The Luminosity model: user perspective

S. Papadopoulou,
on behalf of the HSI lumi team

Beam-Beam and Luminosity Studies meeting
22/03/2019

CERN

LHC Luminosity follow-up tool

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, summary 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

Luminosity model description

Bunch-by-bunch modeling of three main mechanisms:

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

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

Luminosity model description

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- Synchrotron radiation (SR)
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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

F. Antoniou et al., TUPTY020, proc. of IPAC’ 15
F. Antoniou et al., “Can we predict luminosity?”, proc. of Evian 2016

Luminosity model description

Bunch-by-bunch modeling of three main mechanisms:

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

-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)

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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**

LHC Luminosity follow-up

Automated tool **inputs** (*ask the lumi team*):

- BSRT calibration factors (recalibration and calibration periods)
- Config. file: Energy, voltage, …
- Extracting emittance, bunch length and intensities from timber
- Calling the Luminosity model, using as input the measured beam parameters

Automated tool **outputs** (pkl created):

- Measured: emittances along energy cycle, intensities, measured luminosity, ...
- Model: 1 pkl including all 4 cases:
  Pure model, Extra losses, Extra emit. Growth, Calculated

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Run Luminosity model for a Fill (notebook):

- Read the pkl from eos (*access required*)
- Call the preferred model cases
- Comparing to the measured emittances, intensities, luminosity

  -at FB: extra (on top of the model) emittance growth

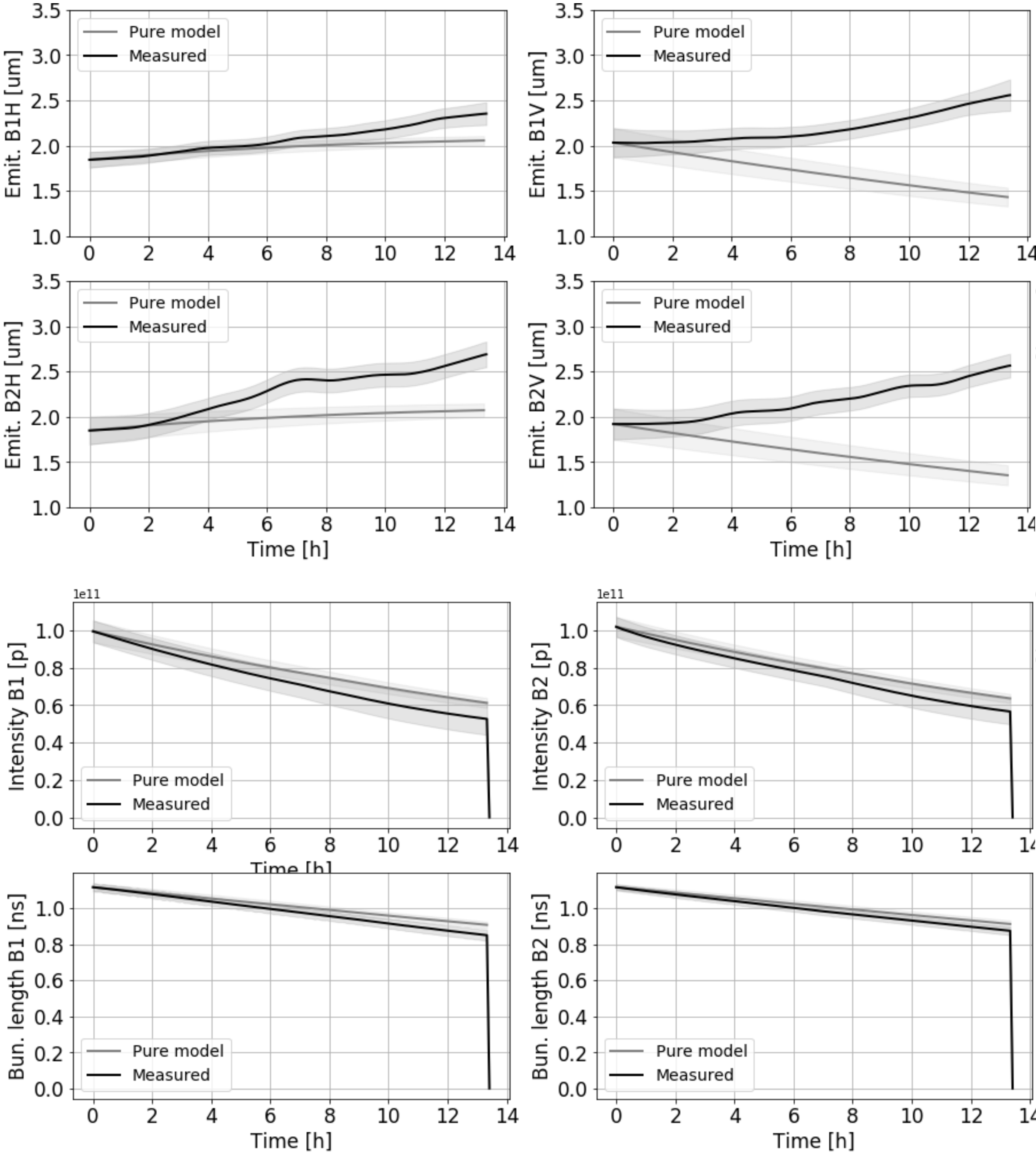
  -at SB: extra (on top of the model) emittance growth and losses → luminosity degradation mechanisms that are beyond the model

