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Status and near future of the Large Hadron Collider (LHC)

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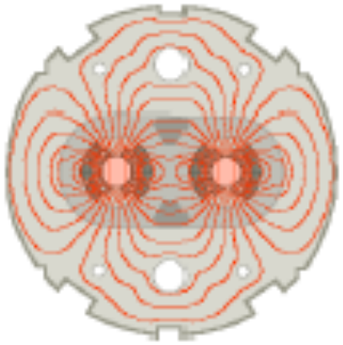
CERN, Beams department — Accelerator and Beam Physics group

Inputs from various colleagues/teams, in particular J. Wenninger, R. Bruce, M. Solfaroli



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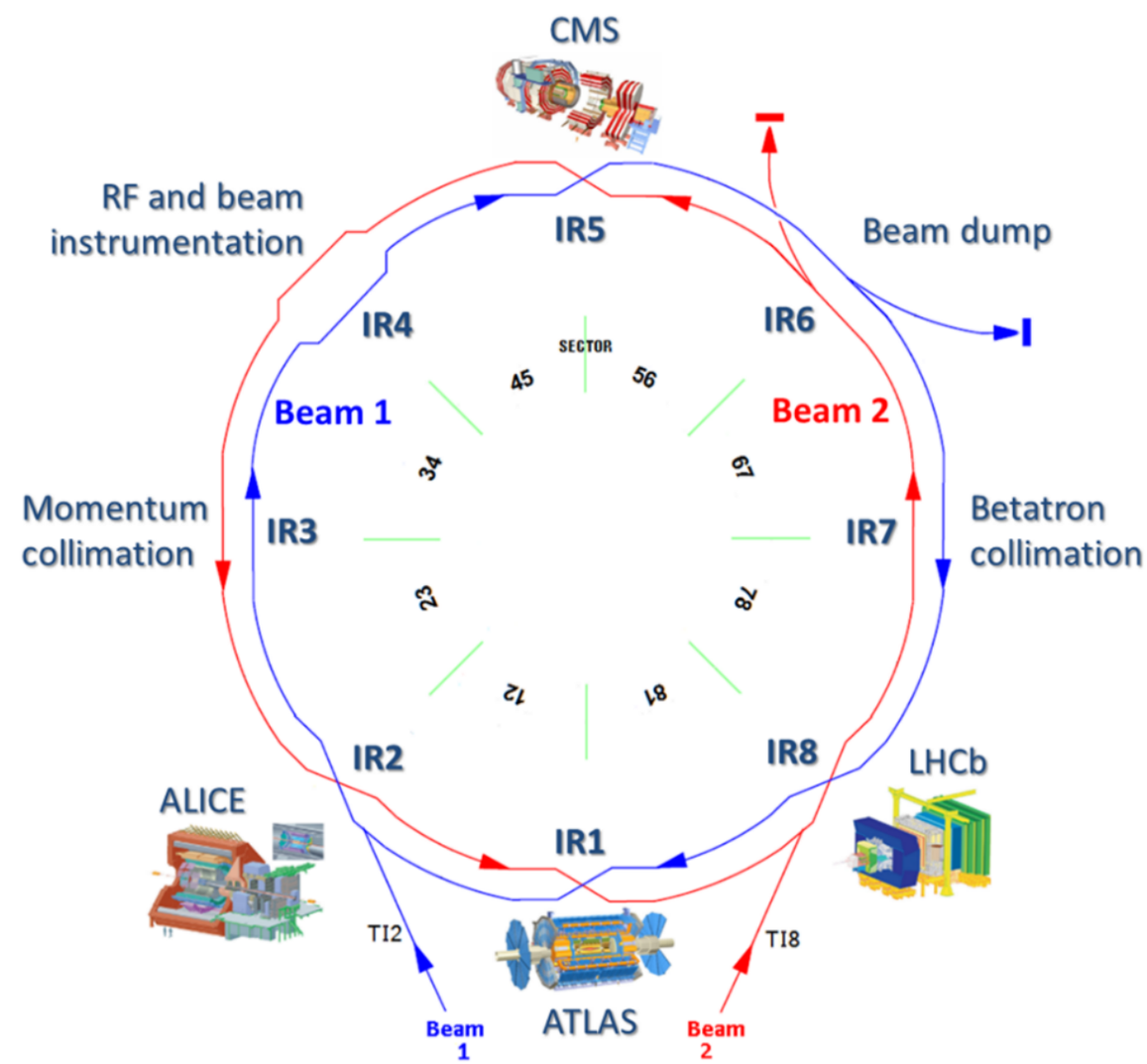
The Large Hadron Collider (LHC)

- Circumference of 27 km
- Eight arcs, 2-in-1 magnet design
- Two warm regions for beam collimation
- Super-conducting RF system
- One beam dump region (warm)
- Beam injection: IR2 and IR8
- Four experimental regions



- **ATLAS** and **CMS**: <u>high luminosity</u> experiments, **L ~ 10^{34} $cm^{-2}s^{-1}$**
  Determine most challenging performance figures…
- **LHCb**: <u>medium luminosity</u> experiment, **L ~ 4 x 10^{32} $cm^{-2}s^{-1}$**
  Levelled luminosity (by separation)
- **ALICE**: <u>low luminosity</u> / ion experiment, **L ~ 10^{31} $cm^{-2}s^{-1}$**
  Levelled luminosity (by separation)
- **TOTEM**, **ALFA** and **AFP**: physics experiments
  Participate to high-luminosity runs + special runs.

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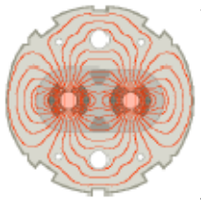

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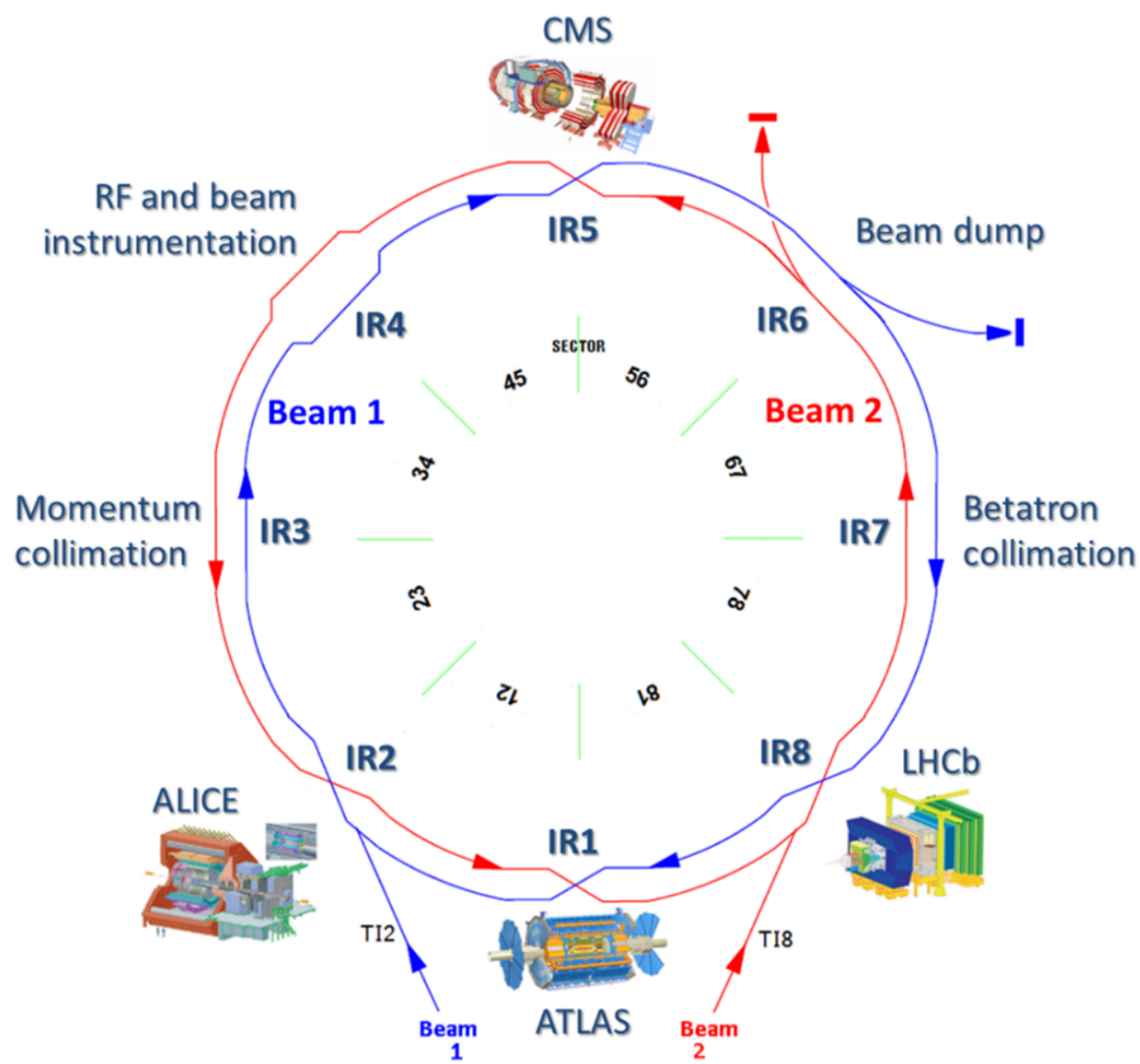

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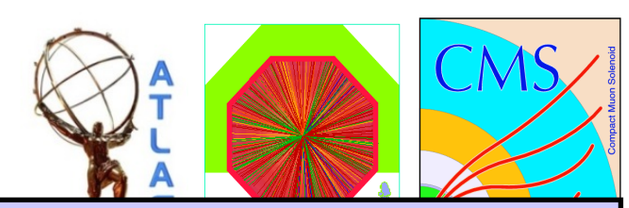
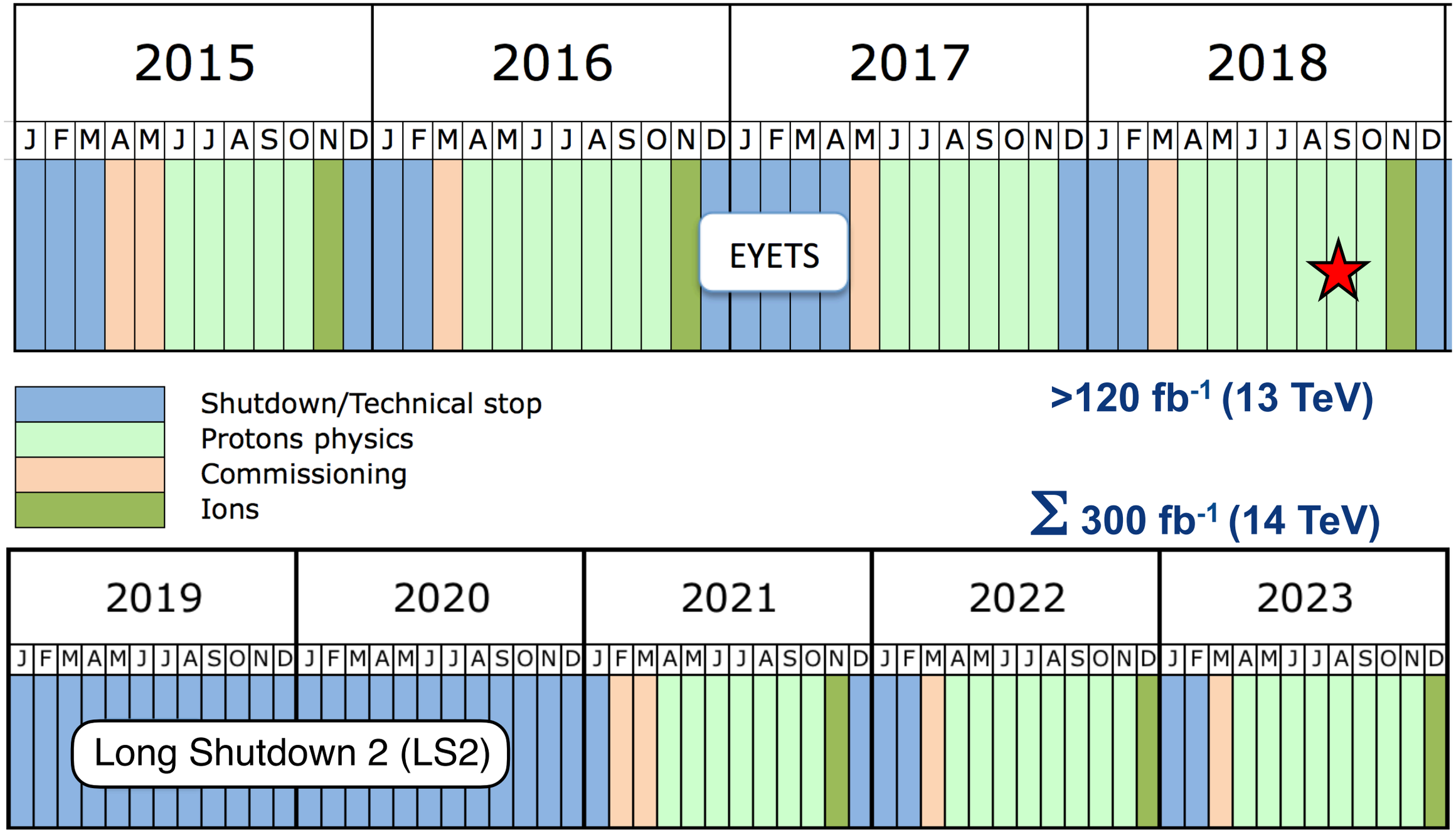


Several operational challenges and demands for high flexibility while handling ~300MJ beams!

The LHC Run II and Run III



>120 fb^{-1} (13 TeV)

Σ 300 fb^{-1} (14 TeV)

Run I (2010-13): operations at **3.5-4.0 TeV**, delivered **~30fb^{-1}**

2015: "Recovery year" before moving into full production years 2016-18.

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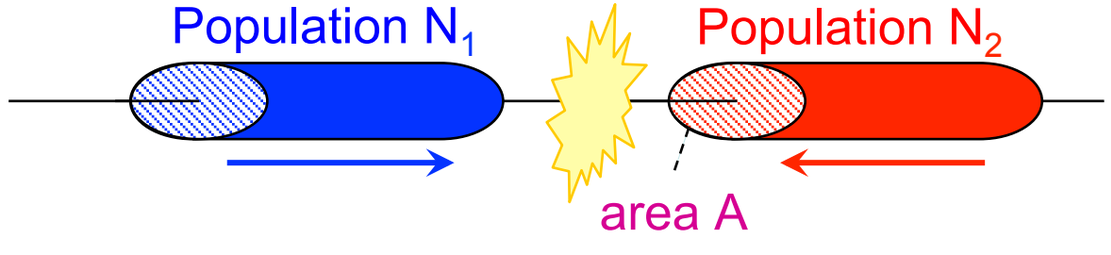
Luminosity at a circular collider

Fixed the **beam energy**, the key parameter for the experiments is the event rate dN/dt. For a physics process with cross-section σ, it is proportional to the collider's **luminosity**: dN/dt = σ x L.

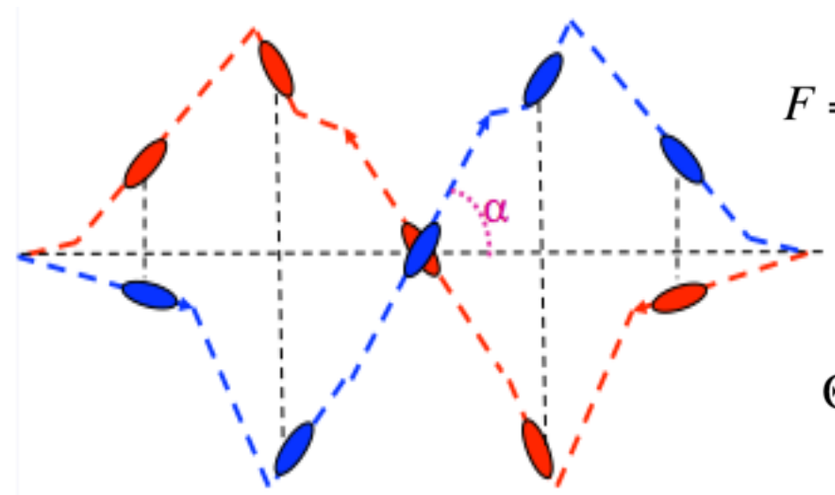


$$\mathcal{L} = \frac{n_b N^2 f \gamma}{4\pi\beta^* \epsilon} F$$

N = bunch population ($N=N_1=N_2$)
n_b = number of bunches
f = revolution frequency
$\sigma^*_{x,y}$ = colliding beam sizes $(\sigma^*_x)^2=\beta_x\varepsilon_x$
F = geometric factor

Depends on machine parameters: charge per bunch (N), number of bunches (n_b) and transverse beam sizes (σ): optics and beam emittance.

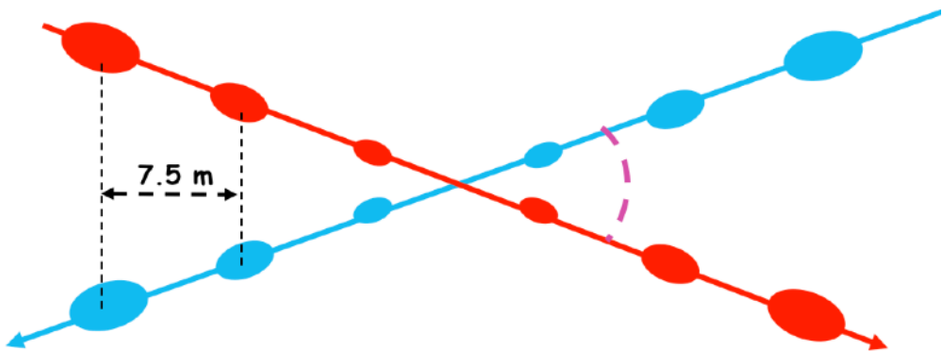
We have seen a continuous improvement of the relevant parameters from the start of LHC operation!

