Evolution of beam quality from the injectors to the LHC

S. Kostoglou, H. Bartosik, I. Efthymiopoulos, Y. Papaphilippou, G. Sterbini on behalf of BE-ABP

With invaluable contributions from:
F. Asvesta, M. Bozatzis, X. Buffat, D. Butti, R. Bruce, A. Calia, R. De Maria, Y. Dutheil, B. Emil Karlsen-Baeck, S. Fartoukh, J. Flowerdew, P. Hermes, M. Hostettler, G. Iadarola, E. Lamb, T. Lefevre, G. Marek, F. Maria Velotti, I. Mases Sole, L. Mether, D. Mirarchi, C.E. Montanari, S. Morales Vigo, T. Persson, S. Redaelli, M. Rakic, B. Salvachua, M. Solfaroli Camillocci, F. Soubelet, A. Lasheen, T. Levens, H. Timko, R. Tomas Garcia, G. Trad, J. Uythoven, A. Valeri Radoslavova, J. Wenninger

Joint Accelerator Performance Workshop 2024

Motivation

- Main indicators of beam quality:
  - ➢ Emittance: avoiding emittance growth
  - ➢ Intensity: minimizing losses & preventing beam dumps
  - ➢ Tail population: preserving tails & avoiding tail increase

  from the injectors to the LHC.
- Degradation starts already in the injectors and continues throughout the LHC.
- Goal is to:
  - **Identify** where the degradation occurs.
  - **Understand** the cause.
  - **Evaluate the impact** on LHC performance & define priorities.
  - Provide **recommendations** to optimize performance for next year & next runs.

Overview

I. Beam quality in the injectors:

1. Emittance growth PSB→ PS → SPS, **standard vs BCMS** beams.
2. Tail population from PSB→ PS → SPS & **"low-tail" BCMS**.
3. Losses from PS → SPS.

II. Beam quality in the LHC:

Injection
1. Tail population SPS→ LHC & transfer line mismatch.
2. Injection losses: 2024 vs 2023.
3. Emittance with **standard & BCMS** beams.
4. Emittance growth at injection beyond IBS & tail evolution.

Ramp
5. Debunched beam at injection & losses at the start of ramp.
6. Power supply ripple at the end of ramp.

Collisions
7. Losses at the end of adjust & correlation with tails.
8. Losses during leveling & DA.
9. ~~Losses beyond burn-off due to collisions in IP8~~
10. Emittance growth during collisions.

III. Impact on integrated luminosity:

- **BCMS vs standard**: model vs measurements
- Reduction of **losses** with **"low-tail" BCMS**.
- Impact of **emittance growth** beyond IBS.

IV. Lessons learned from 2024.

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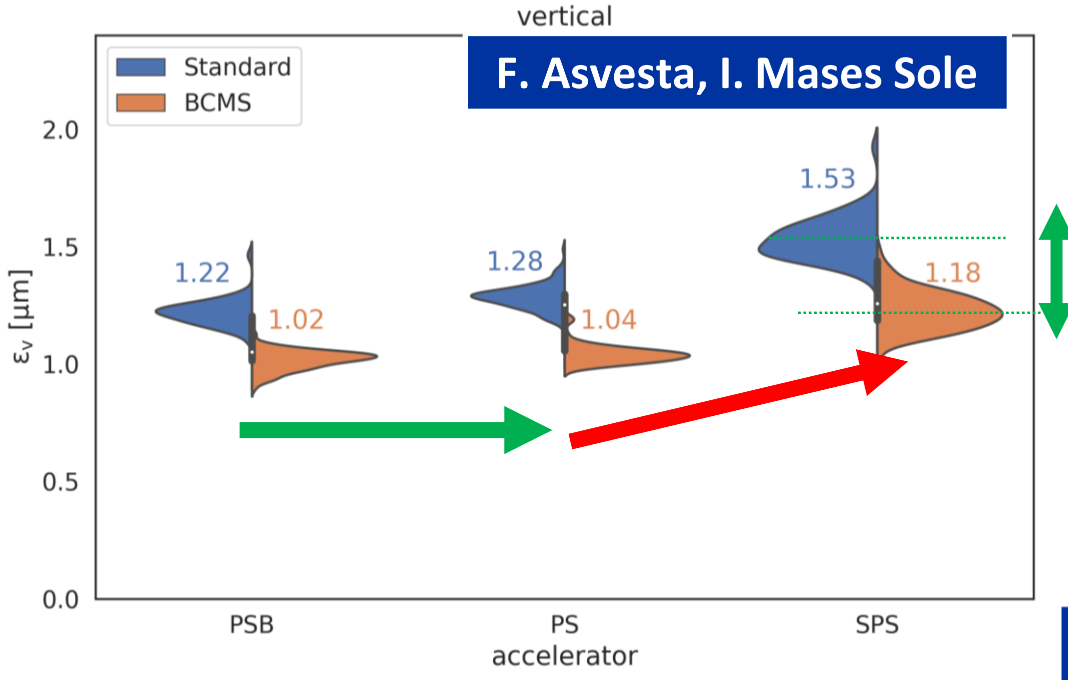
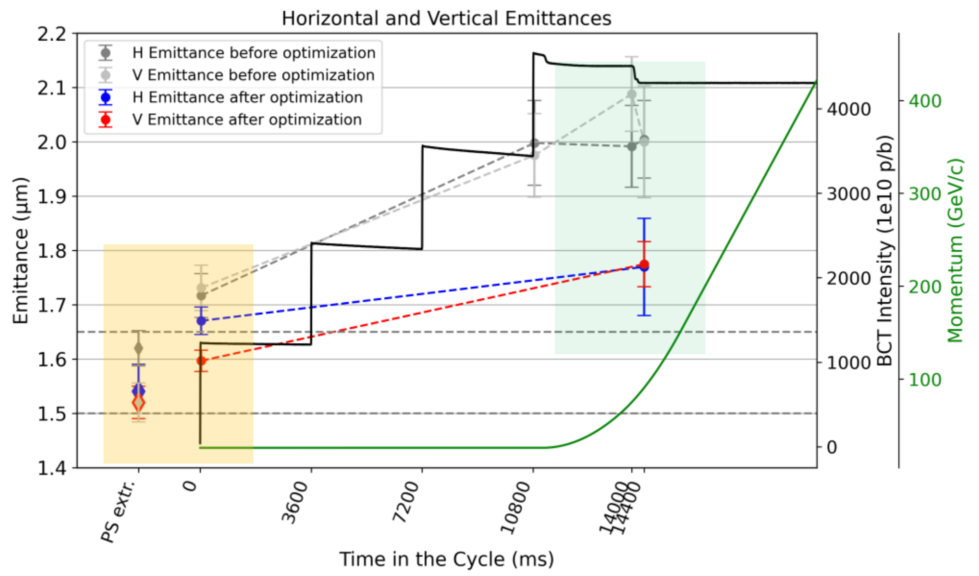
Emittance evolution in the injectors

- Emittance measurements at PSB→ PS → SPS:
  - **Emittance blowup** along the chain:
    - **~5%** PSB extraction→ PS extraction
    - **~15-20%** PS extraction → SPS after scraping:
      - I. PS extraction → SPS injection: emittance growth & tail population, trends similar to observation from SPS → LHC transfer line mismatch, under investigation.
      - II. SPS flat bottom: improved with **tune optimizations** **IPP I. Mases Sole**.
  - **Standard vs BCMS**: **~25%** reduction in emittance with BCMS at SPS after scraping.





Tail evolution & losses in the injectors

- **Systematic q-factor increase (~5-15%)** PS extraction → SPS after scraping.
- **Significant improvements in tail population** during 2024:

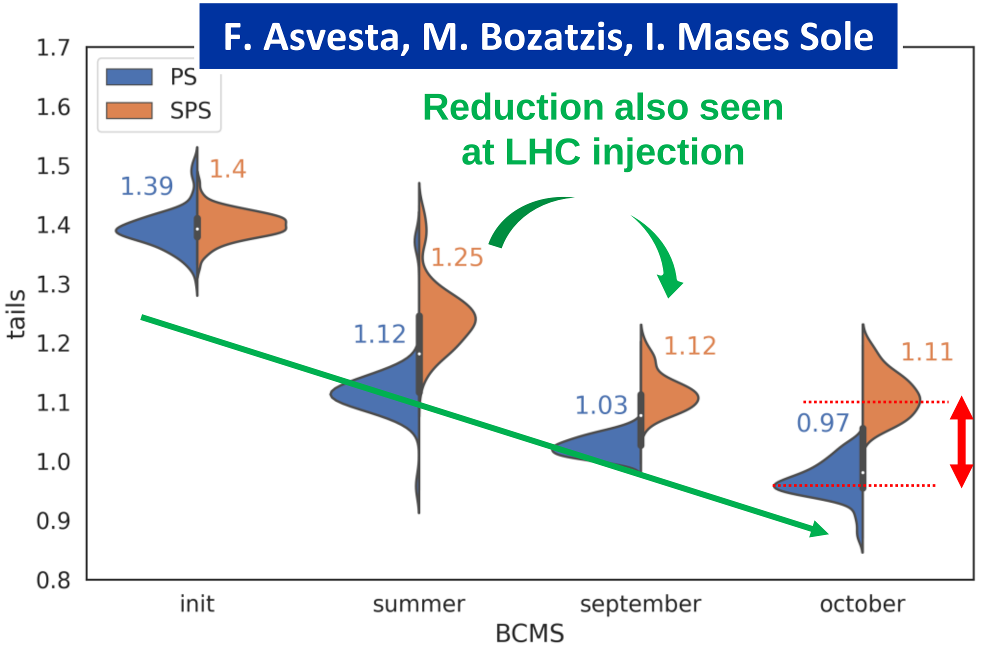
1st "low-tail" BCMS variant:

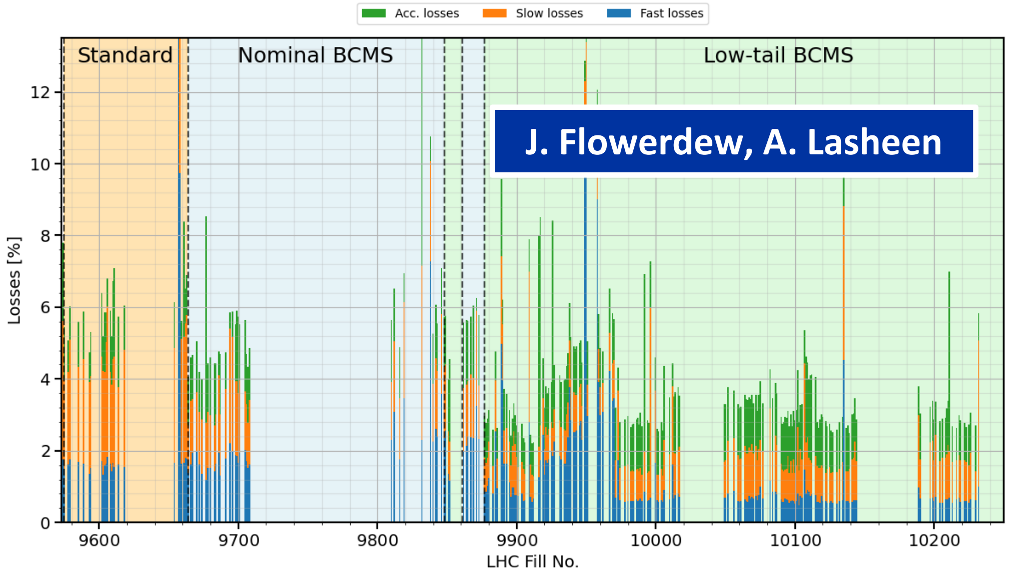
  - Introduction of **PSB scraping,** achieving q=1 at extraction.
  - Significant tail increase during **PS γ_{trans} transition crossing** related to space charge: improved with **PS tune optimizations IPP M. Bozatzis**.
  - **No clear tail improvement at LHC injection.**

2nd "low-tail" BCMS variant:

  - Source of improvement **not fully understood,** traced back to PS.
  - **Clear tail reduction at LHC injection.**

- ~5% losses in SPS before scraping:
  - Injection losses, slow losses, losses during ramp.
  - Improvement with "low-tail" BCMS.





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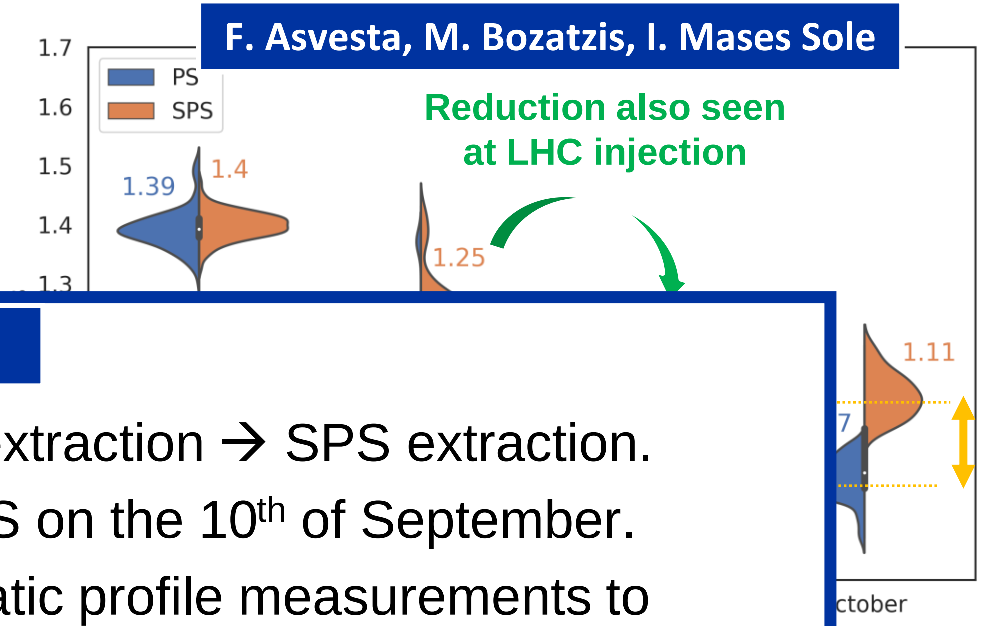
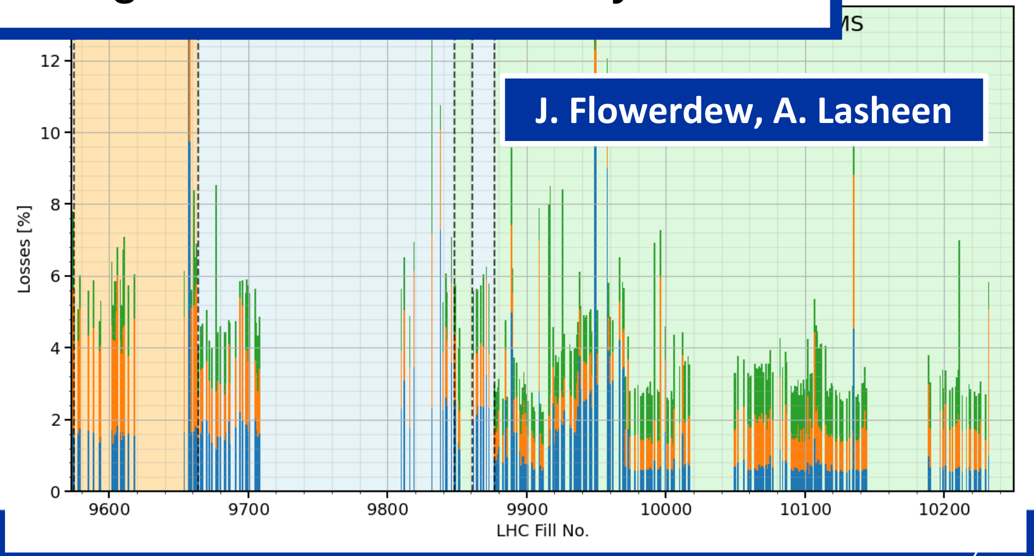


Follow-up

- Further tail & emittance improvements from PS extraction → SPS extraction.
- Try to understand origin of tail reduction in the PS on the 10th of September.
- ➢ Need for online analysis of SPS losses & automatic profile measurements to monitor quality of injected LHC profiles & detect changes fast and efficiently.



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SPS extraction to LHC injection

- Systematically observed **tail population increase** in **B1H** pointing to transfer line mismatch.

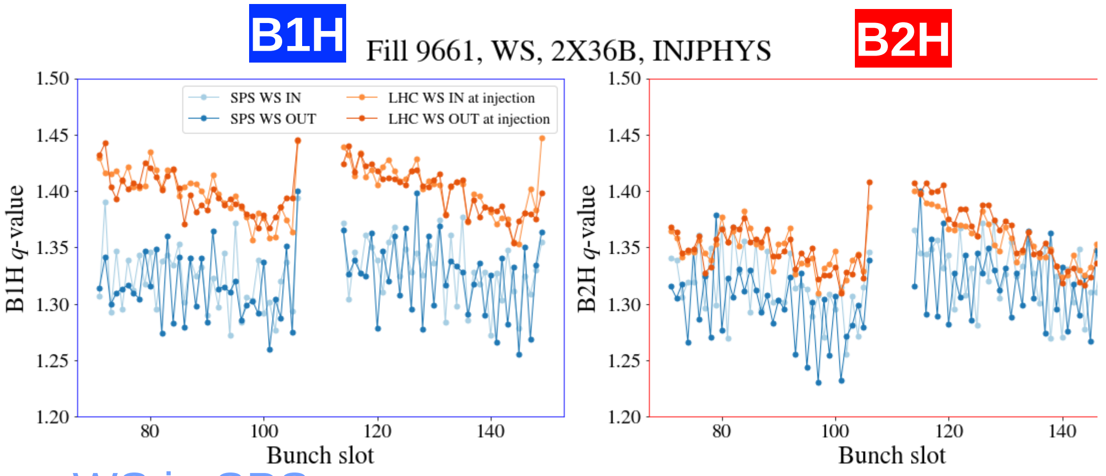
- Tested **new QTL transfer function** prepared by ABT:

  - MD with INDIVs **q=1 at SPS extraction**, achieved with ~18% scraping.

  - **q=1** maintained for **B1V and B2H & V** at LHC injection, while **q=1.2** for **B1H**.

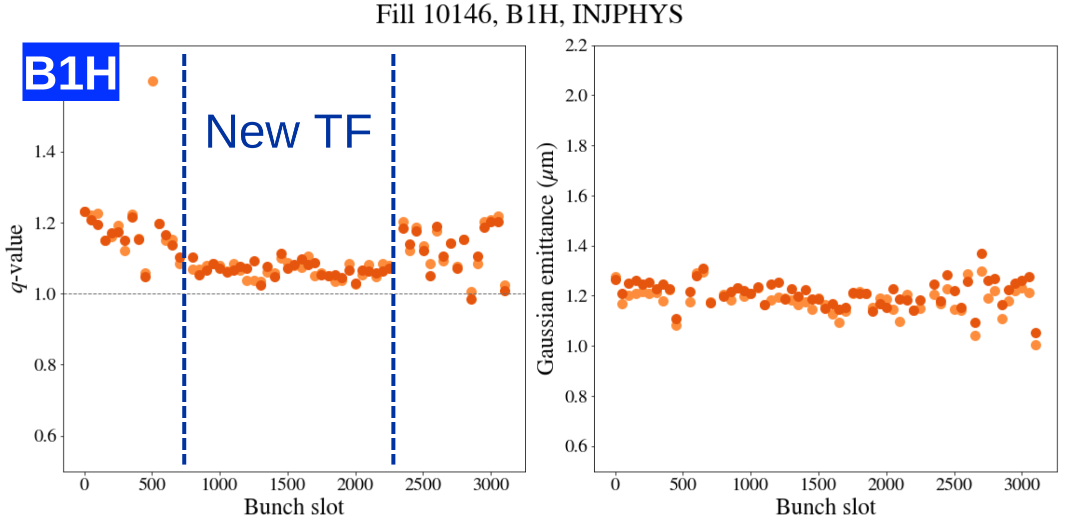
  - Tail comparison at LHC injection with nominal and **new QTL transfer functions clearly shows mismatch improvement**.

- Optimizations to be deployed in 2025.



WS in SPS
WS in LHC

F. Velotti, Y. Dutheil, C. Bracco, M. Hostettler



Injection losses

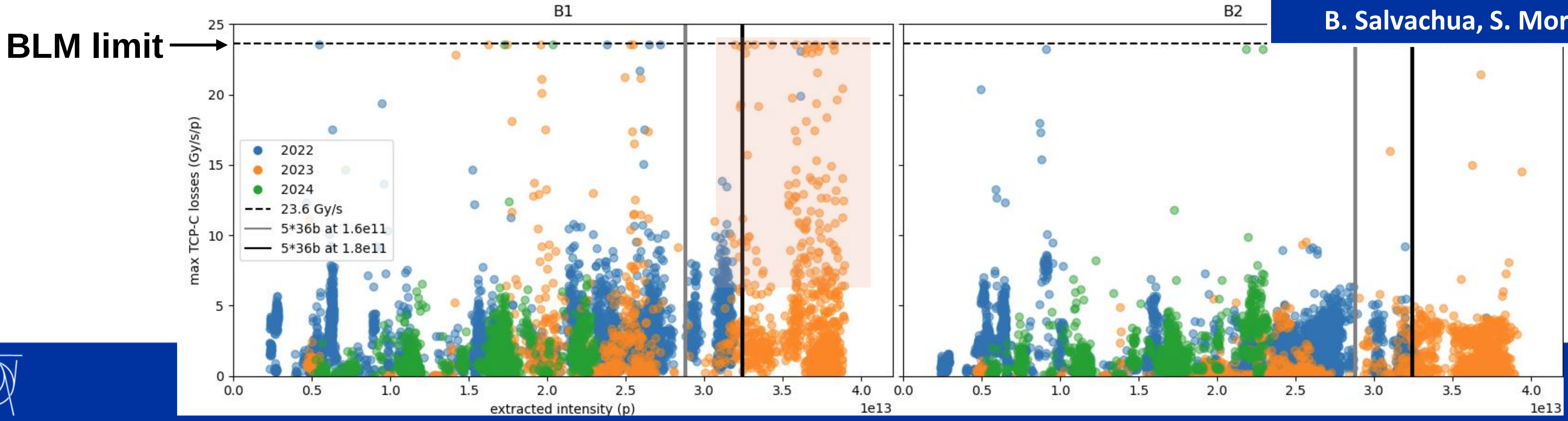
In 2023:

- **High and fast losses** during **B1** injection: BLM saturation limits in TCP-C/B (horizontal & skew) in IR7 for RS01.
- Losses correspond to < 10^9 protons **(less than 1 pilot per injection)**.
- Correlated with losses in TL & steering. Mitigated with **aggressive SPS scraping (~10% → ~20 nominal bunches per injection).**

In 2024:

- **Significant improvement** while SPS scraping at ~4% (BLM talk by S. Morales Virgo & LBOC Y. Dutheil).
- Interlock moved to new BLMs on the WALL increasing margin by factor of ~2 (HL S. Morales Virgo).
- Exact origin of losses remains **unclear**:
  - 2024 vs 2023: shorter trains per LHC injection (i.e. lower intensity per injection).
  - Small improvement with “low-tail” BCMS.

