Space Charge vs. Dispersion as Contributions to Transverse Emittance Blow-up

at PS Injection Plateau

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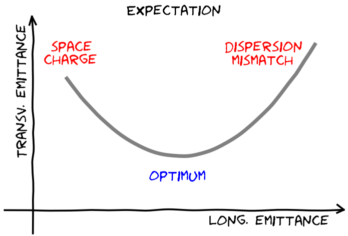
LIU PS Beam Dynamics WG meeting #12

8 March 2018

Motivation

Goal

Find optimal longitudinal emittance ϵ_z to minimise transverse emittances $\epsilon_{x,y}$ at end of PS injection plateau for high-brightness beams.



Opponents

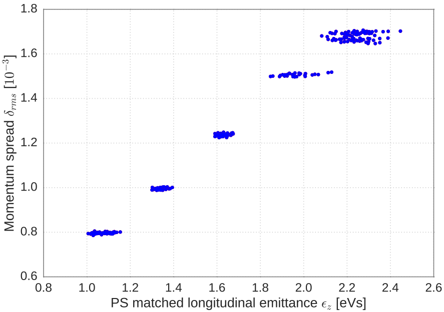
1. small ϵ_z: space charge during injection plateau
2. large ϵ_z: dispersion mismatch in PSB-PS transfer line (due to large momentum deviation δ_{rms})

MD Set-up

Based on last operational `LHC25` cycle set-ups (Nov. 2017):

- PSB longitudinal blow-up achieves $\epsilon_z > 1.3\,\mathrm{eVs}$ via phase noise
- fix bunch length at largest possible value $B_L \approx 210\,\mathrm{ns}$
  - ⟶ adjust RF voltages in both PSB and PS
  - ⟶ PSB: require $h = 2$ in BSM[1] to fit recombination kicker time window

⟹ momentum spreads δ_{rms} increase with longitudinal emittance ϵ_z



[1] bunch shortening mode

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- PS transverse tunes $Q_x \approx 6.19$ and $Q_y \approx 6.24$
- single bunches produced from PSB ring 3
- 2 variants tested with intensities $N = 1.6 \times 10^{12}\,\mathrm{ppb}$ and $2 \times 10^{12}\,\mathrm{ppb}$

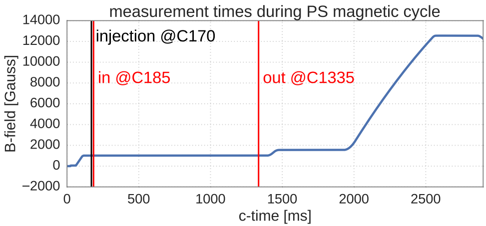
[1] bunch shortening mode

Measurements

Conclusive measurements on 24.11.2017 ↗ and 28.11.2017 ↗:

- tomography at PSB extraction (C795) and PS injection (C185)
- transverse wire scans in PSB and PS (`65_H_ROT` and `85_V_ROT`) at
  - ⟶ PSB extraction (C795)
  - ⟶ PS "in": injection plateau at C185
  - ⟶ PS "out": injection plateau at C1335[2]

⟹ calibration "out" vs. "in" wire scan:
"out" systematically too small by factor 1.1 for ϵ_x and 1.05 for ϵ_y



[2] C1270 for `85_V_ROT` on 28.11.2017 data because of profile problems

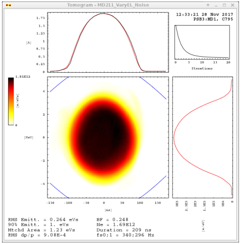
Calibration Factor: PS “Out” Wire Scan

Compare “in” and “out” wire scans in PS:
PS MD logbook 15.09.2017 ↗

- PS `65_H_ROT` wire scanner:
  - ⟶ “in” at C1750: $\epsilon_x = 2.502 \pm 0.04\,\mathrm{mm\,mrad}$
  - ⟶ “out” at C1750 with “in” at C185: $\epsilon_x = 2.26 \pm 0.03\,\mathrm{mm\,mrad}$
  - ⟹ 10% smaller “out” scan ⟹ calibration factor 1.1 for PS “out” ϵ_x
- PS `85_V_ROT` wire scanner:
  - ⟶ “in” at C1750: $\epsilon_x = 2.034 \pm 0.029\,\mathrm{mm\,mrad}$
  - ⟶ “out” at C1750 with “in” at C185: $\epsilon_x = 2.134 \pm 0.018\,\mathrm{mm\,mrad}$
  - ⟹ 5% smaller “out” scan ⟹ calibration factor 1.05 for PS “out” ϵ_y
- scattering influence? Checked with PS `65_H_ROT`:
  - ⟶ “out” at C1385 with “in” at C100: $\epsilon_x = 2.130 \pm 0.068\,\mathrm{mm\,mrad}$
  - ⟶ “out” at C1385 with “in” at C185: $\epsilon_x = 2.155 \pm 0.059\,\mathrm{mm\,mrad}$
  - ⟹ emittance growth due to scattering negligible, $\Delta\epsilon \lessapprox 1\%$

