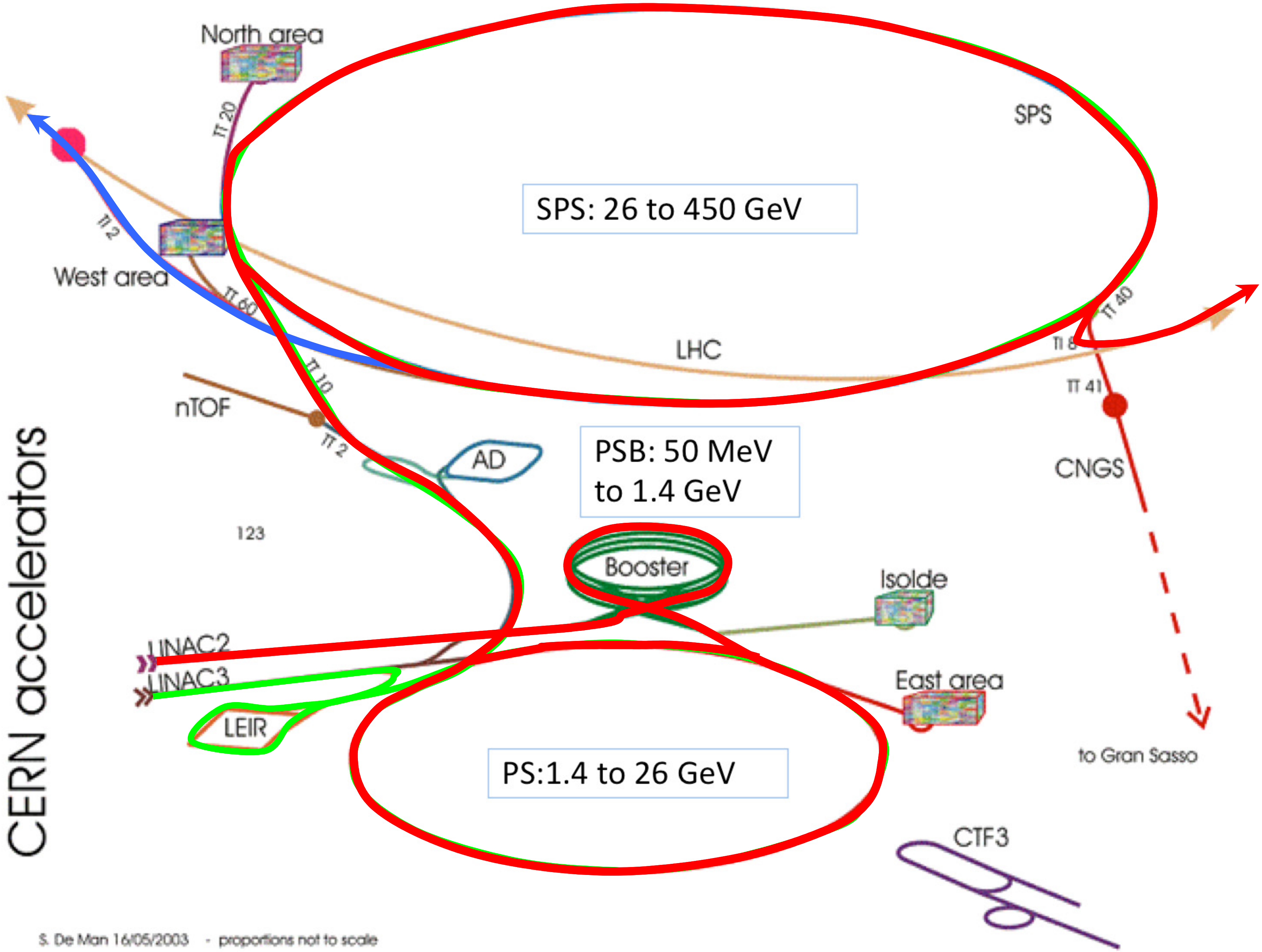
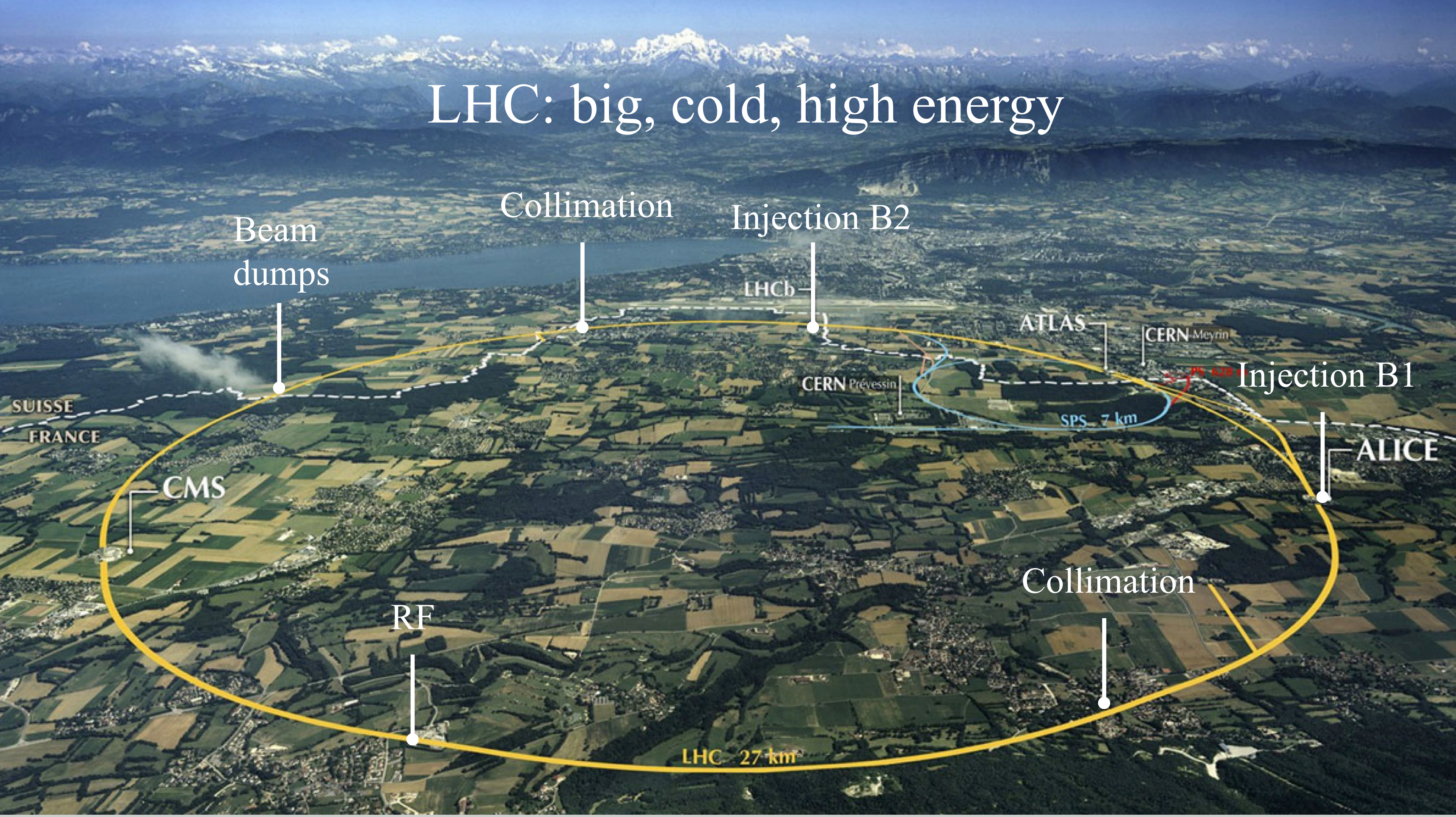
The First Years of LHC Operation for Luminosity Production

Mike Lamont
for the LHC team



CERN accelerators
North area
TT 20
SPS
SPS: 26 to 450 GeV
TI 2
West area
TT 60
LHC
TT 40
TI 8
TT 41
TT 10
nTOF
TT 2
AD
PSB: 50 MeV
to 1.4 GeV
CNGS
123
Booster
Isolde
LINAC2
LINAC3
East area
LEIR
PS:1.4 to 26 GeV
to Gran Sasso
CTF3
S. De Man 16/05/2003 - proportions not to scale

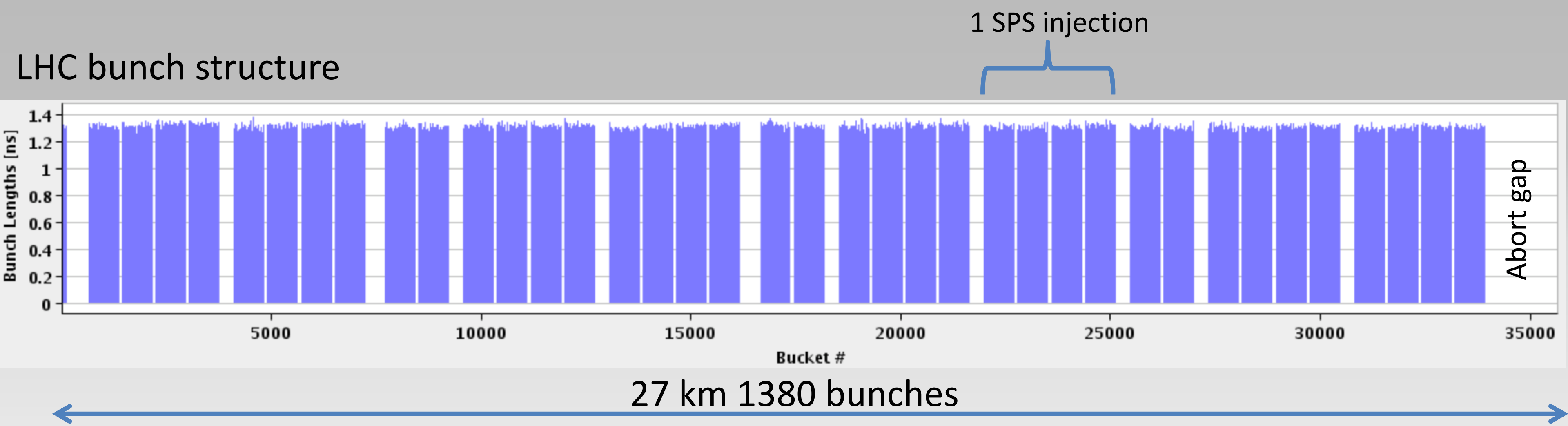
LHC: big, cold, high energy

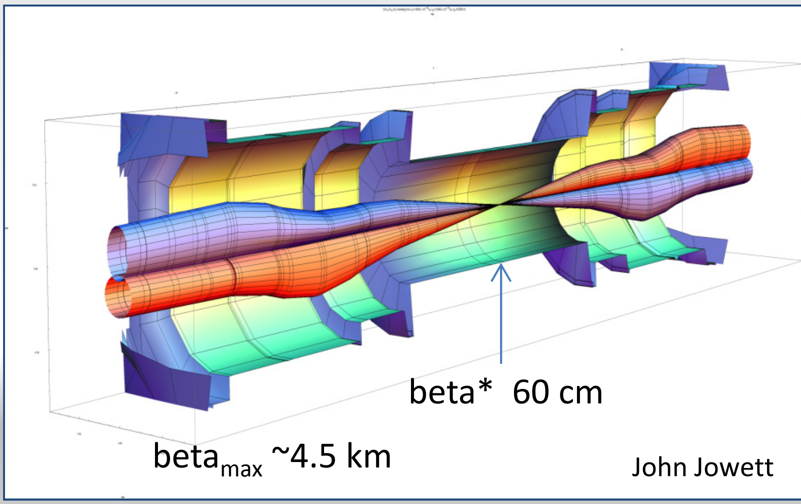


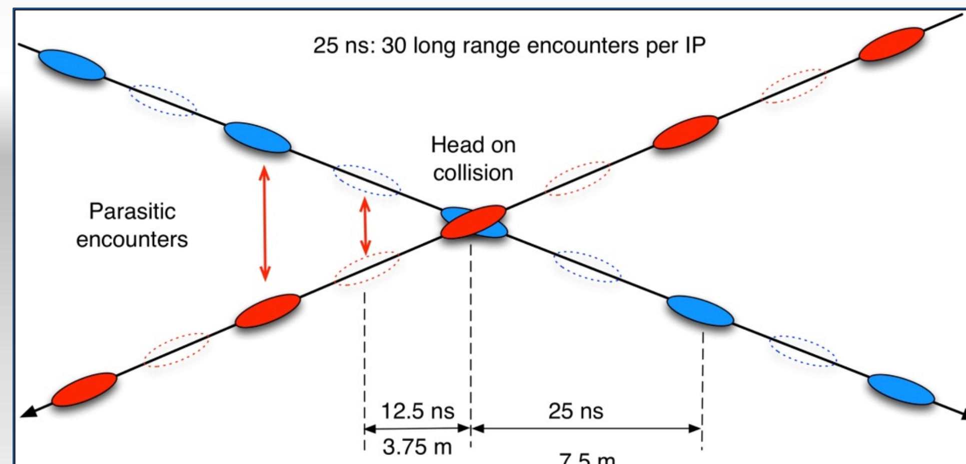
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
450 MJ magnetic energy per sector at 4 TeV