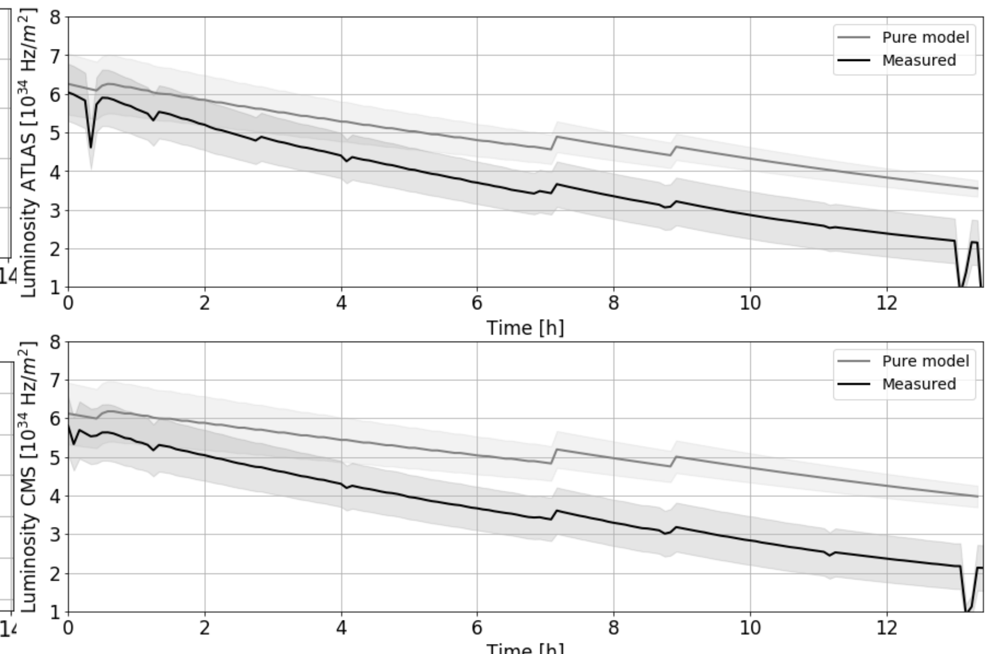
Luminosity evolution prediction

Fill 7334 (one of the 2018 Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

(see notebook)

	Pure model
Emittance	model
Intensity	model





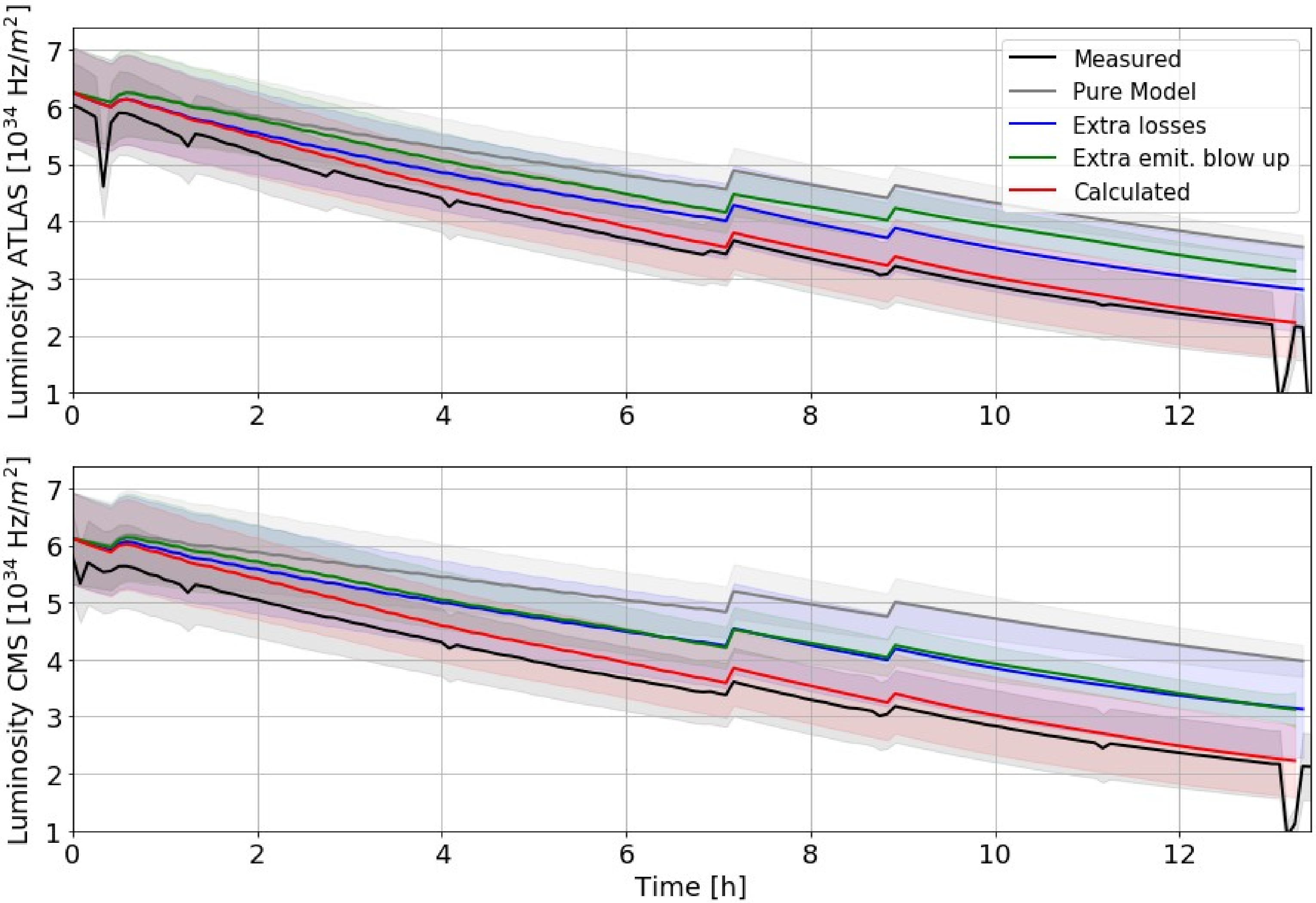
Pure model-Measured comparison

Understanding the impact of the extra emittance blow up and of the extra losses on the luminosity degradation

Luminosity evolution prediction

Fill 7334 (one of the 2018 Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

(see notebook)



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

Summary and next steps

- The Luminosity model is run for all the Run2 Fills.
  The **saved pkl in eos** includes the model results, for all model cases
  (**Pure model, Extra losses, Extra emit. Growth, Calculated**)

- In 2018, transverse emittance **coupling** was included in the model.

