CERN

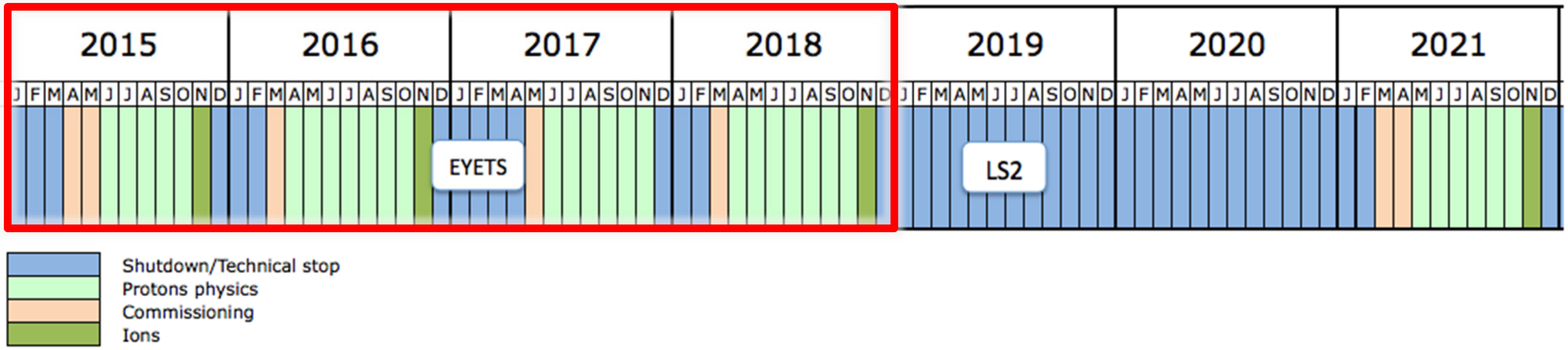
Operation Challenges and Performance of the LHC During Run II

Rende Steerenberg – CERN

With many thanks to the operations team, the LHC machine coordinators and many experts

Scope

- This presentation will only deal with the main protons physics during Run II
- However, noteworthy is the remarkable performance that has been reached with the Pb-Pb, p^+-Pb (and Xe-Xe) runs
  - LIU performance has already been achieved (slip stacking to be added in SPS)
  - Very high machine availability during these runs (low intensity / luminosity)
  - Record stable beams time of 37 hours for a single fill.



Topics

- Introduction
- Performance Through Availability
- Beam Performance & Beam Physics Challenges
- Preparing for the Future
- Summary

- **Introduction**
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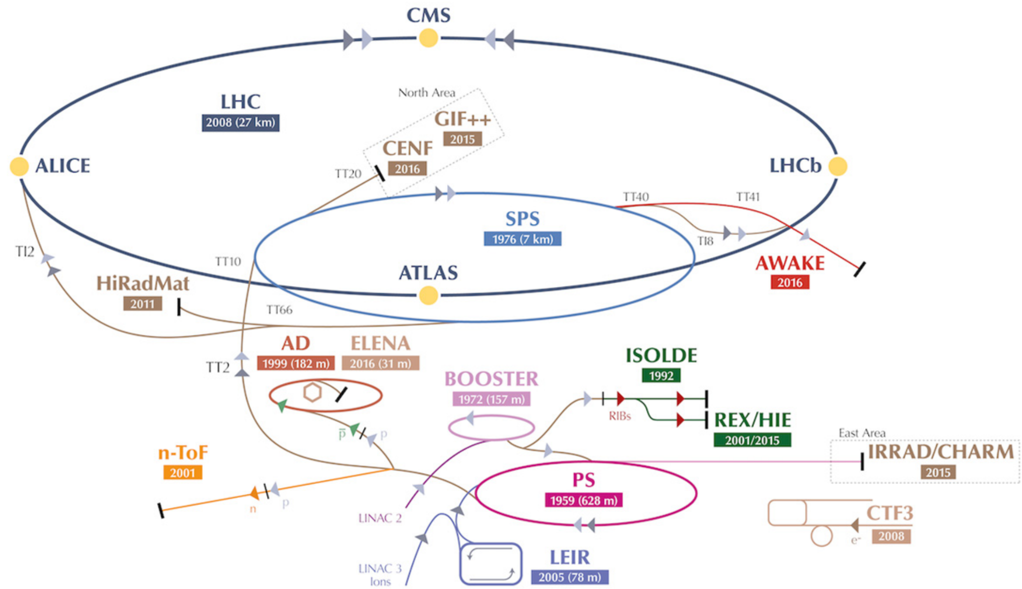
The LHC and its Injector Complex

- The LHC performance is largely determined by injector complex performance
  - Availability
  - Beam quality → Brightness



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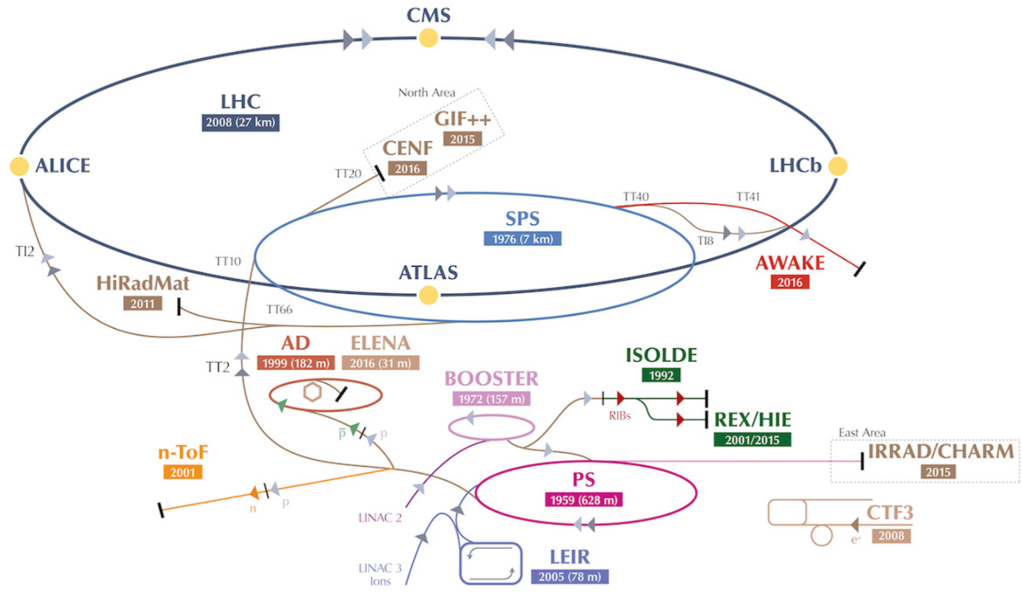
- The **PSB** determines initial beam **brightness**
- The **PS** determines the **timing structure**
  - 25ns, 50ns, BCMS, 8b4e, …



