Luminosity and Lifetime modeling and optimization

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Thanks to: G.Arduini, X. Buffat, M. Hostettler

9th LHC Operations Evian Workshop

References:

https://indico.cern.ch/event/578001/contributions/2366376/attachments/1388316/2222614/Evian2016_Lumi_F.Antoniou.pdf
https://indico.cern.ch/event/663598/contributions/2782463/attachments/1574684/2595874/Evian2017.pdf
https://indico.cern.ch/event/676124/contributions/2767808/attachments/1590667/2517280/LHC_beam_quality_2018_YP_final.pdf
https://indico.cern.ch/event/725848/contributions/3003159/attachments/1650011/2638526/004_bunch_by_bunch_losses.pdf
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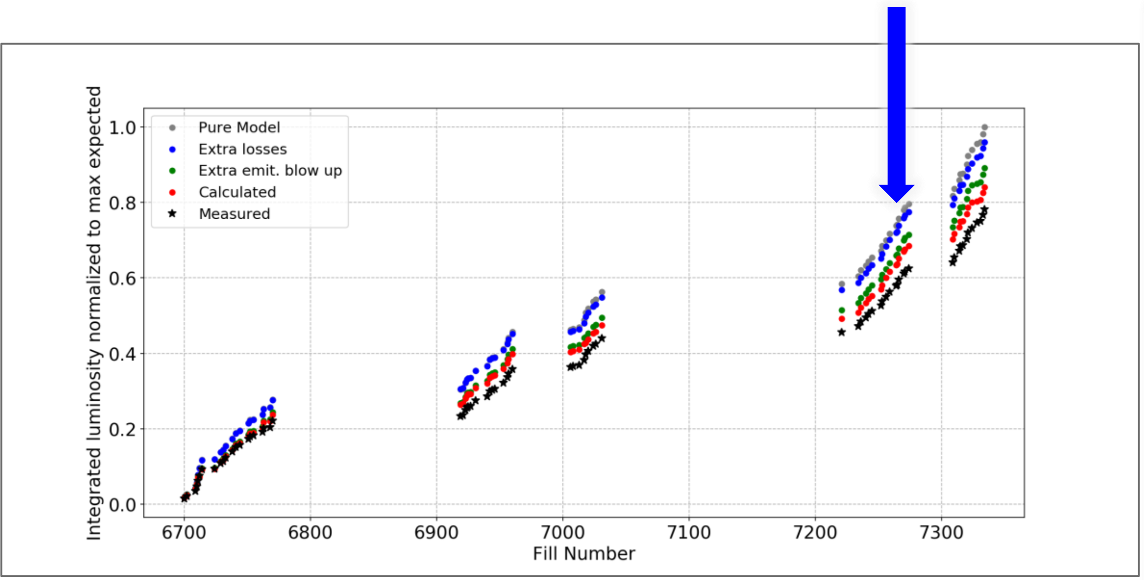
Motivation

Run I & Run II: Additional lifetime degradation mechanisms, above the Luminosity burn-off losses, have been observed.

The extra losses will be addressed in this presentation



From S. Papadopoulou's talk

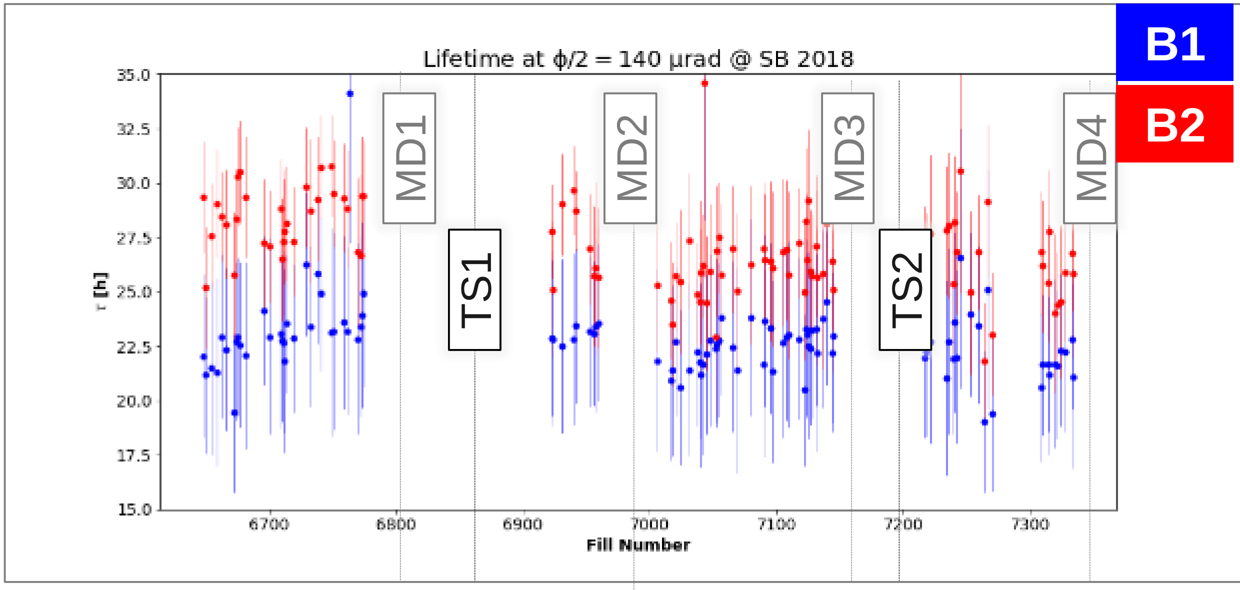
Using tools for luminosity monitoring from experimental data (**Luminosity model ***) and simulations (**Dynamic Aperture studies**):

- Identify **sources of additional losses.**
- Determine **beam modes during the cycle** which are mostly affected.
- Investigate cause of **imbalance between B1 and B2**.
- Investigate possibility to mitigate these effects.

* See appendix "Performance follow up tools"

Summary of Lifetime @ SB

Lifetime B1 < Lifetime B2

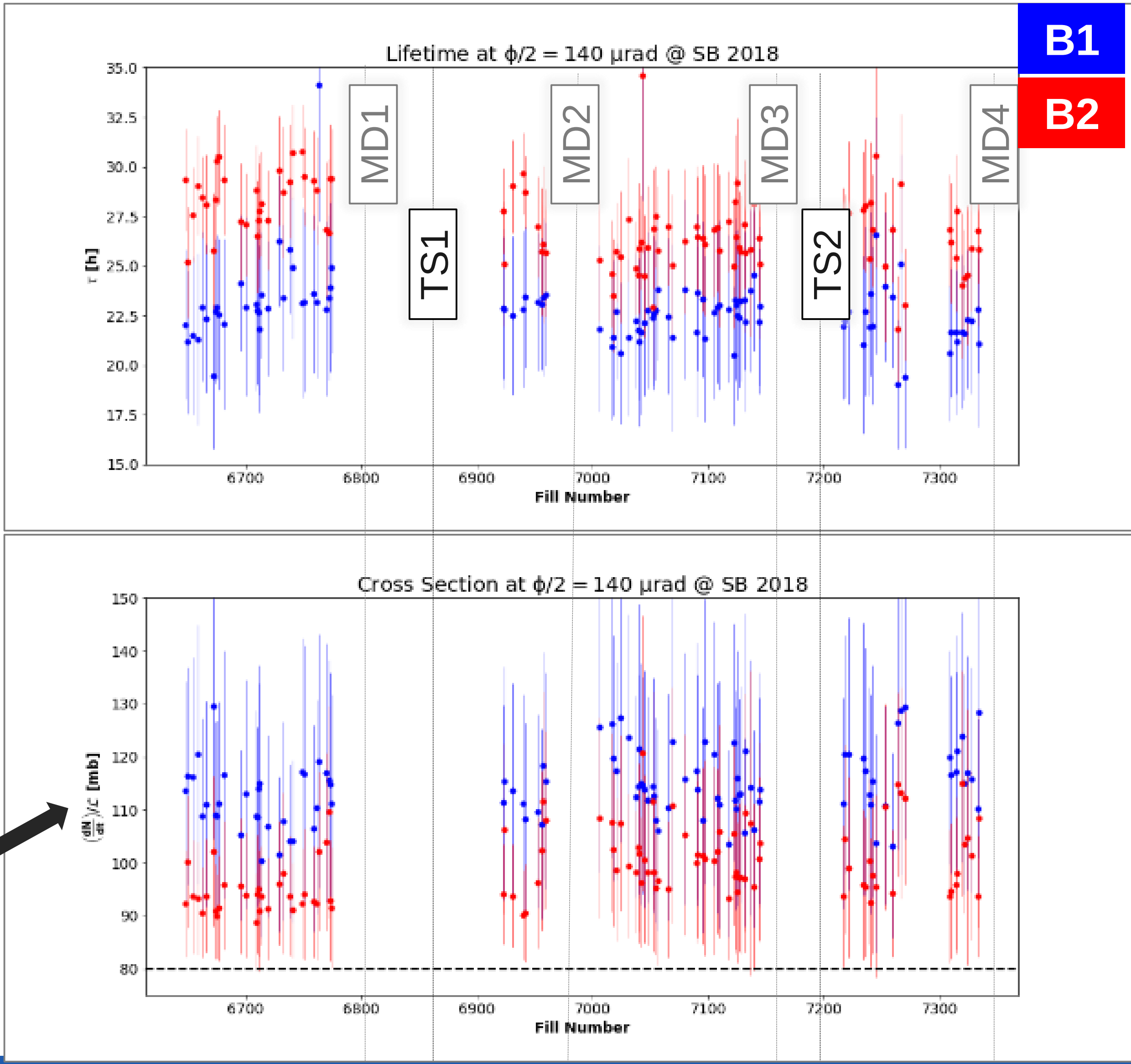


Summary of Lifetime @ SB

Lifetime B1 < Lifetime B2

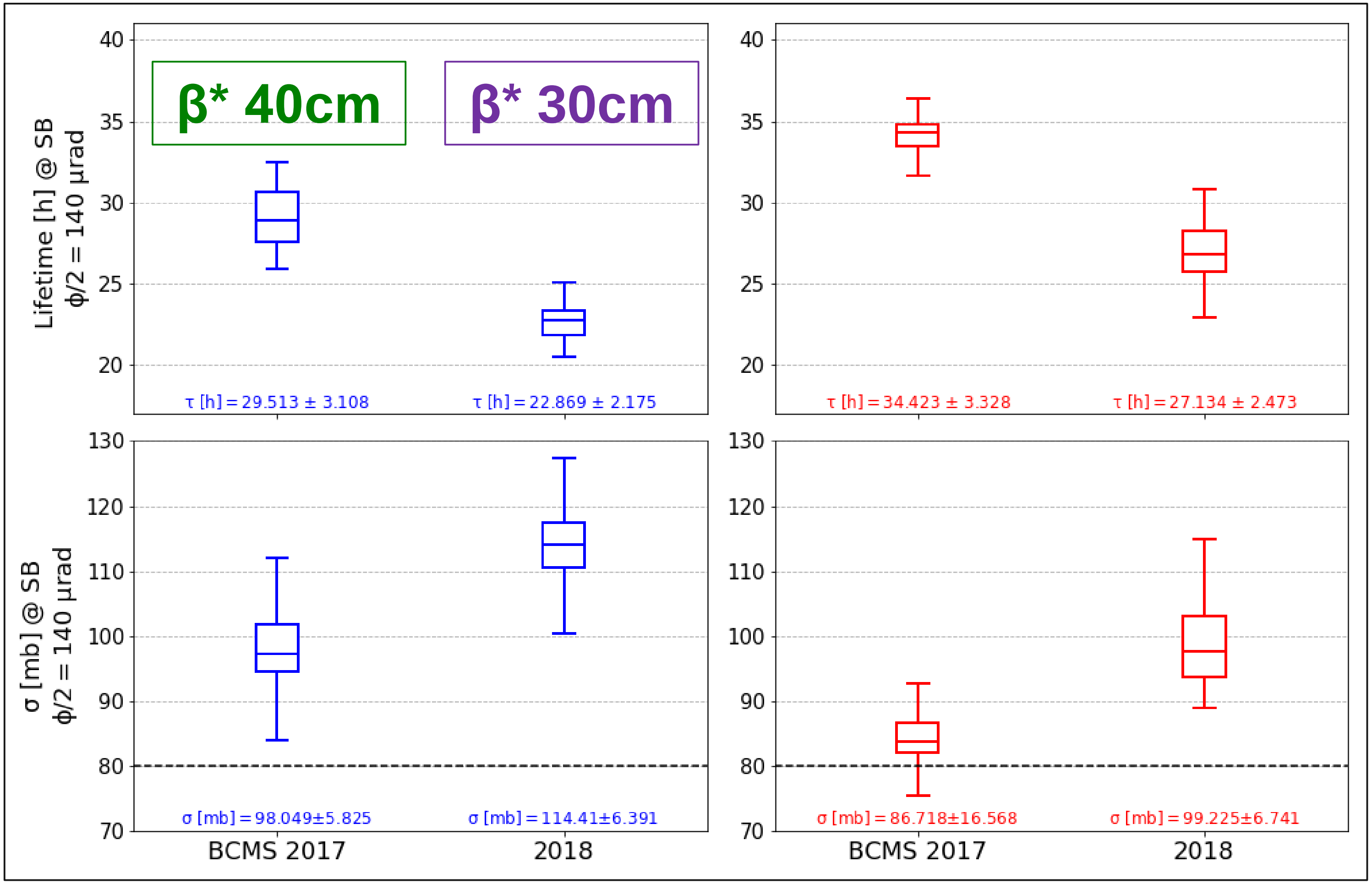
σ_{B1} > σ_{B2} > σ_{Boff}

$$\frac{dN/dt}{L_{measured}}$$



Summary of Lifetime @ SB

- Comparison of **2018** with **BCMS 2017**: Reduction of lifetime, increase in extra losses for both beams.

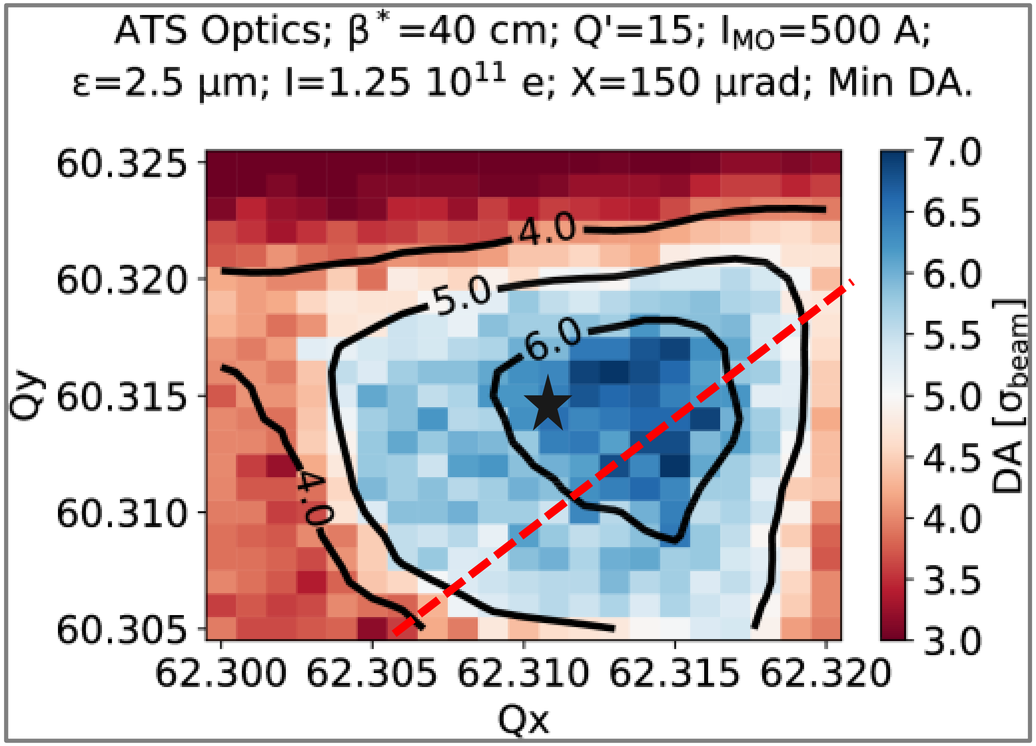


* Similar average lifetime between BCMS, BCS, 8b4e in 2017 (see appendix "Summary of Lifetime @ SB 2017")

Dynamic Aperture optimization

- Since 2016: **multi-parametric DA scans** for lifetime optimization.
- DA with Sixtrack over 1e6 turns for different machine configurations.
- Machine parameters for optimization:

Tune scan for 2017



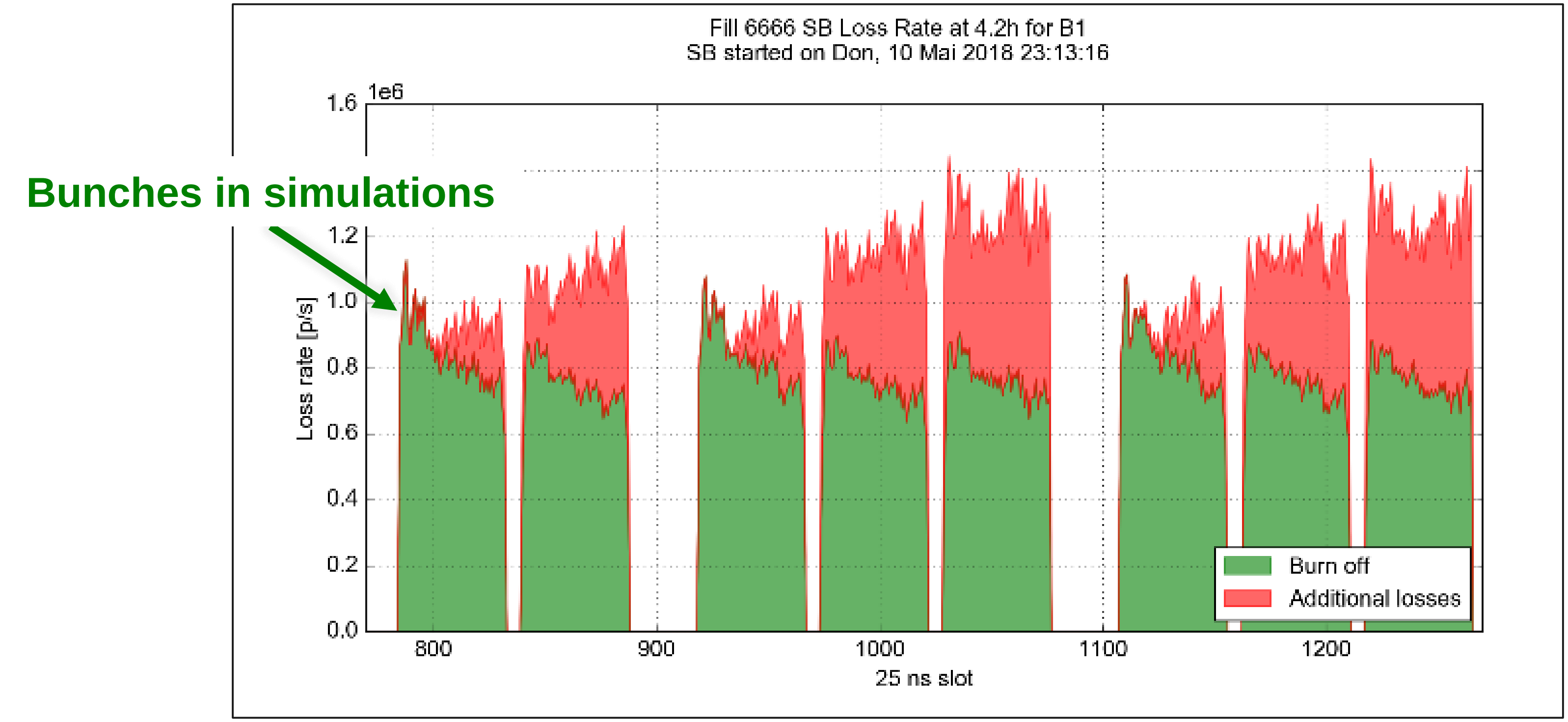
Included in DA simulations:

Tune, Intensity, Crossing angle, β*, chromaticity, octupoles, BB effects

Dynamic Aperture optimization

NOT included in DA simulations:

- **Imperfections (effective machine model) & Electron-cloud & Noise**
- Introduce additional non-linearities reducing further DA.



