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Operation of the LHC with Protons at High Luminosity and High Energy

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and the rest of the LHC team

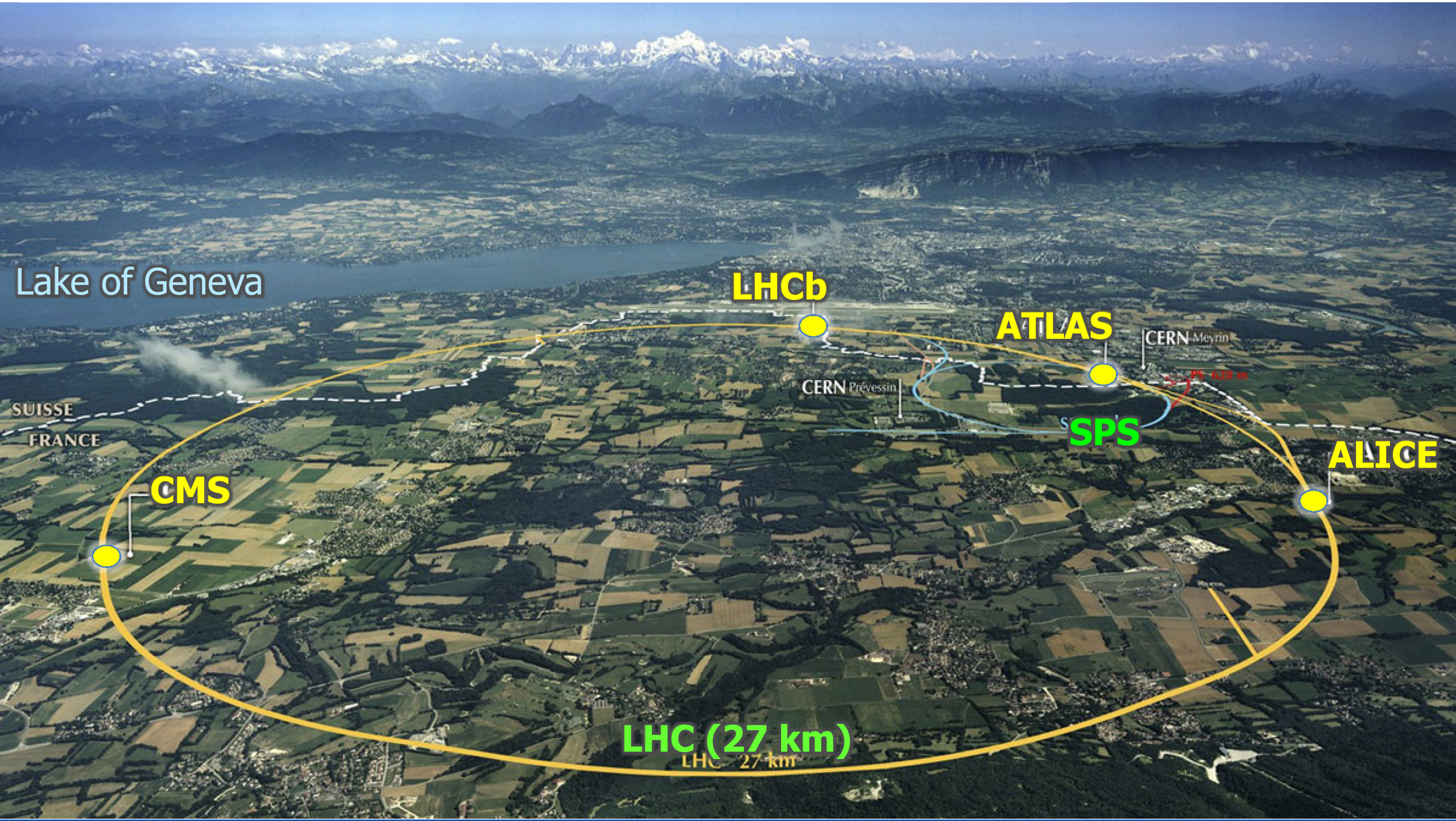
additionally, with material from:

J. Esteban Muller, M. Hostettler, G. Iadarola, K. Li

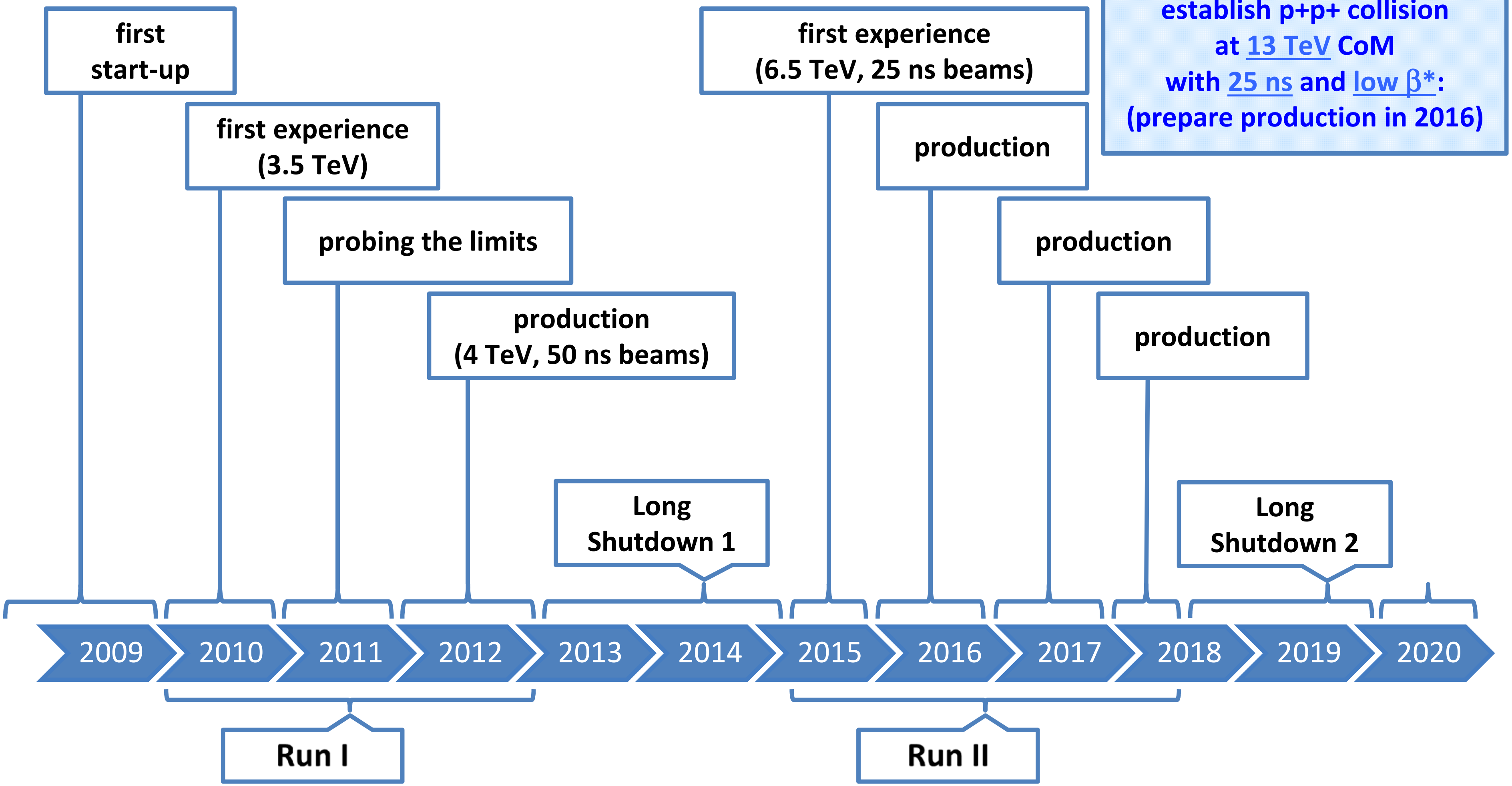
outline

- introduction
- 2015 performance
- some details on selected subjects
    - hardware performance, electron cloud, Unidentified Falling Objects
- 2016: latest news and outlook

