CERN

Closure of the Evian LHC Operation Workshop 2019

R. Steerenberg, with a big thanks to all speakers for their material

First of All, Thanks !!!

Excellent presentations

Well prepared and structured sessions

Very fruitful, open and lively discussions

Very constructive and relaxed atmosphere

Proof of a relaxed atmosphere…

But really relaxed….

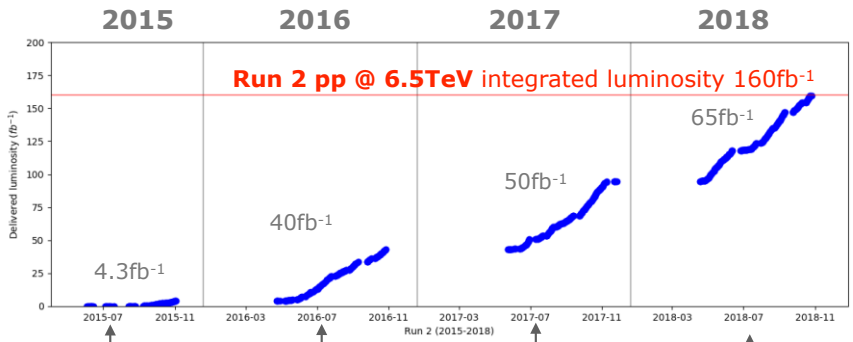
Five Sessions:

1. Overview of Run 2
2. Systems Overview
3. Systems Overview (with some beam dynamics)
4. Beam Performance during Run 2
5. A Preliminary Look Ahead

33 Presentations accumulating to 11 hours
6 hours of discussions

We asked the speakers to address quite a demanding list of topics and questions…

p-p Run 2 = Production^3



First e
6.5TeV and
25ns bunch spacing

Production

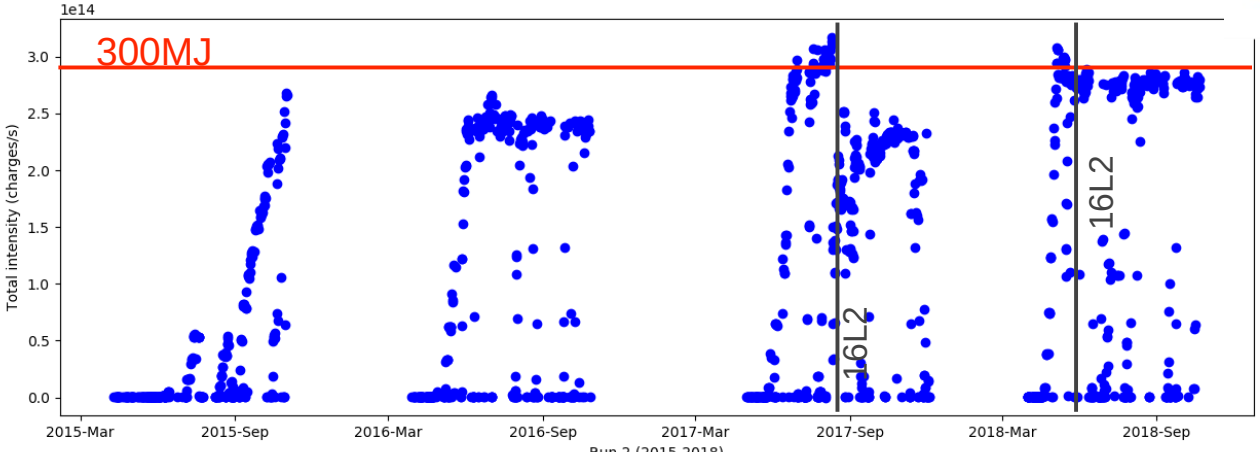
…but every year another unexpected challenge:

- **2015: 6.5 TeV, 25 ns beam, ULO, TDI**
- **2016: SPS beam dump, MKID outgassing, 66 kV Weasel in P8, 31L2 intermittent inter-turn short**
- **2017: 16L2, 8b4e**
- **2018: remains of 16L2**

Also many achievements:

We need a comprehensive list of mysteries

- **Exploring HL-LHC baselines: detuning, low β^*, (anti-)lev**



Heavy ions During Run 2

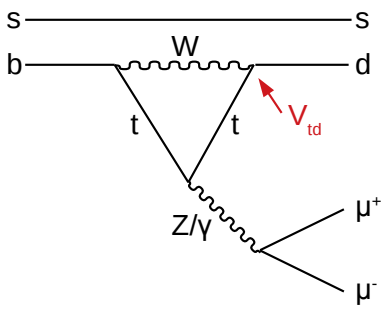
- Design Lumi = 1 x 10^{27} cm^{-2} s^{-1}
- 2015: 18 days of Pb-Pb → Peak lumi >3 x design
- 2016: p-Pb, Pb-p with peak lumi >6 x desing
- 2017: No run schedule, but Xe-Xe for 16 hours
- 2018: Pb-Pb with smallest ever β^* in ALICE & LHCb and partially stripped ions $^{208}Pb^{81+}$

Unfinished business….BFPP quench MD

Official first request for 2021

The LPC view on Run 2

LHCb



Lepton universality broken ?
Stay tuned….
….

The experiments warmly thank the accelerator communities

for the enormous effort which made Run II so successful.

The “Machine People” are also grateful toward the LPC and the experiment for the good collaboration and very constructive discussions

It was a great pleasure to work with you.

Brian will now steer the LPC towards Run III

LPC & Hidden Matter

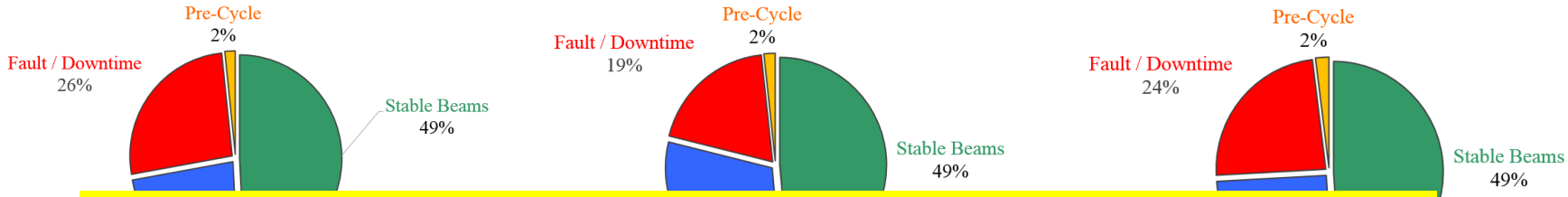
Suggestions for Operation

- Commissioning spread sheet introduced in run 2 was highly appreciated by experiments
- Early release of MD schedules with requests to experiments is very useful for planning of work in experiments
- Page-1 comments could be updated more frequently
- More realistic estimations of down times would be useful to plan work
  - Understood that experiments must stay in the shadow of the work to remove a problem
- ALICE would appreciate a systematically early declaration of SB
- LHCb would like to have the most realistic lumi target possible in order to plan efficient use of computing resources
  - If possible, last minute schedule changes should be avoided.

Availability

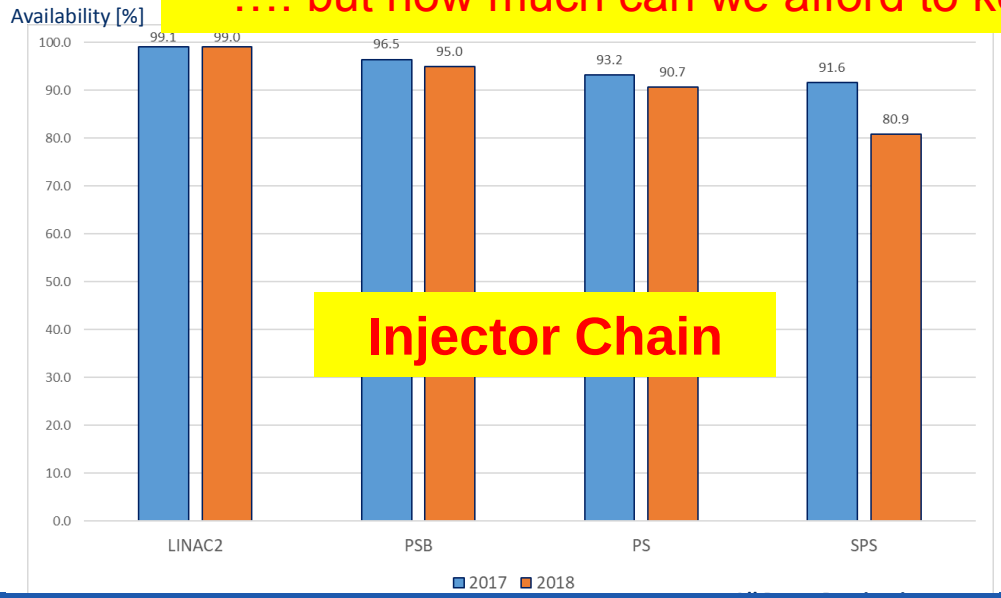
LHC:

2016 —7% less fault / 7% more operations→ 2017 —5% more fault / 5% less operations→ 2018



Consolidation shows to be beneficial for high availability

…. but how much can we afford to keep such high availabilities?



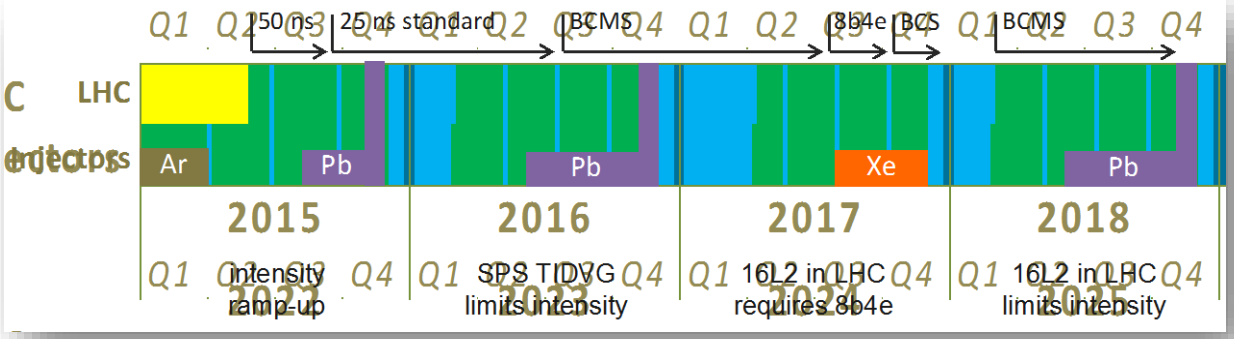
Injector Chain

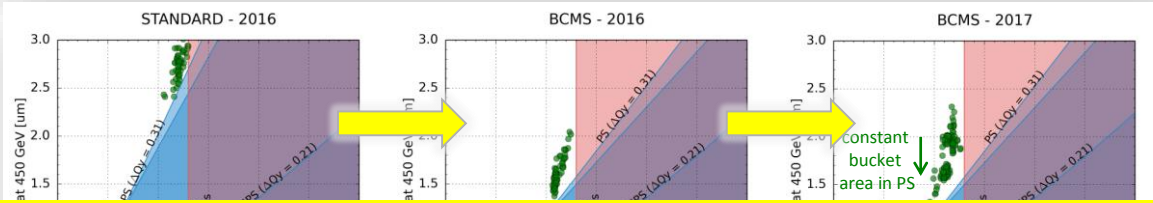
New constant of nature: **49%**

Further developments ongoing

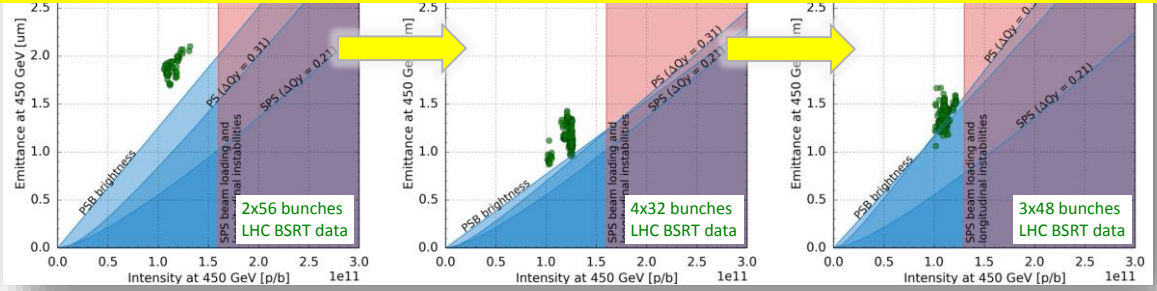
Interesting concept to factor **complexity** into the availability data

