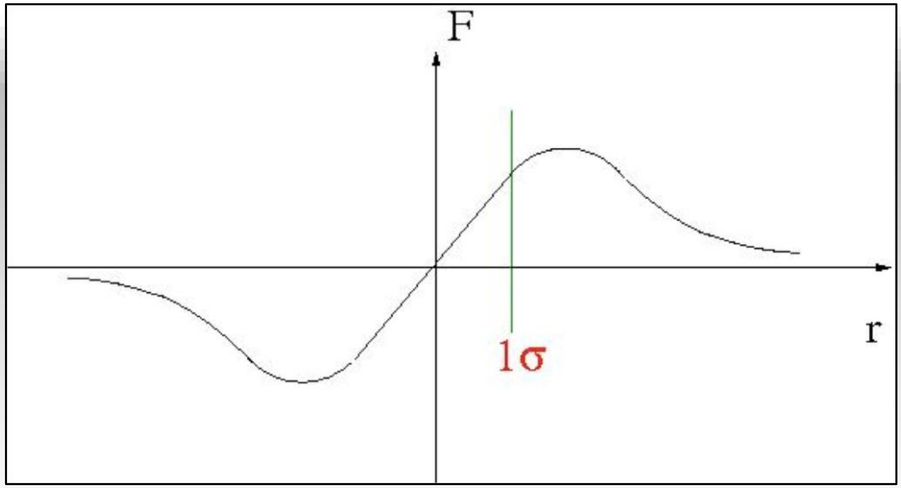
Average turnaround ~5.5 hours

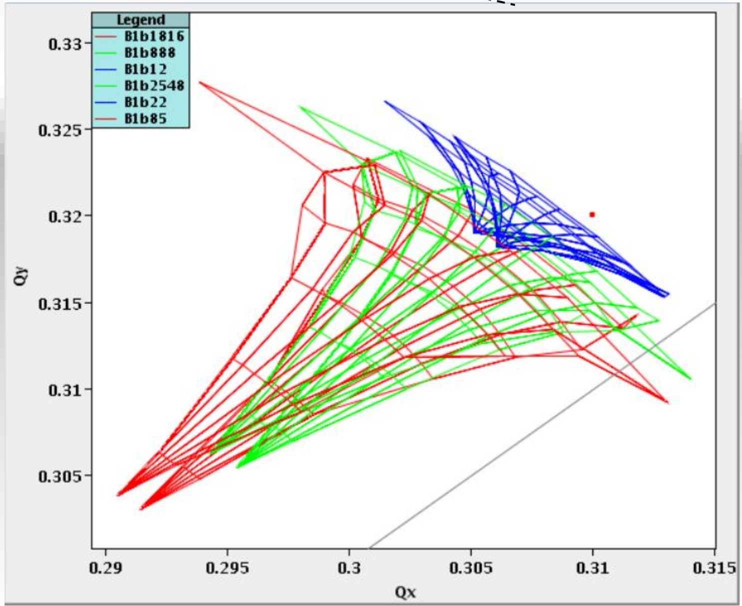
LIMITATIONS

Beam-beam

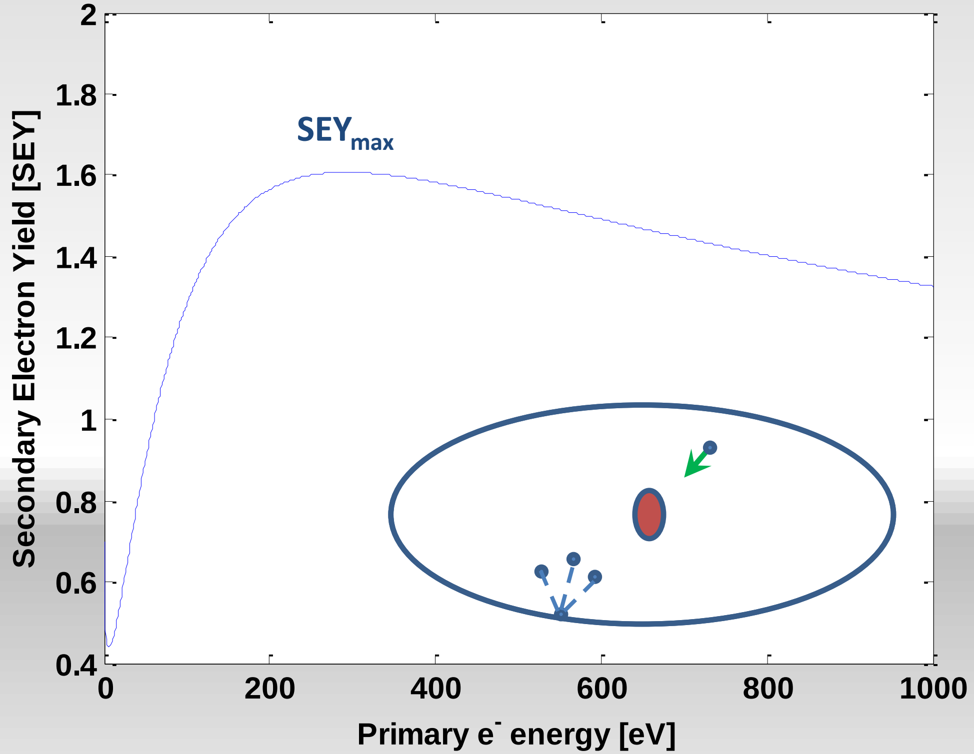
- Head-on beam-beam is not an operational limitation
- Linear head-on parameter in operation ~0.02 (up to 0.034 in MD)
- Long range taken seriously
- Interesting interplay with the instabilities seen in 2012…







When the an accelerator is operated with close bunch spacing an **Electron Cloud (EC)** can develop in the beam chamber due to the Secondary Emission from the chamber's wall.

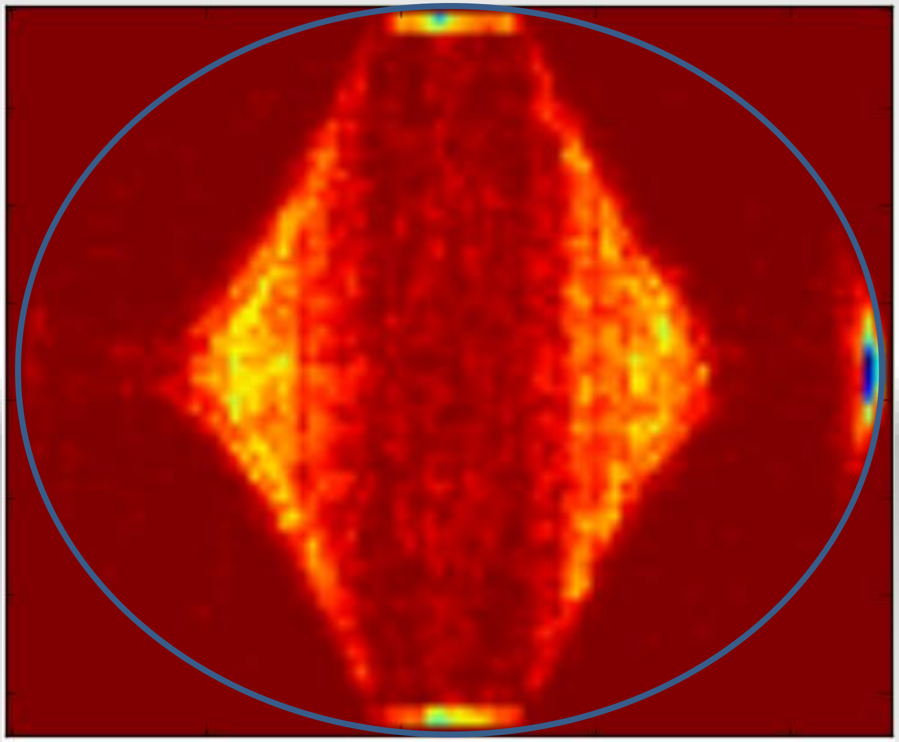


Secondary Electron Yield (SEY) of the chamber's surface:

- ratio between emitted and impacting electrons
- function of the energy of the primary electron

When the an accelerator is operated with close bunch spacing an **Electron Cloud (EC)** can develop in the beam chamber due to the Secondary Emission from the chamber's wall.

Dipole chamber @ 7TeV

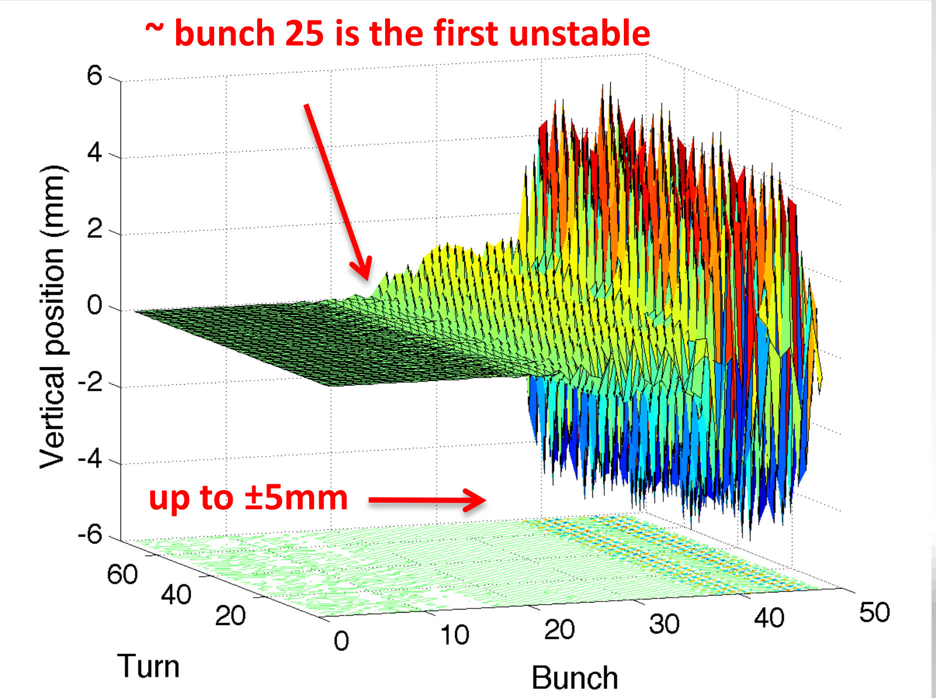


- **Strong impact on beam quality** (EC induced instabilities, particle losses, emittance growth)
- **Dynamic pressure rise**
- **Heat load** (on cryogenic sections)

