CERN

LHC Injectors Upgrade

LHC Injectors Upgrade Workshop

Montreux, 13-15 February 2019

LHC Injectors Upgrade

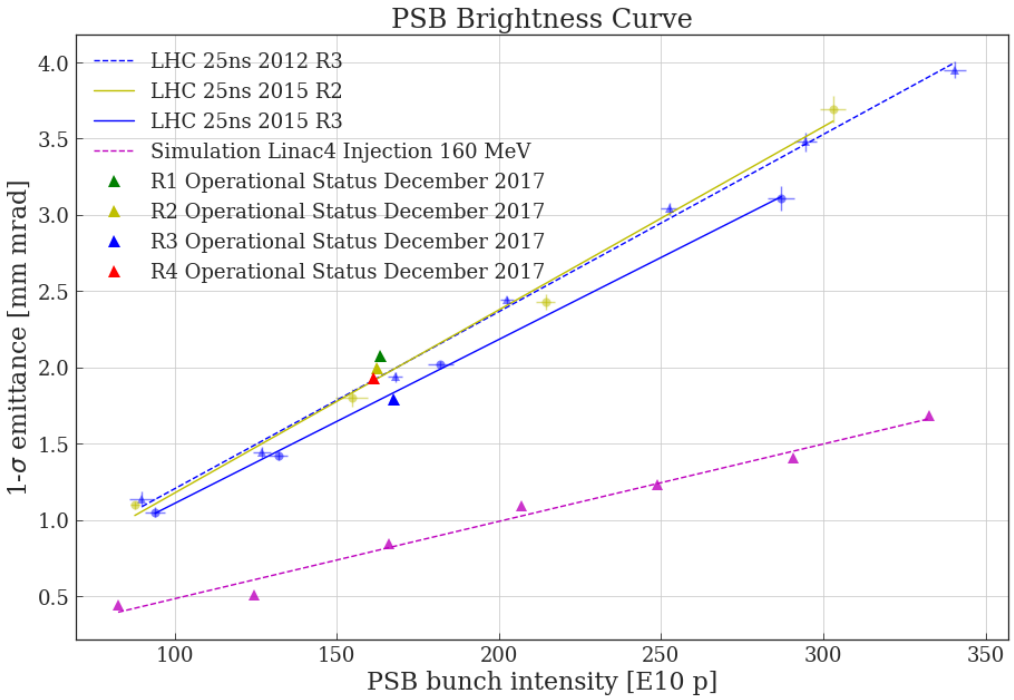
Brightness and transverse emittance from the PSB

S. Albright, F. Antoniou, F. Asvesta , H. Bartosik, E. Benedetto, C. Bracco, H. Damerau, J. Emery, V. Forte, M. Fraser, G. P. Di Giovanni, A. Huschauer, E. Koukovini Platia, G. Kotzian, B. Mikulec, T. Prebibaj, F. Roncarolo, A. Santamaria, E. Senes, J.L. Sirvant, P. Skowronski, A. Valdivieso, PSB and CPS OP crew

Outline

- **Brightness and emittance measurements in the PSB**
- **H- injection challenges**
- **Expectations and limits with the new TFB**

PS-Booster brightness curve



PSB brightness curves dominated by space charge effects at injection

PSB running on a constant brightness curve over the years

PSB LIU requirements

August 25, 2017 – Beam parameters at injection of each accelerator

PSB (H^- injection from Linac4)

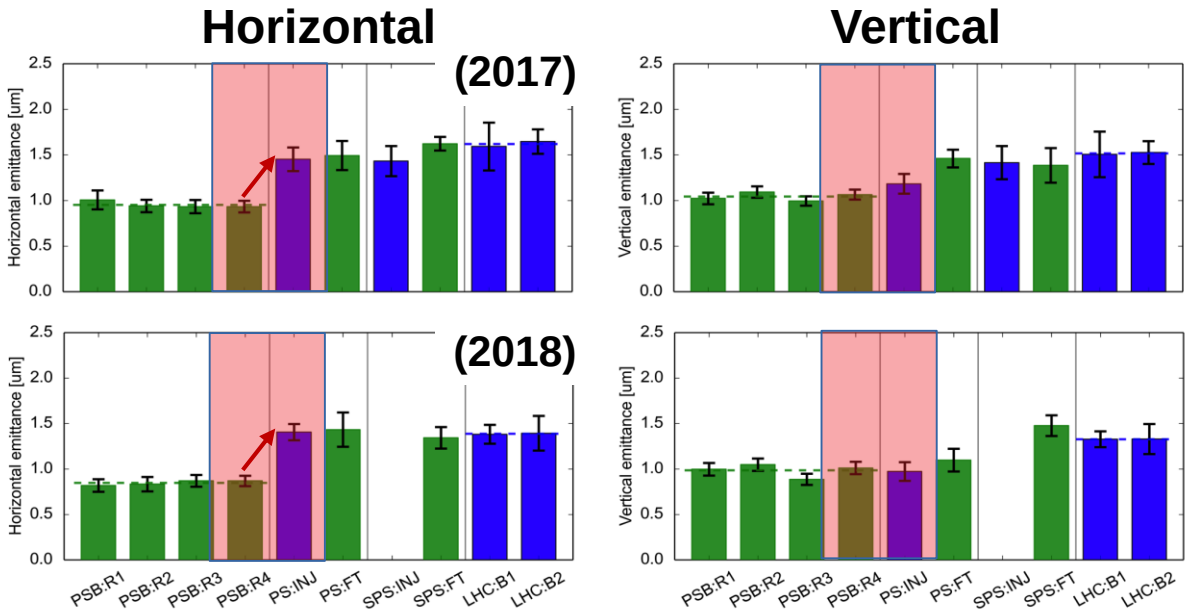
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
Achieved	Standard	17.73	2.14	0.05	1.0	1100	2.4	(0.51, 0.59)
	BCMS	8.48	1.15	0.05	0.9	1000	2.2	(0.46, 0.56)
LIU target	Standard	34.21	1.72	0.16	1.4	650	1.8	(0.58, 0.69)
	BCMS	17.11	1.36	0.16	1.4	650	1.8	(0.35, 0.43)

PS (Standard: 4b+2b – BCMS: 2× 4b)

		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
Achieved	Standard	16.84	2.25	1.4	1.2	180	0.9	(0.25, 0.30)
	BCMS	8.05	1.20	1.4	0.9	150	0.8	(0.24, 0.31)
LIU target	Standard	32.50	1.80	2.0	3.00	205	1.5	(0.18, 0.30)
	BCMS	16.25	1.43	2.0	1.48	135	1.1	(0.20, 0.31)

PSB to PS transverse emittance growth of 5%

Transverse emittance preservation in operation for 25ns BCMS

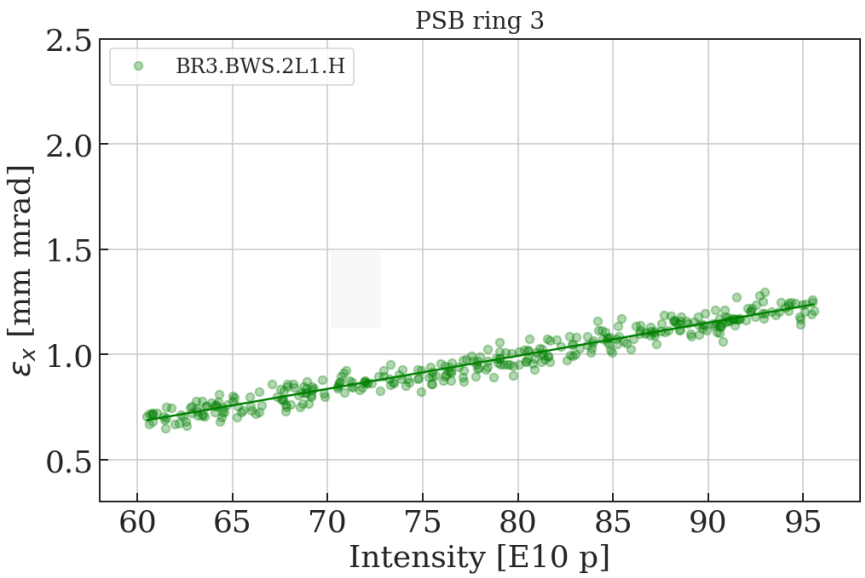


- Significant transverse emittance blow up in the horizontal plane (~40%)
- Emittance taken from OP data (w/o any special treatment)

