What do we understand on the emittance growth?

F. Antoniou, I. Efthymiopoulos, M. Hostettler,
G. Iadarola, N. Karastathis, S. Kostoglou, **S. Papadopoulou**,
Y. Papaphilippou, G. Trad

Special thanks to: G. Arduini, X. Buffat and T. Persson

9th LHC Operations Evian Workshop
31/01/2019

LHC Luminosity follow-up

Motivation

Understanding of the LHC emittance evolution for the overall optimisation of the operation conditions and the maximization of the delivered luminosity to the experiments

LHC Emittance Preservation WG→link: LHCEmittancePreservationWG

HSI LHC-lumi internal meetings→link: HSILumiMeetings

2015

Development of a luminosity model including contributions from IBS, SR and burn-off (MATLAB)

F. Antoniou, Y. Papaphilippou

2016

Luminosity modelling in Python, development of LHC follow-up scripts based on the tools developed for acquiring beam parameters data from the LHC systems (PyCOMPLETE)

F. Antoniou, G. Iadarola, Y. Papaphilippou

2017

Development of a self-complete, version-controlled, automated framework (Python2+BASH) to download LHC systems data, perform the offline analysis and prepare follow-up and sum. plots

N. Karastathis, Y. Papaphilippou

2018

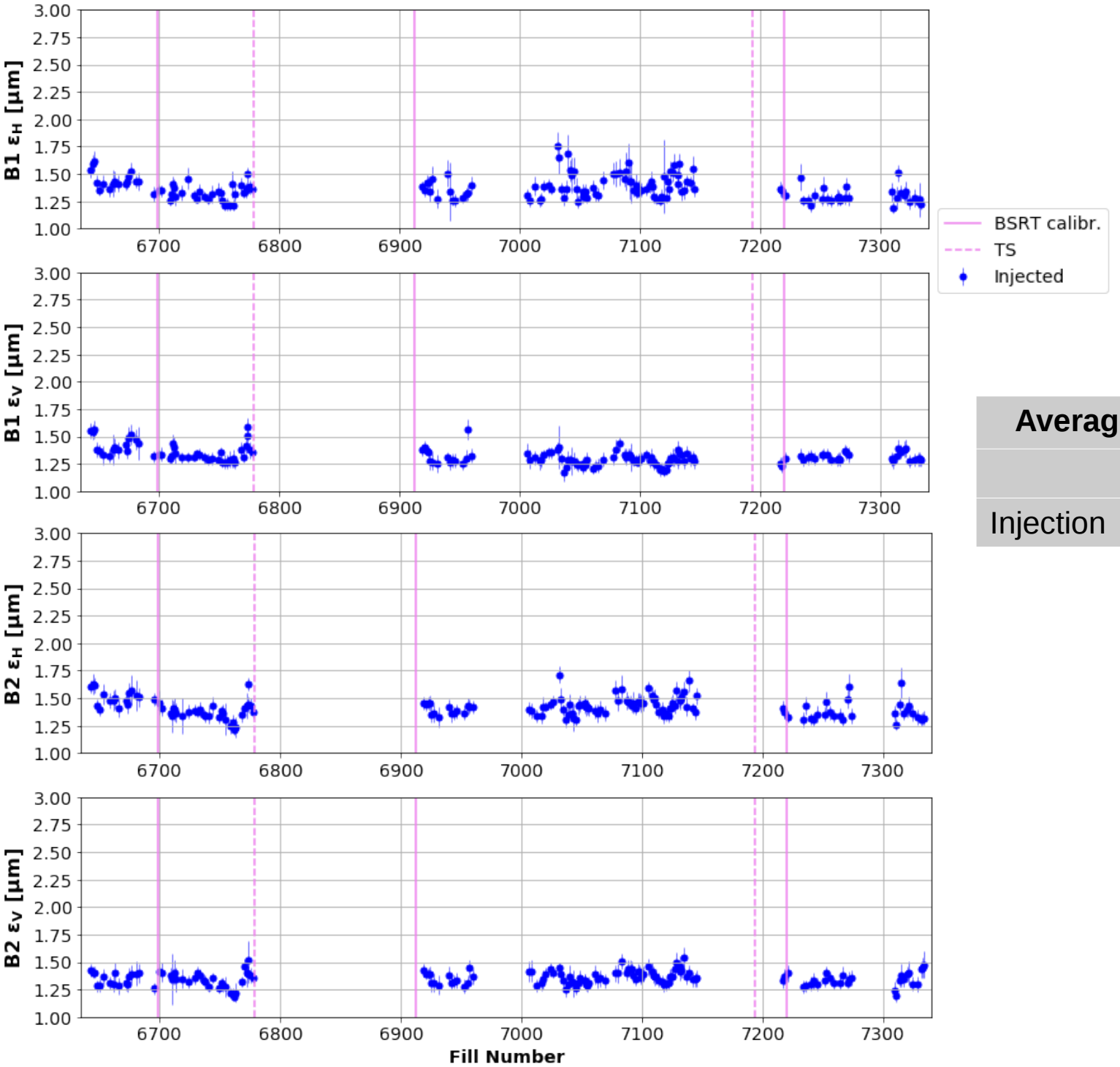
Further development of the luminosity model, including additional mechanisms (coupling, noise, etc). Construction of preliminary web-page→link: LumimodWebPage

I. Efthymiopoulos, N. Karastathis, S. Papadopoulou, Y. Papaphilippou

Outline

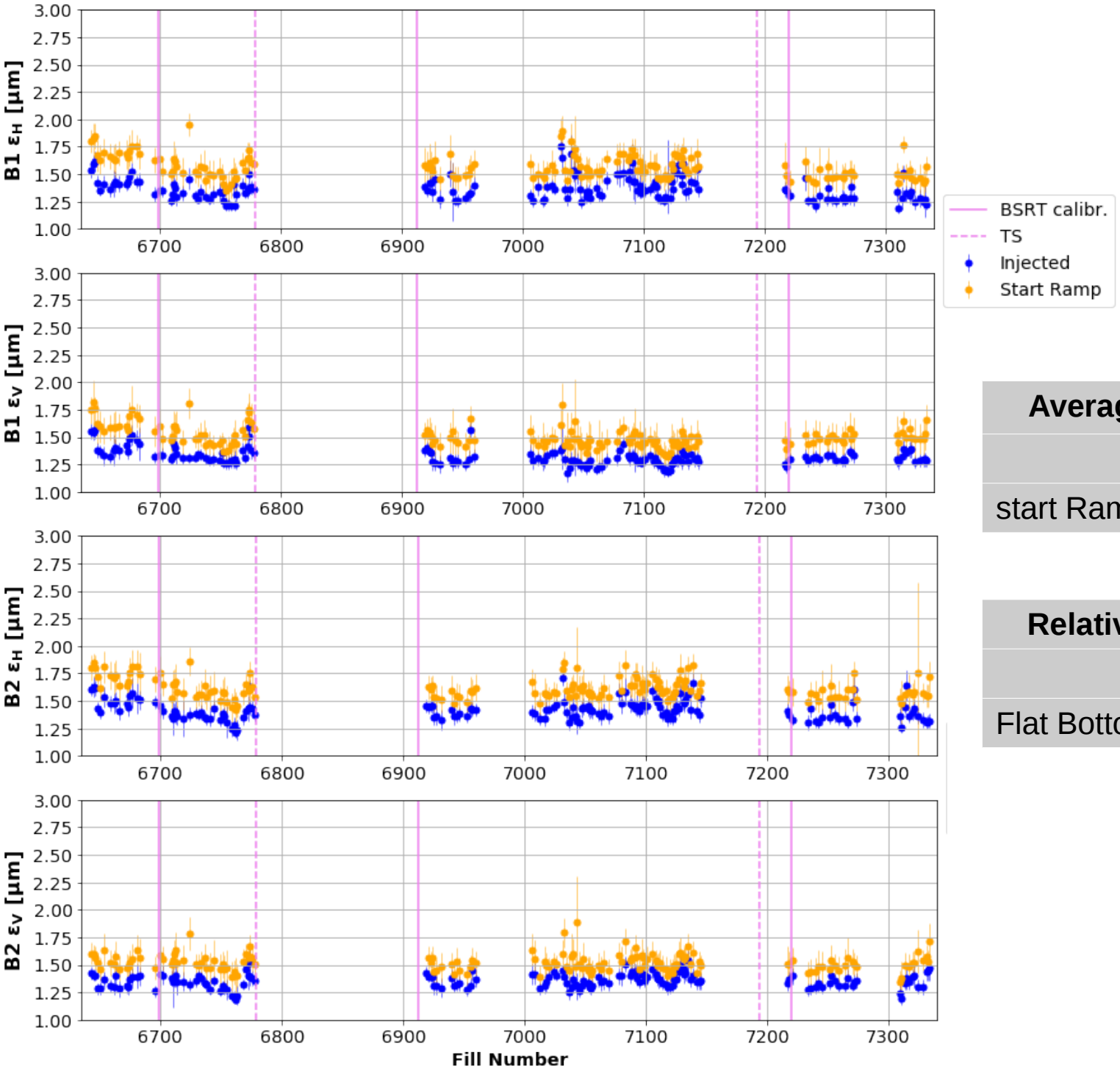
- Run 2 emittances (BCMS) along the LHC cycle
- Luminosity model
  - Model description
  - At FB, extra emittance growth (on top of the model)
  - At SB, luminosity evolution prediction and extra emittance growth (on top of the model)
- Cumulated integrated luminosity
- Summary

2018 emittances along the cycle



Average emittance values [μm]				
	B1H	B1V	B2H	B2V
Injection	1.4	1.3	1.4	1.4

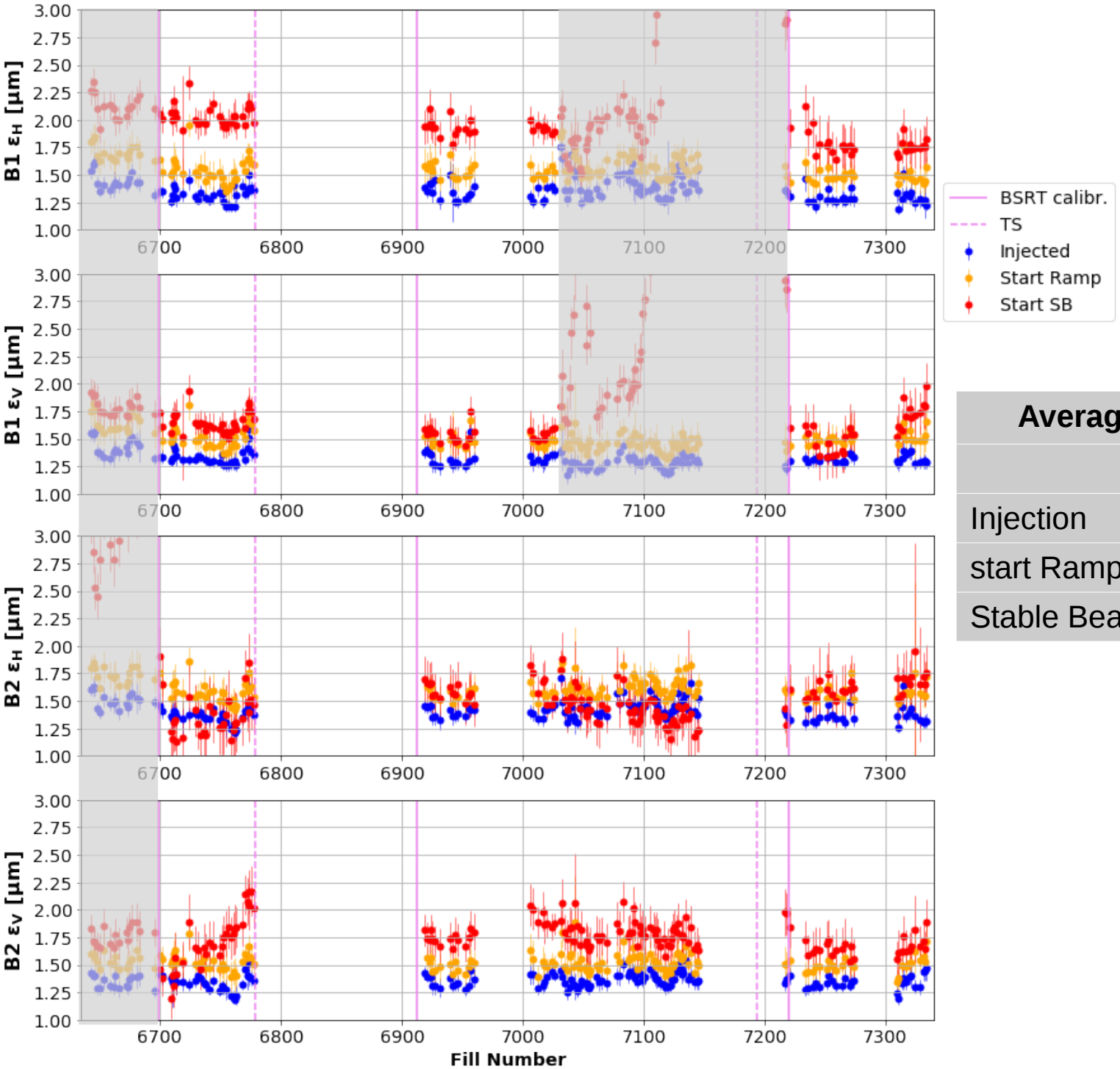
2018 emittances along the cycle



Average emittance values [μm]				
	B1H	B1V	B2H	B2V
start Ramp	1.6	1.5	1.6	1.5

Relative emittance blow-up [%]				
	B1H	B1V	B2H	B2V
Flat Bottom	15	14	14	12

2018 emittances along the cycle



Average emittance values [μm]				
	B1H	B1V	B2H	B2V
Injection	1.4	1.3	1.4	1.4
start Ramp	1.6	1.5	1.6	1.5
Stable Beams	2.0	1.7	1.5	1.7

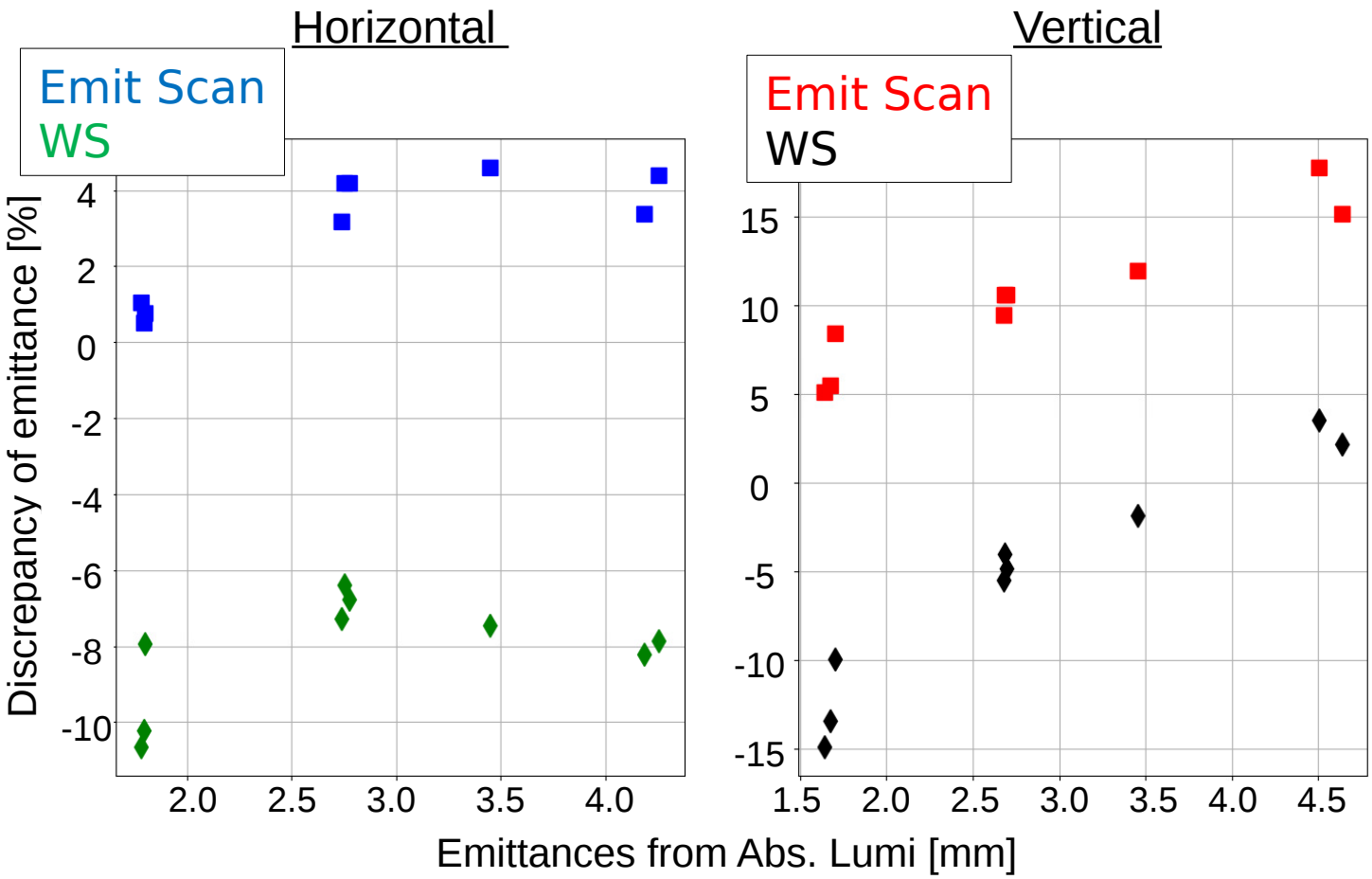
Unphysical B2H emittance at start of SB (smaller than at FB), according to BI this is within the 20% accuracy of BSRT. It improves after last BSRT calibration (Fill 7220)