the Large Hadron Collider

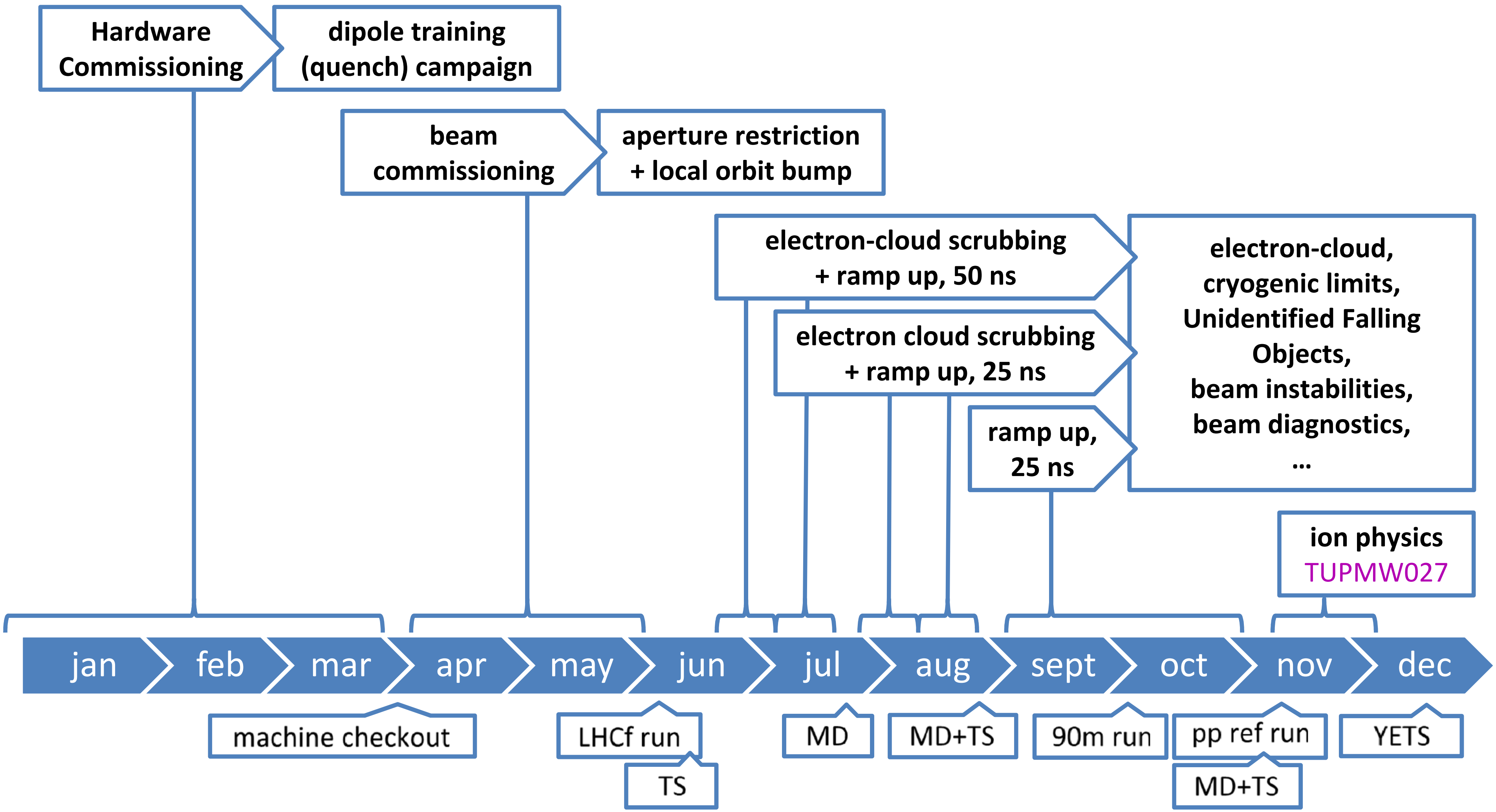


LHC operation history

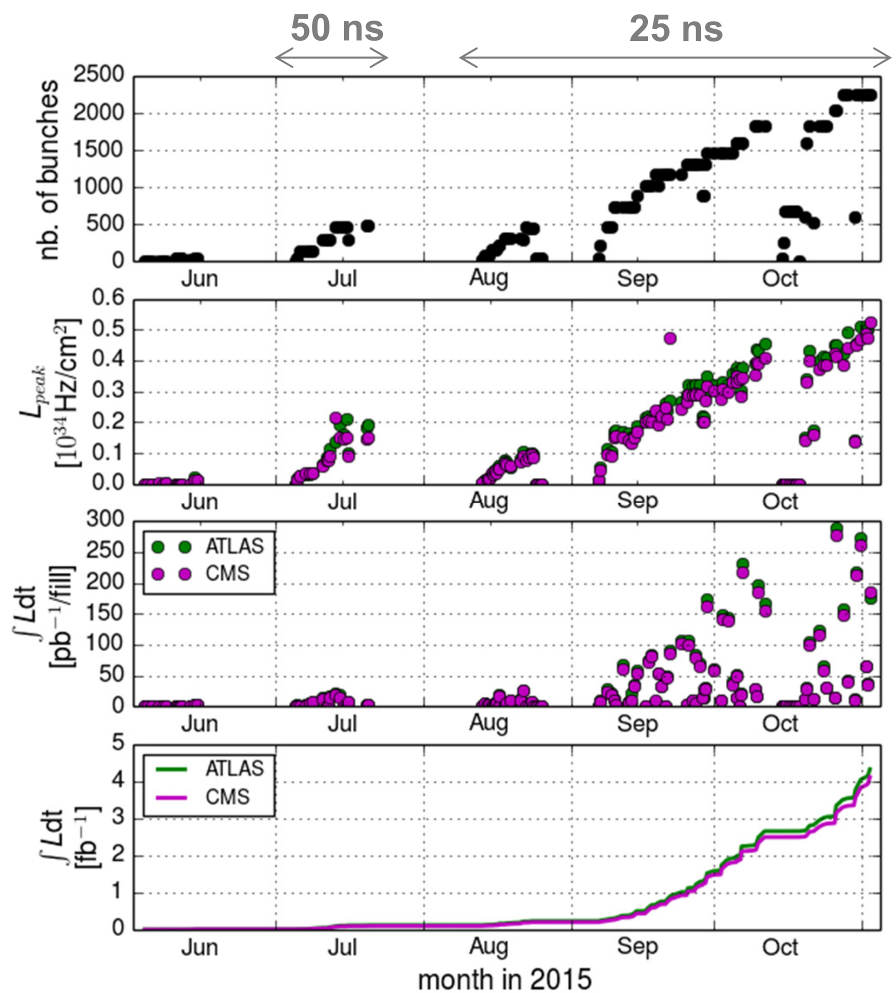


2015 goal
establish p+p+ collision
at 13 TeV CoM
with 25 ns and low β*:
(prepare production in 2016)

2015 timeline

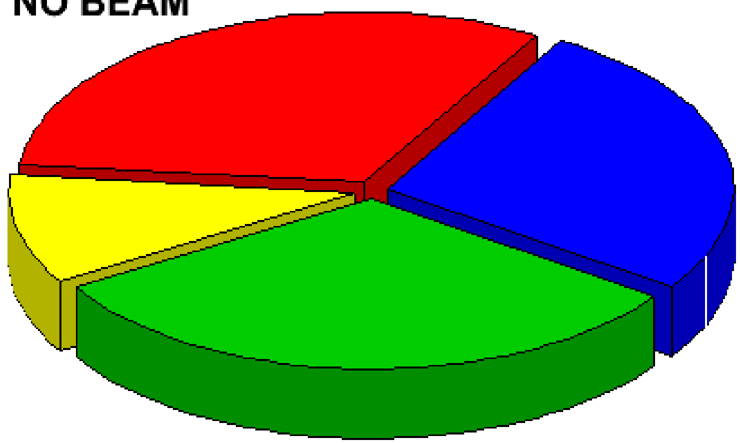


2015 performance



- 25 ns, nominal bunch intensity
  - 2244 bunches/ring (max 2748)
- real production started in Sept. only
  - difficulties in August with radiation to electronics and UFOs
- reached 1 fb^{-1}/week at the end
  - total 4 fb^{-1} at ATLAS/CMS

