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LHC Machine Status Report

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for the LHC team

thanks in particular to M. Lamont and J. Wenninger

additionally, with material from:
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outline

- 2016 performance
- some details on selected subjects
  - electron cloud, Unidentified Falling Objects, Radiation to Electronics
- latest news, schedule and outlook

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peak luminosity

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

	2016
energy [TeV]	6.5
bunch spacing [ns]	25
β^* [cm]	40
ε_N[mm mrad] at start of fill	2
N_b, bunch population [10^{11} p/bunch]	1.12
k, max. number of bunches	2220
max. stored energy [MJ]	260
peak luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/5	**~1.25**
pile-up	41

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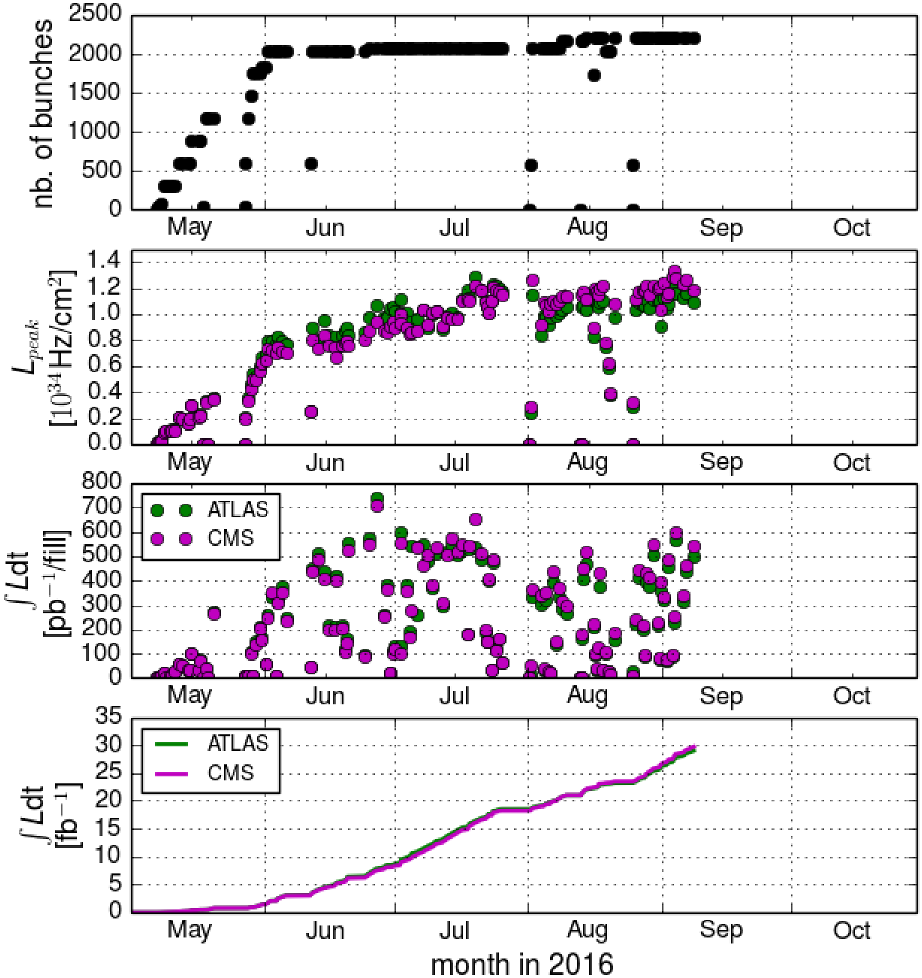
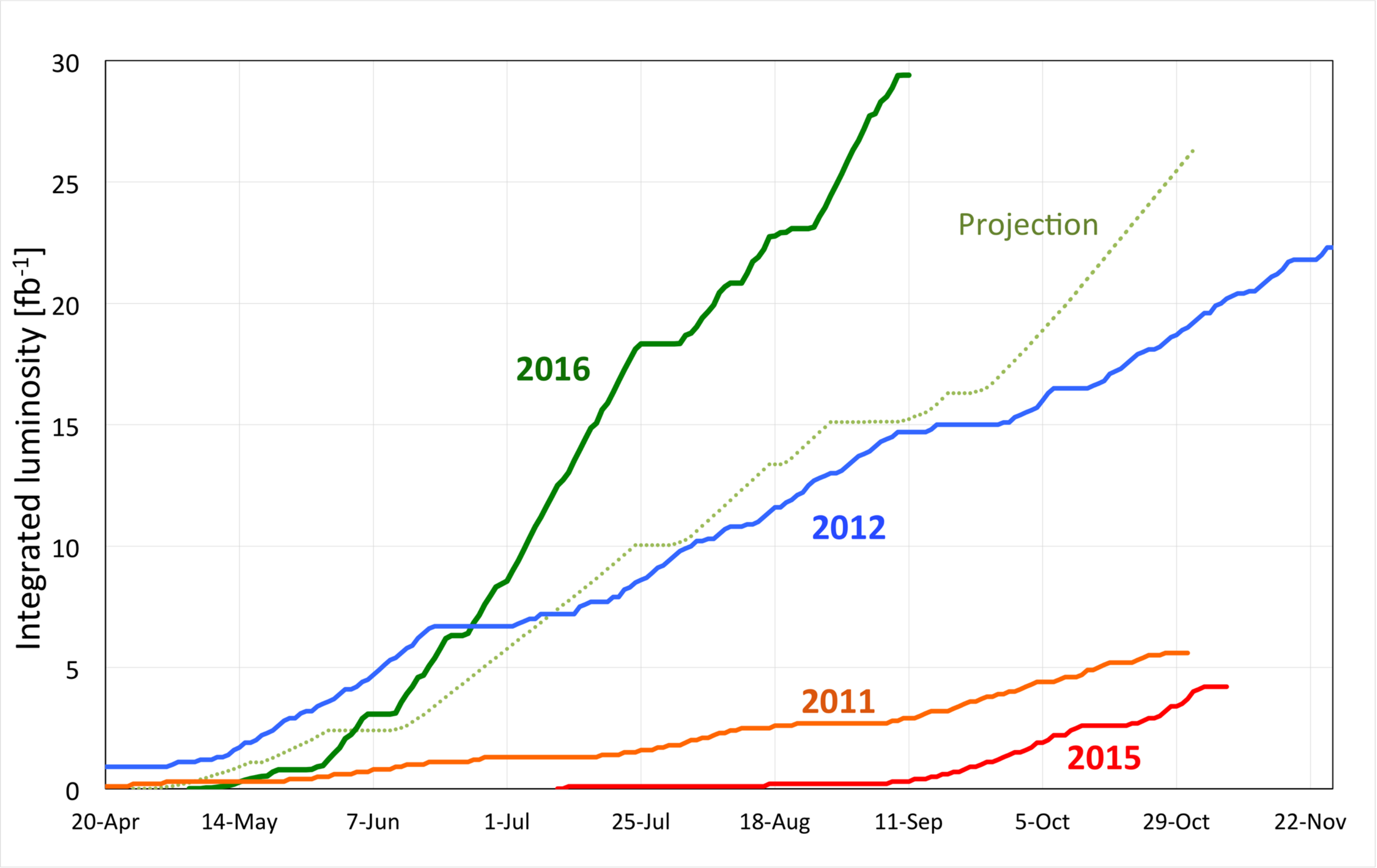
2016 performance so far



