Highlights of the 9th LHC Operations Evian Workshop

- Subjective view on session 1 and 2 of the workshop

Daniel Wollmann

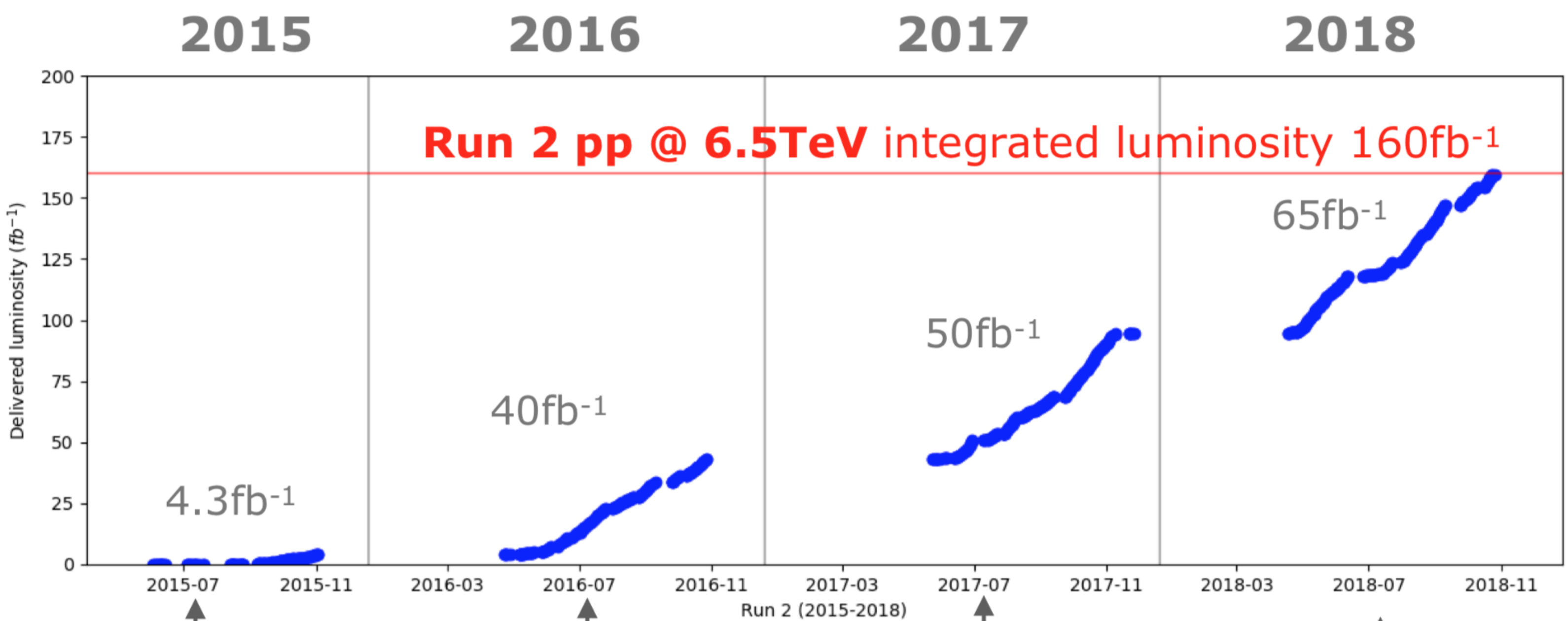
Acknowledgments: Speakers of the Evian workshop

Session 1: Overview of Run 2

- Overview of Proton Runs During Run 2
- Overview of ion runs during run 2
- LPC's View on Run 2
- LHC & Injectors Availability Run 2
- Injectors Beam Performance evolution during run 2
- Run 2 Optics and Corrections
- Powering Tests & Magnet Training