Injectors Beam Performance Evolution

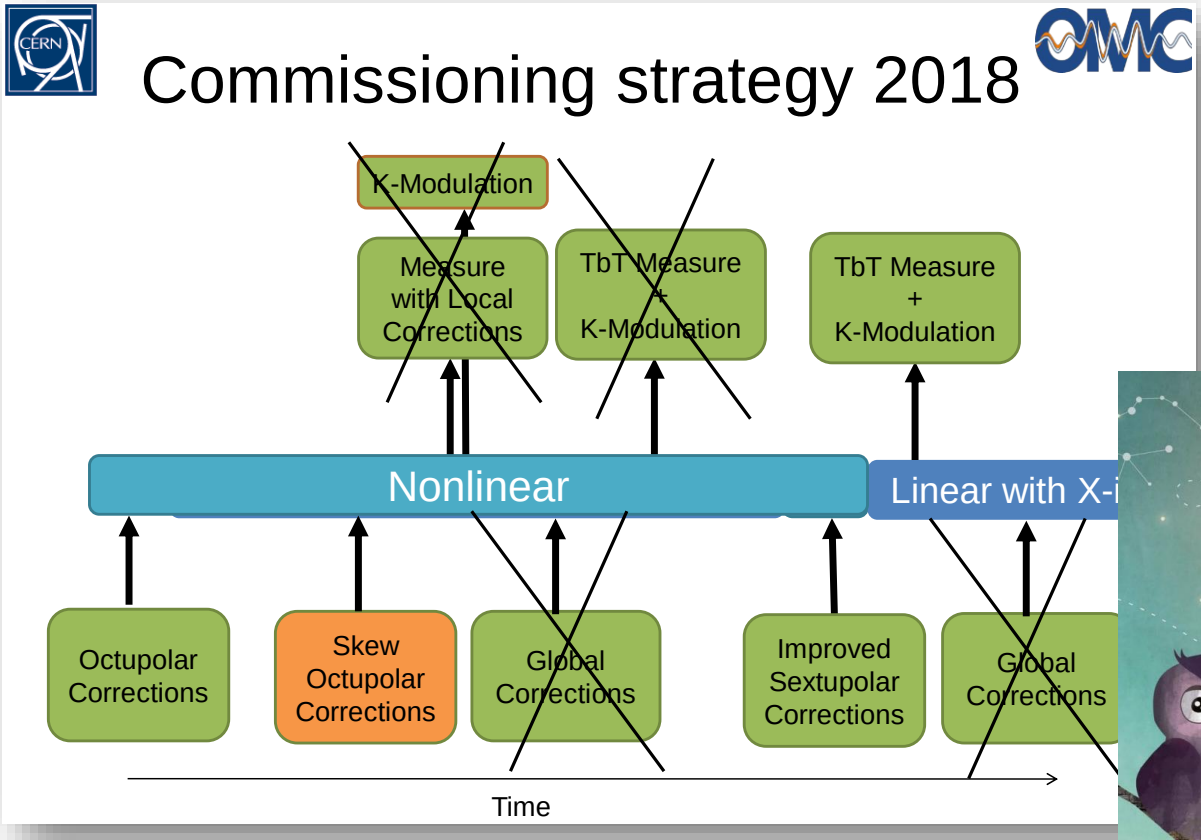




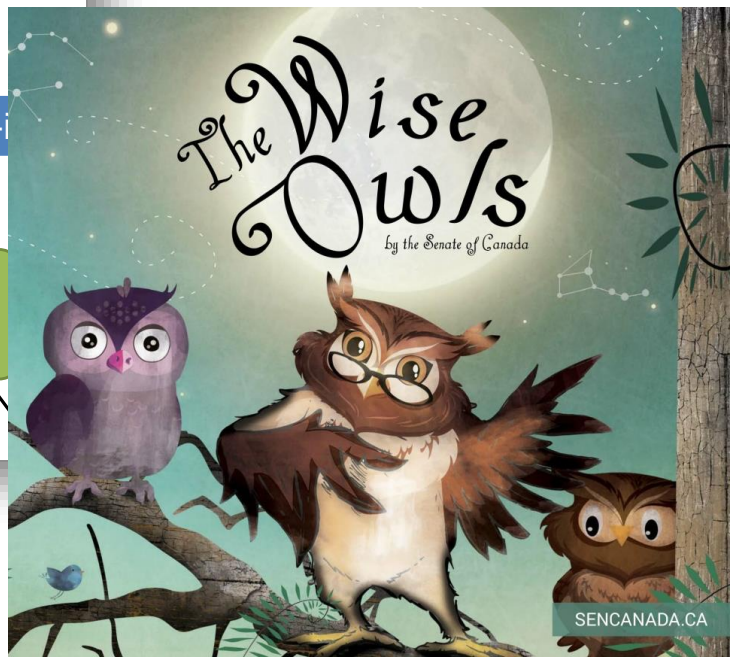
The impressive flexibility of the injector chain was and is key for the performance of the LHC



Run 2 Optics and Corrections



An impressive evolution over the year in the optics correction strategy and quality



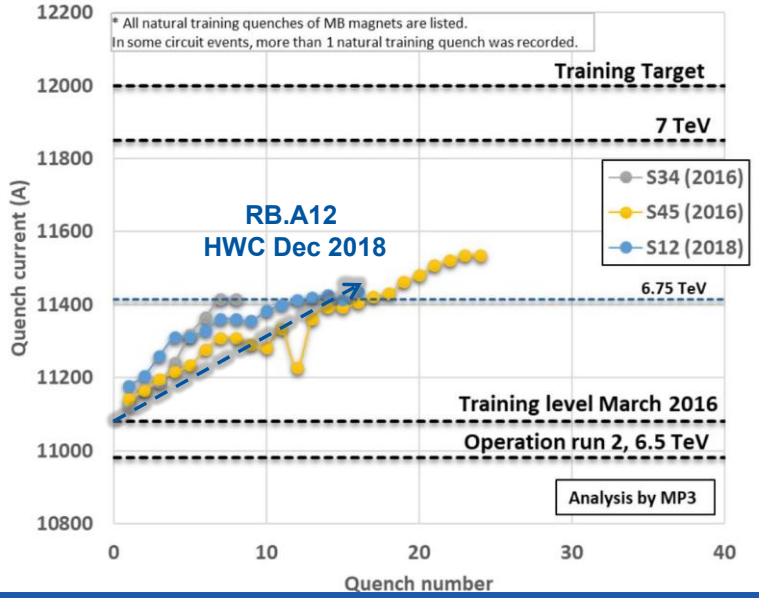
Making use of the good machine reproducibility

Powering Tests & Magnet Training

	2014/2015 (post LS1)		2015/2016		2016/2017		2017/2018	
TOTAL Execution	**24726**		**9863**		**13010**		**10552**	
Success	20631	**83.4%**	9099	**92%**	11949	**91%**	9790	**93%**
Failure	3645	**14.7%**	759	**7.7%**	1015	**8%**	682	**6%**
Signed Only	14130	**57.1%**	3722	**37.7%**	6415	**49.3%**	4607	**43.7%**
False Positive	108	**1.02%**	317	**5.2%**	79	**1.2%**	111	**1.8%**
Automatic PMEA (Excluding SO)	3040	**29%**	868	**14%**	1020	**15%**	1027	**17%**
Automatic eDSL (Excluding SO)	740	**7%**	3176	**51.7%**	3529	**53%**	3609	**60%**

Yes, powering test became more efficient

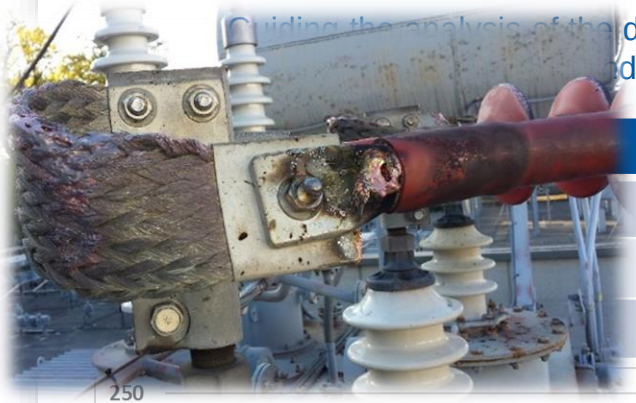
- Efficient tools
- Better understanding
- Enhance automatic analysis
- …



Tev: ***to be or not to be, that's the question…***

General Technical Services

- Over the past few years, the LHC accelerator downtime due to the Technical Infrastructure equipment faults has been reduced
- TIOC has been instrumenta vement
  Guiding the analysis of the data r events
  d m taken to minimize the impact