Giovanni Iadarola

Effects can be quite violent

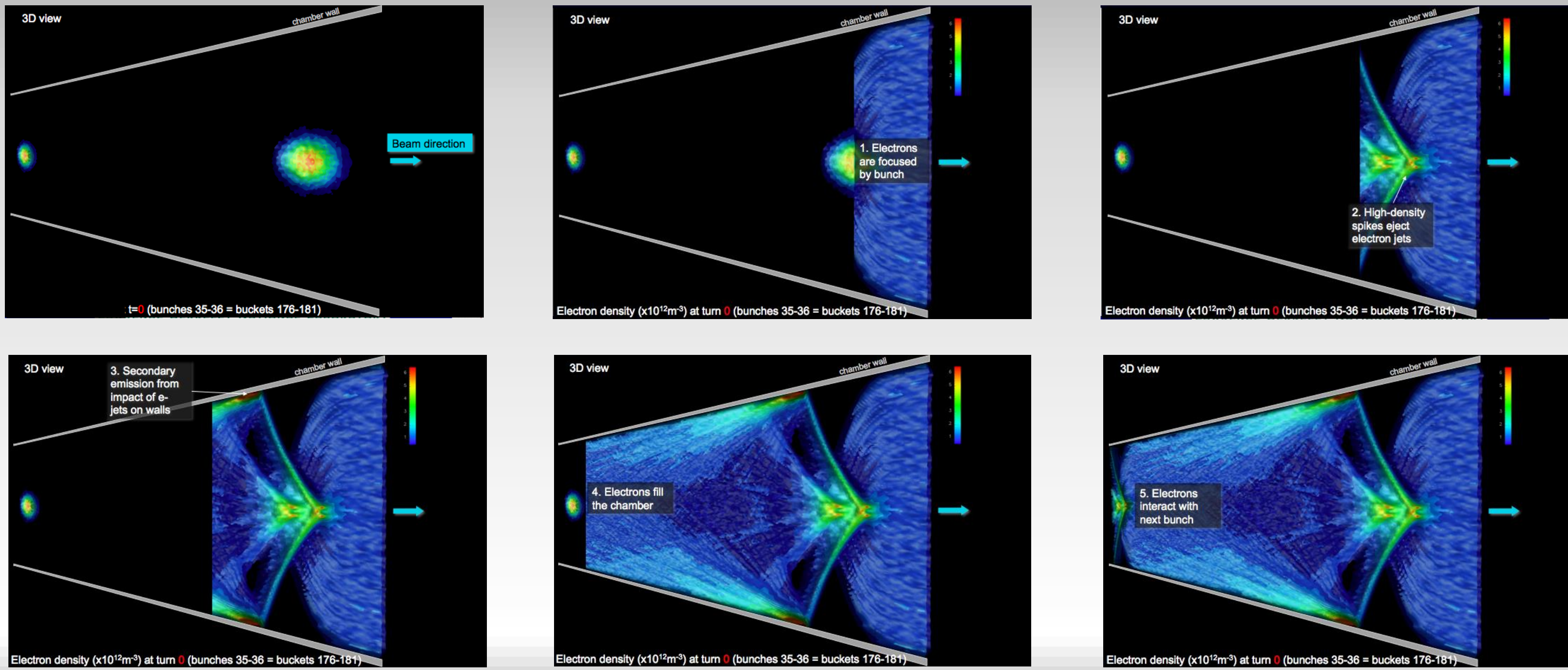
First injection tests with a train of 25 ns 48 bunches on 26/08/2011:



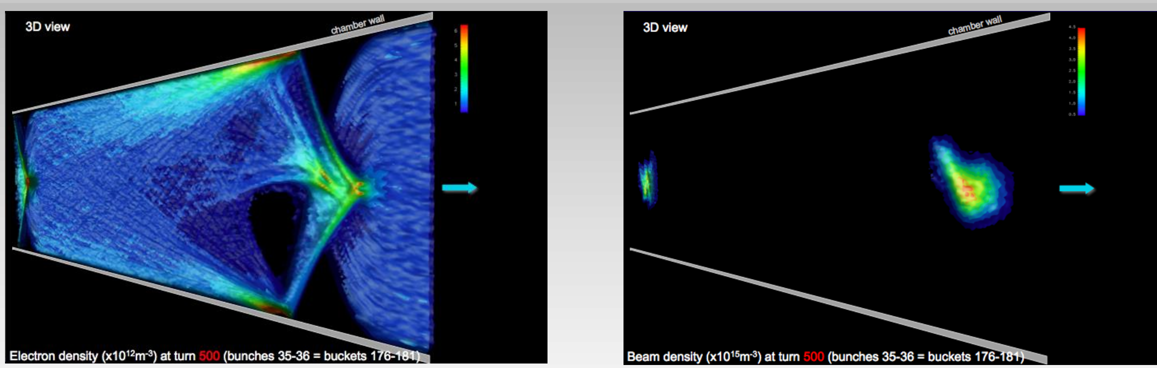
Beam **unstable** right after injection (dump due to losses)

Warp and Posinst have been further integrated, enabling fully self-consistent simulation of e-cloud effects: build-up & beam dynamics

Turn 1



Turn 500

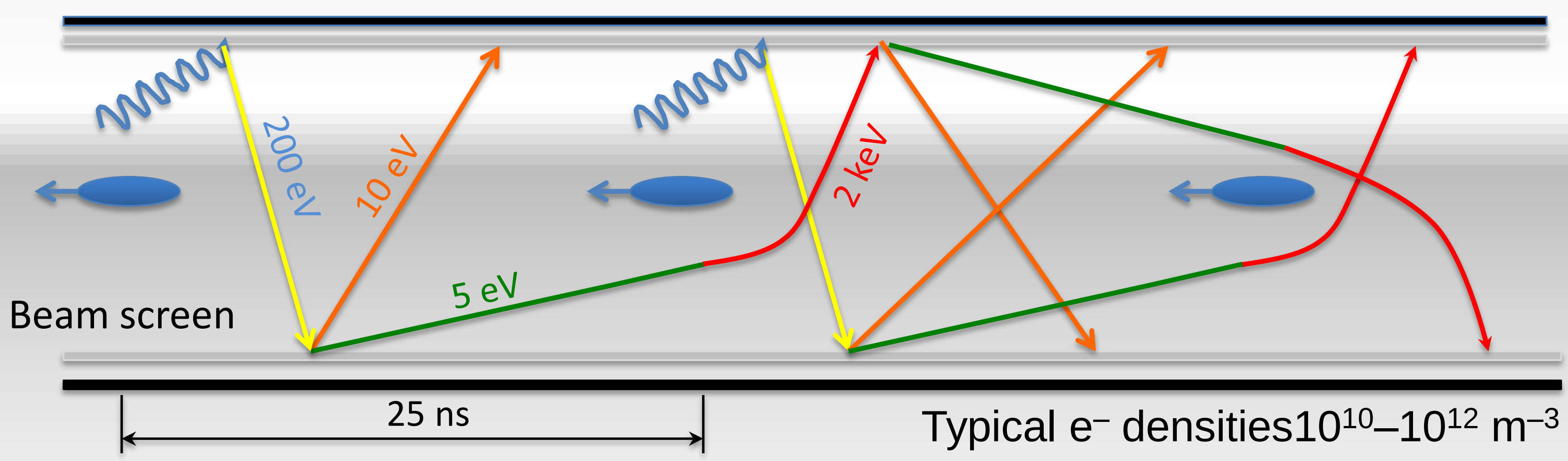


CERN SPS
at injection (26 GeV)

Scrubbing

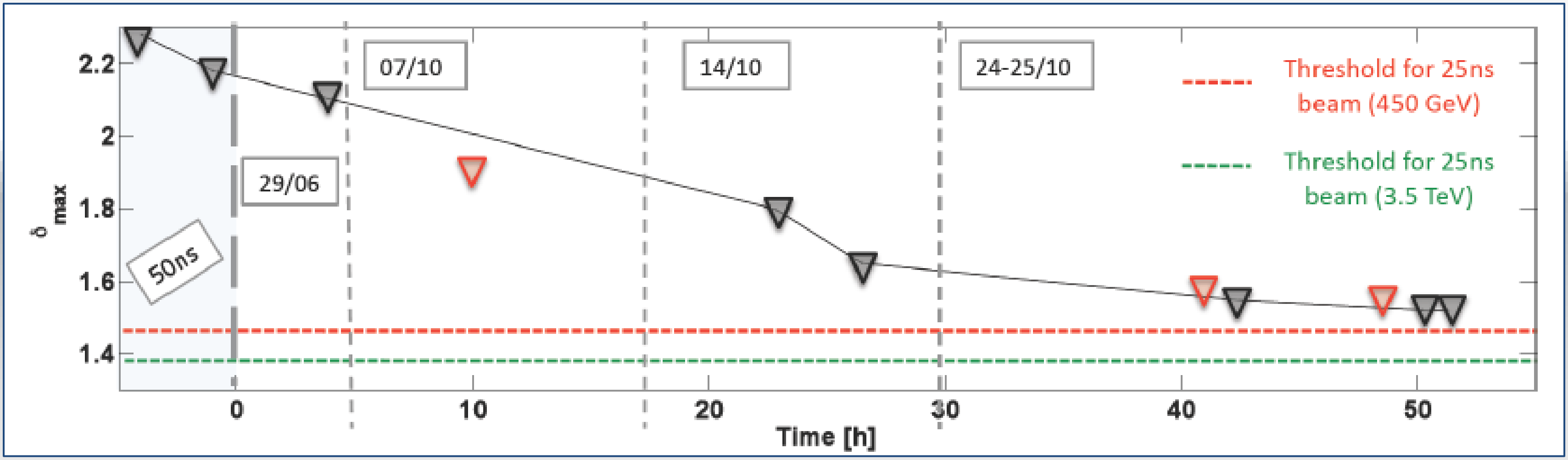
Electron bombardment of a surface has been proven to reduce drastically the **secondary electron yield (SEY)** of a material.