Brightness curves in 2018

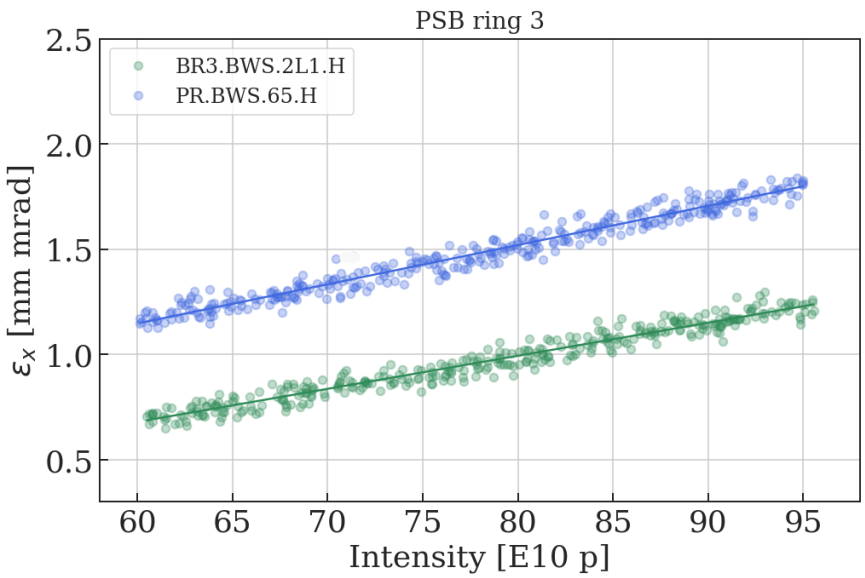
- **In the context of understanding the sources of emittance "blow-up" between the PSB extraction and the PS injection**
- Systematic brightness curves measurements performed simultaneously in the PSB and the PS (using the Wire Scanners) or the PSB WS and SEMGrids:
  - **operational BCMS** beam with **standard and dispersion re-matched transfer line optics**
  - **BCMS 1.5eVs** beam with **standard and dispersion re-matched transfer line optics**
  - Using the **LIU prototype WSs** in both PS and PSB for the operational BCMS beam with standard and dispersion re-matched TL optics
  - Tomoscope data acquired for all set of measurements

Brightness curves in 2018 (BCMS 25ns)



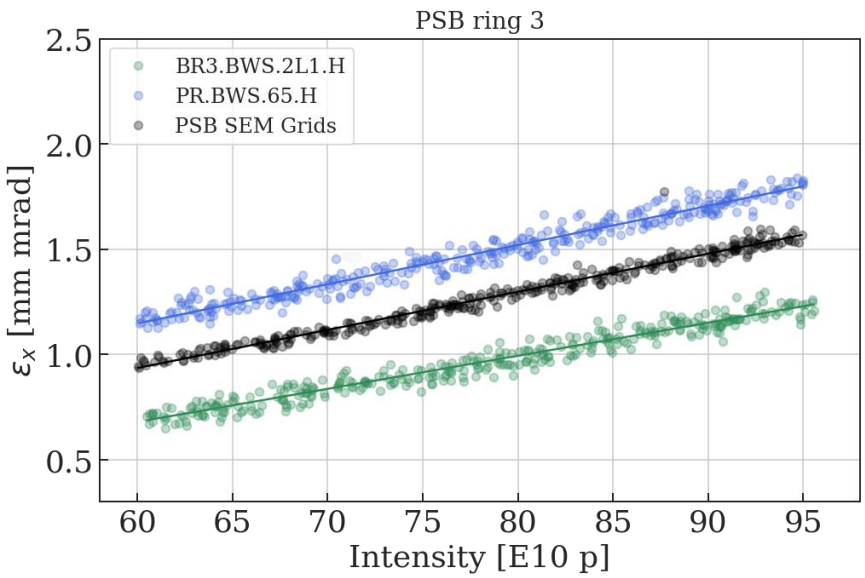
- Brightness curves in the **horizontal** plane for the operational BCMS25
  - **PSB WS**

Brightness curves in 2018 (BCMS 25ns)



- Brightness curves in the **horizontal** plane for the operational BCMS25
  - **PSB WS**, **PS**

Brightness curves in 2018 (BCMS 25ns)



- Brightness curves in the **horizontal** plane for the operational BCMS25
  - **PSB WS**, **PS WS** and **PSB SEM Grids**
- Simultaneous measurements between PSB/SEM or PSB/PS
  - All rings / both planes
- ***Emittance reconstruction based on gaussian beam profiles (transverse and longitudinal) assumption***

$$\epsilon_{x,y} = \left(\frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2 \delta^2}{\beta_{x,y}} \right) \beta_{\mathrm{rel}} \gamma_{\mathrm{rel}}$$

Brightness curves analysis

- Linear fits applied in all cases (between 60-100 E10 p)

$$\varepsilon(N_p) = \text{slope} \times N_p + \varepsilon_0$$

- Ring-to-ring variations both in the **slope** and in **off-set**

$$\epsilon_{x,y} = \left(\frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2 \delta^2}{\beta_{x,y}} \right) \beta_{\text{rel}} \gamma_{\text{rel}}$$

- Optics measurements campaign in both machines
- Dispersion measurements at the location of the WSs

Brightness curves analysis

- Linear fits applied in all cases (between 60-100 E10 p)

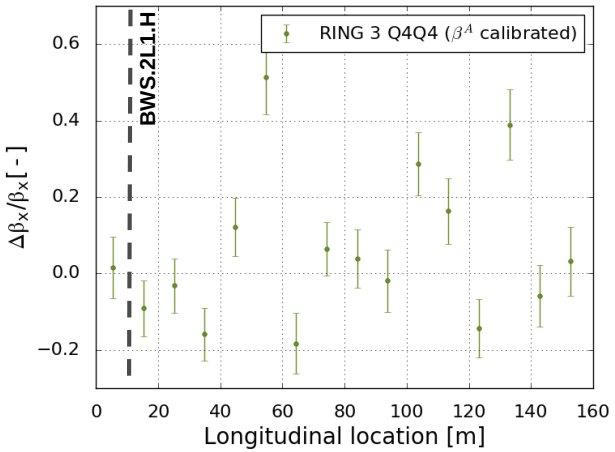
$$\varepsilon(N_p) = \text{slope} \times N_p + \varepsilon_0$$

- Ring-to-ring variations both in the **slope** and in **off-set**

$$\epsilon_{x,y} = \left(\frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2 \delta^2}{\beta_{x,y}} \right) \beta_{\text{rel}} \gamma_{\text{rel}}$$

- Optics measurements campaign in both machines
- Dispersion measurements at the location of the WSs

PSB @ 160 MeV



- Dominated by large error bars due to the 90º phase advance between the BPMs

Brightness curves analysis

- Linear fits applied in all cases (between 60-100 E10 p)

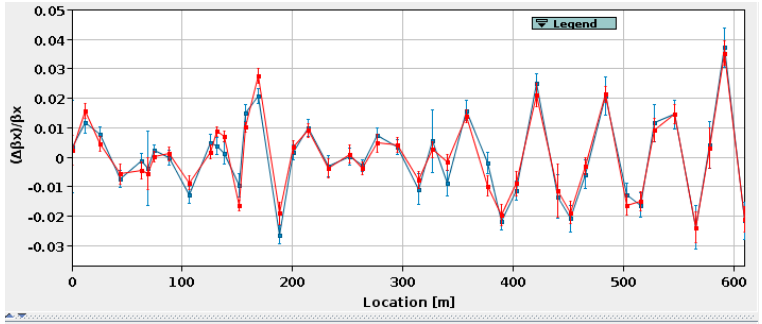
$$\varepsilon(N_p) = \text{slope} \times N_p + \varepsilon_0$$

- Ring-to-ring variations both in the **slope** and in **off-set**

$$\epsilon_{x,y} = \left(\frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2 \delta^2}{\beta_{x,y}} \right) \beta_{\text{rel}} \gamma_{\text{rel}}$$

- Optics measurements campaign in both machines
- Dispersion measurements at the location of the WSs

PS @ 1.4GeV



- Max. beta-beating of 4% around the machine and 3% at the location of the WS

Brightness curves analysis

- Linear fits applied in all cases (between 60-100 E10 p)

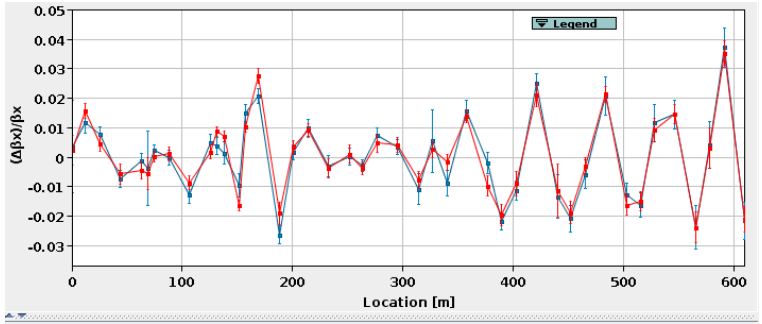
$$\varepsilon(N_p) = \text{slope} \times N_p + \varepsilon_0$$

- Ring-to-ring variations both in the **slope** and in **off-set**

$$\epsilon_{x,y} = \left(\frac{\sigma_{x,y}^2}{\beta_{x,y}} - \frac{D_{x,y}^2 \delta^2}{\beta_{x,y}} \right) \beta_{\text{rel}} \gamma_{\text{rel}}$$

