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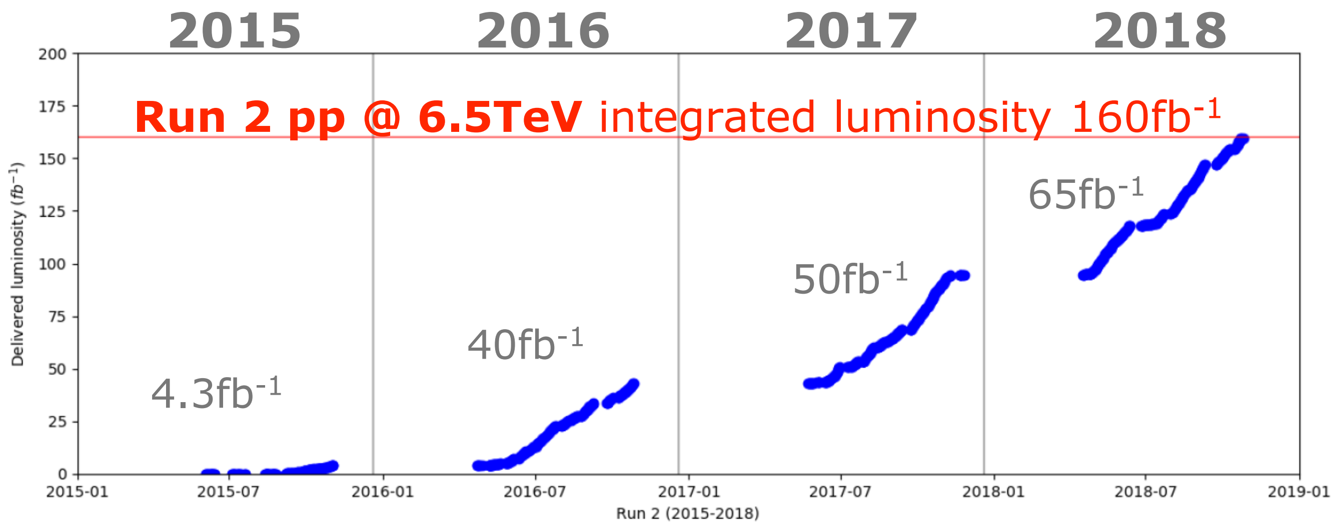
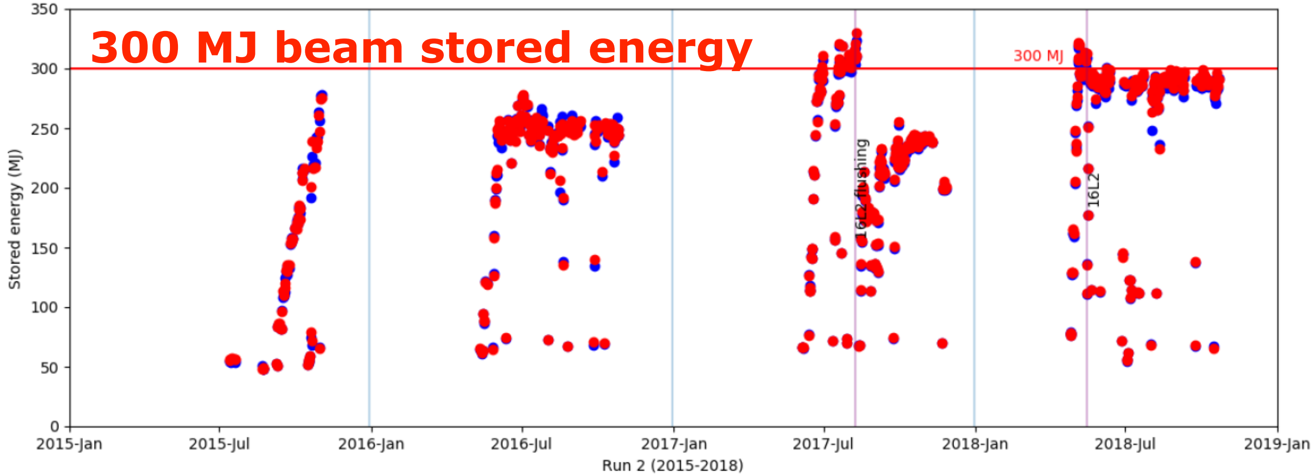
Beam Losses, Lifetime and operational experience at 6.5TeV

B.Salvachua
CERN BE/BI

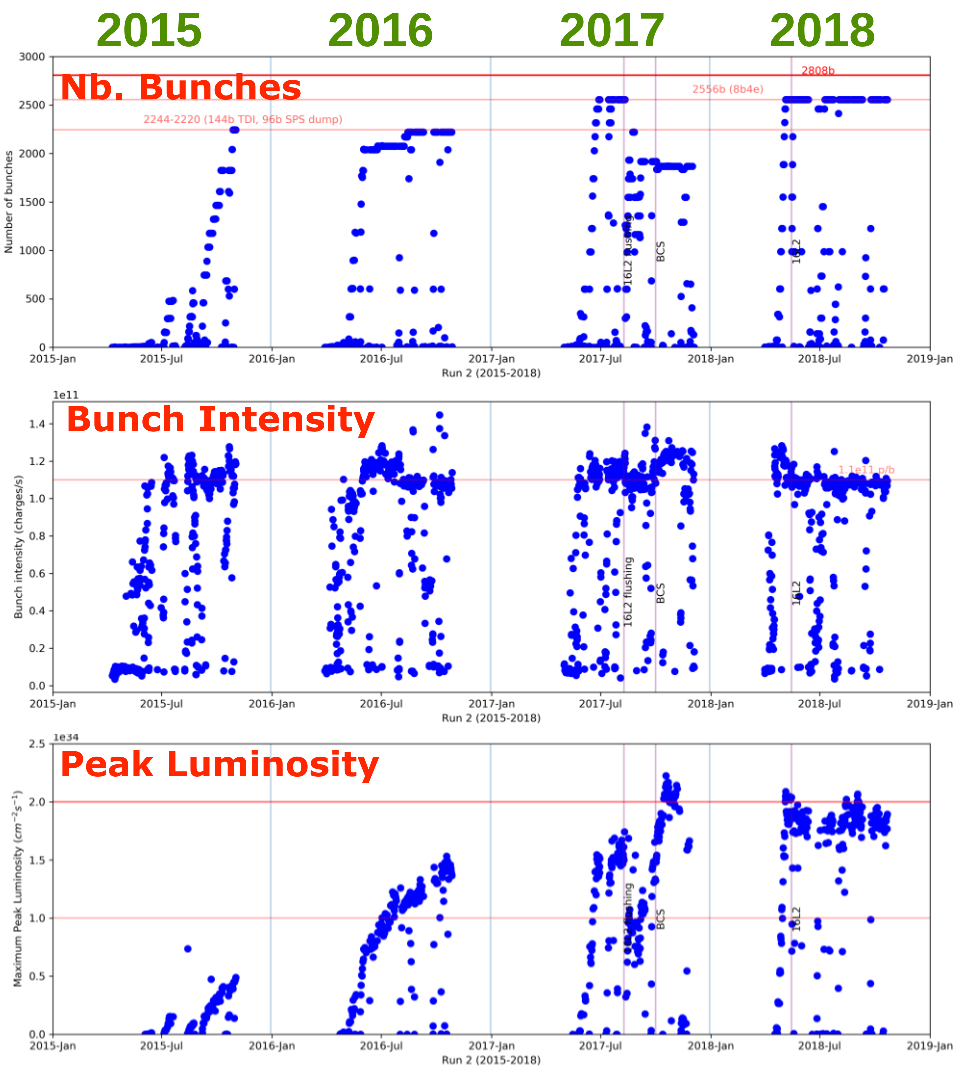
LHC *pp* operations Run 2





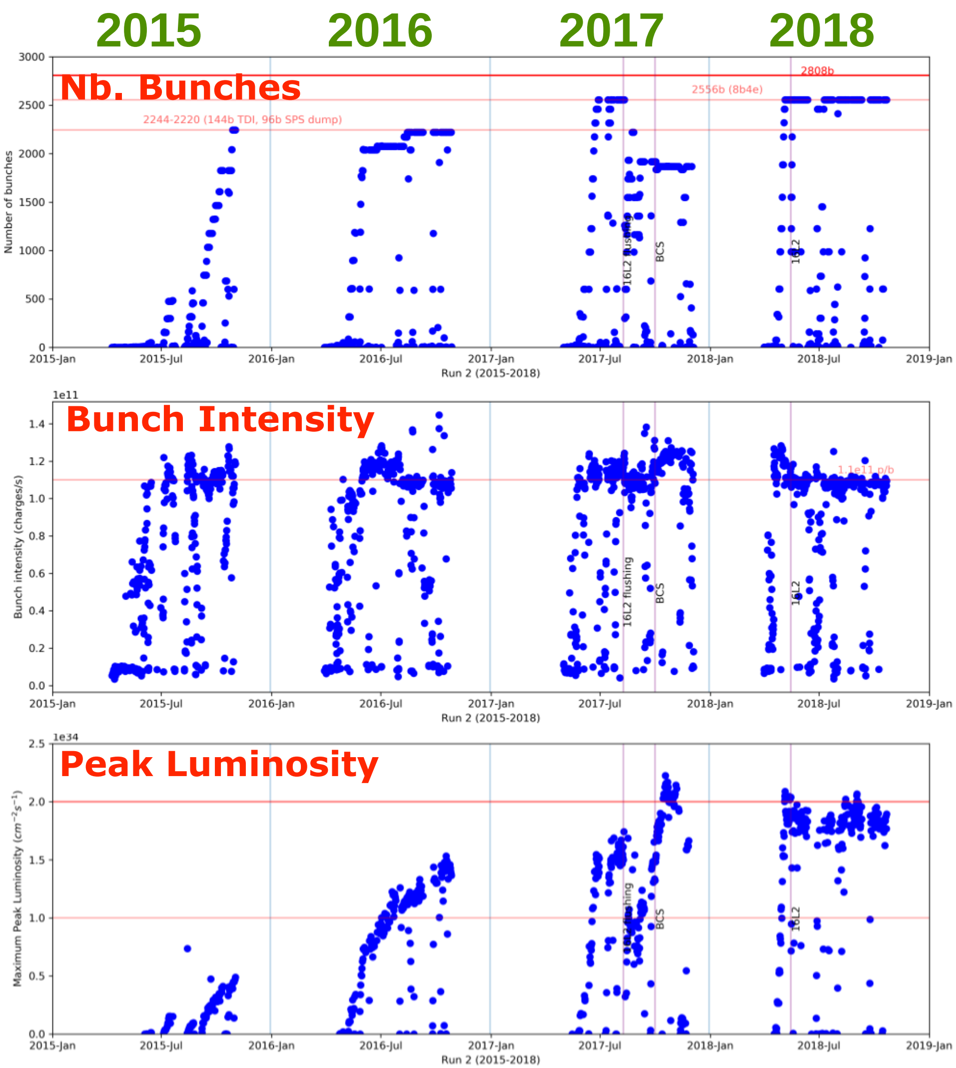
Overview Run 2

- 2015:
  - **Get Experience at 6.5TeV**
  - Start with relaxed scenario:
    - Beta-star 80cm (effective 86cm)
    - 50ns intensity ramp up
      Overcome e-cloud by scrubbing at top energy
    - 25ns intensity ramp up
  - Fast Losses in 15R8 Beam 2: orbit bump after warm up 80K.
- 2016:
  - Combined Ramp and Squeeze:
    - 3m ATLAS/CMS
    - 6m LHCb
  - Squeeze to 40cm
    First time below nominal values
  - BCMS beams (mid July): low emittance
  - Optimisation of abort gap keeper
    Peak luminosity above 1e34cm^{-2}s^{-1}
  - First evaluation of crossing angle reduction in physics:
    - From 379urad to 280urad (23rd Sep)