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



25 ns & electron cloud

- During 25 ns scrubbing run last December the reduction in the secondary electron yield (SEY) flattened out
- A concentrated scrubbing run will probably be insufficient to fully suppress the EC from the arcs for 25 ns beams in future operation.

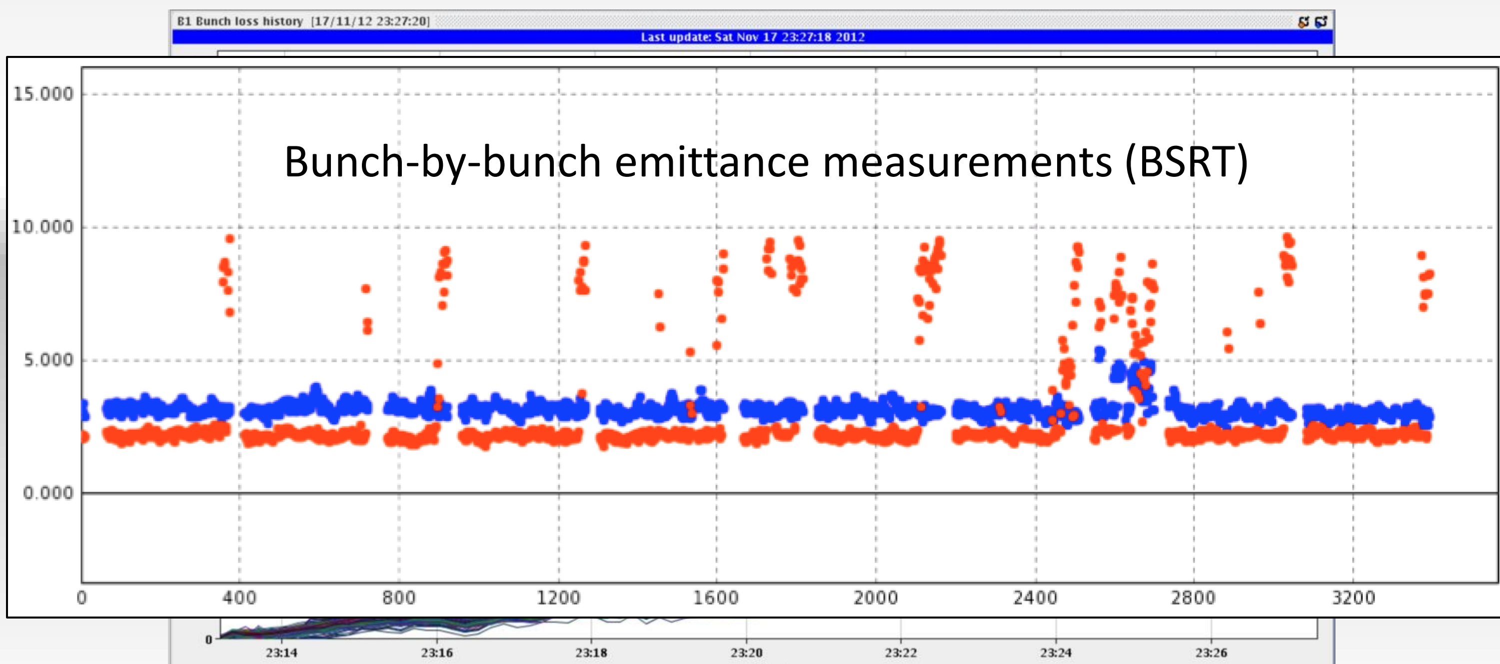


Evolution of δ_{max} on the the beam screen in the dipole magnets in 2011

Instabilities

Lot of effort has gone into studies & simulations

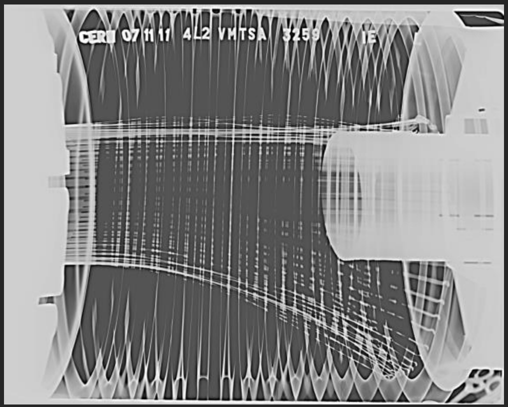
- Note: increased impedance from tight collimators in 2012 and near ultimate bunch intensity
- Instabilities have been observed:
  - on bunches with offset collisions in IP8 only
  - while going into collision
  - end of squeeze, few bunches: emittance blow-up and beam loss
- Defense mechanisms:
  - octupoles, high chromaticity, transverse damper, tune split, head-on collisions, understanding



Some other issues…

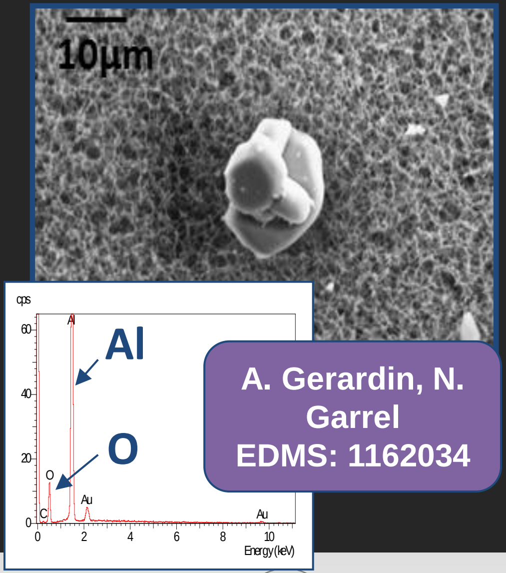
Beam induced heating

- Local non-conformities (design, installation)
  - Injection protection devices
  - Sync. Light mirrors
  - Vacuum assemblies



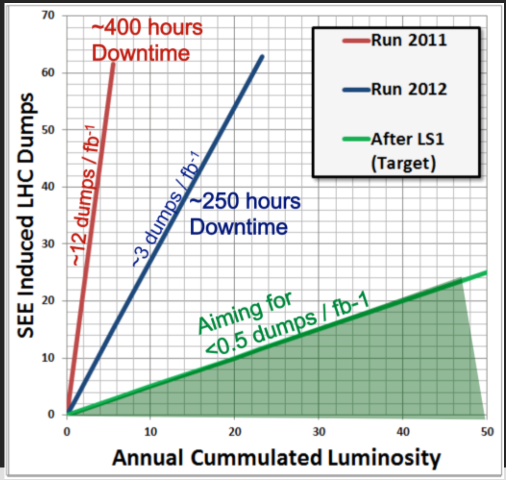
UFOs

- 20 dumps in 2012
- Timescale 50-200 µs
- Conditioning observed
- Worry about 6.5 TeV