Y. Dutheil, F. Velotti, C. Bracco, B. Salvachua, S. Morales



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In 2024:

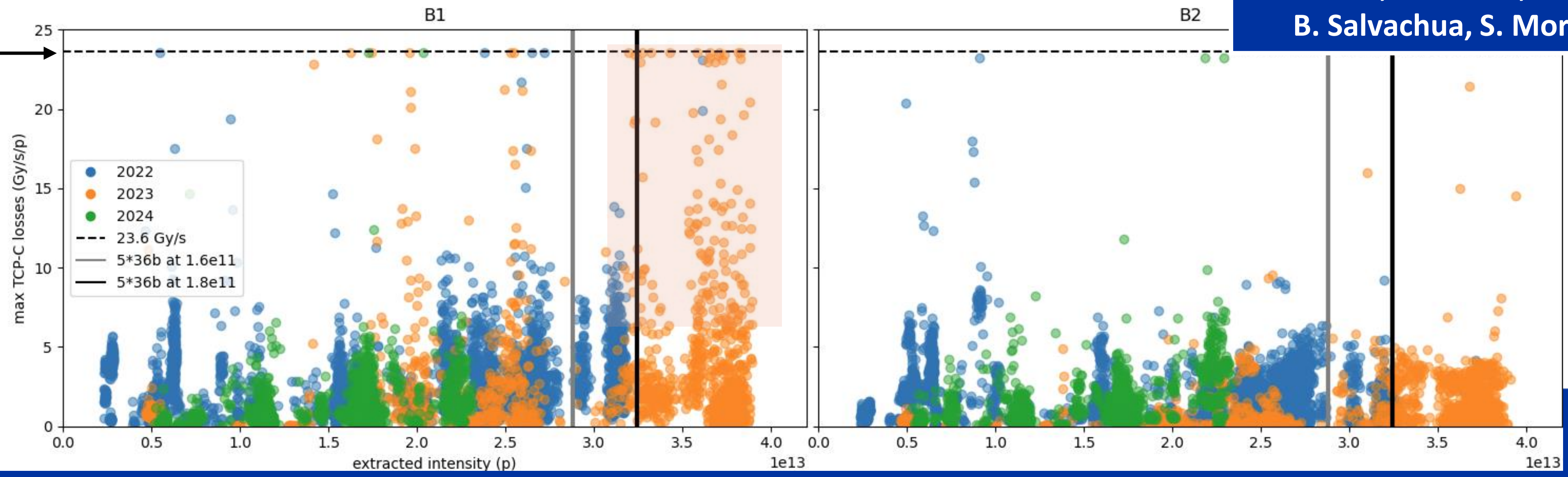
- **Signif**
- Interlo
- Exact
  - 20
  - Sm

Follow-up

- New QTL transfer function for B1 → expect to reduce B1H tails.
- Improved margin with new B1 BLMs on the WALL by a factor of 2 & improved injection losses could allow for longer trains next year.
- ➢ As soon as possible, prepare BLM system for higher acceptable injection losses.

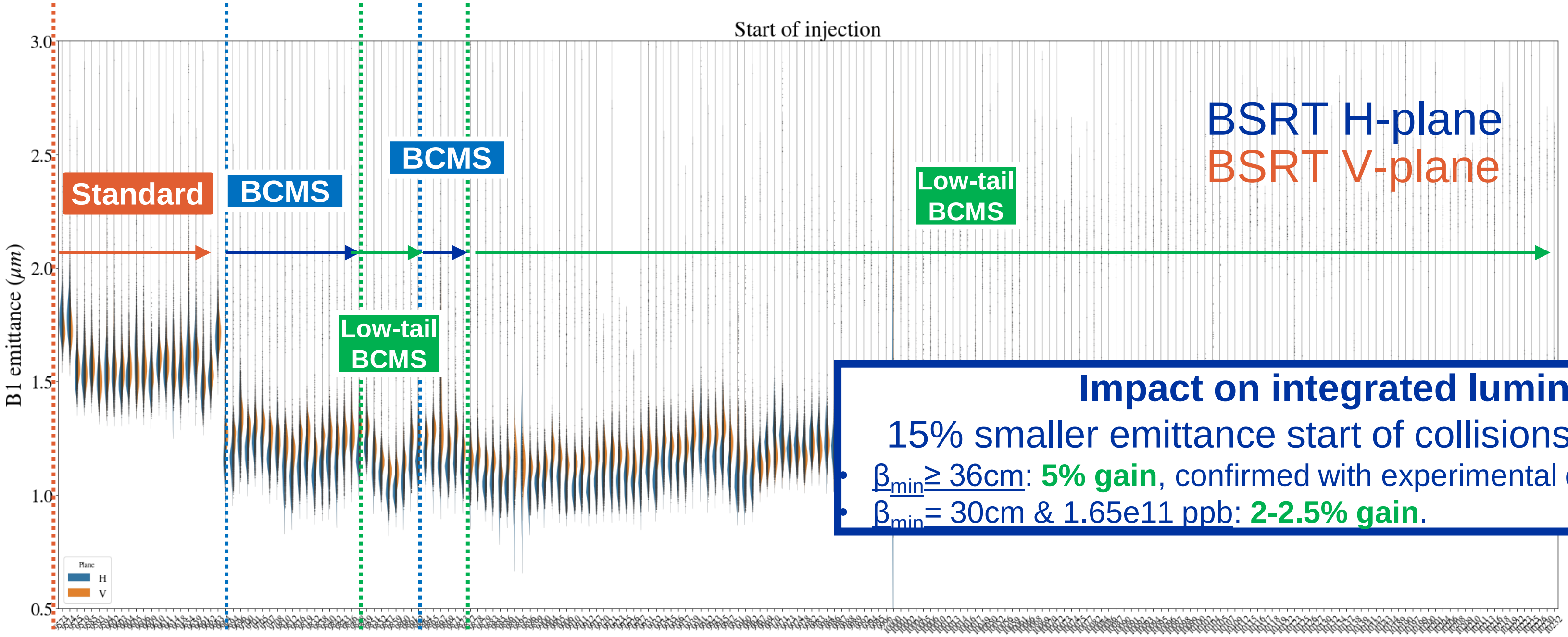
B. Salvachua, S. Morales

BLM limit →



Emittance at injection: standard vs BCMS

- **20-25%** emittance reduction at LHC injection with **BCMS w.r.t to standard**, **10-15%** at start of SB.



Impact on integrated luminosity:

15% smaller emittance start of collisions (nominal BCMS)

- $\beta_{min} \geq 36$cm: **5% gain**, confirmed with experimental data.
- $\beta_{min} = 30$cm & 1.65e11 ppb: **2-2.5% gain**.

Start of injection → **End of injection** → **Start of Stable Beams**

Start of injection

Emittance (μm)	B1H	B1V	B2H	B2V
Standard	1.56	1.58	1.5	1.5
BCMS	1.19	1.27	1.13	1.17
%	**-23.8**	**-19.84**	**-24.96**	**-22.33**

End of injection

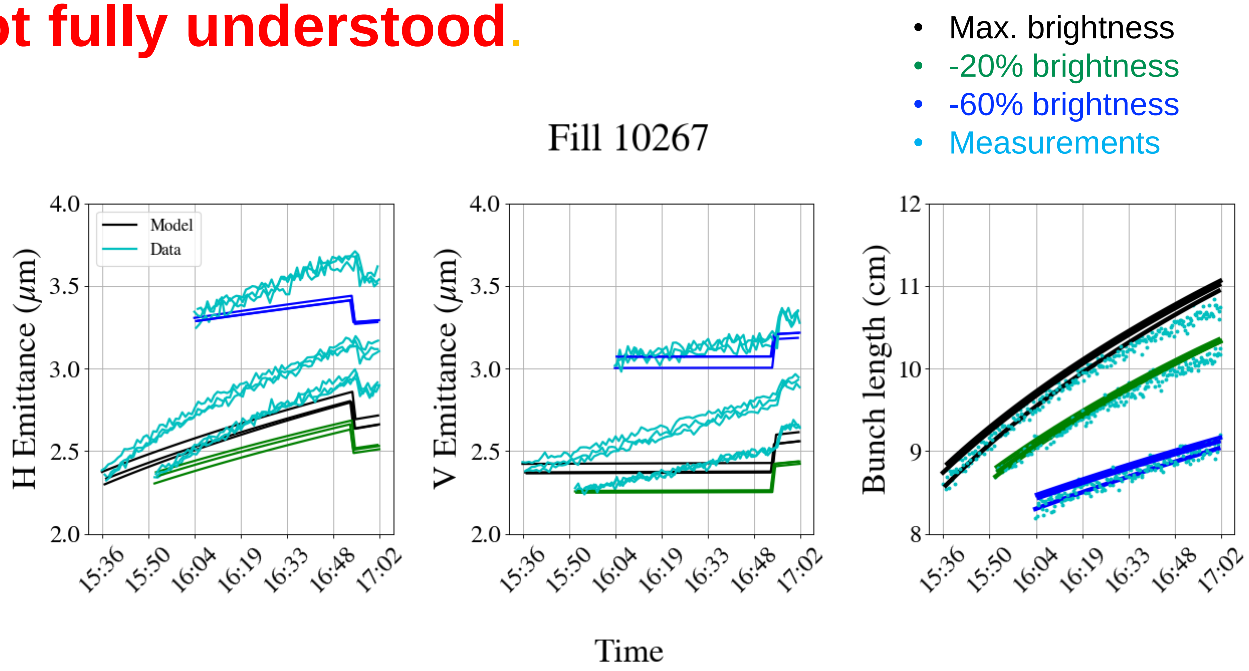
Emittance (μm)	B1H	B1V	B2H	B2V
Standard	1.77	1.71	1.63	1.61
BCMS	1.47	1.42	1.31	1.31
%	**-16.85**	**-16.77**	**-19.55**	**-18.97**

Start of Stable Beams

Emittance (μm)	B1H	B1V	B2H	B2V
Standard	1.84	1.67	2.25	2.3
BCMS	1.57	1.54	1.97	2.02
%	**-14.74**	**-7.38**	**-12.48**	**-12.06**

Emittance growth at injection

- Emittance growth mechanism at injection **not fully understood**.
  - Comparison of measured emittance growth & bunch length evolution against theoretical IBS model.



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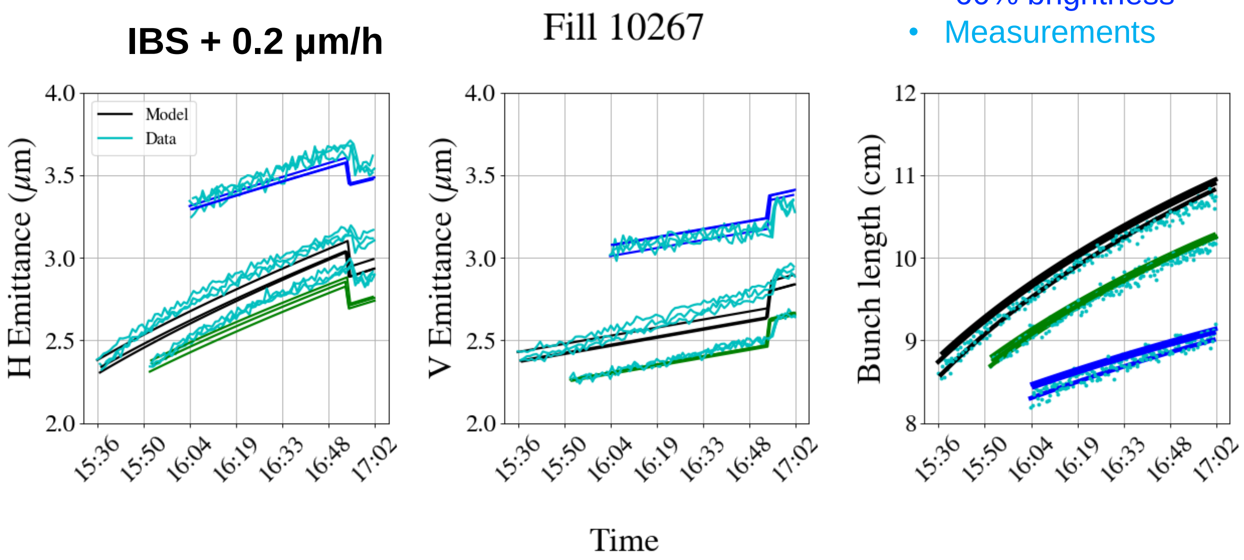
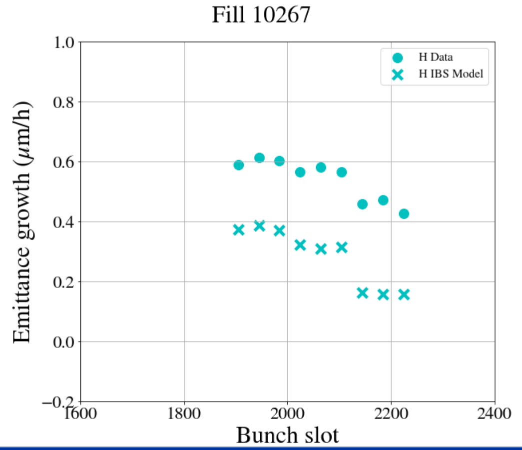
<u>Horizontal plane:</u>

- Systematically larger in **B1H**: **~0.6 μm/h** in addition to e-cloud:
  - **0.4 μm/h** from IBS.
  - **0.2 μm/h** of unknown origin:
    - even with **single bunches.**
    - **brightness independent**.

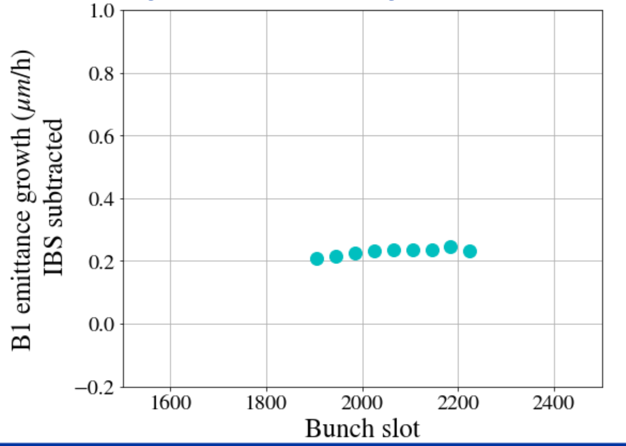
- Max. brightness
- -20% brightness
- -60% brightness
- Measurements



o Measured emittance growth for **H** & **V**
x IBS model emittance growth for **H** & **V**



Emittance growth in H with unknown origin after subtracting IBS contribution



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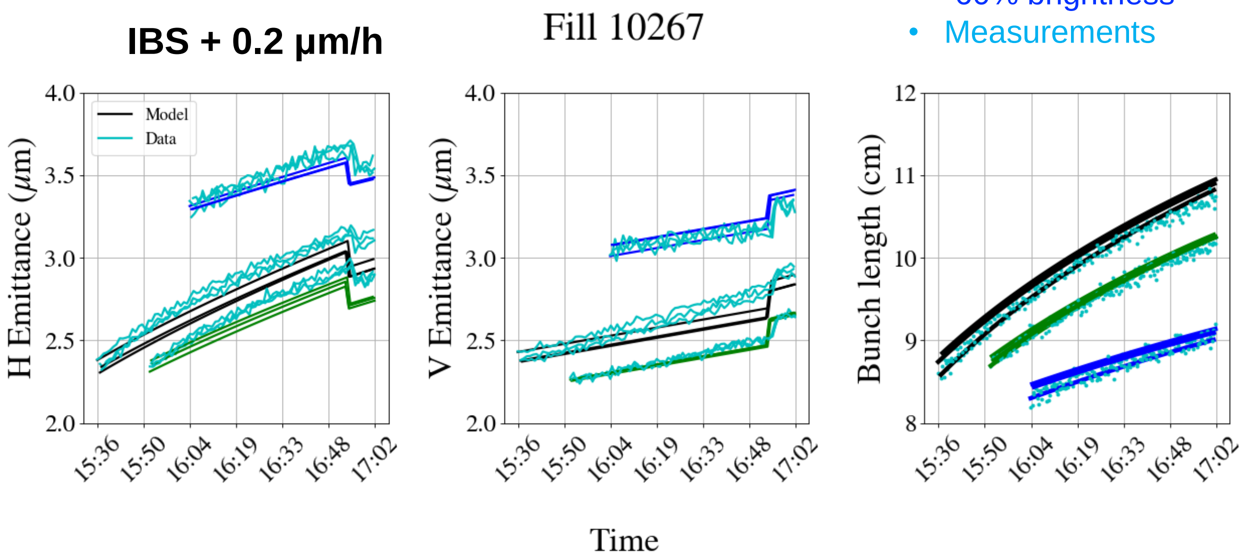
<u>Vertical plane:</u>

- **~0.1-0.3 μm/h** in addition to e-cloud (B1 & B2).
  - Low vertical dispersion & good coupling control → small IBS contribution.
  - Measurements suggest some brightness dependence → possibly underestimating IBS or emittance exchange with horizontal in the modeling.
  - **Linear increase** of emittance over time.

- Max. brightness
- -20% brightness
- -60% brightness
- Measurements

IBS + 0.2 μm/h



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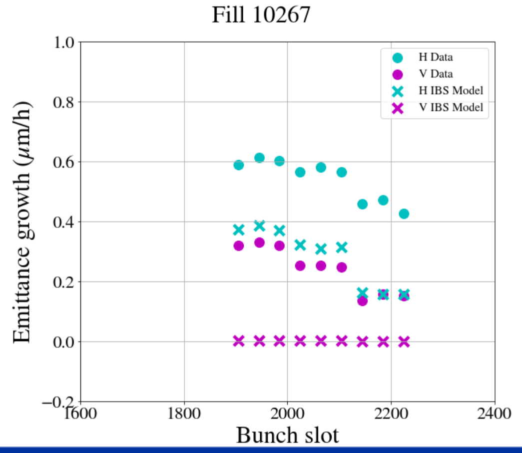

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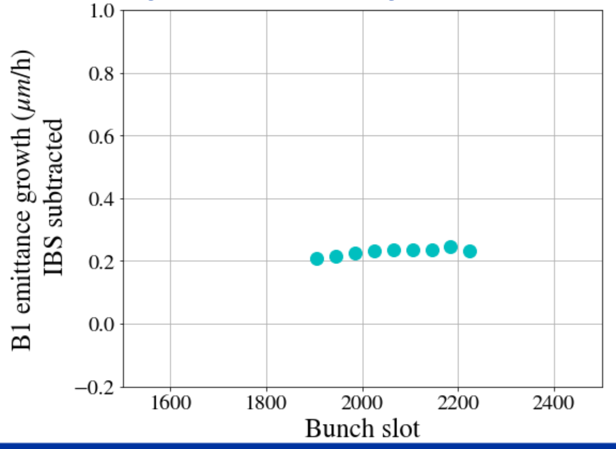

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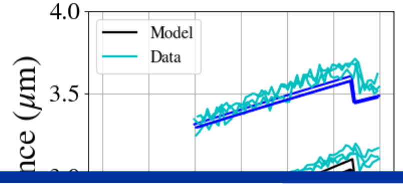

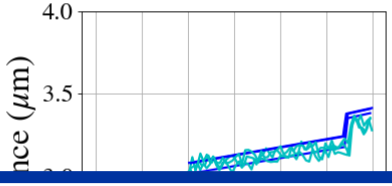

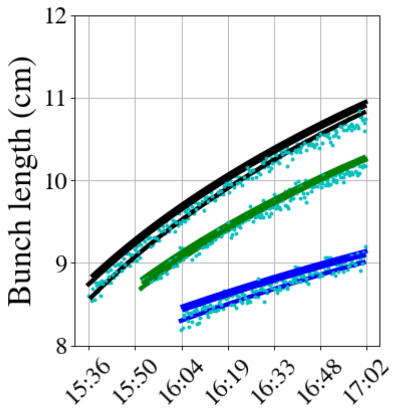

Follow-up

- Continue investigation of unexplained emittance growth.
- ➢ Minimize time spent at injection.

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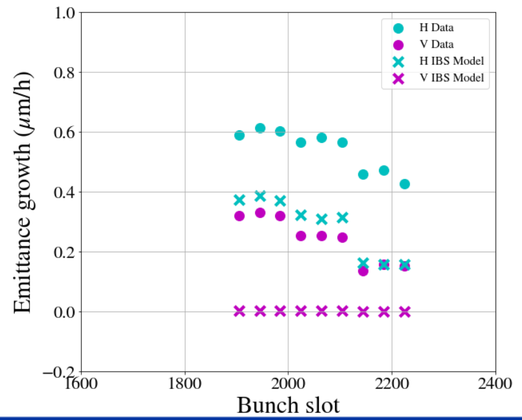
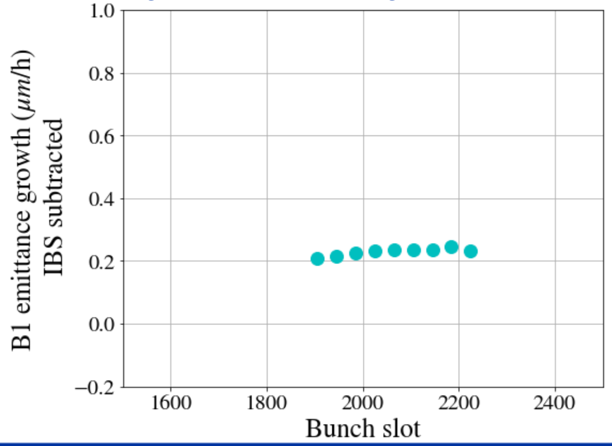
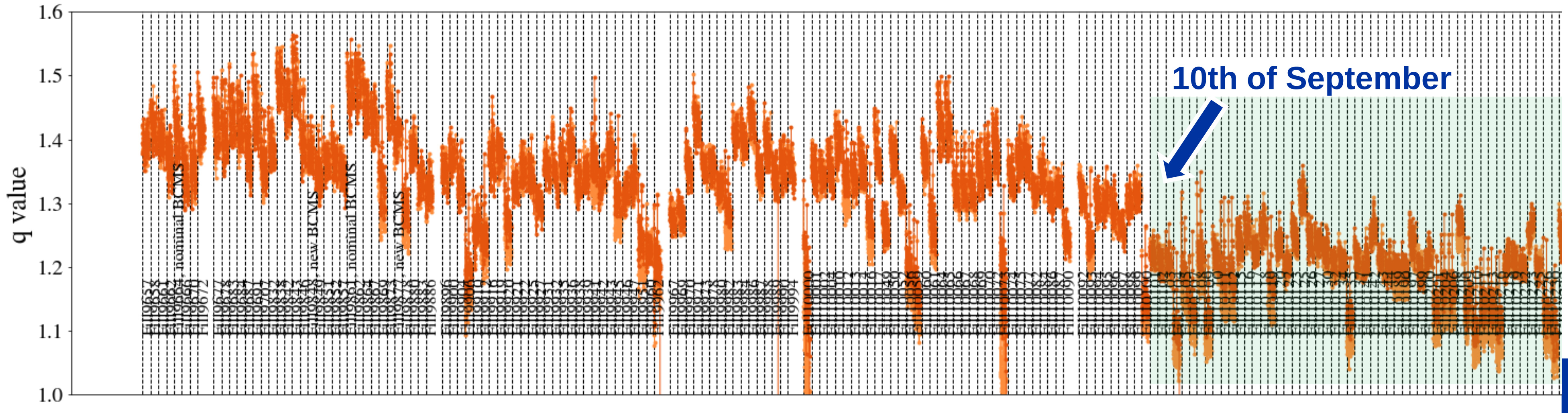




Tails at injection

- Systematic profile monitoring in 2024:
  - From Fill 9912 (July), **full-cycle bunch-by-bunch BSRT profile logging in NXCALS thanks to D. Butti**.
- Profiles at injection had **heavily populated tails**: q~1.4 at the start of 2024.
- **No significant tail reduction with the 1st "low-tail"** BCMS variant (July).
- **Tail reduction (q~1.2) at LHC injection > Fill 10100** (September), linked to injector tail improvement traced back to PS with unknown origin.
- Profile evolution:
  - Tend to **converge to Gaussian over time**, no mechanism of tail population during nominal operation.
  - However, tail increase during LHC injection observed during specific MDs.