BSRT calibration Fill results

E. Bravin, G. Trad
link:BSRTcalibr_LMC

BSRT calibration Fill 7220

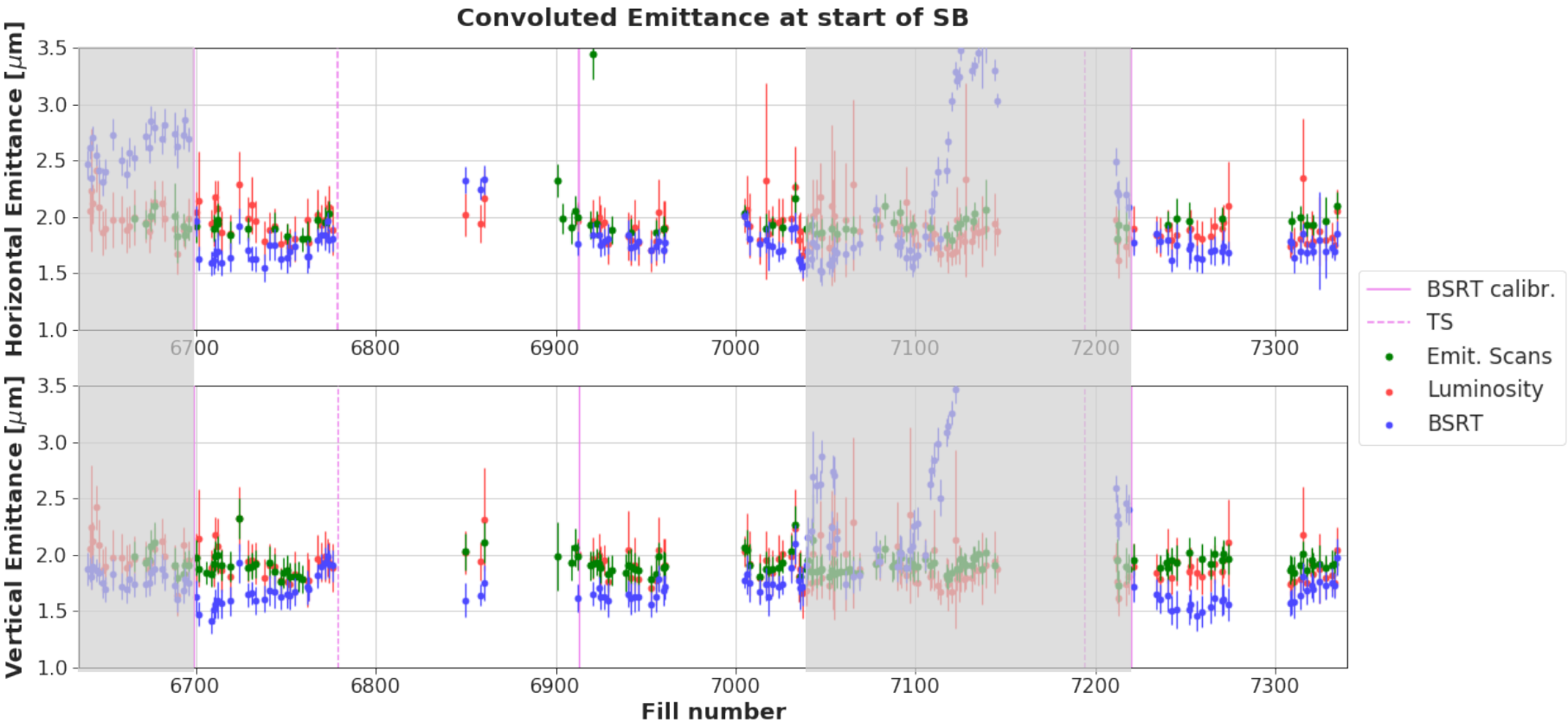
Comparison of convoluted emittances from Emittance Scans and WS with Luminosity



- Agreement of Emittance Scans with the ones from Luminosity is 5-20%
- Emittances from WS up to 10-15% lower than the Luminosity ones

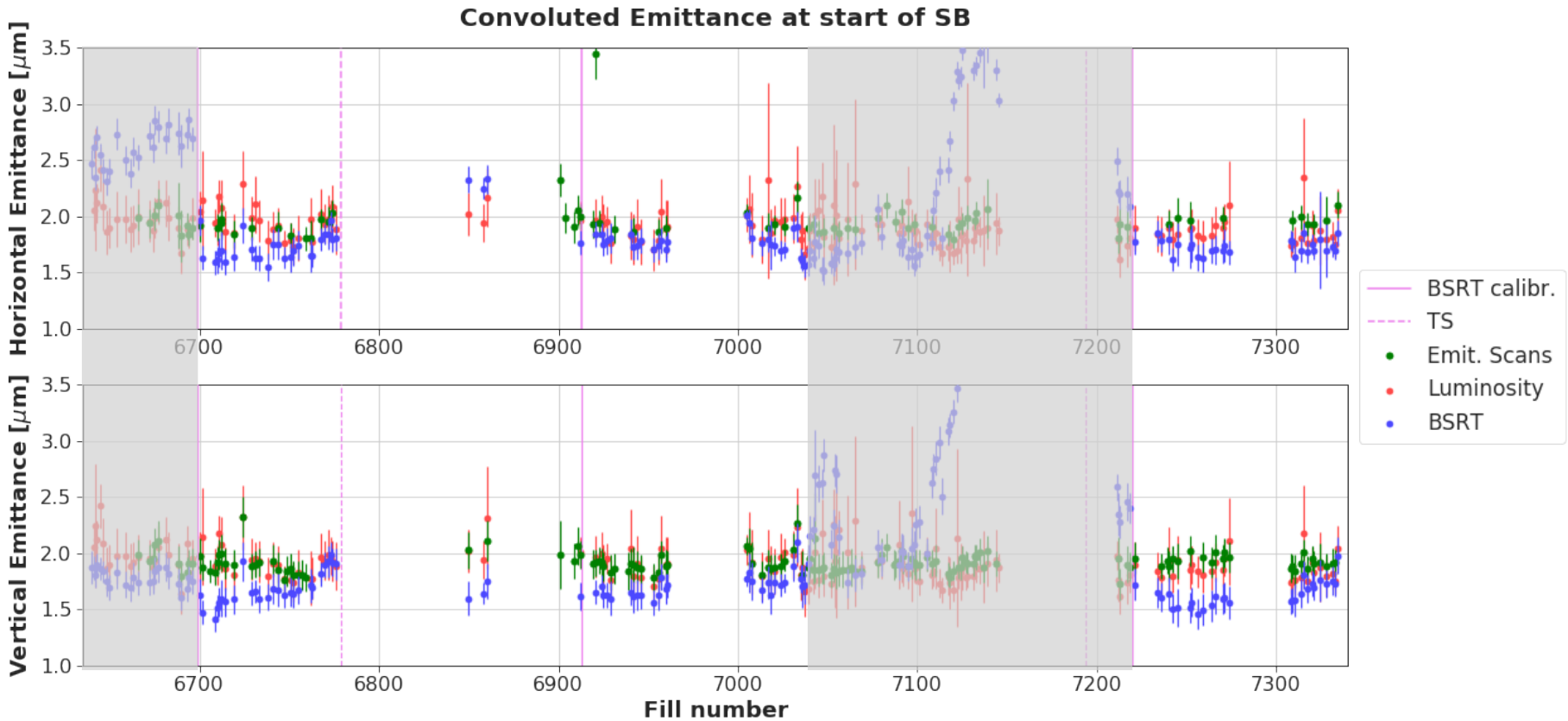
Revealing discrepancy between BSRT (calibrated against WS) and emittance from Luminosity→understanding this difference is important

Convoluted emittances at start of SB



Emittances from Luminosity agree within 10-15% with the ones from Emittance Scans and BSRT (see appendix)

Convoluted emittances at start of SB

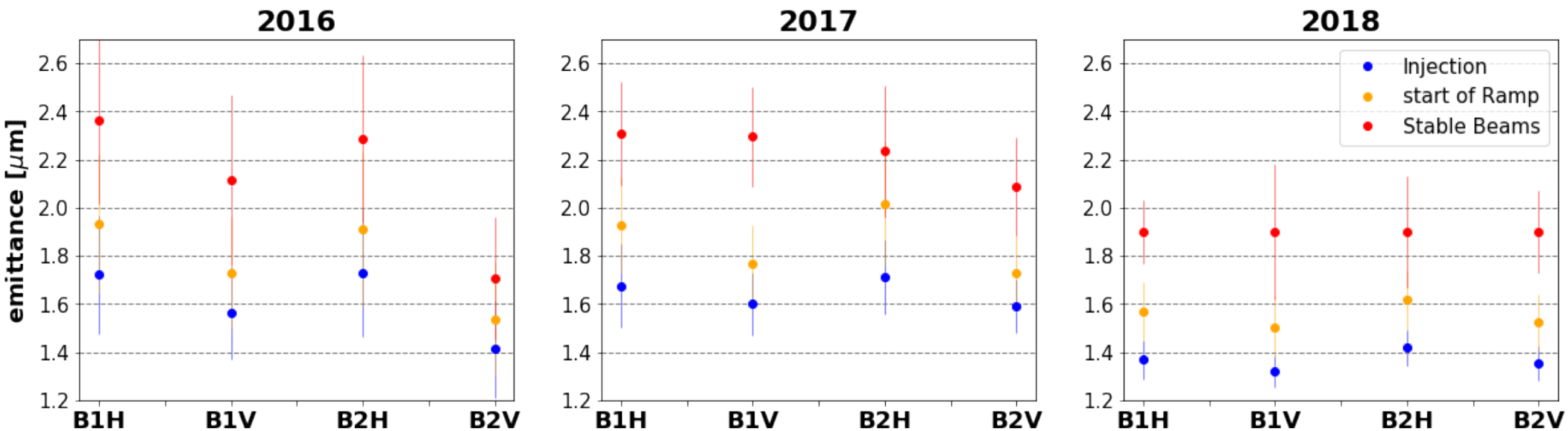


Emittances from Luminosity agree within 10-15% with the ones from Emittance Scans and BSRT (see appendix)

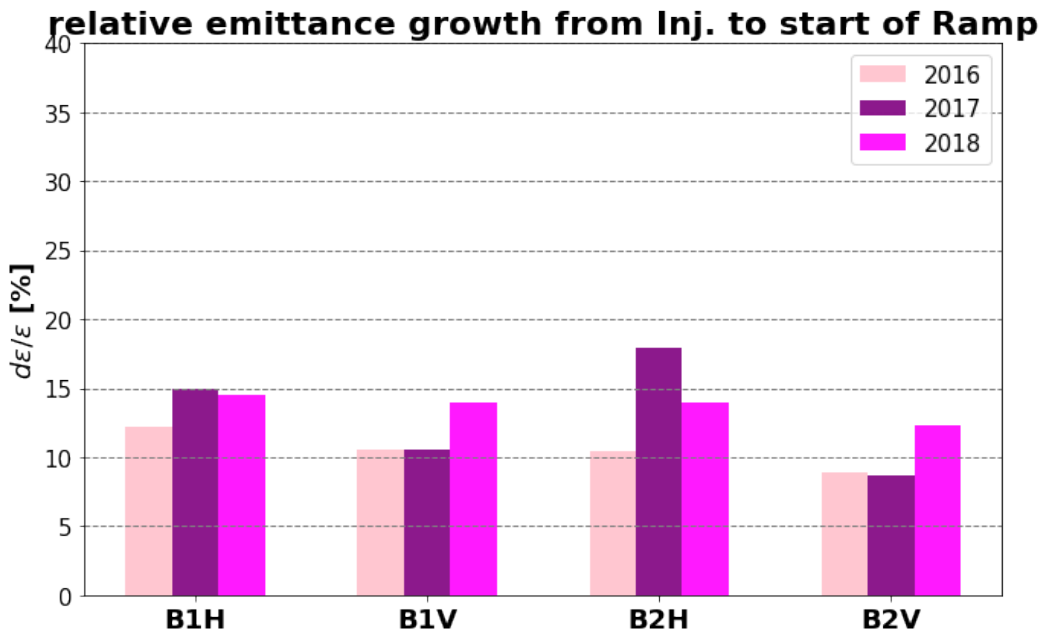
Considering only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%

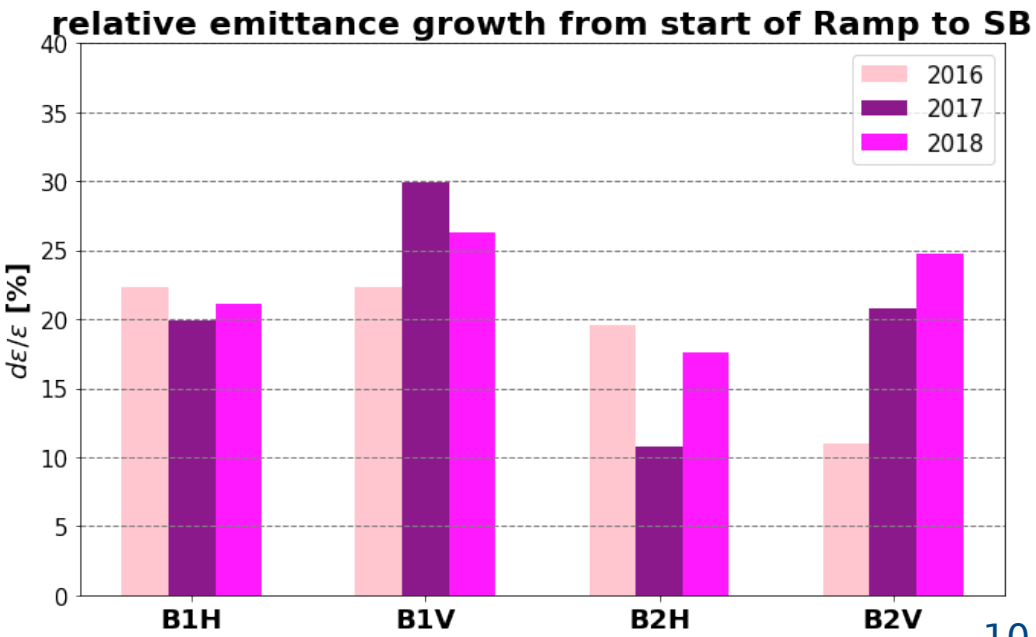
Average emittance values [μm]			Relative emittance blow-up [%]		
	B1H, B2H	B1V, B2V		B1H, B2H	B1V,B2V
Stable Beams	1.9	1.9	Ramp	~20	~25

Run2 emittances along the cycle



2018 emittances along the LHC energy cycle are smaller compared to previous years





Luminosity model description

Bunch-by-bunch modeling of three main mechanisms:

- Intrabeam scattering (IBS)
- Synchrotron radiation (SR)
- Luminosity burn-of

-β*, luminosity leveling, x-ing angle anti-leveling options

-in 2018, coupling of transverse emittances included, small impact (see appendix)

-sensitive to initial conditions (emittances, intensities, etc)

F. Antoniou et al., TUPTY020, proc. of IPAC' 15
F. Antoniou et al., "Can we predict luminosity?", proc. of Evian 2016

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-in 2018, coupling of transverse emittances included, small impact (see appendix)

-sensitive to initial conditions (emittances, intensities, etc)

The model can be applied under different assumptions by using data evolution as:

	Pure model	Extra losses	Extra emit. growth	Calculated
Emittance	model	model	**data**	**data**
Intensity	model	**data**	model	**data**

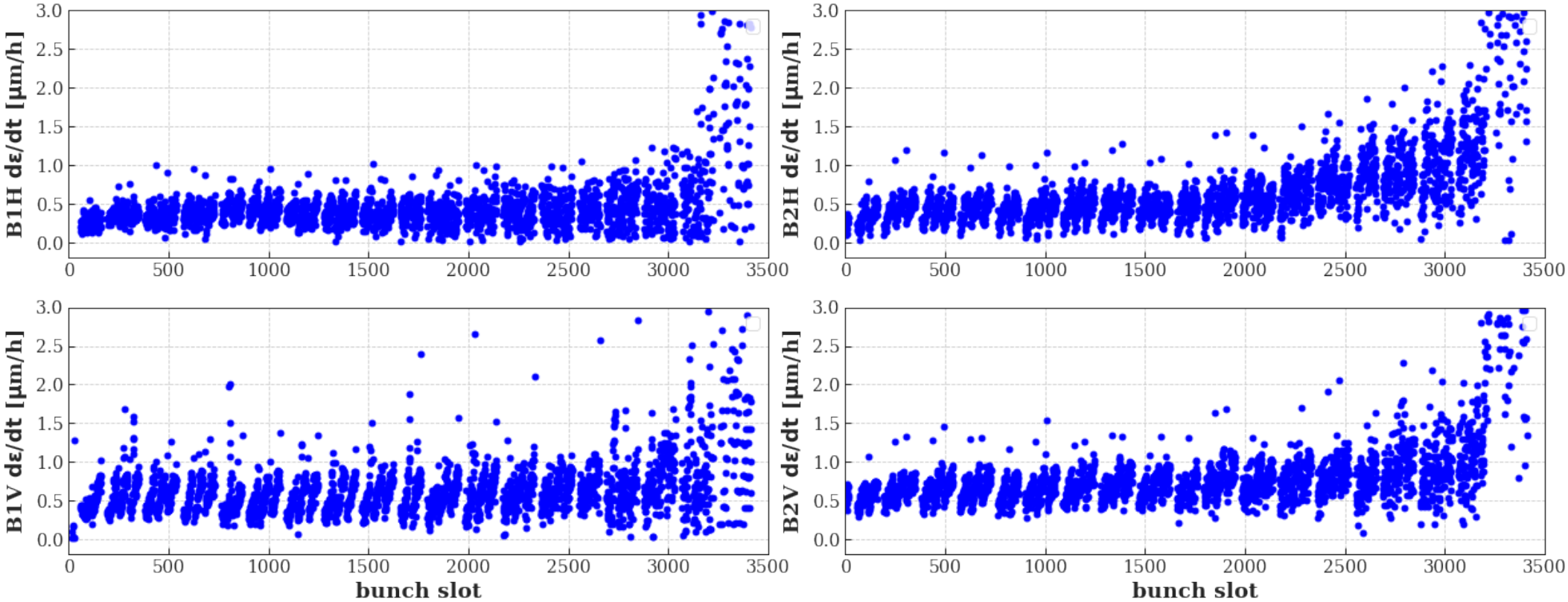
F. Antoniou et al., TUPTY020, proc. of IPAC' 15
F. Antoniou et al., "Can we predict luminosity?", proc. of Evian 2016

Extra emittance growth at FB

Measured-Model emittance difference over time at FB vs bunch slot, for a Fill

dε/dt→extra emittance growth <u>on top of IBS</u>

Fill 7035



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Measured-Model emittance difference over time at FB vs bunch slot, for a Fill