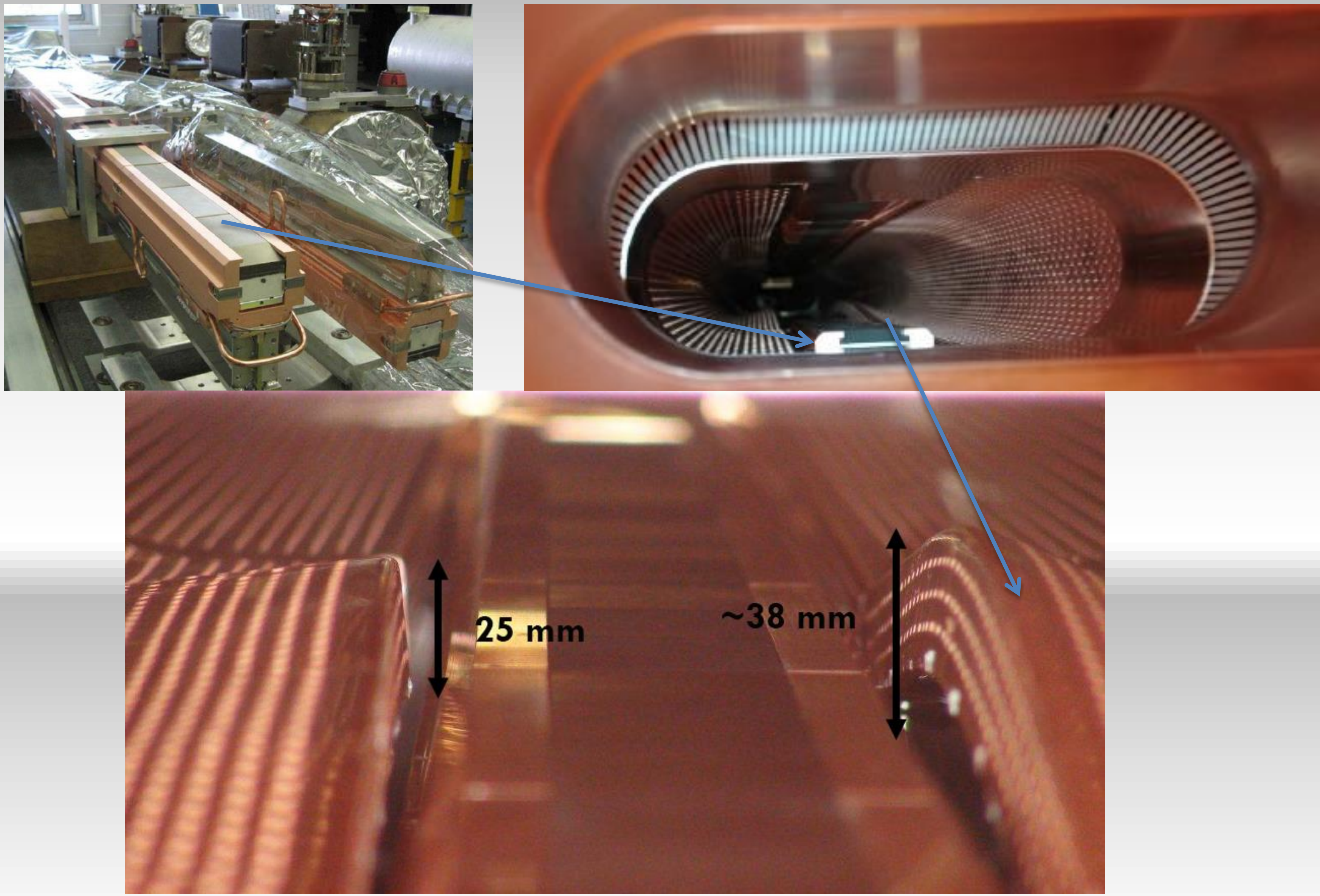
Radiation to electronics

- Concerted program of mitigation measures (shielding, relocation…)
- Premature dump rate down from $12/fb^{-1}$ in 2011 to $3/fb^{-1}$ in 2012

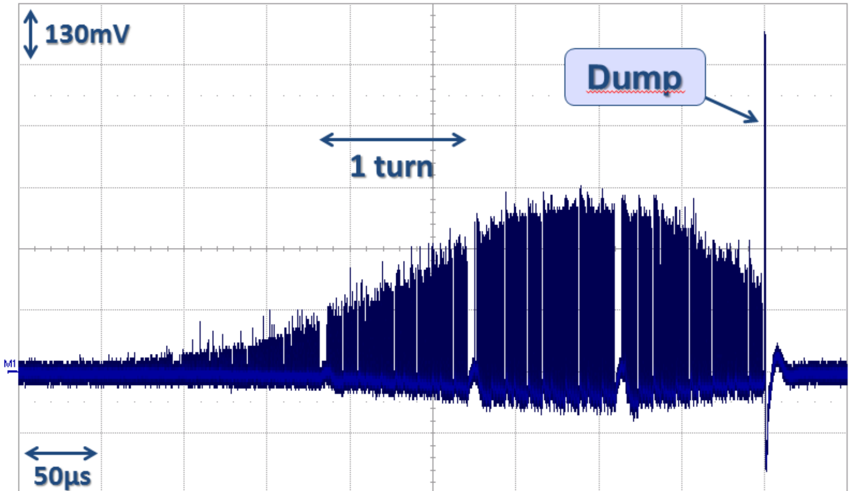


Injection collimators (TDI)

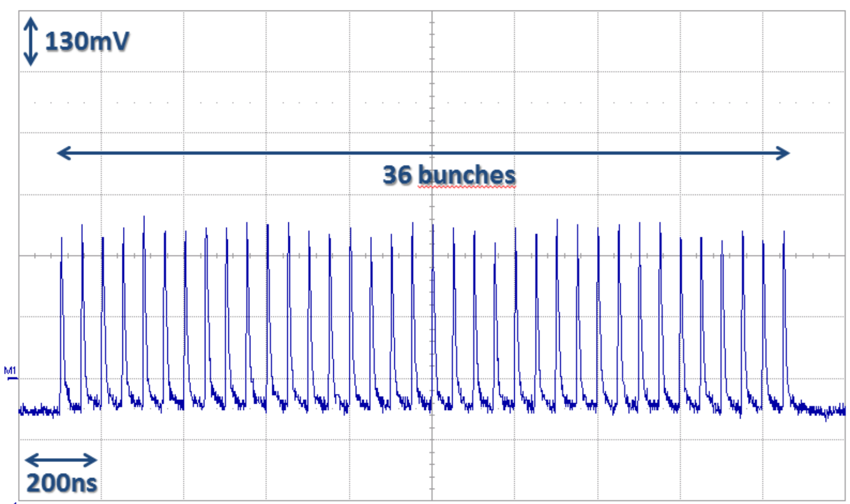
beam screen heating

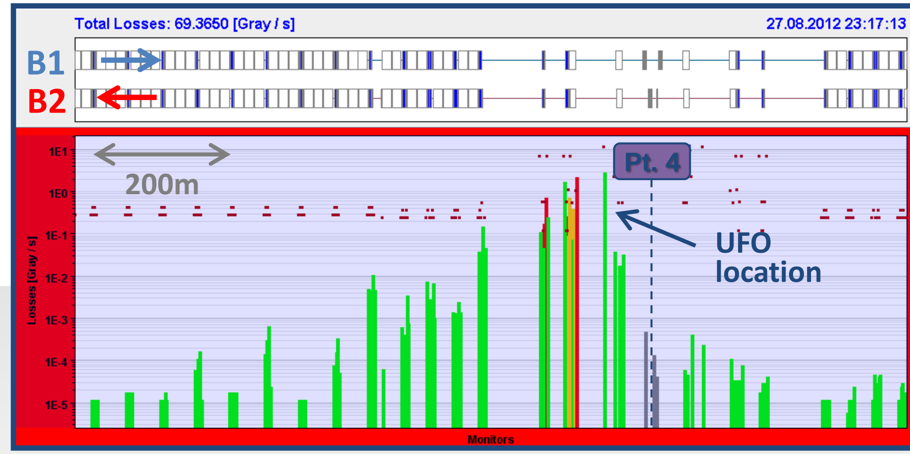


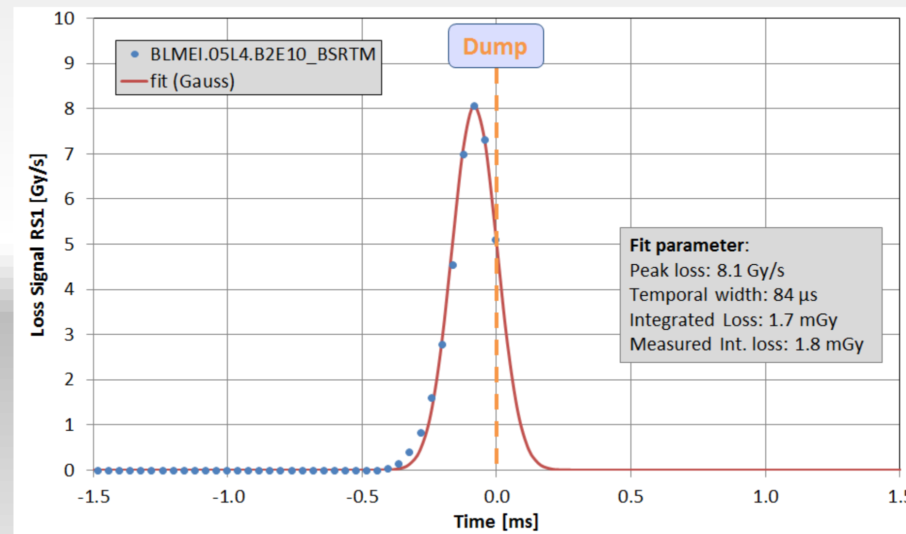
UFO - introduction



Diamond BLM in IR7







Spatial and temporal loss profile of UFO at BSRT.B2 on 27.08.2012 at 4TeV.

UFO Model

- Implemented in dust particle dynamics model, which predicts (among others):
- *Loss duration of a few ms*
- *Losses become faster for larger beam intensities.*

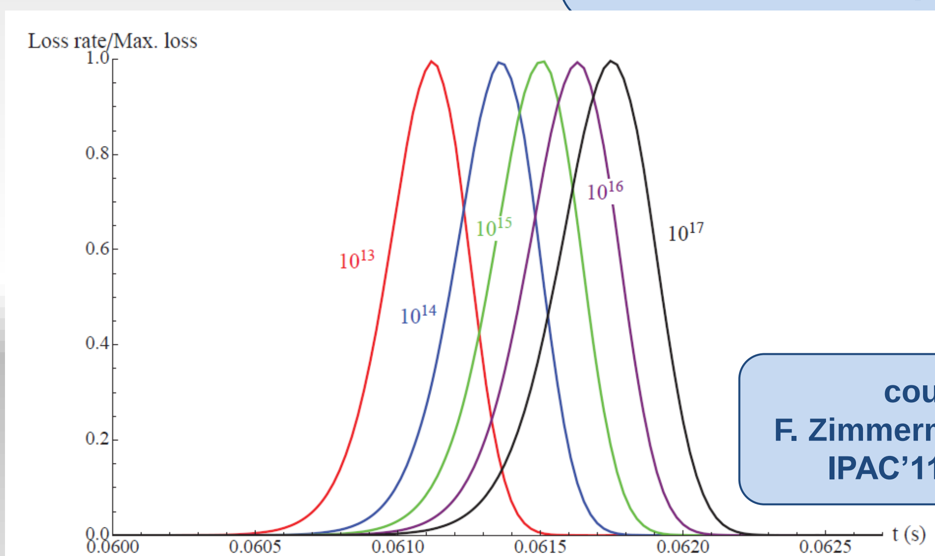
Detaching stimulated by vibration, electrical field during MKI pulse and electrical beam potential.