	Peak Luminosity [cm^{-2}s^{-1}]	**Integrated Luminosity** [fb^{-1}]
ATLAS	1.21 10^{34}	29.3
CMS	1.33 10^{34}	30.5

- cf target for 2016: 25 fb^{-1}
- max. luminosity delivered in 7 days: 3.3 fb^{-1} (ATLAS)
  - Mon 29 Aug – Sun 4 Sep

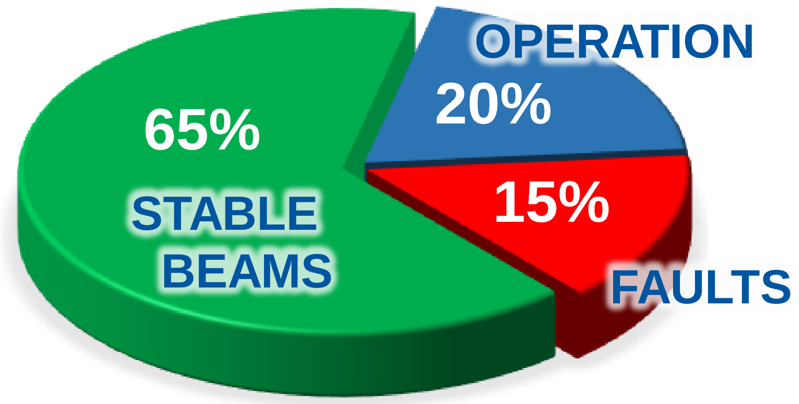
put in perspective



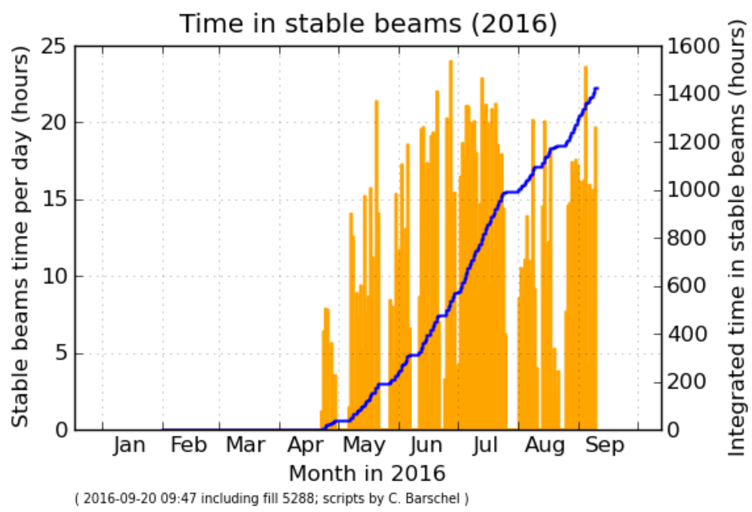
physics efficiency

- improved operational efficiency
  - combine ramp and squeeze
  - shorten precycle
  - minimum turn around <3 h

- amazing system availability!
  - cf ~33-35% in stable beams of the previous years

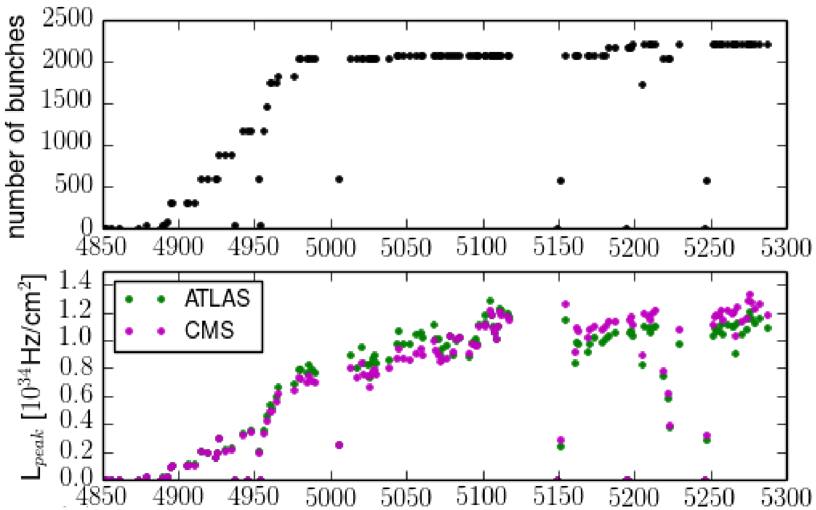


mid-year availability, physics production only (no commissioning, MD, …)

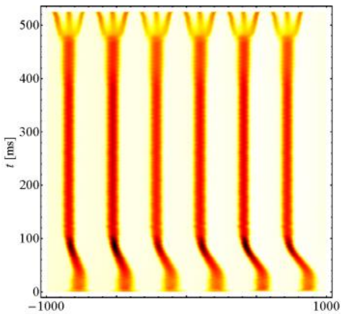


- good luminosity lifetime
  - optimize fill length and dump time

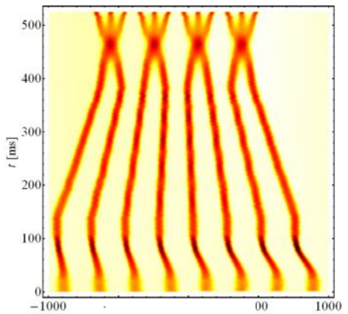
beam parameters



- number of bunches per injection limited to 96 by SPS dump
  - max 2220 bunches/ring
- intensity per bunch limited to 1.1e11 ppb
  - outgassing from ceramic connection in LHC injection kicker
- smaller emittance and high brightness from BMCS beams
  - Batch Compression, Merging and Splitting
  - 2 um into collision, cf 3.75 um nominal



standard



BMCS

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limitations

- SPS beam dump: replace during EYETS
- injection kicker: add pumping during EYETS