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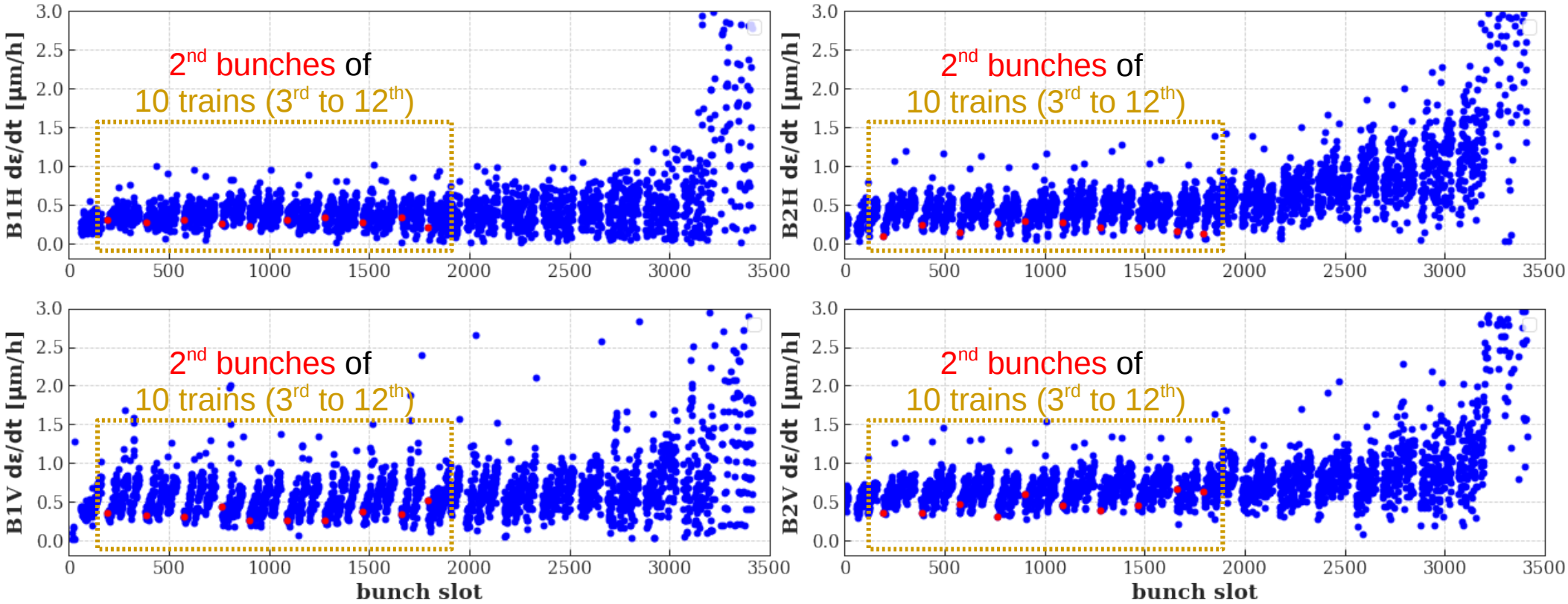
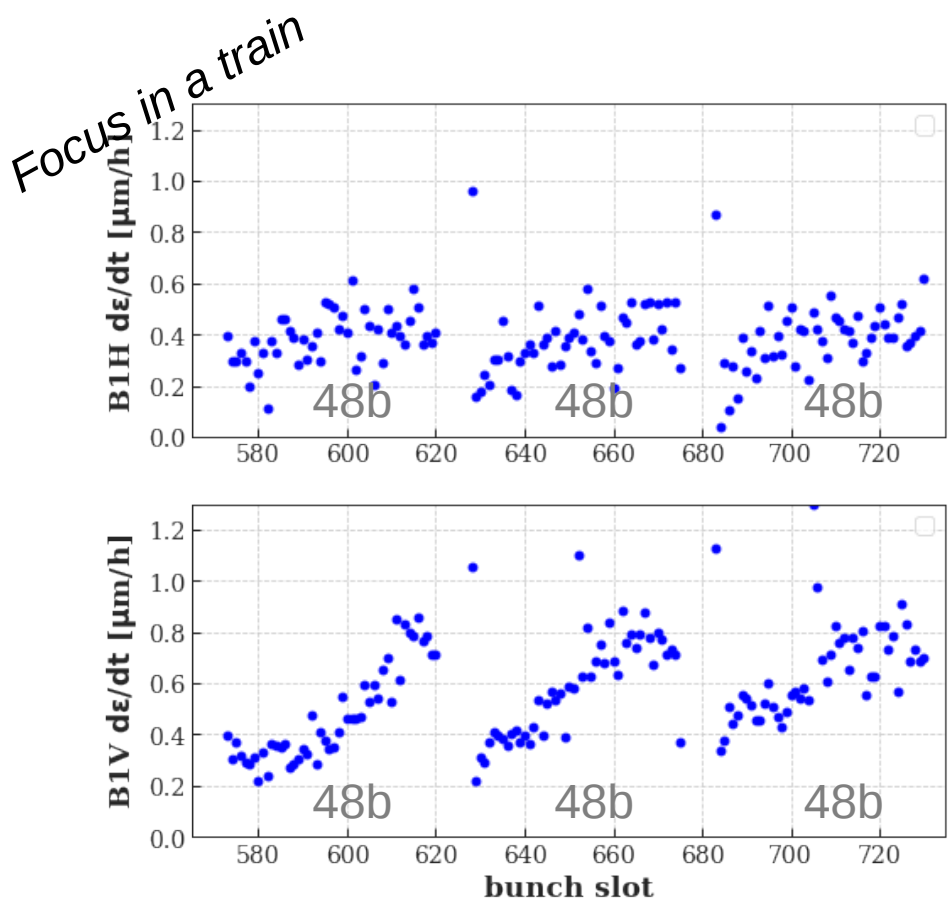


Assuming that the first bunches of a train experience no e-cloud, the **dε/dt** of the 2nd bunch of 10 trains (3rd to 12th) gives the extra emittance growth <u>on top of IBS and e-cloud</u>

Extra emittance growth at FB

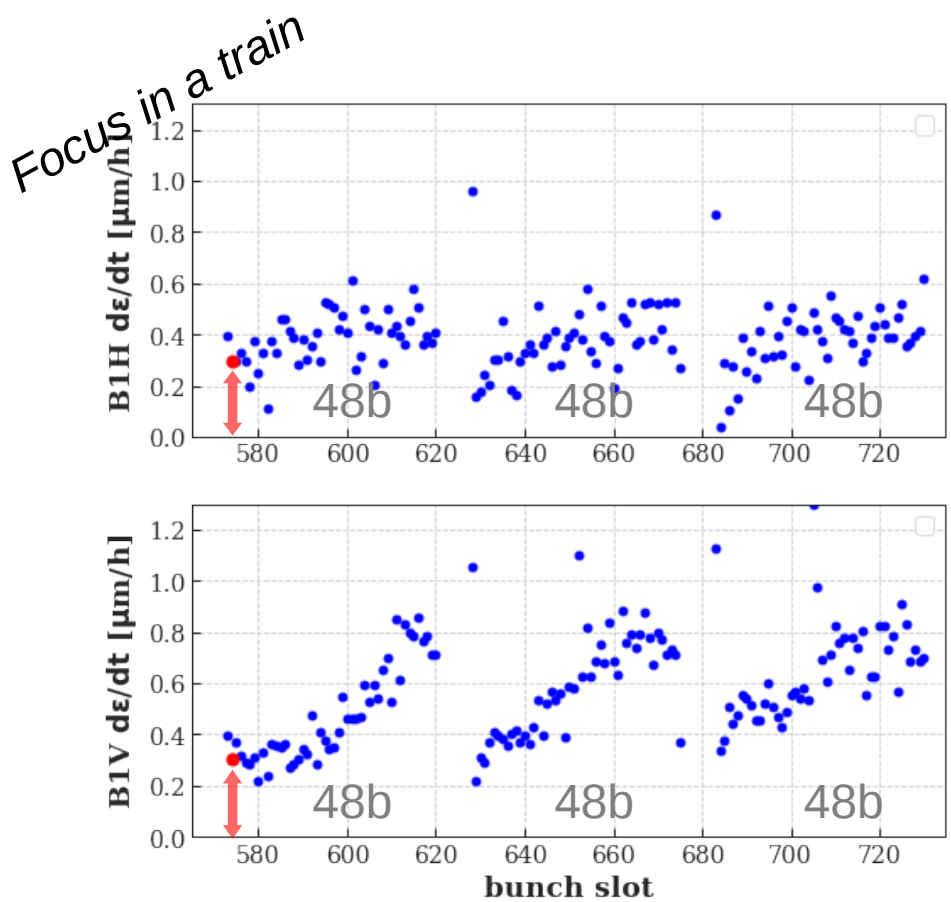


Measured-Model emit. difference over time at FB **for all 2018 Fills**

extra growth [μm/h]				
	B1H	B1V	B2H	B2V
on top of IBS (all bunches)	0.34	0.64	0.41	0.61

- Extra growth **on top of IBS** smaller in horizontal than in the vertical.
- In vertical, where IBS growth is minor, the observed blow up beyond the model is ~0.6μm/h

Extra emittance growth at FB



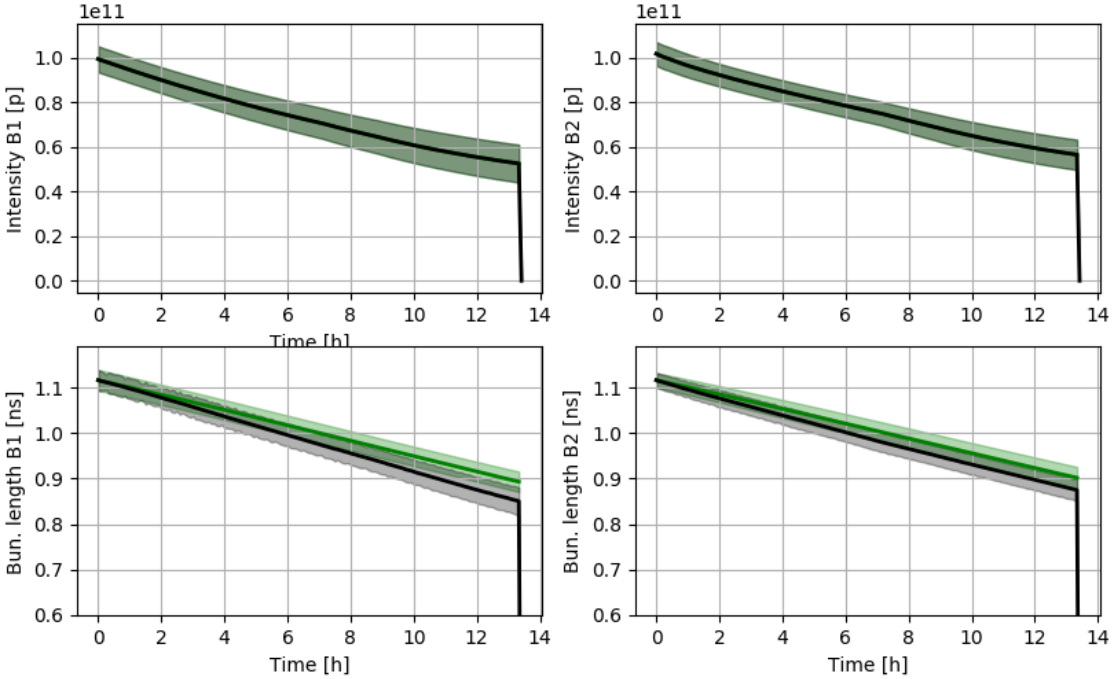
Measured-Model emit. difference over time at FB **for all 2018 Fills**

extra growth [μm/h]				
	B1H	B1V	B2H	B2V
on top of IBS (all bunches)	0.34	0.64	0.41	0.61
on top of IBS&e-cloud (2nd bunches of trains)	0.24	0.44	0.17	0.41

- Extra growth **on top of IBS** smaller in horizontal than in the vertical.
- In vertical, where IBS growth is minor, the observed blow up beyond the model is ~0.6μm/h
- The contribution of **e-cloud** to the emittance growth is ~0.2 μm/h
- The rest of the extra emittance growth at FB is 0.2 μm/h in horizontal and 0.4 μm/h in vertical
- Ongoing studies to correlate this extra growth with noise estimations

Luminosity evolution prediction

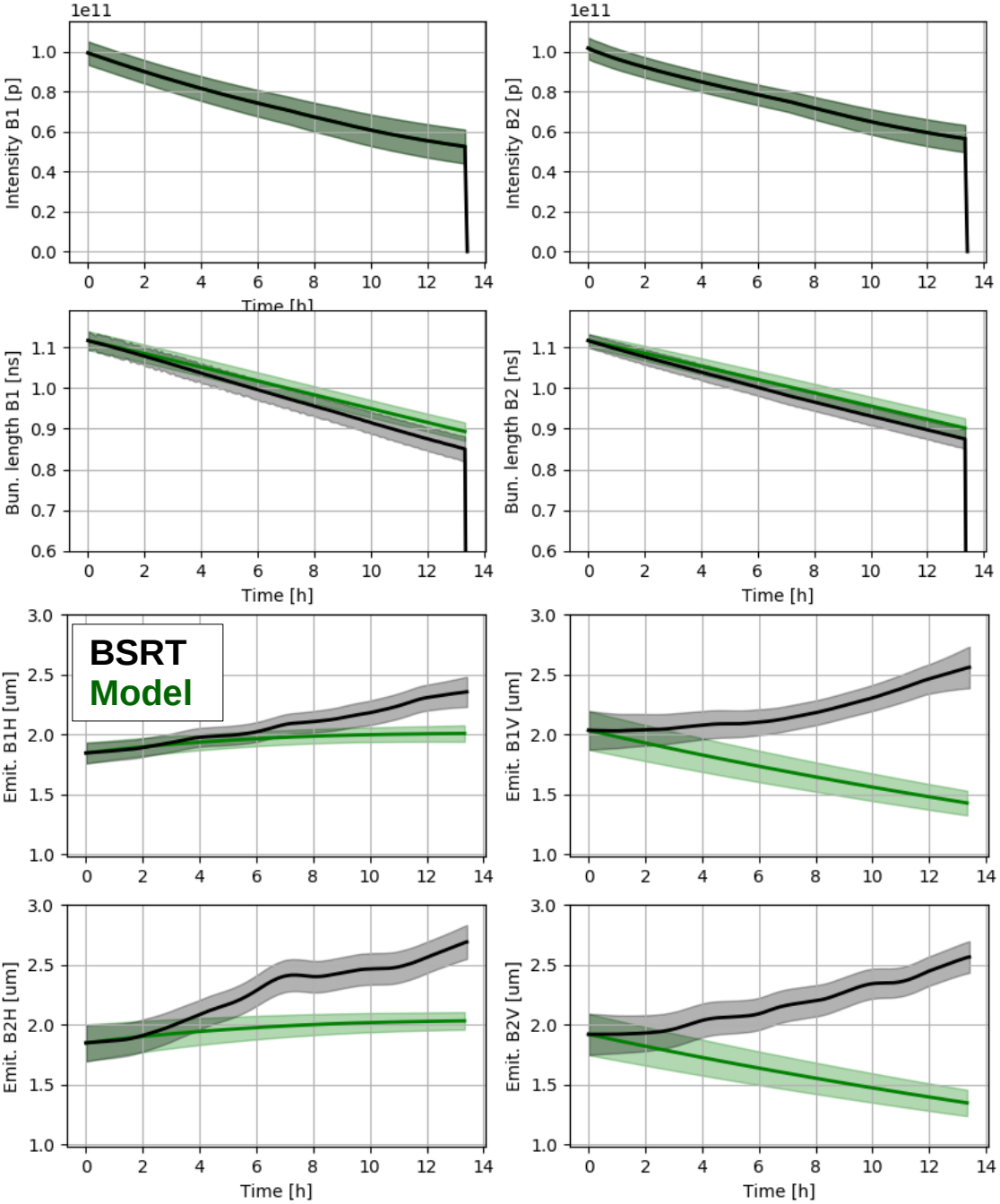
Fill 7334 (one of the Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)



Following the intensity evolution from **data**

Luminosity evolution prediction

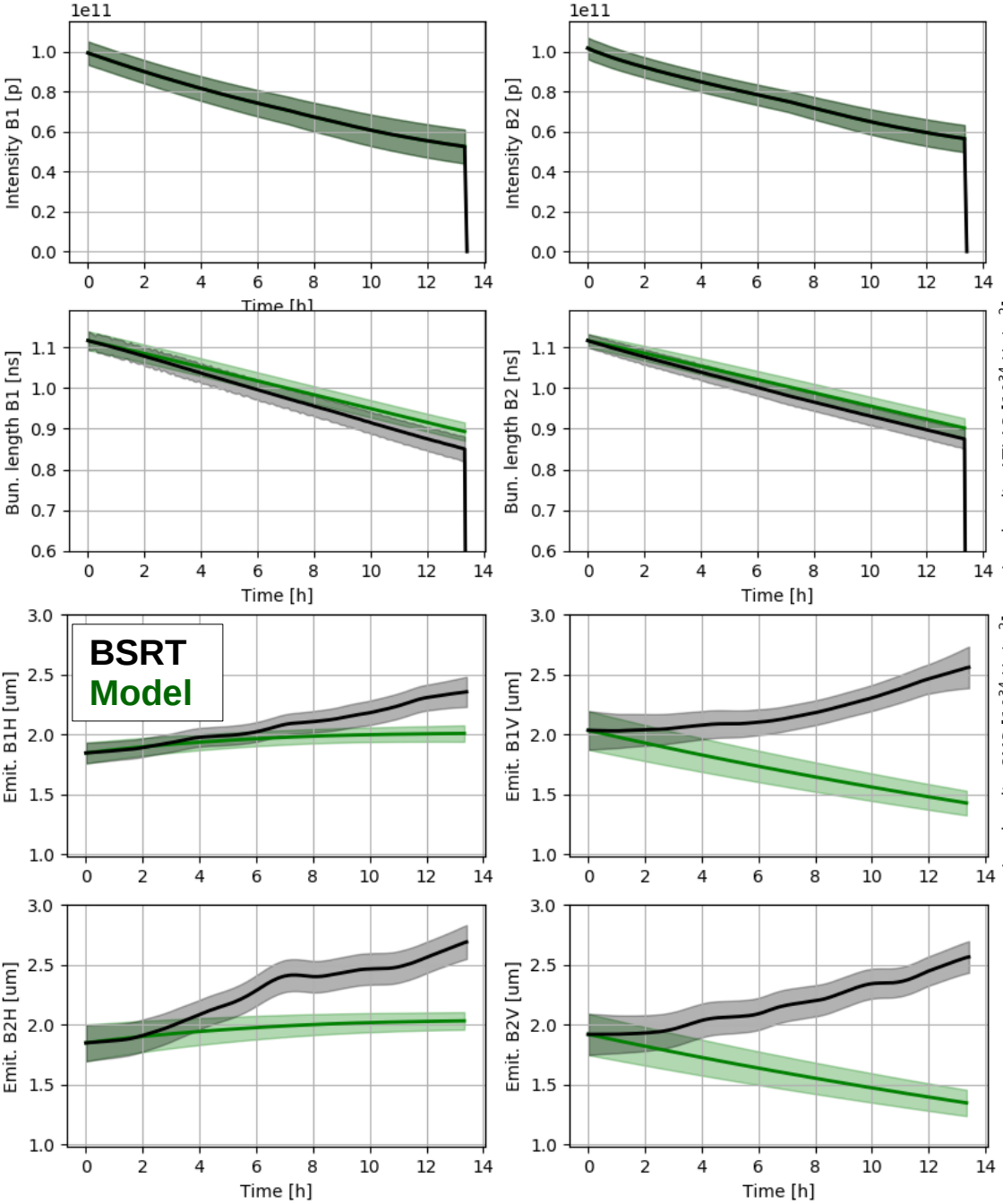
Fill 7334 (one of the Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)