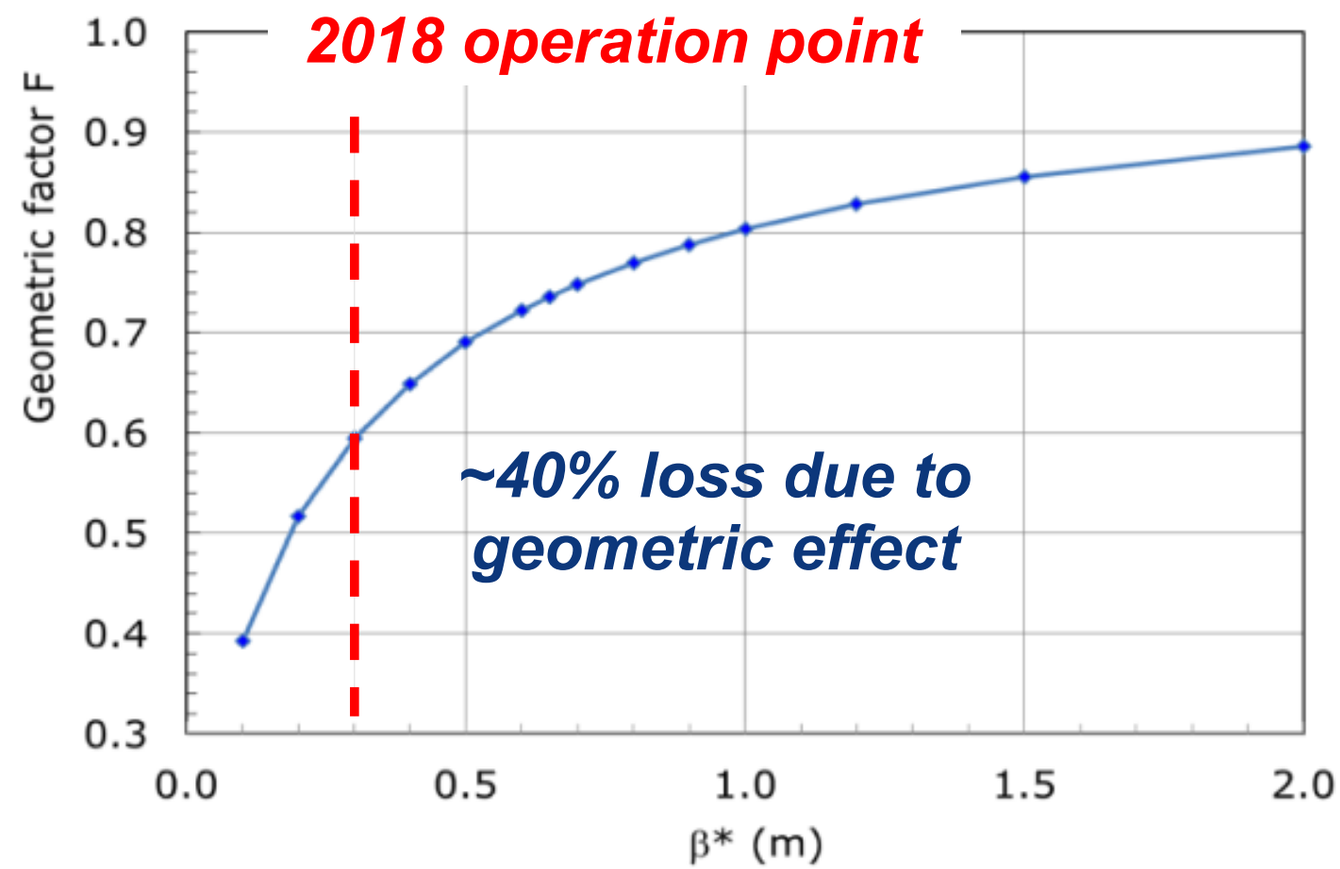


$$F = \frac{1}{\sqrt{1+\Theta^2}};$$

$$\Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

Geometry at the collision points

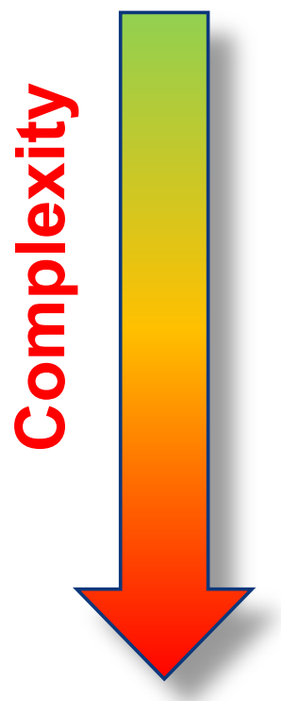




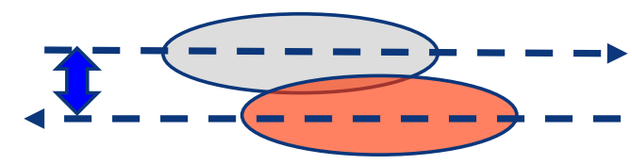
Crossing angle requirements are determined by the beam emittance and bunch charge.
Reduction of aperture and loss of peak luminosity during the collisions can be optimised during the fill.

Luminosity levelling techniques

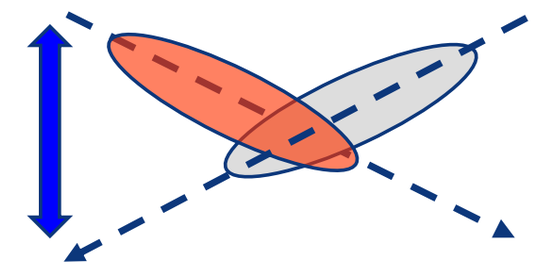
Under certain conditions (too high peak luminosity) and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – luminosity levelling.
Three techniques successfully deployed a the LHC:



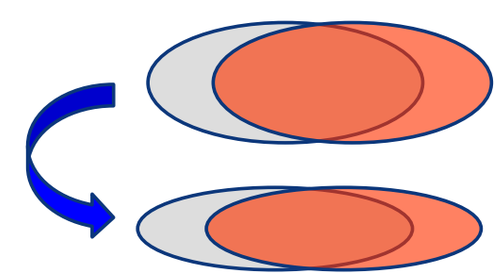
*Levelling by beam offset (since **2011**)*



*Levelling by crossing angle (since **2017**)*

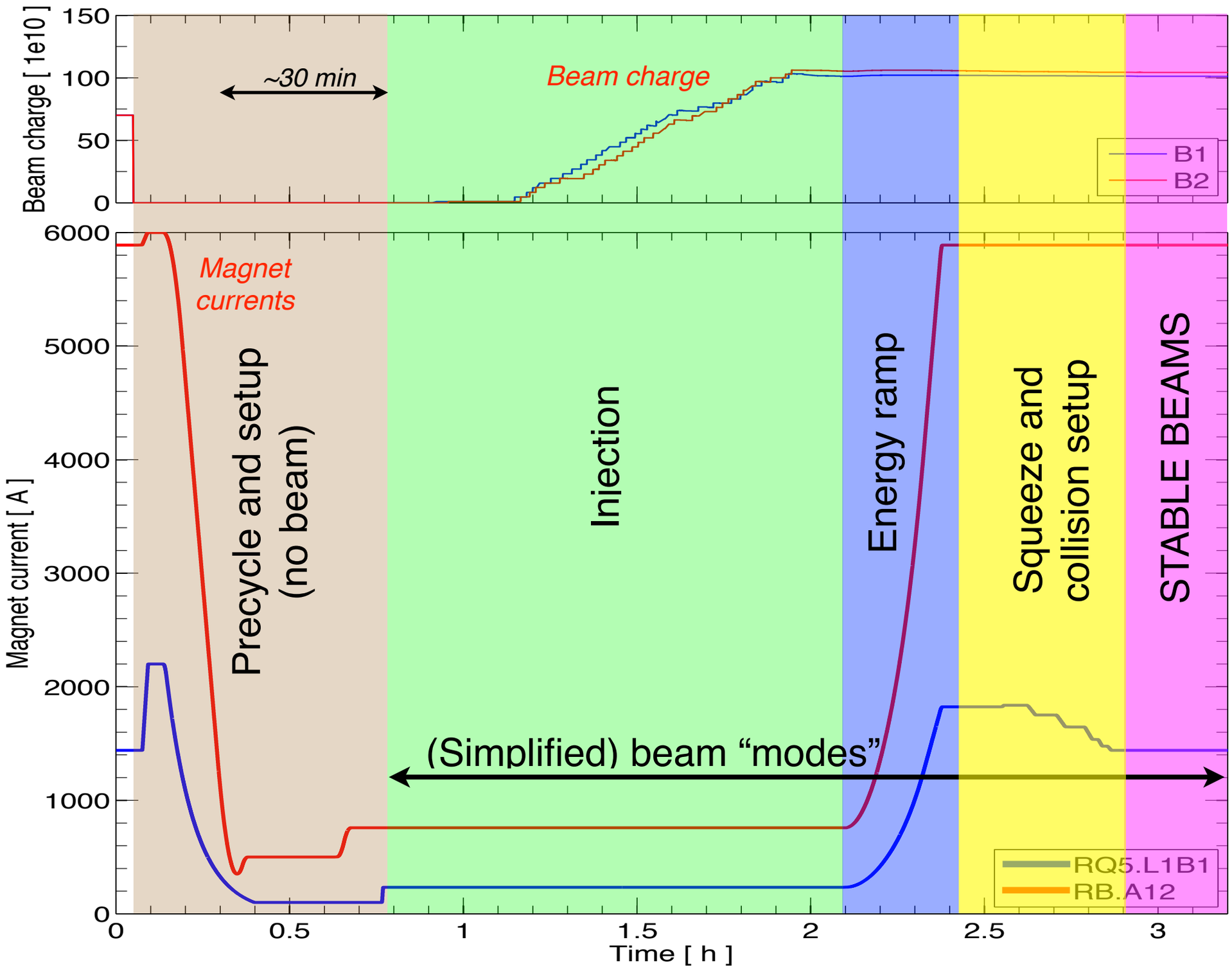


*Levelling by β^* (= beam size at IP) (since **2018**)*



In 2018 we make use of all these techniques in each fill!

Operational cycle



Since 2017: "**combined ramp&squeeze**" where part of the optics changes are done in the shadow of the energy acceleration! Now reach 1 m in IP1/5 and the final 3 m in IP8.

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Achieved running configuration

Parameter	2018	Design
Energy [TeV]	6.5	7.0
No. of bunches	2556	2808
Max. stored energy per beam (MJ)	312	362
β* [cm]	30→25	55
p/bunch (typical value) [10^{11}]	1.1	1.15
Typical normalized emittance [μm]	~1.8	3.75
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	2.1	1.0
Crossing angle IP1/5 [μrad]	285	320

Established a very good performance: twice the design luminosity despite lower energy and number of bunches.

Achieved running configuration

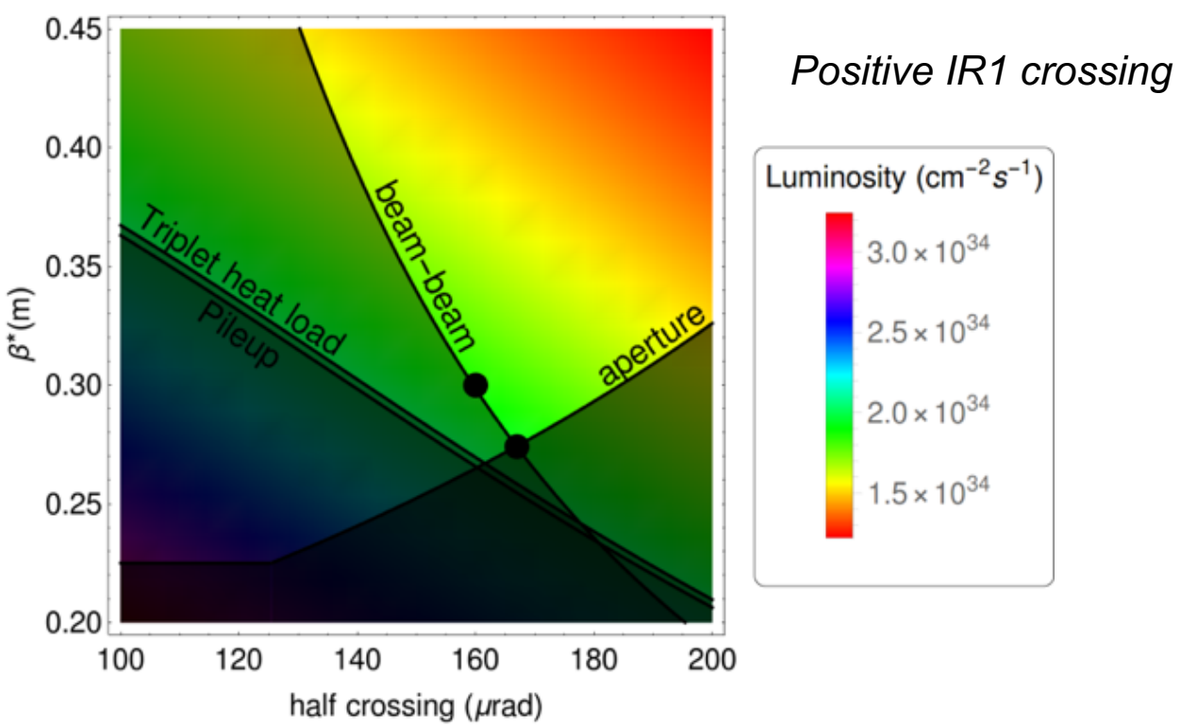
Parameter	2018	Design	Run III
Energy [TeV]	6.5	7.0	7.0
No. of bunches	2556	2808	~2760
Max. stored energy per beam (MJ)	312	362	> 500
β* [cm]	30→25	55	40-30
p/bunch (typical value) [10^{11}]	1.1	1.15	1.8
Typical normalized emittance [μm]	~1.8	3.75	1.5-2.0
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	2.1	1.0	3-4
Crossing angle IP1/5 [μrad]	285	320	340

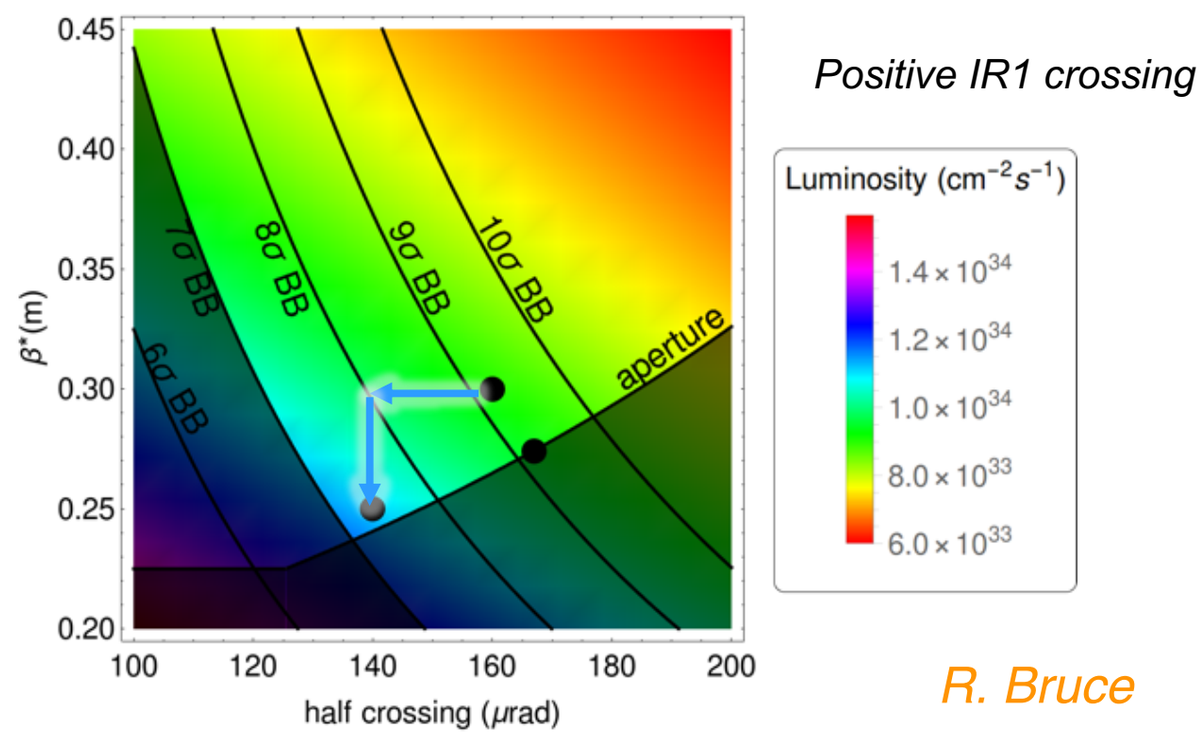
Established a very good performance: twice the design luminosity despite lower energy and number of bunches.

2018: optimized running scenarios

- At smaller bunch intensities later in the fill, better reach in β* as limits from beam-beam, triplet heat load, and pileup are relaxed
- Allows reaching reach 25 cm while staying above 7 σ beam-beam separation
  - Event pile-up remains ≤ 60 up to 1.3×10^{11} ppb.
  - Thanks to a reduction of crossing angle that frees aperture!

Start of fill → *Later in fill – lower intensity*



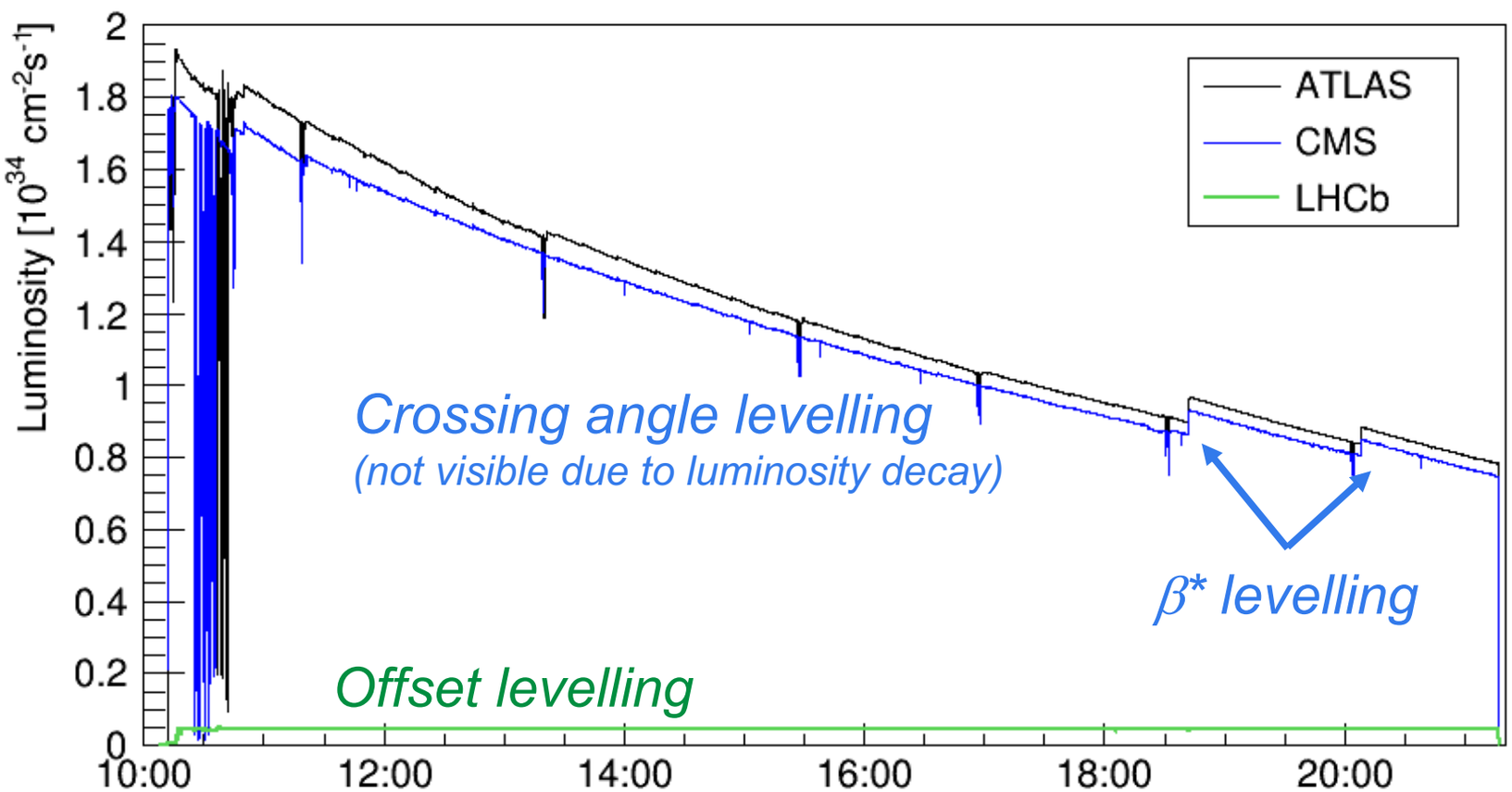


R. Bruce

How it works in practise

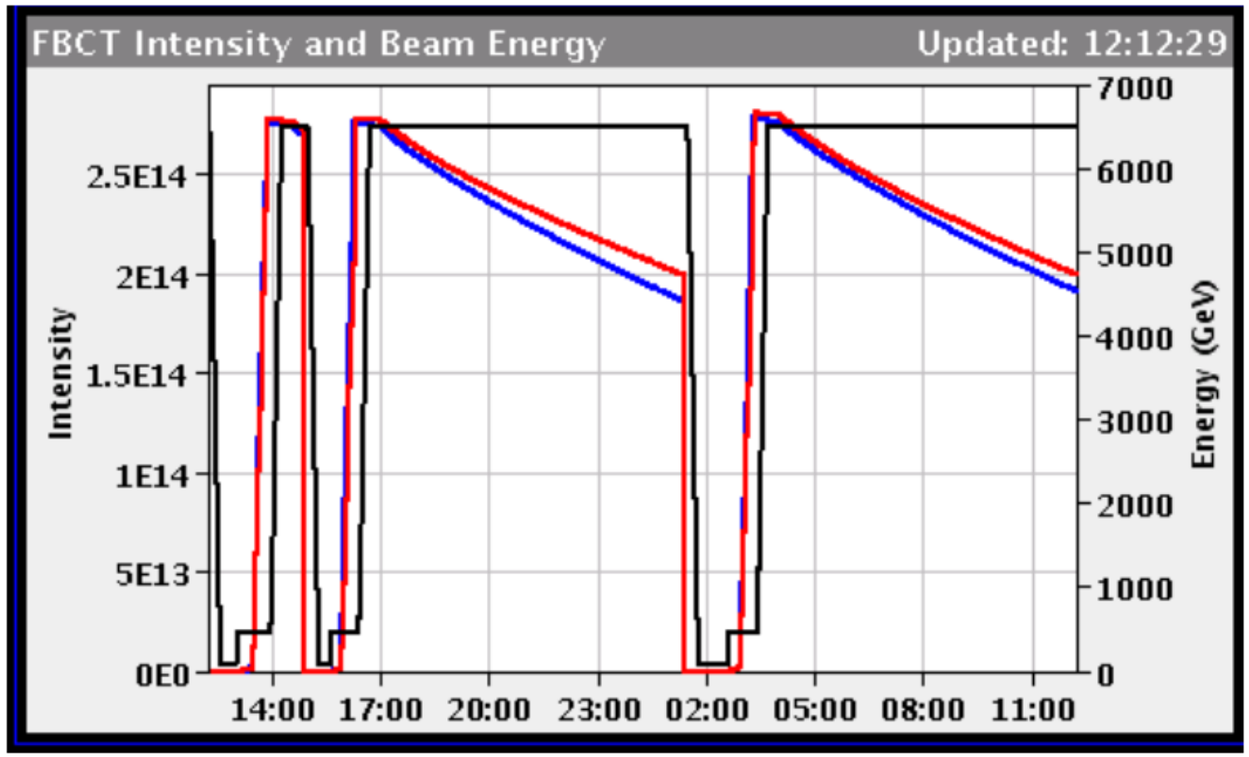
All three levelling techniques are used in operation.