- potential inter-turn short in sector 12
  - being monitored
  - lowered Beam Loss Monitor thresholds to play it safe
  - to be replaced during the EYETS

- electron-cloud
- Unidentified Falling Objects
- Radiation to Electronics (R2E)

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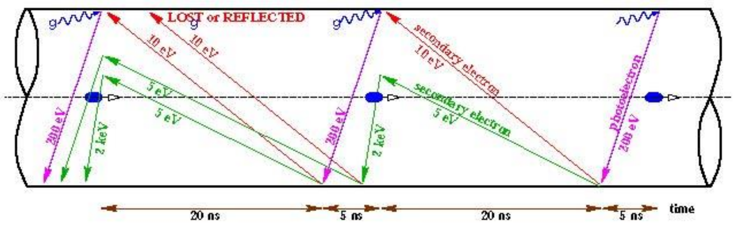
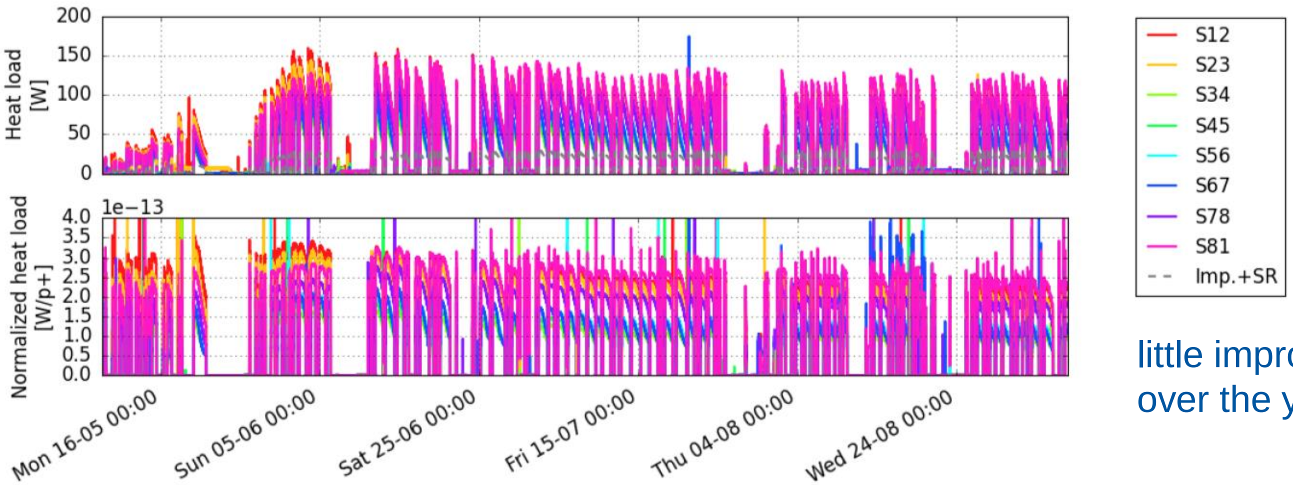
electron cloud

Secondary Emission Yield



- 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 & confirmed to be a challenge with 25 ns
  - 2015: lived at the heat-load limit
- 2016: still significant heat-load within cryogenic limits
  - scrub with physics asap (almost no dedicated scrubbing at the flat bottom)
  - dynamics well handled by cryogenics feed-forward, no impact on operations



little improvement over the year

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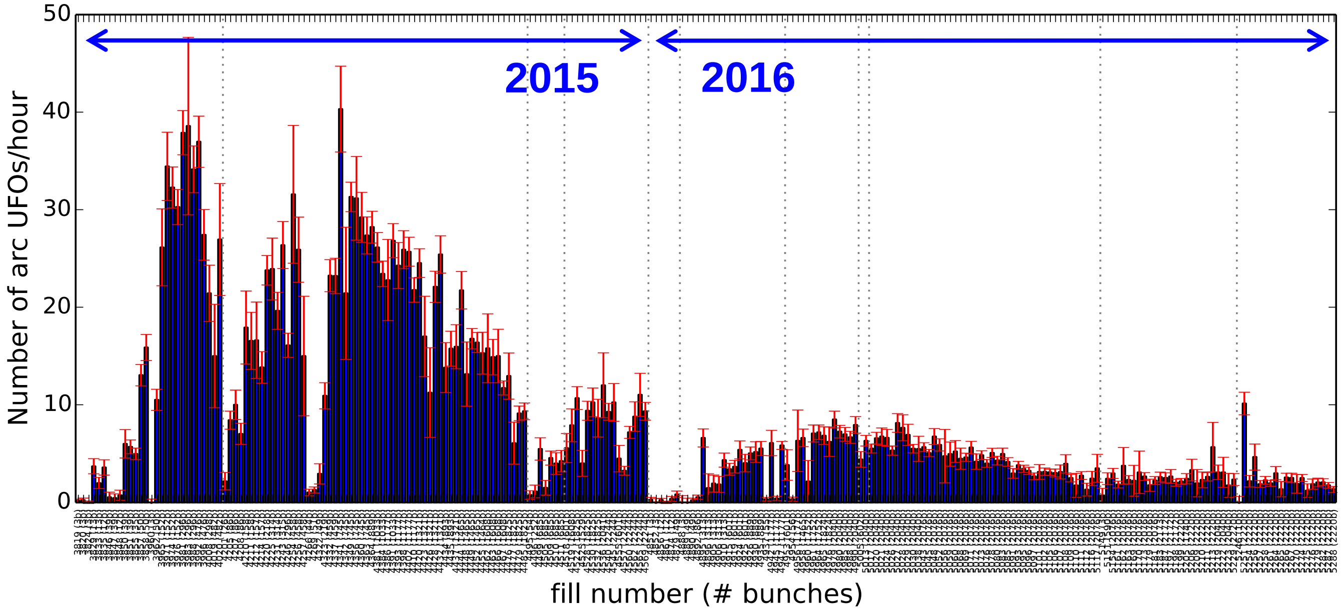
Unidentified Falling Objects (UFOs)