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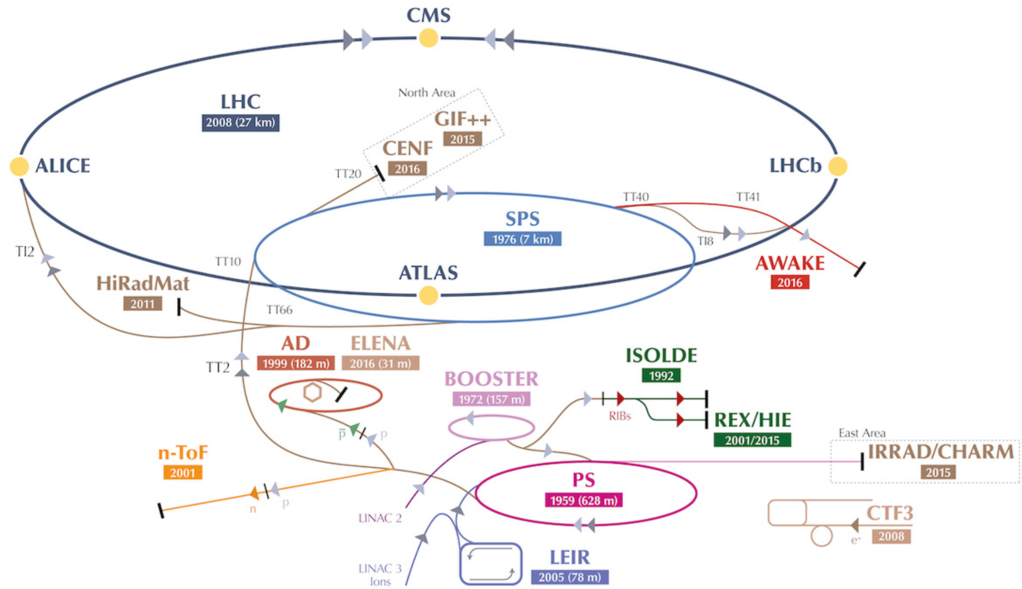
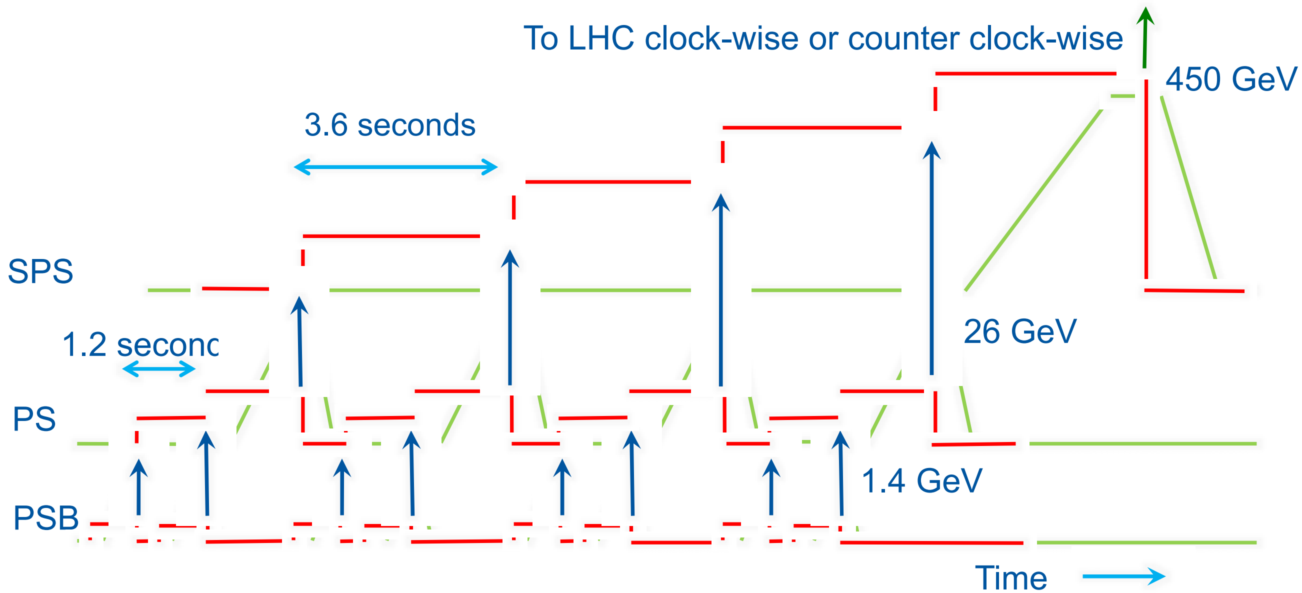
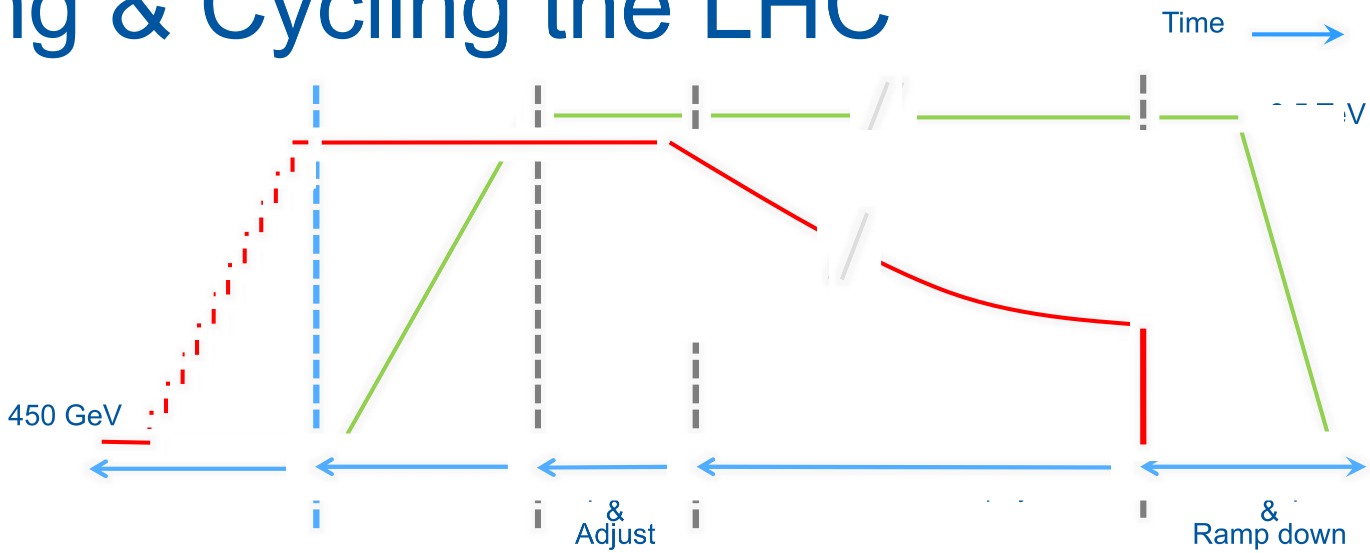


See also:
MOA1PL01, H. Bartosik; MOA1PL02, G. Rumolo; MOA1PL03, G. Bellodi; THA1WD04, K. Hanke

LHC Beam in the Injector Complex



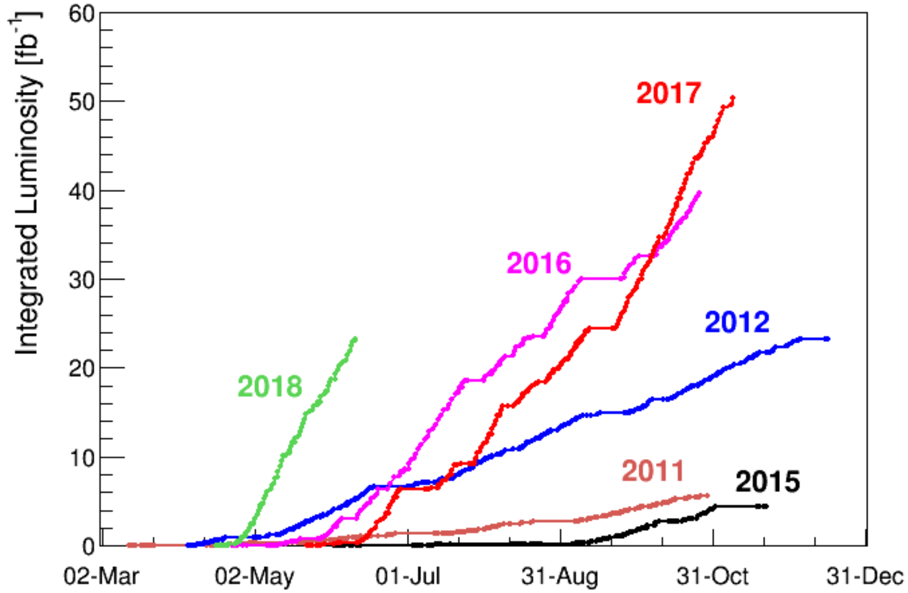
Filling & Cycling the LHC



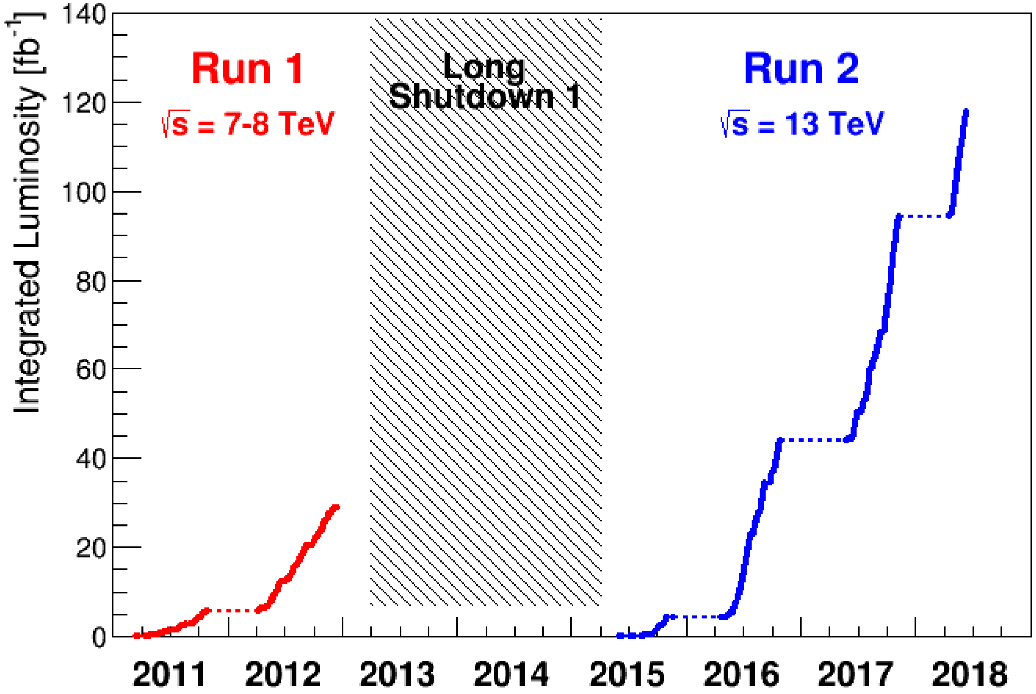
- An increased number of kicker gaps, hence injections, reduces the number of bunches in the LHC