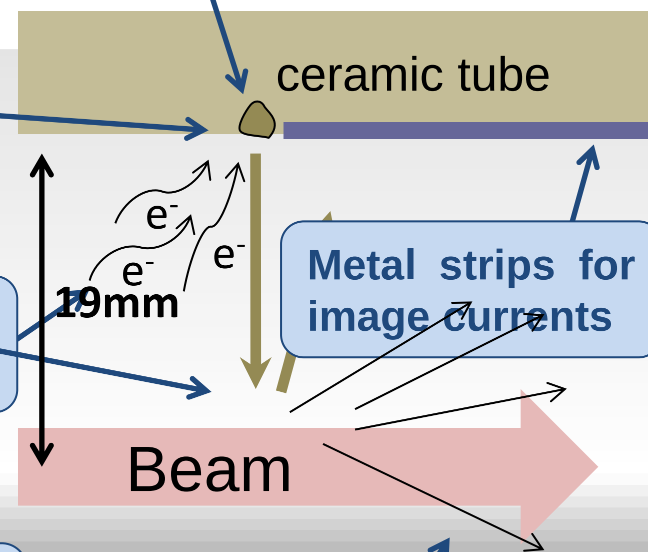
beam charging could be

Al_2O_3 fragment of vacuum chamber. Size: 1-100μm.

Metal strips for image currents

Local beam losses due to inelastic nuclear interaction.

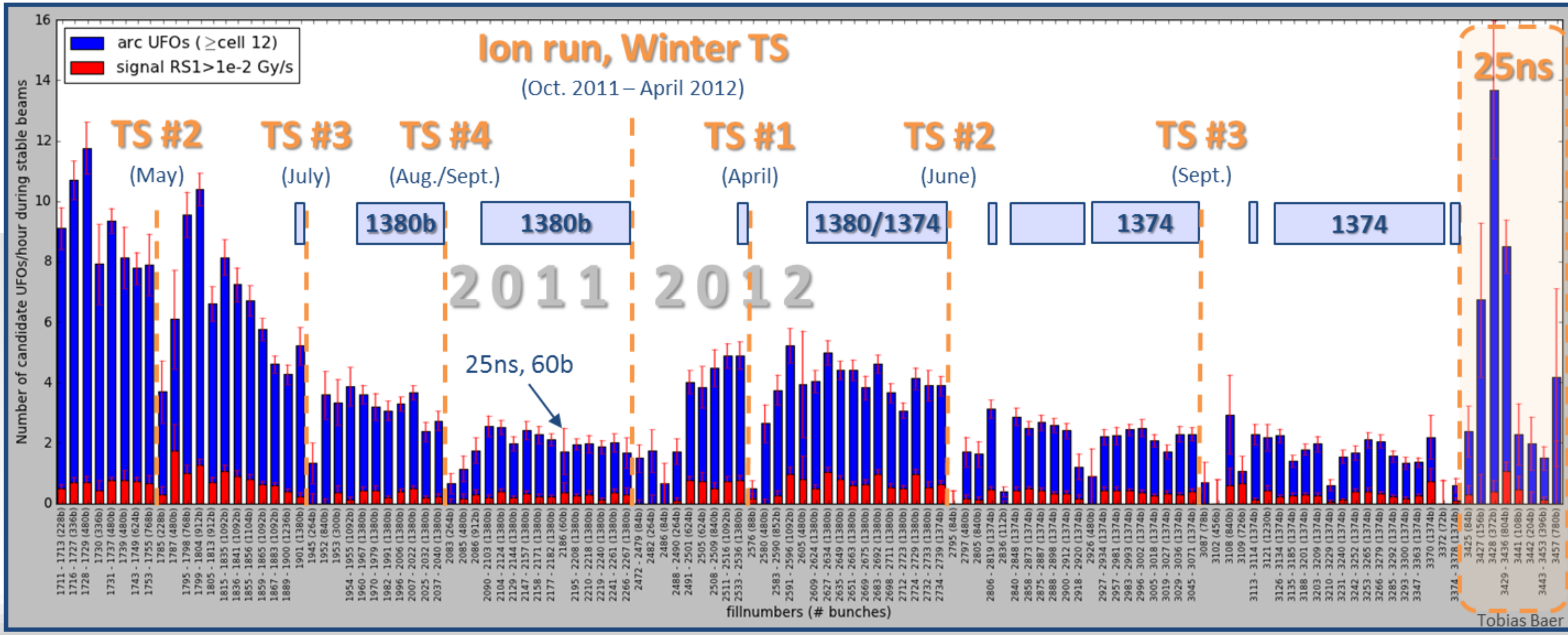




courtesy of
F. Zimmermann, N. Fuster
IPAC'11: MOPS017

Beam loss rate as a function of time for different macroparticle masses. Beam intensity: $1.6 \cdot 10^{14}$ protons.

Arc UFO Rate



- **2011:** Decrease from **≈10 UFOs/hour** to **≈2 UFOs/hour.**
- **2012:** Initially, about **2.5 times higher** UFO rate than in October 2011. **UFO rate decreases** since then.
- Up to **10 times** increased UFO rate with **25 ns**.

UFO Summary

- **20 beam dumps** due to UFOs in 2012.
- Temporal width typically **50-200μs**.

  May be too fast for active protection with smaller emittance at higher energy.
- Arc UFO rate at beginning of 2012 **≈2.5 times higher** than in October 2011. Arc (and MKI) UFO rate decreases since then.
- Energy extrapolation to 7 TeV:

  2011** arc and MKI UFOs would have caused **139 beam dumps.

  2012** arc and MKI UFOs would have caused **112 beam dumps.
- About **5-10 times** increased UFO activity with **25ns**.
- Mitigations:

  For MKI UFOs, different mitigations are in preparation. Observations with improved MKI.D5R8 look promising.
- *For Arc UFOs, optimized BLM distribution allows a better UFO protection.*


25R7 / 27R7

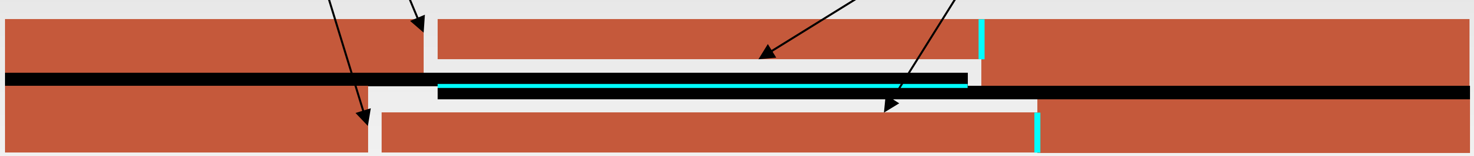
What happened on September 19th*

- Sector 3-4 was being ramped to 9.3 kA, the equivalent of 5.5 TeV
  - All other sectors had already been ramped to this level
  - Sector 3-4 had previously only been ramped to 7 kA (4.1 TeV)
- At 11:18AM, a quench developed in the splice between dipole C24 and quadrupole Q24
  - Not initially detected by quench protection circuit
  - Power supply tripped at .46 sec
  - Discharge switches activated at .86 sec
- Within the first second, an arc formed at the site of the quench
  - The heat of the arc caused Helium to boil.
  - The pressure rose beyond .13 MPa and ruptured into the insulation vacuum.
  - Vacuum also degraded in the beam pipe
- The pressure at the vacuum barrier reached ~10 bar (design value 1.5 bar). The force was transferred to the magnet stands, which broke.

*Official talk by Philippe LeBrun, Chamonix, Jan. 2009

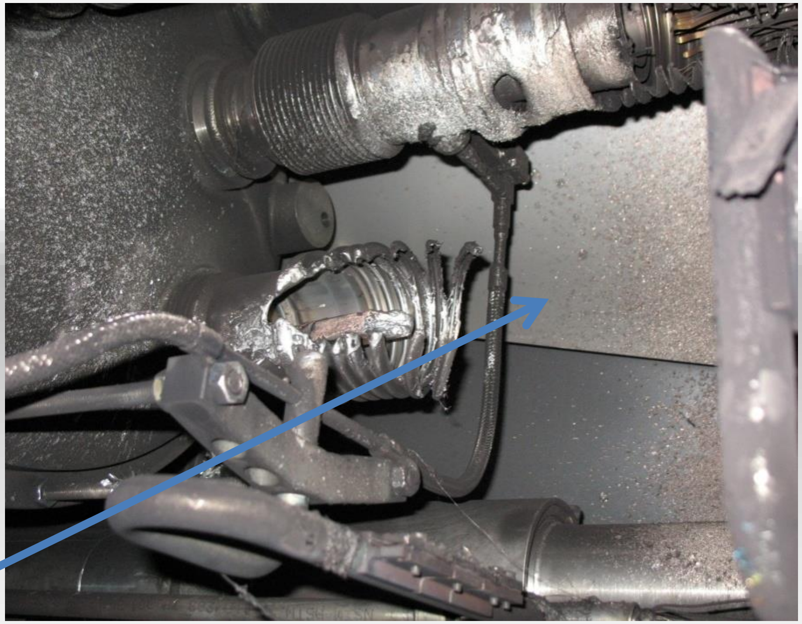
What happened?