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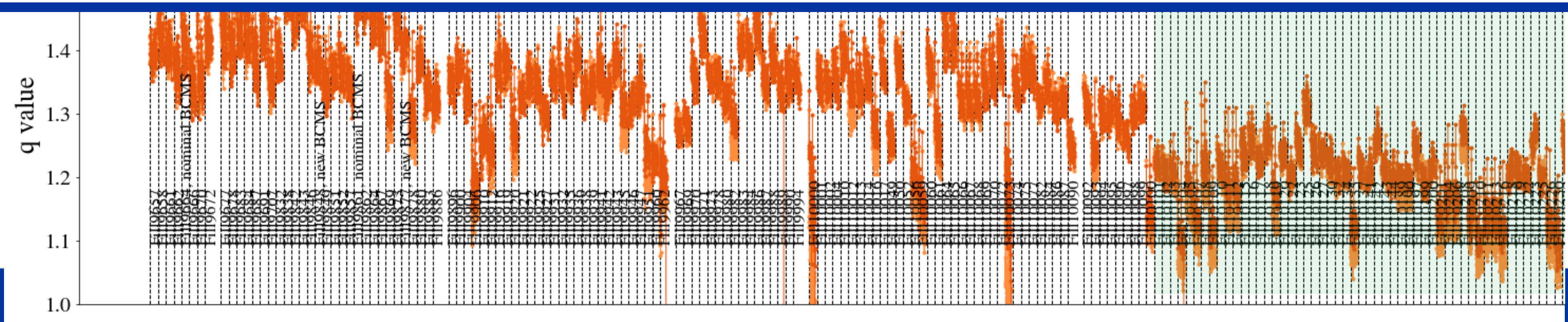
- **Tail re** … vement traced
- Profile
  - Ten … ration.
  - How

Follow-up

- Further improvements on ”low-tail” BCMS.
- Continue systematic BSRT profile logging & monitoring during whole LHC cycle to:
  - Monitor quality of injected profiles & detect changes.
  - Correlate with loss or gain of LHC performance.



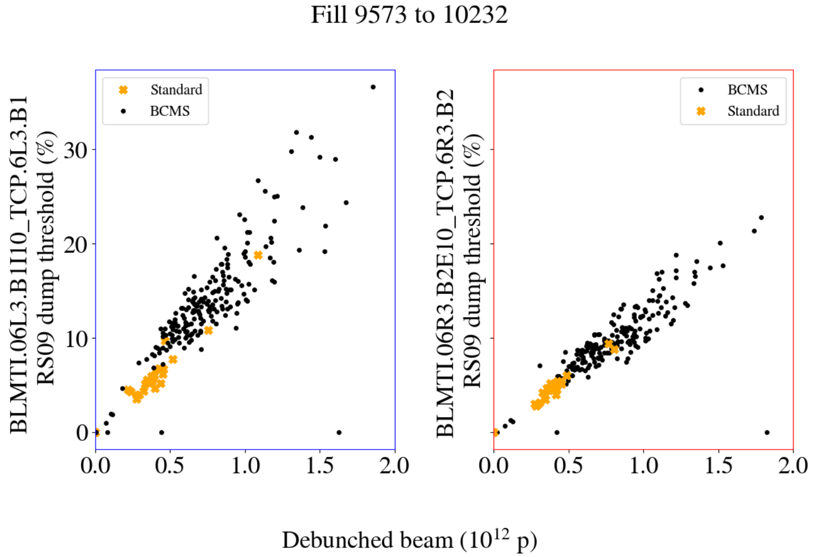
Debunched beam at injection & losses during ramp

H. Timko, B. Karlsen-Baeck, M. Zampetakis, HL-WP5

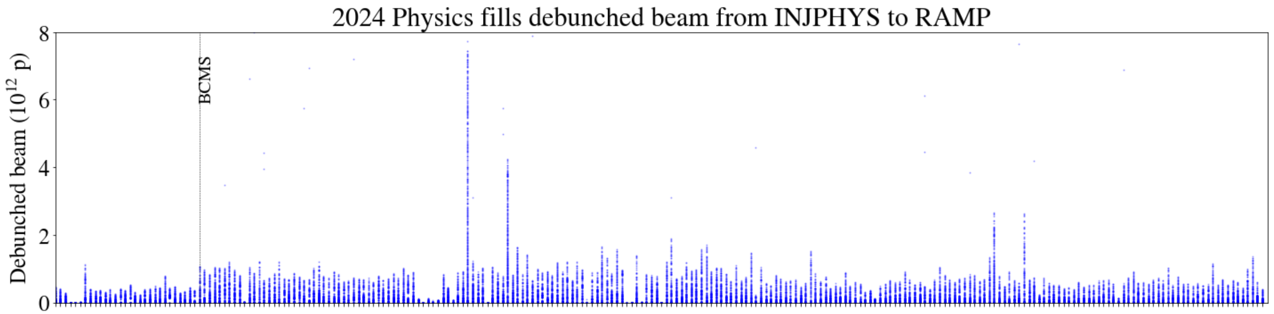
- IR3 high losses at start of Ramp, reaching warning levels on BLMs & causing 3 dumps.
- Strong correlation between **IR3 losses and debunched beam** (~up to 50 nominal bunches).
- Correlation of debunched beam with:
  - **Brightness.**
  - **Time spent at injection.**

  possibly indicating **IBS related mechanism**.
- **More critical for BCMS** compared to standard due to higher brightness.
- Mitigations:
  - Clearly demonstrated by RF that **increase of RF voltage** is beneficial (talk by B. Karlsen-Baeck).
  - Increase of **BLM thresholds** (talk by S. Morales).

Debunched beam vs IR3 losses



Debunched beam in 2024 fills



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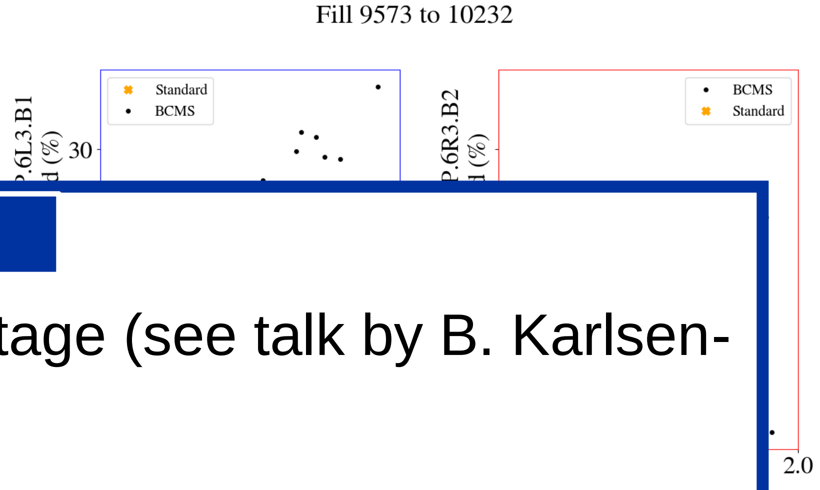
Follow-up

- Investigate possibility to increase RF voltage (see talk by B. Karlsen-Baeck) & review BLM thresholds.
- ➢ Minimize time spent at injection.

Debunched beam vs IR3 losses



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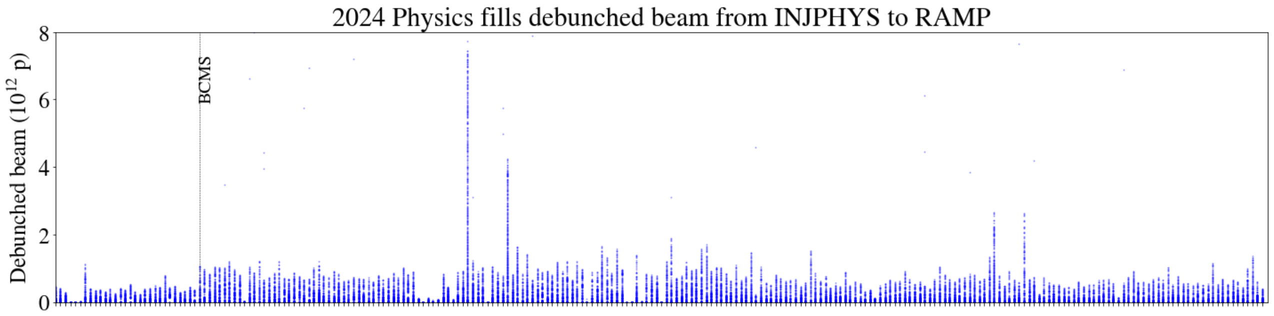
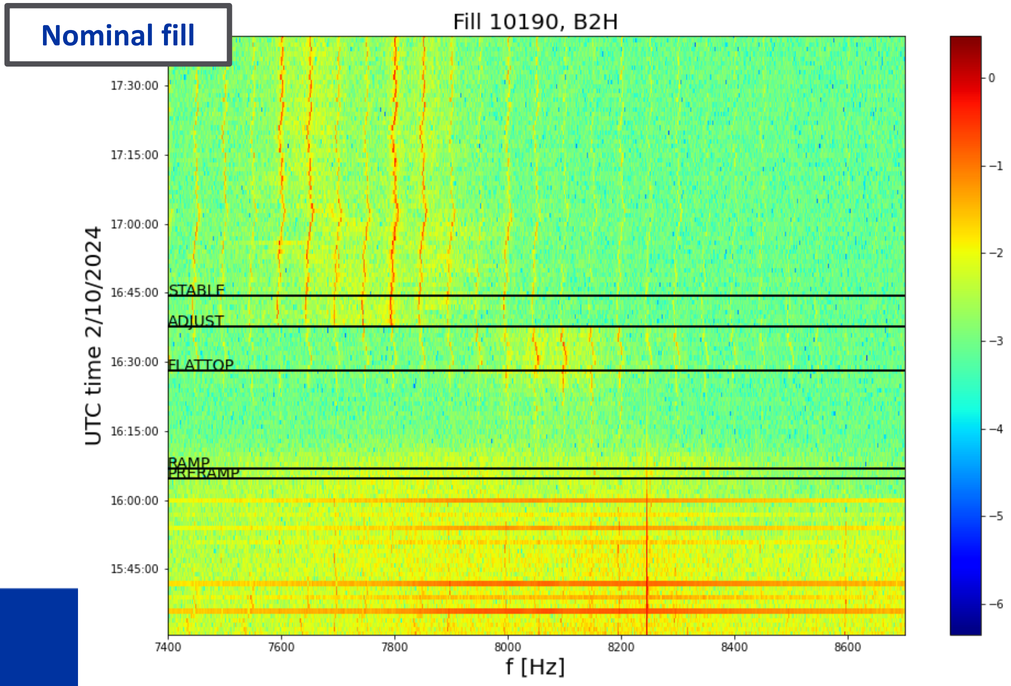
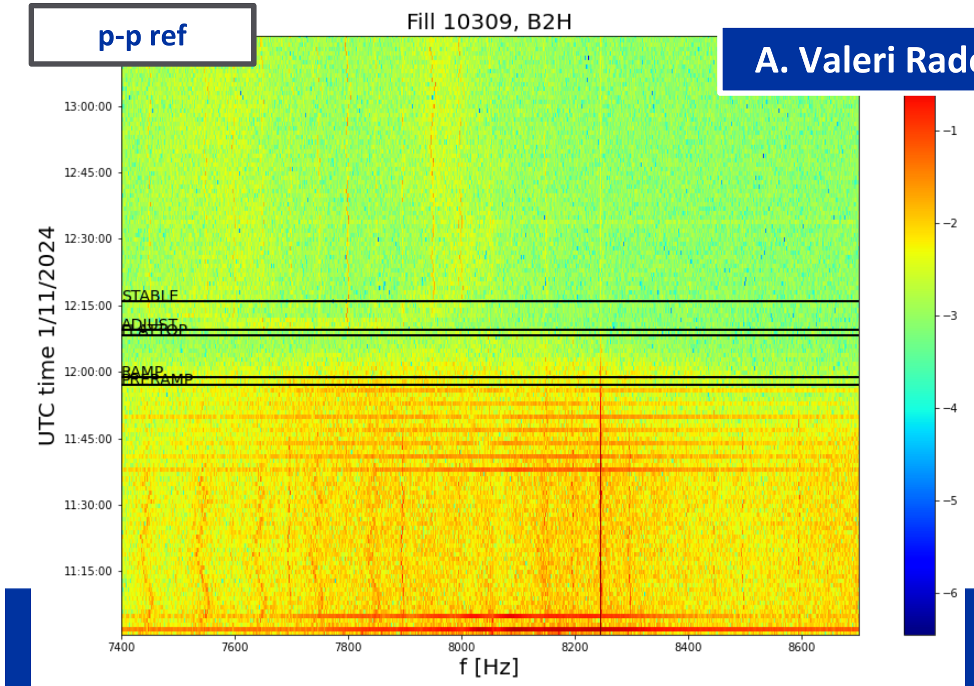


Power supply ripple at the end of ramp

- 50 Hz power supply ripple constantly present throughout LHC cycle, real dipolar beam excitation.
- Origin of high-frequency 8 kHz cluster is **not understood**:
  - Clear **amplitude increase at the end of the ramp** when reaching 6.8 TeV.
  - Sensitivity to tune trims consistent with dipolar excitations.
  - Significantly attenuated amplitude during p-p ref Run (2.68 TeV).
  - Impact on performance is unclear, reproducible fill-by-fill.





A. Valeri Radoslavova

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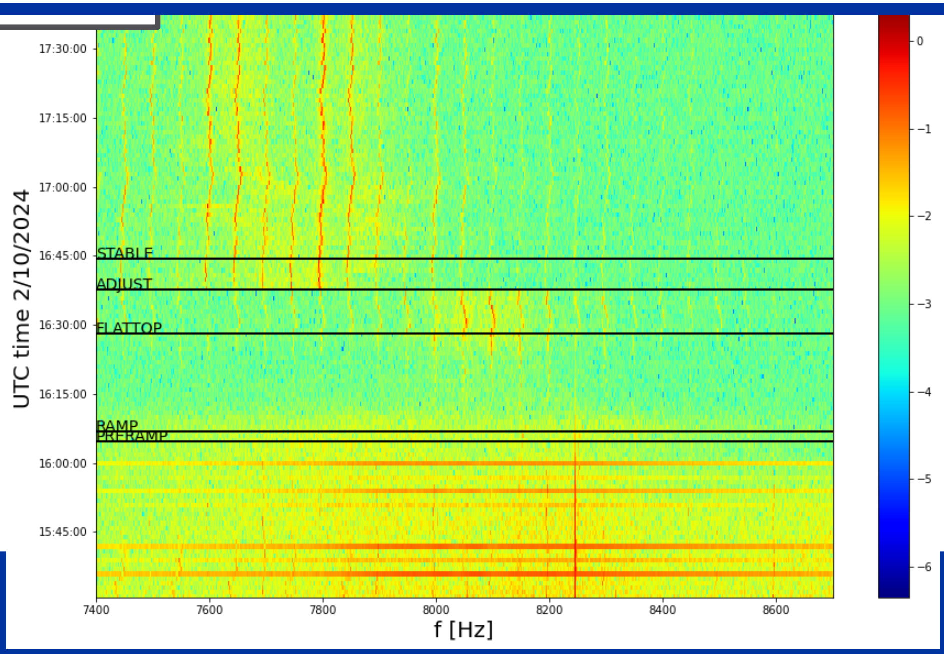
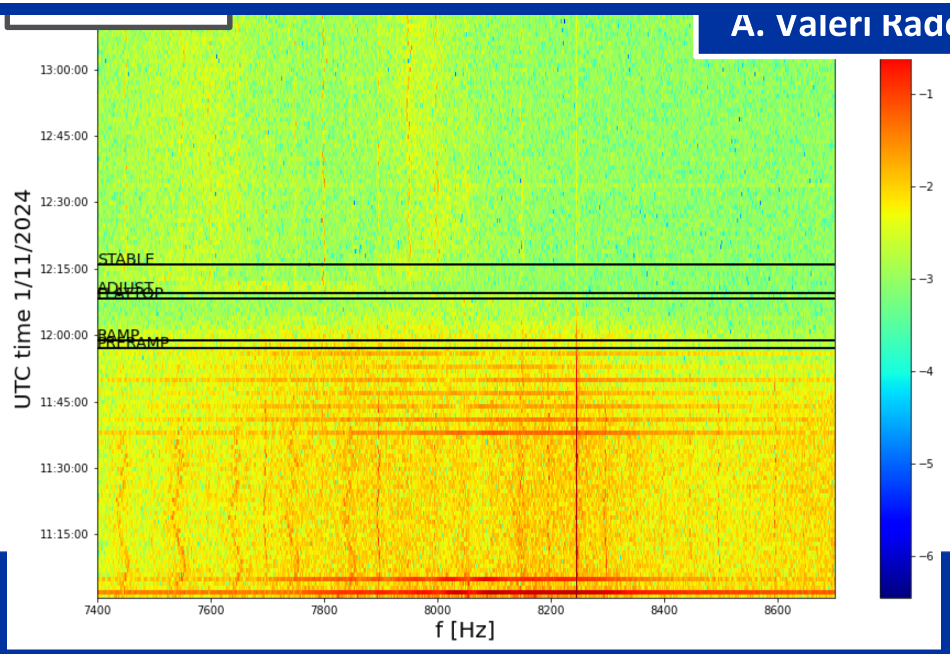
- 50 Hz power supply ripple constantly present throughout LHC cycle, real dipolar beam excitation.
- Origin of high-frequency 8 kHz cluster is **not understood**:
  - Clear **amplitude increase at the end of the ramp** when reaching 6.8 TeV.

Follow-up

- Based on the successful compensation of 50Hz in the SPS, should we finally make a similar effort for the 50Hz ripple in the LHC?

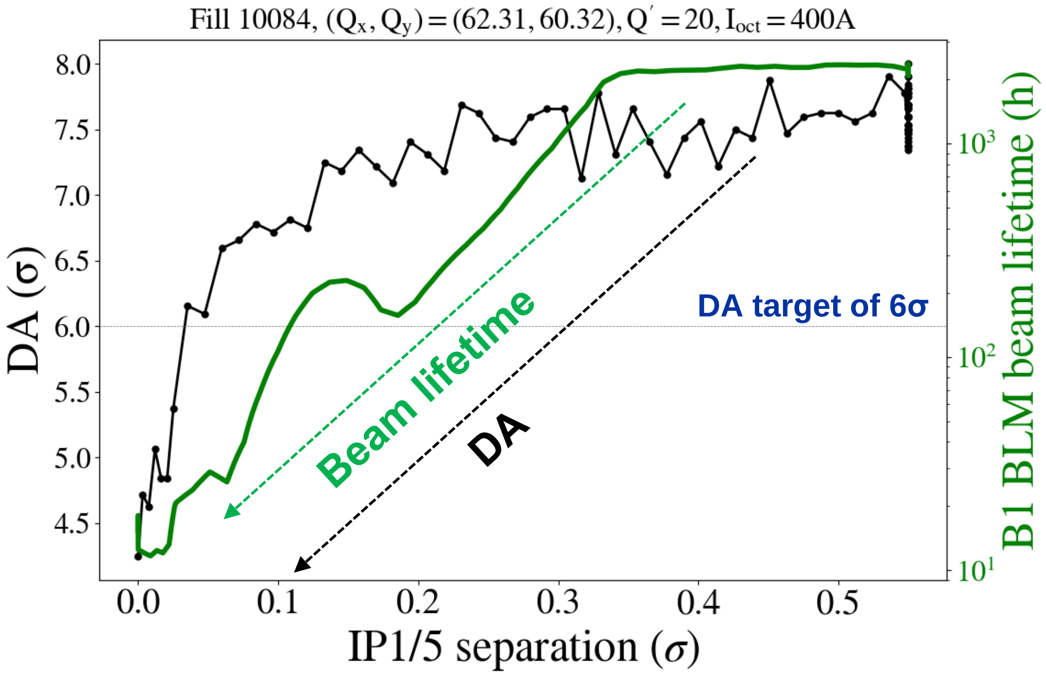
A. Valeri Radoslavova





Losses at the end of adjust/start of collisions

- Large beam **lifetime drop** (<10 h in some fills) during final seconds of Adjust.
- Driving mechanism:
  - **DA reduction** when entering **head-on beam-beam dominated regime**.



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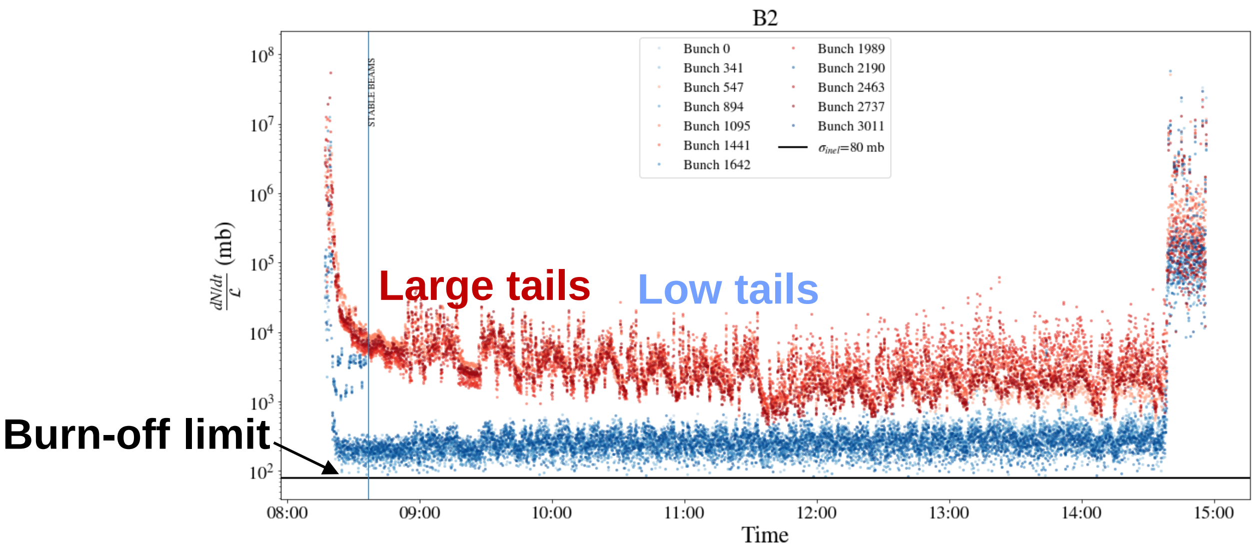
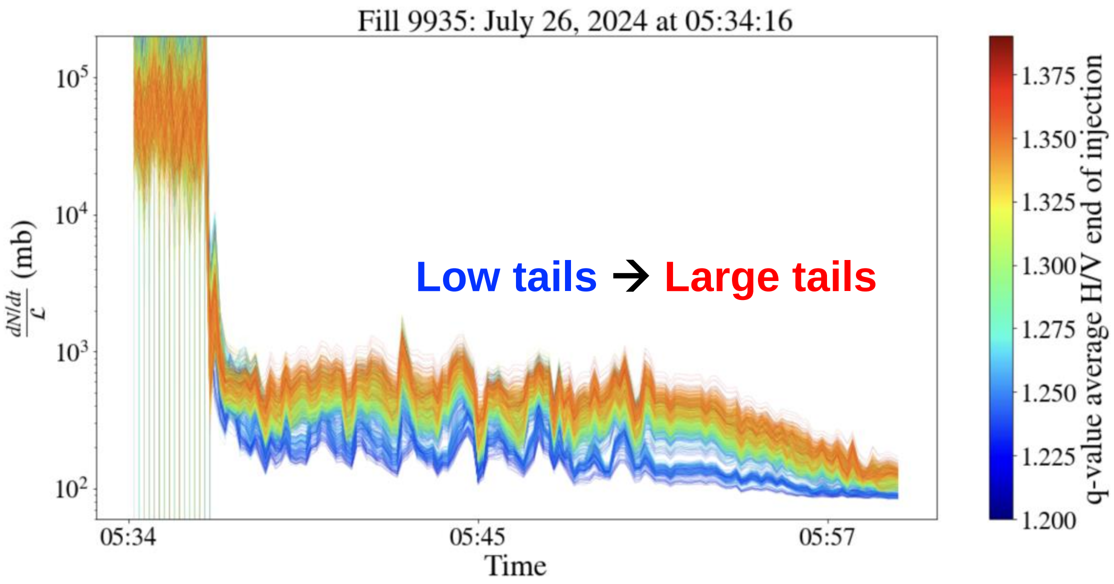
    I. First observations from MDs with groups of low-tail & large-tail bunches.
    II. Confirmed in nominal fills.