Multi-Annual Integrated Luminosity

- **Run I**
  - 2011: Commissioning at 3.5 TeV/beam
  - 2012: Production at 4 TeV/beam
- **LS1**: 2013 & 2014
- **Run II**
  - 2015: commissioning at 6.5 TeV/beam
  - 2016, 2017 and 2018: Production at 6.5 TeV/beam
- **LS2**: 2019 & 2020



Reaching the Run I + Run II Goal



The LHC goal up to LS2 is
150 fb^{-1}

Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	23.2
Total Run 1+ 2	**146.5**

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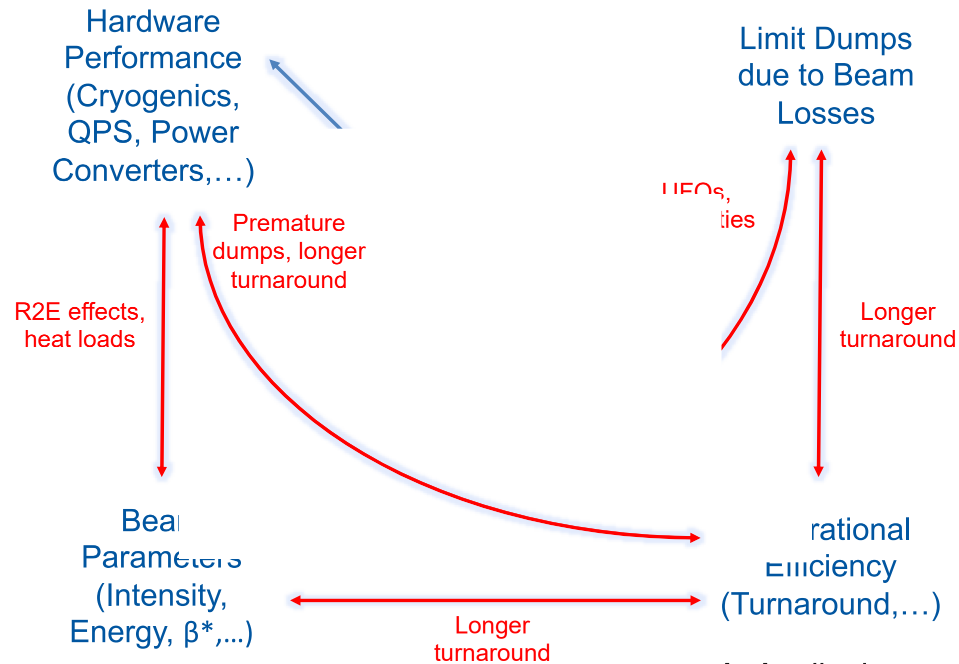
LHC Machine & Beam Performance

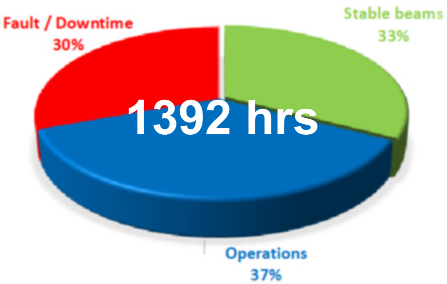
- The performance of a complex collider like the LHC is firstly dominated by machine **availability**, **operational efficiency** and **stable beam time**, hence technical aspects
- Secondly, the **beam performance** will determine the luminosity production rate during the available beam time
- The Goal is **50% Stable beam time**



A. Apollonio

Multi-Annual LHC Availability

2015



SB = 33%

- 2015 was a re-commissioning year after Long Shutdown 1
- In 2015 LHC ran with 50 ns and 25 ns bunch spacing, availability is for 25 ns
- 2016, 2017 and 2018 are the luminosity production years
- For 2018, only at ~1/3 of the year…

Multi-Annual LHC Availability

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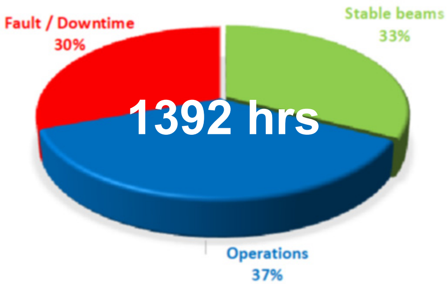

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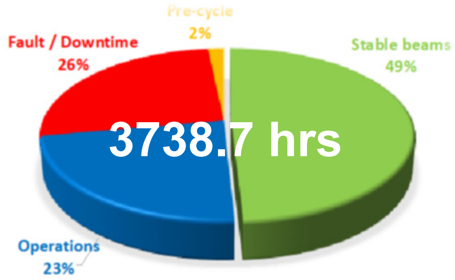
2016



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Multi-Annual LHC Availability

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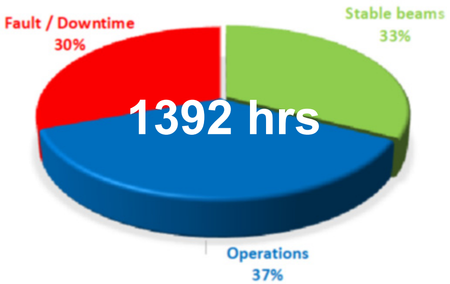

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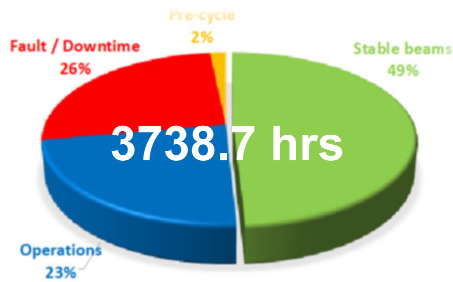

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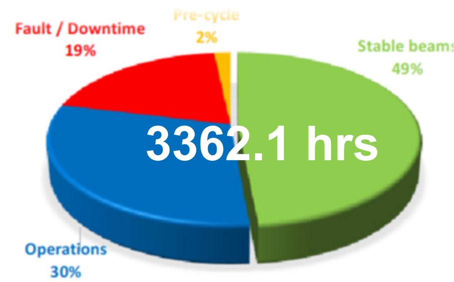
2017



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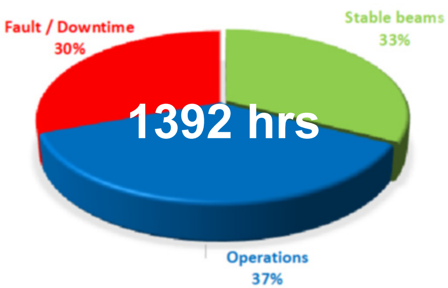

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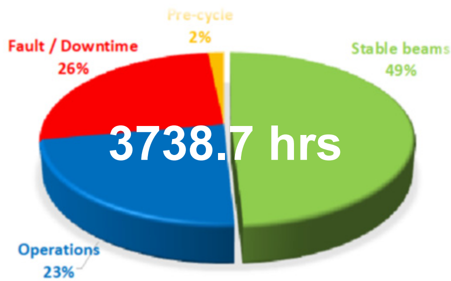

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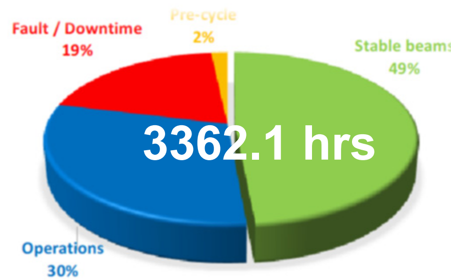
2017



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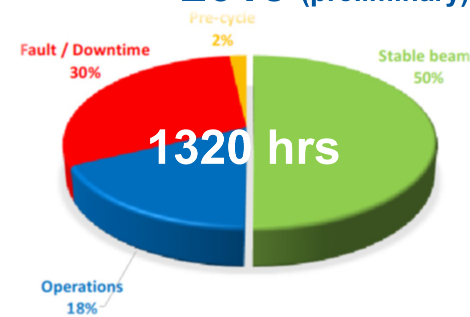
2018 **(preliminary)**



SB = 50%
So far….