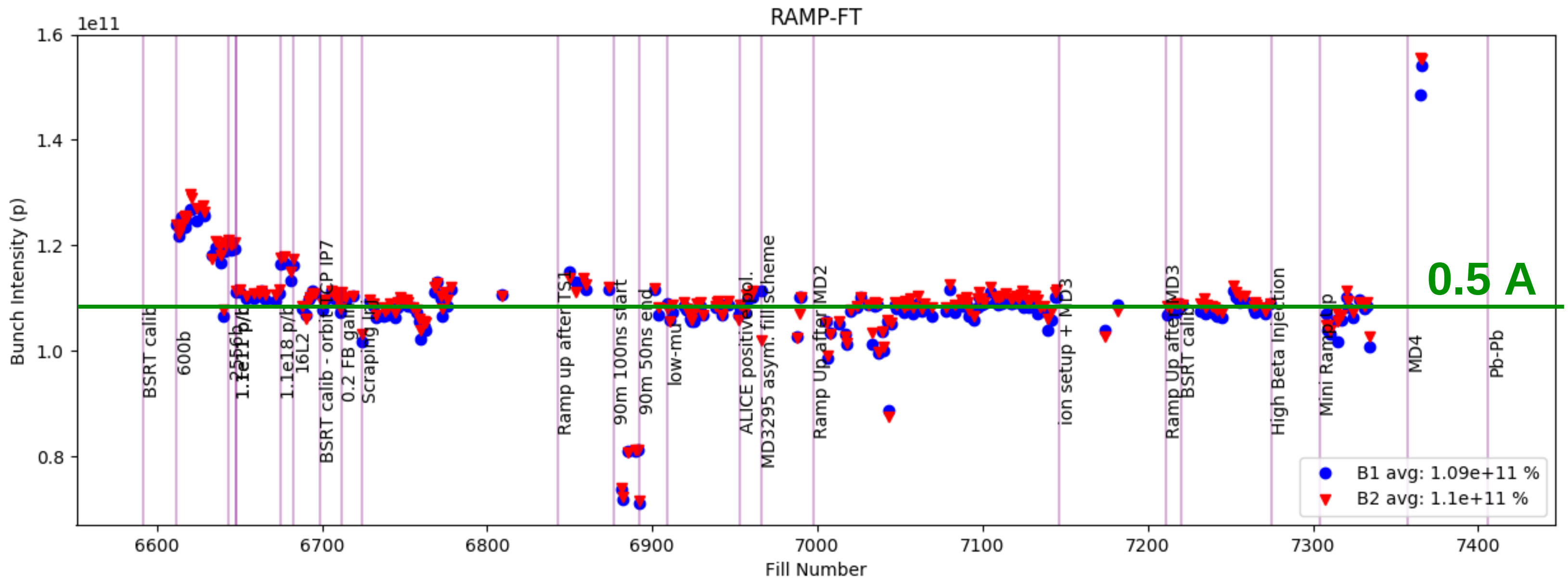


Overview Run 2

- 2017:
  - **Explore HL-LHC options**
  - **Combine Ramp and Squeeze**
    - 1m ATLAS/CMS
    - 3 m LHCb
  - **ATS Squeeze** to 40cm
    after TS2 to 30cm
  - RF detuning —> Reduce RF power
  - **BCS beams**
    Peak luminosity above 2e34cm^{-2}s^{-1}
  - **Explore Levelling options:**
    - Crossing angle anti-levelling in steps: 150urad —> 120urad (10urad)
    - Levelling by separation ATLAS/CMS
  - **High fast losses in 16L2 limiting machine performance**
- 2018:
  - ATS Squeeze to 30cm
  - Solid Levelling in Stable Beams:
    - Beta-star levelling 30 cm -> 25 cm
    - Continuous crossing angle anti-levelling



Bunch Intensity 2018



LHC design:

0.58 A => 2808 bunches x 1.15e11 p/b

0.76 A => 2808 bunches x 1.50e11 p/b

In 2018: 2556 bunches x 1.1e11 p/b = 0.5 A

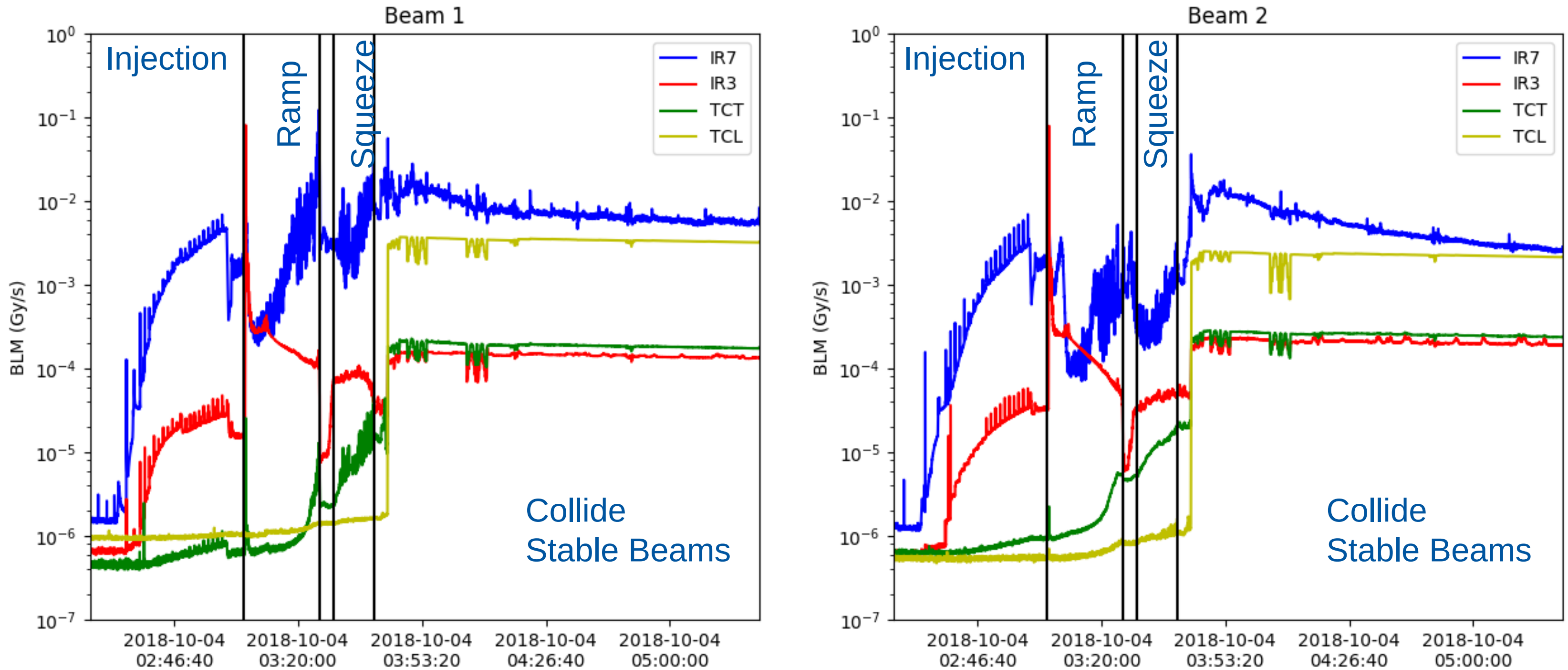
Why losses are important?

- They limit the performance of the machine
  - Continuous losses during the cycle reduce the beam intensity available for luminosity production.
  - Fast losses and beam lifetime drops might quench the LHC magnets or increase the number of beam dumps due to losses.

Losses during the cycle 2018

Standard Nominal fill in 2018 (fill number 7256)

Beam 1 and Beam 2 follow similar pattern, they are relatively low during run 2.
Beam 1 are on average higher than for Beam 2.
Very similar to previous years



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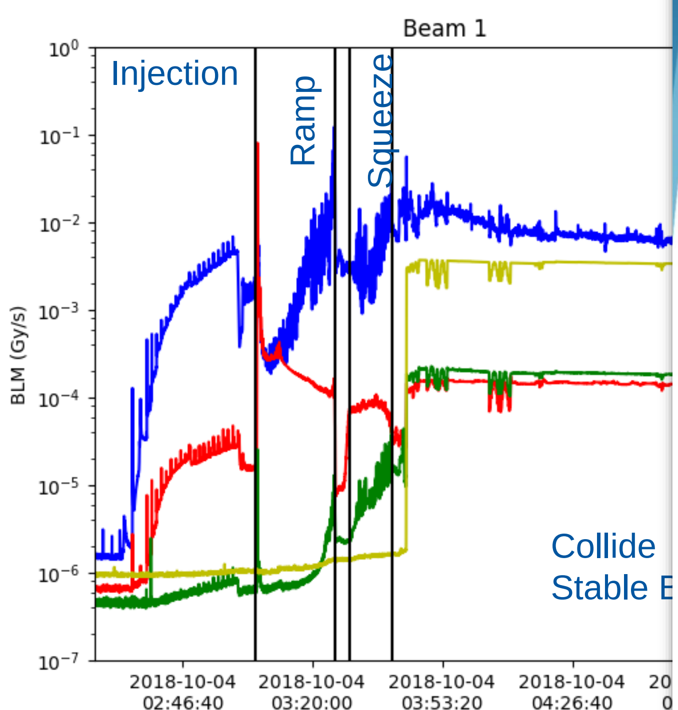
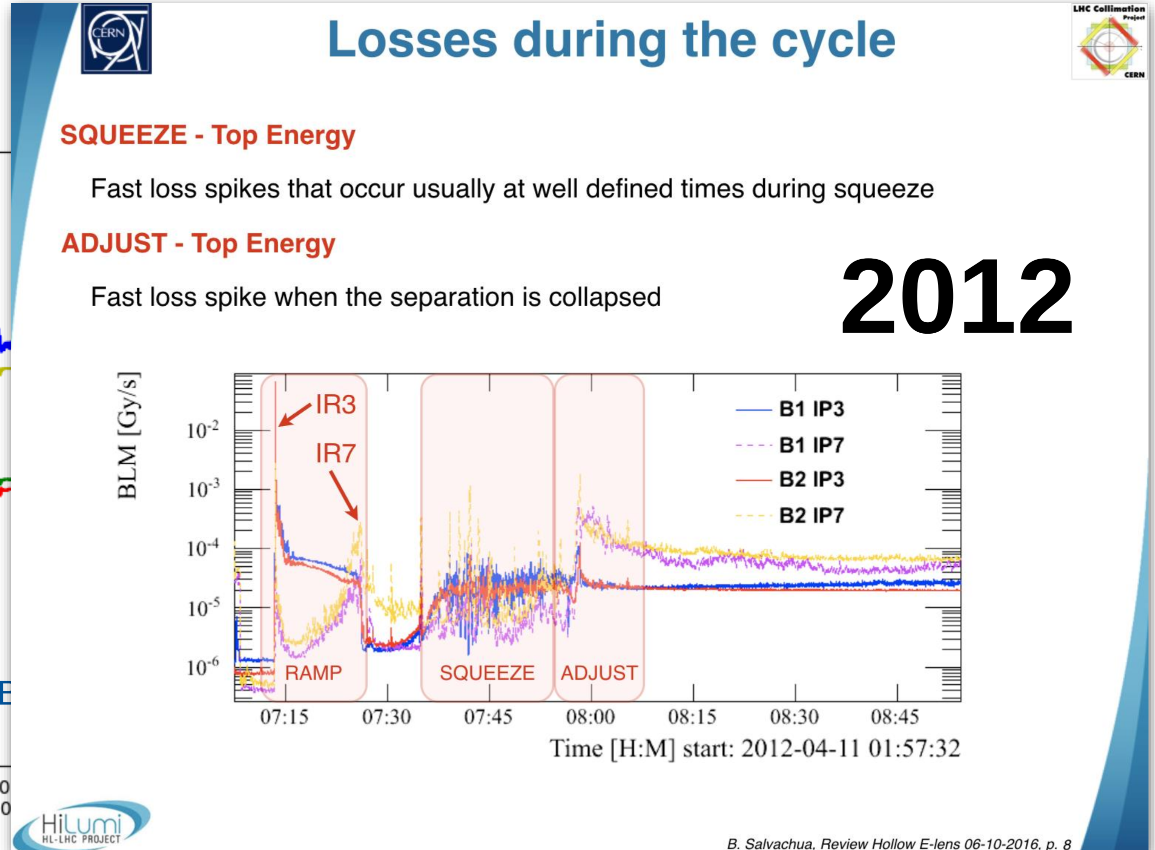
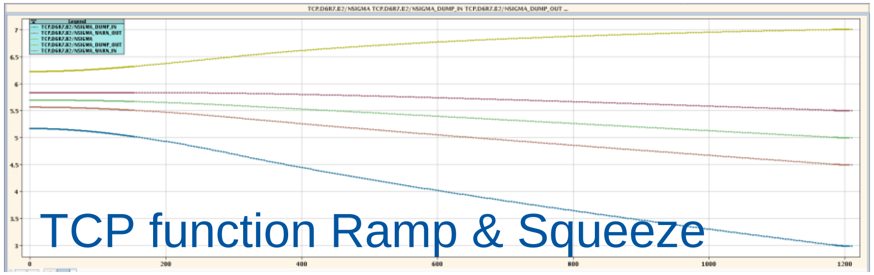
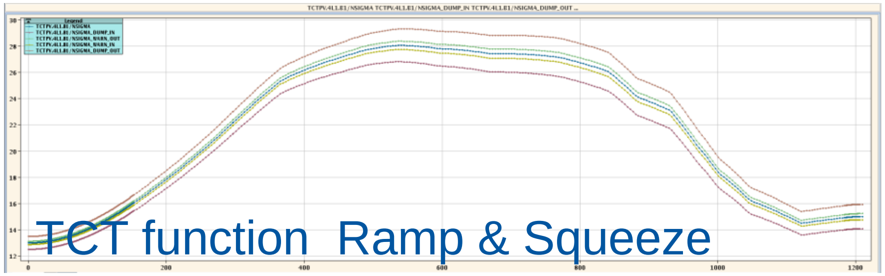