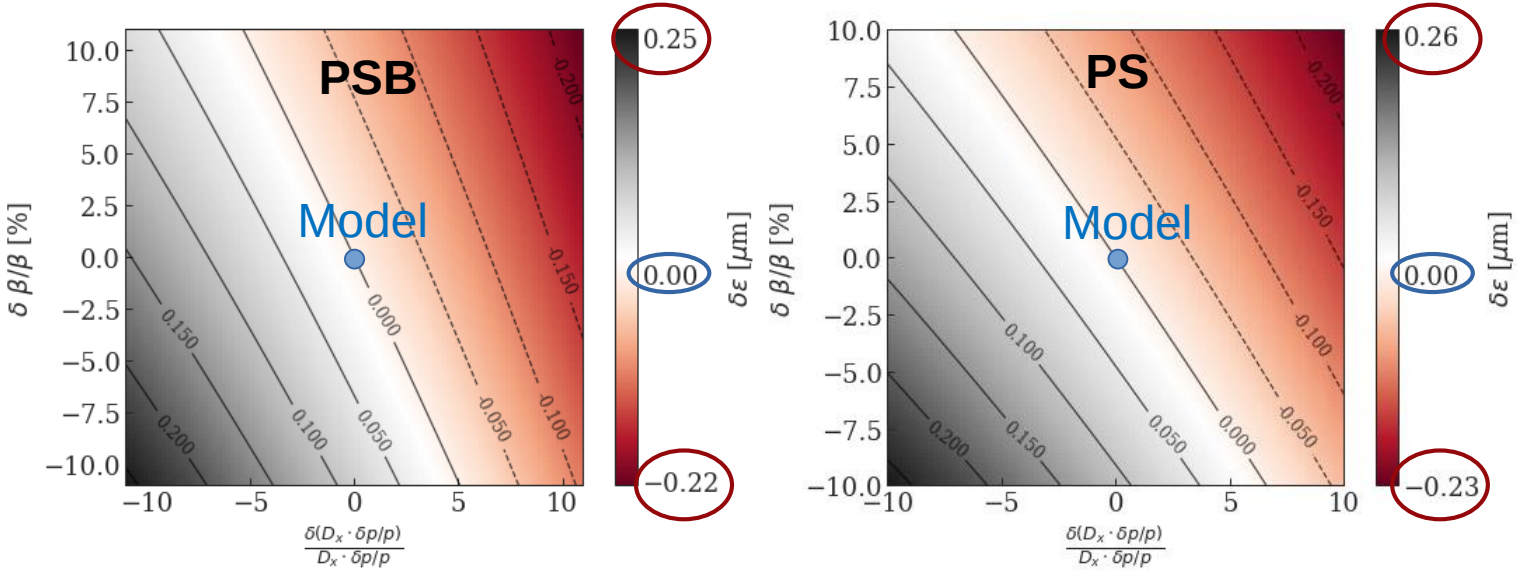
- Optics measurements campaign in both machines
- Dispersion measurements at the location of the WSs
- Important to quantify the impact of
  - Systematic errors (optics, instrumentation) and
  - Transfer line dispersion mismatch (see M. Fraser)

PS



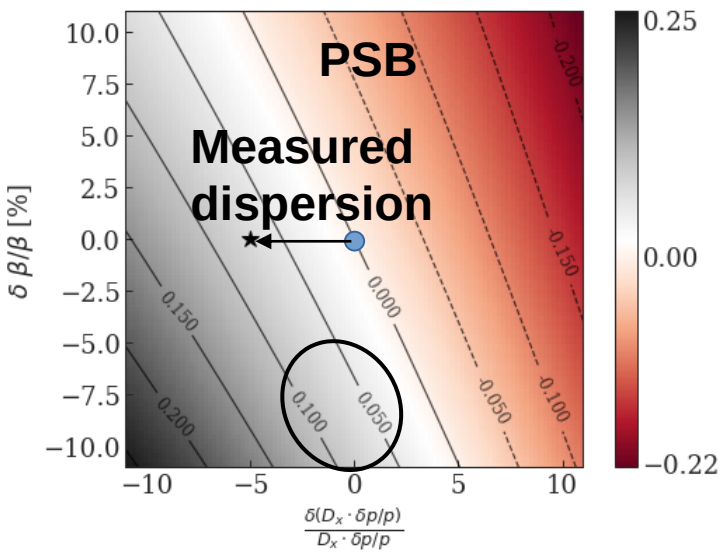
- Max. beta-beating of 5% around the machine and 3% at the location of the WS

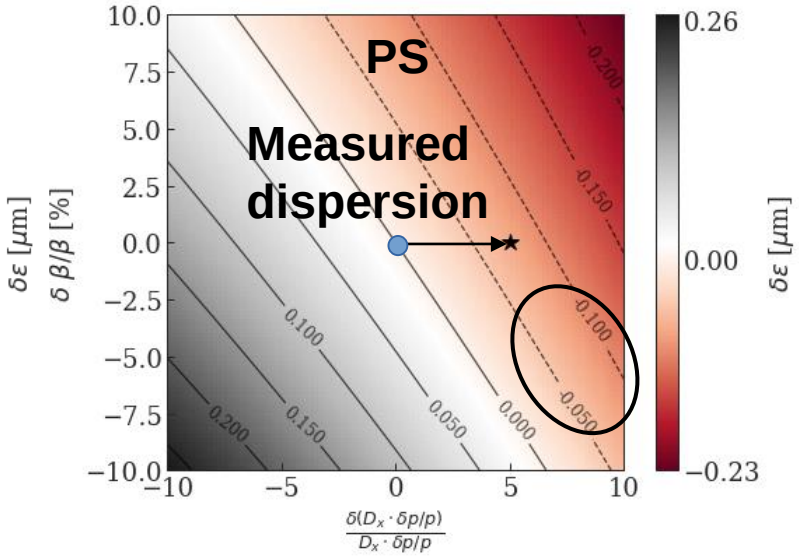
Impact of systematic errors



- δε is the emittance difference with respect to the case without any errors (model)
- Parameterized with the relative beta function and dispersive part error → Introducing a non-negligible error in the emittance

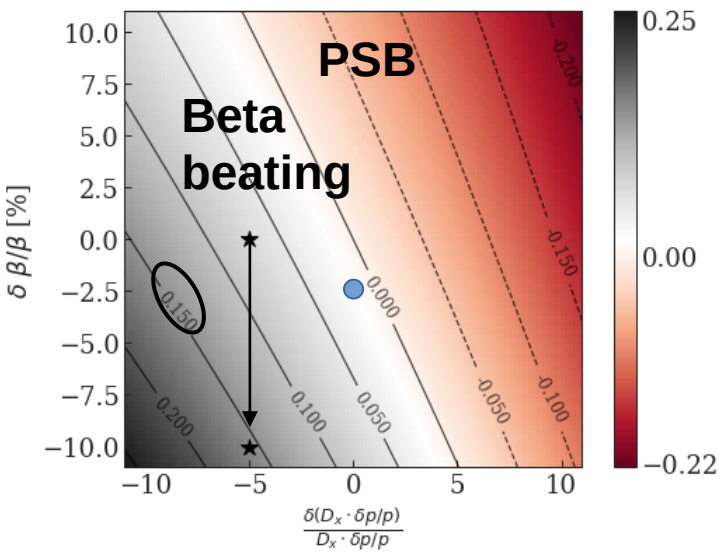
Impact of systematic errors

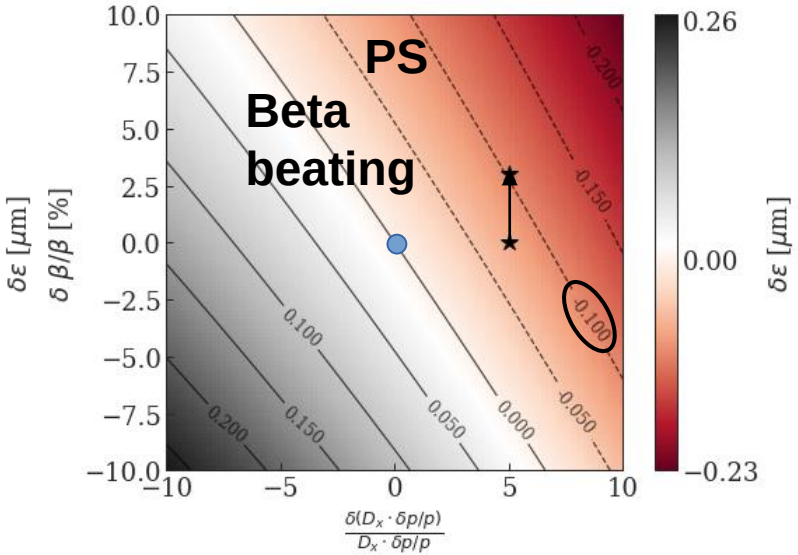




- δε is the emittance difference with respect to the case without any errors (model)
- Parameterized with the relative beta function and dispersive part error → Introducing a non-negligible error in the emittance