Cryogenics

- The last run started January 2015 and will end May 2019
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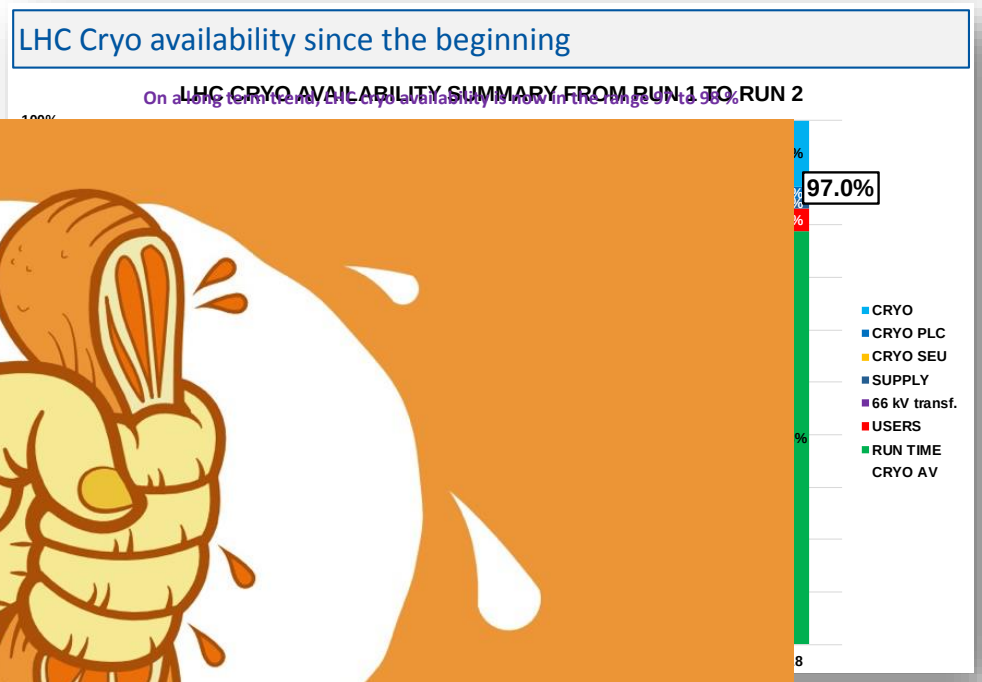
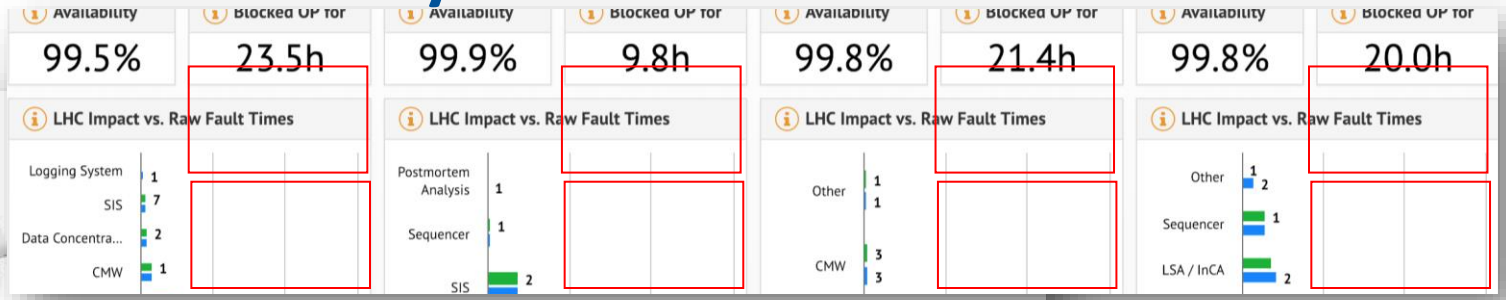


								S8-1
Capa								230
Configuration 2017	200	205	145	?	?	?	195	250
Combined global refrigeration [W/IT ; W/hc]	270 ; 195			270 ; 155	270 ; 155			270; 245

Controls and the AFT Tool

- **Excellent availability for controls**



In 2017, BE-CO embraced Python (finally!).

NXCALS is the next generation CERN Accelerator Logging System based on modern "Big Data" technologies.

AFT Tool arrived at start of Run 2, evolved throughout.

Brings tangible added value, still lots of untapped potential.

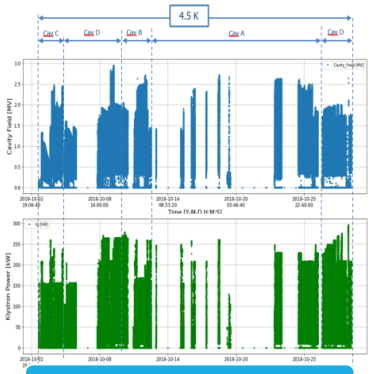
Additional investments and increased data completion by Equipment groups – pre-requisites to go to the next level.

The RF System

A working spare LHC ACS CM is now available

Assembly of new pumping crosses

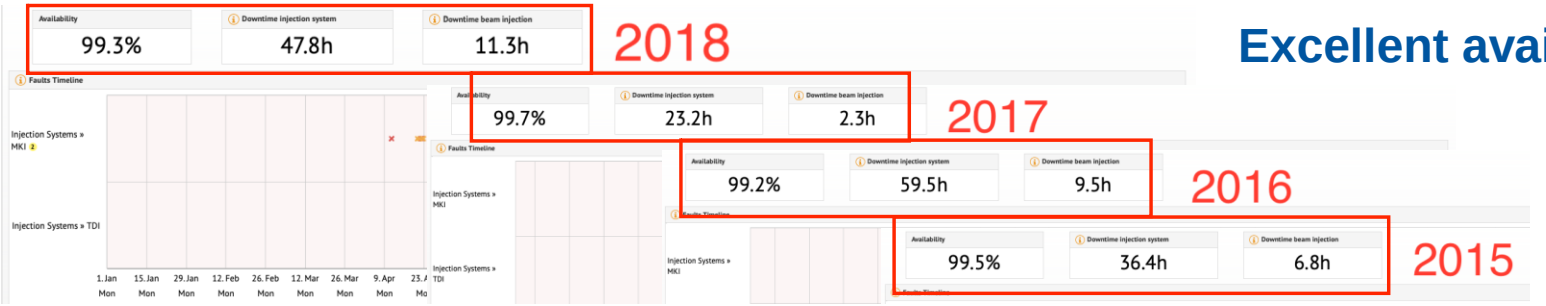
CM installation and RF Test



CM validation

- The LHC RF system is working reliably and successfully throughout the years
- Flexibility of the RF system has been proved: MD requirements, special runs
- Huge amount of work has been performed in 2018
- Preparation for post-LS2 operation under way

Injection Systems



Excellent availability

Improvements: MKI Screens and NEG, TDI hBN blocks changed for copper coated graphite → No problems seen !

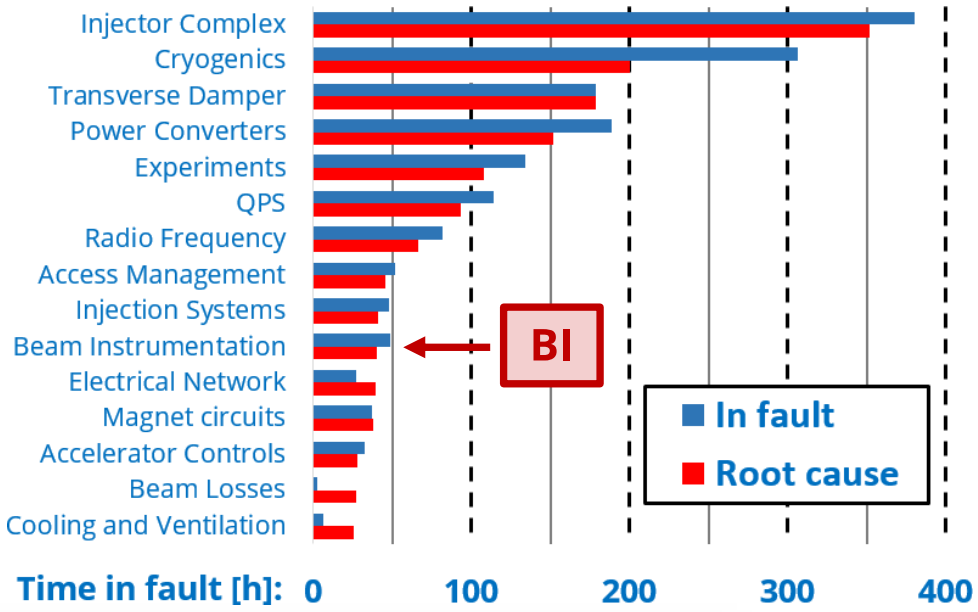
→ **TI2 and TI8 correction and steering strategy:**

- ↳ Proposed to take a clean reference with multi-bunch beam ASAP and use it as golden for steering
  - Perform some SVD cleaning with many eigenvalues after TS (or when time allocated)
- ↳ Place 2 (or better 3) x12bunches in every filling schemes to allow, or better encourage, for possible steering at every fill

Further discussions on TI or SPS extr. steering needed

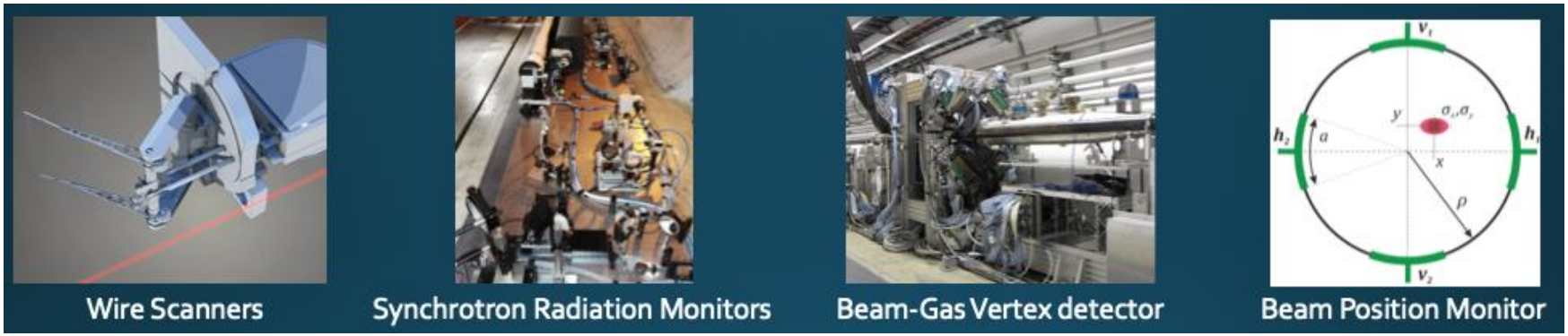
Beam Instr.

47 BI faults in 2018 causing
29 hrs of downtime

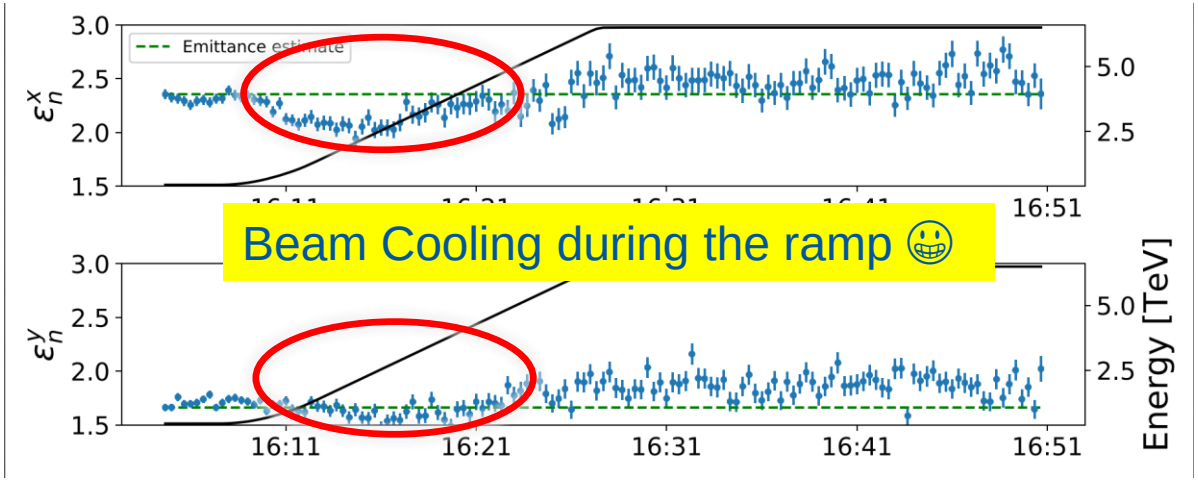


- Major LHC BI systems are ready for Run 3 parameters
  - 1.8e11 ppb within dynamic range
  - For emittance see G. Trad's talk
- LS2 mostly for house-keeping
  - Maintenance, inspections, protection
  - Major SW / FW upgrades, LHC Feedback upgrade, CO changes
  - Testbeds validation
- Focused on avoiding issues during Run 3 commissioning
  - As after LS1, dedicated BI commissioning time needed
  - Detailed commissioning plan to be done later

