Highlights from the 9th LHC Operations Evian Workshop (January 30th to February 1st, 2019)

C. Wiesner, M. Mentik, D. Wollmann

February, 28th 2019

9th LHC Operations Evian Workshop

Five Sessions:

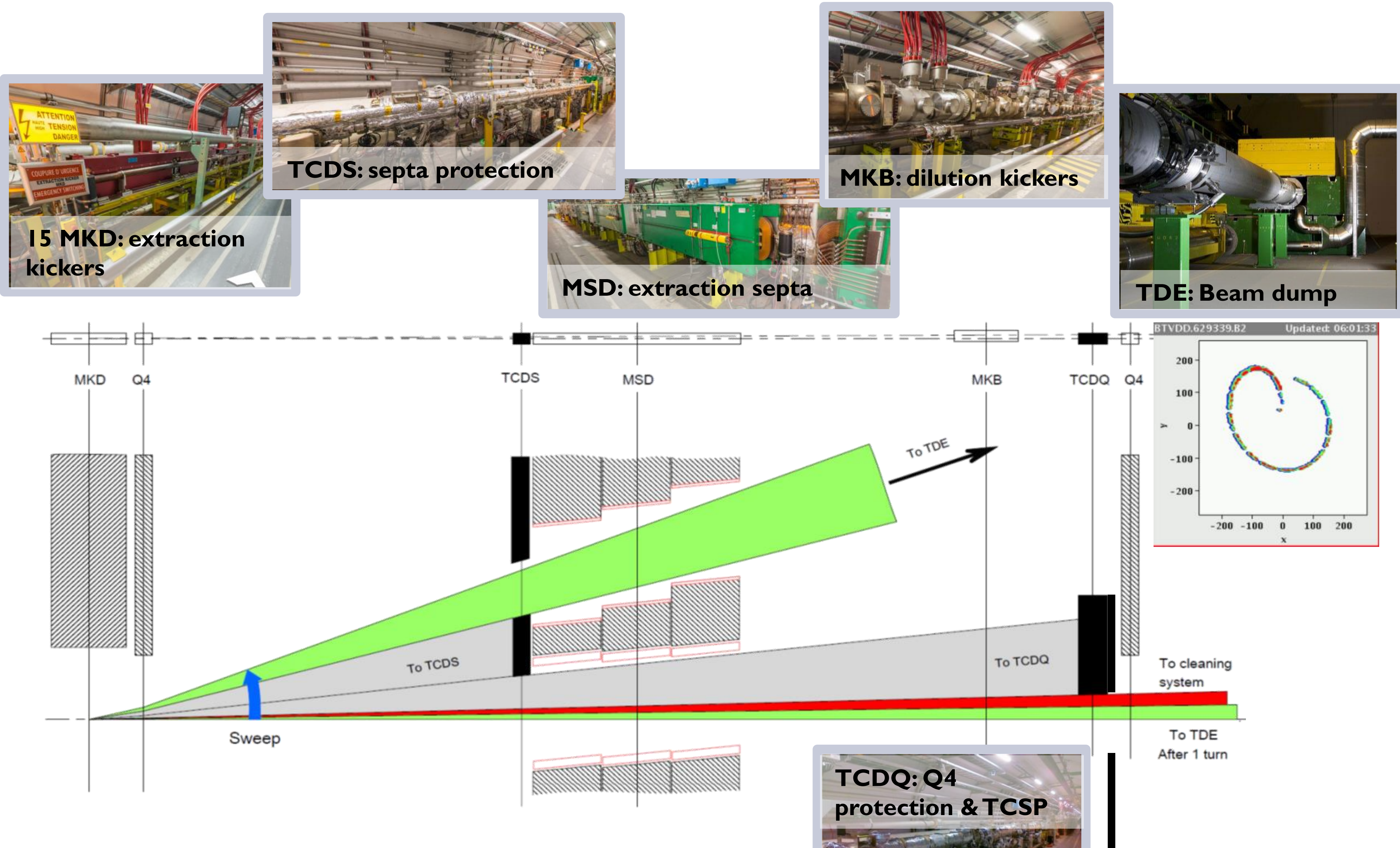
1. Overview of Run 2
2. Systems Overview
3. Systems Overview (with some beam dynamics)
4. Beam Performance during Run 2
5. A Preliminary Look Ahead

33 Presentations accumulating to 11 hours
6 hours of discussions

Personal, not complete, summary focusing
on machine-protection relevant questions

Slides for all presentations (and proceedings/minutes) can be found at:
https://indico.cern.ch/event/751857/timetable/#20190130.detailed