LHC bunch structure



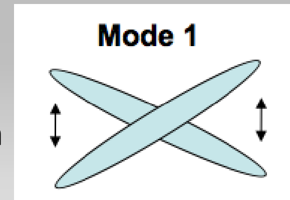




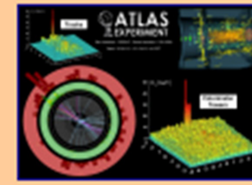
Feb 27
Beam back

March 30
First collisions
3.5 TeV

June
Commission
nominal bunch
intensity



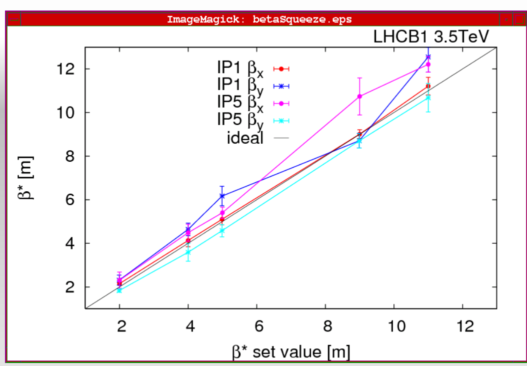
November: jet "quenching" in HI



November 4
Switch to lead
ions

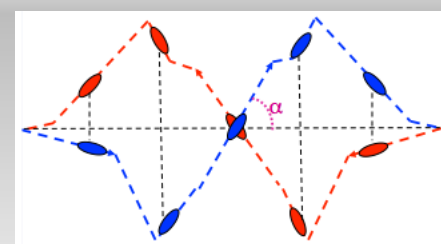
QUALIFICATION

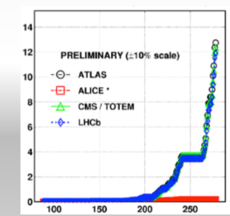
February	March	April	May	June	July	August	September	October	November



April
Commission
squeeze

September
Crossing angles on





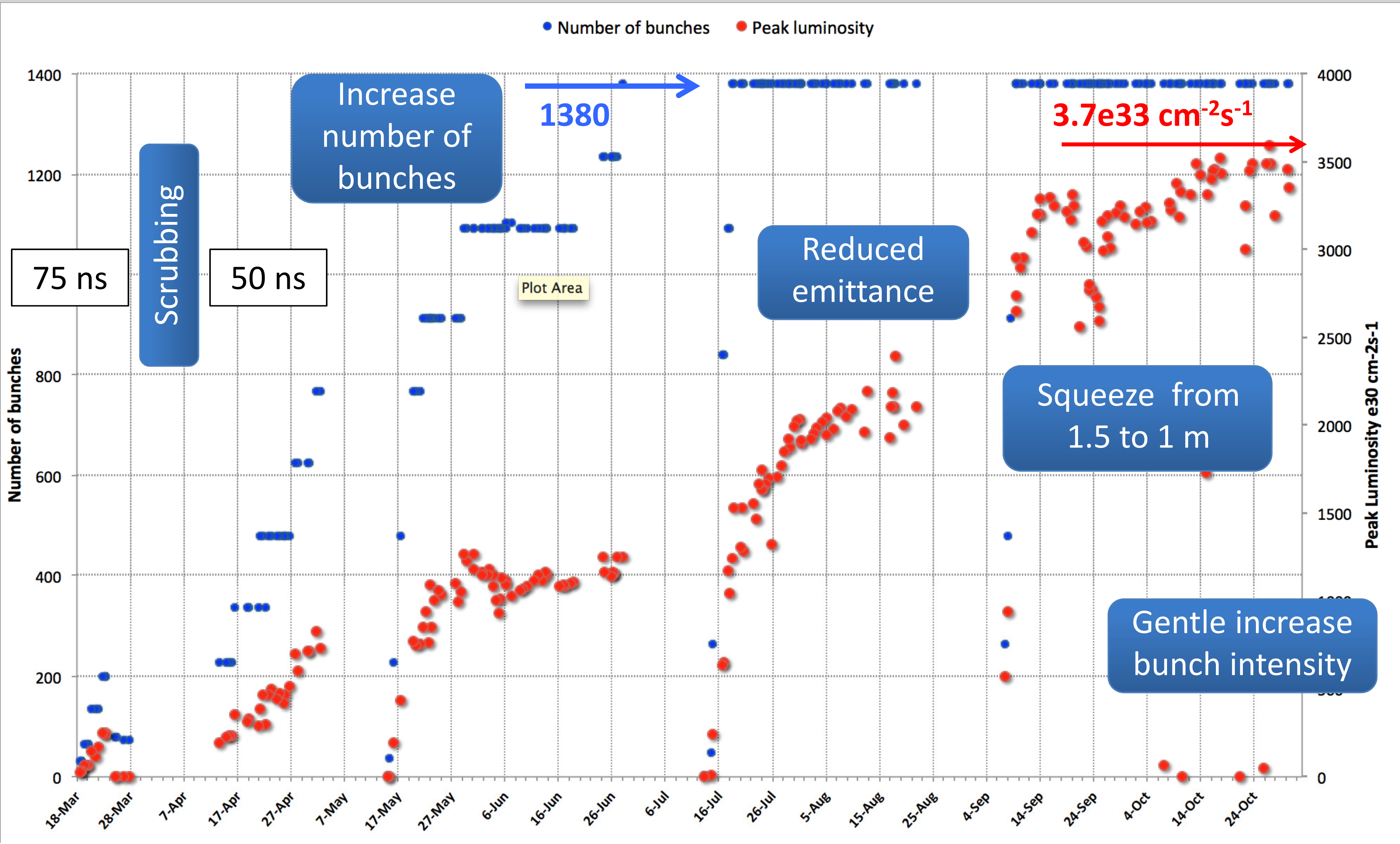
October 14 2010
1e32
248 bunches

2010

Total for year: 50 pb^{-1}

2011

3.5 TeV
Beta* = 1.5 m



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

March 15
Beam back

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

4 July

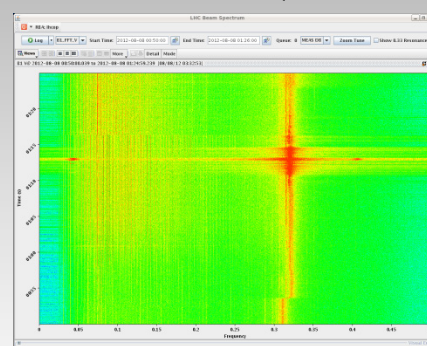
13-14 September
Proton-lead test

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



December
25 ns scrubbing run

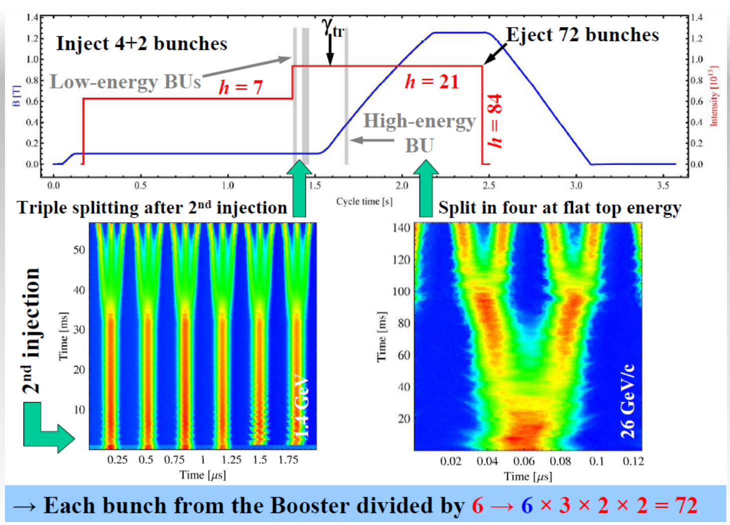
ICHEP2012 Melbourne

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

2012

Performance from injectors 2012

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

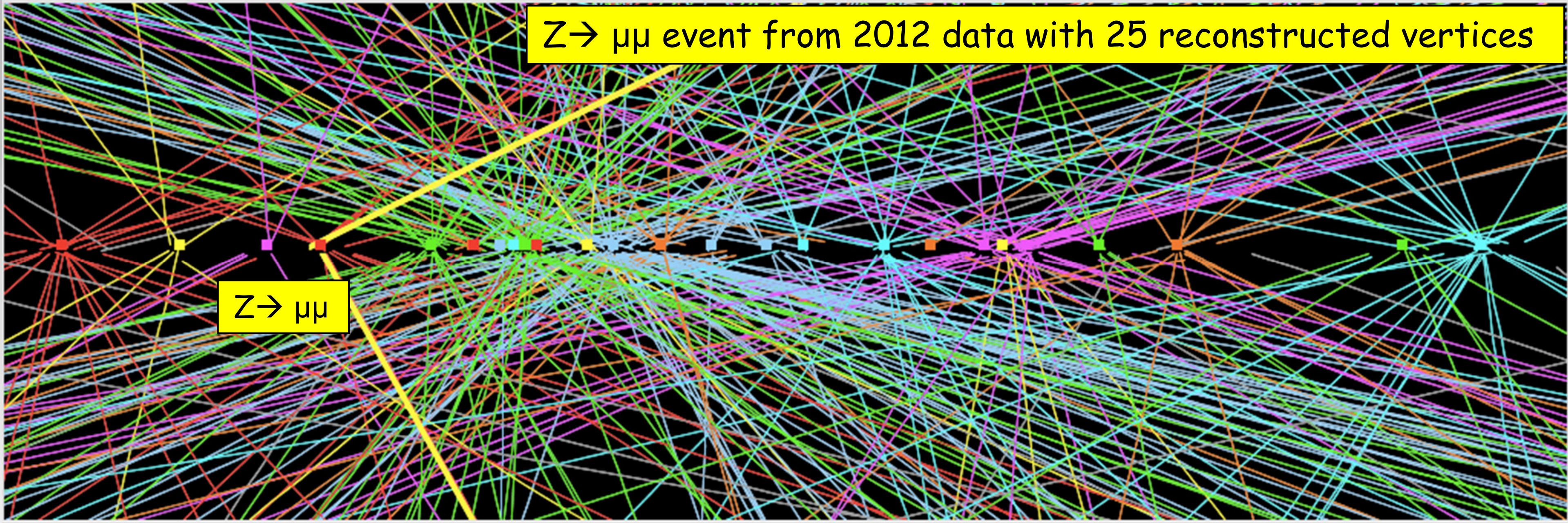


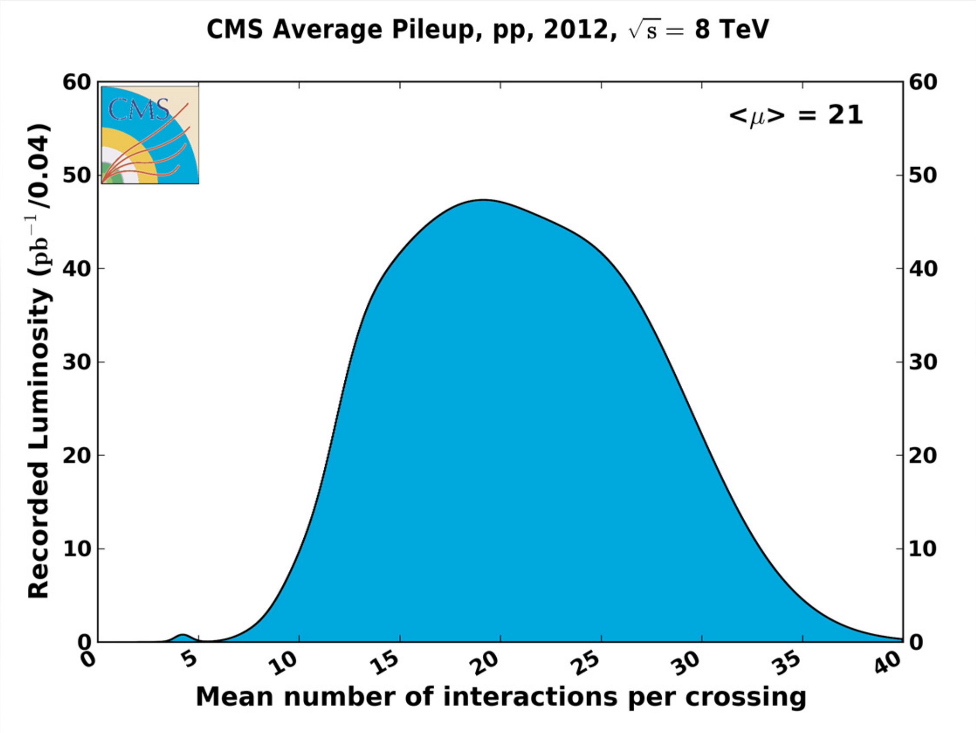
Chose to stay with 50 ns:

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

Peak performance through the years

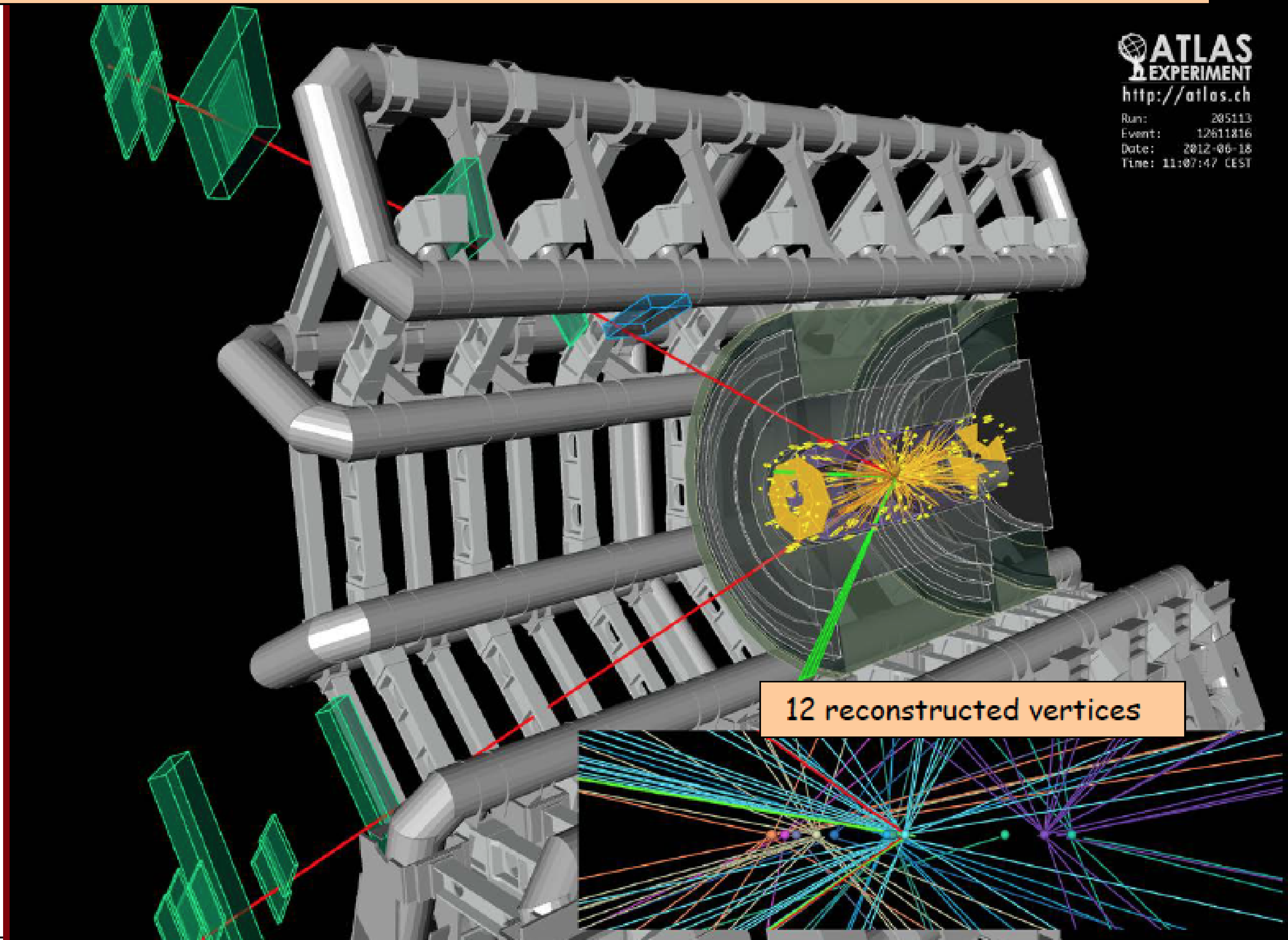
	2010	2011	2012	Nominal
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	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
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60

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

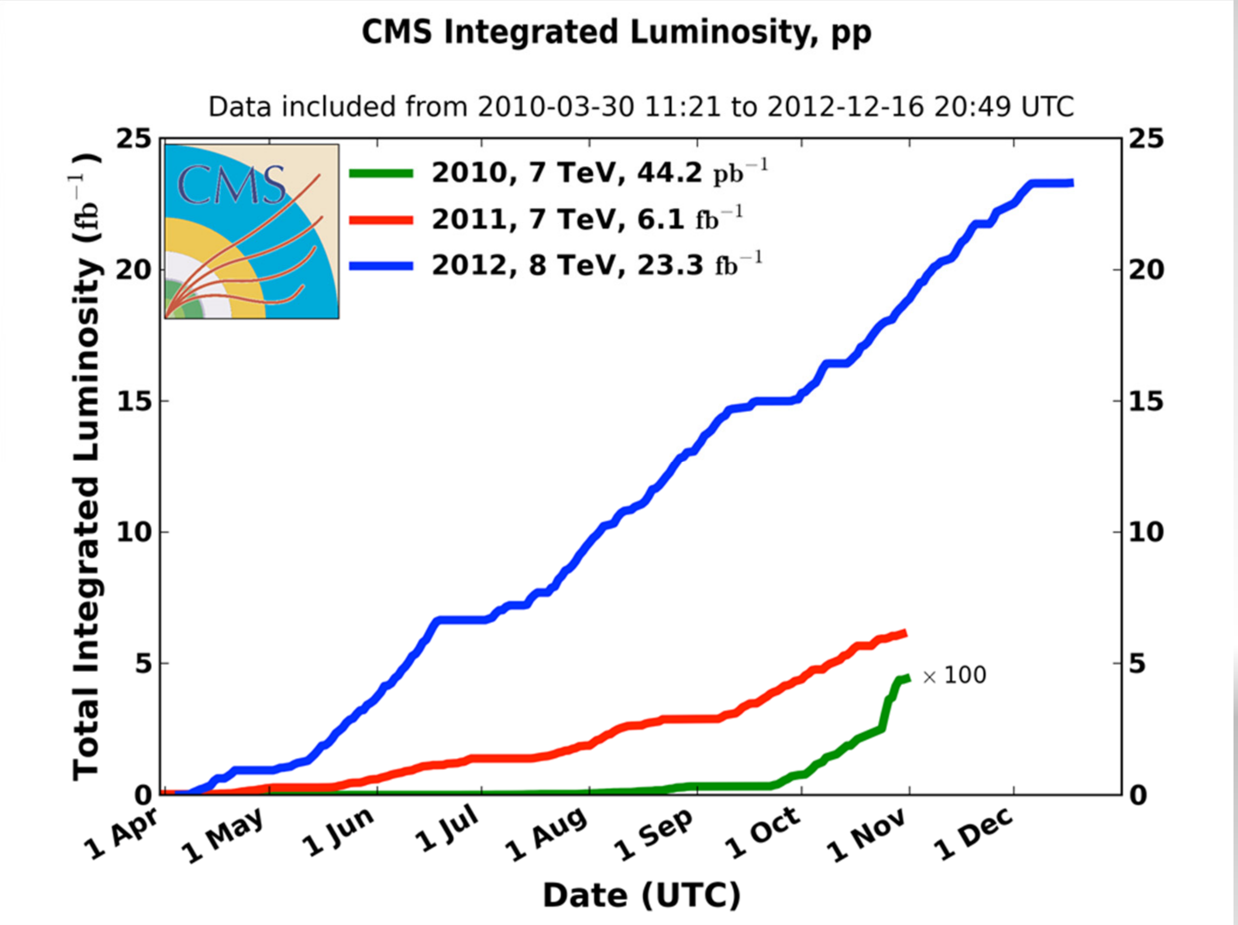
p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV



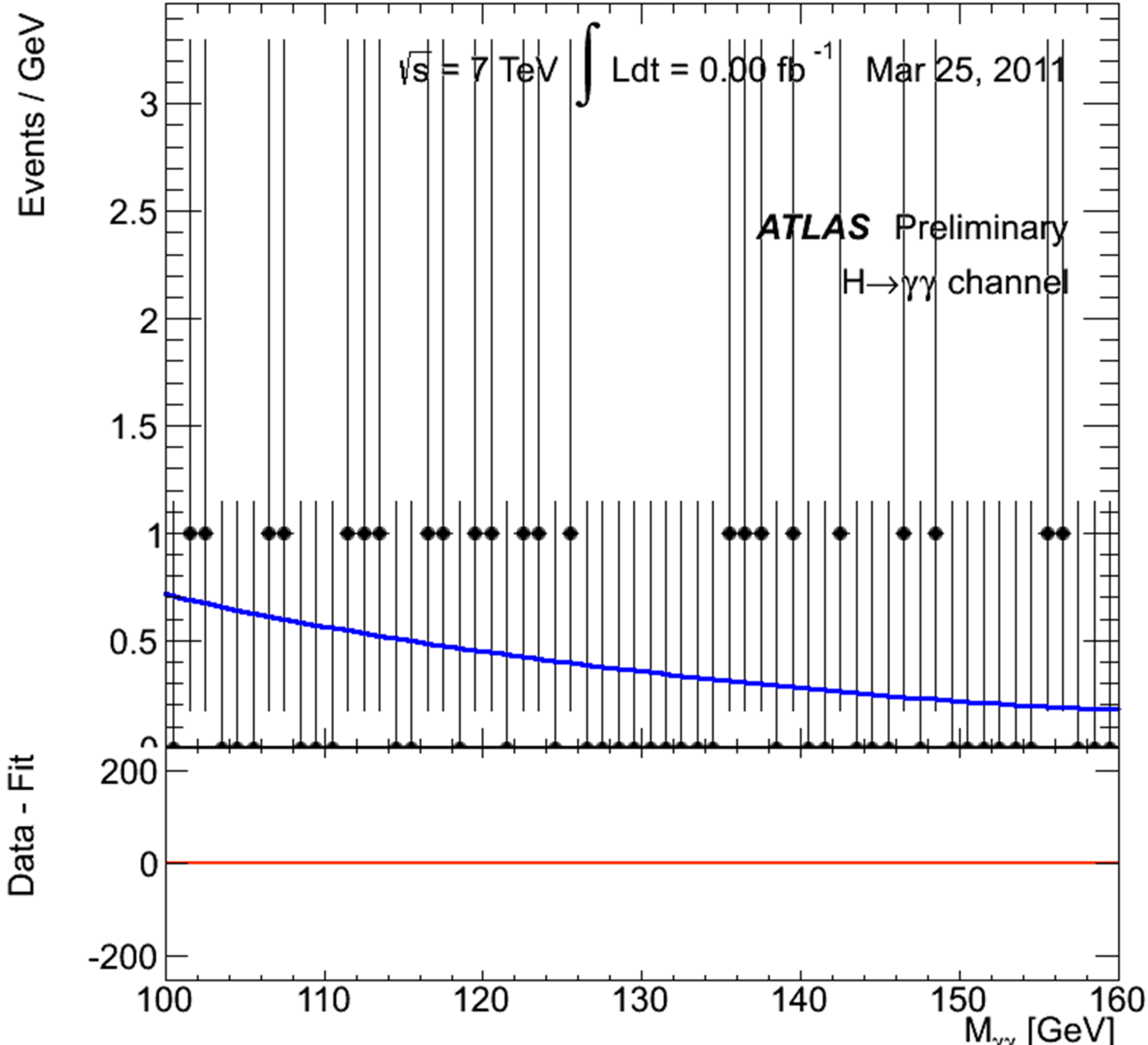
Operational efficiency has, at least occasionally, been not so bad

	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%)

Integrated luminosity 2010-2012

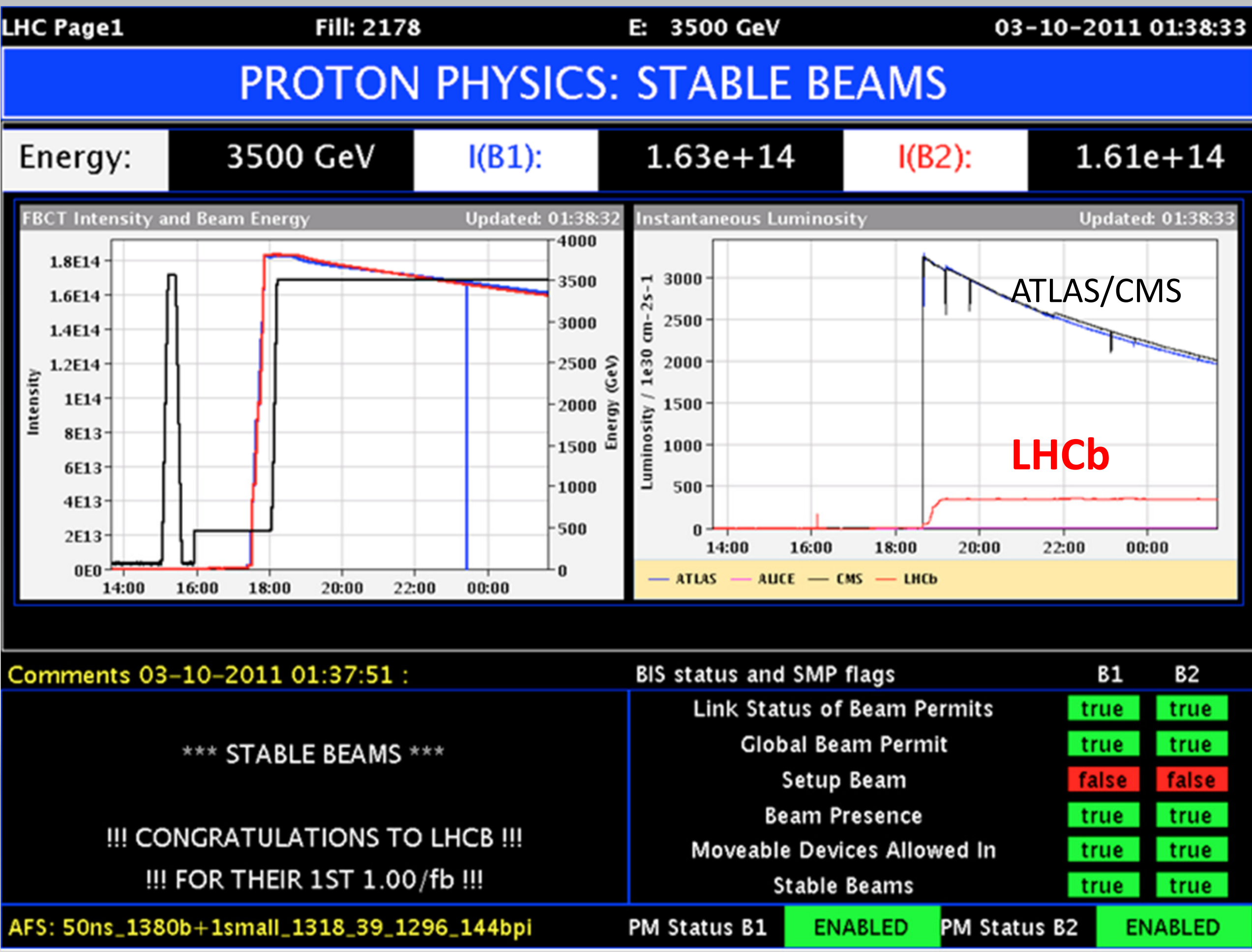


- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production



Events / GeV
$\sqrt{s}$ = 7 TeV
$\int$ Ldt = 0.00 fb^{-1}
Mar 25, 2011
ATLAS Preliminary
H→γγ channel
Data - Fit
$M_{\gamma\gamma}$ [GeV]