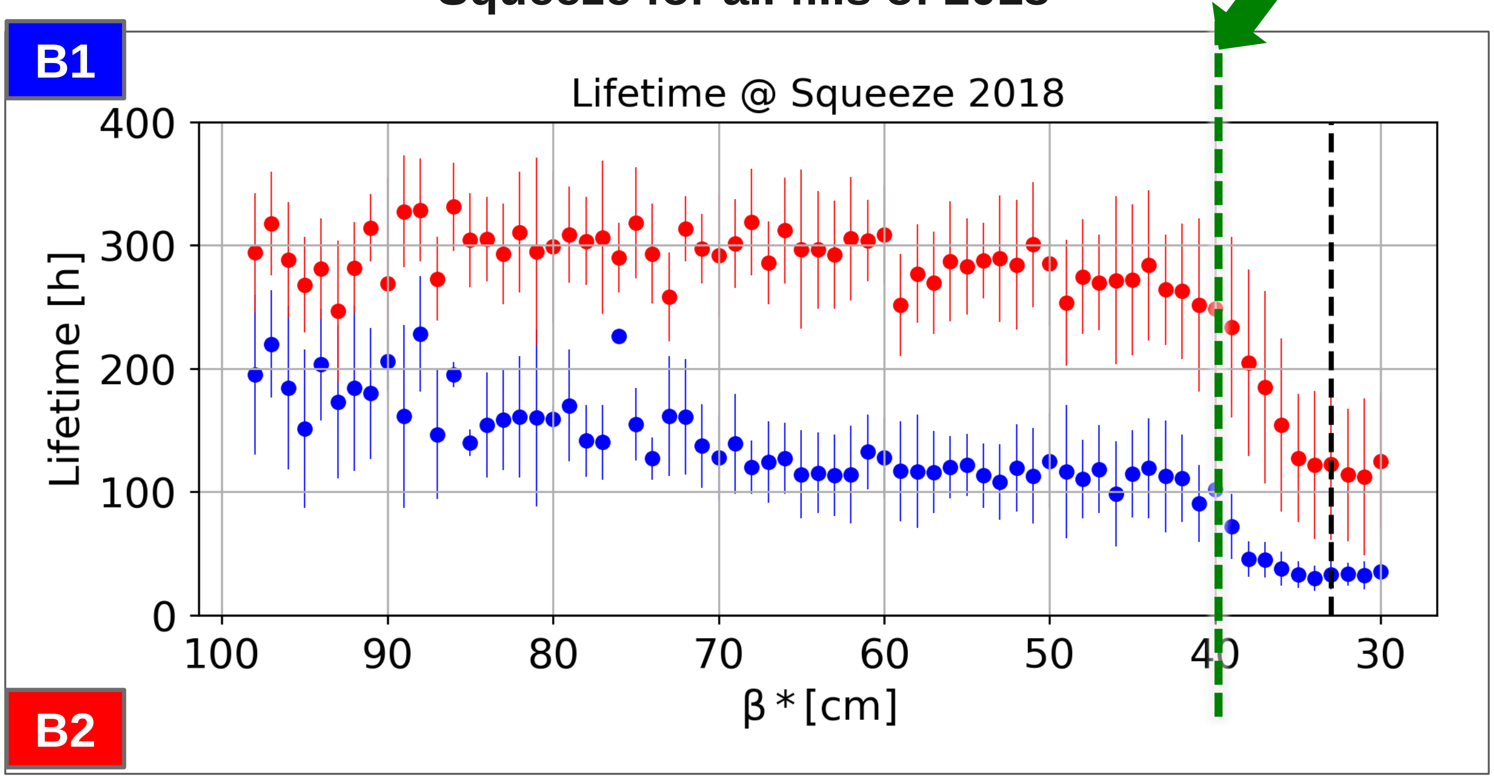
Squeeze

Losses @ Squeeze (2018)

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

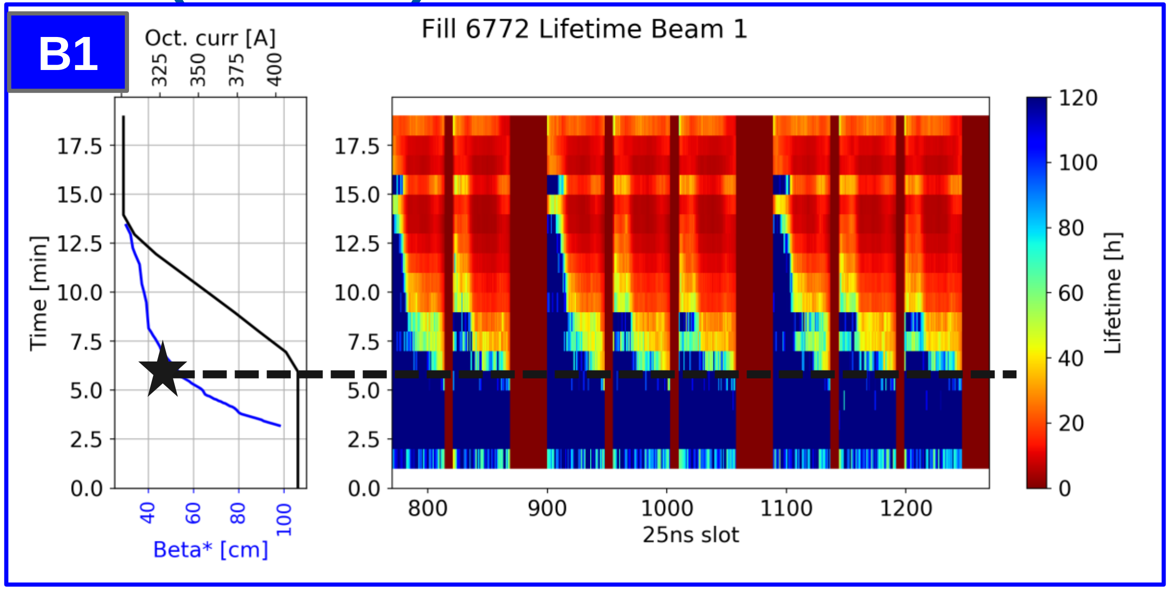
β* in 2017

Average bunch lifetime during Squeeze for all fills of 2018



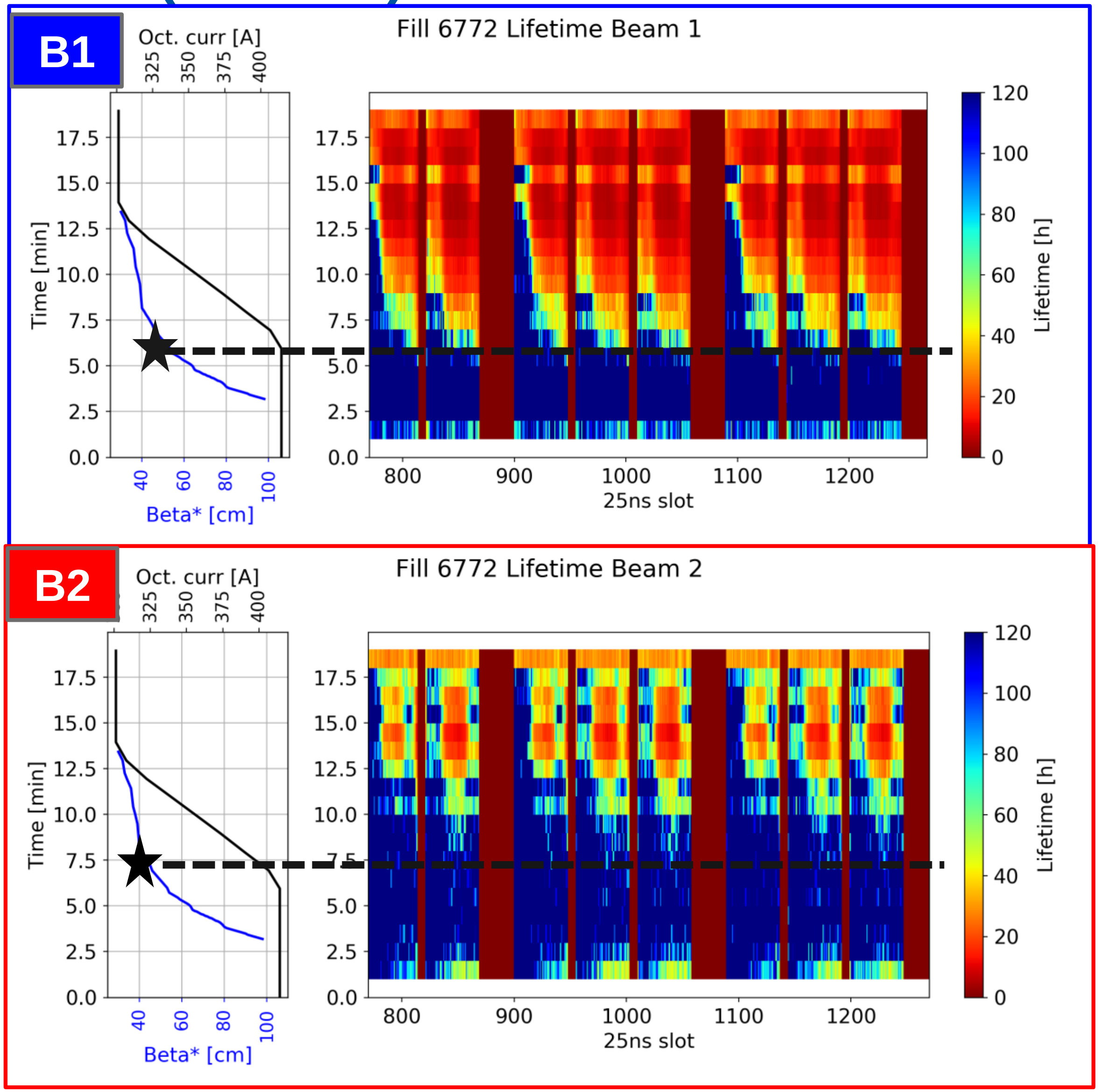
Losses @ Squeeze (2018)

- **Patterns of LR** (middle of the trains) **and e-cloud** (tails of the trains).



Losses @ Squeeze (2018)

- **Patterns of LR** (middle of the trains) **and e-cloud** (tails of the trains).
- More pronounced for **B1** than **B2** and the loss patterns increase as β* decreases.
- ➢ Separate analysis for bunches affected by e-cloud/LR.



Losses @ Squeeze (2018)

Classes:

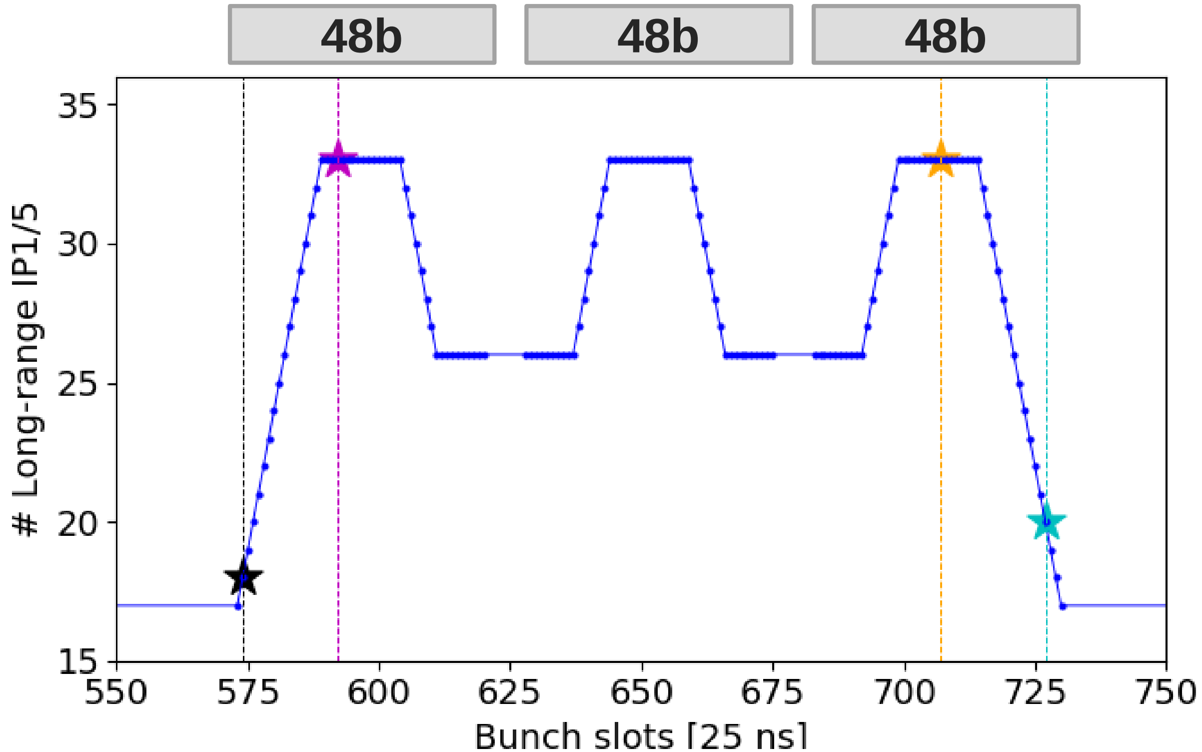
I. **NoBB**: Pacman

II. **BB**: LR

III. **BB-ecloud**: LR & e-cloud

IV. **NoBB-ecloud**: Pacman with e-cloud

Only 3x48b selected



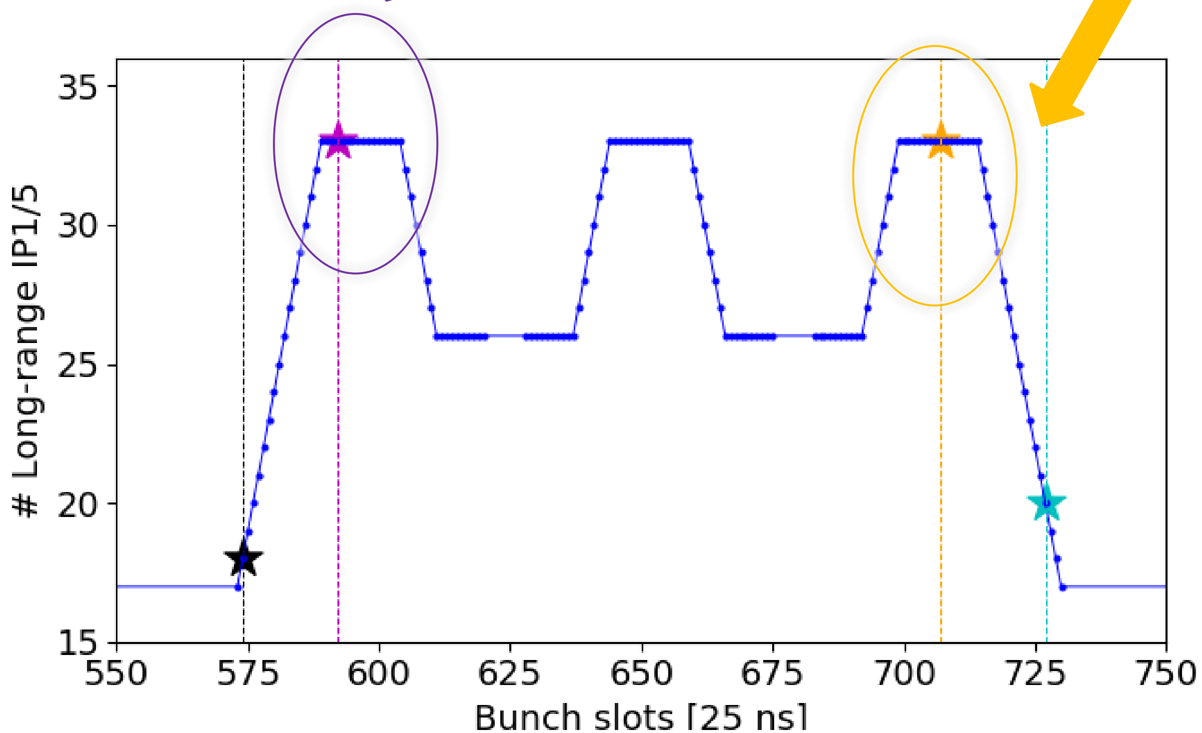
Losses @ Squeeze (2018)

Classes:

I. **NoBB**
II. **BB**
III. **BB-ecloud**
IV. **NoBB-ecloud**

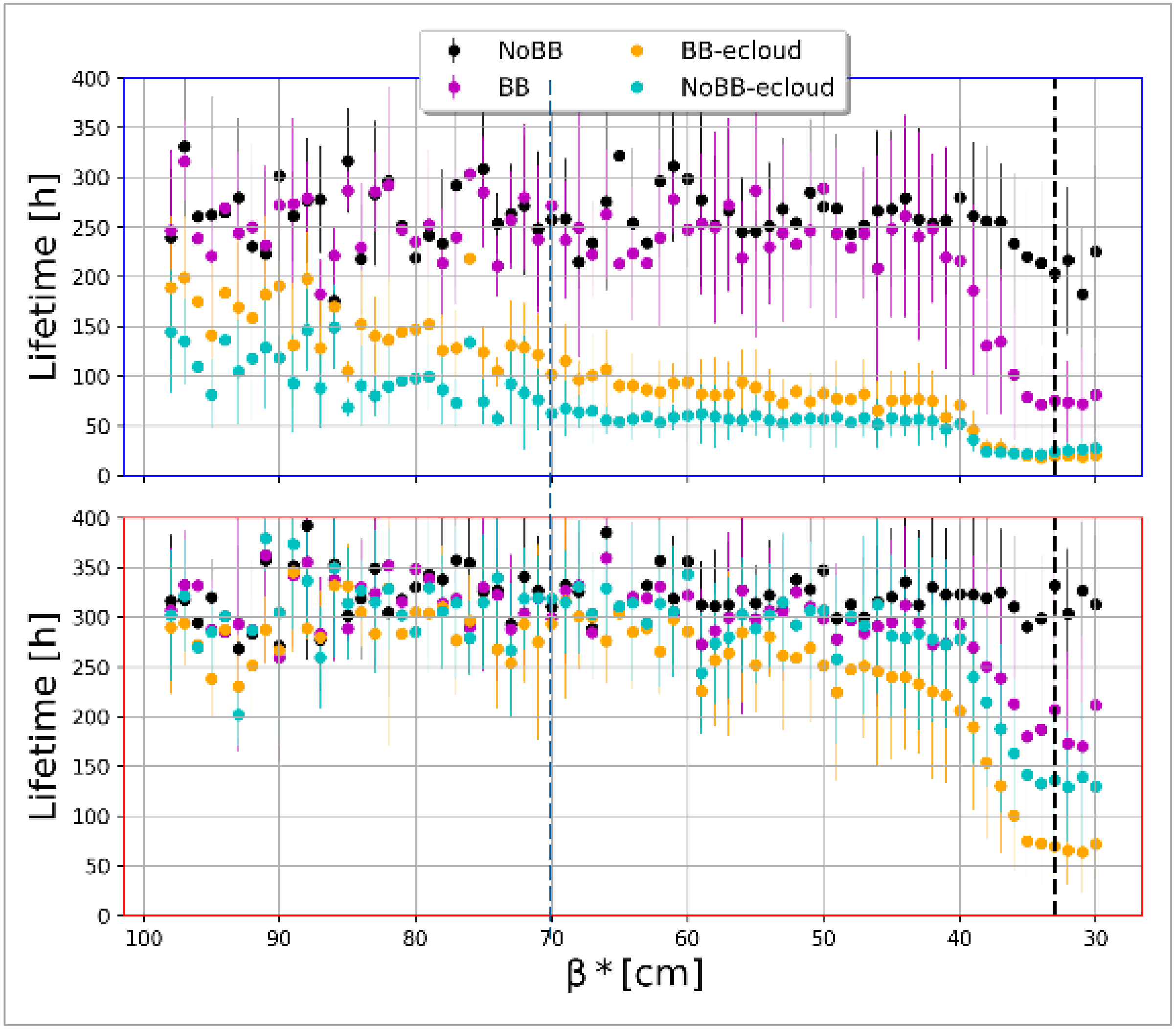
DA optimizations are based on **BB Class**

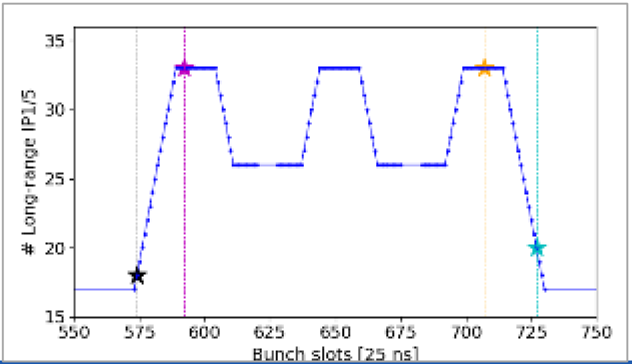
Applied on Class **BB-ecloud**



Losses @ Squeeze (2018)

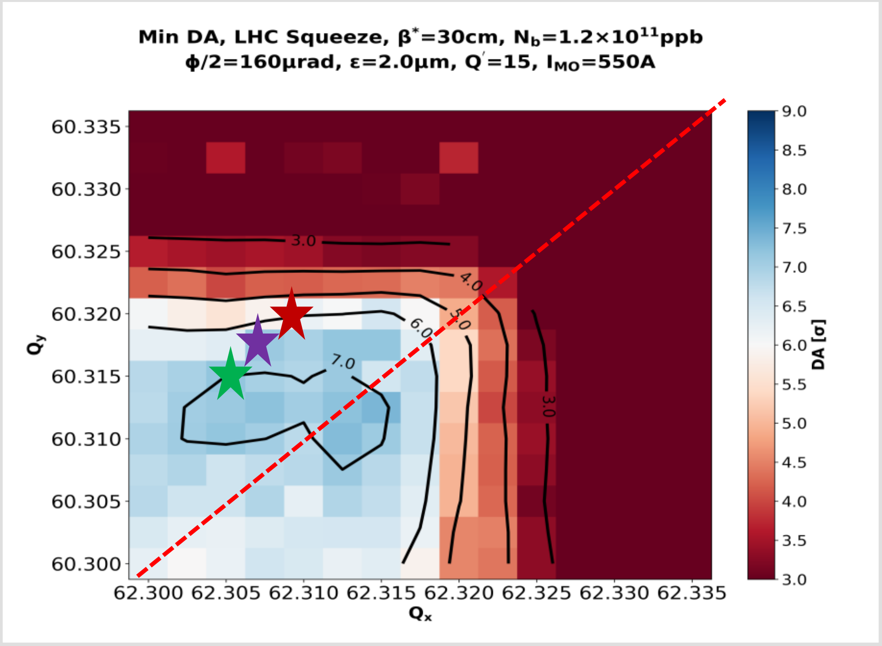
	Lifetime drop β* 33 cm to β* 70 cm [%]	
B1	NoBB	21
	BB	72
	BB-ecloud	**80**
	NoBB-ecloud	62
B2	NoBB	-7
	BB	30
	BB-ecloud	**76**
	NoBB-ecloud	57





Losses @ Squeeze (2018)

- Dependence of losses on **IP1/5 LR encounters**.
- LR effects can be mitigated with **tune optimization.**.



* See appendix “BBLR driven patterns”.

