

Emittance during the cycle and luminosity lifetime: what have we learned and expectations for HL-LHC

F. Antoniou, E. Bravin, I. Efthymiopoulos, M. Hostettler,
G. Iadarola, **N. Karastathis**, S. Papadopoulou,
Y. Papaphilippou, **D. Pellegrini**, H. Timko, G. Trad

7th HL-LHC Collaboration Meeting
16/11/17



Outline

What have we learned

- Emittance evolution over the 2017 run (BCMS vs. 8b4e)
 - At injection as compared to the model
 - During stable beams, colliding vs. non-colliding
- Evolution of bunch profiles in the LHC
- Beam lifetime
 - Losses at the beginning of stable beams
 - For the two beams and beam flavors during run II

Expectations for HL-LHC

- Luminosity prediction based on the model (IBS+SR), including extra emittance blow up

Performance follow-up

- Based on extracted data from TIMBER and modeling
- Automated tool for performance follow-up (emittance, lifetime, luminosity,...) for the whole run

F. Antoniou, G. Iadarola, I. Efthymiopoulos, N. Karastathis, Y. Papaphilippou

Emittance and lifetime evolution

- Only fills that made it to stable beams

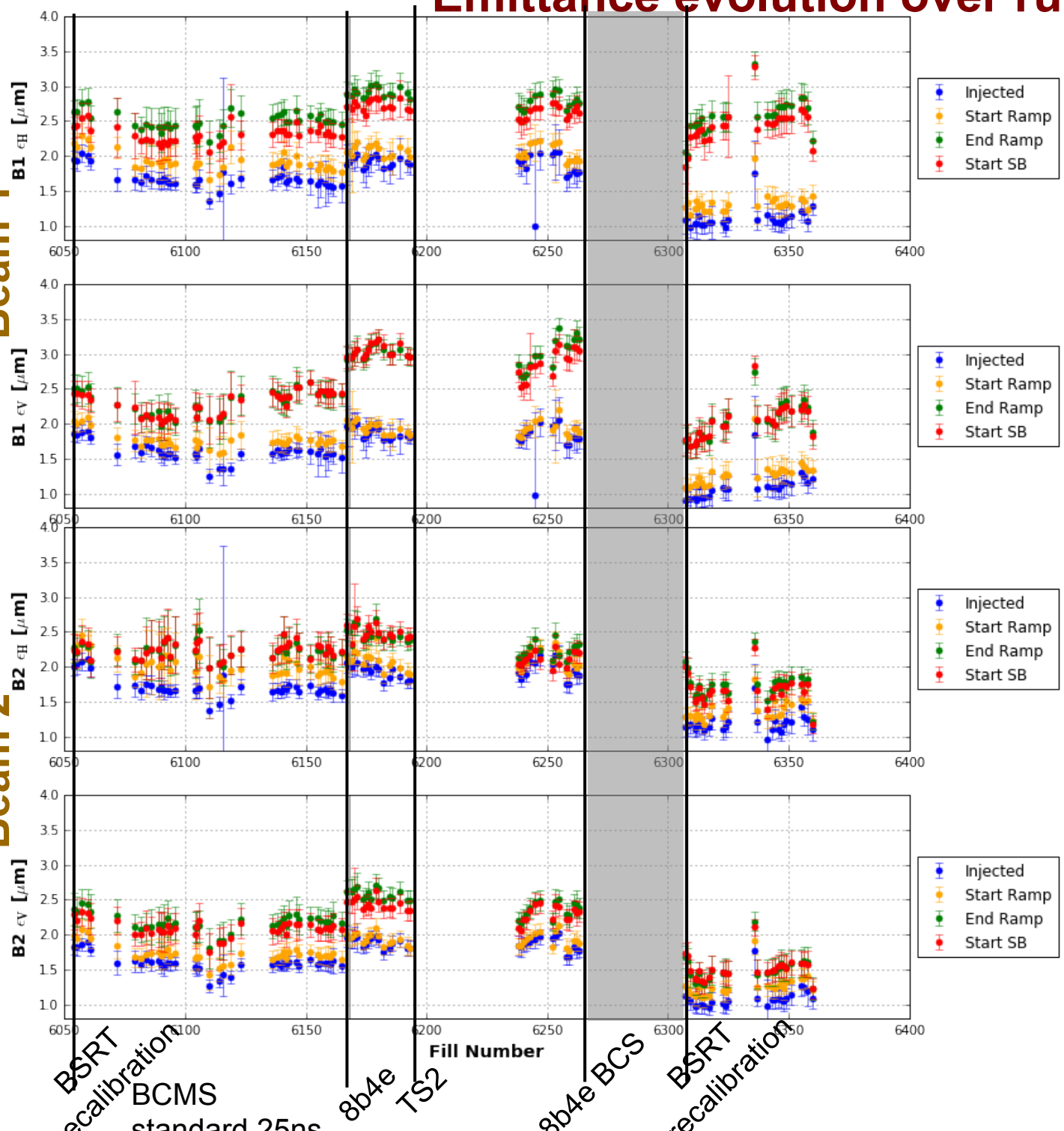
2017 Run periods

- Intensity ramp up until TS1
- BCMS standard 25ns, only after BSRT calibration
- 8b4e
- 8b4e BCS, only after BSRT calibration and new spot

Emittance evolution over run

Beam 1

Beam 2



Injected
Start Ramp
End Ramp
Start SB

Injected
Start Ramp
End Ramp
Start SB

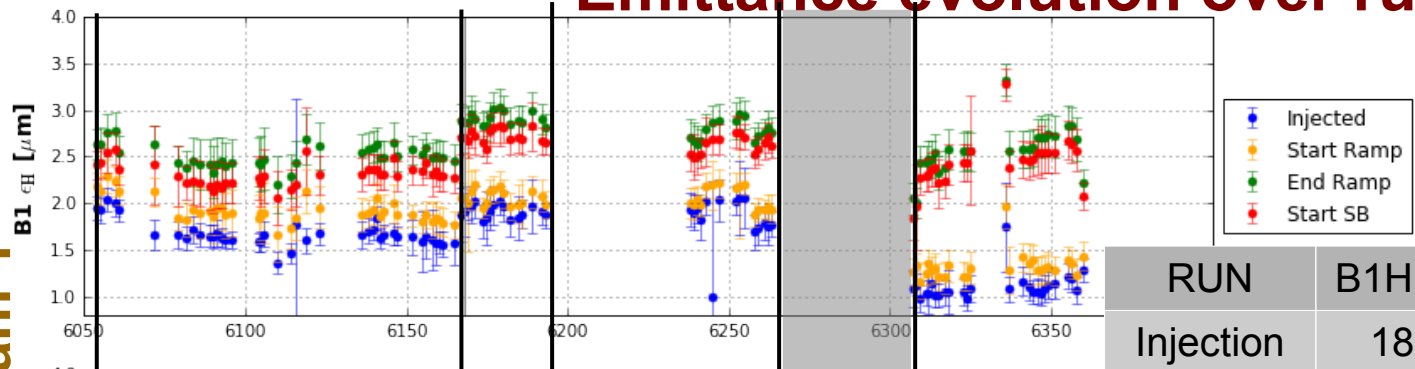
Injected
Start Ramp
End Ramp
Start SB

Injected
Start Ramp
End Ramp
Start SB

BSRT recalibration
BCMS standard 25ns
8b4e
TS2
8b4e BCS
BSRT recalibration

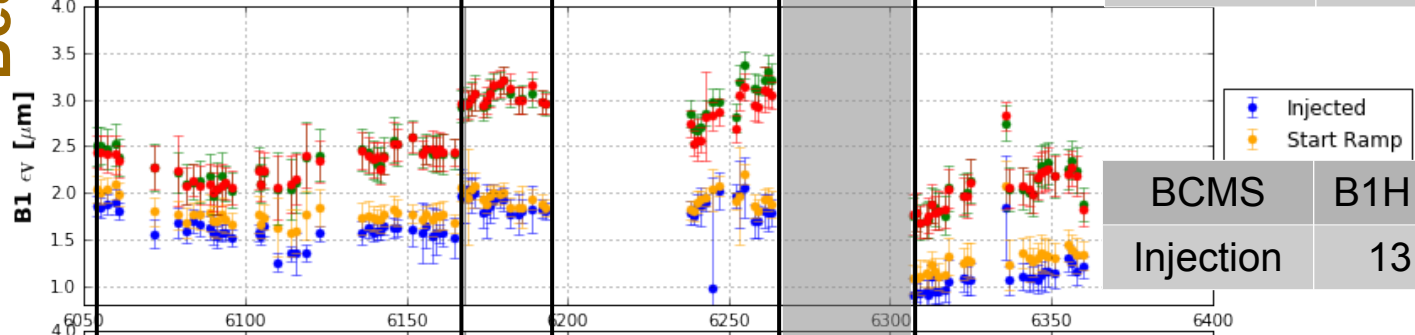
Emittance evolution over run

Beam 1

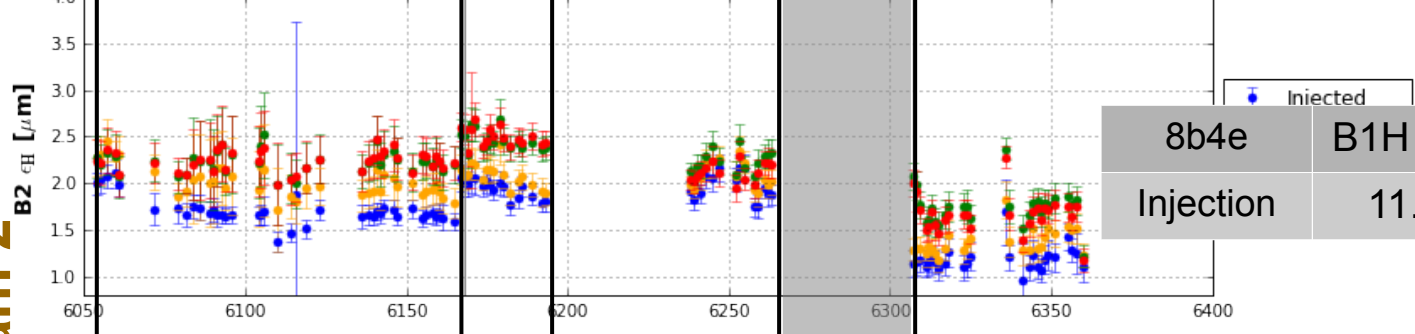


RUN	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	18.8	14.9	18.0	12.6

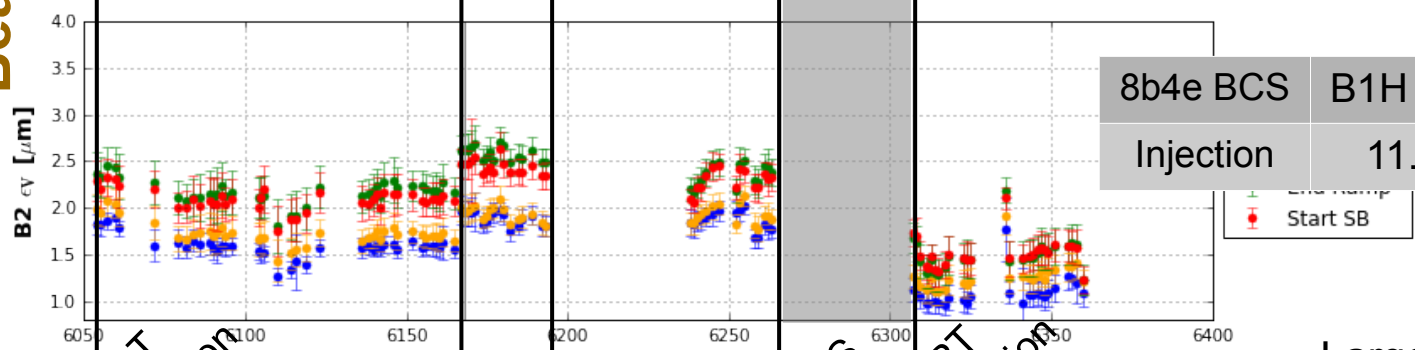
Beam 2



BCMS	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	13.9	9.9	16.3	8.1



8b4e	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	11.4	7.0	7.3	3.2



8b4e BCS	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	11.7	10.1	12.1	11.1

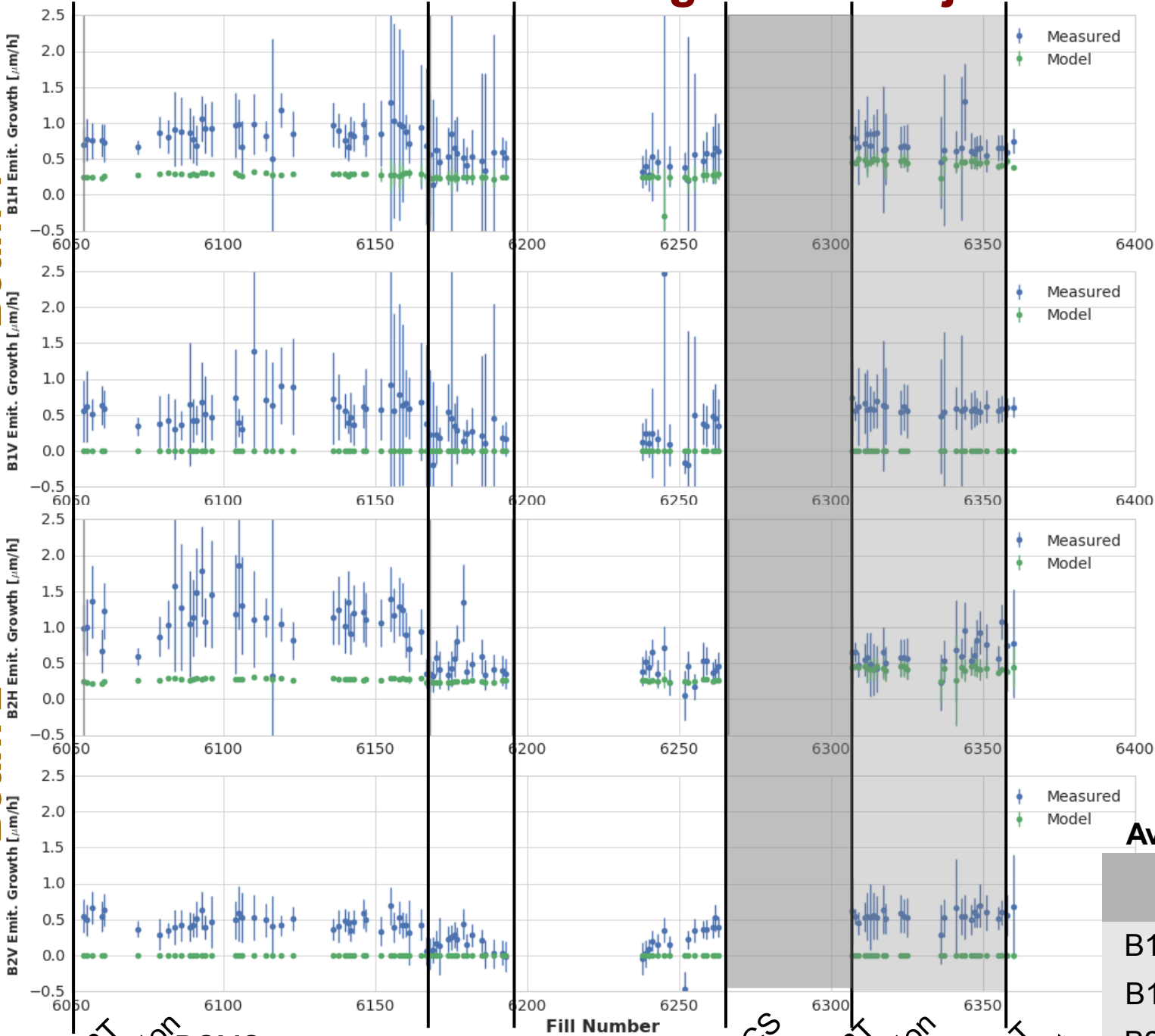
BSRT recalibration
BCMS standard 25ns
8b4e
TS2
8b4e BCS
BSRT recalibration

Larger emittance growth for BCMS at injection, whereas 8b4e closer to the model.