Following the intensity evolution from **data** and the emittance from **model**

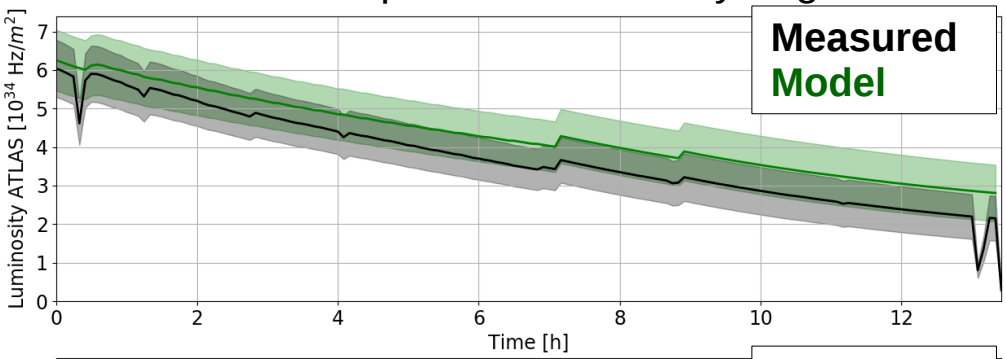
Luminosity evolution prediction

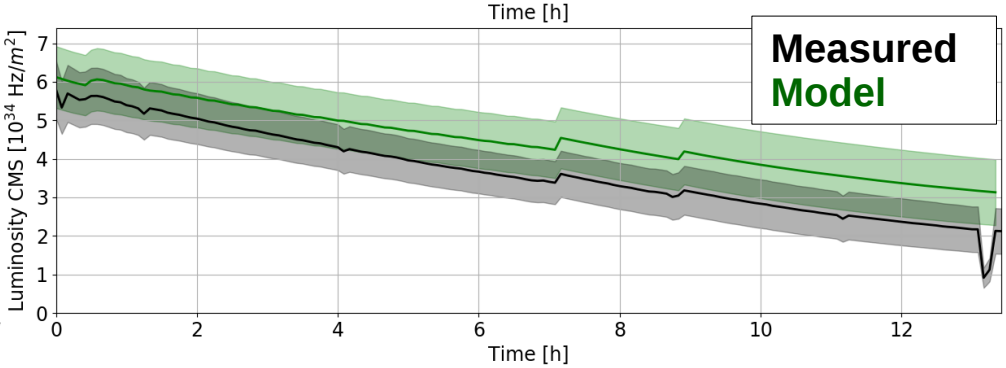
Fill 7334 (one of the Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)



Following the intensity evolution from **data** and the emittance from **model**

➡ understanding the impact of the extra emittance blow up on the luminosity degradation



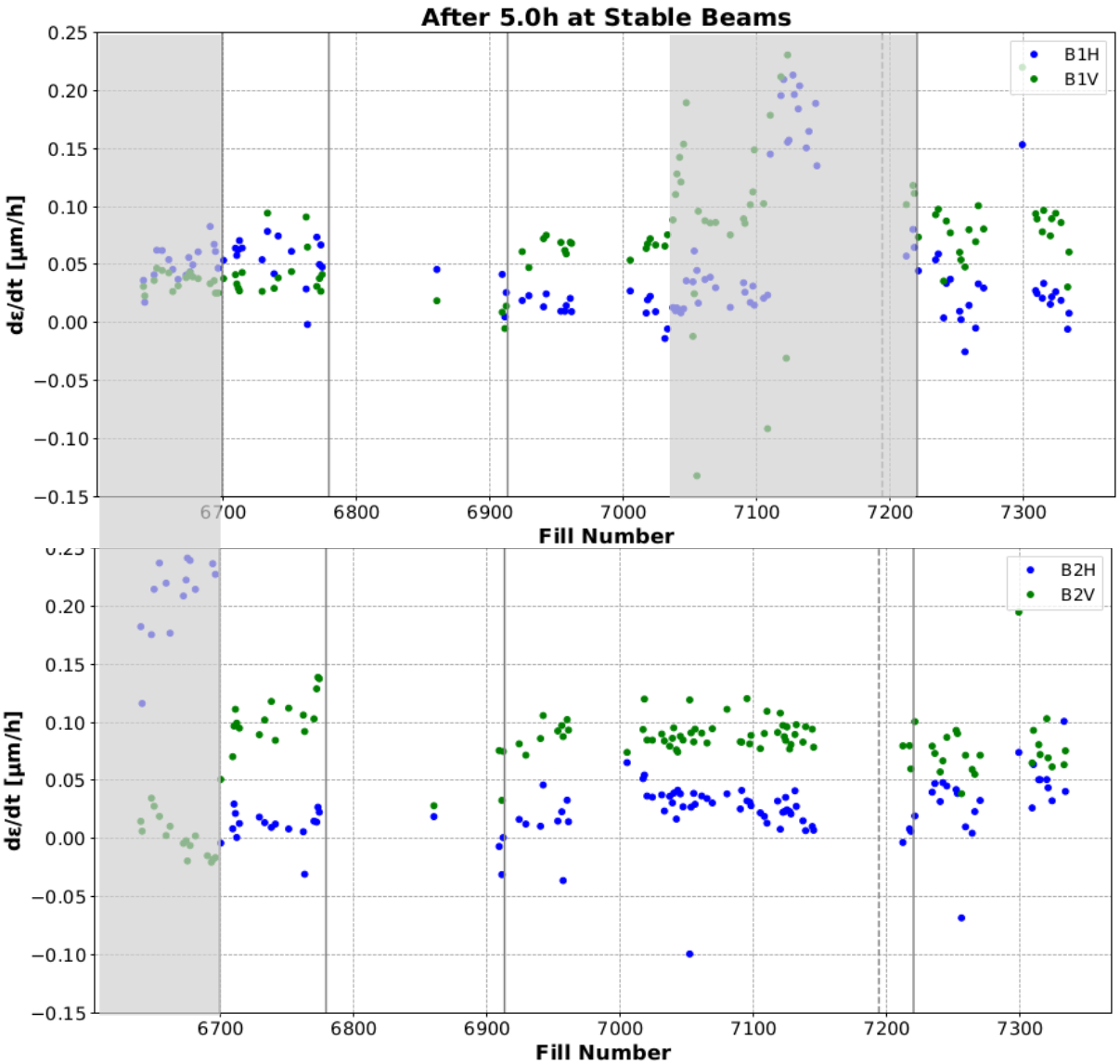


Model → the luminosity expected in case there is no extra emit. growth (on top of the model)

Extra emittance growth at SB

Measured (BSRT)-Model emit. difference after 5h at SB vs Fill number

dε/dt → extra emittance growth <u>on top of IBS</u>



(Taking into account only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

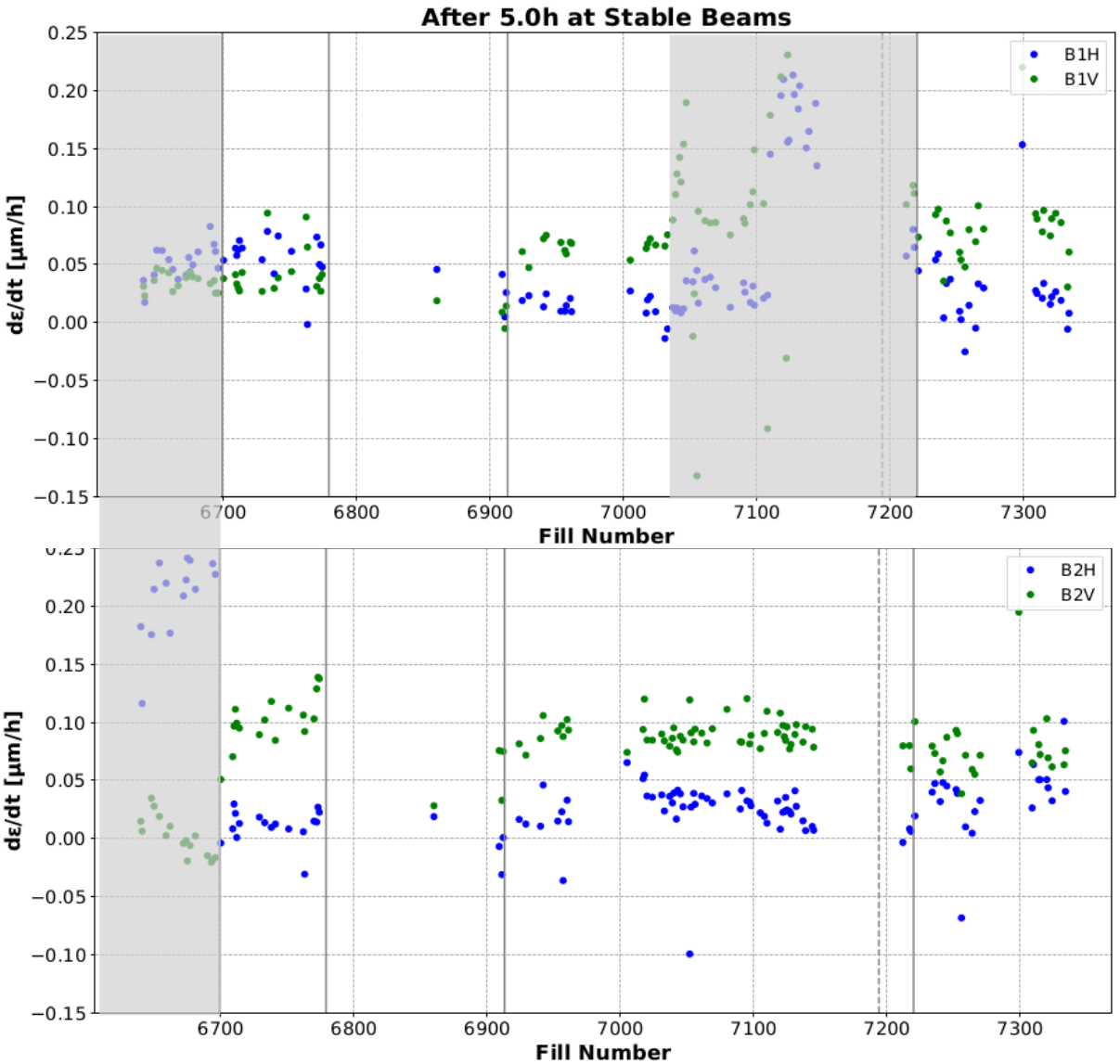
Emit. growth after 5h @ SB [μm/h]				
	B1H	B1V	B2H	B2V
extra	0.02	0.07	0.02	0.09

Not constant extra growth along a fill in horizontal

Extra emittance growth at SB

Measured (BSRT)-Model emit. difference after 5h at SB vs Fill number

dε/dt → extra emittance growth <u>on top of IBS</u>



(Taking into account only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

Emit. growth after 5h @ SB [μm/h]				
	B1H	B1V	B2H	B2V
extra	0.02	0.07	0.02	0.09

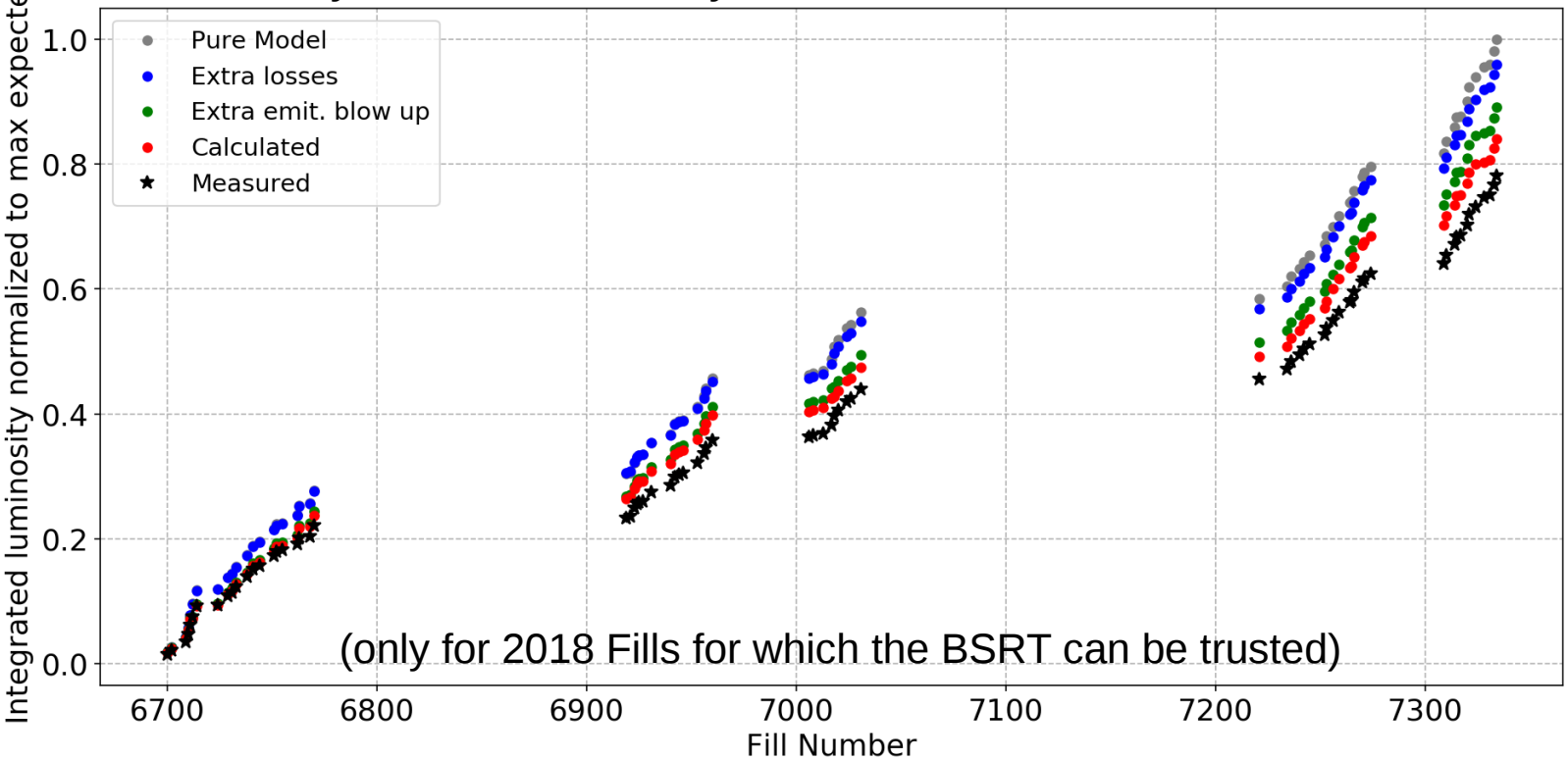
Not constant extra growth along a fill in horizontal

In 2017, the extra emittance growth at SB was around 0.05μm/h and 0.1μm/h in the horizontal and the vertical plane, respectively

These values are close to what is observed as emittance growth from noise at SB (X. Buffat)

Cumulated integrated Luminosity

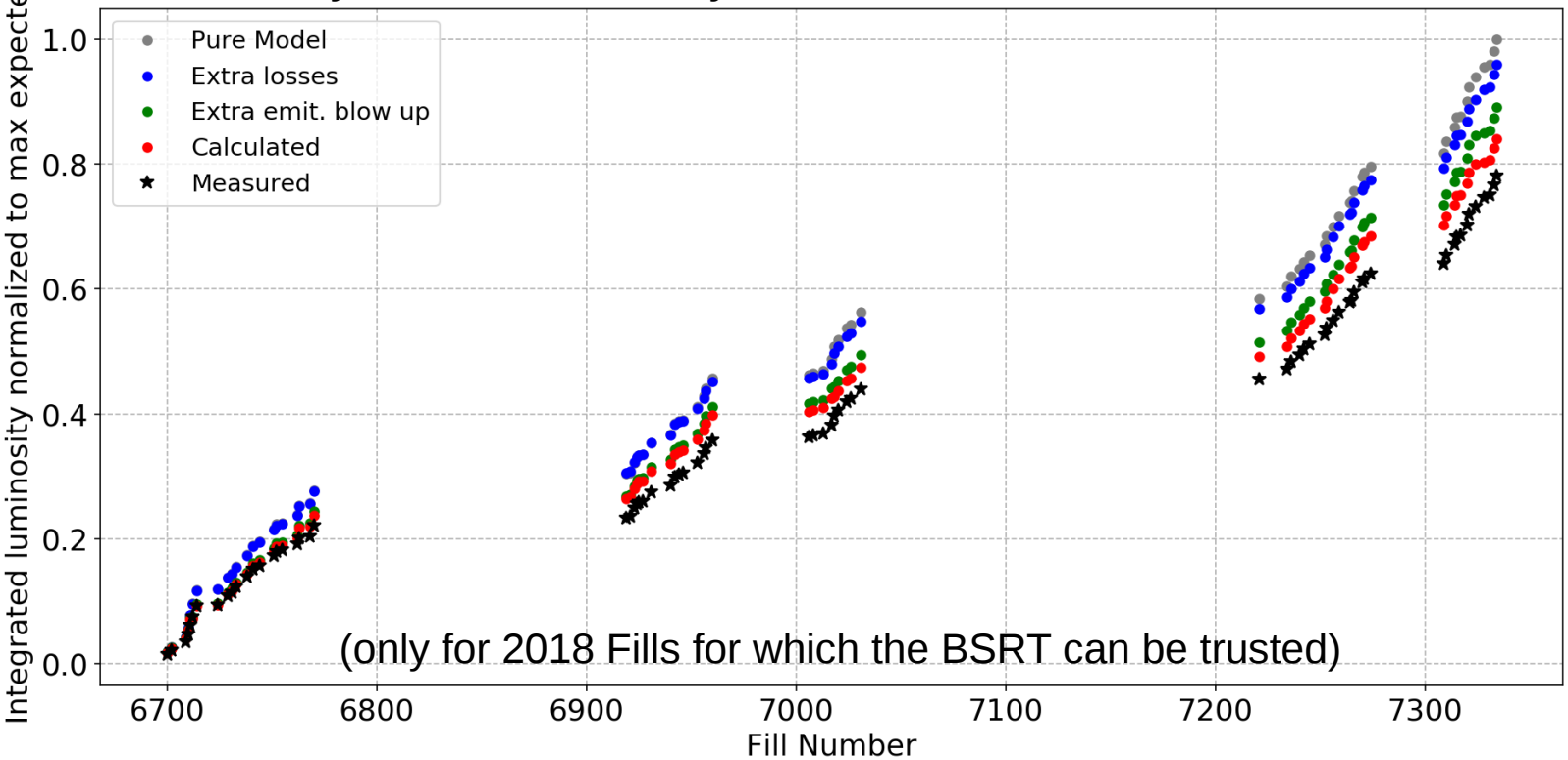
2018 Luminosity degradation due to mechanisms that are beyond the luminosity model