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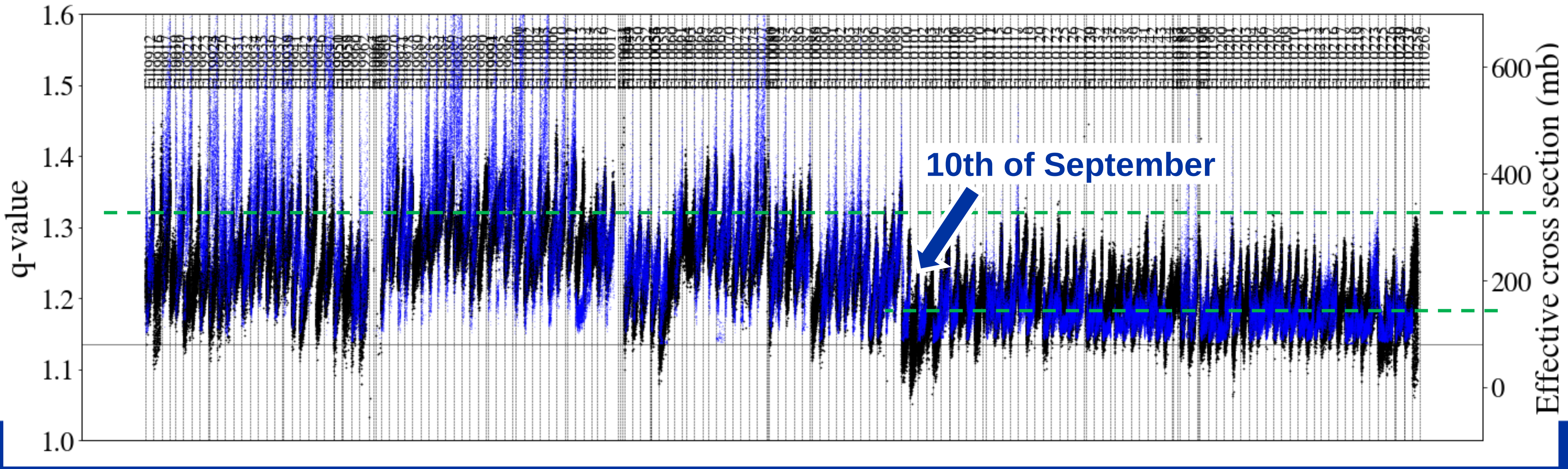
  - Clear correlation between **tails & losses**:
    I. First observations from MDs with groups of low-tail & large-tail bunches.
    II. Confirmed in nominal fills.
    III. **Losses reduced close to burn-off limit** by September with **"low-tail"**: strong correlation of tail reduction & loss reduction at the start of SB.

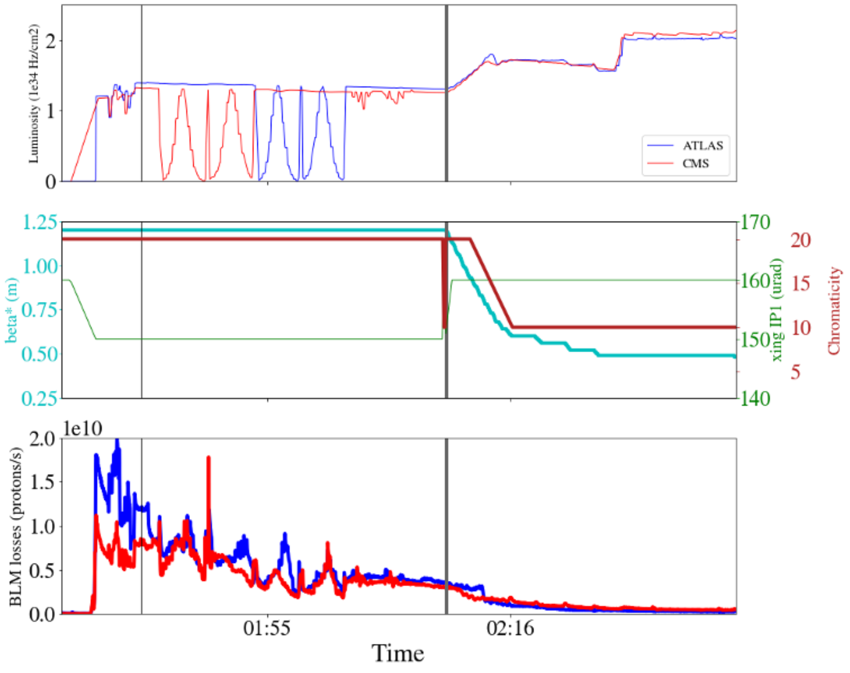


Losses during collisions

- Observed beam **lifetime degradation with extended stay at 1.2 m**, $\mu_{max}<\mu_{target}$ before leveling.

Fill 9864 in July:

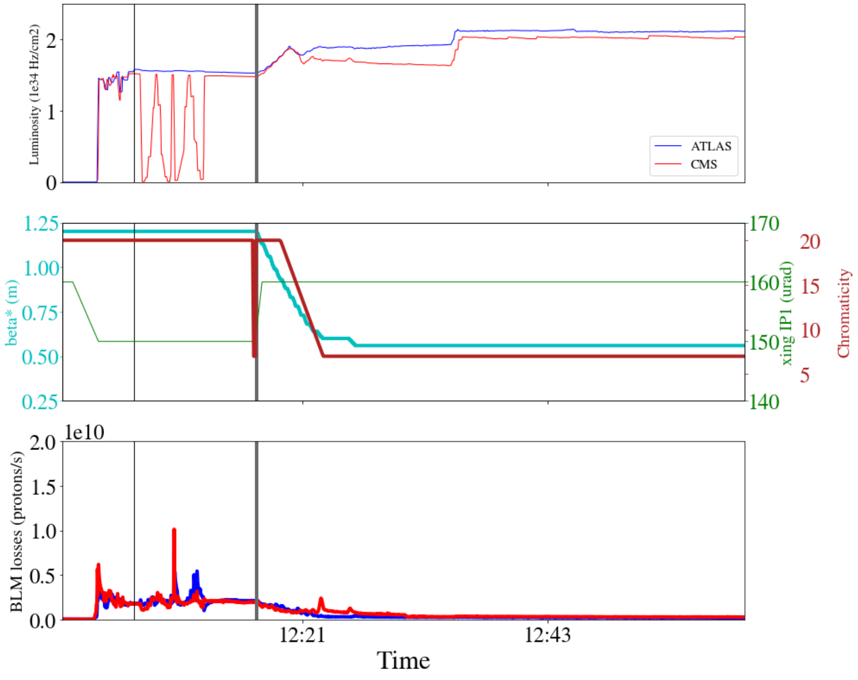
1. Nominal BCMS
2. Extended stay at 1.2 m



Losses equivalent to **~90 nominal bunches** in 1st hour of SB

Fill 10100 in September:

1. "Low-tail" BCMS
2. Short stay at 1.2 m



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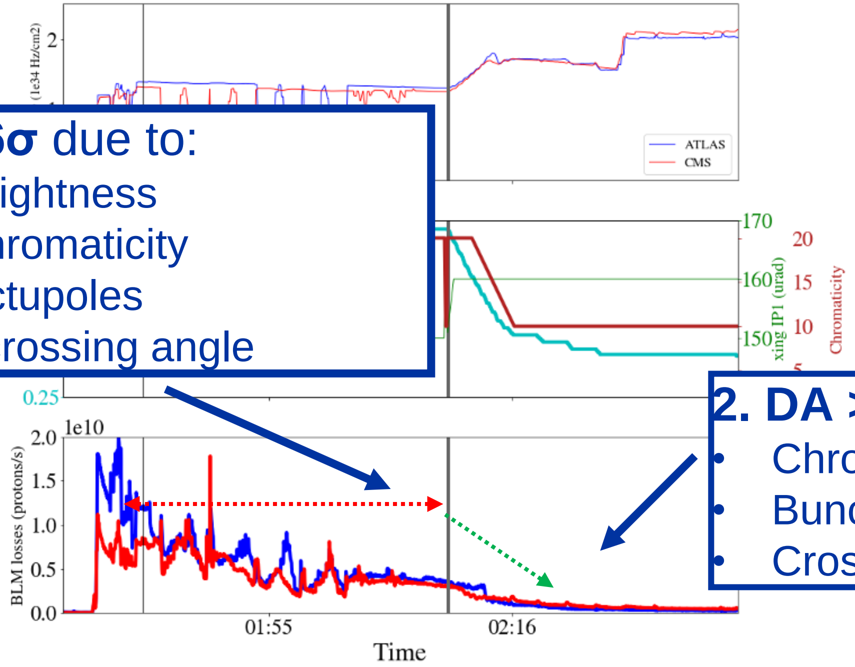


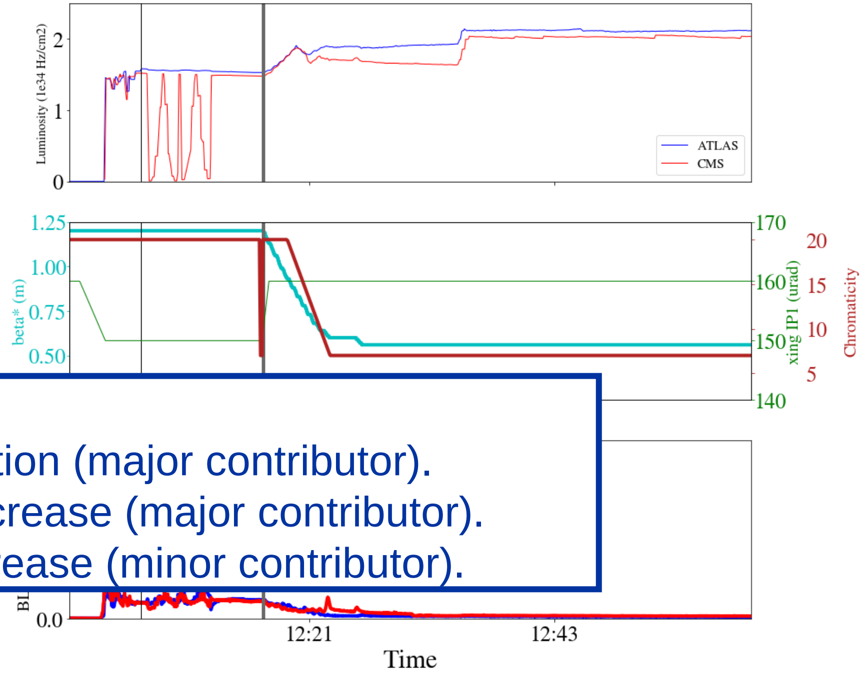
1. DA < 6σ due to:

- High brightness
- High chromaticity
- High octupoles
- Small crossing angle

Losses equivalent to **~90 nominal bunches** in 1st hour of SB

Fill 10100 in September:

1. "Low-tail" BCMS
2. Short stay at 1.2 m



2. DA > 6σ due to:

- Chromaticity reduction (major contributor).
- Bunch intensity decrease (major contributor).
- Crossing angle increase (minor contributor).

Losses equivalent to **~20 nominal bunches** in 1st hour of SB

Losses during collisions

- Observed beam **lifetime degradation with extended stay at 1.2 m**, $\mu_{max} < \mu_{target}$ before leveling.

Fill 9864 in July:

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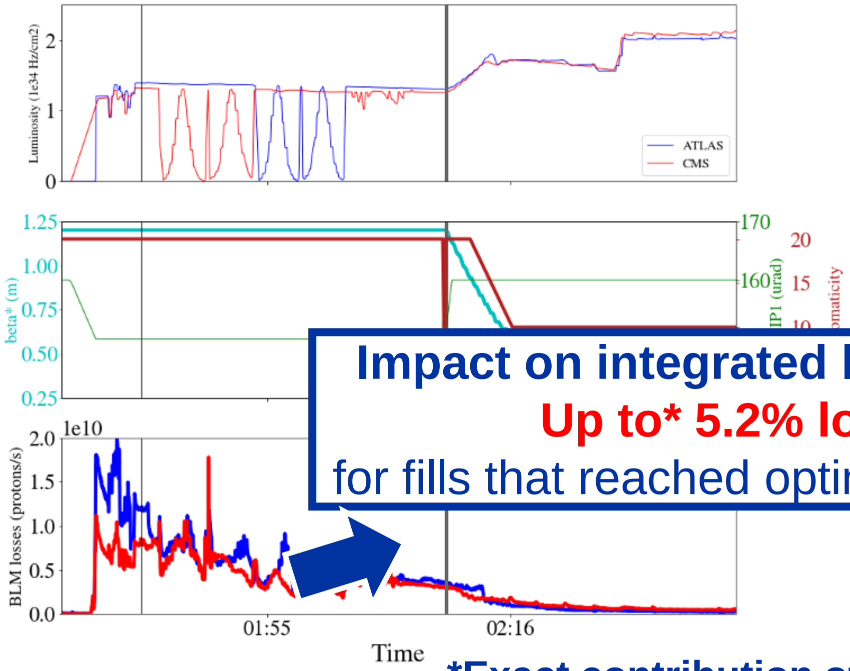
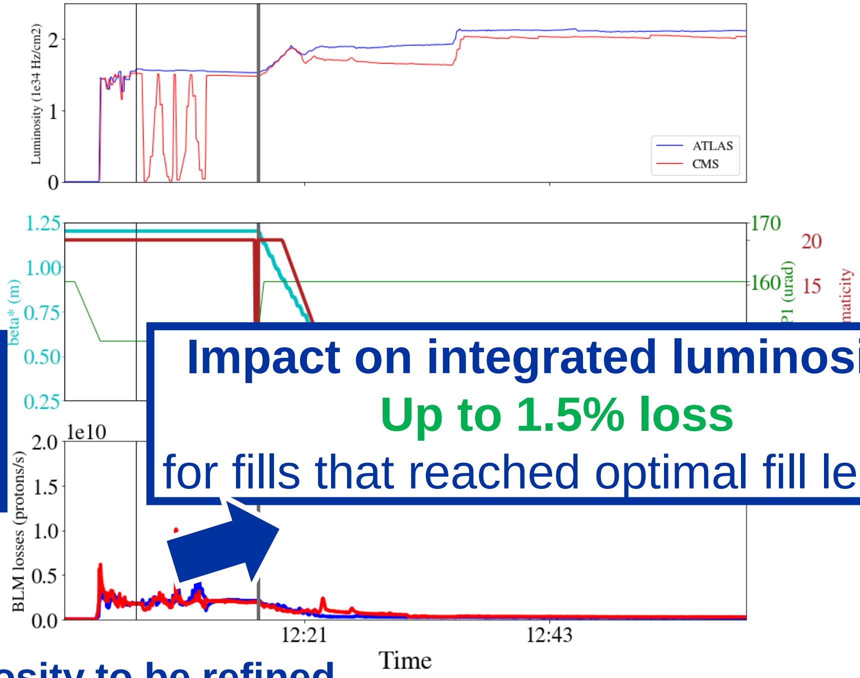


Impact on integrated luminosity:
Up to* 5.2% loss
for fills that reached optimal fill length

Losses equivalent to **~90 nominal bunches** in 1st hour of SB

Fill 10100 in September:

1. "Low-tail" BCMS
2. Short stay at 1.2 m



Impact on integrated luminosity:
Up to 1.5% loss
for fills that reached optimal fill length

Losses equivalent to **~20 nominal bunches** in 1st hour of SB

***Exact contribution of tails on luminosity to be refined**

Losses during collisions

- Observed beam **lifetime degradation with extended stay at 1.2 m**, $\mu_{max}<\mu_{target}$ before leveling.

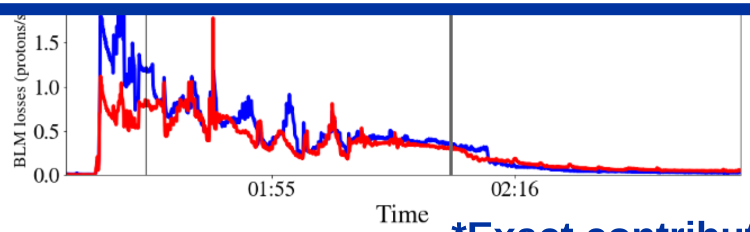
Fill 9864 in July:

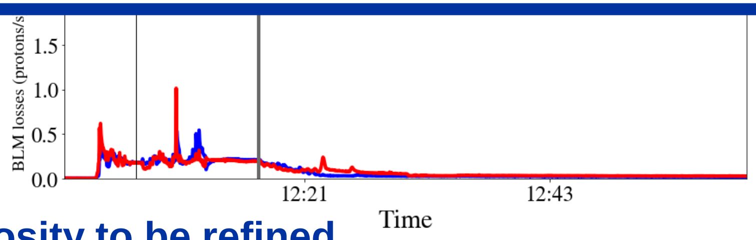
Fill 10100 in September:

Follow-up

- Aim to inject in LHC profiles as close as possible to Gaussian from the injectors.
- Reaching DA ≥ 6σ at end of adjust/start of leveling is critical to minimize losses:
  - chromaticity reduction after emittance scans or as quickly as possible.
  - combined with “low-tail” BCMS.

umi
ngth





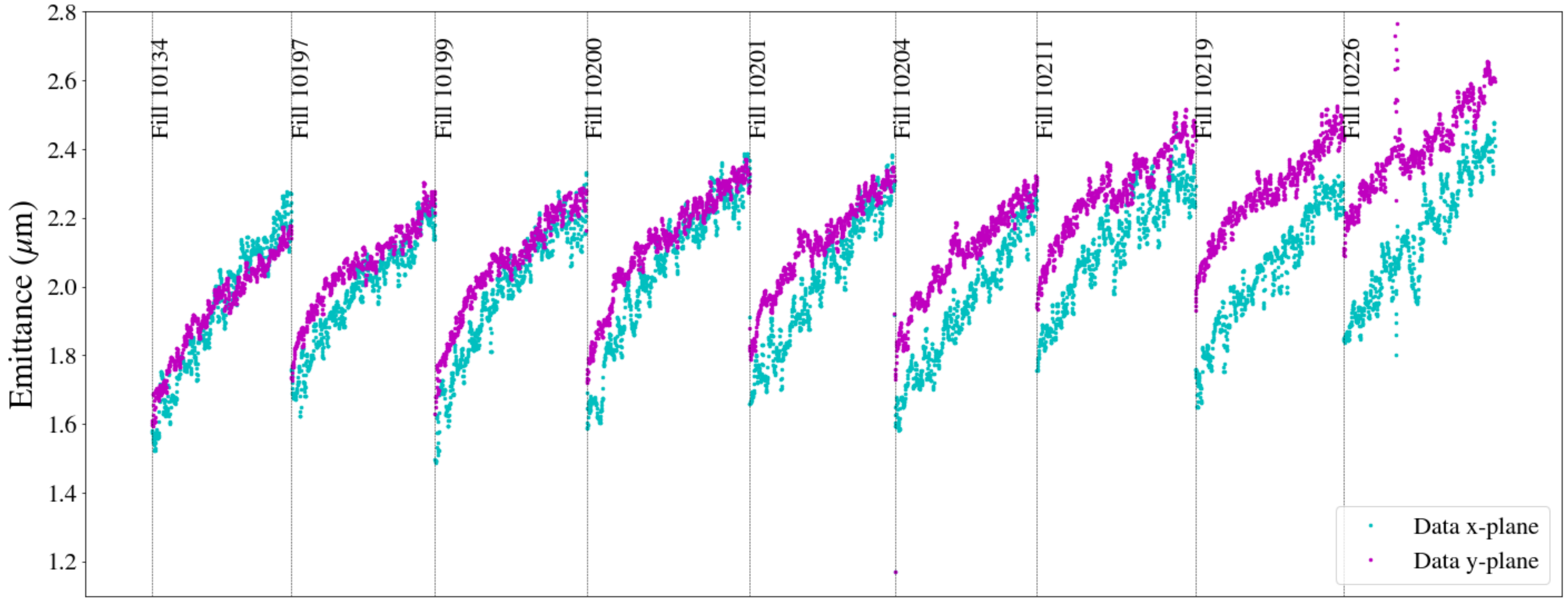
***Exact contribution of tails on luminosity to be refined**

Losses equivalent to **~90 nominal bunches** in 1st hour of SB

Losses equivalent to **~20 nominal bunches** in 1st hour of SB

Emittance growth at collisions

- Emittance growth of unknown origin also during collisions:
  - Cannot be fully explained by IBS models.
  - Vertical emittance expected to be shrinking due to SR.