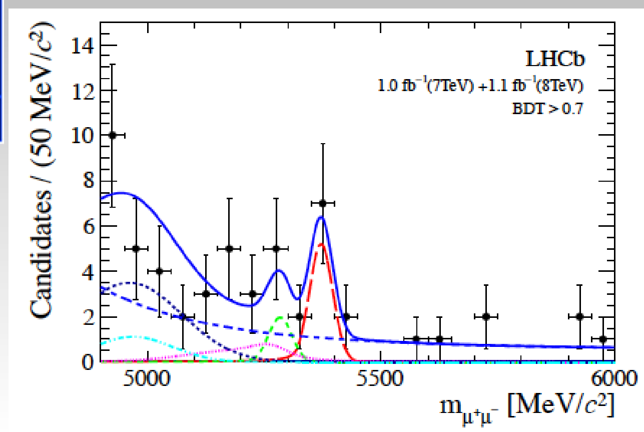
LHCb



Luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation (with a tilted crossing angle)

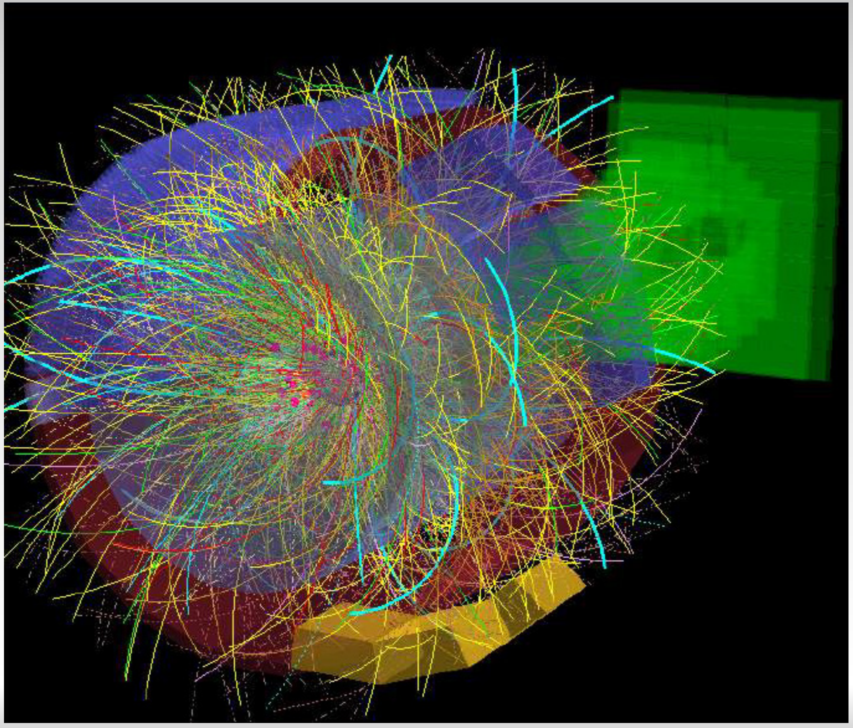
Not completely trivial!

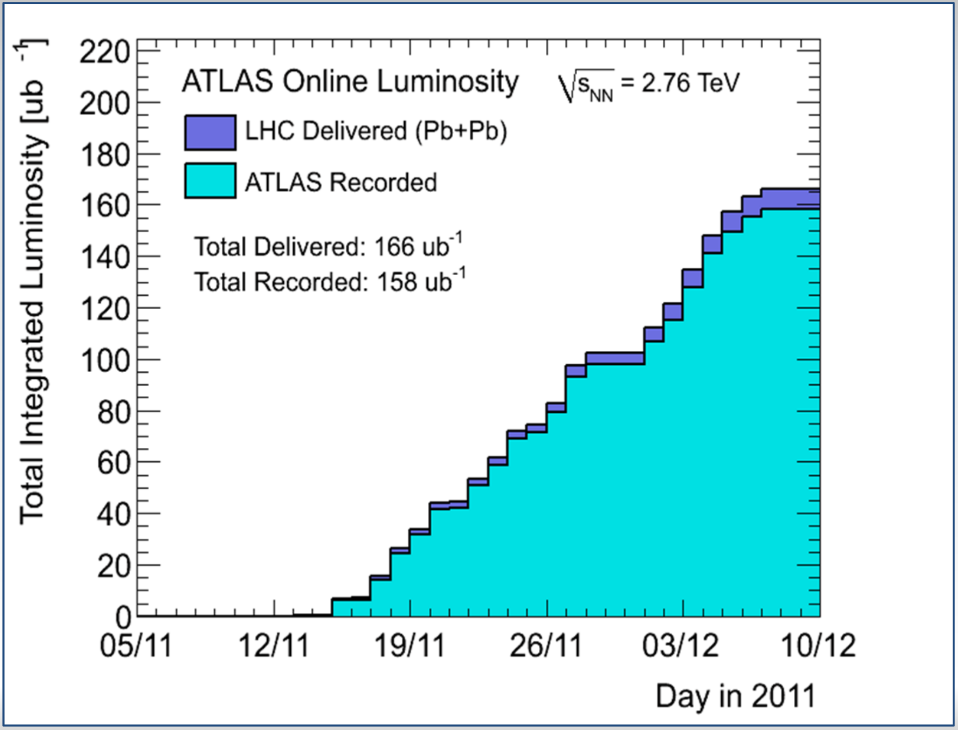
First evidence for the decay Bs -> mu+ mu-



TUPFI010 **The LHCb Online Luminosity Control and Monitoring**
R. Alemany-Fernandez et al

Pb-Pb

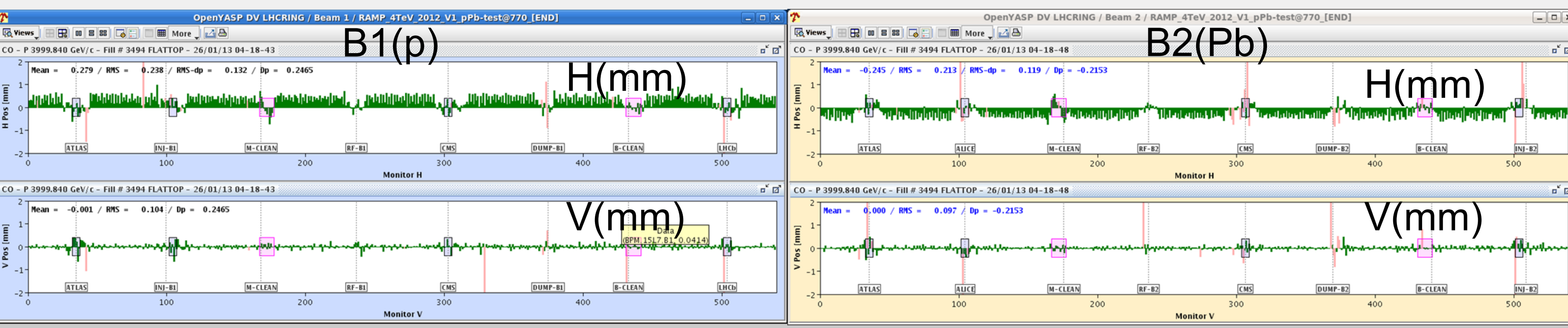




- Good performance from the injectors - bunch intensity and emittance
- Preparation, Lorentz's law: impressively quick switch from protons to ions
- Peak luminosity around 5 x 10^{26} cm^{-2}s^{-1} at 3.5Z TeV – nearly twice design when scaled to 6.5Z TeV

Proton-lead

- Beautiful result
- Final integrated luminosity above experiments' request of 30 nb^{-1}
- Injectors: average number of ions per bunch was ~1.4×10^8 at start of stable beams, i.e. around twice the nominal intensity

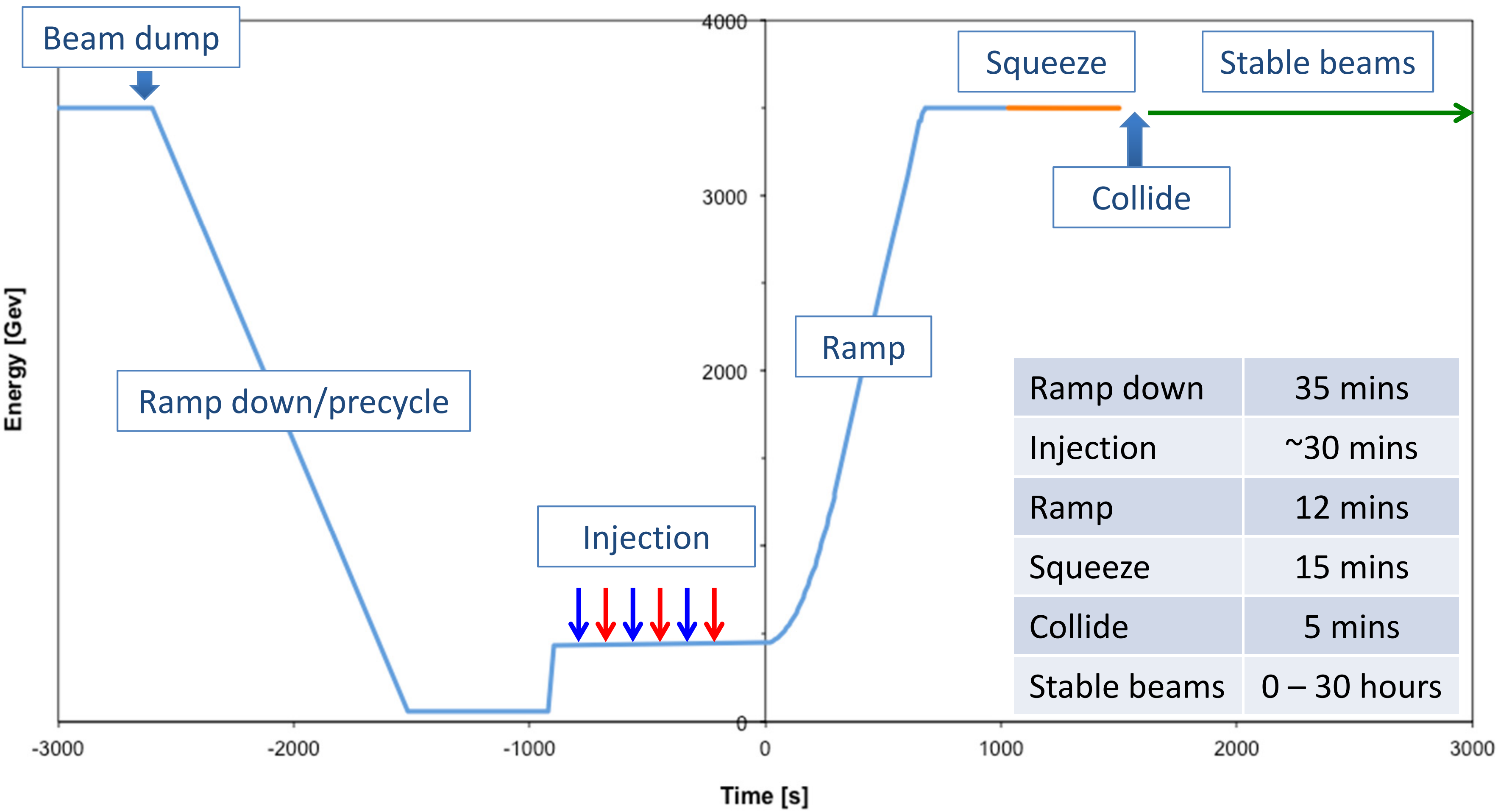


Beam orbits at top energy with RF frequencies locked to B1

MOODB201 **Proton-nucleus Collisions in the LHC**, J. Jowett et al

WEPEA061**, The first LHC p-Pb run: Performance of the heavy ion production complex**, D. Manglunki et al