Emittance Measurements



Good measurement systems for flat bottom and flat top, but none yet for the ramp

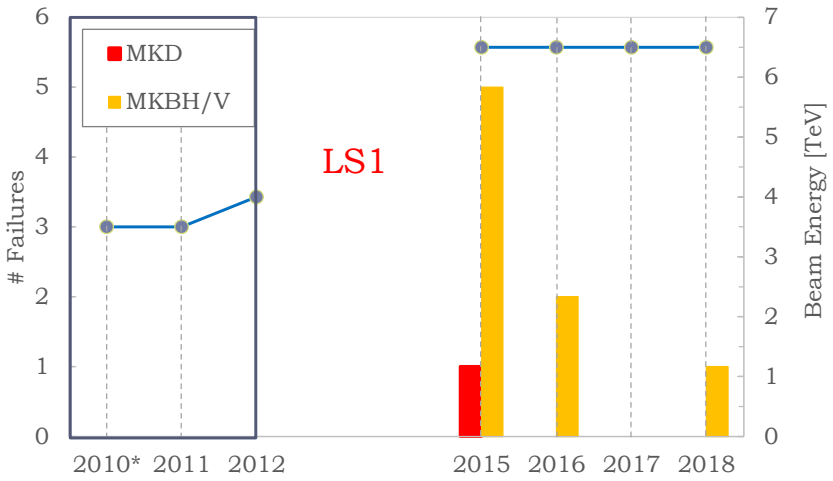


Beam Cooling during the ramp 😀

Relative measurement with quadrupolar pick up looks promising and feasible during the ramp

LBDS Performance

- Highly critical system
  - Many measures taken to minimise erratics and flash-overs



Recommendation for next Commissioning after LS2

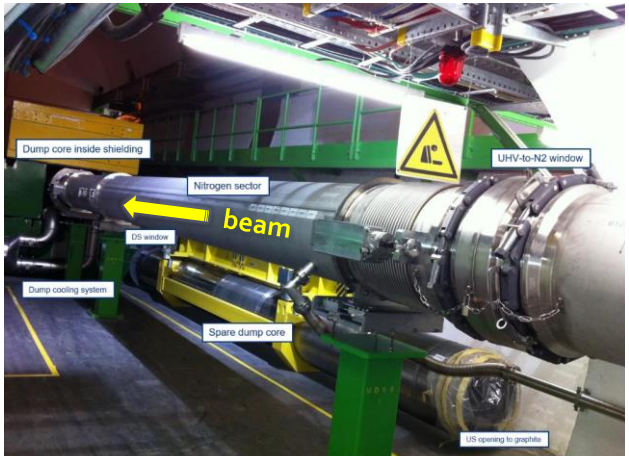
<u>Adequate time to be allocated and insured for LBDS commissioning wo/w beam ➔ time for reaction in case of problems</u> (non-conformities discovered during dry run at the end of LS1)

- Individual System Tests: 6 weeks per beam
- Local Reliability Run: 12 weeks (some tests in parallel)
- Remote Reliability Run: 18 weeks per beam (in parallel)
- Machine check out: 2 weeks
- Commissioning with beam: 1 week

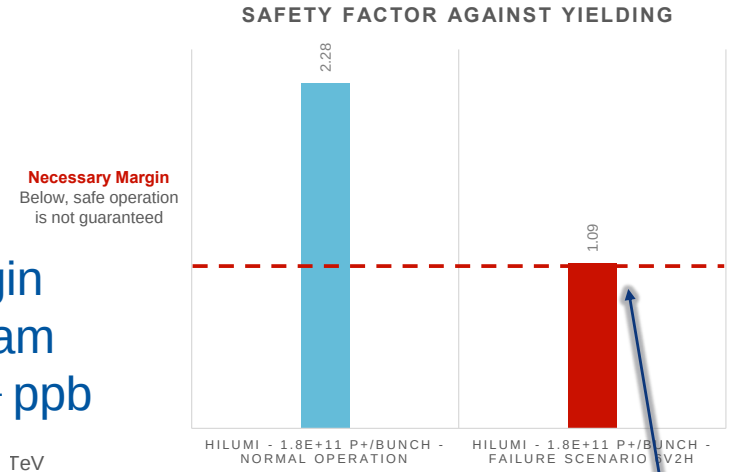
39 weeks is more than a year of LHC physics 😀

LHC Dump Assembly – Operational Feedback and Future Prospective

- **Dump is moving with every beam dump**

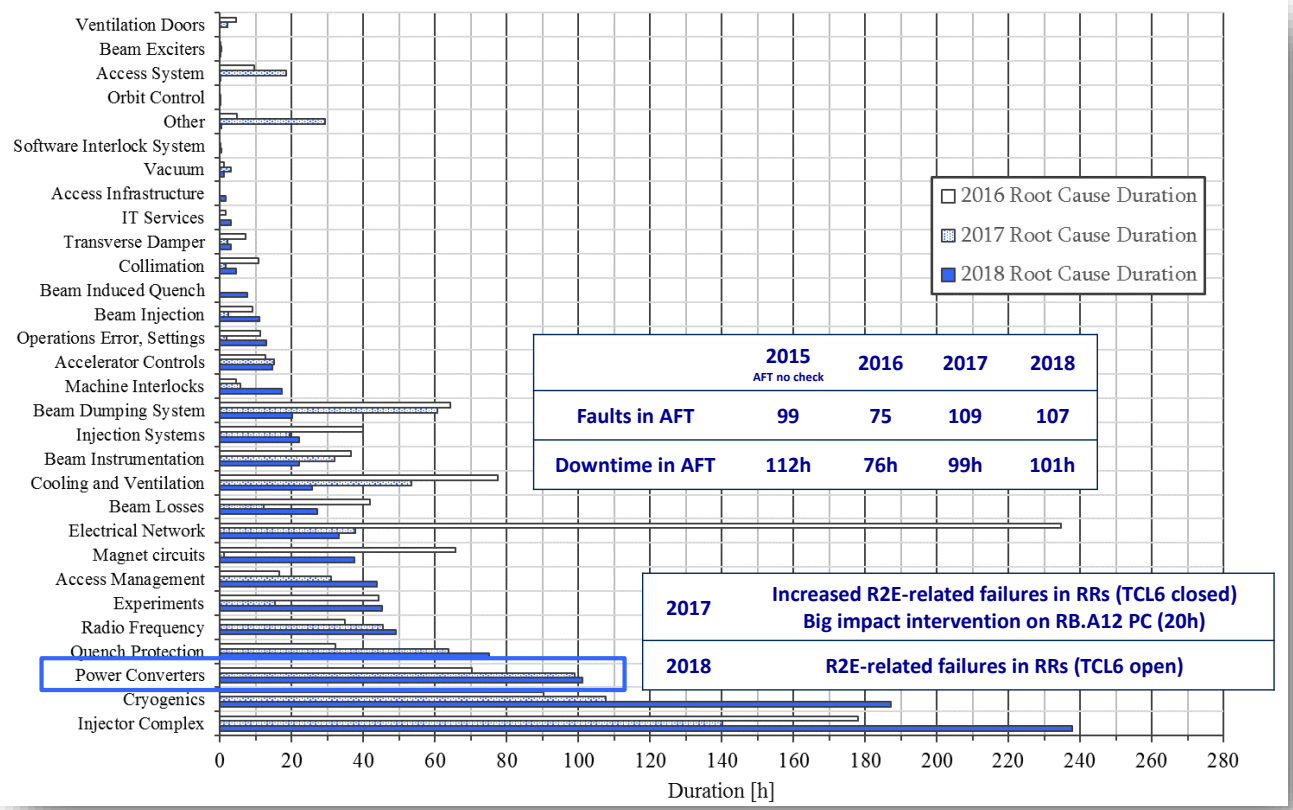


ZERO safety margin with present upstream window and 1.8×10^{11} ppb



Cannot be replace before YETS 2021-2022

Power Converters and their control



	2015 AFT no check	2016	2017	2018
Faults in AFT	99	75	109	107
Downtime in AFT	112h	76h	99h	101h

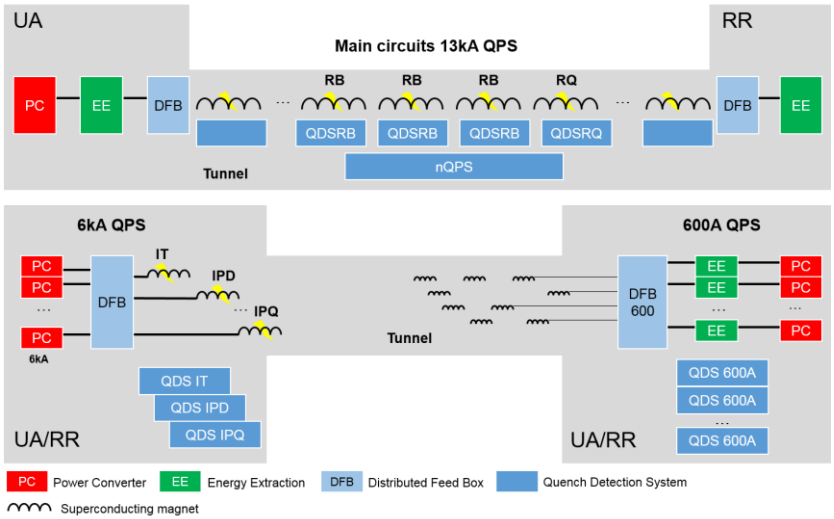
2017	Increased R2E-related failures in RRs (TCL6 closed) Big impact intervention on RB.A12 PC (20h)
2018	R2E-related failures in RRs (TCL6 open)

Massive FGClite deployment during LS2
Lessons learned and experience gained

Quench Protection System

- QPS: **14’000 ways to stop the LHC**
- TCL collimator settings significantly affected QPS downtime → Run 3

QPS Hardware



Item	Count
EE13kA	**32**
EE600	**202**
HDS	**6084**
QDSRB	**1232**
Magnet detector	2464
QDSRQ	**392**
Magnet detector	1568
nQPS	**436**
Magnet detector	1632
Bus-bar detector	4096
QDSIPX	**76**
IP magnet detector	360
IT magnet detector	48
Current lead detector	1124
QDS600	**114**
Magnet detector	624
Rad-tol magnet det.	212
Current lead detector	1672
Total	**8568**
Interlocking	**13800**

Tendency to modernise system to allow for more remote interventions

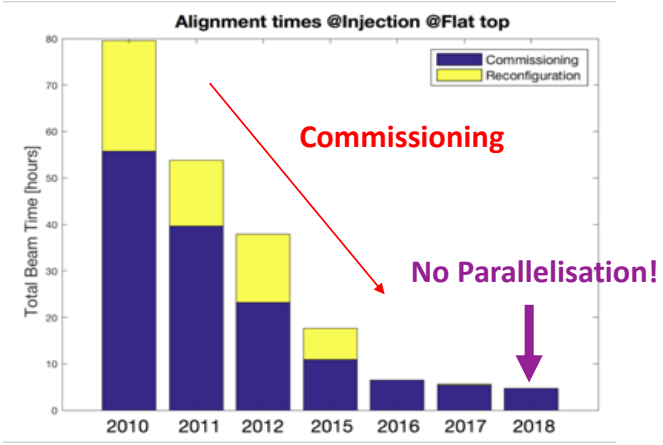
Remarkable availability:

Before LS1 everybody was impressed about the number of faults now we are all impressed by the excellent availability

Collimation

- No magnet quench from circulating proton beam with stored energy of 300 MJ

Collimator Alignment



Collimation milestones over the years:

Run 1 - 2010: Semi-automatic alignment
- 2012: 12 Hz data available

Run 2 - 2015: BPMs introduced
- 2016: 100 Hz data available
- 2018: Fully-automatic alignment

New Collimator hardware for the (near) future:

- Crystals → successfully used during ion run with enhanced cleaning
- TCSPM → coating stripes to assess effect of coating on impedance
- Wire Collimators Long range beam-beam compensation studies
- TCP.C6L7.B1 → with embedded BPMs test for HL-LHC design

ADT and ObsBox

- **As well as normal operation, 15 MDs in the last 2 years relied on the ADT and ObsBox**
- **ObsBox is instrumental for instability studies**
- **Changes during LS2:**

ADT re-commissioning strategy

- New, never before operated beam position modules
- A major upgrade of the high level control
- New way the functions will be generated
- New applications and user interfaces

- After LS2, the ADT will be considered *"as new"* – therefore a much longer commissioning time will be needed
  - A typical time required in Run II: 2-3 shifts
  - A 10dB increase, plus a couple of ramps is a reasonable estimate

"Any specific new requirements have to be communicated now"

Machine Protection System

Re-cap Run 2

No damage to machine equipment or experiments due to beam
No damage to circuits due to powering failures or quenches

Have we been running safely?