Protons

LHC *pp* operations Run 2



First experience at 6.5TeV and 25ns bunch spacing

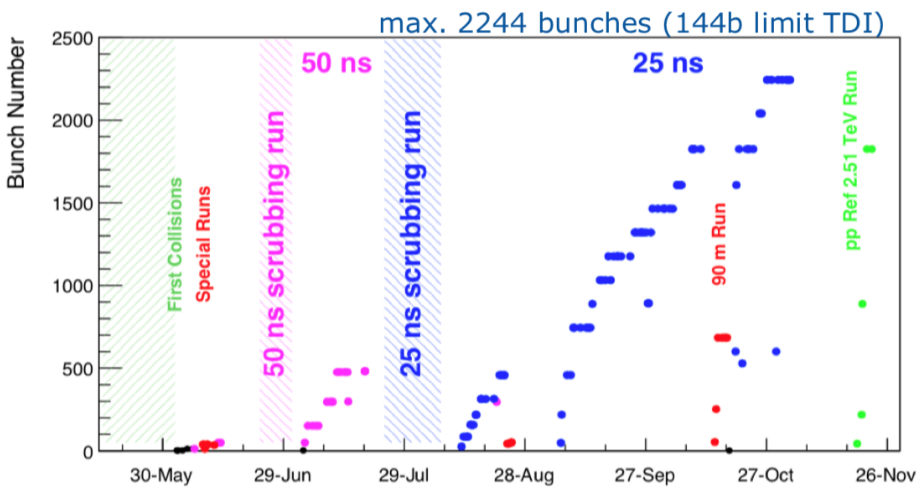
Production

Production

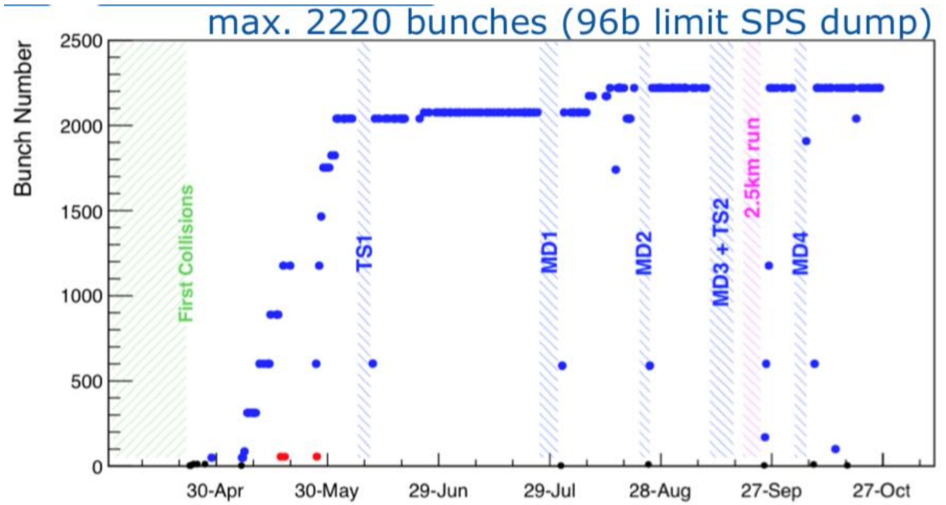
Production

Evolution of stored number of bunches

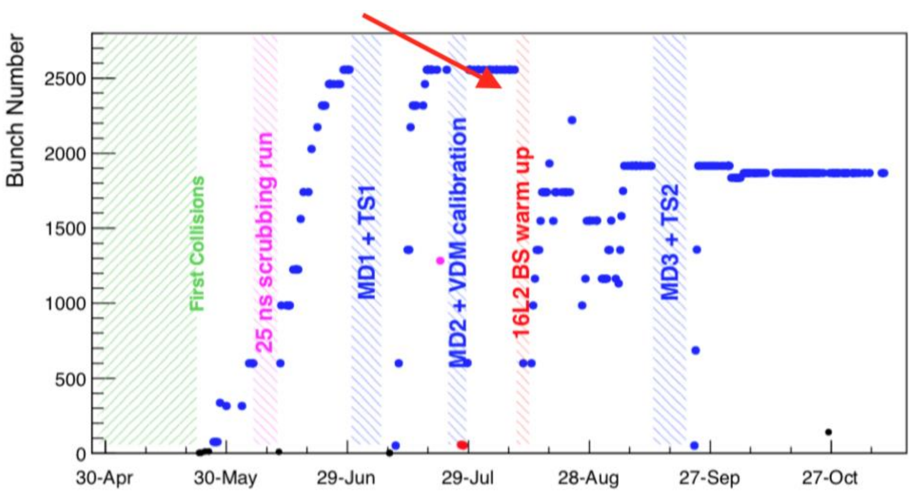
2015



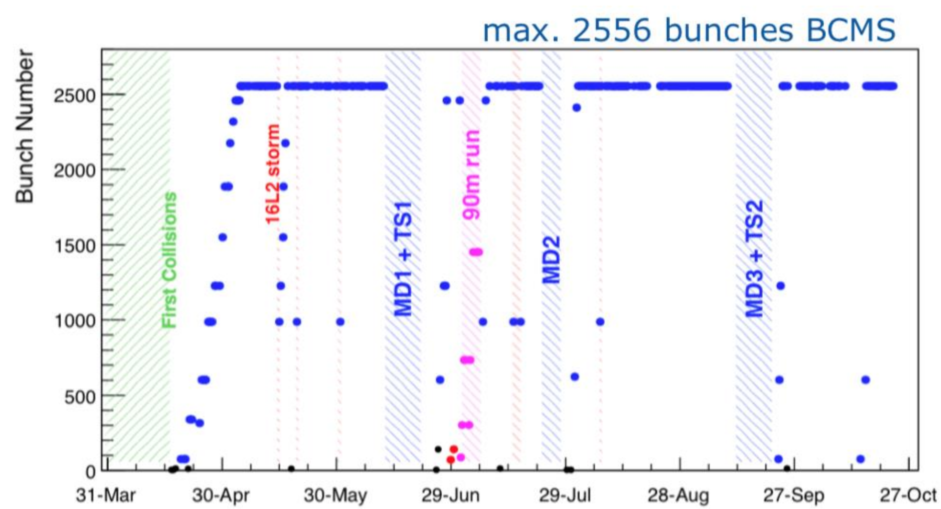
2016



2017

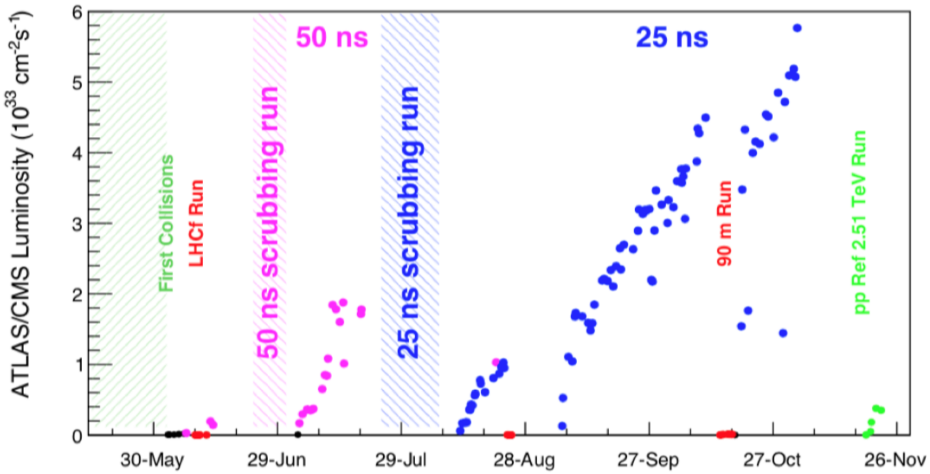


2018

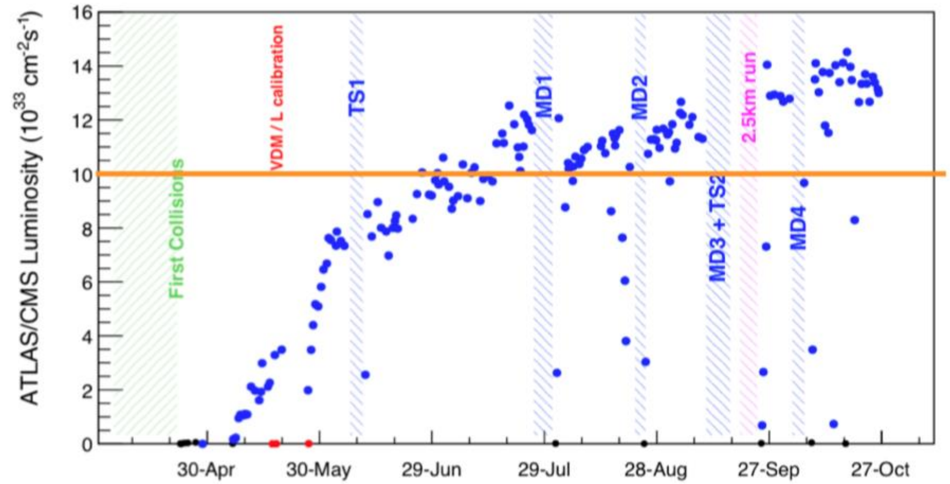


Evolution of Peak Luminosity

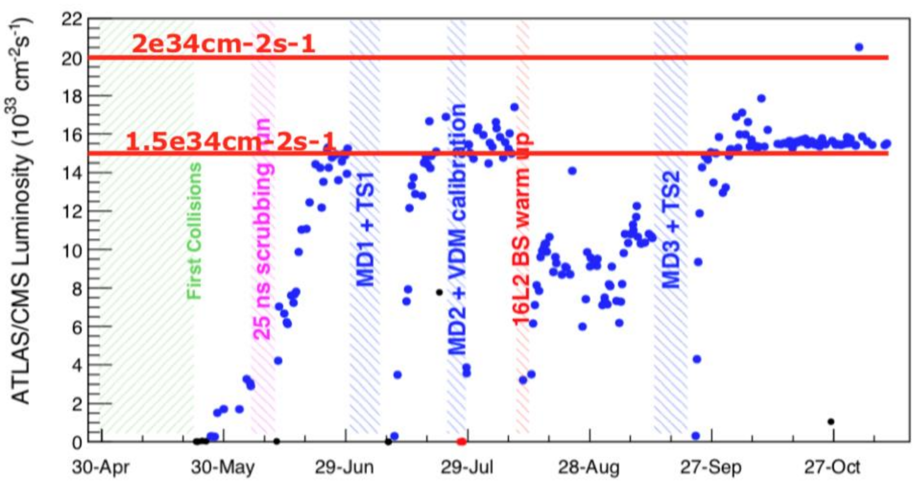
2015



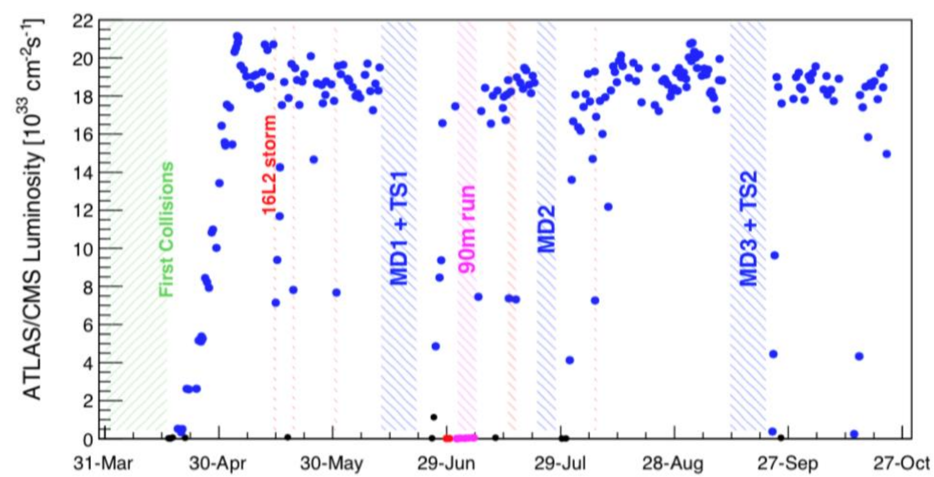
2016



2017



2018

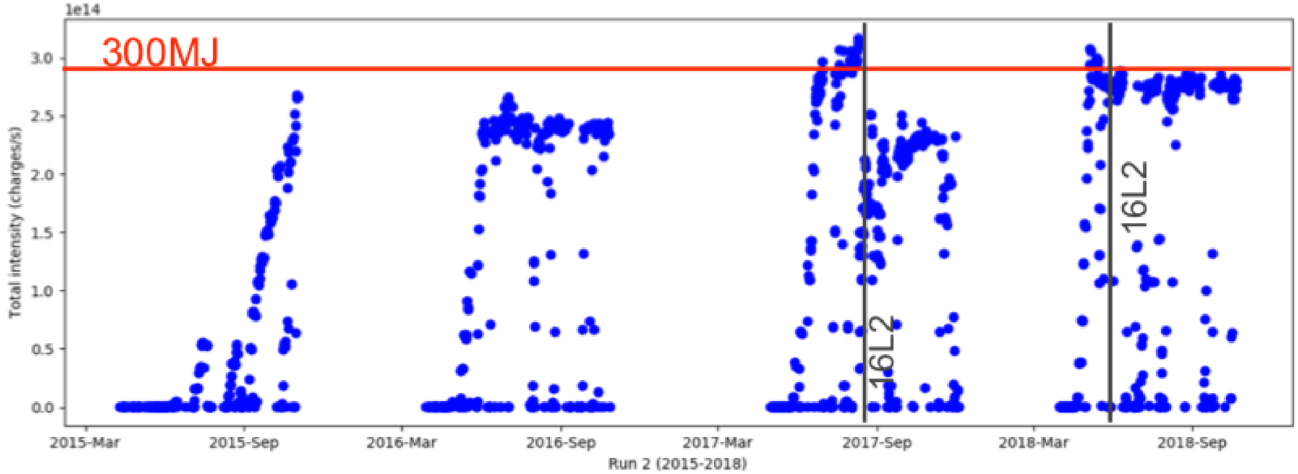


General fill-by-fill overview

Total Intensity during Run 2 (2015 - 2018) at the START RAMP

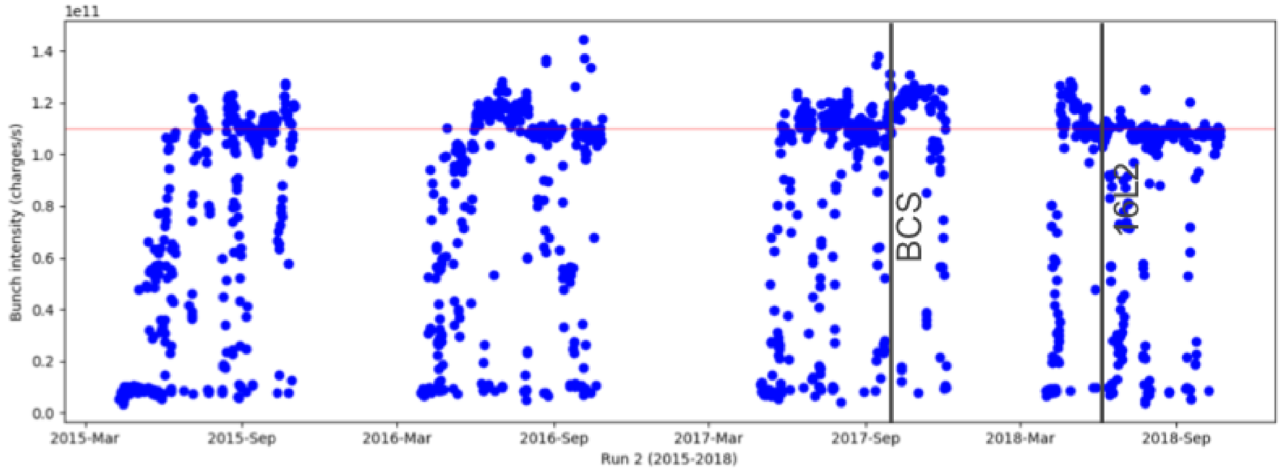
Reaching the 300MJ stored energy beginning 2017 and beginning 2018

Then lower to mitigate the 16L2



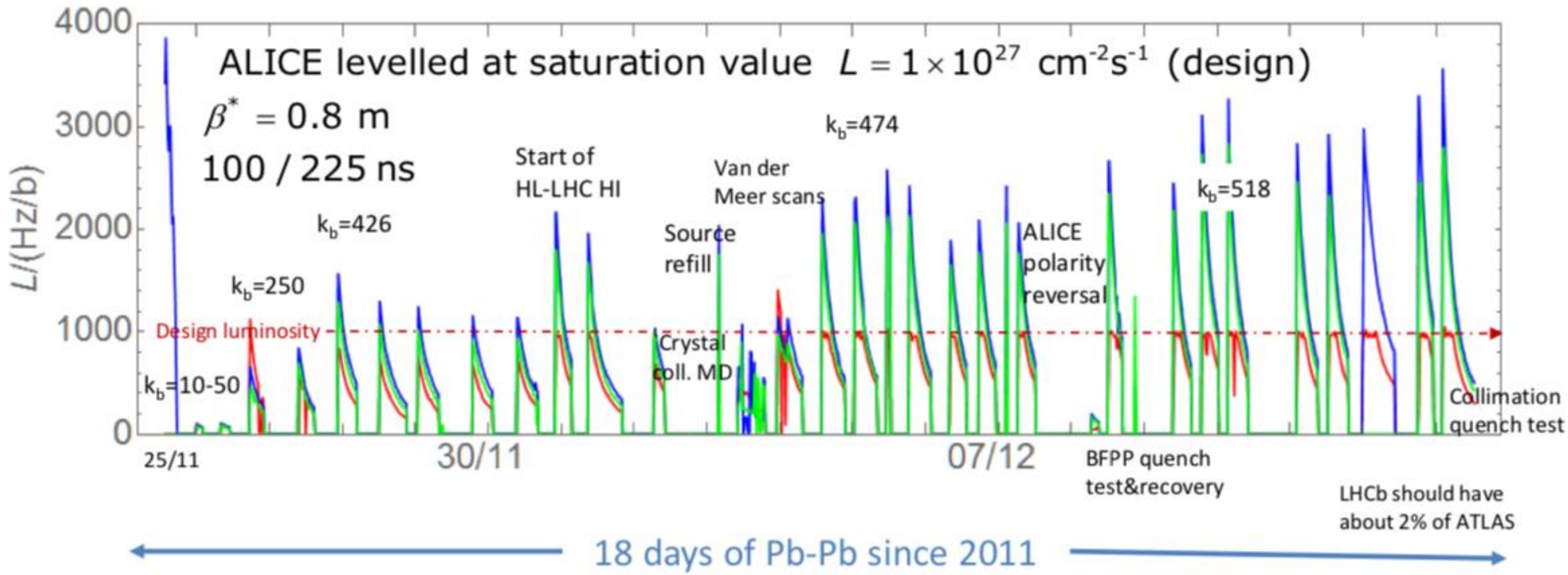
Bunch intensity during Run 2 at the START RAMP

In **2018** with 2556 bunches at 1.1e11 p/b corresponding to **0.5 A of beam current**



Ions

Pb-Pb peak luminosity at 3×design in 2015

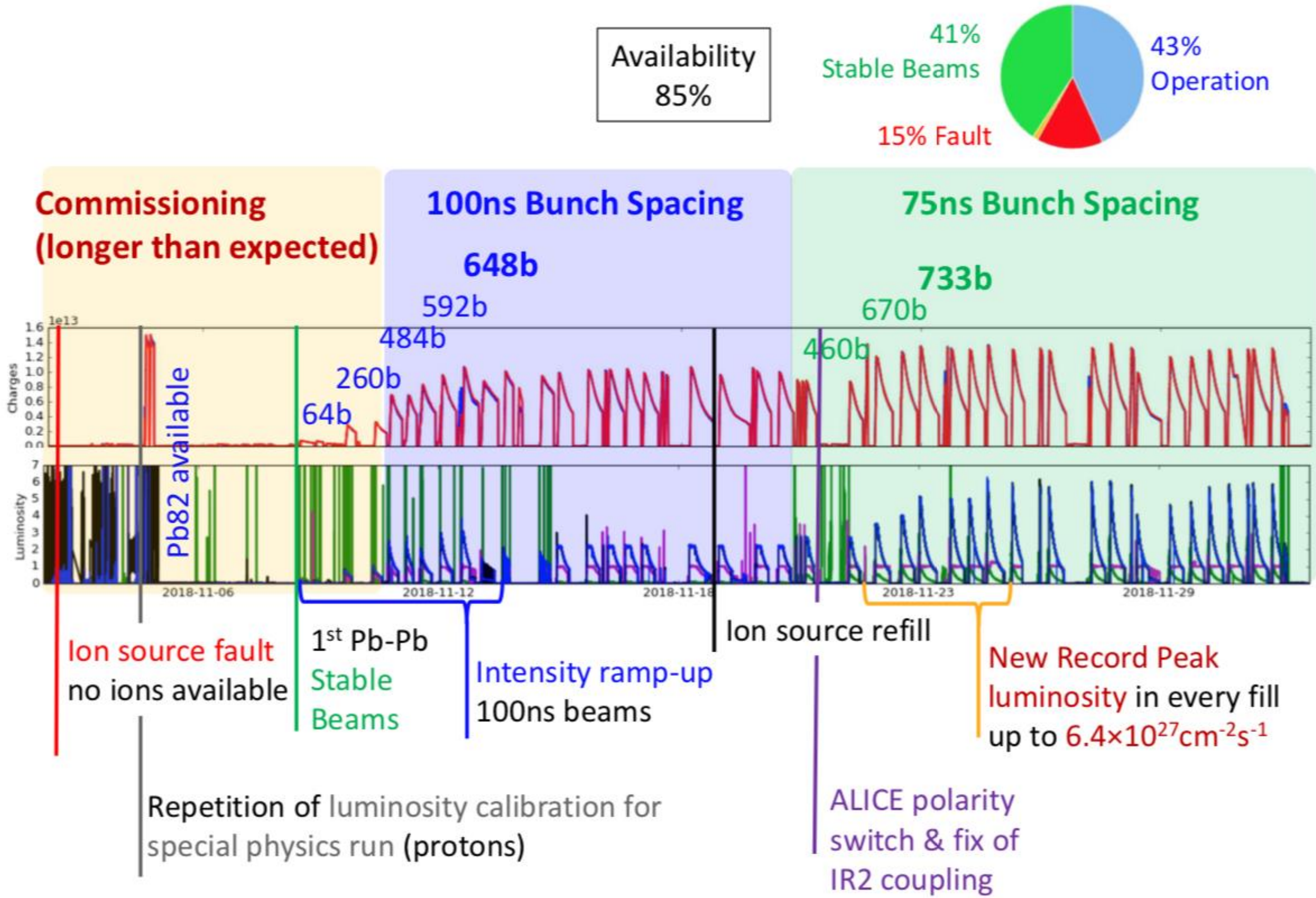


Heavy-ion runs of LHC are very short but very complex.
Experiments have many requests for changes of conditions.

This run was preceded by a week of equivalent energy p-p collisions to provide reference data.

Completely different from classical operation of Tevatron or LHC p-p.

25/11

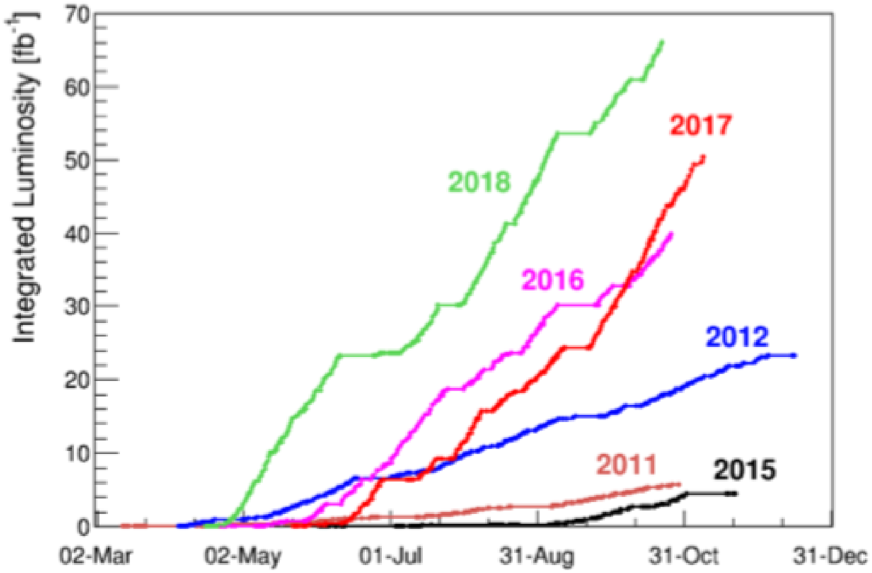


Availability
85%
41%
Stable Beams
43%
Operation
15% Fault
Commissioning
(longer than expected)
100ns Bunch Spacing
648b
592b
484b
260b
64b
75ns Bunch Spacing
733b
670b
460b
Pb82 available
Charges
Luminosity
2018-11-06
2018-11-12
2018-11-18
2018-11-23
2018-11-29
Ion source fault
no ions available
1st Pb-Pb
Stable
Beams
Intensity ramp-up
100ns beams
Ion source refill
New Record Peak
luminosity in every fill
up to 6.4×10^27cm^-2s^-1
Repetition of luminosity calibration for
special physics run (protons)
ALICE polarity
switch & fix of
IR2 coupling