- 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
- 2016 so far: 13 dumps + 3 beam-induced quenches
  - loss monitor thresholds increased to allow few quenches per year
    - most beam dumps would not have quenched
- conditioning with beam time confirmed
  - very high rates observed at start 2015, now settled at ~2 arc UFOs/hour in stable beams
  - deconditioning did not take place after year end stop



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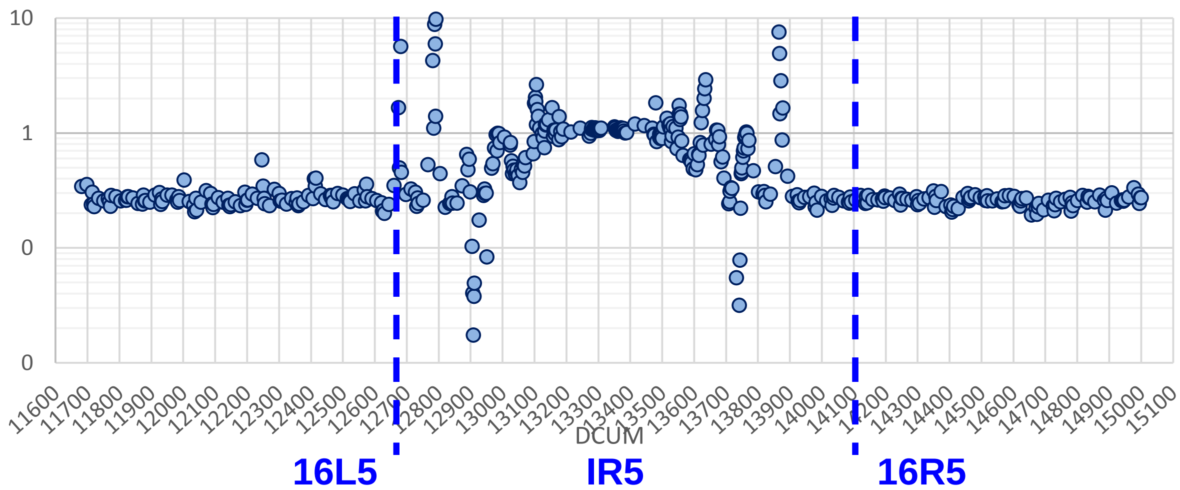
Radiation to Electronics (R2E)

- failure rates proportional to radiation levels
  - IP: rad level mainly from integrated luminosity
  - arc: rad level mainly from beam-gas interaction, thus integrated intensity
- 2016: 3 radiation-related dumps up to 20 fb^{-1} (expected ~1 dump/fb^{-1})
  - arc radiation levels per unit luminosity are lower than in 2015
    - can be due to the lower vacuum pressure in the arc, or to the higher luminosity per proton (smaller beta*), analysis ongoing
    - very clean machine, luminosity losses are burn-off dominated, less e-cloud

loss ratio 2016 vs 2015 per fb^{-1} (over 20 fb^{-1})



IP: ratio is 1
arc: ratio is 0.3

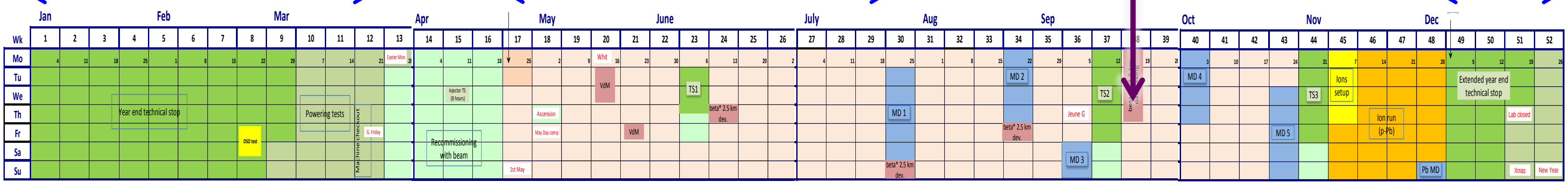
incoming: 2016

year end technical stop
powering tests
machine checkout

full-on
physics production

today

powering tests
year end technical stop



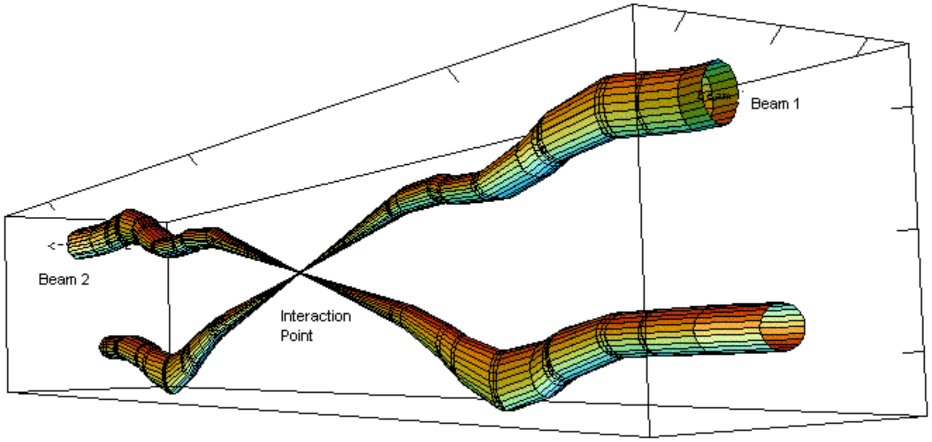
re-commission
with beam

includes
machine developments

ion run

- ongoing this week:
  - 2.5 km beta* run
  - crossing angle reduction for low beta* proton physics
- next:
  - 9 days of machine developments
  - dense ion run: p-Pb at 5 TeV, p-Pb and Pb-p at 8 TeV,
  - 2 weeks of dipole training towards 7 TeV equivalent
    - before Extended Year End Technical Stop (EYETS)

crossing angle reduction



Relative beam sizes around IP1 (Atlas) in collision

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

$$F \propto \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\varphi}{2}\right)^2}}$$

- crossing angle required because of bunch trains
  - otherwise parasitic collisions not in the center of the detector
  - negative impact on luminosity… keep it as small as possible
- constraint: minimum beam separation
  - big beam emittance or small beta* require bigger crossing angle
- BCMS beams are smaller than standard
  - machine setup for standard, now reduce crossing angle
  - plan it well: validation overhead not to dominate!