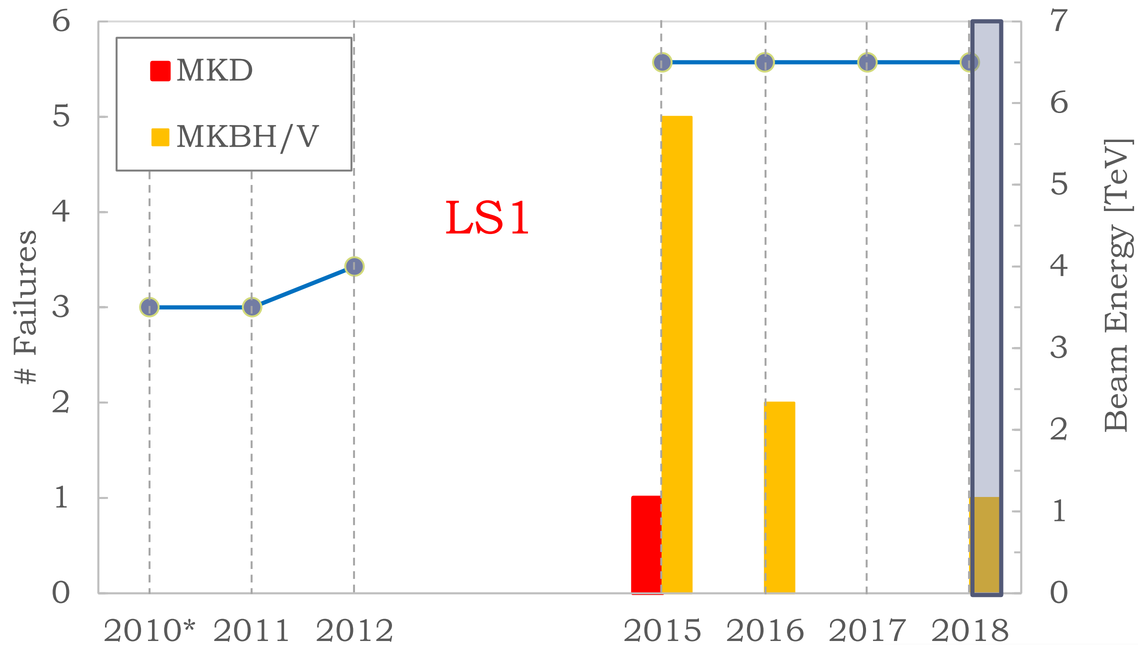
The LHC Beam Dump System



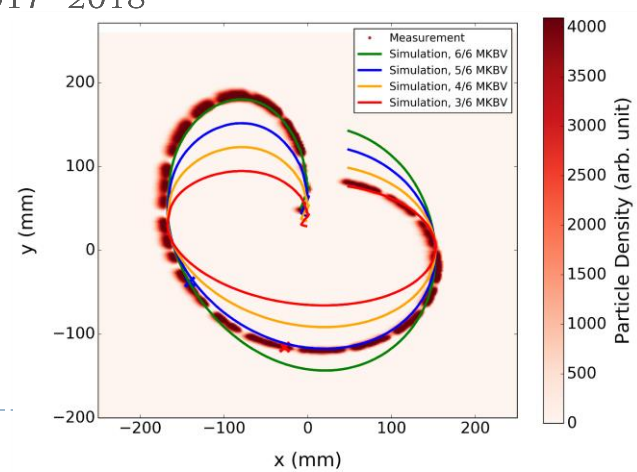
C. Bracco, LBDS Performance in Run II

Run II Performance

MKD/MKB Erratic/Flashover with beam at top energy

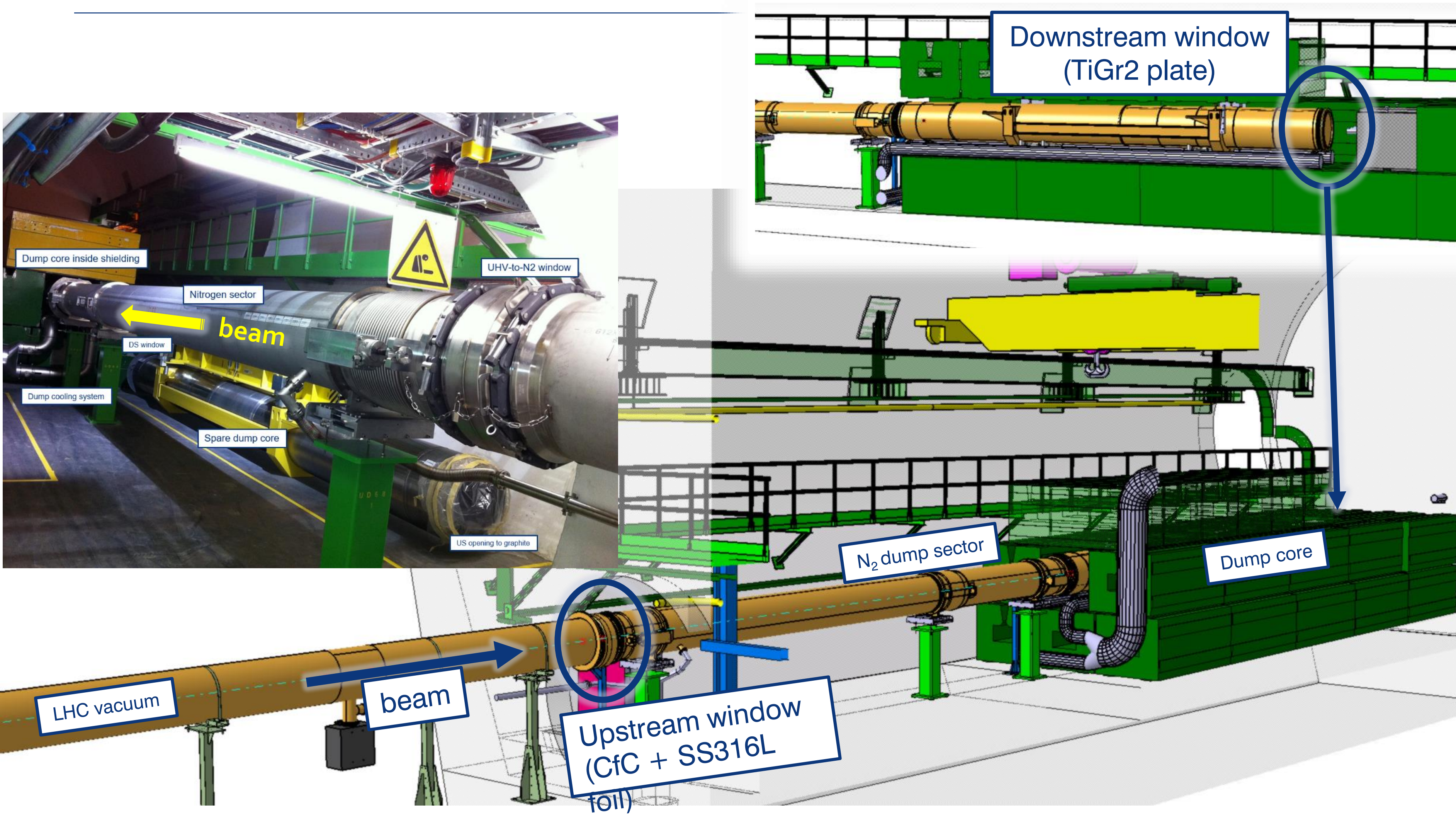


- **A few kicker failures per year** (erratics and flashover) **occurred** and **will continue to occur**, especially when operating at **higher energy** (higher voltage)
- **Weaknesses** and **new kicker failure types** (type 2 MKD erratic, ~3 “missing” MKBs) were identified during past Runs ➔ **impact on** beam load for **dump protection elements and TDE**

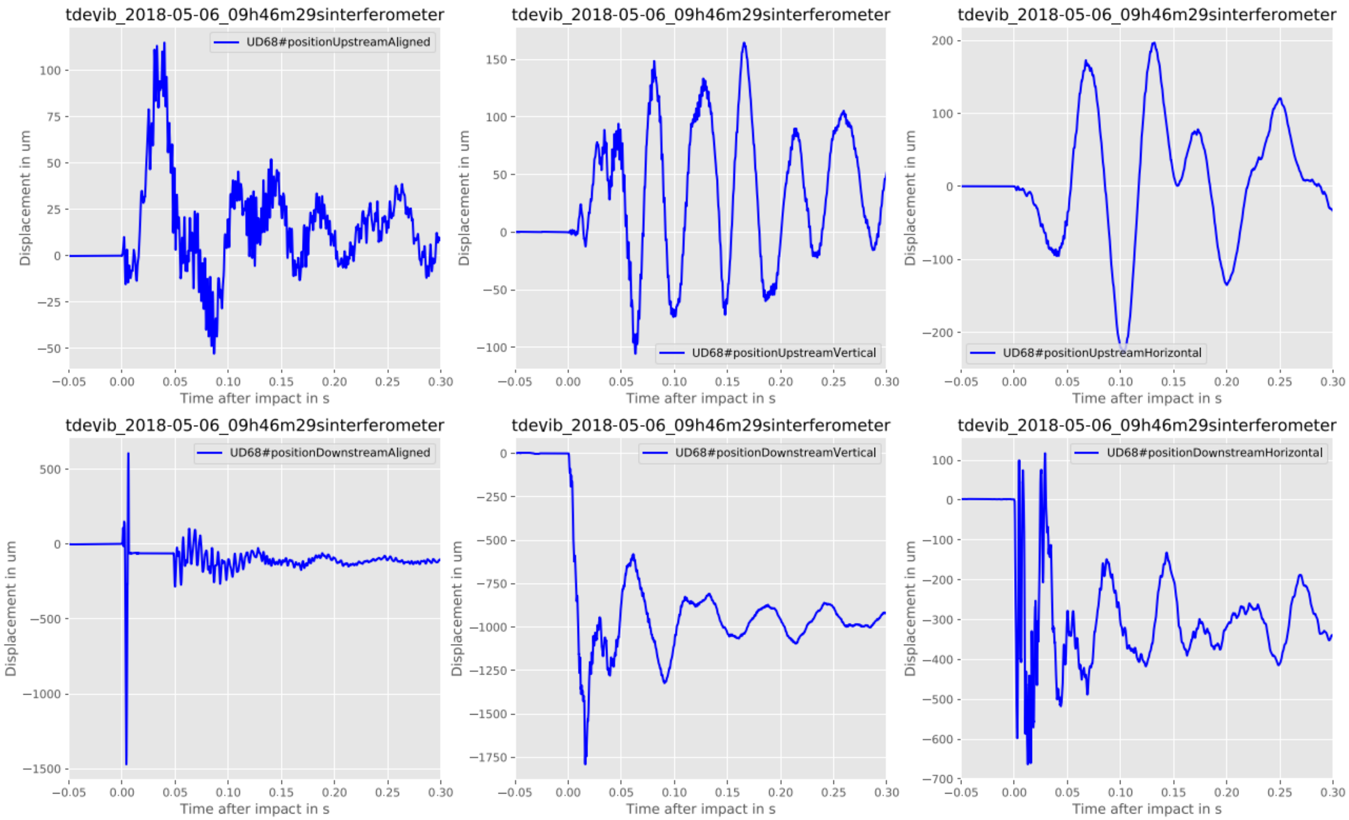


- From C. Bracco, LBDS Performance in Run II

LHC Dump Layout

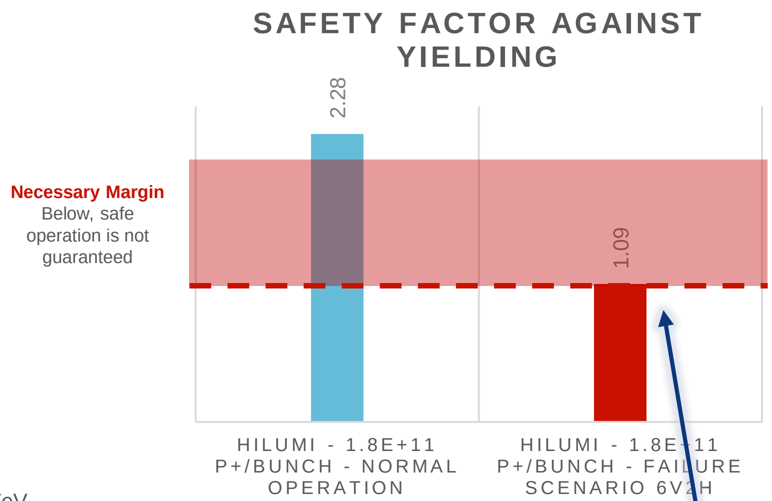


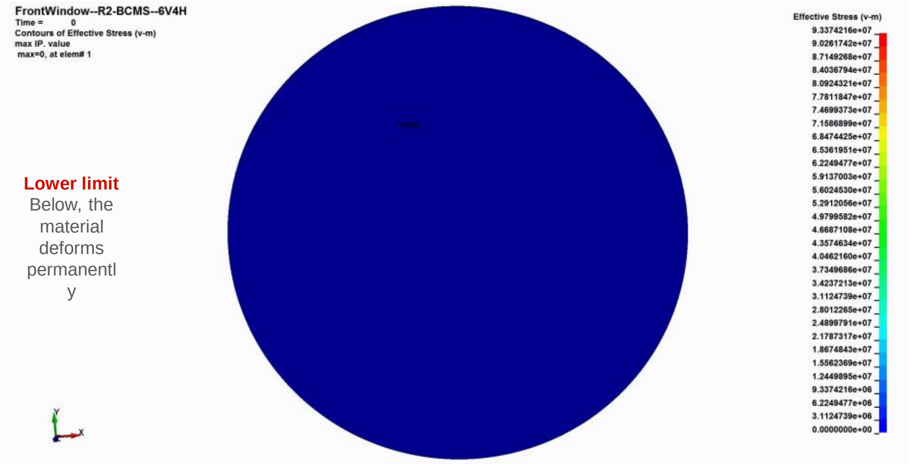
Interferometer measurements



Large displacements measured

Upstream Window under 1.8E+11 ppb





Energy per proton: 7TeV
Number of protons per bunch: 1.8E11
Emittance: 1.7µmrad
Bunch length: 25E-9s
Beam Pattern: HL-BCMS 6V2H with 2604 bunches
Material parameters and yield strength determination according to EDMS **2029814**
LS-Dyna Version: 11.0, double precision

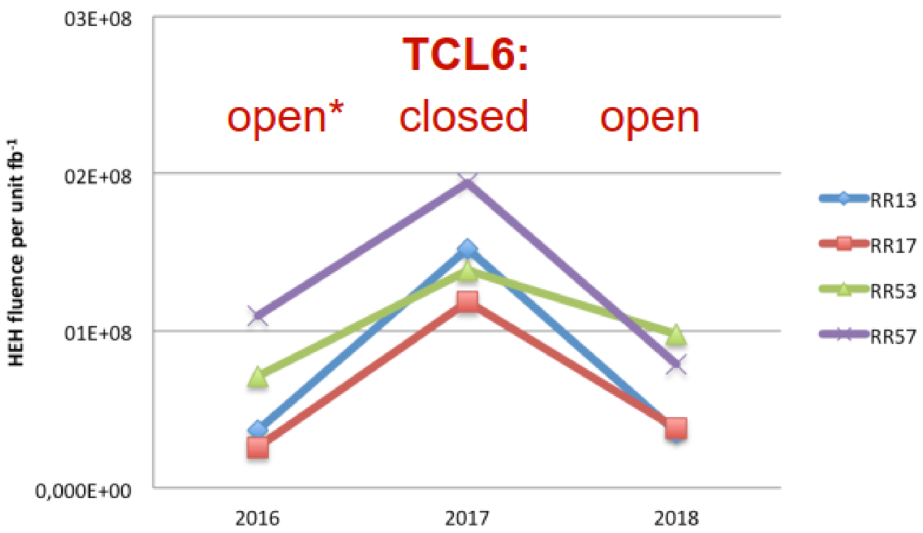
$$S_y = \frac{R_y}{\sigma_{eq}}$$

Too high risk of failure!