M. Schaumann

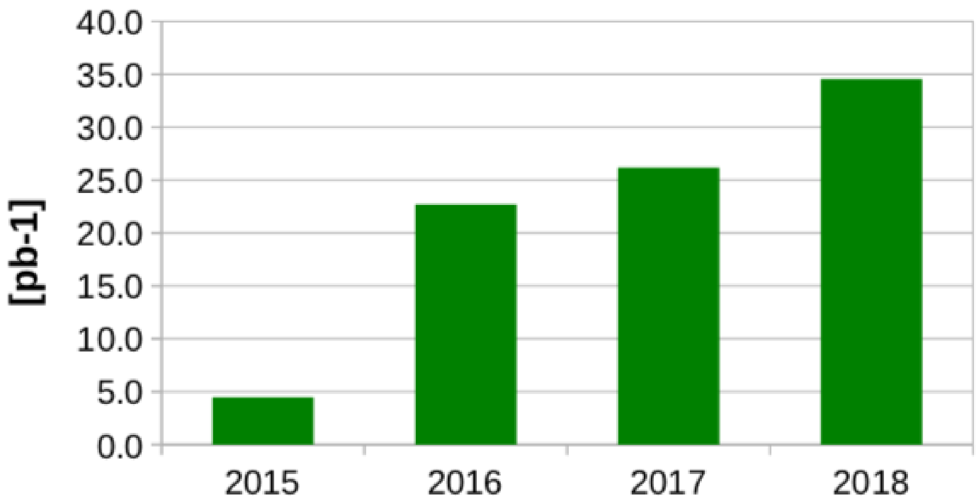
View of the LHC experiments

Summary of the pp run



- Large high quality data sample for all experiments
  - 160 fb^{-1} : ATLAS / CMS
  - 6.7 fb^{-1} : LHCb
  - 66 pb^{-1} : ALICE

Luminosity per hour of SB



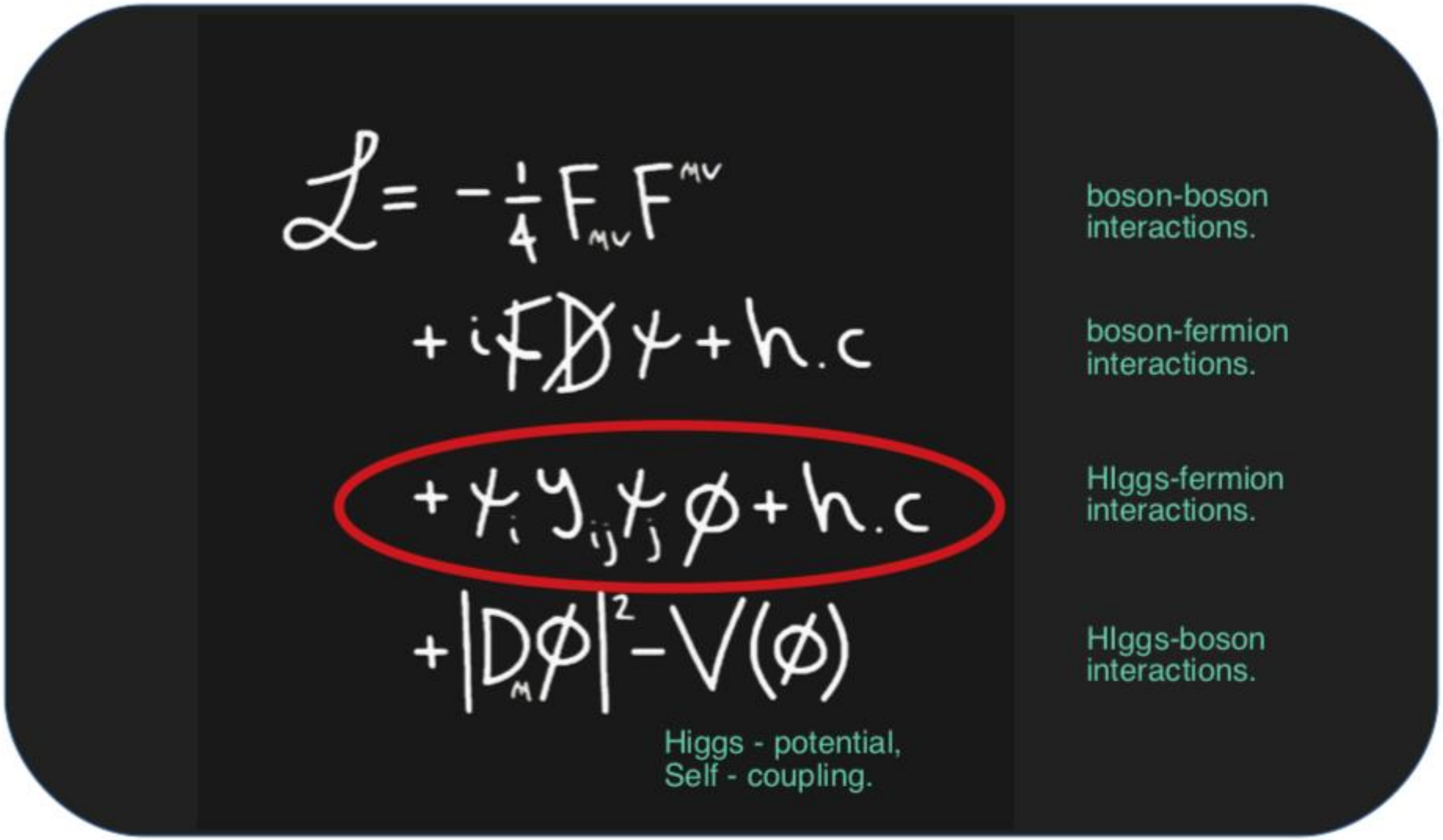
- Continuous performance increase over the 4 years
  - 2015 : commissioning
  - 2018 : minimal amount of configuration changes

→ 32% higher lumi/hour than 2017

And why do we need all this lumi?! Examples from ATLAS/CMS

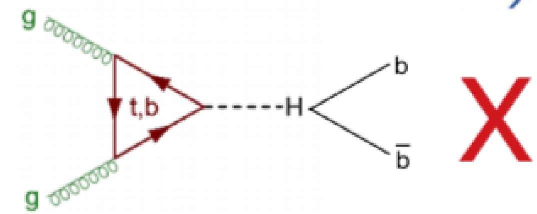
In RUN 2 ATLAS and CMS for the first time measured a fundamental part of the Standard Model Lagrangian: **coupling to fermions**

(bottom & top – quarks and the τ – leptons)

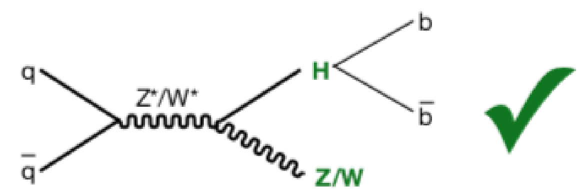


Challenging: $H \rightarrow b\bar{b}$

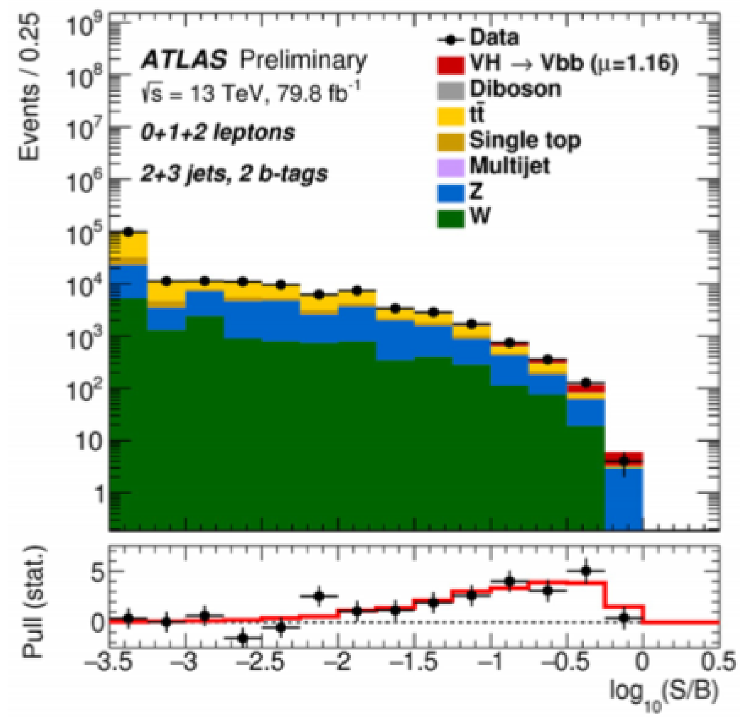
- Dominant Higgs decay channel (58%), however large backgrounds from QCD
  - No chance in gluon fusion production



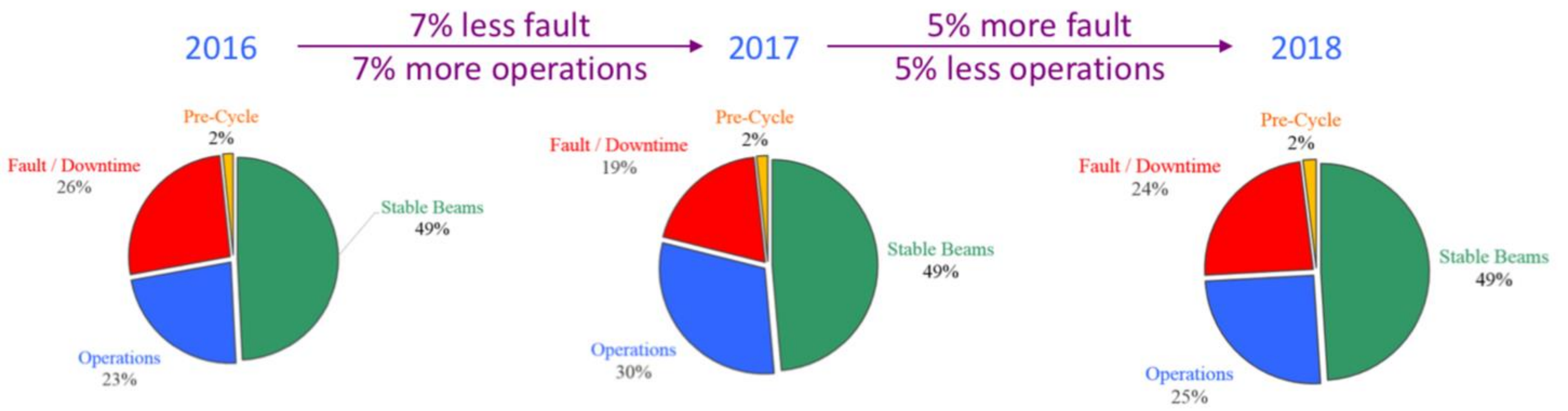
- Only measurable in collisions with associated production with W or Z
  - W or Z decay can be used to "tag" the interaction
  - Many decay modes to consider and combine

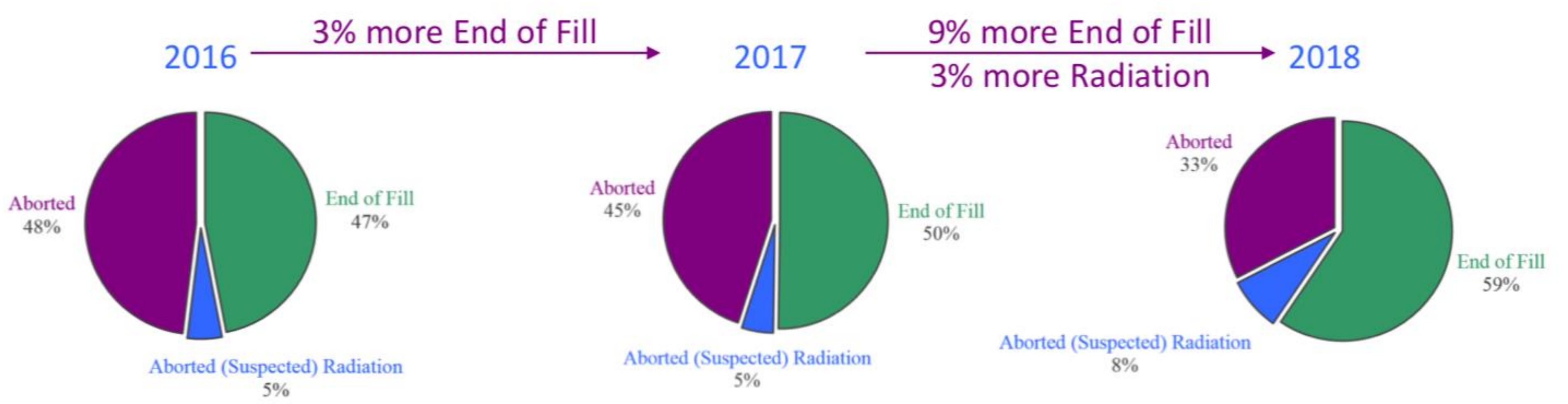


- Significance Run I & 80fb-1 of Run II: **5.4σ**
- Many different analysis combined
  - Different decays of associated W/Z bosons
- Huge background requires large statistics to extract significant results



Availability


2016
7% less fault
7% more operations
2017
5% more fault
5% less operations
2018
Pre-Cycle
2%
Fault / Downtime
26%
Stable Beams
49%
Operations
23%
Pre-Cycle
2%
Fault / Downtime
19%
Stable Beams
49%
Operations
30%
Pre-Cycle
2%
Fault / Downtime
24%
Stable Beams
49%
Operations
25%


2016
3% more End of Fill
2017
9% more End of Fill
3% more Radiation
2018
Aborted
48%
End of Fill
47%
Aborted (Suspected) Radiation
5%
Aborted
45%
End of Fill
50%
Aborted (Suspected) Radiation
5%
Aborted
33%
End of Fill
59%
Aborted (Suspected) Radiation
8%