Emittance growth at Injection

Beam 1

Beam 2



Measured emittance growth approaches model predictions for 8b4e, better for B2. Extra blow-up mostly due to e-cloud.

Average growth rates [$\mu\text{m/h}$]

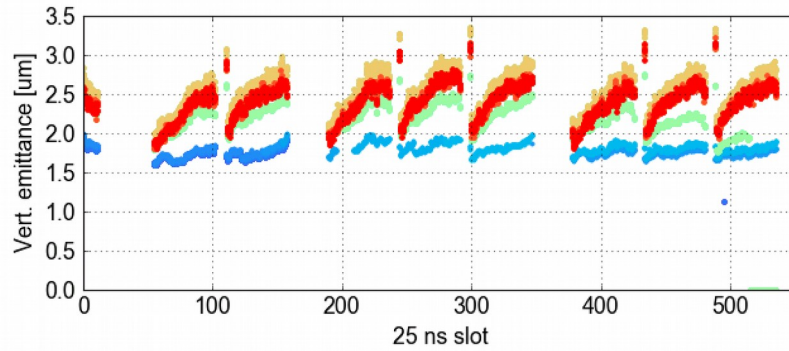
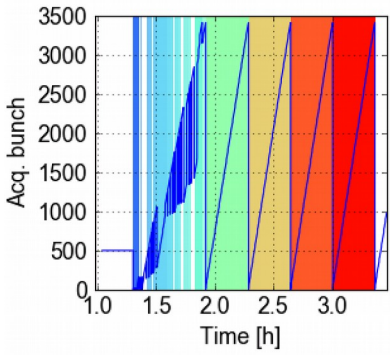
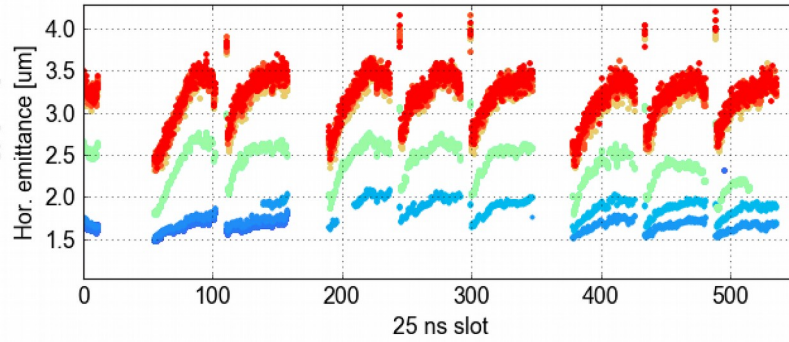
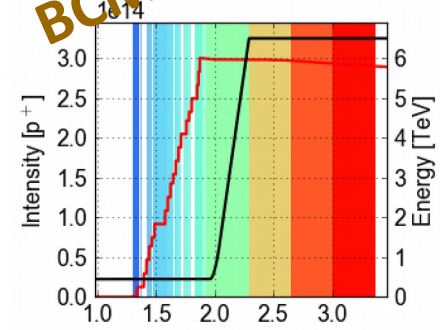
	Measured	Model
B1H	0.73	0.26
B1V	0.46	0.00
B2H	0.83	0.26
B2V	0.34	0.00

BSRT recalibration BCMS standard 25ns 8b4e TS2 8b4e BCS BSRT recalibration BSRT new spot

Emittance along BCMS and 8b4e trains

Fill 5887: B2, started on Thu, 29 Jun 2017 19:51:42

BCMS

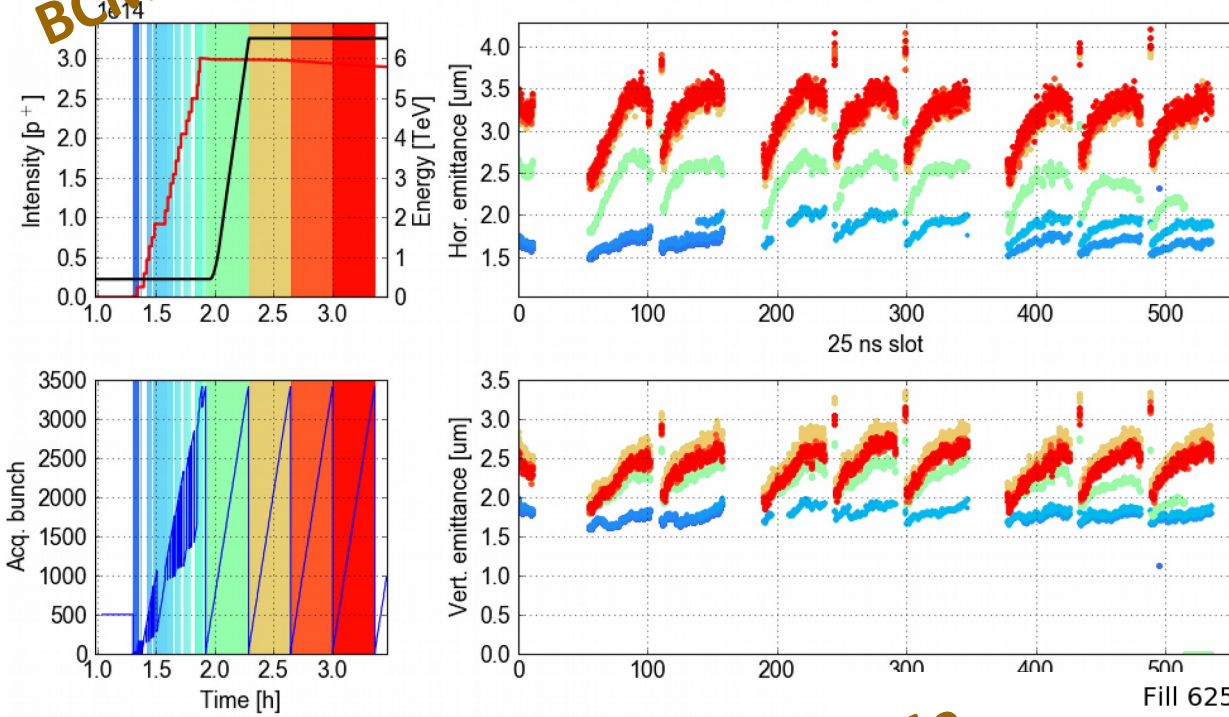


e-cloud pattern for BCMS

Emittance along BCMS and 8b4e trains

Fill 5887: B2, started on Thu, 29 Jun 2017 19:51:42

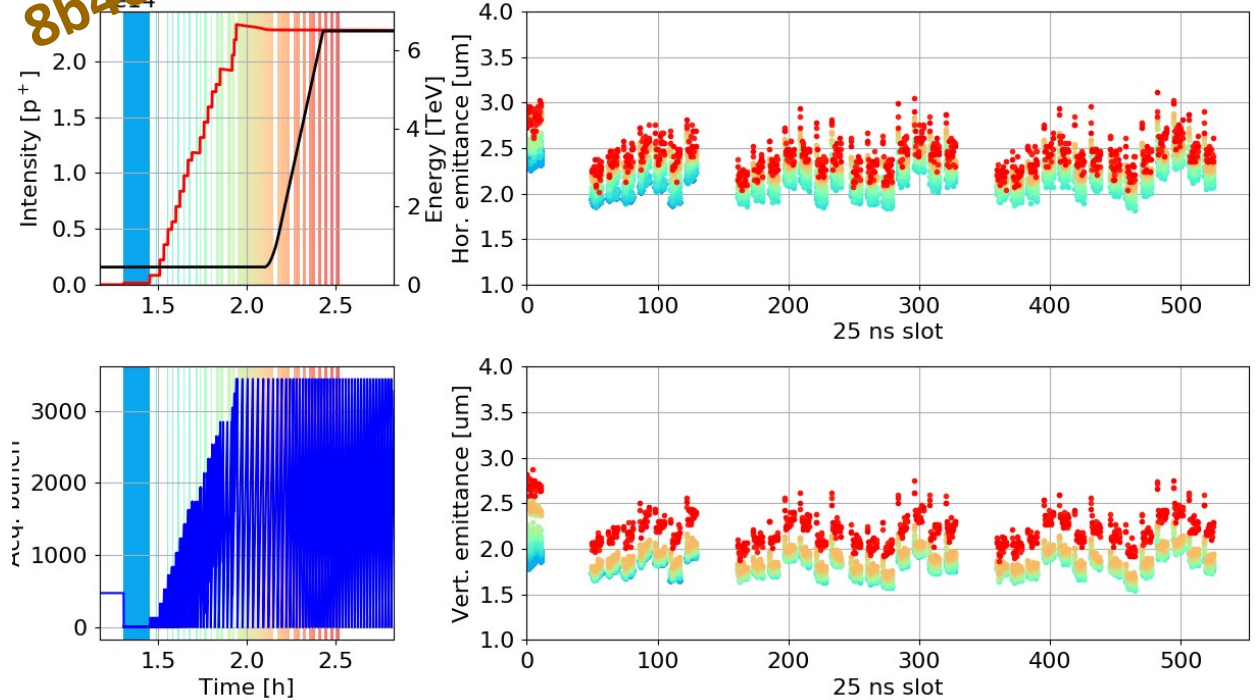
BCMS



e-cloud pattern for BCMS

Fill 6253: B2, started on Thu, 28 Sep 2017 11:29:20

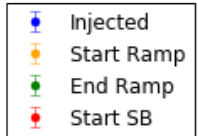
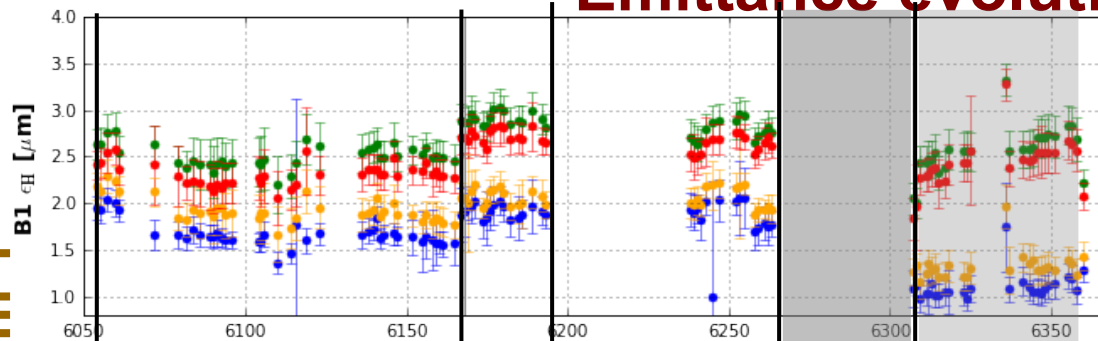
8b4e



no e-cloud pattern for 8be4

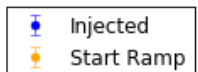
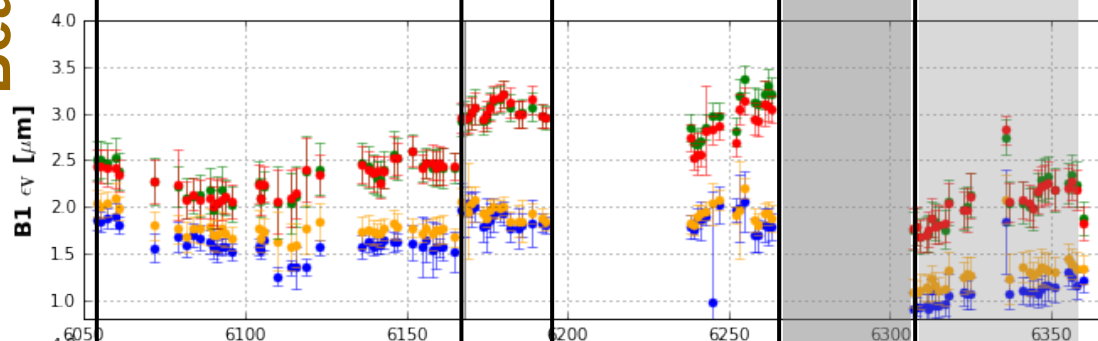
Emittance evolution over run

Beam 1

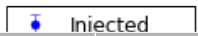
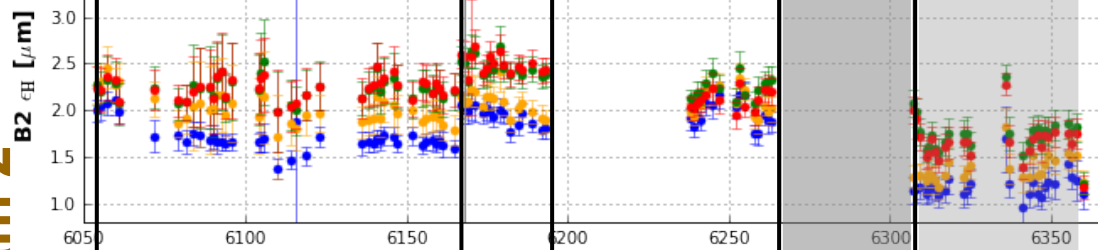


RUN	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	18.8	14.9	18.0	12.6
Ramp	49.1	45.0	20.0	27.2

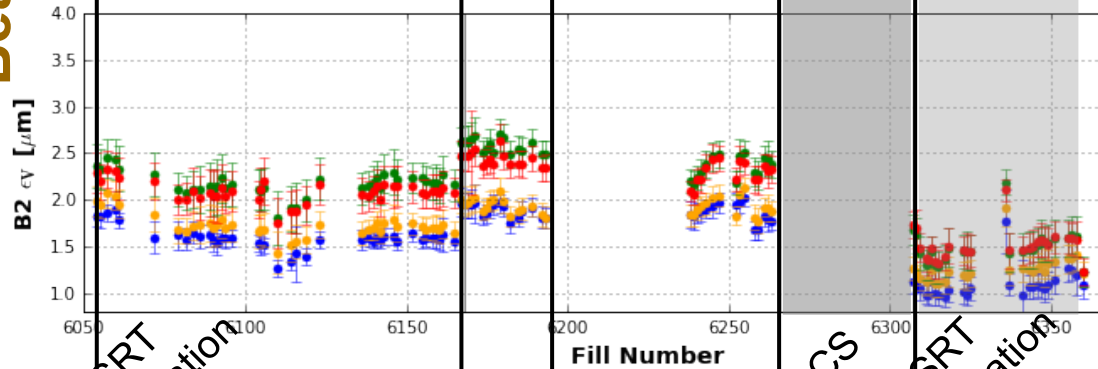
Beam 2



BCMS	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	13.9	9.9	16.3	8.1
Ramp	32.7	26.8	15.1	23.1



8b4e	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	11.4	7.0	7.3	3.2
Ramp	38.7	55.7	13.2	28.3



