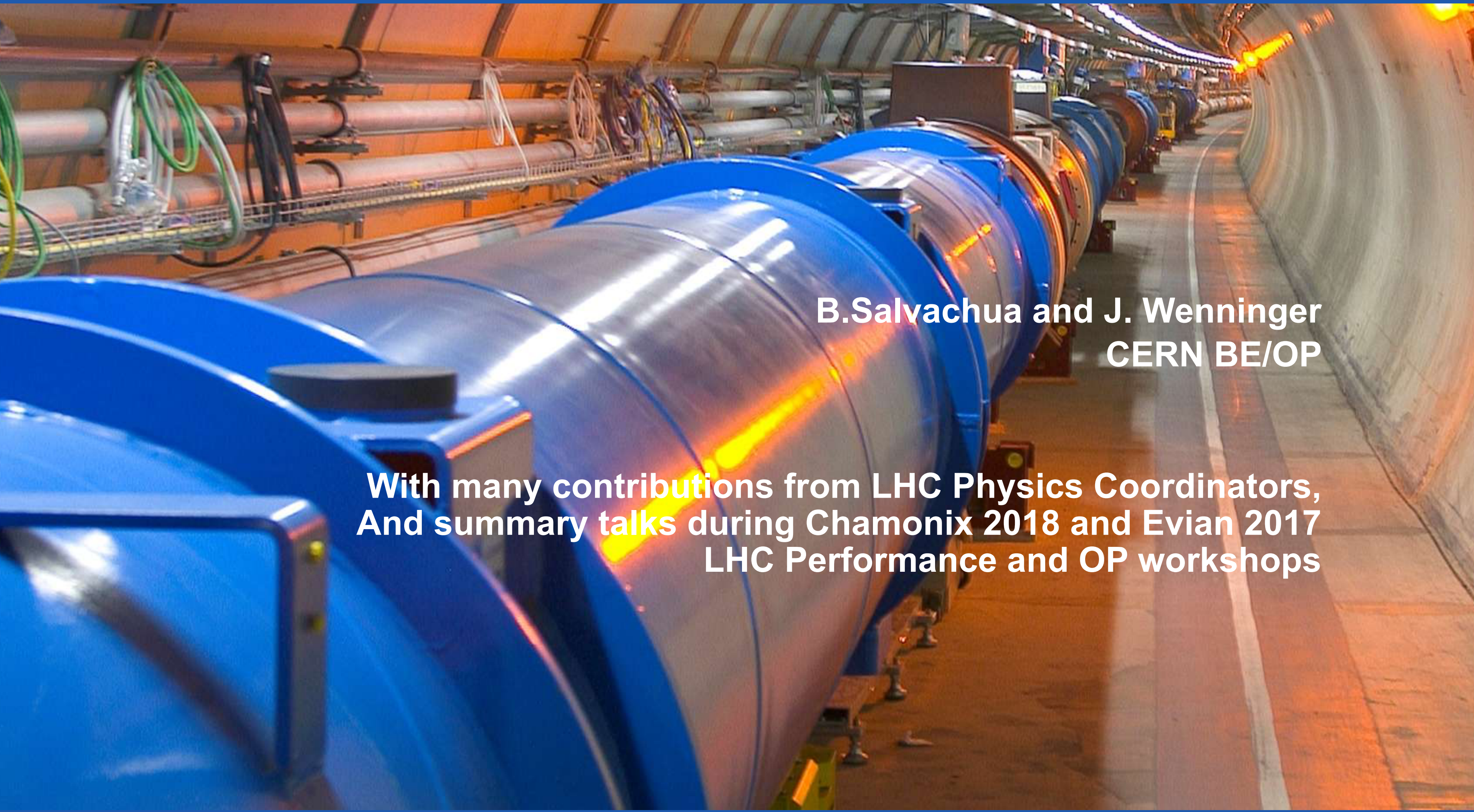
CERN

LHC Luminosity levelling and Beam - Beam



B.Salvachua and J. Wenninger
CERN BE/OP

With many contributions from LHC Physics Coordinators,
And summary talks during Chamonix 2018 and Evian 2017
LHC Performance and OP workshops

Overview

- LHC overview of 2017
- Luminosity Levelling options
- Experience and observations with luminosity levelling.

LHC Main Goals for 2017

Main goal for 2017 was to maximize the integrated luminosity. **Target of 45fb^{-1}** while implementing **new features needed for HL-LHC**

***pp* at 6.5TeV beam energy**

Combine Energy Ramp and Squeeze.

IP1/IP5 down to 1m

IP8 down to 3m

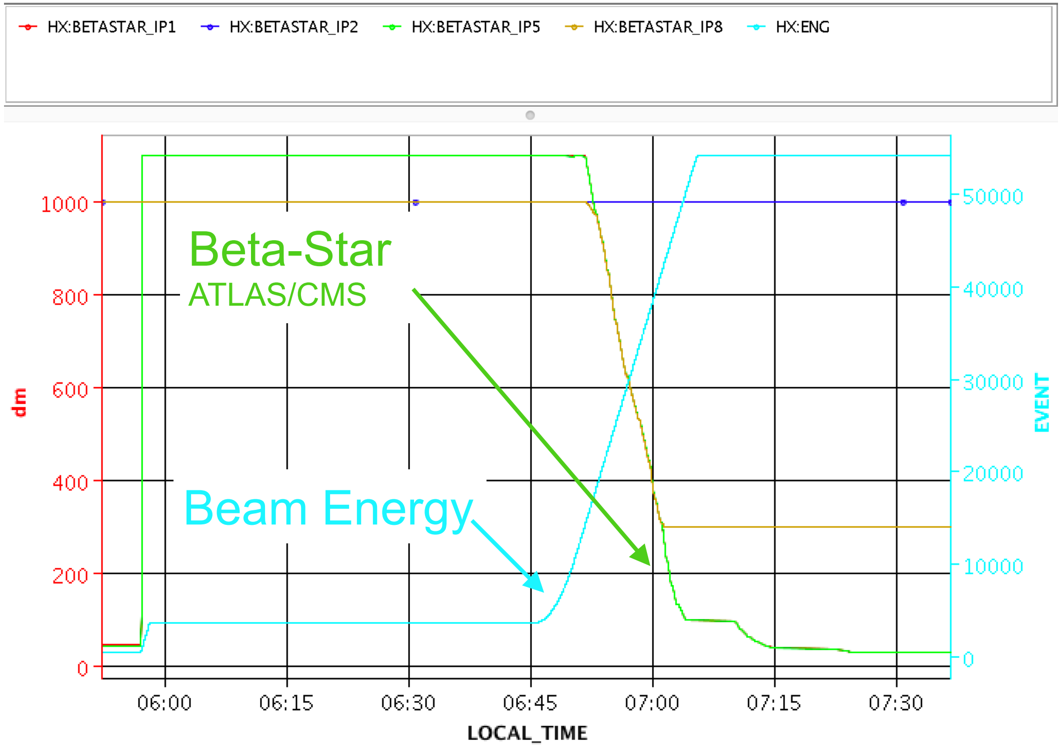
IP2 10m (no squeeze)

New ATS (Achromatic Telescopic Squeeze) **optics** allowing for **smaller beta-star.** Developed during several MDs in 2016.

In 2017:

Pre-squeeze down to 40cm

Squeeze telescopic to 30cm



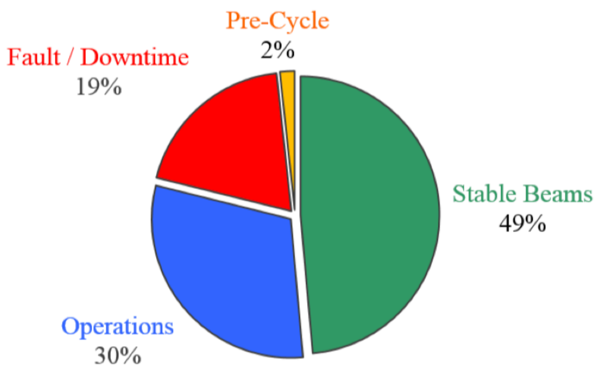
Main achievements 2017

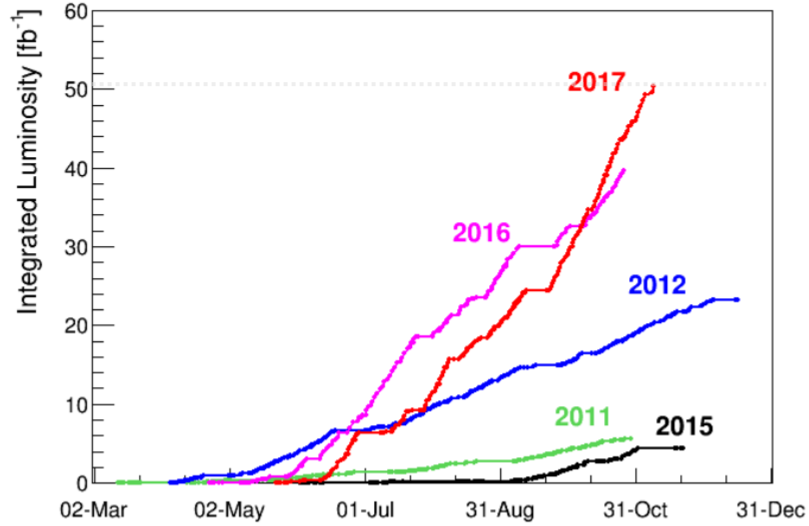
Total integrated luminosity

- **ATLAS/CMS** > 50 fb^{-1}
- **LHCb** = 1.98 fb^{-1}
- **ALICE** = 19.1 pb^{-1}

2017: Best production year
(~0.5 fb^{-1} /day on average after TS2)

Excellent Machine Availability
(~50% in Stable Beams)