Theory: A resistive joint of about 220 nΩ with bad electrical and thermal contacts with the stabilizer



- Loss of clamping pressure on the joint, and between joint and stabilizer
- Degradation of transverse contact between superconducting cable and stabilizer
- Interruption of longitudinal electrical continuity in stabilizer

Problem: this is where the evidence used to be



A. Verweij

Copper stabilizer issue

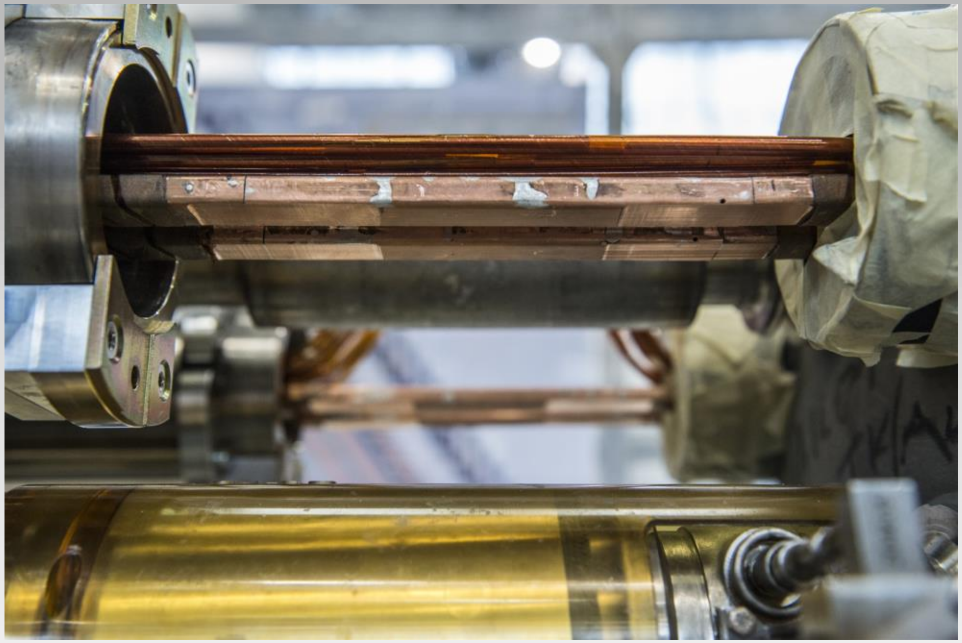
- Despite correct splice resistance between SC cables, a 13 kA joint can burn-out **<u>in case of a quench</u>**, if there would be a bad bonding between the SC cable and the copper bus, coinciding with a discontinuity in the copper stabilizer

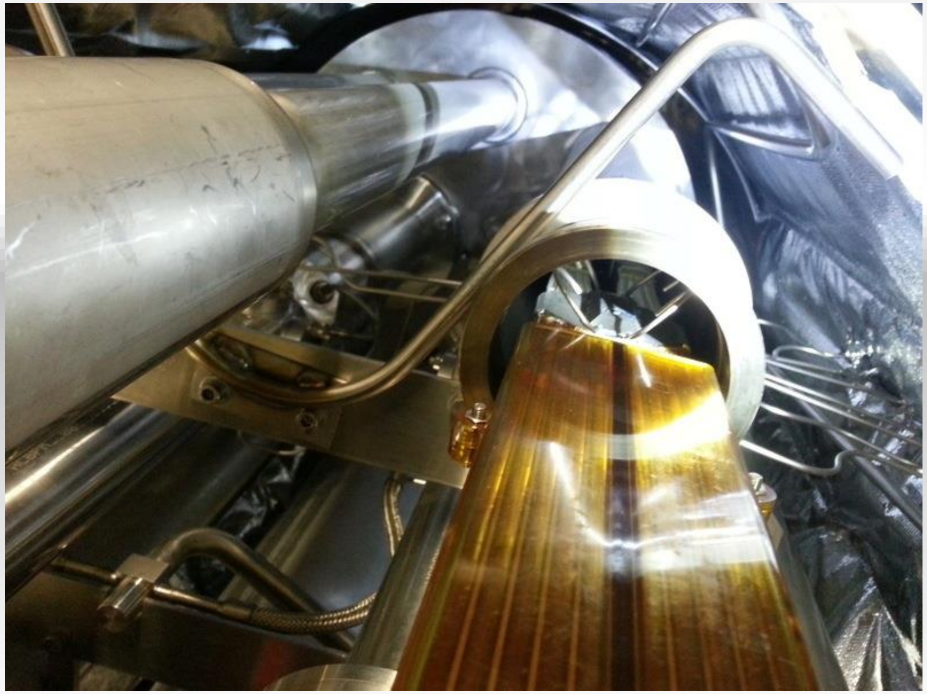
- Resistance measurements and γ-ray pictures have shown the presence of many of such defective joints in the machine, limiting the safe operating current

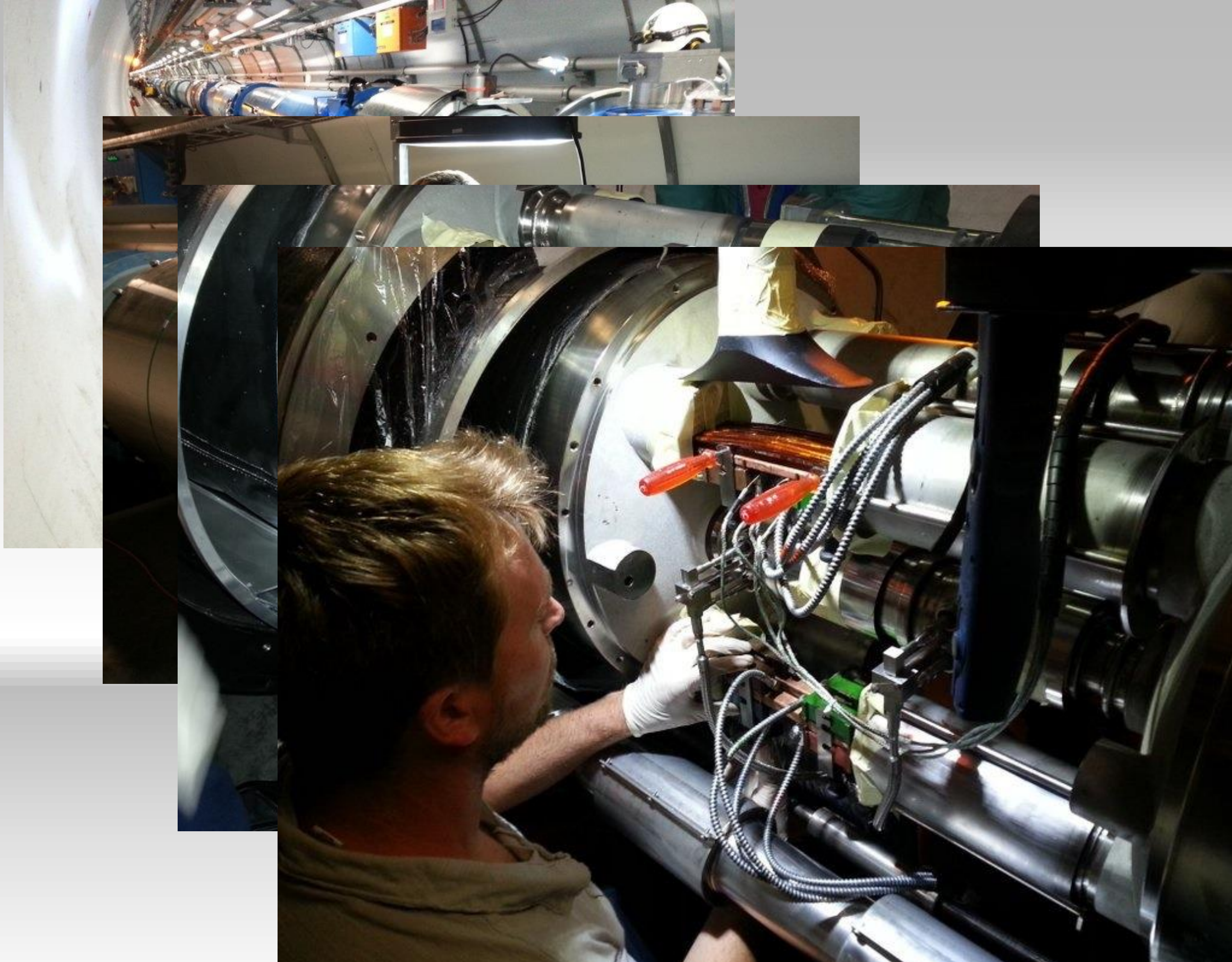
2013 – 2014: LS1

Primary aim: consolidation for 6.5 to 7 TeV

- Measure all splices and repair the defective ones
- Consolidate interconnects with new design (clamp, shunt)
- Finish installation of pressure release valves (DN200)
- Magnet consolidation - exchange of weak cryo-magnets
- Consolidation of the DFBAs
- Measures to further reduce SEE (R2E):
  - relocation, redesign, shielding…
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)
- Experiments consolidation/upgrades