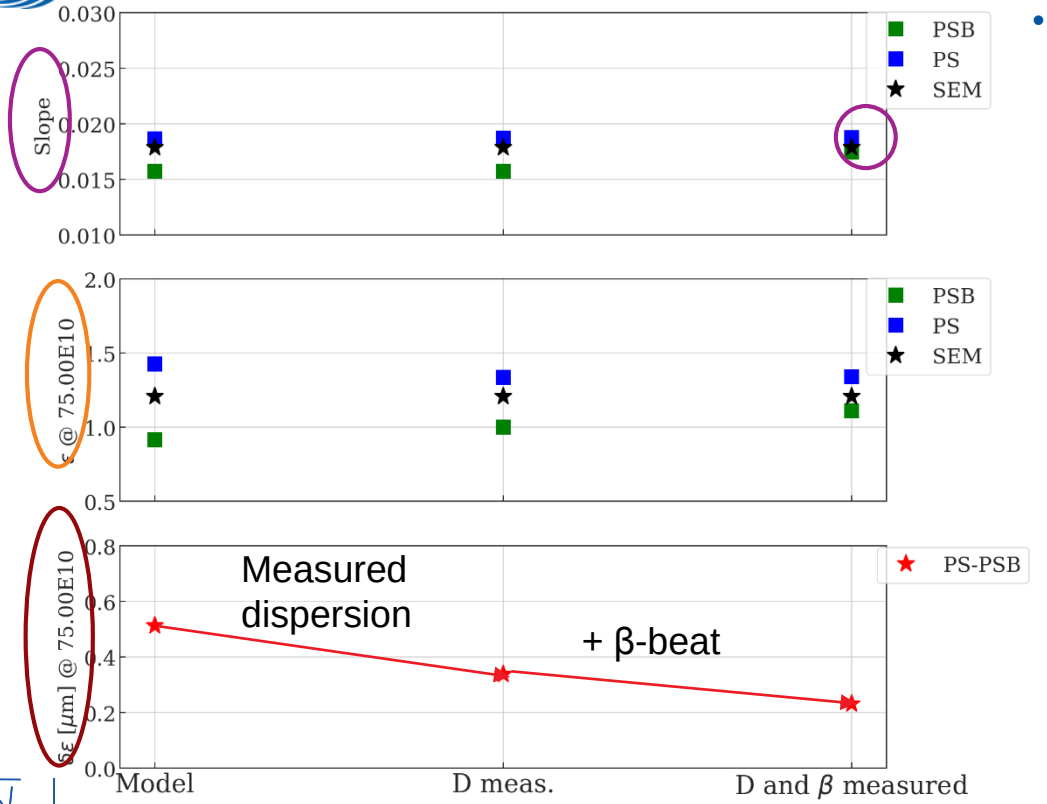
Impact of systematic errors





- δε is the emittance difference with respect to the case without any errors (model)
- Parameterized with the relative beta function and dispersive part error → Introducing a non-negligible error in the emittance

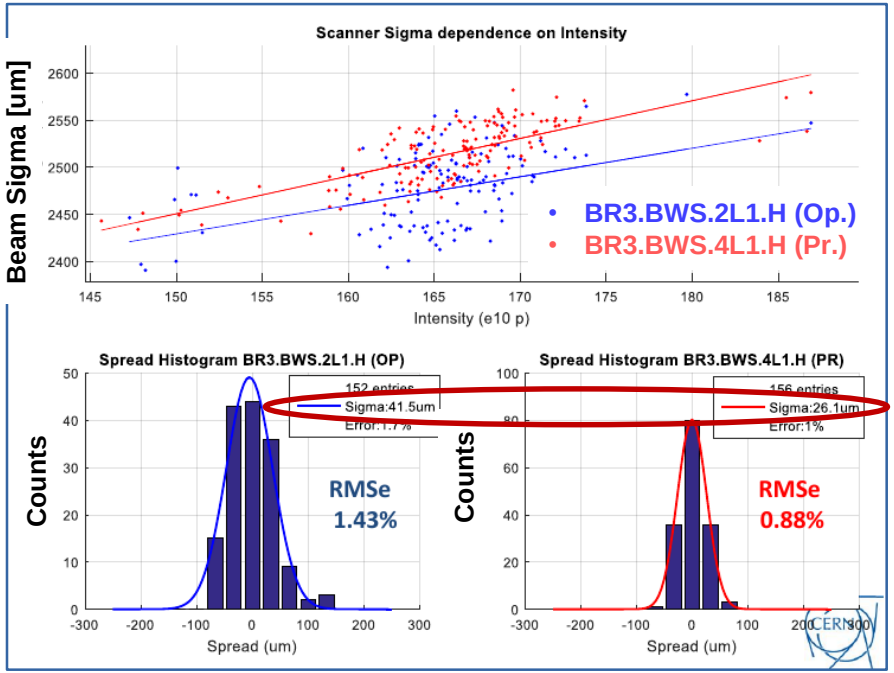
Impact of systematic errors



- Applying measured optics functions at the location of the instruments:
  - The two PS WSs in agreement!
  - PS and PSB come closer
  - Slopes of the brightness curves become very similar!

** Emittance reconstruction based on Gaussian profile assumption in both transverse and longitudinal planes*

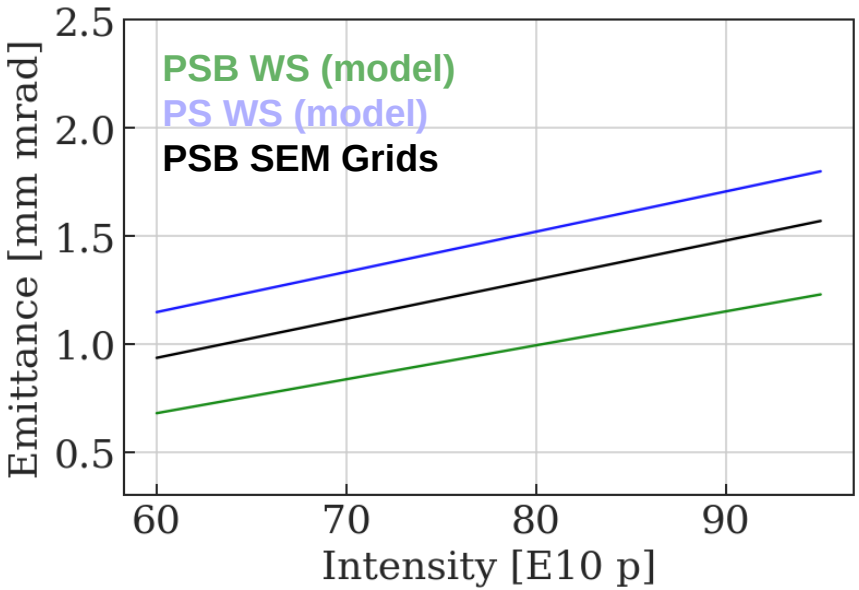
Measurements with the LIU prototypes



Courtesy: J.L Sirven et al, BI Day 2018

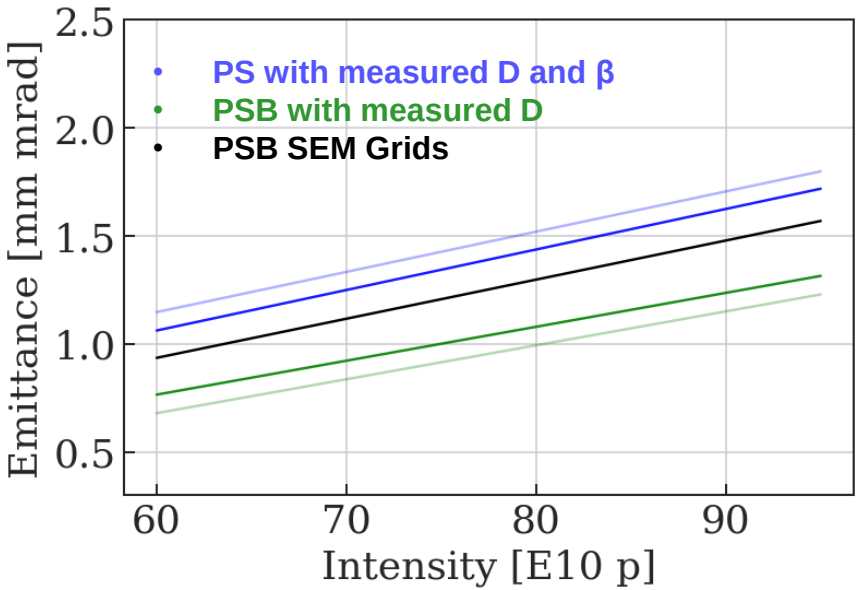
- Simultaneous PSB and PS brightness curves performed also with the **LIU prototype WS** (R3 in the PSB)
  - For the operational and dispersion re-matched transfer line optics
- LIU-WS expected to have better accuracy than the operational ones

Impact of systematic errors



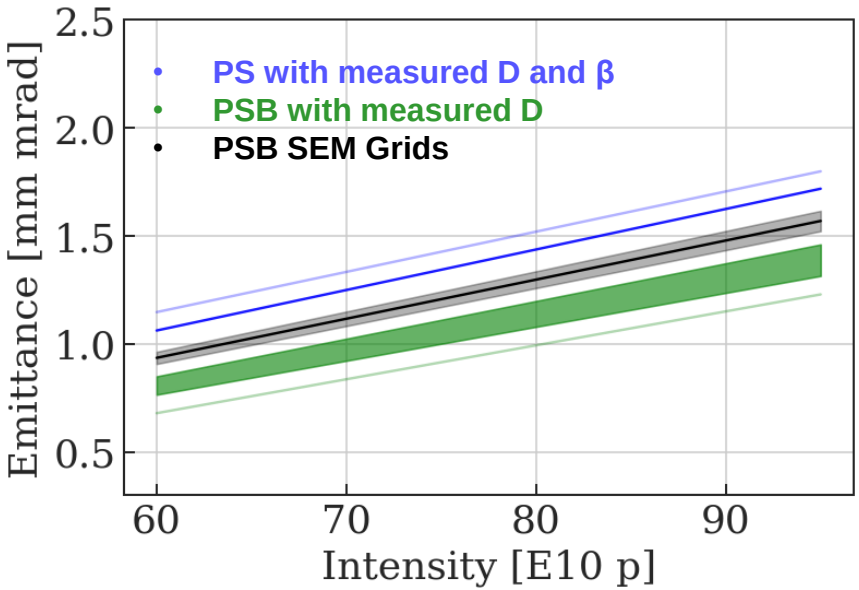
$$\epsilon_{PSB}^{model} - \epsilon_{PS}^{model} = 0.55\ \mu m\ rad$$