statistics



**statistics
for Sept-Oct**

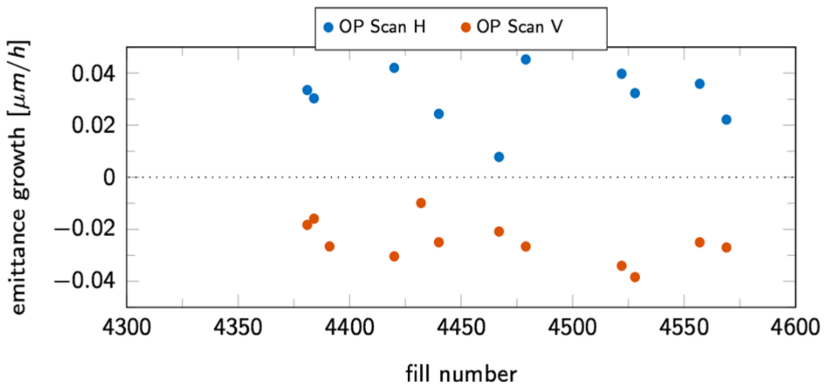
- target system availability
- target operational efficiency
  - combine ramp and squeeze (TUPMW031)
  - shorten the precycle without compromising machine reproducibility
  - improve the injection process

peak luminosity

$$L = \frac{k N_b^2 f \gamma}{4 \pi \beta^* \varepsilon_N} F$$

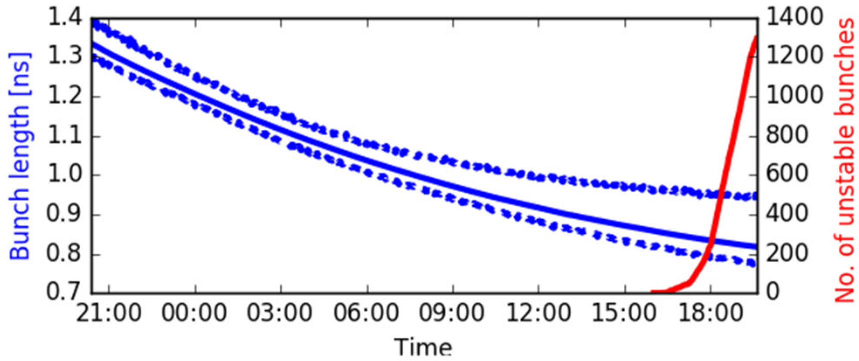
	2015	Design Report	2012
energy [TeV]	6.5	7	4
bunch spacing [ns]	25	25	50
β^* [cm]	80	55	60
ε_N[mm mrad] at start of fill	3.5	3.75	2.5
N_b, bunch population [10^{11} p/bunch]	1.15	1.15	1.65
k, max. number of bunches	2240	2808	1370
max. stored energy [MJ]	270	360	145
peak luminosity [10^{34} cm^{-2}s^{-1}] in IP1/5	~0.5	1	0.75
pile-up	18	20	37

luminosity lifetime



courtesy of M. Hostettler

courtesy of J. Muller



- emittance
  - small horizontal growth, vertical shrinkage (MOPMR025)
    - enjoy benefits of synchrotron radiation, small IBS (TUPMW002)
    - some additional blow up
  - longitudinal shrinkage
    - get to the limit of stability in long fills
- good transmission
  - ~2% losses from start of acceleration to physics
- in physics, mainly losses from burn-off
- healthy luminosity lifetime
  - 30-60 hours
  - long fills are preferred (>20 hours)