2016/17/18 Top Faulty Systems

2016

Root Cause System	Root Cause Duration [h]	% of Total Duration
Injector Complex	313.21	25.4
Technical Services	278.35	22.6
Power Converters	90.32	7.3
Quench Protection	75.05	6.1
Beam Dumping System	68.75	5.6
	= 825.7 hours	= 67.0%

deprecated in 2016-17

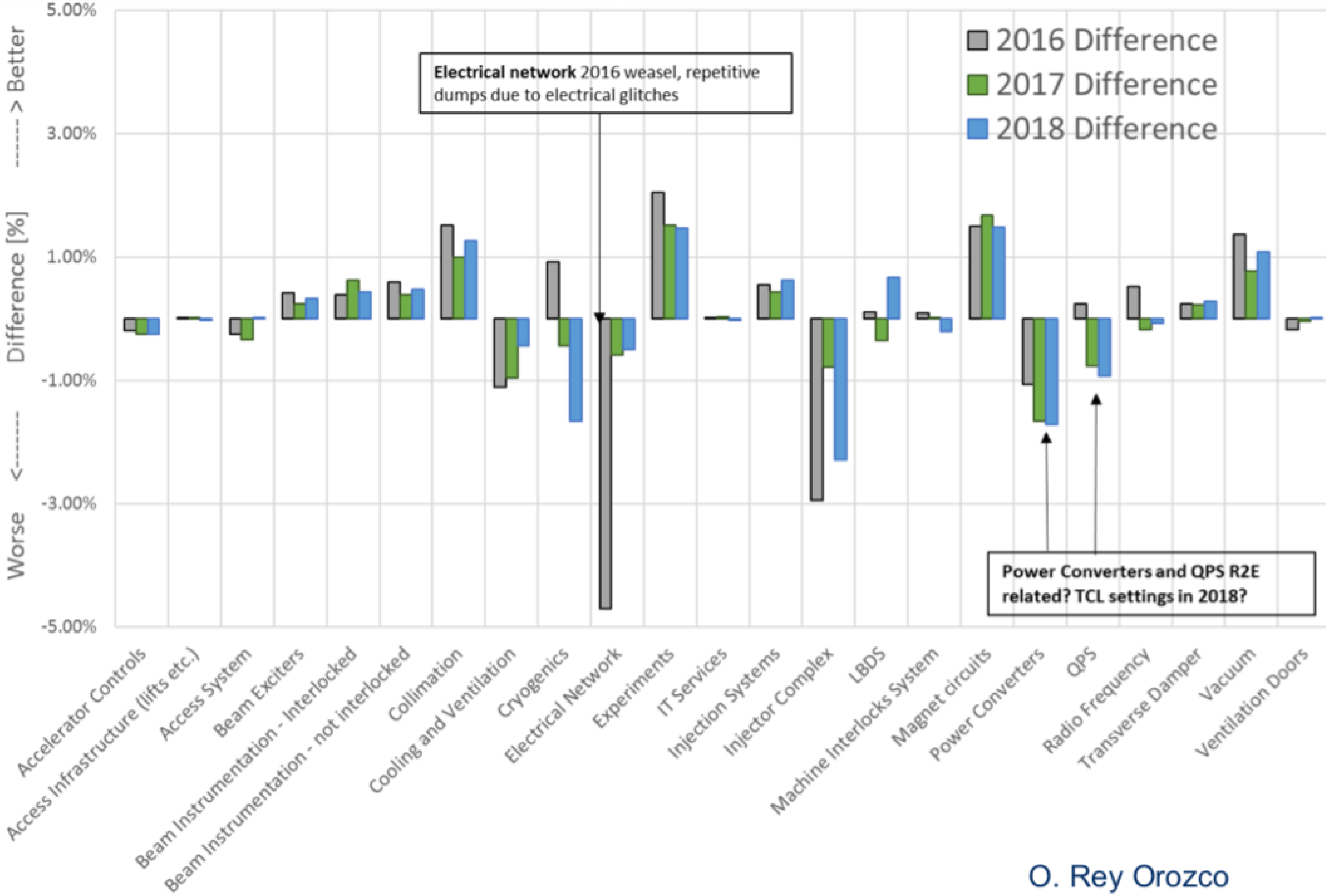
2017

Root Cause System	Root Cause Duration [h]	% of Total Duration
Injector Complex	140.2	17.5
Cryogenics	107.7	13.5
Power Converters	98.9	12.3
Quench Protection	63.8	8.0
Beam Dumping System	60.6	7.6
	= 471.2 hours	= 58.8%

2018

Root Cause System	Root Cause Duration [h]	% of Total Duration
Injector Complex	237.9	23.7
Cryogenics	187.3	18.6
Power Converters	101.0	10.1
Quench Protection	75.2	7.5
Radio Frequency	49.2	4.9
	= 650.6 hours	= 64.7%

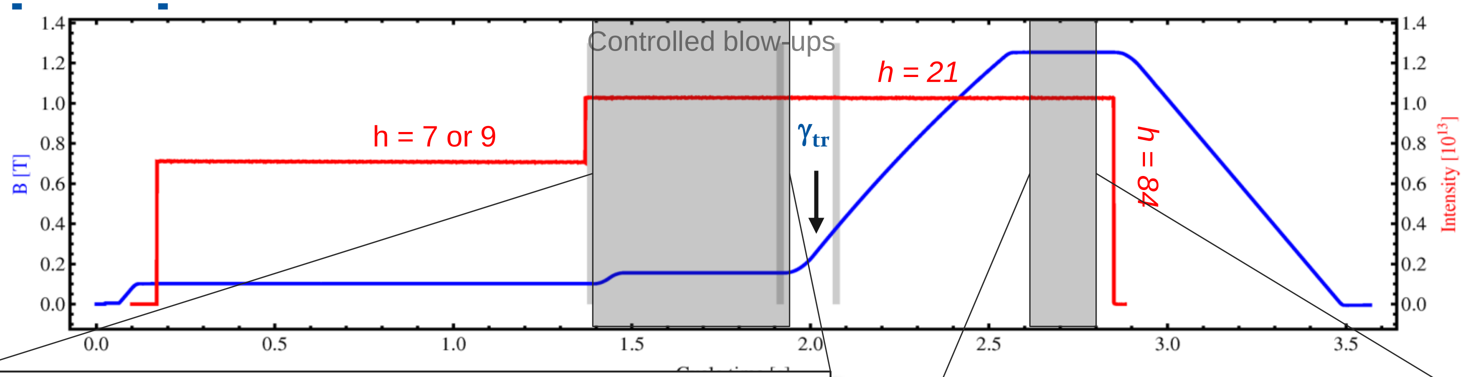
Unavailability Evaluation 2016/17/18



O. Rey Orozco

Injectors

PS – LHC beam production and lim



rge on injection plateau
tion
2 Ge
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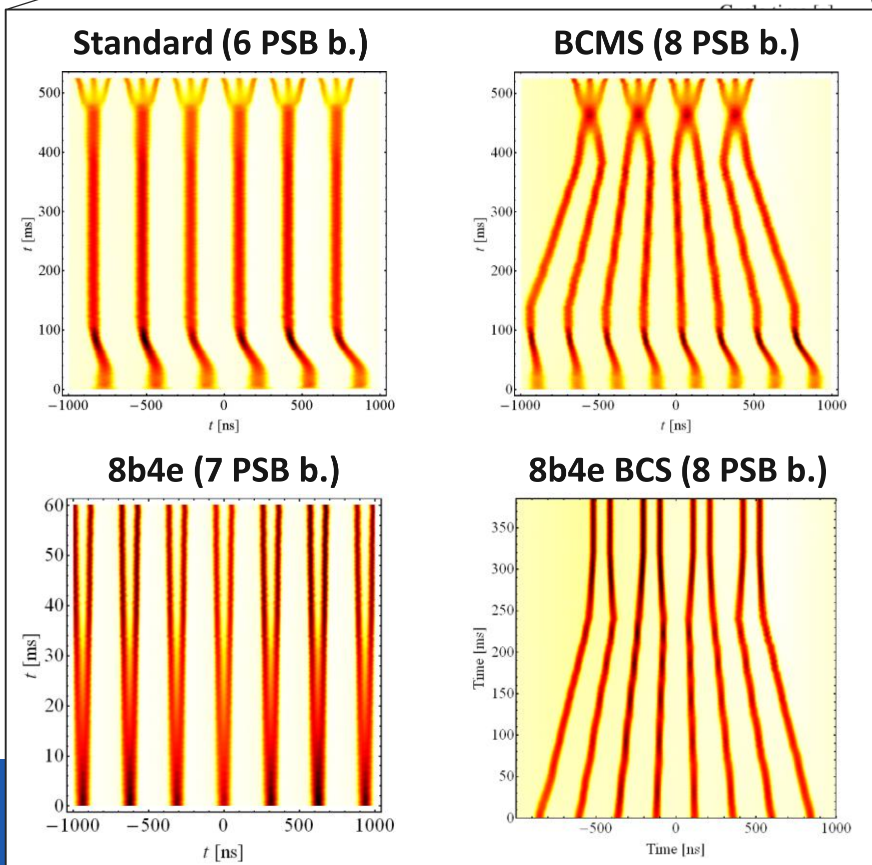
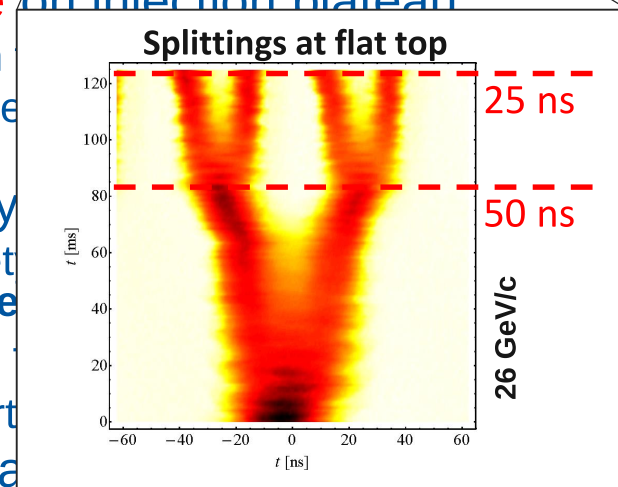
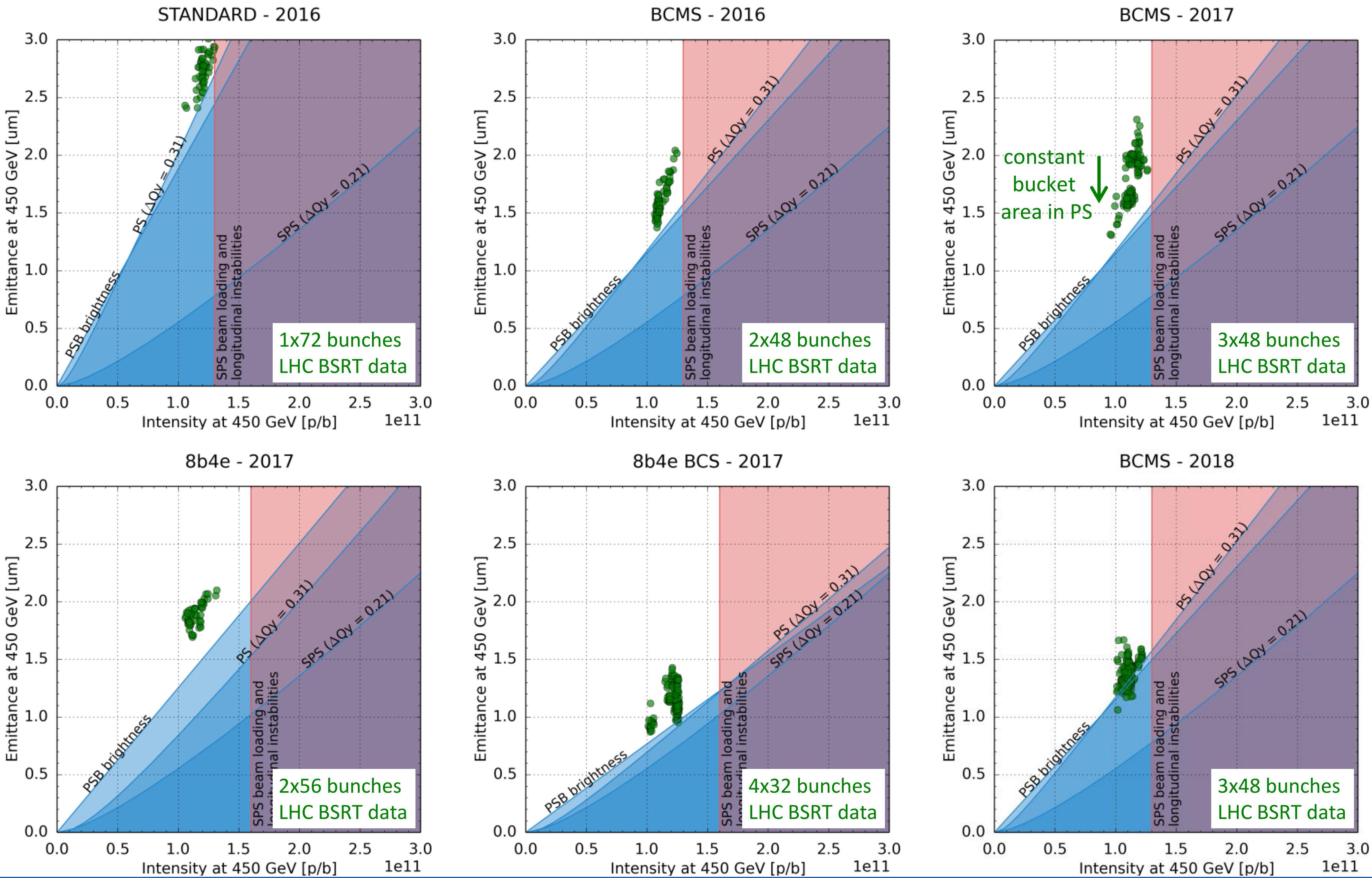