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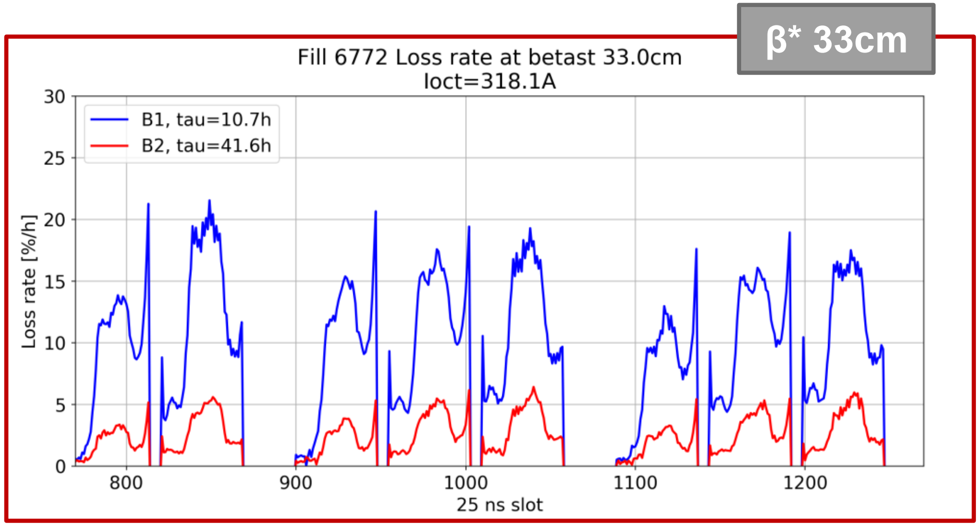
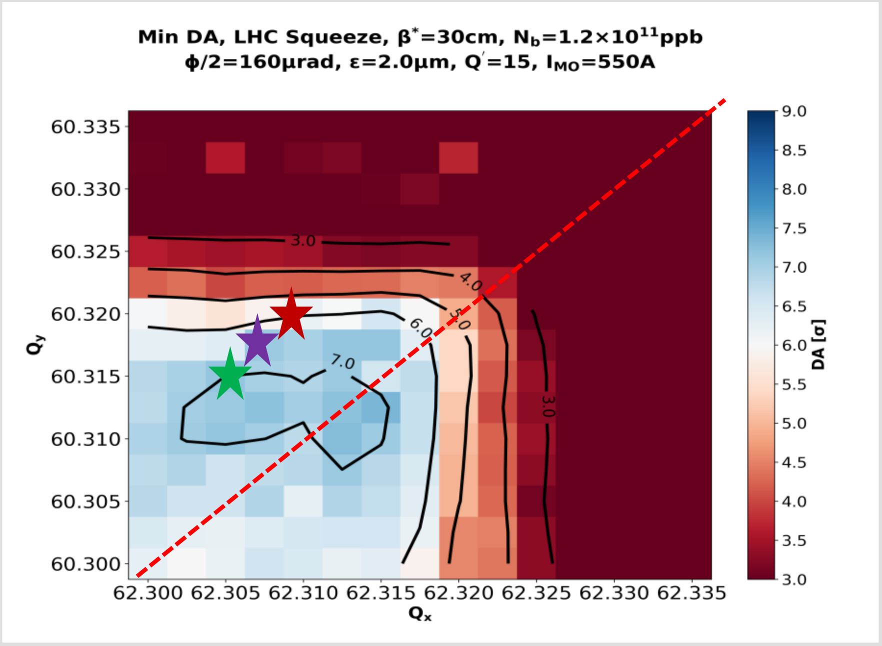
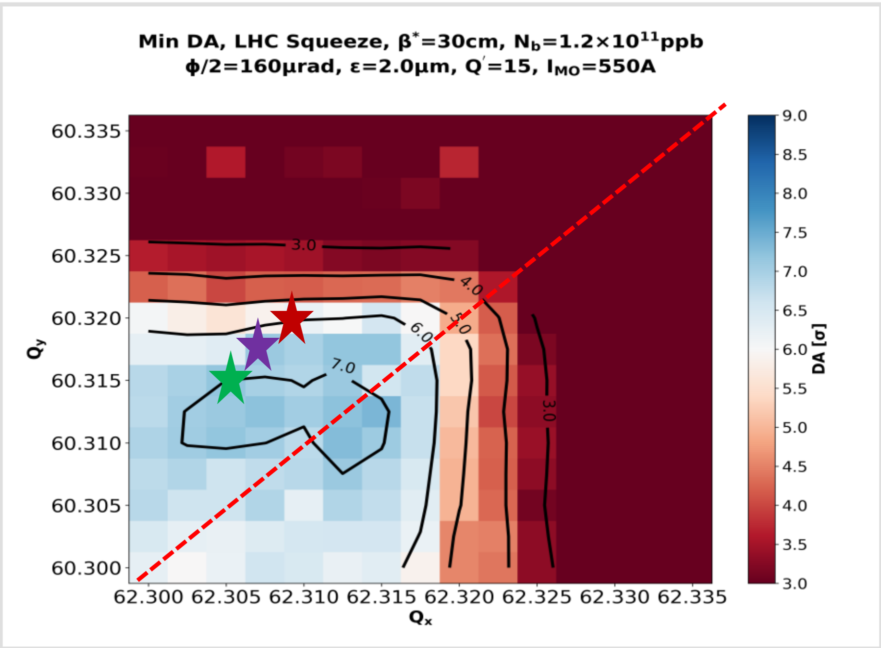


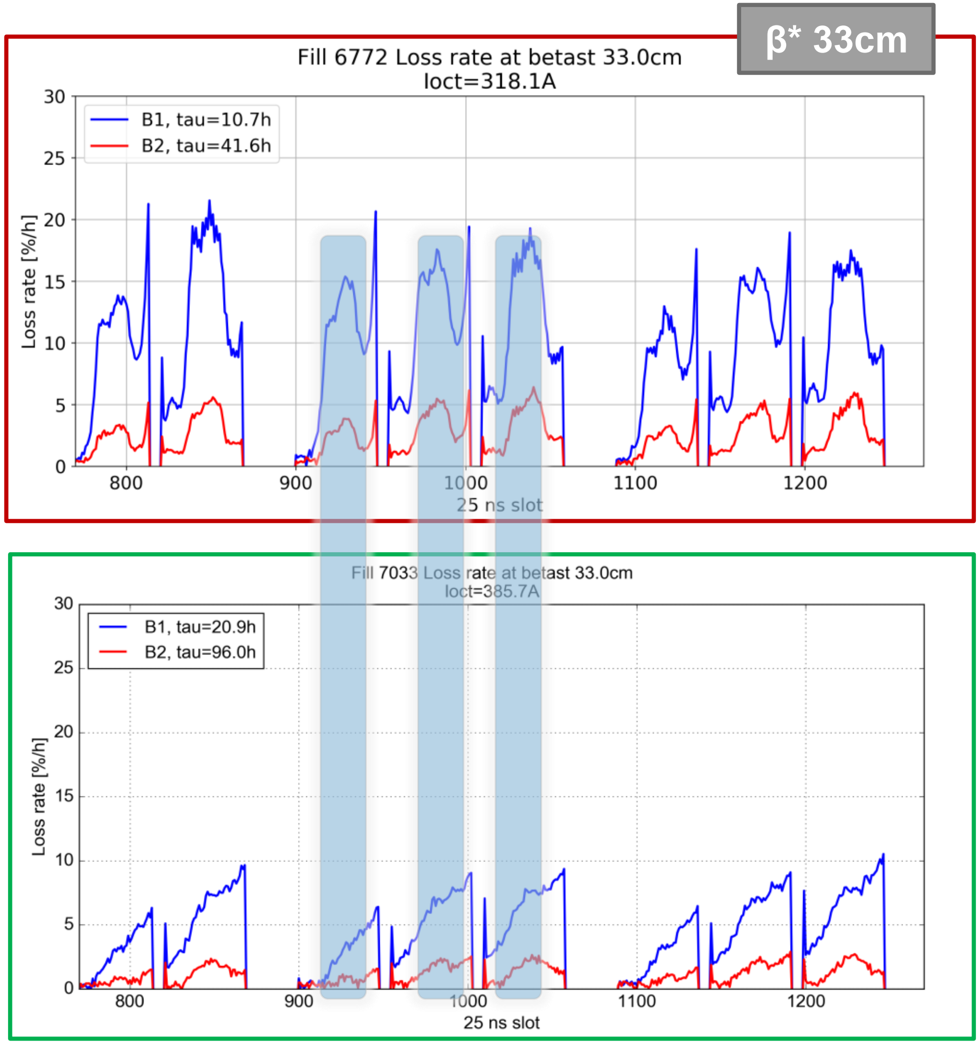


* See appendix "BBLR driven patterns".

Losses @ Squeeze

- Dependence of losses on **IP1/5 LR encounters**.
- LR effects can be mitigated with **tune optimization.**
- Reduction of loss rate for both beams.
- E-cloud patterns still visible.





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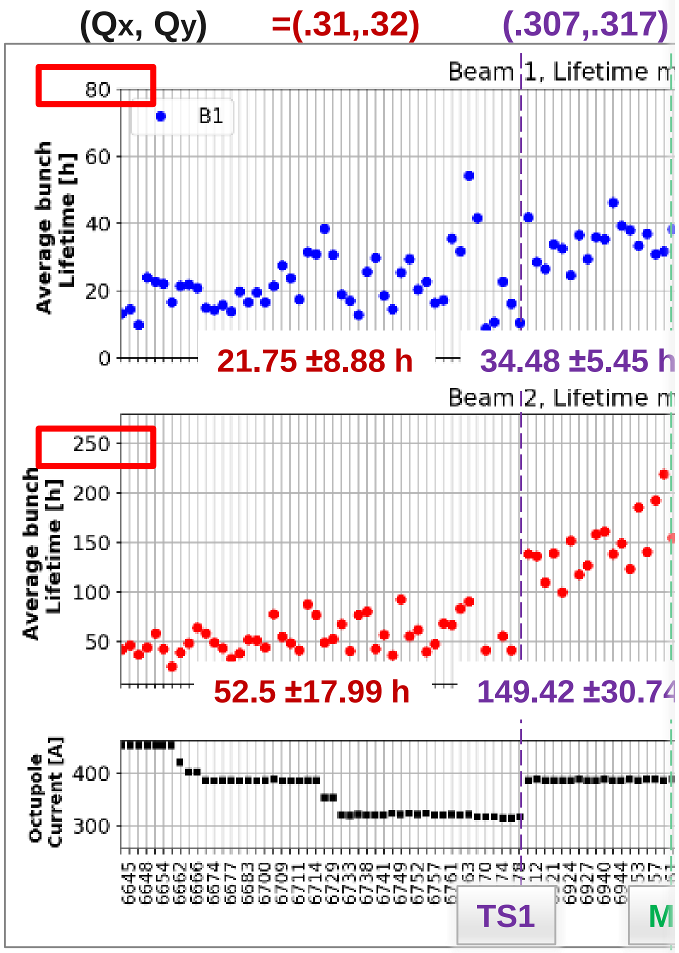
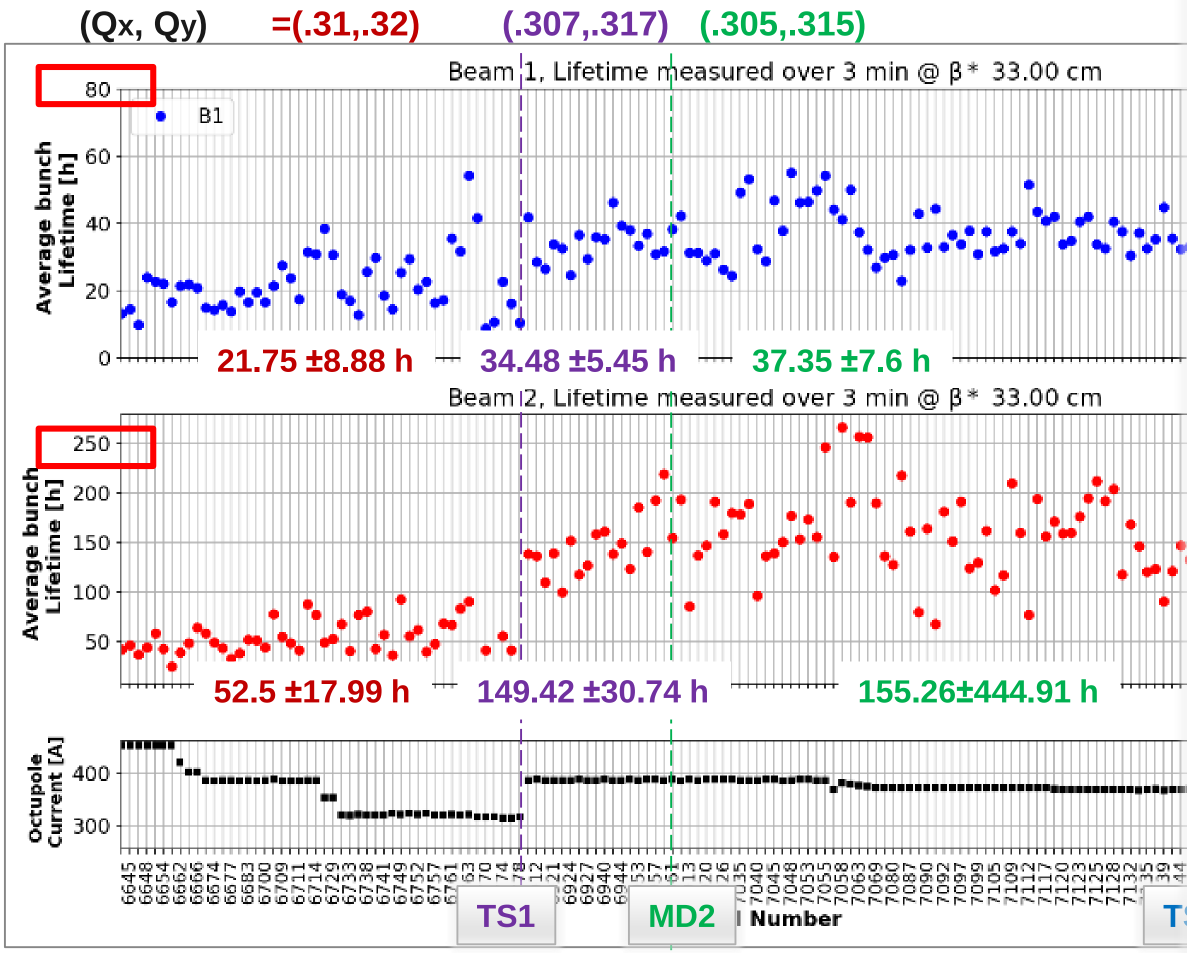
Losses @ Squeeze

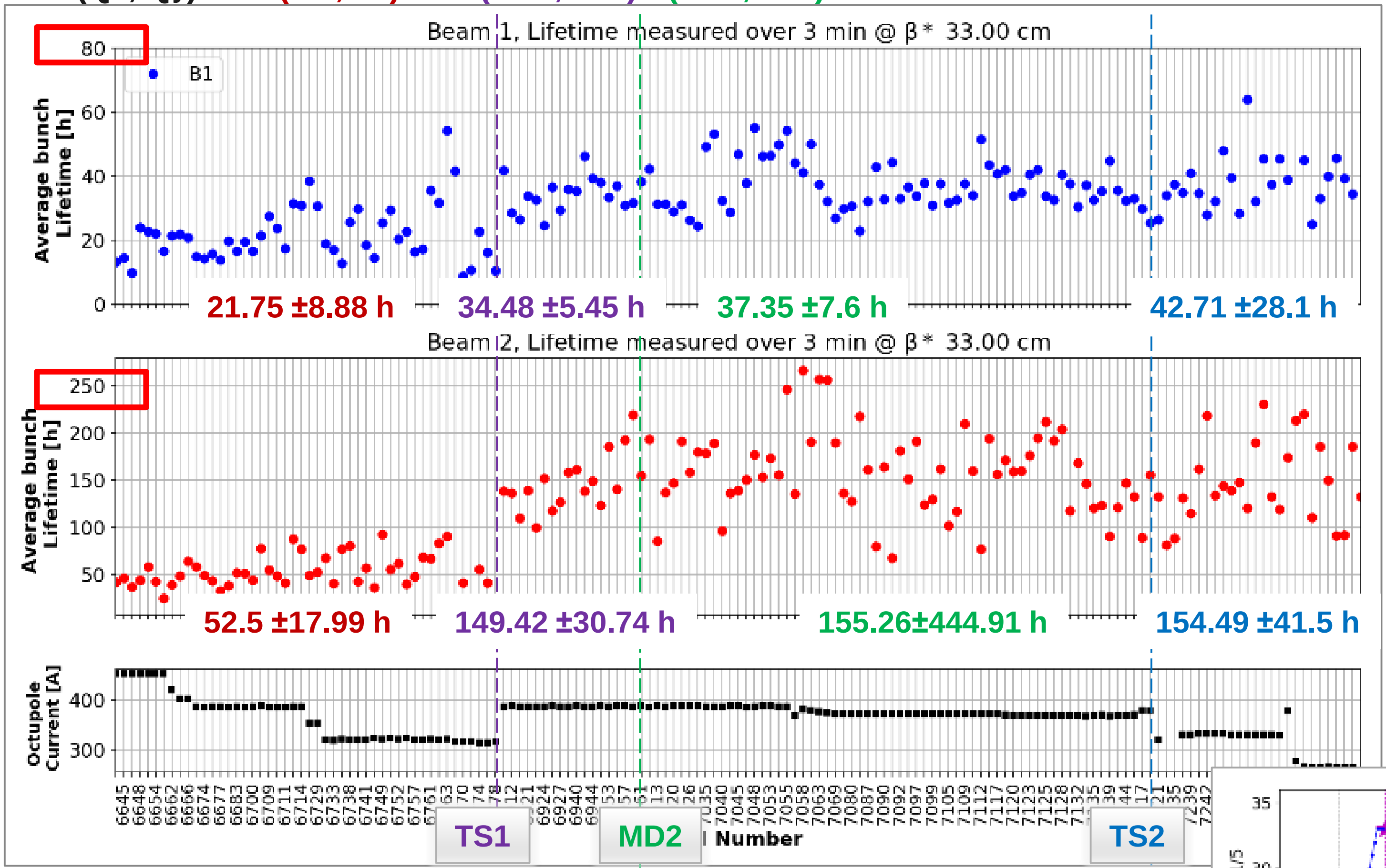


Losses @ Squeeze



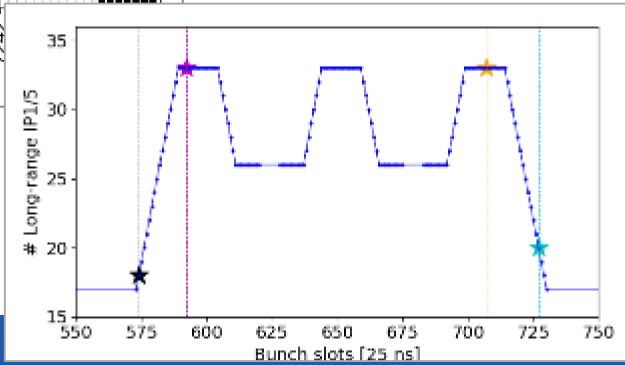
Losses @ Squeeze

(Qx, Qy) =(.31,.32) (.307,.317) (.305,.315)



- Beneficial tune optimizations (mainly the 1st one) for all classes*, mainly Class **BB** & **BB-ecloud**.

- No significant improvement from octupole reduction**.

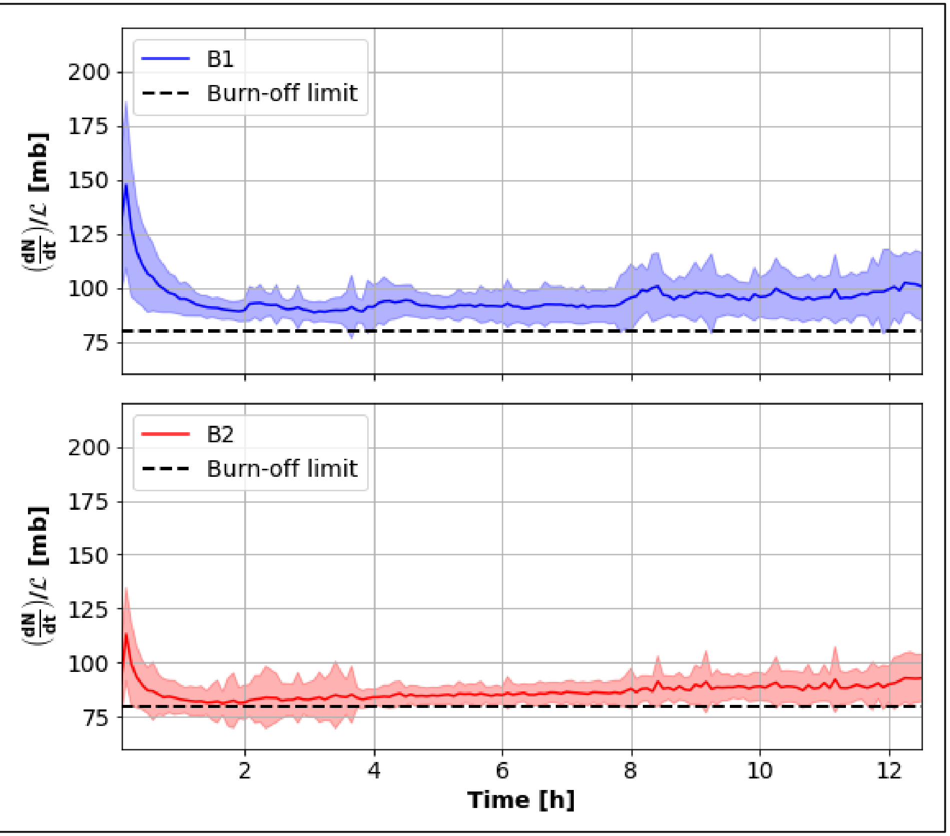


*,** See appendix "Losses @ telescopic squeeze".