LHC machine **protection systems worked well** avoiding damage in accelerator equipment and circuits, **but** we have experienced:

- Wrong parameters in protection systems
- Interlocks not acting as expected
- Operational mistakes
- Running with unvalidated machine configurations
- Software commissioning with hundreds of circulating bunches
- Unvalidated coupling knobs with strong impact in beta*
- Undetected quench heater firing
- Masking of critical interlocks during hardware commissioning
- Procedures not followed

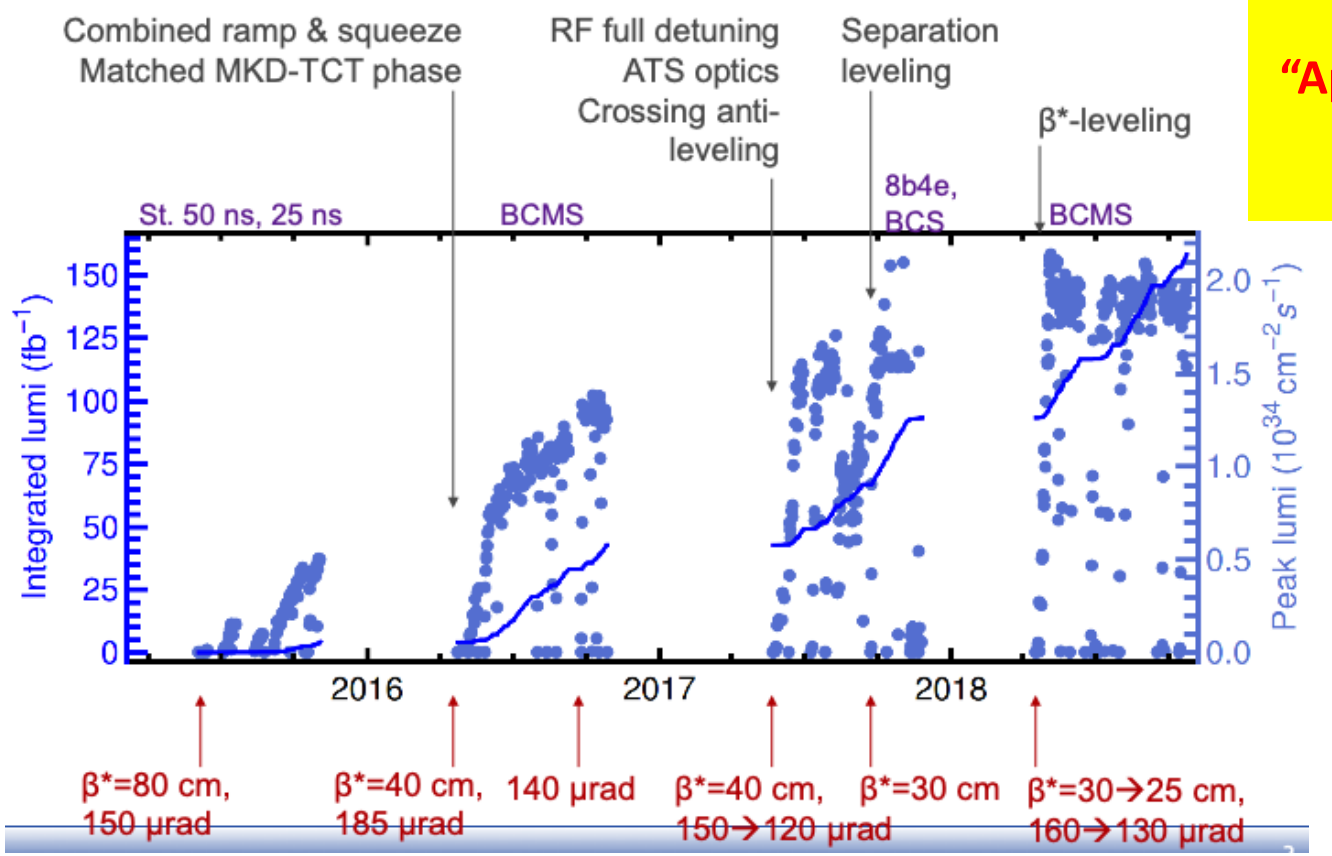
Due to the **diverse redundancy** in the machine protection systems and **vigilant** hardware experts, MP experts & OP teams **no damage happened** in Run 2!

Fortune favours the brave?!

For most cases we lost only 1 protection layer

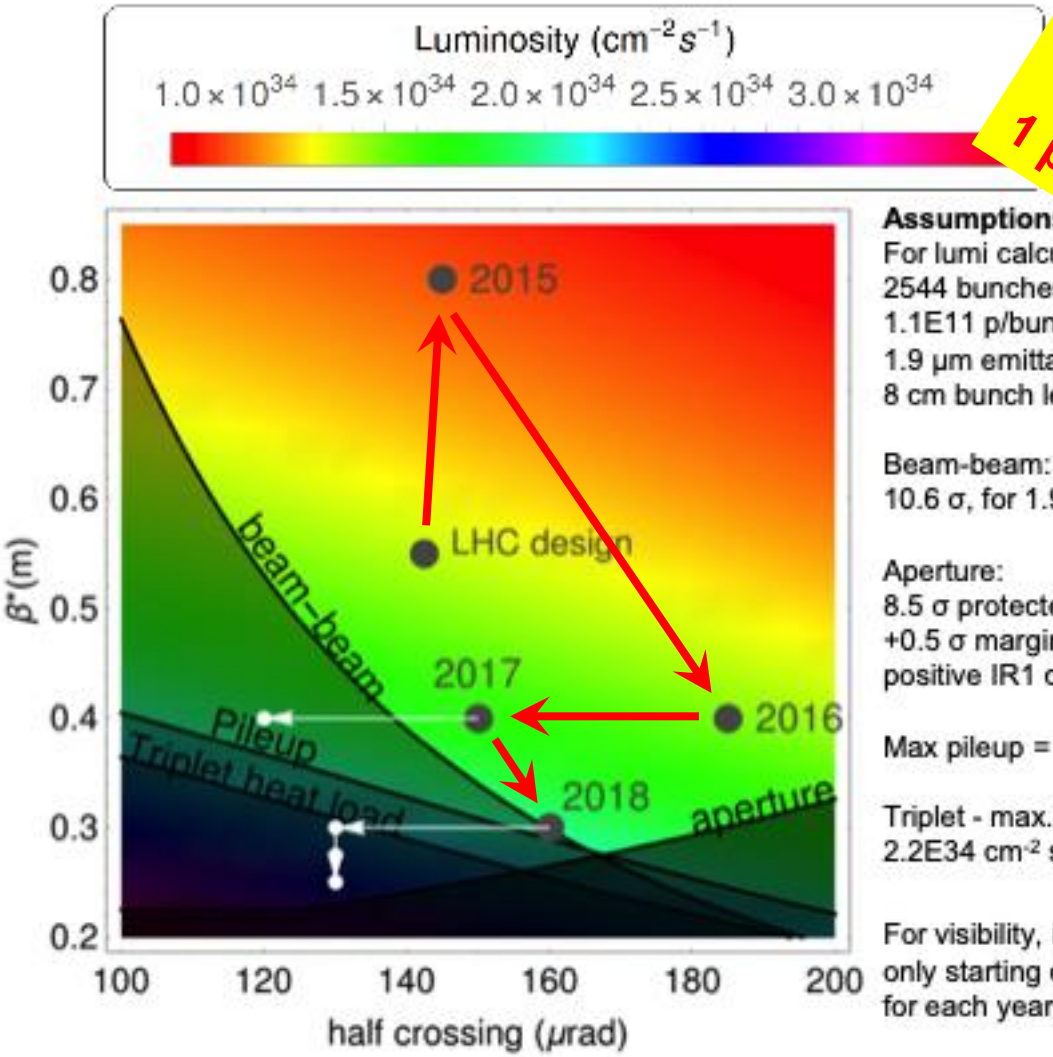
We should become more rigorous and in the future for each such case produce a "major event report"

Machine Configuration



The Run 1 "Aperture Platinum Mine" is depleted

Machine Configuration



Assumptions
For lumi calculation:
2544 bunches
1.1E11 p/bunch
1.9 μm emittance
8 cm bunch length

Beam-beam:
10.6 σ, for 1.9 μm

Aperture:
8.5 σ protected,
+0.5 σ margin,
positive IR1 crossing

Max pileup = 60

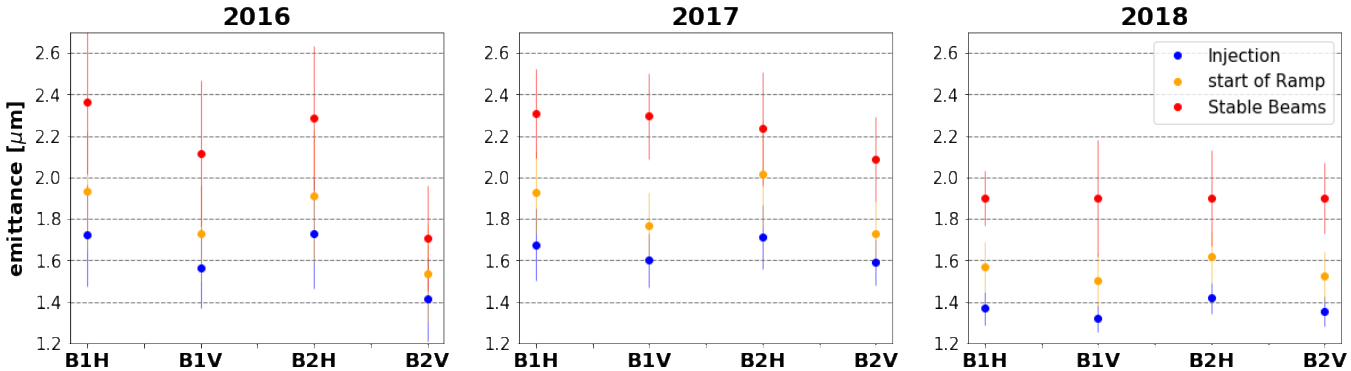
Triplet - max. lumi:
2.2E34 cm^{-2} s^{-1}