Experience with Collimators I

- Collimators should always be the smaller aperture in the machine
  - Even when changing optics
- 76 collimator move synchronously during the energy ramp following predefined functions
  - Change of settings in sigma (INJ -> Flat Top)
  - Change of beam size (change gap in mm)
- Betatron and Off-momentum cleaning follow the energy ramp
  - Functions are smooth
  - Collimator gaps are smaller
- TCT collimators follow the energy ramp AND the change of beta-star





Collimators are aligned to the beam at start/end ramp.

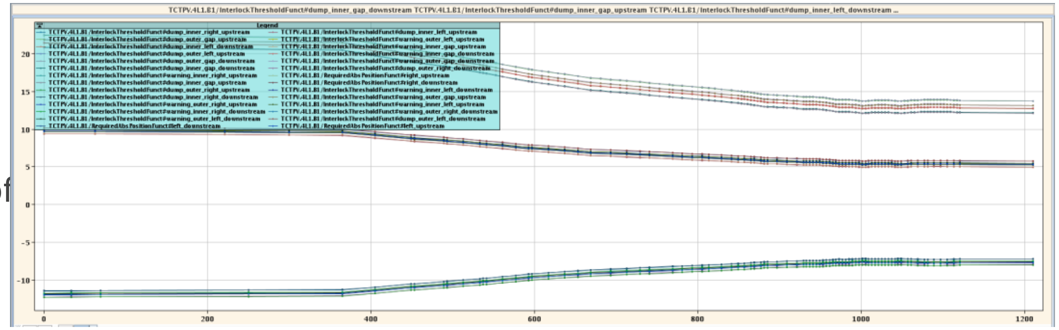
Measurement of the TCT centers along the ramp with the pick-up BPMs at the collimators allows for a better follow up of the orbit.

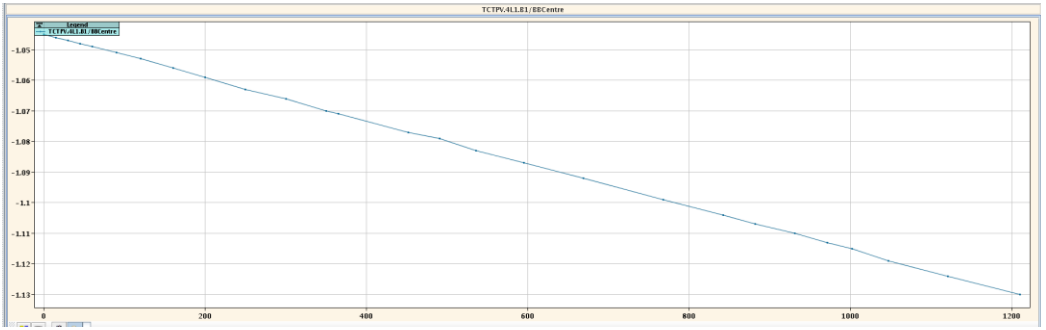
Predefined functions with these values are used and validated with loss maps

Experience with Collimators 2

- During Squeeze TCT collimators move to different settings
  - Aperture
  - New centers
- During Collisions TCT and TCL move to different settings
  - New centers
  - Closing TCLs to clean physics debris

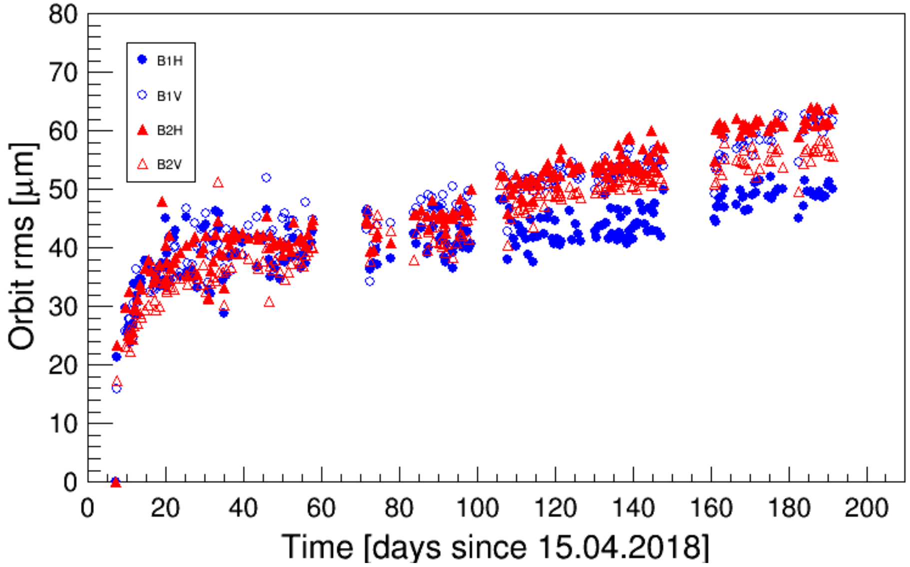
- Collimator Alignment
  - All collimators aligned precisely around the beam
  - Center introduced as a setting in LSA, part of the collimator function
- Functions sent to the hardware in mm
- Collimator limits on the positions and gaps follow the same complex structure
  - Each collimator has 12 position limits (inner/outer/corner/gap) and energy-dependent (outer gap) and bets-star-dependent (inner/outer gap) functions.
  - 18 ways of triggering a beam dump on collimator settings that should vary on time and/or optics





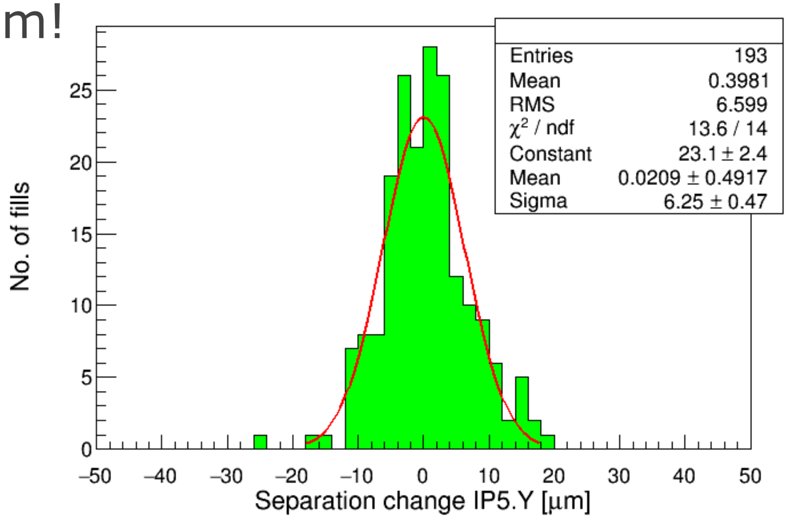
Orbit Stability

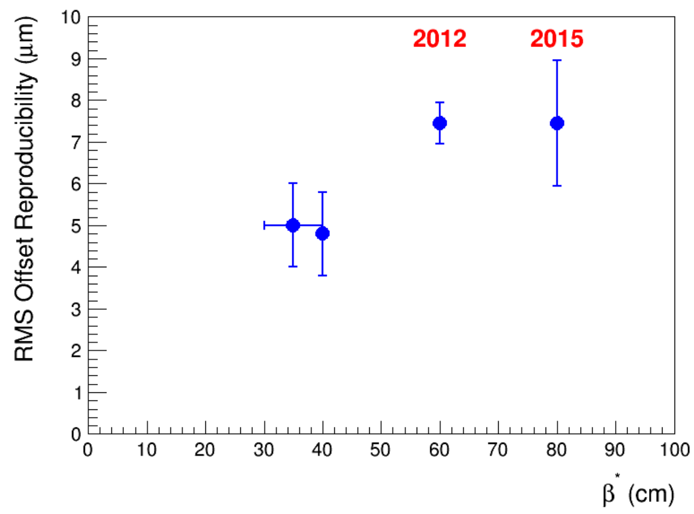
Courtesy of J.Wenninger



Excellent **Orbit stability** in STABLE BEAMS: RMS wrt to day 1 orbit in 2018. Similar to preview years

Reproducibility:
Difference on Beam separation fill after fill in IP5-Y which is the worse case.
RMS is 6.5 um!





