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MD4224: Integer Resonance Investigation in the Proton Synchrotron

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14.05.19

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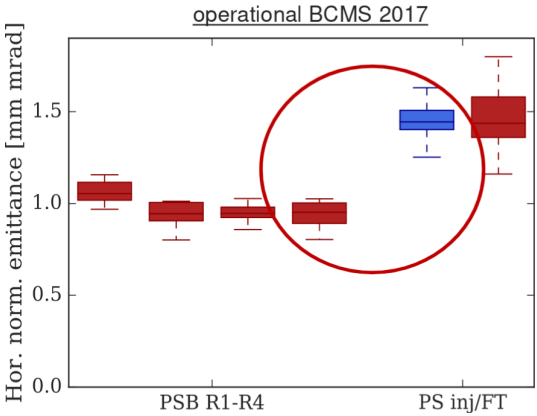
PSB -> PS Emittance Blow-up



Background

- **Observed Emittance Blow-up!** 30% - 40% in **horizontal** between PSB and PS.
- **Possible Contributors:** Dispersion mismatch in transfer line, systematic errors in emittance measurement in both machines, injection bump tune swing, ...
- **Does Space Charge Contribute?** Perform an MD to probe space charge effects on PS injection.
- **Compare MD with Simulations:** Perform simulations to understand MD results.
- **Iterative Process:** Compare MD and Simulation Data -> Improve Models -> Improve Understanding.

MD Summary

- **What We Did:** Perform a static tune scan investigating the beam behaviour close to the integer tune in each plane separately. Using the low energy quadrupoles (LEQs) to vary tune and pole face windings (PFWs) to maintain low chromaticity.
- **Beam:** Clone of operational BCMS: MD4224_LHC_BCMS25_2018_PSB_PN2 MD4224_48b_BCMS

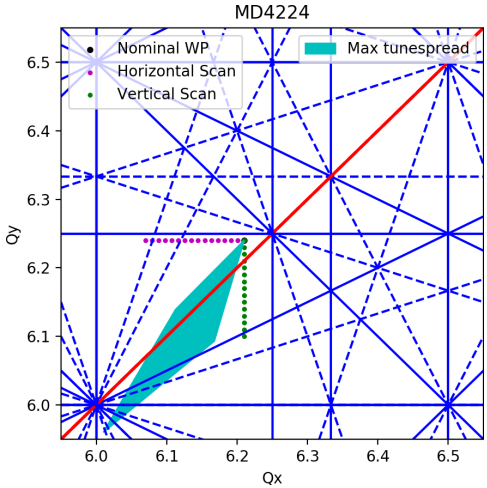
Horizontal Scan:

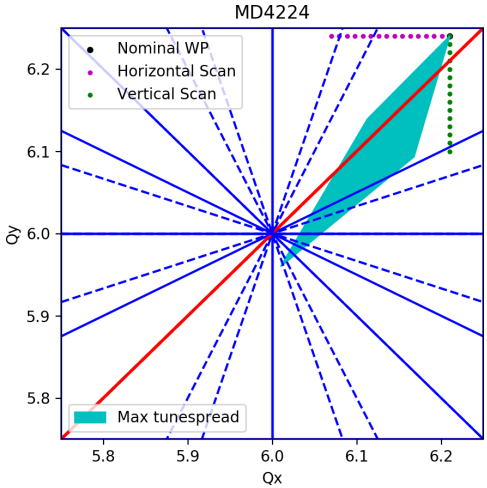
- Q_x = 6.07 - 6.21
- Q_y = 6.24

Vertical Scan:

- Q_x = 6.21
- Q_y = 6.10 - 6.24

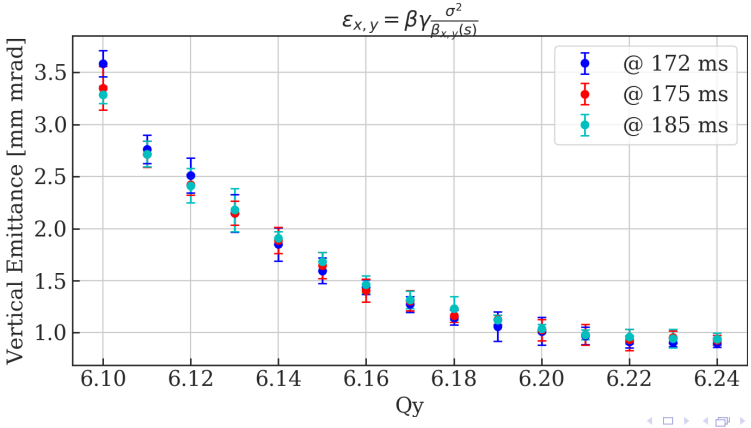
Static Tune Scan





MD Result

Gaussian fit of MD profiles using linear optics (no space charge) functions from MAD-X model for each tune. Measured 2, 5, and 15 ms after injection.



MD4224 Parameters

Parameter	MD	Simulation
Intensity N_p [10^{10}]	≈72.5	72.5
Normalised horizontal RMS emittance ϵ_x^n [mm mrad]	1.2	1.2
Normalised vertical RMS emittance ϵ_y^n [mm mrad]	1	1
Bunch length σ_t[ns]	140	140
Momentum spread $\frac{\Delta p}{p}$ [10^{-3}]	0.87	0.87
Horizontal maximum tune spread $\Delta Q_{x,\max}$	0.2	0.16
Vertical maximum tune spread $\Delta Q_{y,\max}$	0.28	0.24
Harmonic number h	9	9
RF voltage V_{rf} [kV]	21.2	21.2
Horizontal chromaticity Q'_x	0.77	0.80
Vertical chromaticity Q'_y	-2.85	-3.05
Kinetic energy of the stored beam [GeV]	1.4	1.4
Relativistic β	0.916	0.916
Relativistic γ	2.4921	2.4921
Synchrotron Frequency [Hz]	634	634

Table 1: Beam and machine parameters

Simulation Parameters

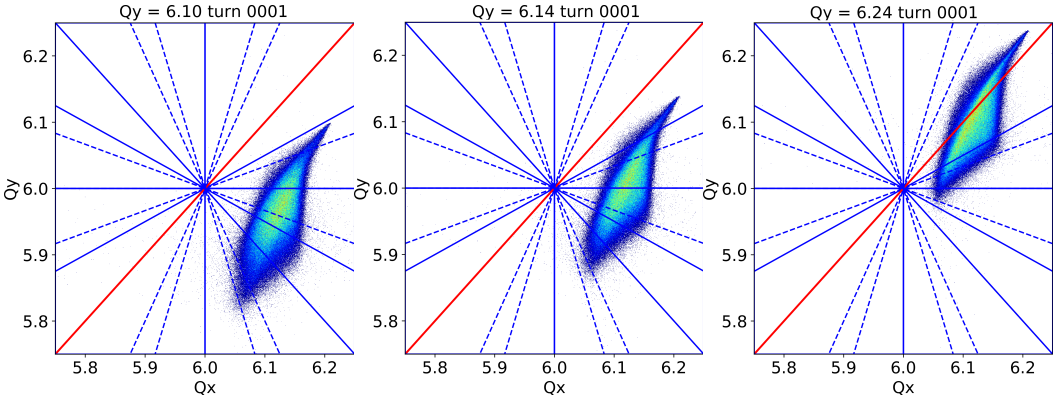
Parameter	Simulation
SC Method	Slice-by-Slice with Longitudinal Kick
SC Grid x	128
SC Grid y	128
SC Grid z	64
N_{mp}	$0.5 \cdot 10^6$
Turns	2200

Table 2: Simulation parameters

Simulation Setup

- Initial distribution used in simulation identical for working points.
- Initial distribution matched to linear optics (without space charge) from MAD-X and tomo for tune (6.21, 6.24).