Prepared Longitudinal Emittances

$\epsilon_z = 1.3\,\mathrm{eV\,s}$ (28.11.)



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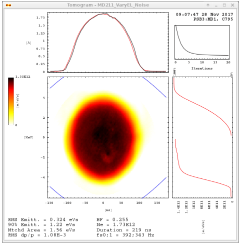

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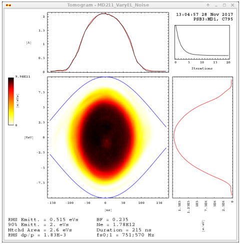

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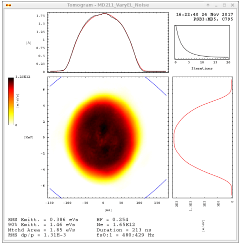

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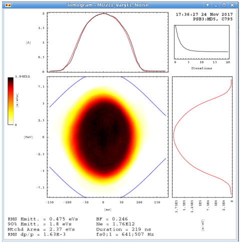

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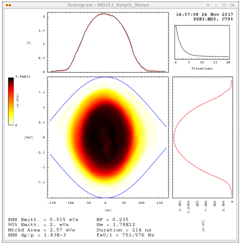
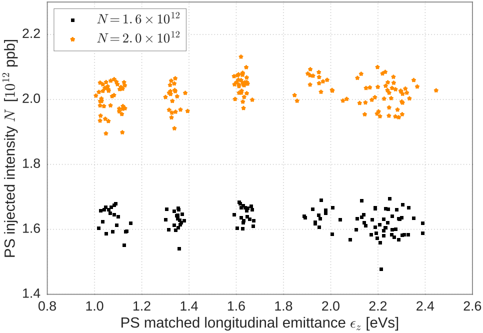


For each longitudinal emittance ϵ_z we tested 2 variants with intensities

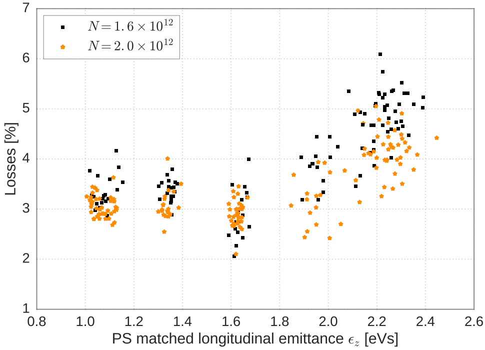
- $N = 1.6 \times 10^{12}$ ppb (≈ 2.3 injected turns) and
- $N = 2 \times 10^{12}$ ppb (≈ 3.0 injected turns)



$\longrightarrow$ intensities well calibrated for scanned ϵ_z!

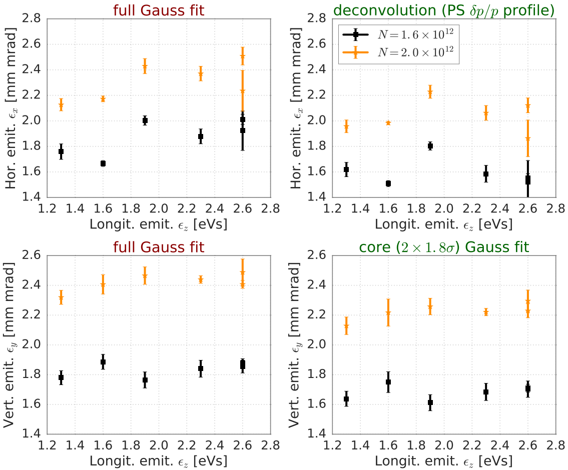
Losses

Beam loss observations from BCT between C185 and C1335:



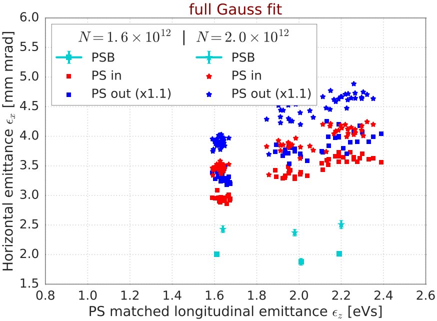
$\Longrightarrow$ no significant dependency on intensity N

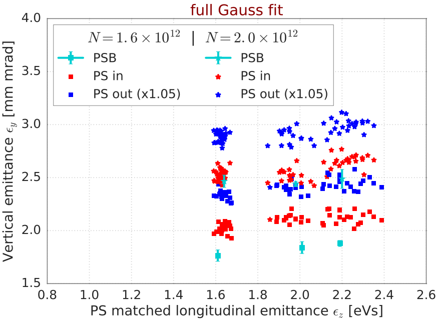
PSB Wire Scans



⟶ prepared beams at PSB extraction have $\epsilon_{x,y} \sim \text{const}$ ✓
(only $\epsilon_z = 1.9\,\text{eVs}$ case seems to be an outlier in horizontal plane)

⟶ for ϵ_x deconv. approach remains const. while Gauss fit grows with ϵ_z



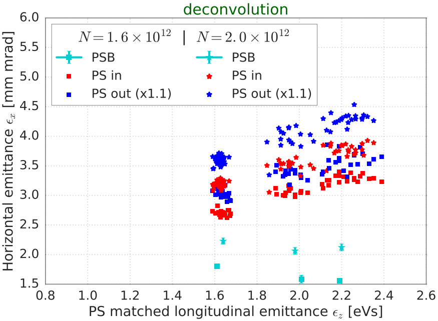


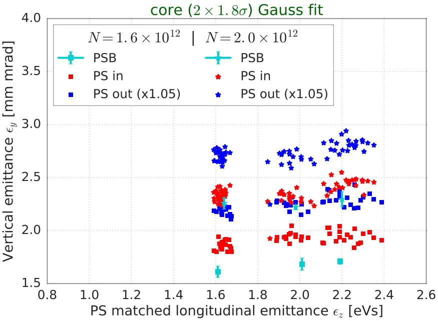
Observations:

- significant horizontal blow-up for received $1.6\,\text{eV s} < \epsilon_z < 2.3\,\text{eV s}$ between PSB and PS in $\longrightarrow$ dispersive mismatch?
- vertical emittances match between PSB and PS in ✓
- significant vertical blow-up between PS in and out, independent of ϵ_z and N?!

calibration factors for PS “out” emittances included!

Results 24.11.2017





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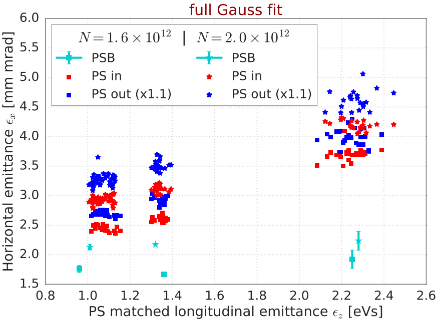

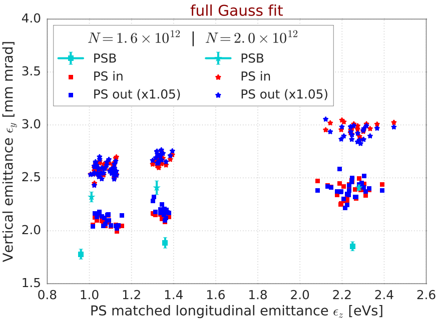

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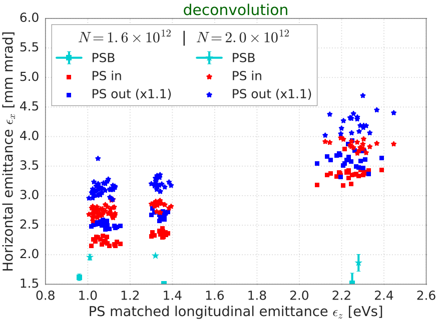