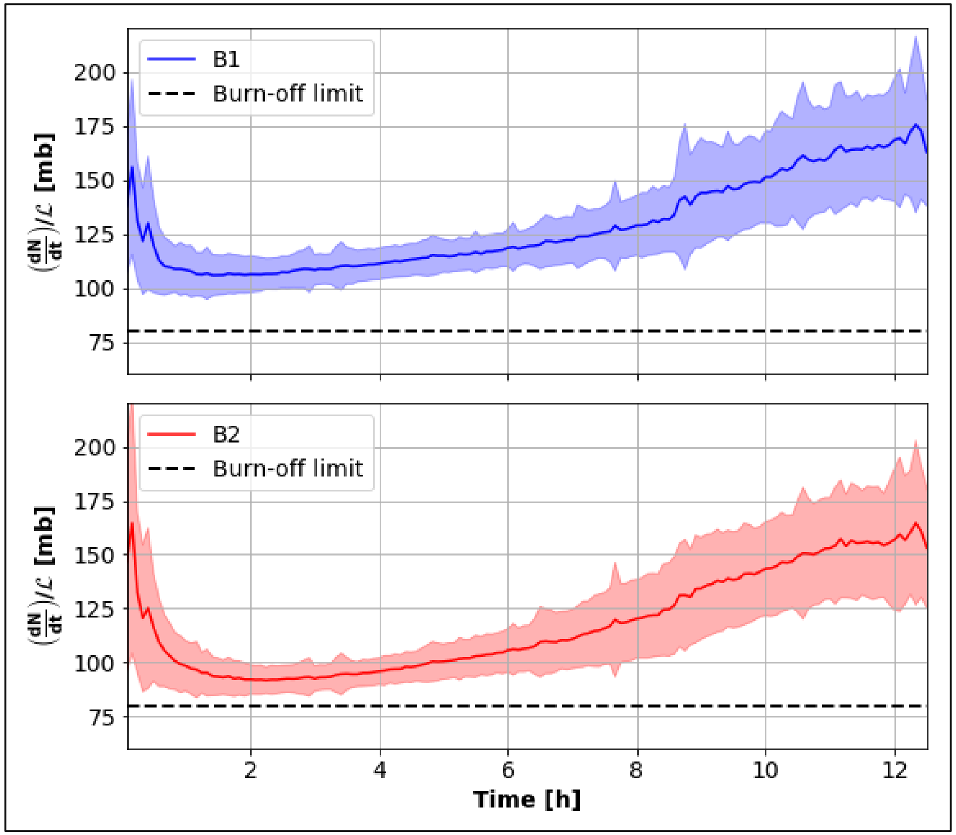
Stable beams

Effective Cross Section

2017

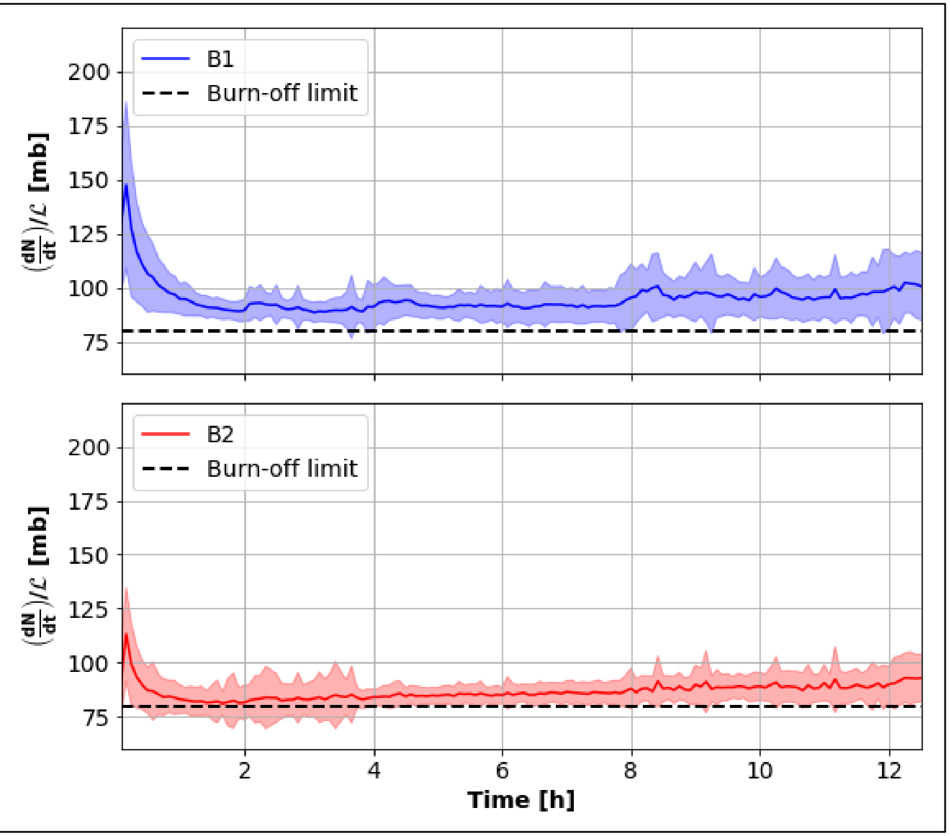


2018



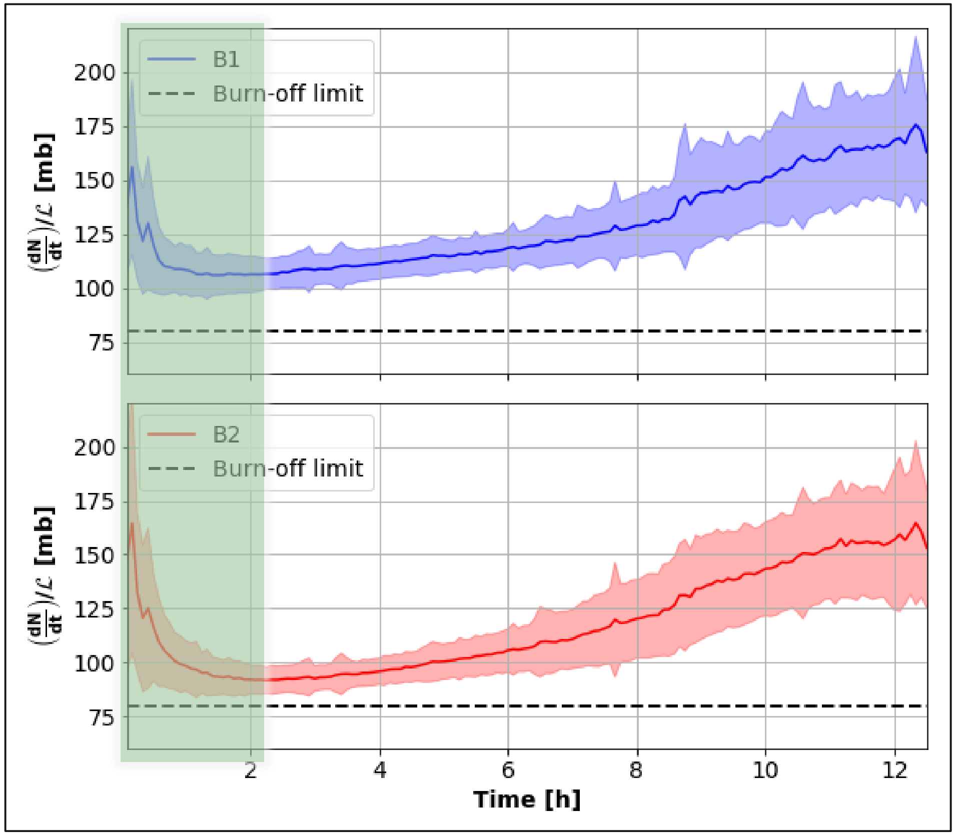
Effective Cross Section

2017



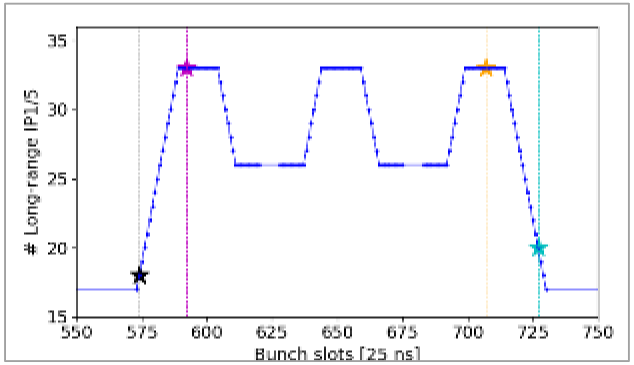
1. Start of Stable beams

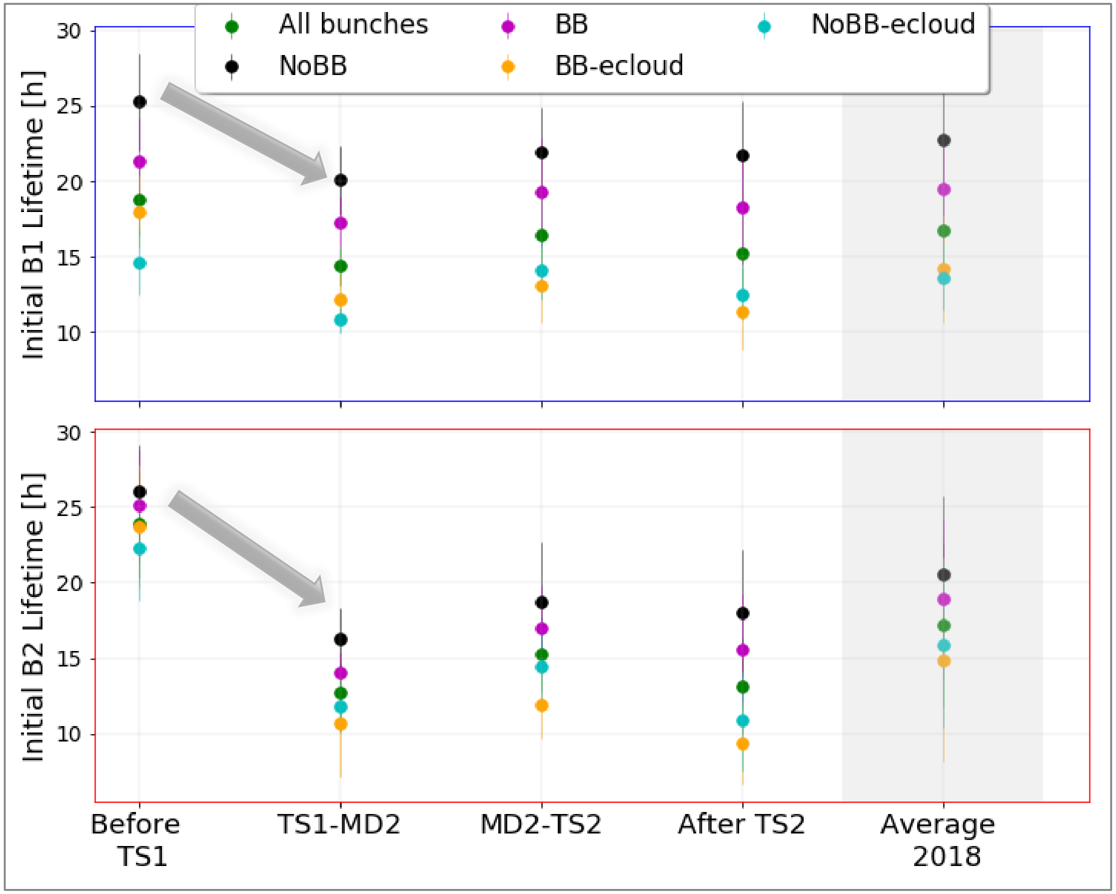
2018



Losses @ Start of SB

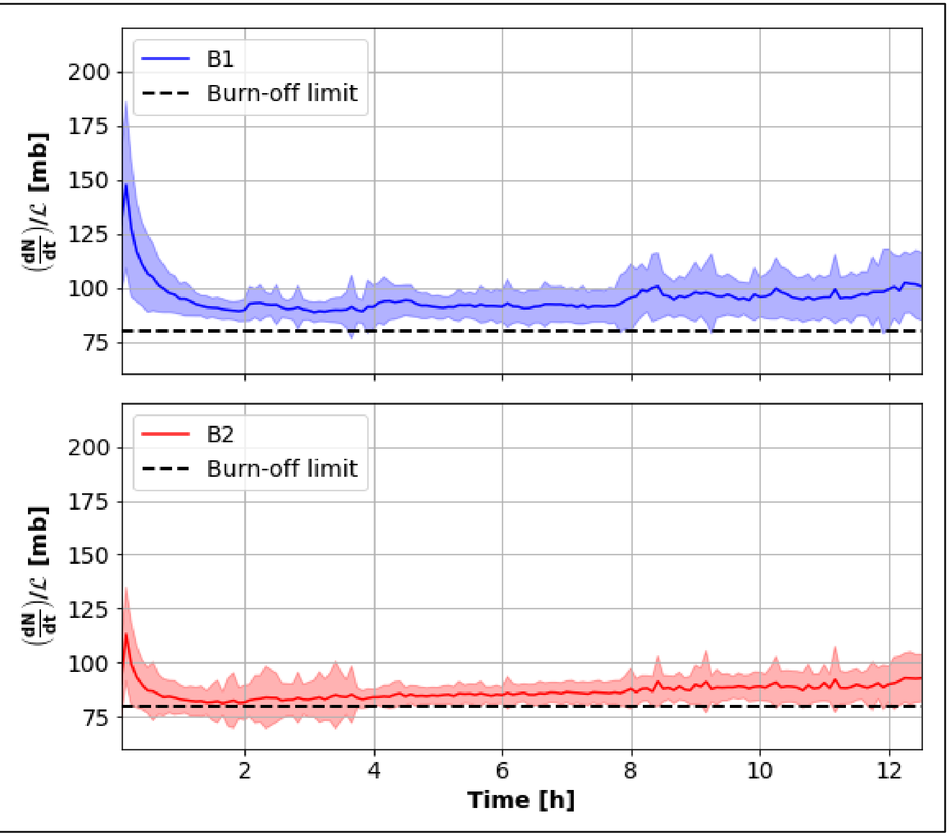
- Reduction of initial lifetime of both beams after TS1, mainly for **B2**
- Probably correlated with tune optimization during Squeeze