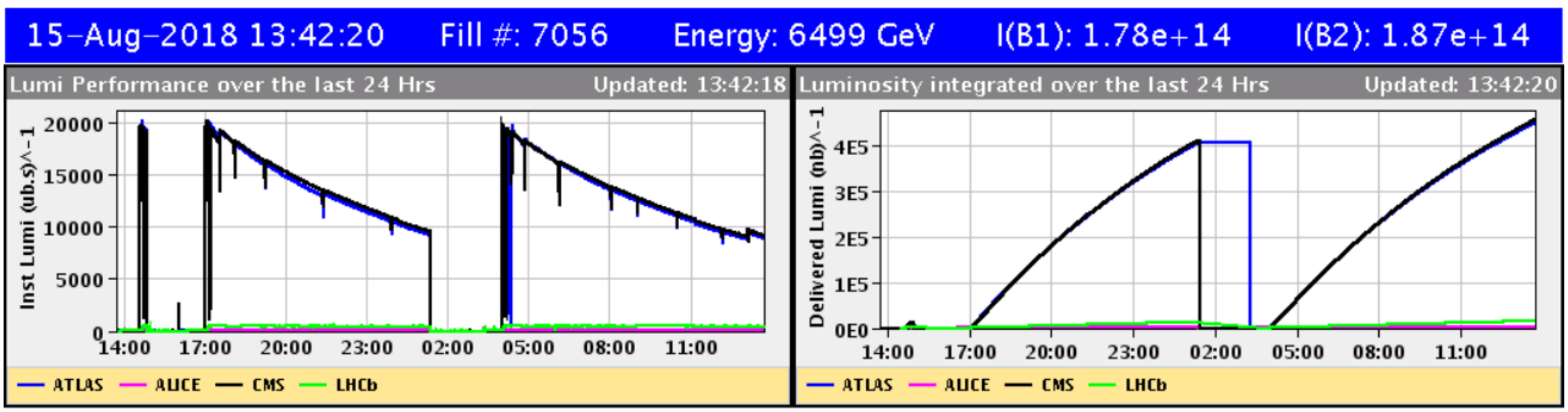
- ***Crossing angle*** *and* ***β* levelling*** ***enhance*** *the luminosity at lower bunch intensity for ATLAS and CMS, when the pile up is already reduced.*
  - ✓ *Important test of β* levelling for Run 3 and HL-LHC.*
- ***Offset levelling*** *is used in LHCb / ALICE to ensure constant luminosity.*



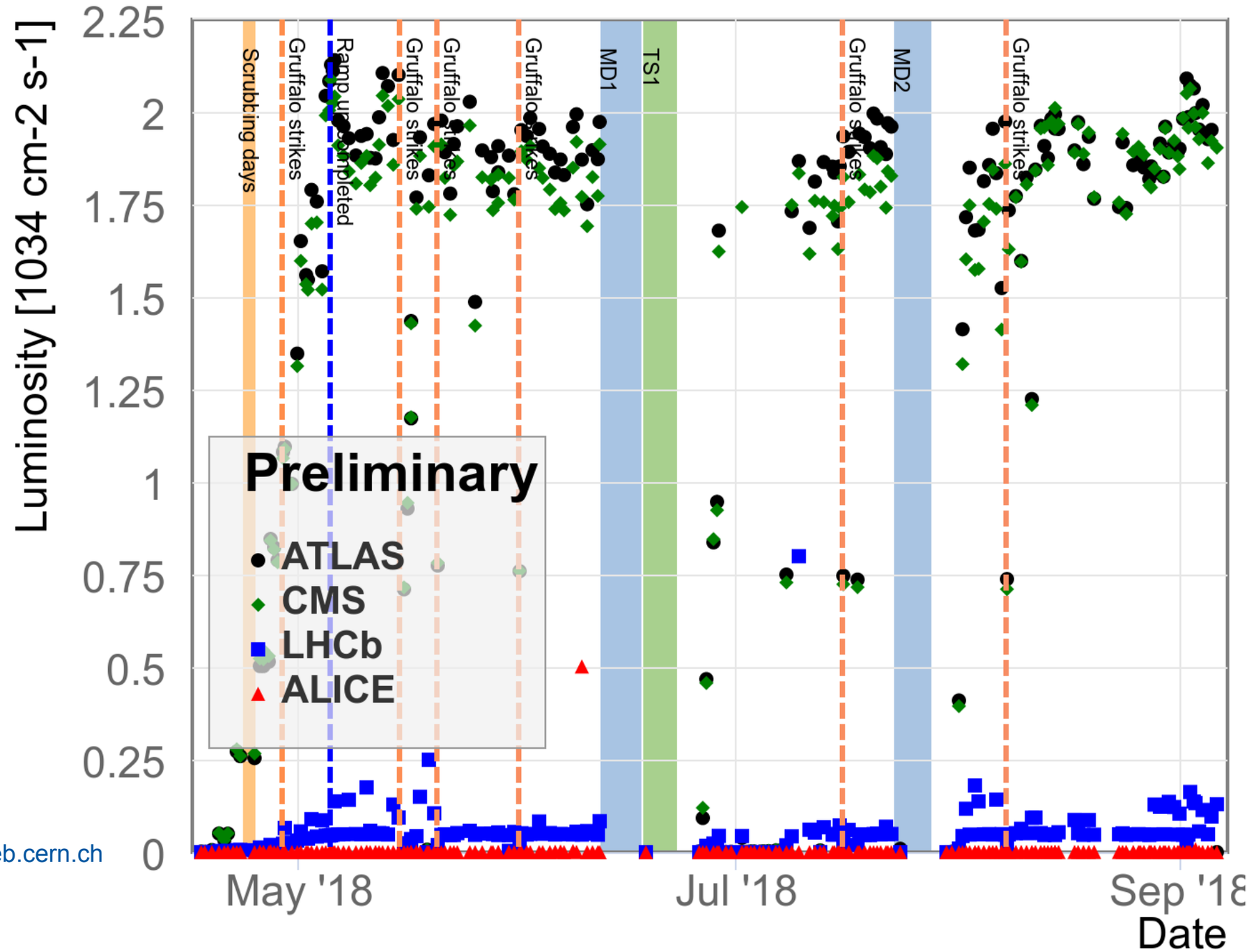
If not dumped prematurely, a good fill can produces ~0.5 fb^{-1} (~12h)

Record: almost 1 fb-1 in 24h





Peak luminosity in 2018



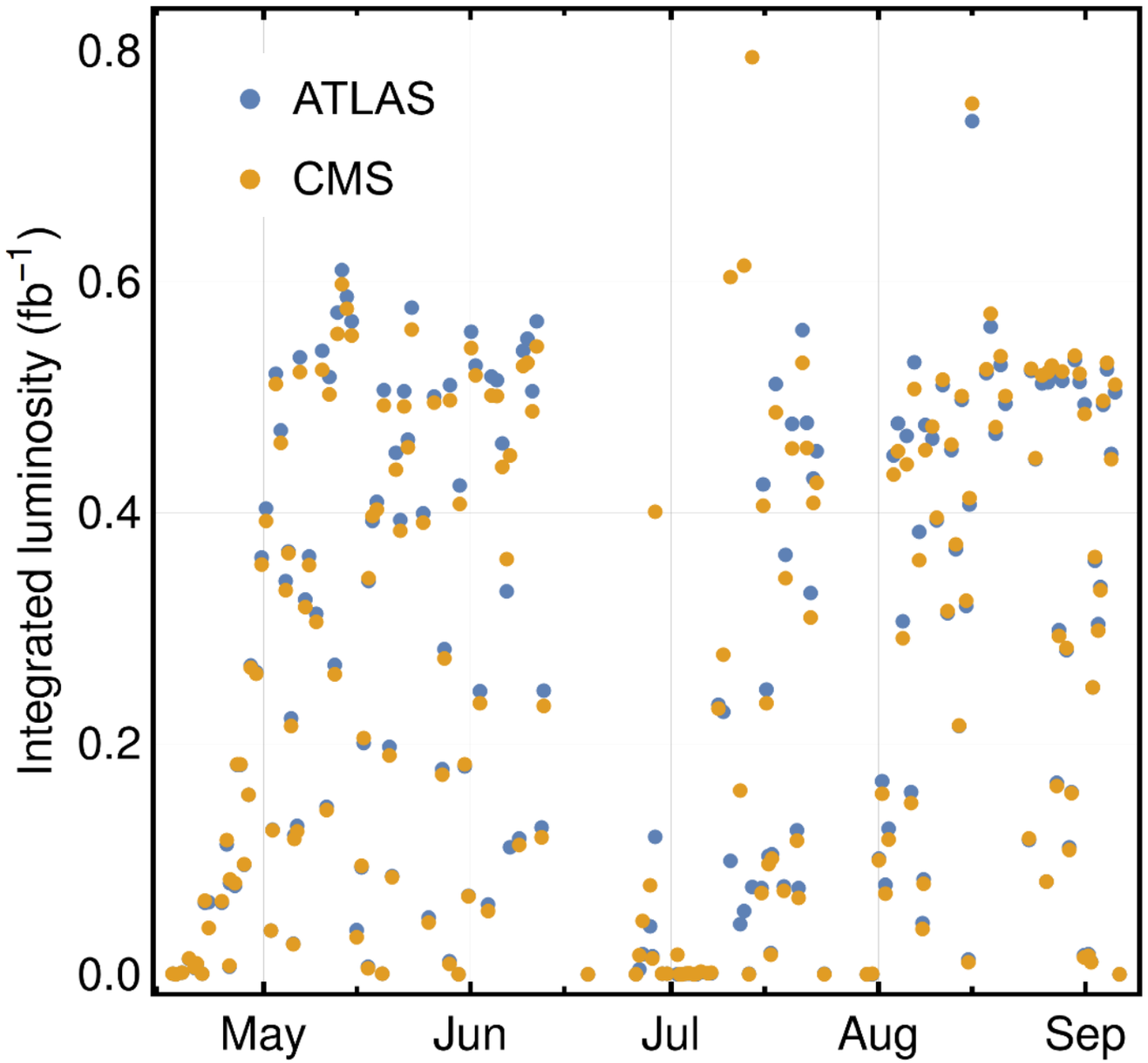
Data from: http://lpc.web.cern.ch

Record: ATLAS and CMS work at **2.1 x 10^{34}cm^{-2}s^{-1}**

(higher "virtual" peak of 2.2 x 10^{34}cm^{-2}s^{-1} in 2017, but levelled down to 1.5 x 10^{34}cm^{-2}s^{-1})

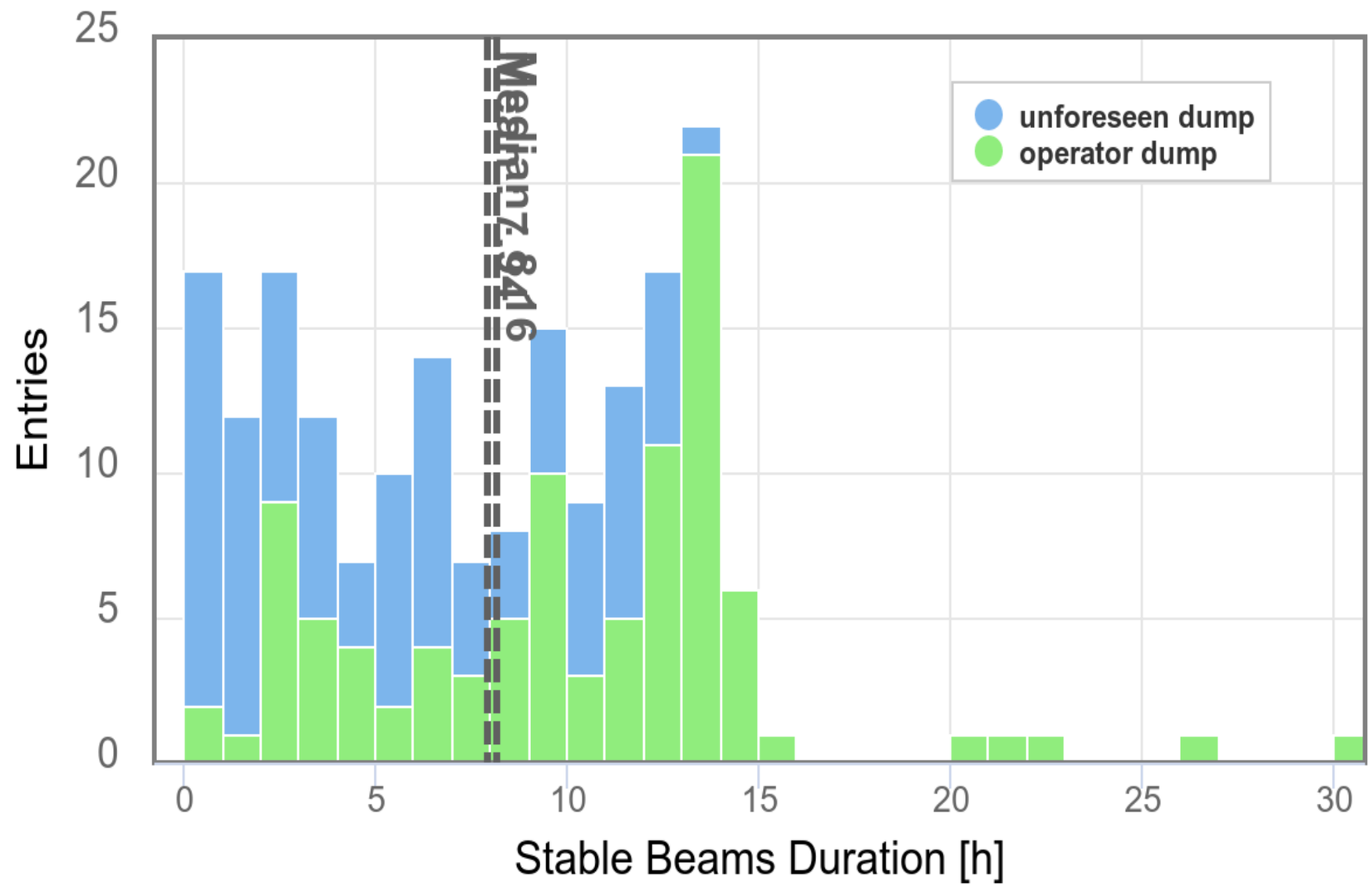
Integrated luminosity per fill

- Fills not dumped prematurely produce regularly around 0.5 fb^{-1} in ATLAS/CMS
- Many fills are well below, though
  … indication of several premature dumps in fills of good peak performance.
- CMS recorded 0.79 fb^{-1} in one fill
  … while ATLAS was levelled down by off-set for a low-pileup run



Data from: http://lpc.web.cern.ch; plot by R. Bruce

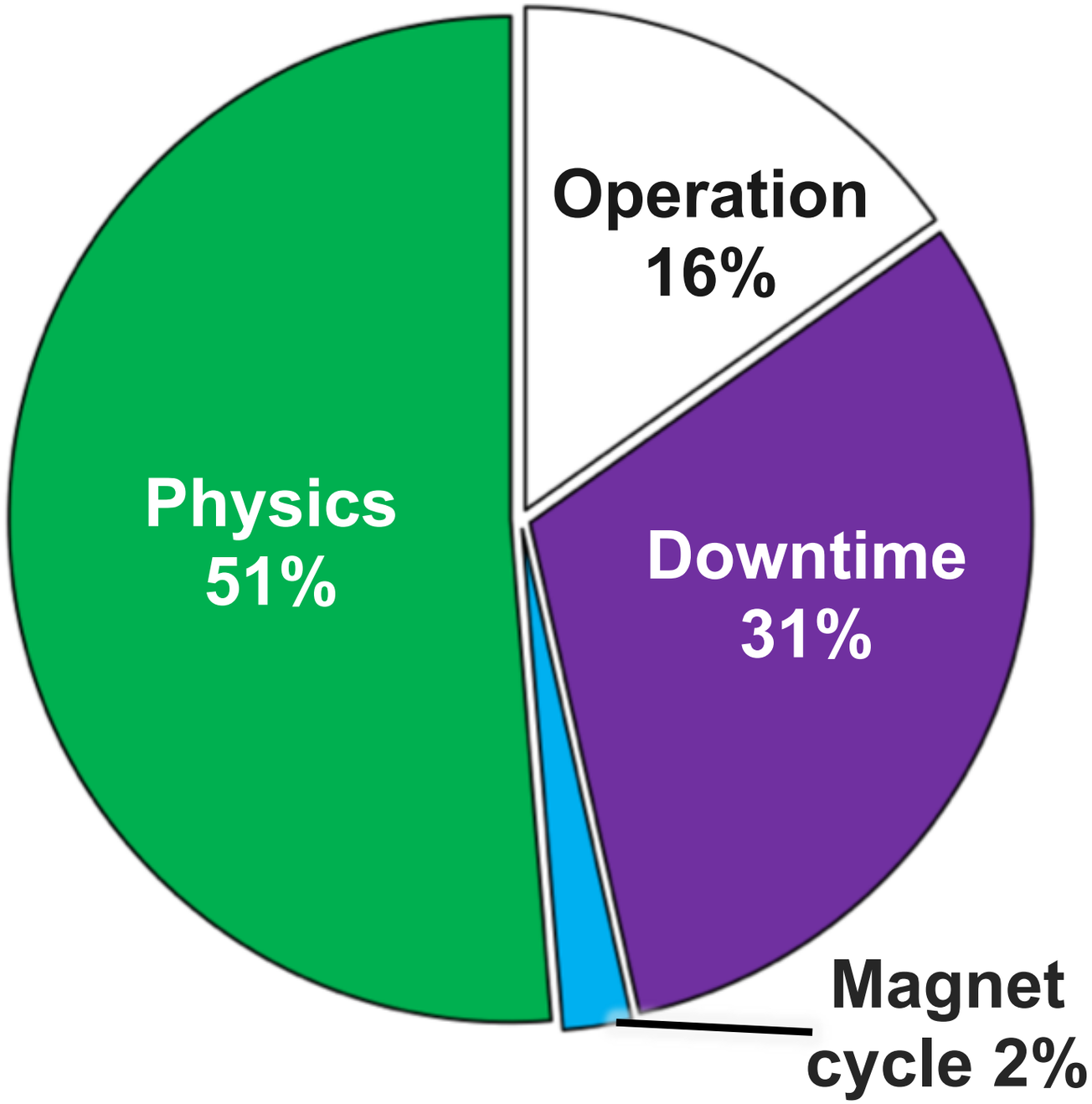
Duration of physics periods per fill



Data from:
http://lpc.web.cern.ch

- About half of the fills dumped by operators
- Other half dumped prematurely by faults
  - Reducing this would increase slope of luminosity production
  - Margin to improve

Overall 2018 availability so far



Ref. period: May- September (without MDs)

Good performance overall: time in stable beam ~ 50% (reaching 54%)
Machine availability above 80%!