- The model is **sensitive to the initial conditions** (emittances, intensities, etc).
  The agreement of the calculated luminosity from the model with the measured one can be used as a **validation of the data quality** (trusted BSRT?).

- **Measurements-Model comparison** → extra emittance blow up and extra losses, that are beyond the model.
  Ongoing studies to correlate the “unknown” extra emittance growth with noise.

- Implementation of various emittance growth mechanisms (“incoherent" noise, burn-off) in model
  (see computing targets, HSI section meeting, link: computingTargets_HSImeet)

AOB

- Transition between the present data extraction tools (Python2 and CALS) to the next available platforms (Python3 and NXCALS).

- From pandas to parquet (see ParquetFormat in shared Folder)

Thank you!

extra slides

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)

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

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

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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

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

<u>Resonance crossing</u>

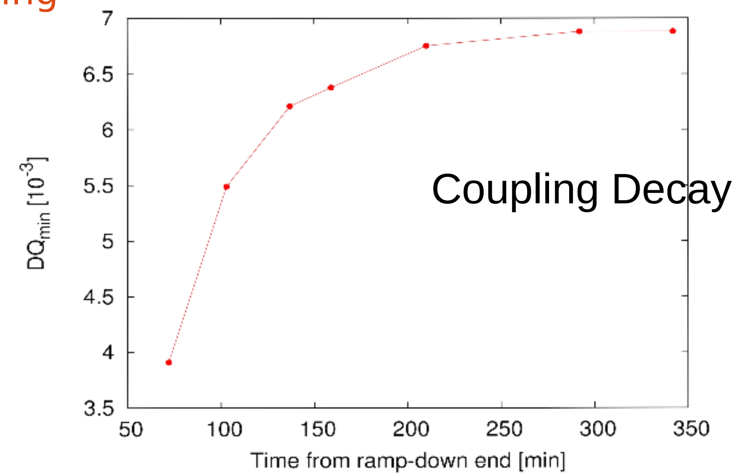
Cfactor2

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

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

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

Coupling coefficient value estimations for FB energies
link: FBcoupling

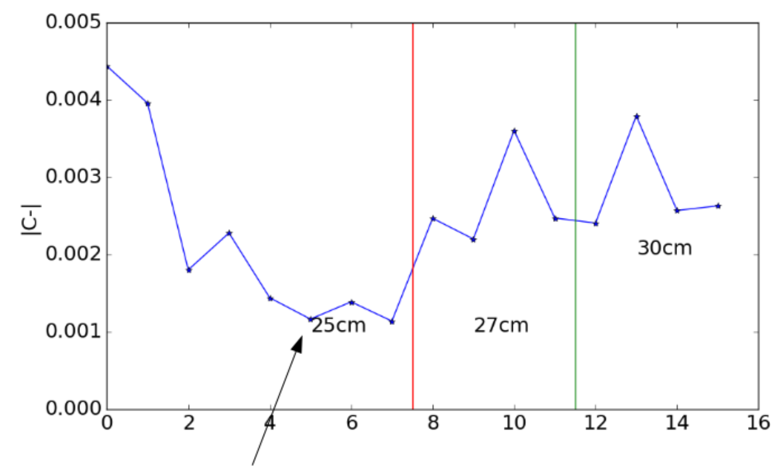


Measured in MD 1850
(also observed in operation)

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

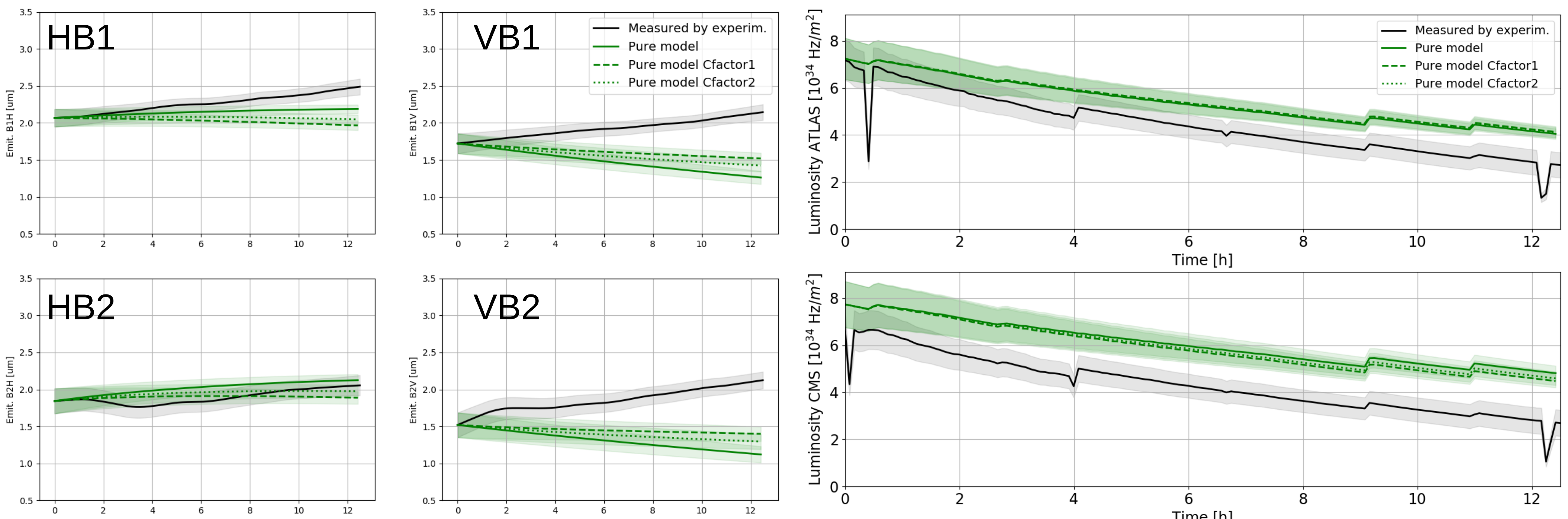
Including coupling in Luminosity model → for a coupling coefficient C=0.001 and an unperturbed tune-split Δ_{FB}=0.025, Δ_{FT}=0.01