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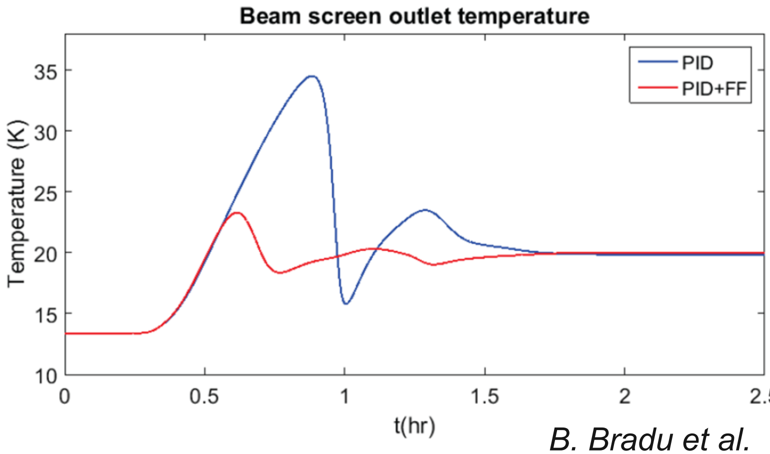
Some Examples of Technical Issues Addressed

- **Cryogenic heat loads with high intensity:**
  - Heat sources:
    - Impedance, photons and electron cloud
  - Beam injection and extraction caused heat load step functions on beam screen
    - Feedforward based on beam intensity, energy and filling scheme implemented



B. Bradu et al.

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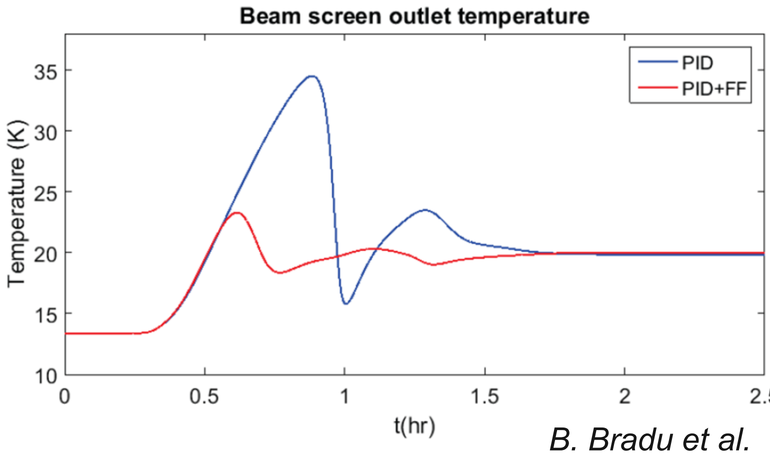

B. Bradu et al.

- **Radiation to electronics (R2E)**
  - Close to the Interaction Points (IP) failure rates are dominated by integrated luminosity
  - In the arcs failure rates are dominated by beam-gas interactions, hence circulating beam intensity
  - Cures:
    - Move electronics further away in shielded areas → was done during Long Shutdown 1 (2013-2014)
    - More radiation hard electronics → was done for part in 2015-2016 YETS

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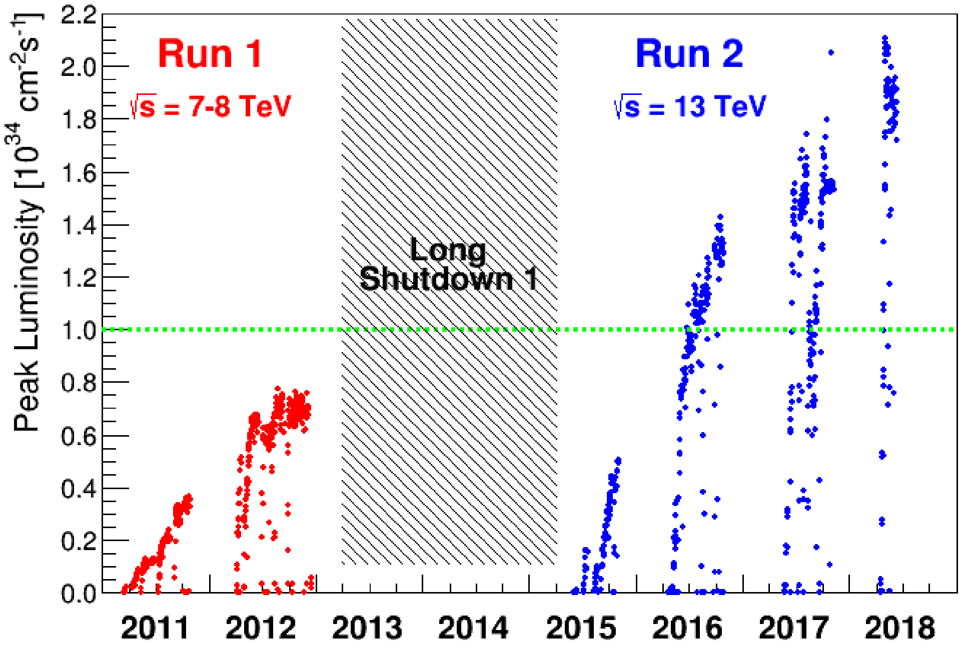
Peak Luminosity and its Evolution



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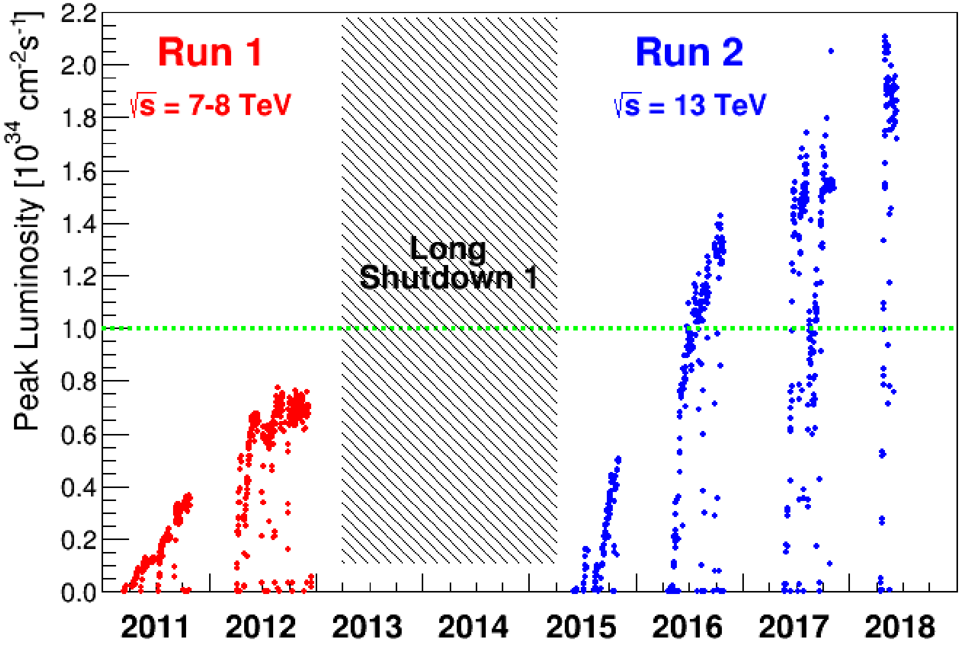

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  - Despite a reduced number of bunches
  - Thanks to the brighter injectors beam

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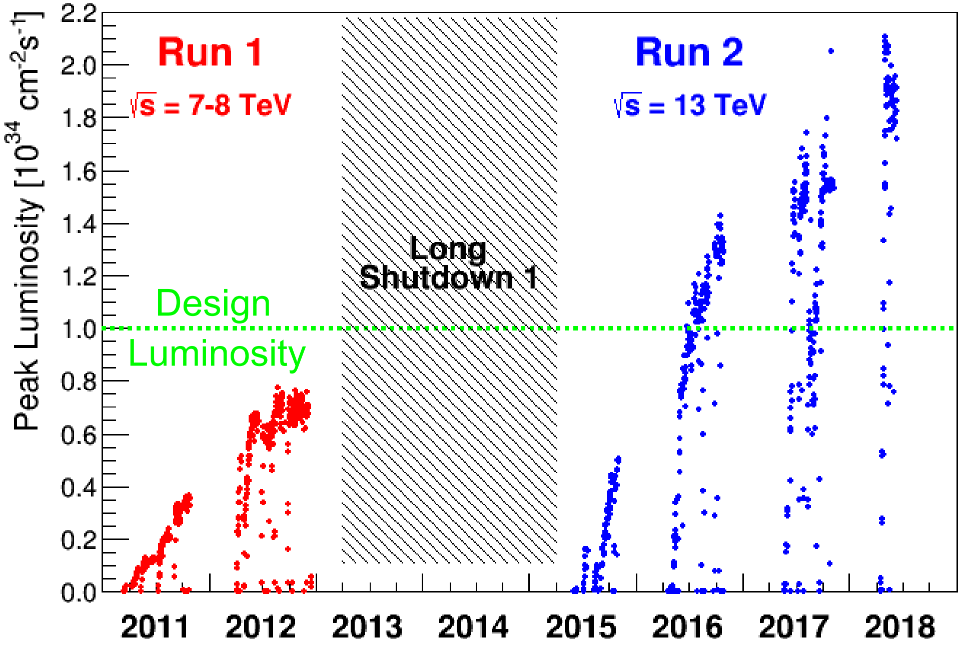