For visibility, including only starting configuration for each year

Excellent Overview plot !!!
1 plot says more than a 1000 words

Transverse Emittance Blow-up

Emittance growth studies well advanced as simulations and calculations can be compared to measurements. **No measurement available for the ramp**



2018 emittances along the LHC energy cycle are smaller compared to previous years

Largest blow up during ramp

Relative emittance blow-up [%]		
	B1H, B2H	B1V,B2V
Ramp	~20	~25

A potential Lumi Gold Mine

For both FB and FT energies, the observed **extra emittance growth (on top of the model):**

-is similar for both beams, larger in the vertical compared to the horizontal plane

-at FB, e-cloud explains almost 50% of the observed extra growth. Impact of e-cloud to the observed extra growth at SB to be studied

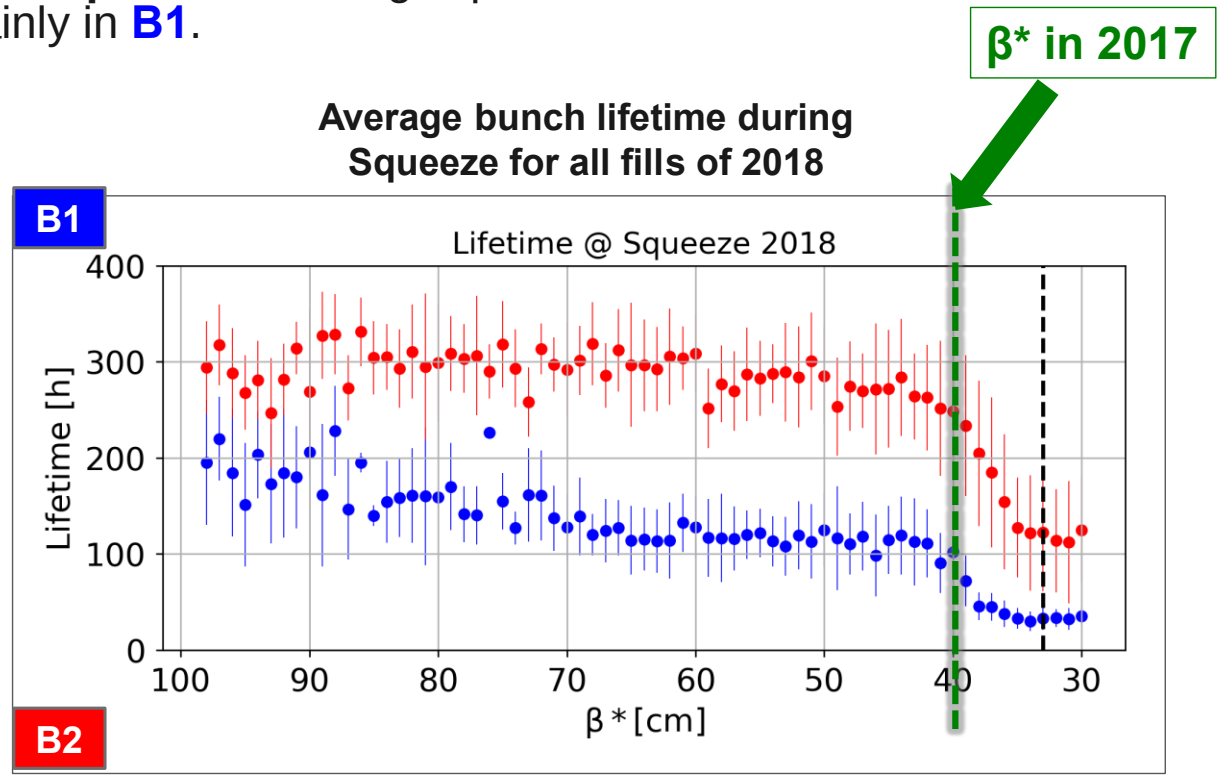
-the “unknown” extra emittance growth at FB is 0.2 μm/h in horizontal and 0.4 μm/h in vertical. Ongoing studies to correlate this extra growth with noise, which also predicts more growth in vertical at SB (see appendix)

-no clear correlation with brightness (see appendix)

Luminosity, lifetime and modelling

Losses @ Squeeze (2018)

- **Below β* 40 cm** during Squeeze, lifetime reduction observed mainly in **B1**.



Luminosity, lifetime and modelling

Conclusions

Squeeze

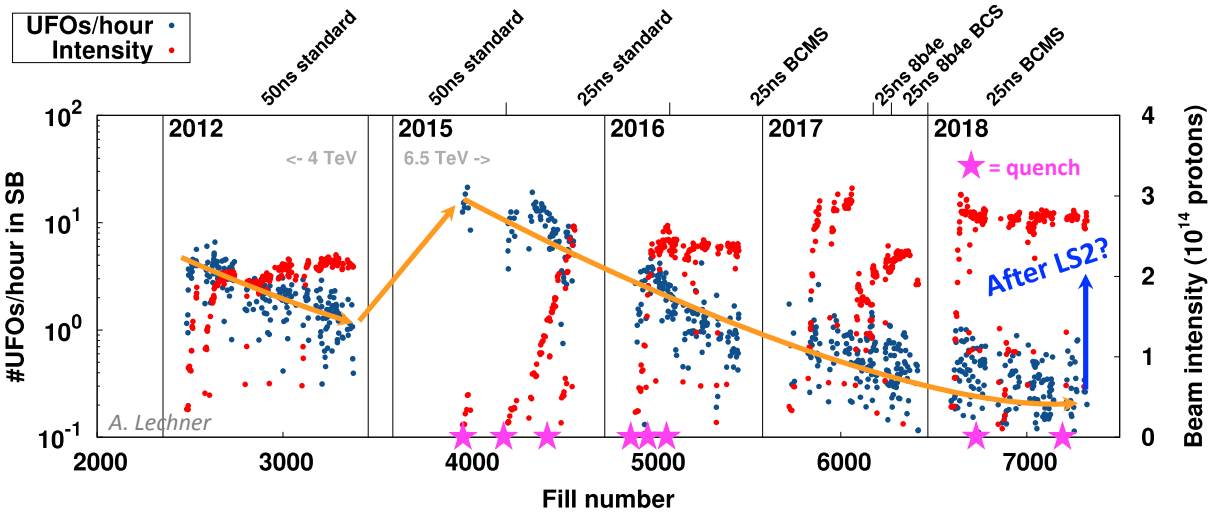
- Reduction of lifetime below β* 40cm.
- Bunch-by-bunch losses revealed **LR and e-cloud patterns** , mostly affecting **B1** (e-cloud in the triplet?).
- Tune optimization can mitigated mostly LR losses and improved lifetime.

Stable Beams

- Lifetime of **B1** systematically lower than **B2** during Run II
- Extra losses observed in the first few hours during the whole run II (not yet understood).
- During 2018 additional losses observed induced by **crossing angle anti-leveling and β* levelling, e-cloud related**
- E-cloud important mechanism of beam lifetime degradation with BCMS beams (and B1 vs B2 difference).

➢ **DA well correlated with lifetime, but model misses important ingredients (imperfections, noise, e-cloud).**

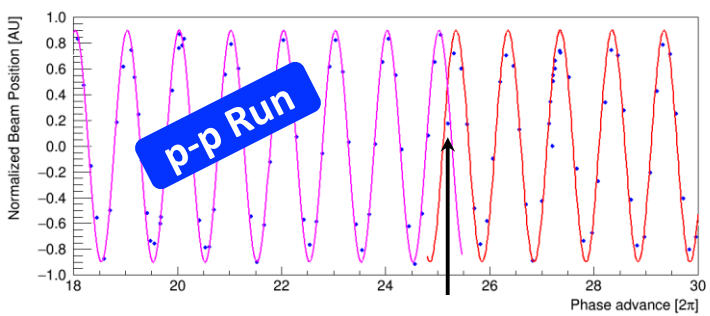
Special Losses (UFO – ULO – 16L2 – 10 Hz)



What about the deconditioning and level of UFOs in 2021 ?

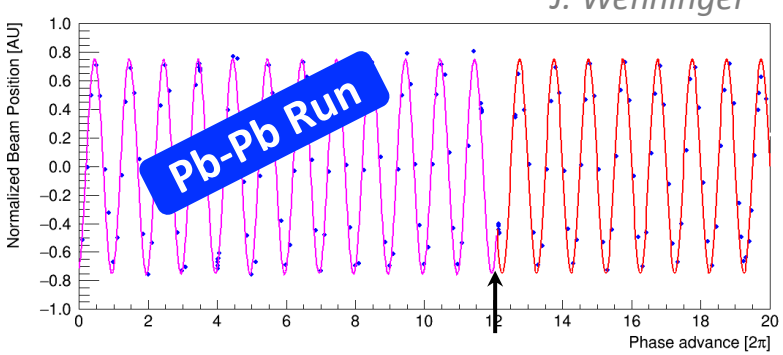
10 Hz: origins of phase shift identified, but real cause not yet !!!

- **Where is the origin** of these oscillations?



Q21L4

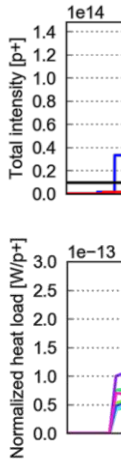
J. Wenninger



ITR2 ↔ Q5R2

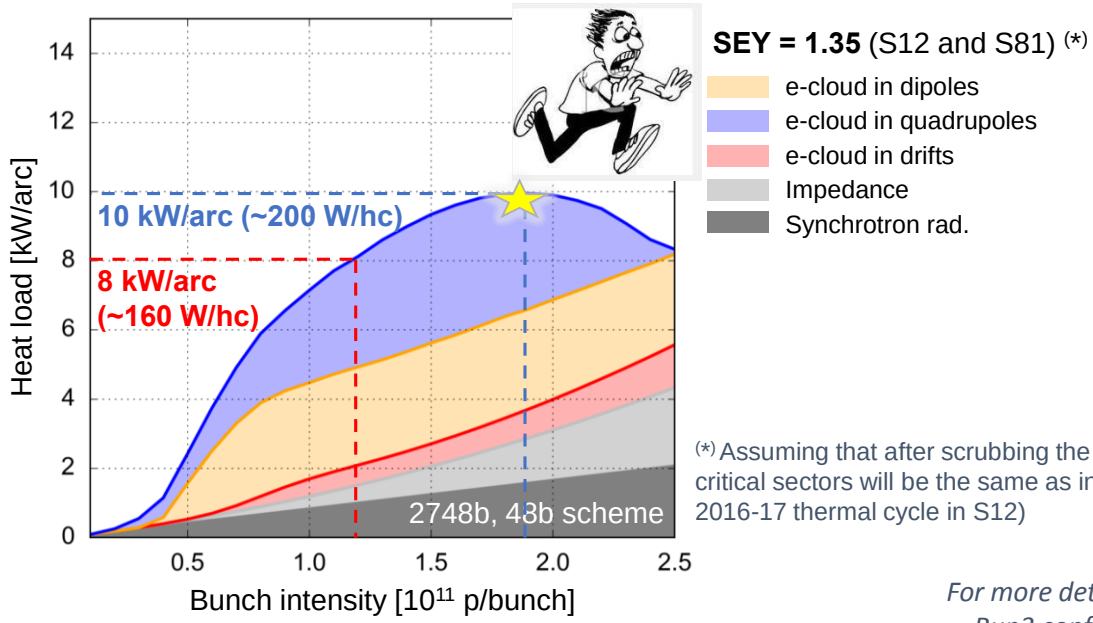
Electron Cloud & Heat Loads

2012 (25 ns test, end of the run)