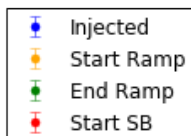
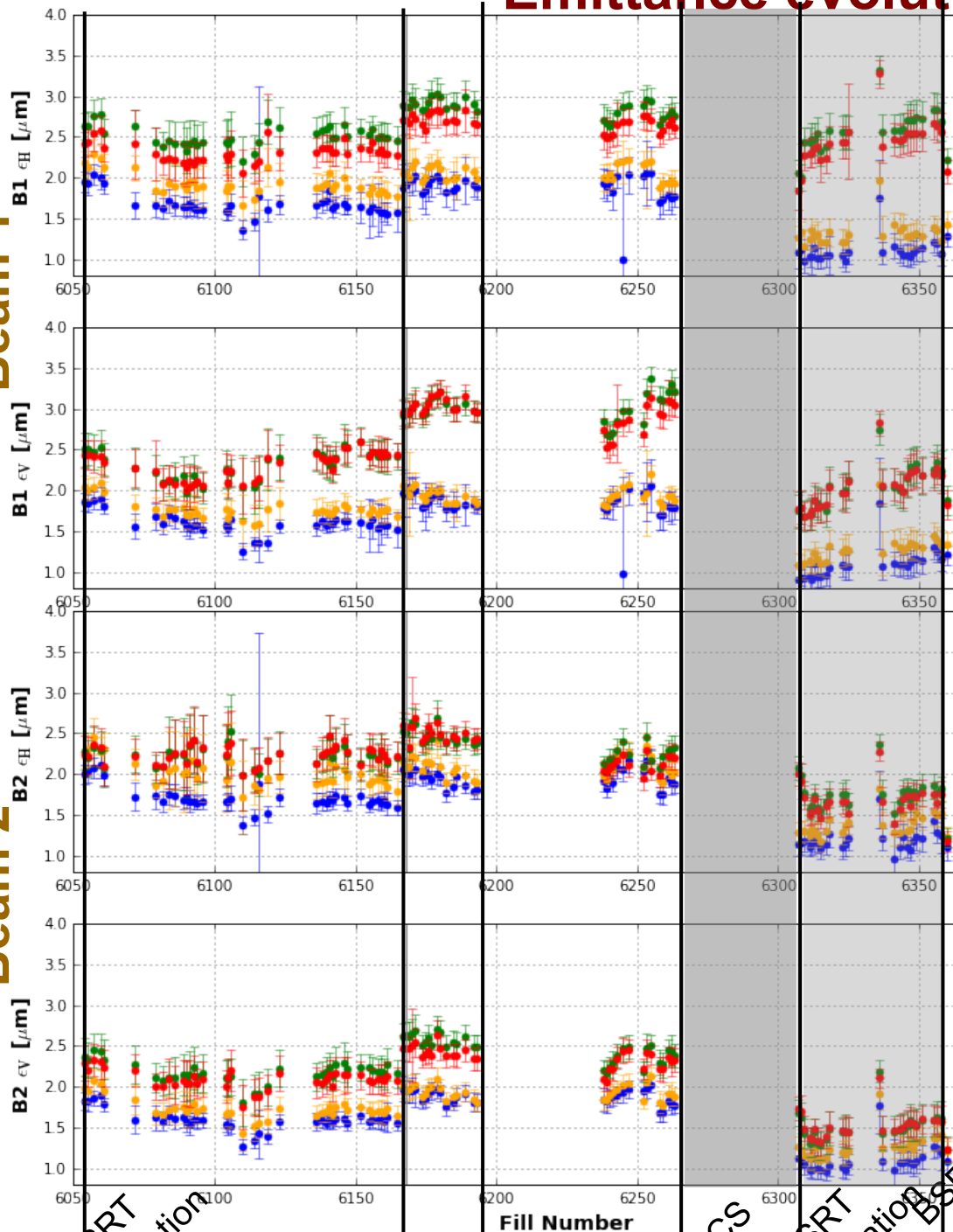
8b4e BCS	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	11.7	10.1	12.1	11.1
Ramp	54.7	40.6	-0.9	2.7

BSRT recalibration
BCMS standard 25ns
8b4e
TS2
8b4e BCS
BSRT recalibration

Large growth during ramp, mostly for B1, significantly increased for the 8be4 and BCS case.

Emittance evolution over run

Beam 1



RUN	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	18.8	14.9	18.0	12.6
Ramp	49.1	45.0	20.0	27.2
Flat Top	-5.6	2.3	1.4	1.1
BCMS	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	13.9	9.9	16.3	8.1
Ramp	32.7	26.8	15.1	23.1
Flat Top	-6.3	-0.6	0.9	-2.5
8b4e	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	11.4	7.0	7.3	3.2
Ramp	38.7	55.7	13.2	28.3
Flat Top	-5.9	-1.7	-0.9	-4.0
8b4e BCS	B1H [%]	B1V [%]	B2H [%]	B2V [%]
Injection	11.7	10.1	12.1	11.1
Ramp	54.7	40.6	-0.9	2.7
Flat Top	-6.2	-2.7	-3.9	-0.7

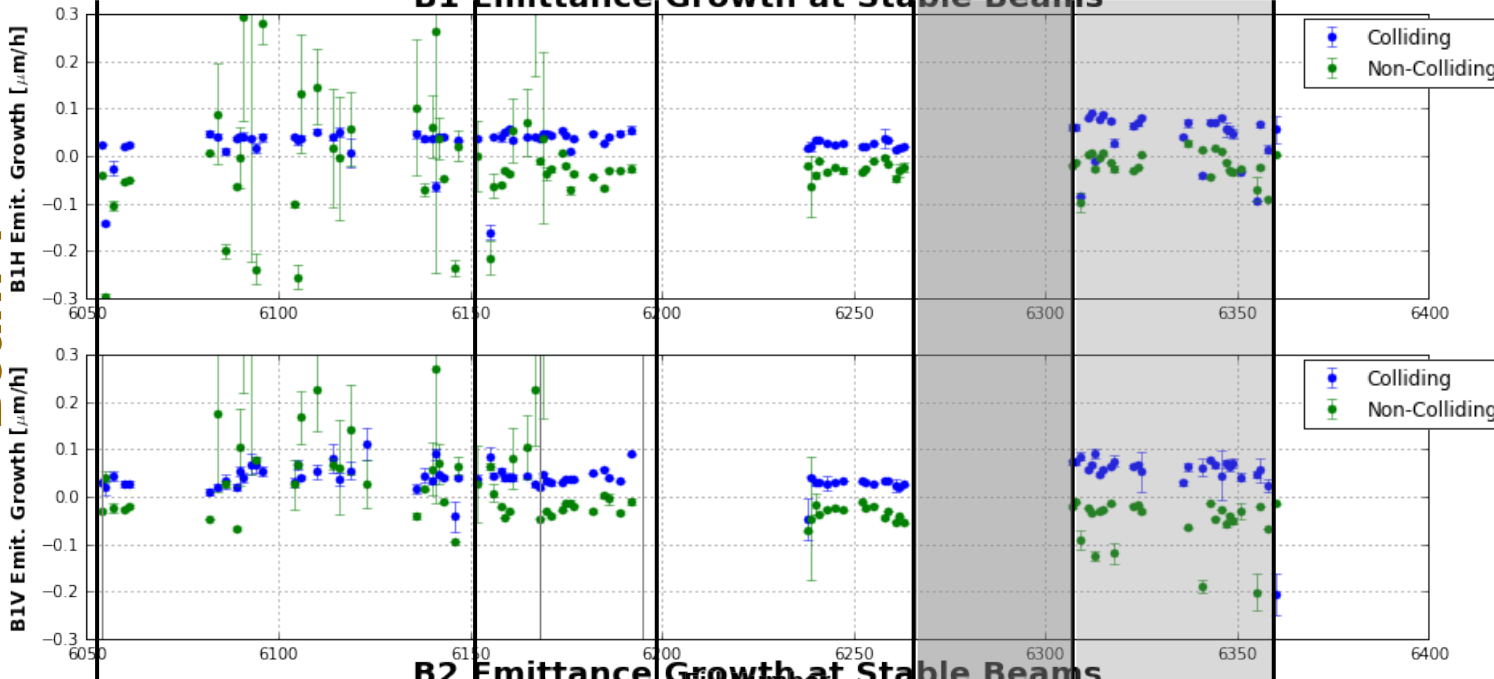
No evolution during flat top (within statistical error).

BSRT recalibration
BCMS standard 25ns
8b4e
TS2
8b4e BCS
BSRT recalibration
BSRT new spot (after fill 6300)
Flat Top

Emittance evolution during stable beams

Beam 1

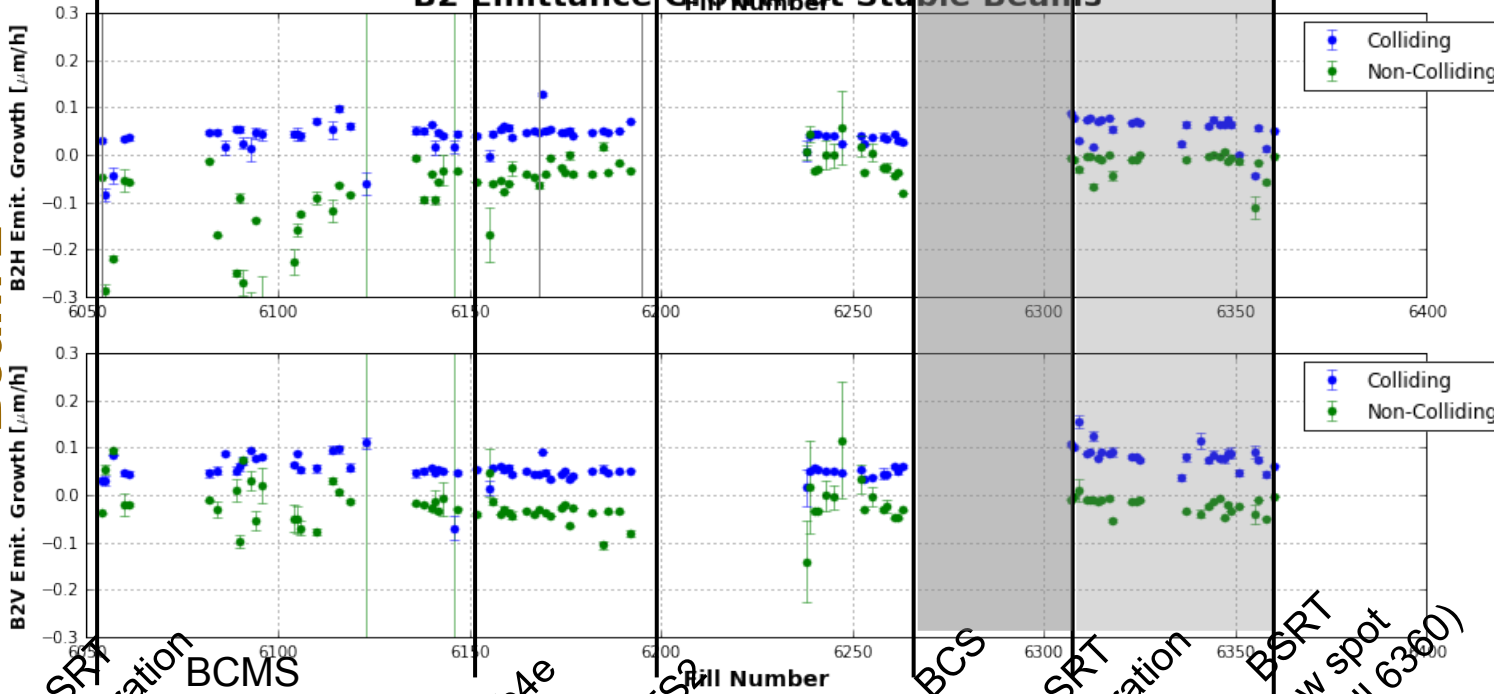
B1 Emittance Growth at Stable Beams



Colliding bunches have similar growth for any beam and plane along the 2017 run.

Beam 2

B2 Emittance Growth at Stable Beams



Non-colliding bunches usually damp, unless they get unstable.

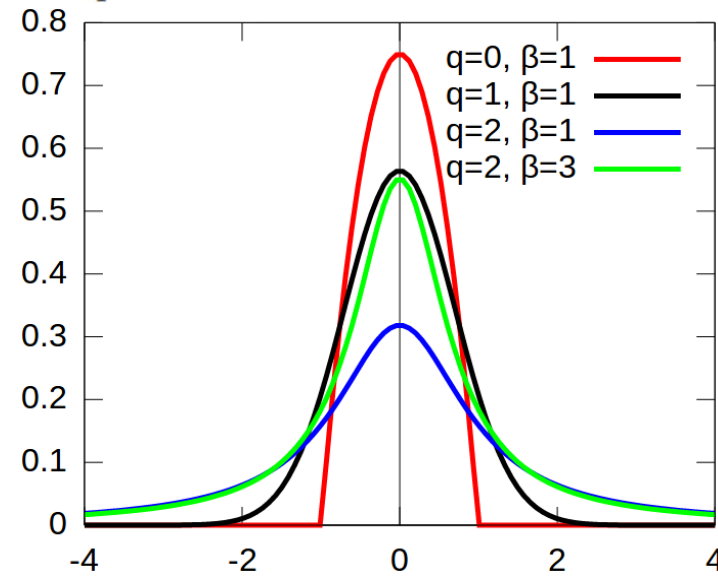
Non-colliding closer to model and colliding over model.

BSRT recalibration
 BCMS standard 25ns
 8b4e
 TSP
 8b4e BCS
 BSRT recalibration
 BSRT new spot (after fill 6360)

Bunch profiles in the LHC

Bunch profiles in the LHC, appear to have tails that differ from the ones of a Gaussian. The **q-Gaussian function** can be used to describe them.

$$f(x) = \frac{\sqrt{\beta}}{C_q} e_q(-\beta x^2), \quad e_q(x) = [1 + (1 - q)x]^{1/(1-q)}$$



q<1 → “light” tailed
q=1 → Gaussian
q>1 → “heavy” tailed

$$\sigma = \sqrt{\frac{1}{\beta(5-3q)}}$$

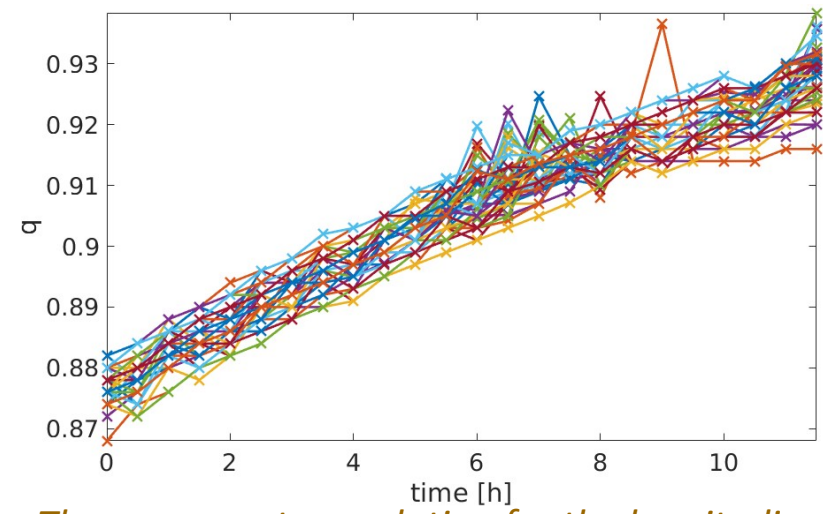
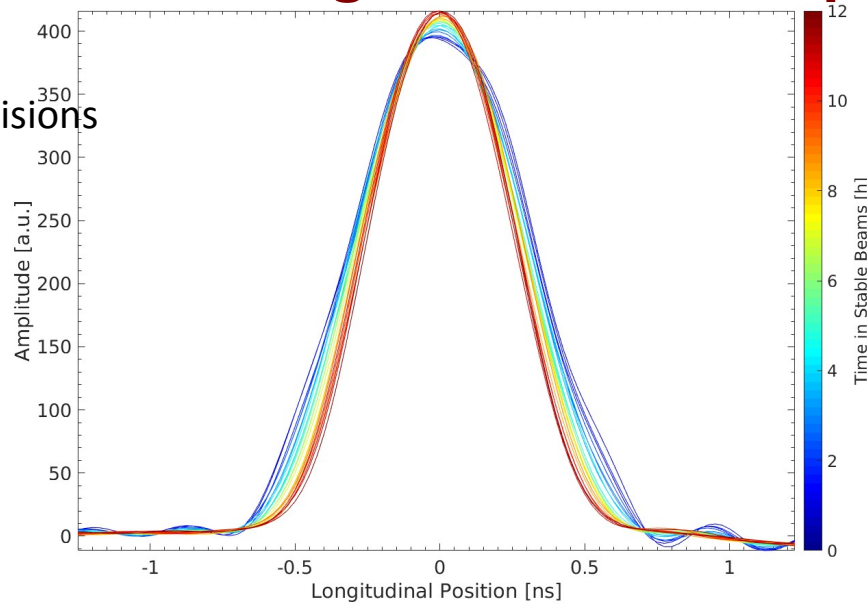
for q<5/3

For a “light”/”heavy” tailed distribution the Gaussian overestimates/underestimates the rms

- At FB non-Gaussian “heavy” tailed profiles are observed for the horizontal plane but not for the vertical
- The longitudinal profiles arrive at FT with a clearly non-Gaussian shape, with “light” tails (already observed by the studies of J. Esteban et al.).
- As time evolves both the transverse and the longitudinal profiles become more Gaussian.