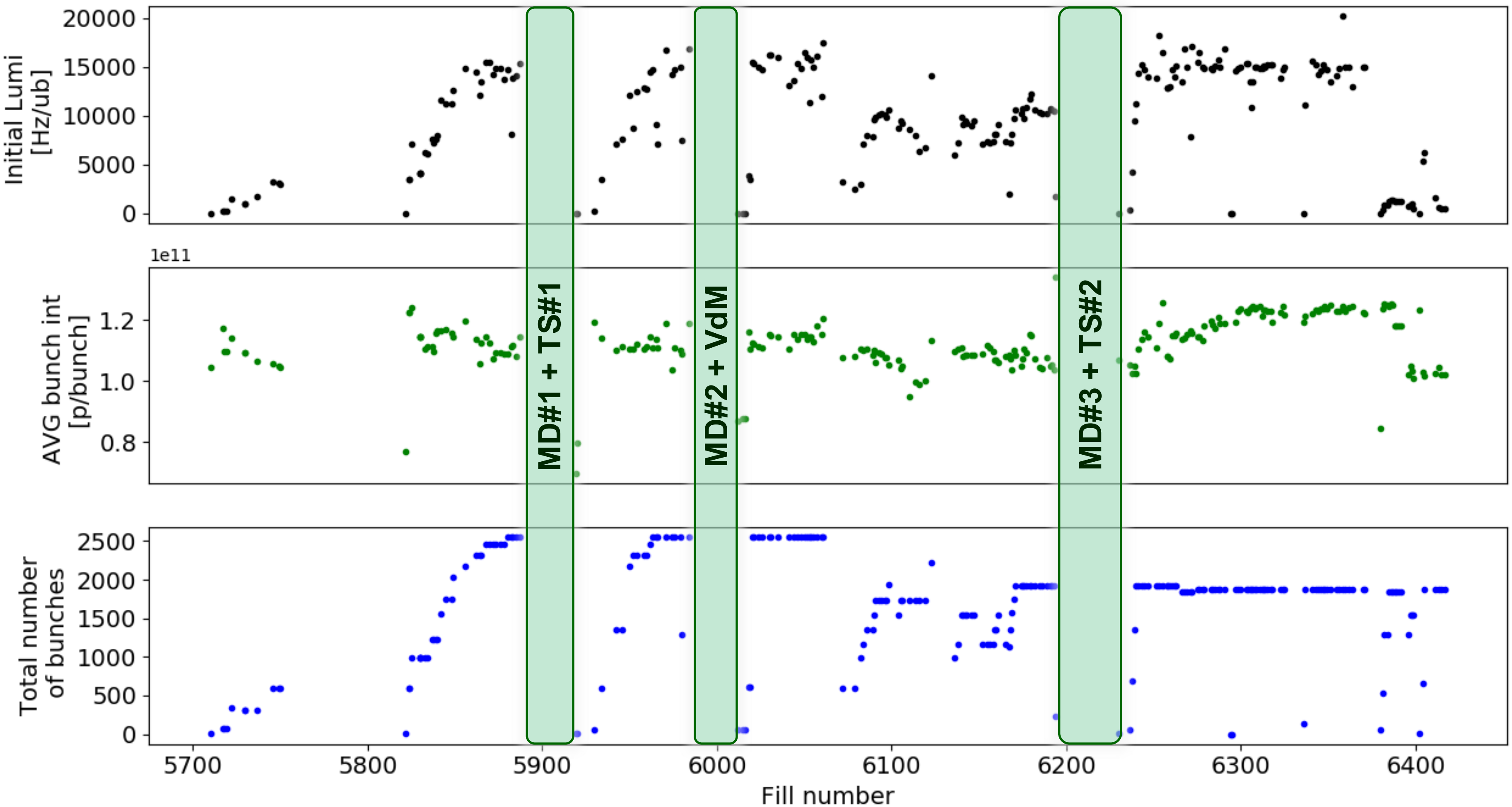




World's record **Peak Luminosity:**
2.2×10^{34} $cm^{-2}s^{-1}$

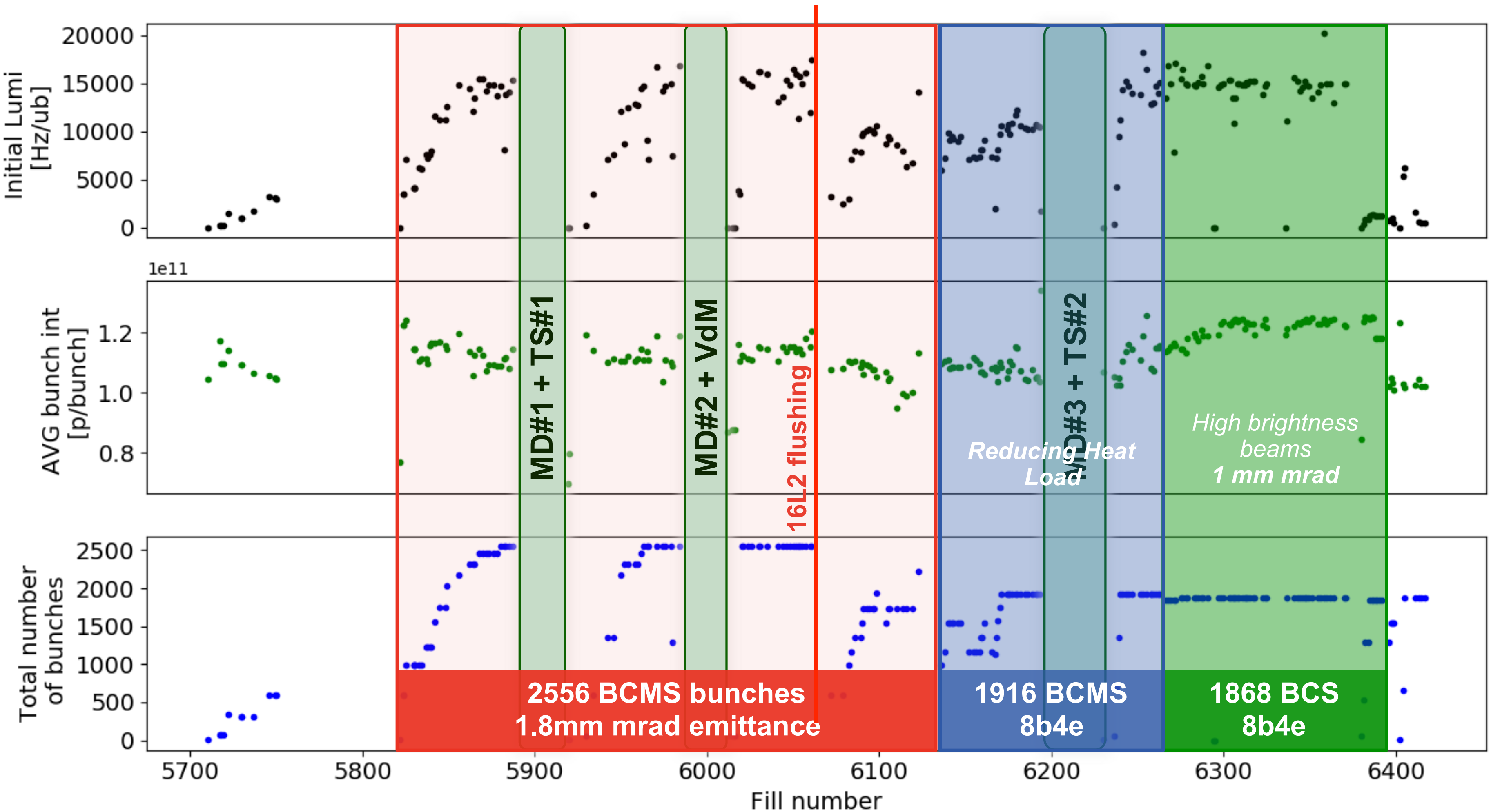
This was achieved by optimising the cycle, better orbit control, smaller beta-star, etc. and by exploring new beam with higher brightness

Beam types



Initial Lumi [Hz/ub]
20000
15000
10000
5000
0
1e11
AVG bunch int [p/bunch]
1.2
1.0
0.8
Total number of bunches
2500
2000
1500
1000
500
0
5700
5800
5900
6000
6100
6200
6300
6400
Fill number
MD#1 + TS#1
MD#2 + VdM
MD#3 + TS#2

Beam types



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Total number of bunches
2500
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1500
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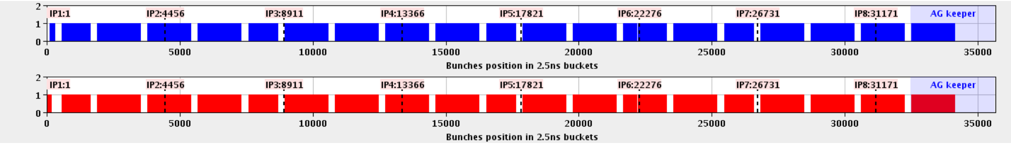
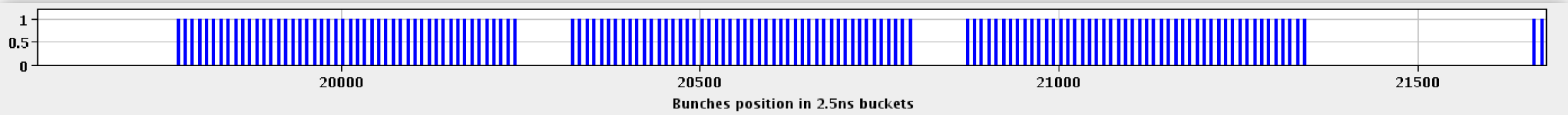
500
0
5700
5800
5900
6000
6100
6200
6300
6400
Fill number
MD#1 + TS#1
MD#2 + VdM
16L2 flushing
MD#3 + TS#2
Reducing Heat Load
High brightness beams
1 mm mrad
2556 BCMS bunches
1.8mm mrad emittance
1916 BCMS
8b4e
1868 BCS
8b4e

Filling schemes

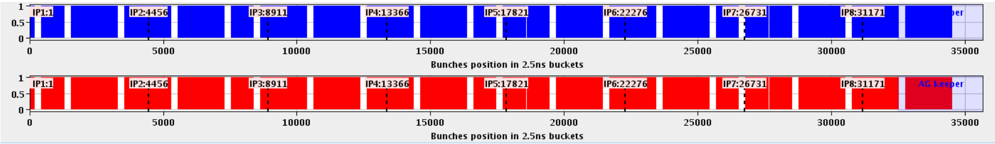
During the first period of 2017, **25ns bunch spacing with up to 144b per injection**. Allows to fill the machine with up to **2556 bunches**.