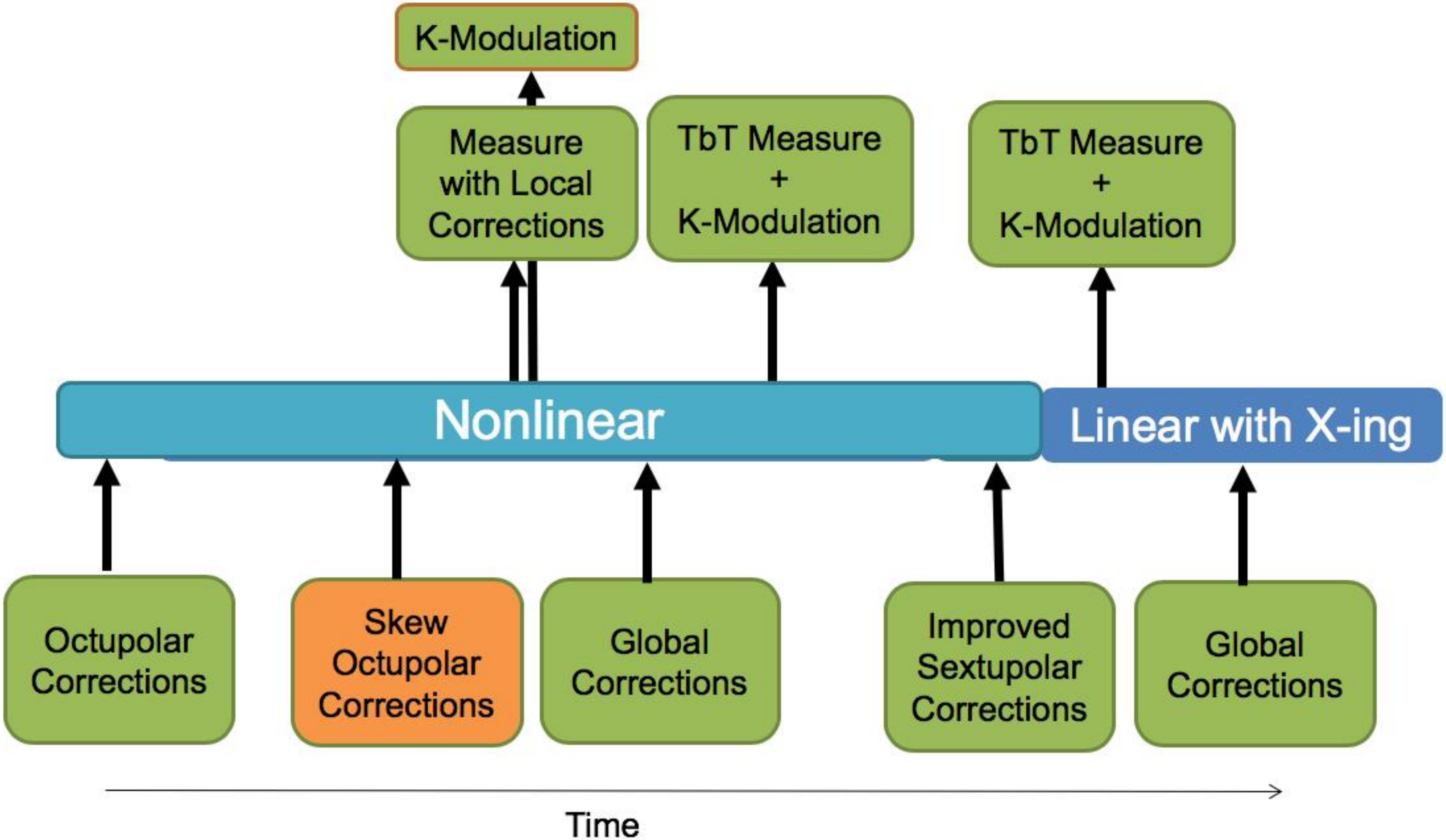


Proton injectors performance over

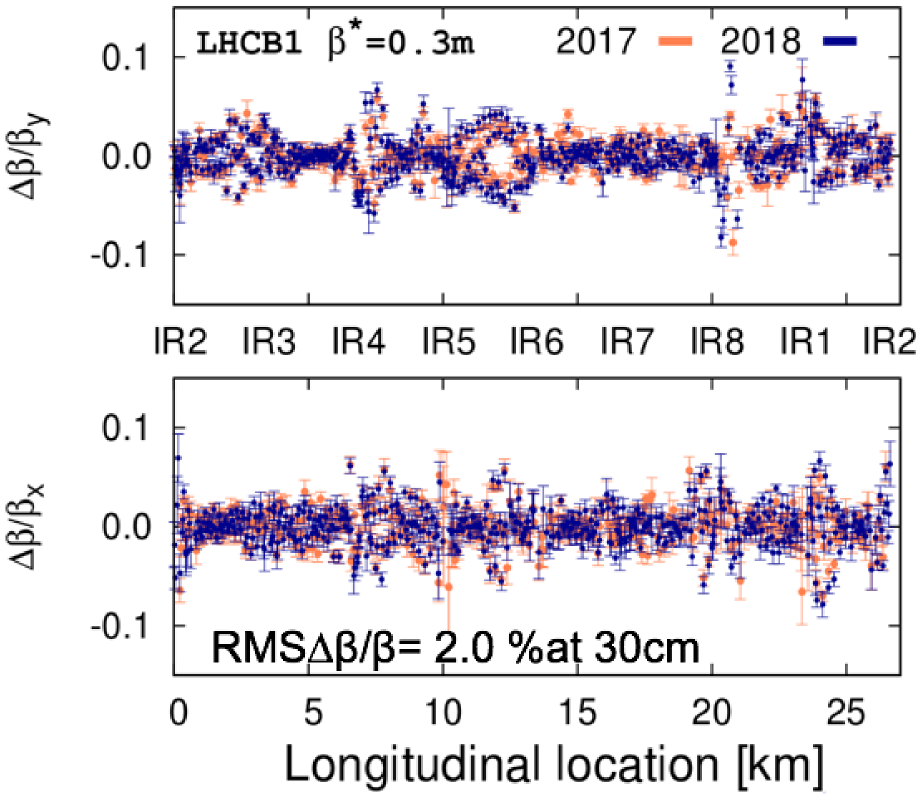


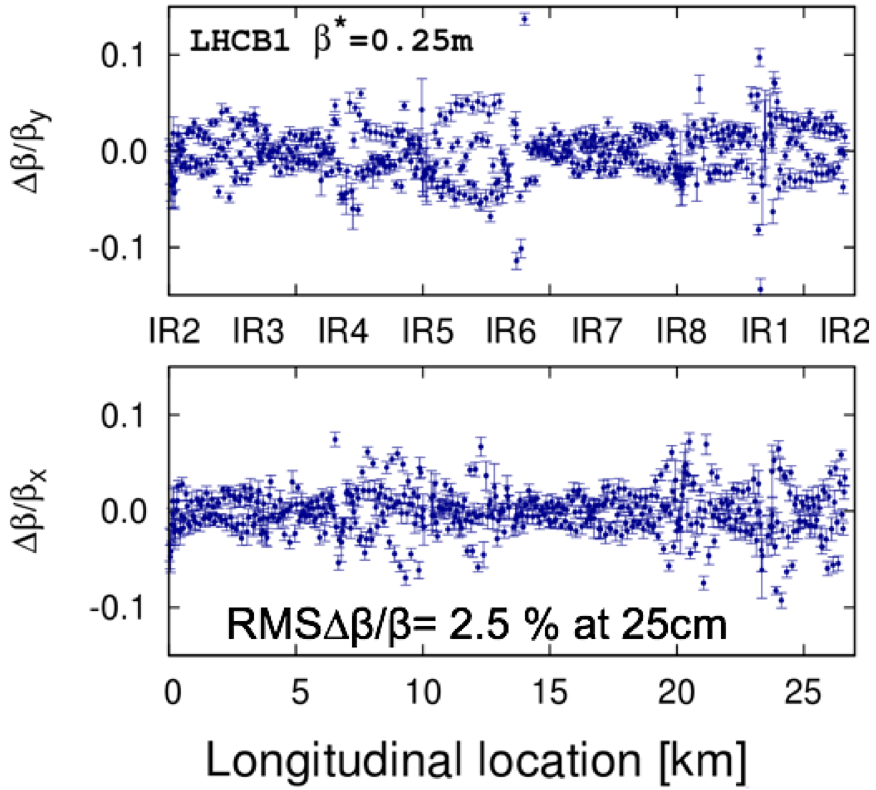
Optics

Commissioning strategy 2018



β-beating 2018 vs 2017





Re-used the correction from 2017 without any degradation in optics quality

Powering tests & training

Powering tests: Did we become more efficient?

	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%

Powering test statistics during period 2014-2018 [3]

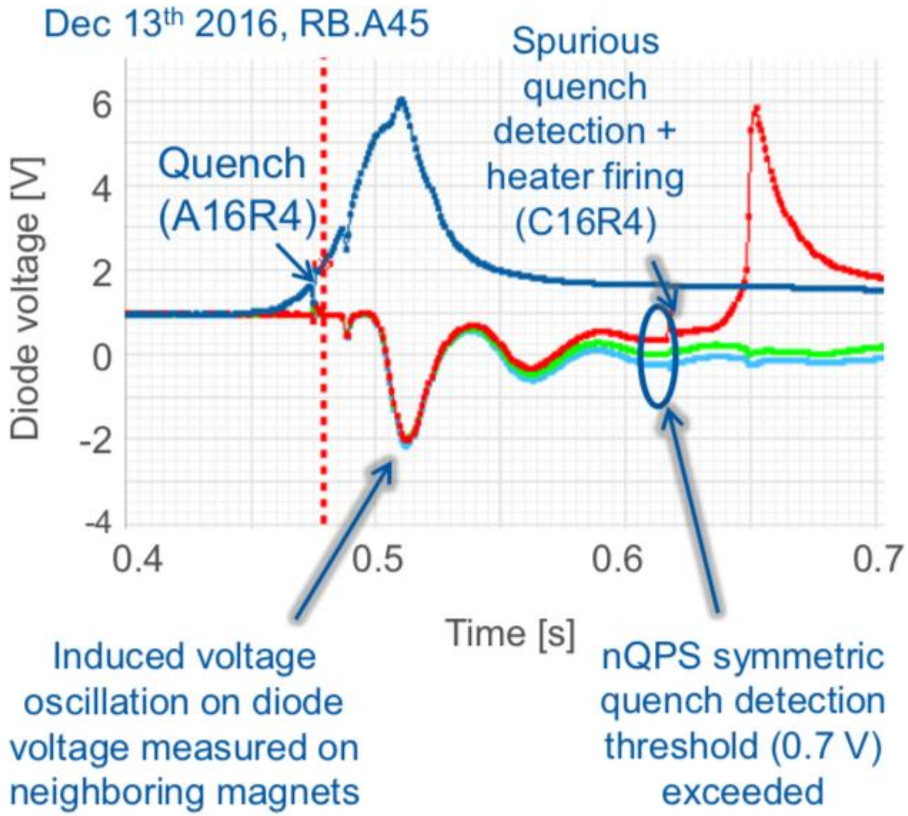
Continuous effort towards:

- Enhanced automatic analysis (PMEA / eDSL) → Reduced manual analysis work-load and faster turn-around → Faster decision whether tests is successfully completed (pass), a repeat is necessary (fail), or an intervention is necessary (flag)
- AccTesting: Circuit powering constraints to avoid spurious triggering due to circuit coupling
- Hardware commissioning → Involved CERN personnel members gain experience

→ Yes, steady progress towards more efficient powering tests

[3]. T. Buffet, "Hardware Commissioning Campaign", TE-MPE TM, 26/4/18

How to train efficiently? (1/2)

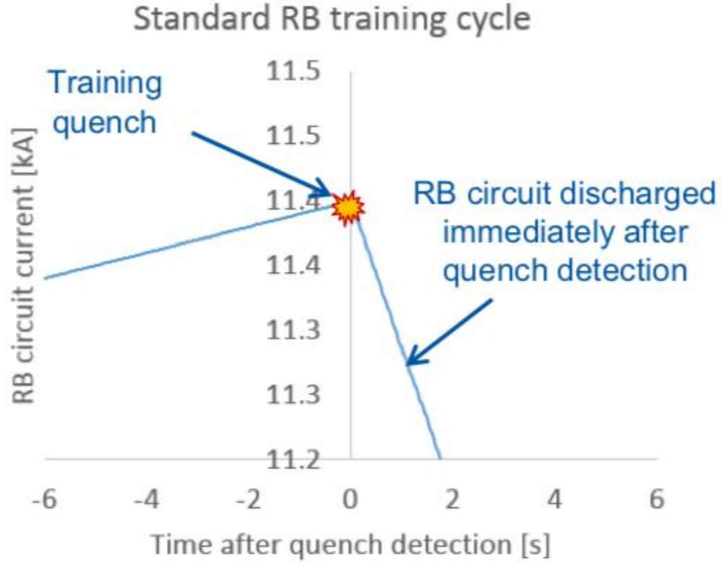


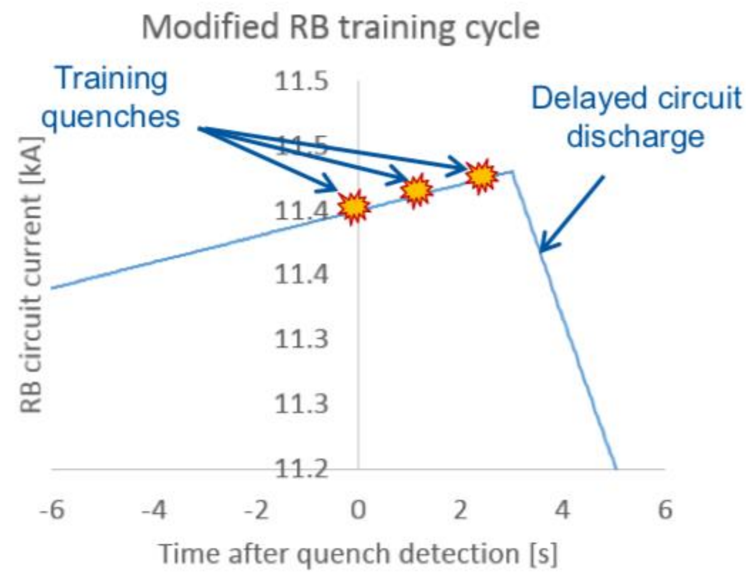
- Spurious secondary quenches in RB circuits → Increase in cryo-recovery time → Slower training
- Electro-magnetic travelling wave phenomenon:
  - After FPA + quench → Ringing in circuit → Spurious quench detection (nQPS / iQPS) resulting in secondary quenches
  - More prevalent at higher currents
- During HWC Dec 2018 [8]: Adjusted nQPS settings and modified energy-extraction timing during training of RB.A12:
  - Previously, about 65% of EM/TW spurious quench detection were due to nQPS triggering
  - During HWC Dec 2018, about 10% of spurious quench detection were due to nQPS triggering (remainder: iQPS)
  - iQPS detection settings to be discussed with MP3 panel

→ **Less spurious secondary quenches → Faster cryo-recovery → Faster training**

[8]. Z. Charifoulline, presented at MP3 panel, 21/11/2018

How to train efficiently? (2/2)





- With standard quench protection scheme, the circuit is discharged once I_Q of a single magnet is reached, even if the next I_Q is only a few amps higher
- Concept (very old idea): Continue to ramp for a few seconds after quench detection → Multiple training quenches per training cycle → Much more efficient training
- Theoretically, highly predictable amount of training cycles for all RB circuits (7 TeV + margin after few weeks)
- But, good electrical integrity required and (modest) increase in heat load on diodes and busbars

→ Special training cycle for accelerated training, to be re-discussed within the MP3 panel

Session 2: Systems Overview (partI)