Longitudinal bunch profiles in the LHC

~11.5h at collisions

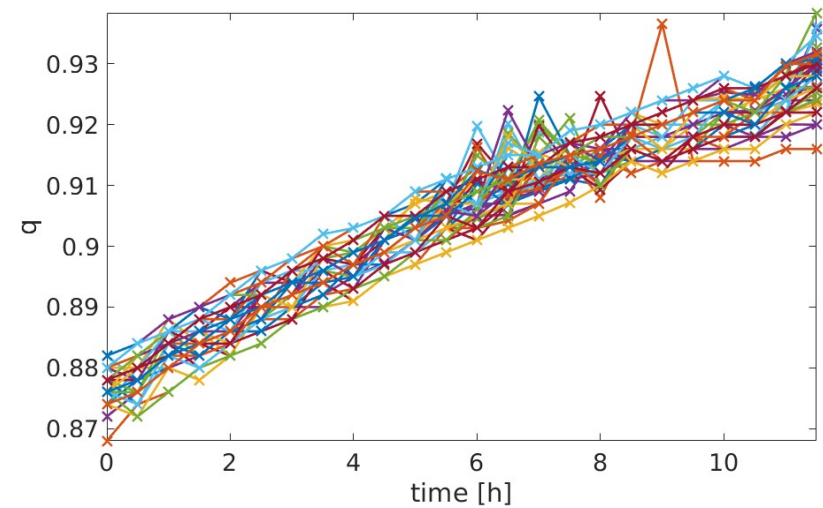
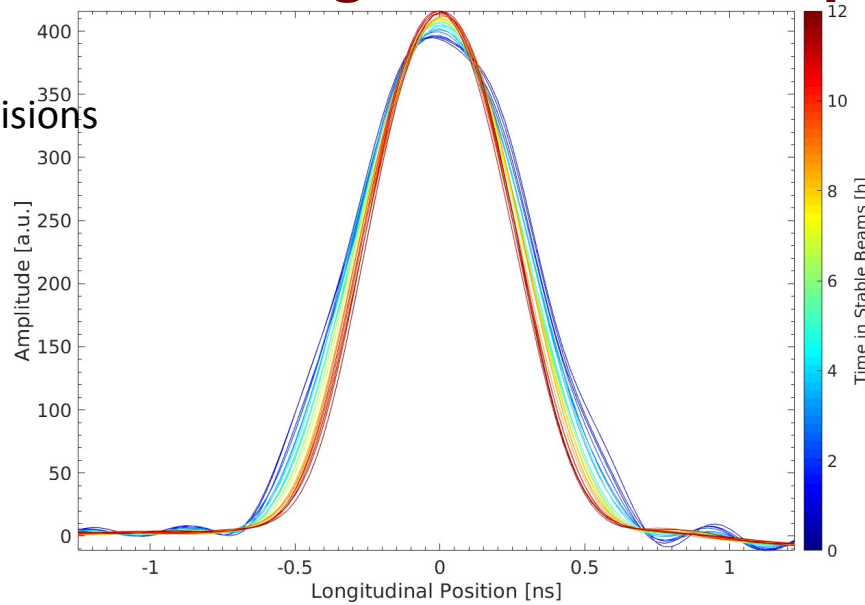


The q parameter evolution for the longitudinal bunches of 1 train, during ~11.5h at collisions.

-Since the q parameter $\rightarrow 1$, the distributions become more Gaussian.

Longitudinal bunch profiles in the LHC

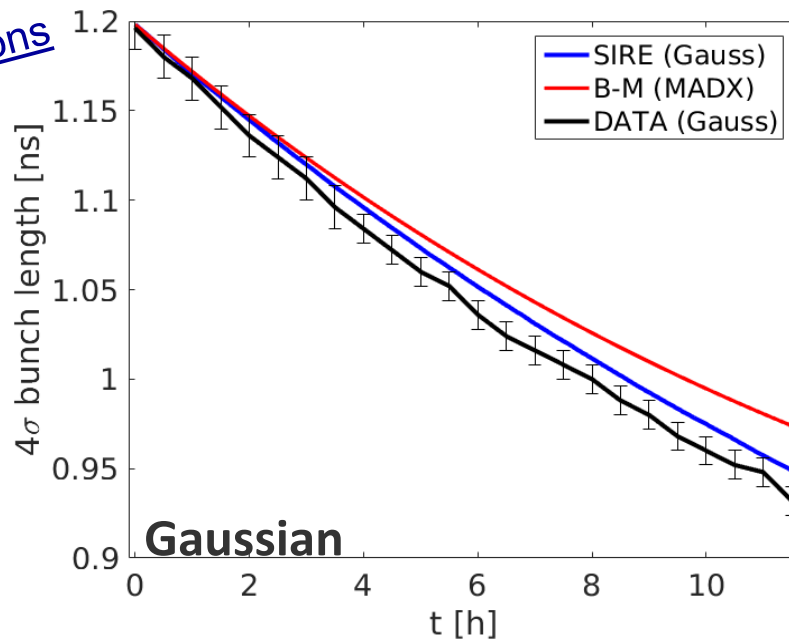
~11.5h at collisions



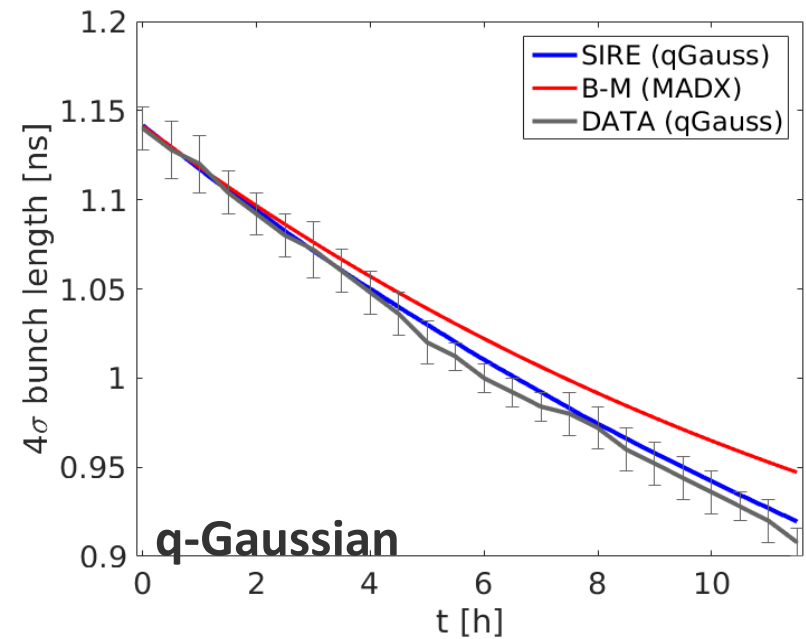
The q parameter evolution for the longitudinal bunches of 1 train, during ~11.5h at collisions.

-Since the q parameter $\rightarrow 1$, the distributions become more Gaussian.

Comparison to simulations
Including intensity degradation and extra transverse emittance blow up.



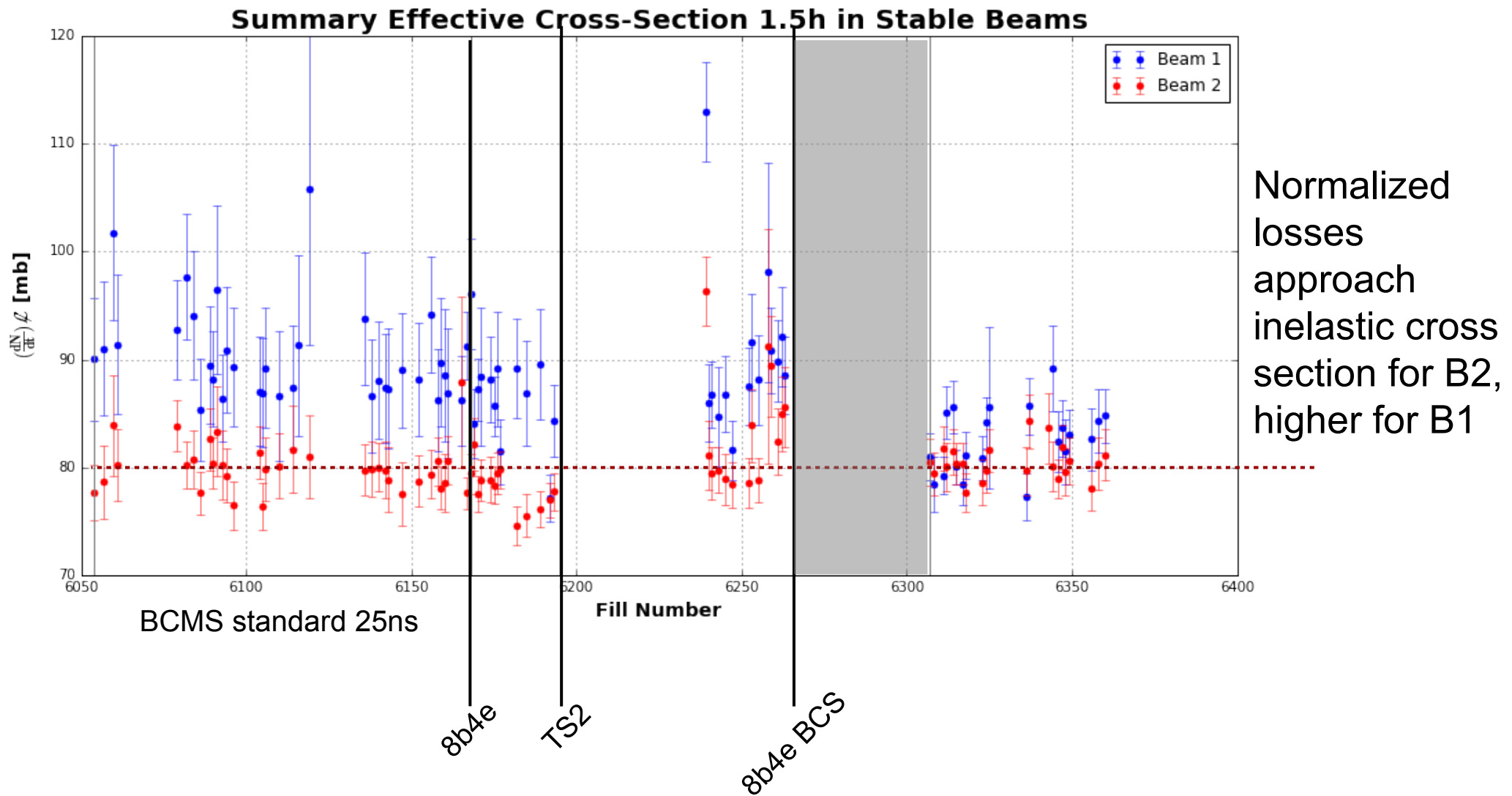
Gaussian



q-Gaussian

-Simulations with **SIRE** (*Software for IBS and Radiations Effects*) better match measurements for the q-Gaussian distribution, which provide different rms

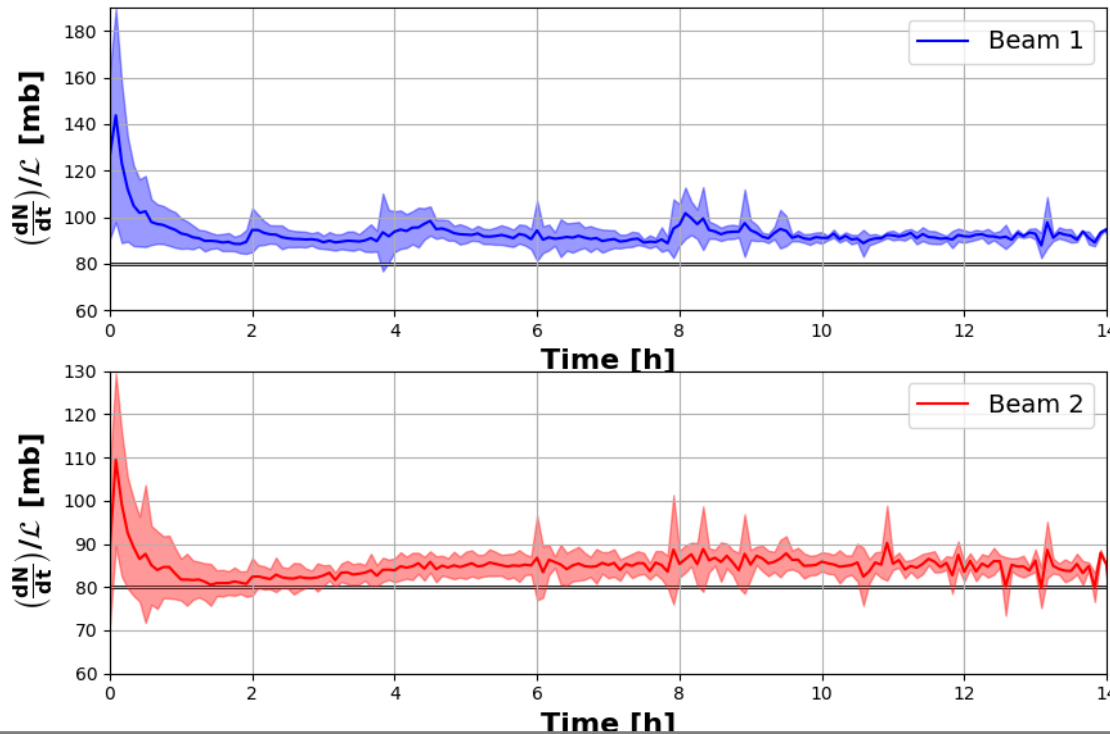
Losses after 1.5 h in Stable Beams



- No extra losses due to reduction of xing angle or β^* after TS2.
- DA simulations used as a guide for tune optimization and loss reduction for different filling schemes, x-ing angles, β^* .
- More relaxed settings after emittance reduction with 8b4e BCS, provide smaller losses as predicted by DA estimations.