	Pure model	Extra losses	Extra emit. growth	Calculated
Emittance	model	model	**data**	**data**
Intensity	model	**data**	model	**data**

Cumulated integrated Luminosity

2018 Luminosity degradation due to mechanisms that are beyond the luminosity model



2018	2017
-5%	-1%
-11%	-10%
-22%	-11%
-16%	-12%

	Pure model	Extra losses	Extra emit. growth	Calculated
Emittance	model	model	**data**	**data**
Intensity	model	**data**	model	**data**

2018 BSRT emittances lower by ~10% than the luminosity ones→ explains difference between **measured** (by the experiments) and **calculated** luminosity

Summary

- Performance followed up with **automated tools** through the whole run →giving feedback to MCs and guiding BSRT calibration

- In 2018, the comparison of WS and Emit. scans with Luminosity emittances during a BSRT calibration Fill, explains the **discrepancy observed between the different measurements** along the year→understanding this discrepancy is important

- The 2018 **emittances along the cycle** are smaller compared to previous years

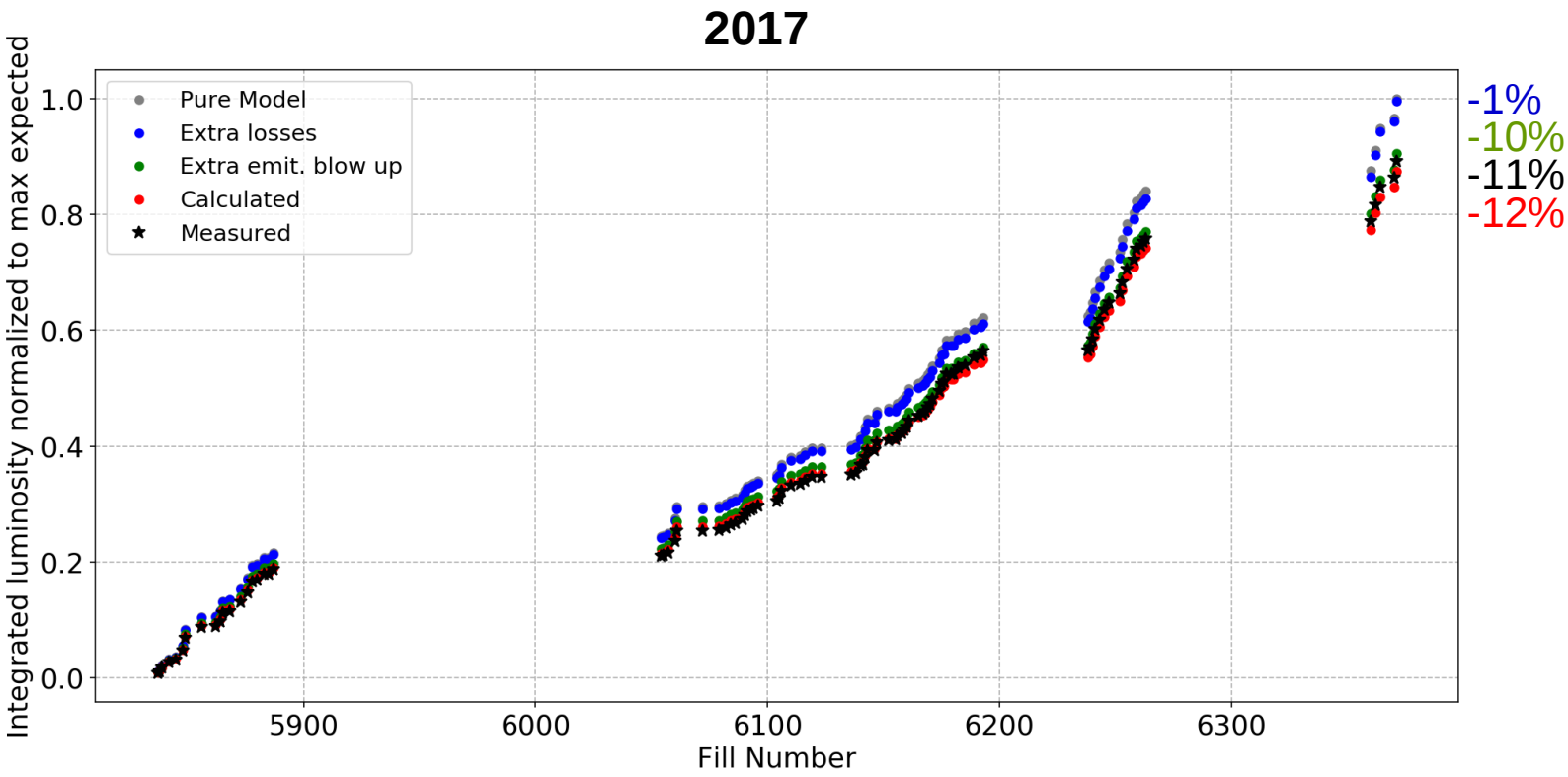
- For both FB and FT energies, the observed **extra emittance growth (on top of the model):**
  -is similar for both beams, larger in the vertical compared to the horizontal plane
  -at FB, e-cloud explains almost 50% of the observed extra growth. Impact of e-cloud to the observed extra growth at SB to be studied
  -the "unknown" extra emittance growth at FB is 0.2 μm/h in horizontal and 0.4 μm/h in vertical. Ongoing studies to correlate this extra growth with noise, which also predicts more growth in vertical at SB (see appendix)
  -no clear correlation with brightness (see appendix)

- Extra emittance blow up plays an important role in the degradation of the **cumulated integrated luminosity.** Extra losses have a smaller impact. In 2018 the impact of the extra losses is larger compared to 2017 (see Sofia's talk)

Thank you!

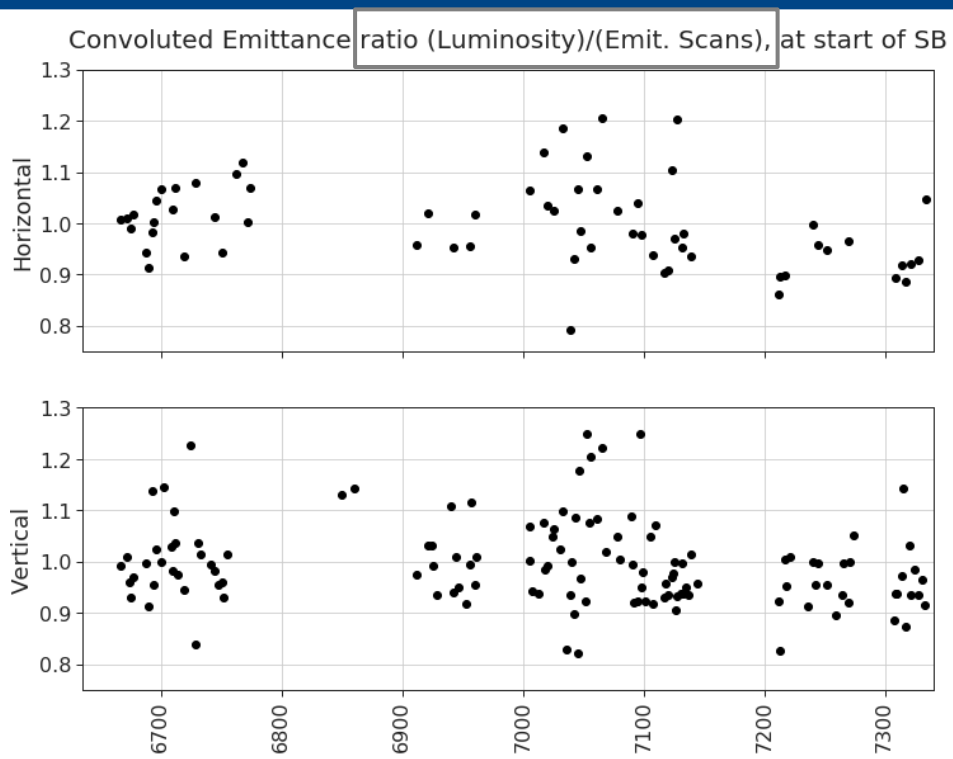
extra slides

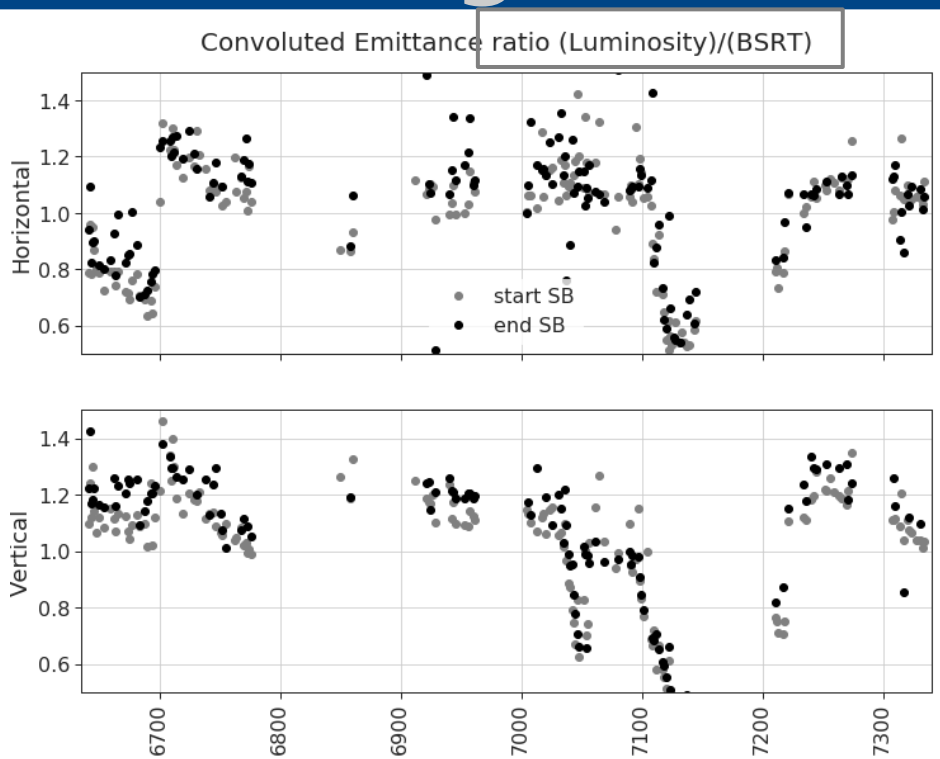
Cumulated integrated luminosity

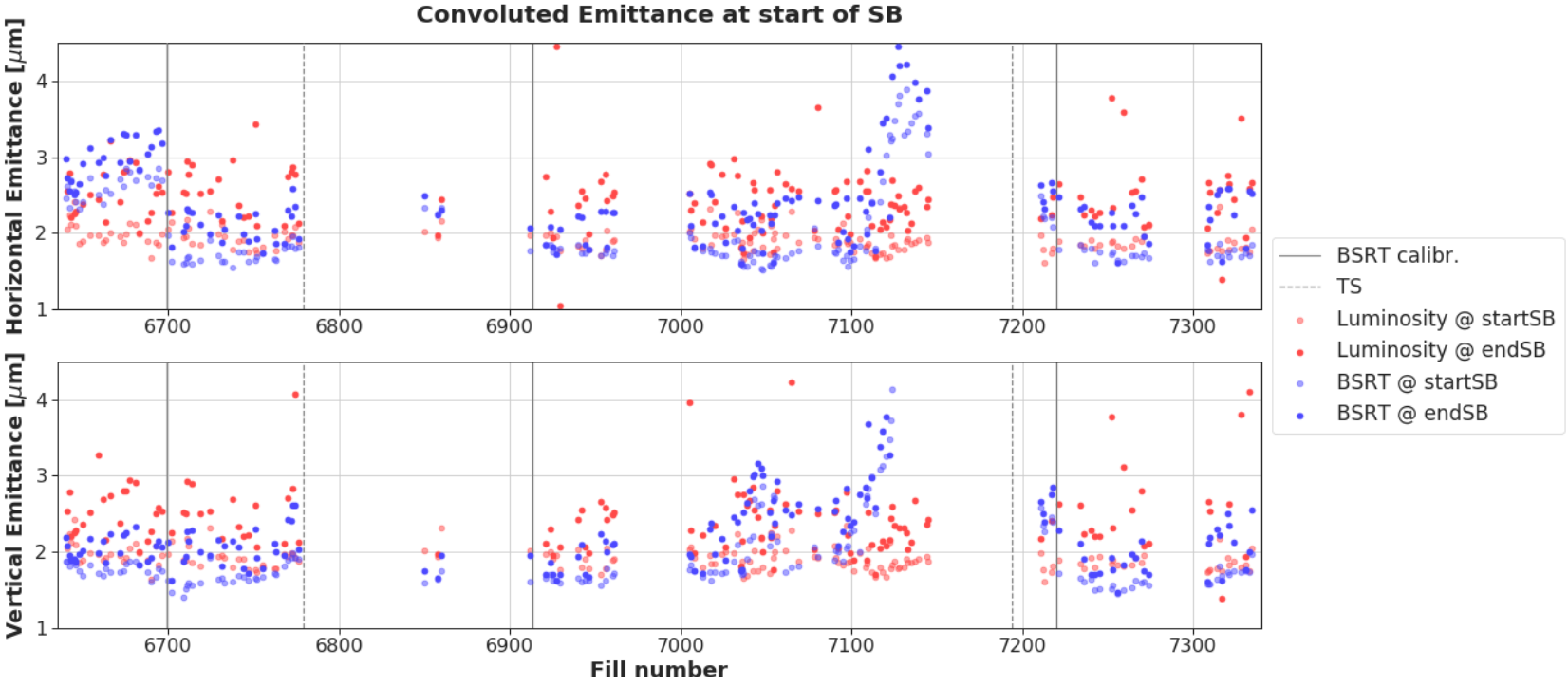


	Pure model	Extra losses	Extra emit. growth	Calculated
Emittance	model	model	**data**	**data**
Intensity	model	**data**	model	**data**