Ti Gr5 required

To be done not before YETS 21/22
In collaboration with TE/VSC

Radiation levels in RRs in P1 & P5 dependency on TCL6 settings



R2E failures **2017** vs. **2018**

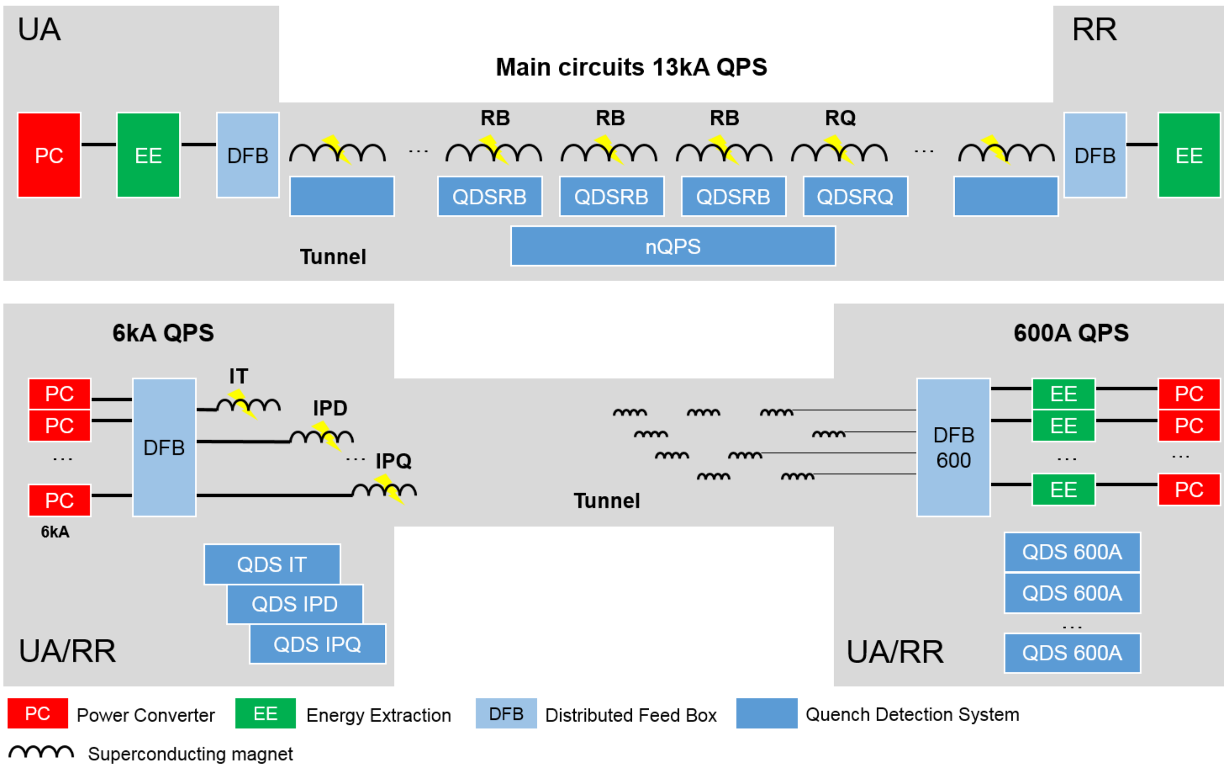
Converter	Power	Controls
LHC4-6-8kA	- / -	- / -
LHC600A-10V	3x / 6x	2x / 2x
LHC120A-10V	- / -	5x / 3x

Reduction of **~4x** for **IP1** & **~2x** for **IP5** in 2018 vs. 2017 but increase in P7 due to betatron losses.
The ARC rad-levels increased due to open TCL6 impacting MPE equipment in DS (increase in cell8).
From the R2E perspective: preferable **post-LS2** configuration will be TCL6 closed, owing to radiation hardness of RR EPC equipment.

OP question: Replace more Power Converters affected by zero-volt crossing?

QPS Hardware

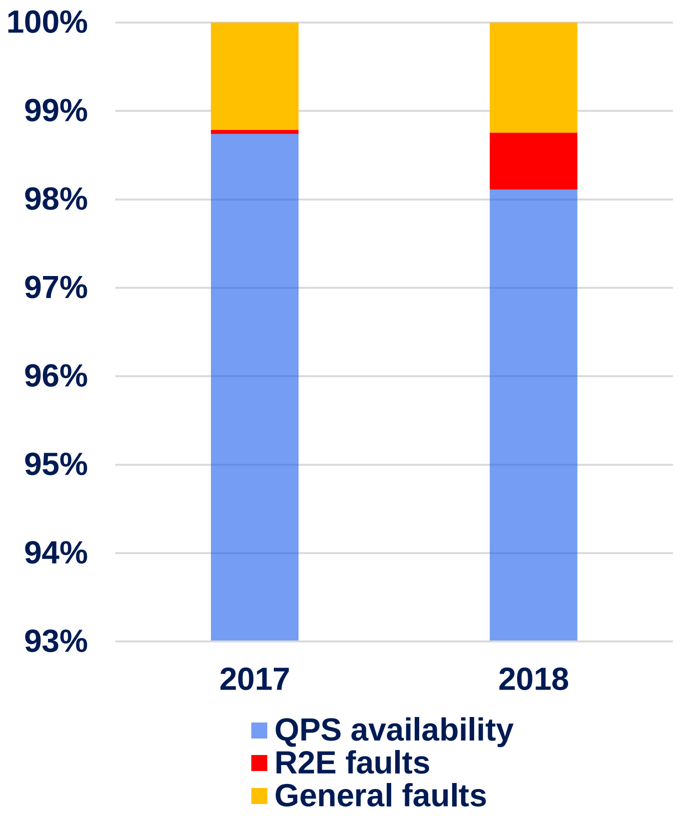
13800 hardwired means to stop LHC



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**

QPS availability

- Overall, excellent availability of QPS
- TCL collimator settings in 2018 significantly affected QPS downtime



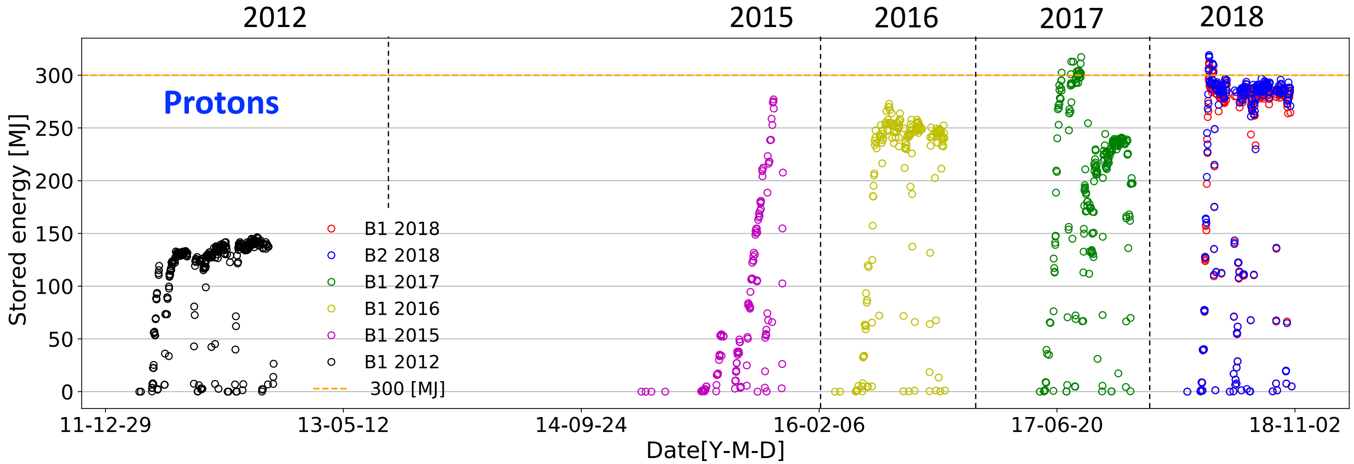
Comment Rende: “Before LS1 everybody was impressed about the number of faults now we are all impressed by the excellent availability”

From T. Podzorny, Quench Protection System

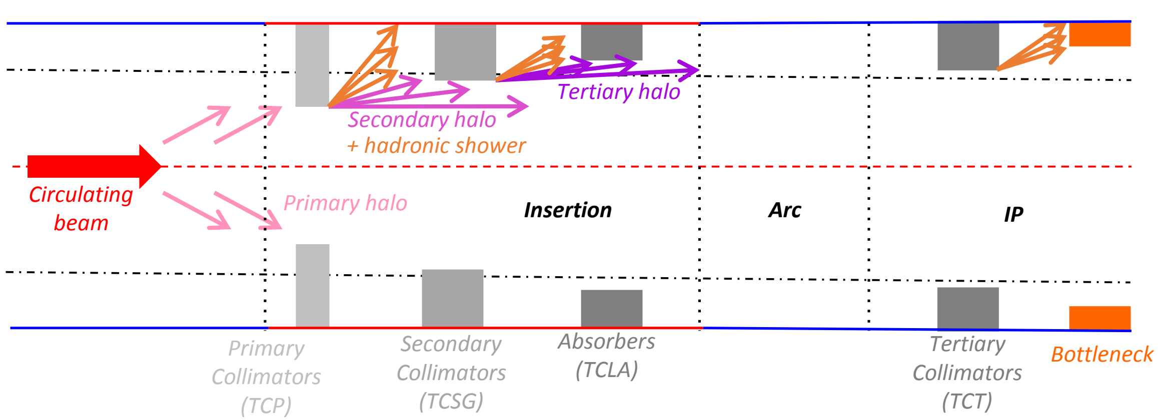
Collimation

Introduction

The multi-stage LHC collimation system aims to control the regular and abnormal losses to reduce the risk of quenches of the superconducting magnets.