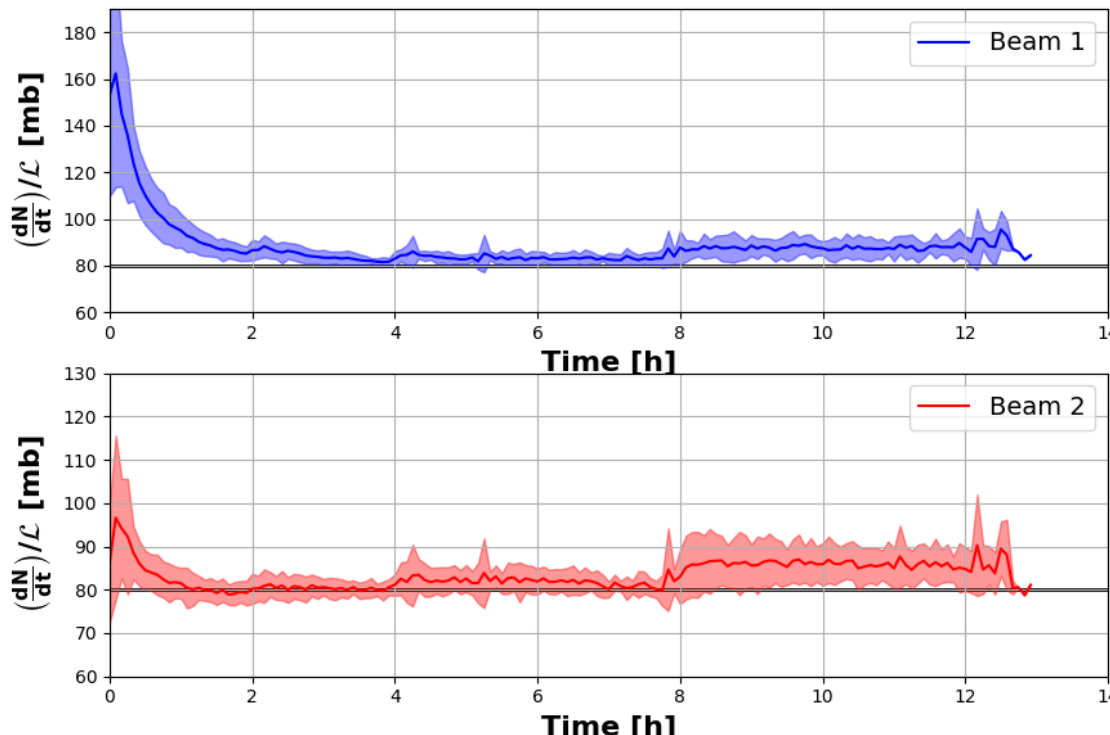
Losses per beam for BCMS and 8b4e

BCMS



- More losses for B1
- B2 losses closer to burn-off limit

8b4e

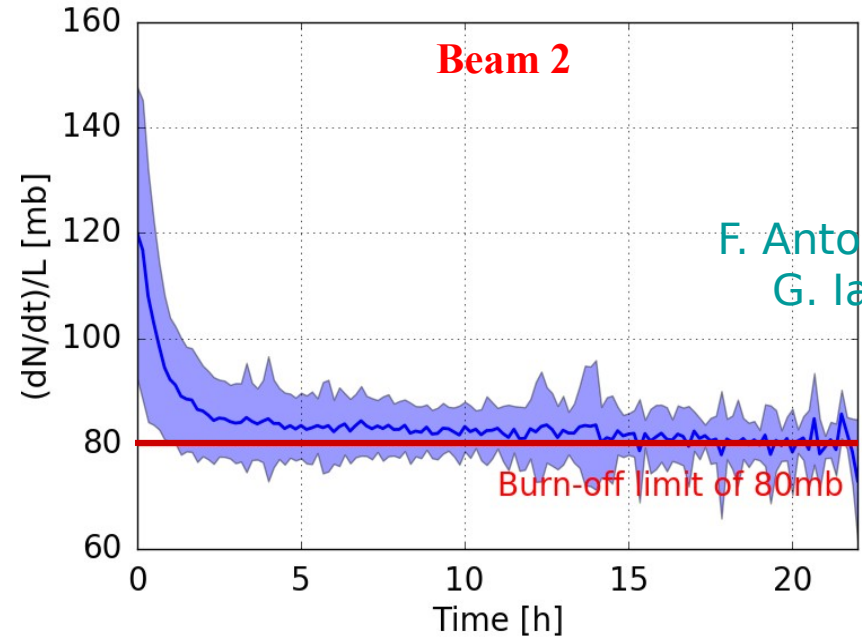
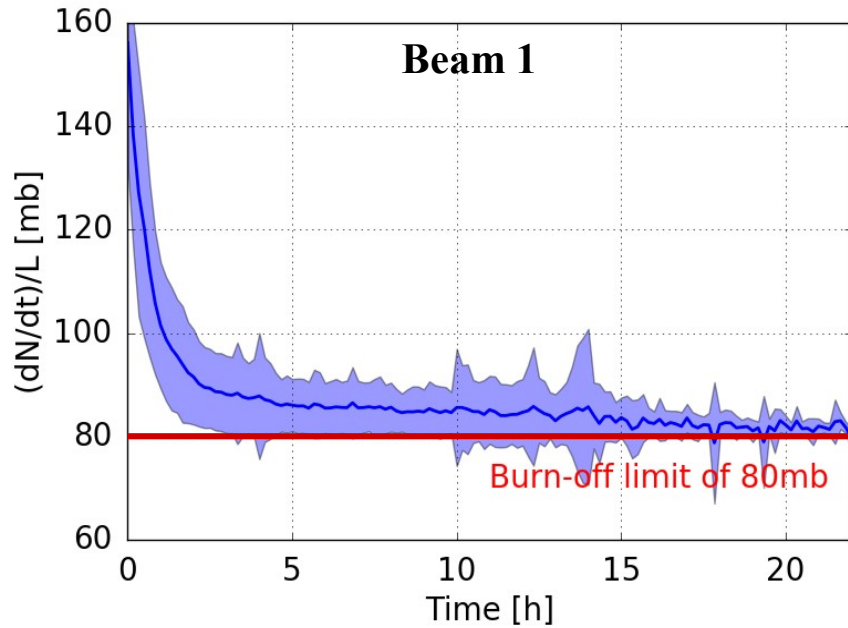


- More losses compared to BCMS B1 at the start of the fill, but evolving closer to the burn-off limit

- Less losses initially compared to BCMS for B2
- x-ing angle steps (at around 2h, 4h and 8h), mainly affect lifetime towards the end of the fill

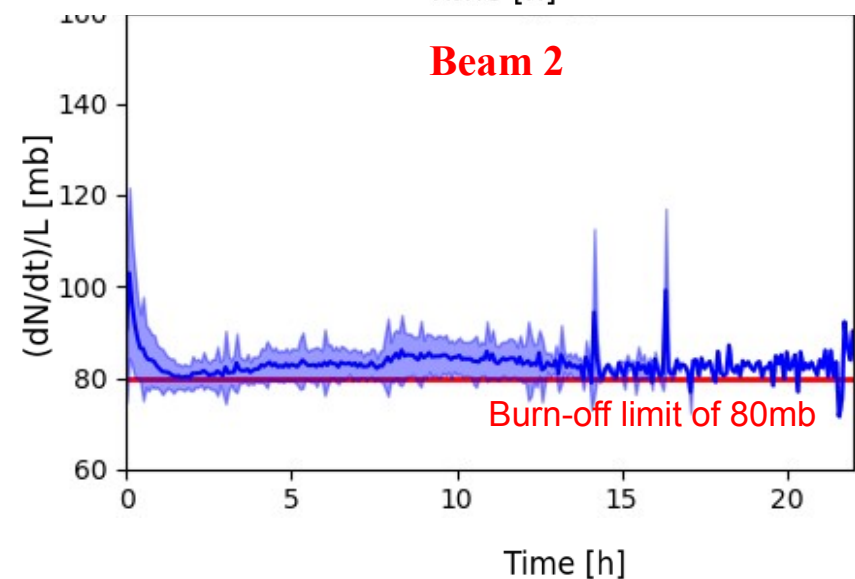
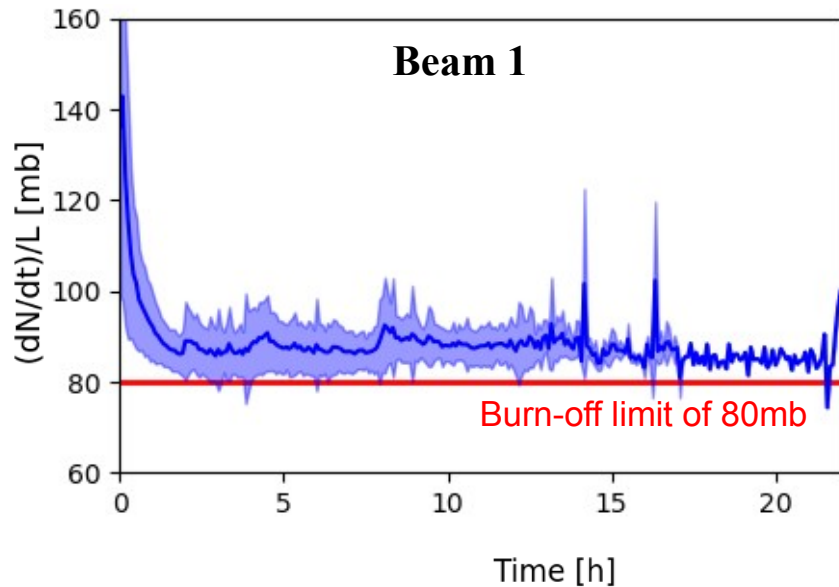
Beam lifetime

2016



F. Antoniou and
G. Iadarola

2017



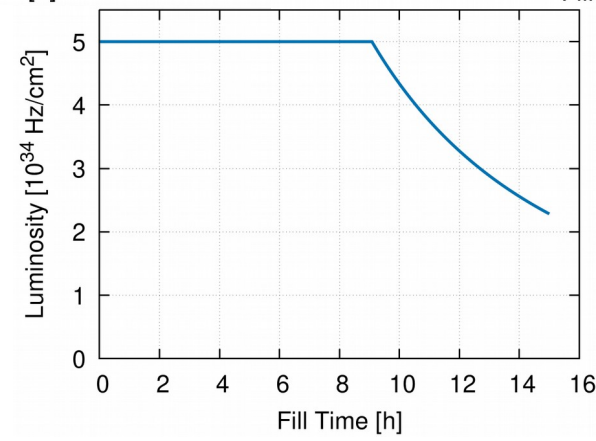
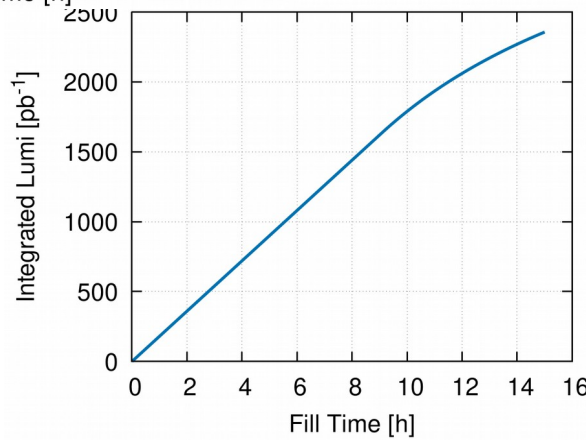
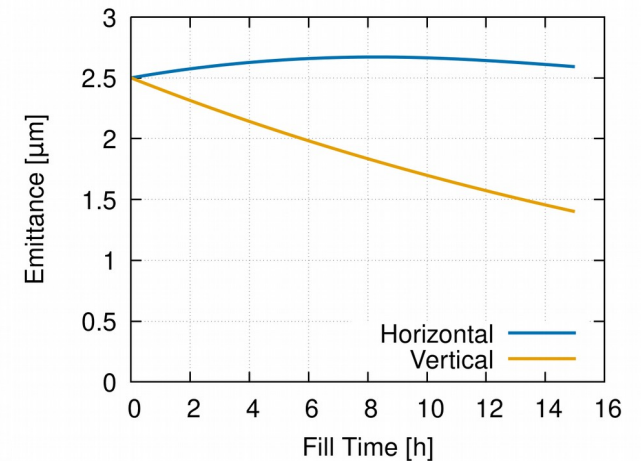
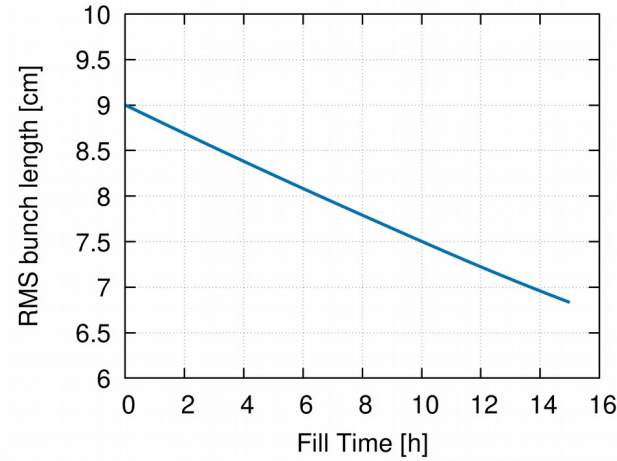
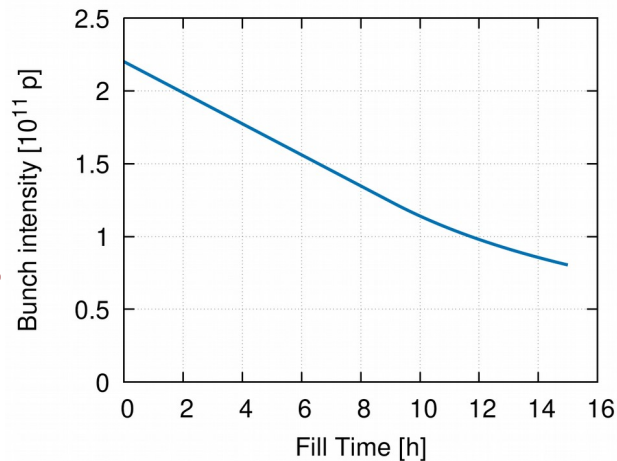
- Normalized loss rate to Luminosity for all fills of 2016 and 2017.
- In 2016 losses become burn off dominated after 3h, while in 2017 this happens earlier.
- In general, 2017 losses are lower than the 2016 ones.

Expectations for HL-LHC

There is an extra (on top of IBS) transverse emittance blow-up observed during SB.

- For the 2016 results, this blow-up is around 0.04 $\mu\text{m}/\text{h}$
- Very weak brightness dependence
- Needs to be updated for 2017 results (under study)

Using the nominal HL-LHC parameters at collisions (E. Métral, et al., “Update of the HL-LHC operational scenarios for proton operation”) and based on the model, estimations for the expected emittance and luminosity are presented.



F. Antoniou,
N. Karastathis,
D. Pellegrini,
Y. Papaphilippou

no extra transverse
emittance blow-up

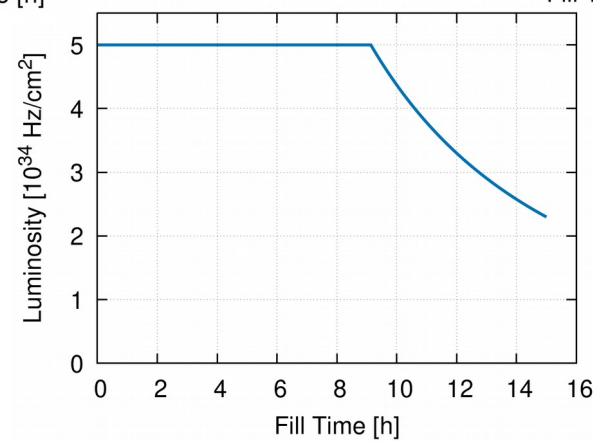
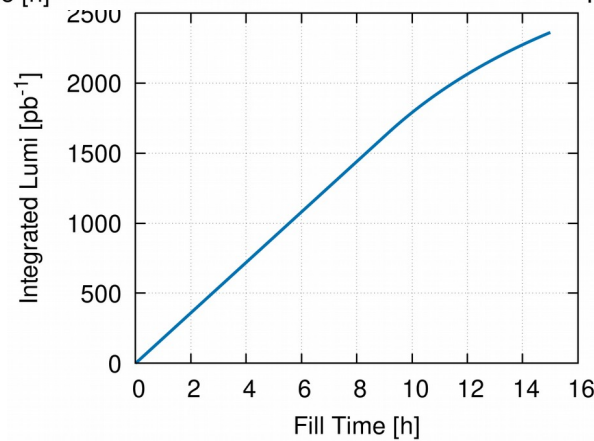
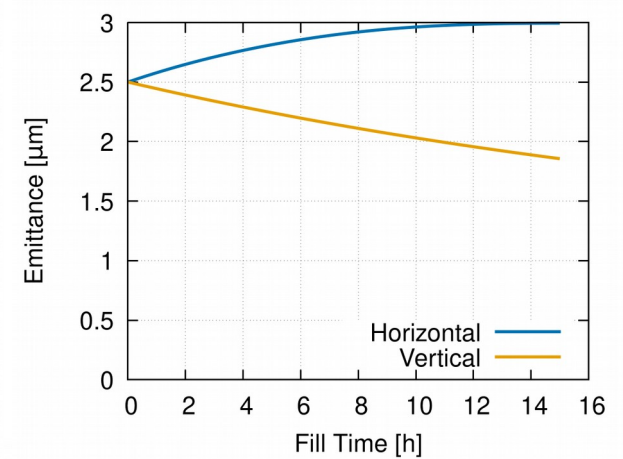
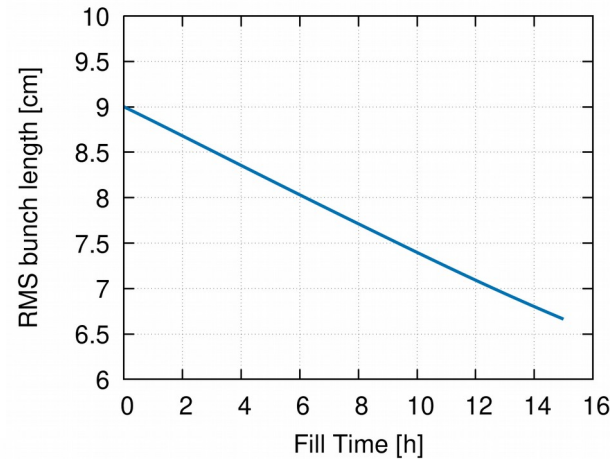
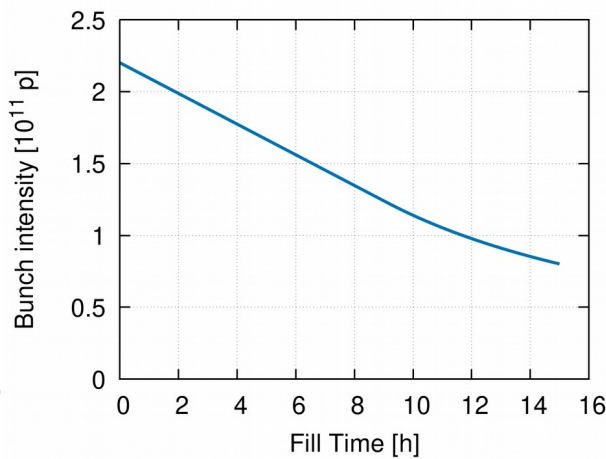
Expectations for HL-LHC

There is an extra (on top of IBS) transverse emittance blow-up observed during SB.