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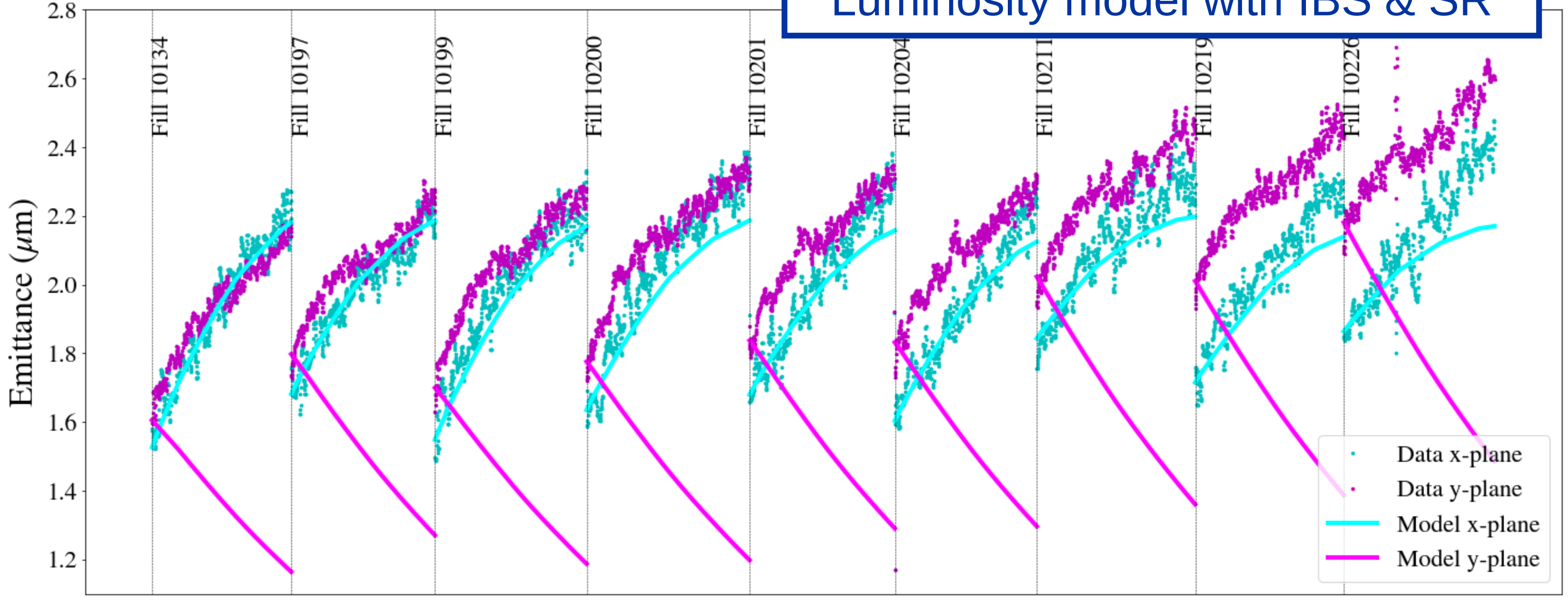
Luminosity model with IBS & SR



Emittance growth at collisions

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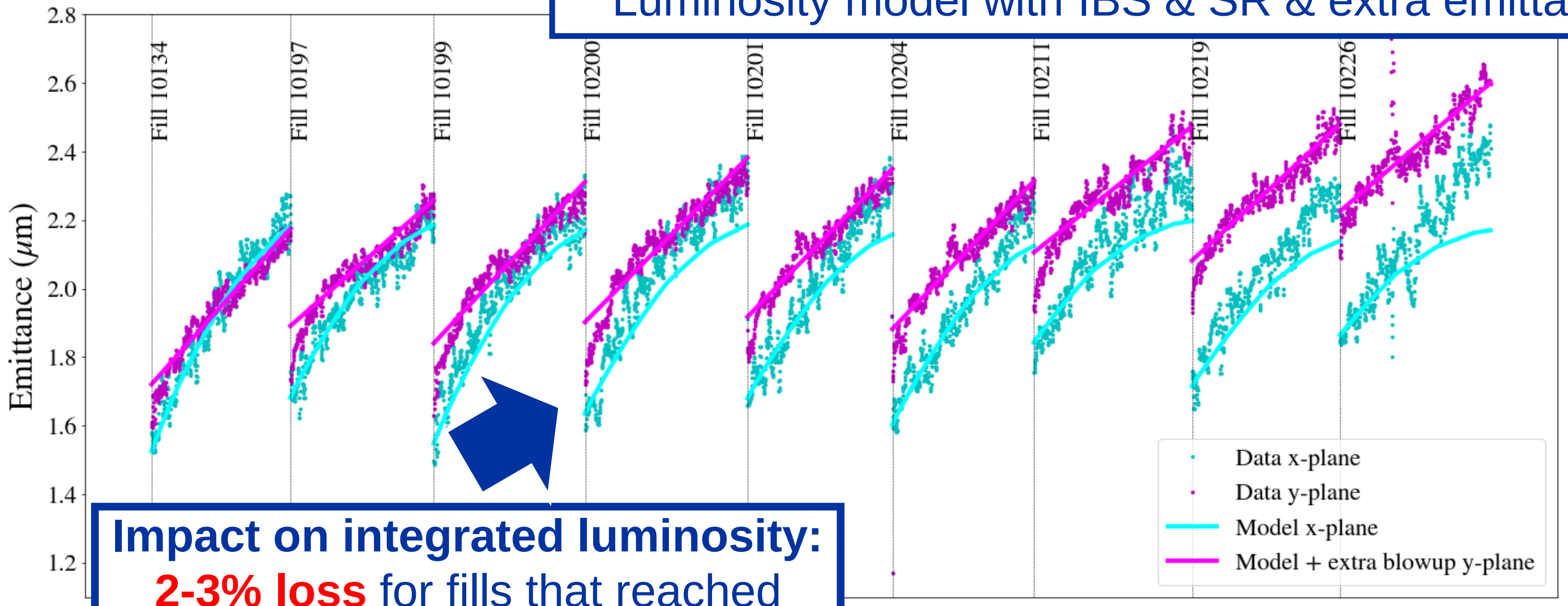
Luminosity model with IBS & SR & extra emittance growth



Impact on integrated luminosity:
2-3% loss for fills that reached optimal fill length & τ=2.5 h

Lessons learned from 2024

- **Need to minimize time spent at LHC injection due to:**
  I. Unexplained **emittance growth** at injection.
  II. Increase of **debunched beam** & eventually losses during ramp.
  - Longer trains for 2025 due to faster injection time & gain in integrated luminosity (see X. Buffat):
    - Injection losses: source remains unclear, increase of margin to BLM saturation for B1 w.r.t 2023.
- **Standard vs BCMS:**
  - Start of collisions with **10-15% smaller emittances**.
  - Depending on virtual luminosity, **2-5% gain** in performance w.r.t to standard for fills that reached optimal fill length.
  - Main gain comes from **“low-tail” BCMS**:
    - **Clear correlation between losses at the end of collapse/start of collisions and tail population**: reduction of tails observed Fills>10100 (10^{th} of September), starting from tail reduction in the injectors, resulted in loss improvement at start of collisions:
  - Preparation from the injectors has direct impact on LHC performance: to be considered not only for nominal operation but also for special beams (VdM & BSRT calibration fills).

Lessons learned from 2024

- **Minimize losses during collisions:**
  I. Start LHC injection with **profiles as close as possible to Gaussian from the injectors**.
    - **Tail increase for B1** from SPS to LHC due to transfer line mismatch, **expected to improve with new transfer function.**
    - ➢ Further improve & optimize “low-tail” BCMS in the injectors.

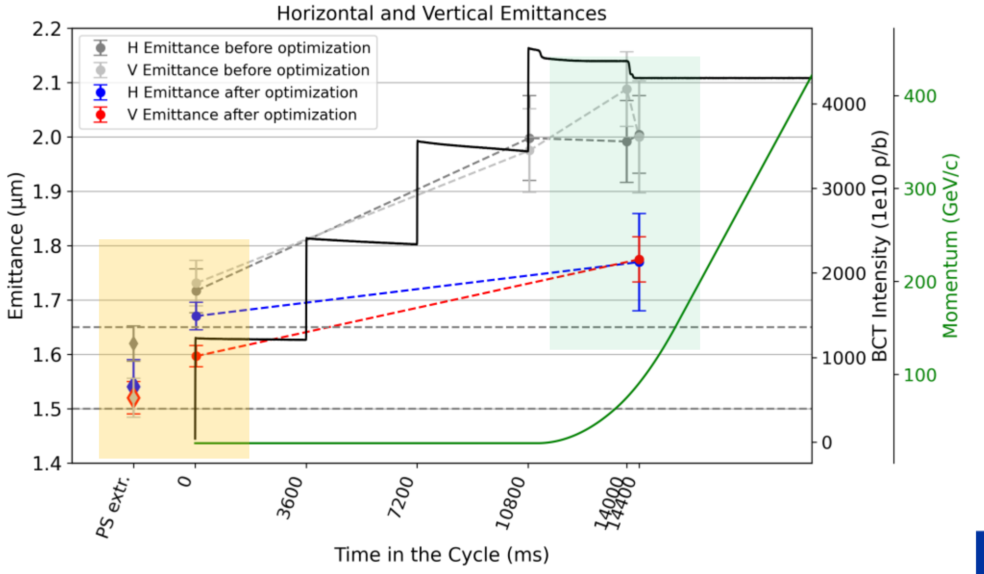
  II. Critical to maintain **DA target of 6σ at end of adjust/start of leveling**:
    - 2024 DA below target at this stage & improved during leveling → seen on beam lifetime.
    - DA can be increased by reducing non-linearities (e.g. chromaticity reduction after emittance scans, switching to negative octupole polarity).
- **Other issues**: unknown emittance growth at injection & collisions, 50 Hz ripple..
- **Need for more automatic tools for profile monitoring and losses in the injectors & throughout the whole LHC cycle to detect changes fast & efficiently and eventually connect with gain or loss of LHC performance.**

Thank you!

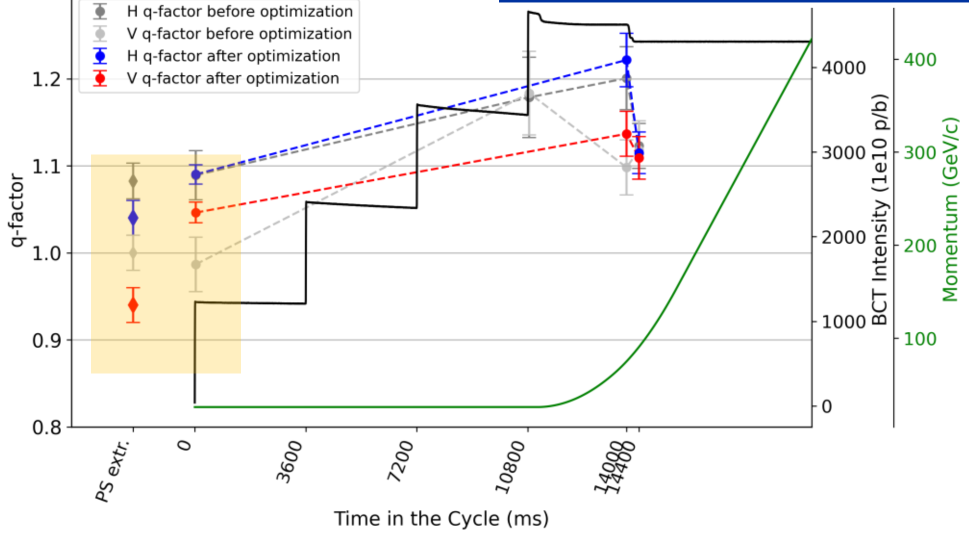
Backup

A closer look in the SPS

- Measurements from high-intensity MDs (4x48b, ~2.3e11 ppb at SPS extraction), similar observations with 2024 nominal configuration.
  - **Emittance and q-factor increase PS extraction→SPS injection**:
    - ➢ Similar trends observed between SPS extraction→LHC injection due to transfer line mismatch.
  - **Emittance blowup & tail population at SPS flat bottom**:
    - ➢ Emittance reduction through **tune optimizations**.
  - SPS scraping fully correlated with tails at SPS extraction/LHC injection: In 2024, Gaussian bunch profiles and nominal intensity with ~15% scraping.

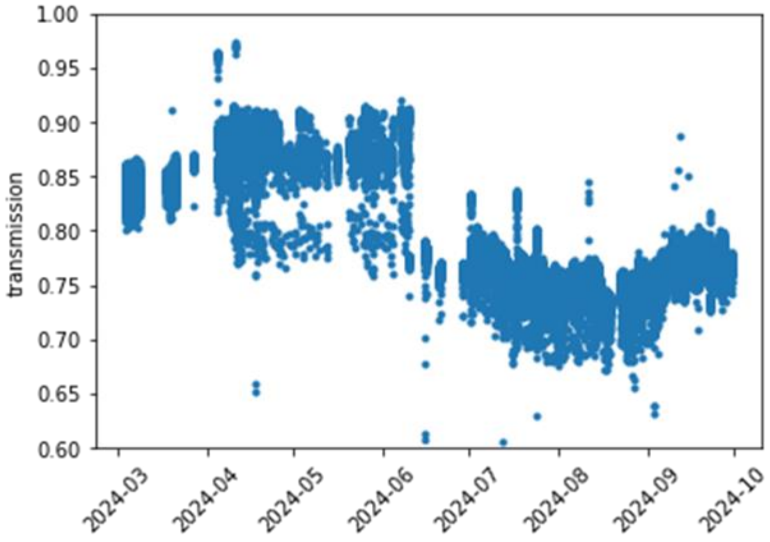


I. Mases Sole, F. Asvesta



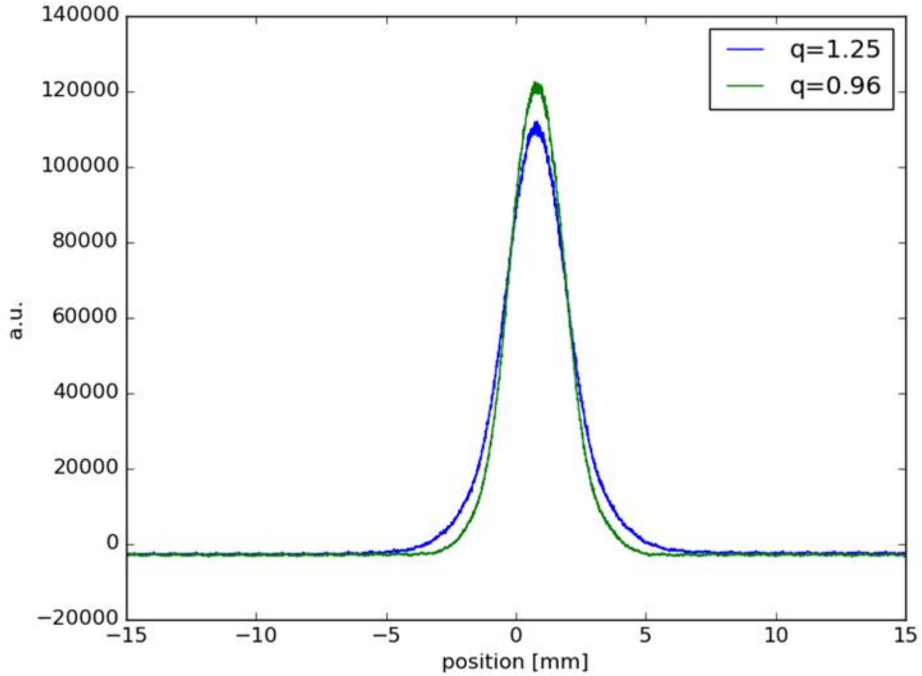
PSB scraping

PSB Transmission



F. Asvesta

Tails before/after scraping



PS optimization during γ_{trans} crossing

Tune Optimization on PS: Step #1

- *Horizontal tune decrease before and after transition crossing using the LEQs and the PFWs respectively*

Tune Optimization on PS: Step #2

- *Vertical tune decrease after transition crossing using the the PFWs*

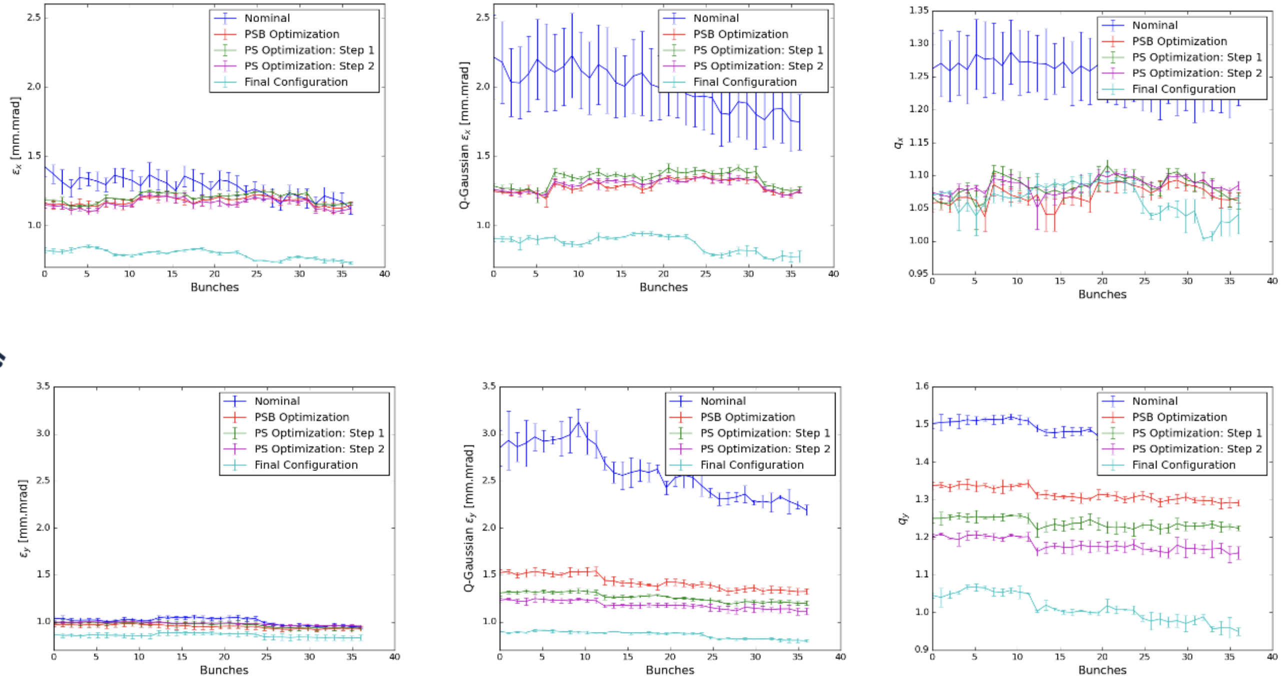
- *Use of low emittance beam from PSB (Triple harmonic operation)*
- *Extend the PS tune optimizations at the transition crossing period*