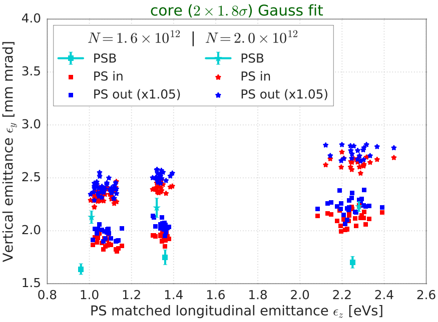

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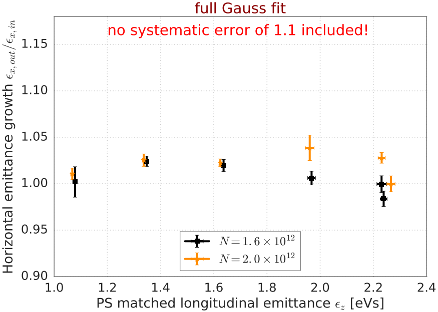

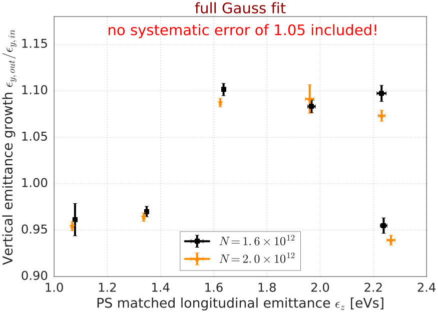

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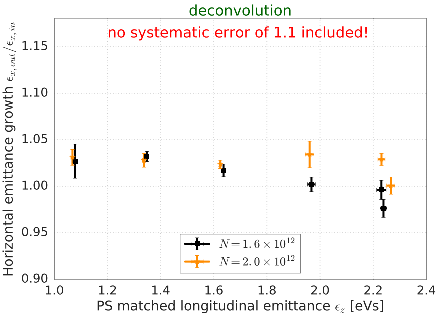

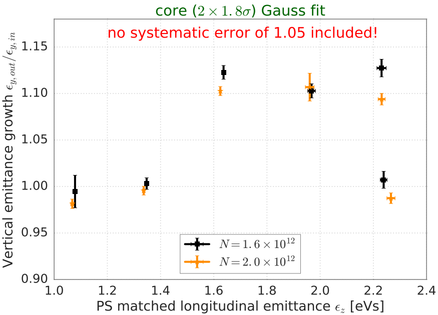

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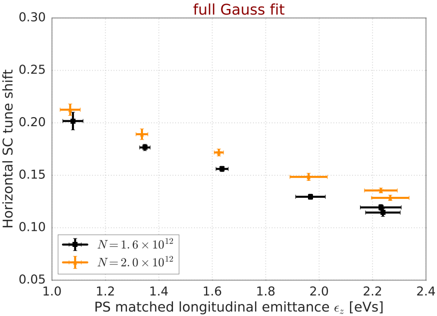
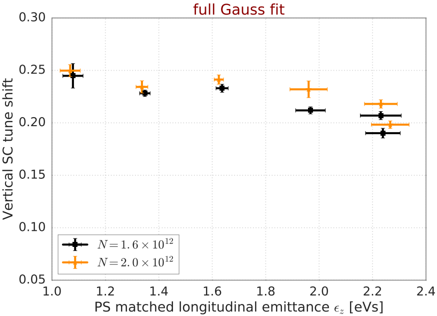
Space Charge Tune Spreads

Gaussian tune spreads due to space charge integrate along machine:

$$\Delta Q^{SC}_{x,y} = -\frac{r_p \lambda_{\max}}{2\pi\beta^2\gamma^3} \oint ds \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)\,(\sigma_x(s)+\sigma_y(s))} \quad \text{with} \quad \sigma_x = \sqrt{\frac{\beta_x \epsilon_x}{\beta\gamma} + D_x^2 \delta_{\mathrm{rms}}^2}$$





$\longrightarrow$ $\lambda_{\max}$ based on longitudinal peak current (rescaled to BCT value)

cf. appendix to compare with PSB extraction figures for emittances and tomogram data

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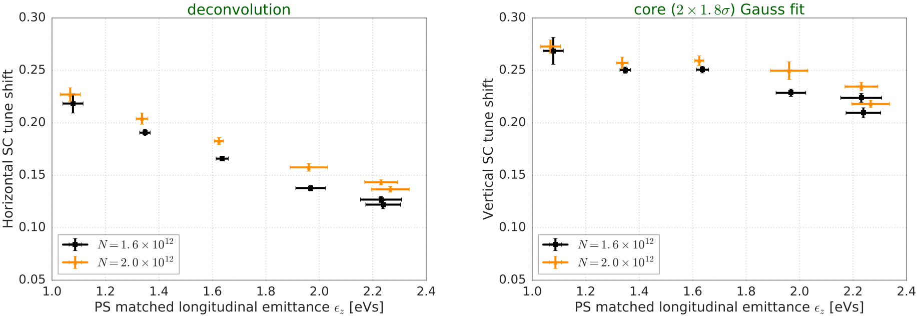