Impact of systematic errors



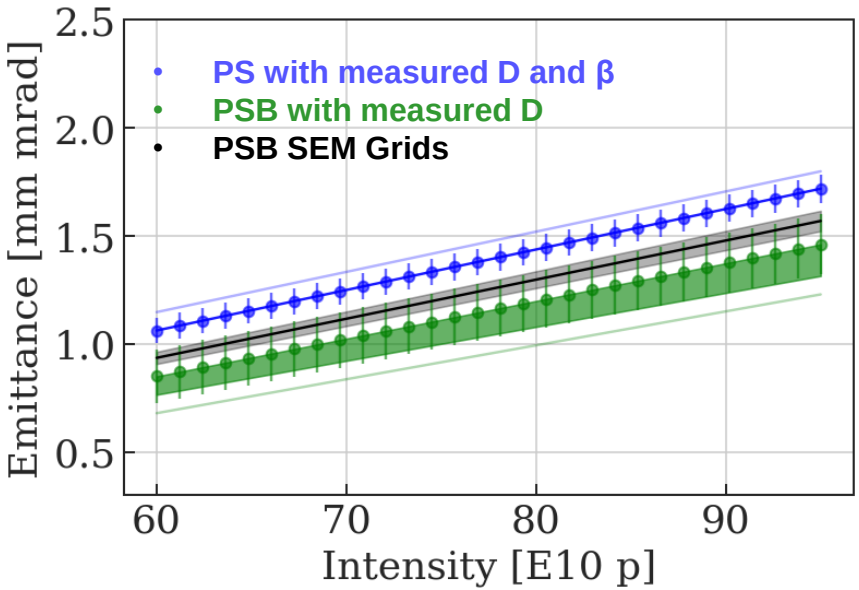
$$\epsilon_{PSB}^{Dmeas}\text{-}\epsilon_{PS}^{meas} = 0.35\ \mu m\ rad$$

Impact of systematic errors



Spread corresponds to up to – 10% beta beating

Impact of systematic errors

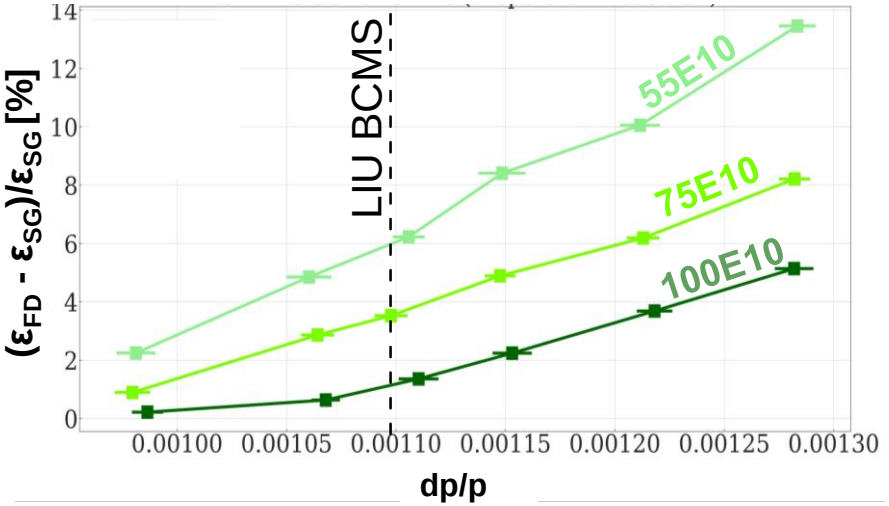


$$\epsilon_{PS}^{meas} - \epsilon_{PSB}^{SEM} = 0.15\ \mu m\ rad$$

- Applying measured optics and uncertainties of measurement, the PSB and PS brightness curves come closer but the spread is large!
- The upper limit of the PSB brightness curves in agreement with the PSB SEM Grids
- Our measurements are dominated by the systematic errors!

Note: Expected horizontal emittance blow up due to the dispersion mismatch in the transfer line ~0.15 μm rad (see M. Fraser)

Impact of de-convolution algorithms



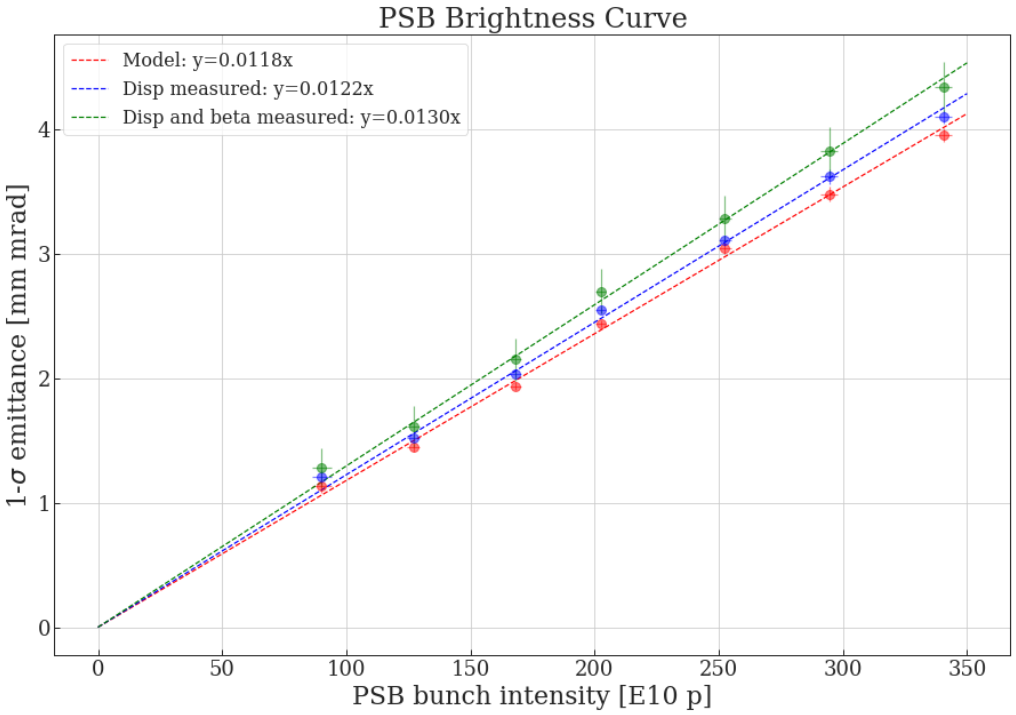
FD: Full Deconvolution
SG: Standard Gaussian subtraction

- PSB brightness curves measurements for the **BCMS with 1.5eVs** long. emittance showed a **much larger blow up effect**!
- Comparison between the **Standard Gaussian (SG)** subtraction and **Full Deconvolution (FD)** algorithms, using measured data, shows an increasing discrepancy with the dp/p

Next step:

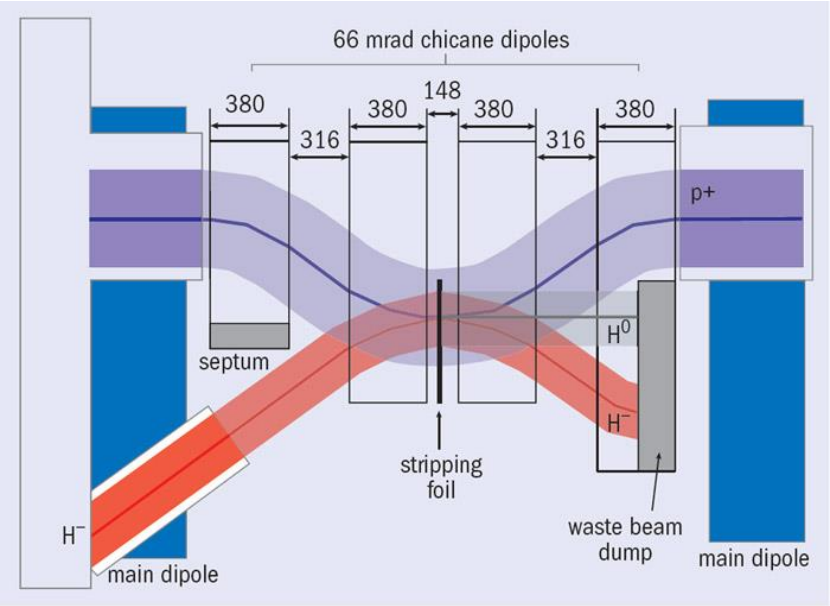
Simulations to benchmark measurements and identify the optimal emittance deconvolution algorithm (minimize the emittance estimation error) for non-Gaussian beam distributions

Impact on LHC brightness curves



- Applying the same assumptions on the brightness curves from 2012, the slope increases by 3% in the case of the measured dispersion
- It can increase up to 10% for a -10% error in beta function.