Tune Footprints



PyORBIT Emittance Calculation

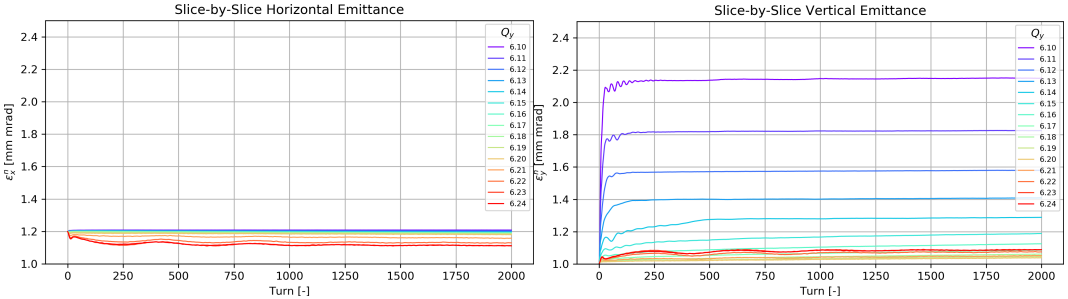
$$\epsilon = \sqrt{\left(< x^2 > - \frac{< x\ dE >^2}{< dE^2 >}\right)\left(< x'^2 > - \frac{< x'\ dE >^2}{< dE^2 >}\right) - \left(< x\ x' > - \frac{< x\ dE >< x'\ dE >}{< dE^2 >}\right)^2} \quad (1)$$

$$\epsilon^n = \epsilon \beta_L \gamma_L \quad (2)$$

Emittance

Fast emittance growth (<200 turns) dependent on tune

Montague Resonance results in emittance exchange near 6.21.



Beam Profiles

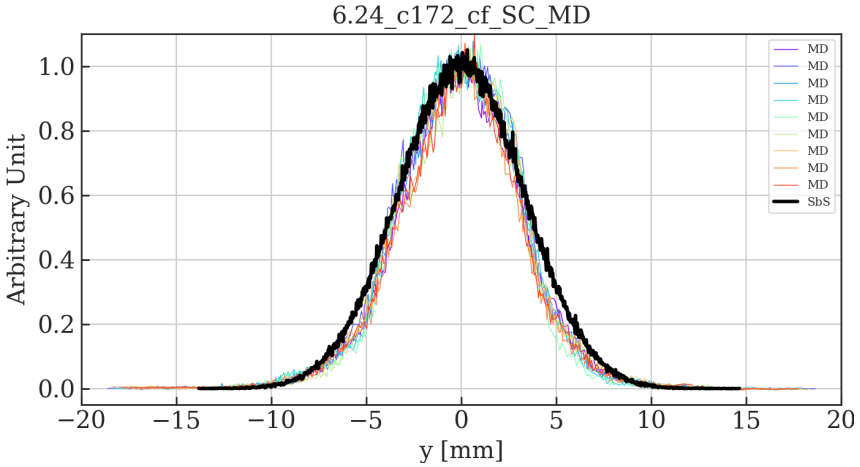
Measured and simulated beam profiles

PS turn $\approx$ 2.287 μs. Using maximum of each data set to normalise to 1.

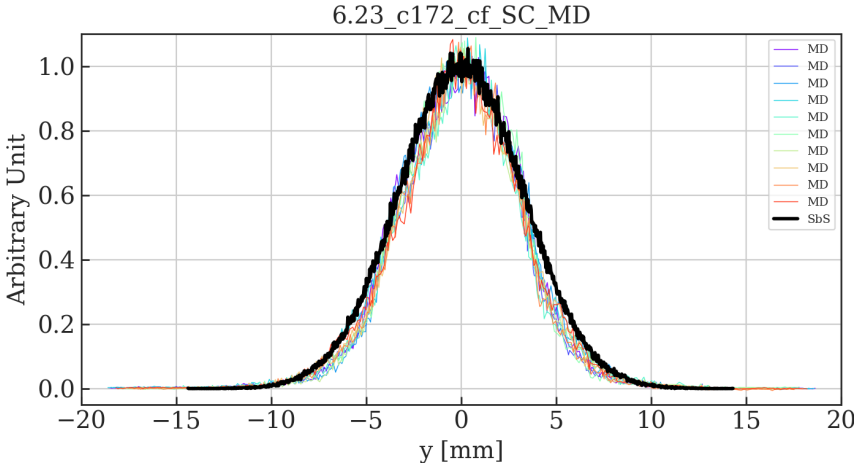
MD measurement times:

- **c172 = 172 ms = 2 ms after injection = turn 875**
- c175 = 175 ms = 5 ms after injection = turn 2186
- c185 = 185 ms = 15 ms after injection = turn 6559 turns

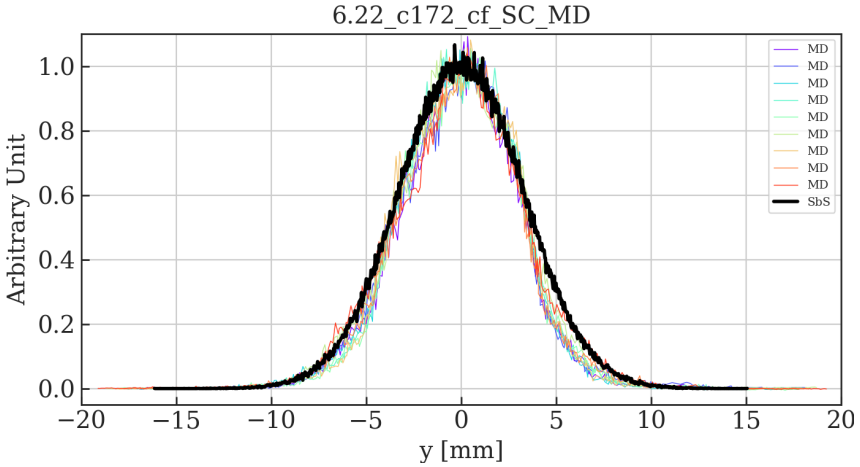
Q_y = 6.24, t = 172 ms



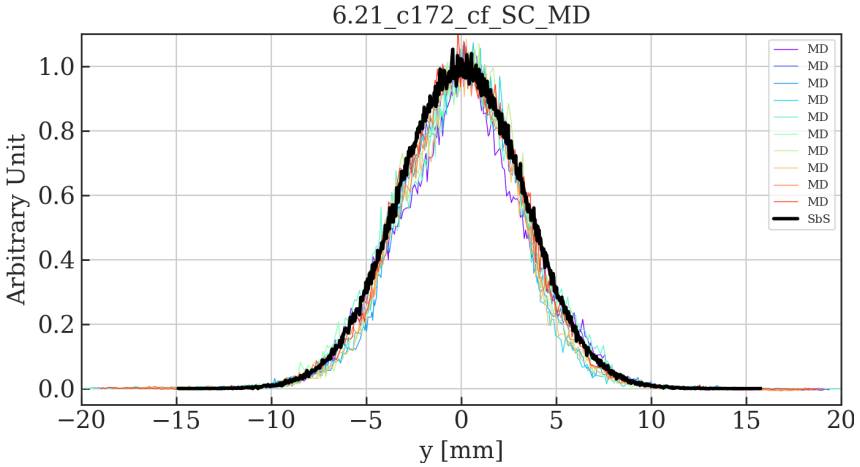