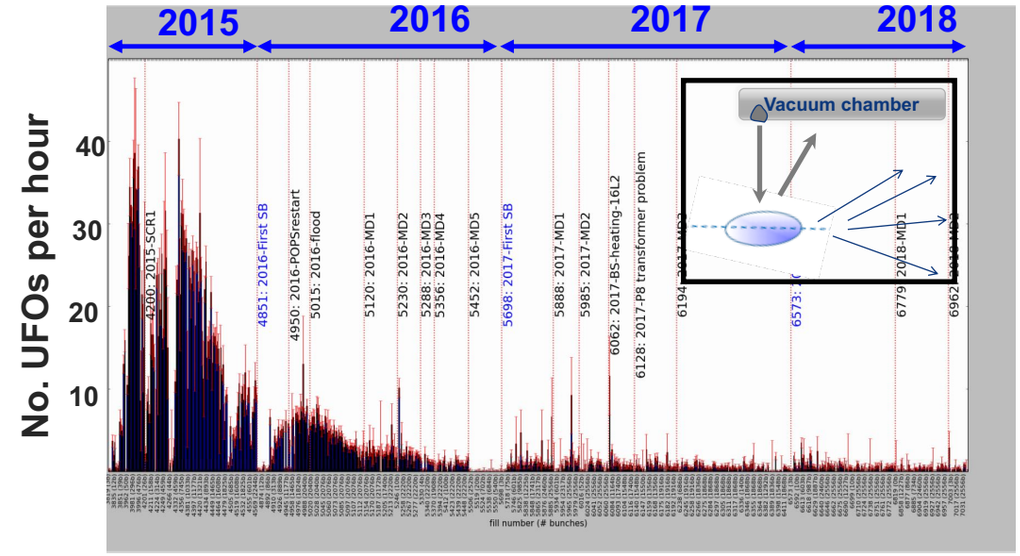
Events driving downtimes in 2018

- PS RF issue following 18 kV transformer failure
  - Several knock-on effects of transformer failure: Trip of transmission lines and injectors, PSB main power supply failed, RF problem in the PS
  - No beam for 1.5 days, then only single bunches and later 12b trains possible
- SPS dipole replacement
  - Magnet damaged by beam, causing vacuum leak

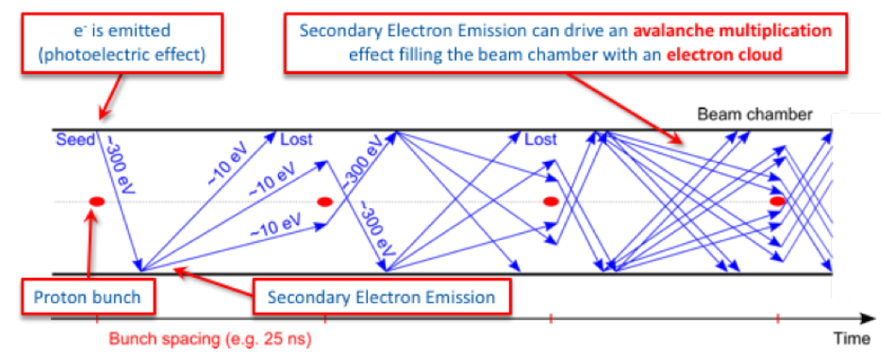
- Example of other faults
  - A few issues with the cryogenics system
  - Various trips of LHC power converters and quench protection system
  - Trip of ALICE dipole
  - Quenches
    - Quenches triplet magnets
    - UFO in 21R3 quenched 8 magnets
  - Sparks at dump dilution kickers
  - Injection kickers

Possible performance limitations

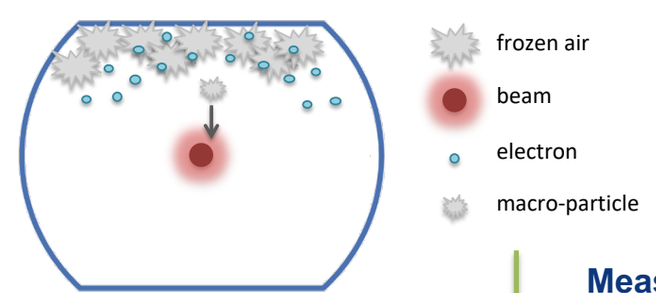
- "UFO": Unidentified Falling Objects
  - Falling dusk particles (most credible theory) generate beam losses and possible quenches
  - Conditioning!



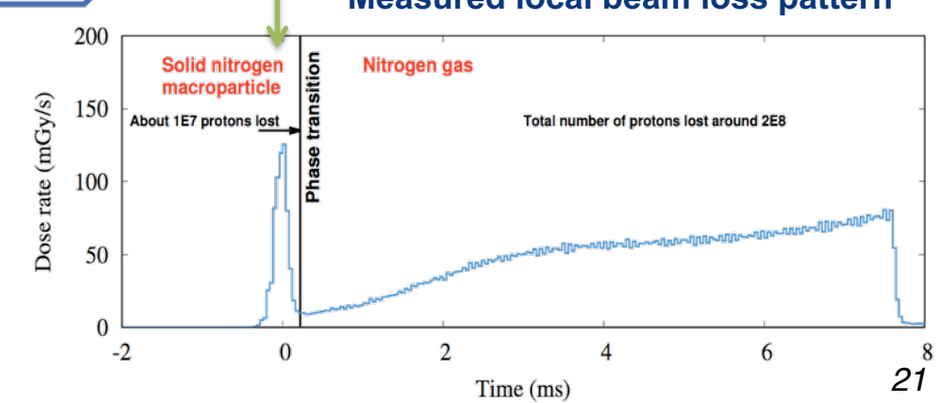
- Electron cloud
  - Electron cloud produced and accelerated by the beam in an avalanche effect (multi-pacting)
  - Degrading vacuum, poor beam quality, excessive loads on cryogenics system
  - Under control in 2018, concern for the future



- "16L2": UFO-like losses observed in 2017 at a specific location in sector 12 [cell 16L2]
  - Caused by frozen air that "falls" into the beam
  - Beam loss spike followed by a fast beam instability
  - About **60 dumps in 2017**, requiring new filling scheme
  - 6 dumps in 2018m after various mitigations

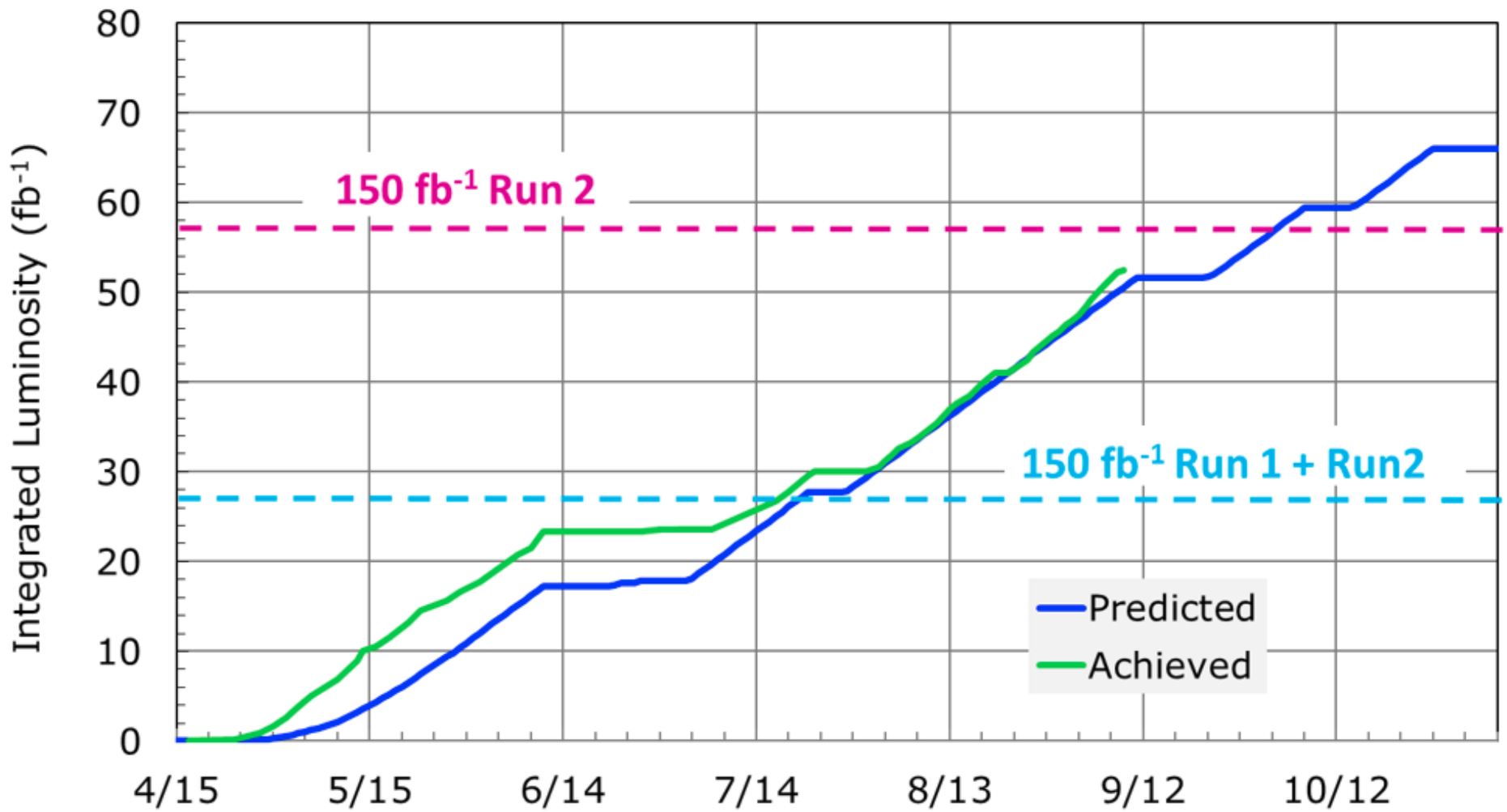


Measured local beam loss pattern



Details in backup slides.

Status of 2018 luminosity production

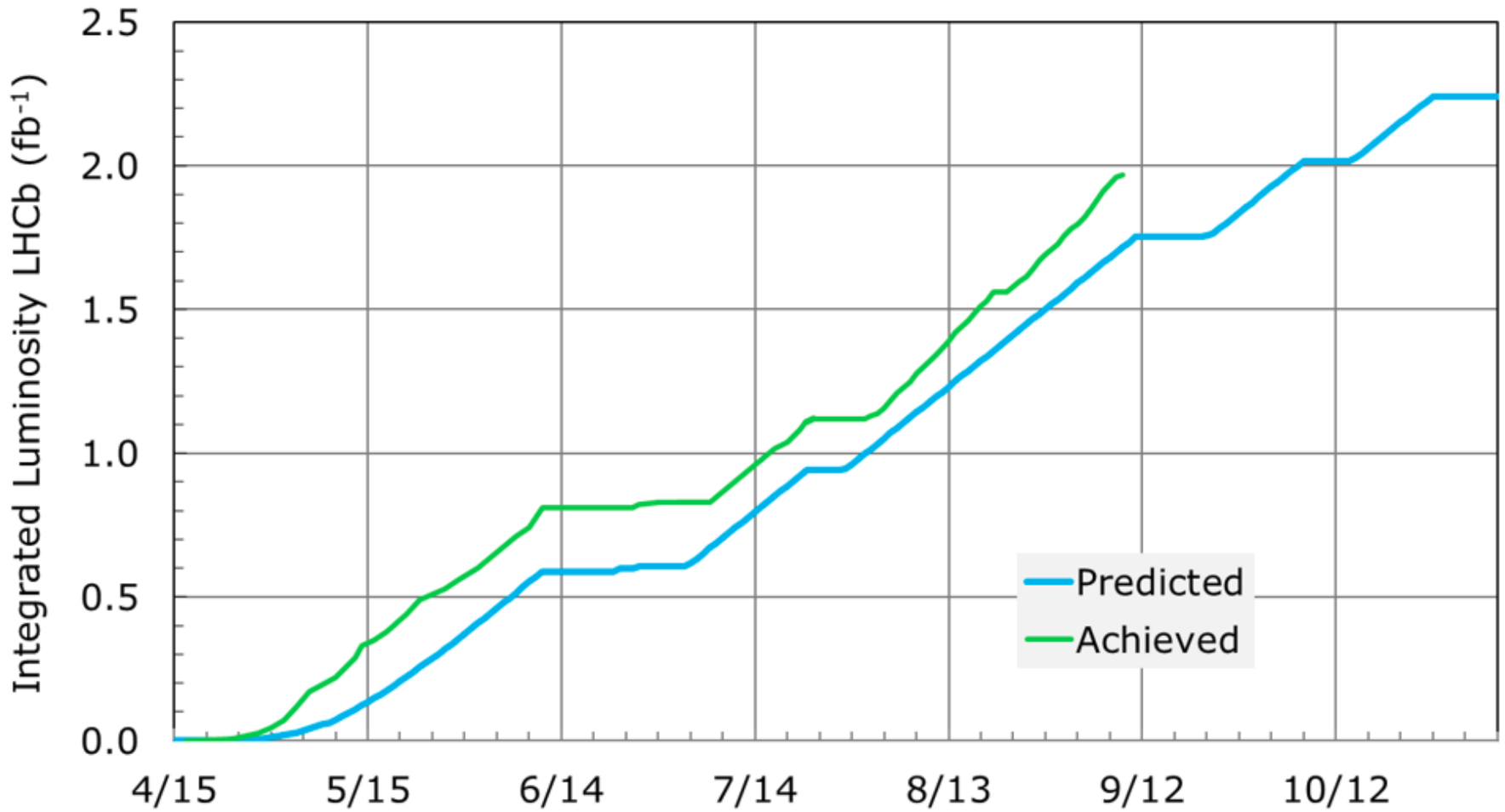


Data from https://twiki.cern.ch/twiki/bin/viewauth/LhcMachine/LhcCoordinationMain

On a good track to achieve the 2018 goal of 60fb^{-1}!

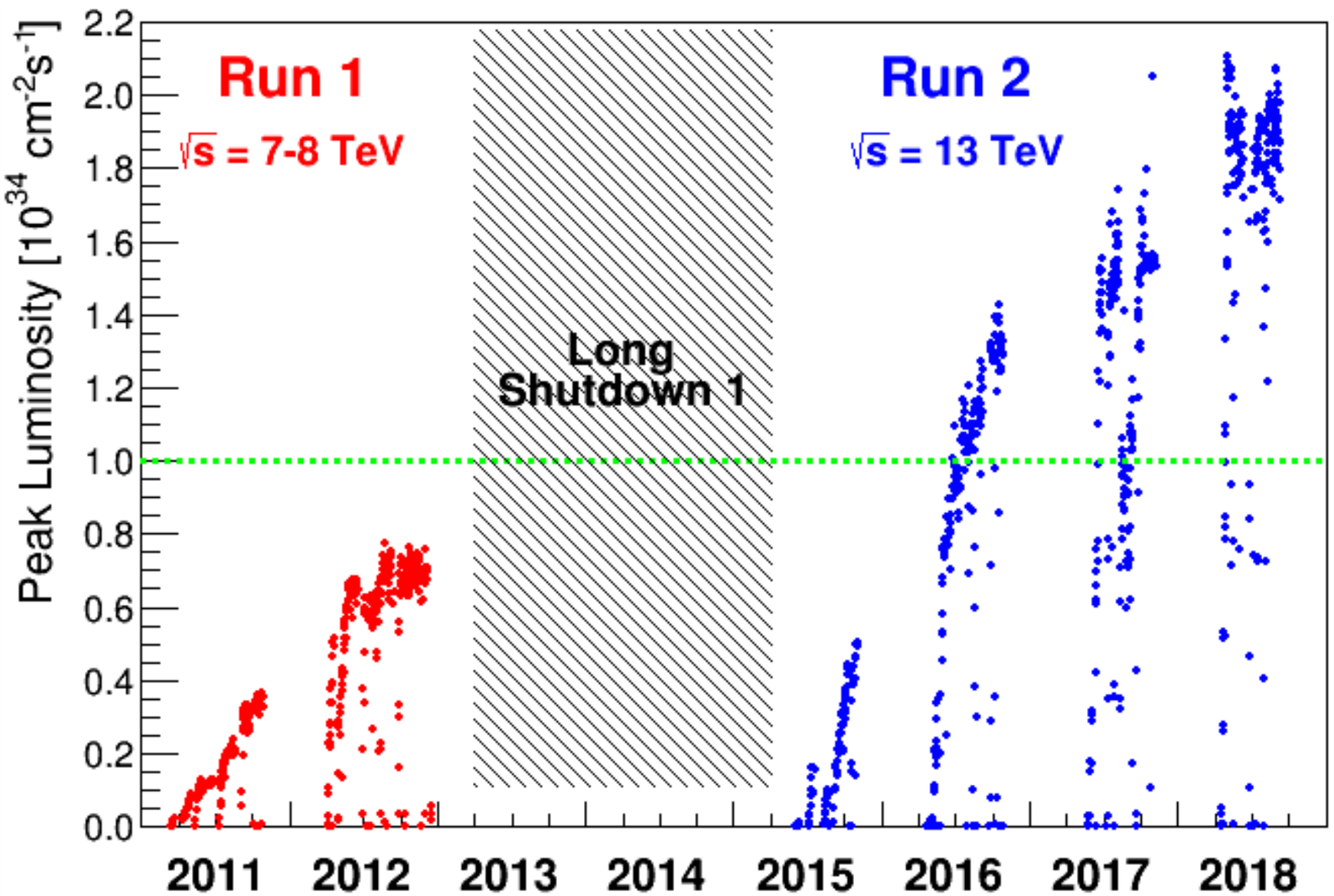
"Flat" regions: special runs, machine developments (MDs), faults.

LHCb performance — Great!



LHCb reached already the goal of 2 fb^{-1}.
Now aiming at reaching 10fb^{-1} by the end of the Run II!