ϕ [μrad]	370	280
F	0.59	0.70
L_{pk} [10^{34}cm^{-2}s^{-1}]	1.27	1.5

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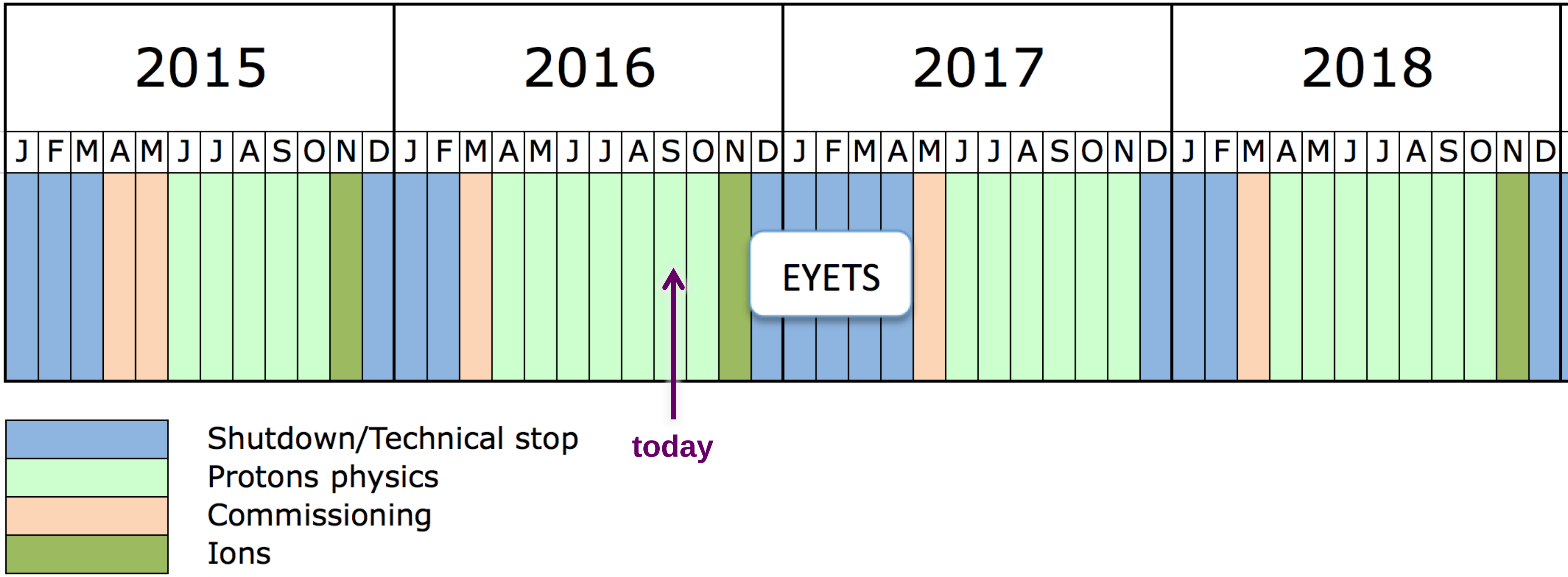
Run 2 schedule



- Extended Year End Technical Stop (20 weeks)
  - driven by CMS pixel upgrade
  - push 2 sectors towards 7 TeV, to gain knowledge on how long it takes to reach higher energy
- ~40-45 fb^{-1}/year in 2017 and 2018 (goals fixed at Chamonix 2017)
  - max peak luminosity ~1.7e34 $cm^{-2}s^{-1}$, limited by inner triplets

projections until LS2

- BCMS or not?
  - BCMS: low emittance, thus low crossing angle: higher luminosity/bunch pair
    - TDI limits on number of bunches/SPS transfer: less bunches/ring
    - less electron-cloud thanks to the shorter trains
  - standard beams: +30% bunches, but higher emittance: likely less luminosity
    - less pile-up
  - choice requires input from experiments

- if pile-up is an issue, level down

- need to start the year with the correct parameter set!
  - commissioning and validation are non-negligible overhead

- availability is the key to good integrated luminosity!
  - max peak luminosity is limited
  - 2016, 2017, 2018: similar run length

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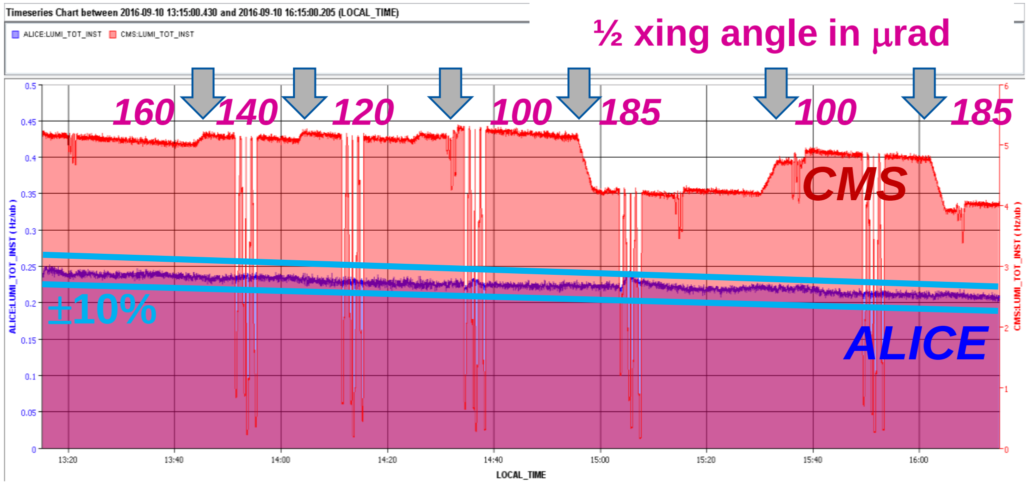
machine developments