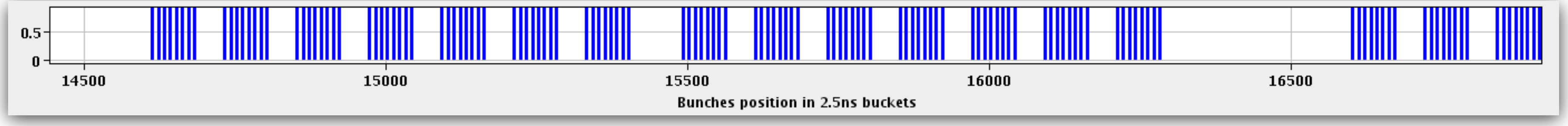
Zoom



Second part of the year, **8b4e**. New Injection scheme with **8 bunches filled and 4 empty**, reducing heat load from electron cloud. The machine is then filled with ~ 1900 bunches but intensity and emittance are pushed in order to increase the peak luminosity.



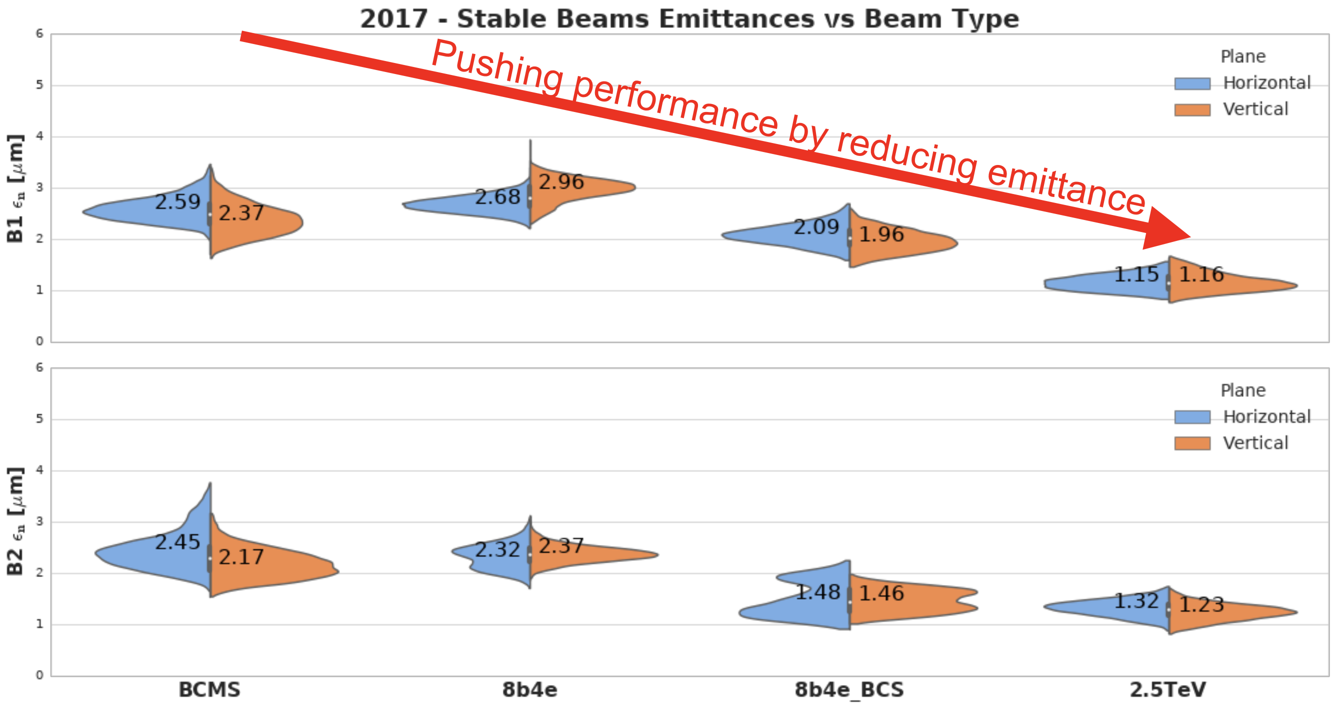
Zoom



Luminosity increase

Need to switch to 8b4e type beam to cope with LHC vacuum issues, this reduced the total number of bunches that could be injected.
However, switch to **BCS** 8b4e **to maximize beam brightness**

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta *} F$$

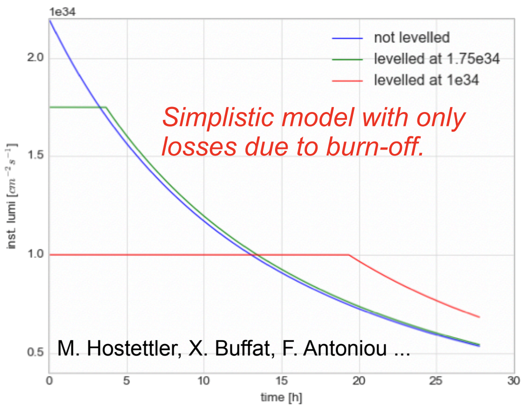


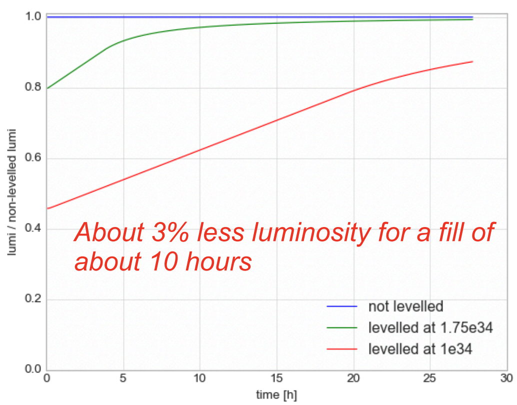
***Higher peak luminosity** at the cost of **higher pile-up** due to reduced number of bunches*

N. Karastathis, S. Papadopoulou et al., LMC 29/11/2017

Why levelling?

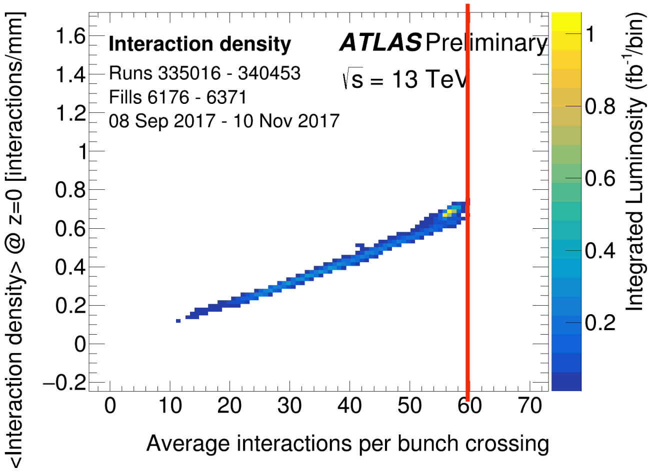
Luminosity production is one of the goals of a collider. How do you deliver this luminosity is important for the experiments. **Use levelling to control peak luminosity.**





Levelling might decrease the total integrated luminosity or push it with "anti-levelling".

We kept pile-up below 60 in 2017 thanks to levelling with separation



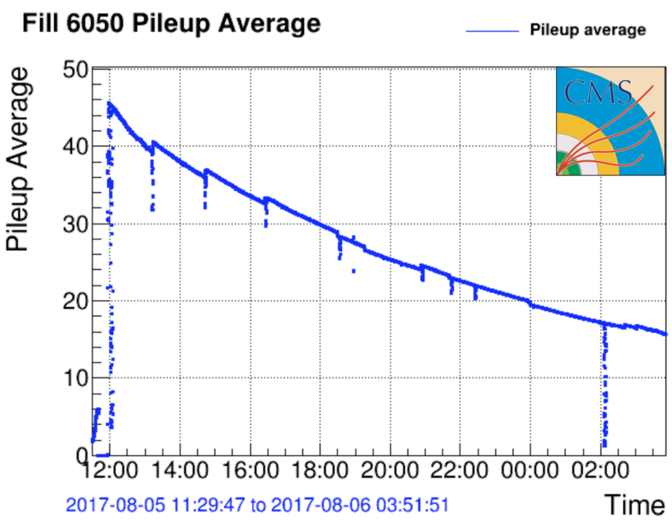
The experiments have constrains on number of pile-up events that could be accepted. Levelling could be used to mitigate this effect. It was advice to explore the possible techniques at the LHC in view of HL-LHC

Pile-up CMS 2017

Courtesy of S. Paramesvaran and C.Schwick for CMS collaboration

Pile-up CMS 2017

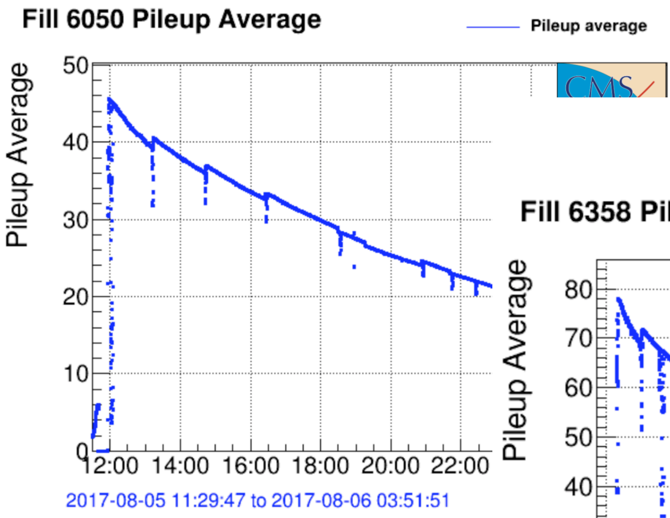
Standard 25ns



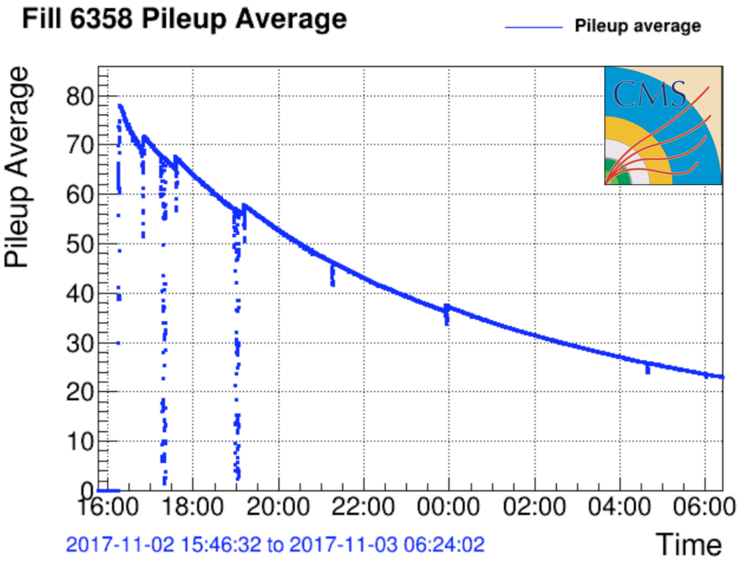
Courtesy of S. Paramesvaran and C.Schwick for CMS collaboration