M. Bozatzis, F. Asvesta

emittance *rms emittance* *tails*

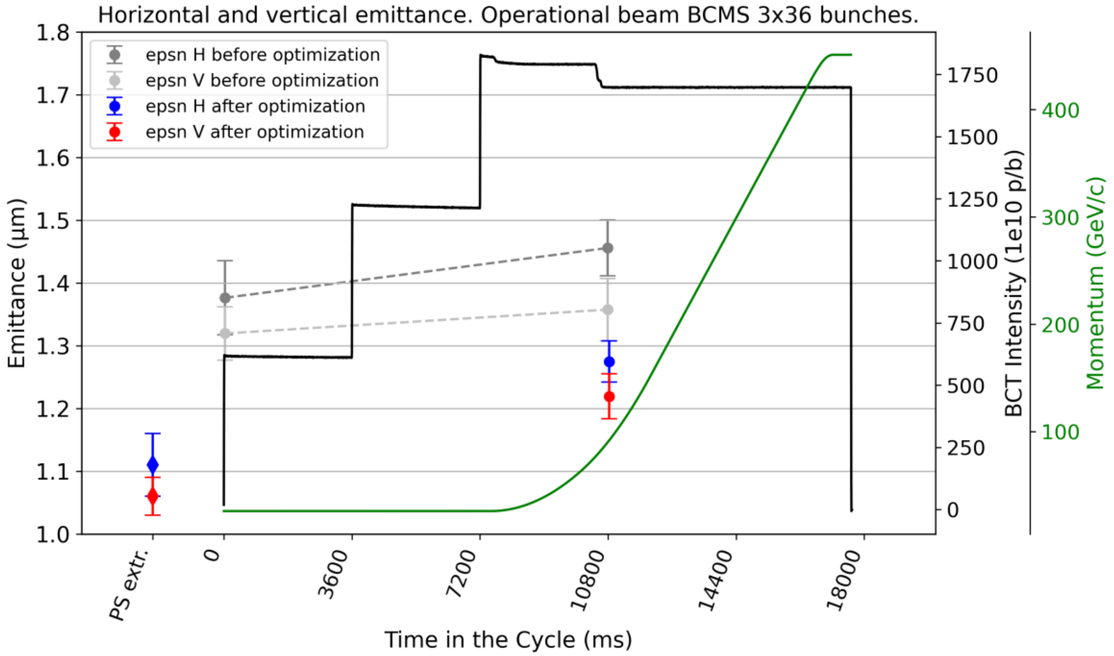
Horizontal

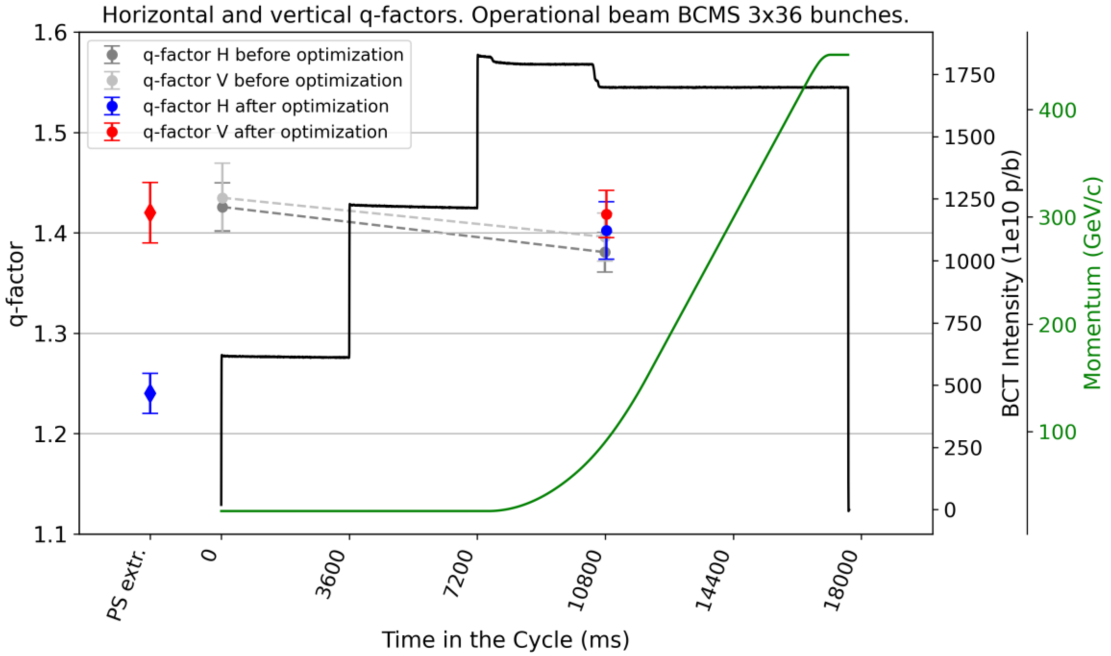
Vertical



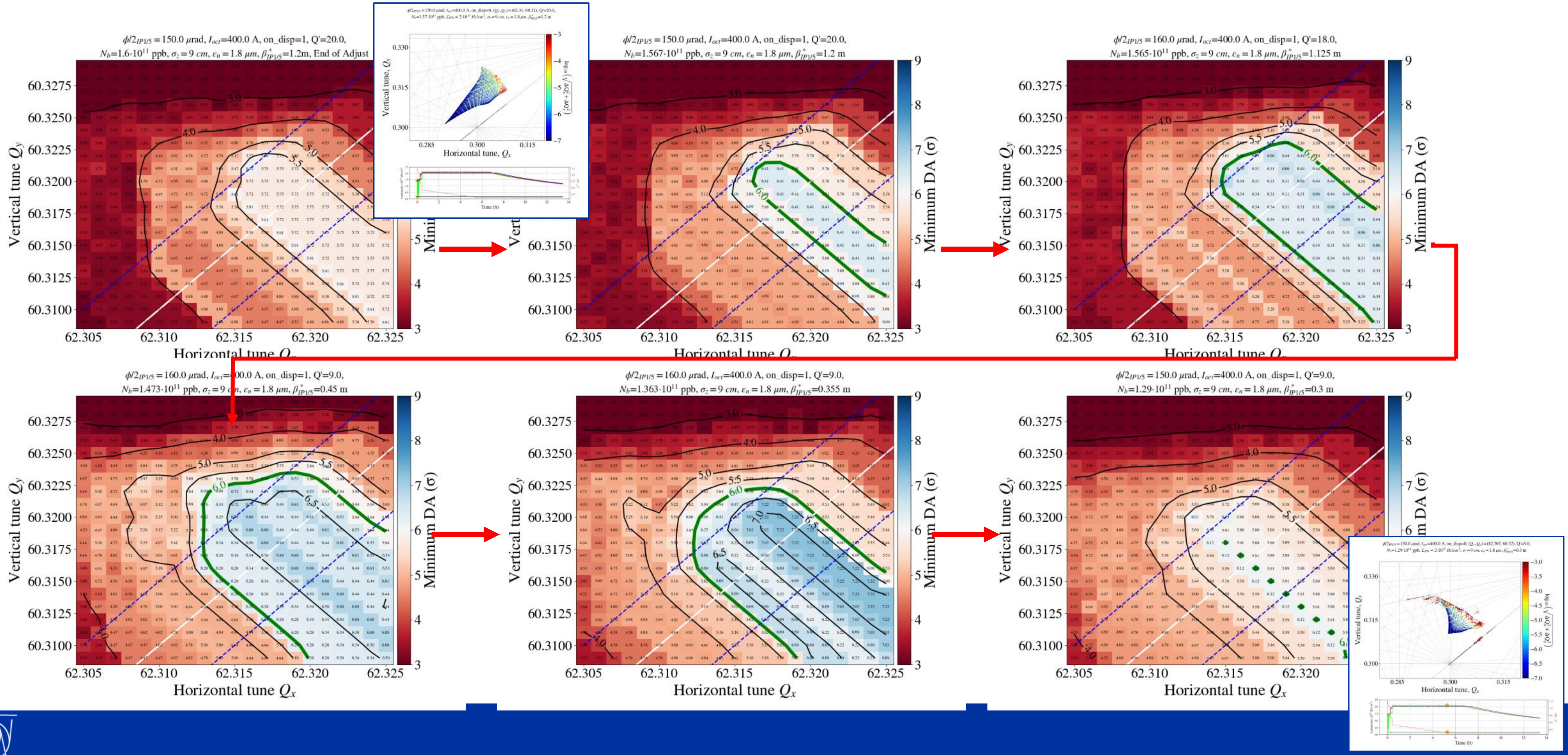
SPS measurements with 3x36 1.6e11 ppb

I. Mases Sole, F. Asvesta

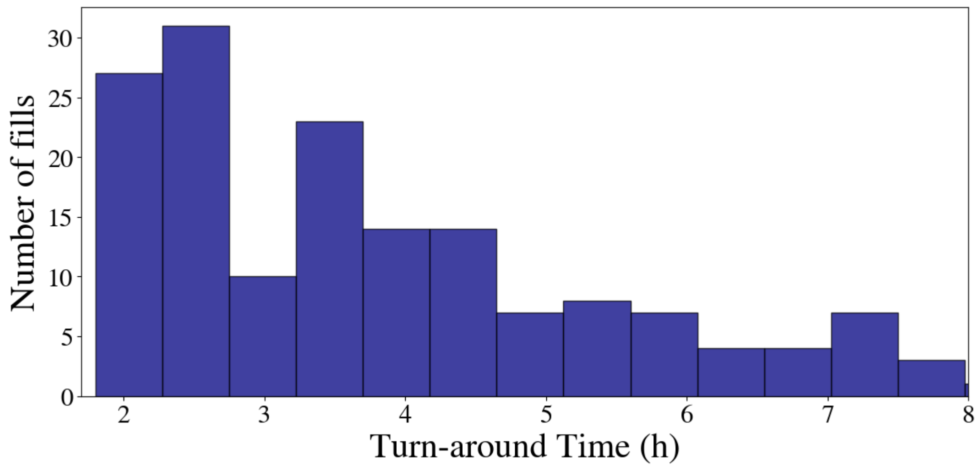


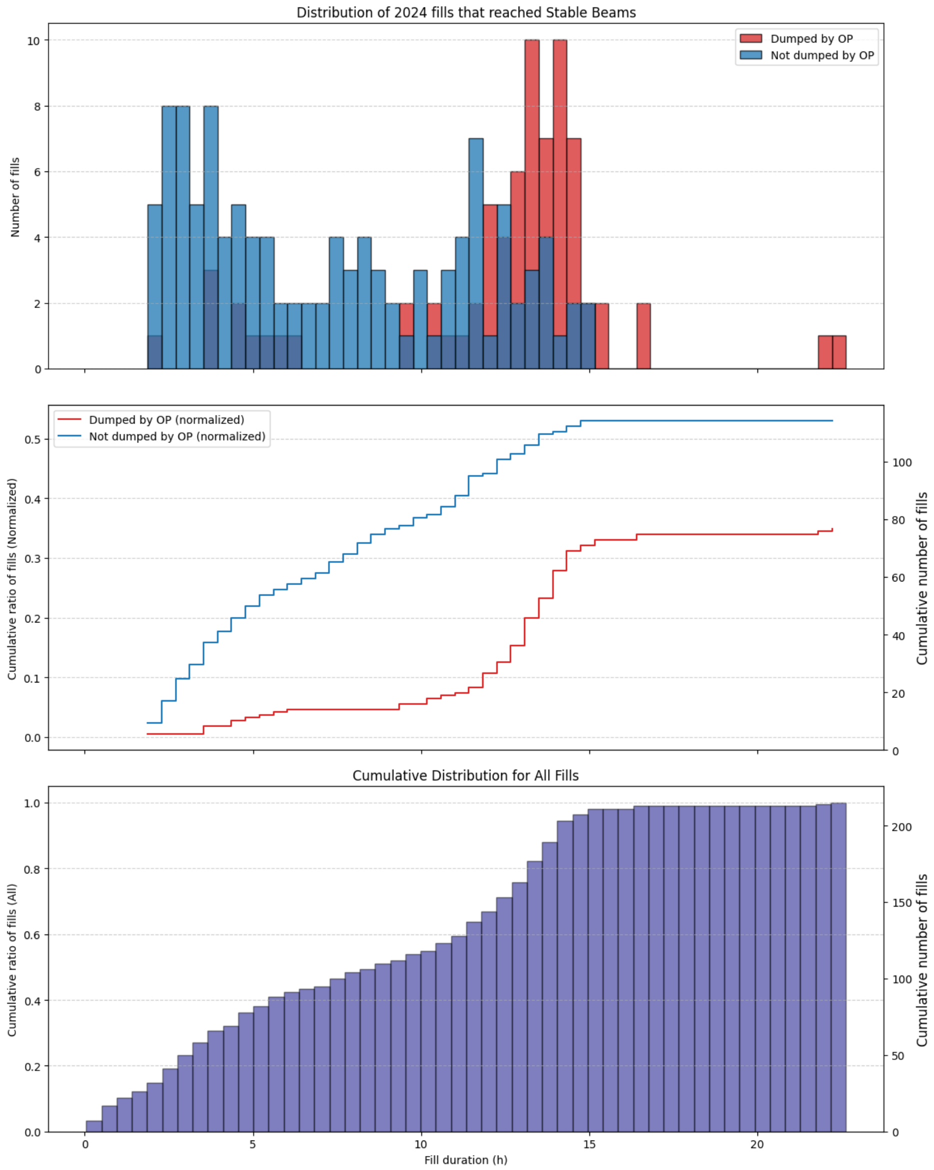


Losses during collisions: DA for 2024

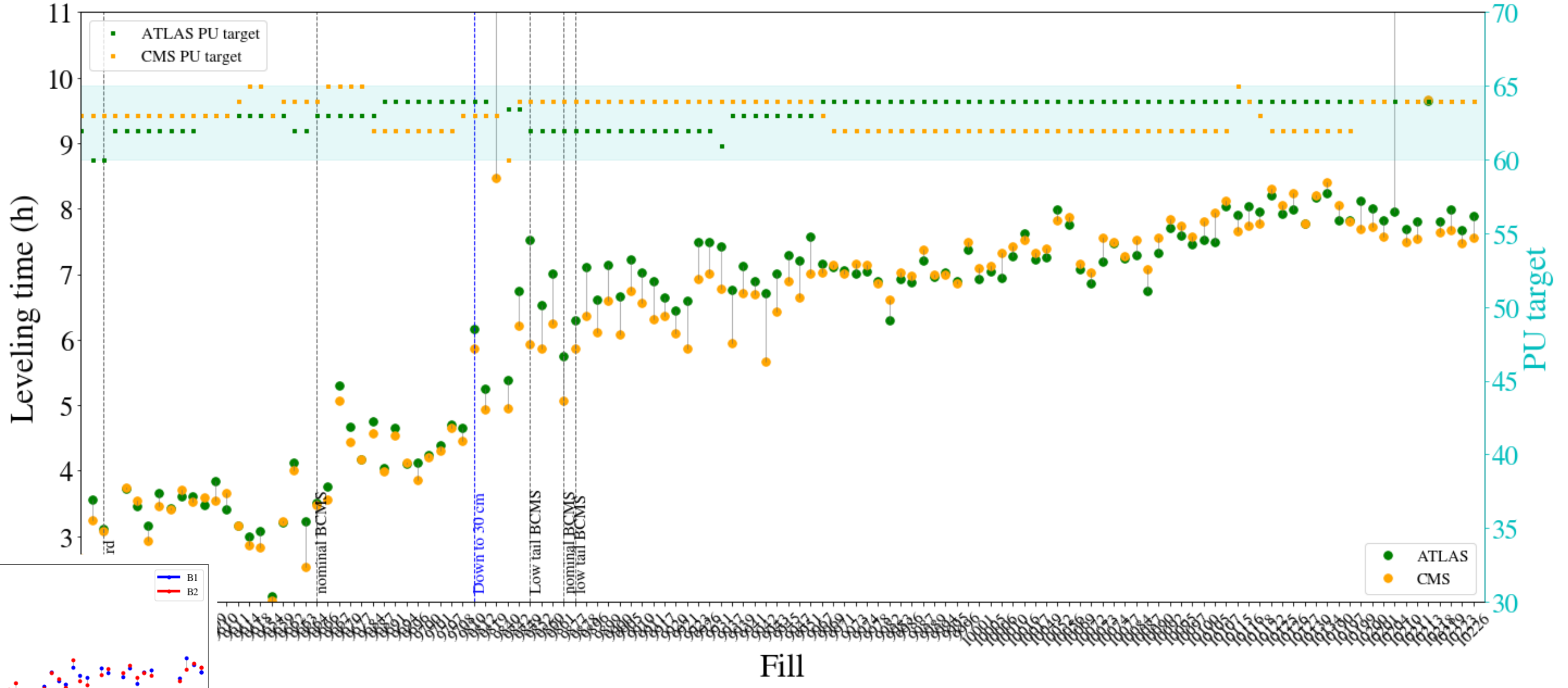


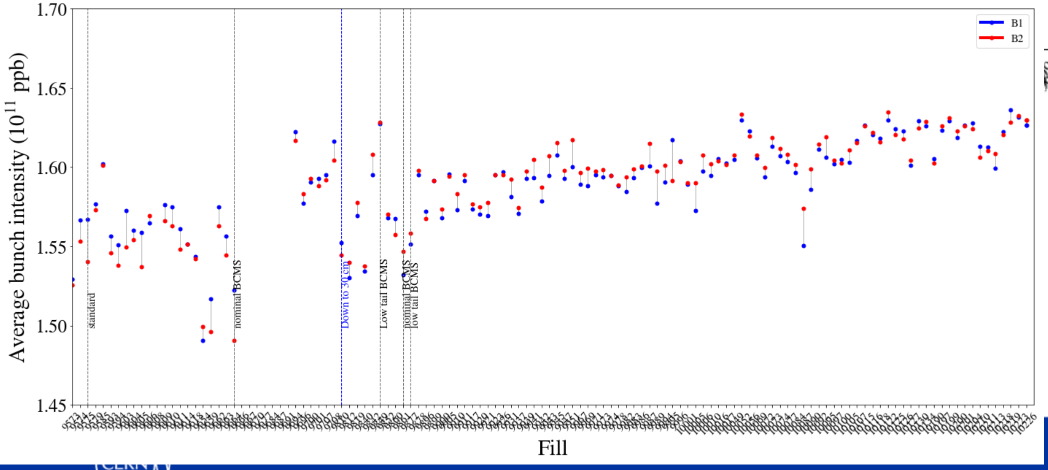
Statistics from 2024



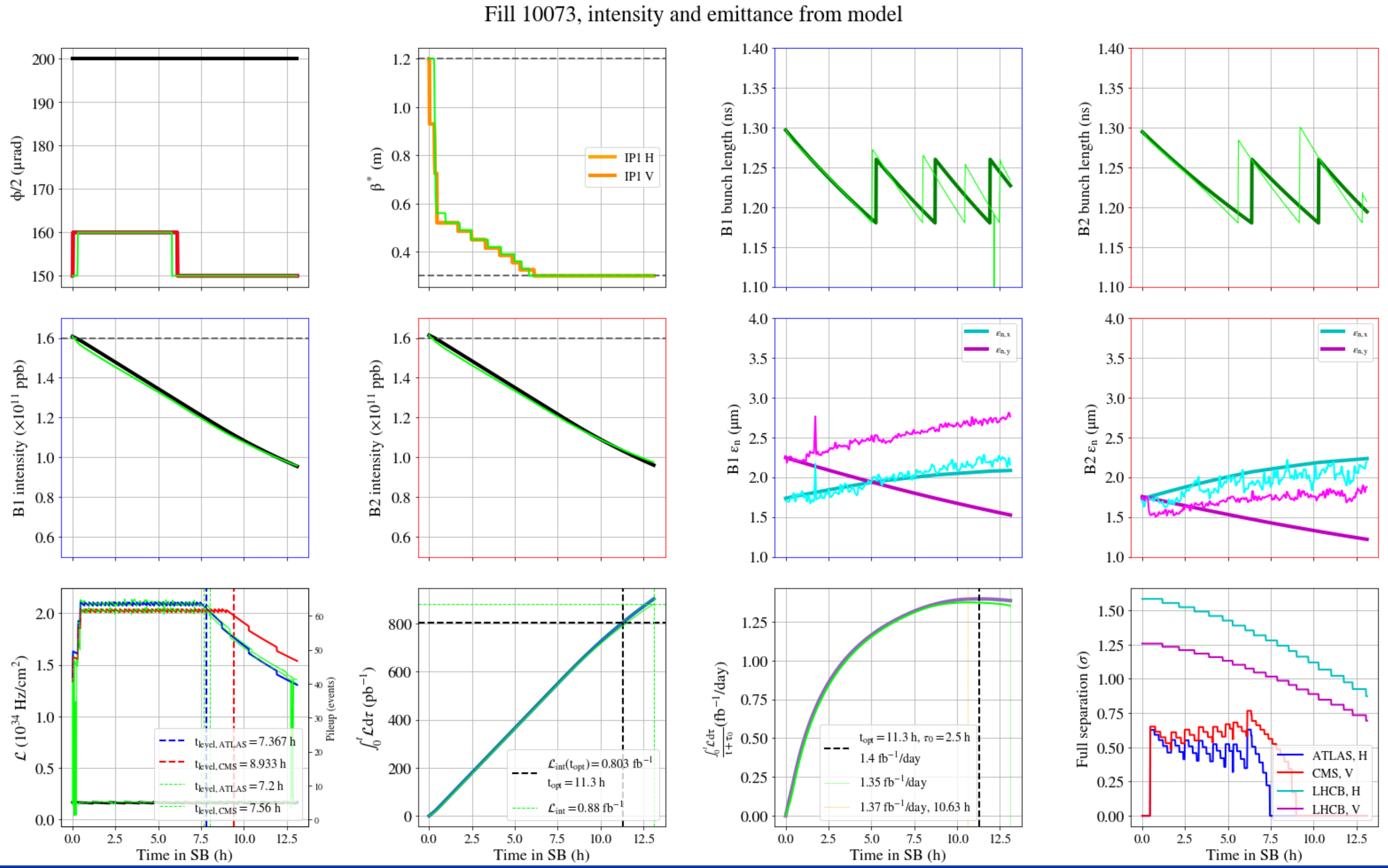


Leveling time

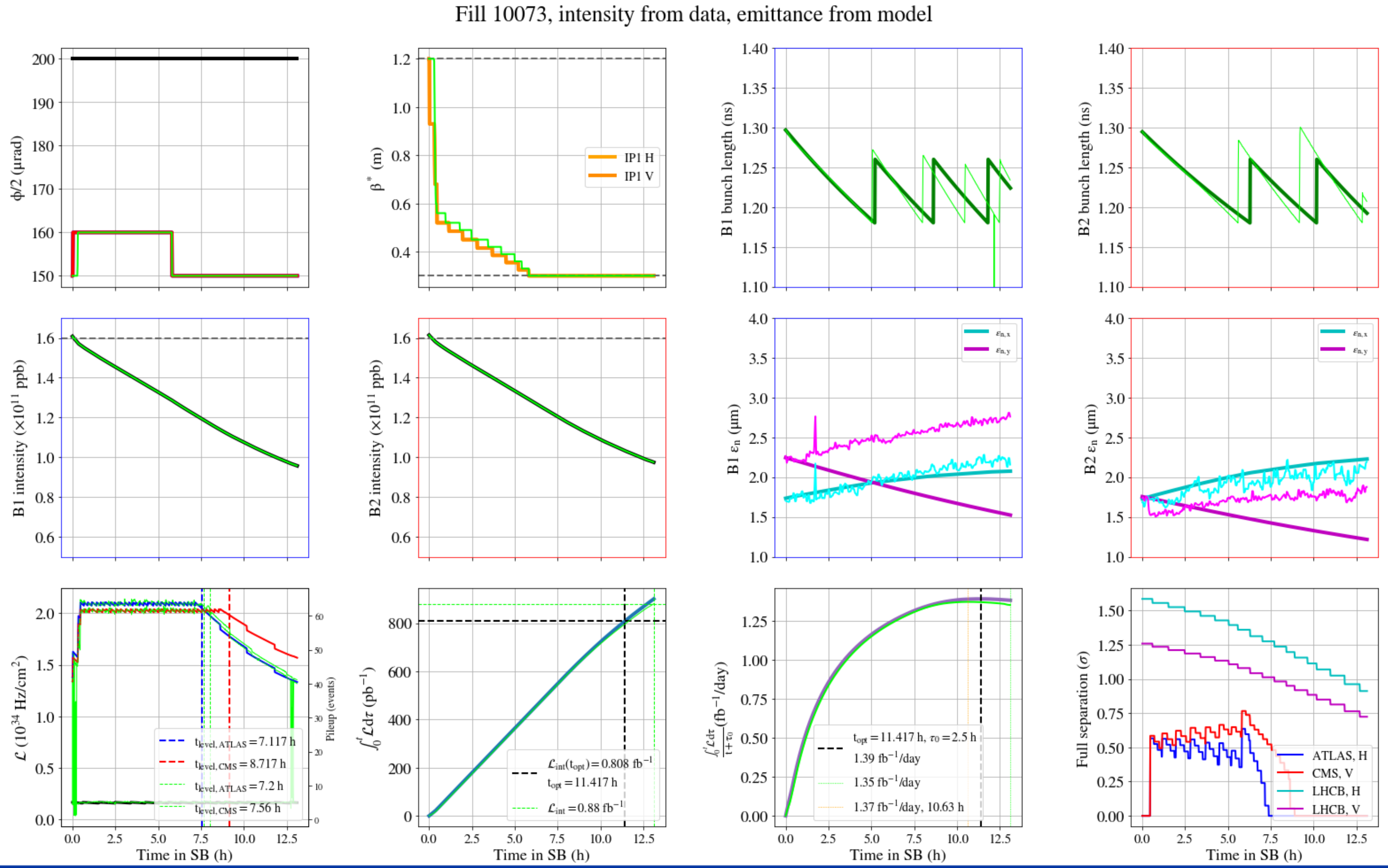




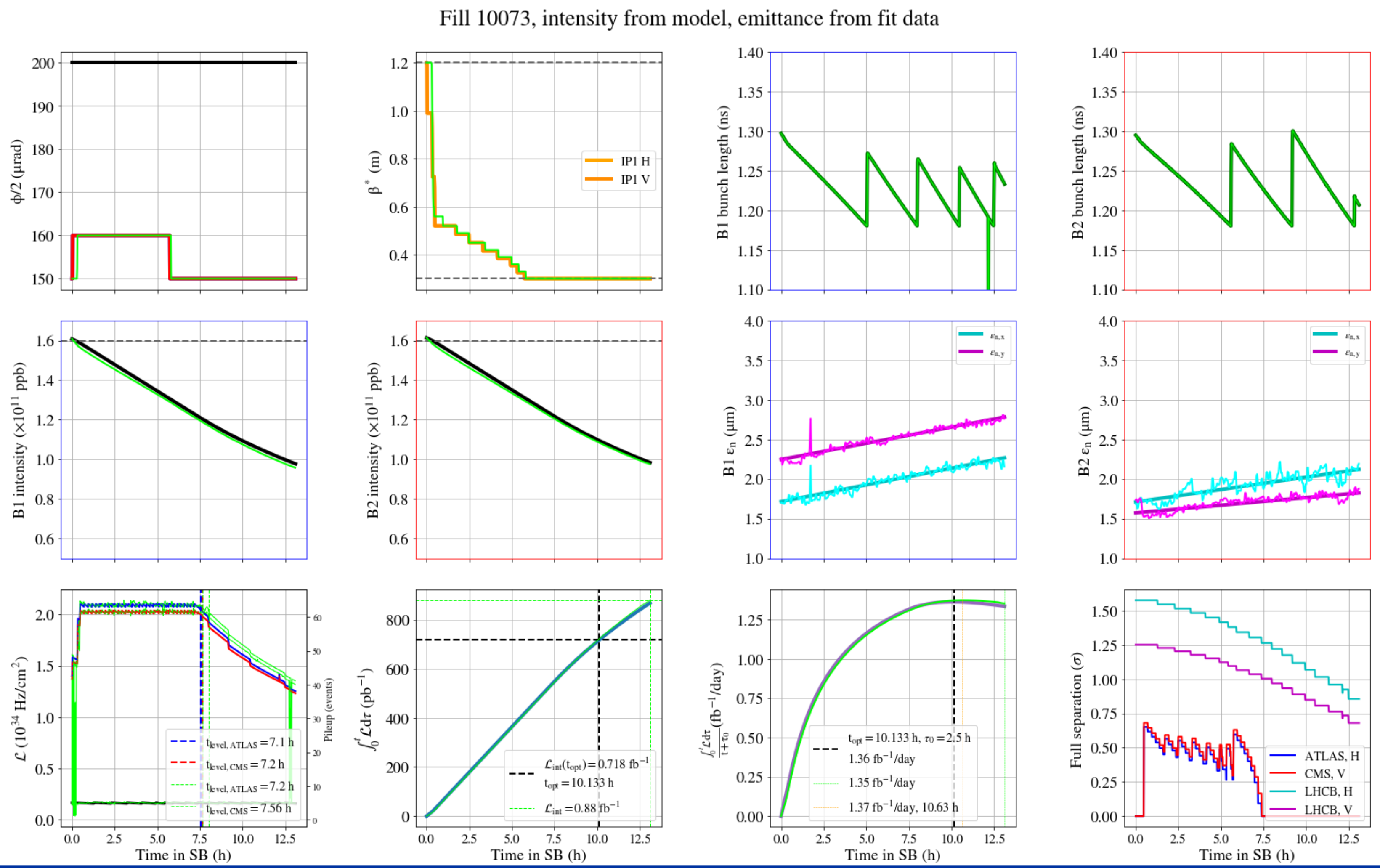
Luminosity model: pure model