Thanks to D. Mirarchi

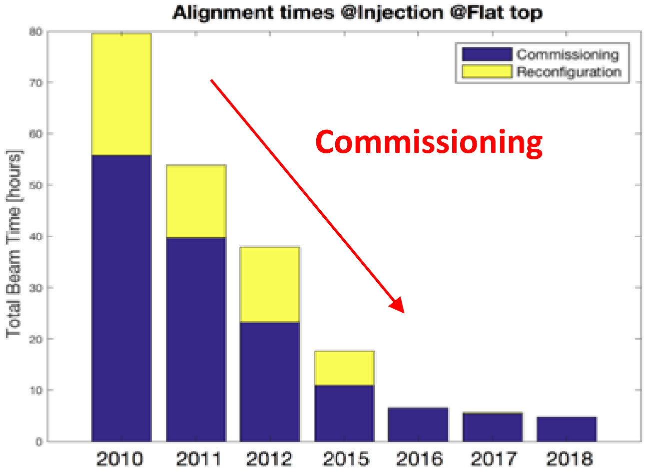


No magnet quenches from circulating proton beams with stored energy close to 300 MJ accommodating all machine configurations! Thanks to the good performance of the collimation system

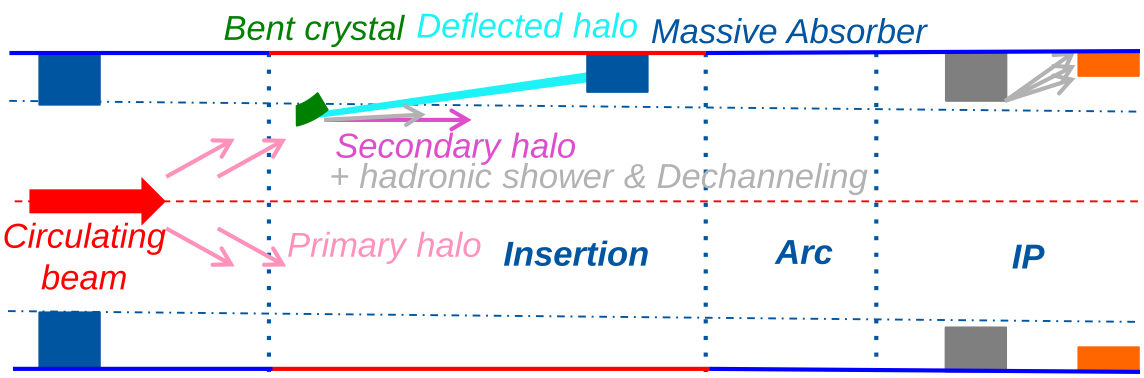
and also to the very good beam lifetime and orbit stability!

Collimation

Collimator Alignment



Crystal Collimation



From N. Fuster-Martínez, Collimation

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?!

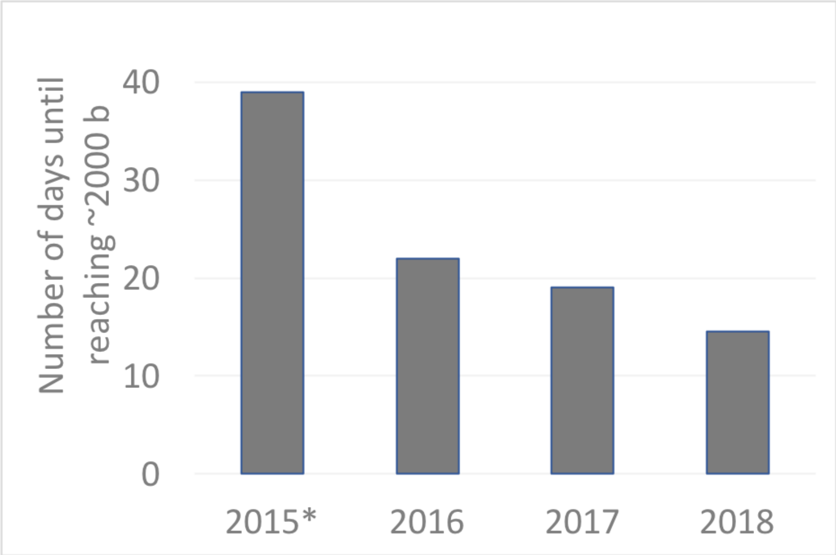
For most cases we lost only 1 protection layer

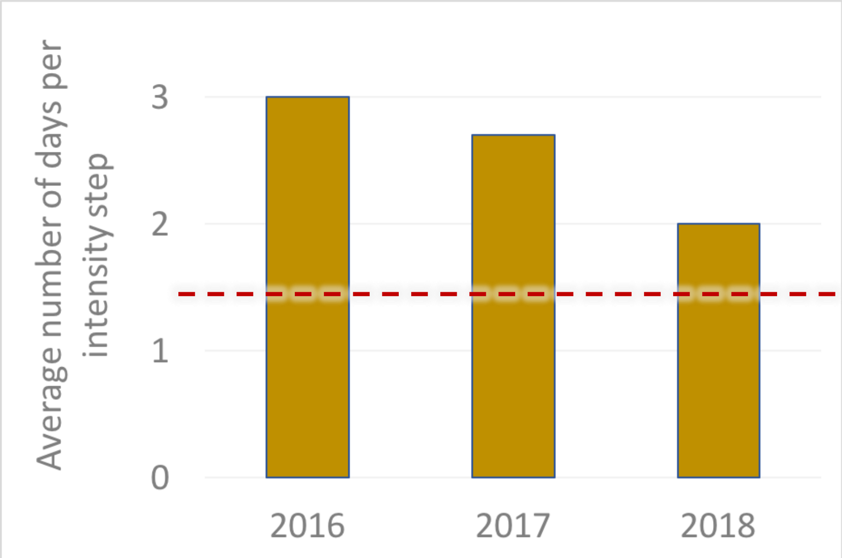
We should become more rigorous and in the future for each such case produce a "major event report"

Intensity ramp-ups Run 2

- 2015: commissioning year
  - 50 ns & 25 ns ramp-up
  - Increase of intensity until end of proton run
- 2016/17/18: 7 steps to reach 2000+ bunches
  - 3/12 - 75 - 300 - 600 - 900 - 1200 – 1800
  - 2016 → 2018: reduction ramp-up length by 35 %

Establish cycle
MP dominated
Intensity dominated

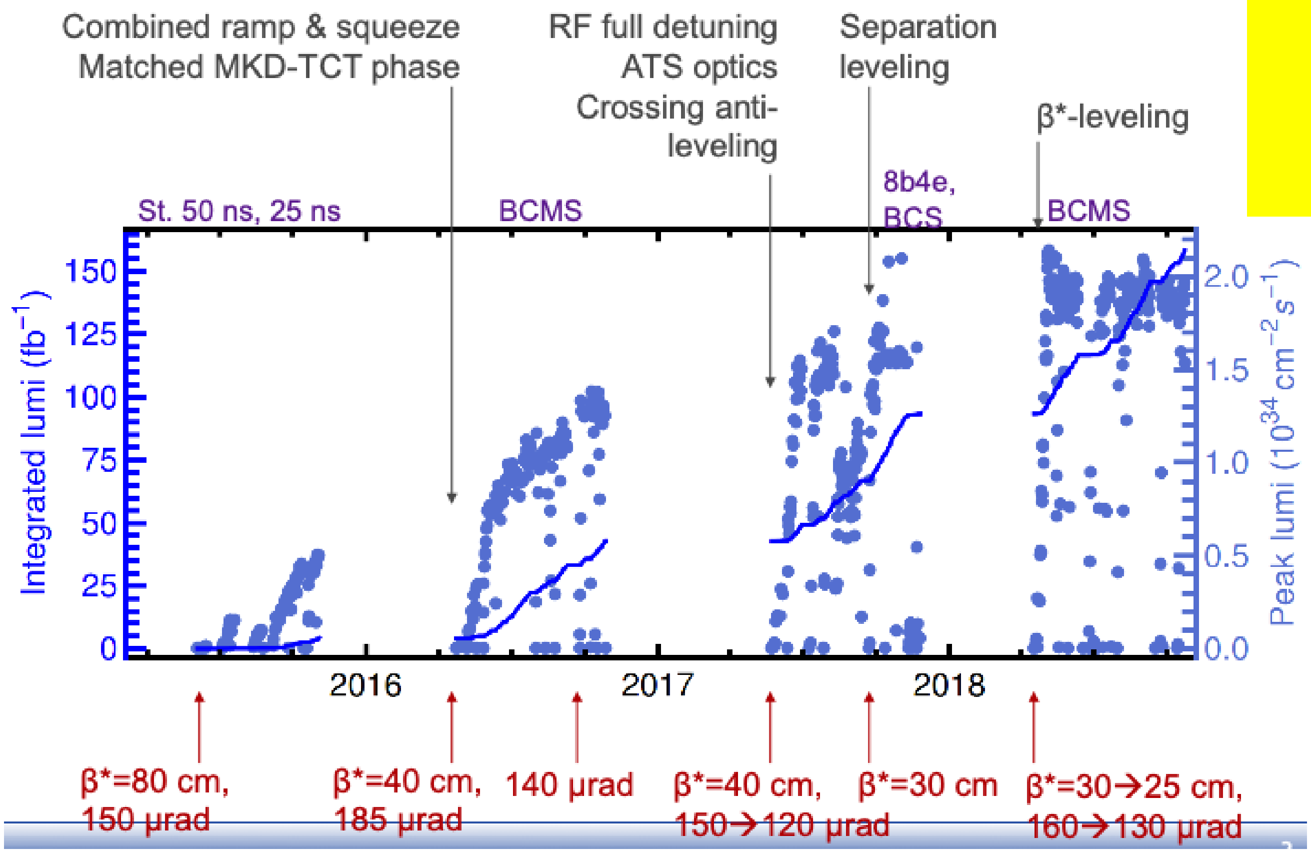




* 2015: 25 ns up to 1825 b

Machine Configuration

The Run 1
"Aperture Platinum Mine"
is depleted



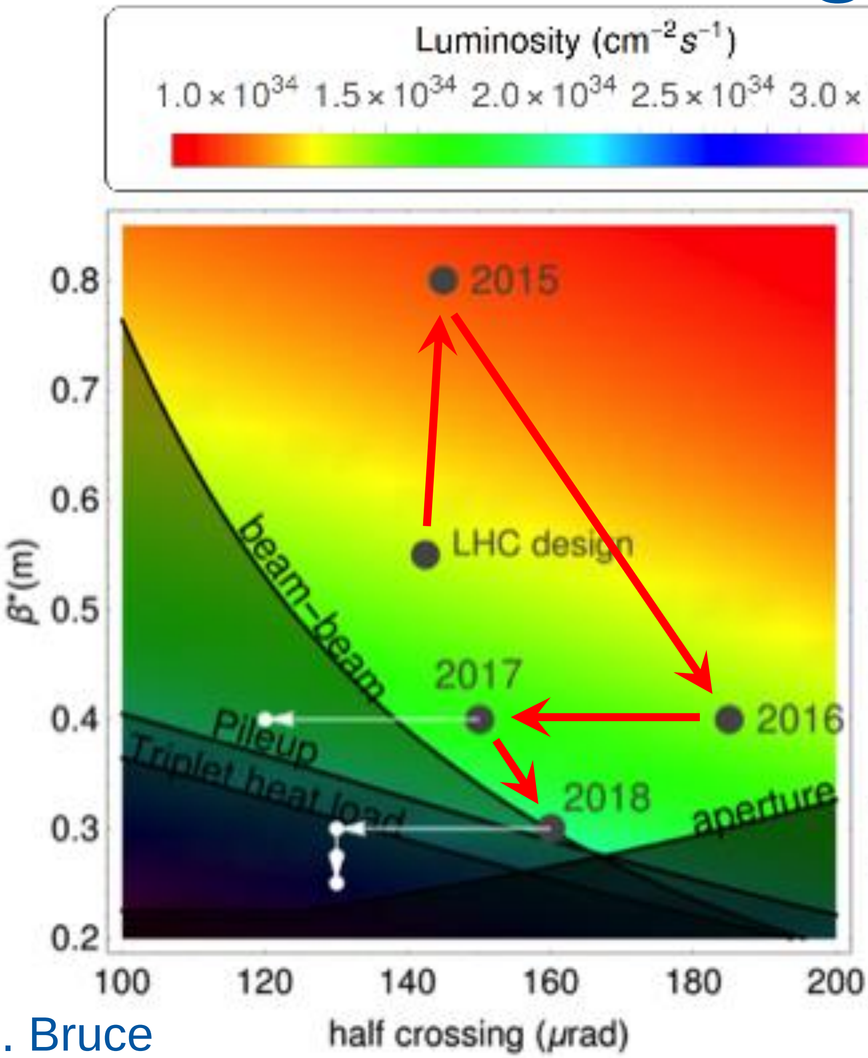
R. Bruce

Comparison: 2018 vs LHC design

- Some keys to good peak performance:
  - Small emittance
    - See talks H. Bartosik, S. Papadopoulou
  - Small β* at collision point
    - Focus of this talk