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

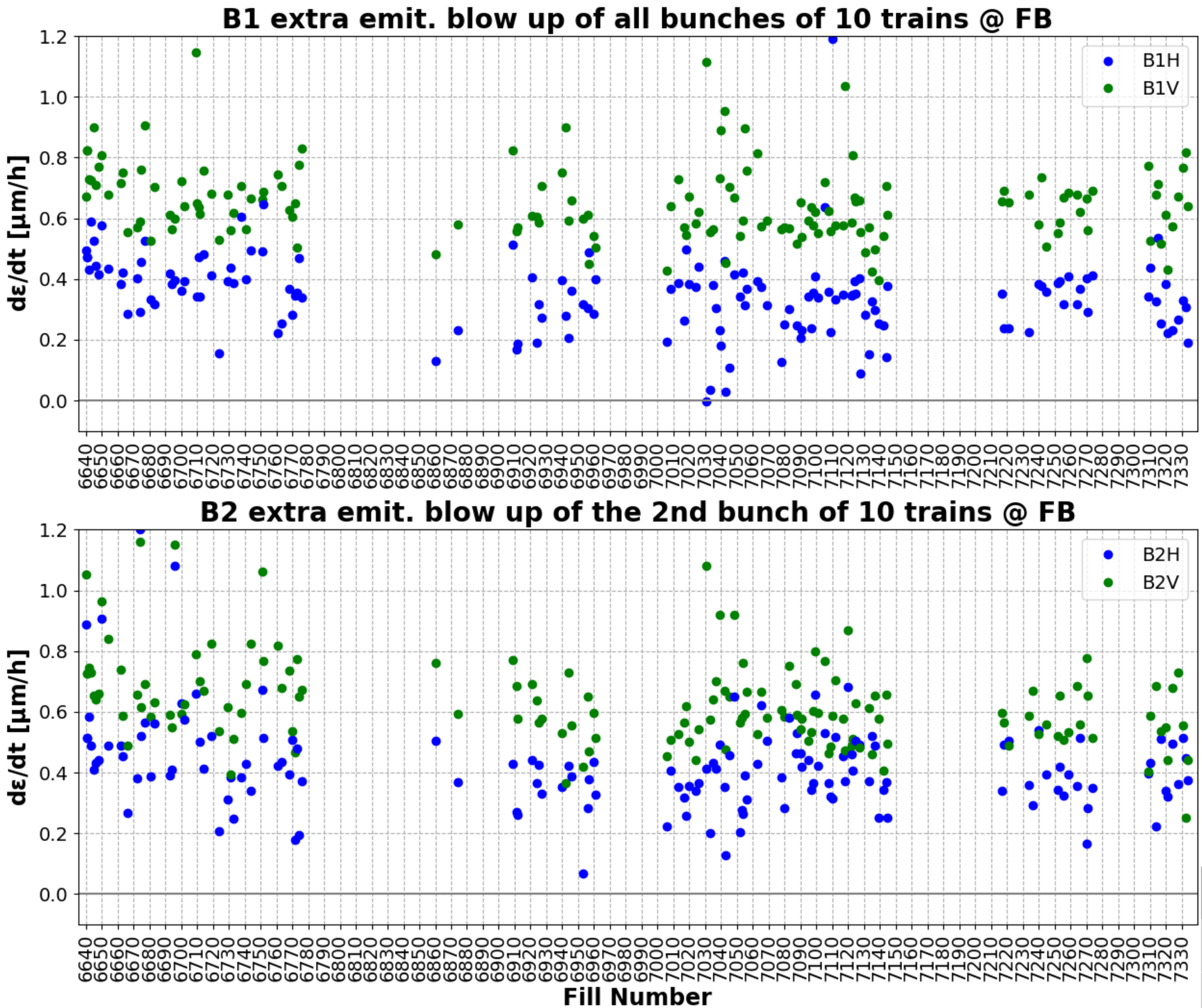


By including coupling in the luminosity model the vertical emittances of the model approach better the measured ones. Also, the estimation of the pure model luminosity agrees slightly better with the measured one