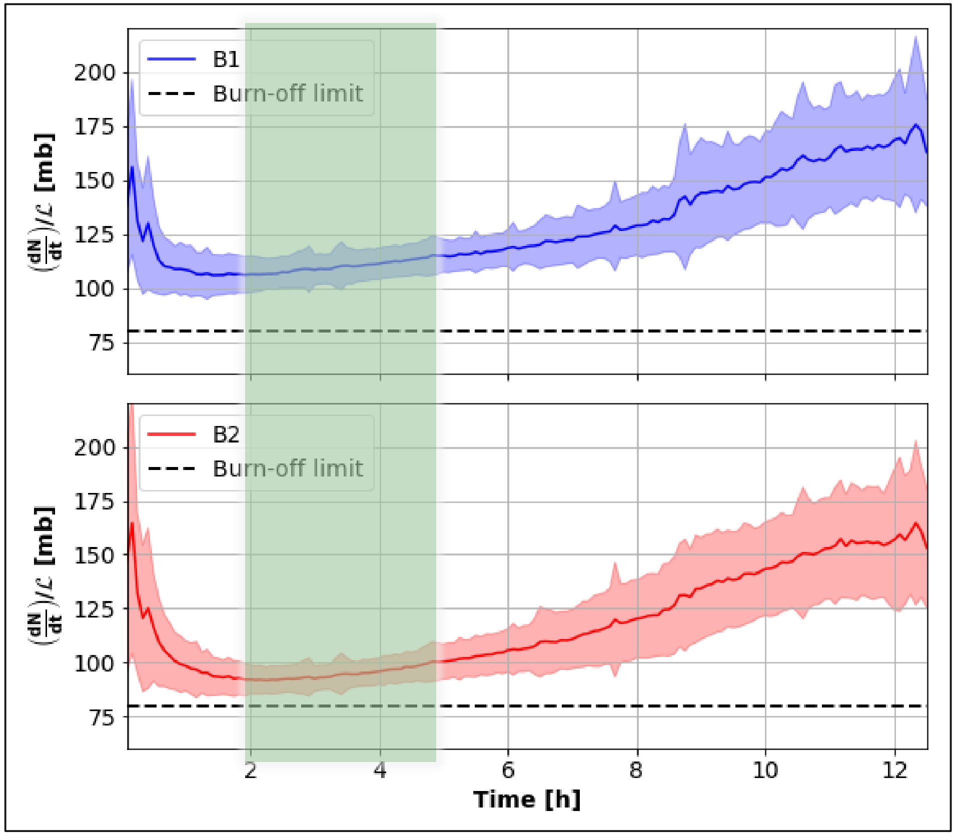
Effective Cross Section

2017

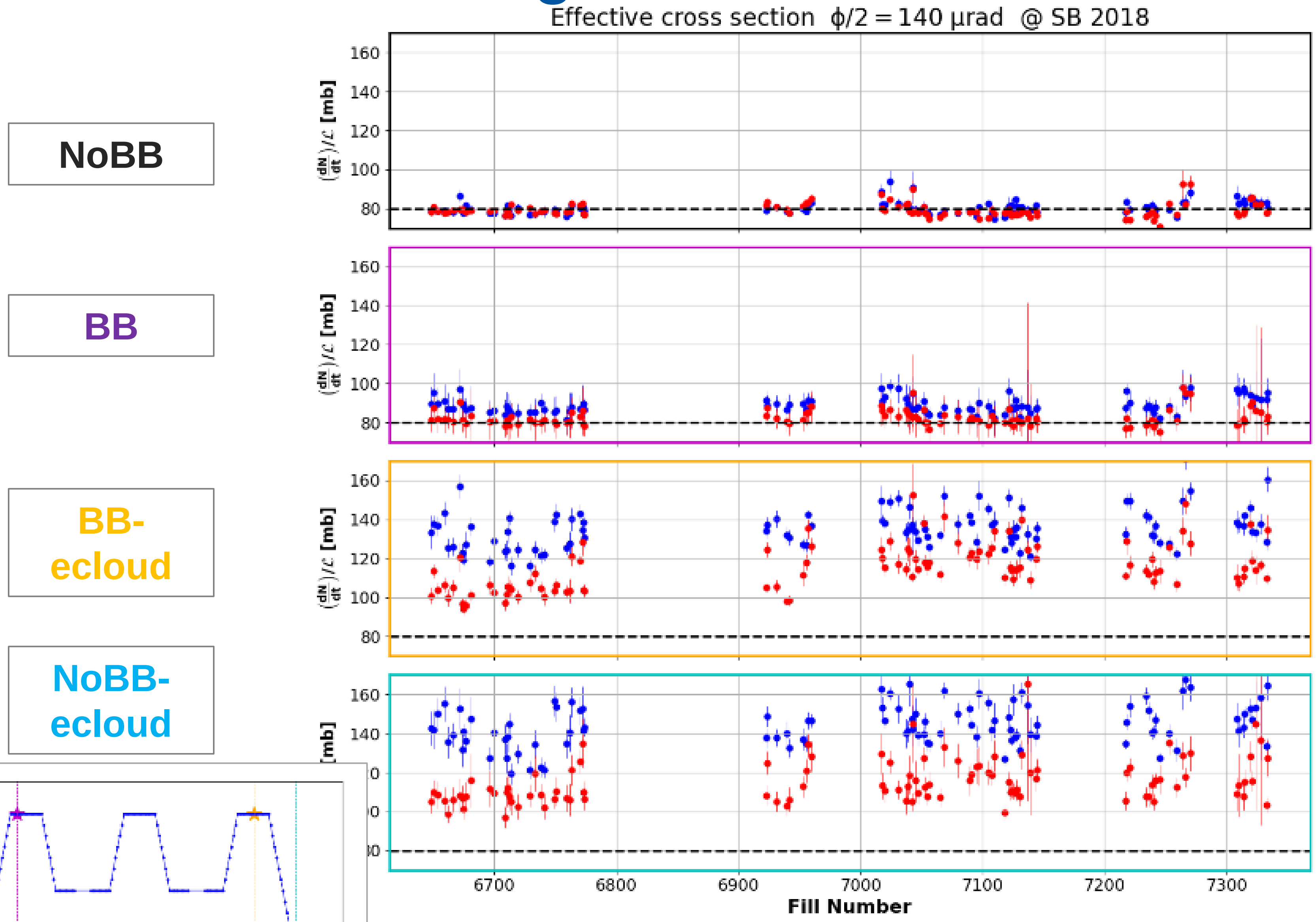


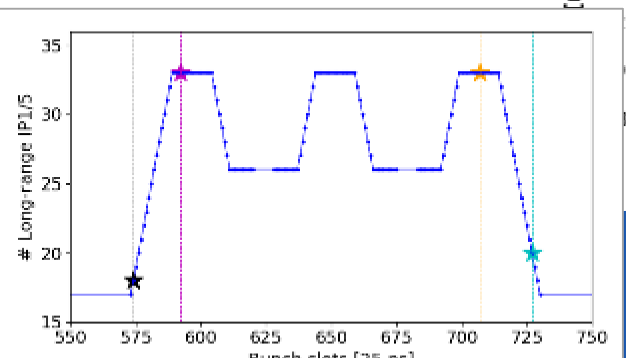
2. Stable beams

2018



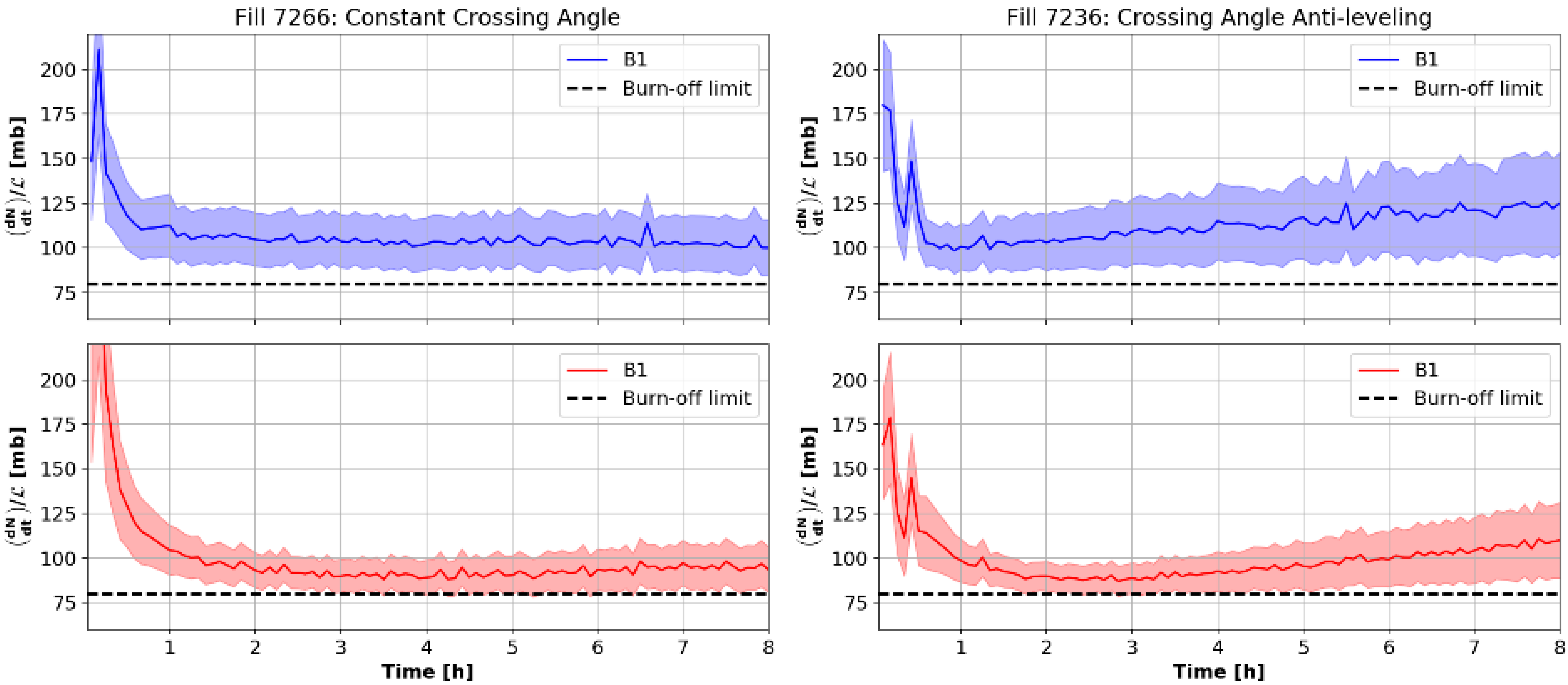
Losses @ SB during 2018





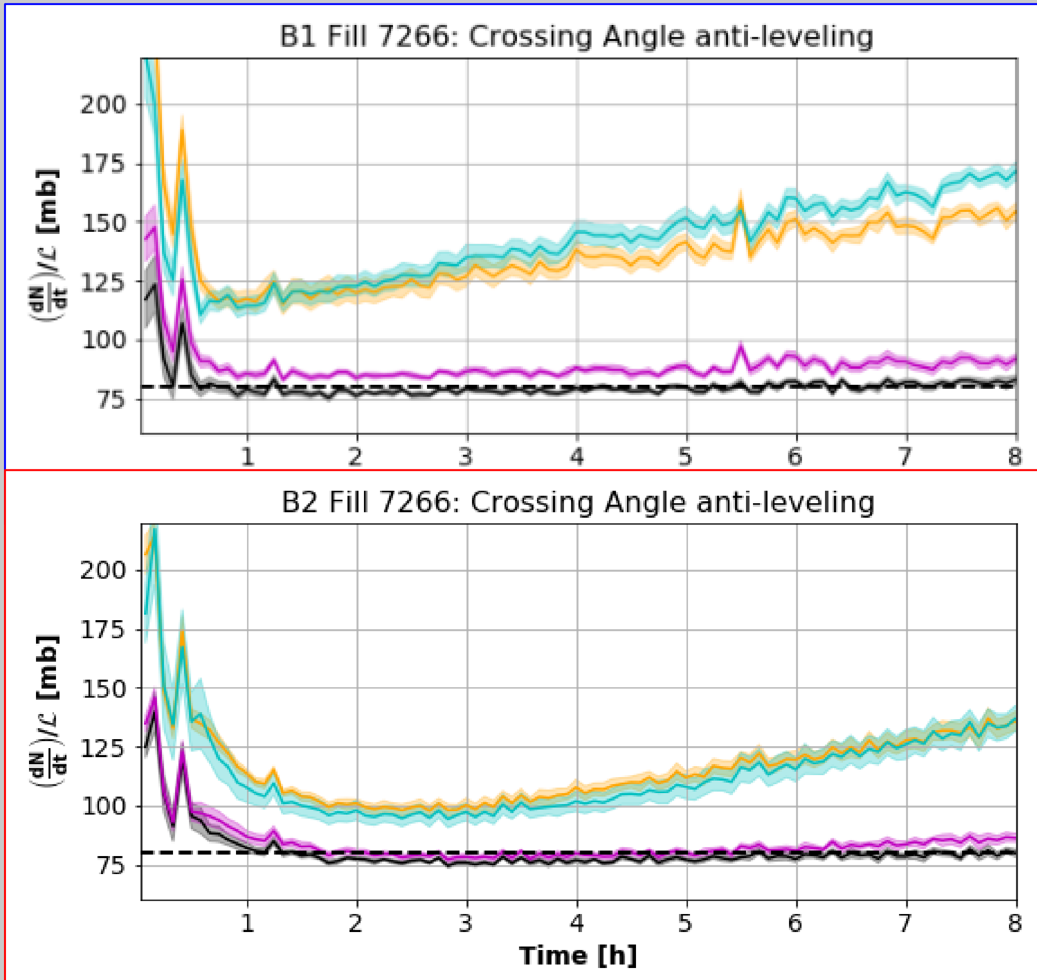
Losses @ SB during 2018

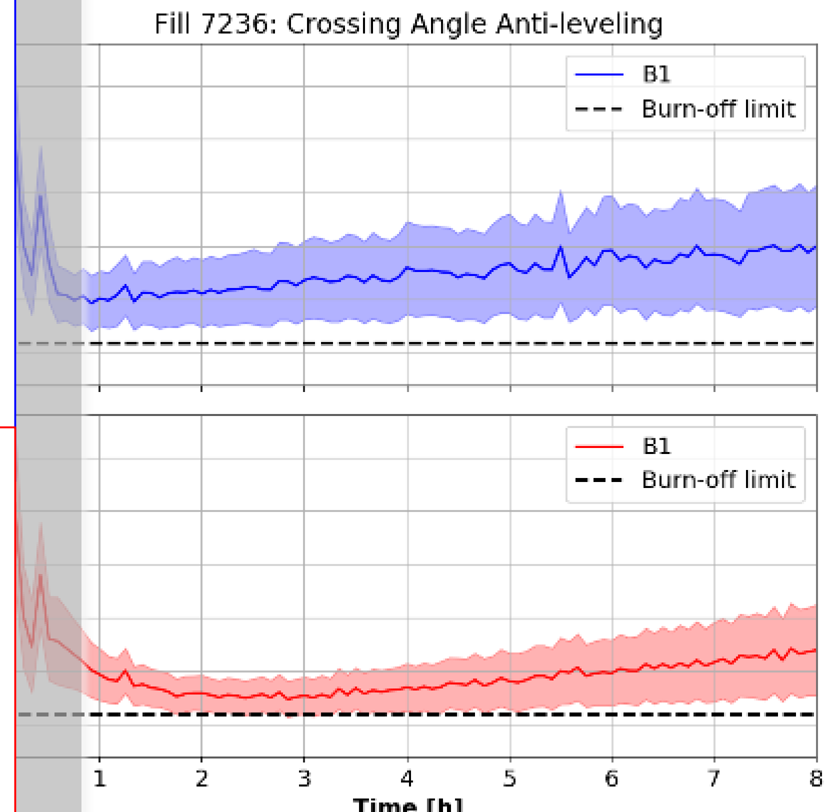
2018, Constant crossing angle | **2018, Crossing angle anti-leveling**

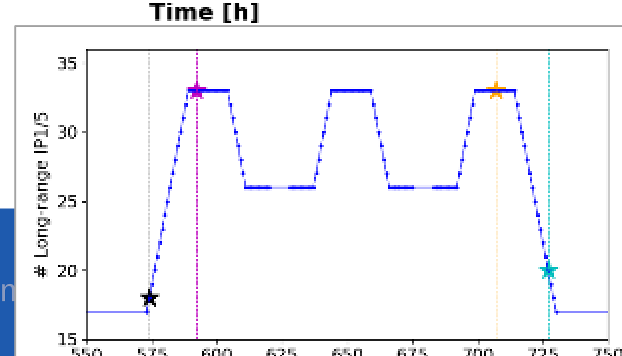


β*=30 cm

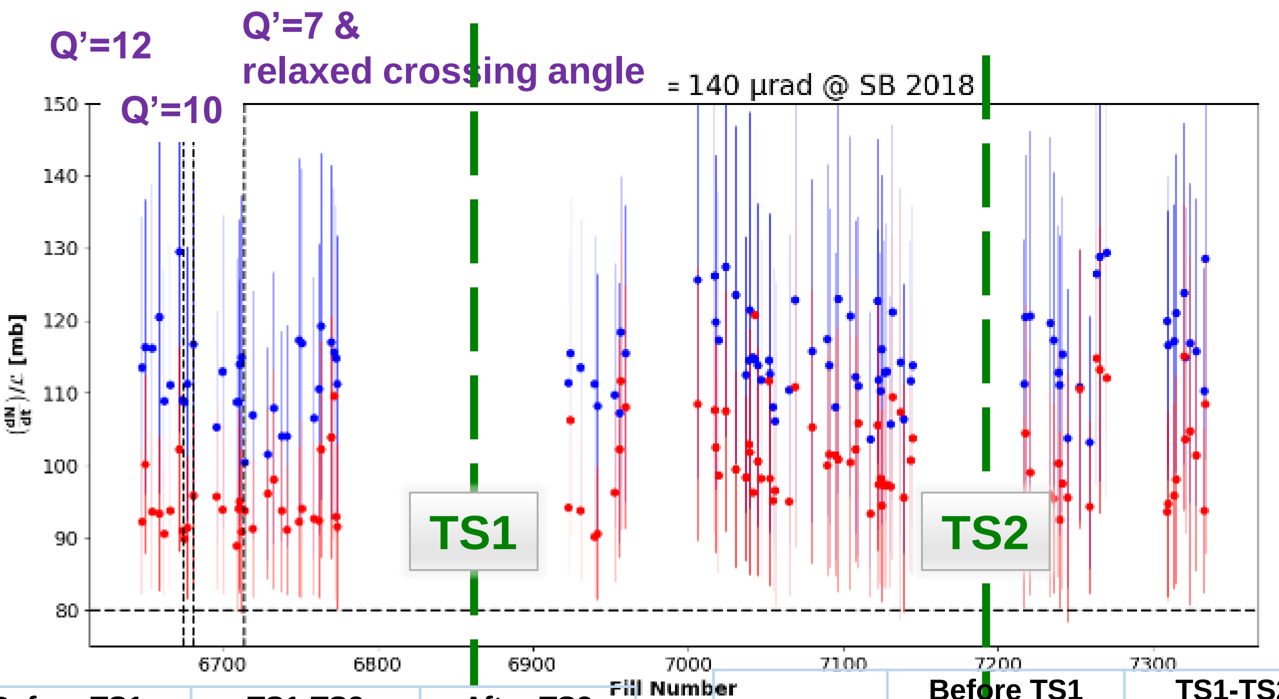
Losses @ SB during 2018







DA optimizations in 2018

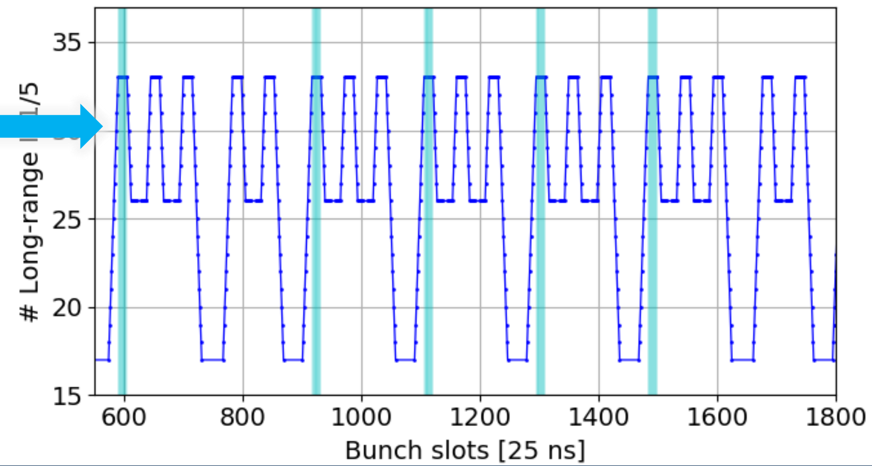


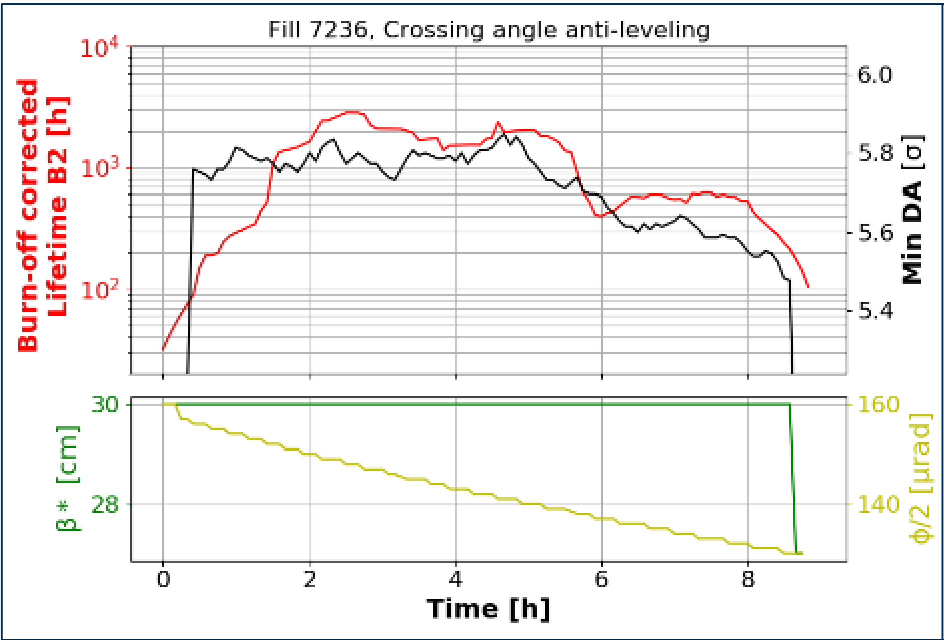
	Before TS1	TS1-TS2	After TS2
	Effective Cross section [mb] @ φ/2 140μrad SB		
B1	111	114	117
NoBb	79	80	81
BB	**87**	**88**	**91**
BB-ecloud	130	136	139
NoBB-ecloud	139	145	148

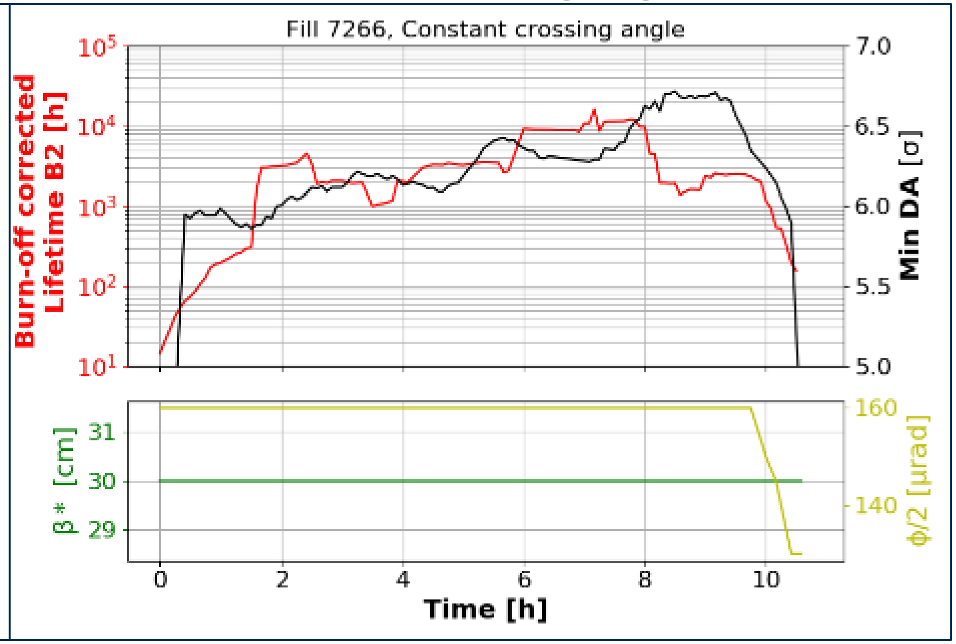
	Before TS1	TS1-TS2	After TS2
	Effective Cross section [mb] @ φ/2 140μrad SB		
B2	94	101	101
NoBb	78	78	79
BB	**81**	**82**	**83**
BB-ecloud	105	120	119
NoBB-ecloud	109	117	118

DA-Lifetime Correlation

- Intensity, chromaticity, octupole current, crossing angle evolution and emittance from the data.
- DA simulations more consistent with **B2**.
- **DA 5σ ~ 100 h of B2 BO corrected lifetime.***







* See appendix “Correlation of DA with lifetime”

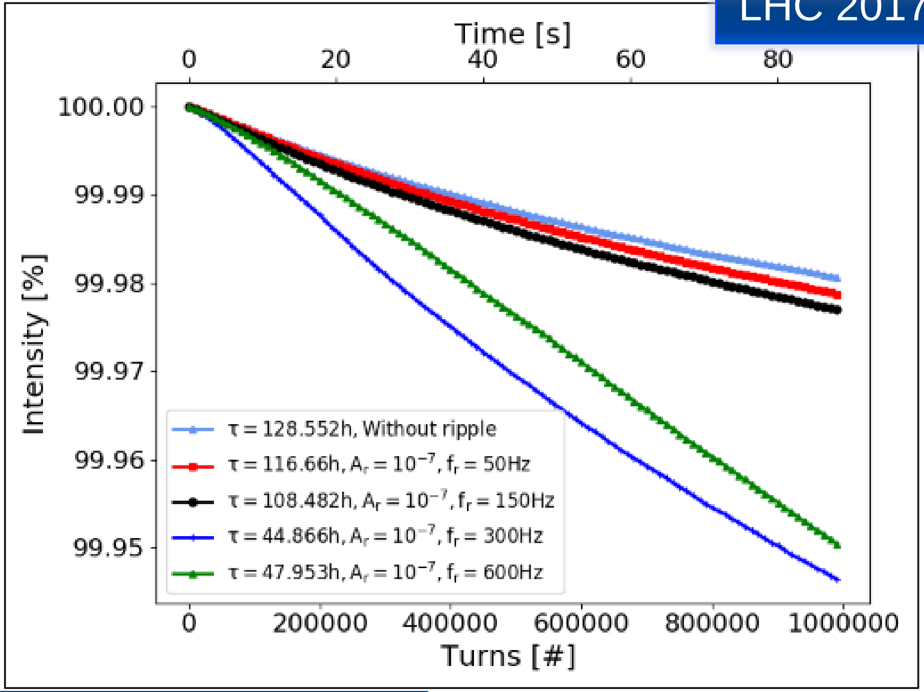
Noise effects

- Noise effects can lead to lifetime degradation by **introducing additional resonances.**

eg. Tune modulation (Inner triplet)

LHC 2017

Burn-off corrected Lifetime [h]		
fr [Hz]	**ΔQ**	**Lifetime [h]**
Without noise	-	128.552
50	2e-4	116.6
150	2e-4	108.482
300	2e-4	44.866
600	2e-4	47.953



Approximations:

- Impact from beam screen, cold bore **not included** in the transfer function.
- **Inductance** is considered **constant** for different frequencies.
- Evaluation of the impact from **individual frequencies**, not multiple harmonics.

Inner triplet & 50 Hz: https://indico.cern.ch/event/779650/contributions/3244747/attachments/1770859/2877607/TCC_noise_131218.pdf
50 Hz: https://indico.cern.ch/event/436679/contributions/1085928/attachments/1136594/1627012/LMC05082015_50Hz_04082015.pdf

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.

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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).

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➤ **DA well correlated with lifetime, but model misses important ingredients (imperfections, noise, e-cloud).**

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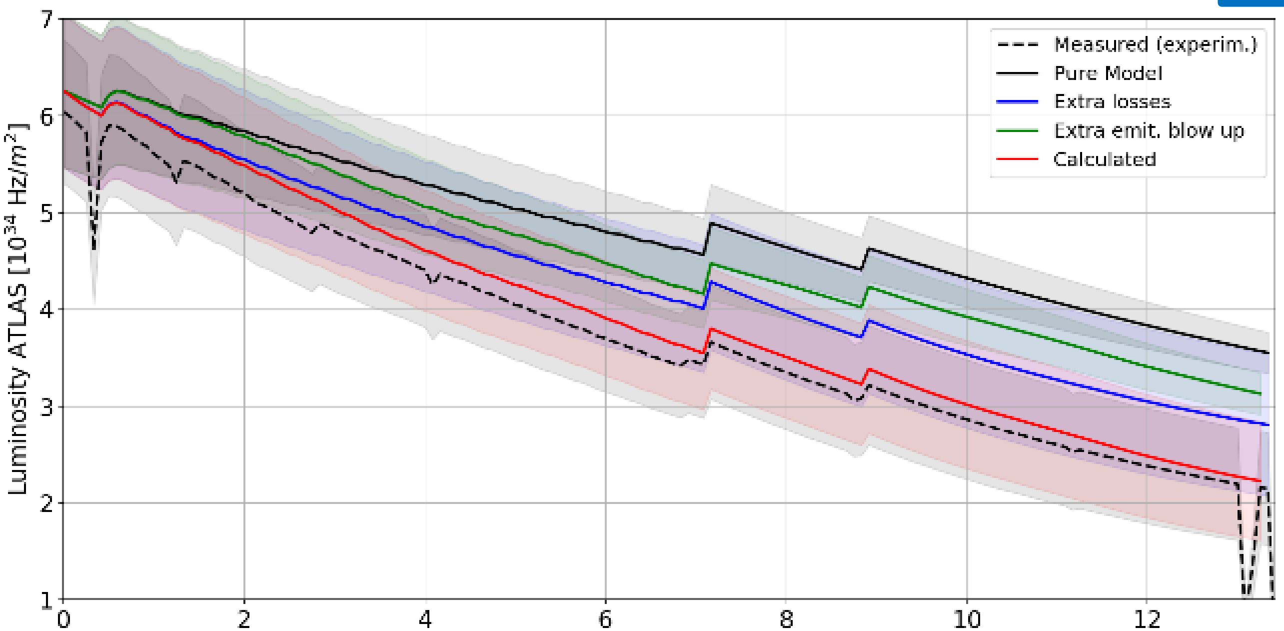
➢ **DA well correlated with lifetime, but model misses important ingredients (imperfections, noise, e-cloud).**

Thank you for your attention

Backup slides

Luminosity evolution

Impact of different degradation mechanisms on the Luminosity of Fill 7334



	Pure model	Extra Losses	Extra emittance blow up	Calculated
Emittance	model	model	**data**	**data**
Intensity	model	**data**	model	**data**

Performance follow-up tools

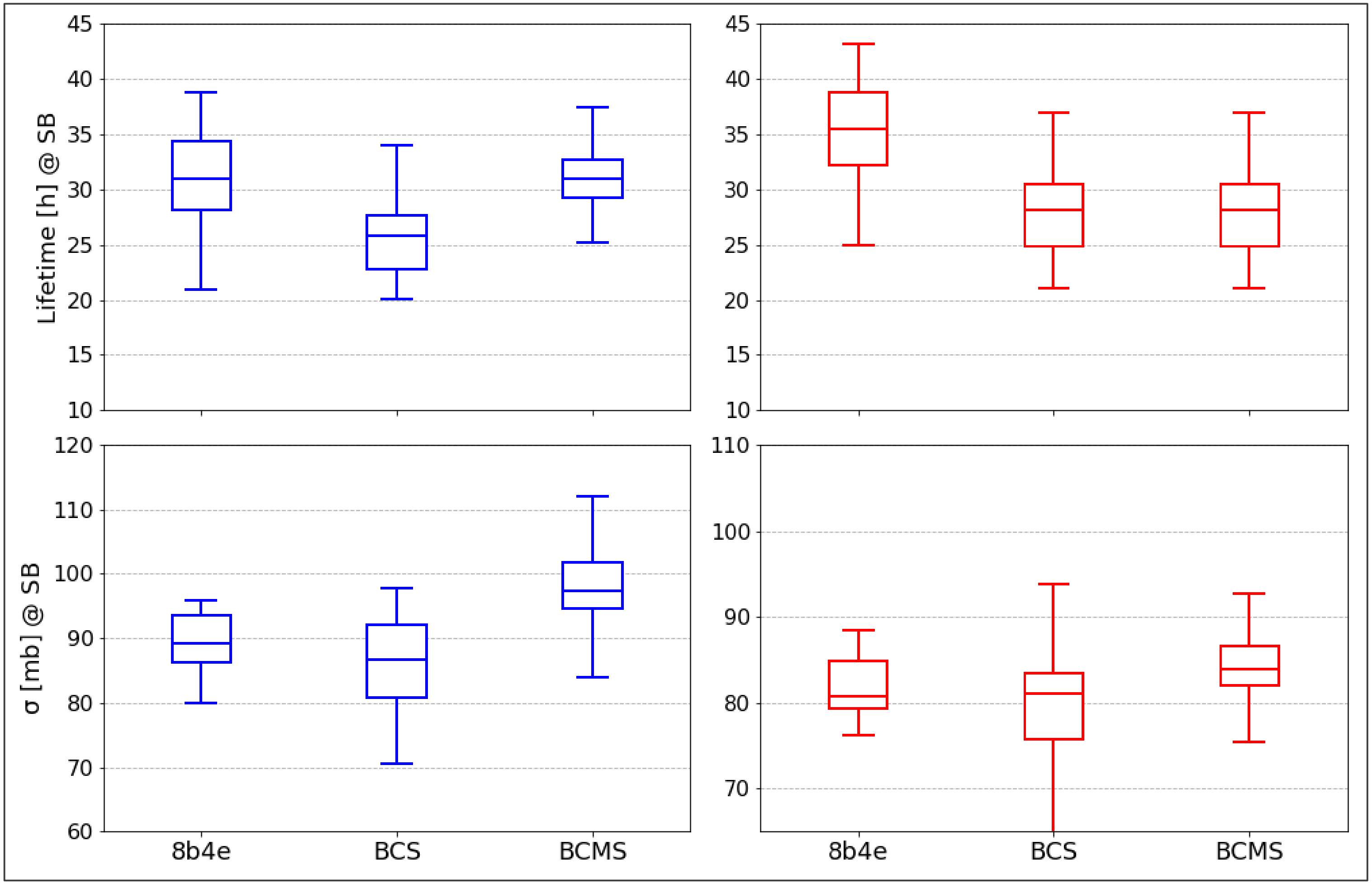
- Development of tools for the analysis of the emittance evolution during **Run I** and then for monitoring the performance in **Run II** (F. Antoniou & G. Iadarola).
- **Automated tool for performance follow-up** since 2017 based on extracted data from the logging system (Timber Timber) and modeling.
  - https://lhc-lumimod.web.cern.ch/lhc-lumimod/summaryPlots.html