- For the 2016 results, this blow-up is around 0.04 $\mu\text{m}/\text{h}$
- Very weak brightness dependence
- Needs to be updated for 2017 results

Using the nominal HL-LHC parameters at collisions (E. Métral, et al., “Update of the HL-LHC operational scenarios for proton operation”) and based on the model, estimations for the expected emittance and luminosity are presented.

0.04 $\mu\text{m}/\text{h}$ extra transverse emittance blow-up



F. Antoniou,
N. Karastathis,
D. Pellegrini,
Y. Papaphilippou

Conclusions

Emittance evolution from injection to SB

- Higher emittance growth for BCMS at injection (probably due to the impact of e-cloud), whereas 8b4e close to the model
- Larger growth during the ramp, mostly for B1, significantly increased for B1V for 8b4e
- Future work:
 - Investigate the impact of optimized injection tunes, chromaticity, octupoles, damper gain, effect of noise, etc
 - Explore diagnostics for getting better idea of the emittance during the ramp

At SB

- During collisions, the growth is similar among different beam flavors, beams and planes
- Luminosity lifetime better for B2 than for B1
- Less losses for 2017 compared to 2016

Bunch profiles

- At FT, the bunch profiles become more Gaussian in time.
- Indications that tail population affects rms beam size estimation
- Initiated continual logging of profiles for post-processing, to be included in follow-up

Expectations for HL-LHC

- An extra emittance blow-up on top of the model of the order of $0.04\mu\text{m}$, does not have a significant impact on luminosity performance.

Thank you!

Luminosity model description

Python scripts built for extracting TIMBER data for parameter evolution observations, luminosity reconstruction and comparison with model.

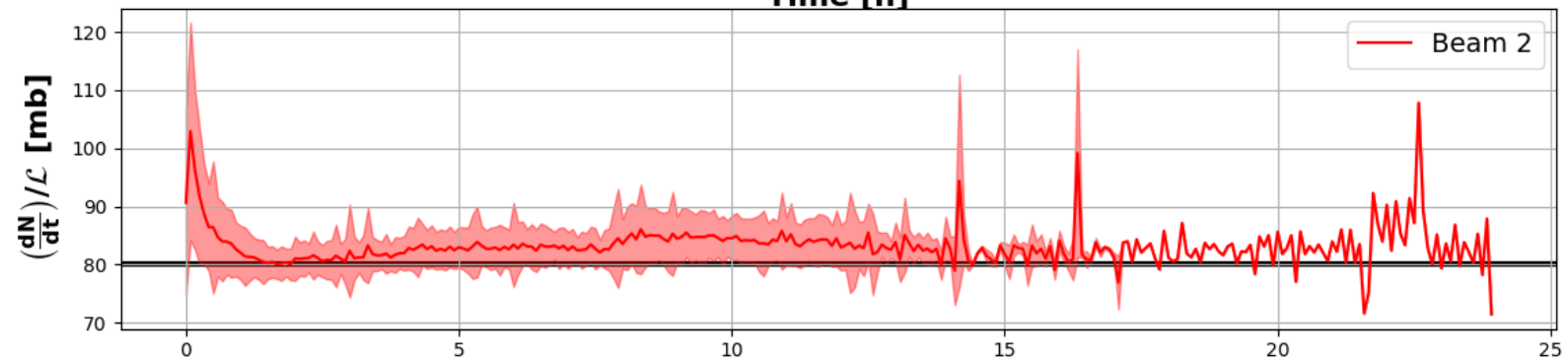
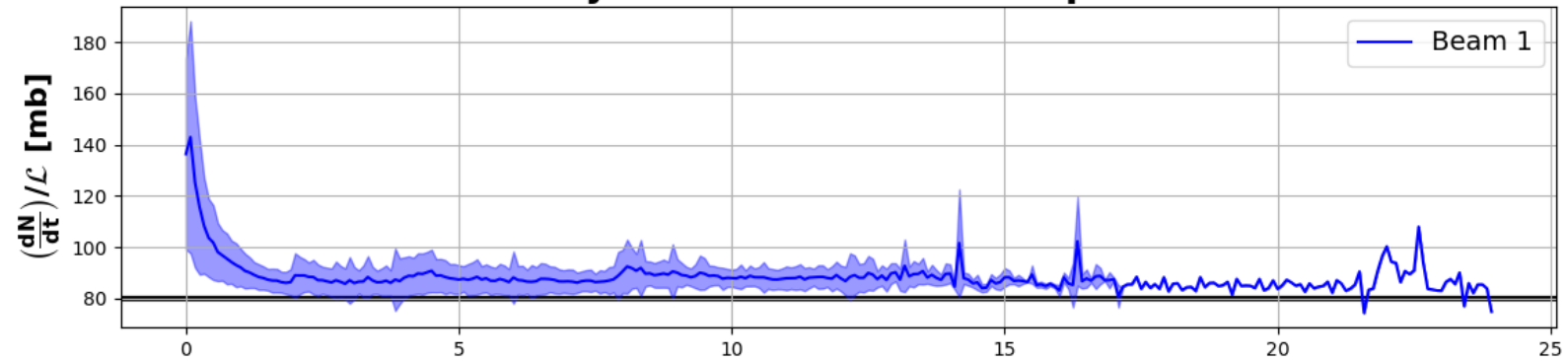
Modelling of emittance evolution

- IBS evaluation based on multi-parametric fit functions depending on 3D emittances, bunch current, energy and synchrotron radiation damping.
- At stable beams, adding a self-consistent evaluation of current decay due to burn-off, emittance growth due to elastic cross section.

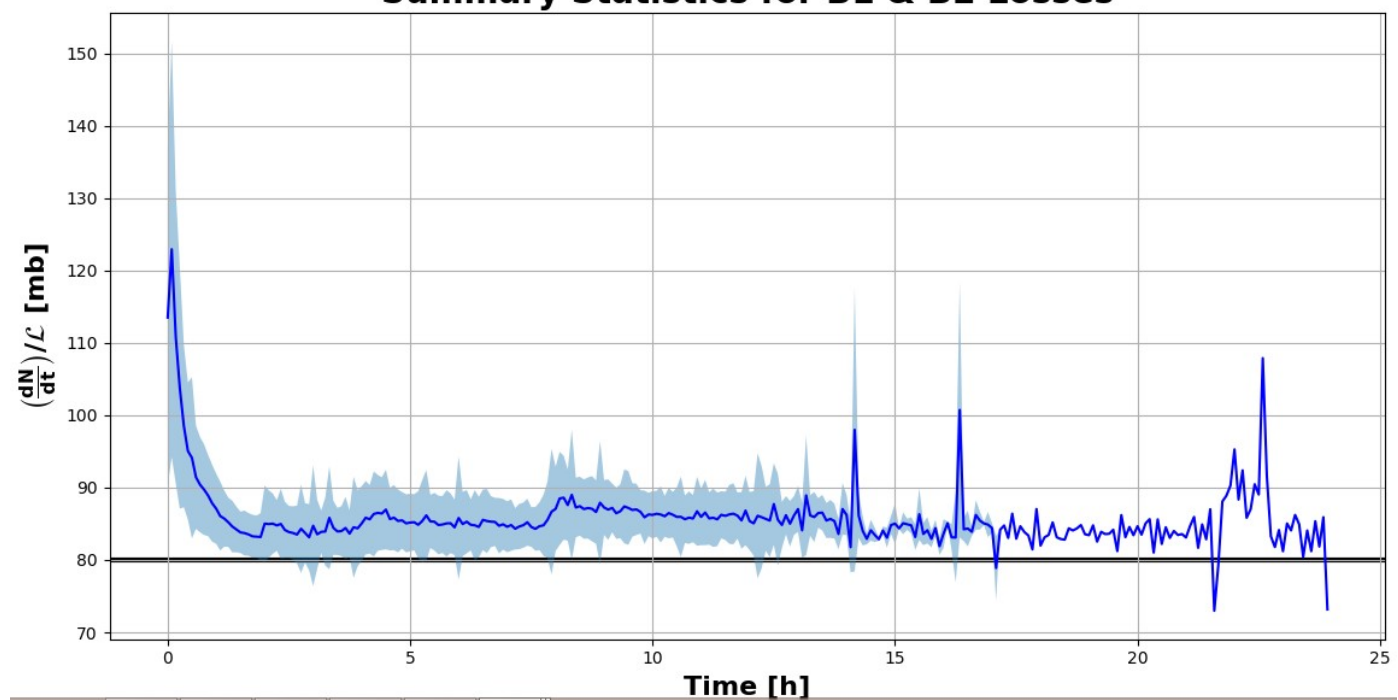
Luminosity evolution can be followed-up either from pure modelled, empirical or measured LHC quantities (or combination of the above).