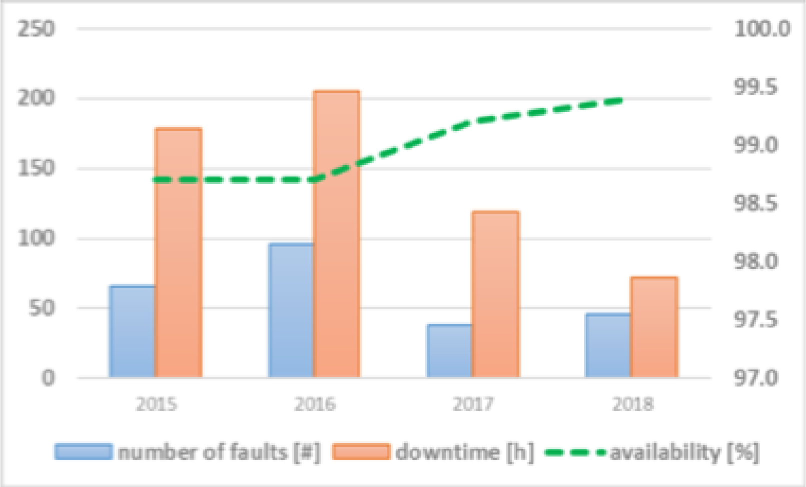
- General Technical Services
- Cryogenics
- Controls and the AFT Tool
- The RF System
- Injection Systems
- Beam Instrumentation
- Emittance Measurements

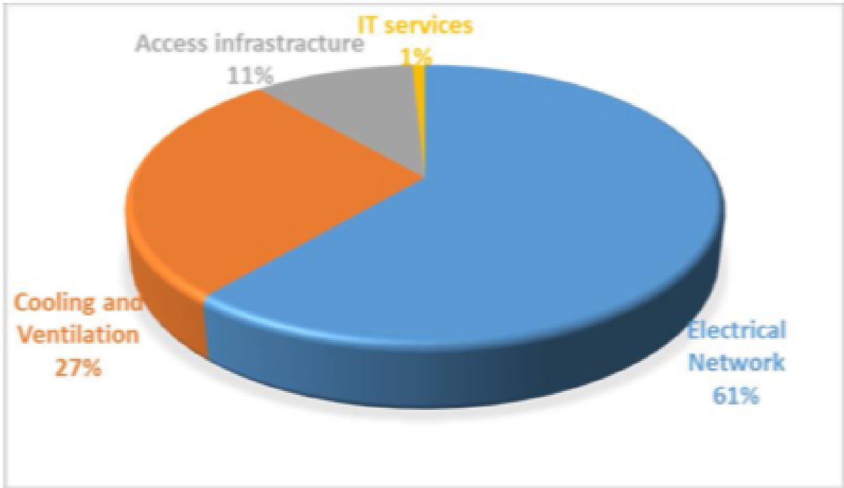
General Technical Services

Overall performances assessment 1/2

- Over the past few years, the LHC accelerator downtime due to the Technical Infrastructure equipment faults has been reduced
- TIOC has been instrumental in the availability improvement
  - Guiding the analysis of the data acquired during occurred major events
  - Assessing, coordinating and monitoring the interventions undertaken to minimize the impact

	2015	2016	2017	2018	Run 2
# of faults	66	97 (96)	38	46	247 (246)
downtime	178 h	367 (205) h	119 h	72 h	736 (574) h
availability	98.7 %	97.1 (98.7)%	99.2 %	99.4 %	98.6 (99.0) %





Most significant failures and faults

2016:	66/18 kV transformer fault Pt 8 (weasel) [6 d] & Flooding Pt3 [3 d]
2017:	Multiple failures on HTA transformers [3 d] & Power outage due to PSEN interv. [1 d]
2018:	Worst than usual weather conditions – 90 days of thunderstorm/98 % of summer days with thunderstorms - 400 kV power cut, glitches and floodings

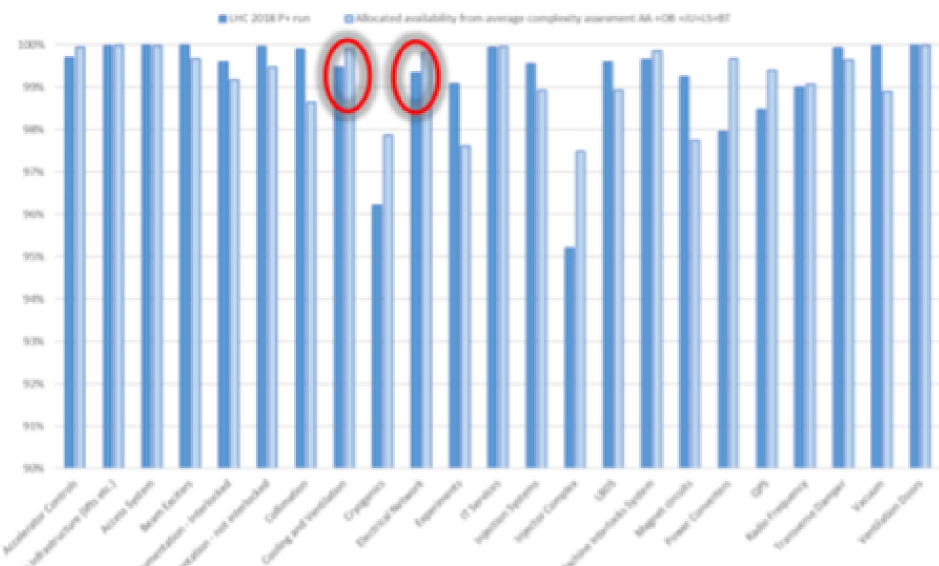
Electrical glitches:
2016: 31 events
2017: 19 events
2018: 23 events

Outlook and perspectives: KPIs

Ack data D. Widegreen

INFOR EAM based KPIs

- **Maintenance Cost / Replacement Asset Value** (MC/RAV) is a KPI to analyze maintenance costs.
- Rule of thumb number used in industry: 3-5%*
- Technical services average MC/RAV **~ 1 % well below targets and decreasing!!!**

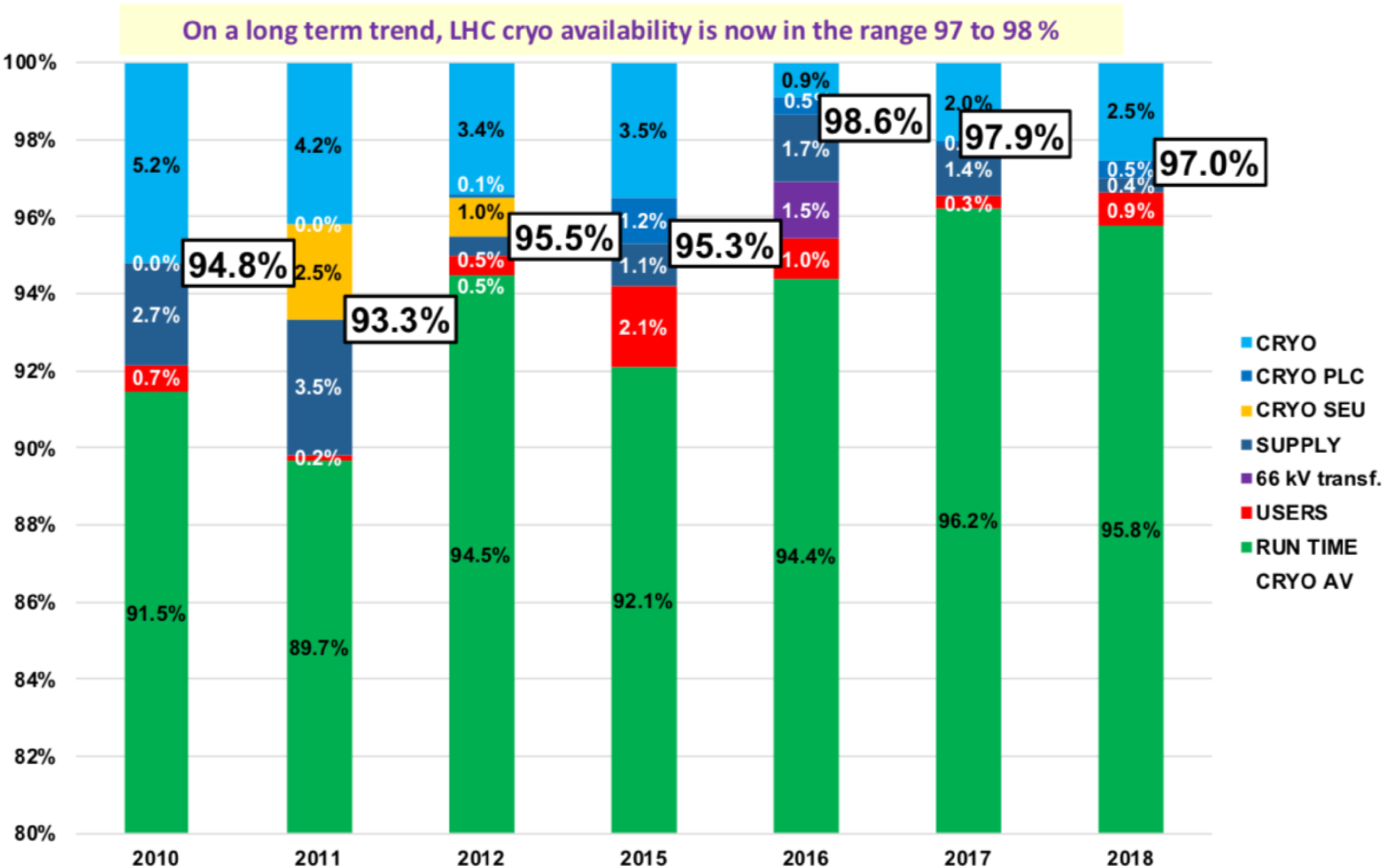


Estimates of allocated availabilities per systems - Andrea's talk

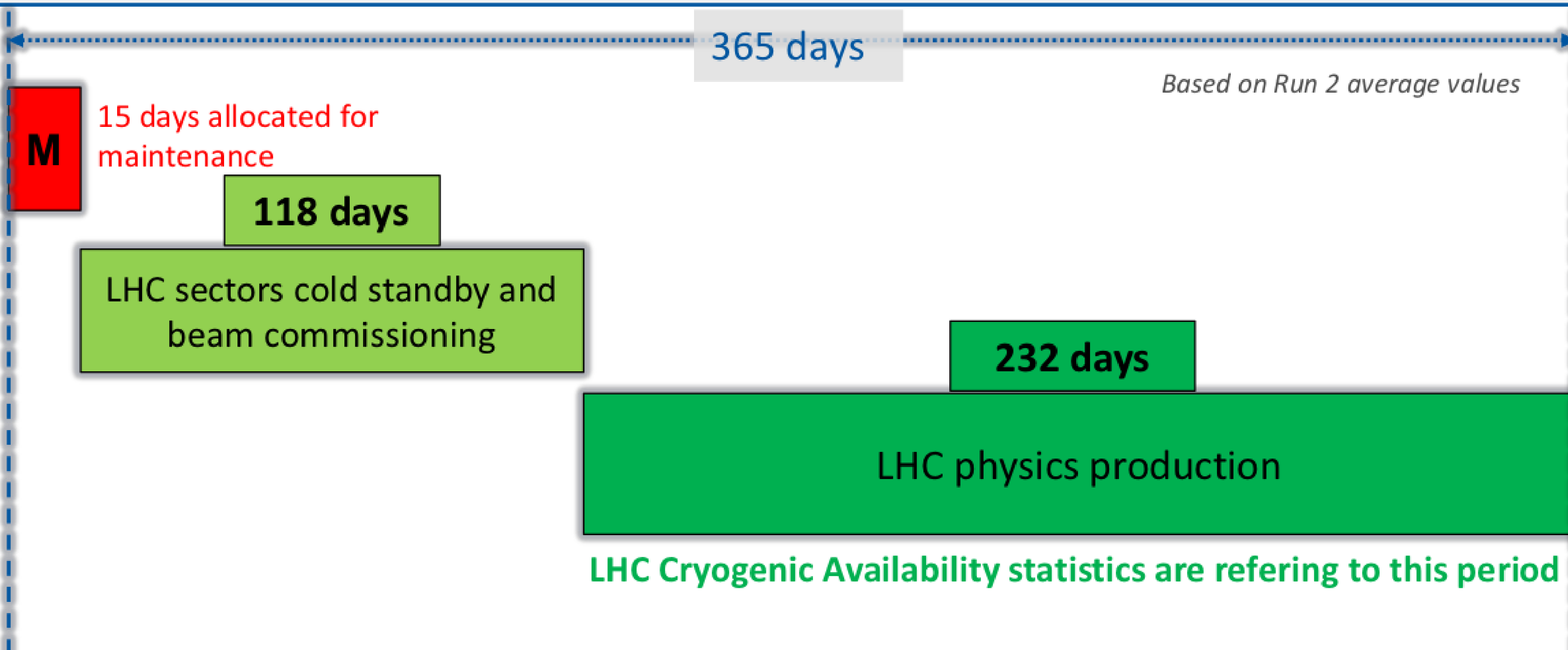
*) Maintenance & Reliability Best Practices, R. Gulati: 3-9%
Physical Asset Management Handbook, J. Mitchell: ~3%
Asset Life Cycle Engineering, S. McNair: 2-4%