See S. Papadopoulou's talk

- Allows for a **bunch-by-bunch and fill-by-fill analysis** of:
  - Emittance, **Lifetime, Luminosity**
  - Comparison with luminosity model (Emittance & Intensity evolution)

- Comparison between different beam and machine configurations during **Run II**:
  - **2015**: β* 80 cm.
  - **2016**: transition to BCMS, β* 40 cm.
  - **2017**: BCMS, 8b4e, BCS, separation leveling & anti-leveling, ATS optics, β* 40/30 cm.
  - **2018:** β* leveling, smoother crossing angle anti-leveling

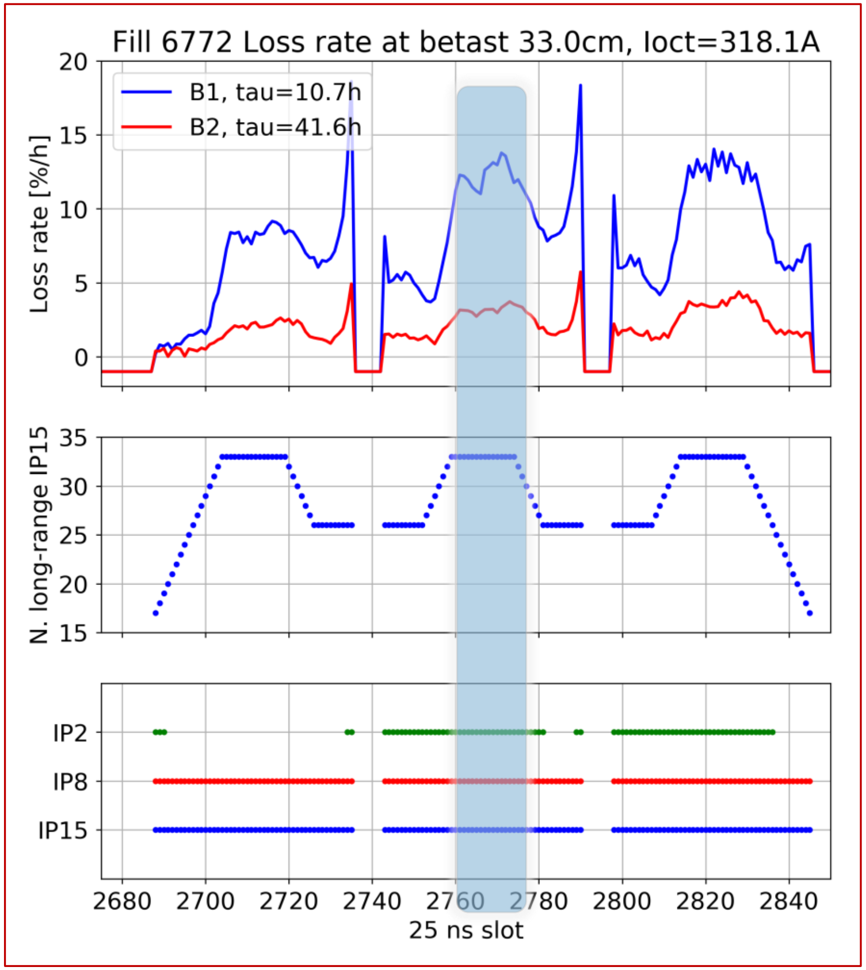
Summary of Lifetime @ SB 2017

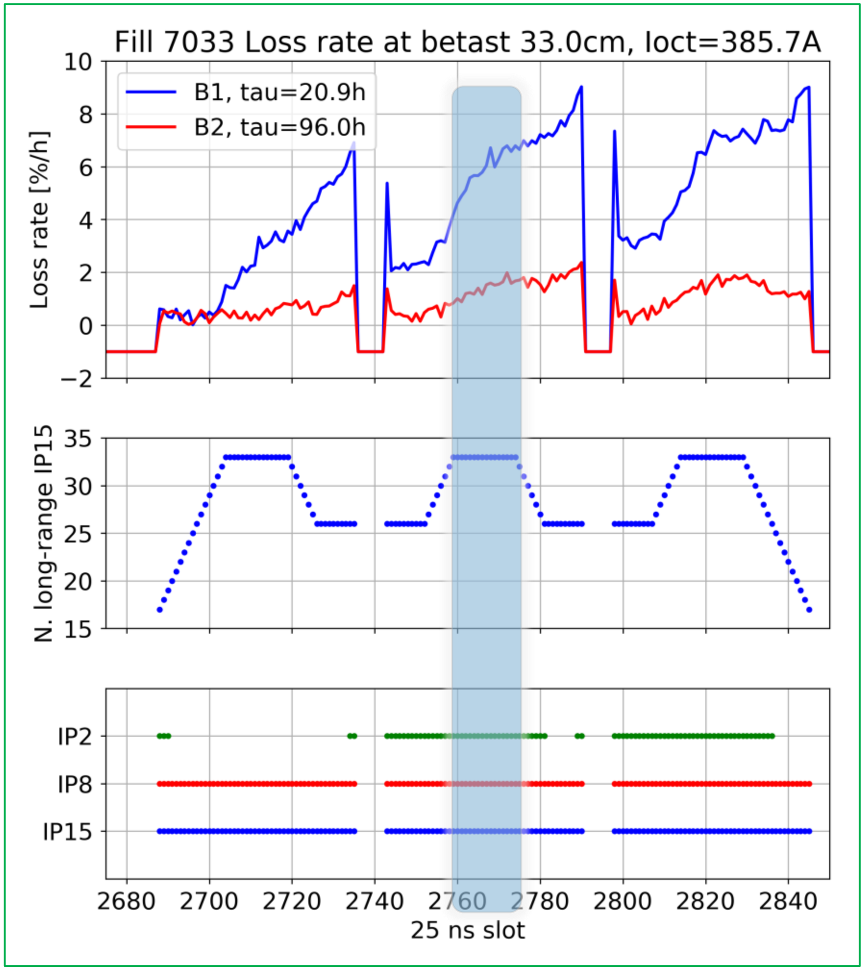


BBLR driven patterns

- Dependence of the loss rate on the **LR encounters in IP1 & IP5**

(Qx, Qy) =(.31,.32) (.305,.315)

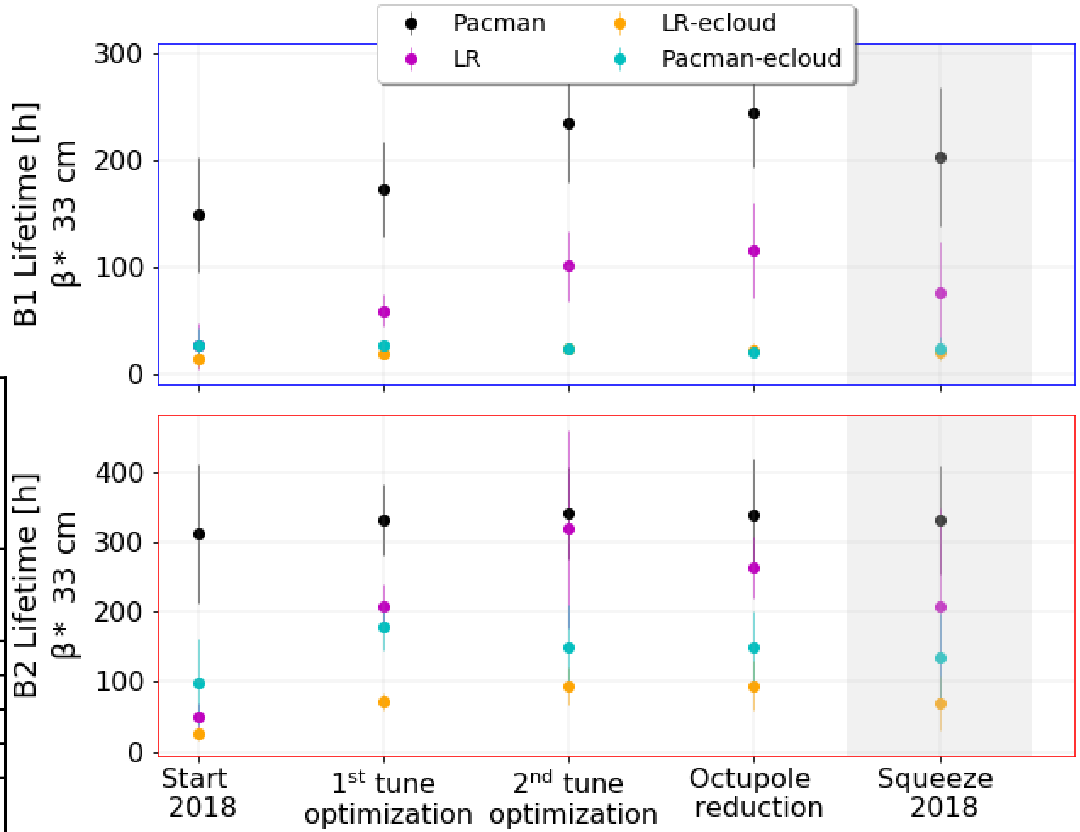




Losses @ telescopic squeeze

- Positive impact of tune optimizations (mainly the 1st one) for all classes, mainly Class **LR** & **LR-ecloud**.
- No significant improvement from the octupole reduction.

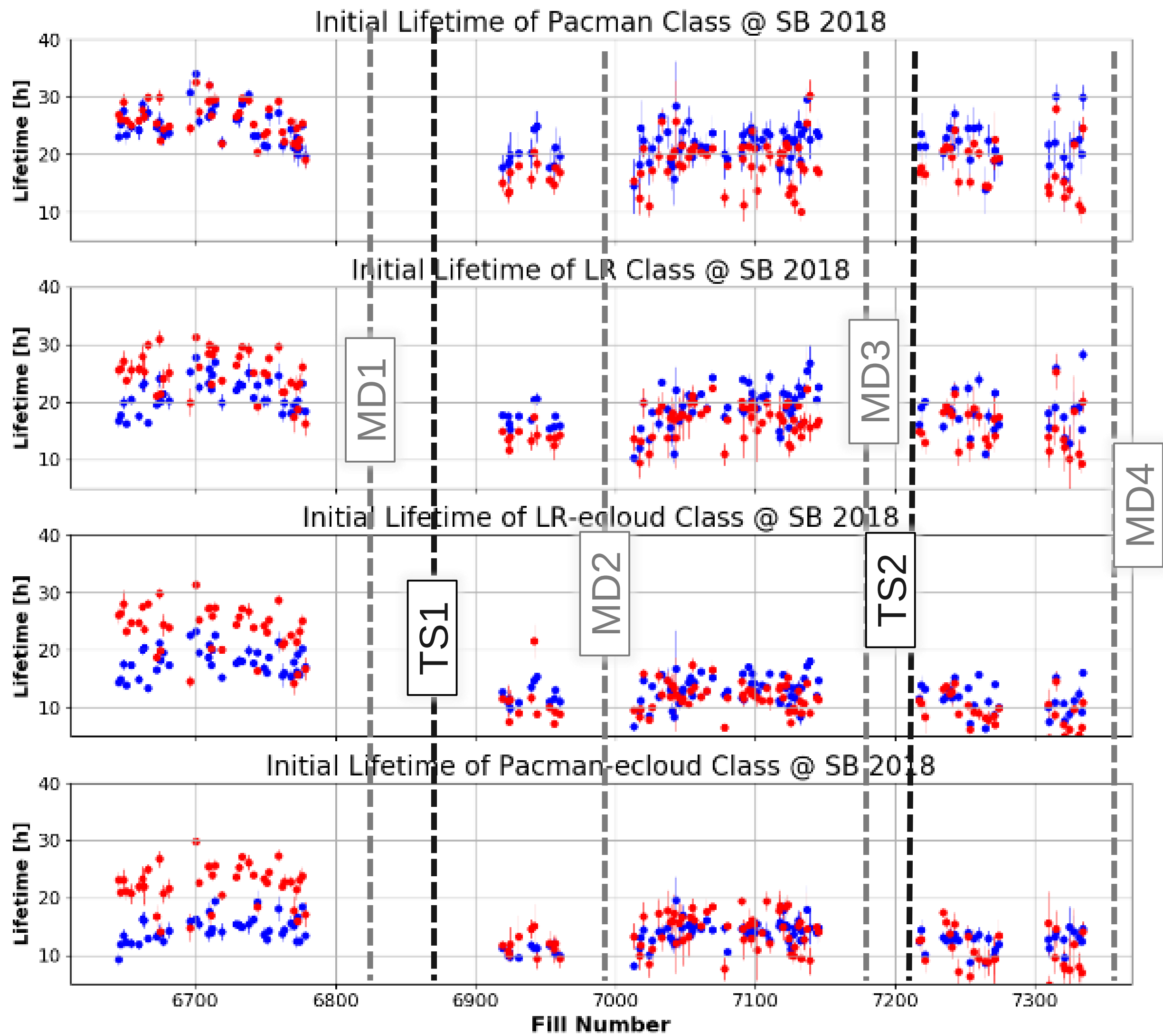
	β* 33 cm	All fills [h]	Lifetime change 1st tune optimization [%]	2nd tune optimization [%]	Octupole reduction [%]
B1	**All bunches**	32.8	**48.8**	**19.3**	-6.2
	Class 1	203	**15.9**	**35.3**	4.3
	Class 2	75.9	**129.1**	**70.2**	14.6
	Class 3	19.5	**40.6**	**25.1**	-5.1
	Class 4	23.9	**3.7**	-11.3	-16.5
B2	**All bunches**	122.5	**188.6**	**16.2**	-2.2
	Class 1	331.8	**6.1**	**3.2**	-0.6
	Class 2	207	**315.4**	**54.1**	-17.1
	Class 3	69.3	**177.7**	**32.3**	-0.003
	Class 4	135.8	**80.8**	-15.9	-0.3



Losses @ Start of SB

- Reduction of initial lifetime of both beams after TS1.

Lifetime [h] @ Start of SB		
	B1	**B2**
Class 1	22.75 ± 3.57	20.60 ± 5.18
Class 2	19.53 ± 3.56	18.94 ± 5.33
Class 3	14.18 ± 3.57	14.91 ± 6.73
Class 4	13.63 ± 2.20	15.88 ± 5.48



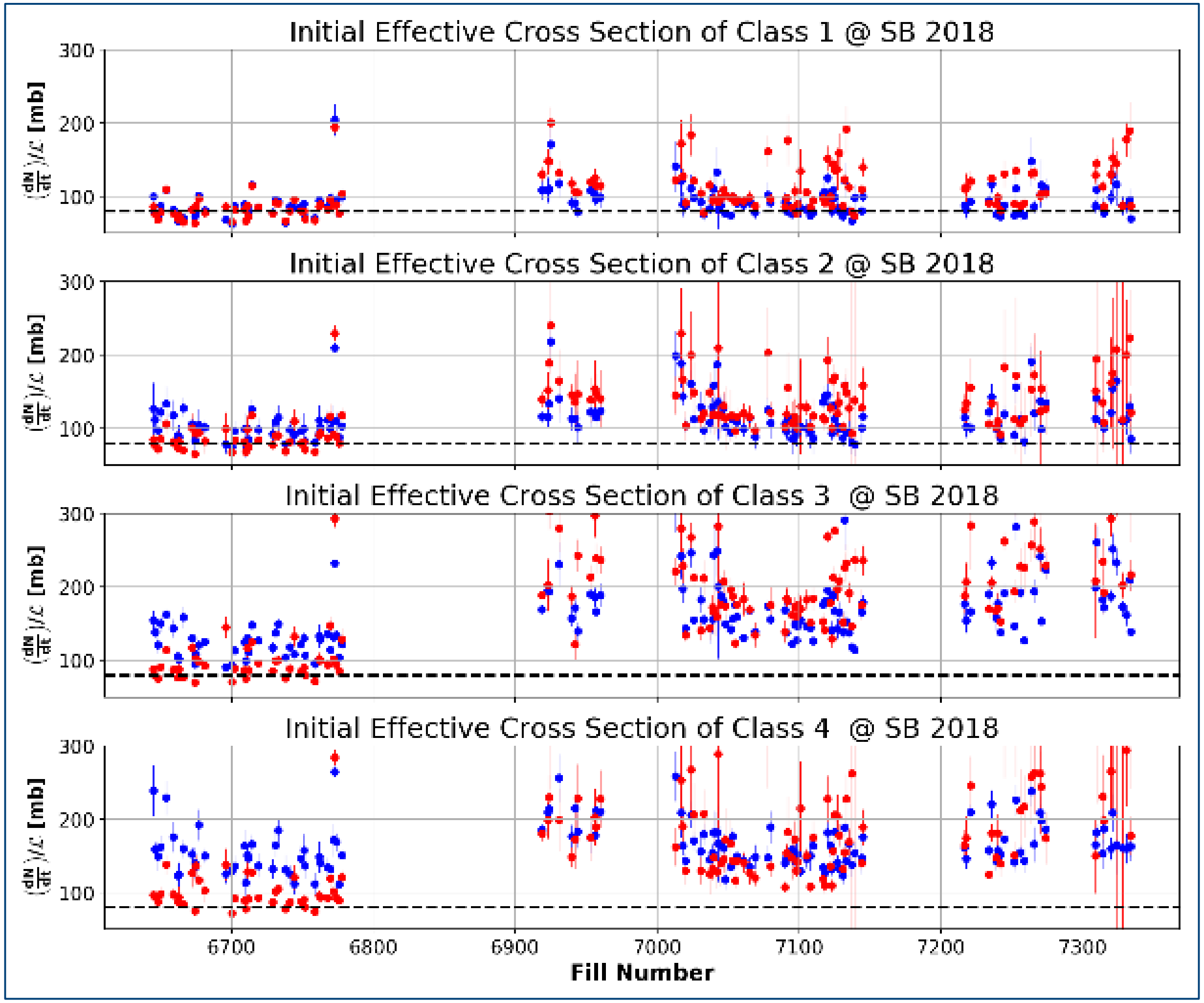
Next steps: Online Luminosity model

The goal of an online luminosity model is:

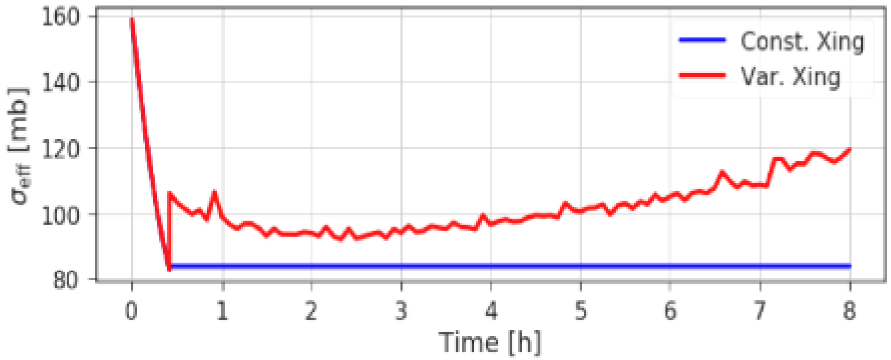
- Promote the maturity and results of the luminosity model
  - Luminosity ⇄ emittance
  - Our best knowledge of the machine including all effects that we could describe : IBS, BB, noise, collisions, e-cloud

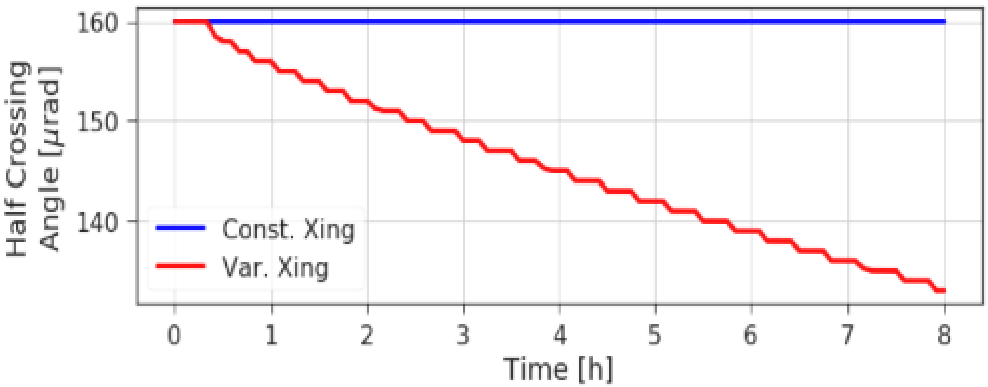
- Provide information/results in two fronts:
  - **Folllow-up**: how different is this fill with respect to previous ones?
    - Follow luminosity/emit between fills (historical data)
  - **Prediction:** what would be the achieved luminosity of a given fill as injected
    - Follow-up if indeed reached the predicted value.