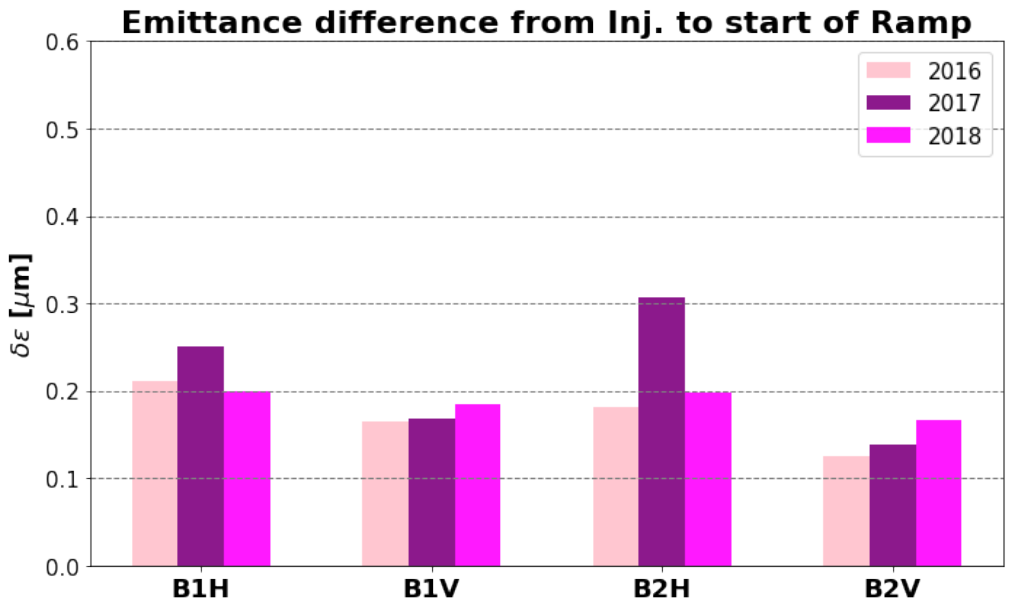
Lumi-BSRT convoluted emit. agreement

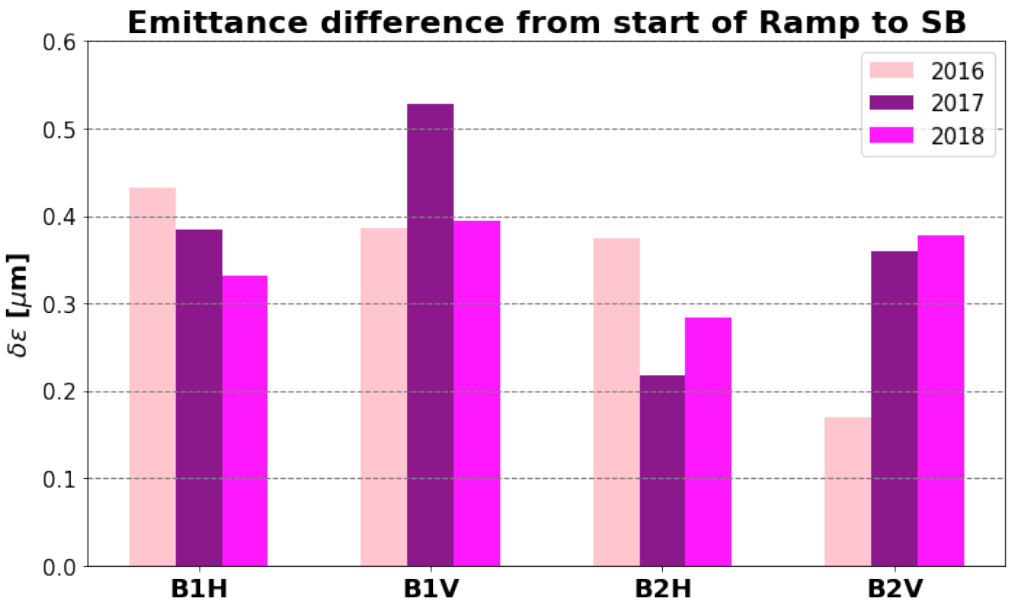




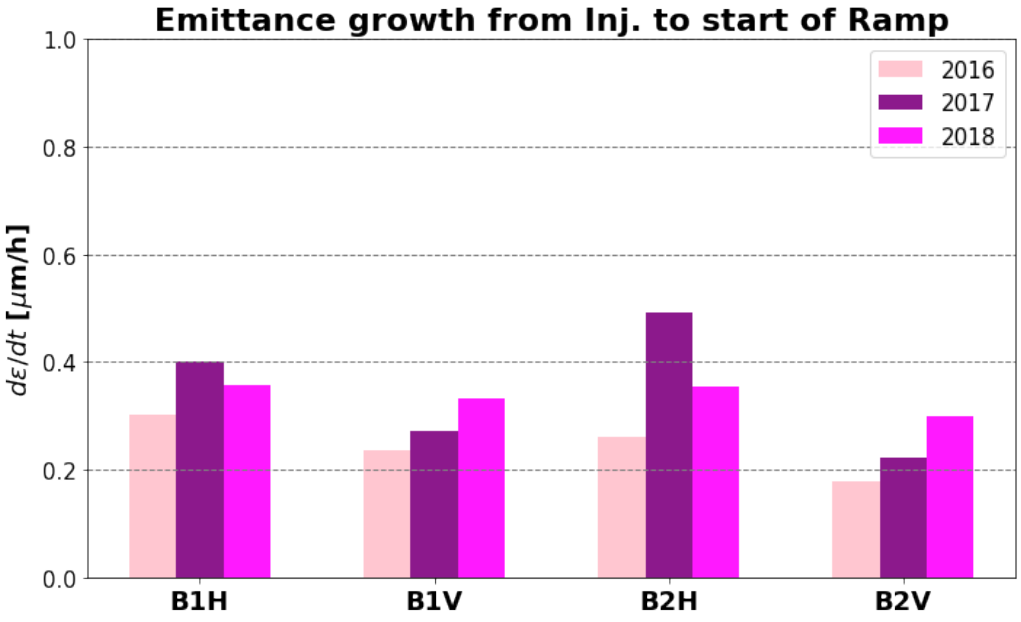


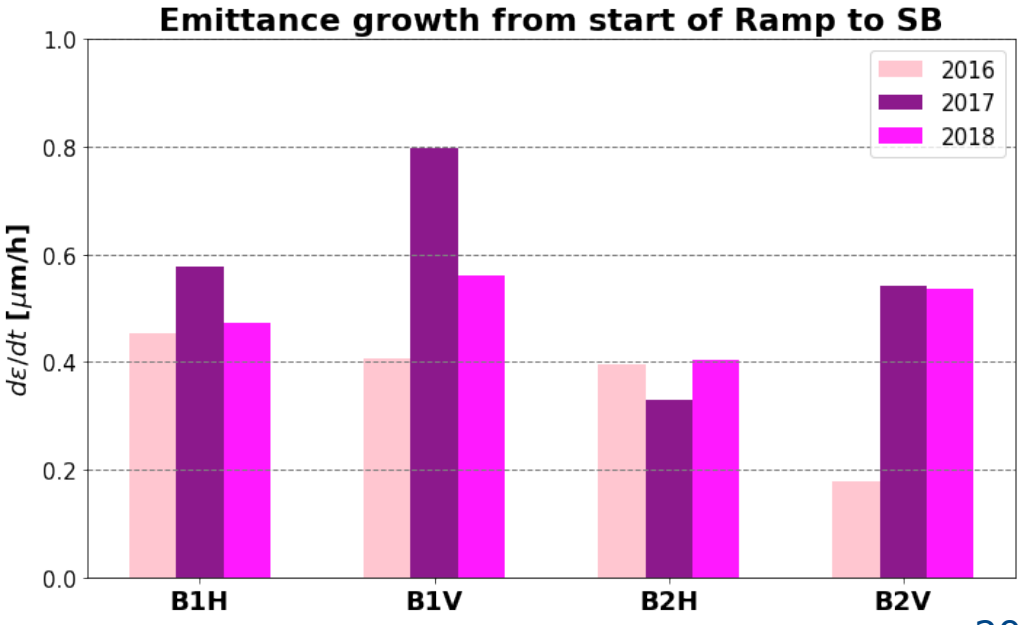
Run2 emittances along the energy cycle



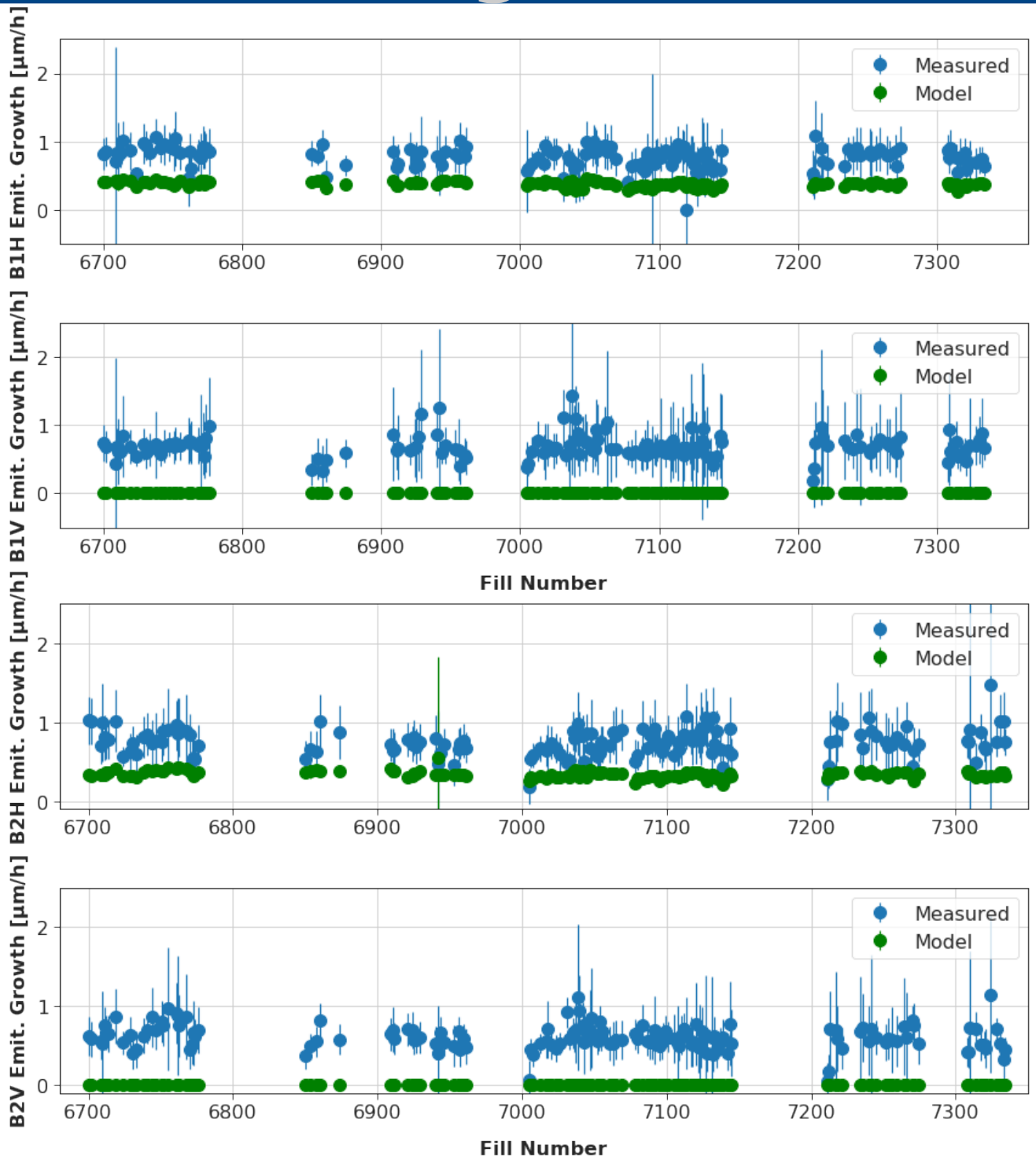


2016: t_{FB}=42, t_{Ramp}=57 [min] and INJ intensity [1e11]: B1=1.082, B2=1.065
2017: t_{FB}=37, t_{Ramp}=39 [min] and INJ intensity [1e11]: B1=1.115, B2=1.116
2018: t_{FB}=33, t_{Ramp}=42 [min] and INJ intensity [1e11]: B1=1.104, B2: 1.100





Emittance growth at FB



Emittance growth at FB [μm/h]				
	B1H	B1V	B2H	B2V
Measured	0.76	0.68	0.75	0.60
Model	0.31	10^{-3}	0.28	10^{-3}

Measured-Model difference

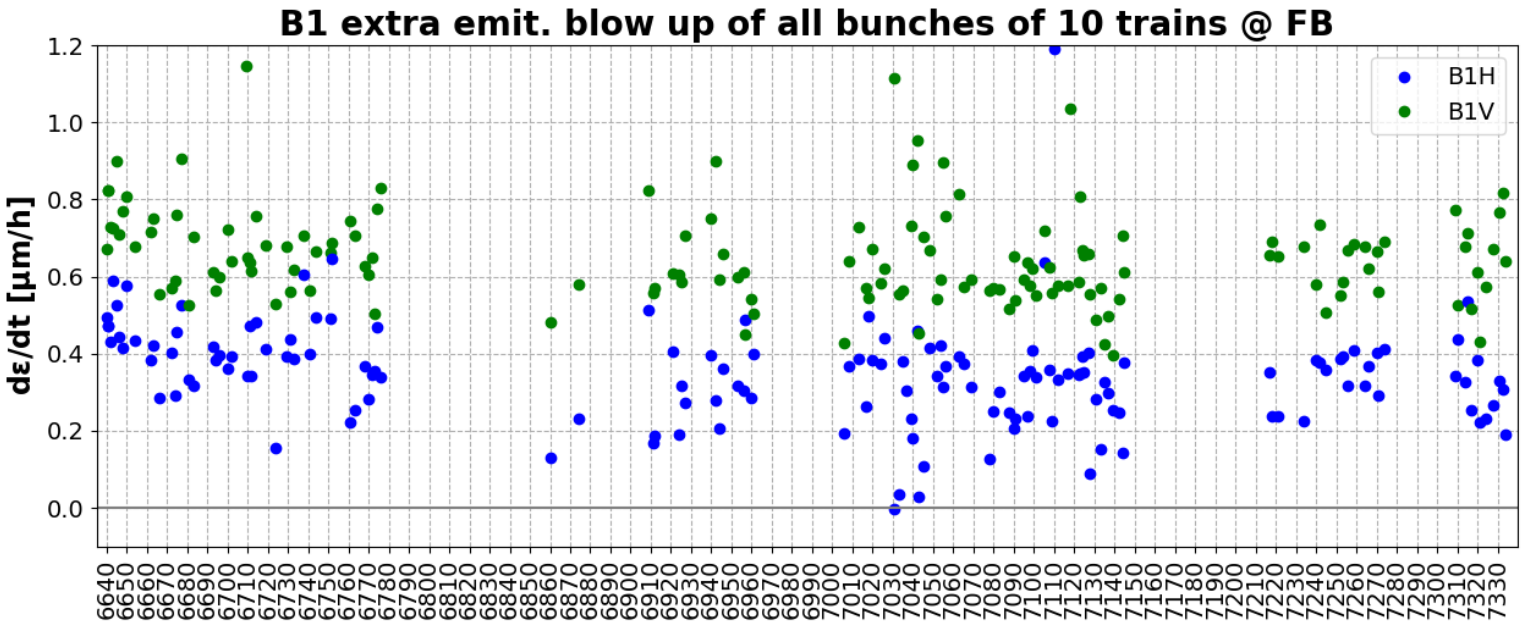
Extra growth	0.45	0.68	0.47	0.61

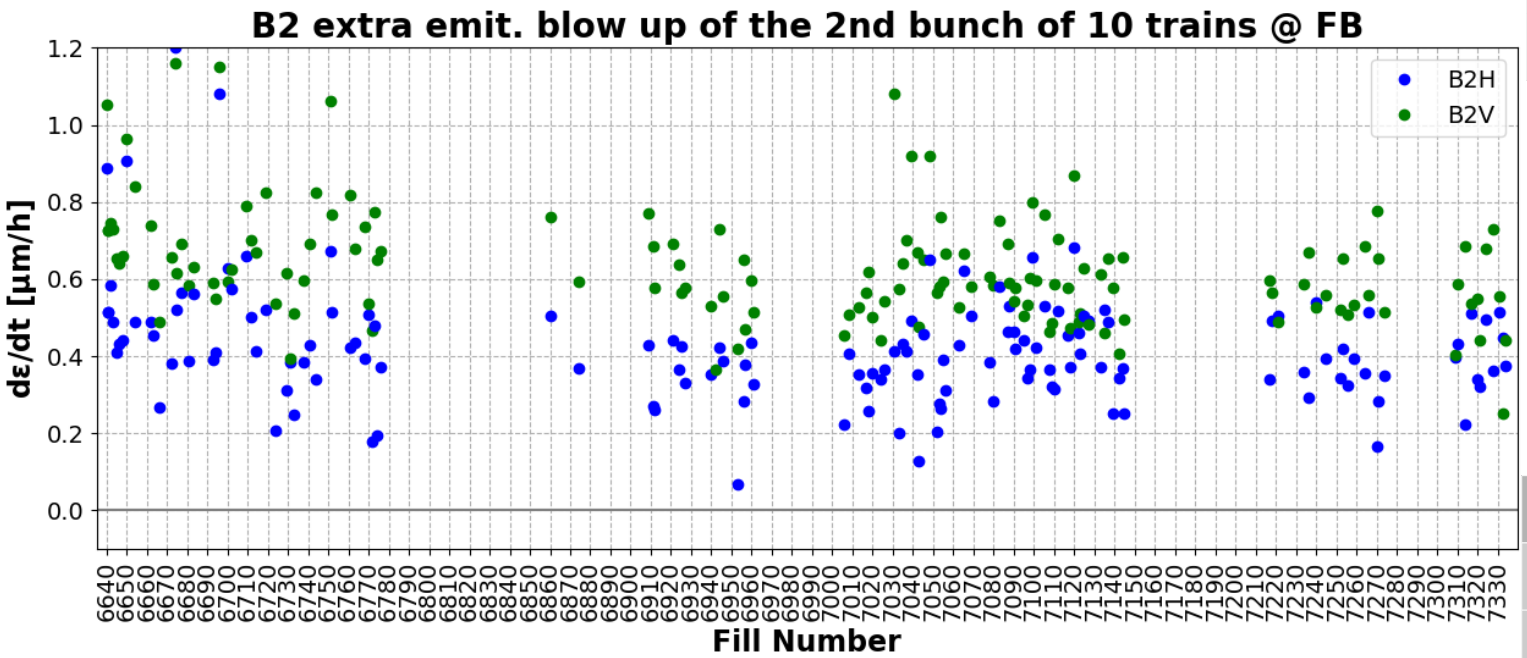
on top of IBS

Extra emittance growth at FB

Measured-Model emittance difference over time at FB of all bunches of 10trains vs Fill number

de/dt→extra emittance growth <u>on top of IBS</u>





dε/dt [μm/h] of all bunches
of 10 trains
extra blow up <u>on top of IBS</u>

	H	V
B1	0.34±0.21	0.64±0.26
B2	0.41±0.31	0.61±0.25

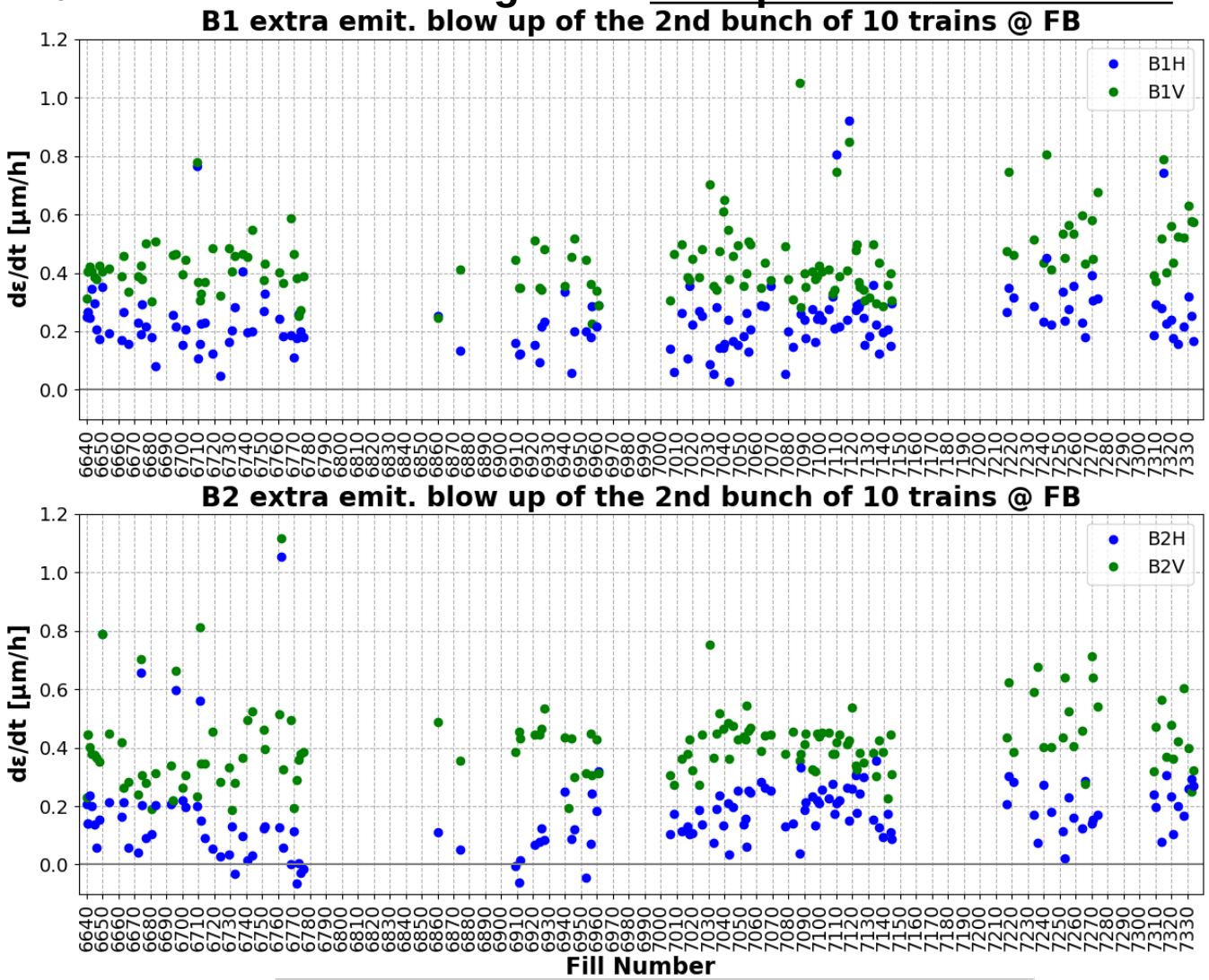
dε/dt [μm/h] of all bunches
extra blow up <u>on top of IBS</u>