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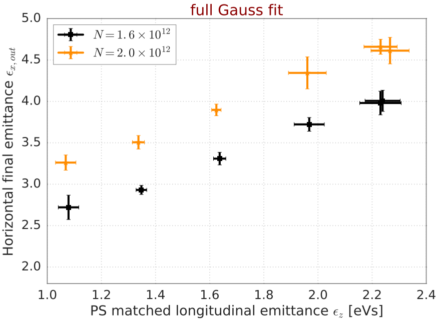
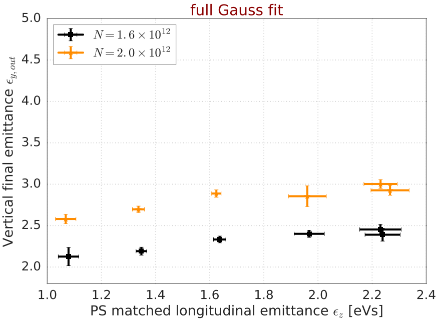
Final Emittance after PS Injection Plateau

Using the LHC25 beams, the final transverse emittances at the end of the PS injection plateau look as follows:





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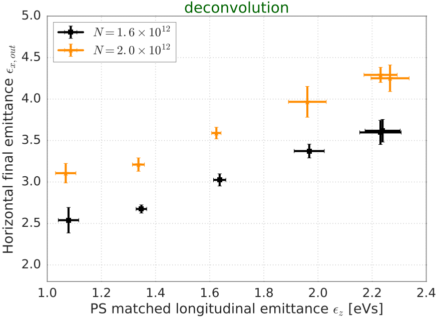

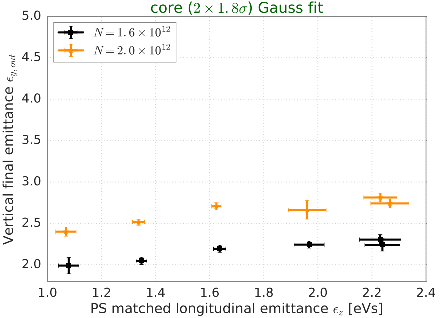

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Dispersion Mismatch: Optics Measurements (VincenzoF)

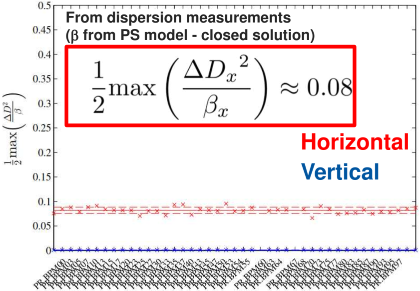
Measured dispersive mismatch evaluation

- Emittance growth from dispersion mismatch can be approximated to (~constant at every BPM location):

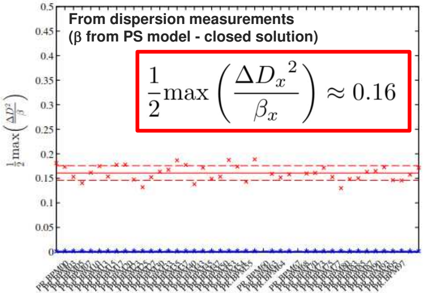
$$\frac{\Delta\epsilon_{x,y,geom}}{\epsilon_{0,x,y,geom}} = \frac{1}{2}\frac{\Delta D_{x,y}{}^2 + (\beta_{x,y}\Delta D'_{x,y} + \alpha_{x,y}\Delta D_{x,y})^2}{\beta_{x,y}\epsilon_{0,x,y,geom}}\left(\frac{\delta p}{p}_{rms}\right)^2 \approx \boxed{\frac{1}{2}\max\left(\frac{\Delta D^2_{x,y}}{\beta_{x,y}}\right)}\frac{1}{\epsilon_{0,x,y,geom}}\left(\frac{\delta p}{p}_{rms}\right)^2$$

The term $\boxed{\frac{1}{2}\max\left(\frac{\Delta D^2_{x,y}}{\beta_{x,y}}\right)}$ is a constant and can be directly derived from dispersion measurements at every BPM in the PS

From BCMS (RF OFF) measurements

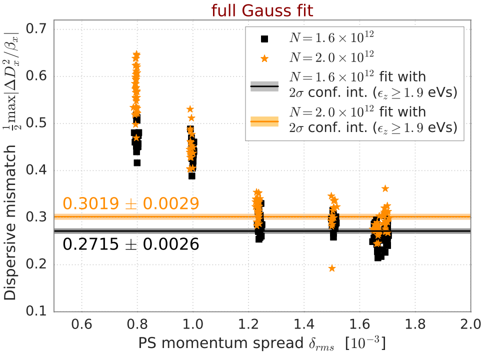


From BCMS (RF ON) it increases of a factor 2!