Pile-up CMS 2017

Standard 25ns



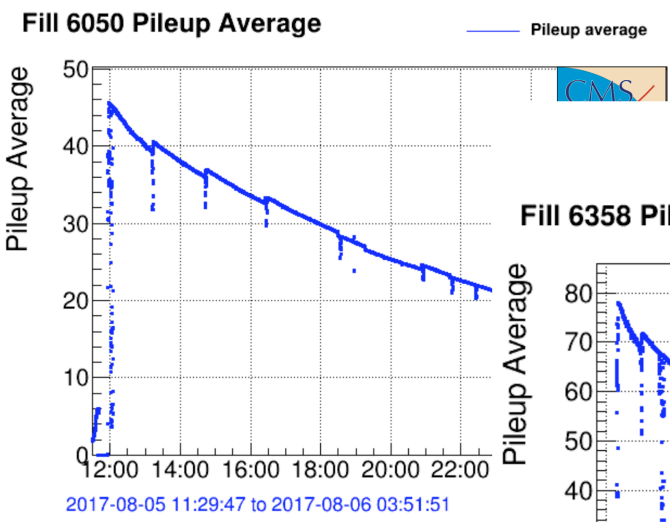
Unlevelled fill, 8b4e.



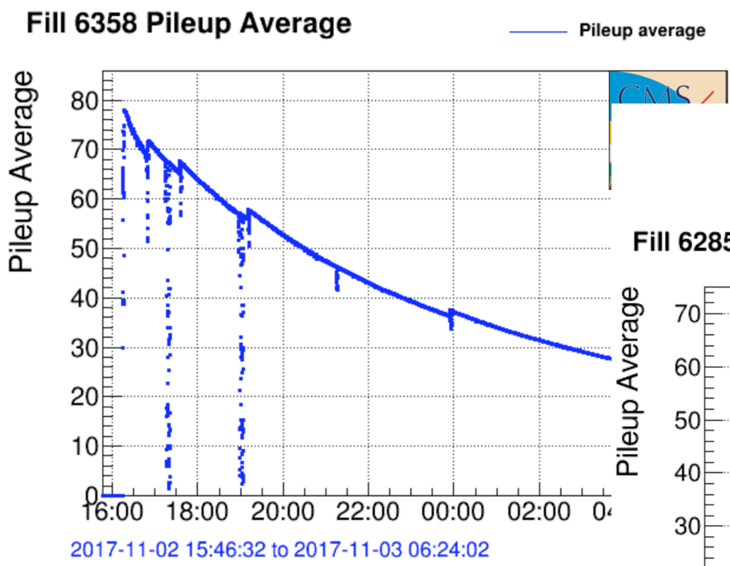
Courtesy of S. Paramesvaran and C.Schwick for CMS collaboration

Pile-up CMS 2017

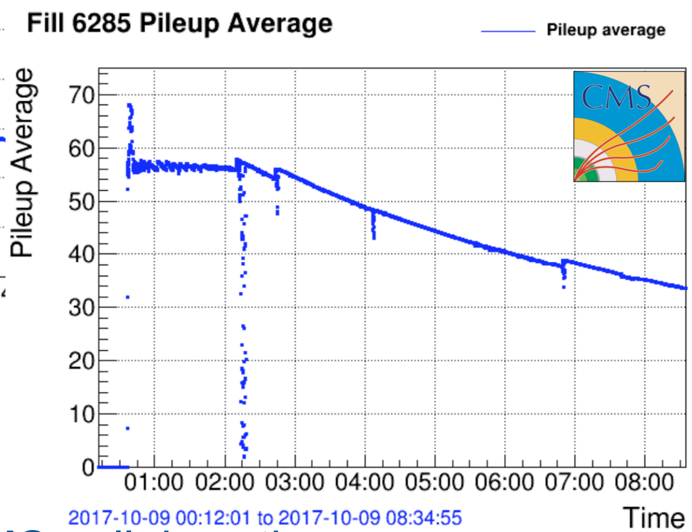
Standard 25ns



Unlevelled fill, 8b4e.



8b4e - levelled



Courtesy of S. Paramesvaran and C.Schwick for CMS collaboration

Exploring levelling at LHC

Separation Levelling

- ➡ *Adding a small transverse offset (local orbit bump) to the beams.*
- ➡ *It is the simplest way of implementing the levelling*

Crossing angle levelling

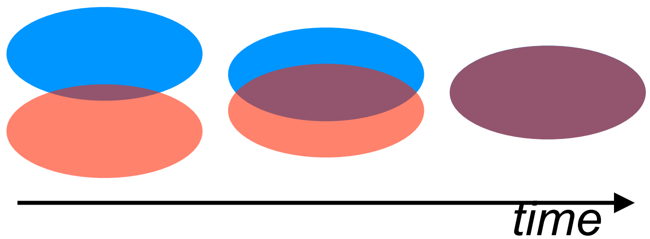
- ➡ *Modification of large local orbit bump*
- ➡ *Requires changes on the Orbit Feedback (Reference)*
- ➡ *Requires collimator movement to protect triplet aperture*

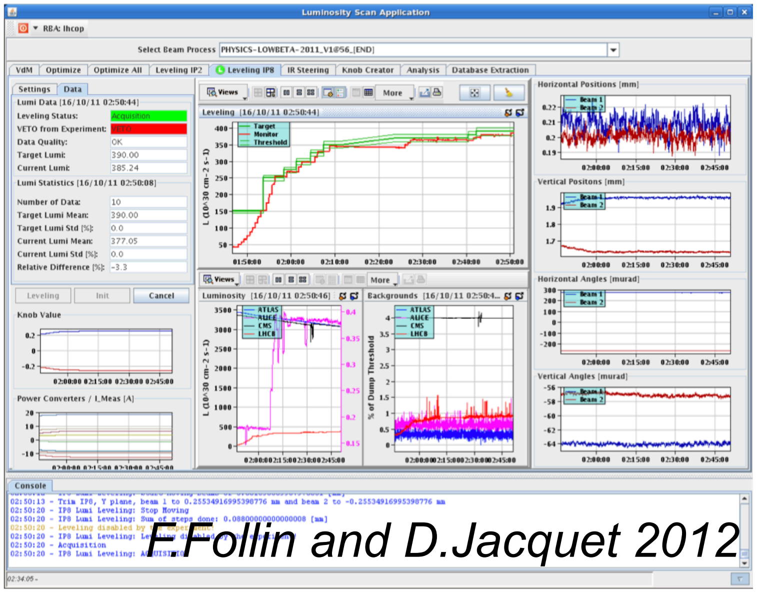
Beta-star levelling

- ➡ *Quoting Jorg Wenninger: "All the glory and complexity of a squeeze step"*
- ➡ *Changes on local optics, orbit, etc.*
- ➡ *Orbit Feedback and Collimators have to follow*

Separation Levelling

Levelling by separation is implemented at LHC since 2011. **Trim of a small local orbit bump to separate or merge the two beams.** Initially done manually by operators and automatised in 2012.





F.Follin and D.Jacquet 2012

The model/feedback converts the step size from beam size to millimetres and uses the LSA knobs to trim the new values.

Experiments request/configure several parameters: target luminosity, levelling step, etc. and publish their measurement of peak luminosity.

Feedback based on above parameters.

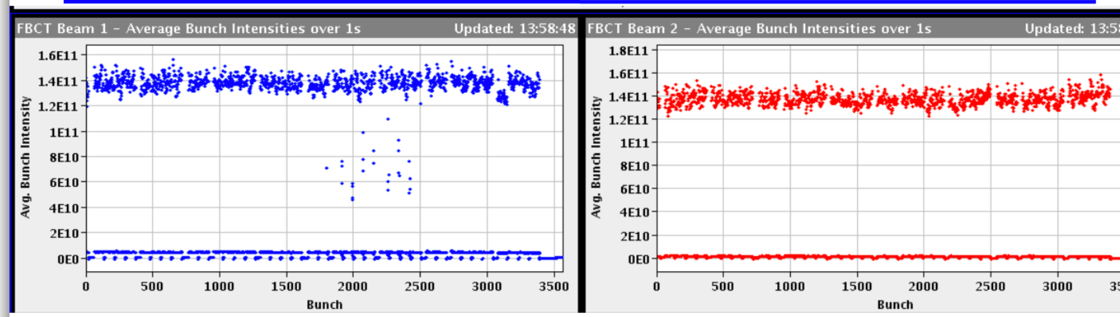
Separation Levelling: Stability

Cons: *Since no head-on collisions the stability area is small, bunches are more sensitive to instabilities with respect to head-on. Expect variable tune shift depending on the levelling conditions.*

Example:

Run I observation of bunches colliding only in IP8 with too low Landau damping and became unstable. Cured by damping with head-on collisions in IP1/IP5.

loss of Landau damping



- some bunches in ring 1 were losing very quickly due to instabilities
  - interlock kicked in at ~4e10 ppb, and fills terminated prematurely
  - bunches colliding only in IP8 (levelled by separation)
- changed collision pattern to have head-on collisions in IP1/5 for all bunches
  - need the beam-beam tune spread
  - kept 3 non-colliding for background studies at IP1/5