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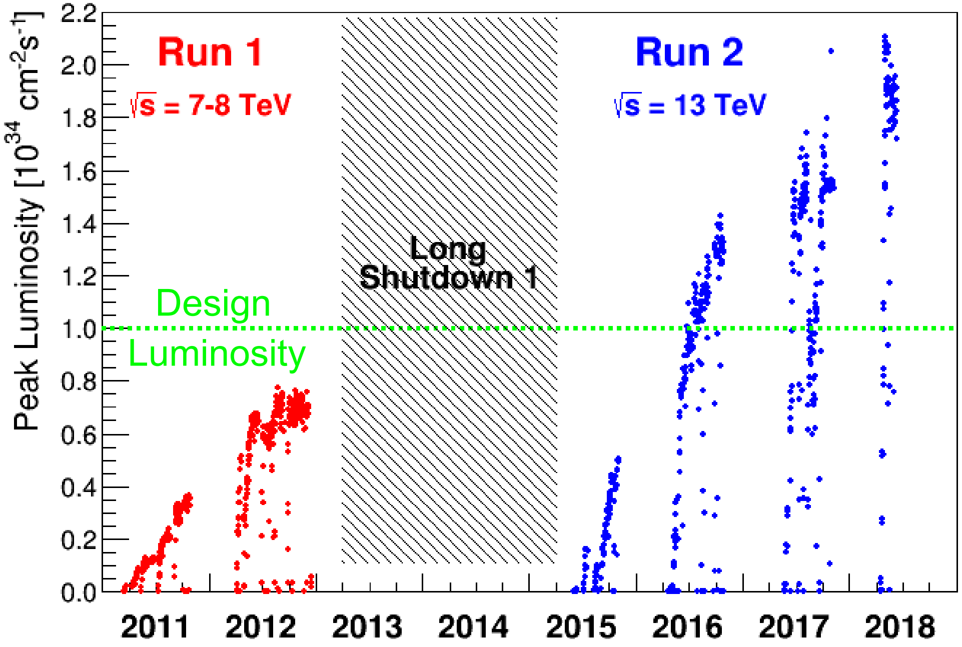

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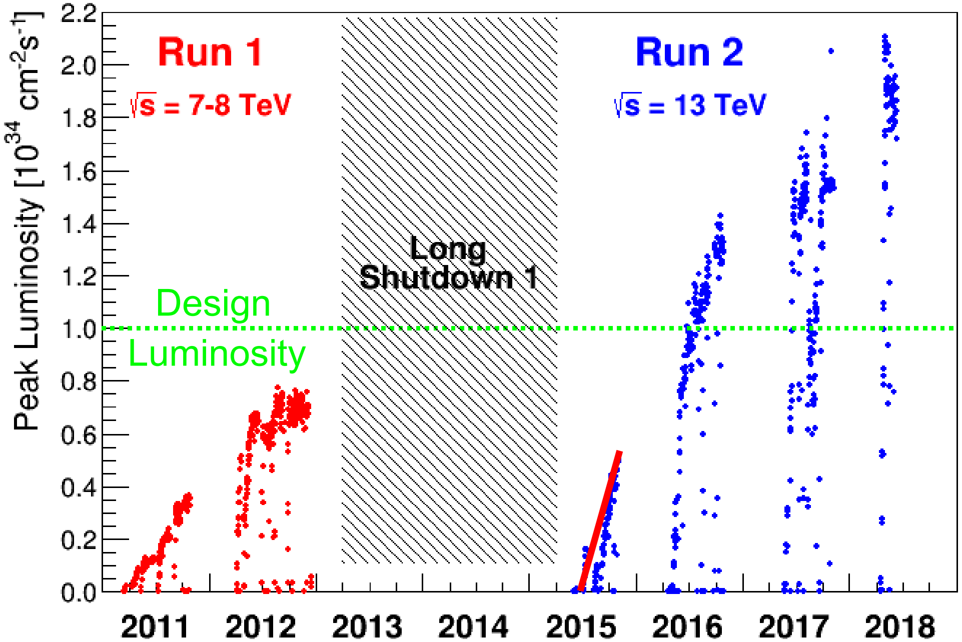

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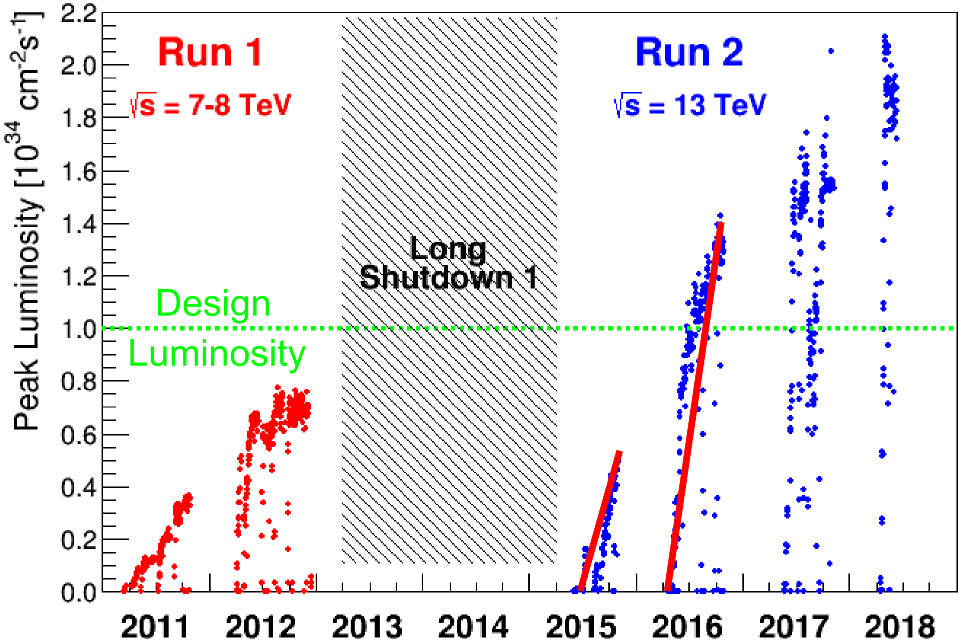

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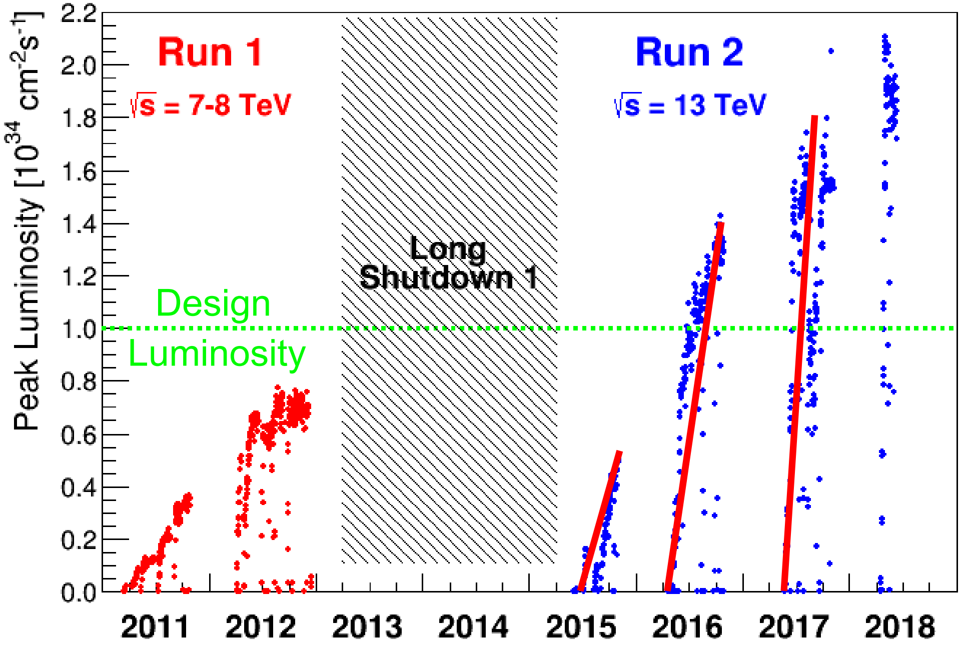