Levelling and Anti-levelling

Run II was characterised for ability to SAFELY make changes on the machine configuration during Stable Beams

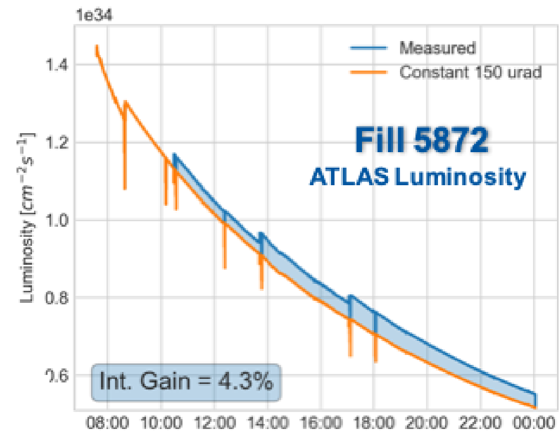
Several processes need to be synchronised when levelling is operational: collimators, orbit referenc

Luminosity server was setup to implement the “Orchestration of settings”

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

- *Optimizations*
- *Emittance Scans*
- *VdM*
- *Levelling by separation and crossing*
- *Dynamic squeeze in Stable Beams: 30cm -> 27 cm -> 25 cm*

M. Hostettler and OP SW Team



Challenge:

- Validate the machine in those configurations: Asynch. beam dump and loss maps tests
- Achieve the correct stability of orbit and lifetime needed during Stable Beams.

Beam Transmission Run 2

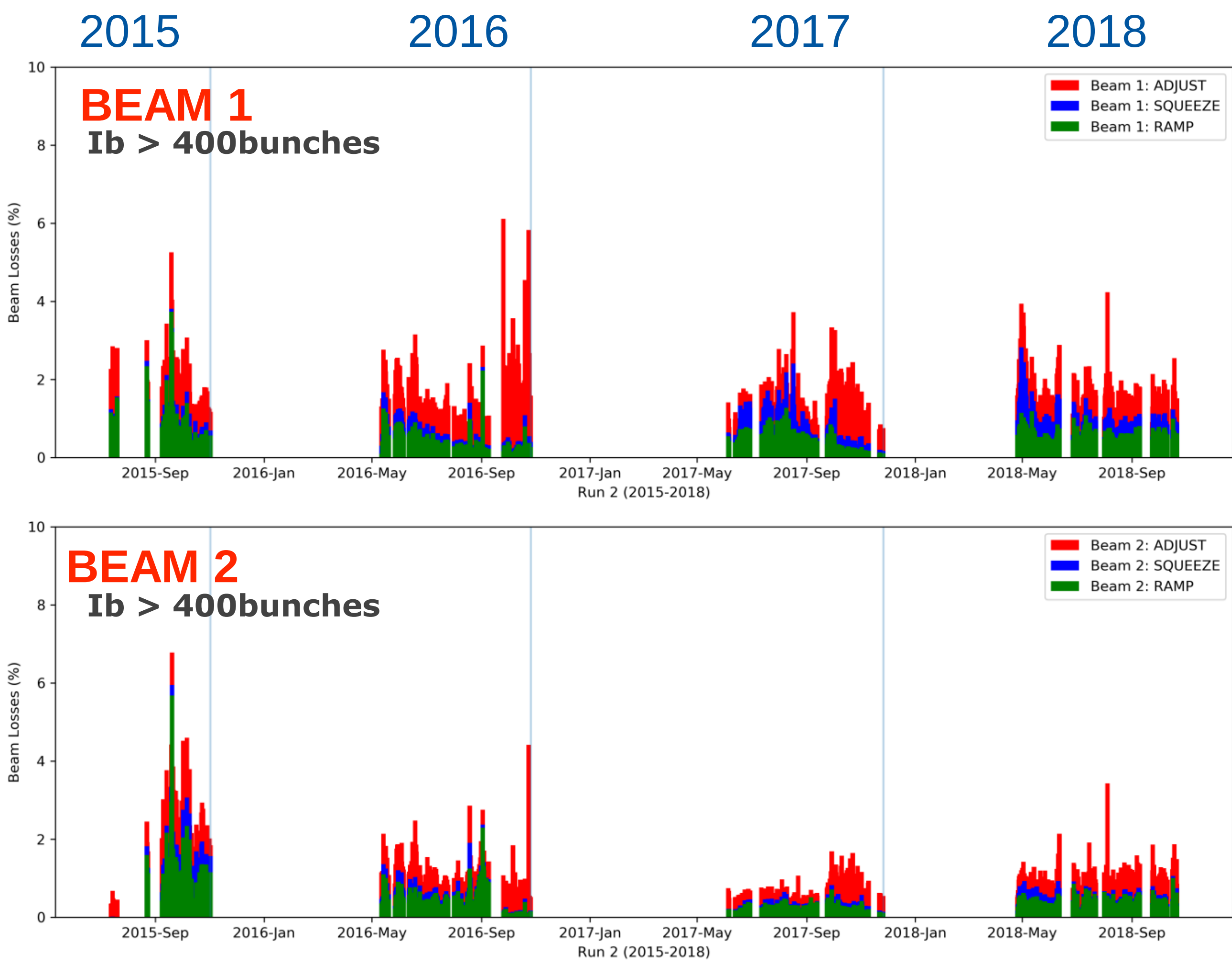
Relatively small losses throughout the LHC cycle.

SQUEEZE
On general very clean, with losses well below 0.5% for Beam 1 and close to 0% for Beam 2.

RAMP and **ADJUST**
Close to 1% since 2016

Summary transmission for RUN 2

Transmission	Beam 1	Beam 2
RAMP	99.4%	99.6%
SQUEEZE	99.7%	99.9%
ADJUST	99.2%	99.5%
TOTAL	**98.3%**	**98.9%**



Beam Lifetime

- **The beam lifetime quantifies how fast/slow are the beam losses.**
- **It is one of the key parameters to asses the performance of the collimation system.**
- **Intensity reach: the minimum beam lifetime defines the maximum number of charges that can be in the machine without the risk of magnet quench.**

$$N_p^{max} = \tau_{beam} \times \frac{dN_p}{dt} \approx \tau_{beam} \times R_{loss}^{tcp} = \tau_{beam} \times \frac{\tilde{R}_q}{\tilde{\eta}_c}$$

quench limit

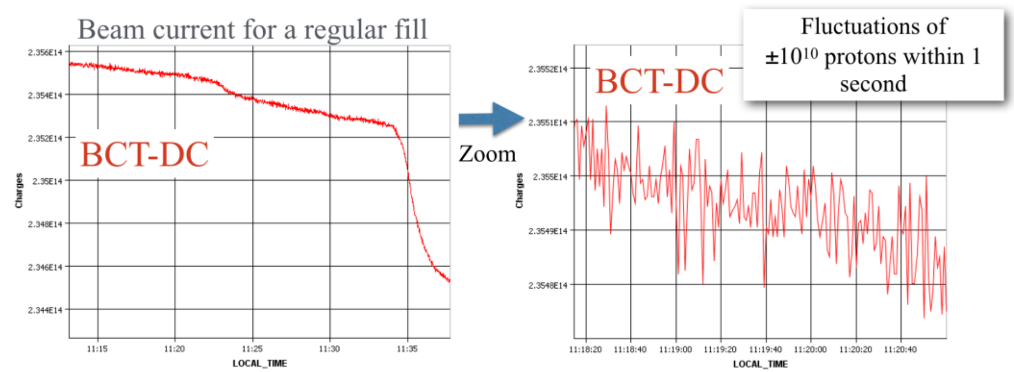
Min. Beam Lifetime

cleaning inefficiency

Beam Lifetime from losses

Beam lifetime can be monitored using the measured beam current from the **BCT.** However, this method requires **smoothing with large times** ~ few seconds. Not ideal to measure beam losses.

Disclaimer note:
During Run II ADC24BIT of BCTDC has improved significantly the lifetime calculation.



Other devices such as **beam loss monitors** could be used for this measurement **with calibration measurement of the proton loss rate.**

Primary losses occur at the collimators.

BLMs downstream each collimator have a direct measurement of the beam losses

BLMs had a wide range of integration times (we used 1.3sec) and are usually more sensitive to losses than the BCT

Lifetime during the RAMP

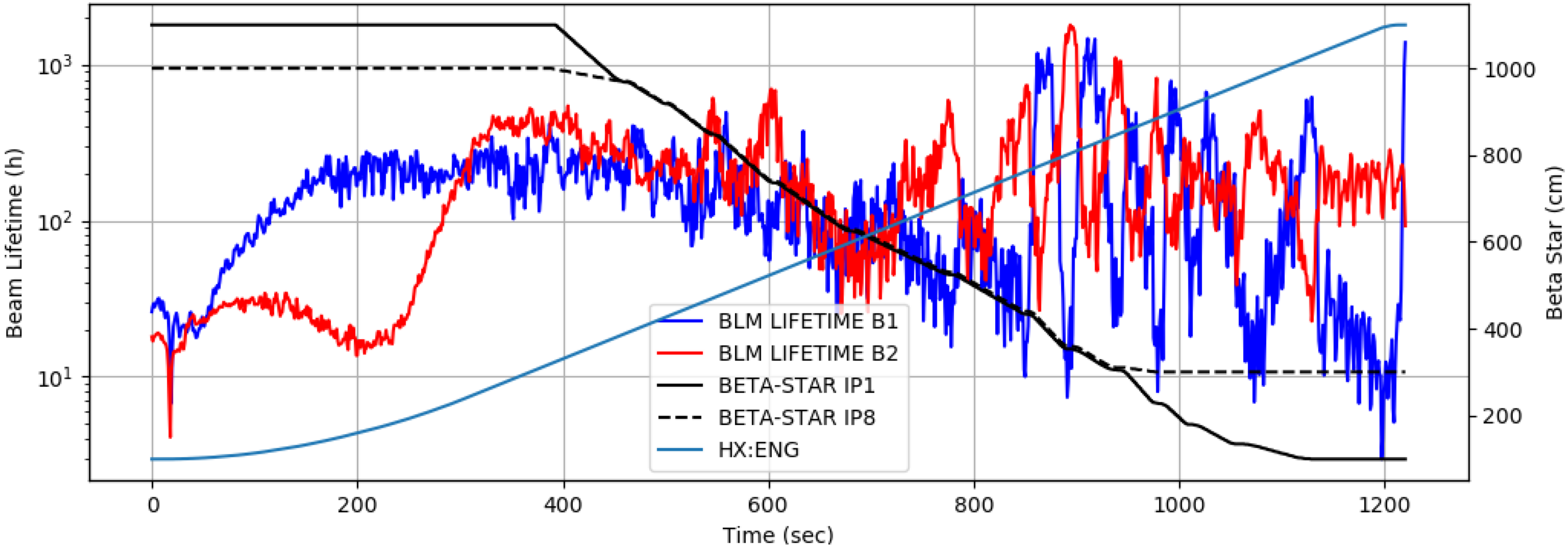
BLM lifetime during RAMP fill 6663

Start of the ramp with **slow losses in Beam 2** that last over 5 minutes.

Beam 1 and Beam 2 lifetime **recovers until about beta-star of 6m**.