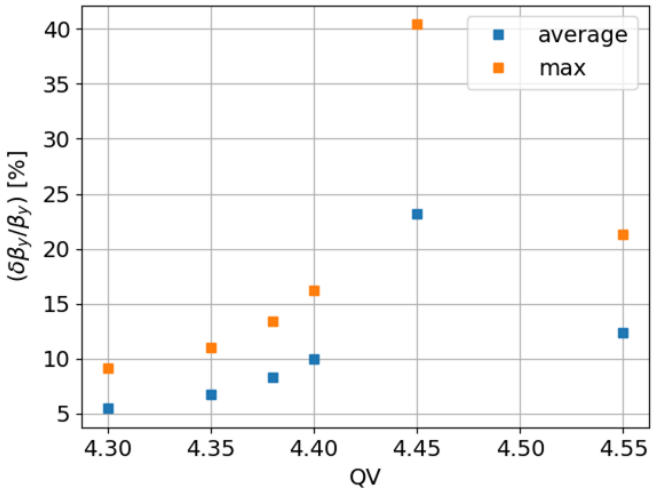
PSB H- Injection

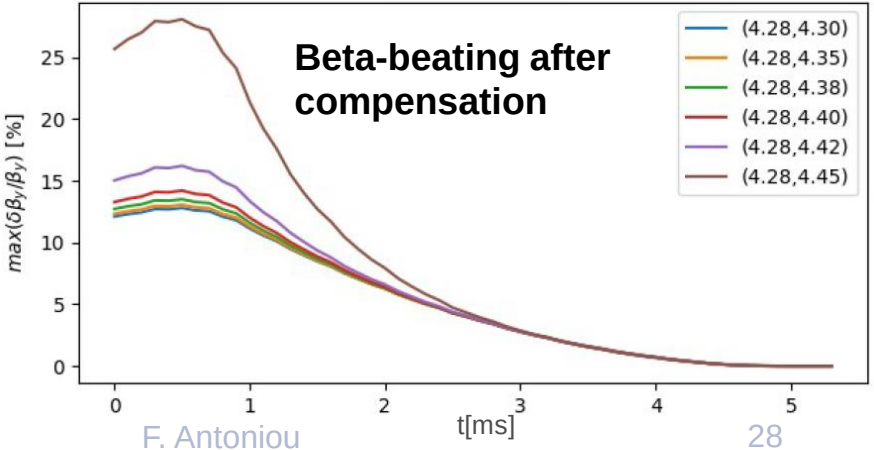


- A new **H- charge exchange injection scheme** (first time at CERN)
  - Increase the injection energy from 50 MeV to 160 MeV
  - Double brightness within the same space charge tune spread
- Allows the implementation of painting procedures
- It has to be integrated in the fixed lattice of the existing PSB (2.6m long straight section)

PSB H- Injection

- Vertical beta beating introduced by edge effects and eddy currents during the fall of the chicane
- Uncompensated beta-beating can lead to undesirable losses
- Two additional trims are foreseen on top of the standard quadrupoles of cells 3 and 14 to compensate the induced beta beating
- Compensation functions calculated for different vertical tunes

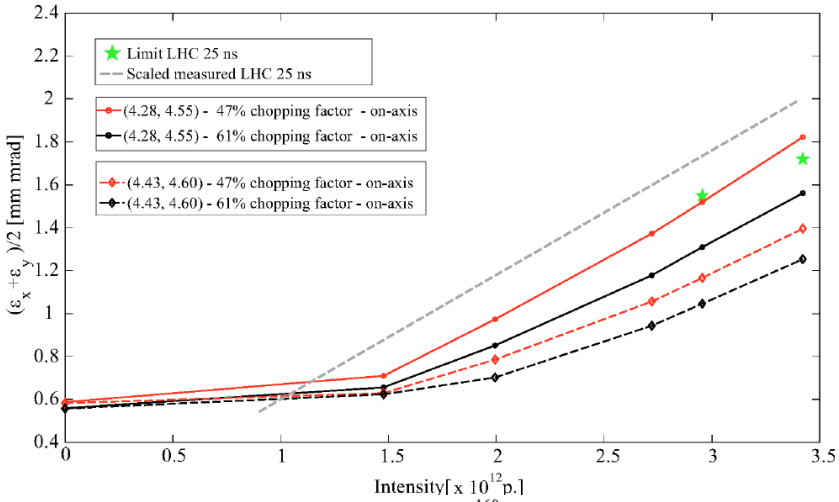


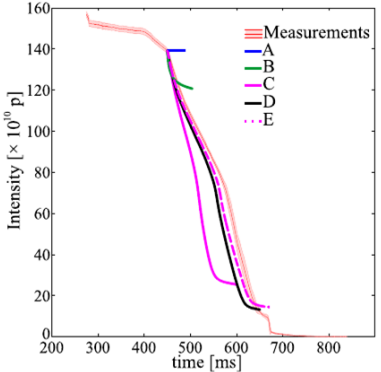


Next step

- Include Space charge

PSB H- Injection





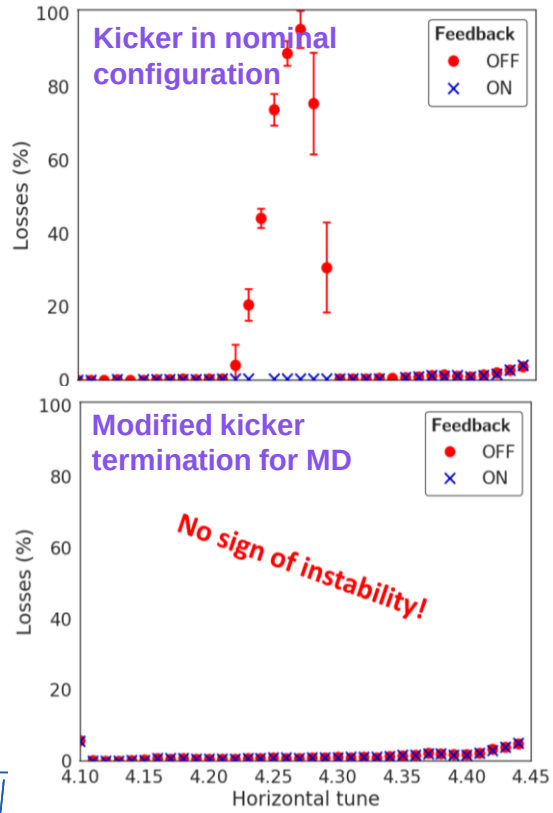
Courtesy V. Forte, PhD thesis

- Brightness curve simulations for the new H^- injection, including the multi-turn injection and chicane induced beta-beating compensation
- Injection above the vertical half-integer foreseen both for LHC and high intensity beams
- Benchmarking simulations including space charge reproduced the measured losses close to the half-integer

Next steps

- Brightness curve simulations including errors, non-perfect beta-beating compensation and sources of jitter and mismatch which might affect the emittance
- Identify the optimum injection scenario WP

Expectations and limits with the new TFB



- **Horizontal instability observed at 160MeV** with clear dependence of losses on the horizontal tune
- MD performed at the end of the proton run, proved that the **extraction kicker's unmatched termination is the impedance source of the instability**!
- Very important to have the TFB acting on the beam right from the beginning
- New H- injection scheme with direct injection into the bucket and new TFB electronics (successfully tested in 2018) give confidence that we can rely on the TFB for suppressing instabilities at all energies

Next Step

- Injection simulations to follow including the TFB

Summary and Outlook

Brightness studies

- Systematic brightness curve studies showed a strong impact of the systematic errors on the computation of the horizontal emittance (OP/BI/ABP/ABT/RF)
- Applying the measured optics functions the difference between the PSB and PS becomes smaller
- Important to identify the optimal emittance deconvolution algorithm in the presence of dispersion and non-Gaussian distributions and eventually agree on a strategy between the machines how to operationally implement the findings for the emittance measurements

Summary and Outlook

H- injection challenges

- Strong beta-beating (tune dependent) induced by the chicane in combination to the half-integer crossing can lead to undesirable beam degradation
- Simulations including space charge, machine errors and non-perfect beta-beating compensation will follow to identify the optimal injection scenario

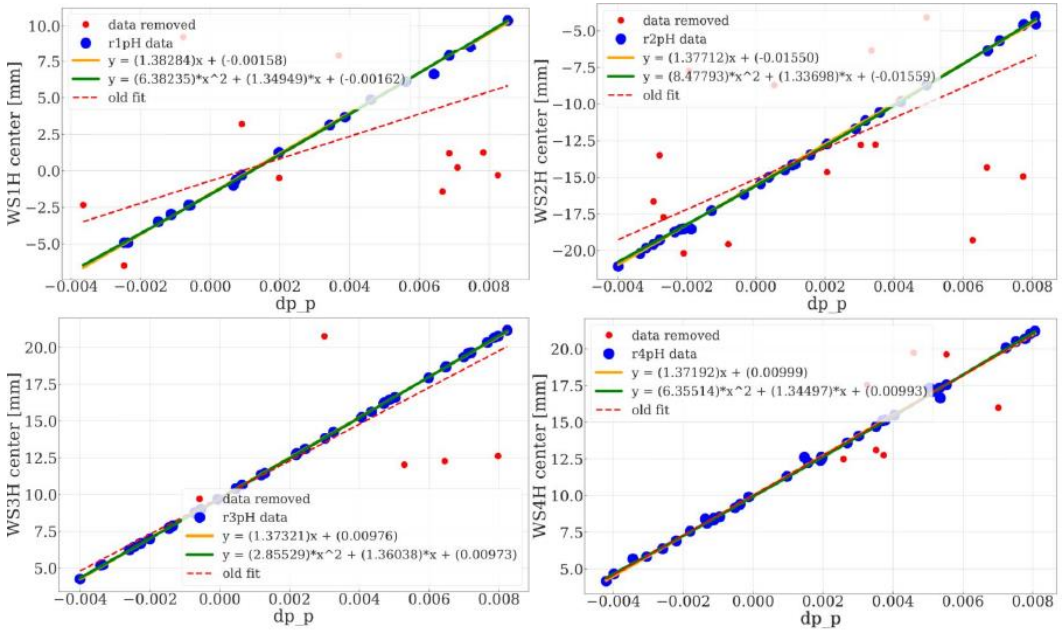
Expectations and limits with the new TFB