	H	V
B1	0.45±0.16	0.68±0.17
B2	0.47±0.17	0.61±0.16

Extra emittance growth at FB

Measured-Model emit. difference over time at FB of the 2nd bunch of 10 trains vs Fill number

dε/dt → extra emittance growth <u>on top of IBS and e-cloud</u>



(Measured-Model emit.)/time$_{FB}$ [μm/h]				
	B1H	B1V	B2H	B2V
2nd bunches of trains	0.24	0.44	0.17	0.41

Including coupling in luminosity model

The transverse emittances, are coupled according to:

Cfactor1

$$\varepsilon_x = \varepsilon_{x0} - \left(\varepsilon_{x0} - \varepsilon_{y0}\right)\frac{|C|^2/2}{\Delta^2 + |C|^2}$$

$$\varepsilon_y = \varepsilon_{y0} + \left(\varepsilon_{x0} - \varepsilon_{y0}\right)\frac{|C|^2/2}{\Delta^2 + |C|^2}$$

G. Guignard, CERN ISR-BOM/77-43, 1977

Resonance crossing

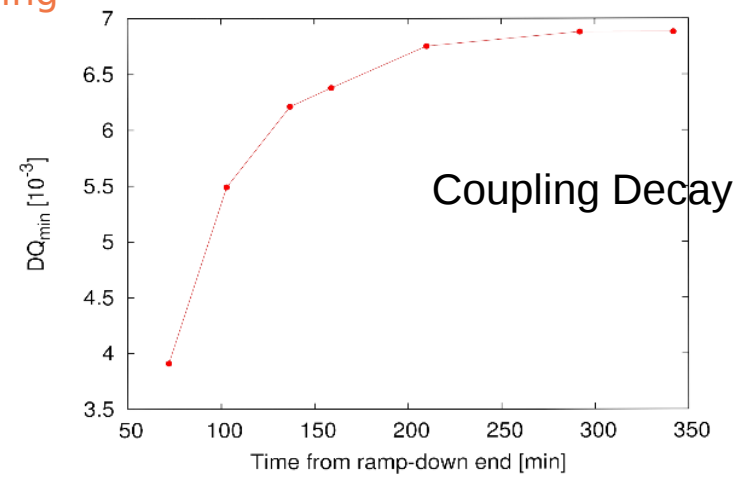
Cfactor2

$$\varepsilon_x = \varepsilon_{x0} - \left(\varepsilon_{x0} - \varepsilon_{y0}\right)\frac{|C|^2/2}{\Delta^2 + |C|^2 + \Delta\sqrt{\Delta^2 + |C|^2}}$$

$$\varepsilon_y = \varepsilon_{y0} + \left(\varepsilon_{x0} - \varepsilon_{y0}\right)\frac{|C|^2/2}{\Delta^2 + |C|^2 + \Delta\sqrt{\Delta^2 + |C|^2}}$$

E. Metral, CERN/PS 2001-066 (AE), 2001.

Coupling coefficient value estimations for FB energies
link: FBcoupling

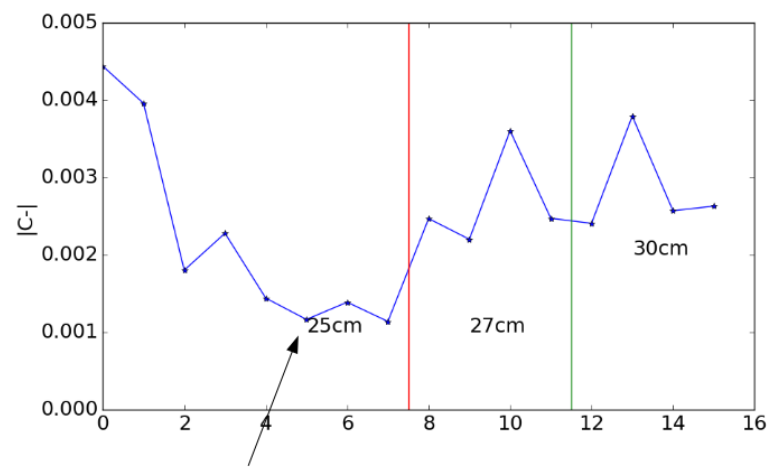


Measured in MD 1850
(also observed in operation)

Coupling coefficient value estimations for FT energies
link:FTcoupling

Coupling for beam 1 from 30cm to 25cm β*

Measurements taken over the weekend and on the night between Monday and Tuesday



Long Range in IP2 and IP8 (done during the MD period)

Including coupling in Luminosity model → for a coupling coefficient C=0.001 and an unperturbed tune-split Δ_{FB}=0.025, Δ_{FT}=0.01

Thanks to T. Persson

Including coupling in luminosity model

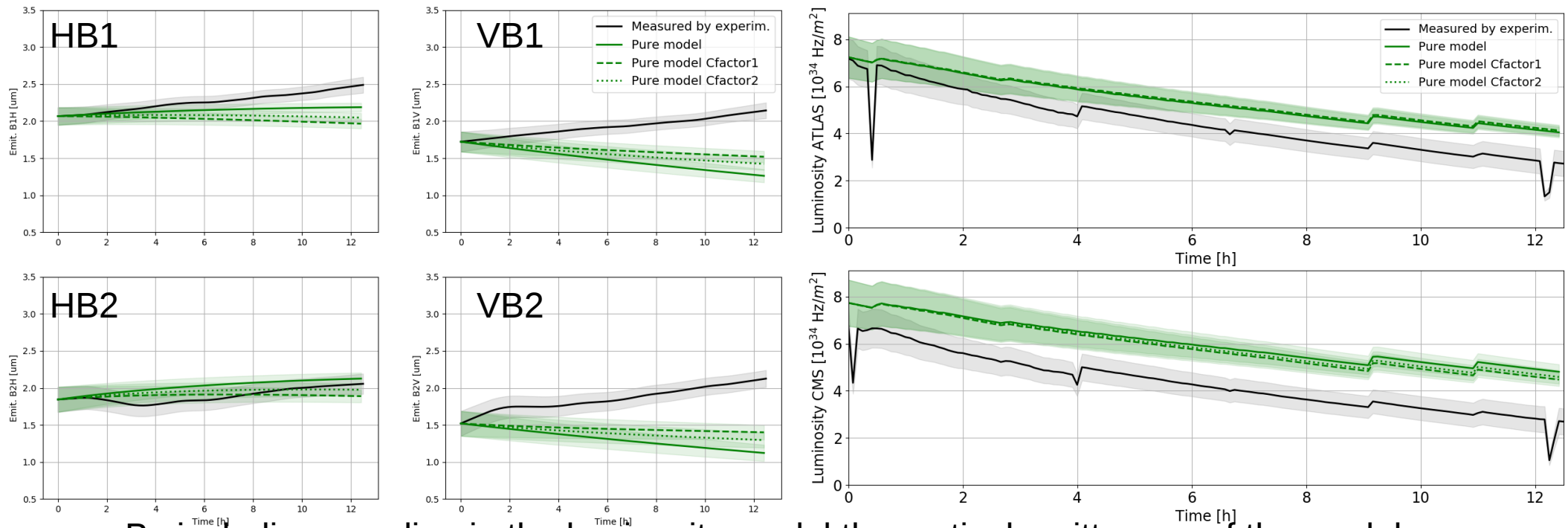
Including coupling in Luminosity model → for a coupling coefficient C=0.001 and an unperturbed tune-split Δ_{FB}=0.025, Δ_{FT}=0.01

FB energy

Since in our FollowUp we use only the injected emittance and the emittance at the end of FB, we assume that C is constant and that it is 0.0015 at the FB end → The difference of coupling and no coupling in terms of emittance growth is +/-1e-3 mm/h

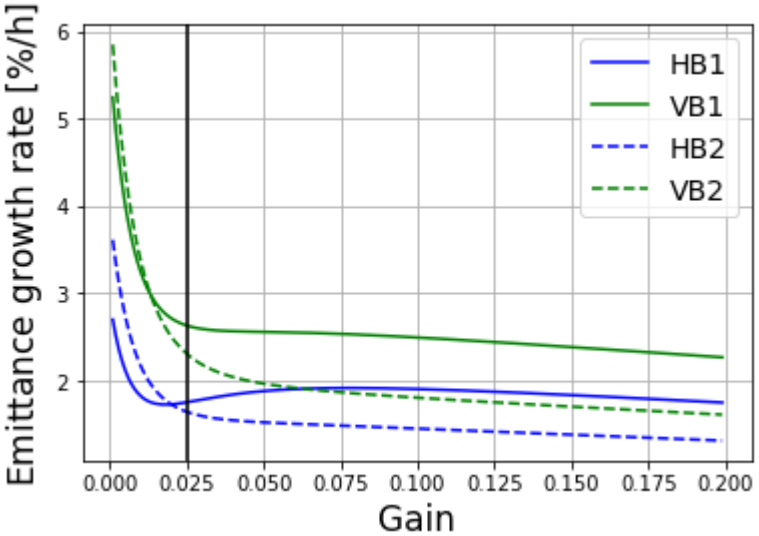
FT energy

Fill6700



By including coupling in the luminosity model the vertical emittances of the model approach better the measured ones. Also, the estimation of the pure model luminosity agrees slightly better with the measured one

Emittance growth due to noise at SB



Input beam parameters:
-an emit. at start of SB of 2.3um for both planes and beams and a bunch length of 1.1ns=0.0824m
-a betastar that is 30 cm
-a xing of 2*160urad
-a GainSB=0.025

X. Buffat, et al.
https://cds.cern.ch/record/2304603

noise MD results

δ_0 the noise floor of the machine normalised to the beam size
δ_{BPM} the noise floor of the transverse feedback pickup normalised to the beam size

$\delta_0$hb1 = 3.8e-5	δ_{BPM}hb1 = 220e-5
$\delta_0$vb1 = 5.3e-5	δ_{BPM}vb1 = 250e-5
$\delta_0$hb2 = 4.4e-5	δ_{BPM}hb2 = 190e-5
$\delta_0$vb2 = 5.6e-5	δ_{BPM}vb2 = 210e-5

```
HB1 noiseGrowth at SB: 0.040 um/h
VB1 noiseGrowth at SB: 0.061 um/h
HB2 noiseGrowth at SB: 0.038 um/h
VB2 noiseGrowth at SB: 0.053 um/h
```

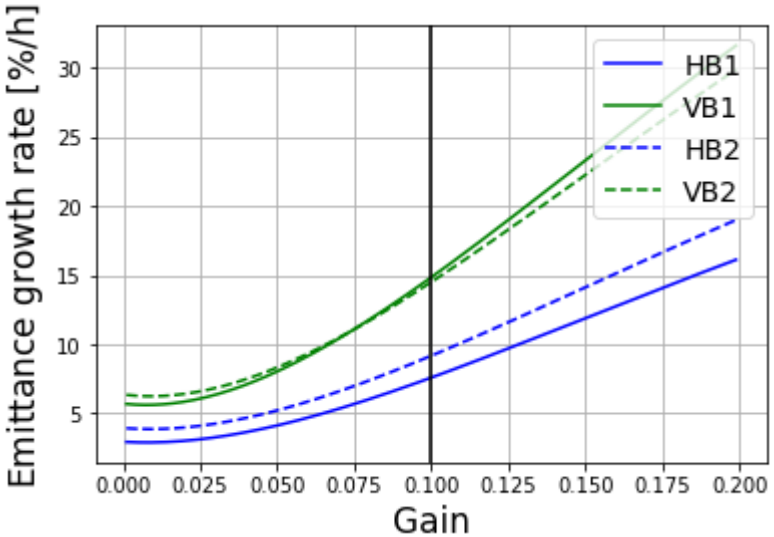
-This values are close to what we observe as extra emit. growth at SB.
-The noise growth at SB is larger in the vertical plane. The extra growth (on top of IBS and ecloud) at FB is also larger in vertical.

Thanks to X. Buffat

Emittance growth due to noise at FB

Using the FB beam parameters, the extra emittance growth at FB and the δ_0 values from the noise MD

Estimations for the δ_{BPM} values at FB, keeping in mind that $\sigma^*\delta_{BPM}$ should be the same at FB and FT energies



Input beam parameters:
-an injected emit. of ~1.35um
-a GainFB=0.1
-ΔQ_{FB}= 0.025, for estimations including ecloud

$\delta_0$hb1 = 3.8e-5	δ_{BPM}hb1 = 66e-5
$\delta_0$vb1 = 5.3e-5	δ_{BPM}vb1 = 93e-5
$\delta_0$hb2 = 4.4e-5	δ_{BPM}hb2 = 71e-5
$\delta_0$vb2 = 5.6e-5	δ_{BPM}vb2 = 89e-5

```
HB1 noiseGrowth at FB: 0.10 um/h
VB1 noiseGrowth at FB: 0.20 um/h
HB2 noiseGrowth at FB: 0.13 um/h
VB2 noiseGrowth at FB: 0.20 um/h
```

The estimations for the noise emittance growth at FB are ~3 times lower than the observed extra emittance blow up (on top of IBS)

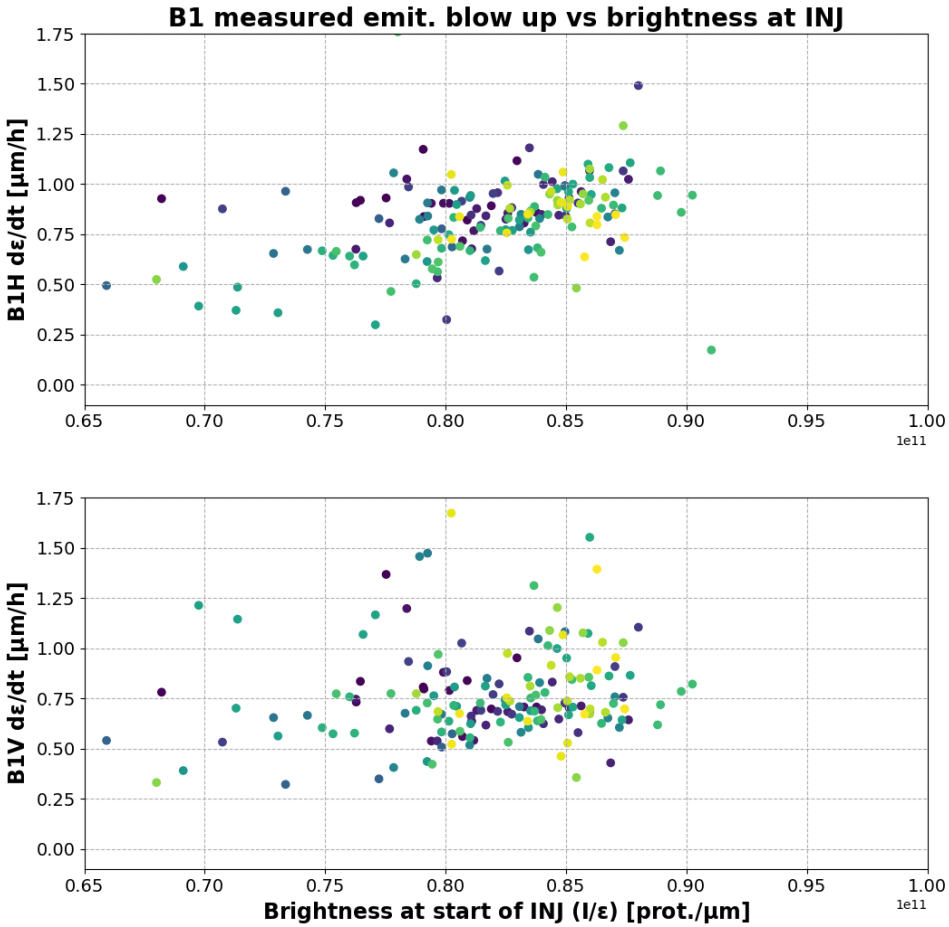
(Measured-Model emit.)/time$_{FB}$ [μm/h]				
	B1H	B1V	B2H	B2V
all bunches of 10 trains	0.34	0.64	0.41	0.61