After 6m beta-star a loss oscillation between the two beams start but stronger for Beam 1

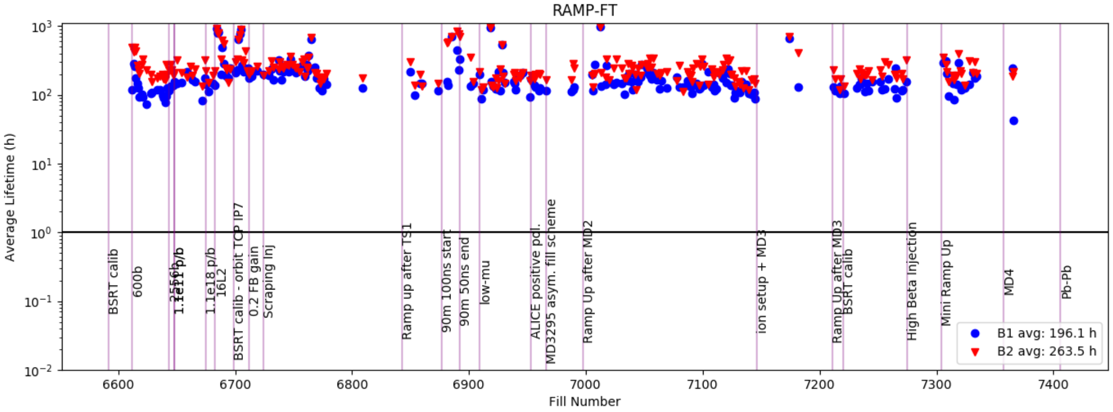
Orbit is very smooth, losses appear at the optics match points.



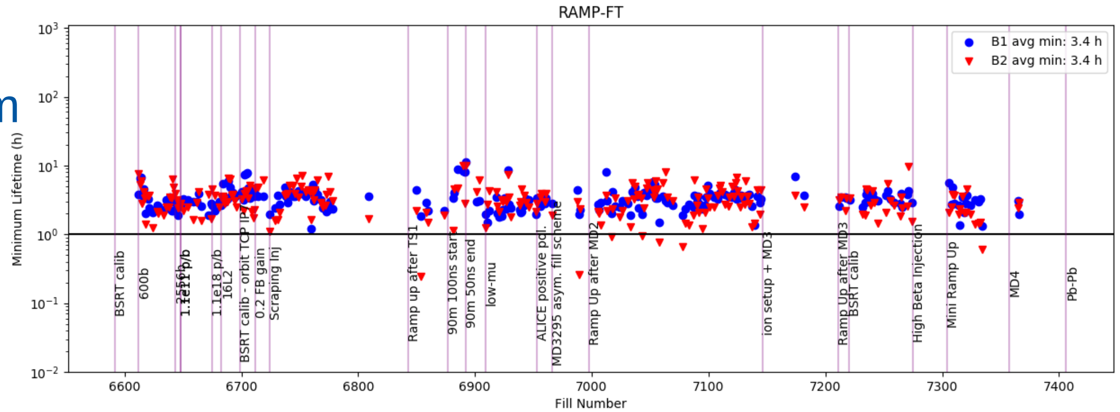
Beam Lifetime: RAMP + FT

Calculated from Beam Losses at Collimators in IR7
Average beam lifetime during the RAMP
Minimum beam lifetime during the RAMP

Average lifetime



Minimum lifetime



Fill Average Lifetime:

B1	196 h
B2	263 h

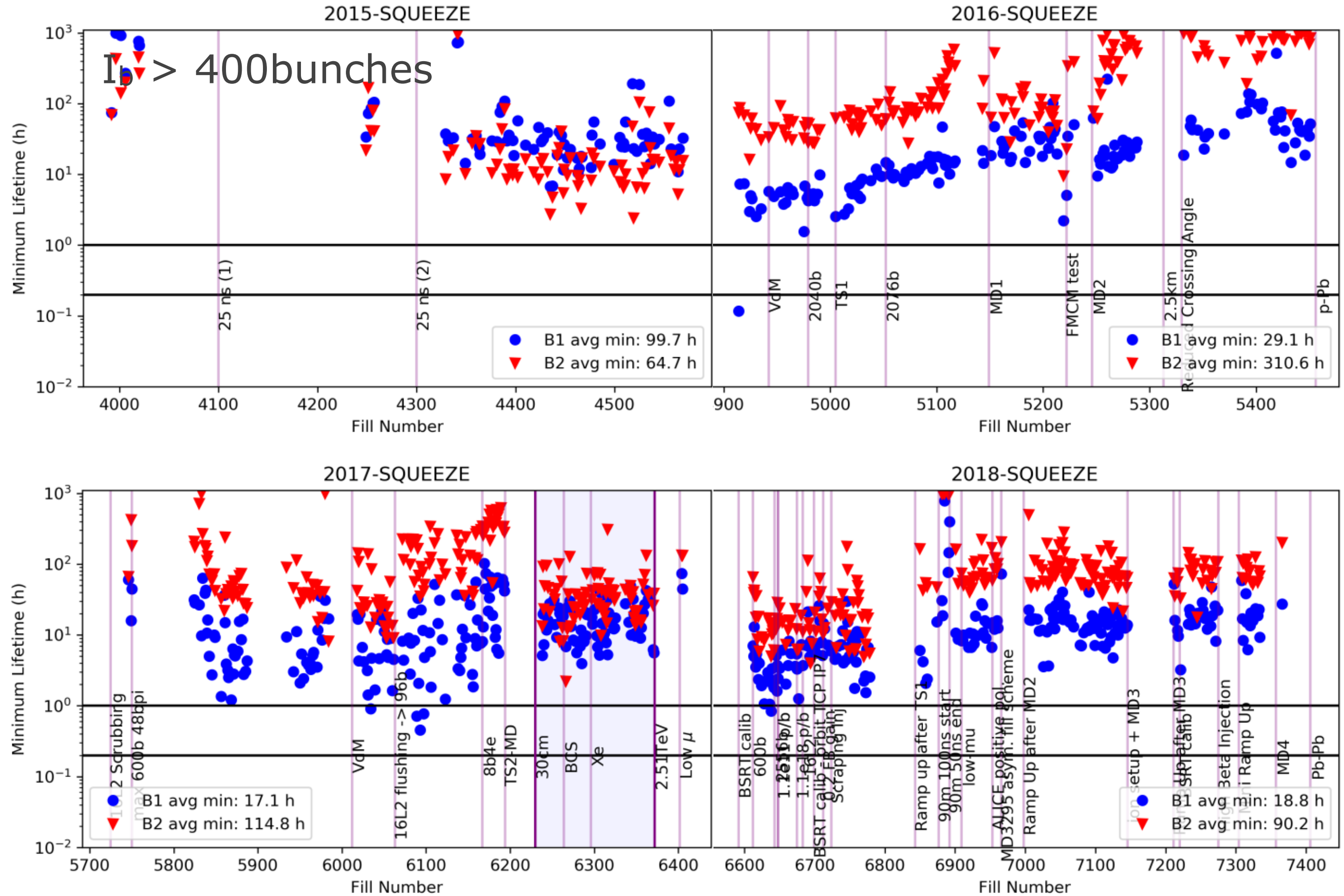
Average Minimum Lifetime:

B1	3.4 h
B2	3.4 h

Beam Lifetime SQUEEZE

The beam lifetime reflects also the good machine reproducibility and excellent orbit stability and optics corrections. Very few cases below 1hour and mostly corresponding to ramp up fills and after 16L2 flushing.

- **Beam 1** is systematically worse than for Beam 2. on average **minimum beam lifetime of ~20hours** but with large spreads in 2017.
  - ✴ The difference is more pronounce in 2016



The **average lifetime** during the full squeeze is even better, **above 200 hours for Beam 1 and 600 hours for Beam 2**

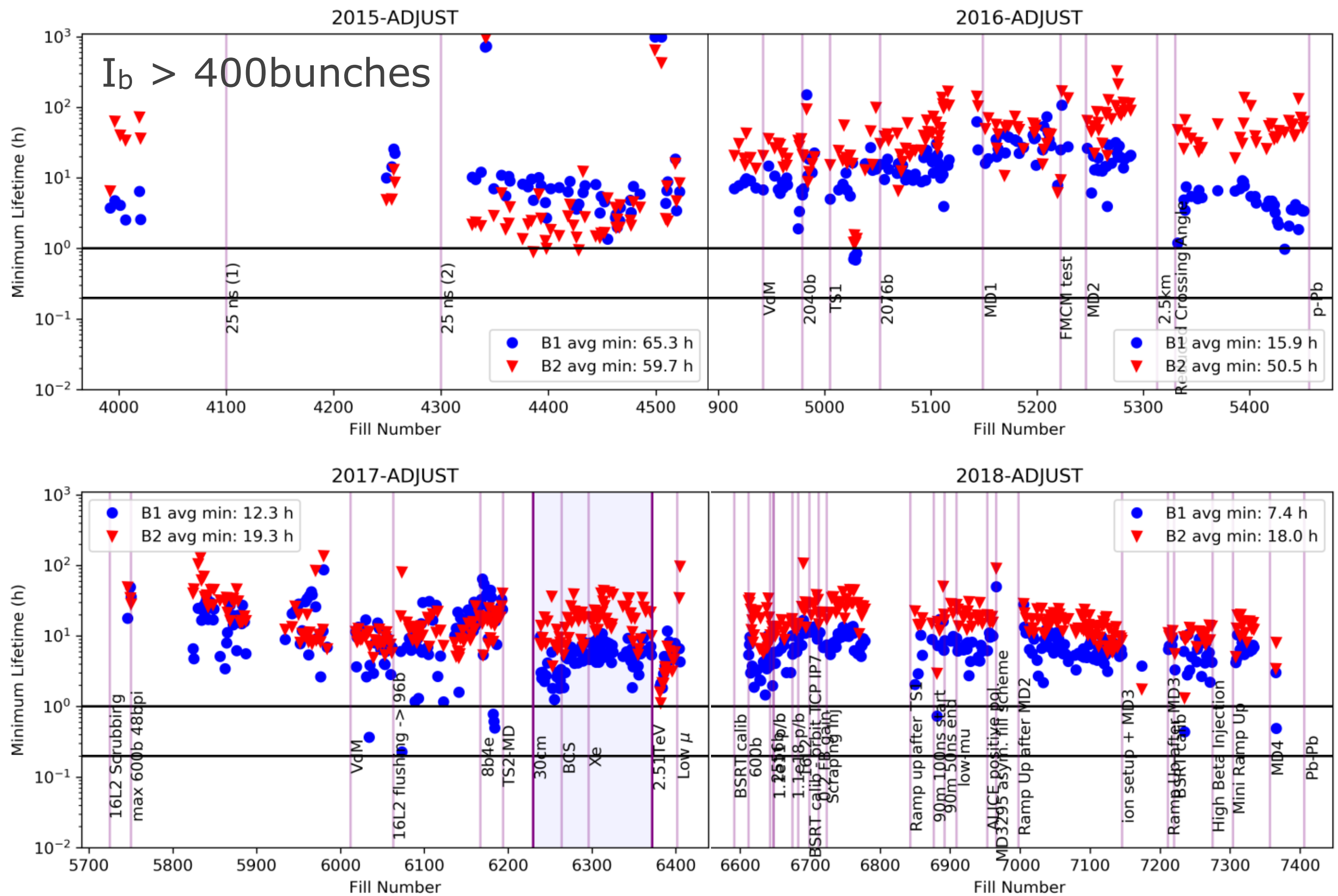
Beam Lifetime ADJUST

A fast loss happens when the beam separation is collapsed in the main colliding IRs (ATLAS/CMS)
After the “ramp up year” the drop of beam lifetime in collisions was very similar.

For 2018
- **Beam 1:** ~ 7 hours minimum beam lifetime
- **Beam 2:** ~ 18 hours minimum beam lifetime

However, the average lifetime remains high above 60 hours for both beams.

Optimisation of beam parameters such as octuples, tunes and coupling had a significant contribution to the lifetime.