some details

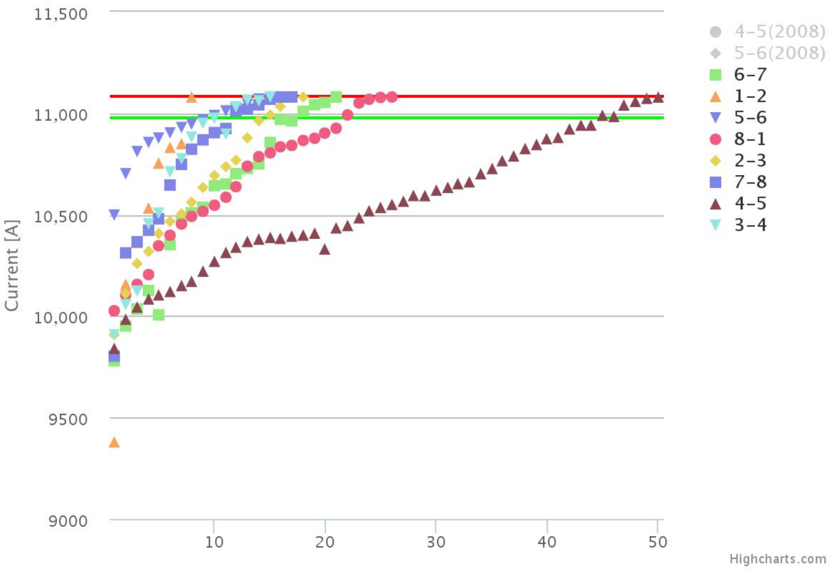
hardware performance

electron cloud

Unidentified Falling Objects

hardware performance at 6.5 TeV

- dipole quenches
  - slow training of main dipoles to 6.5 TeV
    - had 175 quenches, while expected ~100
  - only 5 training quenches during beam operation
  - possible test of 7 TeV before Long Shutdown 2



- magnets behave well at 6.5 TeV
- excellent magnetic reproducibility
  - allow control and feedforward of tune and chroma (TUPMW029, TUPMW026)

- cryogenic system handling electron-cloud driven heat-load transients
  - new algorithm, first 2016 test look excellent (TUPMB048)

TUPMW017

electron cloud

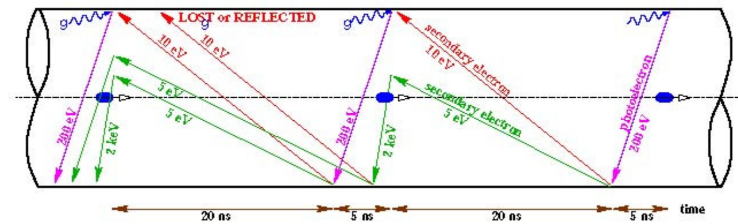
- SEY>threshold: avalanche effect (multipacting)
  - effect depends on bunch spacing and population
  - SEY decreases with accumulated dose: “scrubbing”
- e-cloud effects observed in LHC with bunch trains
  - vacuum pressure rise, heat load on cryogenic systems
  - beam size growth, single- and multi-bunch instabilities

- anticipated to be a challenge with 25 ns: it was
- in 2015: 3 weeks dedicated to scrubbing
  - SEY reset after Long Shutdown
  - operated with 50 ns first, then 25 ns

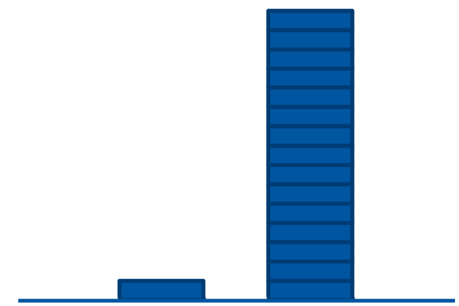
- lived at the heat-load limit
  - defined the max number of bunches achieved
  - some limitations on cryogenics have to be understood

- new strategy:
  - shortest possible scrubbing at the flat bottom
  - scrub with physics as soon as possible
  - possibly have to run with permanent e-cloud in quadrupoles