Run

Summary Statistics for Losses per Beam

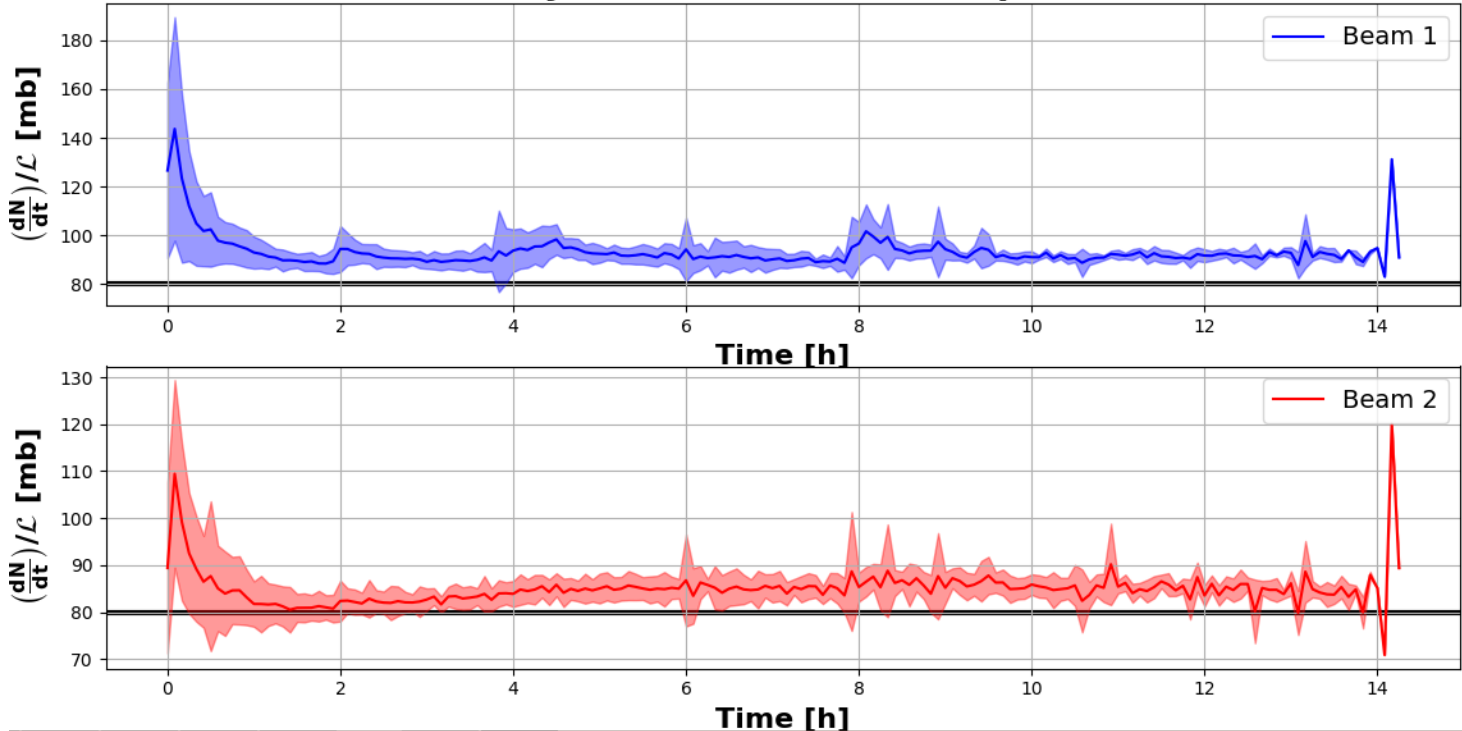


Summary Statistics for B1 & B2 Losses

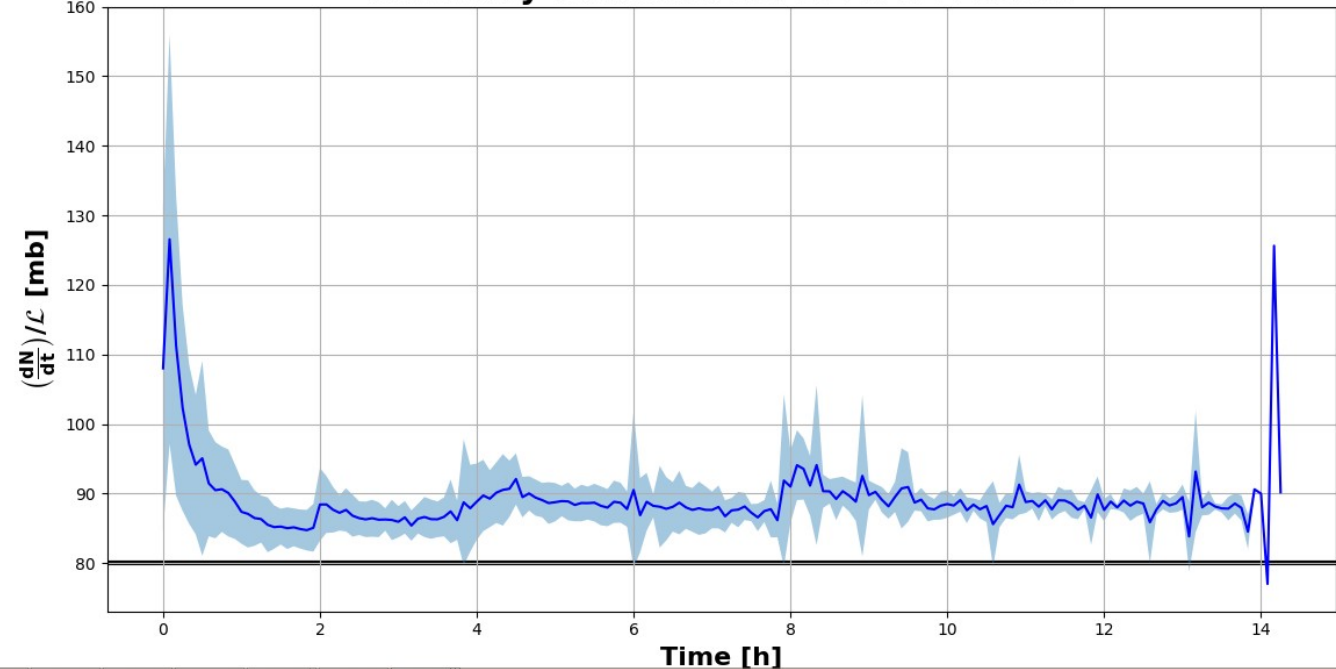


BCMS

Summary Statistics for Losses per Beam

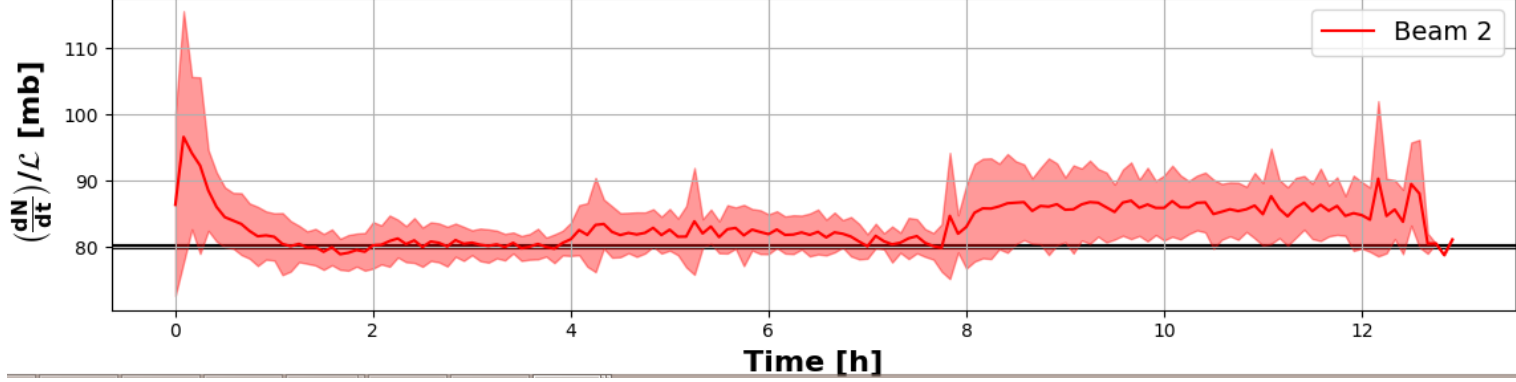
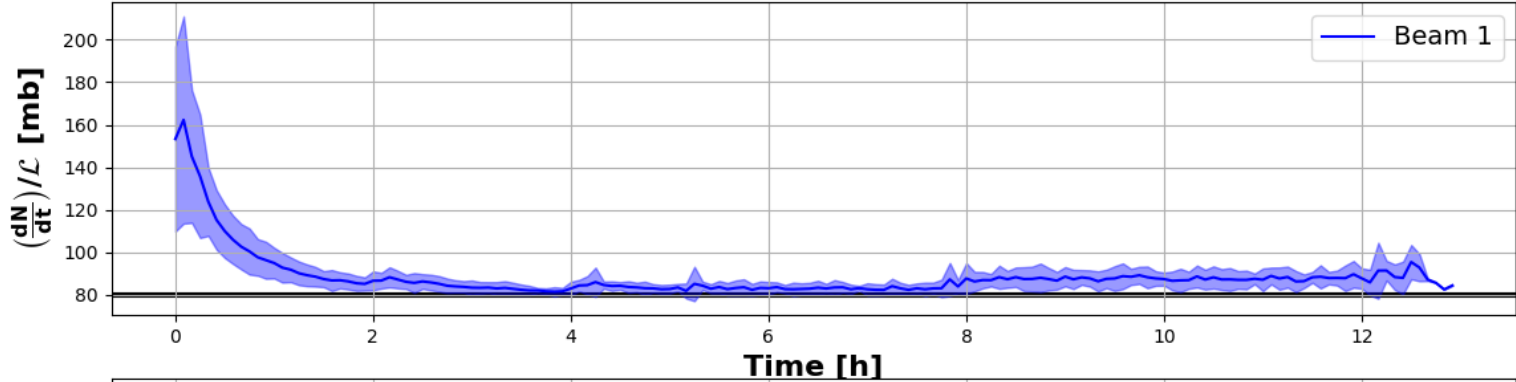


Summary Statistics for B1 & B2 Losses

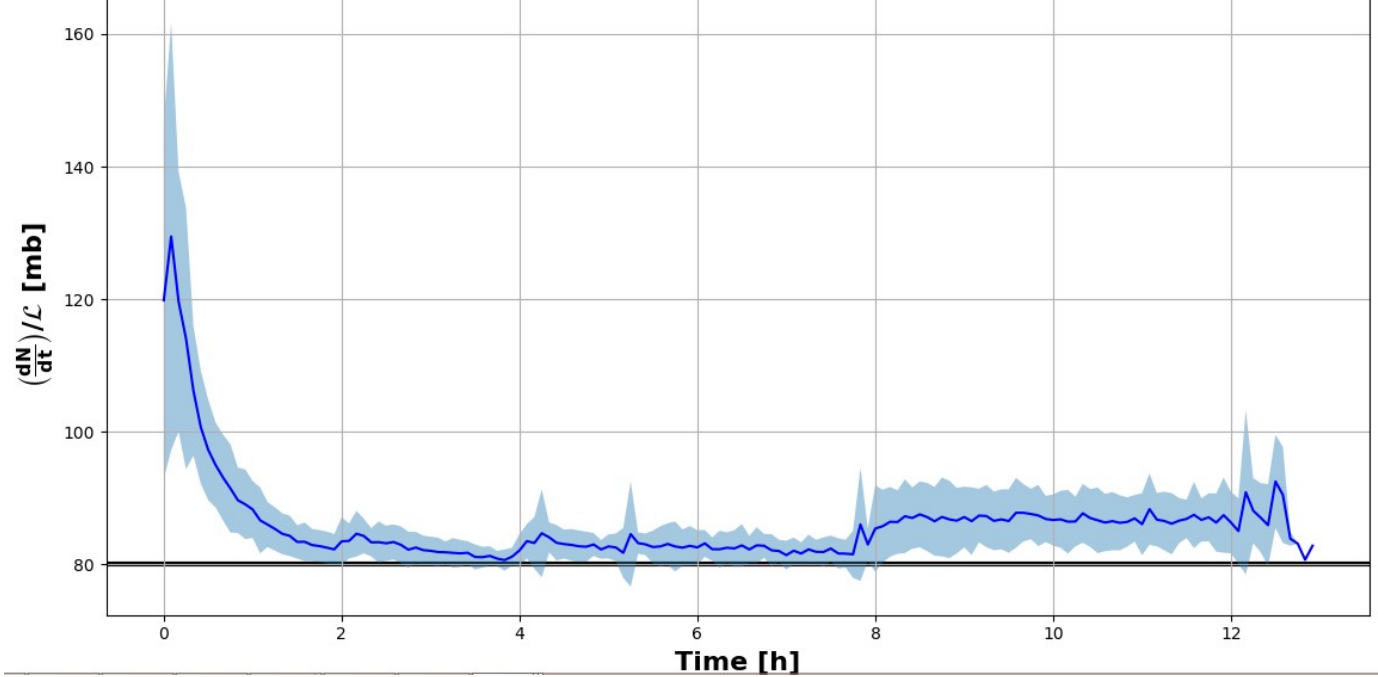


8b4e

Summary Statistics for Losses per Beam

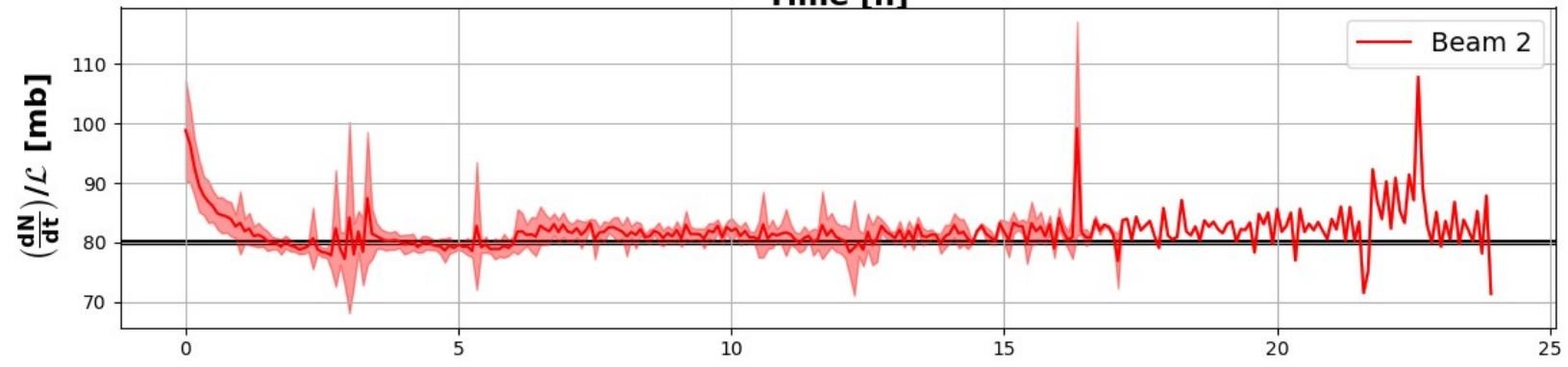
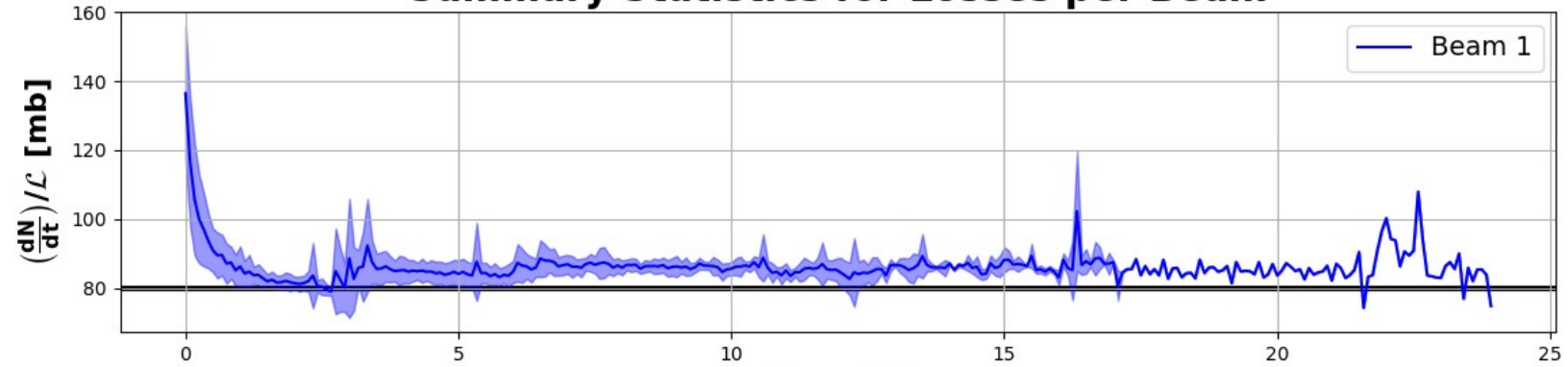