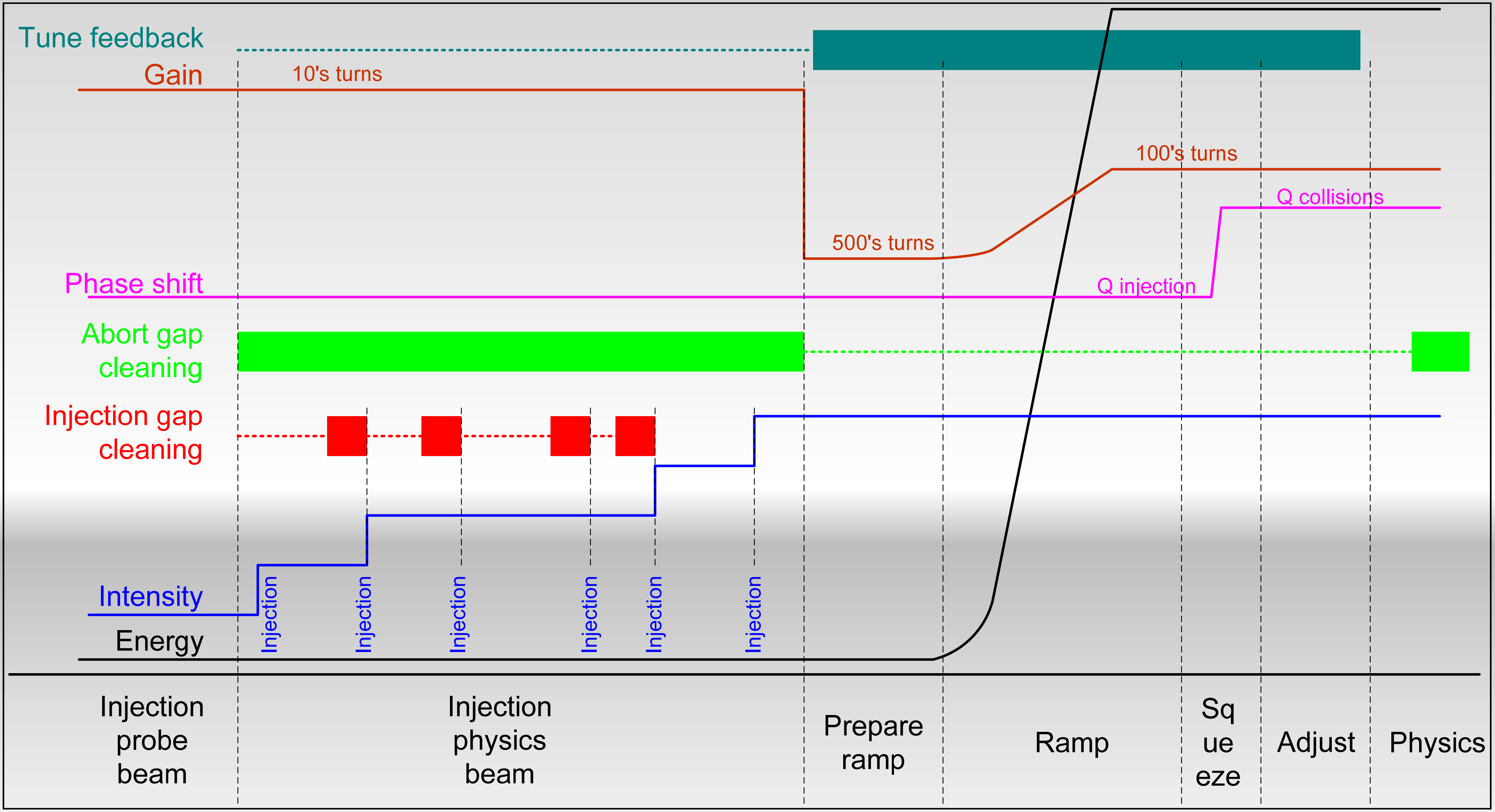
Operational cycle



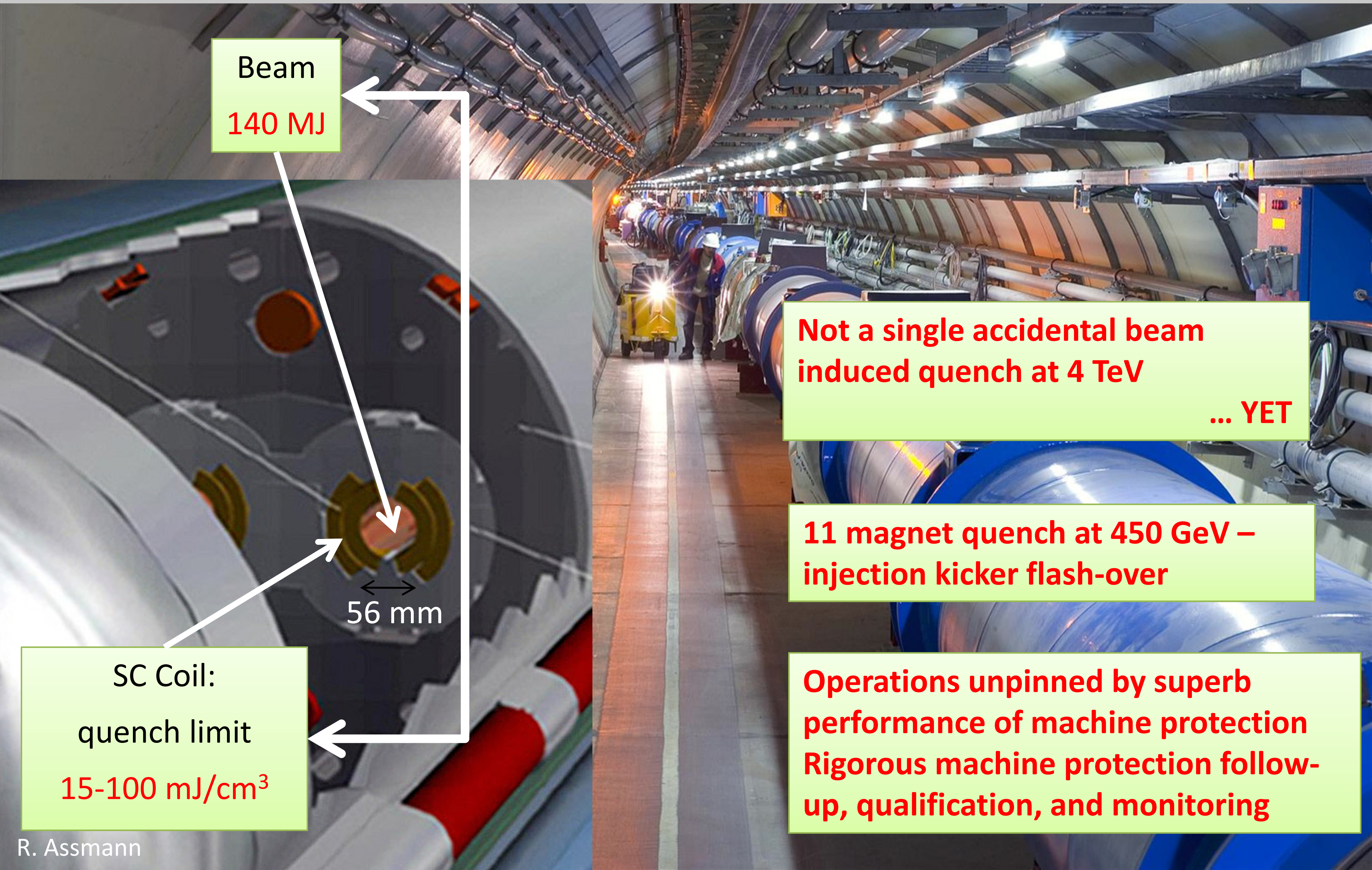
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

Turn around 2 to 3 hours on a good day

Example – transverse feedback

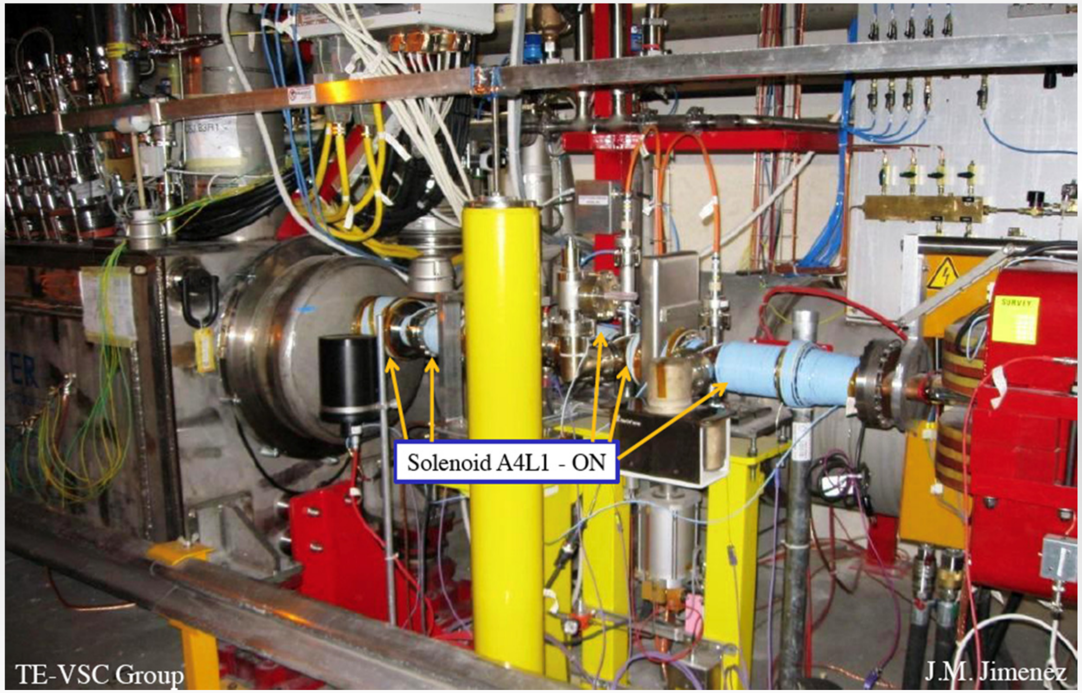


Machine protection



System performance

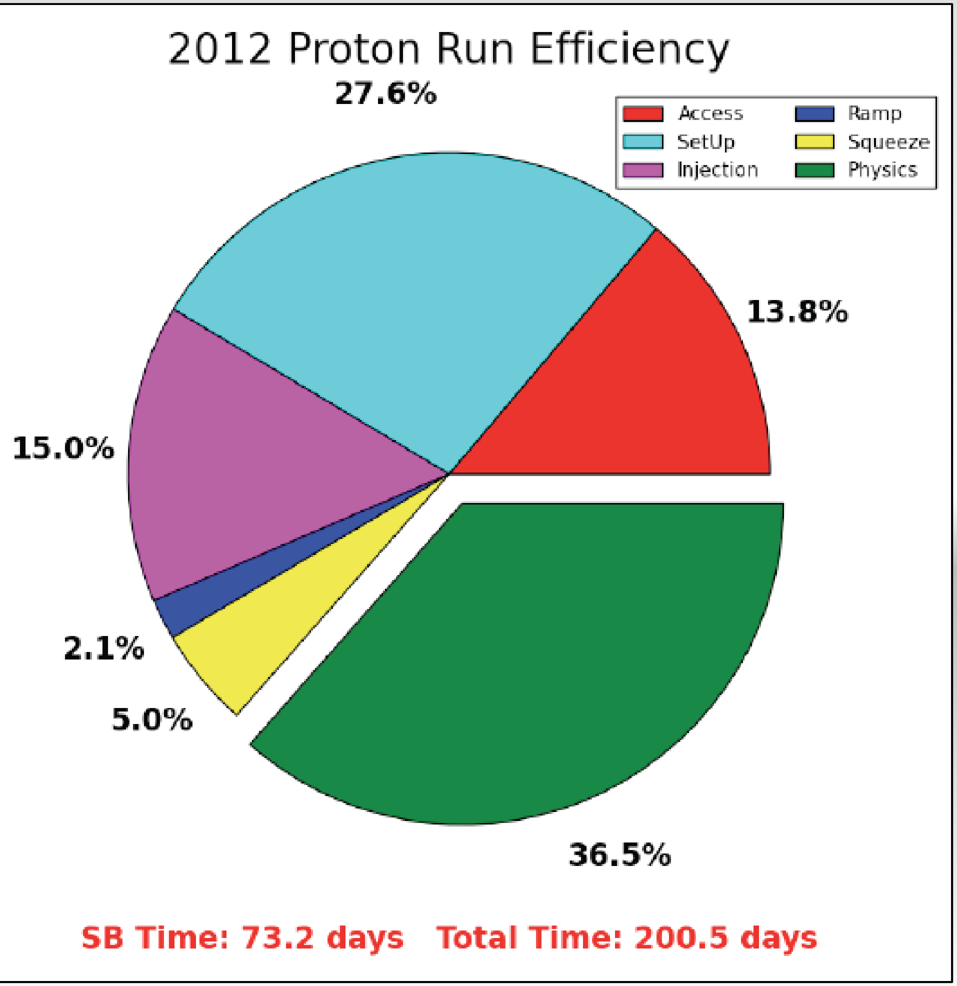
- RF, power converters, collimators, beam dumps, injection, magnets, vacuum, transverse feedback, machine protection
- Magnets, magnet protection & associated systems
- Beam instrumentation and beam based feedbacks
- Controls, databases, high level software
- Cryogenics, survey, technical infrastructure, access, radiation protection