X. Buffat, "Stability diagrams of colliding beams"

X. Buffat, "Consequences of missing collisions, beam stability and Landau damping"

G.Papotti BB workshop 2013

11 March 2013, MP Worskshop giulia.papotti@cern.ch

Separation Levelling: 2017

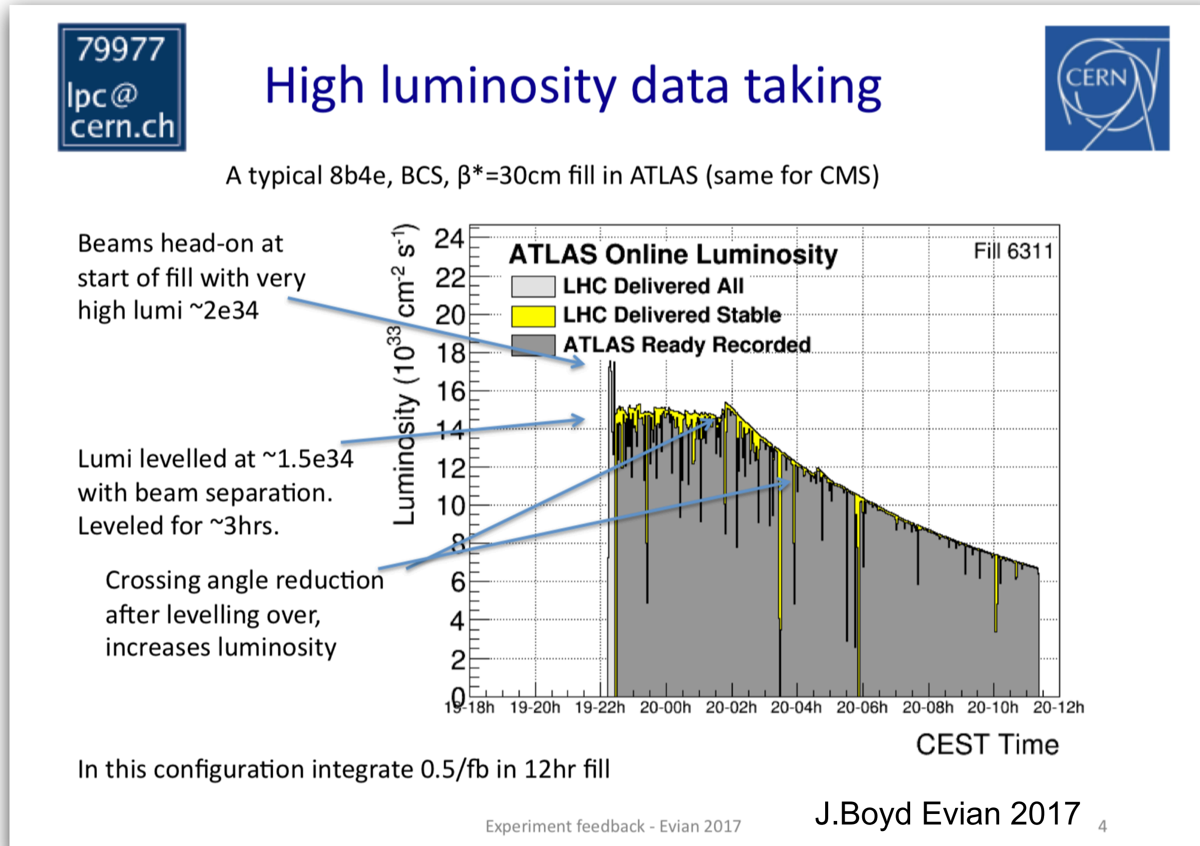
In 2017, due to high pile-up conditions with the new hight brightness beams levelling with separation was also successfully used for IP1/IP5.

About 3 hours of levelling in IP1/IP5

From peak luminosities above 2×10^{34} levelled to 1.5×10^{34}

No observed issues.

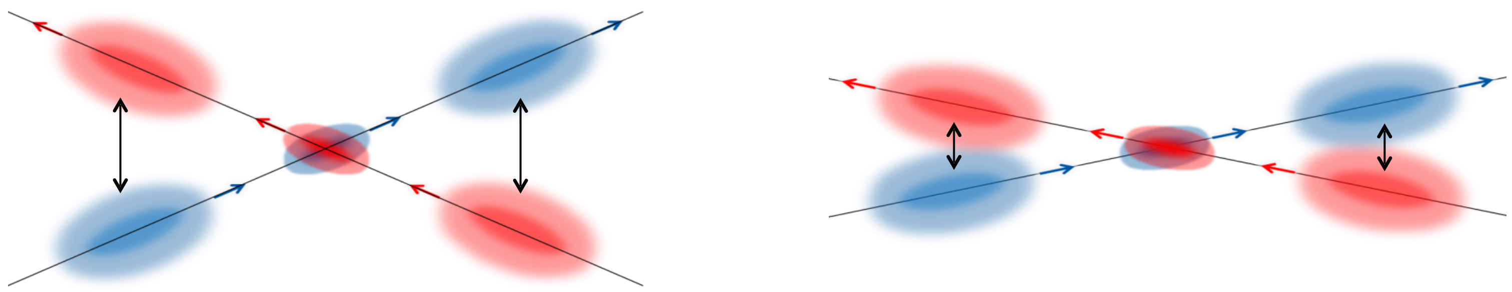
Beam Lifetime maintained around 30 hours for both beams (including burn-off from luminosity)



Crossing Angle Levelling

Or anti-levelling…

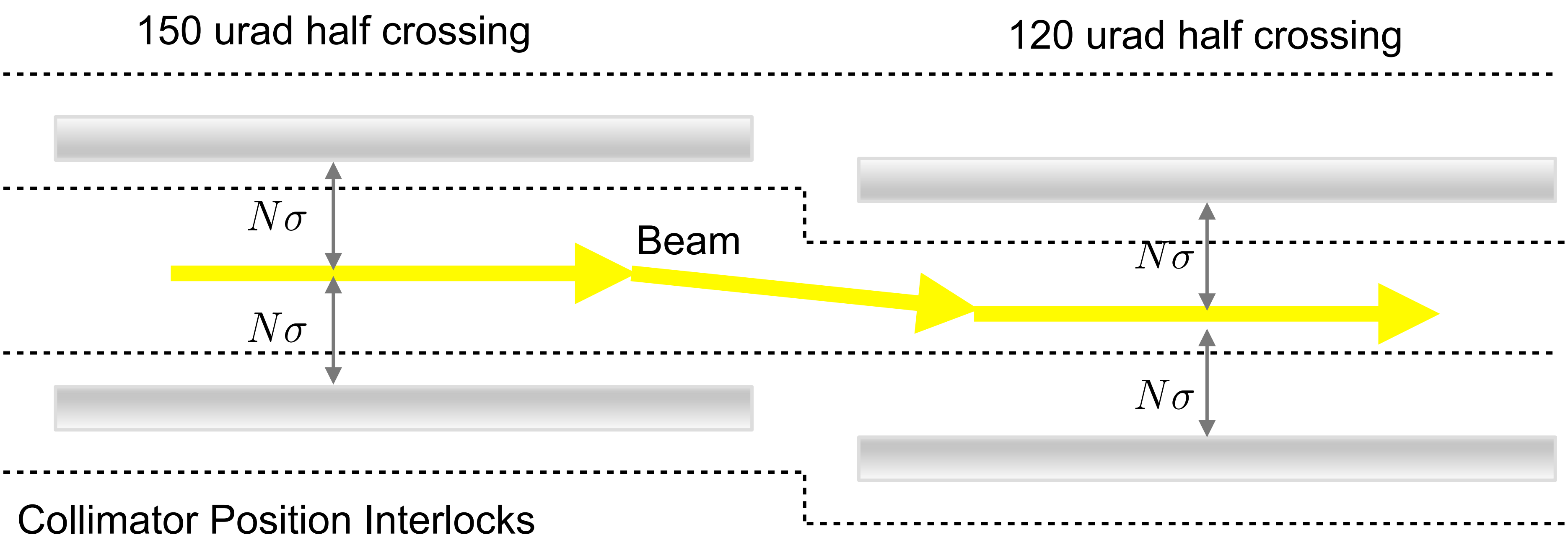
Crossing angles at the colliding IRs are necessary to decrease the Beam Beam force.
As intensity decrease over time the initial Beam Beam separation can be reduced.



Implementation is more complex. The orbit needs to be controlled during change
Feedback must be ON (see Michi's talk) and the knob is larger.

TCT Collimators protecting the triplet should be moved at each crossing bump steps.

Crossing Angle Levelling: Collimators



The collimator position interlocks are opened in Stable Beams (just “inner” limit towards the zero crossing angle)

The machine protection validation is done in the two extreme configurations.

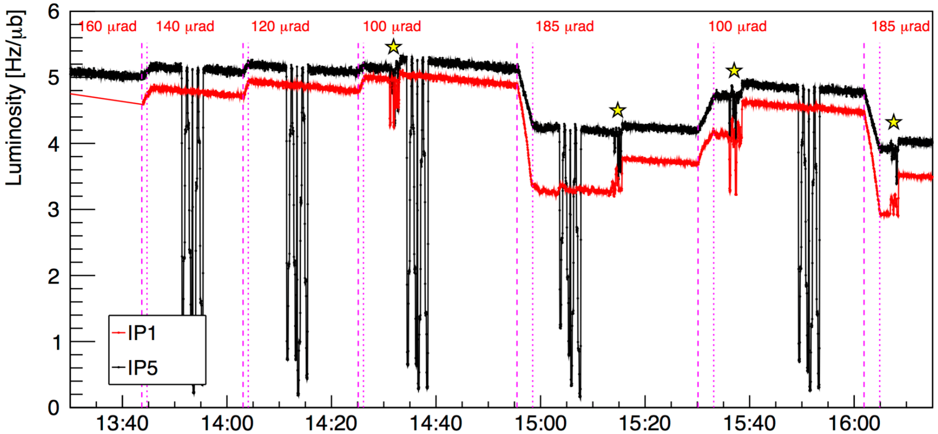
Exploring Crossing Angle Levelling I

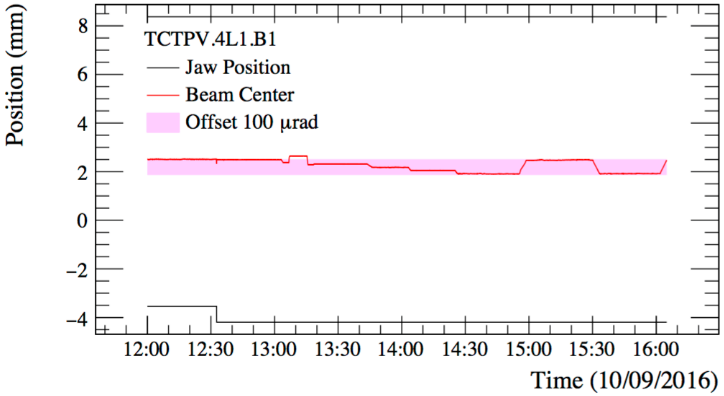
A smooth crossing angle reduction was tested during Machine Developments 2016.