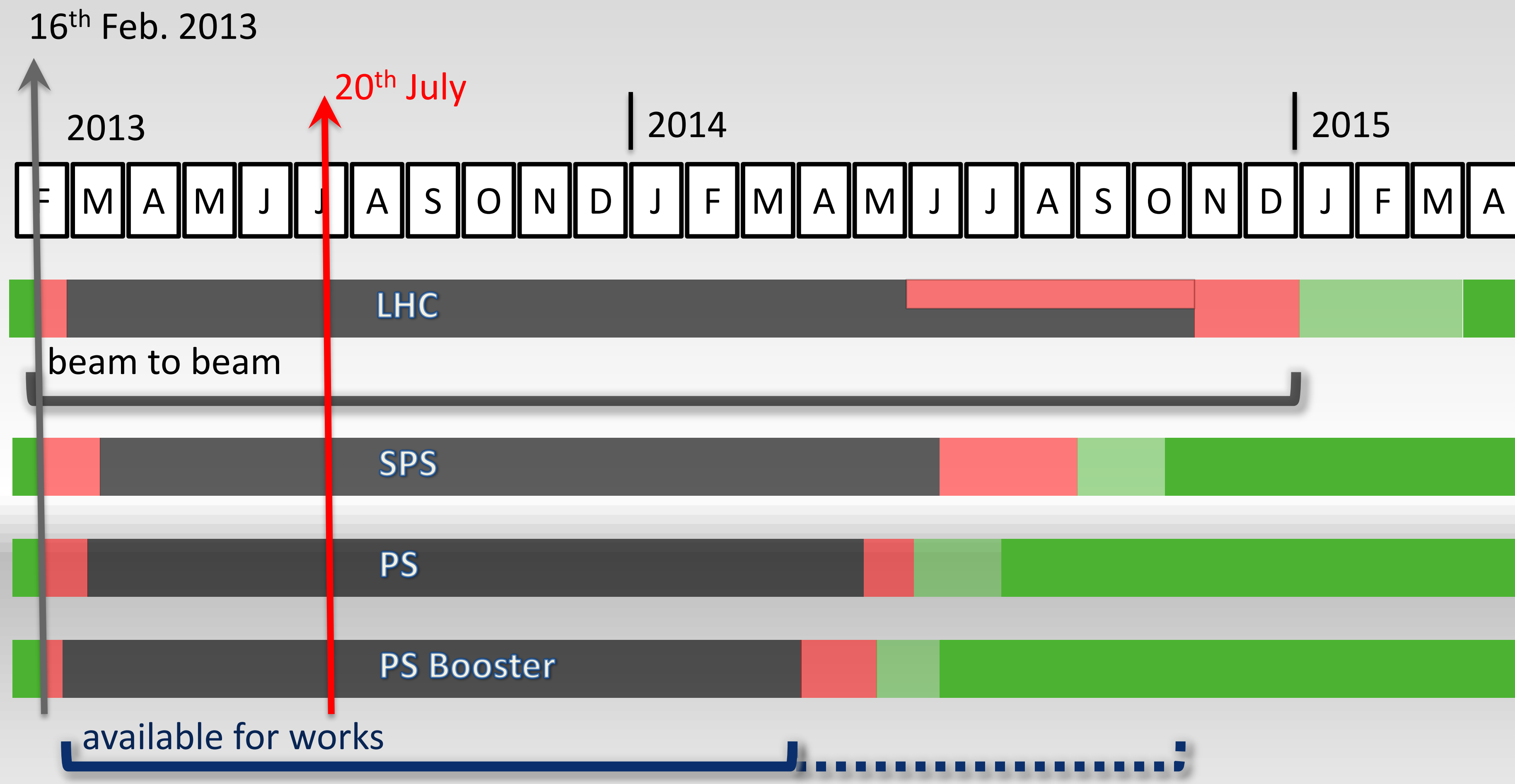


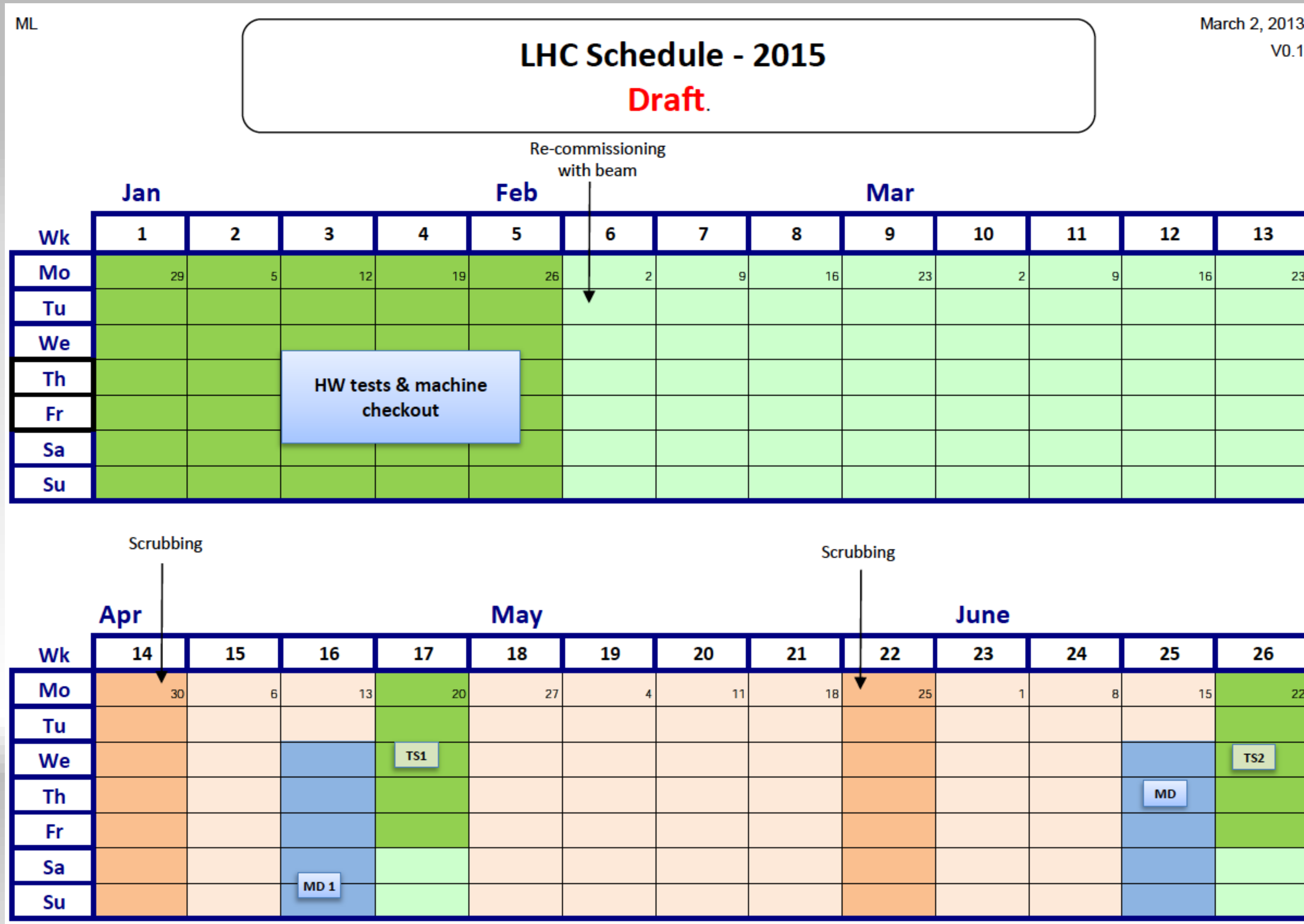


LS1

from 16th February 2013 to end December 2014

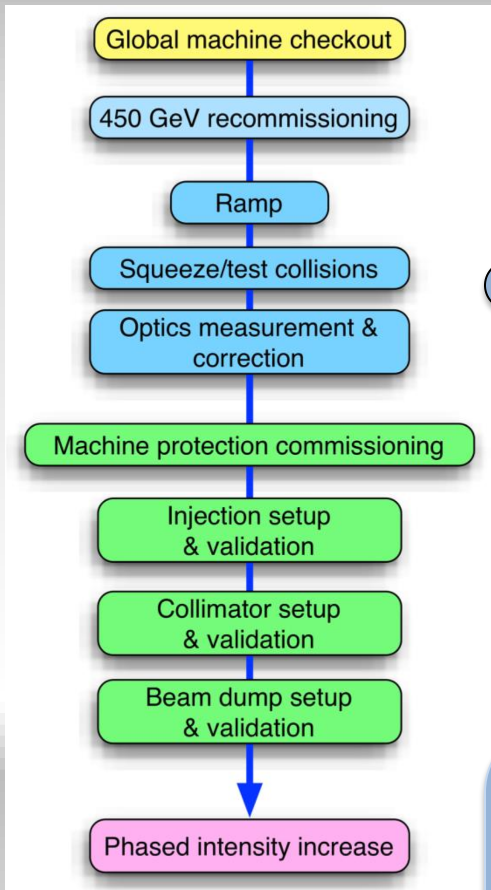
- Physics
- Beam commissioning
- Shutdown
- Tests




ML
LHC Schedule - 2015
Draft.
March 2, 2013
V0.1
Re-commissioning with beam
Jan
Feb
Mar
Wk
1 2 3 4 5 6 7 8 9 10 11 12 13
Mo
Tu
We
Th
Fr
Sa
Su
29 5 12 19 26 2 9 16 23 2 9 16 23
HW tests & machine checkout
Scrubbing
Scrubbing
Apr
May
June
Wk
14 15 16 17 18 19 20 21 22 23 24 25 26
Mo
Tu
We
Th
Fr
Sa
Su
30 6 13 20 27 4 11 18 25 1 8 15 22
TS1
TS2
MD
MD 1

POST LS1

Initial commissioning (2 months)



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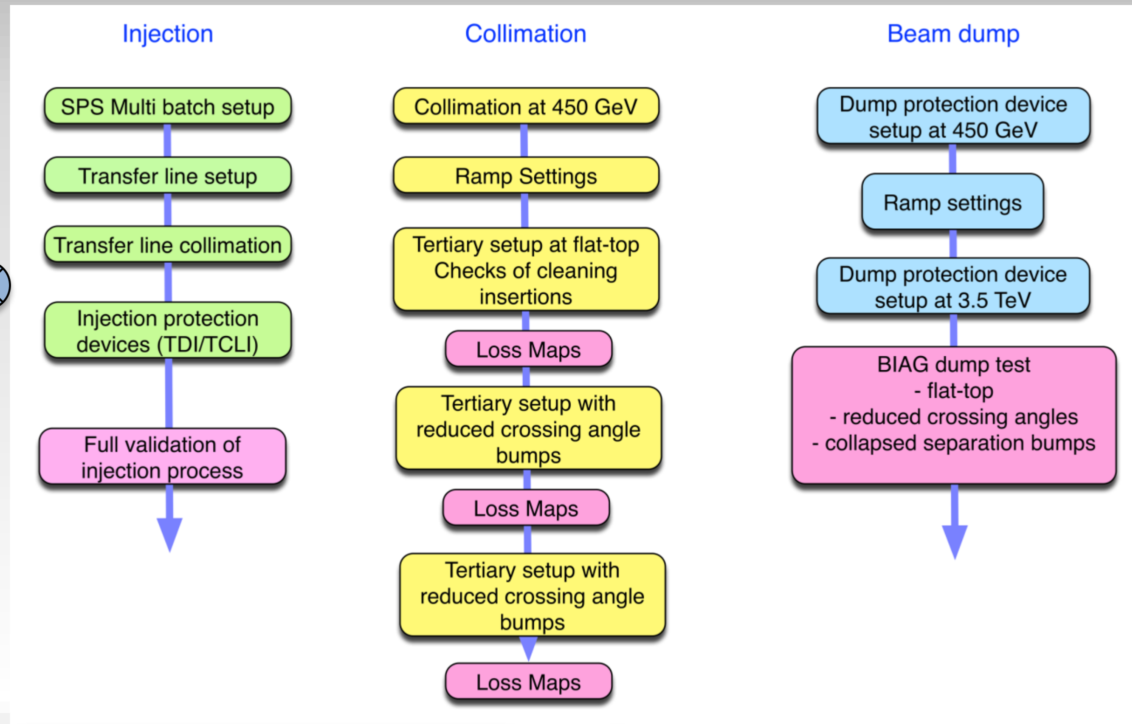