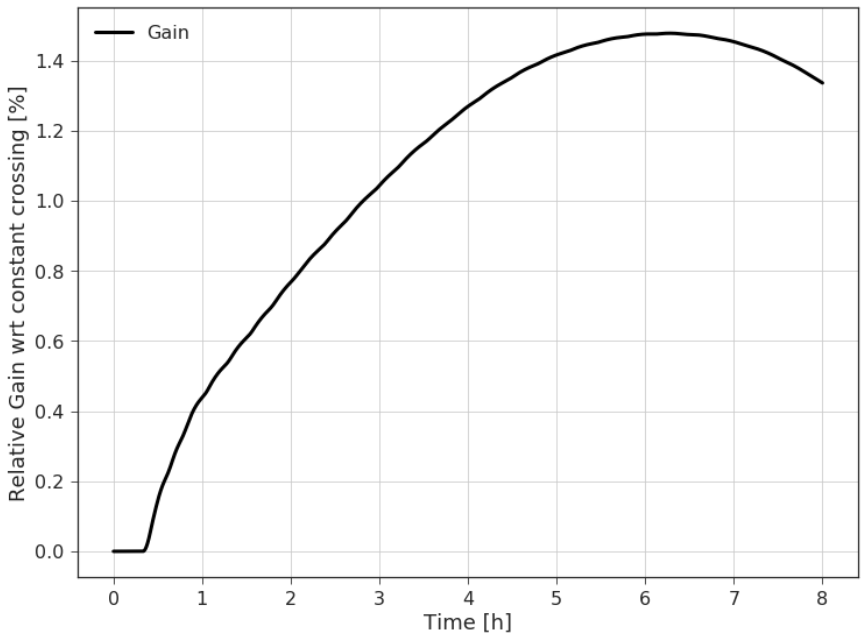
Initial effective cross section @ SB



Luminosity during anti-leveling



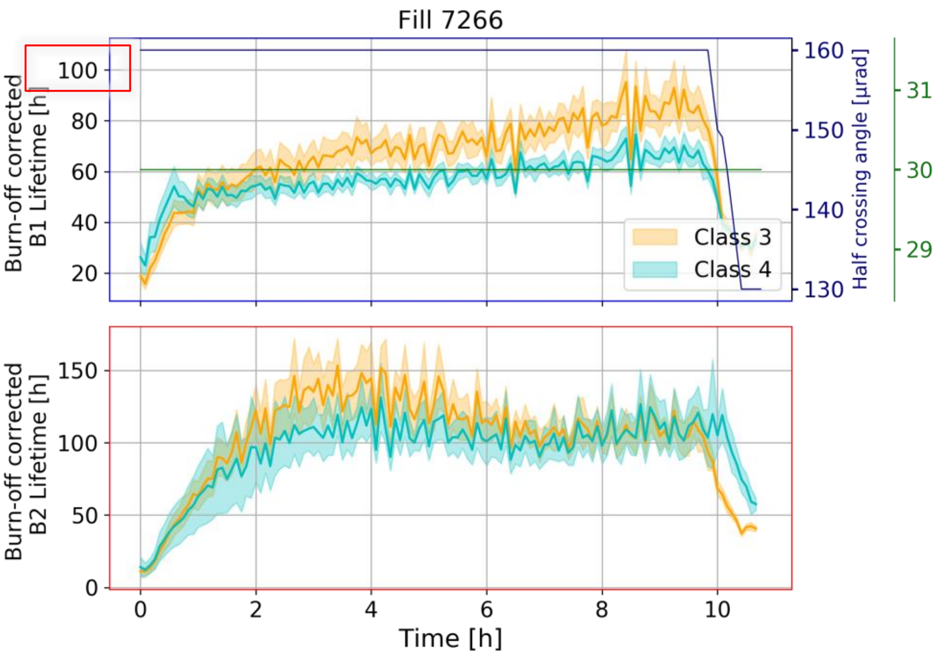




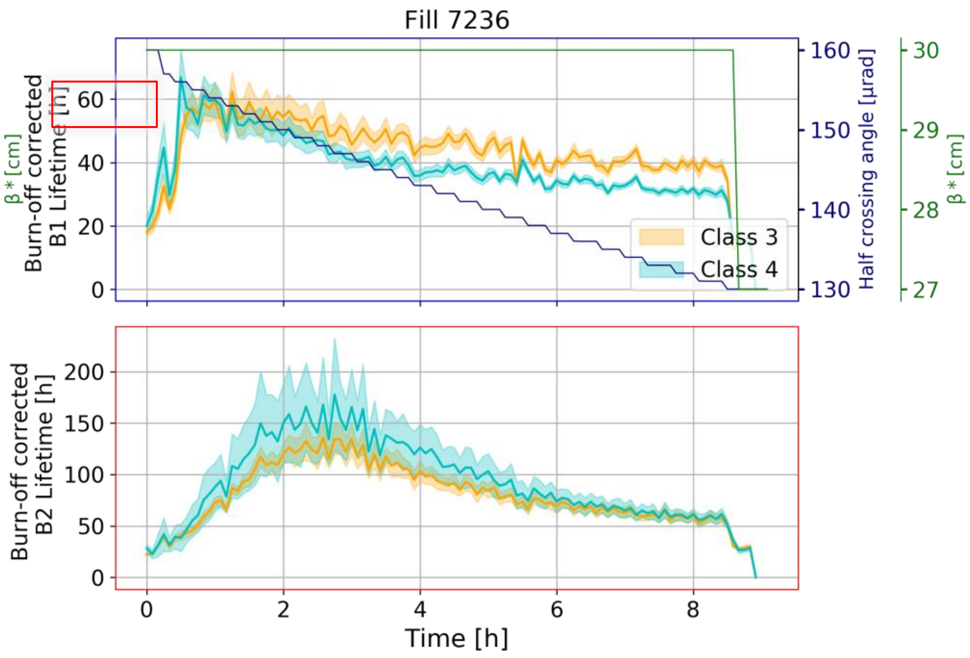
Crossing Angle Anti-Leveling

- Burn-off corrected lifetime as a function of time indicates that there is a reduction of lifetime during crossing angle anti-leveling for B1 Class LR-ecloud & Pacman-ecloud
- Pacman-ecloud is more affected in B1 , which indicates that e-cloud is the dominating effect.

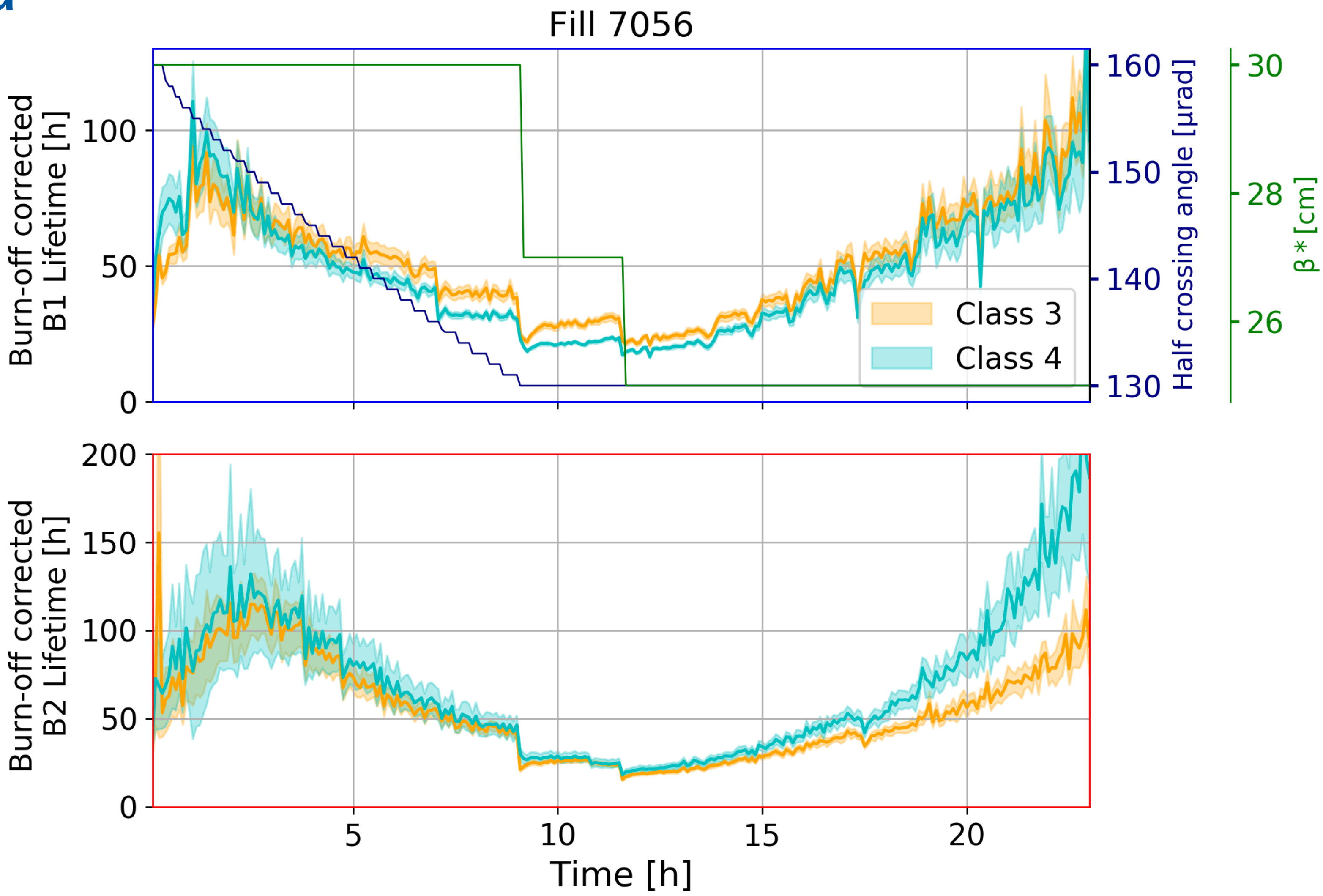
Fill 7266: Constant Crossing angle



Fill 7236: Crossing angle anti-leveling



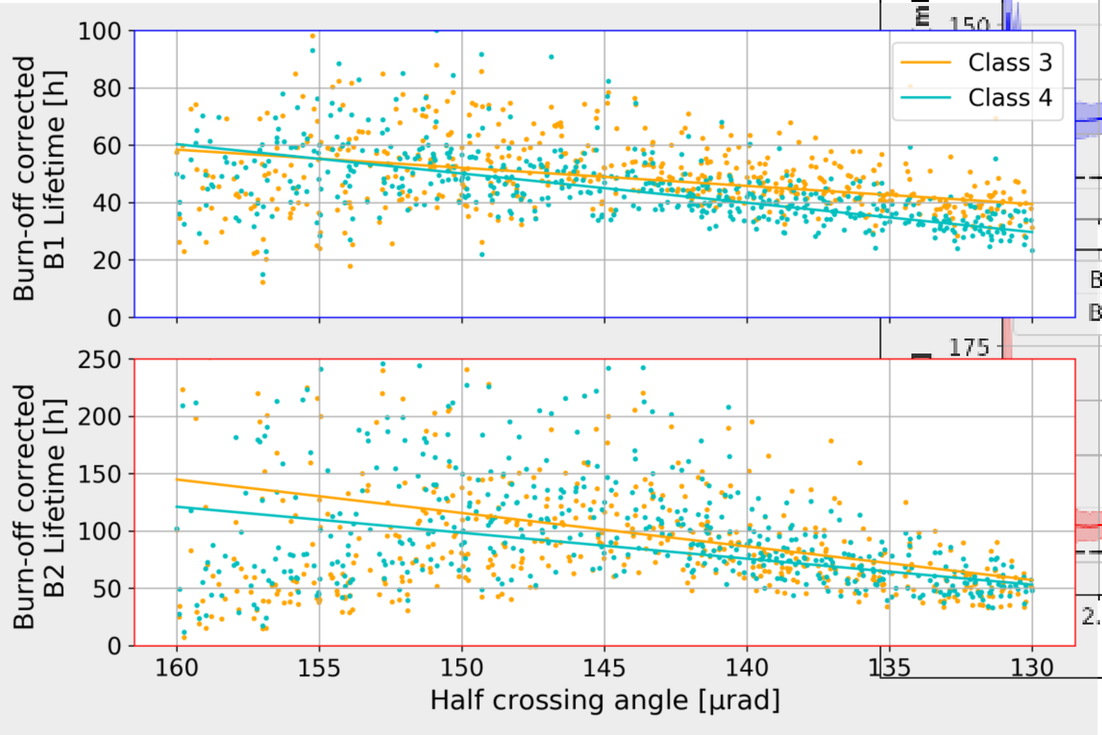
BO corrected lifetime LR-ecloud & Pacman-ecloud

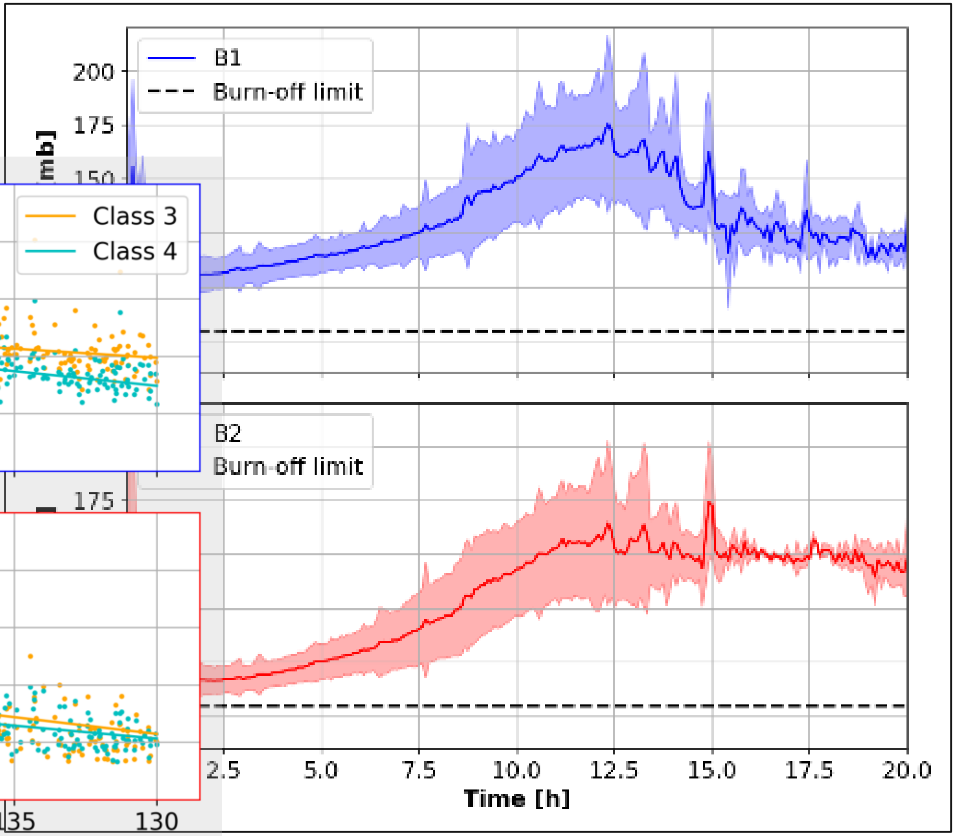


Effective Cross Section

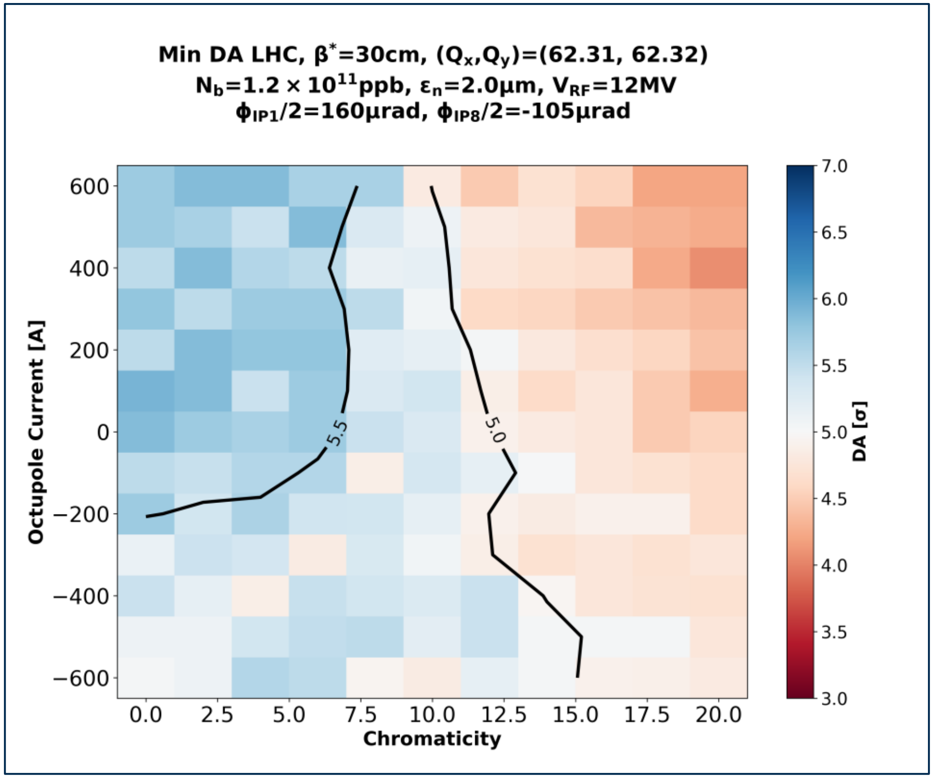
2018

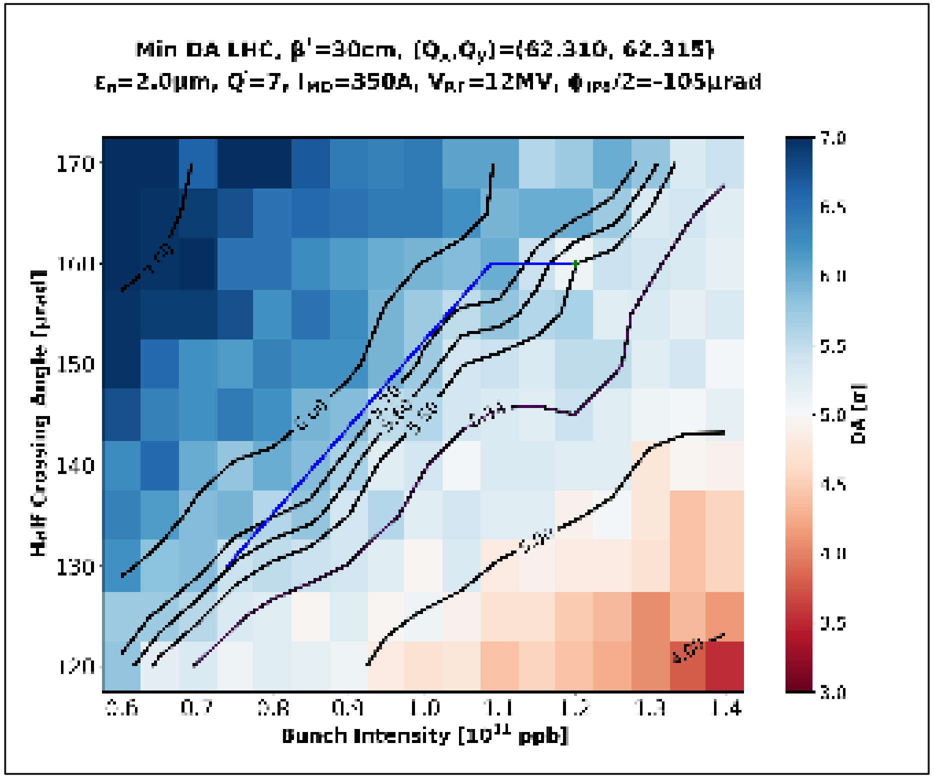
Class LR-ecloud, Pacman-ecloud burn-off corrected lifetime as a function of the crossing angle



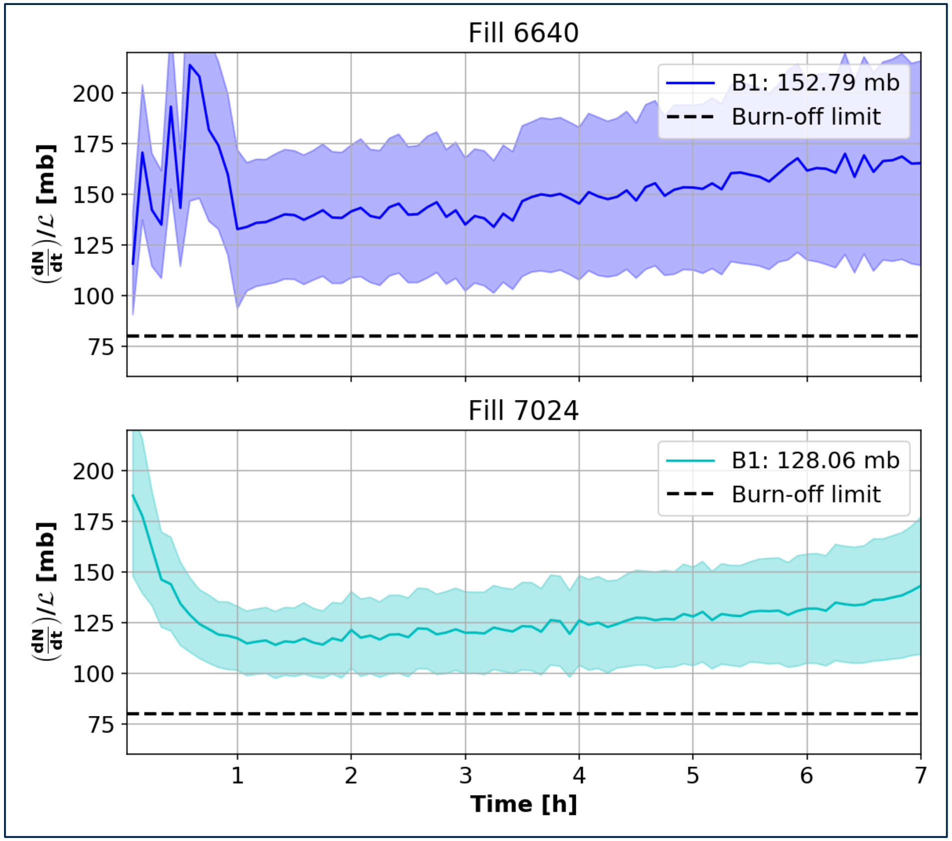


DA optimizations in 2018





DA optimizations in 2018

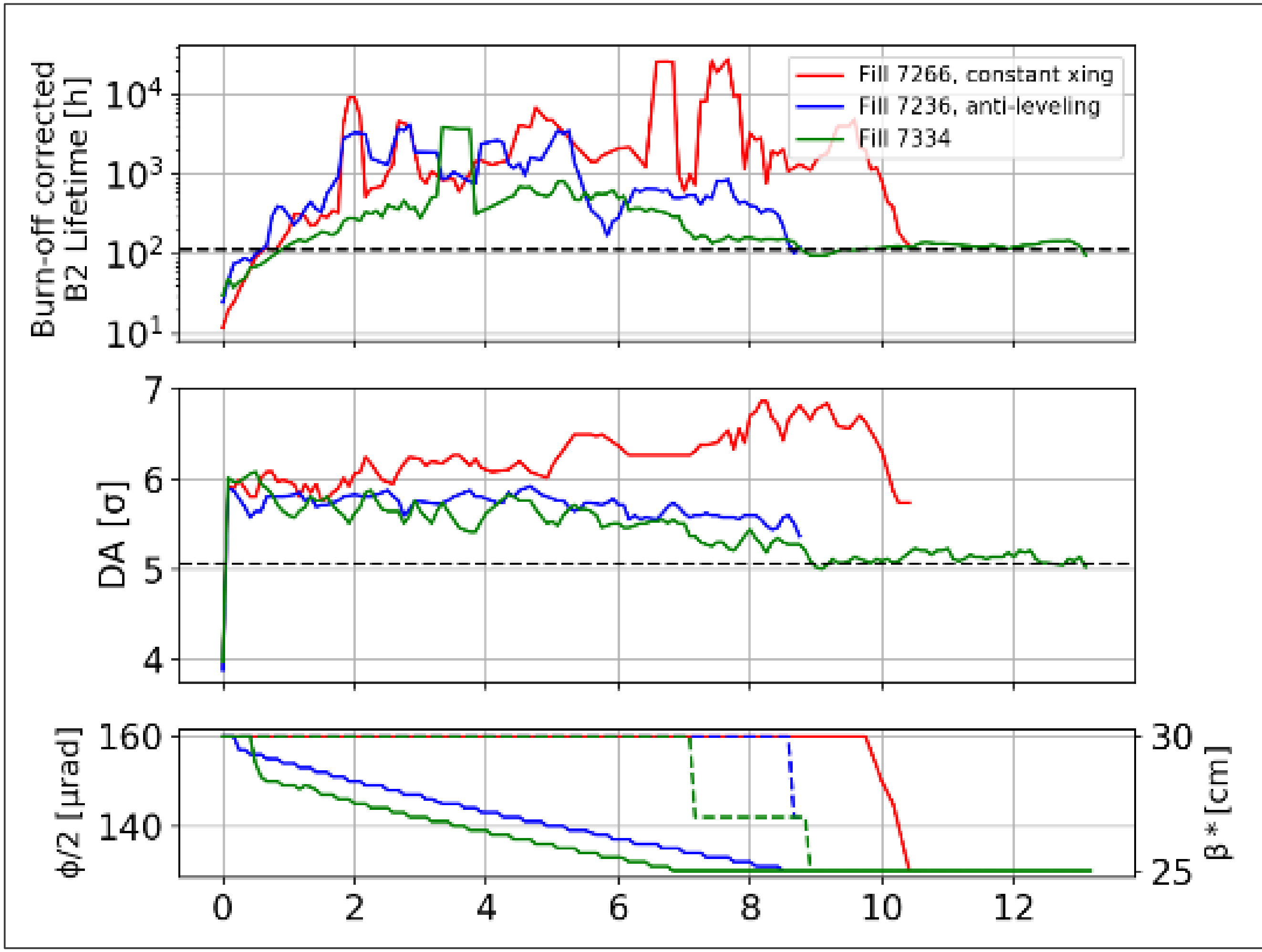


Before DA optimizations (chroma, octupoles, smoother crossing angle anti-leveling)