Crossing angle changes were done to increase/decrease luminosity.

Steps between 20-85 urad
Two nominal bunches colliding ATLAS/CMS.

Monitoring of beam position at TCT collimators. Reproducible orbit





Demonstrating compatibility with Stable Beams.
Deployed operationally at the LHC in 2017

CERN-ACC-NOTE-2016-0058

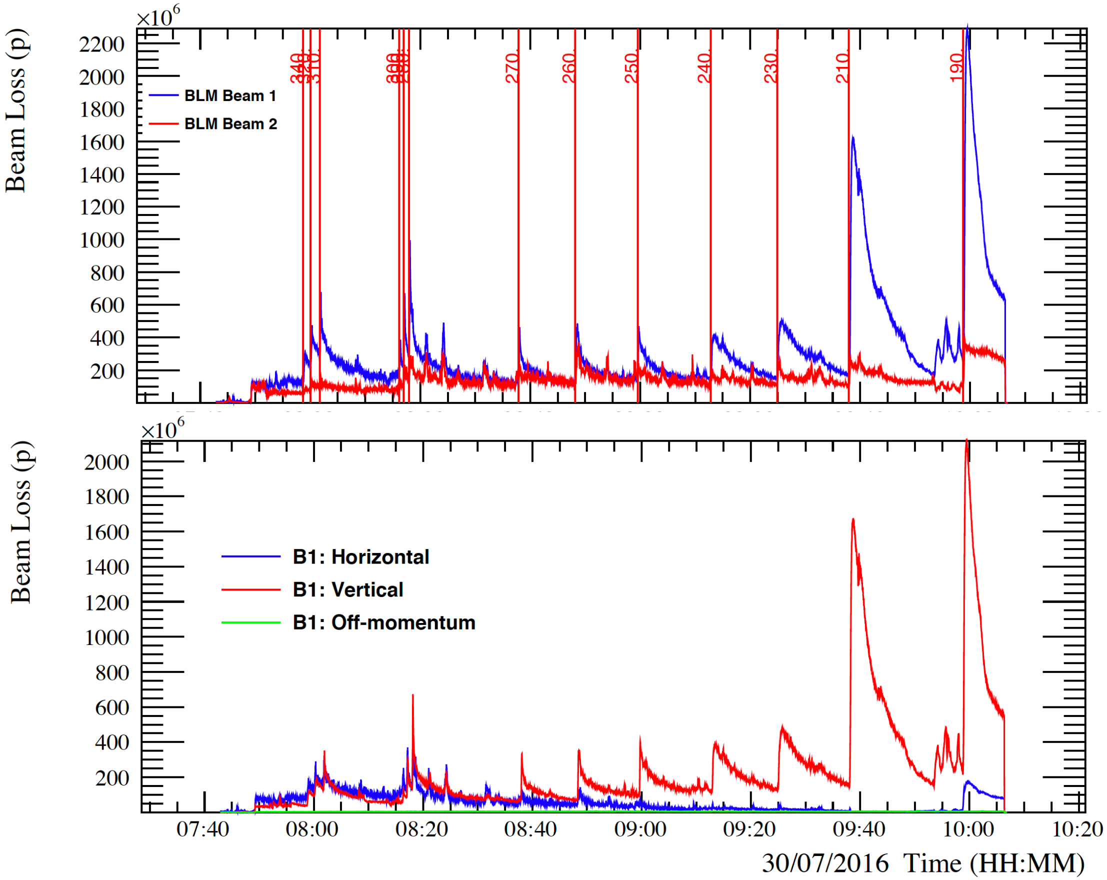
Different Crossing Angles at LHC

Implact of different crossing angles were in addition tested in other MDs in order to explore the limitation due to long range beam-beam effects.

A train of 144 bunches colliding ATLAS/CMS

Half-Crossing from 185-90 urad
Both ATLAS/CMS

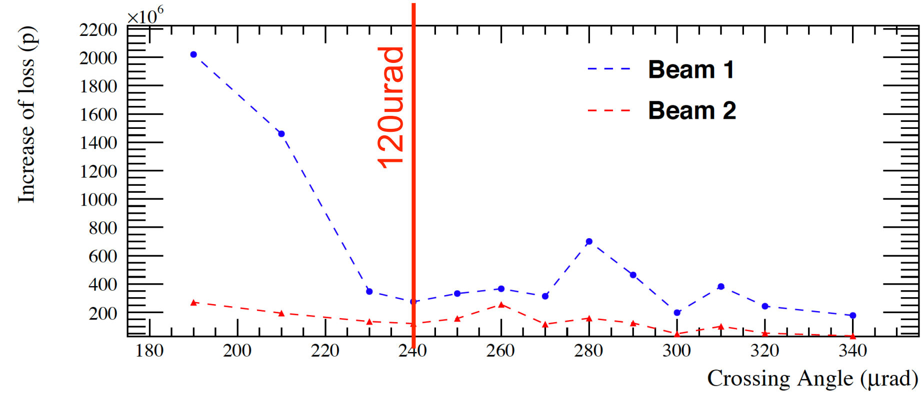
Losses only in Beam 1
Mainly in the Vertical Plane



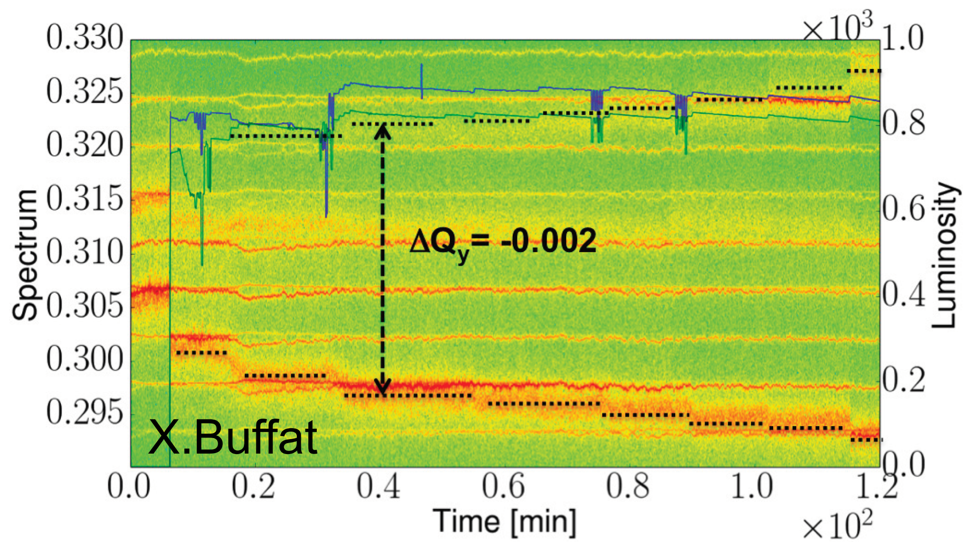
IPAC 2017 B.Salvachua et al.

Different Crossing Angles at LHC

Small losses until ~120urad



Main reason of these losses was a vertical tune shift that appears when changing the crossing angle, driving the beam close to the third order resonance.



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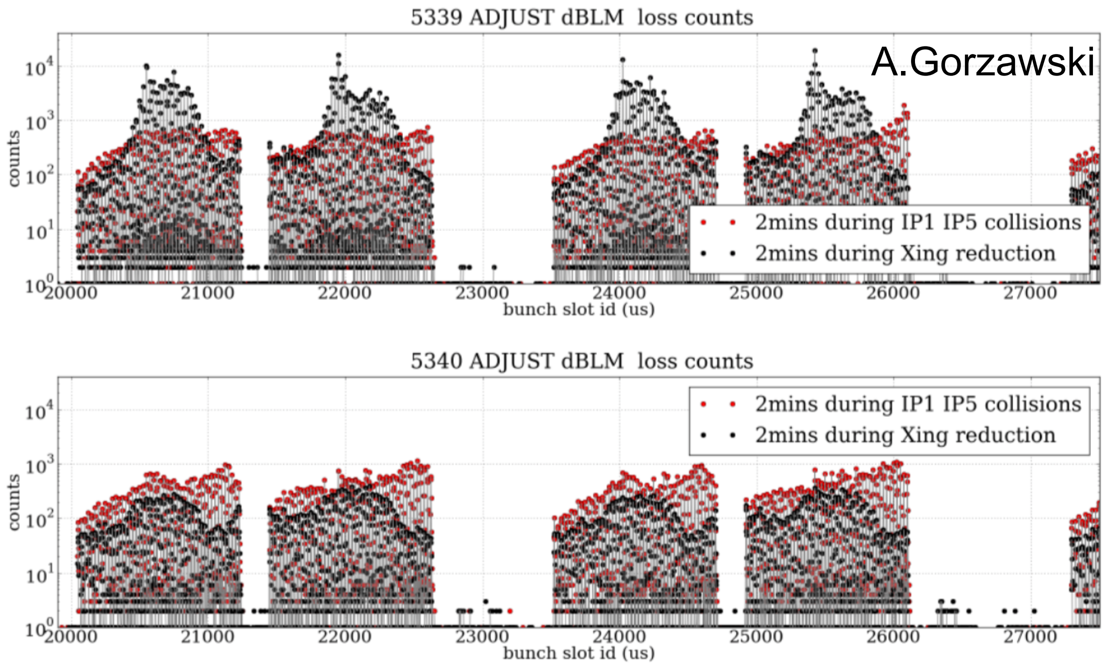
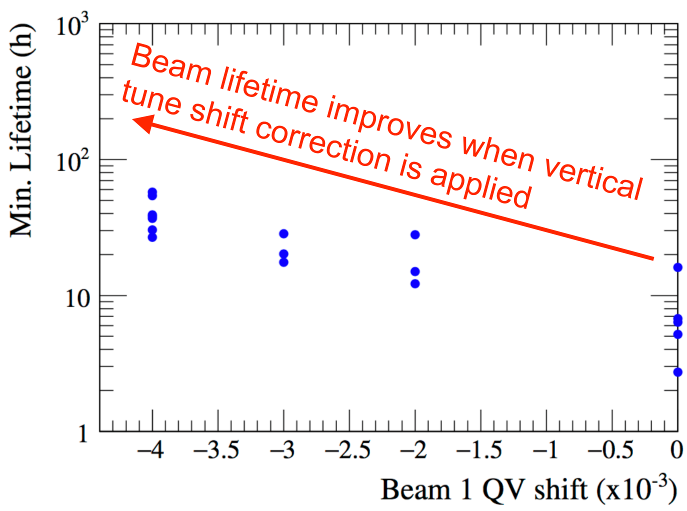
Different Crossing Angles at LHC

Analysis of bunch-by-bunch losses shows that the losses occur mainly on the bunches with more Long Range encounters.