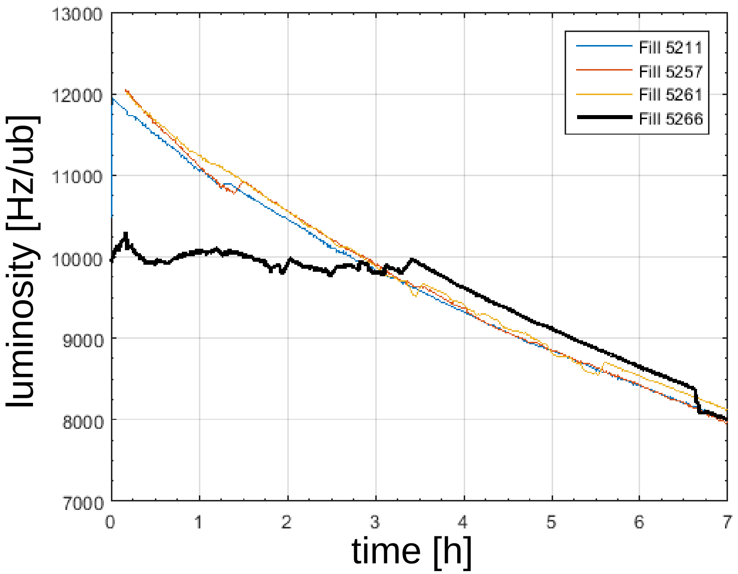
- reserve ~10% of beam time per year
- invest it in short & long term performance improvements

- examples in 2016:
  - luminosity performance: beta* reach, reduced crossing angle, luminosity levelling options
  - HL-LHC optics (ATS) for possible deployment in Run 2
  - collective effects & instability limits
  - hardware performance (collimators, RF, ...)
  - many many others!

ex 1: leveling by crossing angle



ex 2: leveling by separation



conclusions

- excellent peak performance
  - above design luminosity (squeeze further, bright beams from injectors)
  - still some margin for improvement in Run 2
- good delivery of integrated luminosity
  - stunning availability
  - good luminosity lifetime
  - electron cloud conditioning very slowly
  - fortunately UFOs have conditioned down

- the LHC has moved from commissioning to exploitation
  - enjoying the benefits of the decades long international design, construction, installation effort: the foundations are good
  - huge amount of experience & understanding gained and fed-forward
- astounding results and progress represent a phenomenal ongoing effort by all the teams involved

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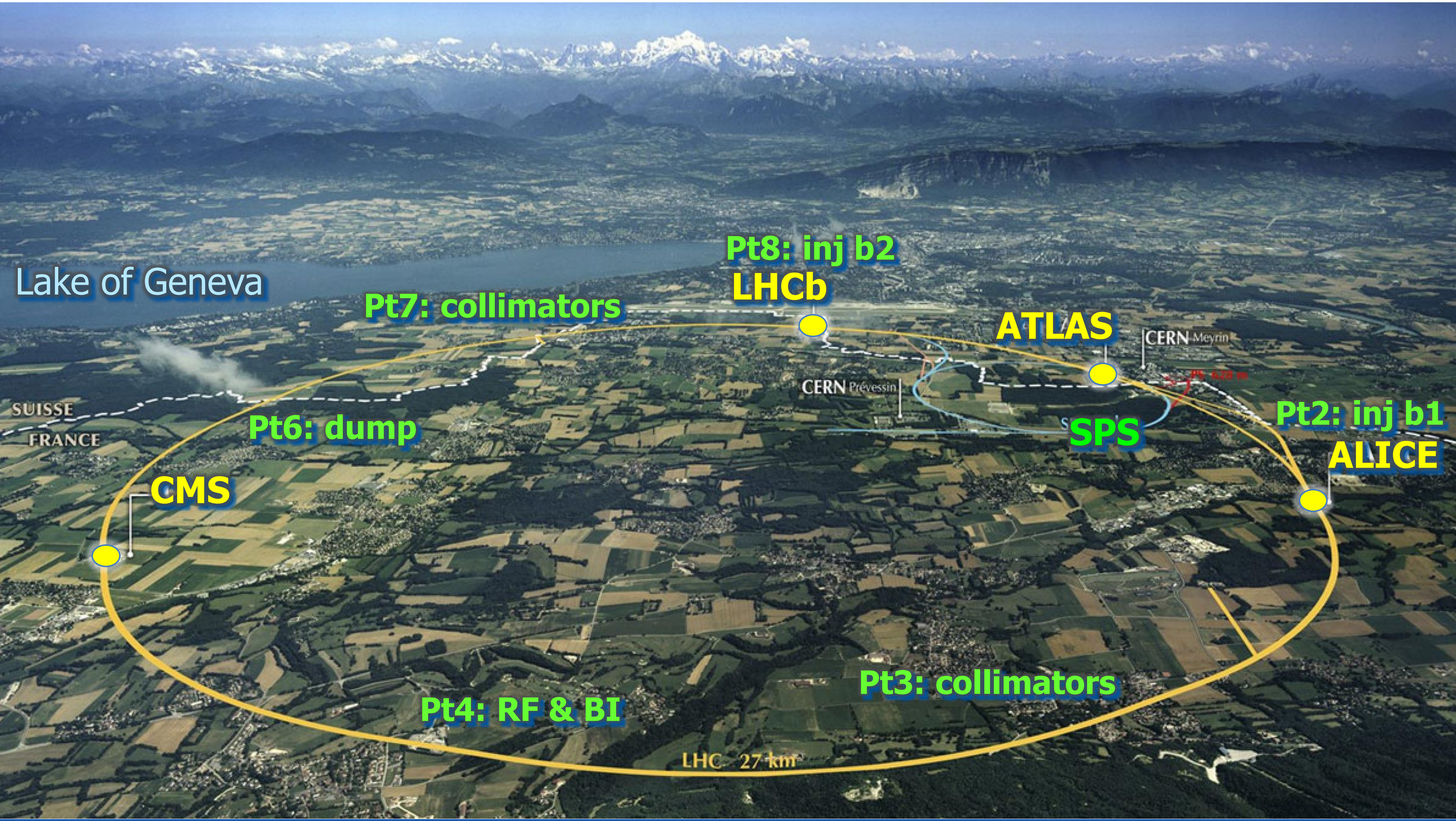
the Large Hadron Collider