Parameter	2018	LHC Design
Energy [TeV]	6.5	7.0
No. of bunches	2556	2808
Max. stored energy per beam (MJ)	312	362
β* IR1/5 [cm]	**30→25**	**55**
Half crossing angle IR1/5 [μrad]	160→130	142.5
Normalized beam-beam separation	10.6→7.9	9.4
p/bunch (typical value) [10^{11}]	1.1	1.15
Typical normalized emittance [μm]	**~1.9**	**3.75**
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	**2.1**	**1.0**

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

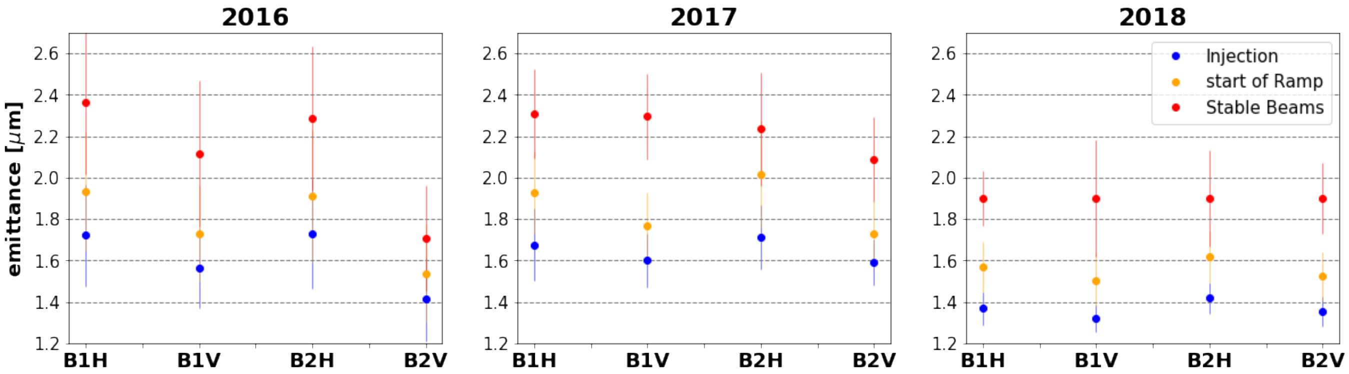
Triplet - max. lumi:
2.2E34 cm^{-2} s^{-1}

For visibility, including only starting configuration for each year

R. Bruce

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

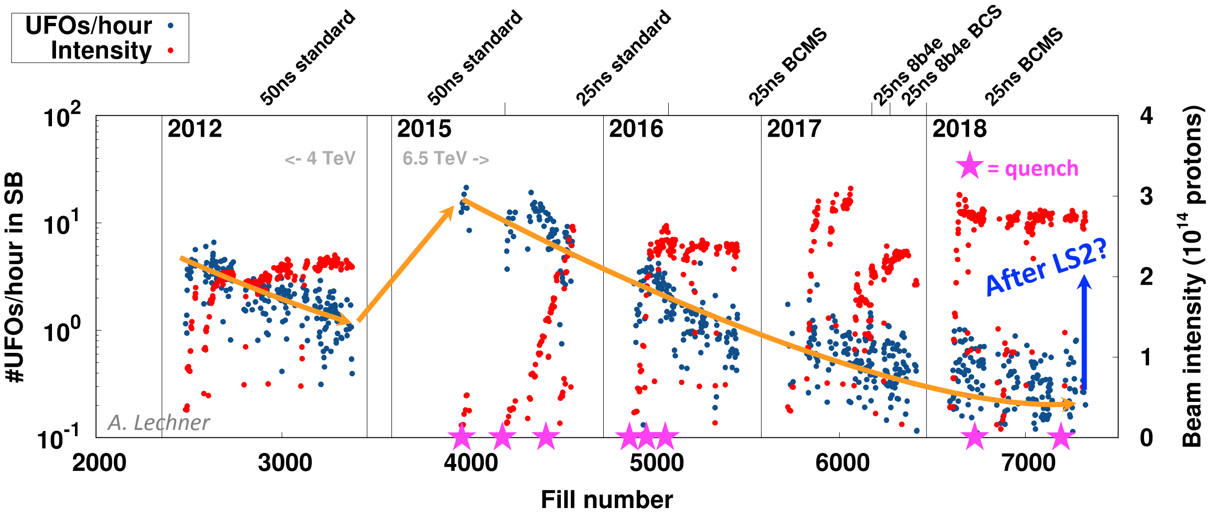
Largest blow up during ramp

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)

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

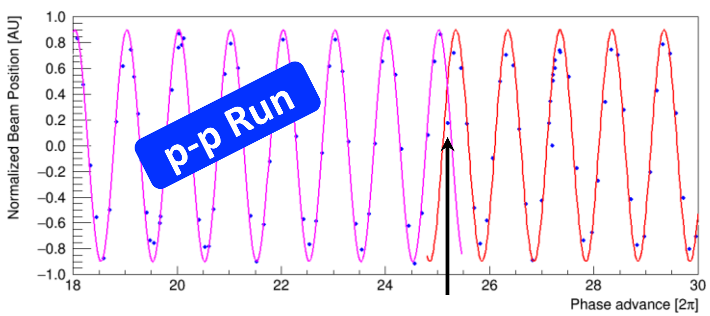


What about the deconditioning and level of UFOs in 2021 ?

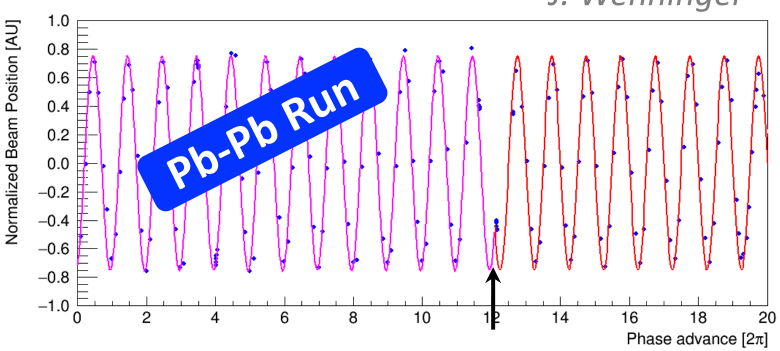
10 Hz: origins of phase shift identified, but real cause not yet !!!