Dispersion Mismatch Prediction from Emittance Growth

Dispersion mismatch as predicted by the measured emittance growth:



Observations:

- from $\epsilon_z \geq 1.9\,\text{eV s}$ ($\delta_{\text{rms}} \geq 1.2 \times 10^{-3}$), prediction for dispersive mismatch seems constant around $\frac{1}{2}\max\left|\Delta D_x{}^2/\beta_x\right| \approx 0.3$

$\Longrightarrow$ independent of approach to determine transverse emittance!

- low ϵ_z (low δ_{rms} figures) feature more emittance growth

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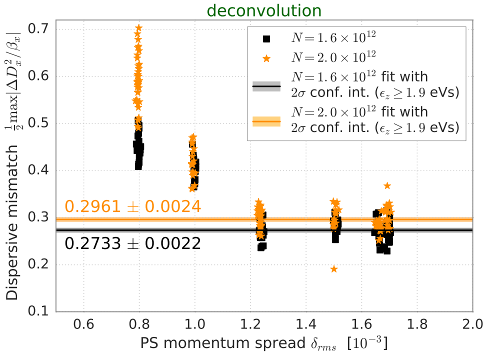

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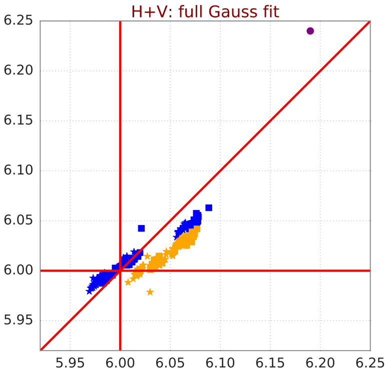
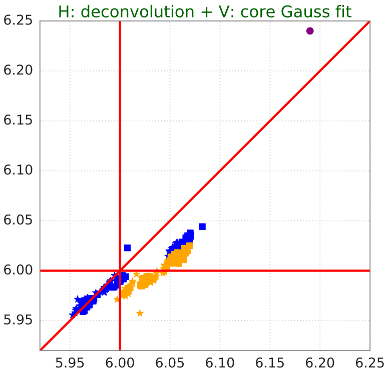


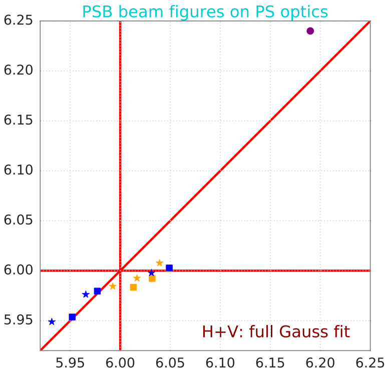


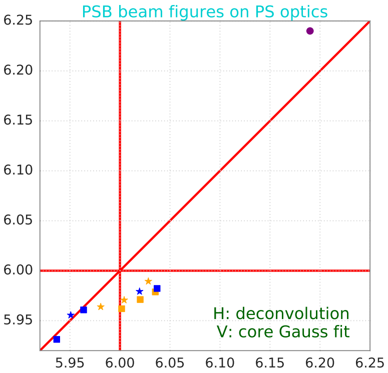
- 24.11. data systematically shifted to lower values than 28.11. data

⟶ emittance exchange in 24.11. case? (→ vertical blow-up)

⟹ large horizontal detuning for low ϵ_z could explain larger $\Delta\epsilon_x$ and correspondingly too large ΔD_x estimates!
(C185: 15 ms might be enough for integer resonance blow-up)

Tune Diagrams: Space Charge Tune Spreads





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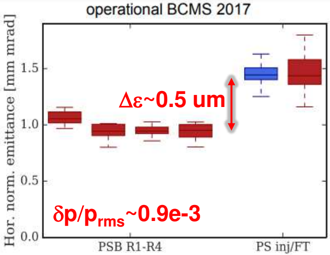
Emittance Growth for BCMS (AlexH + VincenzoF)