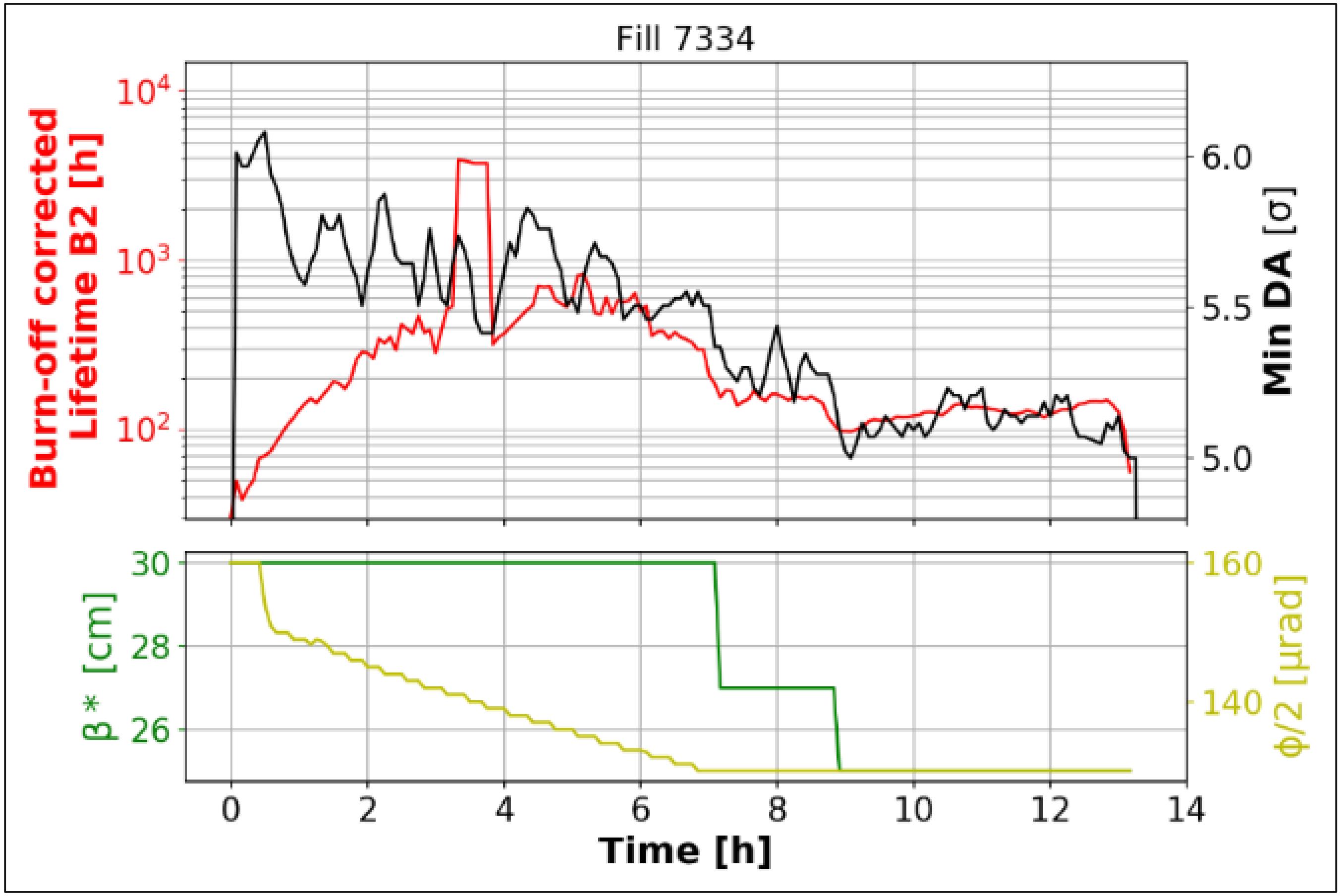
After DA optimizations

Correlation of DA with Lifetime

- 5σ ~ 118 h of lifetime for B2



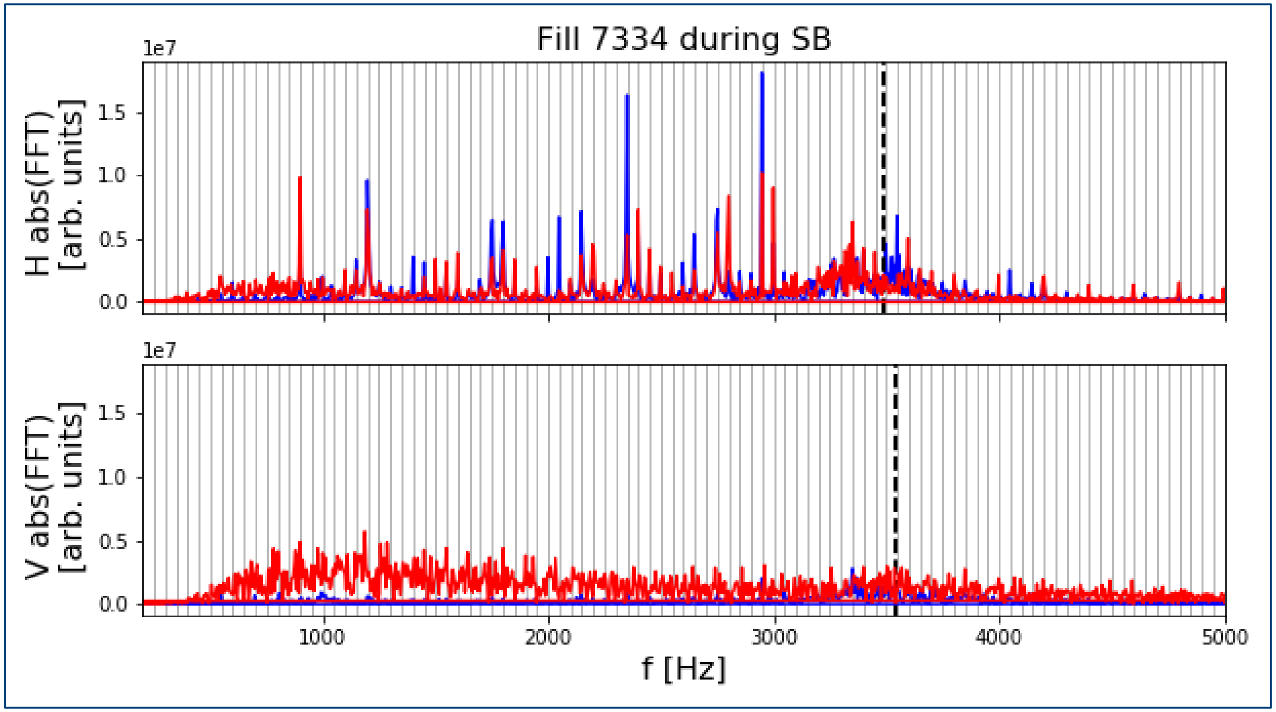
Correlation of DA with Lifetime: Fill 7334



Noise effects

- Noise effects can lead to lifetime degradation by **introducing additional resonances.**

2. **50 Hz harmonics**



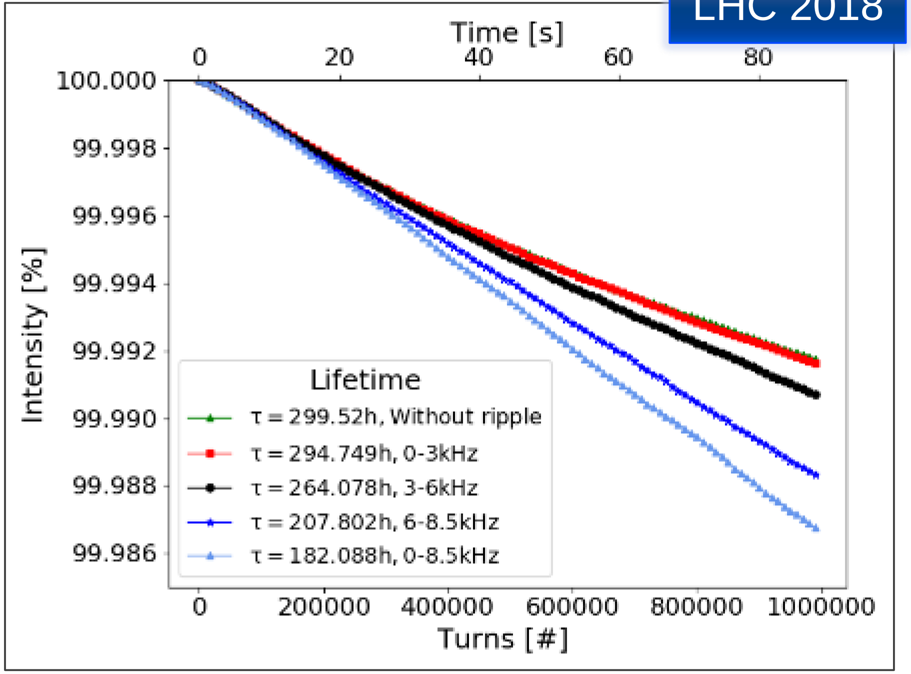
Noise effects

- Noise effects can lead to lifetime degradation by **introducing additional resonances.**

2. **50 Hz harmonics** (Based on a realistic spectrum)

LHC 2018

Burn-off corrected Lifetime [h]	
fr [kHz]	**Lifetime [h]**
Without noise	299.52
0-3	294.749
3-6	264.078
6-8	207.802
0-8.5	182.088

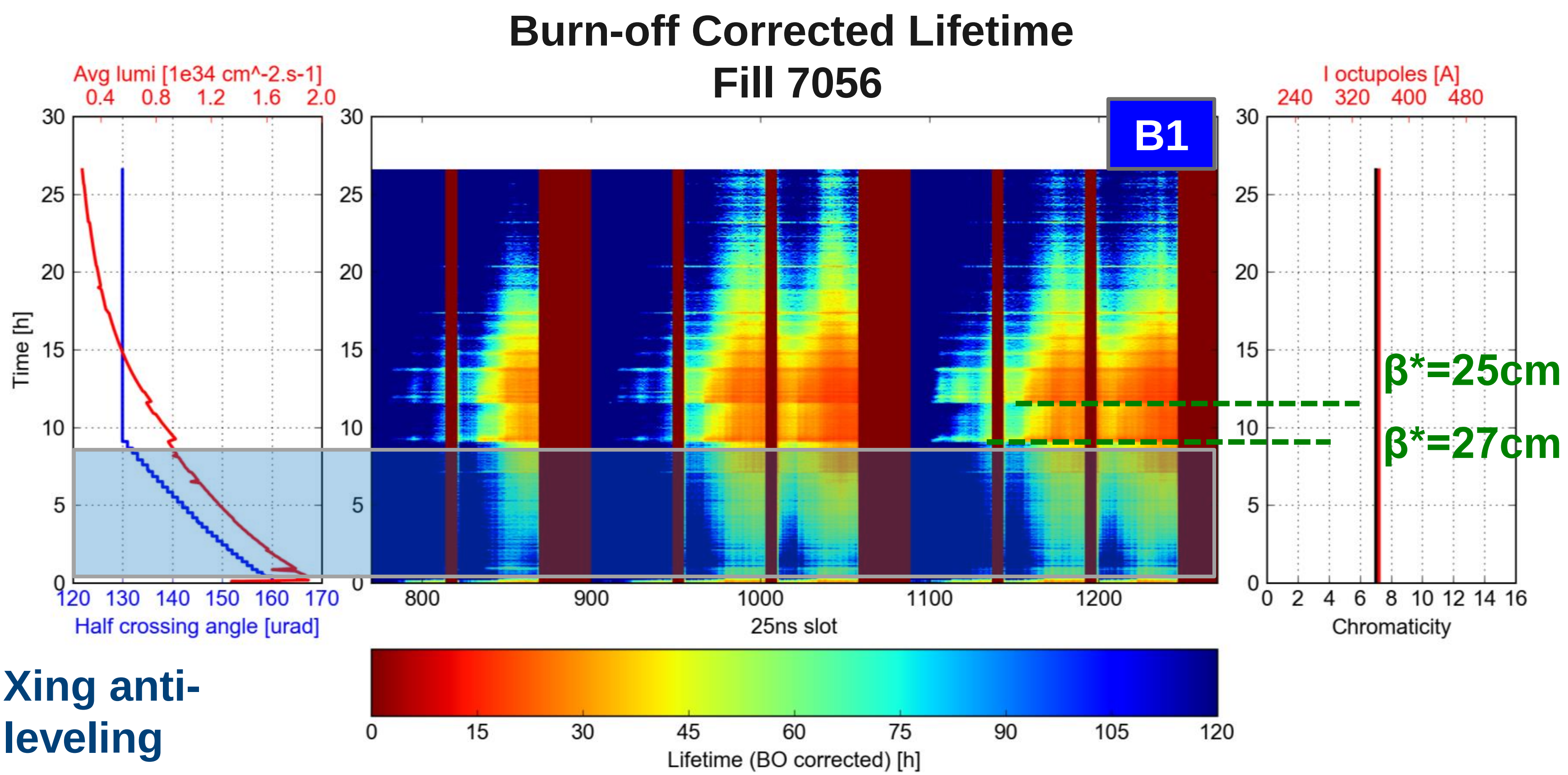


Approximations:

- Transfer function of chain of dipoles **not included**, localized kicks.

Losses @ SB: BBB patterns

- Increase of losses in the bunches mostly effected by e-cloud during **crossing angle anti-leveling.**
- Mainly affecting Classes LR-ecloud & Pacman-ecloud (for B1 Pacman-ecloud is worse)*
- Spikes in losses during the transition from **β* 30 cm to β* 25 cm.**

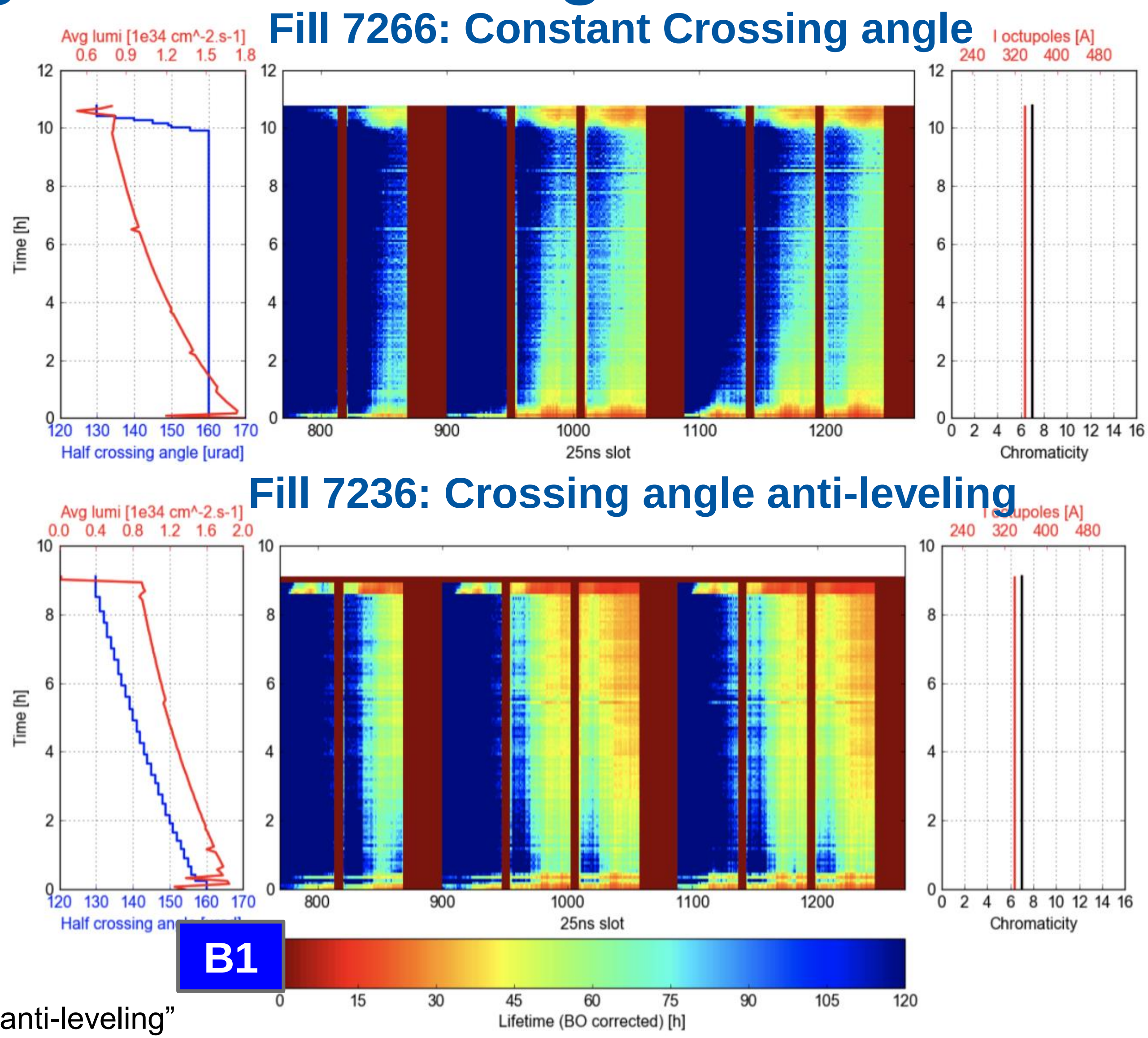


* See appendix "Crossing angle anti-leveling"

Crossing Angle Anti-Leveling

- **Increased losses** due to e-cloud are observed **during the crossing angle anti-levelling**. Not observed with constant crossing angle.

- However, **adapting the crossing angle leads up to ~1.4% more integrated luminosity*.**

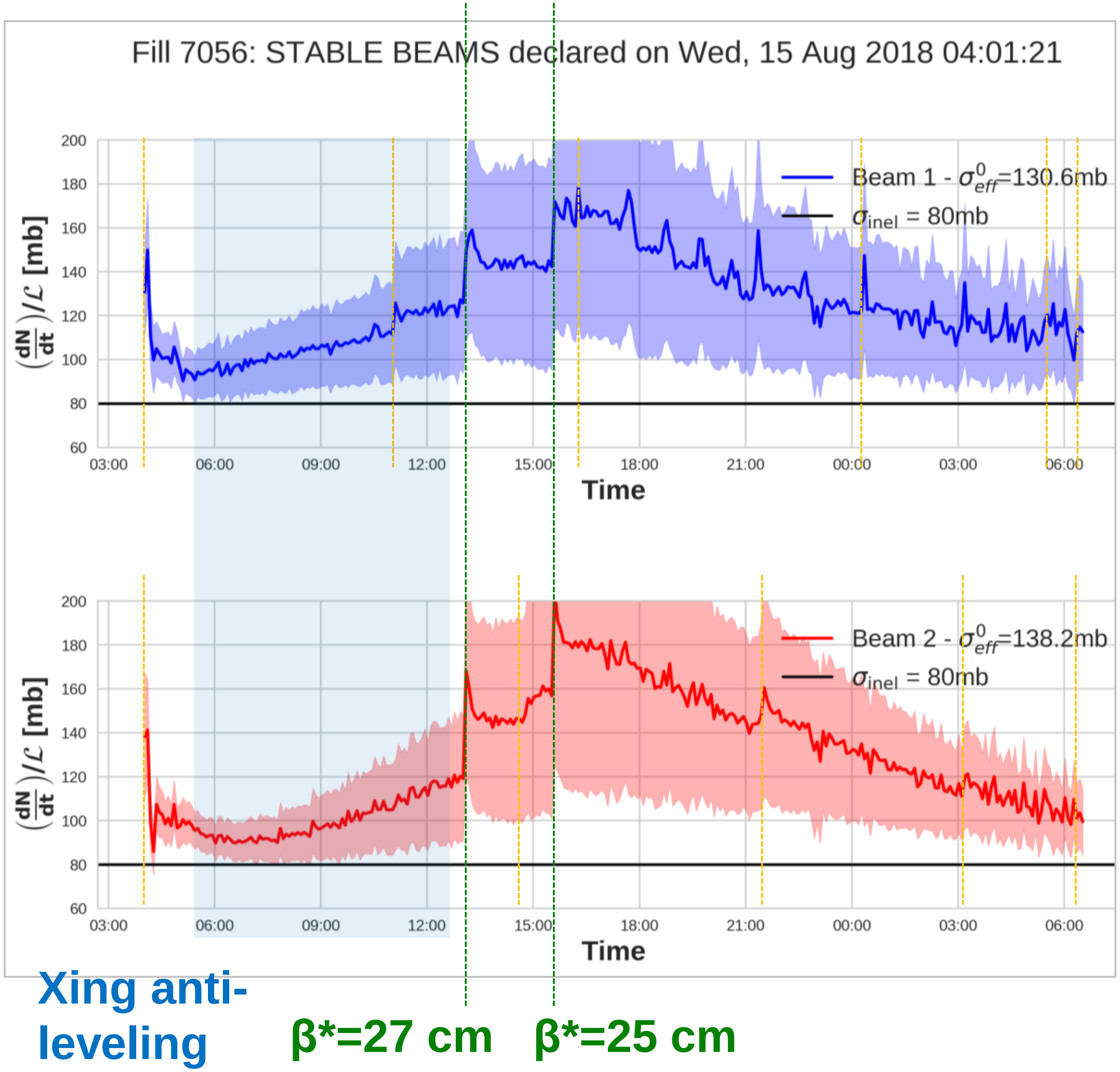


* See appendix “Luminosity during anti-leveling”

Effective Cross Section

From the effective cross section as a function of time:

- Extra losses in the few first hours
- Increase of losses during **crossing angle anti-levelling***
- Increased losses during **β* steps**
- **Longitudinal blow-up** induces small spikes in the evolution



* See appendix "Effective cross section"