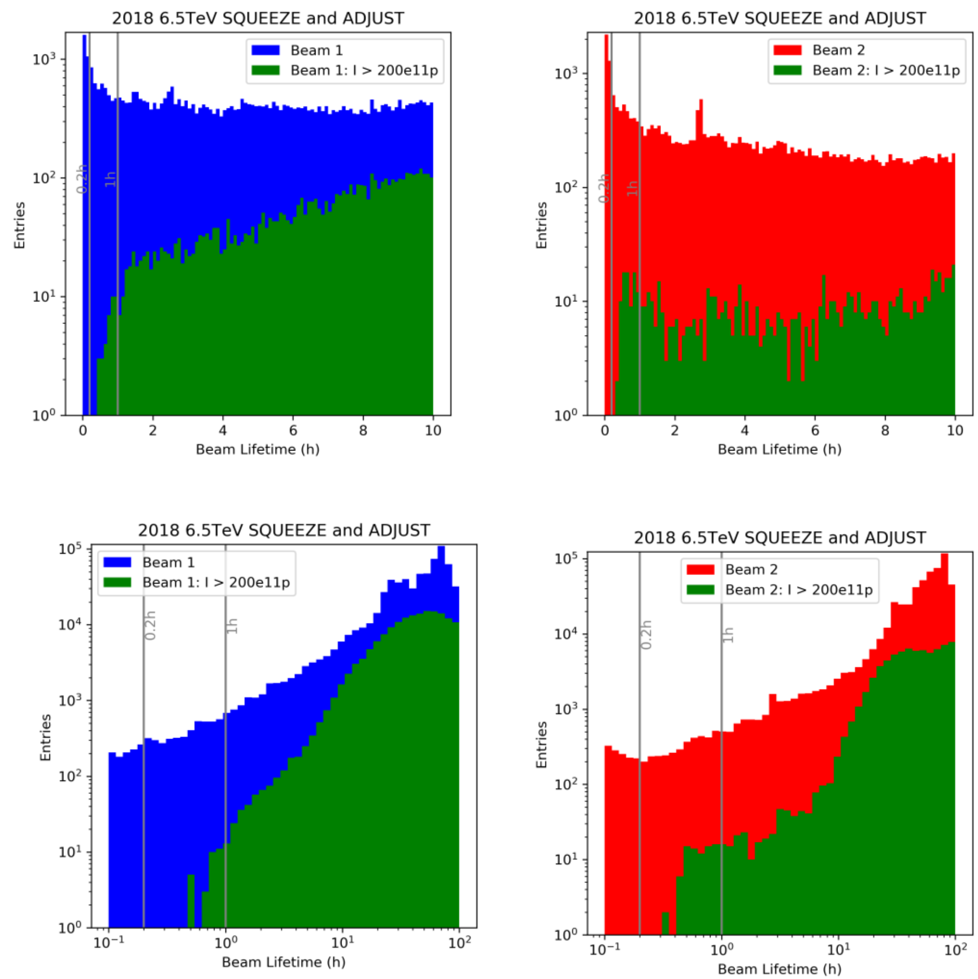


Lifetime 2018: SQUEEZE + ADJUST

Histogram of the number of times we had a certain beam lifetime

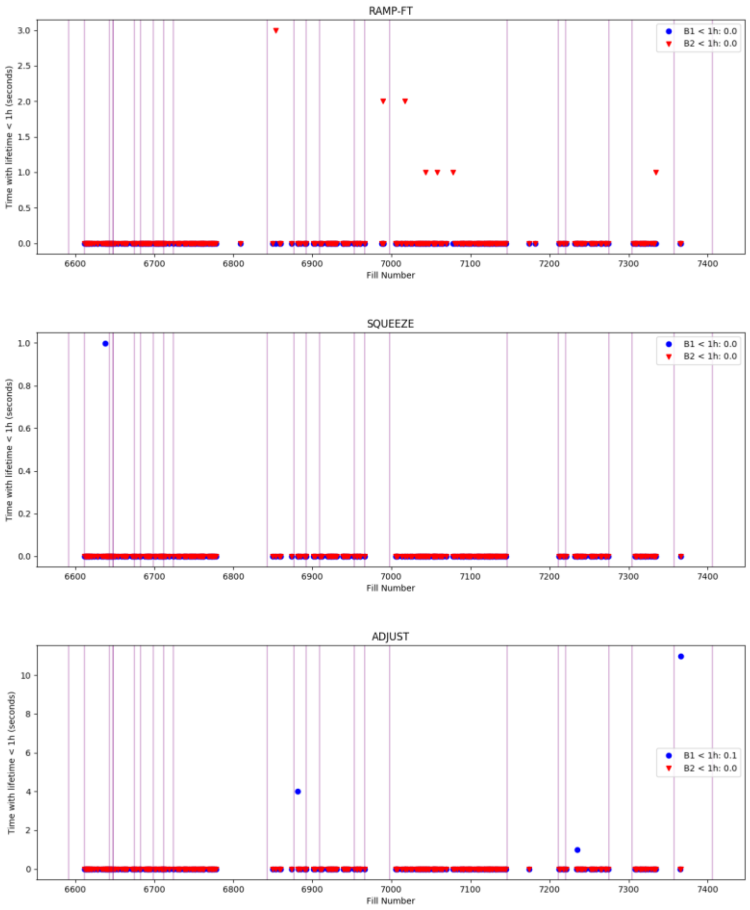
For intensity above 2e13protons we have 0 cases with lifetime below 0.2 hours

However, we had beam lifetimes below 0.2h with beam intensities below ~ 200 bunches

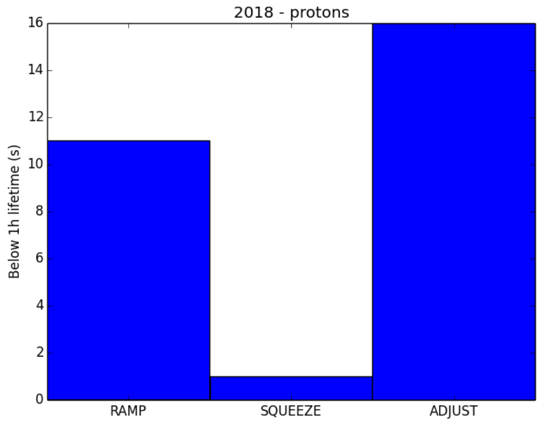


Beam lifetime below 1 hour?

Counter in each fill with number of seconds below 1 hour of lifetime



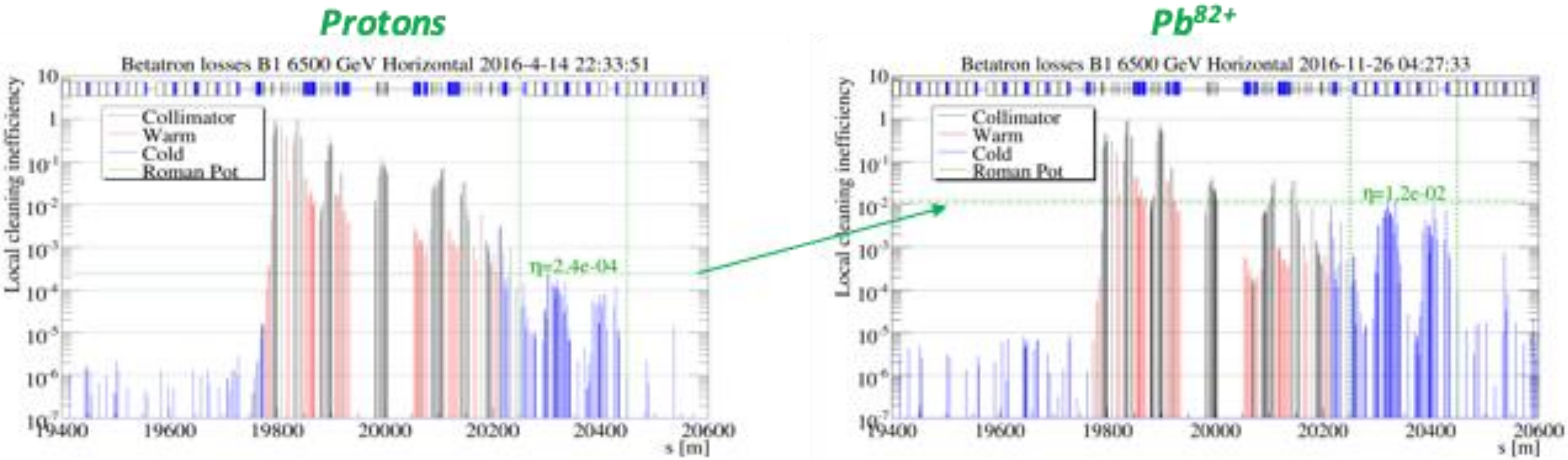
Over the full 2018, number of seconds below 1 hour lifetime (separated per beam mode)



I_b > 400bunches

Lifetime drops during IONs

Due to the reduced cleaning inefficiency Lifetime drops during ions could have a stronger impact in the machine: Quenches of Super conducting magnets and Beam dumps



For the following analysis the lifetime is calculated directly from the BCT signal with a custom smoothing function during 3 seconds.

This analysis has been done by D.Mirarchi

2015 Pb-Pb run

Courtesy of D.Mirarchi

Counting of beam lifetime drops during 2015 Pb-Pb run:

- Below 1 hour (TOP plots)
- Below 0.2 hours (BOTTOM plots)

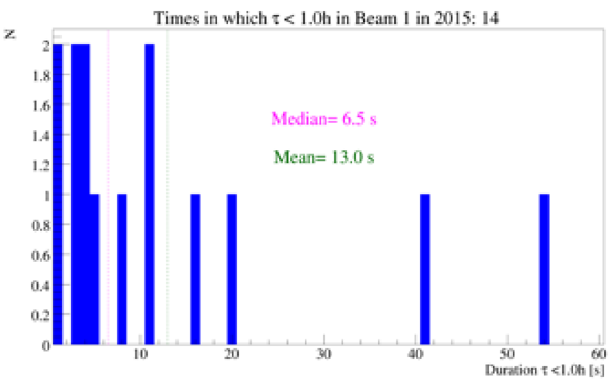
Like in the proton run, for ions in 2015 Beam 1 also shows systematically worse beam lifetime than Beam 2.

Most of the lifetime drops occur during the energy ramp.