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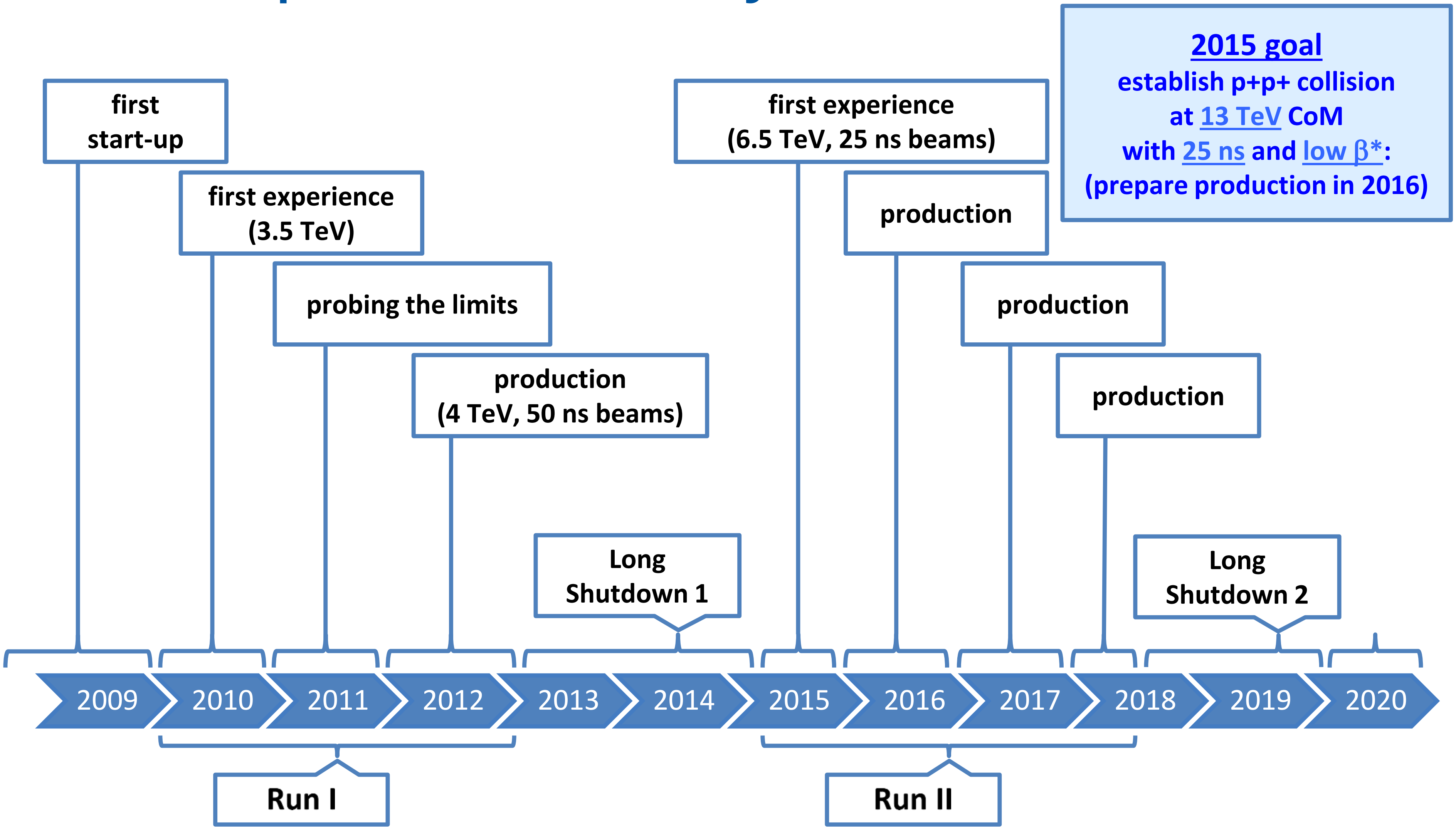
LHC operation history



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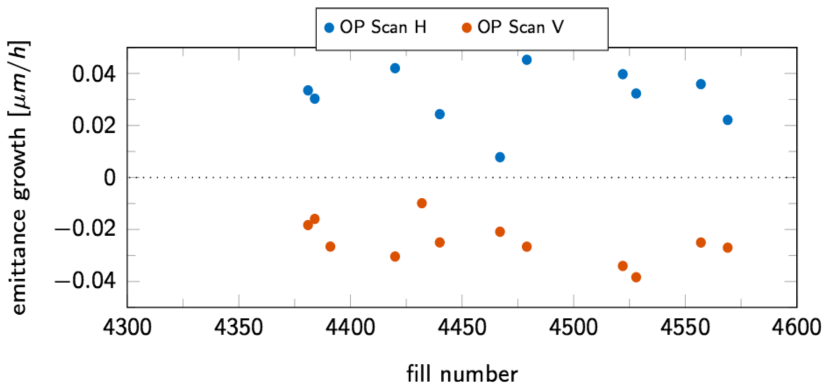
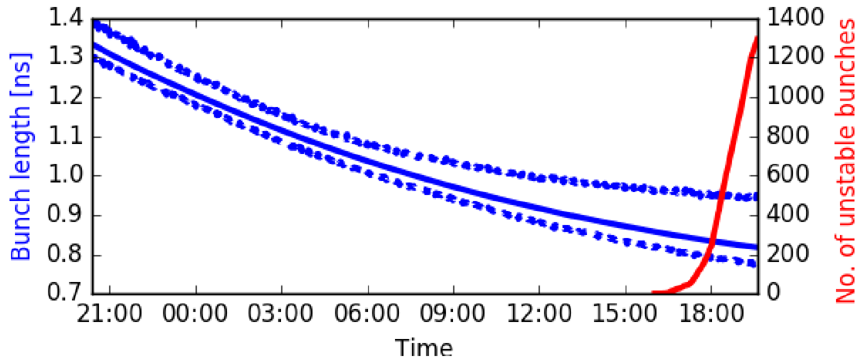
luminosity lifetime



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)

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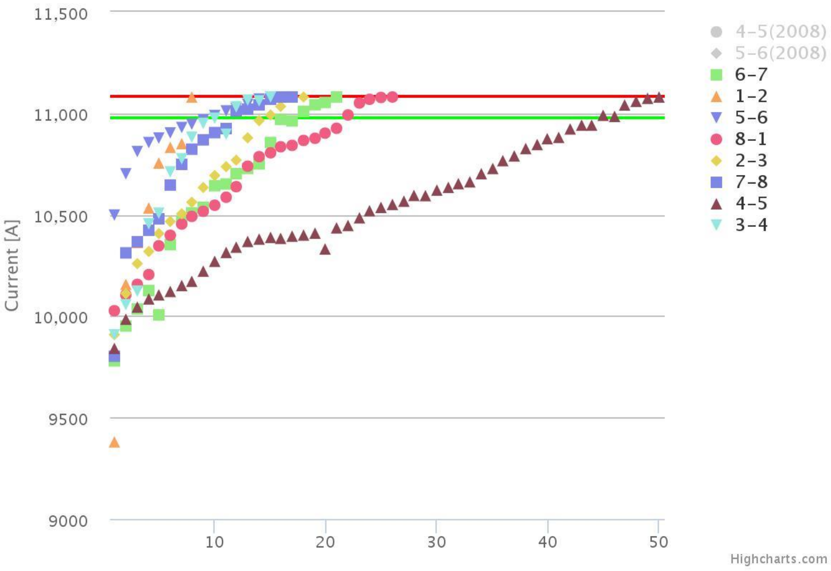
hardware performance at 6.5 TeV