Q_y = 6.23, t = 172 ms



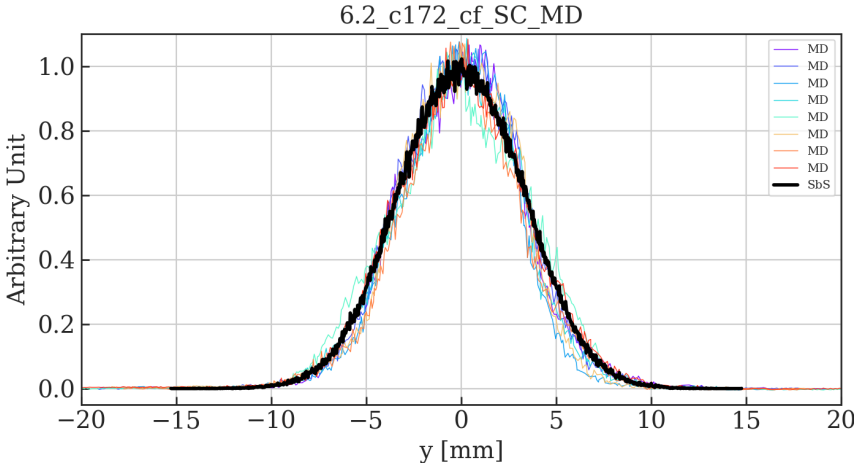
Q_y = 6.22, t = 172 ms



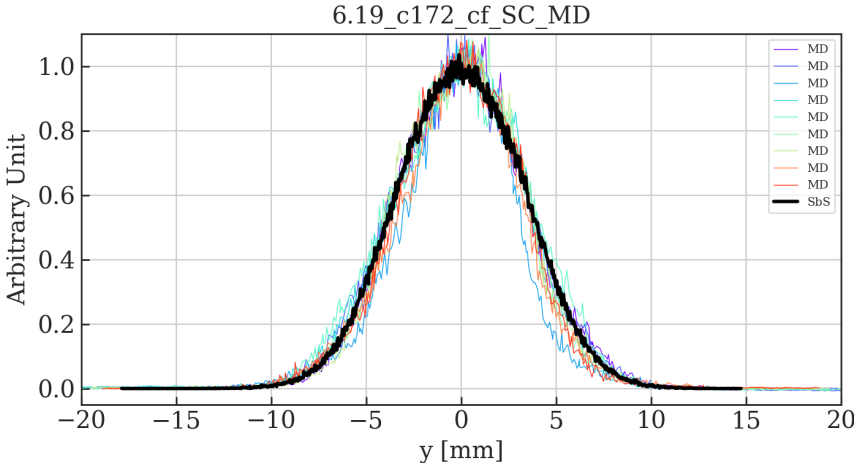
Q_y = 6.21, t = 172 ms



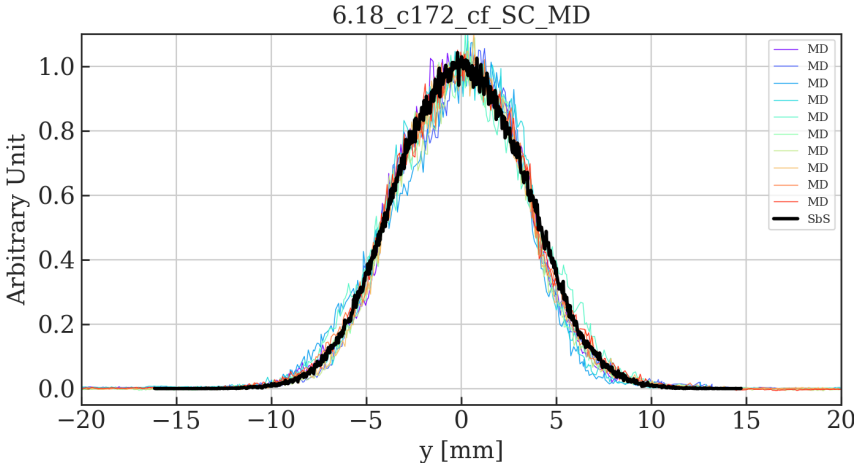
Q_y = 6.20, t = 172 ms