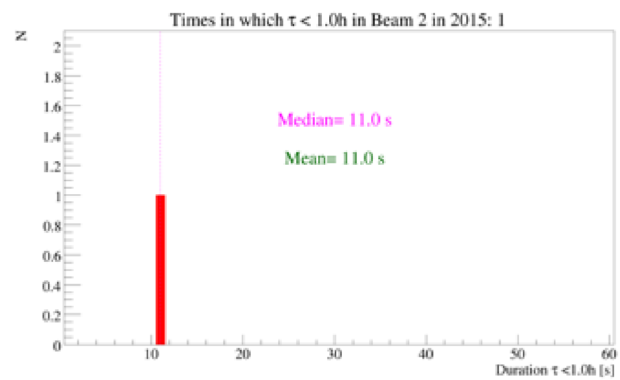
During SQUEEZE:

- Beam 1: 2 times
- Beam 2: 1 time

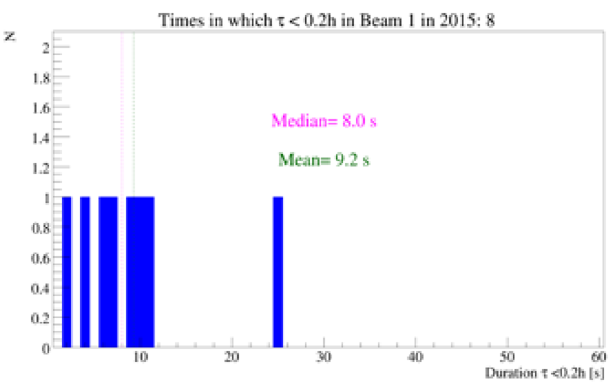
Beam 1



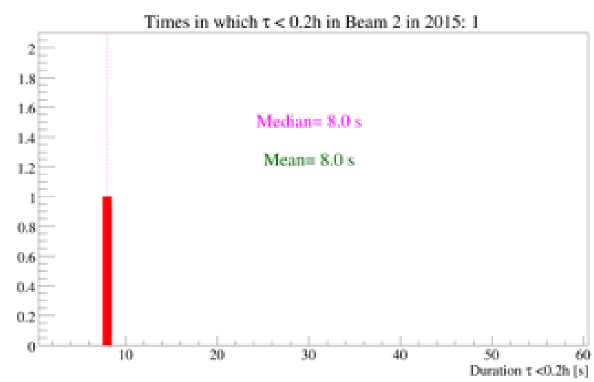
Beam 2



Beam 1



Beam 2



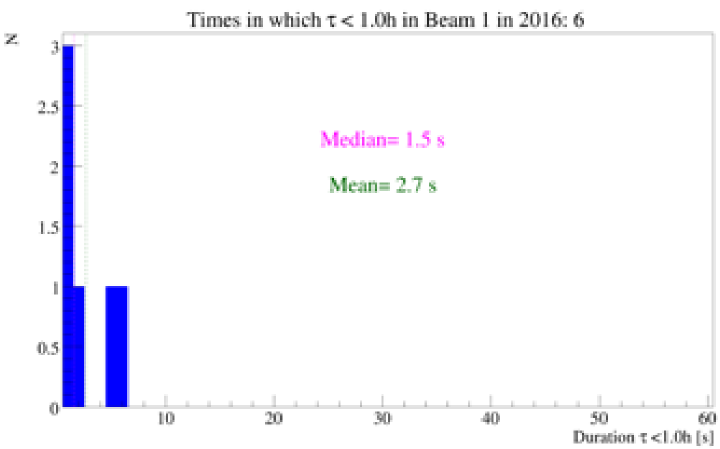
2016 p-Pb run

Courtesy of D.Mirarchi

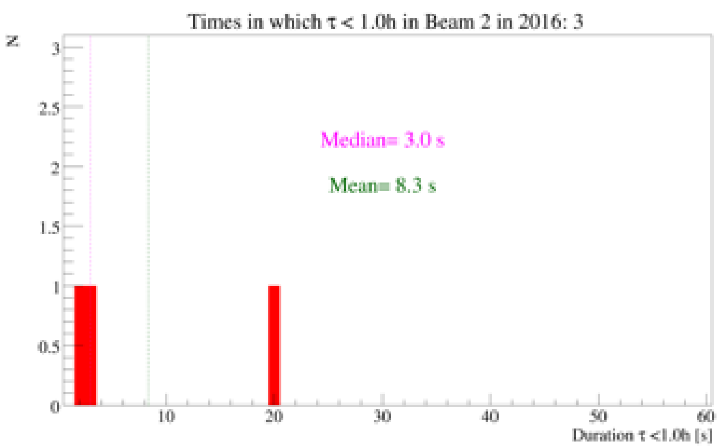
Counting of beam lifetime drops during 2016 p-Pb run (showing only Pb beams):

- Below 1 hour: showing significant less lifetime drops than in 2015
- Below 0.2 hours: none of the beams show drops below 0.2 hours

Beam 1



Beam 2



No cases below 1hour during 2018

Halo Studies

- Use of collimator beam scraping to study beam halo:
  - Halo diffusion —> time evolution of losses
  - Beam tail population —> beam intensity and loss measurements
- Two types of studies:
  - End-of-fill tests

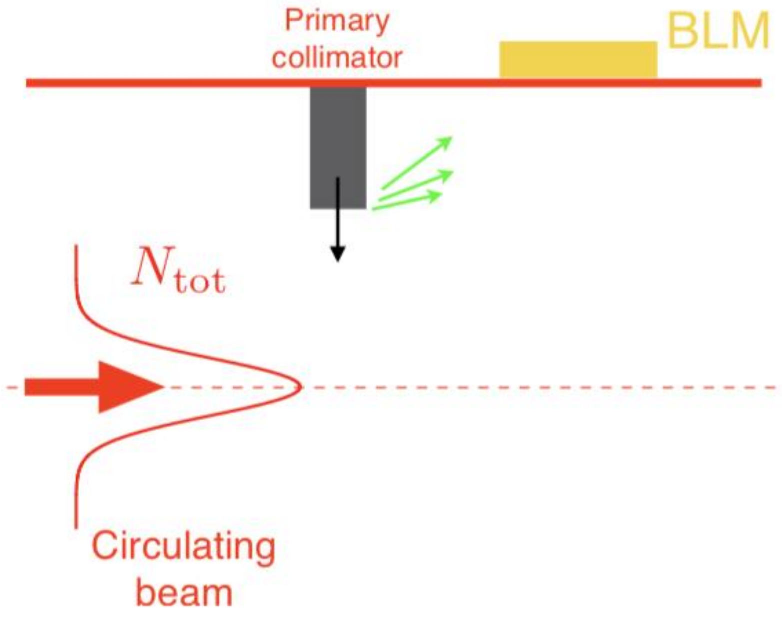
A.Gorzawiski and G.Valentino

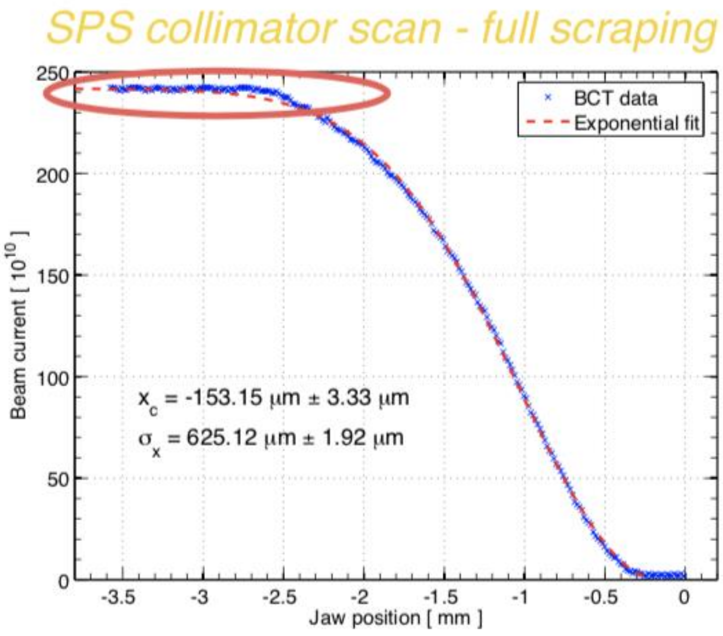
    - Full intensity stored at the LHC
    - Study in collisions and with separated beams
    - Many bunches -> each bunch with different emittance
    - Experiment more complex but more realistic conditions
      - Only tails could be scrape
  - Dedicated MD studies

H.Morales, P.Racano

    - Better control of the beam
    - Less beam intensity
      - Possibility of wire scanners
      - Full beam scraping is possible

Collimator scraping





Move collimator towards the beam while monitoring beam current measurements and beam loss signal.

End-of-fill results

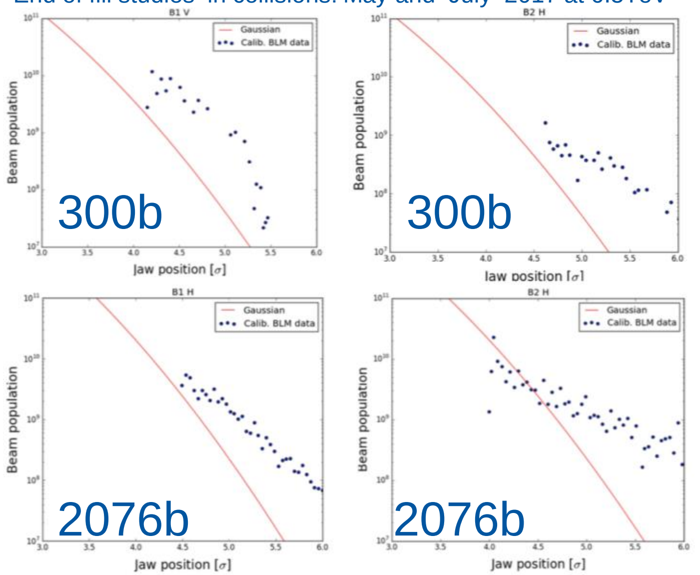
Run 1 - early Run 2

Studies during Run 1 and early Run 2 showed that the tails were overpopulated compared to gaussian beams:

Around 5% of the beams in the tails (> 3.5 sigmas), compared to 0.22% Gaussian

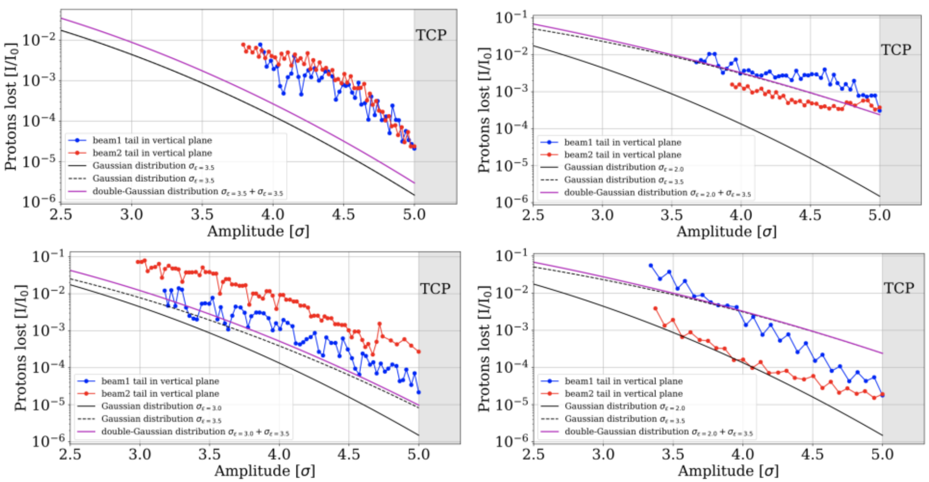
scaling to HL-LHC parameters = 33.6 MJ vs 1.48 MJ

End of fill studies in collisions: May and July 2017 at 6.5TeV



2017 - 2018

End of fill tests after 12hours of production at 6.5TeV with squeeze at 30 cm



An overpopulation is visible wrt to all the proposed profiles for tests in 2017

An overpopulation wrt to the Gaussian but less strong wrt to Double-Gaussian for tests in 2018