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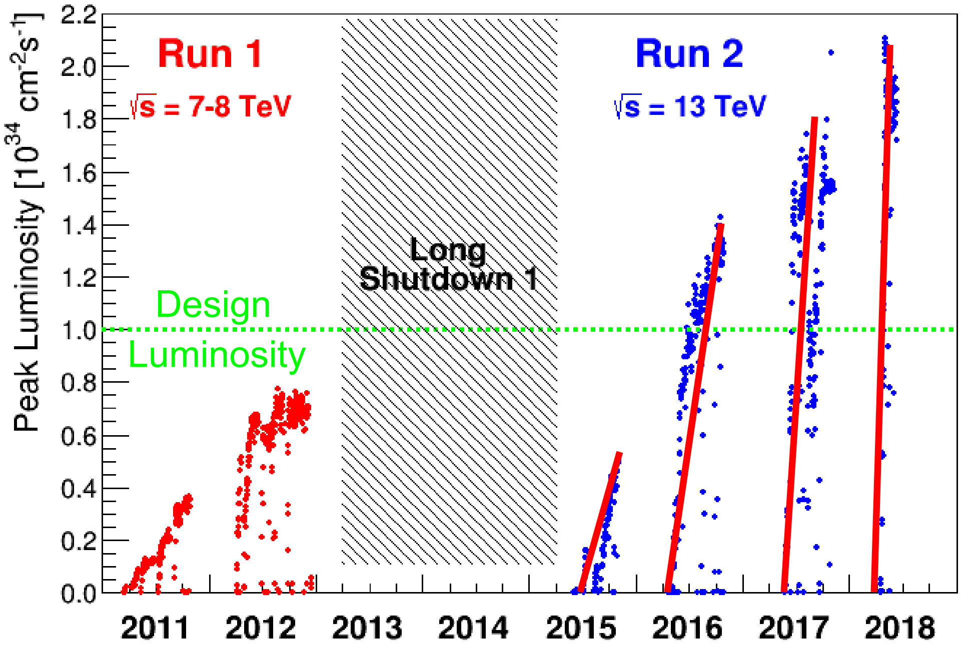

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Machine & Beam Parameters

Parameter	Design
Beam type:	Std
Energy [TeV]	7
Number of bunches per ring	2808
Bunch spacing [ns]	25
Bunch population N_b [10^{11} p/b]	1.15
Transv. norm. emittance SB ε_n [mm mrad]	3.75
Betatron function at IP1 and IP5 β^* [m]	0.55
Half crossing angle [µrad]	142.5
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1
Maximum pile up μ (per bunch crossing)	~20
Stored beam energy [MJ]	360
Integrated luminosity per year [fb^{-1}]	n.a.

Machine & Beam Parameters

Parameter	Design	2015
Beam type:	**Std**	**Std**
Energy [TeV]	7	6.5
Number of bunches per ring	2808	$\boxed{2244}$
Bunch spacing [ns]	25	25
Bunch population N_b [10^{11} p/b]	1.15	1.15
Transv. norm. emittance SB ε_n [mm mrad]	3.75	$\boxed{3.5}$
Betatron function at IP1 and IP5 β^* [m]	0.55	$\boxed{0.8}$
Half crossing angle [μrad]	142.5	145
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	$\boxed{0.55}$
Maximum pile up μ (per bunch crossing)	~20	~15
Stored beam energy [MJ]	360	270
Integrated luminosity per year [fb^{-1}]	n.a.	4.2

Machine & Beam Parameters

Parameter	Design	2015	2016
Beam type:	Std	Std	Std/BCMS
Energy [TeV]	7	6.5	6.5
Number of bunches per ring	2808	2244	2040/2076
Bunch spacing [ns]	25	25	25
Bunch population N_b [10^{11} p/b]	1.15	1.15	1.2
Transv. norm. emittance SB ε_n [mm mrad]	3.75	3.5	3.5/2.1
Betatron function at IP1 and IP5 β^* [m]	0.55	0.8	0.4
Half crossing angle [μrad]	142.5	145	185
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	0.55	0.83/1.4
Maximum pile up μ (per bunch crossing)	~20	~15	~20/35
Stored beam energy [MJ]	360	270	345
Integrated luminosity per year [fb^{-1}]	n.a.	4.2	39.7

Reduction of β^* → increase of crossing angle

Limited by the SPS internal beam dump that suffered a vacuum leak

- Initially 72 std bunches/inj. Later 96 BCMS bunches/inj.

Machine & Beam Parameters

Parameter	Design	2015	2016		2017	
Beam type:	Std	Std	Std/BCMS	BCMS	8b4e	8b4e-BCS
Energy [TeV]	7	6.5	6.5	6.5	6.5	6.5
Number of bunches per ring	2808	2244	2040/2076	2556	1916	1868
Bunch spacing [ns]	25	25	25	25	25	25
Bunch population N_b [10^{11} p/b]	1.15	1.15	1.2	1.35	1.2	1.25
Transv. norm. emittance SB ε_n [mm mrad]	3.75	3.5	3.5/2.1	2.1	2.3	1.8
Betatron function at IP1 and IP5 β^* [m]	0.55	0.8	0.4	0.4	0.4/0.3	0.3
Half crossing angle [μrad]	142.5	145	185	150	150	150/110(1)
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	0.55	0.83/1.4	1.74	1.9	2.06/1.5(2)
Maximum pile up μ (per bunch crossing)	~20	~15	~20/35	~45	70/60(2)	80/60(2)
Stored beam energy [MJ]	360	270	345	360	240	245
Integrated luminosity per year [fb^{-1}]	n.a.	4.2	39.7		50.2	

(1) Minimum crossing angle during crossing angle anti-levelling
(2) Value after luminosity-levelling by separation
(3) Minimum betatron function during betatron anti-levelling

Various beam configurations due to gas condensate in interconnection (16L2)

Machine & Beam Parameters

Parameter	Design	2015	2016		2017		2018
Beam type:	Std	Std	Std/BCMS	BCMS	8b4e	8b4e-BCS	BCMS
Energy [TeV]	7	6.5	6.5	6.5	6.5	6.5	6.5
Number of bunches per ring	2808	2244	2040/2076	2556	1916	1868	2556
Bunch spacing [ns]	25	25	25	25	25	25	25
Bunch population N_b [10^{11} p/b]	1.15	1.15	1.2	1.35	1.2	1.25	1.2
Transv. norm. emittance SB ε_n [mm mrad]	3.75	3.5	3.5/2.1	2.1	2.3	1.8	2
Betatron function at IP1 and IP5 β^* [m]	0.55	0.8	0.4	0.4	0.4/0.3	0.3	0.3/0.25(3)
Half crossing angle [µrad]	142.5	145	185	150	150	150/110(1)	150/110(1)
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	0.55	0.83/1.4	1.74	1.9	2.06/1.5(2)	2.1
Maximum pile up μ (per bunch crossing)	~20	~15	~20/35	~45	70/60(2)	80/60(2)	60
Stored beam energy [MJ]	360	270	345	360	240	245	320
Integrated luminosity per year [fb^{-1}]	n.a.	4.2	39.7		50.2		n.a.