- 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

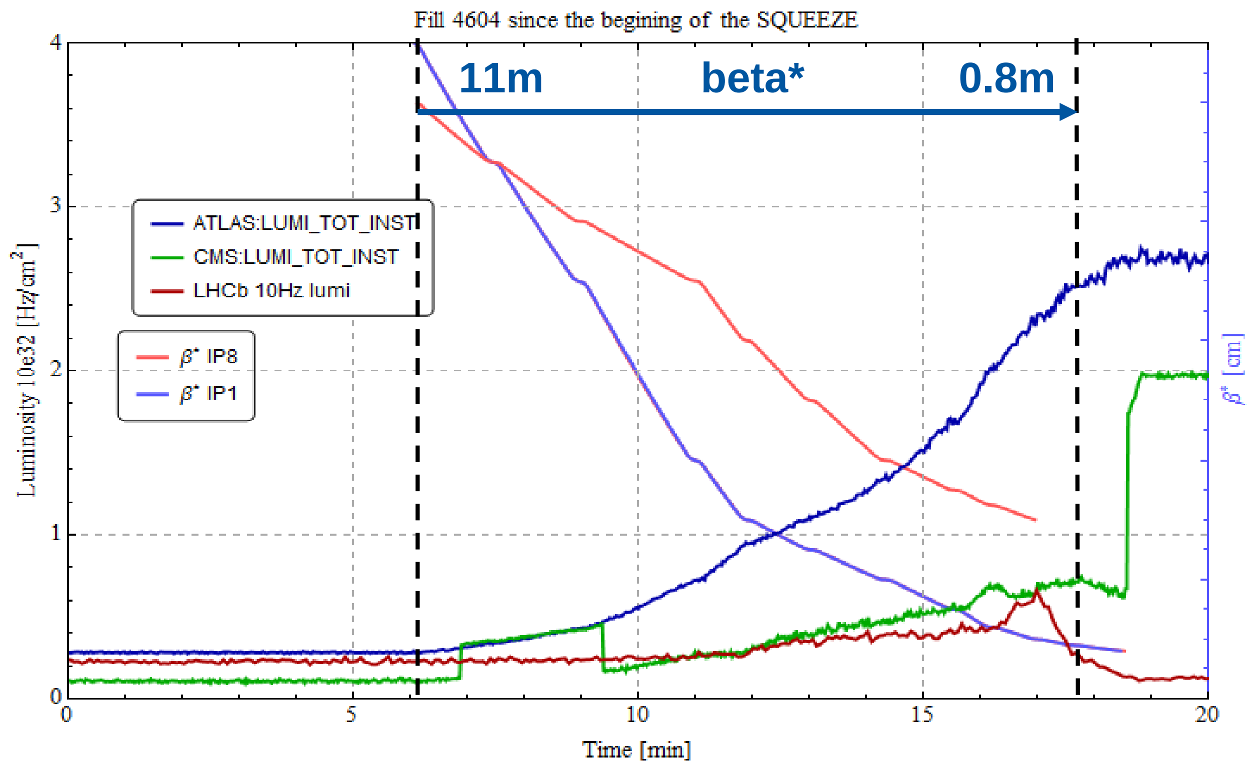


- magnets behave well at 6.5 TeV
- excellent magnetic reproducibility
  - allow control and feedforward of tune and chroma

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

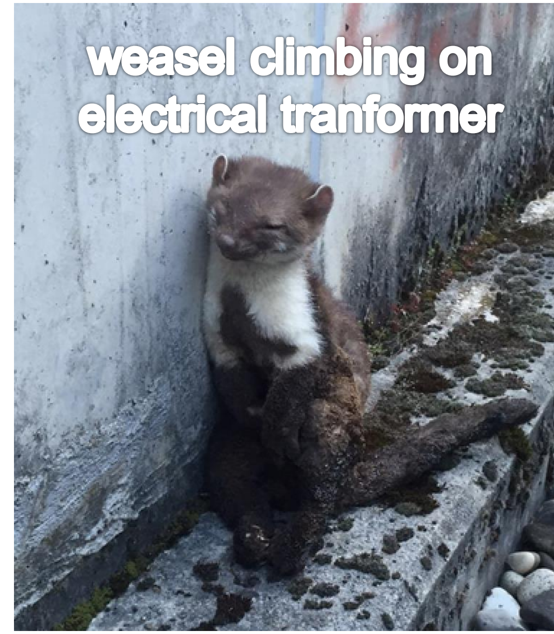
machine studies: beta* levelling

- 10% of time with beam invested in machine studies
- pick one highlight among many
  - TUPMW013: beta* leveling, and collide + squeeze fully demonstrated
    - see the beta* go down and lumi increase smoothly, over 12 minutes



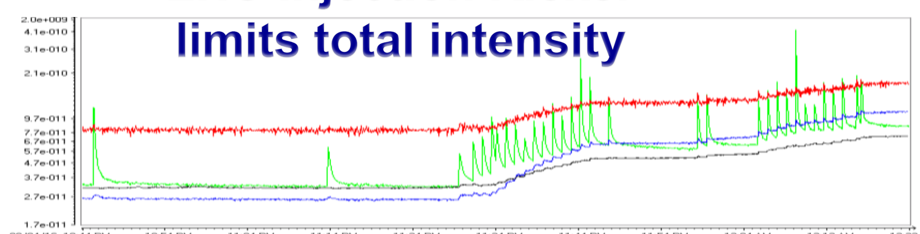
courtesy of
A. Gorzawski

A few problems



SPS beam dump:
limit to 96 b/inj,
2220 b total

LHC Injection Kicker
limits total intensity



turnaround

- finally starting clipping fill length!