Cryogenics

LHC Cryo availability since the beginning



Run 2 allocated time distribution for Cryogenic equipment's



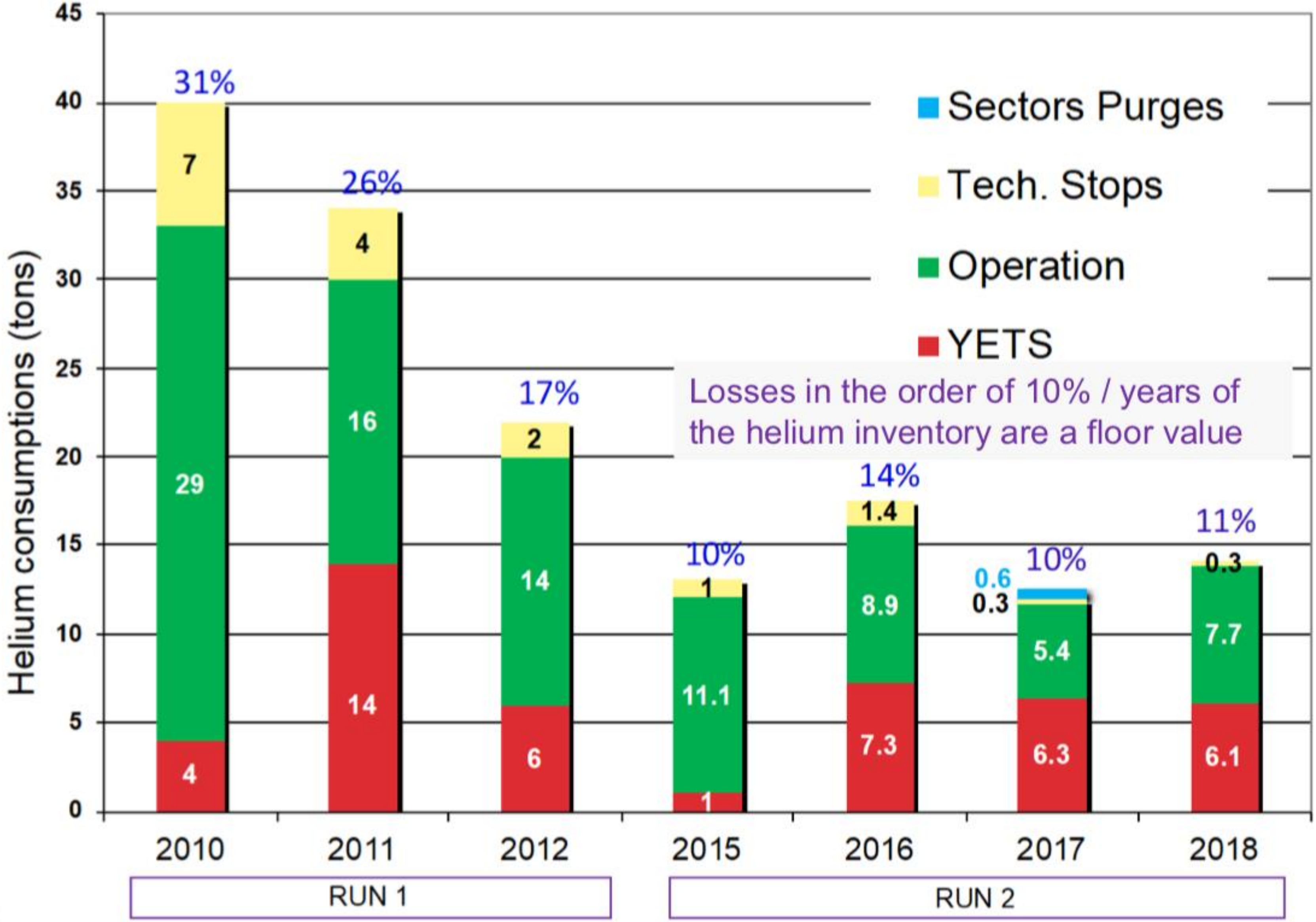
During YETS period, each cryo island must keep its 2 sectors in cold standby. For this purpose only one plant is stopped for maintenance at the same time (maximum maintenance duration of 15 days).

No major intervention is possible on the parts remaining cold.

For Cryogenic equipment, Run 2 duration is in the range 40000 running hours. This length is high compare to the Main Time Between Maintenance (MTBM) of equipment.

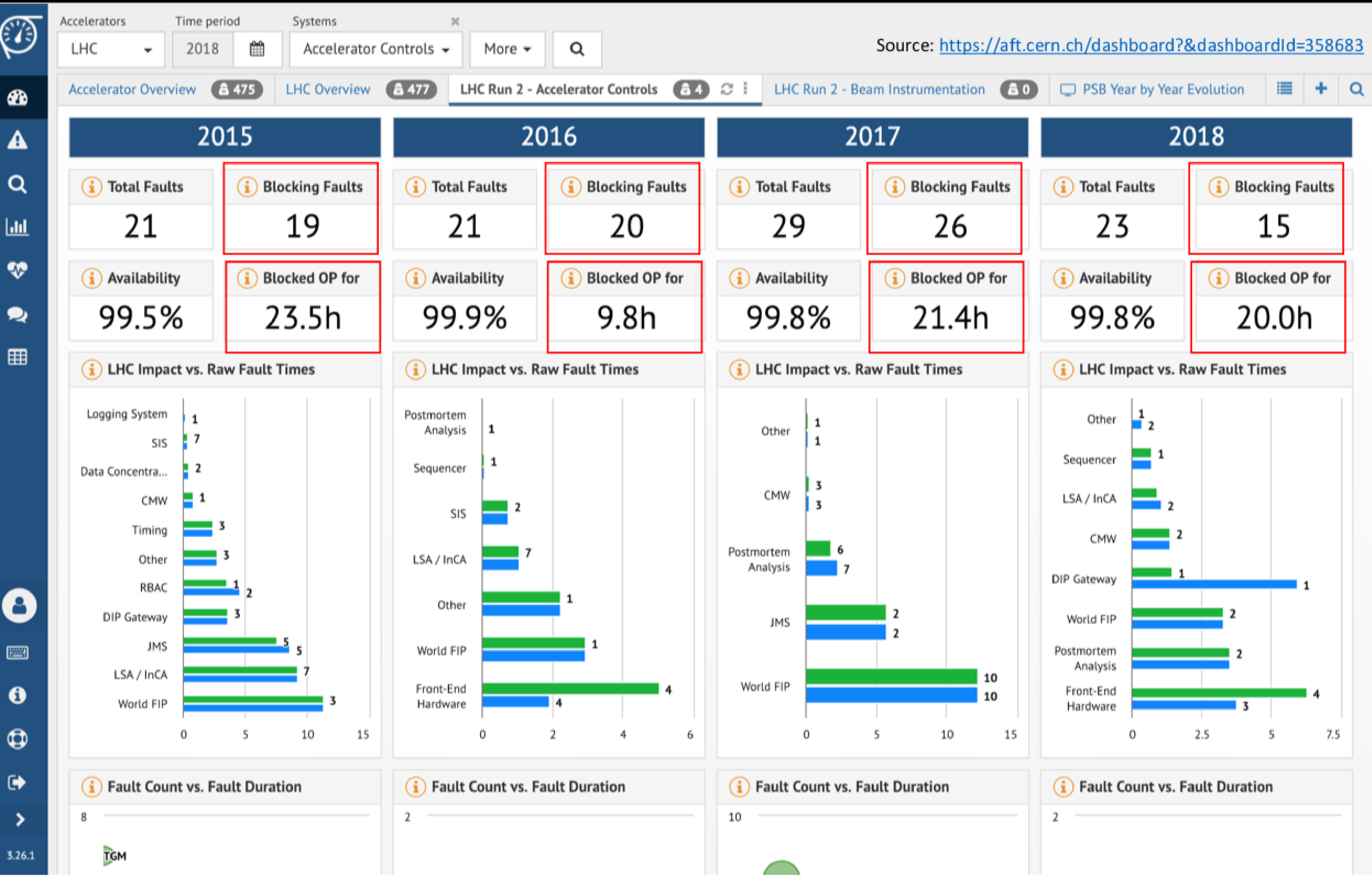
Run2 type duration (4.5 years of run) is the maximum acceptable limit for current equipment compatible with availability in the range 97 to 98%

LHC Cryo Helium balance overview over Run 1&2



Controls & AFT

Controls Performance 2015 – 2018



NXCALS Status

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

The core is essentially ready:

- Production hardware (20 machines, 960 Cores, 8 TB RAM) since April 2018, with internal storage compaction, metadata service, etc.
- CMW data ingestion processes operational.
- New logging can be configured with a click in CCDE (no more Excel).
- WinCCOA data ingestion processes developed in collaboration with BE-ICS – undergoing final testing.
- Apache Spark based data extraction / analysis software & SWAN integration (Web based analysis notebooks).

Part of the core has been developed via a very positive collaboration between BE-CO and TE-MPE, with the aim of using NXCALS for the new Post Mortem Archiving.

see status@LMC 360 for more details

NXCALS Data Analysis & Extraction I

How can I extract and analyse data?

Data can be extracted or analysed via the NXCALS client API (based on Spark).

For best performance, data analysis should be performed on the NXCALS cluster and only return the results.

Users can also perform interactive analysis using SWAN.

NXCALS Extraction Documentation with CALS equivalent examples: http://nxcals-docs.web.cern.ch

Work started on adapting the current CALS data extraction client API to pull data from NXCALS.

- Aim: enable existing CALS clients to move to NXCALS without re-writing their code.
- A first release with only the most common methods will be available ASAP and before mid-2019.

NXCALS Data Analysis & Extraction 2

What about Performance compared with CALS?

Based on feedback from early adopters in ABP, BI & ABT:

- CALS currently outperforms NXCALS for *extraction* of relatively small data sets.
  - There is scope to tune NXCALS, but this is time consuming and not currently a priority (will come back to this in the future).
  - On-going 3rd party developments should also help improve.
- NXCALS far outperforms CALS for *analysis* of big data sets.
  - Requires learning and using Spark to run analyses on the cluster.
  - Satisfy use cases not possible with CALS e.g.
    - Diamond BLM analysis at IP7 & 16L2 (20-50GB/day ~1 hour) J. Kral, BE-BI
    - Annual intensity analysis (~2 hours) A. Huschauer, BE-ABP

Reminder – change of paradigm:

- from: "extract, then analyse"(CALS)
- to: "send algorithms to where the data is" (NXCALS)

NXCALS Data Analysis & Extraction 3

Will "Variables" continue to exist?

"Variables" continue to exist with NXCALS in addition to new support for Device/Property based data extraction and analysis, which in-turn can facilitate "replay" functionality.

What about PyTIMBER?

PyTIMBER will continue to exist with NXCALS and users will not need to change their code.
Users should eventually use PySpark for best performance by running their processing on the NXCALS cluster.

What about TIMBER?

A new TIMBER web application will replace the current Java Swing application. Expect a first version before the end of 2019. Ideally it will combine with Statistics and be accessible from outside CERN (requires further analysis & discussions with IT).

Radio Frequency System

RF power limitation at injection

Initially the energy ramp and flat top were consider as a limitation for the HL-LHC (target intensity of 2.3×10^{11} ppb) → full-detuning beam loading compensation scheme since 2017

Available klystron power

Klystron HV	Cathode current	DC power	RF power(*)	Measured saturation
50 kV	7.8 A	390 kW	230 kW	190 – 220 kW
58 kV	8.6 A	500 kW	300 kW	250 – 280 kW

* assuming a klystron efficiency 60% (the expected ageing effect may reduce performance)

MD#3 and MD#4 on power consumption at injection (optimized loaded Q and cavity tune)

- MD#3 at 50kV, 1.15×10^{11} ppb
  - 9MV → all lines saturated
- MD#4 at 58kV, 1.3×10^{11} ppb (with circulating beam instead of injection transient)
  - 10MV → with the voltage partition

to be continued

see Helga's talk

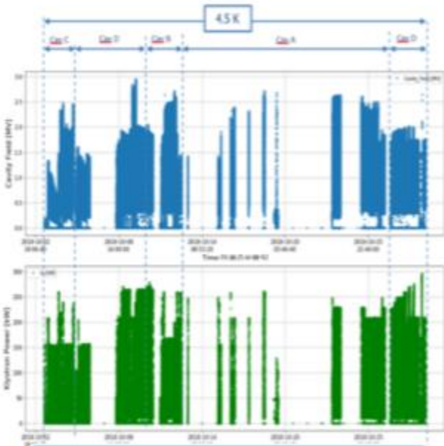
Successful test of the spare LHC ACS CM

Test of spare LHC ACS module with new pumping crosses in October 2018 (America, taken out in LS1)

- **2.5MV @ Qx=60k (flat top) and 1.5MV @ Qx=20k (injection position), all cavities were able to work stably for several hours**
- Additional studies and tests such as HOM measurement and TDR of field antenna have been performed
- The M9 horizontal test bench in SM18 was brought back in operation → **to be continued**
- A significant number of software updates and improvements have been introduced following the user interface adaptation → **to be continued**

Assembly of new pumping crosses

CM installation and RF Test



CM validation

LHC injection system

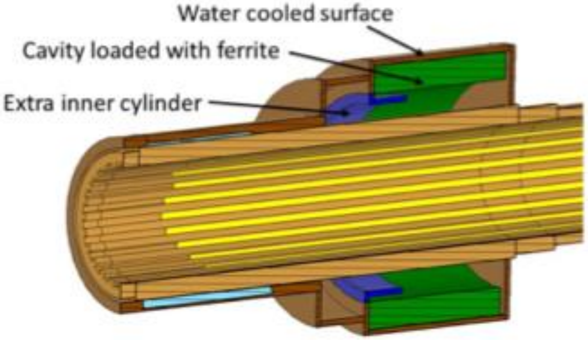
LHC injection system availability 2018

→ 99.3% availability (48h on average) of the LHC injection system in 2018

↳ Slightly worse than 2017, which was the best year in terms of availability for run II

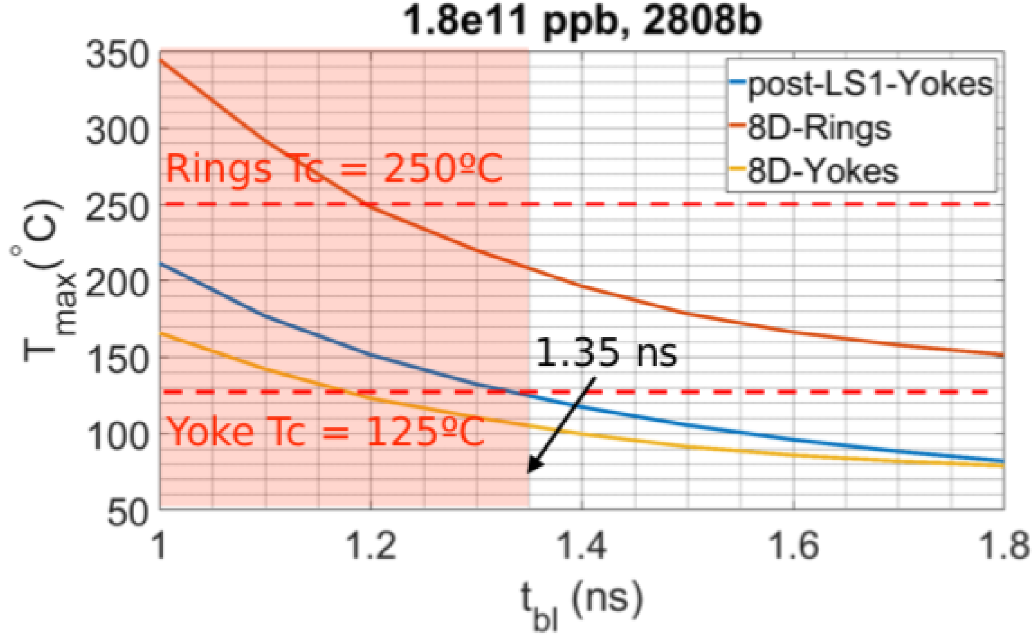
What will change after LS2?