2018 (25 ns, during scrubbing)

- **Actual capacity** of the cryoplants was **assessed with measurements** by TE-CRG
  - → In the most **critical sectors** (S12, S23 and S81) we can count on **~200 W/hcell**
  - → **1.8e11 p/bunch should be within reach (with no margin)!**
- In case of problems (further degradation during LS2, lower cryo performance) heat loads can be mitigated using **"mixed filling schemes"** (8b4e inserts in 25 ns beams)

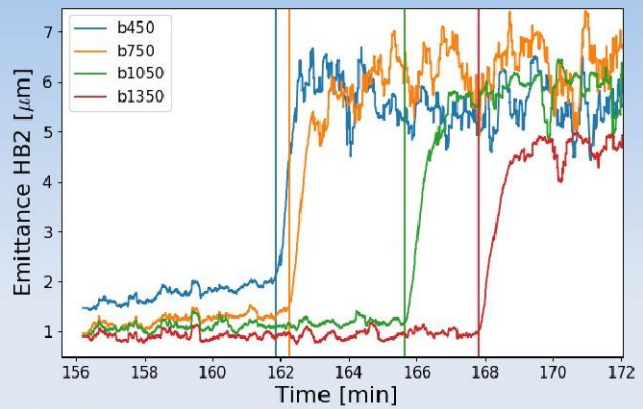


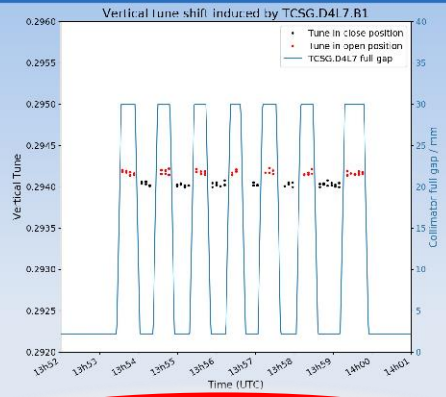
(*) Assuming that after scrubbing the SEY for the critical sectors will be the same as in Run 2 (as for 2016-17 thermal cycle in S12)

For more details see presentation at Run3 config meetings (#2 and #4)

Transverse Instabilities

Ongoing investigations



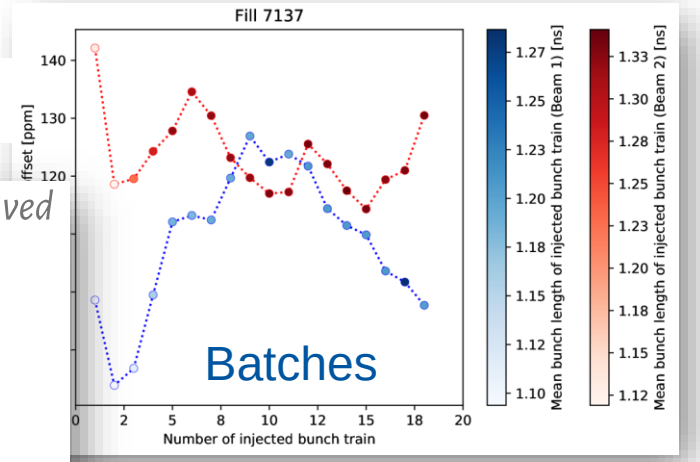


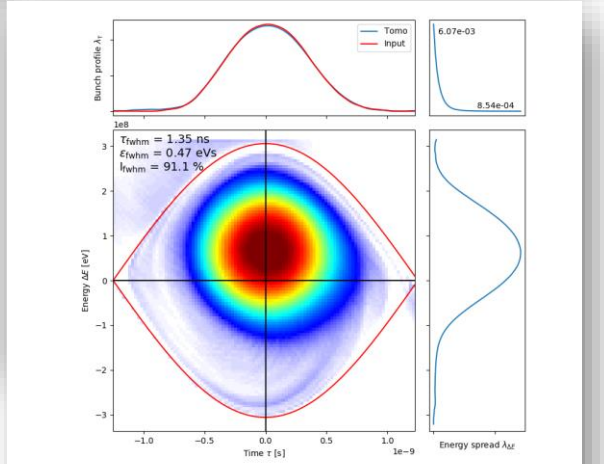
- Diffusion models
  - Effect of noise spectrum (e.g. 50 Hz noise lines)
  - Optimal damper settings (gain, bandwidth) and machine/beam parameters
- *Dark impedance* searches
  → Strongly constrained by measurements of
  - Single collimator tune shifts
  - Instability threshold
  - Head-tail signals
  - Rise time vs. chromaticity
- Interplay between the ADT and Landau damping
  (validity of the uncoupled-mode approximation)
- Weak electron cloud instabilities

Longitudinal dynamics

Further improvement of quality and performance

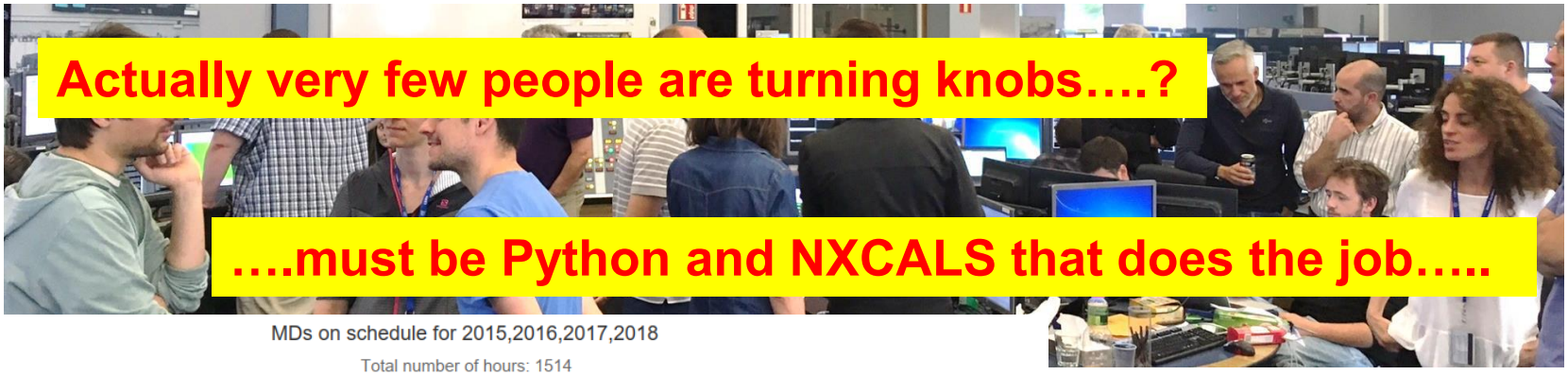
- Power limitations at injection: *dynamic circulator adjustment, improved calibration schemes, understand line-by-line differences and define appropriate operational margins*
- Damping of energy errors: *longitudinal damper using ACS*
- Blow-up: *divergence, PPLP ramp, and alternative methods*
- Firmware modifications expected (2020-2023):
  - Alternative beam-loading compensation schemes during injection
  - Alternative emittance blow-up
  - Cavity detuning before the first batch injection
  - Longitudinal damper; potentially first commissioning/MDs in 2021
  - Modification of digital feedback (for larger detuning)



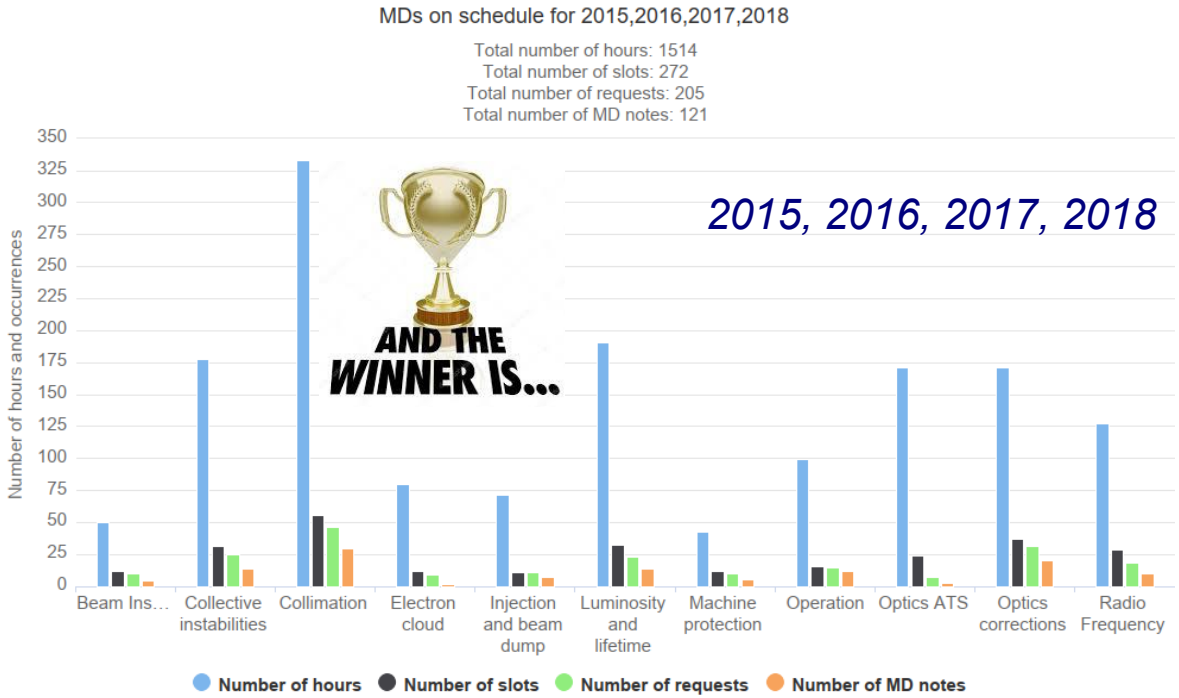


Energy error at injection: tomographic reconstruction (2018)

Machine Developments

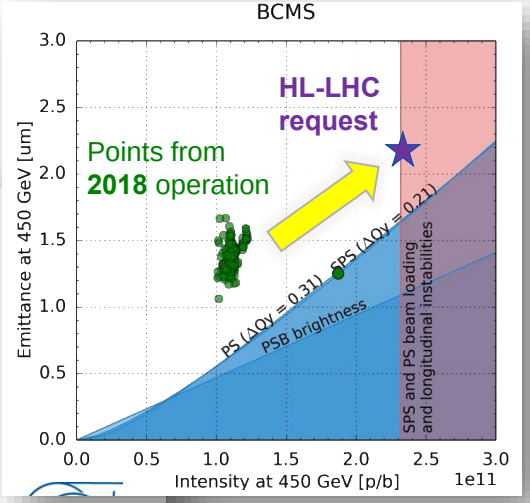


MD was the place to be (or not)



MDs are an excellent investment for (future) machine performance

What to expect from the injectors during Run 3



To summarise and conclude

- LIU project in its **final phase**
  - LIU equipment installation, IST, HW commissioning during LS2
  - Expected **LIU beam parameters** match HL-LHC request with present baseline
    - Proton beams can be also produced in **different flavors** (BCMS, 8b4e)
    - Pb ion beams rely on **momentum slip stacking** in SPS and mitigation scenario with 75 ns bunch spacing has been demonstrated to potentially provide ~70% of target lumi
- **LIU beam commissioning** during Run 3: Ramp up strategy in place