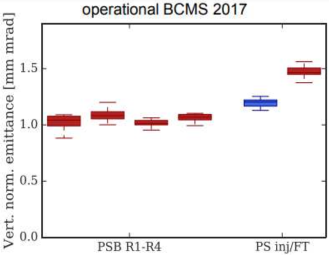
Measured dispersive mismatch evaluation

The term $\boxed{\frac{1}{2}\max\left(\frac{\Delta D_{x,y}^2}{\beta_{x,y}}\right)}$ **can be also derived (from the other side) from absolute emittance growth and δp/p (rms) measurements, as:**

$$\frac{1}{2}\max\left(\frac{\Delta D_{x,y}{}^2}{\beta_{x,y}}\right) = \frac{\Delta\epsilon_{x,y,geom}}{\left(\frac{\delta p}{p}_{rms}\right)^2} = \frac{\Delta\epsilon_{x,y,norm}}{\beta_{rel}\gamma_{rel}\left(\frac{\delta p}{p}\right)^2}$$

Example (operational BCMS)





$$\frac{1}{2}\max\left(\frac{\Delta D_x{}^2}{\beta_x}\right) = \frac{\Delta\epsilon_{x,norm}}{\beta_{rel}\gamma_{rel}\left(\frac{\delta p}{p}_{rms}\right)^2} = \frac{0.5\times10^{-6}}{0.92\cdot2.49\cdot(0.9\times10^{-3})^2} = 0.27$$

Too large!

Plots from A. Huschauer presentation at Chamonix 2018)

Conclusion & Next Steps

Extracting transverse emittances $\epsilon_{x,y} \approx 2\,\mathrm{mm\,mrad}$ from PSB:

✓ established $\epsilon_{x,y}$ figures at end of injection plateau for `LHC25` beams

✓ horizontal blow-up between PSB and PS injection depending on ϵ_z (dispersion mismatch) $\Longrightarrow$ present for all ϵ_z though!

✓ no horizontal blow-up dependance on ϵ_z across PS injection plateau

✓ vertical emittance match between PSB and PS injection

$\longrightarrow$ horizontal integer resonance could explain large $\Delta\epsilon_x$ figures!

$\longrightarrow$ dispersion mismatch estimate from blow-up: $\frac{1}{2}\max\left|\Delta {D_x}^2/\beta_x\right| \approx 0.3$

$\Longrightarrow$ consistent between `LHC25` and operational `BCMS` beams

Next steps for 2018:

$\longrightarrow$ compare same set-up with `BCMS` beams (higher brightness!)

$\longrightarrow$ use ≈ 0 chromaticity, decoupled planes + TFB (avoid V blow-up!)

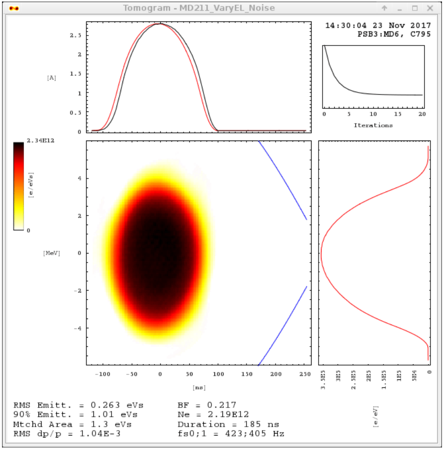
$\longrightarrow$ dispersion-matched optics (Vincenzo): $\Delta\epsilon_x$? $\Rightarrow \frac{1}{2}\max\left|\Delta {D_x}^2/\beta_x\right|$?

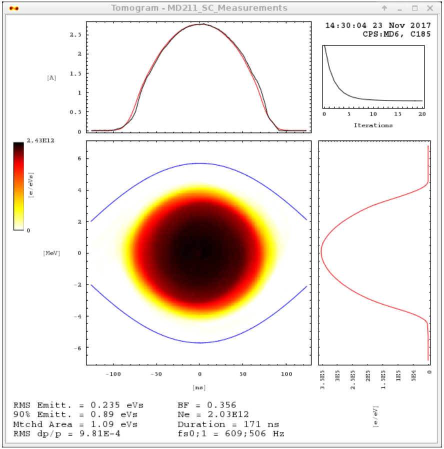
$\Longrightarrow$ finally compare between hollow and large ϵ_z parabolic bunches

Thank you for your attention!