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

J. Wenninger



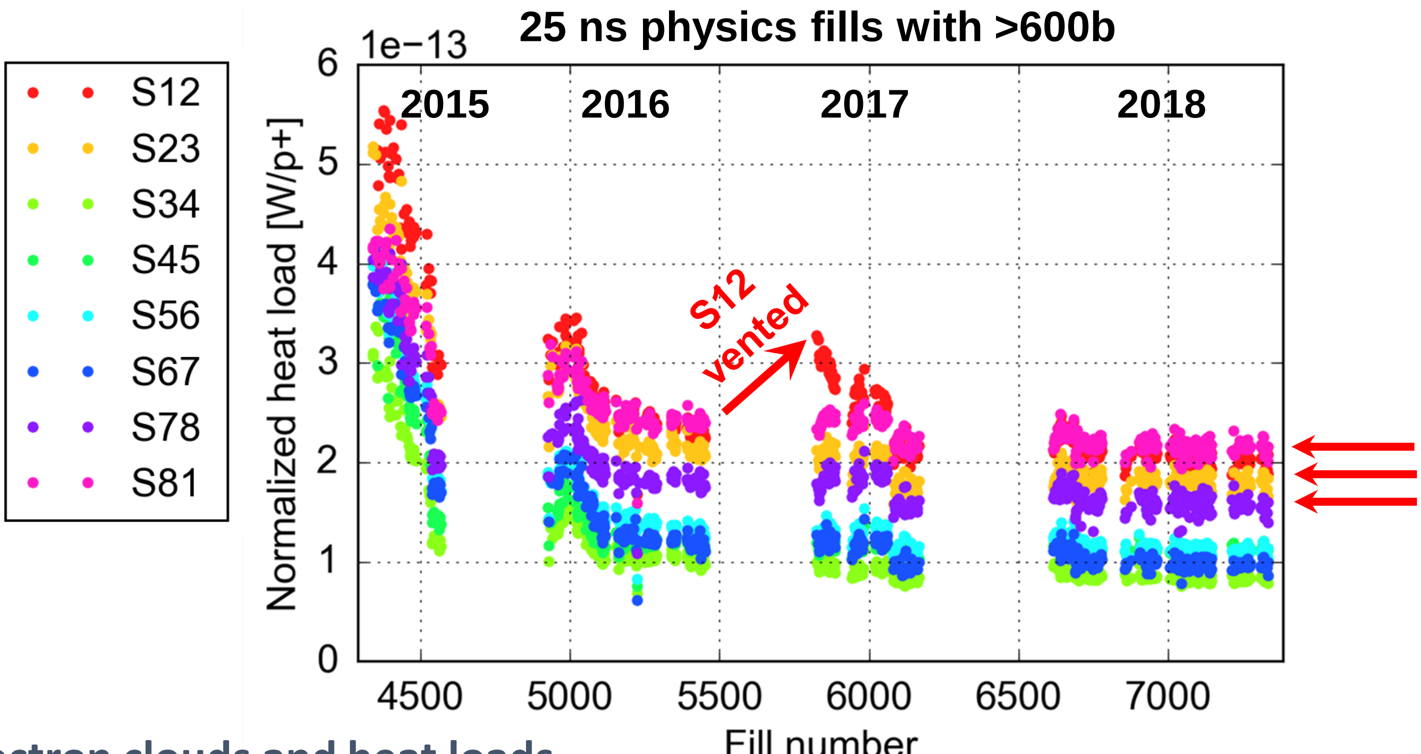
Q21L4



ITR2 ↔ Q5R2

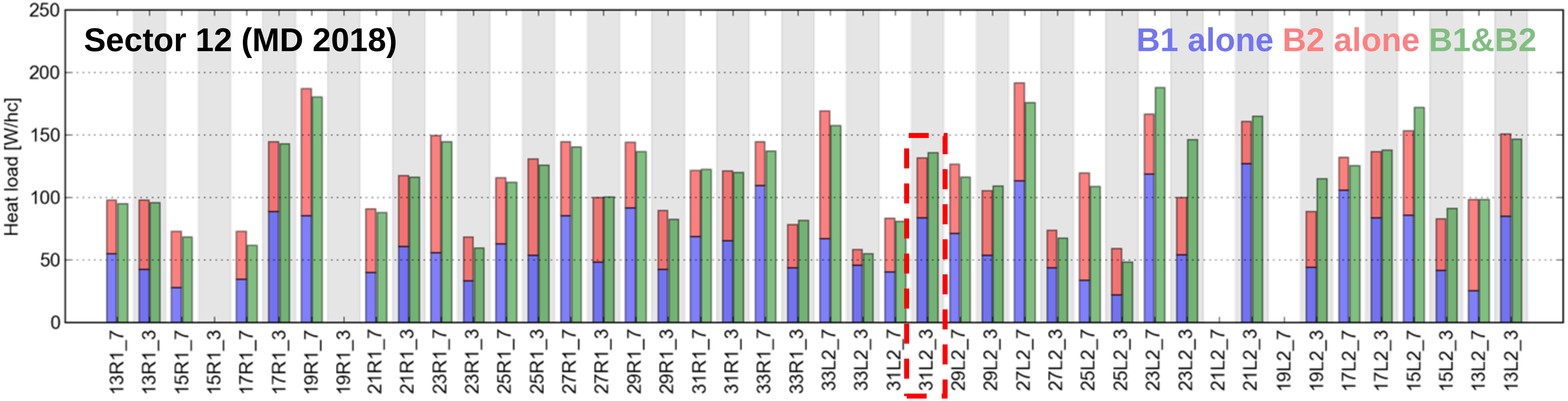
Heat loads: differences among sectors

- Heat loads in **S12, S23, S81** much larger than for the other sectors
  → close to cryo-plant design capacity
- These differences are **very reproducible** and were observed in **all 25 ns fills** over **4 years** (2015-18)

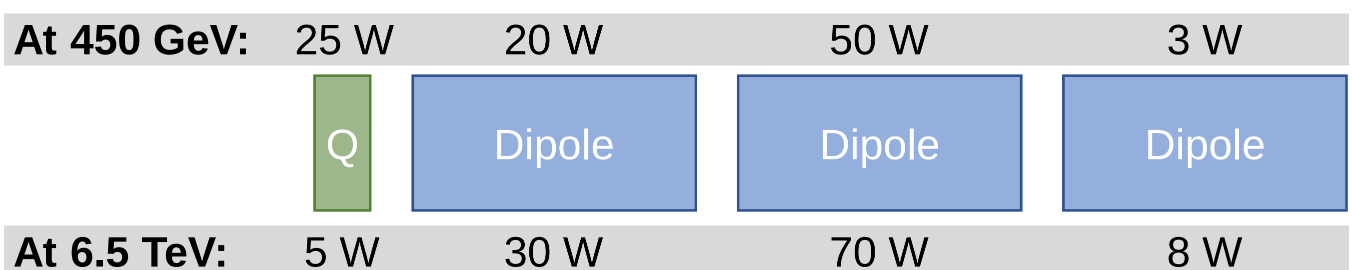


Heat loads: distribution along the ring

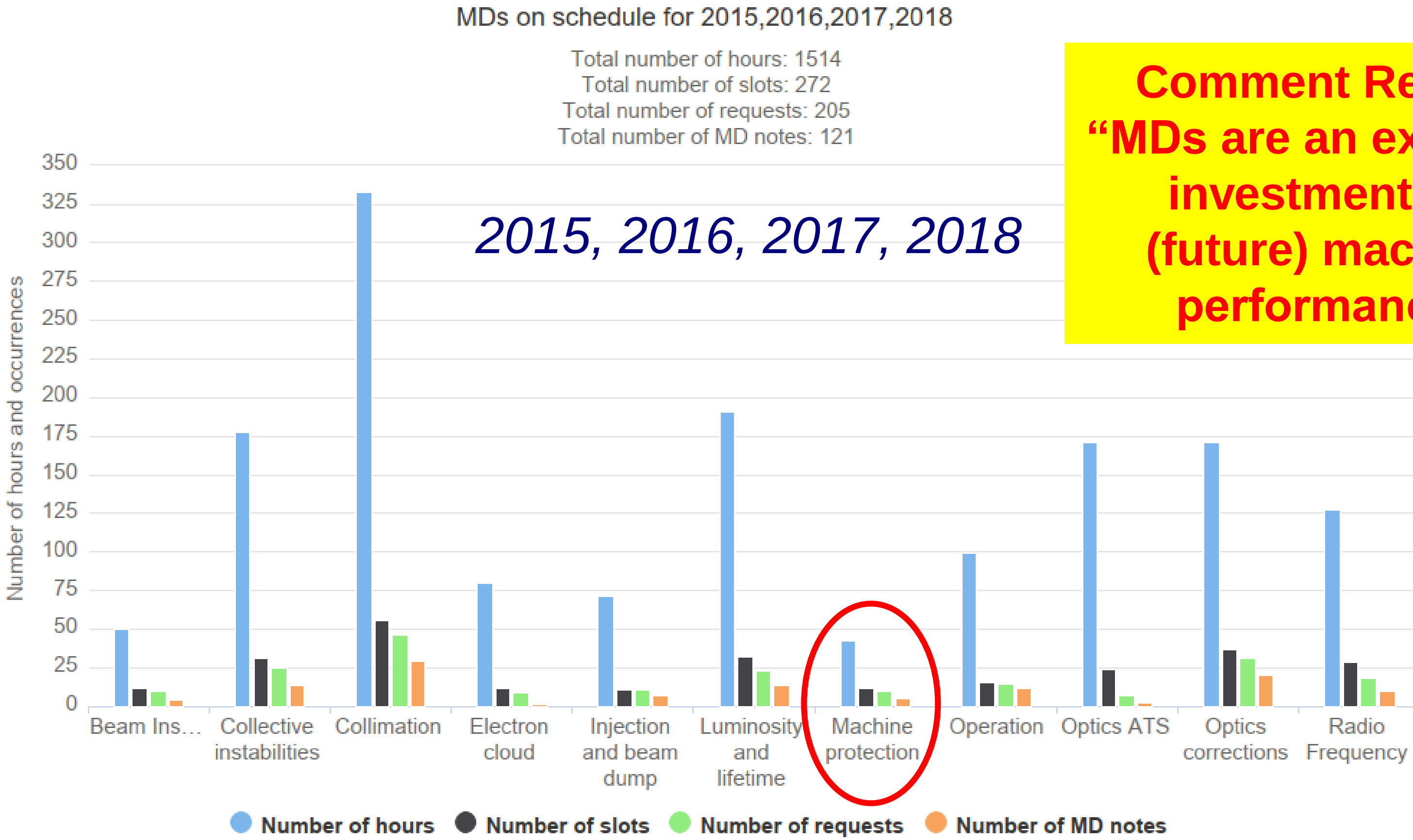
- Especially in the high load sectors, we observe **large differences from cell to cell**
- Heat loads can be different for the **two apertures of the same cell**
- **Differences** are present even **among magnets of the same cell**



<u>Cell 31L2</u> (equipped with extra thermometers)



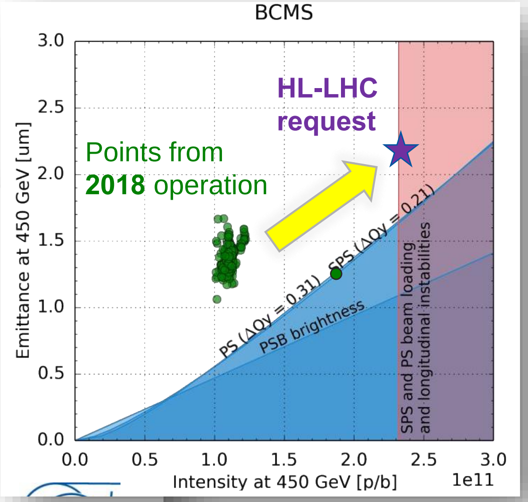
MDs per category [hours]



Comment Rende: "MDs are an excellent investment for (future) machine performance"

- Collimation wins – lots of new hardware in prep for HL
- Followed by collective instabilities, lumi and lifetime, …

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

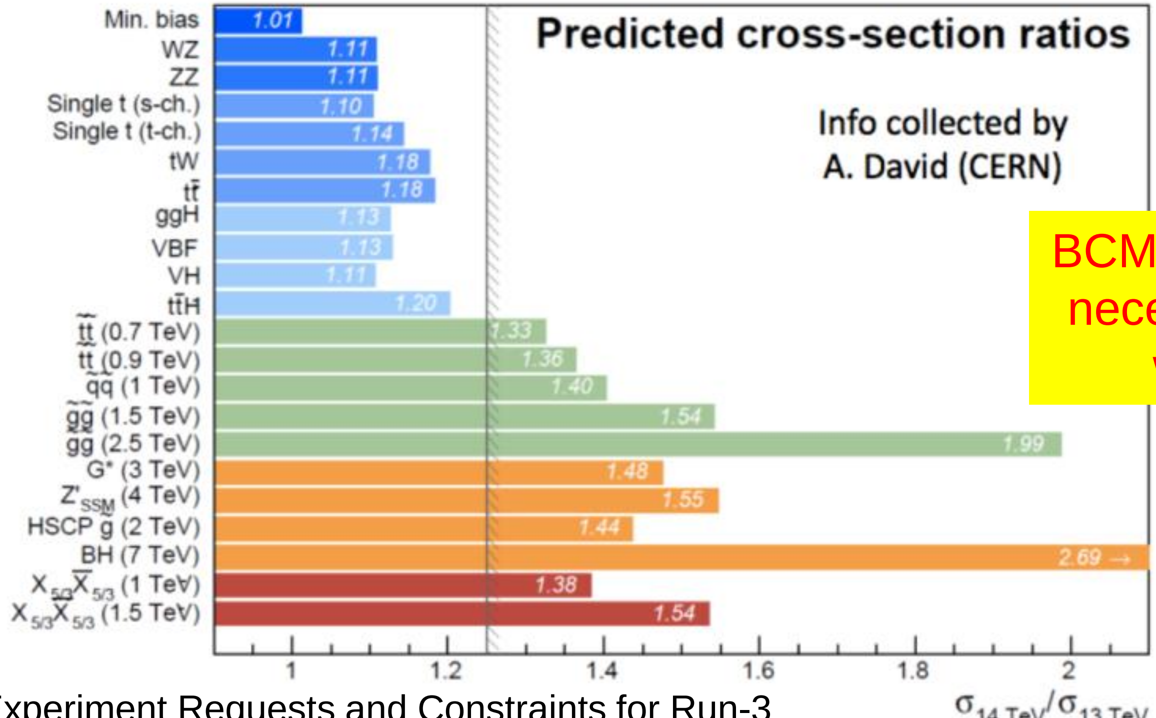
2021 → **2022** → **2023-2024**

- 2023-2024: Ramp up to HL-LHC intensity of 2.3e11 p/b (with 1.7 um for BCMS beams) for post-LS3 readiness
- 2022: Intensity and brightness ramp up to 1.8e11 p/b (with 1.3 um for BCMS beams)
- 2021: 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 ?