Peak performance Run I and Run II



Peak luminosity limited to ***≈ 2.2×10^{34} cm^{-2}s^{-1}*** *by the cryogenic cooling capacity*

Peak luminosity:

Run 1: 7.6×10^{33} cm^{-2}s^{-1}

Run 2: 2.1×10^{34} cm^{-2}s^{-1}

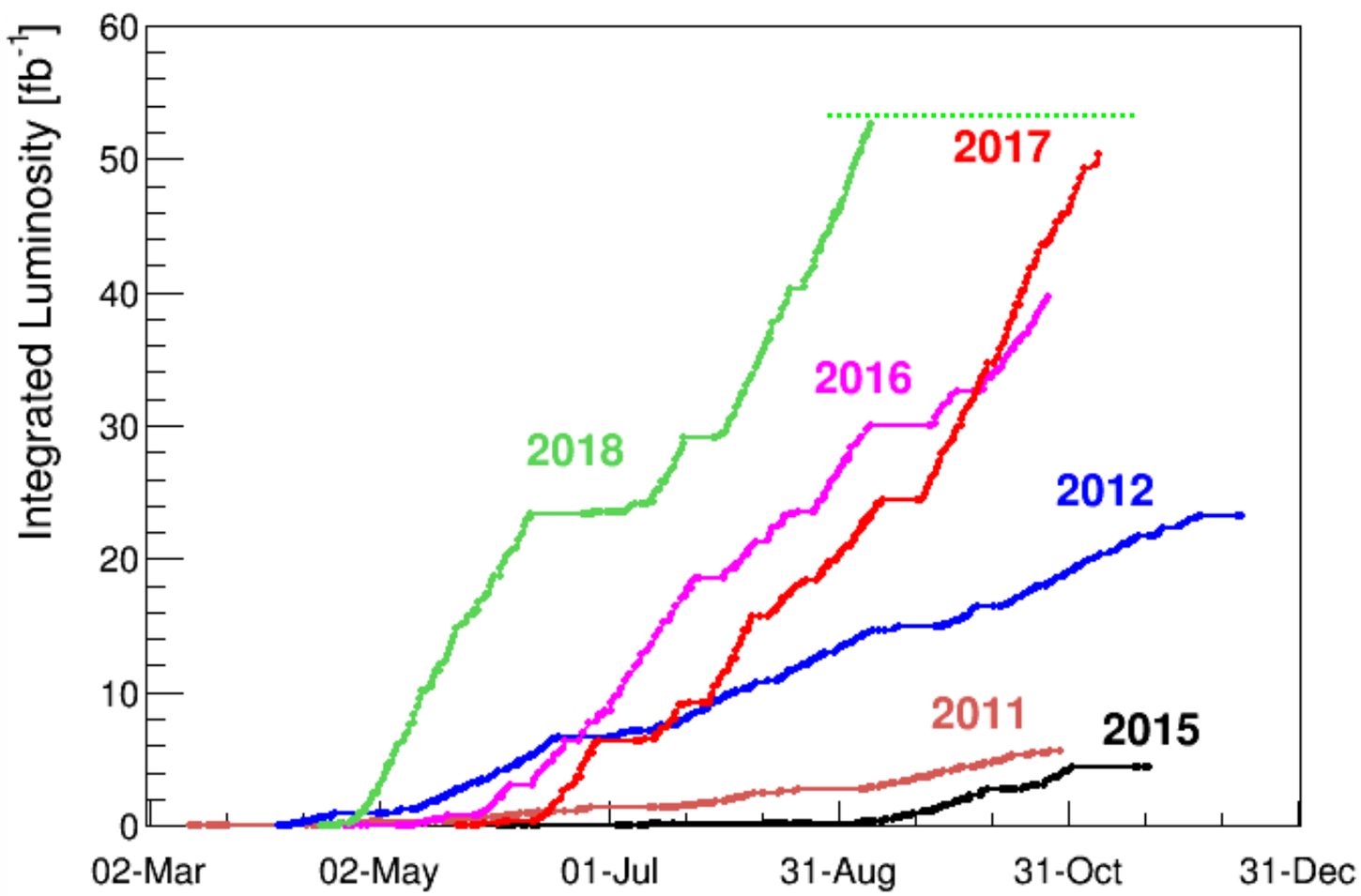
Design luminosity:

1×10^{34} cm^{-2}s^{-1}

Status of integrated luminosity

The yearly integrated luminosities exceed now 50 fb^{-1} thanks to

- ✓ ***Record peak luminosity***,
- ✓ ***Excellent machine reproducibility***,
- ✓ ***Better efficiency*** *of ~ 50% of the time spent in physics data taking compared to ~35% between 2009-2015.*

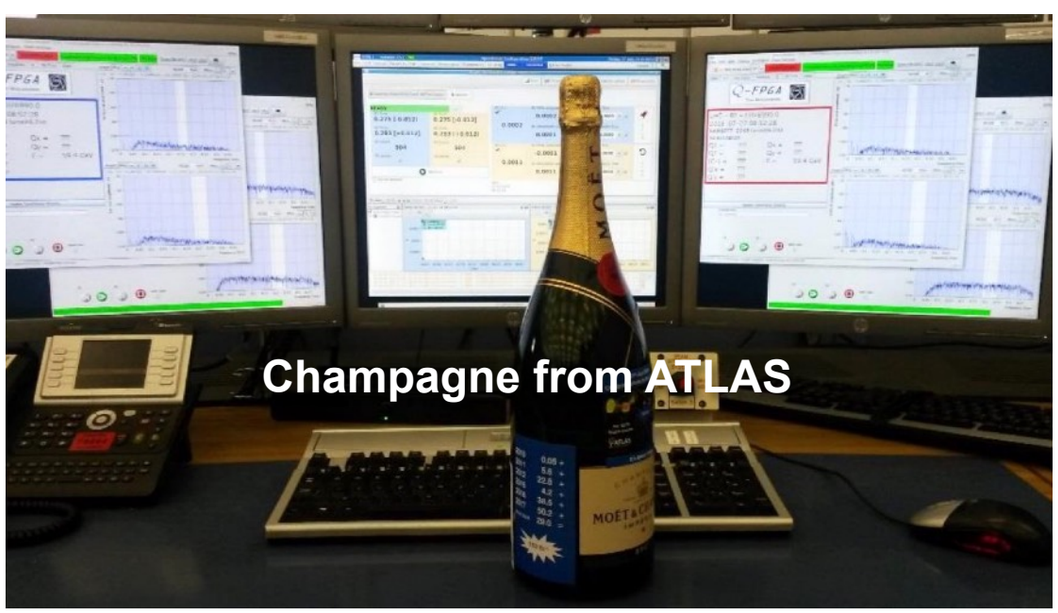


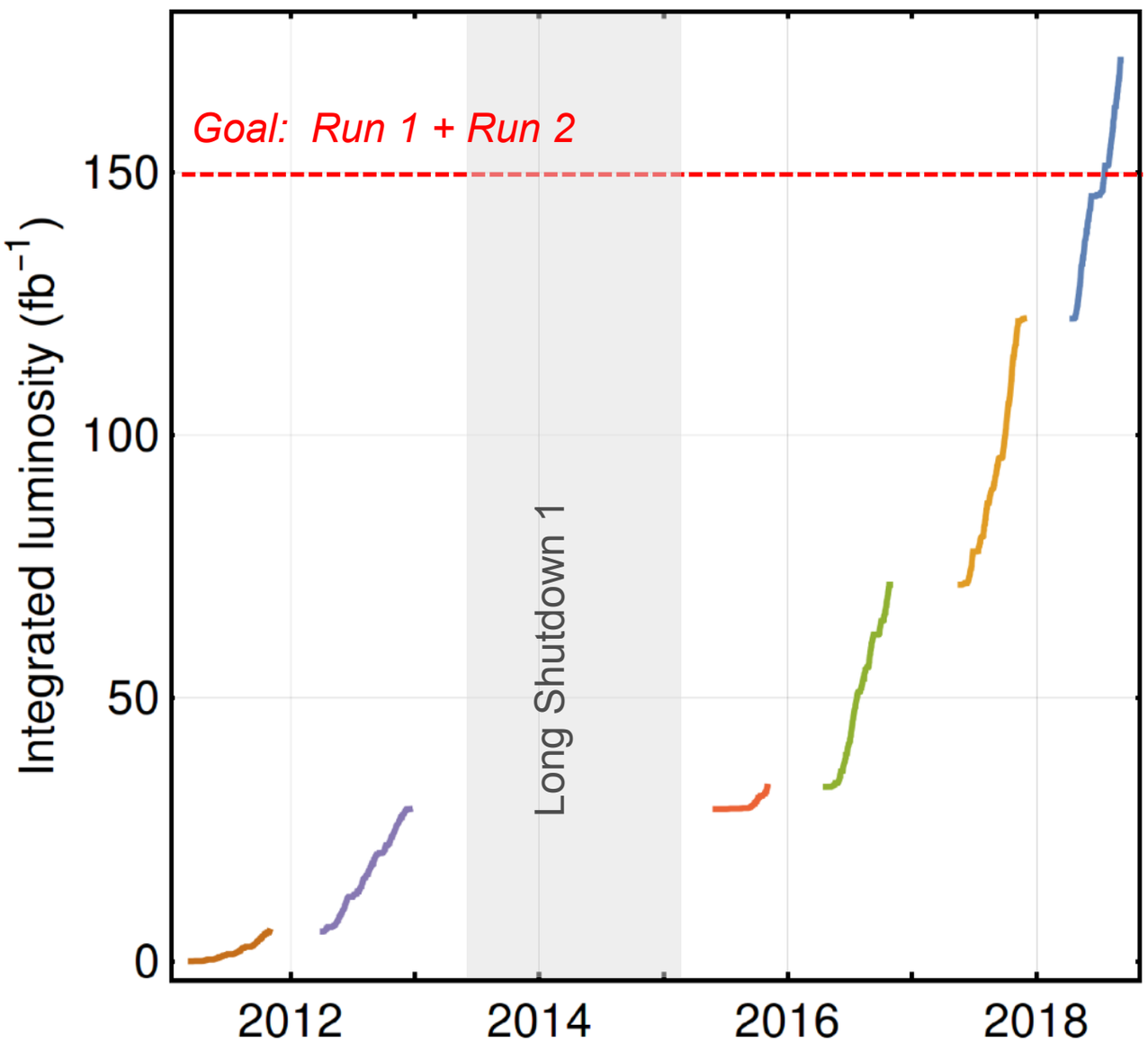
Expect to integrate over 60 fb^{-1} in 2018

2018 surpassed 2017

Overall performance so far

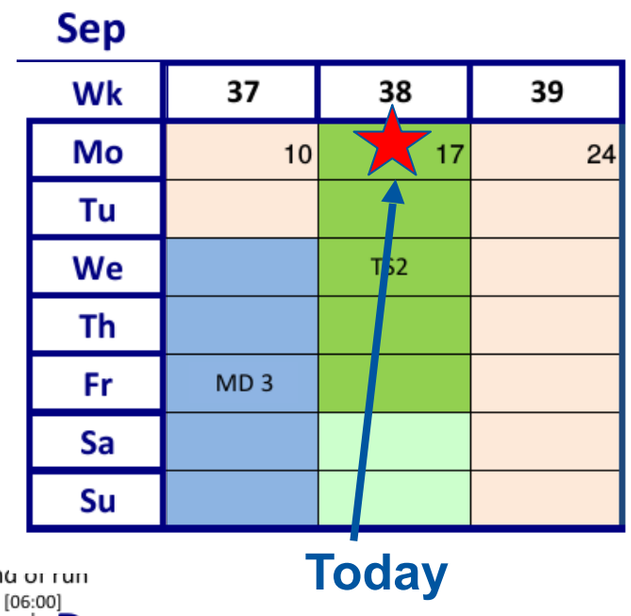
- Reached goal of 150 fb^{-1} in Run 1 and Run 2 combined (~120 fb^{-1} in Run 2 only)
- Good hope to reach 150 fb^{-1} in Run 2 alone

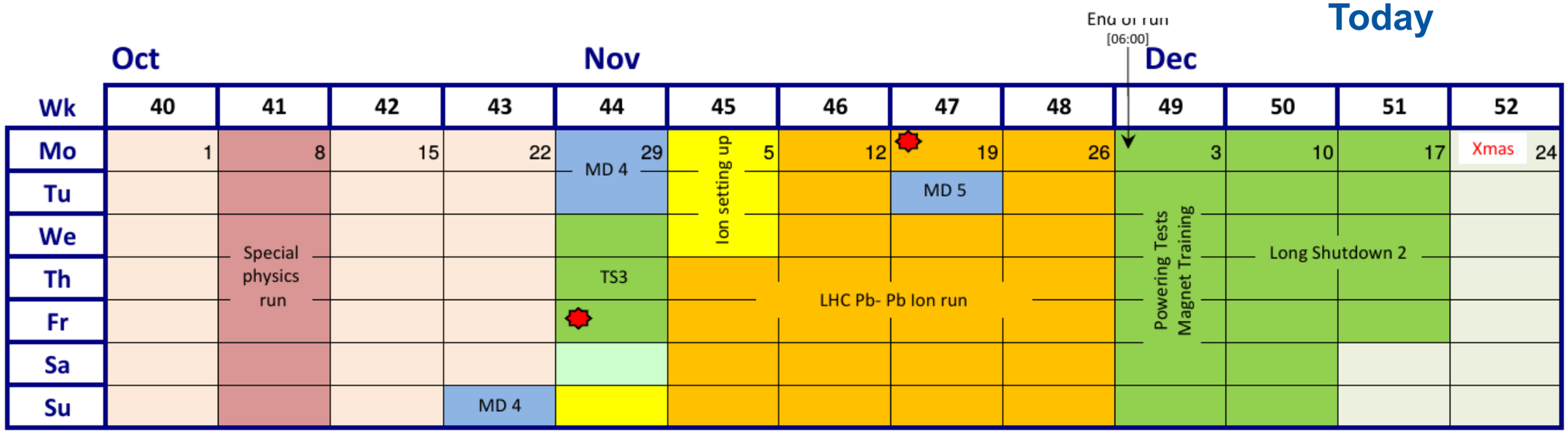




Unti the end of the year

- Still interesting period ahead!
- Another 4-5 weeks of proton physics before the end of pp run
- Special physics run: high-β* at injection
  - Forward physics measurements
  - Issues with high background under study
- Heavy-ion run from beginning of November





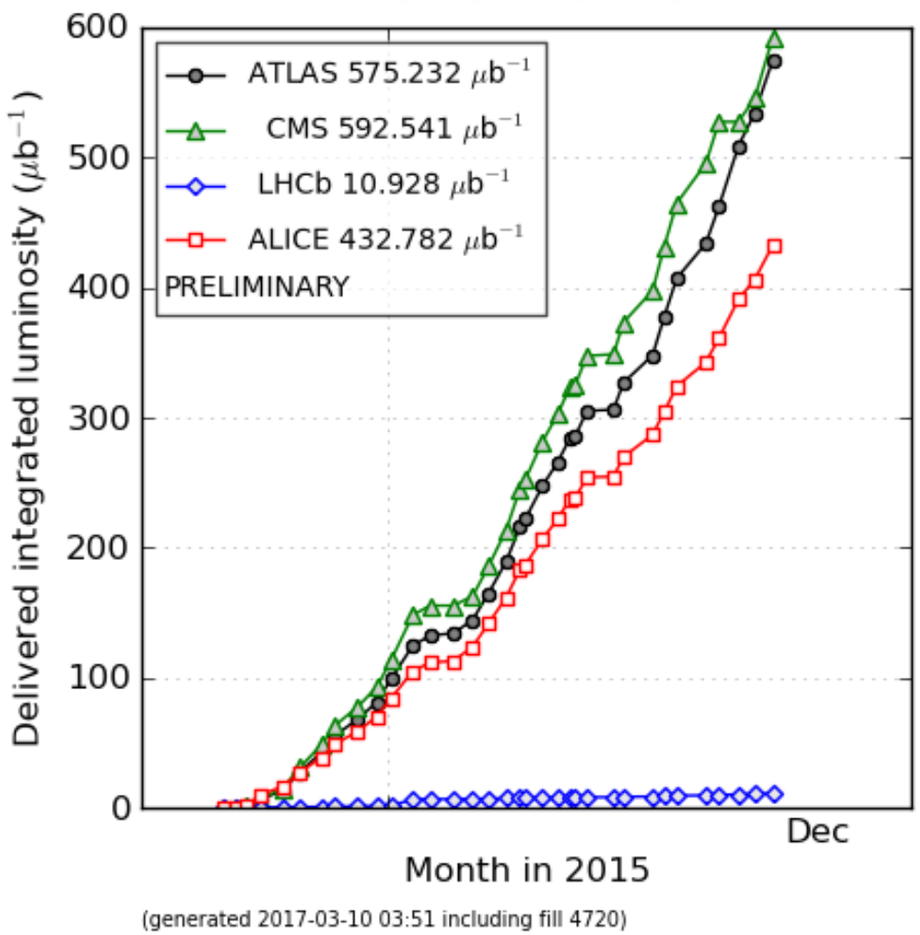
LHC ion runs

- Successful lead-lead (2015) and proton-lead (2016) runs took place after each proton run before going into winter shutdown.
- Peak luminosities:

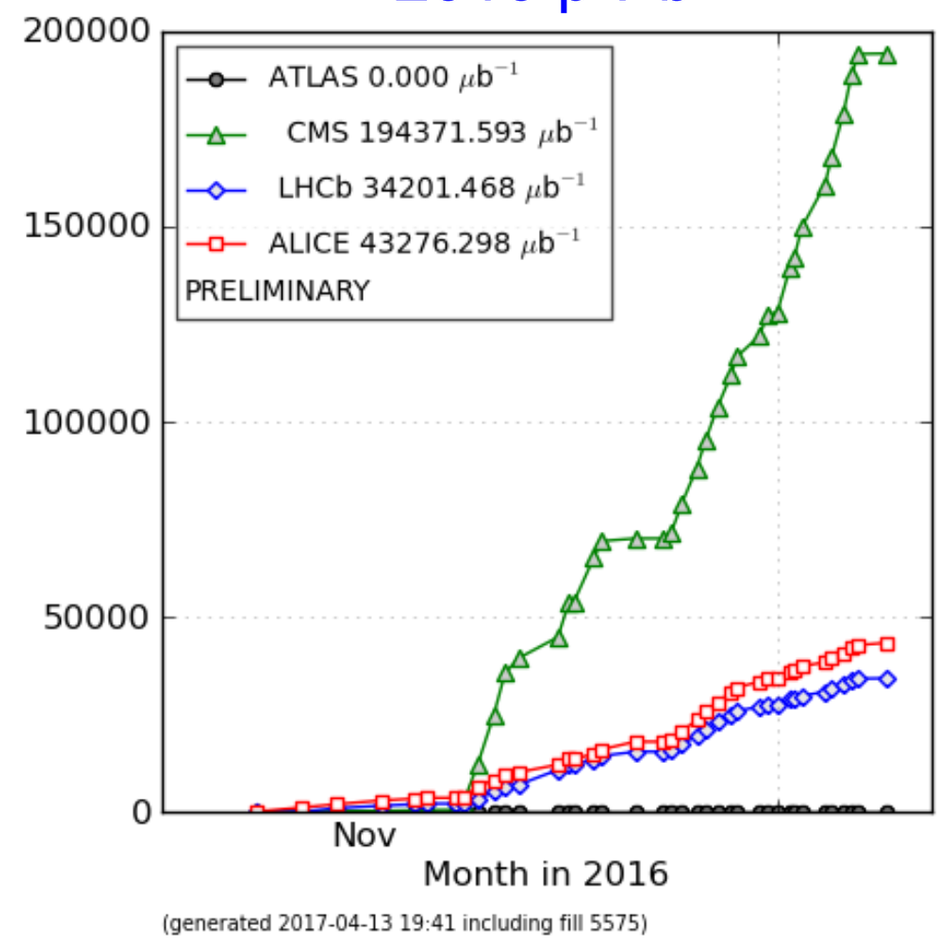
Pb-Pb : 3×10^{27} cm^{-2}s^{-1}

p-Pb : 8×10^{29} cm^{-2}s^{-1}

2015 Pb-Pb



2016 p-Pb



J. Jowett

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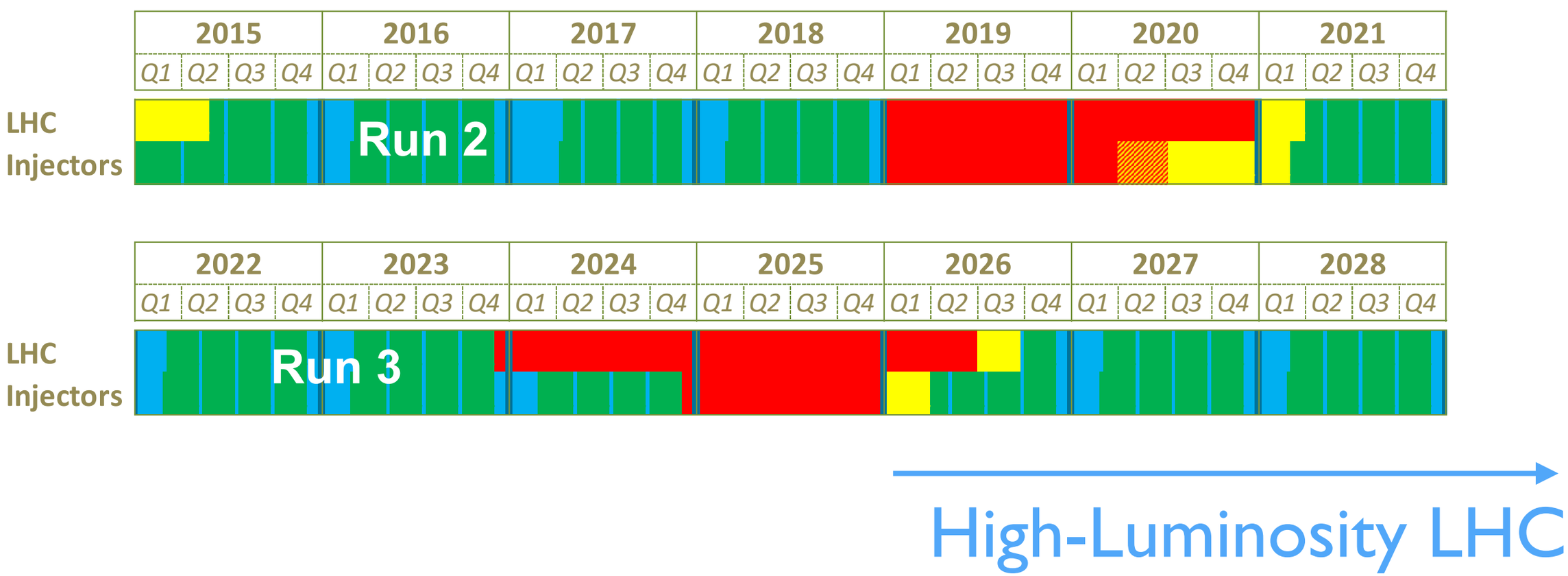
Outlook for Run III

- A major upgrade of the LHC injectors is foreseen during Long Shutdown 2 (2019-2020) to reach the HL-LHC beam parameter targets during Run 3.
- During Run 3 the LHC may operate at **7 TeV** following the LS2 consolidation and a major magnet training campaign (~500 quenches).
- With the **LHC operating beyond design luminosity in 2018**, the prospects to reach **150 fb^{-1}** integrated in Run 3 (2021-2023) are very good despite the short duration of the run.