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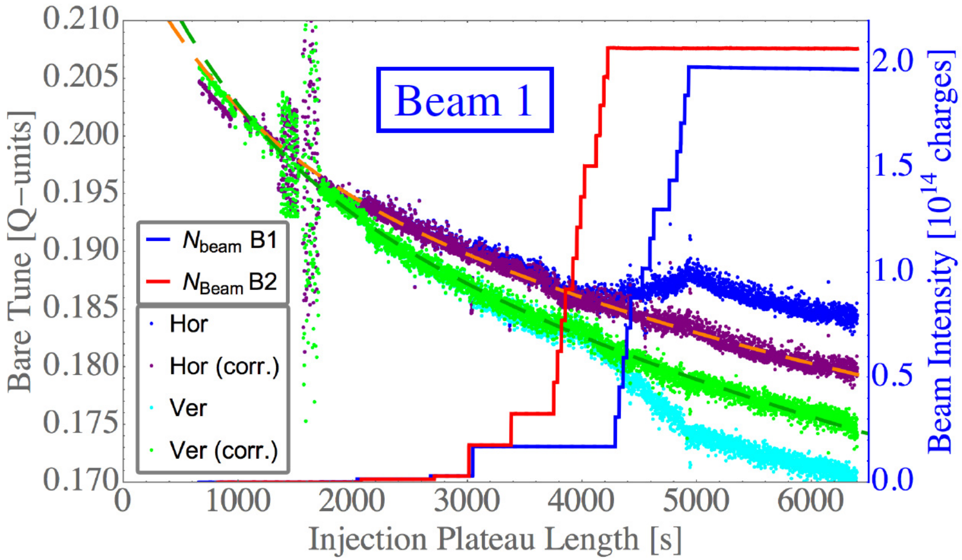
Dealing With Tune & Chroma Shifts

1. On a plateau the magnetic field multipoles drift due to current redistribution in superconducting cables
   - This leads to a decay of Q and Q'

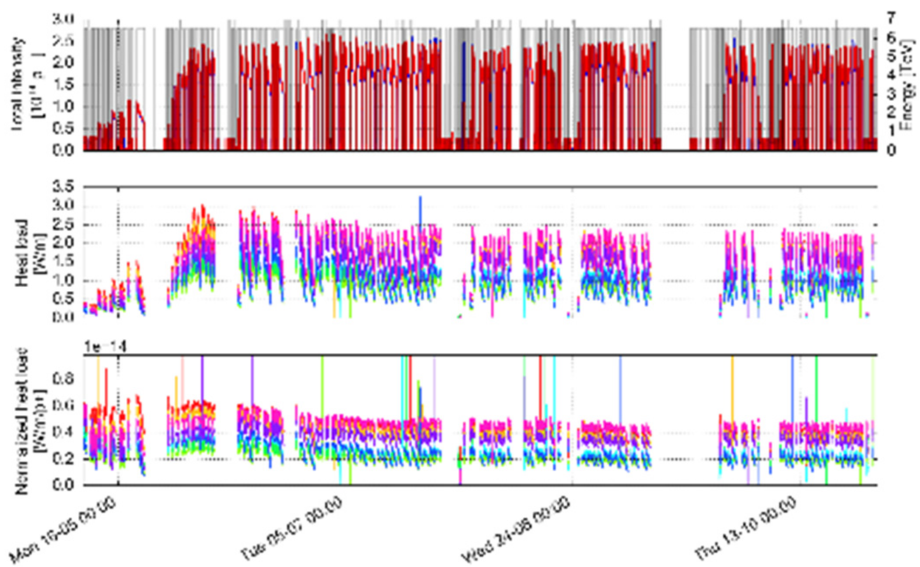
2. Laslett tune shift feedforward
   - An automated correction based on calculations, using the measured beam intensity was operationally deployed in 2016



Michaela Schaumann et al.

Electron Cloud / Heat Load

- E-cloud causes beam induced heat load, which differs for each sector
- Cause for emittance growth and instabilities
- Mitigated by reducing secondary electron emission yield through:
  - Scrubbing run at the start of the run/year
  - Continuous scrubbing during the physics run
- Different heat loads for different sectors not yet understood



G. Iadarola et al.

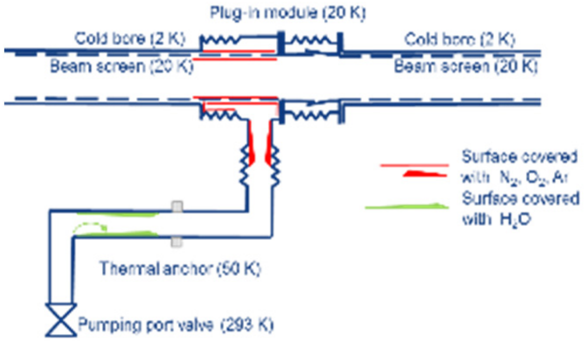
See also: MOA1PL01, H. Bartosik

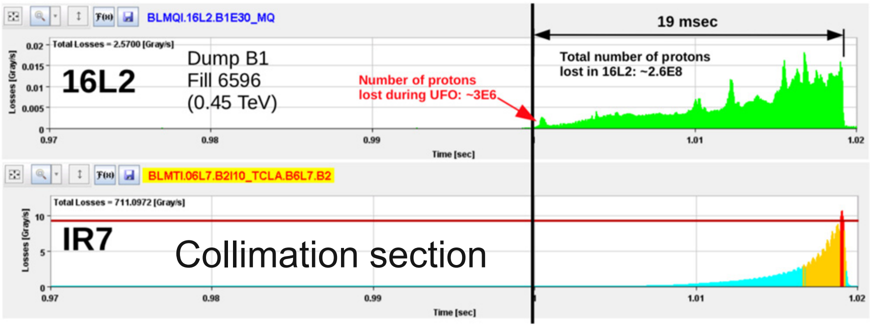
Instabilities

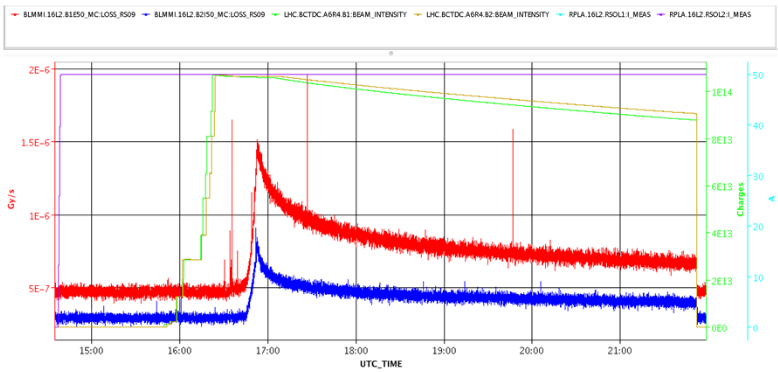
- Emittance and intensity are constantly pushed toward higher brightness, leading to increased effects from wake fields on the transverse stability
- Sources:
  - Impedance, like collimators, kickers etc.
  - e-cloud
  - Noise from magnets and transverse damper
- Rather good impedance model available, benchmarked with measurements, allows predicting and understanding observations
- Usual knobs to mitigate instabilities:
  - Chromaticity
  - Octupoles
  - Coupling

Beam Dumps due to Fast Losses

- Accidental air Inlet in beam vacuum in half cell 16 left of IP2 (16L2) during 2016-2017 Technical stop
- Initially mitigated by 8b4e beam that suppresses e-cloud and “home-made” solenoid
- Later by partial warm-up an vacuum pumping
- Not fully recovered yet, but no longer limiting performance





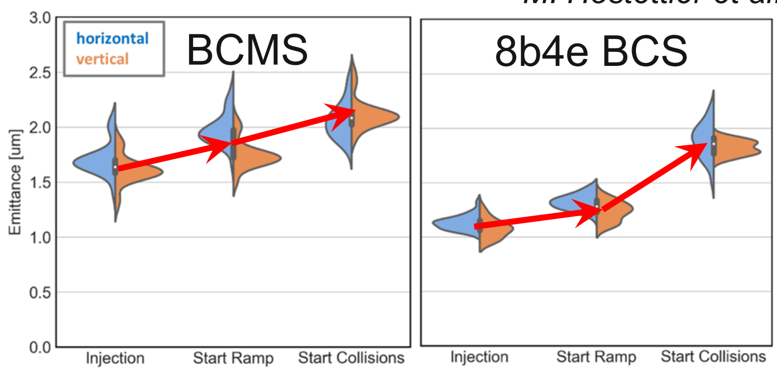


See also: WEP1WA01, L. Mether

Transverse Emittance Growth

- Injection plateau
  - Usual IBS, but also additional growth due to e-cloud
- Ramp
  - Important blow up, not yet understood, with high potential gain for luminosity
- Stable beams
  - Normally no or little net blow up also thanks to synchrotron damping

M. Hostettler et al.



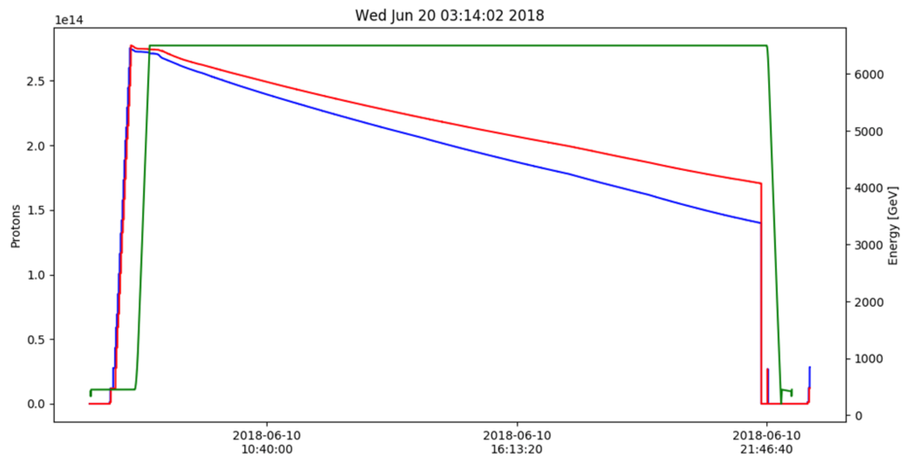
	BCMS		8b4e-BCS	
	H [%]	V [%]	H [%]	V [%]
Inj.	15 % 0.3 um	9 % 0.1 um	17 % 0.2 um	15 % 0.15 um
ramp	5 % 0.1 um	22 % 0.4 um	43 % 0.6 um	45 % 0.6 um