Beam Energy in Run-3

- Highest possible energy favored by ATLAS/CMS as it increases reach of their new physics search program
  - Also worth going to 13.5 TeV if implies much shorter training
    - Experiments would like to know target well in advance
  - If needed, can increase energy in 2022, but not 2023
  - Beam energy not critical for LHCb, but prefer same energy throughout Run-3 (at least 2022-23) for sample uniformity



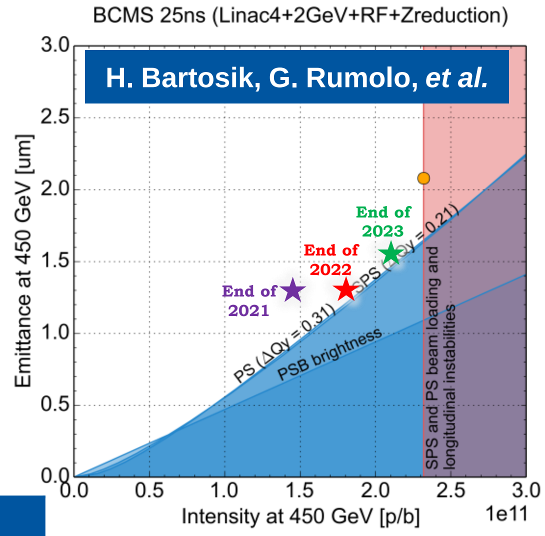
BCMS is preferred and if necessary complement with some 8b4e

Deliverables & Equipment Group Constraints

- Very clear forecast from LIU for the commissioning plan:
  - Gradual intensity ramp up over Run-III.

	2021	2022	2023*	Comment
# bunches	Up to 2748 (BCMS)			
ϵ_n [μm]	1.3	1.3	1.3 → 1.55	Intensity Ramp Up
N_b [10^{11}p]	0 →1.4	1.4 →1.8	1.8 → 2.1	Max intensity at the end of each year

* Not including 2024 when the LHC is in shutdown but the injectors are fully operational.



At the LHC, can we inject, accelerate, collide and safely dump such a beam?

System	1.7e11	1.8e11	Comment
MKI	OK	OK	One new MKI prototype to be installed in 2022/2023 in IR8. 1.8×10^{11}ppb should be within reach with 1.3ns → Studies are on-going for 1.2
RF	OK	OK	Klystron power limitation at INJ: 1.8×10^{11}ppb → out of reach with Q22, ok for Q20 with >1.2ns in RAMP.
Alignment	NA	NA	Vertical realignment of LSS5 (Q10-Q10) by up to -3 mm
Cryogenics	OK	OK	Total heat load measured at 306W → $L_{peak} = 2.05 \times 10^{34}$ Hz/cm^2 at 7.0 TeV. Impact of running the triplet at the cryo limit is marginal (<2%) on the cooling capacity of the beam screen in the adjacent arcs.

N. Karastathis, Report from the LHC Run-III Configuration Working Group

M. Barnes, K. Brodzinski, B. Goddard, A. Lechner, J. Maestre Heredia, A. Mereghetti, D. Missiaen, F.X. Nuiri, B. Salvant, H. Timko, J. Uythoven, J. Wenninger, *et al.*

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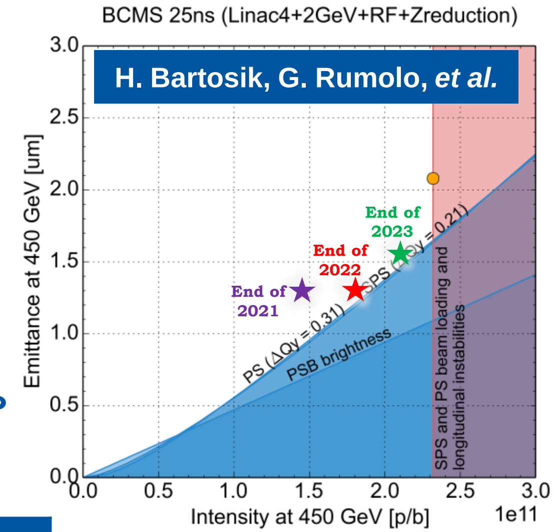


At the LHC, can we inject, accelerate, collide and safely dump such a beam?

System	1.7e11	1.8e11	Comment
TCDQ	OK	OK	For 2.5mm gap and $N_b = 1.7 \times 10^{11}$ppb safety factor up to 2.5. Studies on-going for other gap values (2.0mm). TCDQ leveling MD successful!
TCDS	OK	?	Already designed for $N_b = 1.7 \times 10^{11}$ppb, but in plastic deformation already ➔ Studies on-going.
TDE	?	?	New downstream window installed in LS2. Not sufficient margin for the upstream window ➔ YETS 2021/2022. Material re-characterization needed for the body at 2500ºC . Study on-going.
Collimation	OK	OK	No issue on finding suitable settings for Run-III (with the help of partial upgrade in Run-III and thanks to dedicated telescopic optics).

The LHC should be available to accept **a max bunch population of**

$$\mathbf{N_b = 1.8 \times 10^{11} ppb}$$

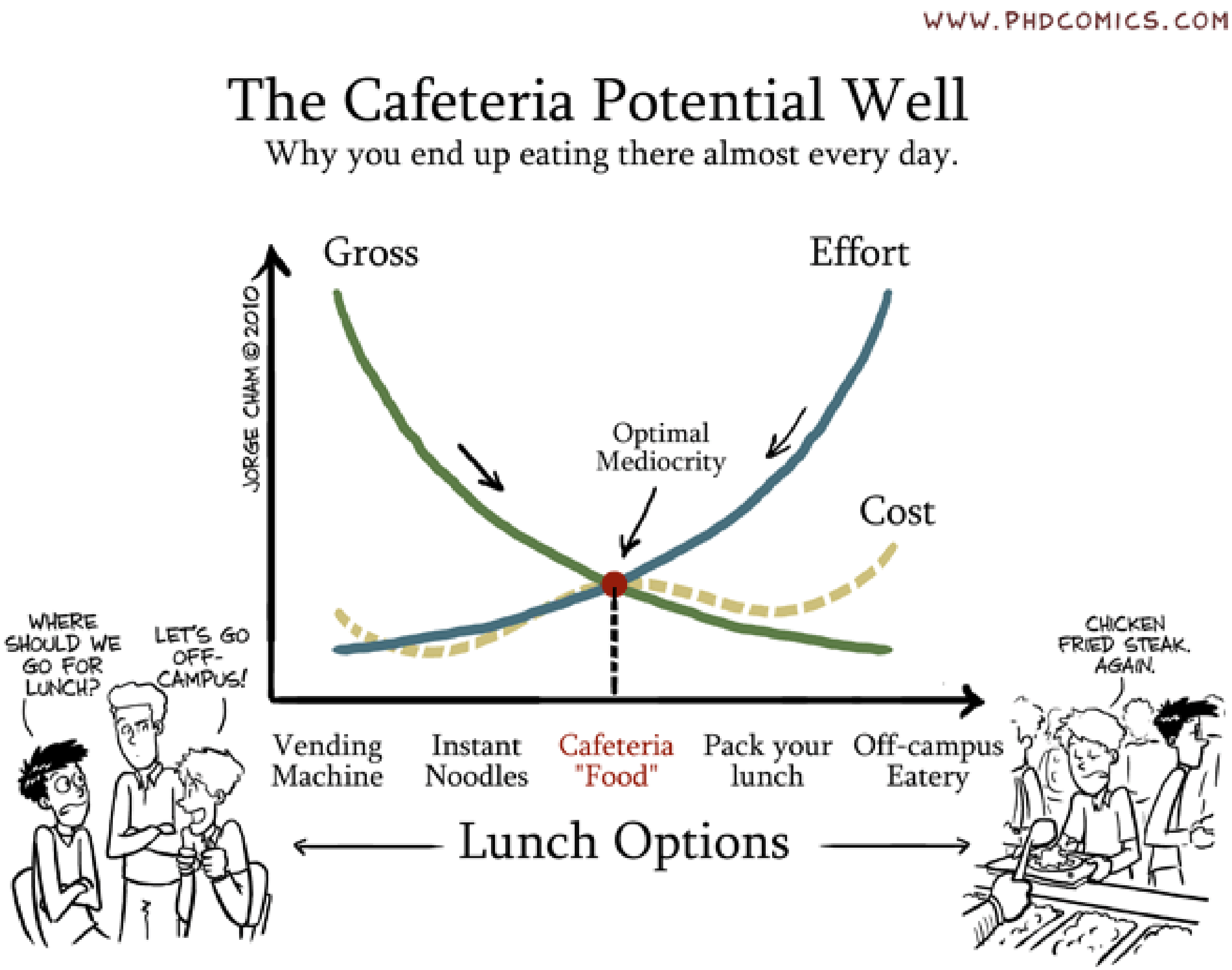
Especially, after the TDE downstream window upgrade.