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 on top of IBS



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

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

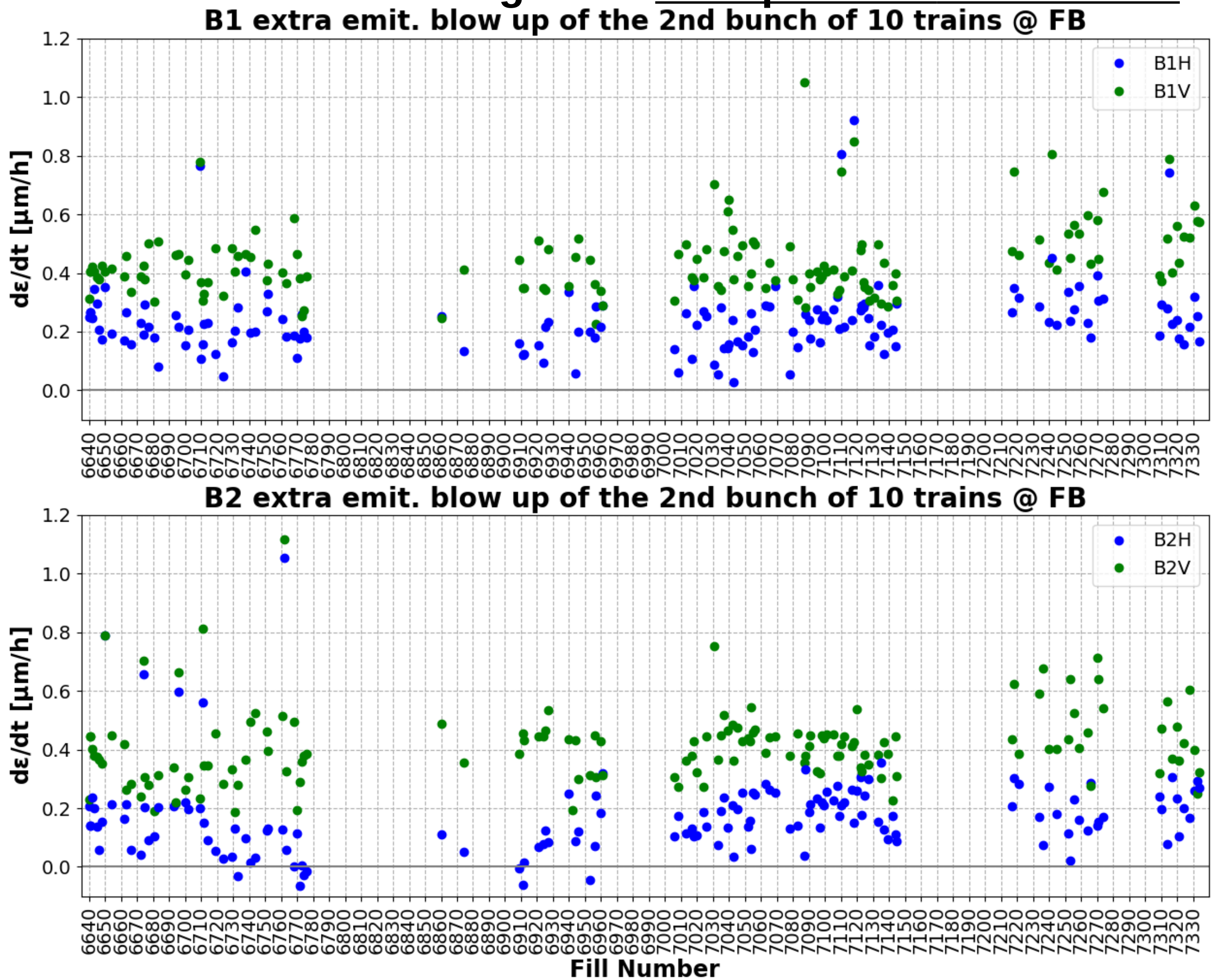
dε/dt [μm/h] of all bunches
extra blow up on top of IBS