Thanks to X. Buffat

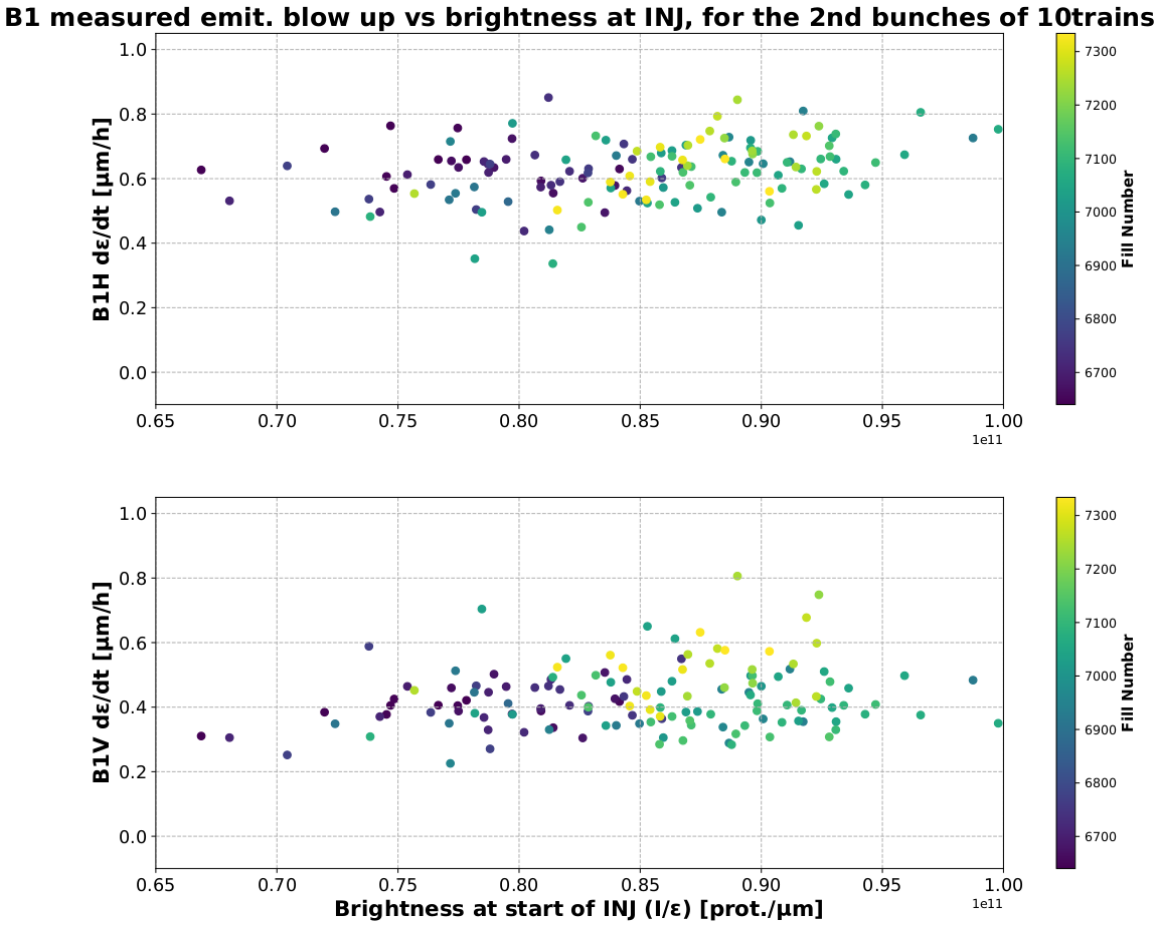
Emit. growth-brightness correlation, FB

Measured emittance growth vs INJ brightness at FB, for B1

Measured emittance growth (on top of IBS)



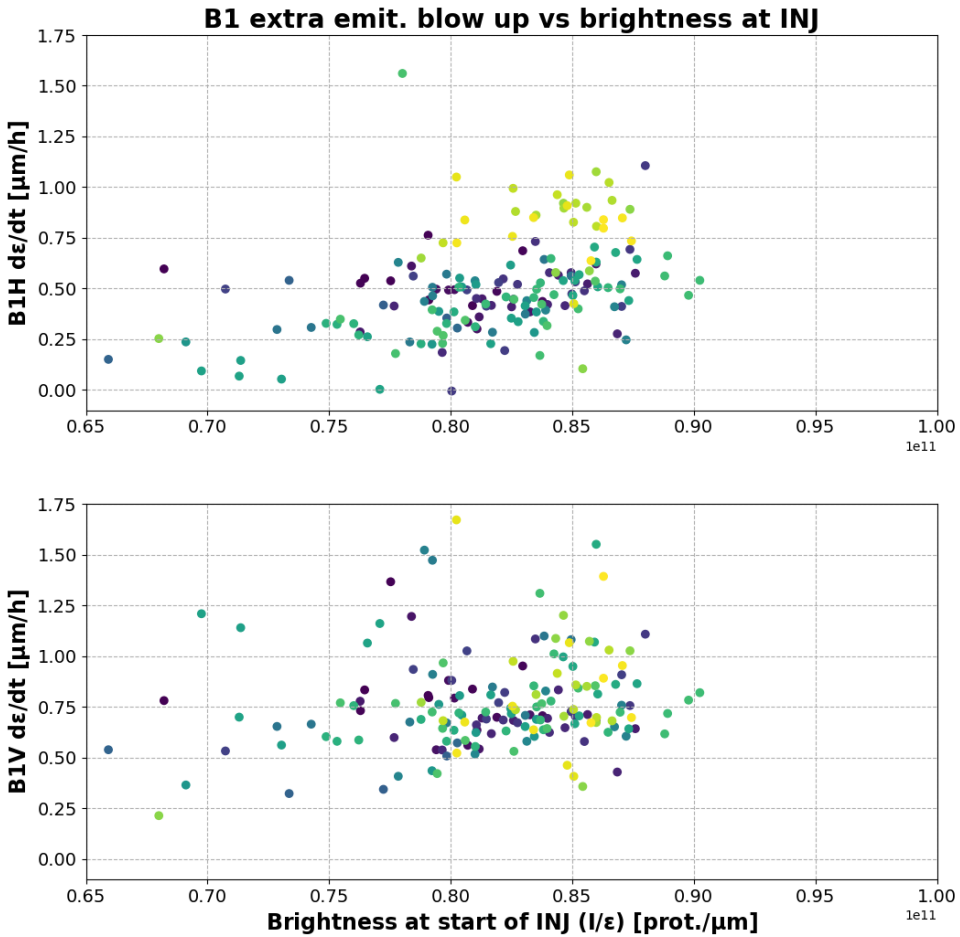
Measured emittance growth (on top of IBS&ecloud)



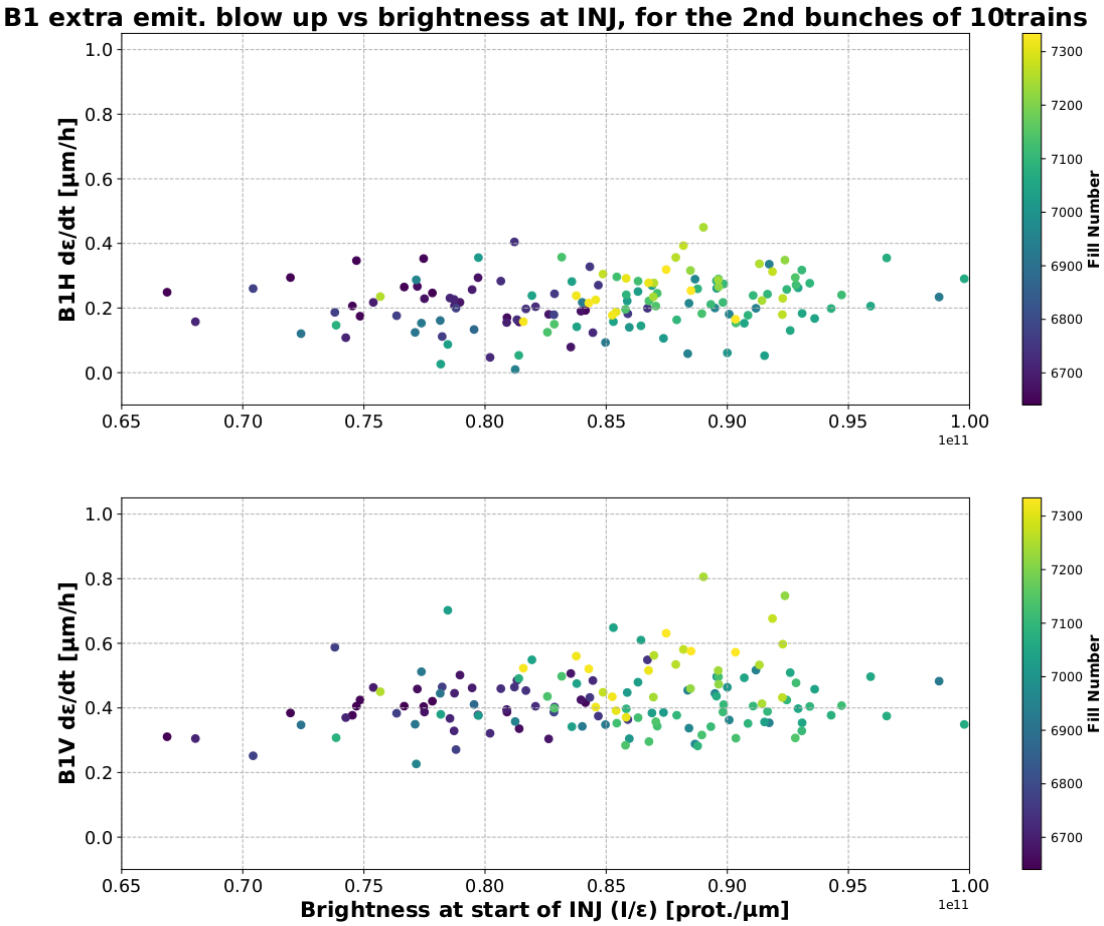
Emit. growth-brightness correlation, FB

Extra emittance growth vs INJ brightness at FB, for B1

Extra emittance growth (on top of IBS)

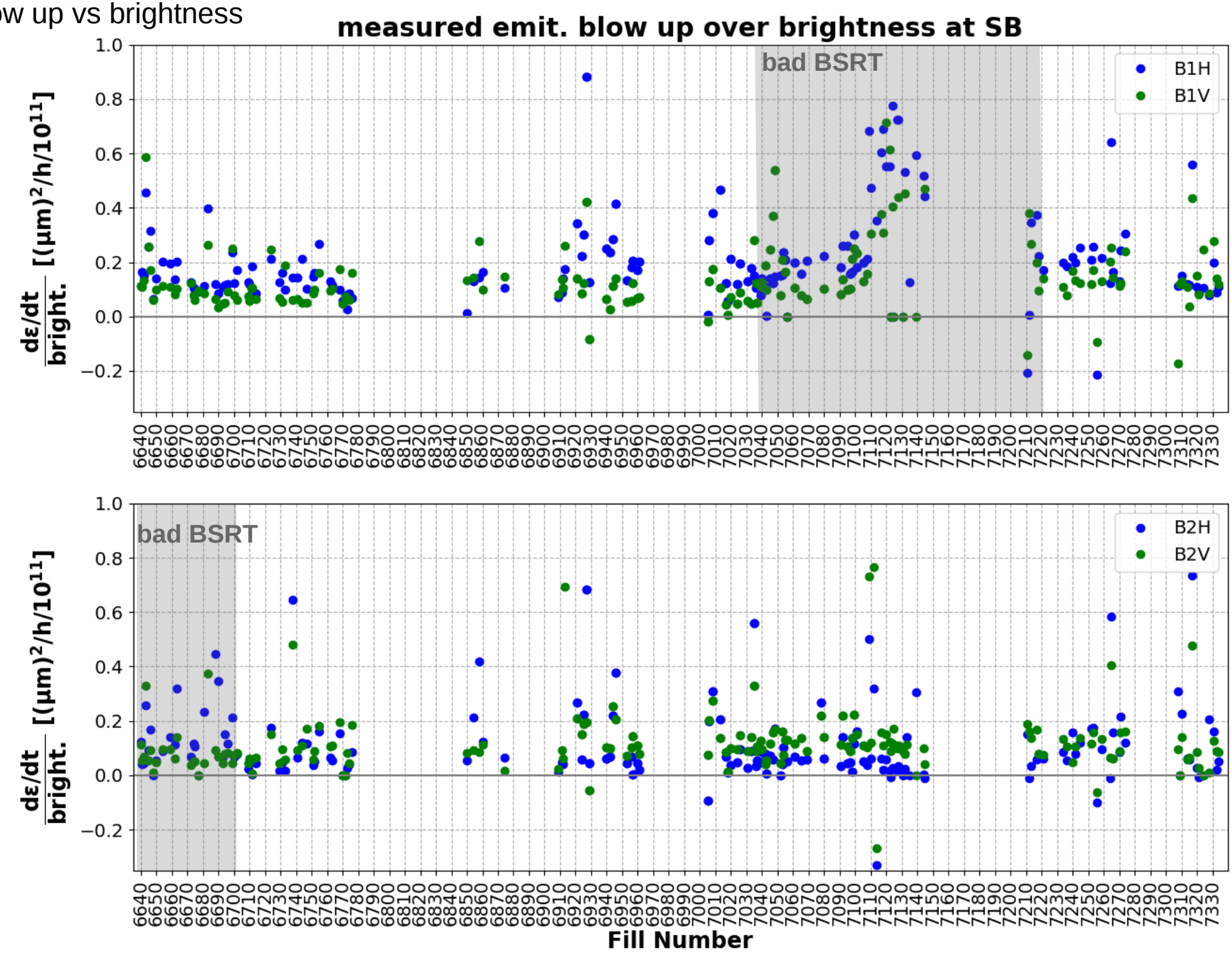


Extra emittance growth (on top of IBS&ecloud)



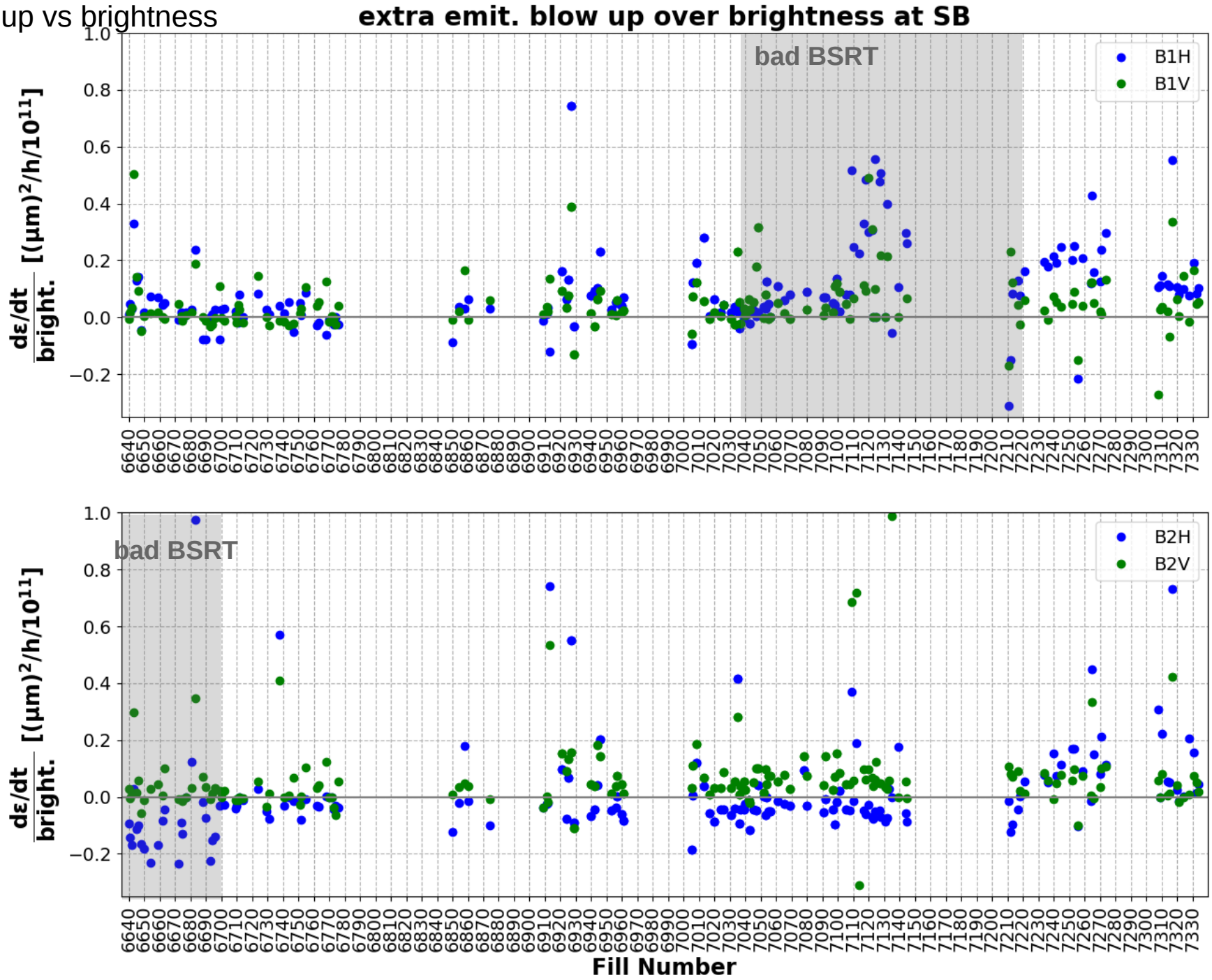
Emit. growth-brightness correlation, SB

Based on the slopes of bbb measured emit. blow up vs brightness



Emit. growth-brightness correlation, SB

Based on the slopes of bbb extra emit. blow up vs brightness



Luminosity model description

A bunch-by-bunch model based on the three main mechanisms of luminosity degradation in the LHC: intrabeam scattering (IBS), synchrotron radiation (SR) and luminosity burn-of

Emittance evolution:
Intrabeam scattering (IBS), Synchrotron Radiation (SR), elastic scattering (including coupling)

$$\frac{d\varepsilon}{dt} = \left(\frac{d\varepsilon}{dt}\right)_{IBS+SR} + \left(\frac{d\varepsilon}{dt}\right)_{elastic}$$

$$\left(\frac{d\varepsilon_x}{dt}, \frac{d\varepsilon_y}{dt}, \frac{d\sigma_s}{dt}\right)_{IBS+SR} = f\left(En, N_b(t_0), \varepsilon_x(t_0), \varepsilon_y(t_0), \sigma_s(t_0), dt\right)$$

$$\left(\frac{d\epsilon_{x,y}}{dt}\right)_{elastic} = N_{IP}\beta^*_{x,y}\mathcal{L}\sigma_{el}\left\langle\theta^2_{x,y}\right\rangle/(n_b N_p)$$

Bunch intensity evolution: Luminosity burn-off

$$\frac{dN}{dt} = \left(\frac{dN}{dt}\right)_{BOff}$$

Bunch length evolution: IBS and SR

$$\frac{d\sigma_s}{dt} = \left(\frac{d\sigma_s}{dt}\right)_{IBS+SR}$$

Combination of the transverse emittance, bunch length and bunch intensity estimations (or observations) in a self consistent way to compute the luminosity at each time step

β*, luminosity leveling, x-ing angle anti-leveling options

F. Antoniou et al., TUPTY020, proc. of IPAC' 15
F. Antoniou et al., "Can we predict luminosity?", proc. of Evian 2016