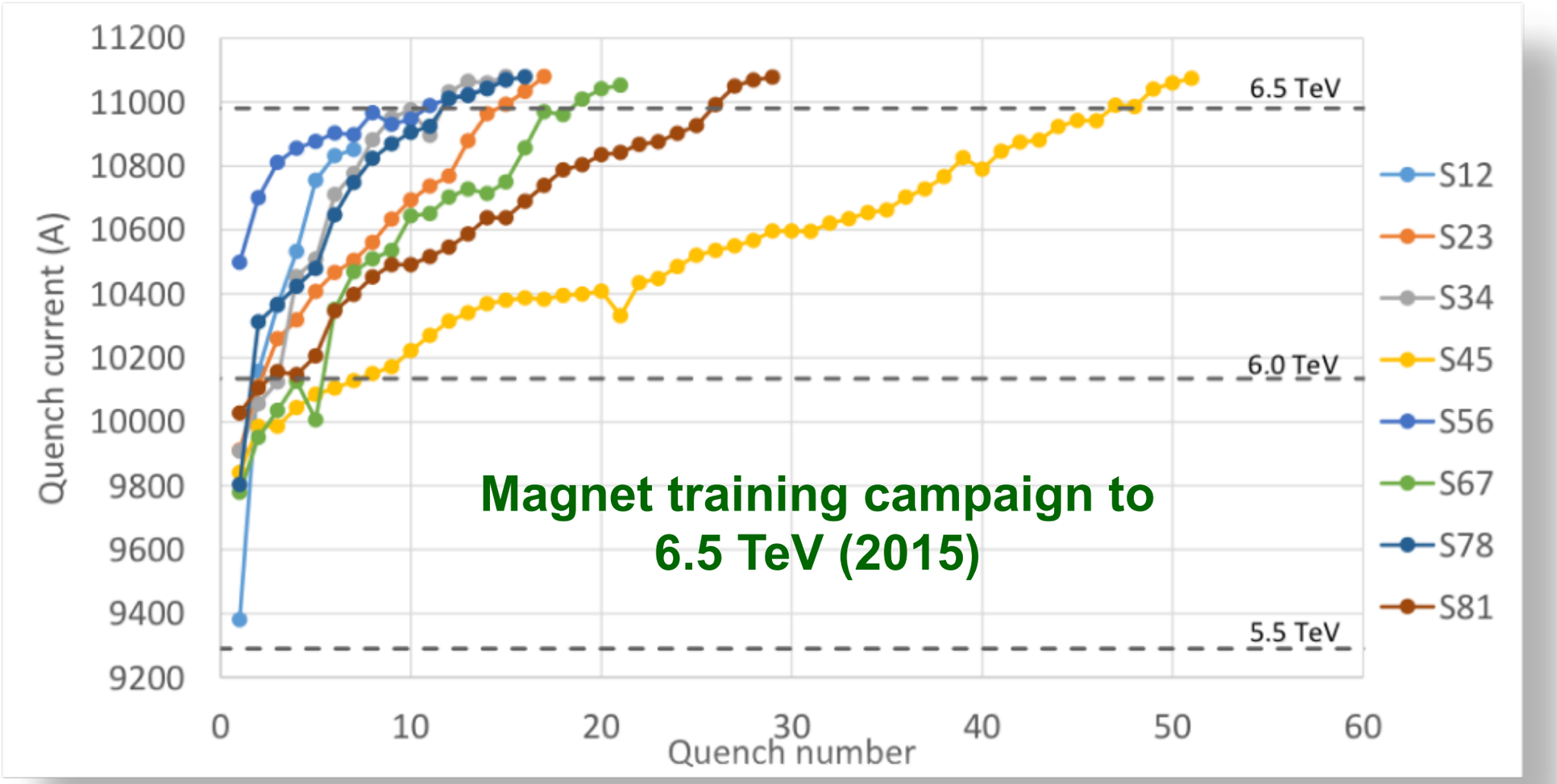
Towards 7TeV

- All dipole magnets were trained for **6.5 TeV** operation in 2015. Just **over 150 quenches** were required to reach 6.5 + ε TeV

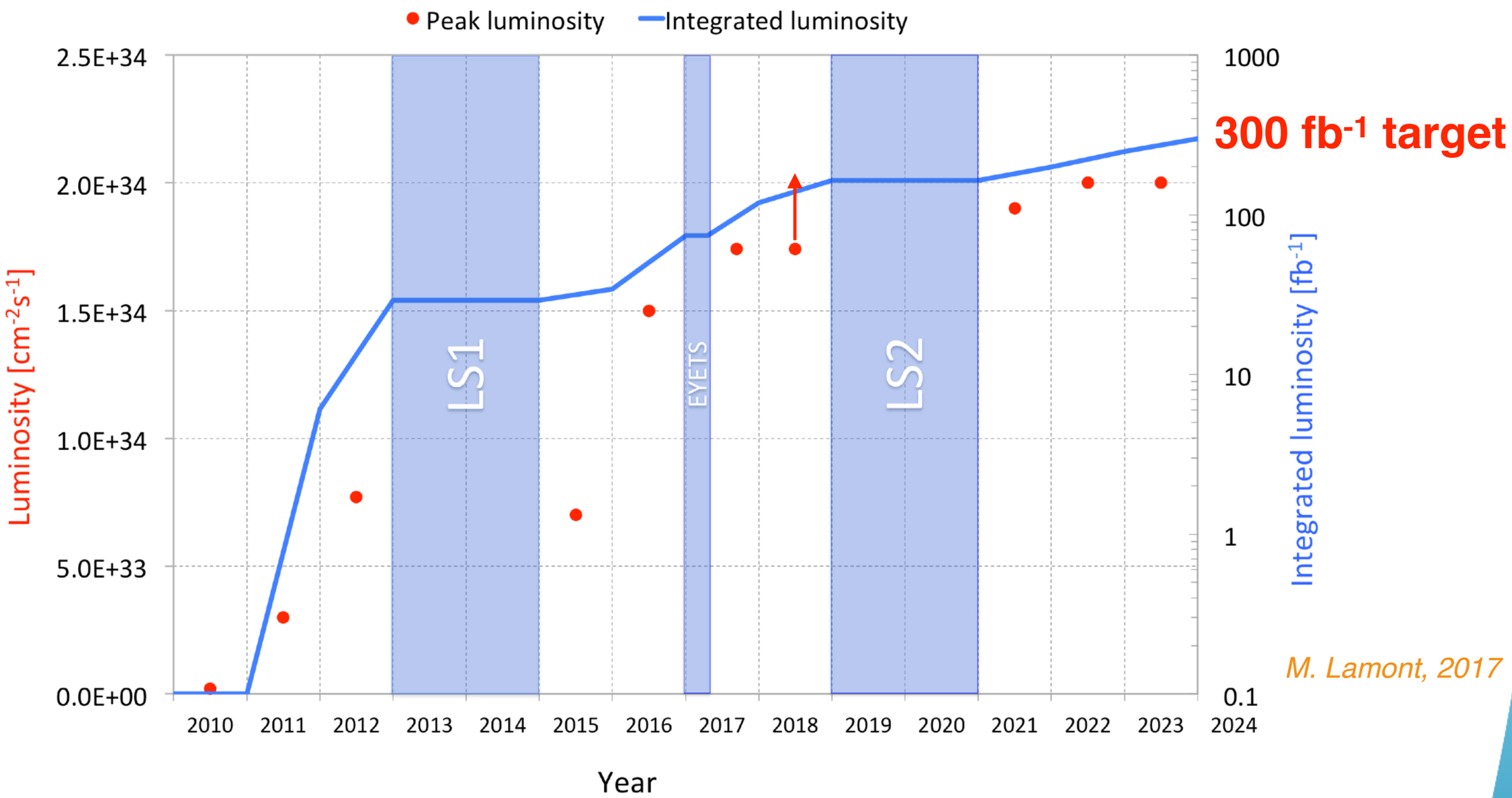
  Spread in number of quenches between sectors is due to the mixture of producers.

  Two sectors pushed to 6.75 TeV in December 2016

- Current estimate to train magnets to **7 TeV** is ~ 500 training quenches.



LHC: Projected target performance

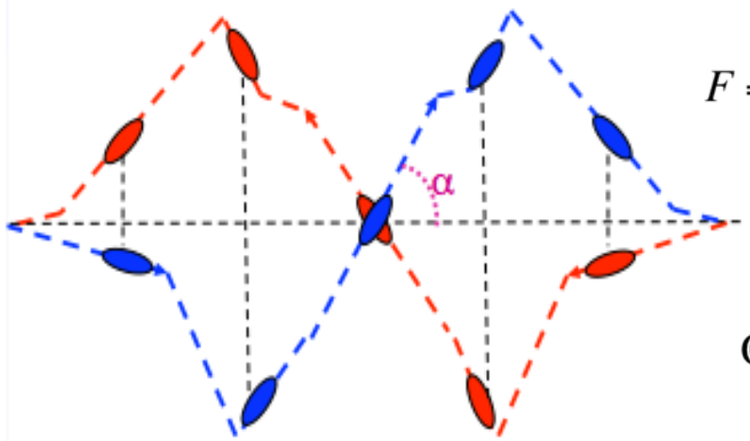


M. Lamont, 2017

Luminosity upgrade: key ingredients

Luminosity formula for round beams with crossing angle:

$$\mathcal{L} = \frac{N_1 N_2 k_b f \gamma}{4\pi\epsilon_n \beta^*} F$$



$$F = \frac{1}{\sqrt{1+\Theta^2}};$$

$$\Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

1) maximize bunch intensities, N_i
2) minimize the beam emittance, ε_n
3) minimize beam size, $\sqrt{\varepsilon_n \beta^*/\gamma}$ (constant beam power);
4) maximize number of bunches, k_b (beam power);
5) compensate for geometric 'F';
6) Improve machine 'Efficiency'

➔ Injector complex (LIU), impedance reduction, new collimation systems

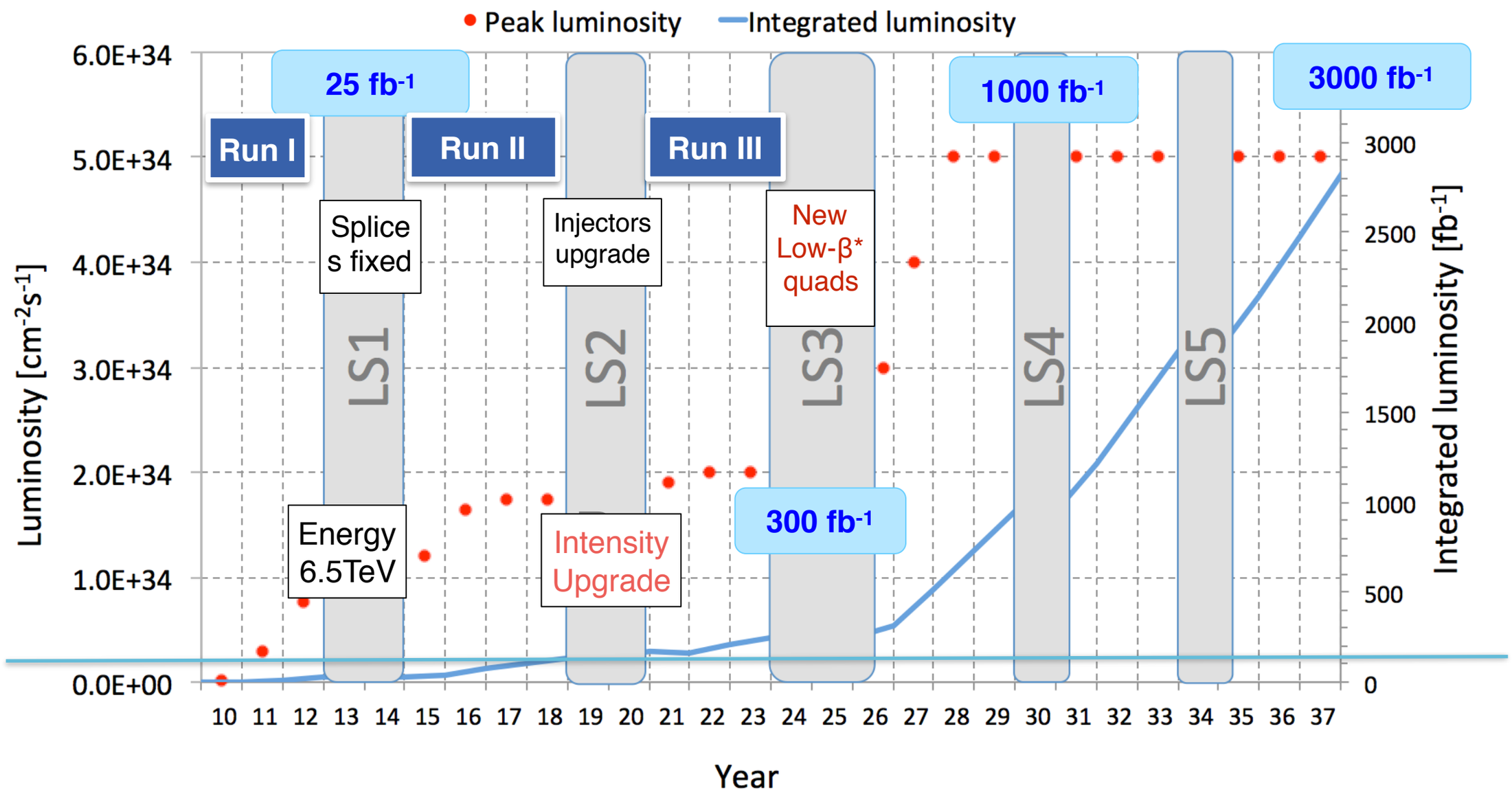
➔ triplet aperture

➔ 25ns

➔ Crab Cavities

➔ minimize number of unscheduled beam aborts

Predicted luminosity (baseline)



A bright and luminous future ahead of us!

Conclusions

- The LHC operation proceeds very well!

  Unprecedented complexing to fulfil experiment's requirements, under control.

  In 2018: various levelling technique, combined ramp&squeeze, new optics…

- Excellent luminosity production achieved in Run II !

  Machine performance pushed to 2 twice the design

  Thanks to small β and small-emittance beams from injectors.*

  Good availability, with some bumps on the way.

  Close to 2018 target of 60fb^{-1}, with still a few weeks of proton run ahead

  Surpassed already the Run II goal of 150fb^{-1} already.

  Looking forward to seeing the lead ion run.

- A major injector upgrade is planned for LS2 (2019-2020)

  Brighter beams will become available during Run III.

  Important consolidation and upgrades starting in 4 months.

- Plan to run the LHC at 7 TeV in Run III following the LS2 consolidation and a major quench training campaign.

  Reaching 150fb^{-1} in Run III alone within reach in light of the present good performance and availability.