System commissioning

- Transverse damper
- RF
- Beam instrumentation
- Machine protection
- Feedbacks

⊕

- Optics meas. & correction
- Magnet model meas. & correction
- Aperture measurements

Post LS1 energy

Issue: during training in 2008 in sector 56, one manufacturer dipoles showed de-training having been above 7 TeV in SM18 – 30 quenches to reach 6.6 TeV equivalent

- Magnets coming from 3-4 do not show degradation of performance
- Our best estimates to train the LHC (with large errors)
  - ~ 30 quenches to reach 6.25 TeV
  - ~ 100 quenches to reach 6.5 TeV
- The plan
  - Try to reach 6.5 TeV in four sectors in **JULY to SEPTEMBER 2014**
  - Based on that experience, we will decide if to go at 6.5 TeV or step back to 6.25 TeV

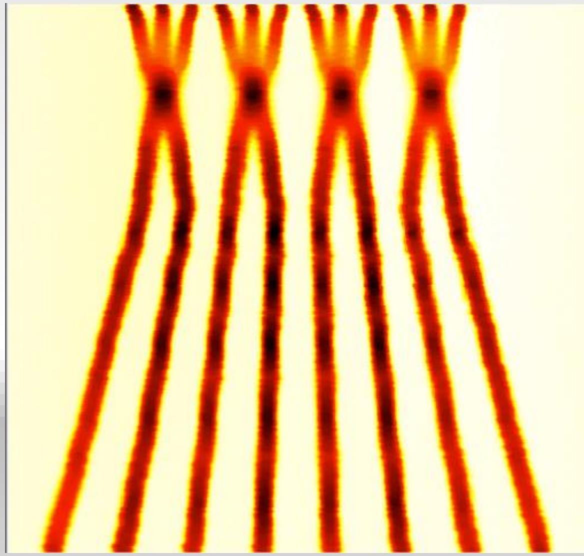
Challenges of high energy

- Quenches
  - Less margin to critical surface
- Protons have higher energy
  - acceptable loss level is reduced (losses in ramp, UFOs…)
  - set-up beam limit reduced
- Magnets run into saturation
  - field quality (although this is modelled)
- Hardware nearer limits
  - Power converters, beam dump (higher voltages), cryogenics (synchrotron radiation…)

Injectors post LS1

Injectors potentially able to offer nominal intensity with even lower emittance

BCMS = Batch Compression and Merging and Splitting



	Proton per Bunch [1e11]	ε_N [um] 6.5 TeV
25 ns BCMS	1.15	1.9
25 ns design	1.15	3.75
50 ns BCMS	1.6	1.6

25 ns beam with lower intensity from the Booster
– lower transverse emittance

50 versus 25 ns

	50 ns	25 ns
GOOD	• Lower total beam current • Higher bunch intensity • Lower emittance	• **Lower pile-up**
BAD	• **High pile-up** • Need to level • Pile-up stays high • High bunch intensity – instabilities…	• More long range collisions: larger crossing angle; higher beta* • Higher emittance • Electron cloud: need for scrubbing; emittance blow-up; • Higher UFO rate • Higher injected bunch train intensity • Higher total beam current

Expect to move to 25 ns because of pile up…

β* & crossing angle

- β* reach depends on:
  - – available aperture
  - – collimator settings, orbit stability
  - – required crossing angle which in turn depends on
    - emittance
    - bunch spacing

Beta* reach at 6.5 TeV

- Pessimistic scenario:
  - ➡β* = 70cm at 25ns
  - ➡β* = 57cm at 50ns
- Optimistic scenario:
  - ➡β* = 37cm at 25ns
  - ➡β* = 30cm at 50ns

Working hypothesis
β* = 40 cm

Run II – potential performance

- Energy: 6.5 TeV
- β* = 40 cm

- 1.1 ns bunch length
- 160 days proton physics
- 85 mb visible cross-section
- * different operational model – caveat - unproven

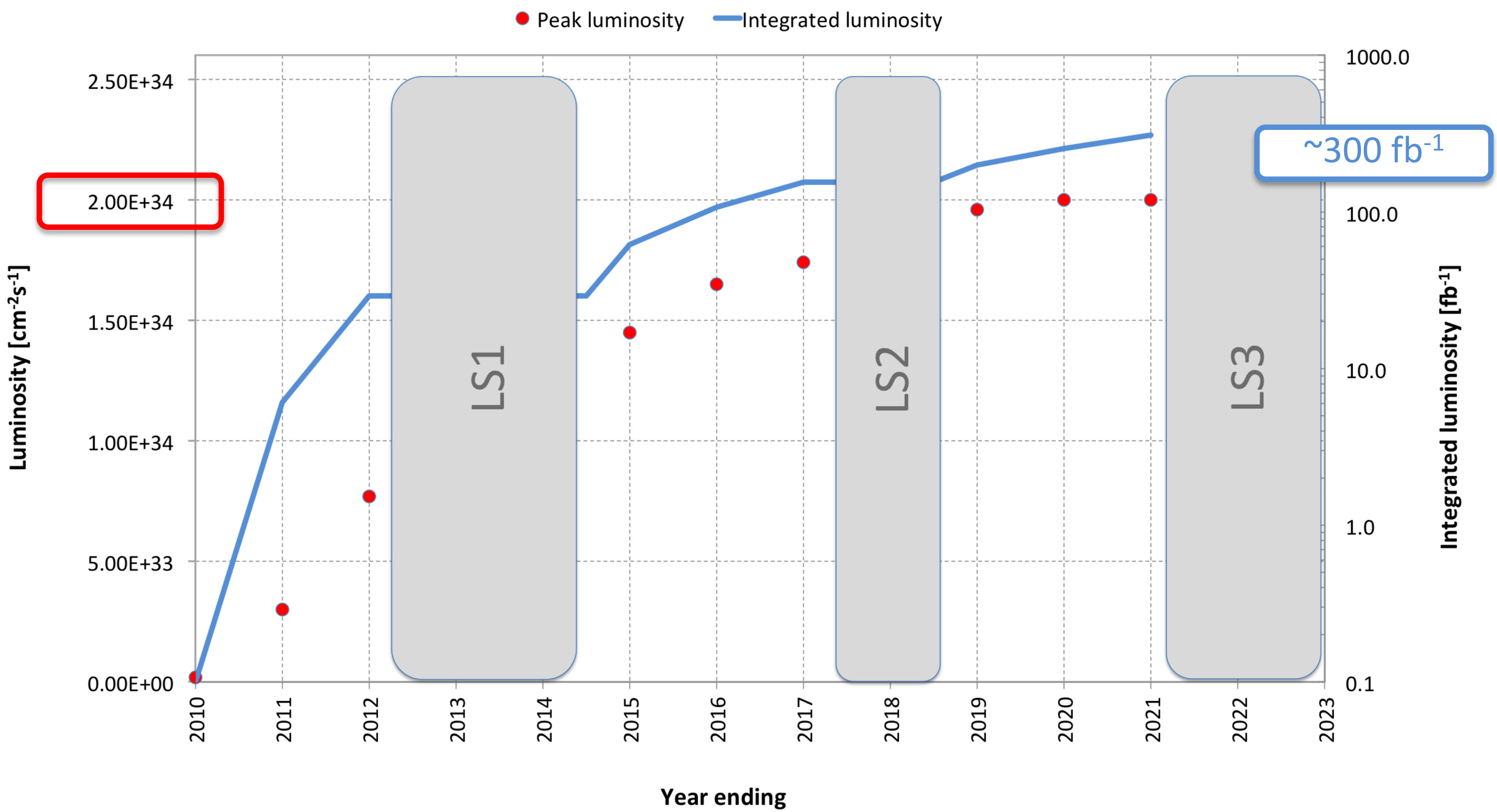
	Number of bunches	Proton per Bunch [1e11]	ε_N [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per full year [fb^{-1}]
25 ns BCMS	2590	1.15	1.9	**1.7e34**	49	~45
50 ns low emit	1260	1.6	1.6	2.3×10^{34} level to 0.8×10^{34}	**138 level to 44**	**~40***

Next 10 years

2012	Run I	4 TeV, peak luminosity 7.7e33
2013	LS1	Splice consolidation, R2E, DN200…
2014		Experiments' consolidation and upgrades
2015	Run II	6.5 to 7 TeV, peak luminosity 1.7e34
2016		
2017		
2018	LS2	LHC phase 1 and **injector** upgrades Experiments' consolidation and upgrades
2019	Run III	7 TeV, peak luminosity 2.0e34
2020		
2021		
2022	LS3	HL-LHC upgrade (insertions, crab cavities…)
2023		Experiments' HL upgrades

Review of LHC and Injectors Upgrade Plans
this October – expect changes

“Baseline” luminosity evolution



Usual caveats apply

~310 fb^{-1} by end 2021

Conclusions

- Reasonably good performance from commissioning through run I
  - 2 years 3 months from first collisions to Higgs
- Foundations laid for run II (and beyond)

Acknowledgements

- LHC enjoying benefits of the decades long international design, construction, installation effort.
- Progress with beam represents phenomenal effort by all the teams involved, injectors included.
- On the hardware side, I hope you've got a glimpse of the dedication and professionalism involved in keeping this remarkable machine operating well (and safely!).
- On the accelerator physics side - huge amount of experience & understanding gained
  - impressive work by the various teams (collective effects, beam-beam, optics, RF, beam transfer, beam loss, TFB, collimation, BI…)