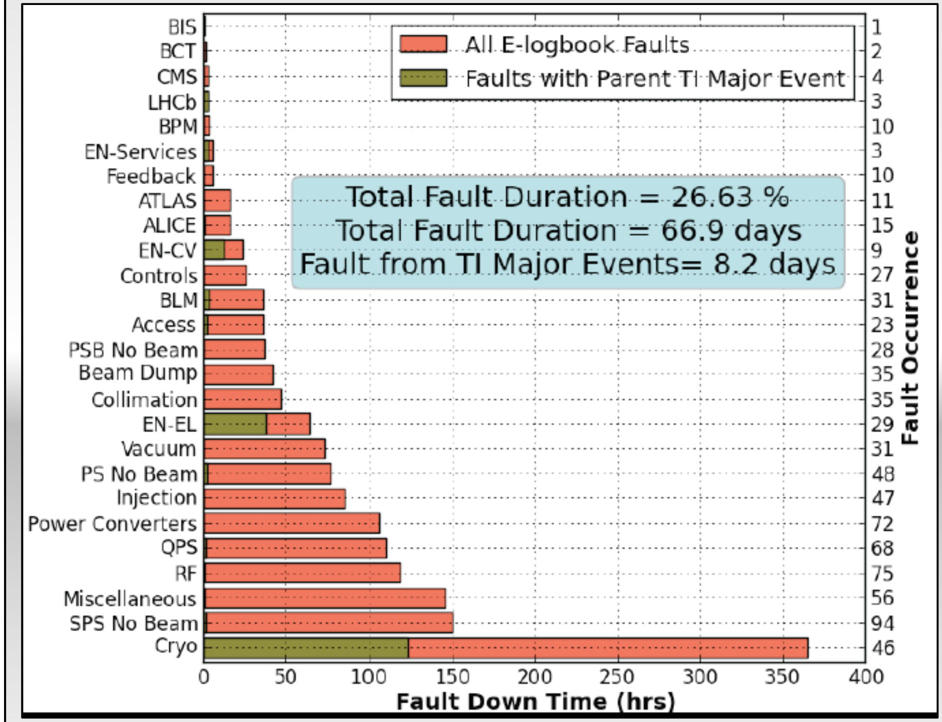


Impossible to do justice to the commitment and effort that's gone in to getting, and keeping, the LHC operational

Availability

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

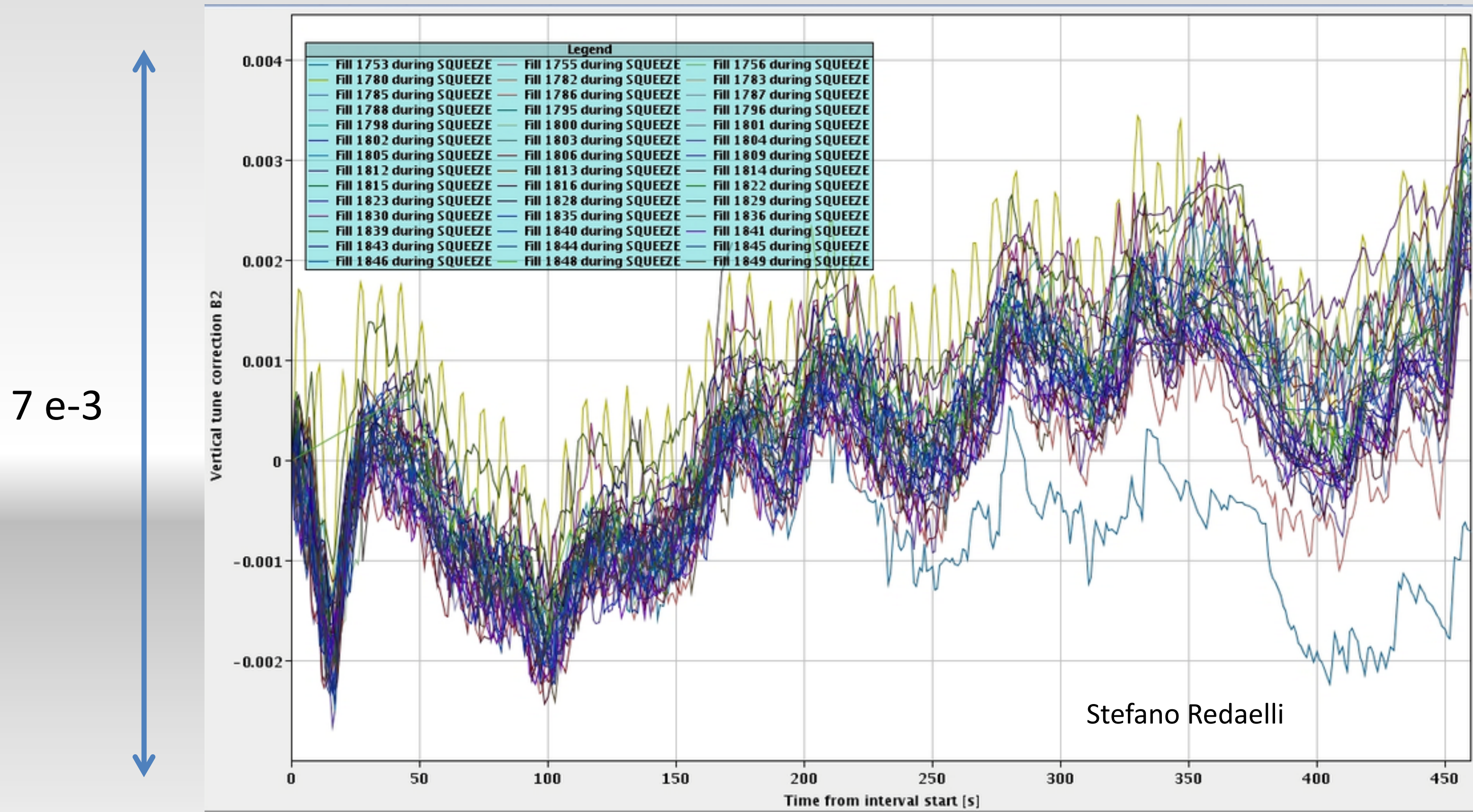




Cryogenics availability in 2012: 93.7%

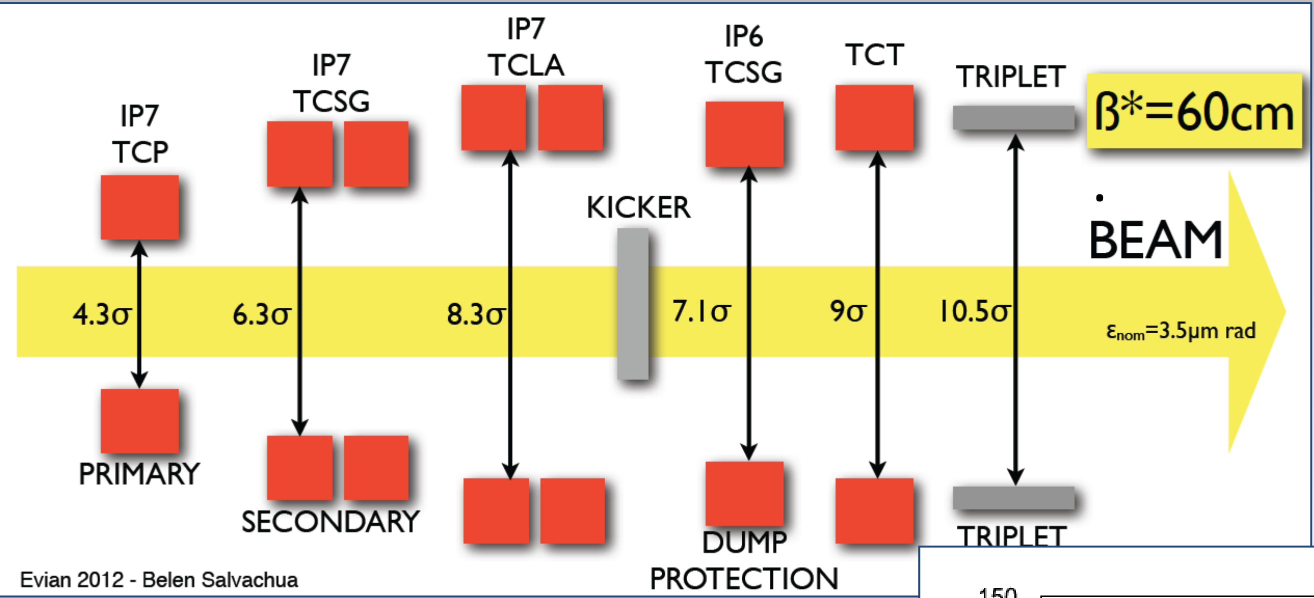
Reproducibility

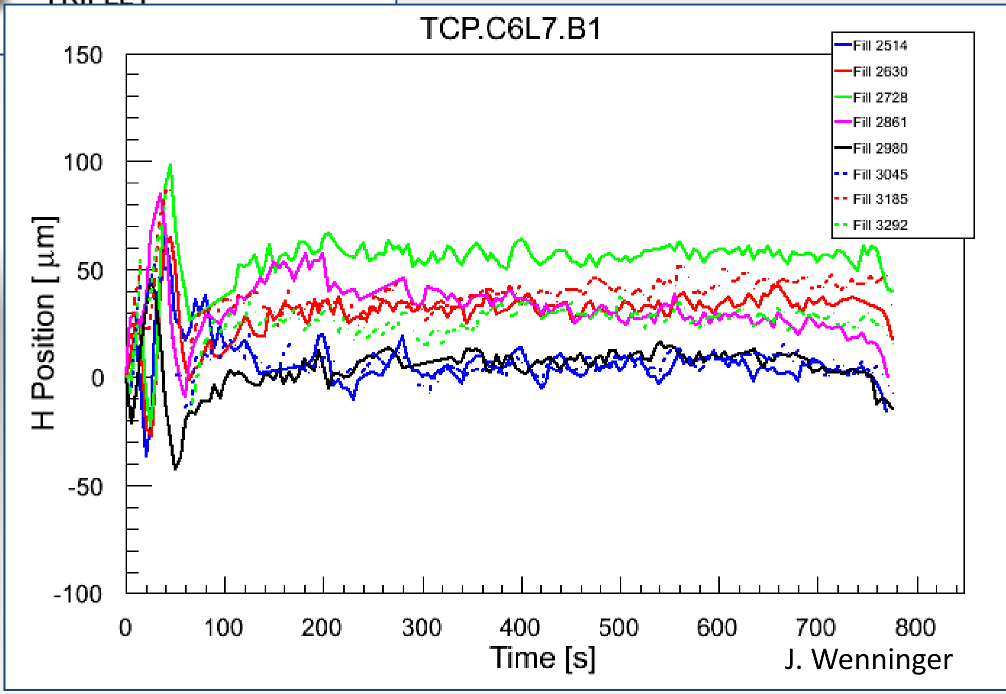
LHC magnetically reproducible with rigorous pre-cycling:
optics, orbit, collimator set-up, tune, chromaticity…