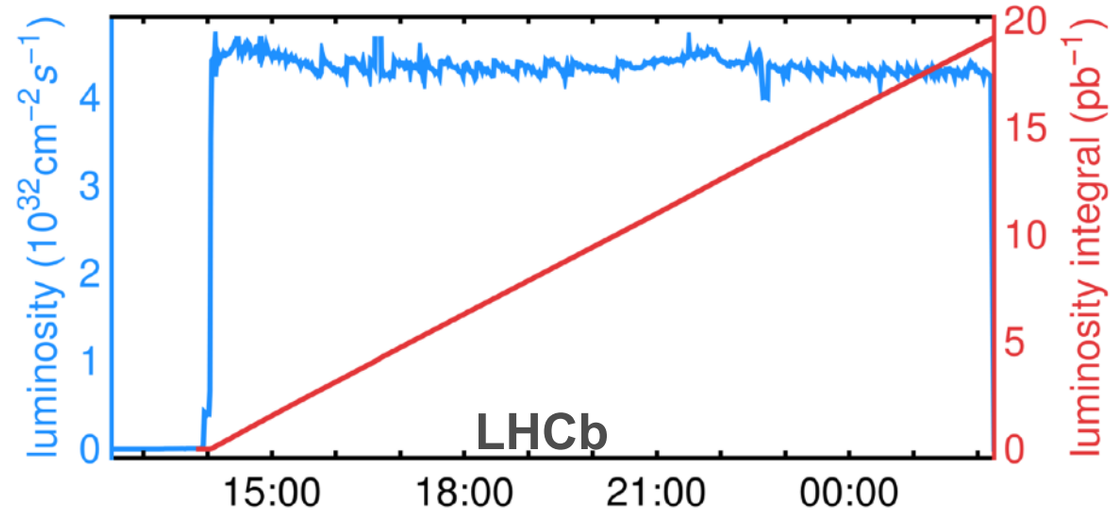
Reserve slides

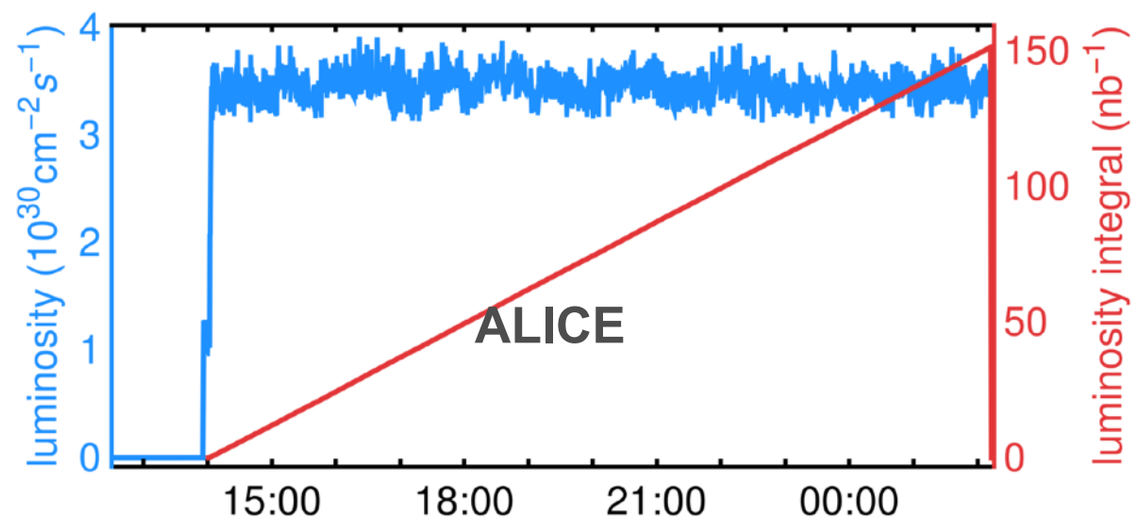
2018 heavy-ion run

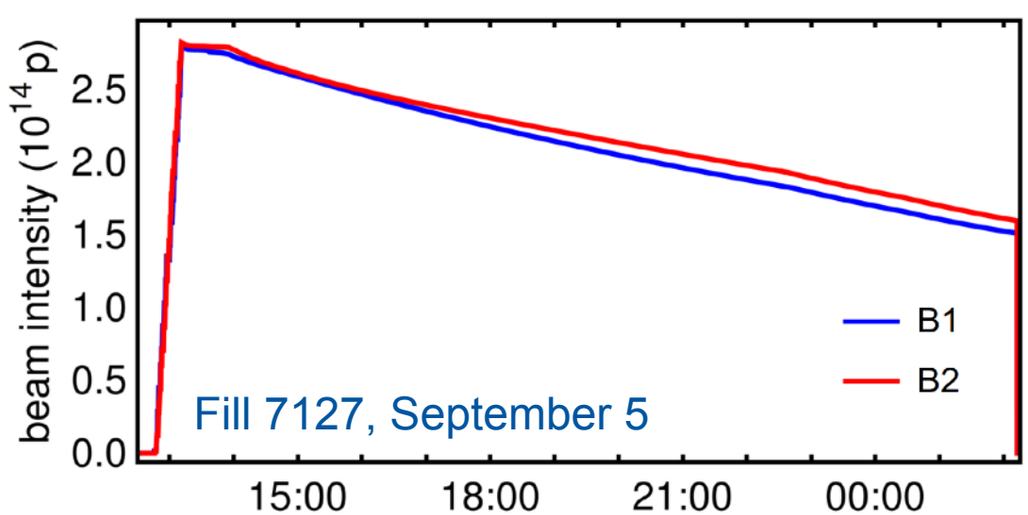
- 24 days of physics run envisaged
- Completely new machine configuration
  - New optics through the cycle – commissioning started
  - Intend to switch to 75 ns bunch spacing (to be confirmed by injectors) → ~40% more bunches. Highest Pb intensity ever!
- Potential to reach very high peak luminosities
  - Planned to level all experiments
  - Plan to test 6 times design luminosities (ATLAS/CMS)
  - LHCb also squeezed and will be taking data
- Approaching already the HL-LHC regime!
- Challenges: collimation, small beam-beam separation at ALICE polarity switch

LHCb and ALICE

- LHCb:
  - separation levelling around 4.4×10^{32} $cm^{-2}s^{-1}$
  - typical production around 20 pb^{-1} in a good fill
- ALICE
  - separation levelling around 3.5×10^{30} $cm^{-2}s^{-1}$
  - typical production around 150 nb^{-1} in a good fill







R. Bruce

2018 schedule

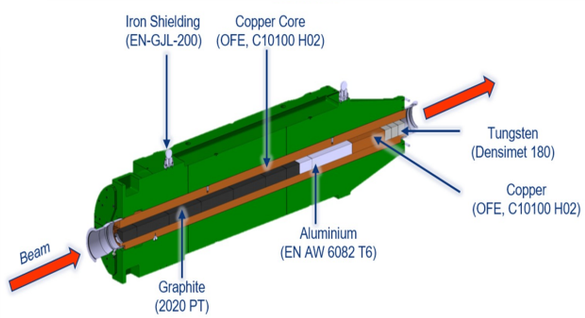
Phase	Days
Initial Commissioning+ intensity ramp up	34
Scrubbing	1
Proton physics 25 ns	131
Special physics runs	8 + 1
Machine development	20
Setting-up fo Pb-Pb ion run	4
Pb-Pb ion run	24
Technical stops (3)	13
Technical stop recovery (3)	5
Total	241 days

The LHC Run II in a nutshell

April 10
First beam at

E: 6500 GeV

April 25,
SPS beam dump vacuum leak, **limited bunch train length**



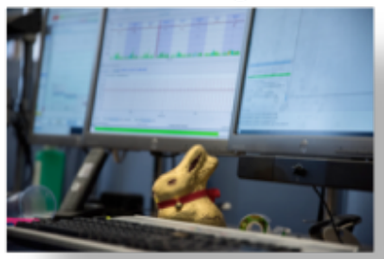
$\mathcal{L} > 2 \times 10^{34} cm^{-2}s^{-1}$

October,
2 x design luminosity

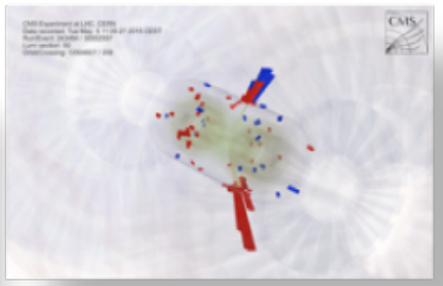
April,
Physics at $\beta^* = 25cm$
> 2 design luminosity

2015 | **2016** | **2017** | **2018**

Easter,
First beam circulating

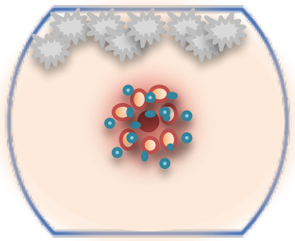


June 3,
Start of physics operation for run 2



July,
Design luminosity
$\mathcal{L} > 10^{34} cm^{-2}s^{-1}$

June,
First signs of 16L2 beam loss events
Intensity limitation



July,
150 fb^{-1} !

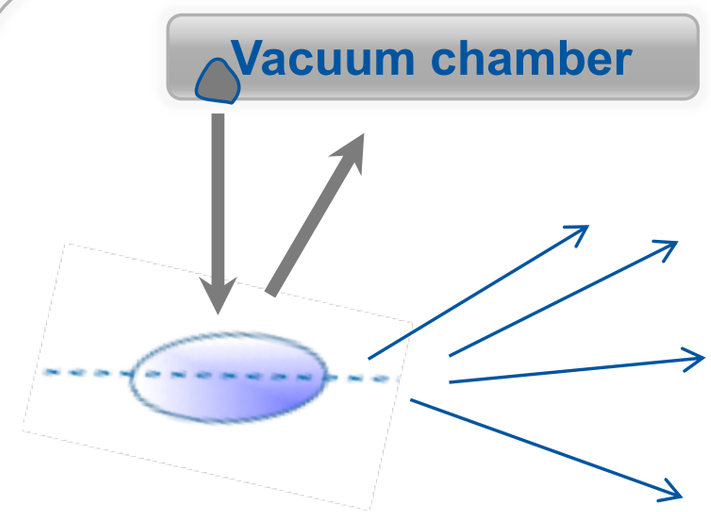
After a recovery year in 2015, the LHC moved into production in 2016, pushing the performance step by step from one year to the next despite intensity limitations.

UFOs

The most credible theory is that **Unidentified Falling Objects** are dust particles that fall into the beam and generate beam losses due to inelastic collisions with the beam.

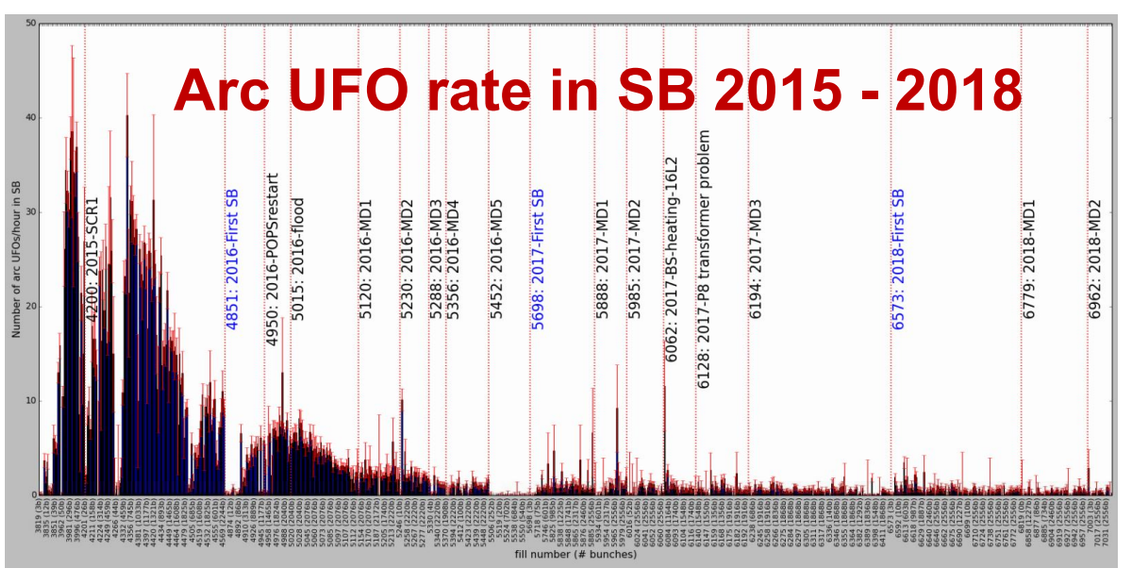
These losses result in **energy deposition** on the superconducting magnets, risking to **quench** them

UFO were already Identified during Run 1



Dust particle dynamics model predicts:

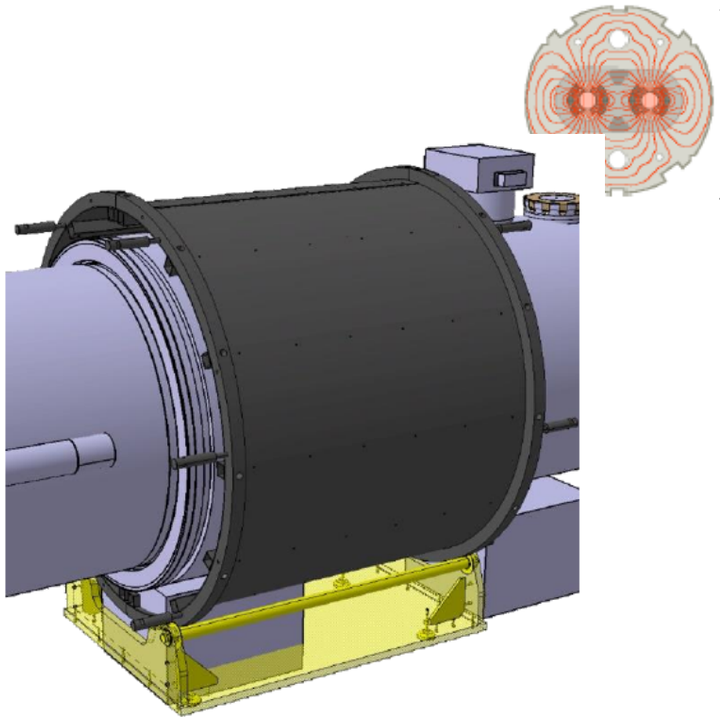
- *Loss duration few ms* ✓
- *Faster losses for larger beam intensities* ✓



Every year **10-20 dumps** due to UFOs, rarely magnets quench:

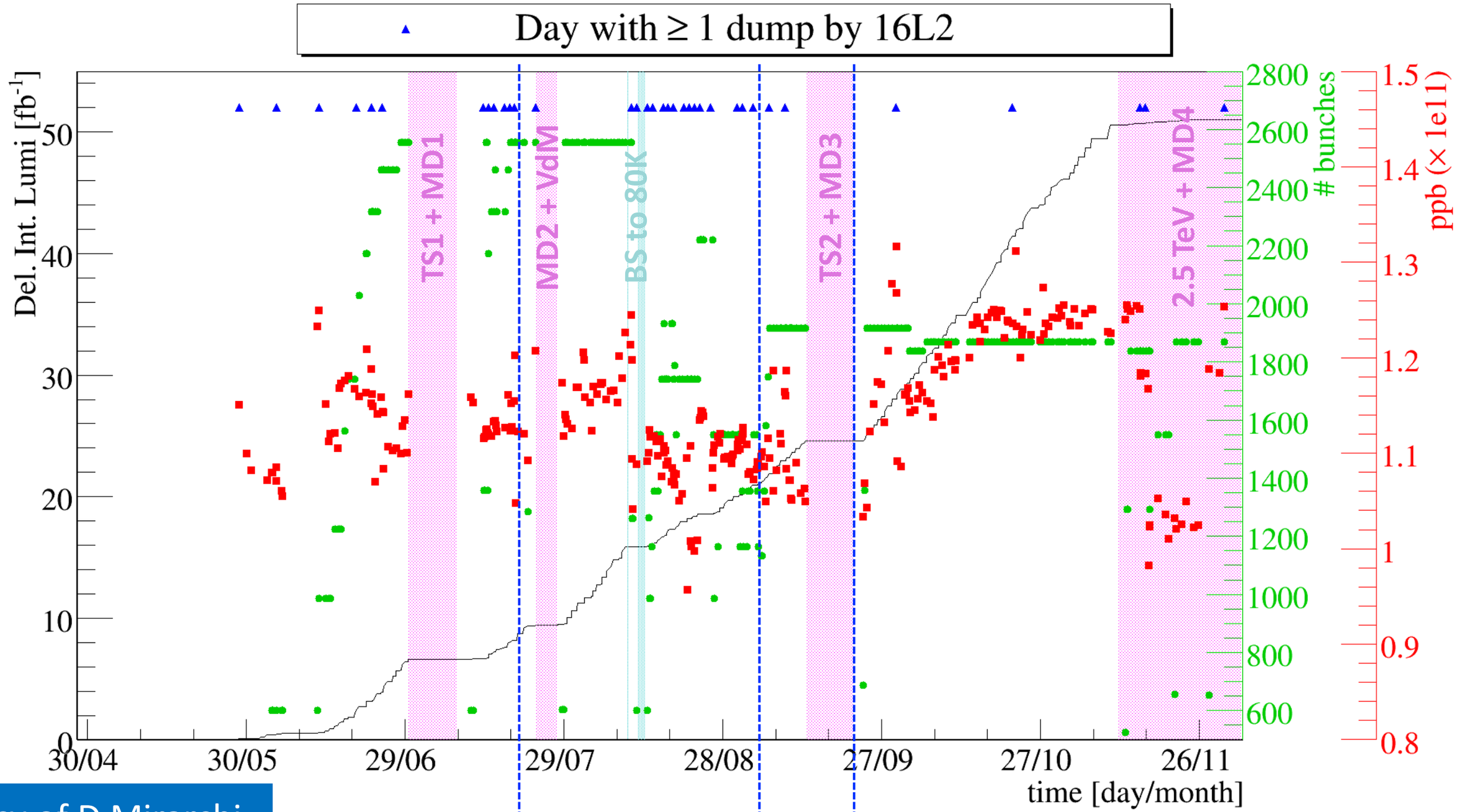
- **Loss monitor thresholds adjusted** to balance the risk of spurious dumps and need for quench prevention
- A **clear conditioning** has been observed along the years

“16L2”



- In June 2017 strange **beam losses** were observed together with **small UFO-like** losses
- **Mitigations** were put in place in 2017:
  - Change of beam type to ‘**8b4e**’ (low e-cloud) ➔ smooth operation up to ~1.25×10^{11} p/bunch but limitation on number of bunches (especially for LHCb)
  - **Orbit bump** (dependency of losses on orbit corrector current)
  - Installation of a **solenoid** to reduce e-cloud
- **Partial warm up** (to 80K) of the sector (winter stop 2017-18), pumping out the N_2 gas
- In 2018, 16L2 problem is **still present**, but operation with **25 ns** beams is **possible** (contrary to 2017)

“16L2” in 2017



Courtesy of D.Mirarchi

Main mitigation steps of the year:

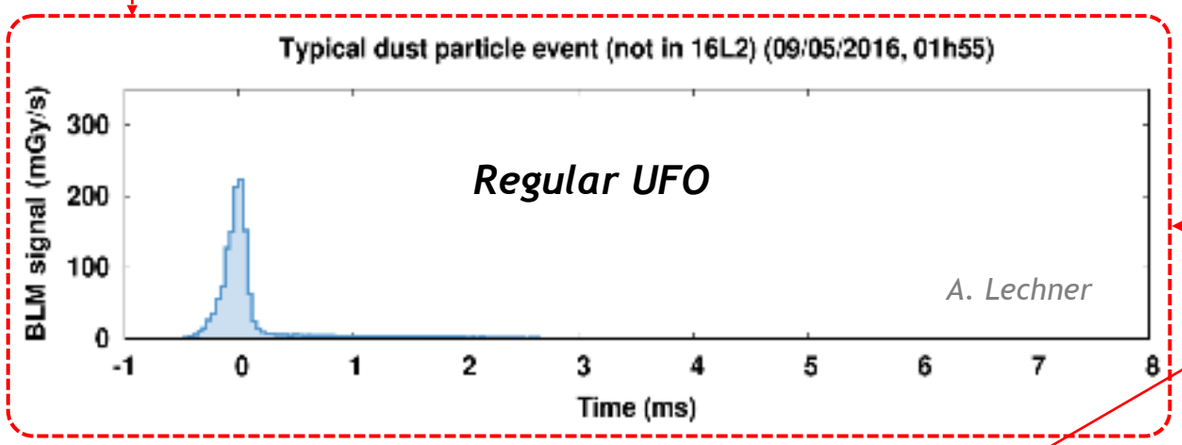
*Installation of **solenoid***

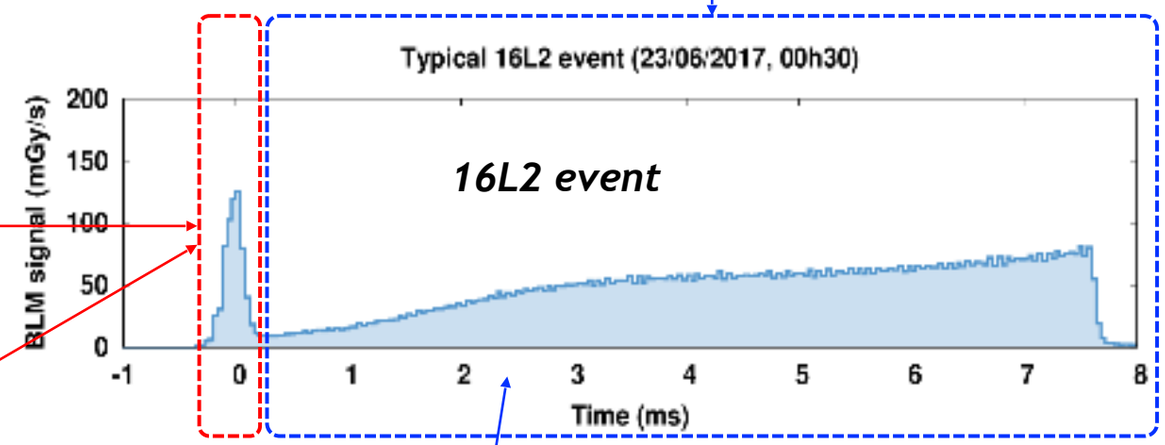
*Change to **8b4e** filling scheme*

*Change of **16L2 orbit corrector** (MCB) current*

Loss observation for 16L2

- *Three stages of loss rate:*
  1. Steady loss in 16L2 arising during the ramp along the entire fill (~ few 1e-6 Gy/s)
  2. Sharp rise of losses in 16L2 "UFO-like" (1e-3 ÷ 1e-2 Gy/s)
  3. Very fast rise of losses at collimators triggering a dump (few ms)