Data shown here corresponds to 2 fills in 2016. The second fill (bottom) a vertical tune shift correction was applied ind to compensate for the expected shift. Losses are clearly reduced. Beam lifetime improves when shifting the vertical tune Beam 1.



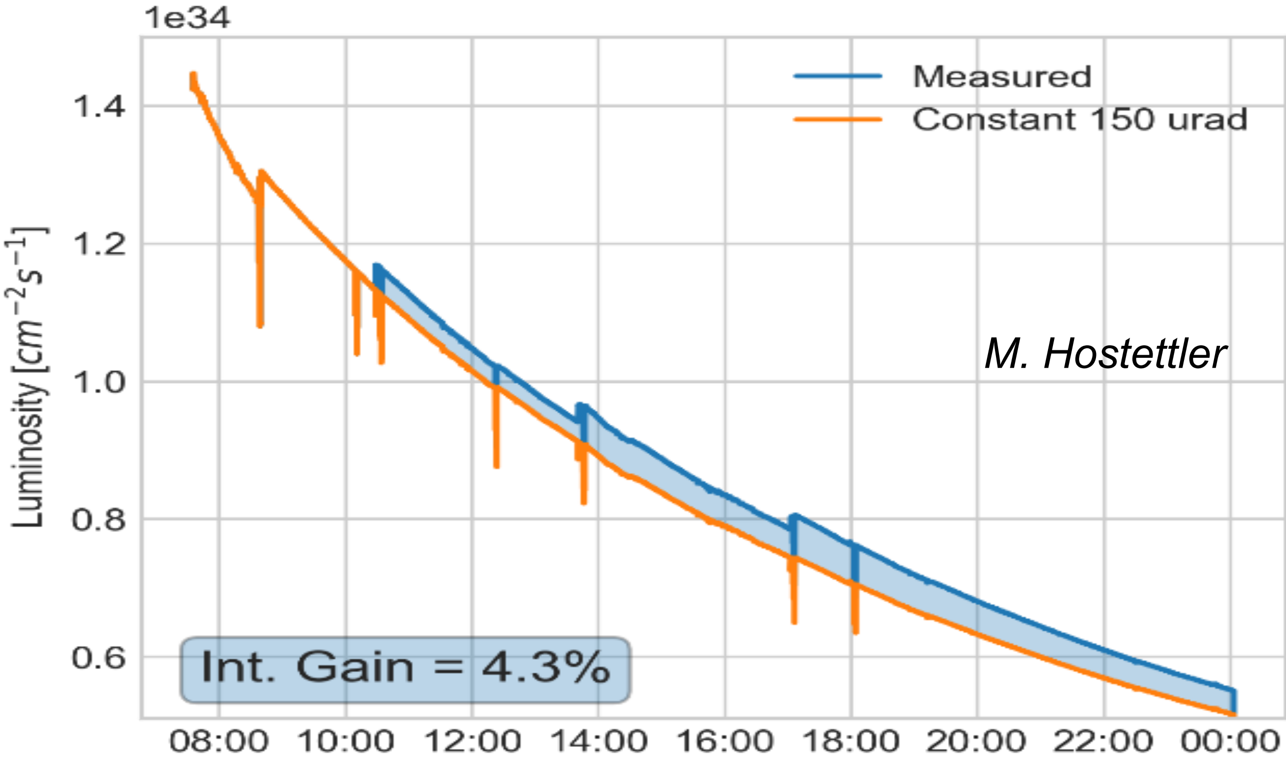


Collaboration with T.Pieloni

Experience with Crossing 2017

Smallest Half-Crossing angle used at beta-star of 30 cm : down **120 urad,** corresponding to a beam-beam separation of 6.9sigma

Parasitic collisions observed if we go below.



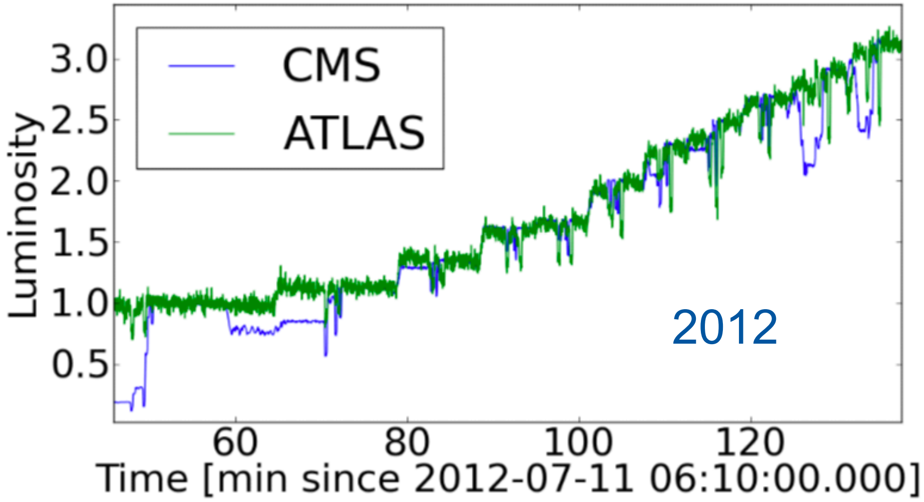
Beta-star Levelling

Consists of squeezing or de-squeezing the beam at the IR while colliding in order to control the peak luminosity, in Stable Beams.

Since beams are colliding head-on there will be much larger tune spread and Landau damping

Requires all the complexity of a squeeze step: magnets, collimators, optics, orbit, etc.

Proof of principle was already demonstrated in 2012.

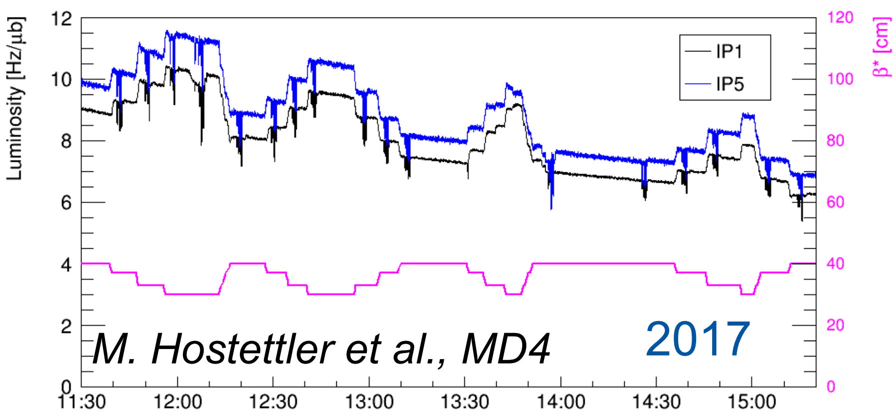


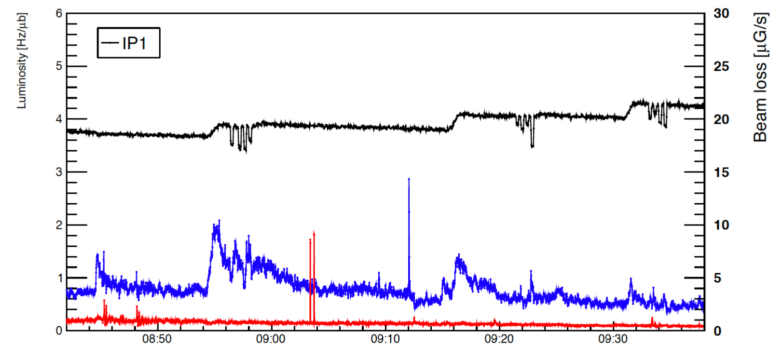
However the machinery to synchronise all the suspects was tested during MD in 2017

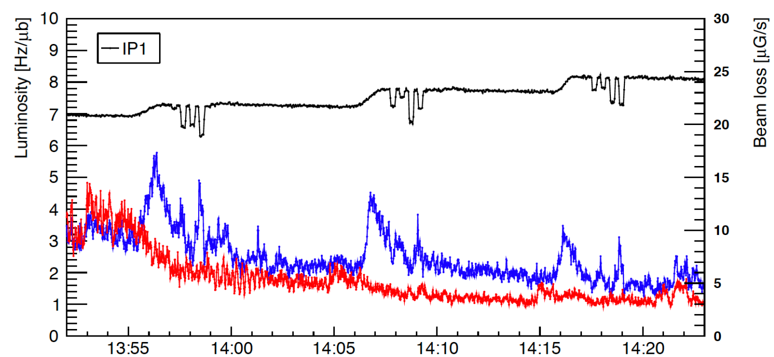
Beta-star Levelling

Tested 2017 in MDs with 2 nominal bunches colliding in IP1/IP5.
Three beta-star steps executed from 40cm: **37cm, 33, 30cm**

Evolution of luminosity in ATLAS/CMS while squeezing/de-squeezing, interleave with luminosity scans.







Some developments may still be needed to optimise the optics transitions and collimators settings.

Start using it at end-of-fill tests.