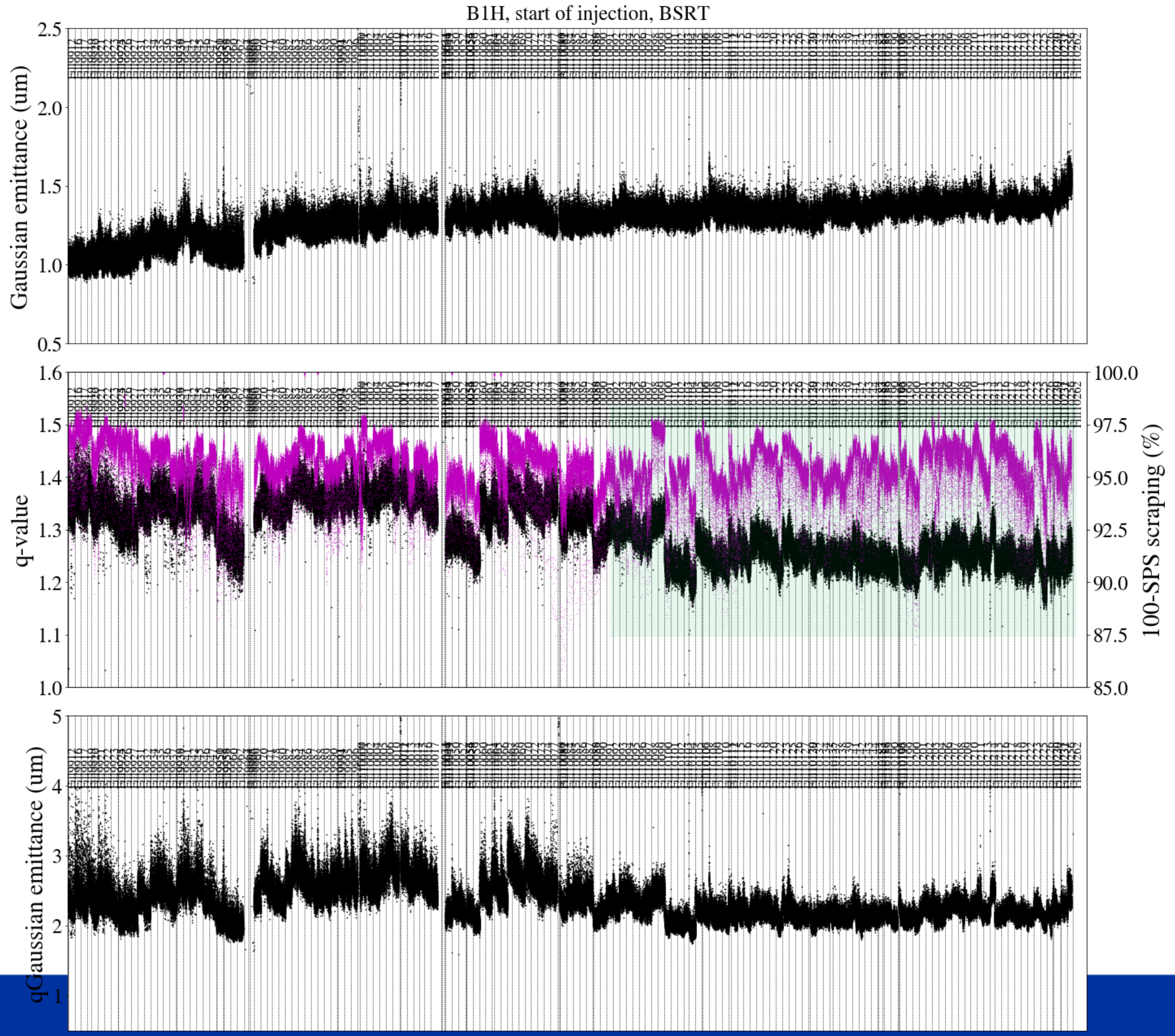
Luminosity model: extra losses



Luminosity model: extra losses & emit growth



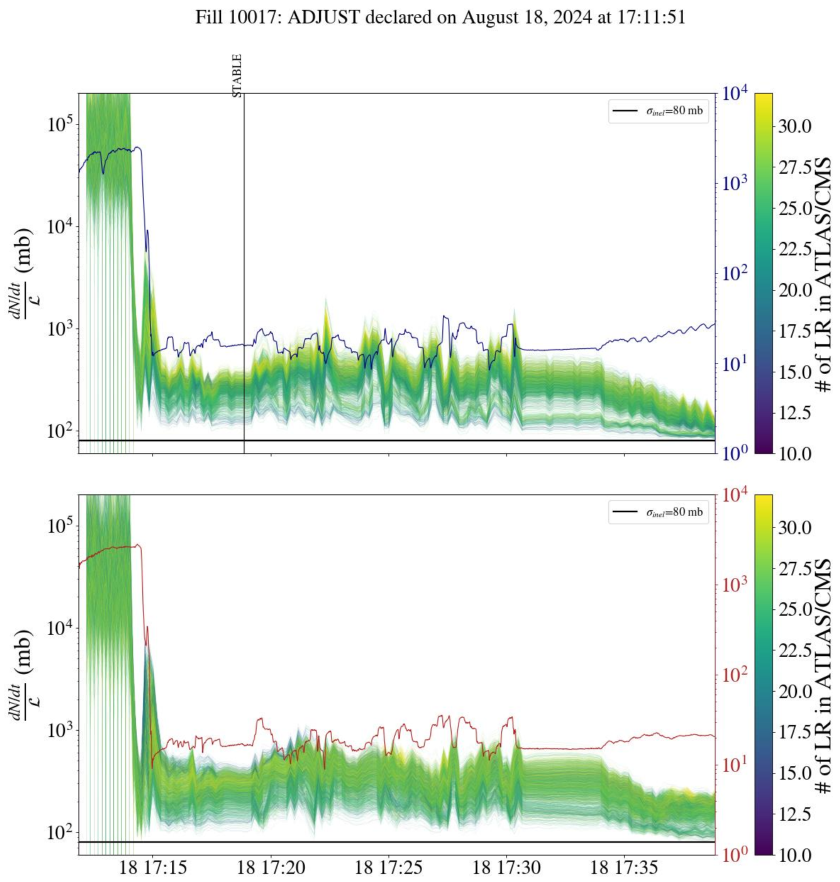
LHC injection profiles vs SPS scraping



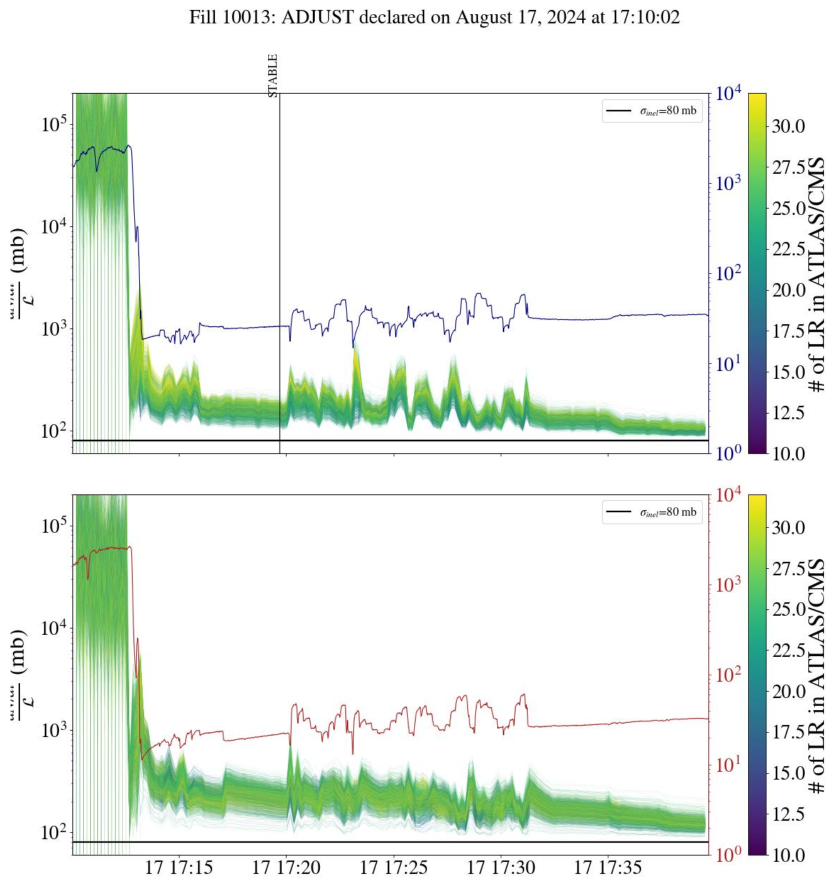
Losses during the collapse of the separation bump & start of collisions

- First year where we also observe impact from LHCb: LHCb luminosity 2e33 Hz/cm^2 while ATLAS/CMS 2e34 Hz/cm^2

Collisions in IP1/2/5/8



Collisions in IP1/2/5



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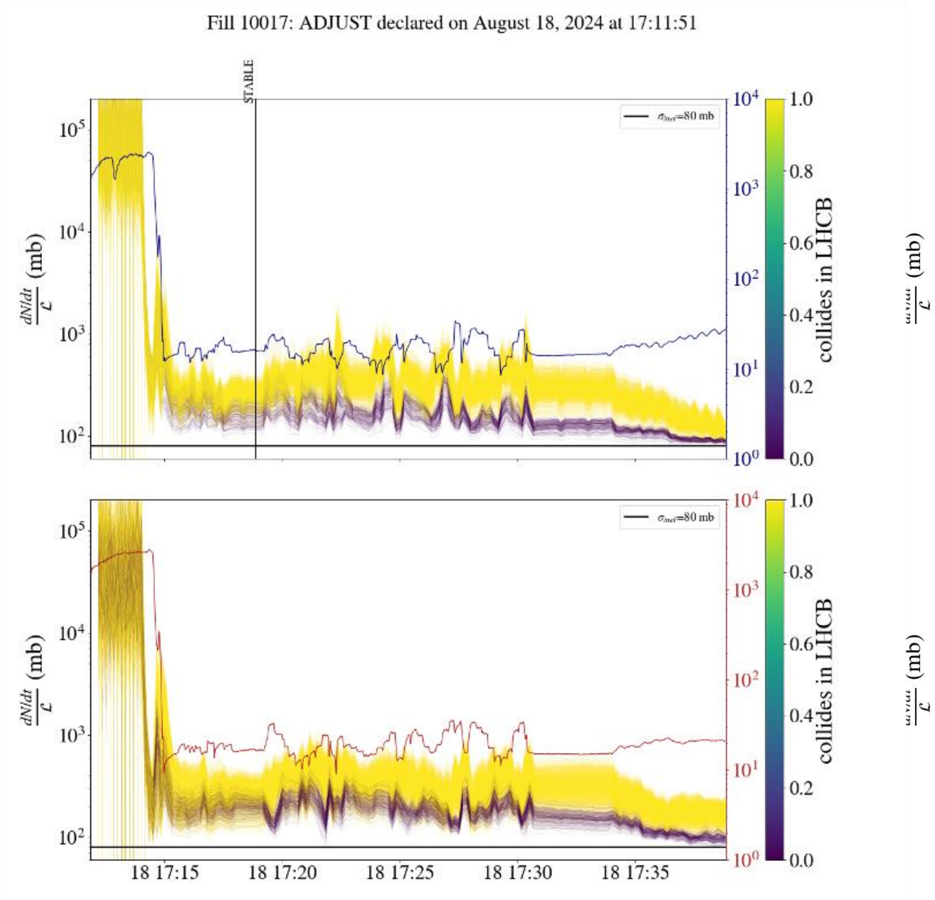
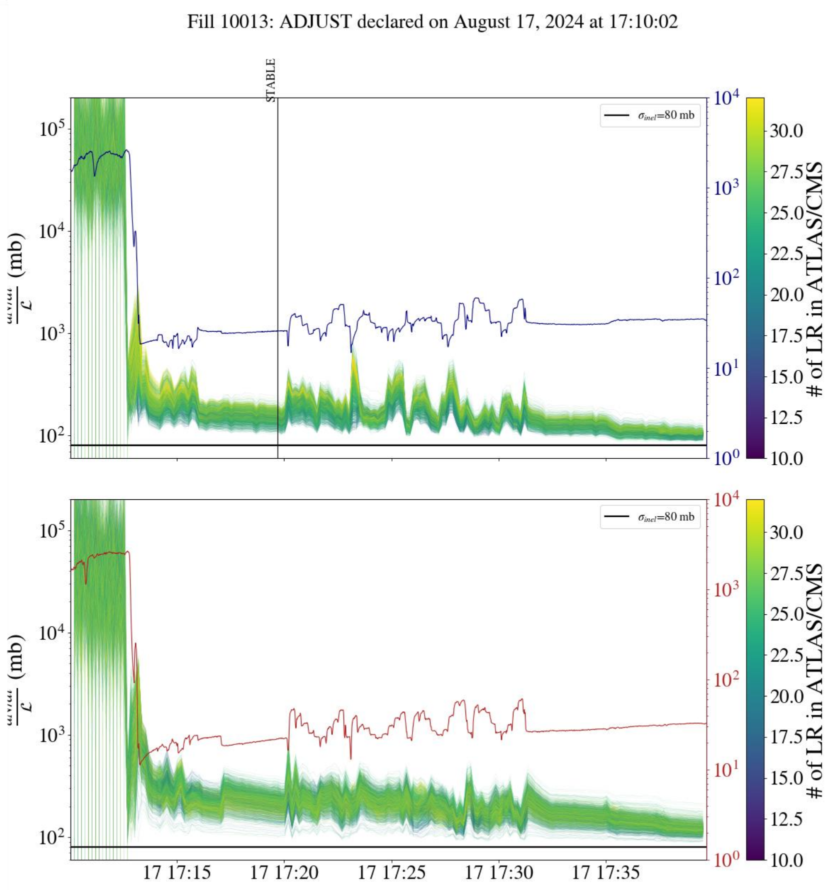
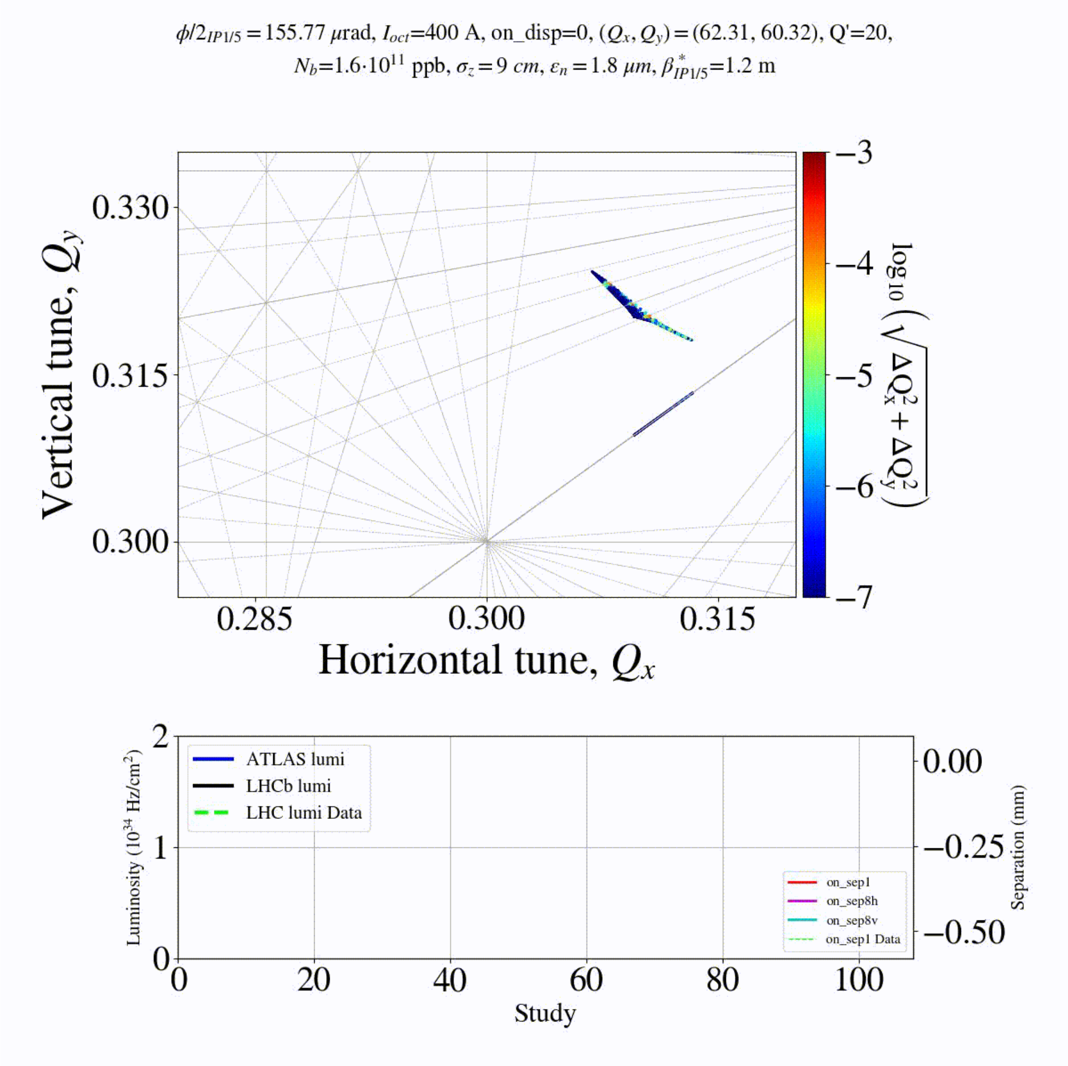
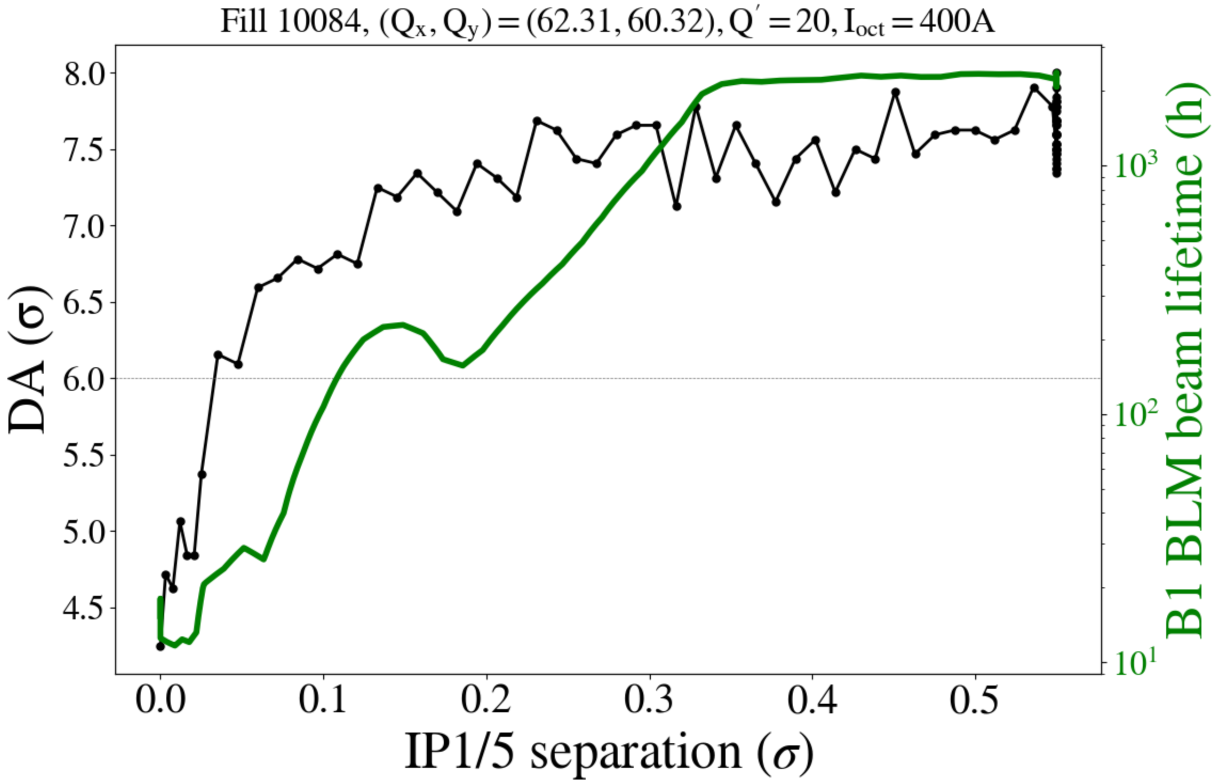