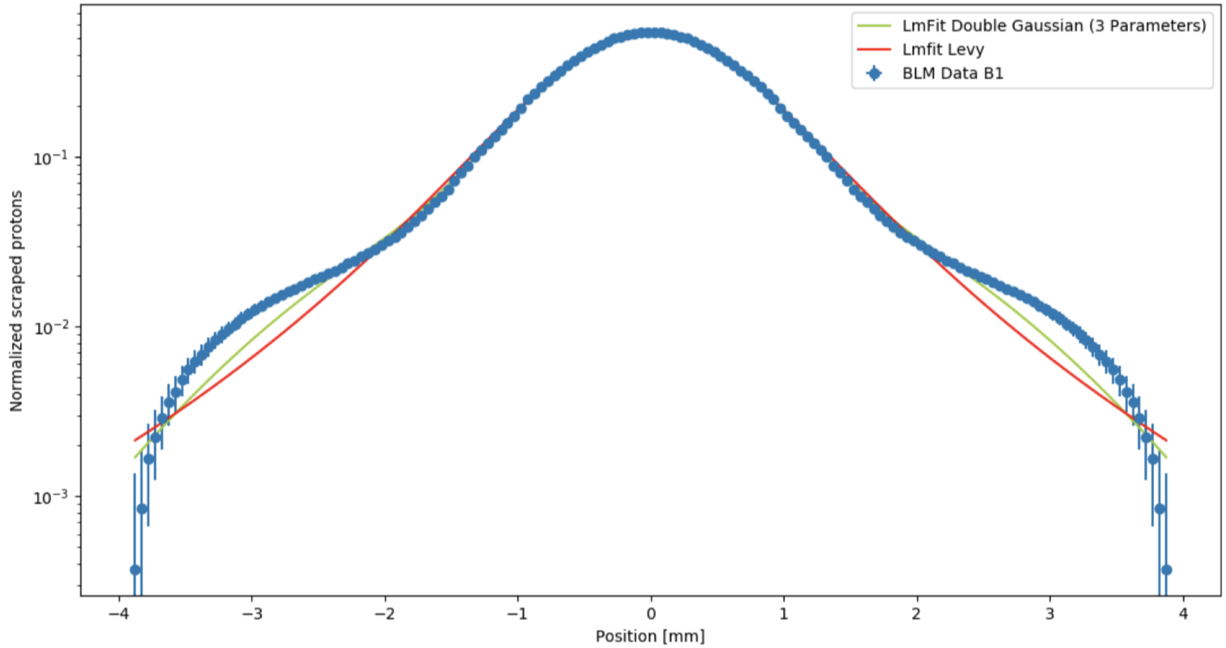
A.Gorzawiski and G.Valentino

MD results

Studies at injection, step size 50um/5s, with 1 bunch

Measurements confirm overpopulation of beam tails.The fraction of particles in the **tails over 4σ** has also been evaluated, from which it has obtained that in the **horizontal plane it is in a range between 2% and 3%**, while in the **vertical plane between 3% and 6%.**

Scraping at **injection** performed with a step size of 50 µm every 5 seconds (1 Hz data)



H.Morales, P.Racano

Summary

- Excellent Beam Transmission in general during Run 2. Less than 2% of the beam is lost smoothly over the full LHC cycle (Ramp, Squeeze, Adjust).
- Very few cases were the beam lifetime was below 1 hour at top energy. The cases are mainly during intensity ramp up (Squeeze and Adjust). In general, optimisation of tunes, octuples and chromaticity played a role on optimising these points.
- Losses could appear also at the optics match points (see Ramp)
- Beam tails are consistently measured overpopulated compared to Gaussian profiles

CERN

References: Beam Lifetime

- 2011 - 2016 Beam lifetime LMC 19/10/2016: https://indico.cern.ch/event/578380/contributions/2343179/attachments/1357832/2053301/BSalvachua-BeamLifetime.pdf#search=salvachua
- 2011 - 2016 Beam lifetime, Review Hollow e-lense 06/10/2016 https://indico.cern.ch/event/567839/timetable/#all.detailed
- 2017 lifetime, Evian 2017 https://indico.cern.ch/event/663598/contributions/2781849/attachments/1570200/2485170/2017-12-12_AM.pdf
- 2018 Lifetime, ColUSM 15/11/2018 https://indico.cern.ch/event/773737/
- 2018 Lifetime, TCC 29/11/2018 https://indico.cern.ch/event/776391/
- Evaluation of signal/threshold ratios for the last Pb runs, CollWG 1/10/2018 https://indico.cern.ch/event/760786/
- Lifetime analysis during heavy-ion runs, CollWG 8/10/2018 https://indico.cern.ch/event/763571/
- Lifetime analysis during heavy-ion runs, TCC 1/11/2018 https://indico.cern.ch/event/767512/

Halo Studies: references

- 2011-2016 Halo Studies, Review Hollow e-lense 06/10/2016 https://indico.cern.ch/event/567839/timetable/#all.detailed
- Beam Loss and Beam Shape at Collimators, F. Burkart, CERN-THESIS-2012-046 + IPAC'11 paper
- Meausrements of transverse beam halo diffusion rates in the LHC with collimator scans, G. Stancari et al., FERMILAB-FN-0950-APC
- Beam diffusion measurements using collimator scans in the LHC, G. Valentino et al., Phys. Rev. ST Accel. Beams, 16 021003 (2012)
- Collimation down to 2 sigma in special physics runs in the LHC, H. Burkhardt et al., IPAC'13
- Experience with high-intensity beam scraping and tail population at the Large Hadron Collider, S. Redaell et al., IPAC'13
- Diffusion and halo population measurements with collimator scans at 6.5 TeV, G. Valentino et al., CERN-ACC-NOTE-2016-0010.

LHC Run II

2015 | 2016 | 2017 | 2018

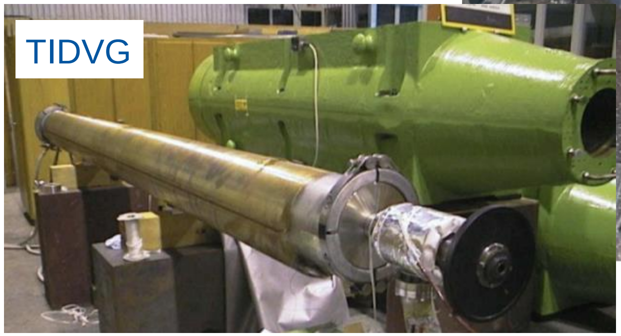
But it wasn't all good…

PS main power supply (POPS)

POPS Short circuit with storage capacitors (link to FOM 24th May)
Backup Rotating machine fails 6kV switch board, short circuit on the generator.
Re-start with degraded POPS end May.

Vacuum leak on SPS dump

Leak found in the TIDVG core (link to FOM 3rd May)
Limiting bunches per train to 96b
Max. Number of bunches in LHC 2220b



LHC injection kicker outgassing from ceramic connection MKID Q5.R8 Beam 2

Limiting total intensity
Max. Bunch intensity to 1.1e11 p/b

Remember the weasel?

Short circuit caused by a weasel on a 66kV transformer in point 8

Internal short dipole 31L2

Intermittent inter-turn short dipole circuit in 31L2 (link to LMC 17th Aug).
Continue operations with:

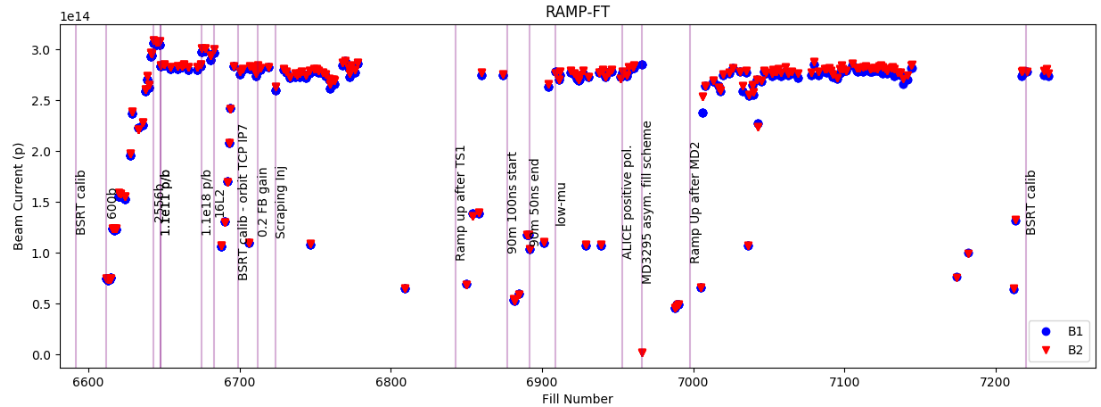
- *Reduce probability to quench at high current (training or losses)*
- *Reduced BLM thresholds to avoid quenches on this magnet*
- *Increase QPS thresholds on A31L2*
- *Disable global protection mechanism to avoid FPA*
- *Schedule to replace in EYETS16-17*

2015 Exchange of QPS card TS2

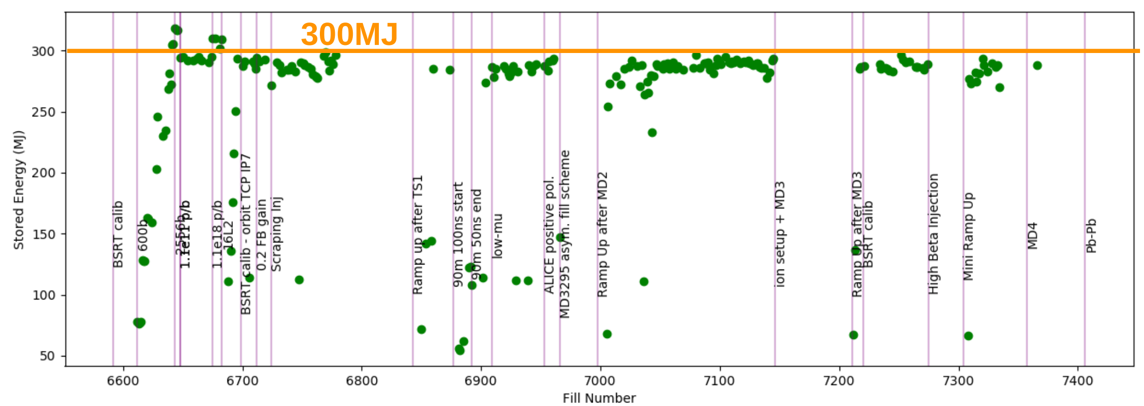
Stored Energies

- Data Sample:
  - 2018 Proton Run from 1st April - 5th Nov
  - Including all fills with ***Intensity > 400x10^{11}p***

Beam current @ START of RAMP



Stored Energy @ START of SQUEEZE



Summary Run 2

Parameter	Design	2018	2017	2016	2015
Energy [TeV]	7.0	6.5	6.5	6.5	6.5
No. of bunches	2808	2556	2556 - 1868	2220	2244
No. of bunches per train	288	144	144 - 128	96	144
Max. stored energy per beam (MJ)	362	312	315	280	280
β* [cm]	55	30 —> 27 —> 25	40 —>30	40	80
Bunch Population N_b [10^{11}p]	1.15	1.1	1.25	1.25	1.2
Typical normalized **emittance** [µm]	3.75	~1.8 / 2.2 SB	1.8 / 2.2 SB	1.8 / 2 SB	2.6 / 3.5 SB
Peak **luminosity** [10^{34} cm^{-2}s^{-1}]	1.0	2.1	2	1.5	< 0.6
Half Crossing Angle [µrad]	142.5	150 —> 130	150 —> 120	185 —>140	185

Excellent Run 2 despite the different events encountered along the way. Thanks to all the involved teams we always found a way to push to new limits.

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Losses during Squeeze

Both Beam 1 and Beam 2 show constant losses from squeeze step. Beam lifetime trend very similar but always worse for Beam 1.