Secondary Emission Yield



accumulated dose



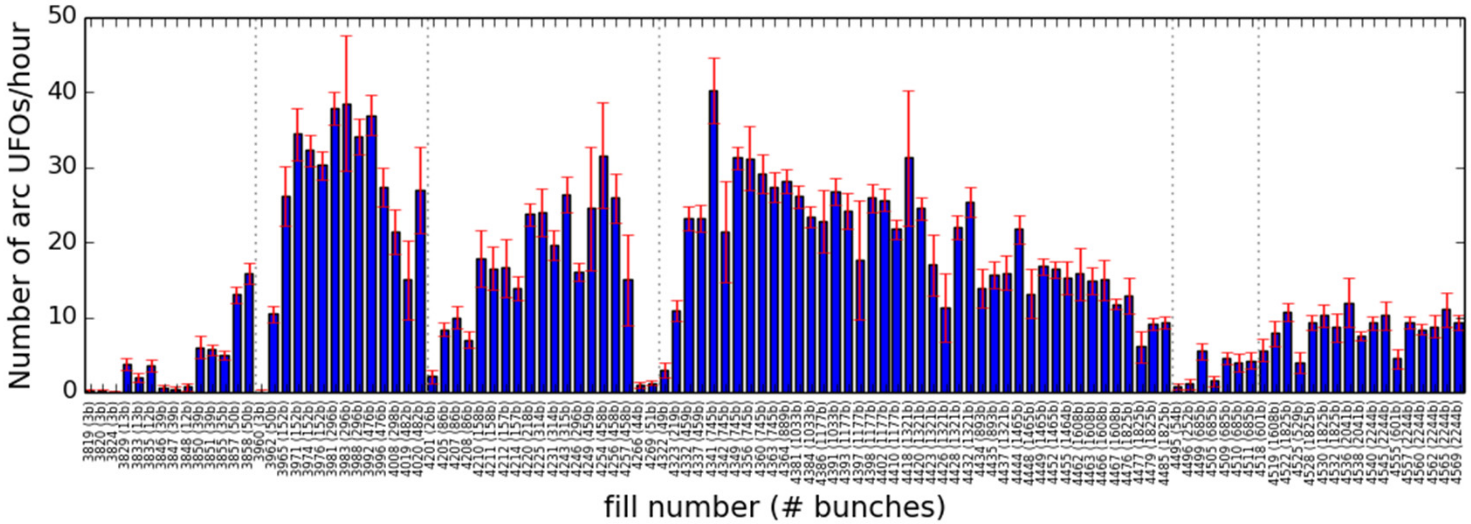
dedicated scrubbing (~2 weeks) 6 mC/mm^2

25 ns physics (~2 months) 94 mC/mm^2

TUPMW023

Unidentified Falling Objects (UFOs)

- fast loss events (ms timescale) due to dust particles falling into the beam
  - feared for availability at high energy operation: less margin for magnets, more losses per event
- very high rates observed
  - conditioning with beam time confirmed over the year
- 17 dumps + 3 beam-induced quenches
  - became at times limiting for operation, peaked at 5 events in two days
- loss monitor thresholds increased to allow few quenches per year
  - most beam dumps would not have quenched
- deconditioning expected after year end stop



conclusion: a long and successful year

- 2244 bunches at **25 ns** at **6.5 TeV** in physics
  - 80 cm beta*, reached 1 fb^{-1}/week, 4 fb^{-1} total for ATLAS/CMS
  - performance:
    - excellent luminosity lifetime and transmission
    - acceptable emittance growth
- main issues encountered
  - electron-cloud, and heat-load limiting cryo
  - slow dipole training towards nominal current
  - UFOs, one aperture restriction, radiation to electronics

- machine ready for production starting in 2016
  - a lot of lessons learnt in Run 1
  - much improvement gained in the understanding during operation, scrubbing and machine developments
  - excellent & improved system performance
    - RF& transverse dampers, instrumentation, collimation, machine protection, injection and dump systems, vacuum, …

2016: latest news and outlook

- just coming out of commissioning
  - machine looks in good shape
  - β^* = 40 cm at the general purpose experiments
    - optics corrected to unprecedented levels: 1.5 % rms beating
      - MOYCA01, THPMB044, THPMR040

- performance reach: 2748 bunches at 25 ns
  - 1.2e11 p/bunch, 3.5 mm mrad, 40 cm β^* should give >1e34 $cm^{-2}s^{-1}$
  - 25/fb in 2016, given reasonable availability

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