Collisions in IP1/2/5



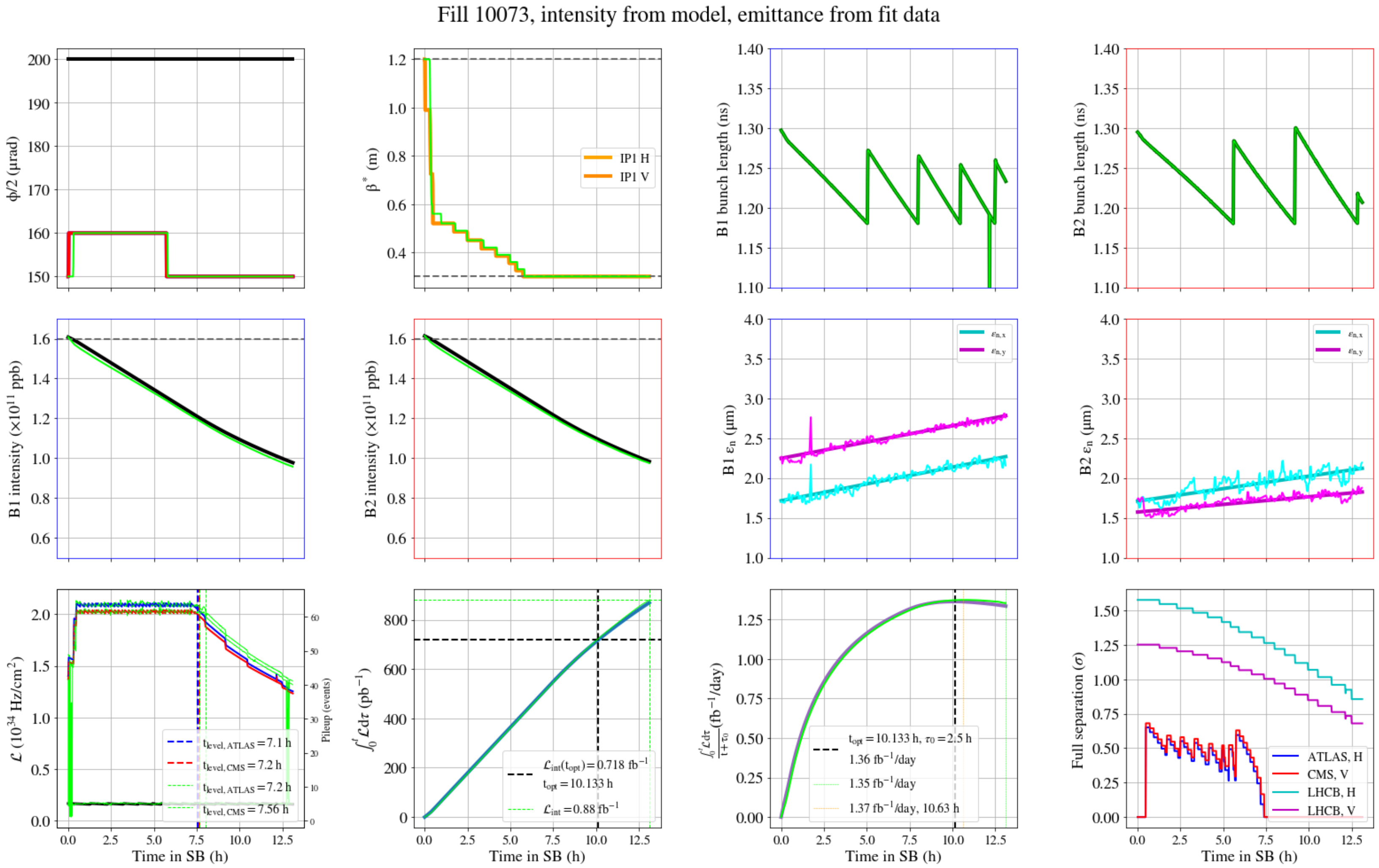
Losses during collapse and collisions





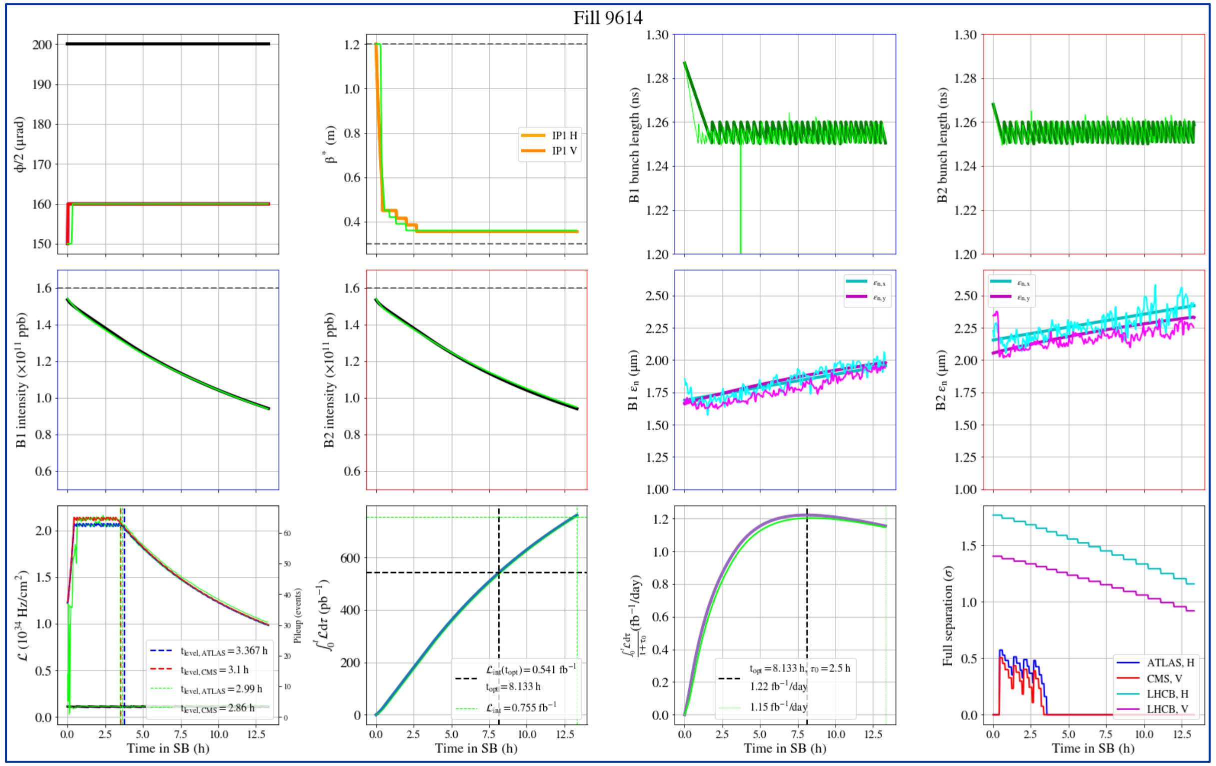
- Good correlation between DA and beam lifetime.
- Beam lifetime of ~10h indicates DA<4.5 σ

Luminosity model

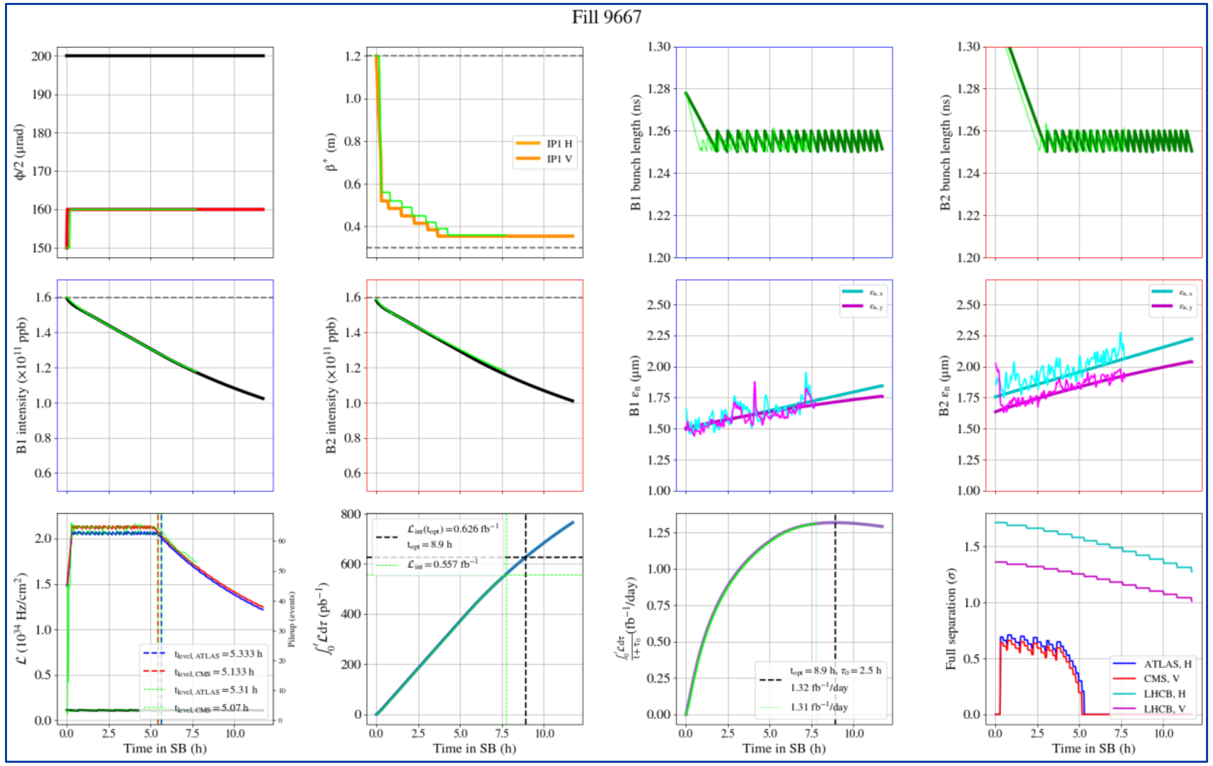


Performance gain BCMS vs standard

Fill 9614, Standard



Fill 9667, BCMS

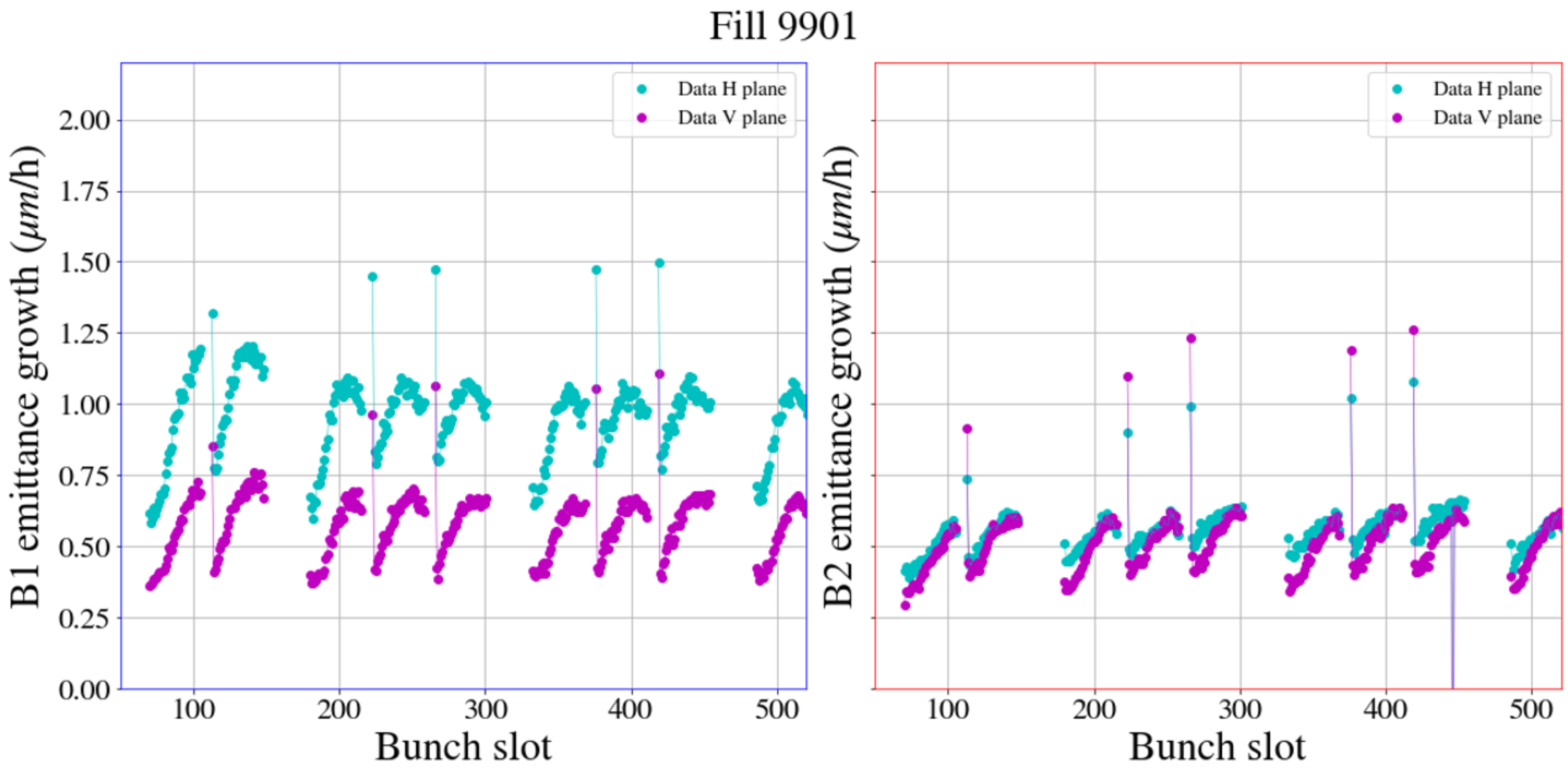


Considering a turn-around time of **2.5h**:

- From 1.22 fb^{-1}/day with standard to 1.32 fb^{-1}/day with BCMS: **+8.2%** integrated luminosity for fills that make it to the optimal fill length (>8h), **5%** from the lower emittance and **3.2%** from the intensity increase.

Emittance growth at injection

- Emittance growth mechanism at injection **not fully understood**:



Emittance growth at injection

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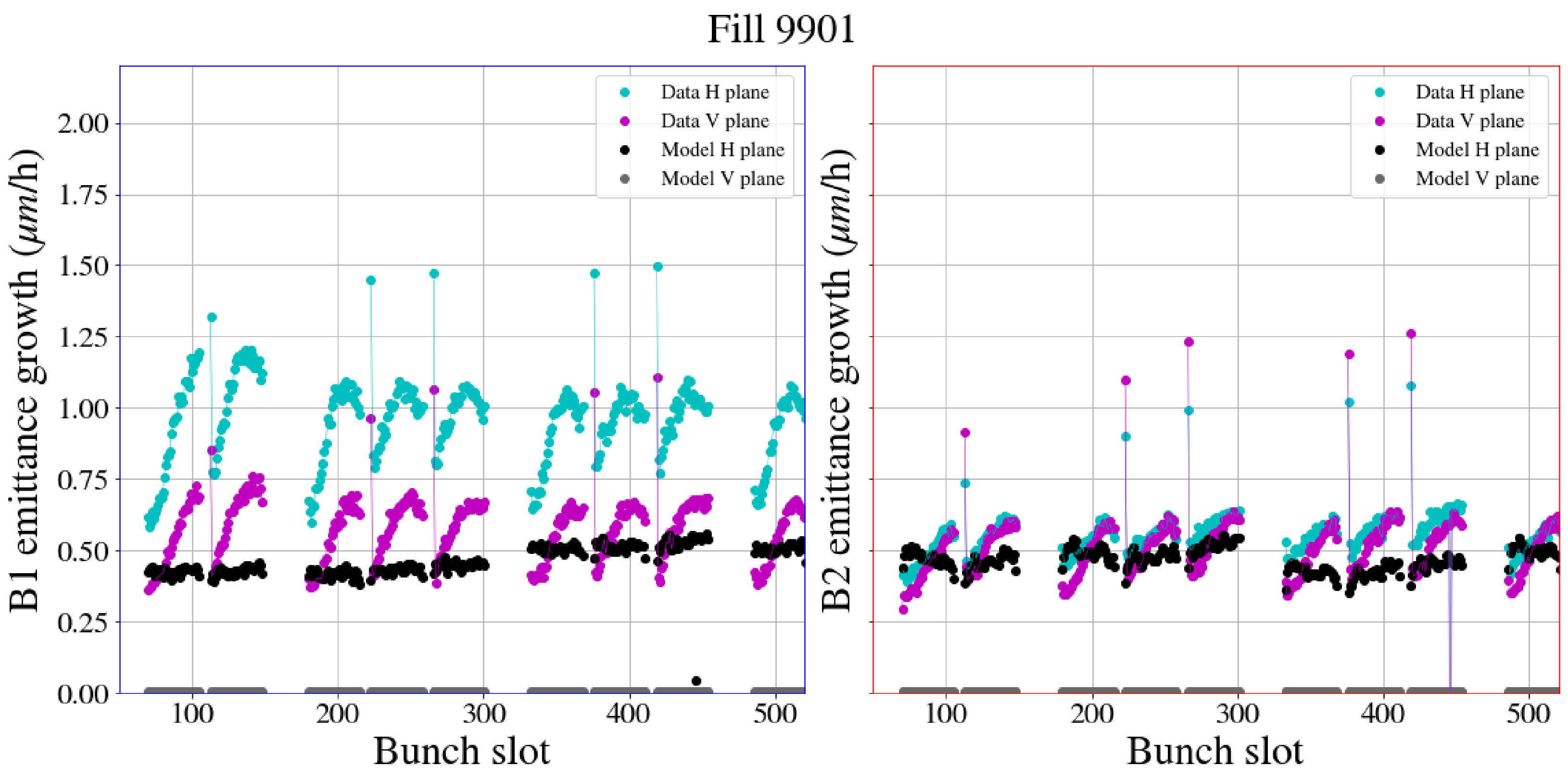
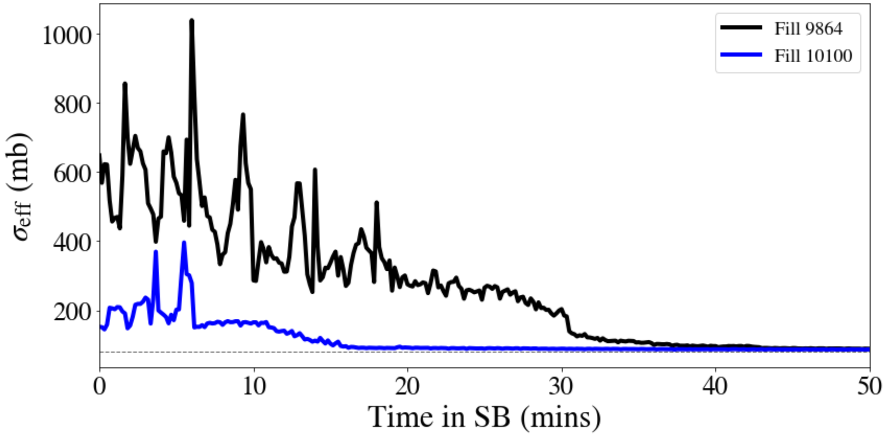
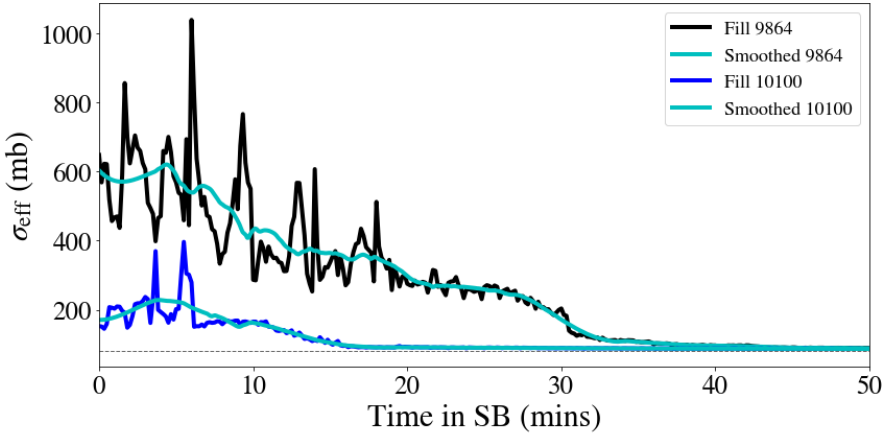
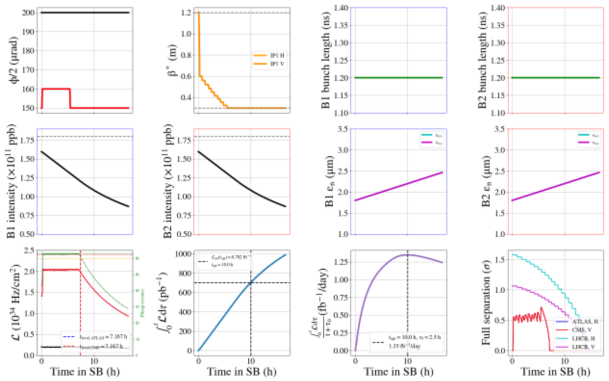


Impact of improved losses

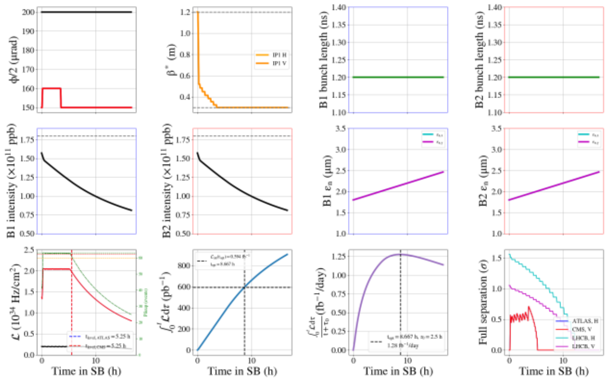




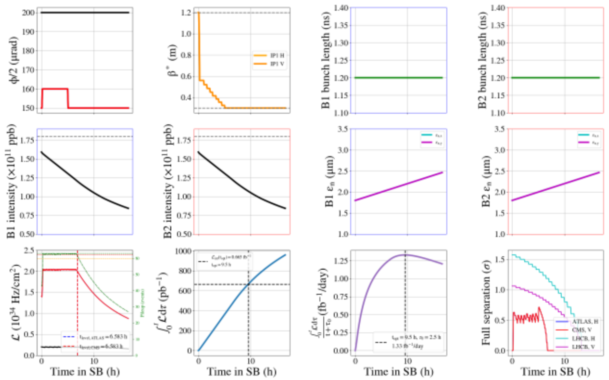
Nominal



Fill 9864



Fill 10100



Tails at injection

- Systematic profile monitoring in 2024:
  - From Fill 9912 (July), **full-cycle bunch-by-bunch BSRT profile logging in NXCALS thanks to D. Butti**.

Note on special beams (1/2):

- BSRT profiles must be deconvoluted.
- Deconvolution relies on specific information obtained during BSRT calibration fills.
- In 2024 preparation & effort from the injectors to provide Gaussian beams during these fills & simplify deconvolution, similar type of preparation for next year.

Impact on integrated luminosity

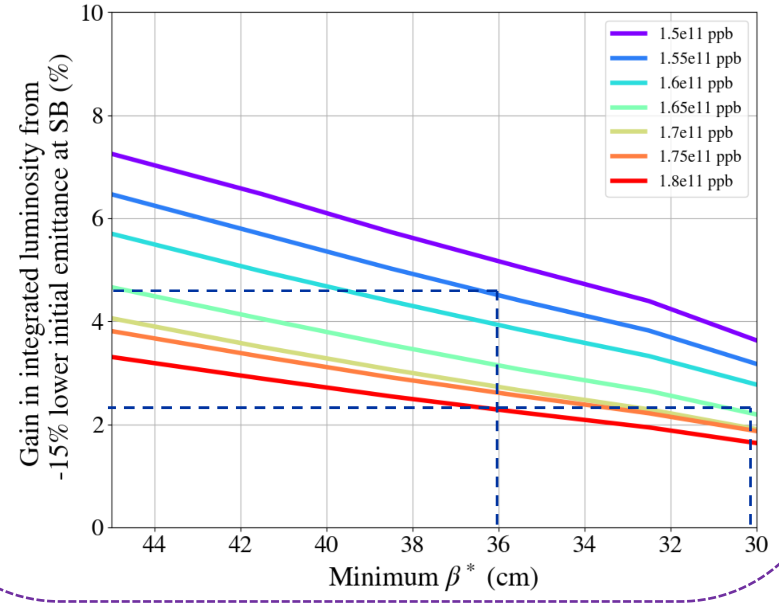
- Luminosity model provides **accurate predictions for beam parameter evolution & luminosity estimates** throughout a fill: can include additional effects beyond theoretical models to match the data.
- Considering ideal case where fills are dumped at **optimal fill length** and **turn-around of 2.5 h.**

Standard vs nominal BCMS in 2024

Assuming **-15% emittance reduction** at start of SB **as only difference**:

- $\beta_{min} \geq$ 36cm: **5% gain**, confirmed with experimental data.
- β_{min} = 30cm & 1.65e11 ppb: **2-2.5% gain**.

for fills that made it to optimal fill length (10h) with τ=2.5 h



"Low-tail" BCMS:

- On average, reduction of σ_{eff} from ~100 mb to ~85 mb after Fill 10100.
- Exact contribution of tails on luminosity to be studied.
- **Maximum gain up to 4%** for fills reaching optimal fill length with τ=2.5 h.