- The source of horizontal instability observed at 160 MeV has been identified to be the unmatched termination of the extraction kicker
- The new TFB electronics successfully tested in 2018 and direct injection into the bucket give confidence that we can rely on the TFB for suppressing instabilities at all energies

CERN

www.cern.ch

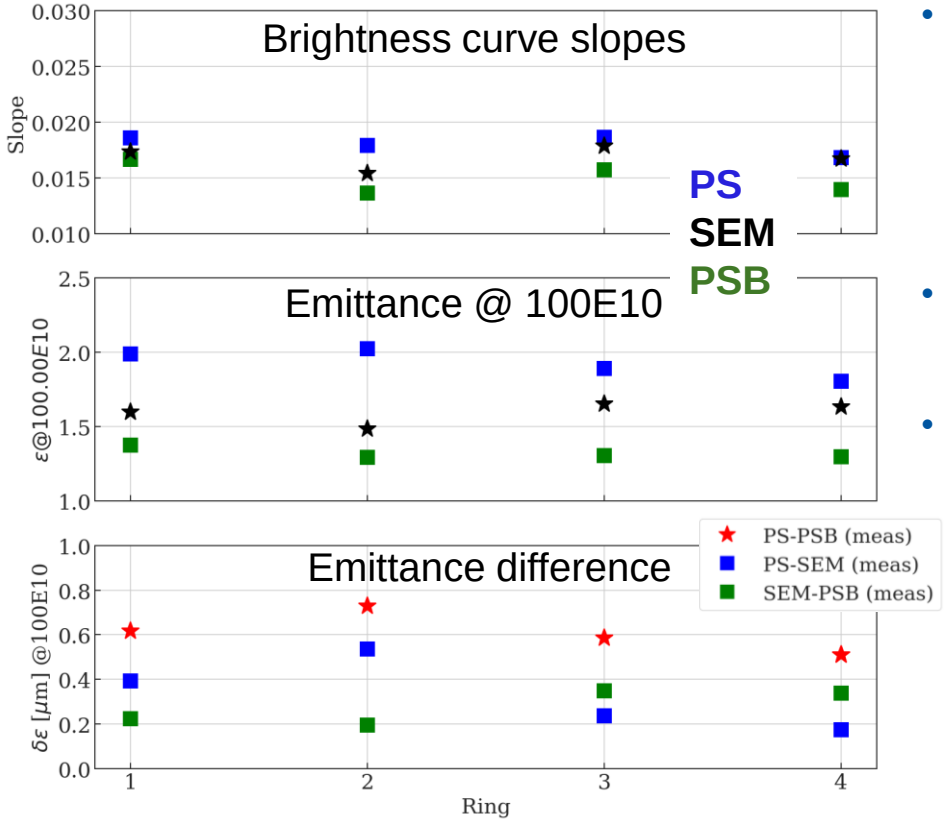
PSB WS Dispersion measurements



WS pH Measured Dispersions (abs.)		
Ring	2018 [m]	2017 [m]
1	1.383 ± 0.014	1.3619
2	1.377 ± 0.023	1.3884
3	1.3732 ± 0.0024	1.3634
4	1.372 ± 0.014	1.3827

- Not all points were included on the fit: we have considered the red points as random measurements
- Dispersion error: the error of the fitting parameters
- Red values are from previous measurements (G.P. Di Giovanni et al.)
- ~5% lower than the model dispersion (plot in a few slides)

Brightness curves in 2018

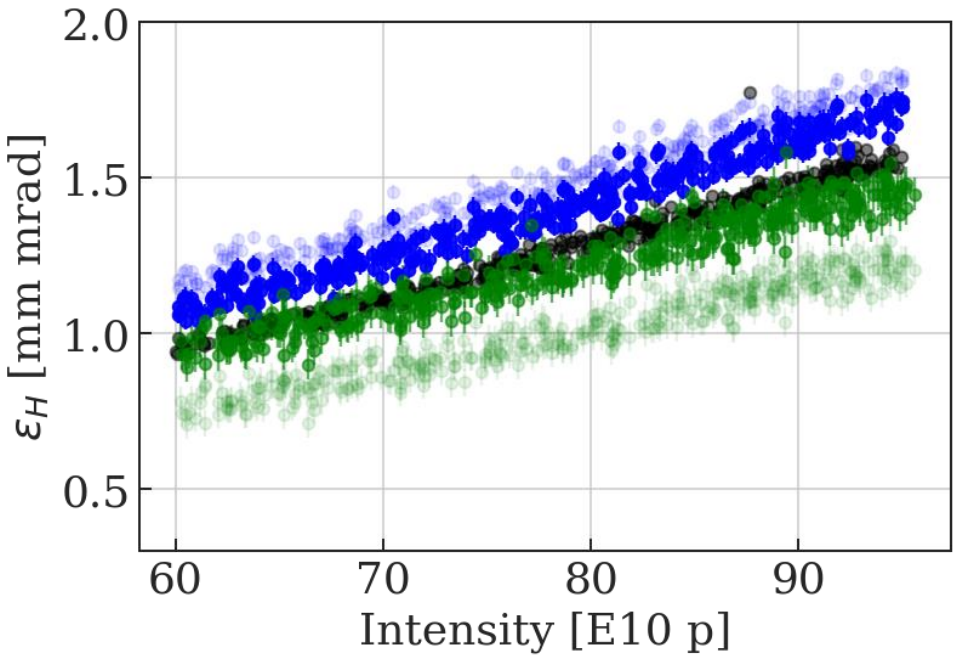


- Linear fits applied in all cases (between 60-100 E10 p)

$$\varepsilon(N_p) = \text{slope} \times N_p + \varepsilon_0$$

- Ring-to-ring variations both in the slope and in displacement
- Exploring the impact of
  - Systematic errors
  - Transfer line optics (more in Matt's presentation)