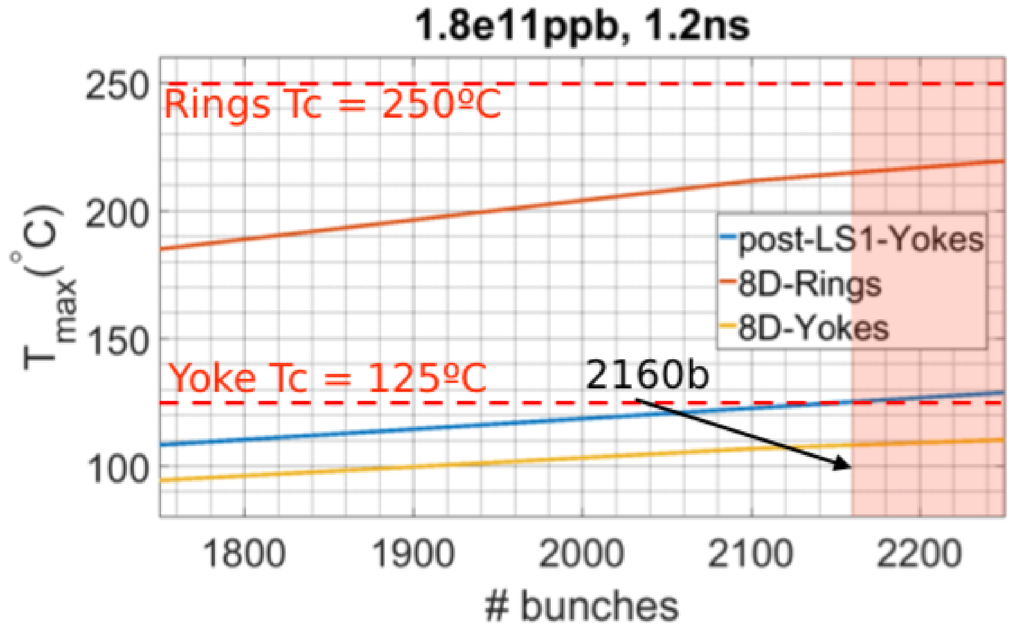
- **New transfer line collimators to cope with the increased beam brightness towards HL-LHC**
  - TCDI from 1.2 m to 2.1 m graphite (and/or 3DCC)
  - Designed to withstand 288 bunches of 2.0e11 p/b in 1.3 um emittance
  - Re-matched optics in TI2 and TI8 to satisfy beam size requirements at $\beta_x \times \beta_y > 3600 m^2$
- **New LHC injection protection/dump - TDIS (segmented)**
  - From 4.185 m single-block device to 3-block device of 1.6 m length each - individually movable
    - Design to withstand all LIU/HL-LHC baseline beams up to 2.0e11 p/b in 1.37 um emittance
- **Replacement of MKI2B with "MKI Cool" to complete new MKI design validation**
  - Water cooling of surface in contact with ferrite rings
  - It will give even better thermal performance than MKI8D
  - Limits for run III still dictated by post-LS1 design (6 of 8 magnets)



Can we reach 1.8e11 p/b in 1.8 μm?

- **OK for TCDIL and TDIS**
- **MKI:**
  - Steady state approach used
  - Assuming 2808b with 1.8e11 p/b, equidistant and equi-populated bunches with Gaussian longitudinal profile
  - Assuming 1.8e11 p/b, t_{bl} = 1.2ns, equidistant and equi-populated bunches with Gaussian longitudinal profile





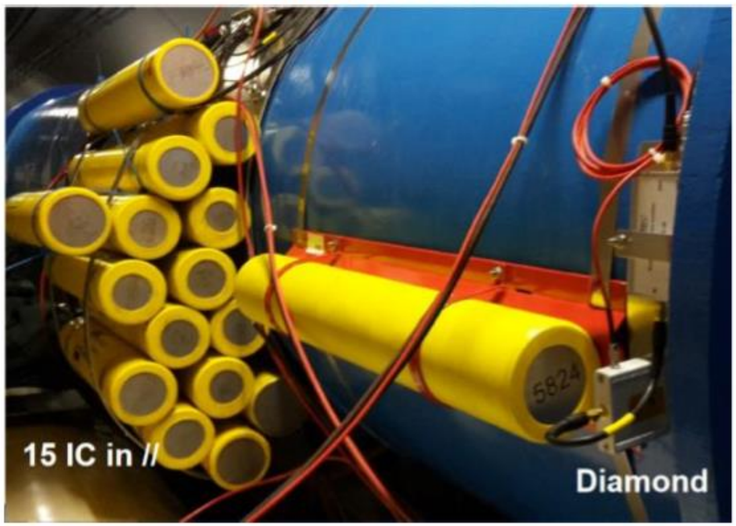
- <u>These limits are intended for normal operation.</u> In case of usage for specific tests, **depending on the operational conditions foreseen (previous cool down, time at flat top, etc.), allowed parameters (N of bunches and bunch length) to be evaluated**

=> <u>1.8e11 p/b not excluded and OK for normal operation with limitations as indicated in the plots!</u>

LHC Beam Instrumentation

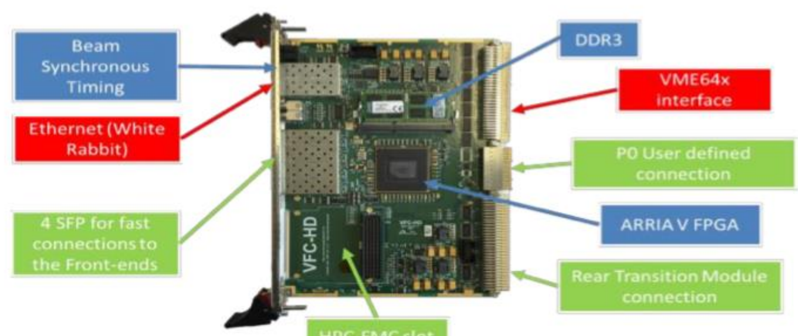
- **BPM** (orbit, interlock, DOROS), **BLMs** (main, diamond), **BCTs** (DC, fast), **feedbacks**, **BBQ**, **Schottky**, **instability**, **special** diagnostics

BLMs for 16L2



TIM-based irradiation station

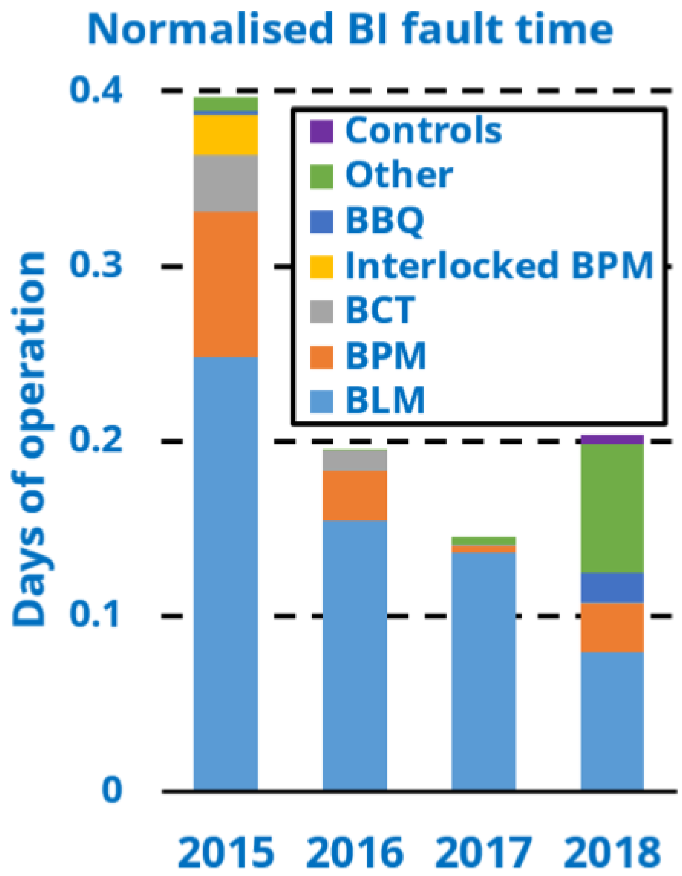
VFC-based processing module



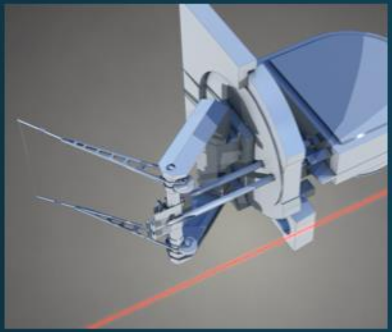
VFC-HD with optical SFPs

Run 2 LHC BI availability

- Decreasing trend until 2018
  - Spike mainly due to “Other” (WS: 54%, BTV: 29%, BSRA: 17%)
  - Best BLM performance ever
  - Increased availability due to actions taken in LS1
- Since 2018 tracking of “Controls”
  - Mostly software faults reassigned to BI after analysis
- AFT could be a good tool for internal BI fault tracking and analysis



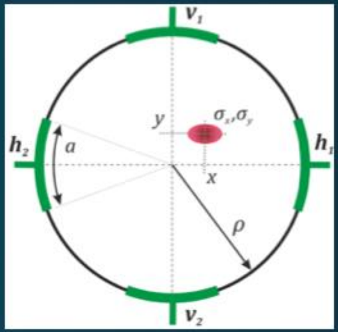
Emittance measurements



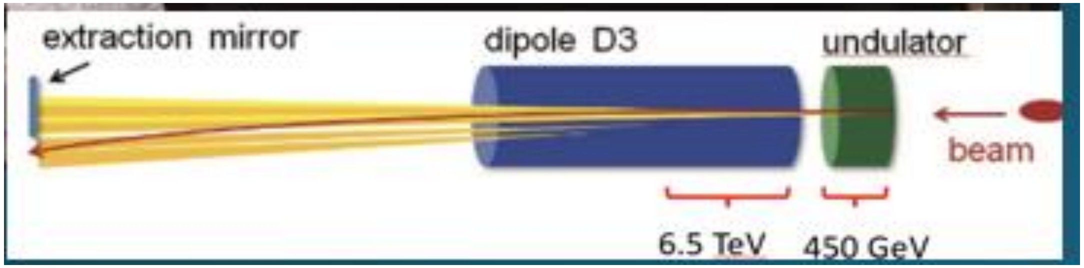
Wire Scanners

Synchrotron Radiation Monitors

Beam-Gas Vertex detector



Beam Position Monitor



BSRT Issues

Run II :optical damage on filters and camera observed

I.I. non uniformity response

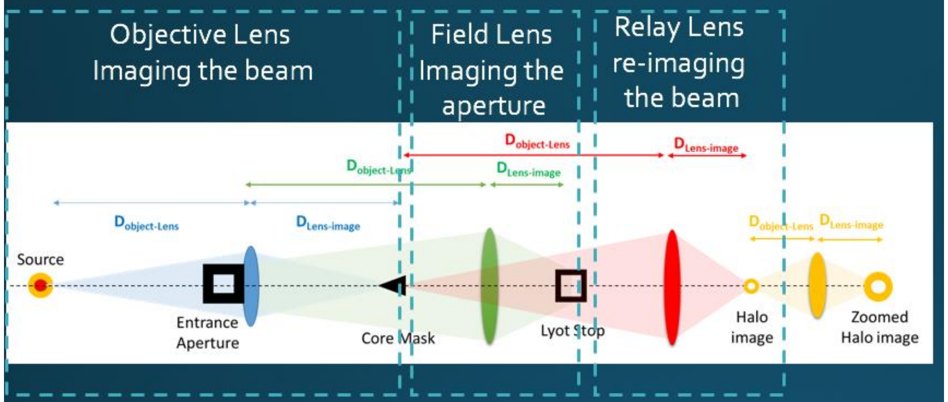
Mitigated with the implementation of the "spot painting" (x,y camera TS)

Observed etching of the viewport material
During YETS change of the viewport (same issue appeared again end RunII)

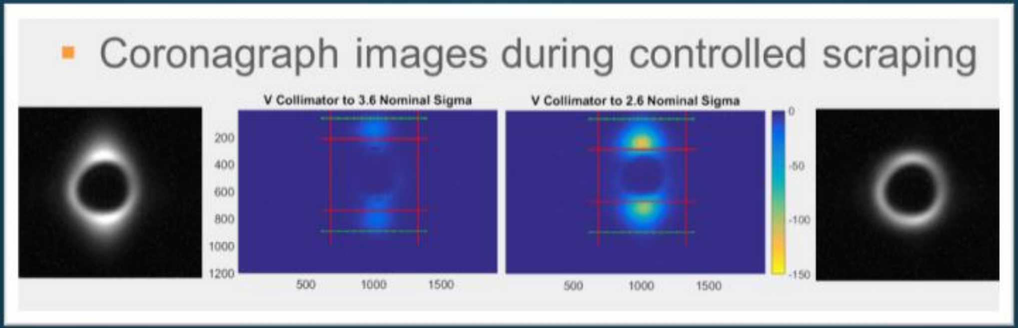
Focused SR power damaged the 250nm band pass filters

Mitigated via relocating in the SR path to a less focused spot

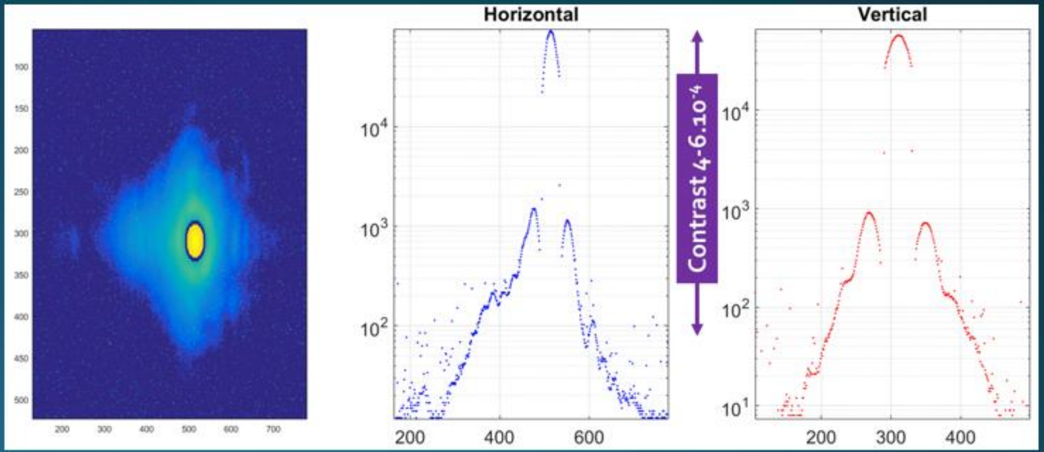
Coronagraph



Demonstrated capability to measure halo during controlled experiment (both at 450 GeV and 6.5 TeV)



- At top energy, sensitivity to halo variation was found 10 times worse in horizontal than in vertical.
- Hypothesis: linked to the extended source
- Simulations ongoing to overcome this issue with a better angular selection of SR light.



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