	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>

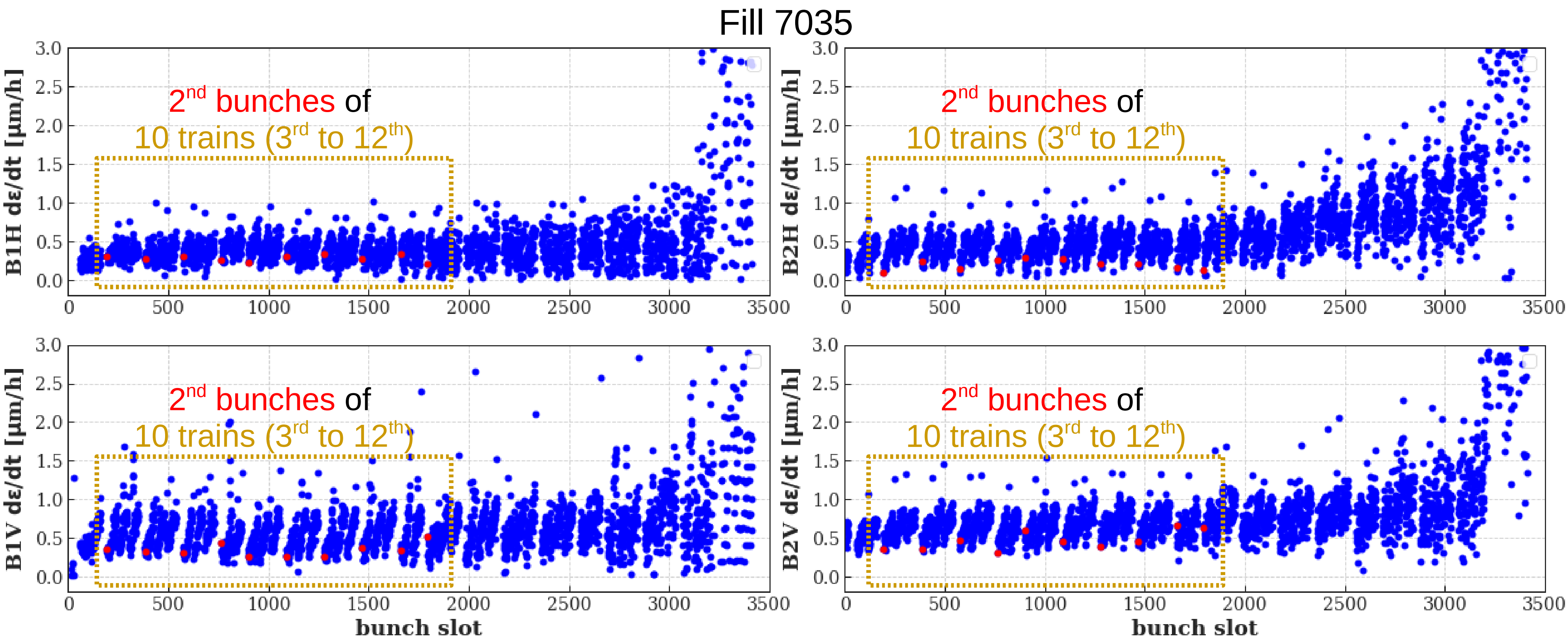


(Measured-Model emit.)/time$_{FB}$ [μm/h]				
	B1H	B1V	B2H	B2V
2nd bunches of trains	0.24	0.44	0.17	0.41

Extra emittance growth at FB

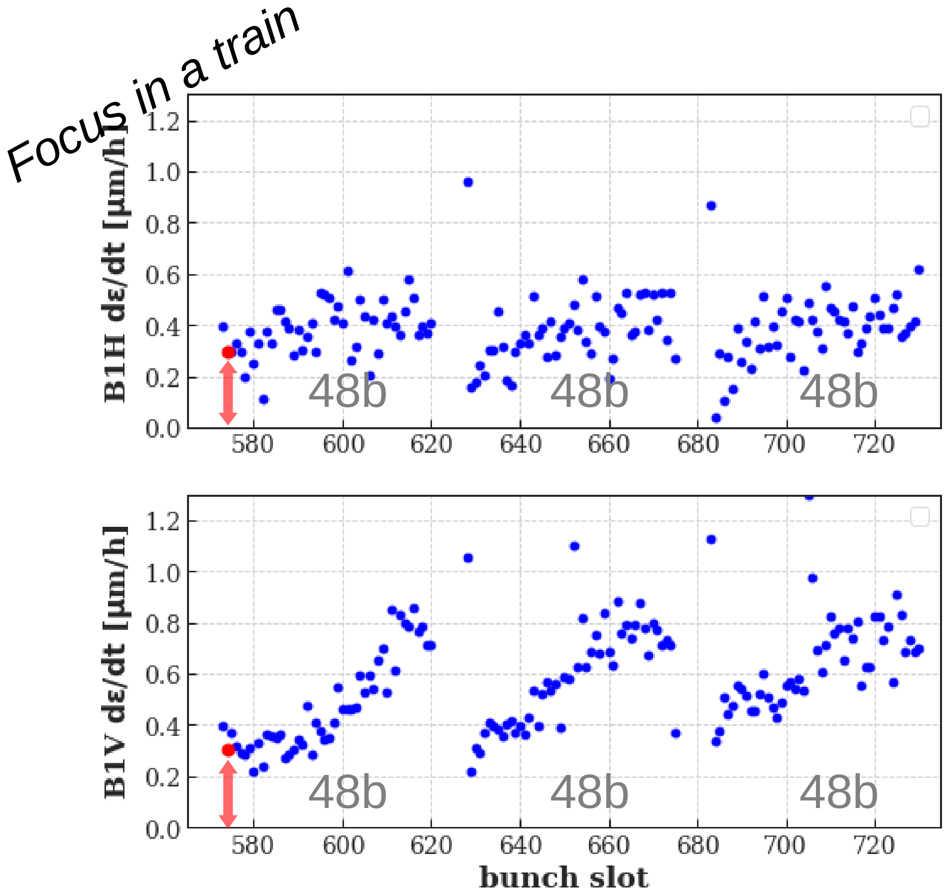
Measured-Model emittance difference over time at FB vs bunch slot, for a Fill

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



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**

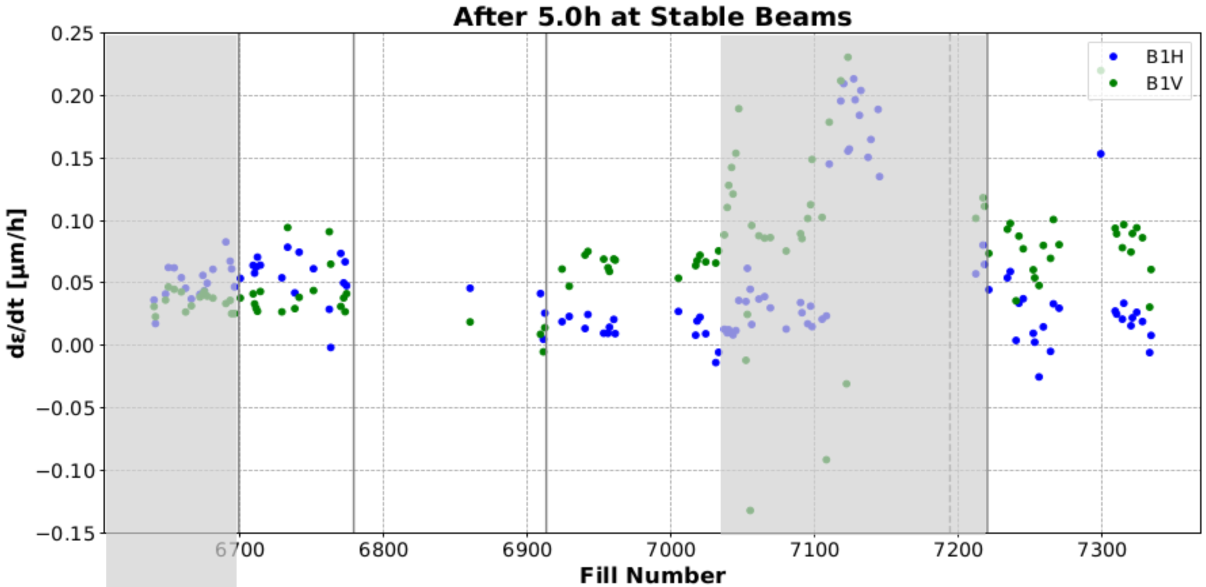
extra growth [μm/h]				
	B1H	B1V	B2H	B2V
on top of IBS (all bunches)	0.34	0.64	0.41	0.61
on top of IBS&e-cloud (2nd bunches of trains)	0.24	0.44	0.17	0.41