Tune corrections made by feedback during squeeze

Collimation/reproducibility

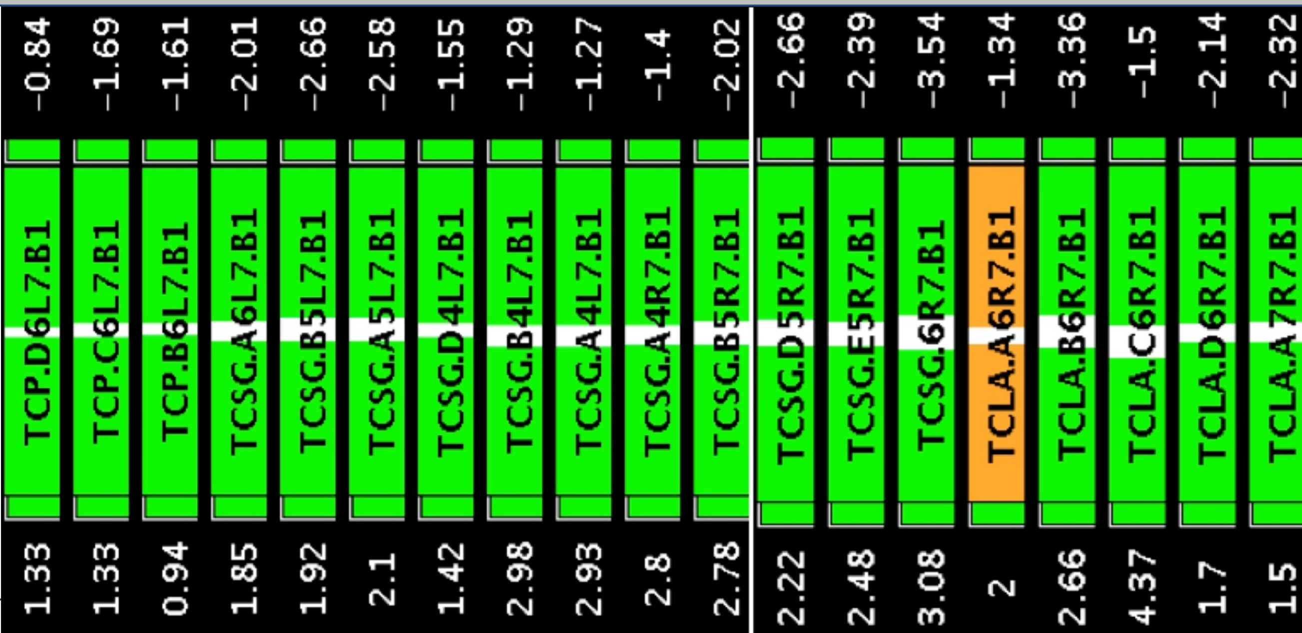




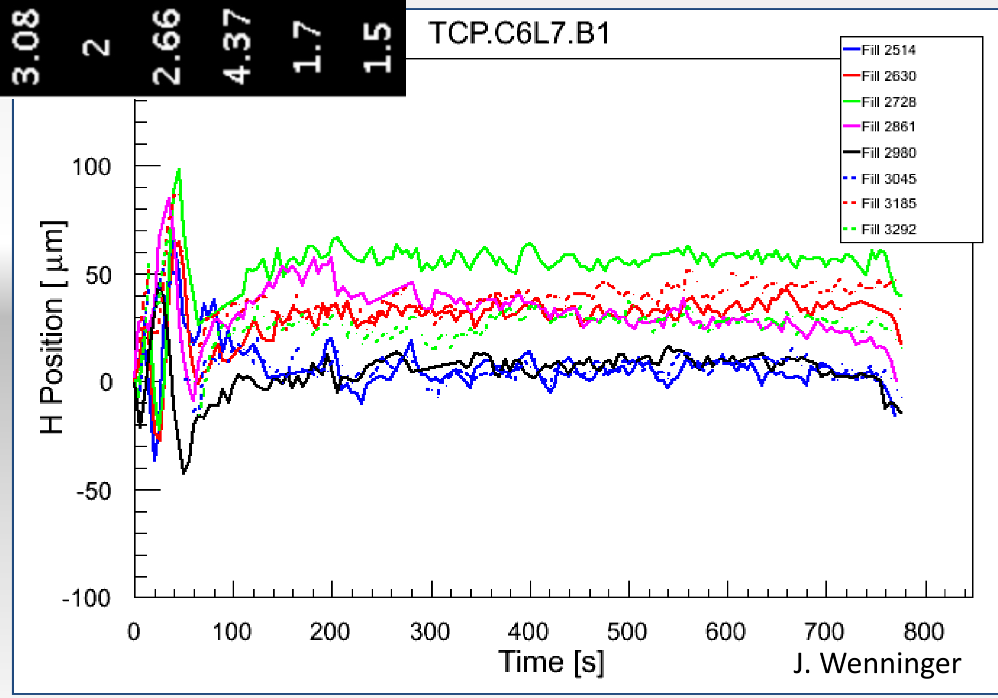
2011-2012: only ONE full alignment in IR3/IR7

MOPWO048 **Cleaning Performance of the LHC Collimation System up to 4 TeV** – B. Salvachua et al

Collimation/reproducibility



IR7 collimators – beam 1

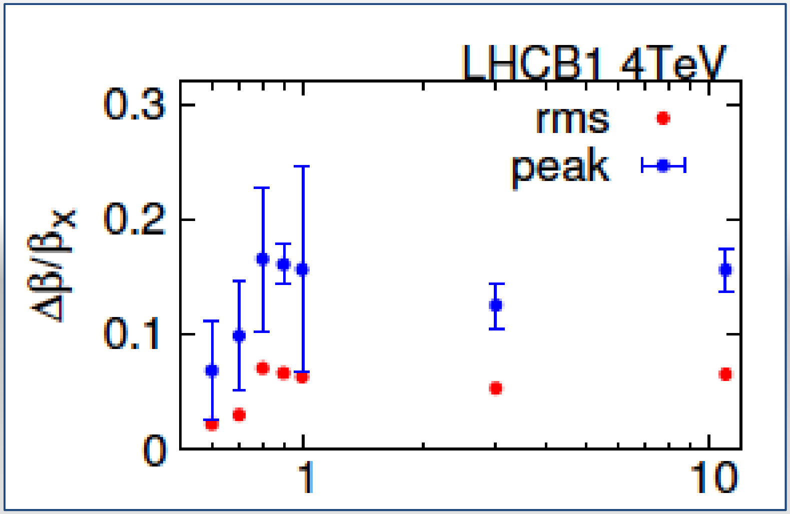


2011-2012: only ONE full alignment in IR3/IR7

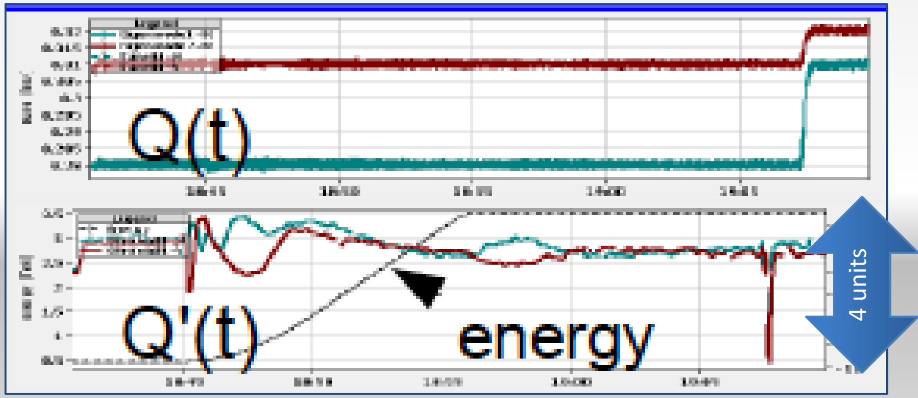
MOPWO048 **Cleaning Performance of the LHC Collimation System up to 4 TeV** – B. Salvachua et al

Optics, magnet model, aperture

- **Very good magnetic model**
  - including dynamic effects
- **Linear optics**: close to model, corrected to excellent
- **Non-linear dynamics** well understood
- **Better than expected aperture**



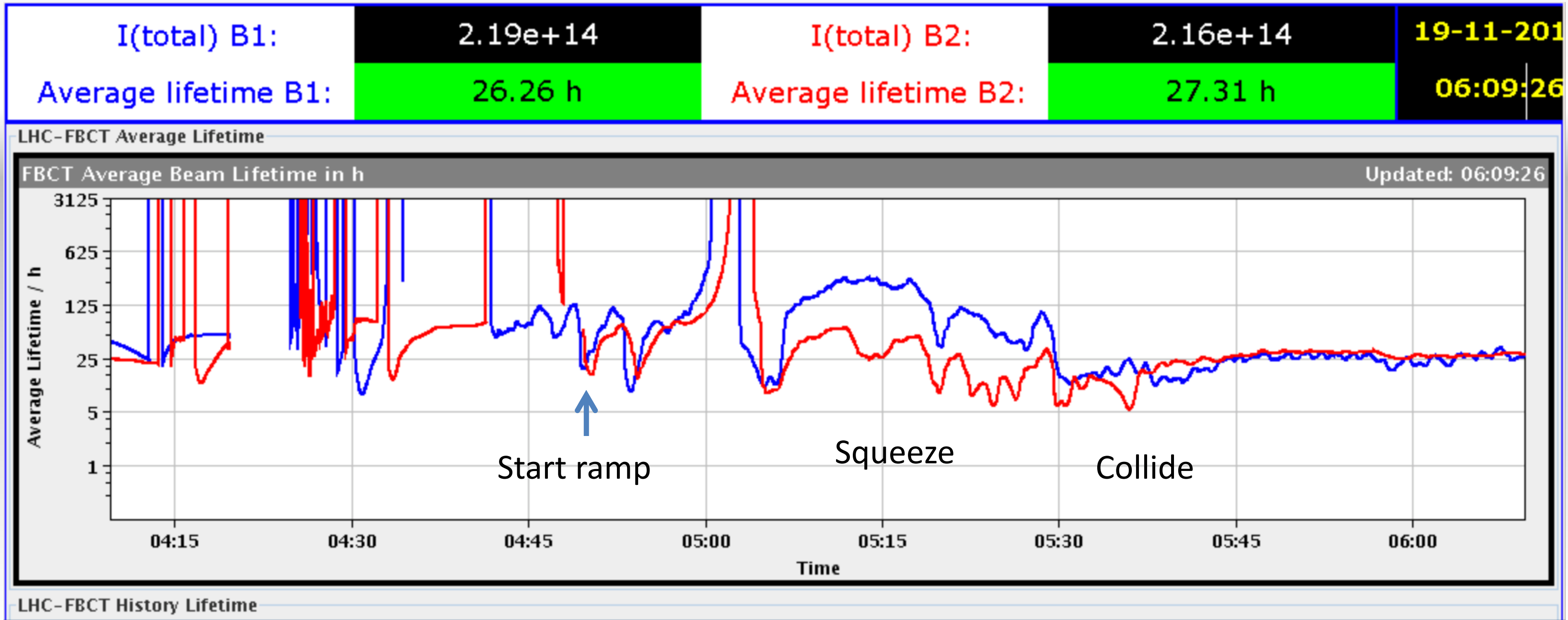
Beating in squeeze after local and global corrections



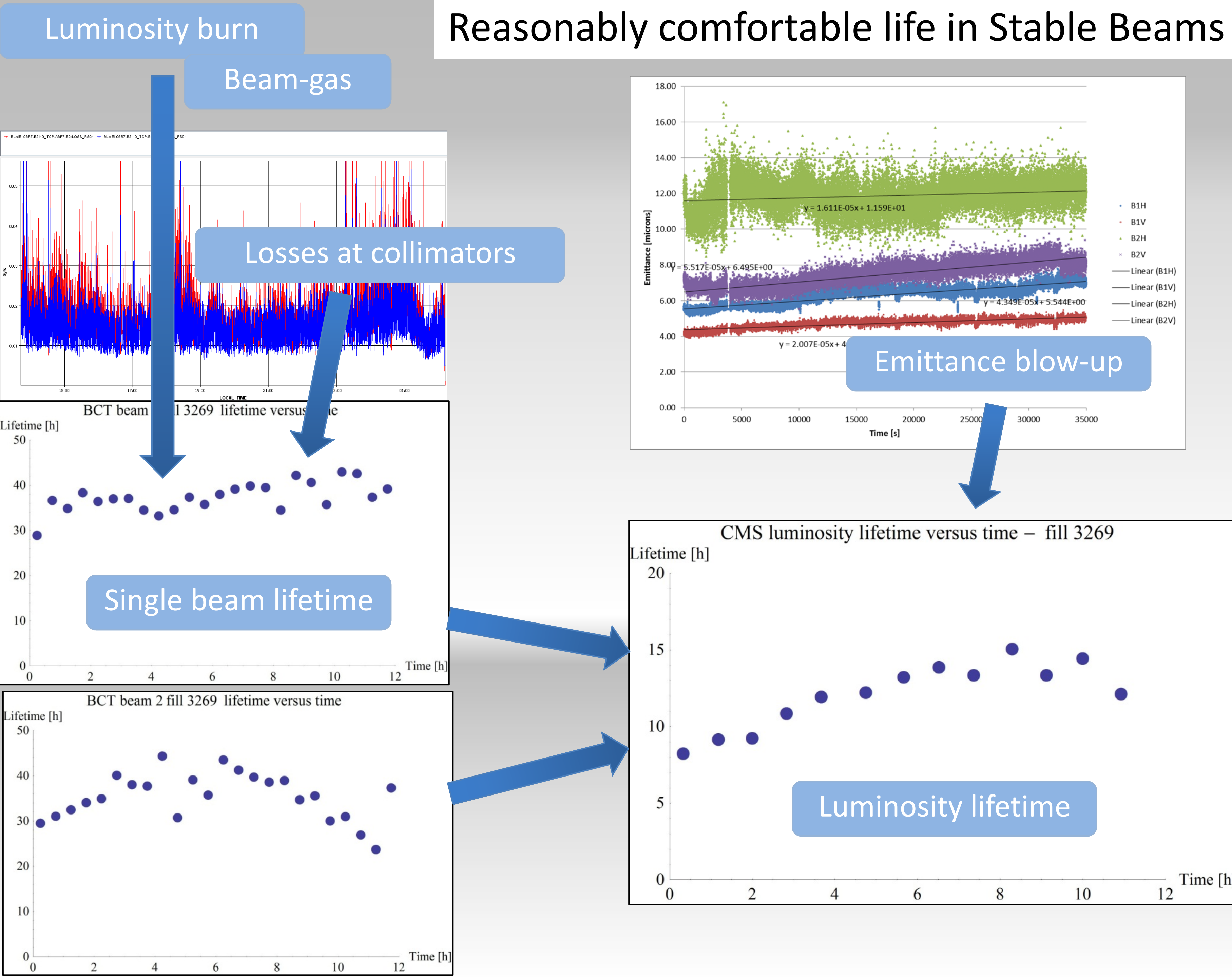
Model based feed-forward reduces chromaticity swing from 80 to less than 10 units