Summary Statistics for B1 & B2 Losses

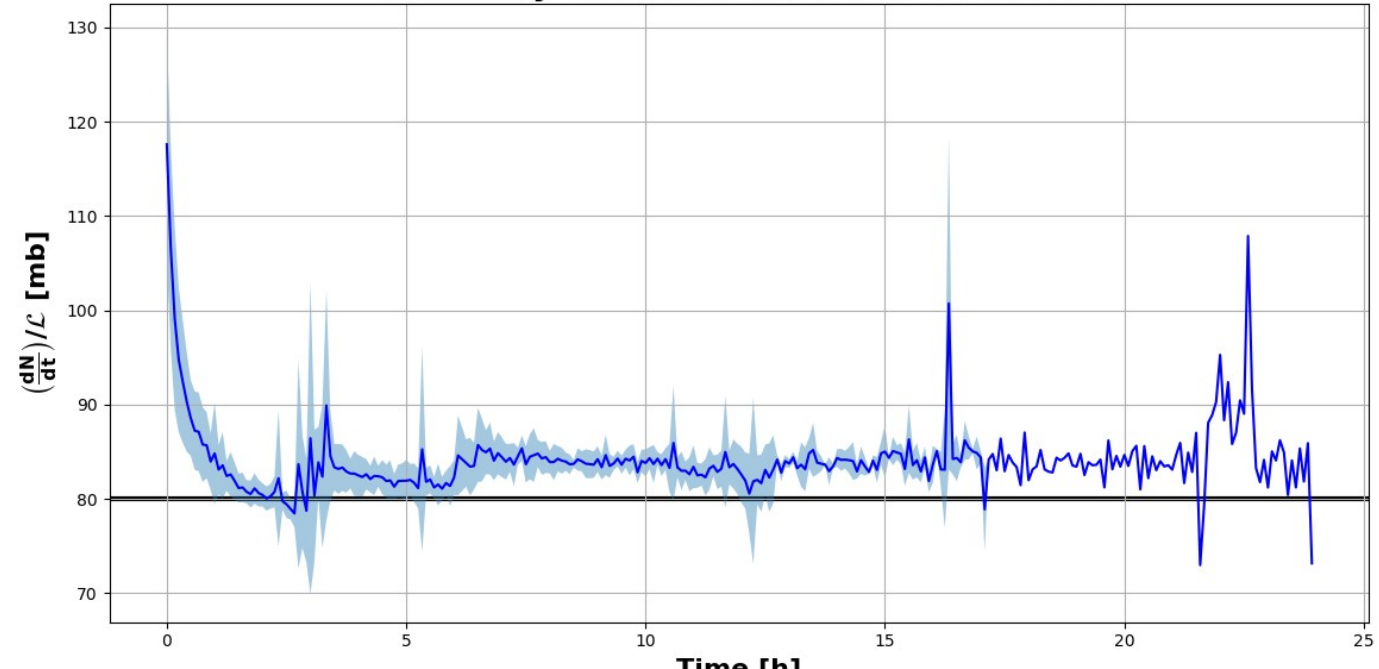


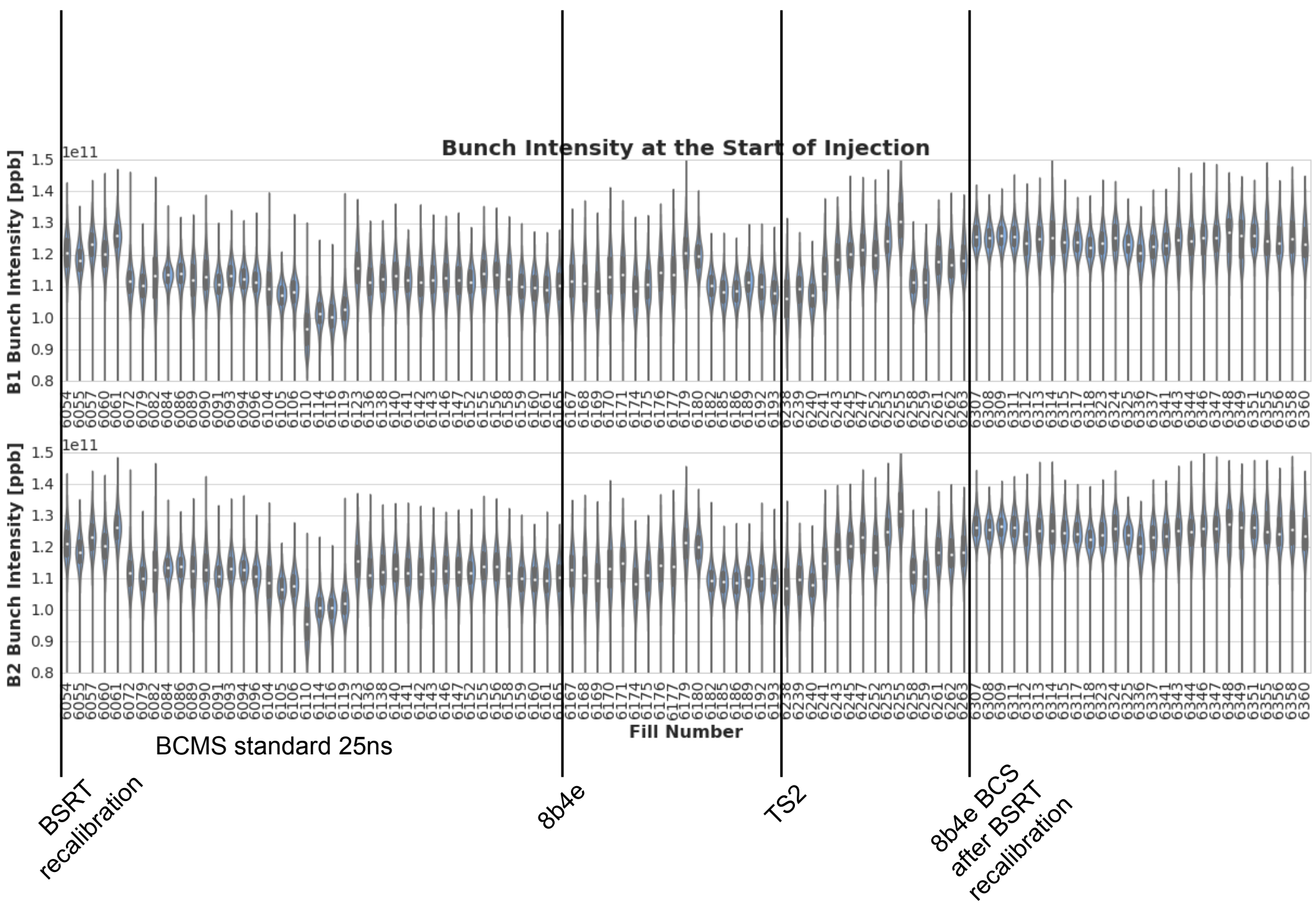
8b4e_BCS

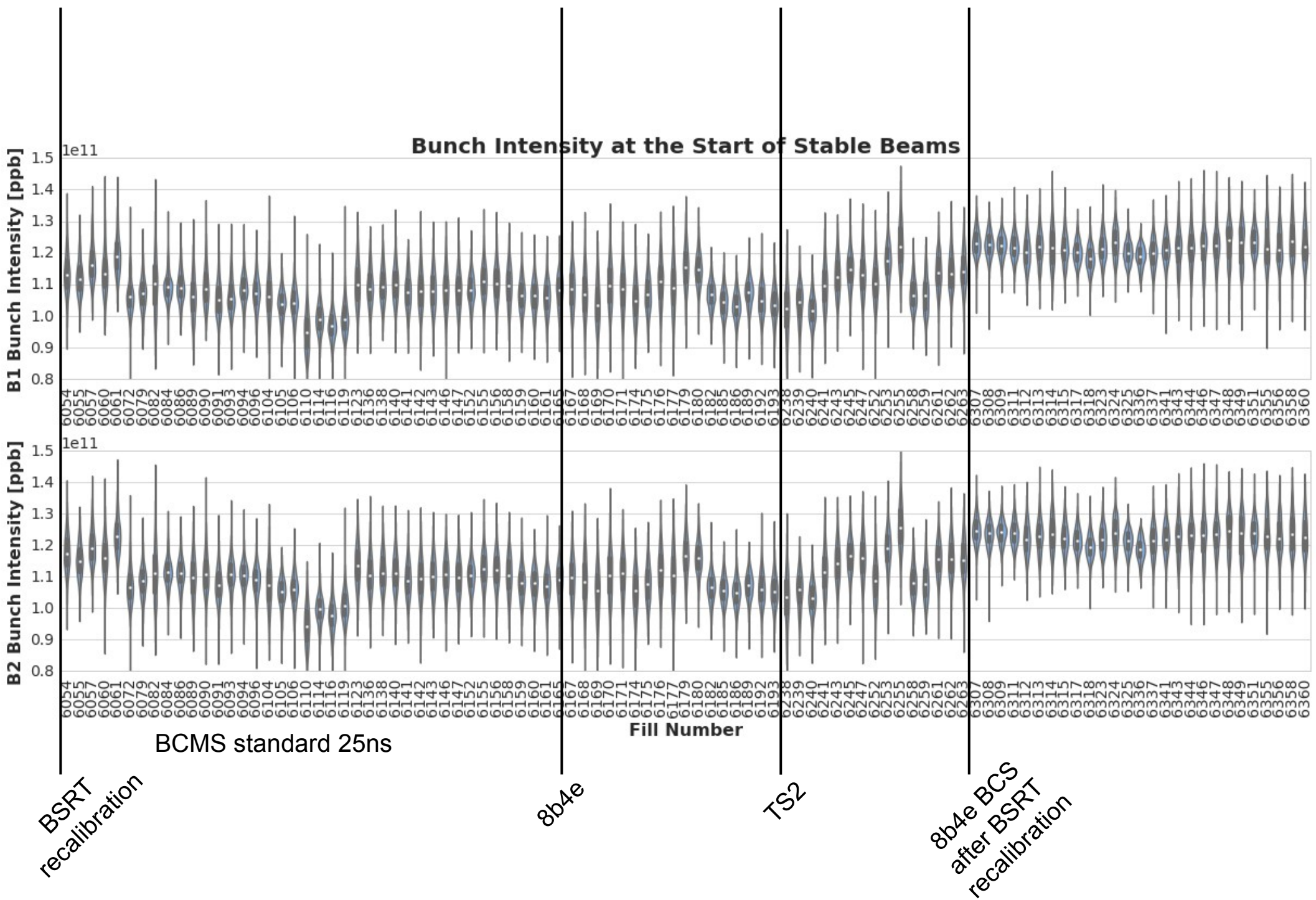
Summary Statistics for Losses per Beam



Summary Statistics for B1 & B2 Losses

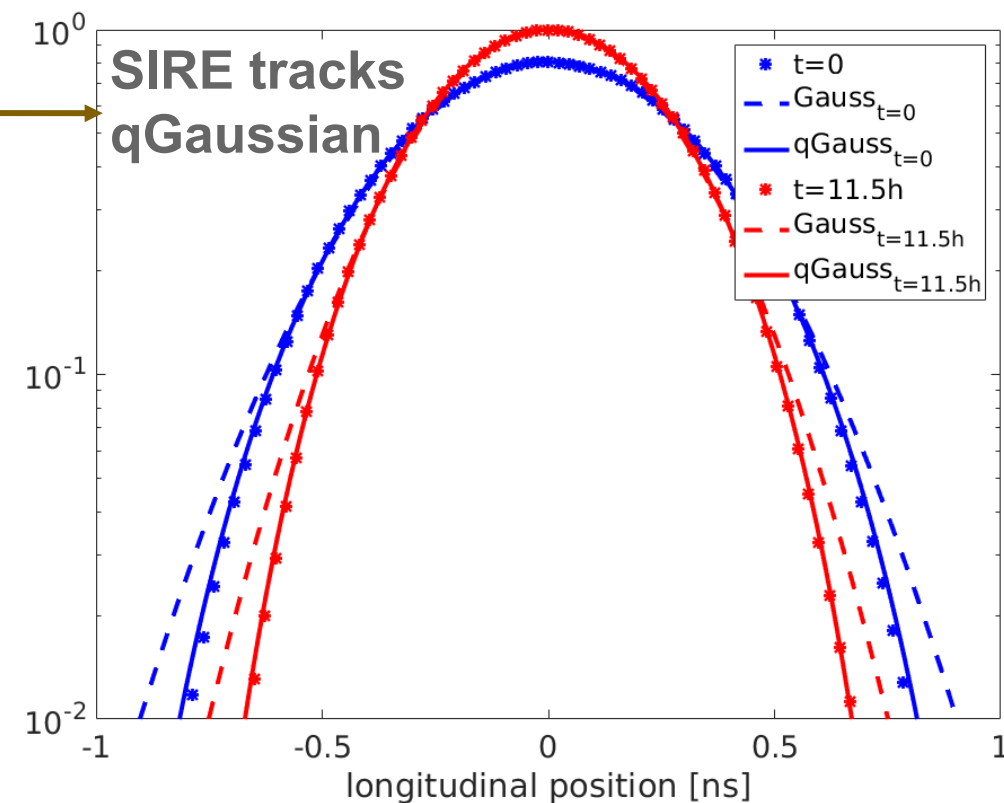
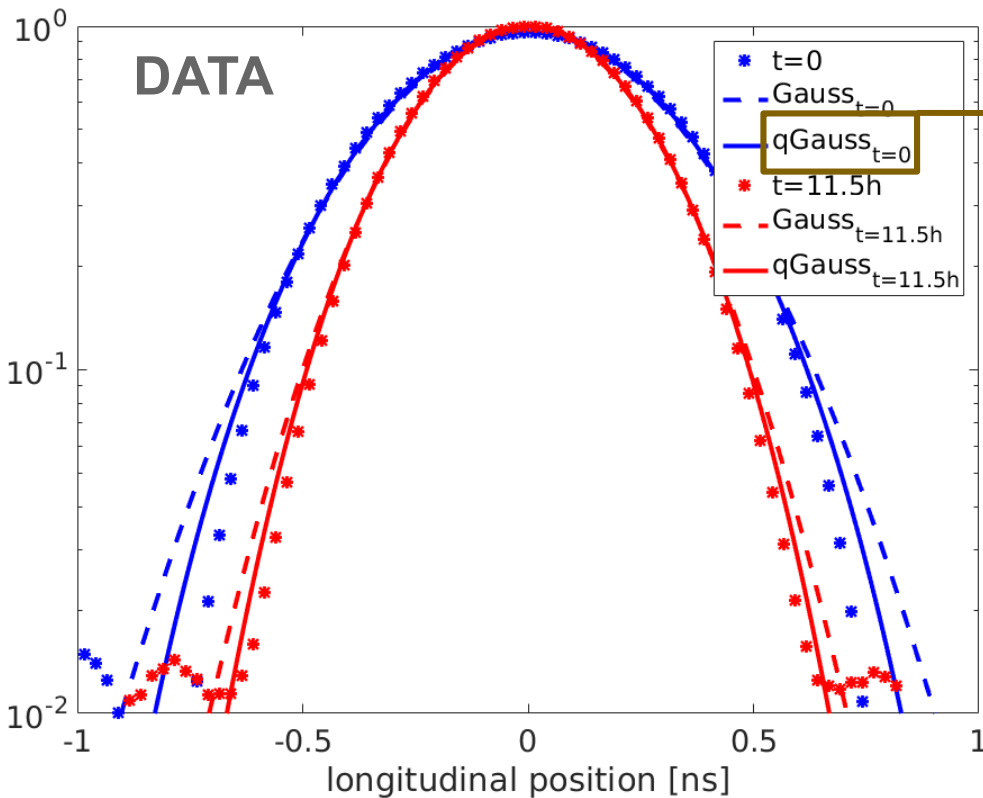






SIRE comparison with experimental data

- Taking into account the bunch population change
- Keeping the bunch profiles in transverse plane Gaussian
- Track in the SIRE code the distributions coming from the initial data fits.

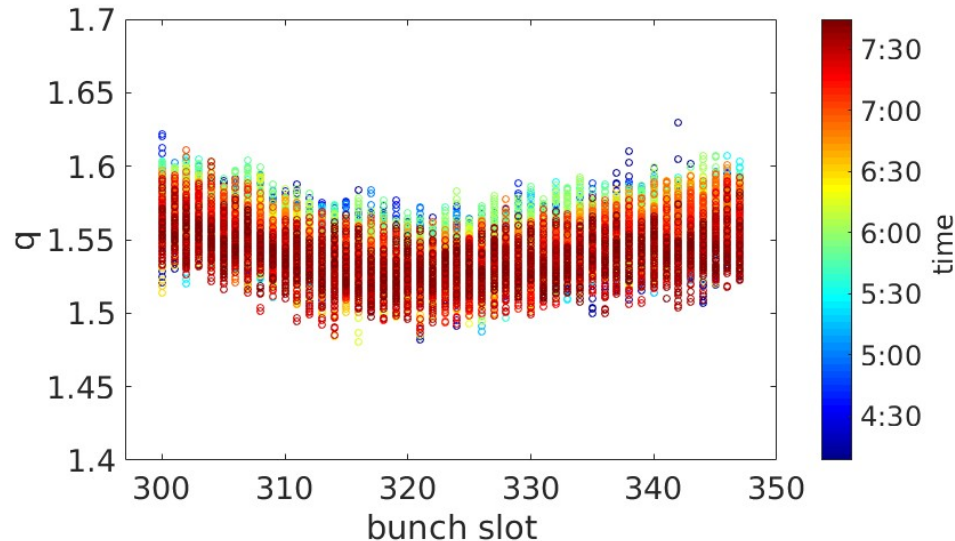


	q initial	sigma initial	q final	sigma final
DATA	0.88±0.03 (rmse=0.010)	0.286±0.004 (rmse=0.010)	0.93±0.03 (rmse=0.010)	0.227±0.002 (rmse=0.010)
SIRE qGaussian	0.85±0.01 (rmse=0.003)	0.290±0.001 (rmse=0.003)	0.86±0.01 (rmse=0.004)	0.235±0.001 (rmse=0.004)

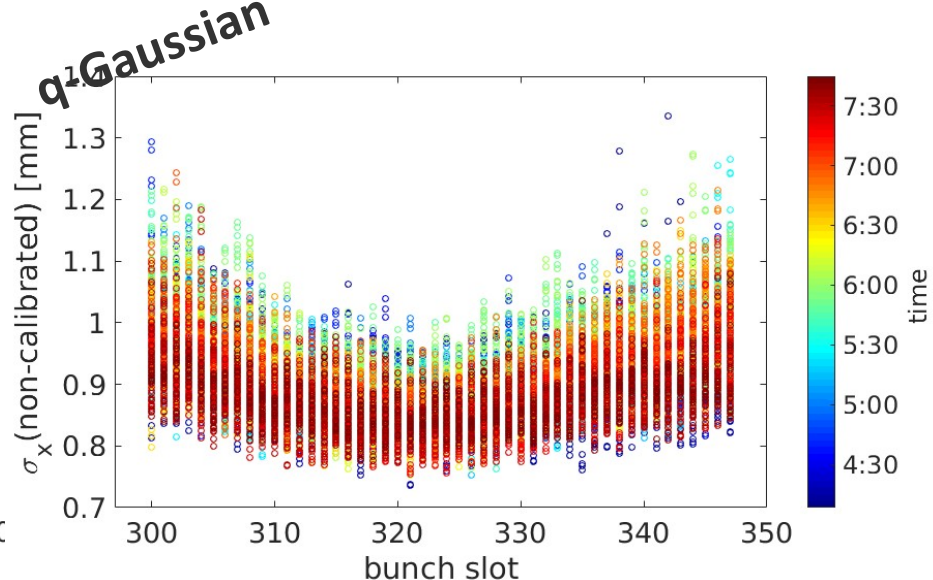
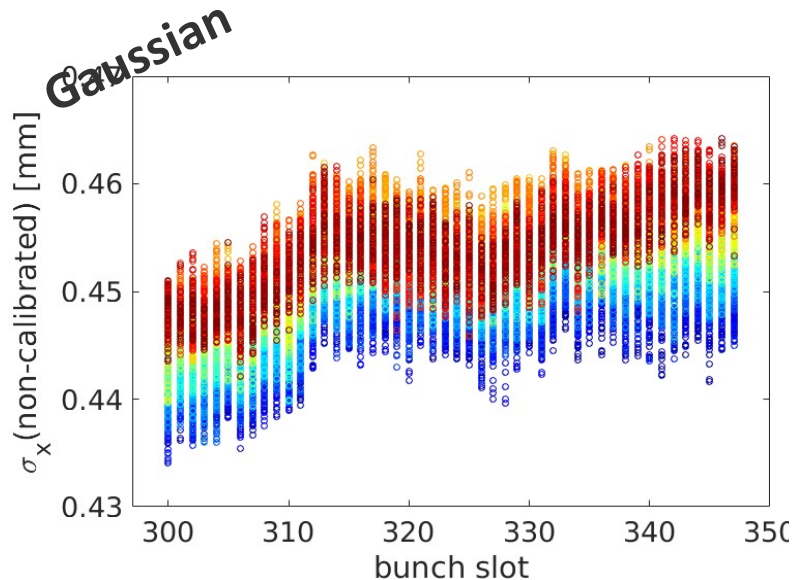
@FT, transverse HB2

MD2201 on 17/9/17

- Filling 2 trains of BCMS and 1 train of 8b_4e per beam
- Reducing crossing angle by steps of -10urad (from 150 to 90), while optimizing IP 1/5 and tune.



The evolution of the q parameter for a train of BCMS bunches at FT energy, while reducing the xing angle from 150 until 90 μ rad within 3.5h.



The evolution of the non-calibrated horizontal rms beam size for a train of BCMS bunches at FT energy, while reducing the xing angle from 150 until 90 μ rad within 3.5h.

- The q parameter is reduced, meaning that the bunches become more Gaussian.
- Only the q-Gaussian shows correlation to BBLR patterns.