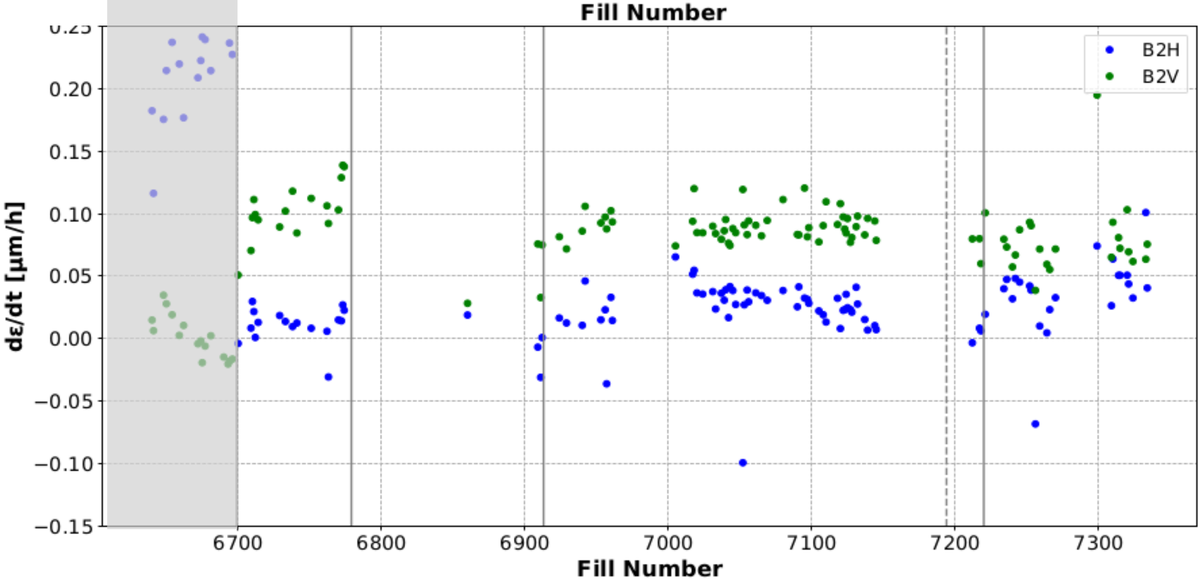
- Extra growth **on top of IBS** smaller in horizontal than in the vertical.
- In vertical, where IBS growth is minor, the observed blow up beyond the model is ~0.6μm/h
- The contribution of **e-cloud** to the emittance growth is ~0.2 μm/h
- The rest of the extra emittance growth at FB is 0.2 μm/h in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

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%)

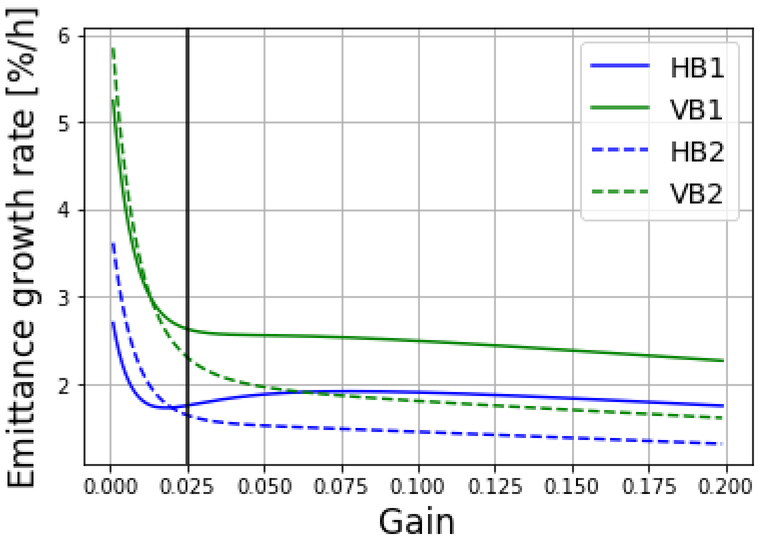
Emit. growth after 5h @ SB [μm/h]				
	B1H	B1V	B2H	B2V
extra	0.02	0.07	0.02	0.09

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)