Beam

- 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

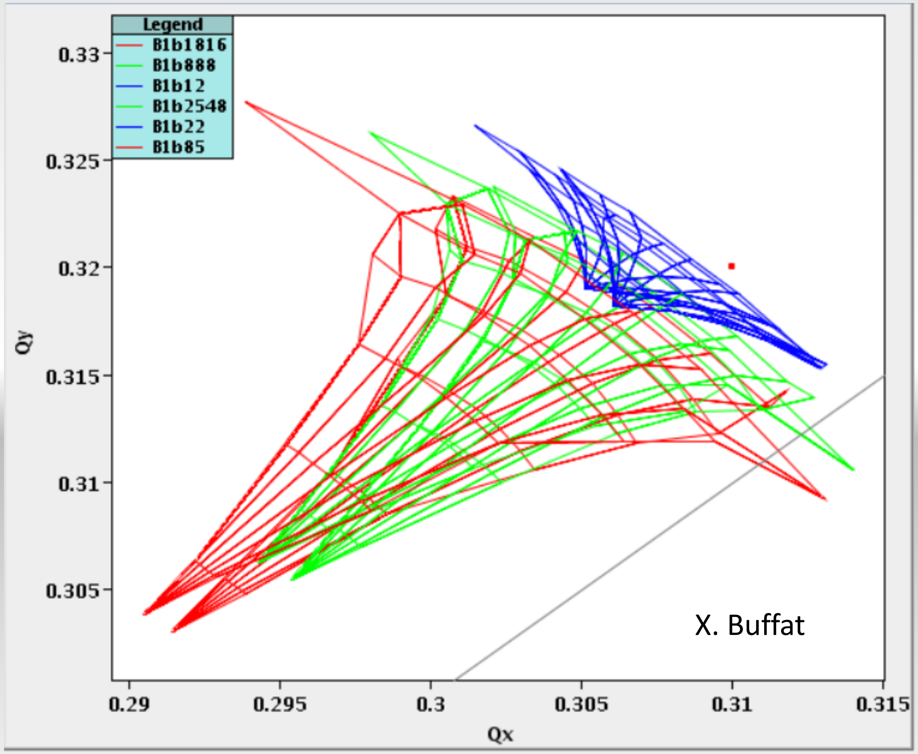


Reasonably comfortable life in Stable Beams



Beam-beam

- Head-on 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…



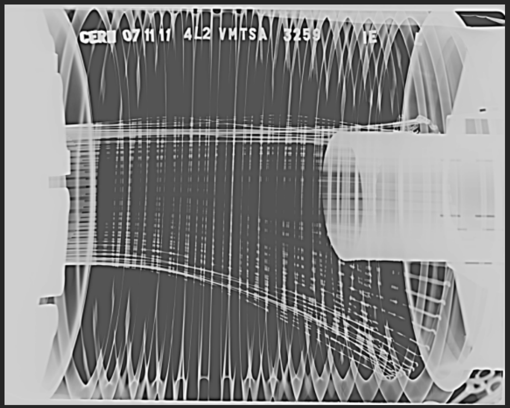
TUPFI035 **Head-on and Long range Beam-beam Interactions in the LHC**, X. Buffat et al

WEPEA071 **Performance limitations in the LHC due to parasitic beam-beam encounters**, W. Herr et al

Some issues…

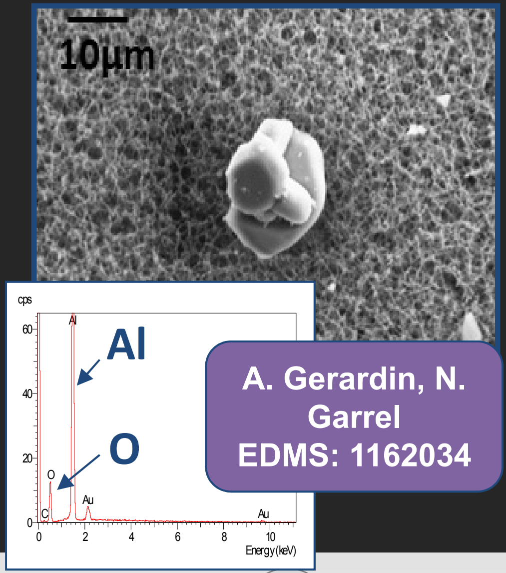
Beam induced heating

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



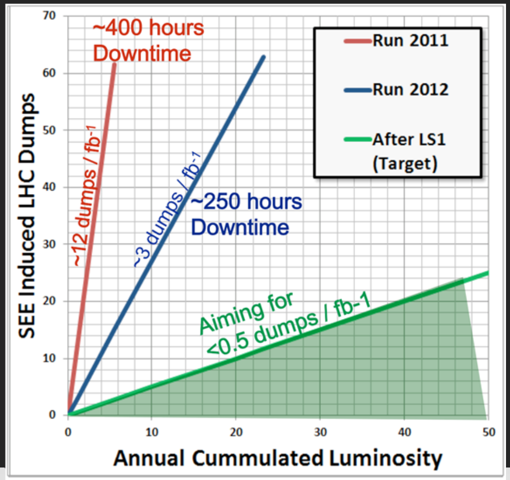
UFOs

- 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

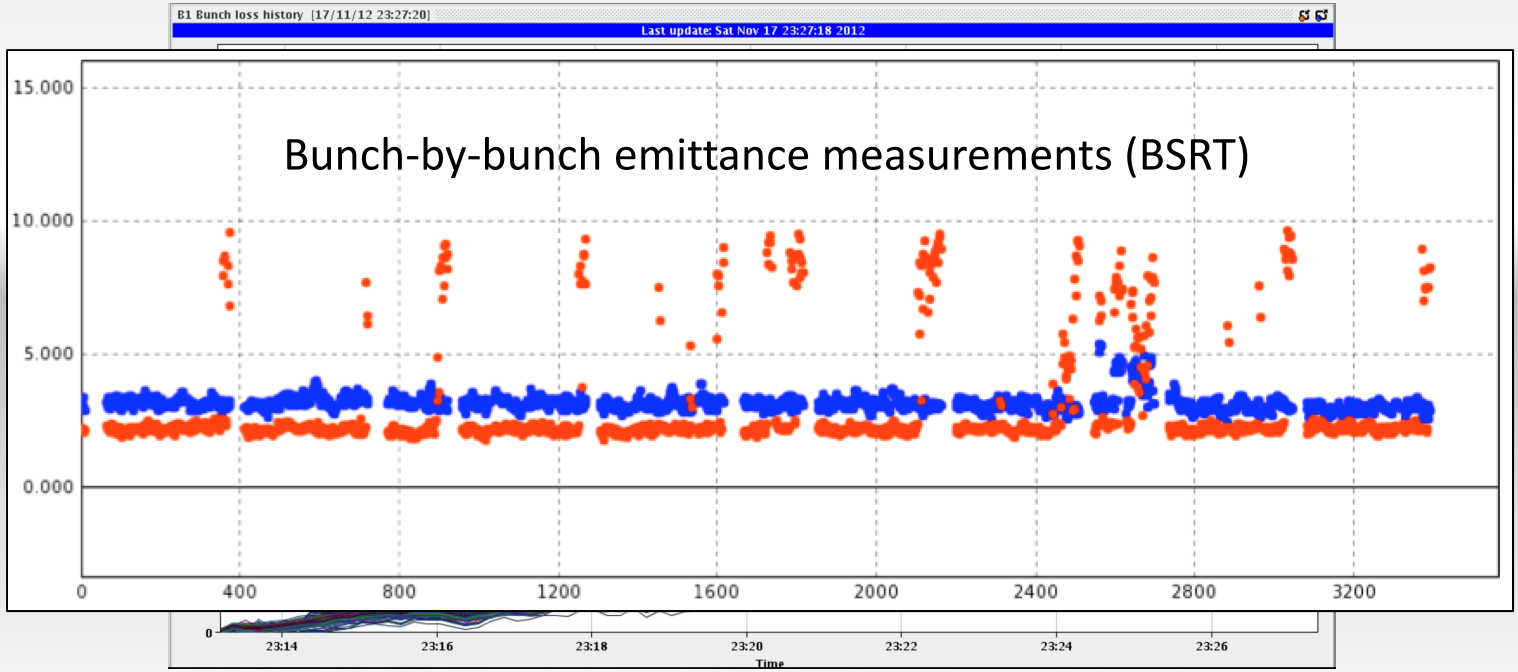


TUPME032 **Update on Beam Induced RF Heating in the LHC** – B. Salvant et al

TUPFI013 **LHC Long Shutdown: A Parenthesis for a Challenge** – K. Foraz

Instabilities

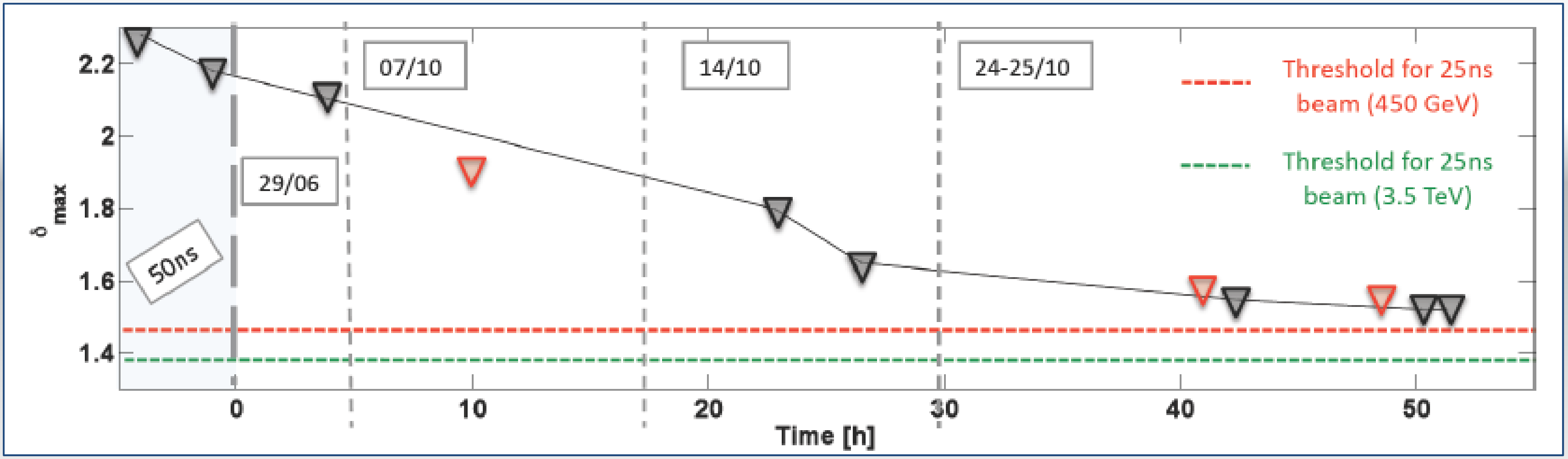
- Note: increased impedance from tight collimators in 2012
- Instabilities have been observed:
  - on bunches with offset collisions in IP8 only
  - while going into collision
  - end of squeeze, few bunches: emittance blow-up and beam loss
- Defense mechanisms:
  - octupoles, high chromaticity, transverse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



TUPFI034 **Observations of two-beam instabilities during the 2012 LHC physics run**, T. Pieloni et al

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.

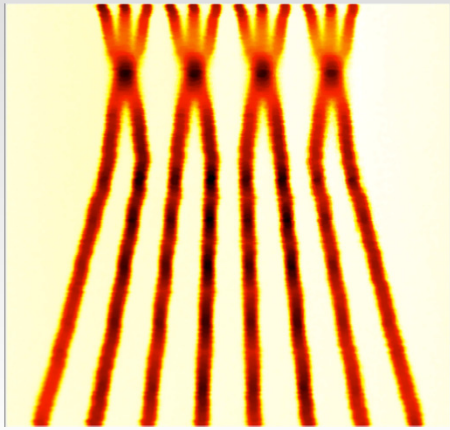


Evolution of δ_{max} on the the beam screen in the dipole magnets in 2011

2015 – post LS1

- Energy: 6.5 TeV
- Bunch spacing: 25 ns
  - pile-up considerations
- Injectors potentially able to offer nominal intensity with even lower emittance

BCMS = Batch Compression and Merging and Splitting



	Number of bunches	Ib LHC FT[1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns low emit	2520	1.15	1.9	**1.7e34**	52	~45

MOZB202 **The First Long Shutdown (LS1) for the LHC** – F. Bordry

WEPEA044 **RF Manipulations for Higher Brightness LHC-type Beams** – H. Damerau et al

Conclusions

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

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 accelerator physics side - huge amount of experience & understanding gained
  - impressive work by various teams (collective effects, beam-beam, optics, RF, beam transfer, beam loss, collimation…)
  - pushing diagnostics and instrumentation
  - backed by a vigorous MD program