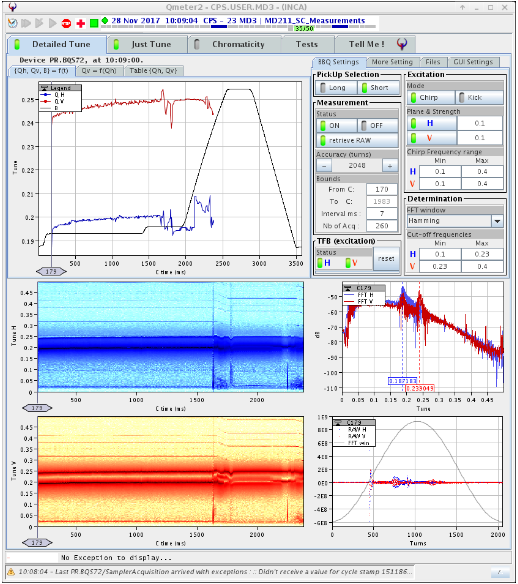
Acknowledgements:
Vincenzo Forte, PSB and CPS OP teams

Matched area in PS is systematically lower by $\approx 15\,\%$ than in PSB (no quadrupolar longitudinal oscillation etc, i.e. longitudinally matched, transverse injection oscillations minimised):

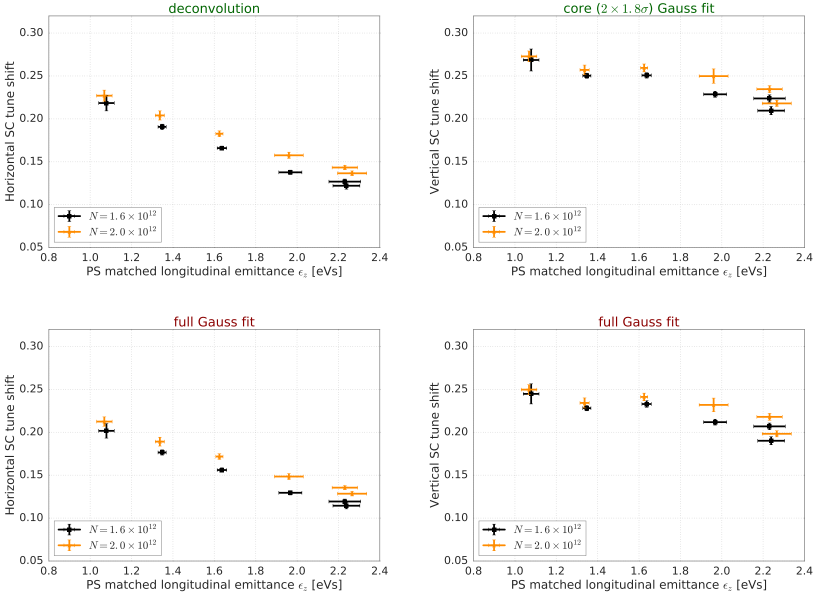




$\Longrightarrow$ exact figure depends on the actual ϵ_z


Qmeter2 - CPS.USER.MD3 - (INCA)
28 Nov 2017 10:09:04 CPS - 23 MD3 | MD211_SC_Measurements
35/50
Detailed Tune
Just Tune
Chromaticity
Tests
Tell Me !
Device PR.BQS72, at 10:09:00.
{Qh, Qv, B} = f(t)
Qv = f(Qh)
Table {Qh, Qv}
Legend
Q H
Q V
B
Tune
C time (ms)
179
BBQ Settings
More Setting
Files
GUI Settings
PickUp Selection
Long
Short
Measurement
Status
ON
OFF
retrieve RAW
Accuracy (turns)
2048
Bounds
From C: 170
To C: 1983
Interval ms : 7
Nb of Acq : 260
TFB (excitation)
Status
H
V
reset
Excitation
Mode
Chirp
Kick
Plane & Strength
H 0.1
V 0.1
Chirp Frequency range
Min Max
H 0.1 0.4
V 0.1 0.4
Determination
FFT window
Hamming
Cut-off frequencies
Min Max
H 0.1 0.23
V 0.23 0.4
Tune H
Tune V
C179
FFT H
FFT V
dB
0.187183
0.239049
Tune
RAW H
RAW V
FFT win
Turns
No Exception to display...
10:08:04 - Last PR.BQS72/SamplerAcquisition arrived with exceptions : :: Didn't receive a value for cycle stamp 151186...

Space Charge Tune Spreads (Comparing to PSB)



Space Charge Tune Spreads (Comparing to PSB)