2021 | 2022 | 2023-2024

Ramp up to HL-LHC intensity of 2.3e11 p/b (with 1.7 um for BCMS beams) for post-LS3 readiness

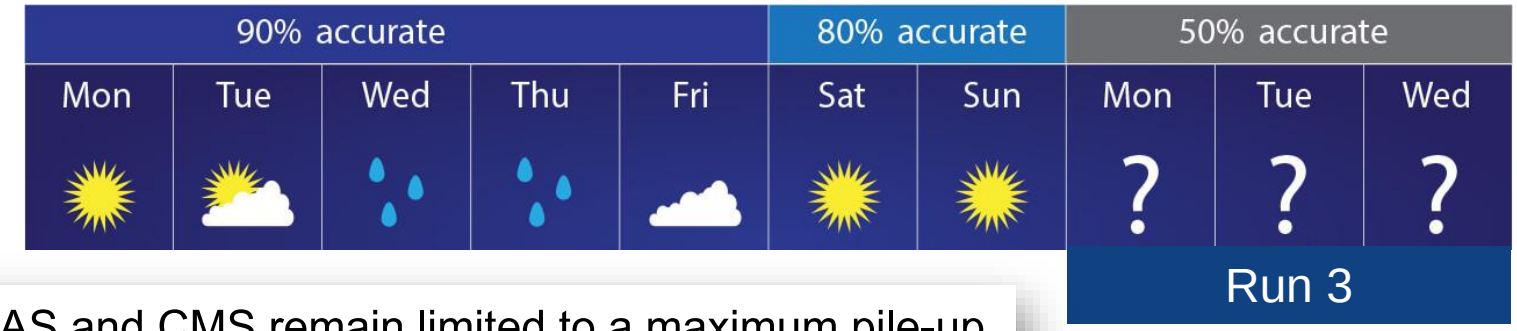
Intensity and brightness ramp up to 1.8e11 p/b (with 1.3 um for BCMS beams)

Recovery of pre-LS2 proton beams (including LIU beams in PSB and PS) + commissioning of LIU ion beams

What will the LHC and Experiments be able to swallow during run 3 ?

Desiderata and constraints from the experiments

- **Requirements…. trying to look ahead……**



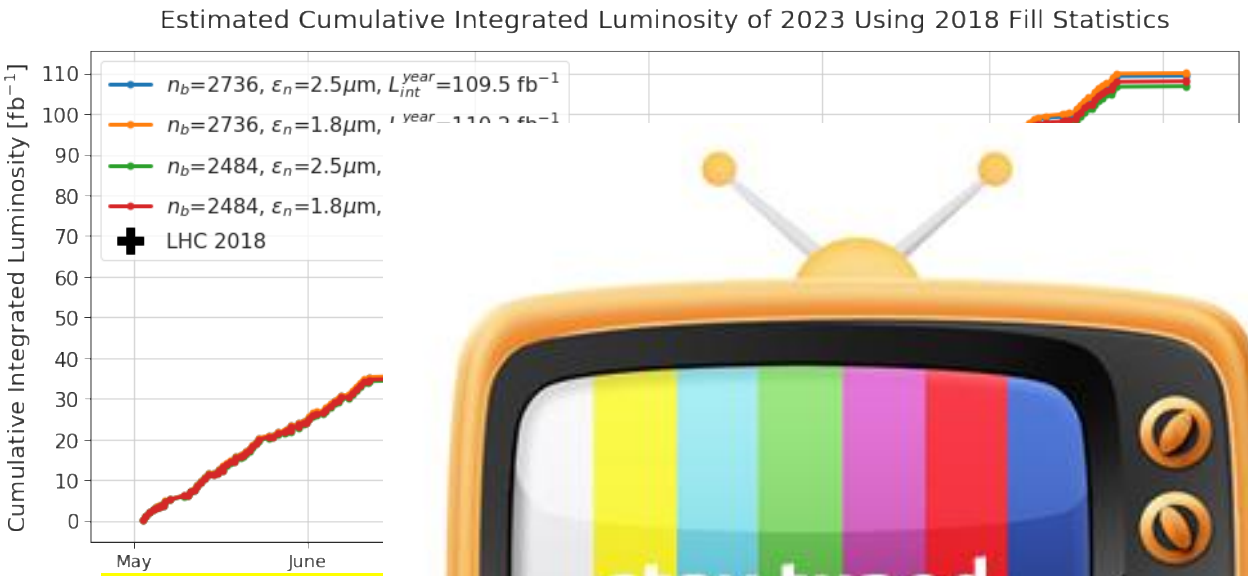
- ATLAS and CMS remain limited to a maximum pile-up level of about 60-65
  - Expect to run leveled at $2x10^{34}cm^{-2}s^{-1}$ (triplet heating limit)
  - As much luminosity as possible...
- Upgraded LHCb detector can handle $2x10^{33}cm^{-2}s^{-1}$
  - Want to run at constant pile-up level – see next slide
  - As much luminosity as possible...
- Upgraded ALICE detector can run at higher luminosity
  - Expect to level at $1.3\text{-}1.4x10^{31}cm^{-2}s^{-1}$ (~1MHz interactions)
  - Luminosity goal for Run-3 is ~200/pb of p-p data

BCMS is preferred and if necessary complement with some 8b4e

Pb-Pb:
Is running with a mix of 50 ns and 75 ns an option?

Gives a good first idea…. not only the machine are upgrading

Report from the Run 3 conf. WG



Most of **alysis of**

- **Finalize the st** **0^{11} ppb.**
- Test the validity
- Prepare the com
- Validate the optics in terms of collimation, stability, beam-beam, estimated performance, etc.

➔ **1st report to the LMC : 6th of March**

Now going back to the principal Aims of the Workshop

- Review and document the whole run 2 and take lessons learned for the re-commissioning after LS2
- Perform a critical review of individual system performance and address main issues encountered together with their mitigation;
- Examen beam related issues for the adopted operational scenarios
- Highlight known open points
- List principal work and changes foreseen for LS2
- A preliminary outlook to the possible Run 3 performance reach.

I think we ticked all the boxes, but one…

Next step - Proceedings

- **Editors:**
  - **Michaela Schaumann**
  - **David Walsh**
  - **Sylvia Dubourg**

- **1 paper per talk by the speakers and 1 paper per session on the discussions by the convenres**
  - **no page limit, but recommended length approx. 5 pages**
  - **Use the JACoW templates**

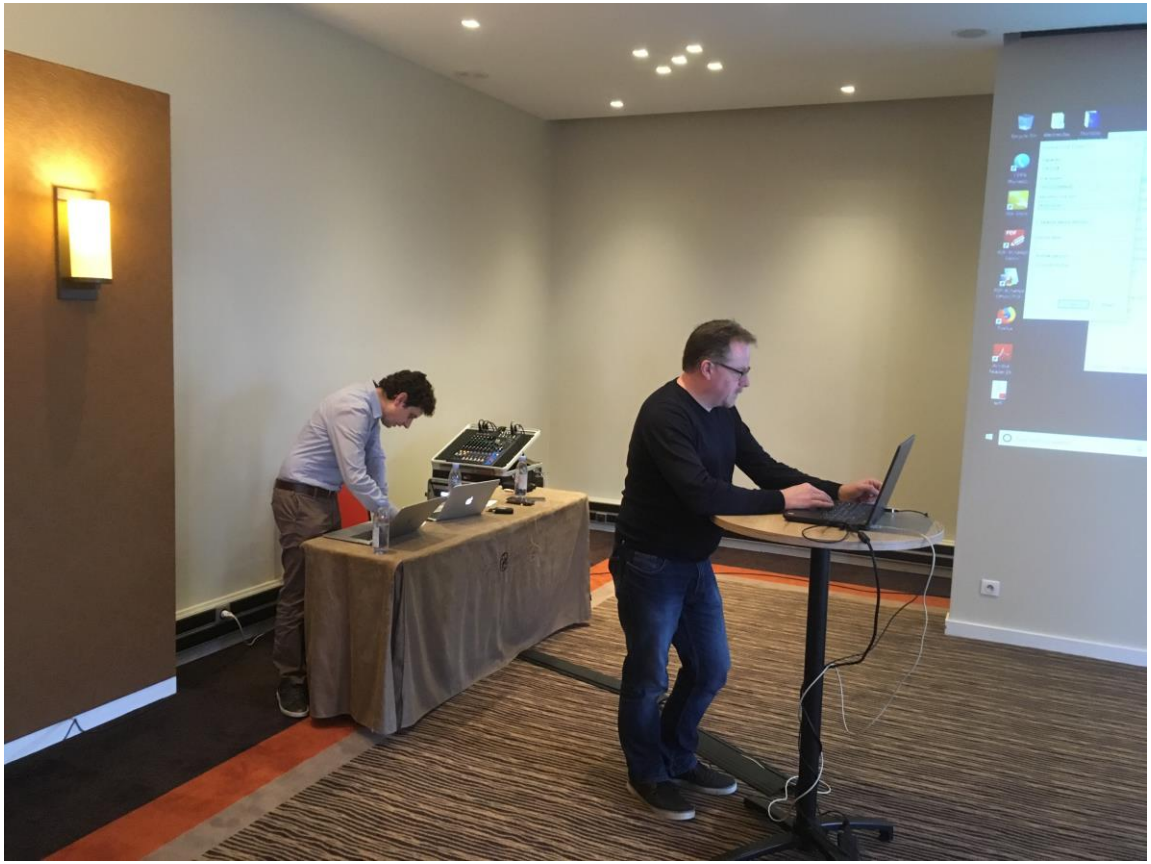
- **Submission deadline: 30.03.2019**

Special thanks to

- **Richard Jacobsson for his very instructive and entertaining special talk**

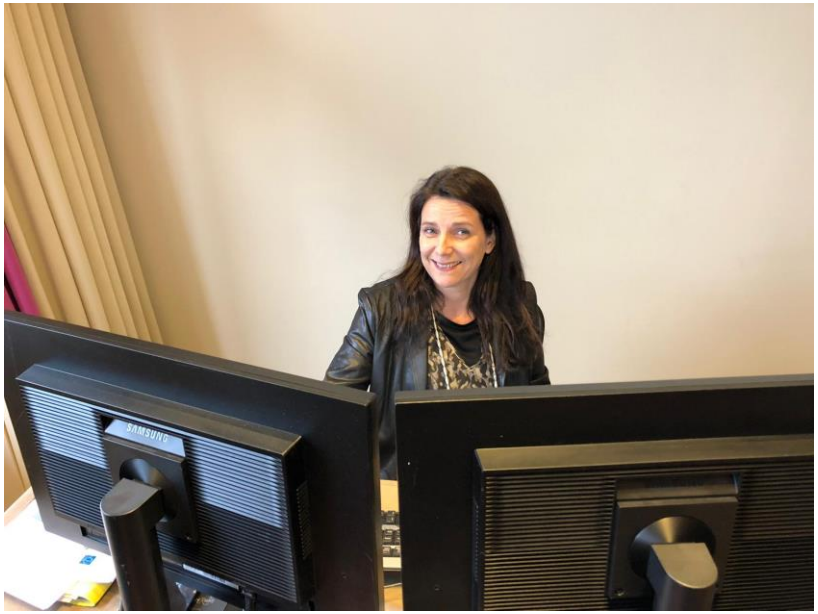
Special thanks to

- **Hervé Martinet for the technical infrastructure**



Special thanks to

- **Sylvia Dubourg, Workshop Secretary**



Have a save trip back….

The bus will leave at 13:45

..also for those who came by car…

Enjoy the weekend !!!

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