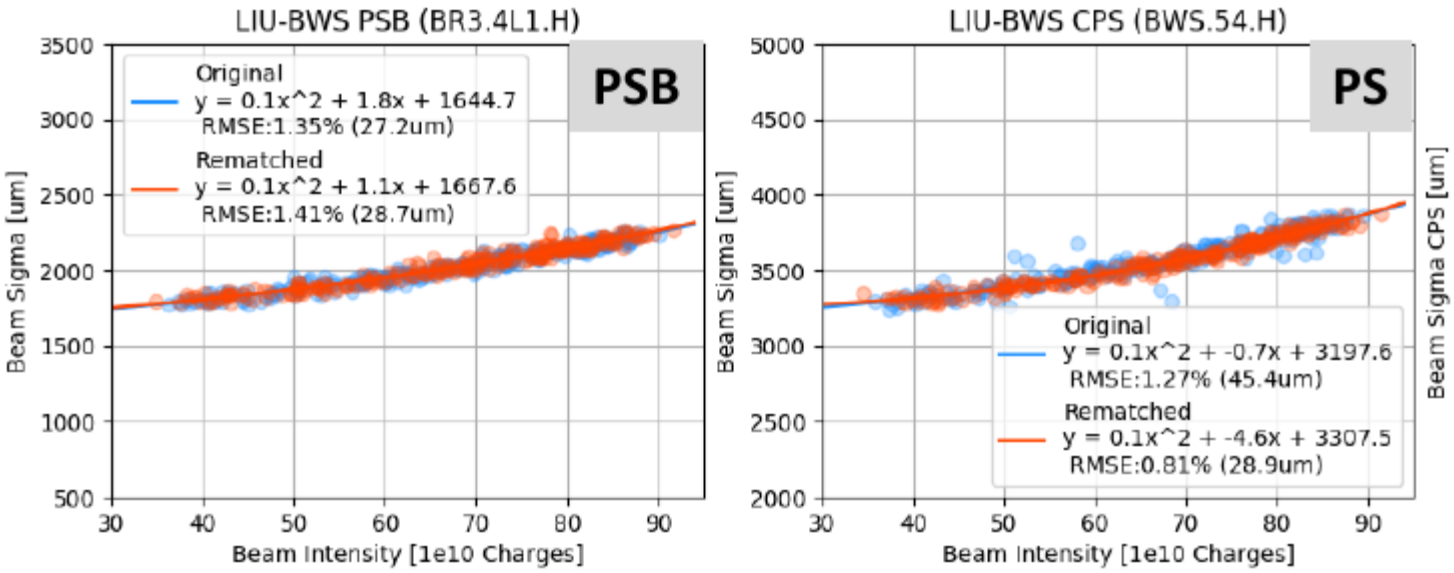
Impact of systematic errors



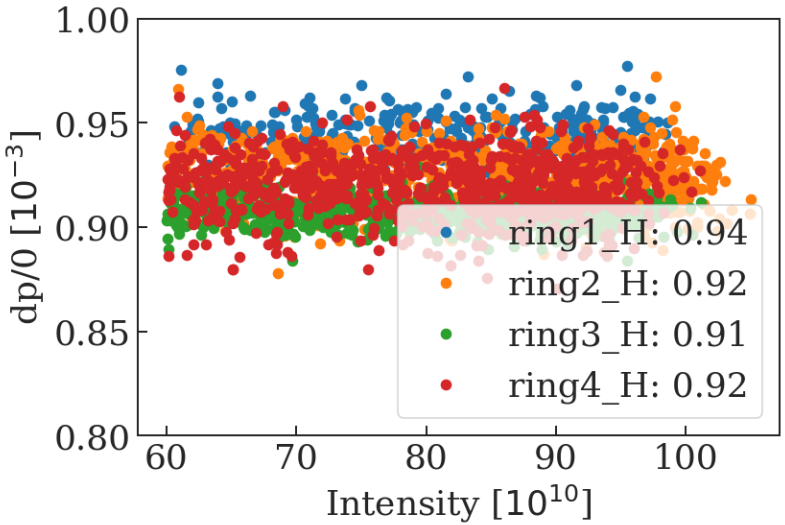
List of errors assumed

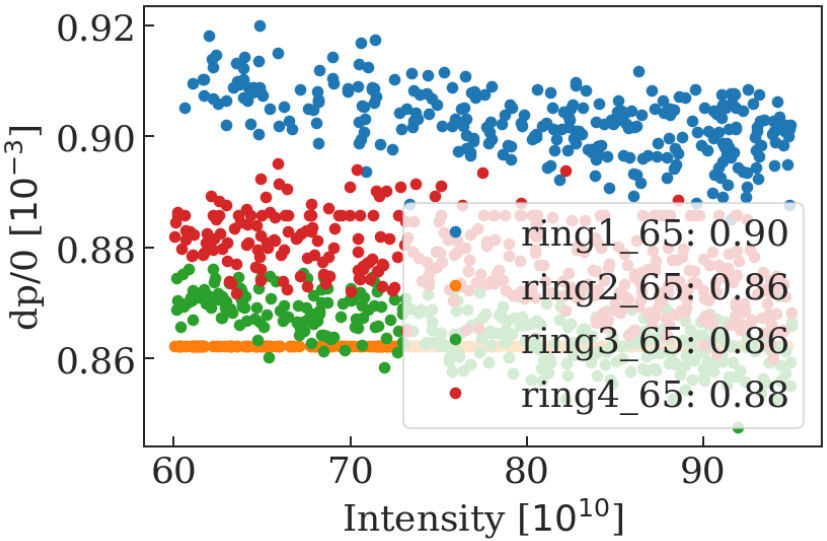
PSB	model	measured	uncertainty
β_{WS} [m]	5.7	-10%	0.5
D_{WS} [m]	1.465	-5%	0.02
σ [mm]	-	-	62e-3
PS	**model**	**measured**	**uncertainty**
β_{WS} [m]	22.3	+3%	1
D_{WS} [m]	3.02	5%	0.02
σ [mm]	-	-	55e-3

Measurements with the LIU prototypes

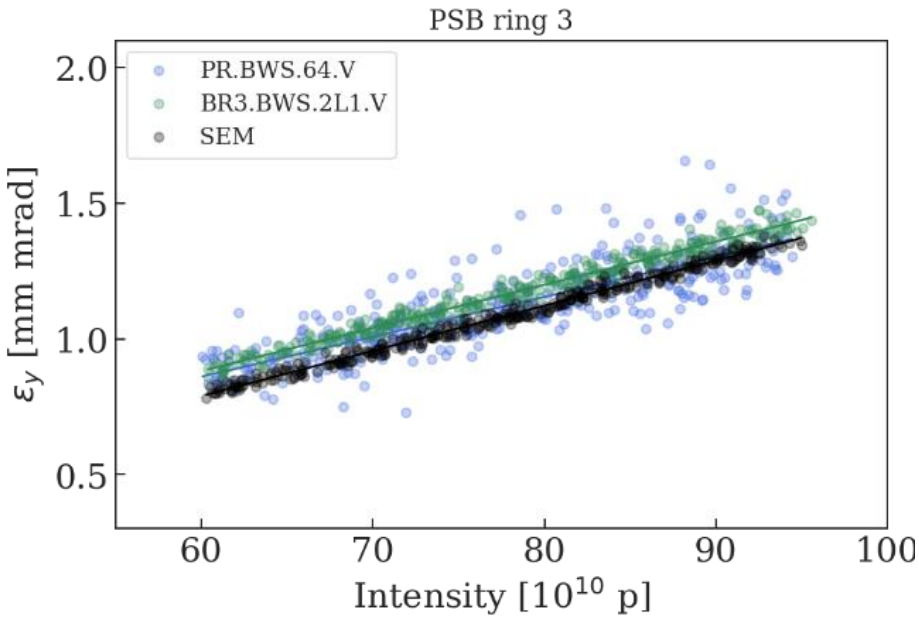


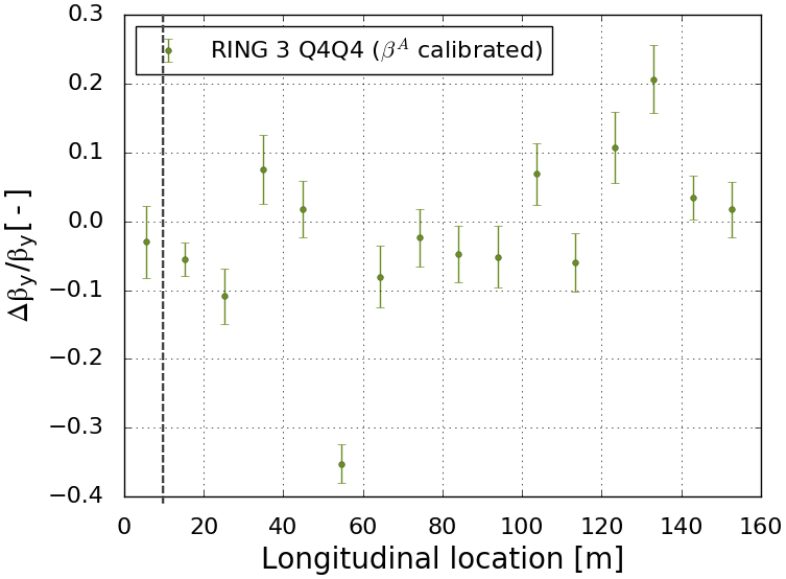
Tomoscope extracted dp/p





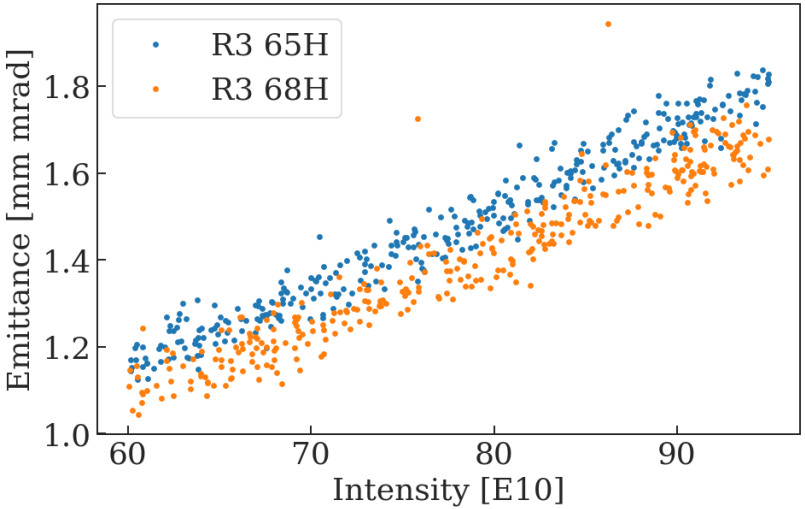
Brightness curves: Vertical plane



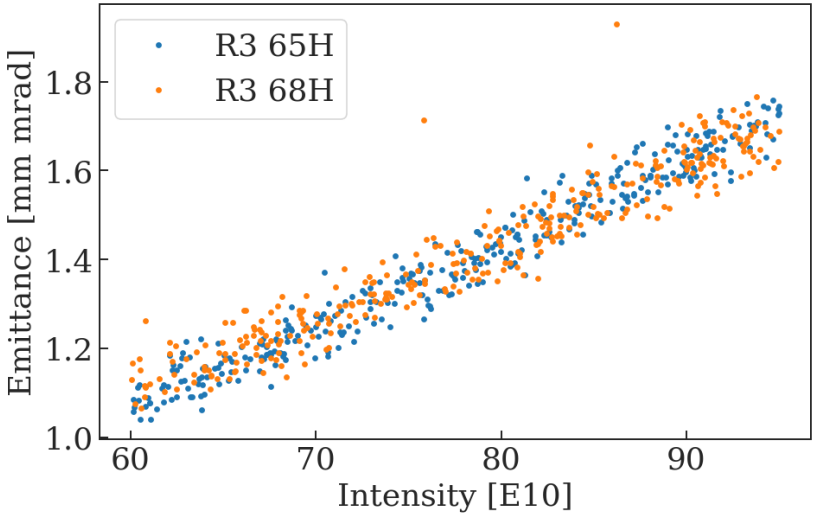


PS Brightness curves: 65H vs 68H

Optics functions from the model



Measured optics functions



Impact of systematics: LIU