Beam Life time

- Long beam lifetimes are of prime importance for luminosity production
- Presently :

- Higher than luminosity burn off losses at the start of collisions
- Large difference between beam 1 and beam 2

- Being investigated…



See also: WEPWA02, Y. Papaphilippou

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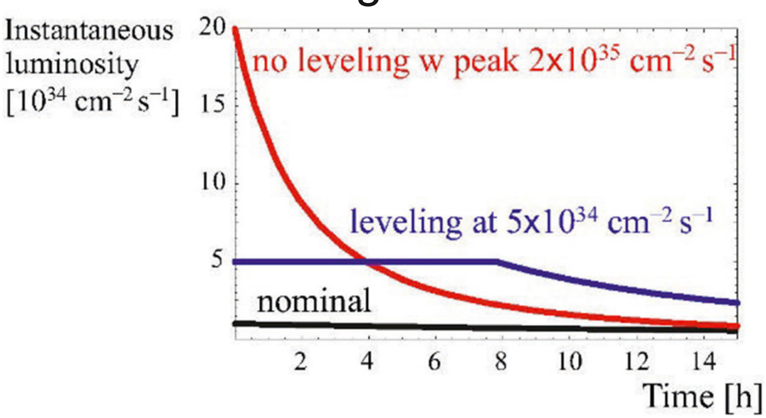
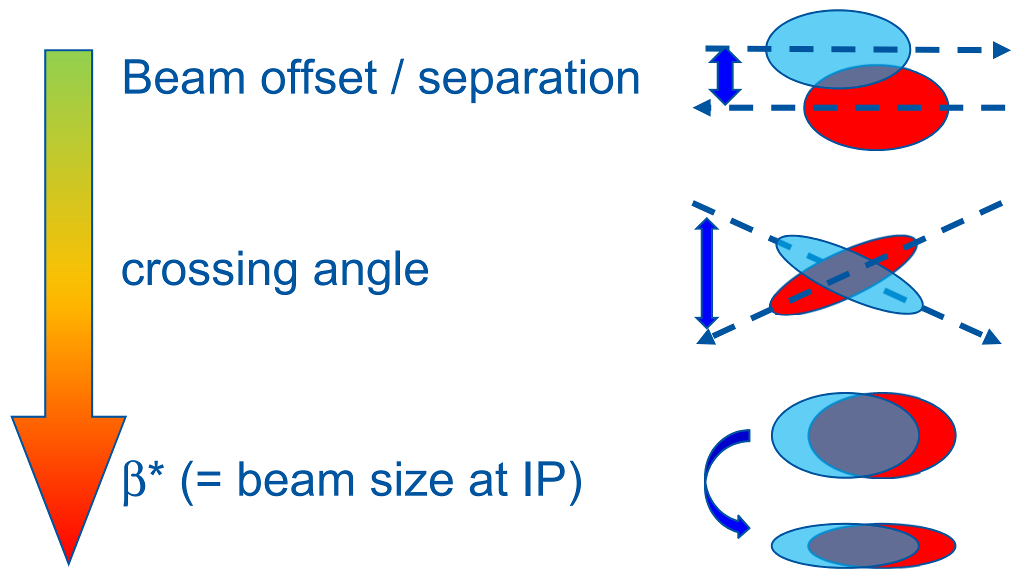
- **Preparing for the Future**
- Summary

Levelling & Anti-levelling

- In certain conditions and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – **levelling**.

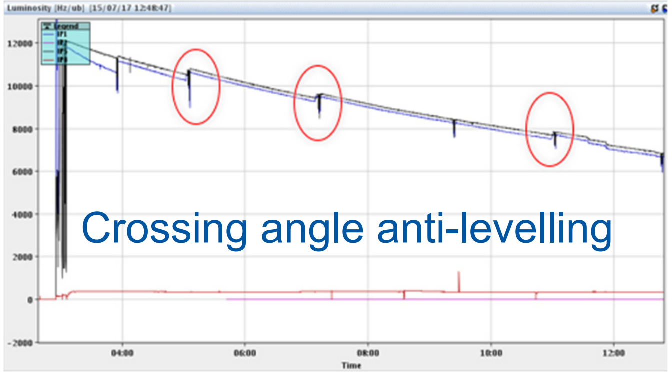
Levelling for HL-LHC

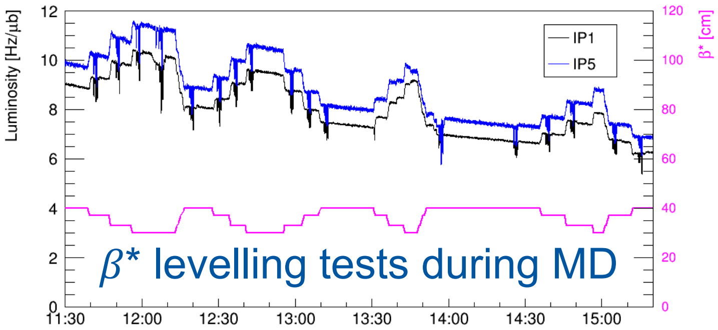




Luminosity Anti-levelling

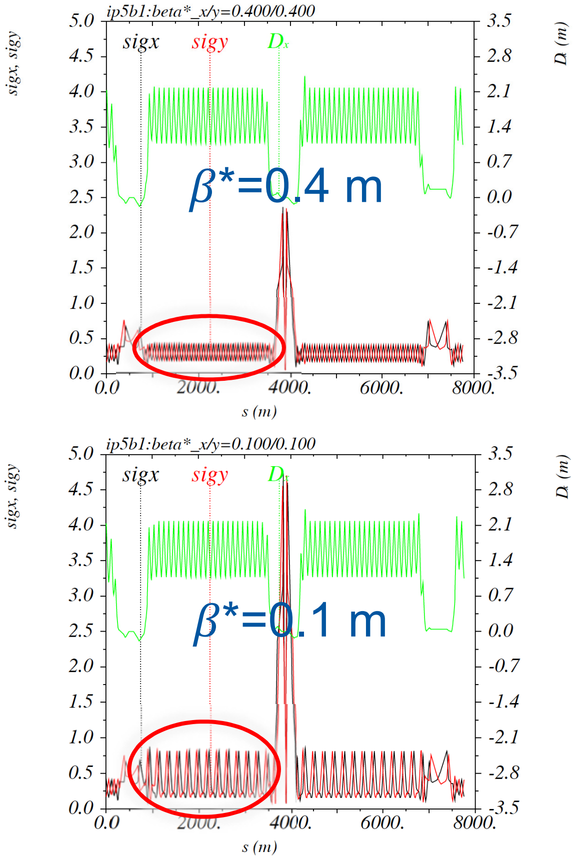
- In 2017 step-wise crossing angle anti-levelling was introduced
  - 3 steps depending on the luminosity burn-off
- In 2018:
  - The crossing angle anti-levelling is done continuously, down to 130 μrad
  - A step-wise β^* anti-levelling has been added
  - β^*=30 cm → 27.5 cm → 25 cm
- Allows few % gain in integrated luminosity, but is a vital exercise for future (HL-LHC) levelling





ATS Optics

- ATS = Achromatic Telescopic Squeeze
  - Increase β-function in the arcs to enhance effect of inner triplets around the experiments
  - Baseline optics for the HL-LHC, to allow for β*=0.15 m
- In addition, depending on the "telescopic factor" octupoles will have more effect for same current, thanks to larger β-functions in the arcs
- Deployed as proof of principle and to gain operational experience
- Further development continues during MD sessions



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Summary

- During the production years 2016, 2017, 2018 (so far) the 50% stable beam ratio has been achieved
- The LHC is presently only 3.5 fb^{-1} away from the goal until LS2 of 150 fb^{-1}
  (Run I + Run II)
- The peak luminosity is beyond twice the design luminosity
  (2.1×10^{34} $cm^{-2}s^{-1}$ versus 1×10^{34} $cm^{-2}s^{-1}$)
- Beam physics challenges have been or are being addressed and for most mitigation measures are in place, others are being investigated
- The future for HL-LHC is being prepared and operational experience is gained with future principles/methods and tools


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HB2018
Workshop
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Questions ?

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