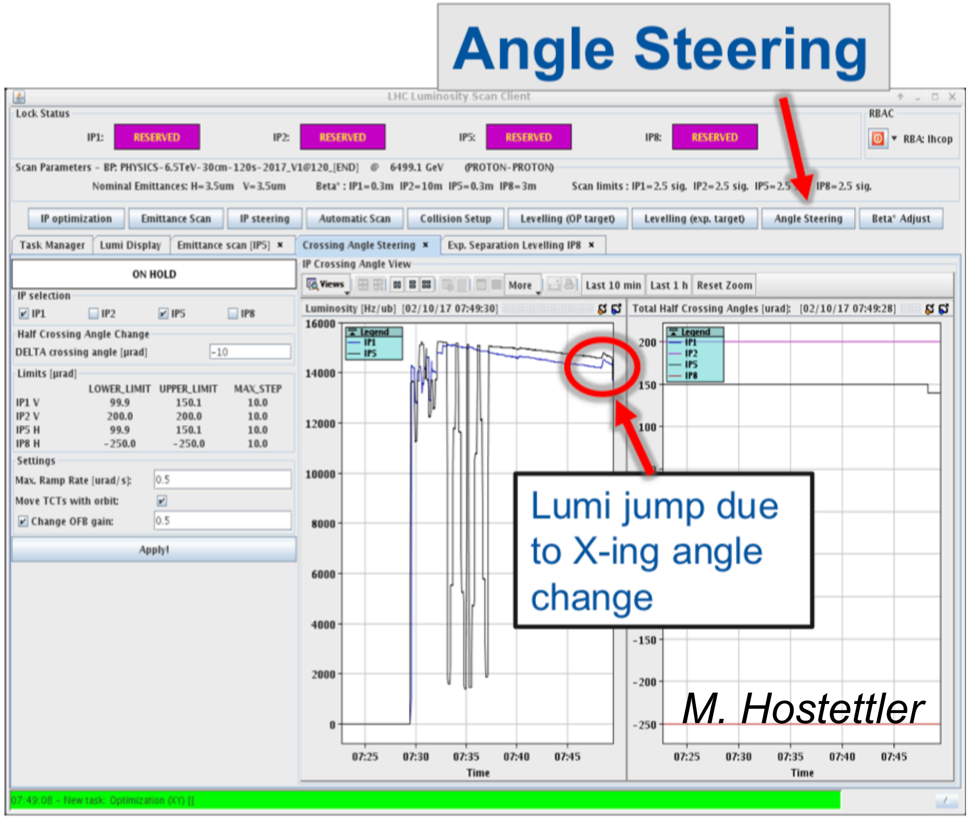
Luminosity Server

Several processes need to be synchronised when levelling is operational

This is done in the new luminosity server.

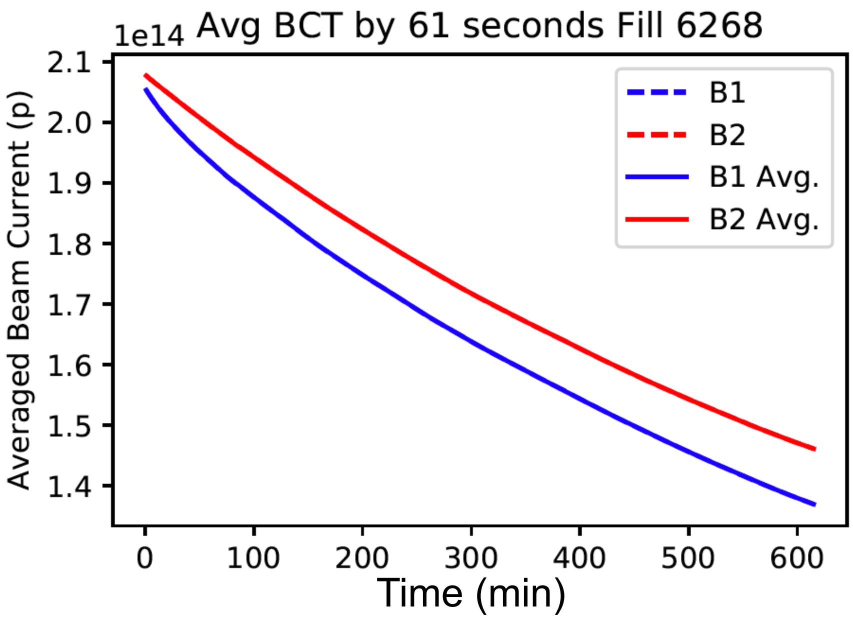
Settings Database trims, Monitoring of Luminosity from experiments, control of different levelling options, etc.

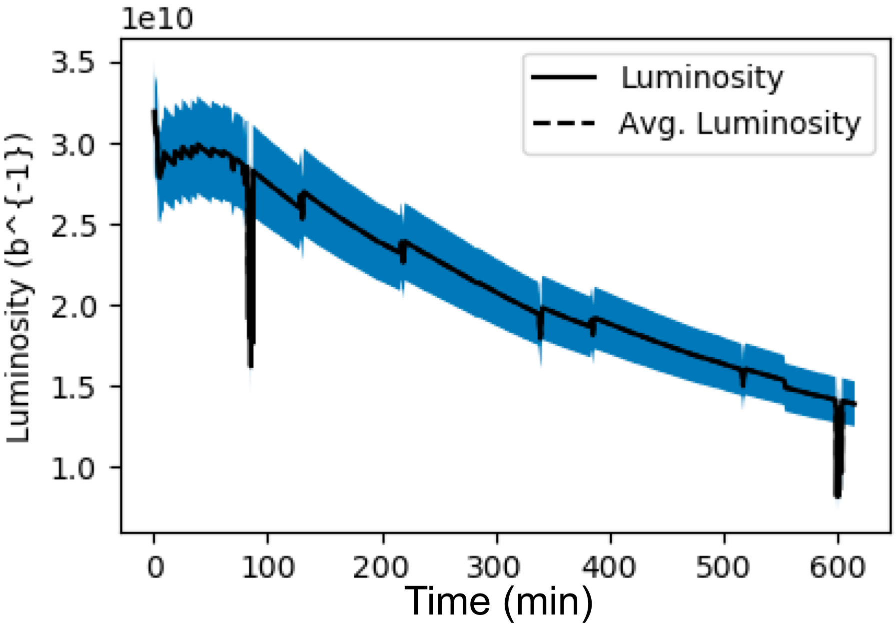
Includes:
- Separation Levelling
- Crossing angle Levelling
- Beta-star to come…



A look into the beam losses

Take a standard fill BCSM in Stable Beams…





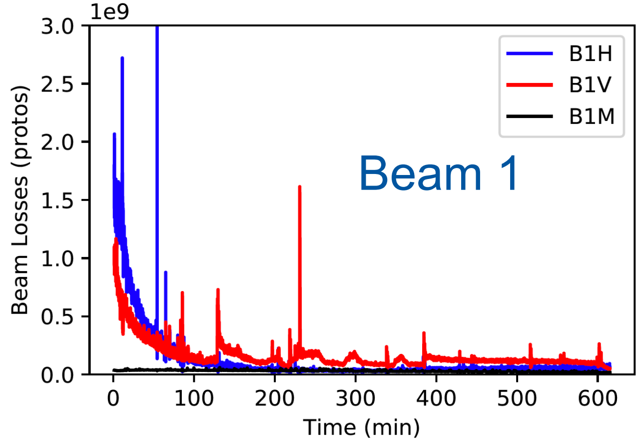
A look into the beam losses

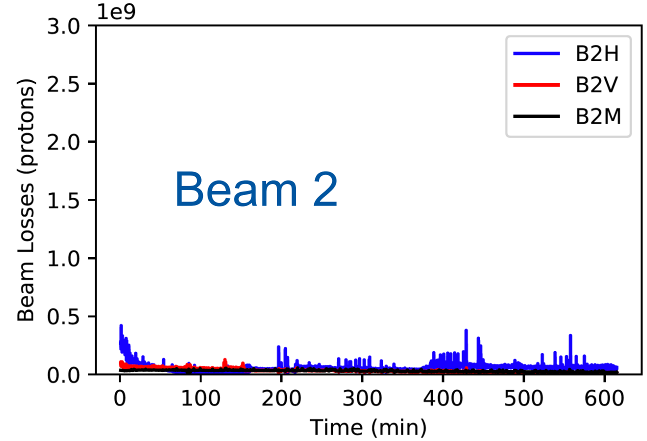
Estimate how much we loose at the collimators and on burn-off

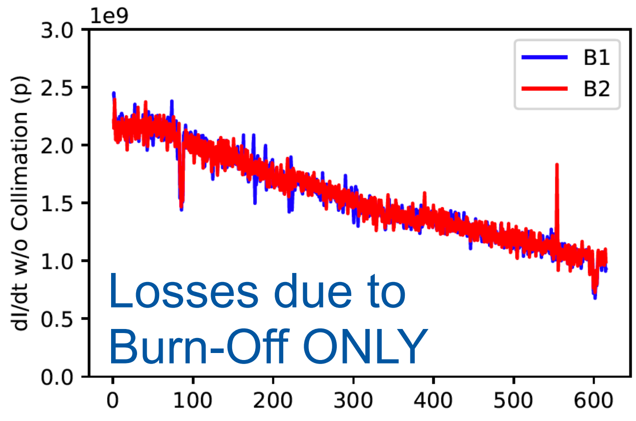
Beam 2 has very small losses.

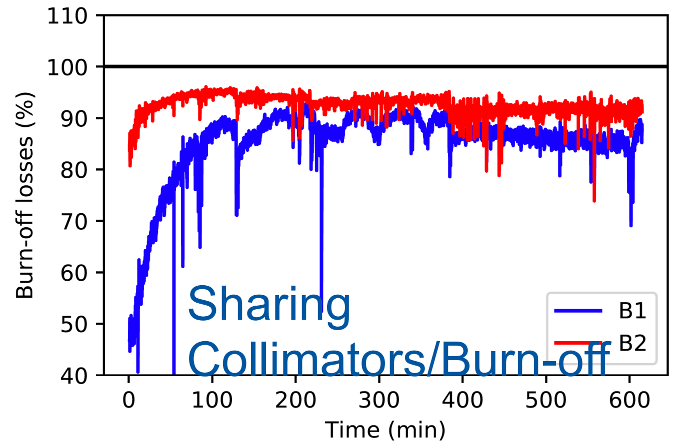
During the first hour of stable beam we loss as much at the Collimators and of burn-off.

Beam lifetimes recover slowly but after 1 hour losses are very similar to the ones of Beam 2.









Summary/Conclusions

- Luminosity Levelling Operational at LHC:
  - With Separation
  - With Crossing Angle (anti-levelling)
- Mechanism for luminosity levelling with Beta-star tested and will be deployed operationally in 2018 as end-of-fill tests (initially)
- Losses are kept relatively small in 2017. Only during the first hour of Stable Beam losses in Beam 1 are similar to burn-off.

Thank you!