N. Karastathis, Report from the LHC Run-III Configuration Working Group

M. Barnes, K. Brodzinski, B. Goddard, A. Lechner, J. Maestre Heredia, A. Mereghetti, D. Missiaen, F.X. Nuiri, B. Salvant, H. Timko, J. Uythoven, J. Wenninger, *et al.*

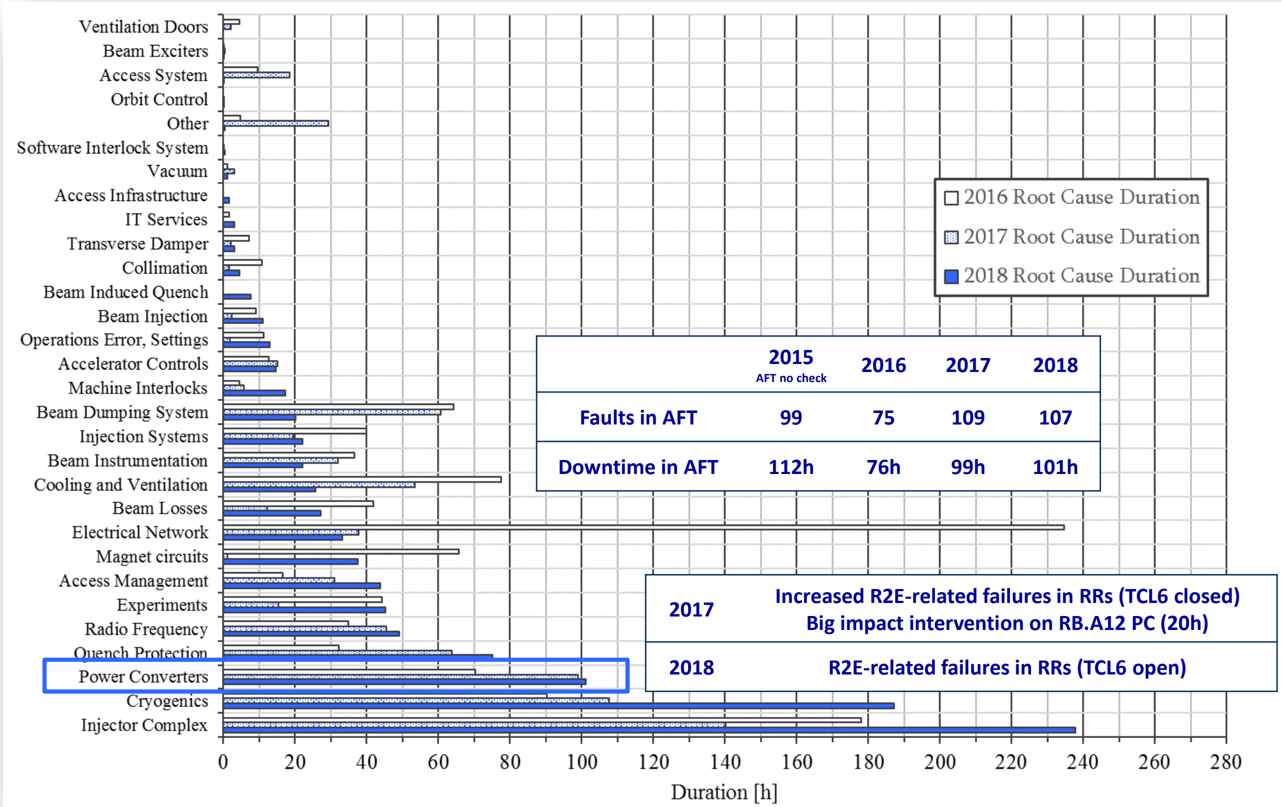
Thank you for your attention!

Et bon appetit !



CERN

Power Converters and their control



Massive FGClite deployment during LS2
Lessons learned and experience gained

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

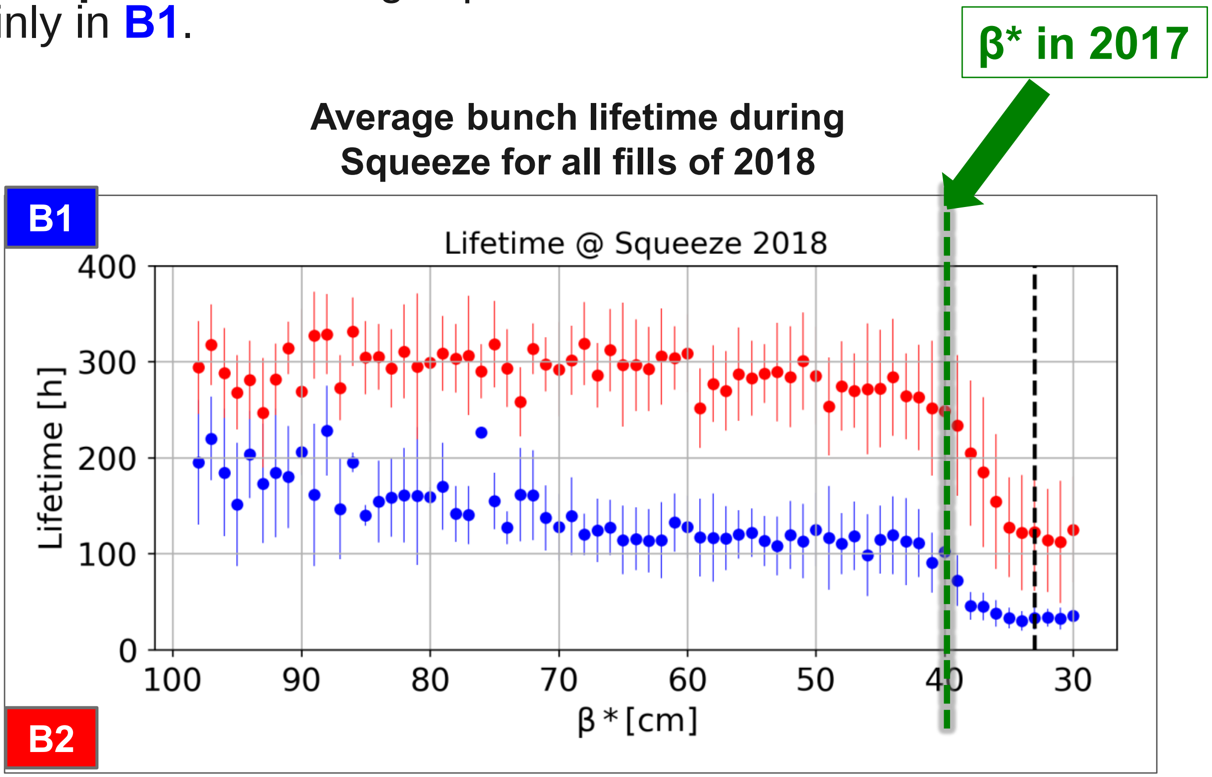
"Any specific new requirements have to be communicated now"

Luminosity, lifetime and modelling

Losses @ Squeeze (2018)

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

Average bunch lifetime during Squeeze for all fills of 2018



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.

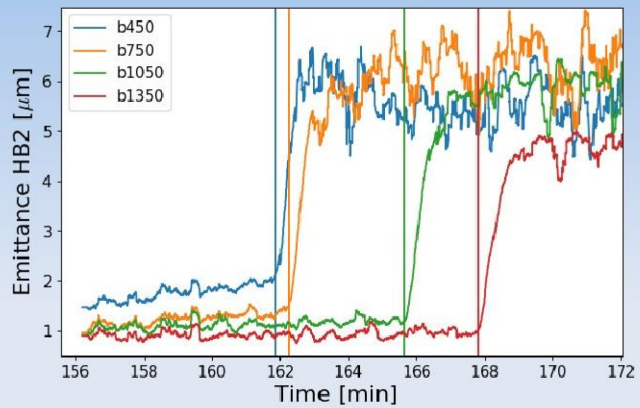
Stable Beams

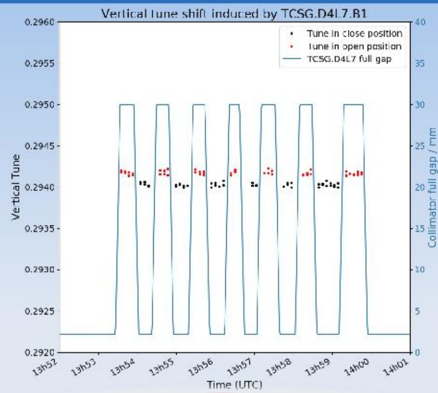
- Lifetime of **B1** systematically lower than **B2** during Run II
- Extra losses observed in the first few hours during the whole run II (not yet understood).
- During 2018 additional losses observed induced by **crossing angle anti-leveling and β* levelling, e-cloud related**
- E-cloud important mechanism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

Transverse Instabilities

Ongoing investigations



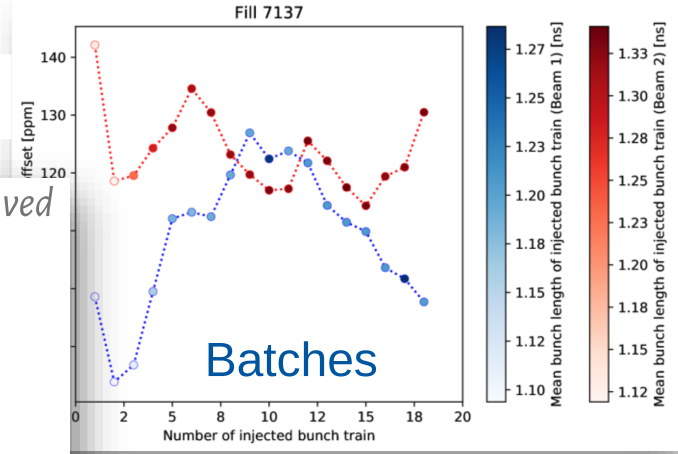


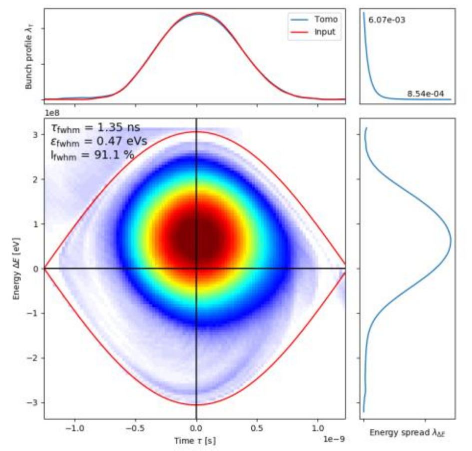
- Diffusion models
  - Effect of noise spectrum (e.g. 50 Hz noise lines)
  - Optimal damper settings (gain, bandwidth) and machine/beam parameters
- *Dark impedance* searches → Strongly constrained by measurements of
  - Single collimator tune shifts
  - Instability threshold
  - Head-tail signals
  - 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)