FFT BLM: Revolution frequency in 16L2
dBLM: Vertical losses from all bunches

Something touched at every turn

FFT BLM: Tune at primary collimators
BLM: Losses in the plane of MQ.16L2 polarity

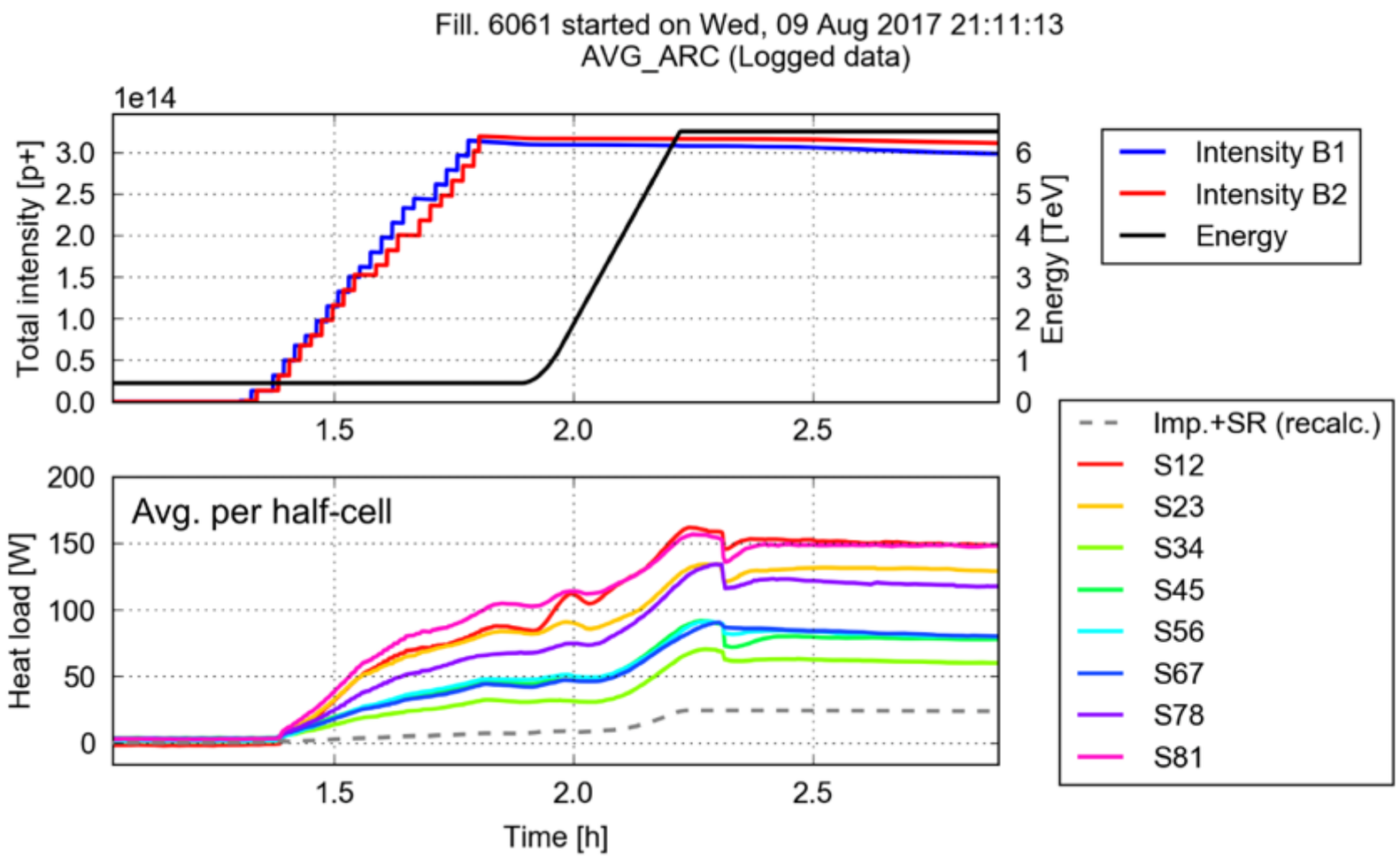
Beams undergo betatron oscillations
Scattered particles reach primary collimators

Electron cloud — I

- At high intensity the LHC is operated in the **presence of electron clouds**.
- Conditioning observed in 2015 and 2016 has stopped.
  - *The difference between sectors is not understood. This was not present in Run 1, it appeared in 2015 – cause not understood.*
  - *Intensity may be limited in Run 3 by this effect.*

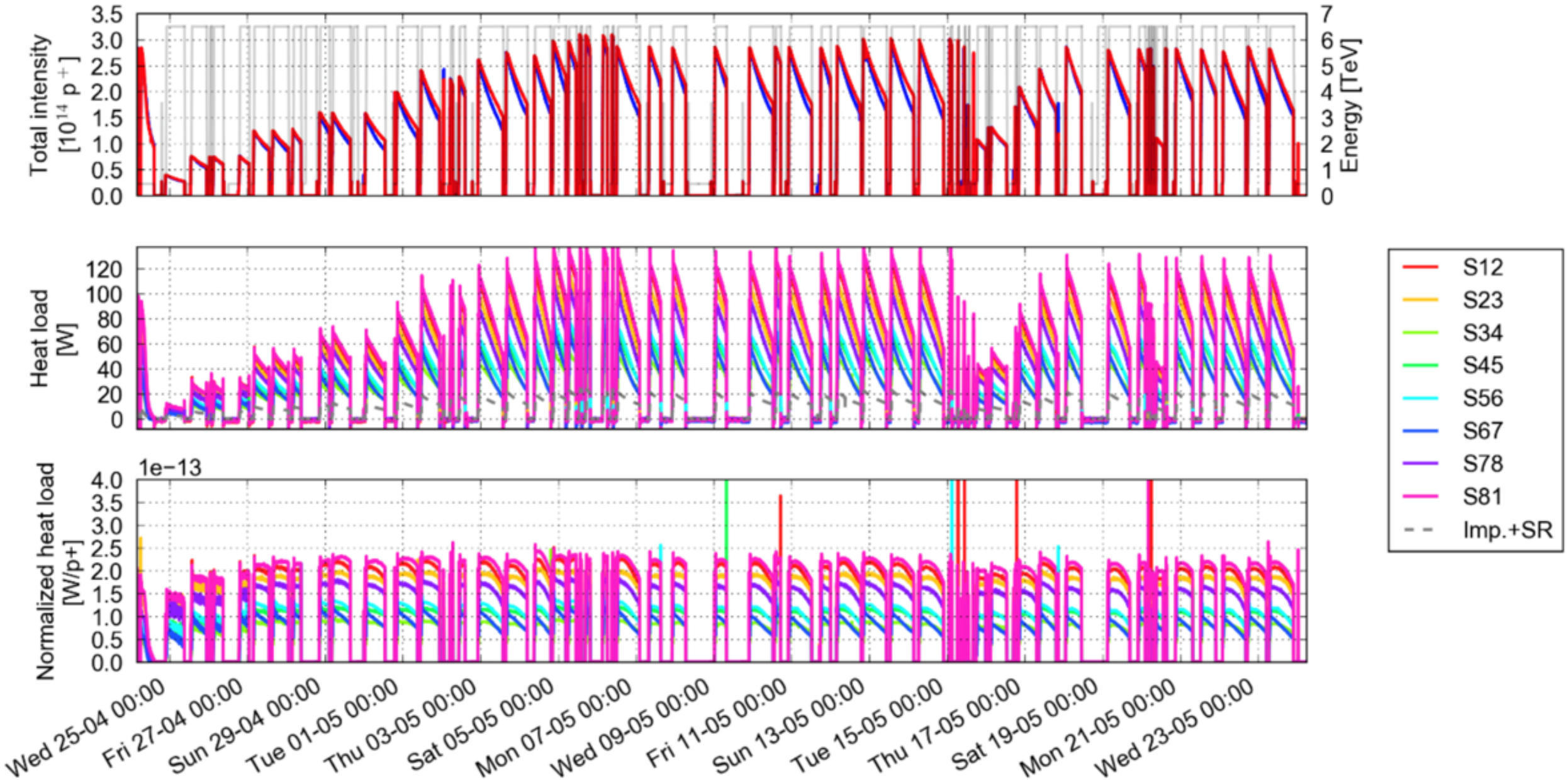
Beam intensity

Heat load (W/ 100 m)



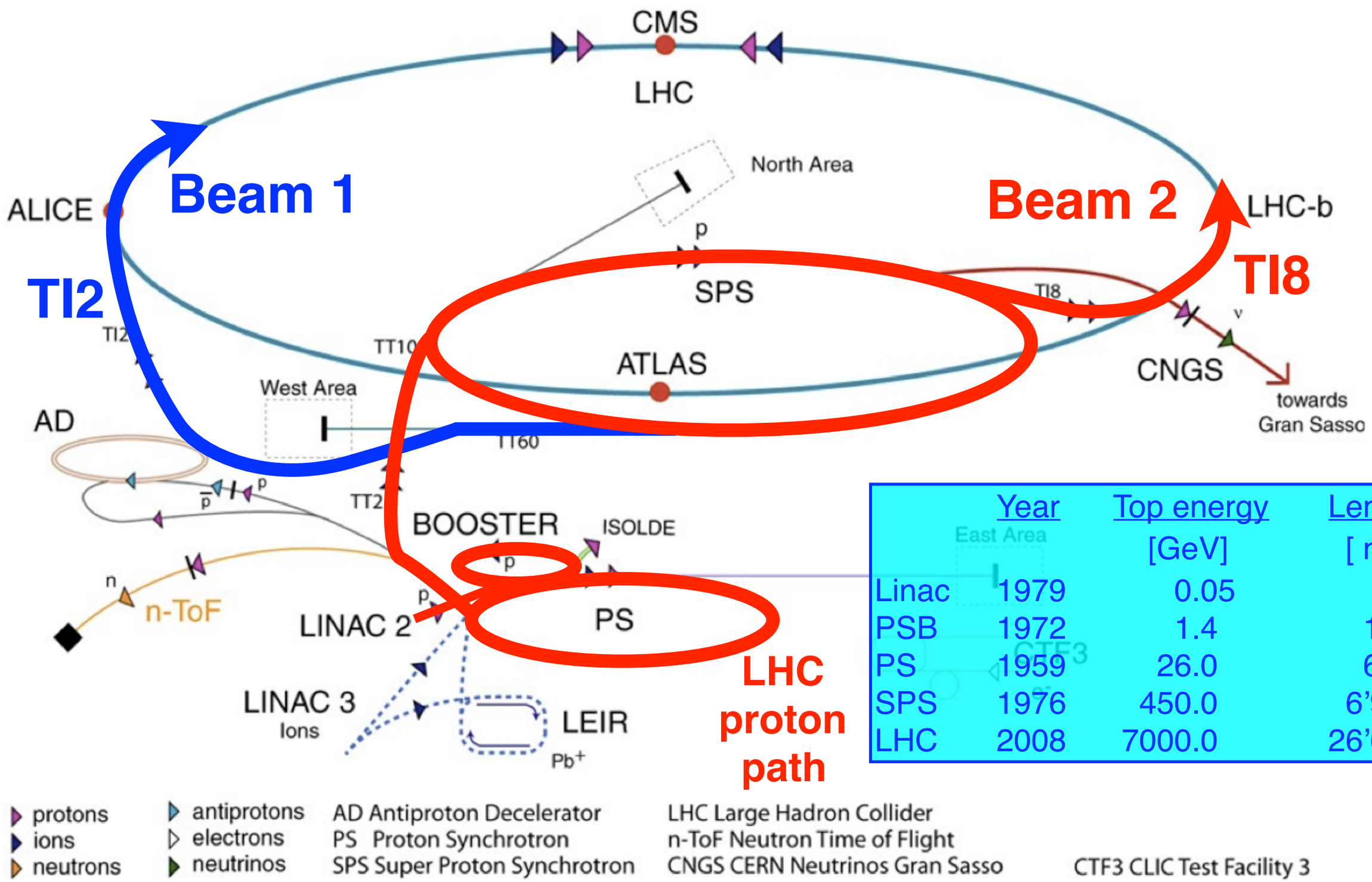
The 8 sectors (arcs) behave differently

Electron cloud — II



- Efficient conditioning with initial 24h scrubbing and during intensity ramp-up
- Stable normalized heat-loads and well below current limits, however still large spread (>2) between sectors which is not understood → LIU & HL-LHC

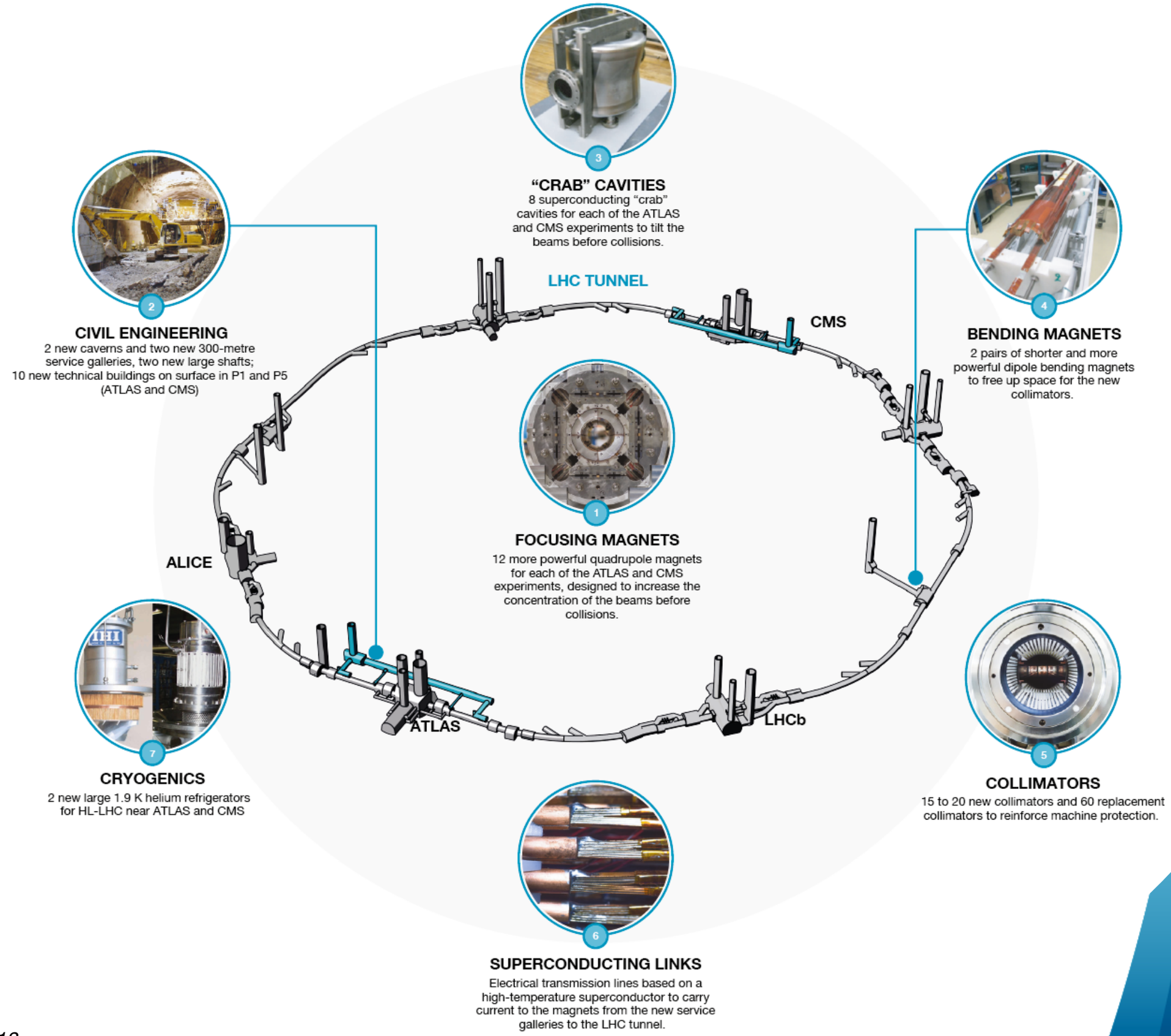
The LHC accelerator complex



	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6'911
LHC	2008	7000.0	26'657

Injector complex will undergo a major upgrade in the long shutdown 2: LIU project

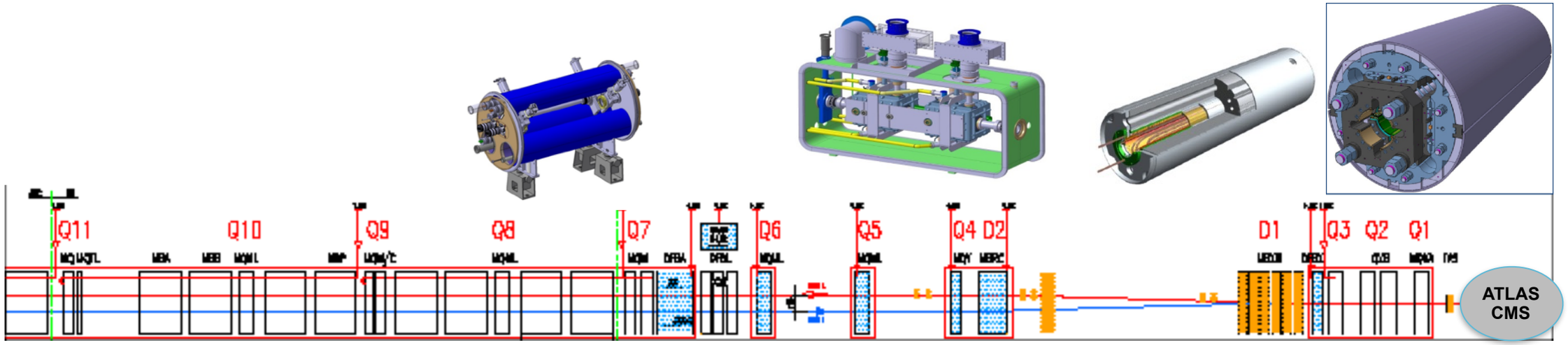
Key systems of the HL-LHC project



New IR-quads Nb_3Sn (inner triplets)

- **New 11 T Nb_3Sn (short) dipoles**
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection

Largest HEP accelerator project!



Dispersion Suppressor (DS) in P2 + P7

Modifications
1. In IP2: new DS collimators in the connection cryostat.
2. In IP7 new DS collimation with 11 T dipoles

Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr, Controls, new UG and surface infrastr.

Matching Section (MS)

Change/new lay-out
1. TAXN
2. D2
3. Crab cavities
4. Correctors
5. Q5
6. Q5@1.9K in P6
7. New collimators

Interaction Region (ITR)

Complete change and new lay-out
1. TAXS
2. Q1-Q2a-Q2b-Q3
3. D1
4. All correctors
5. Heavy shielding (W)

More than 1.2 km of LHC !!
Infrastructure.
Civil engineering (surface+ underground)

HL-LHC goals and parameters

Target for FP7 HiLumi design study:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing an integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

In 2015-2016, established an ultimate performance reach with same hardware and same beam parameters, by using **engineering margins:**
$L_{peak\ ult} \cong 7.5\ 10^{34}$ cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult} \sim 4000$ fb^{-1}**

Protons per bunch in collision	2.2×10^{11}
Number of bunches	2760
Normalized emittance	2.5 micron
Beta*	15 cm
Crossing angle	510 microrad
Geometric reduction factor	0.369
Levelled luminosity [ultimate]	5.32 [7.5] x 10^{34} cm^{-2}s^{-1}
Levelled <pile-up> [ultimate]	140 [200]
Operational efficiency [ultimate]	50% [60%]