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
```

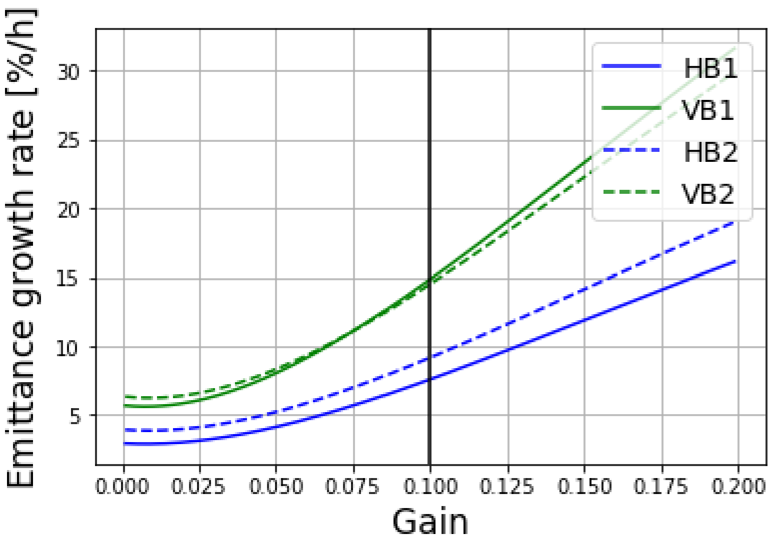
-This values are close to what we observe as extra emit. growth at SB.
-The noise growth at SB is larger in the vertical plane. The extra growth (on top of IBS and ecloud) at FB is also larger in vertical.

Thanks to X. Buffat

Emittance growth due to noise at FB

Using the FB beam parameters, the 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
```

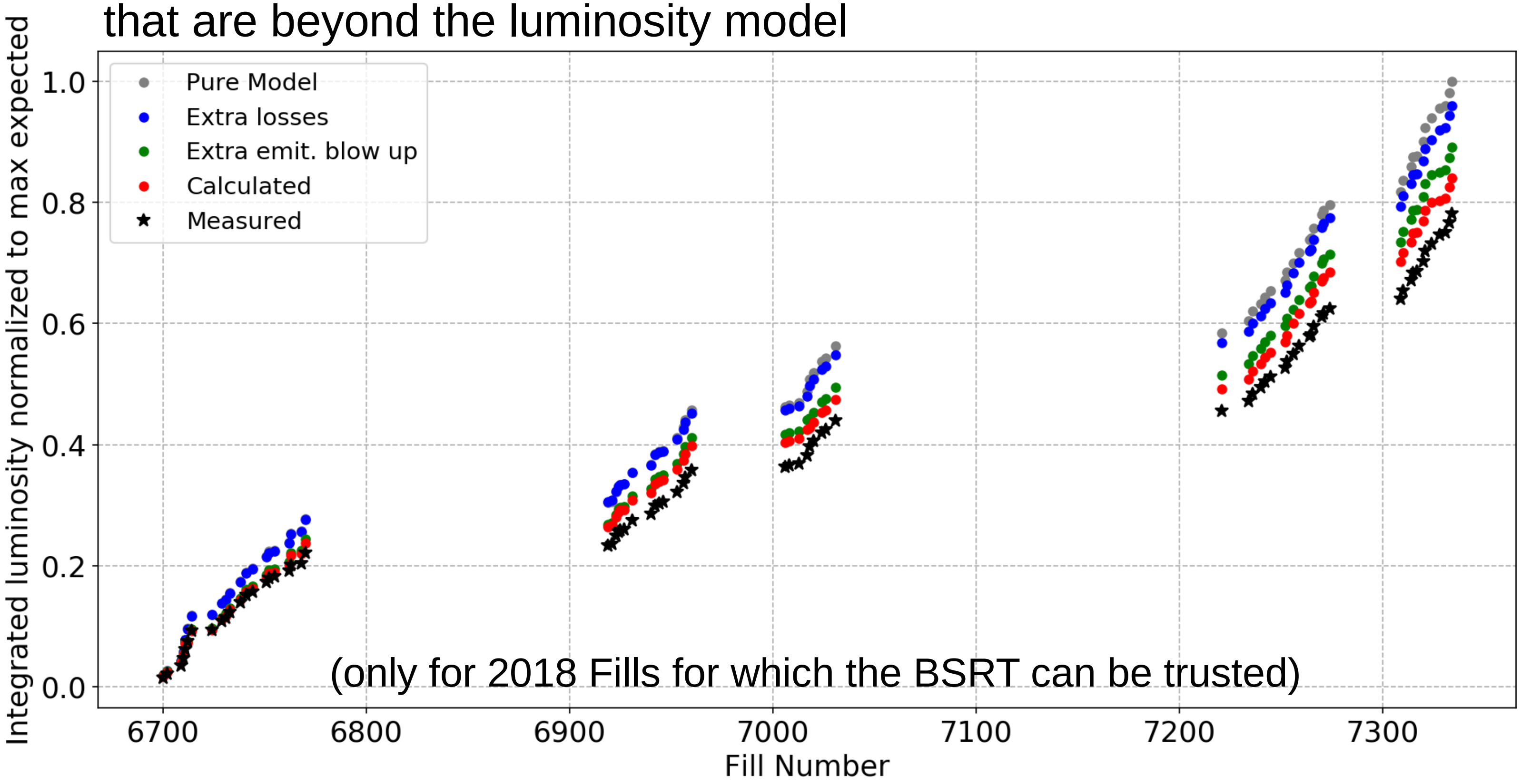
The estimations for the noise emittance growth at FB are ~3 times lower than the observed extra emittance blow up (on top of IBS)

(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

Cumulated integrated Luminosity

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



	2018	2017
Extra losses	-5%	-1%
Extra emit. growth	-11%	-10%
Measured	-22%	-11%
Calculated	-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