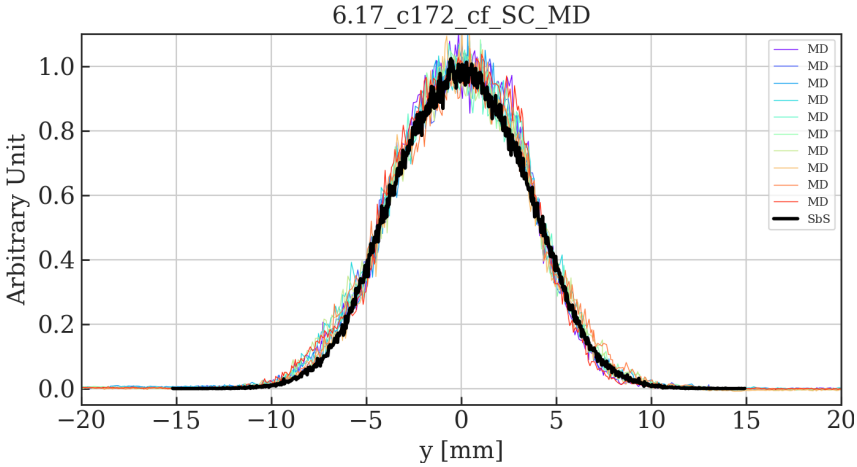
Q_y = 6.19, t = 172 ms



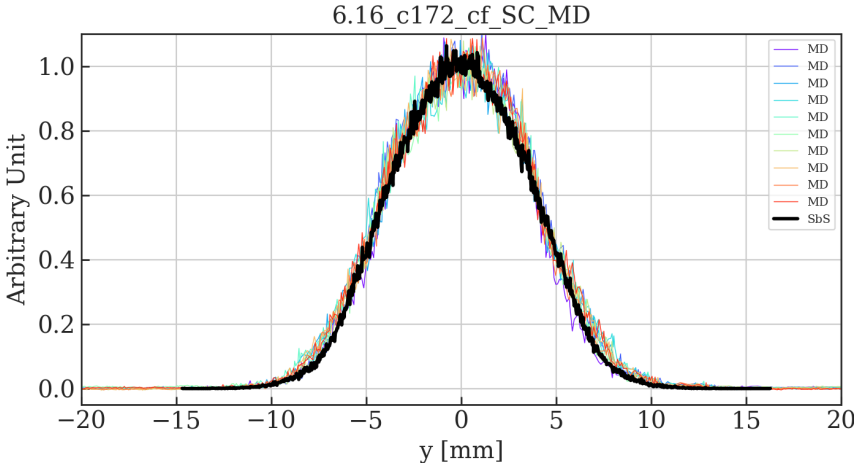
Q_y = 6.18, t = 172 ms



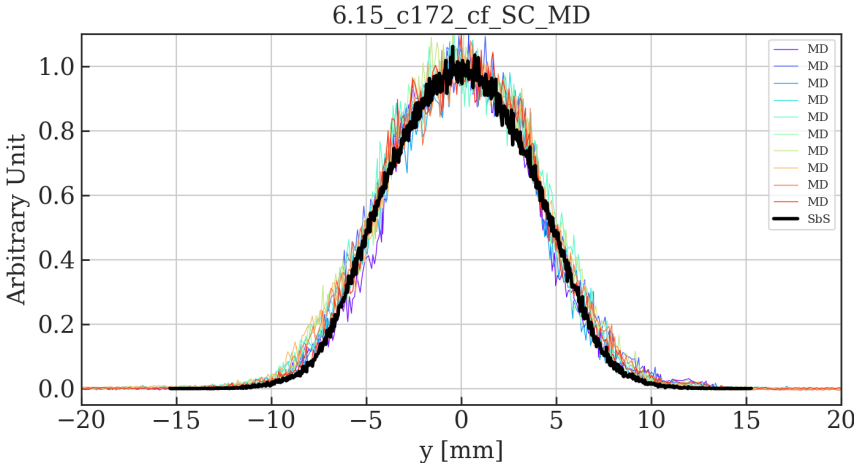
Q_y = 6.17, t = 172 ms



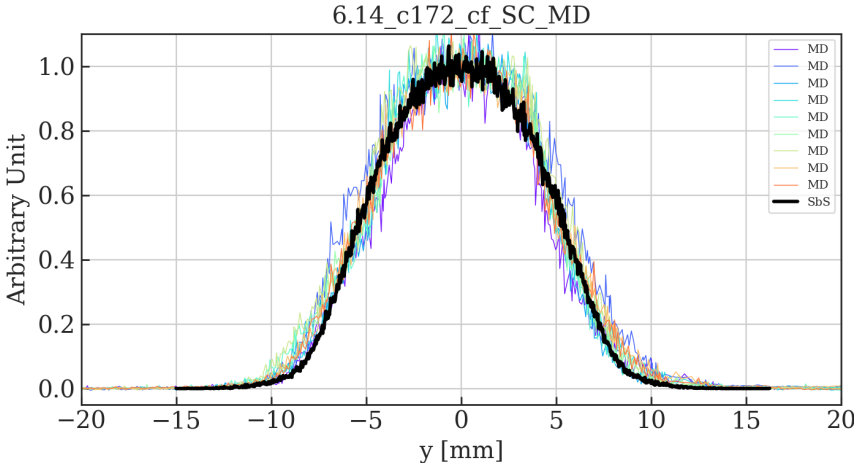
Q_y = 6.16, t = 172 ms



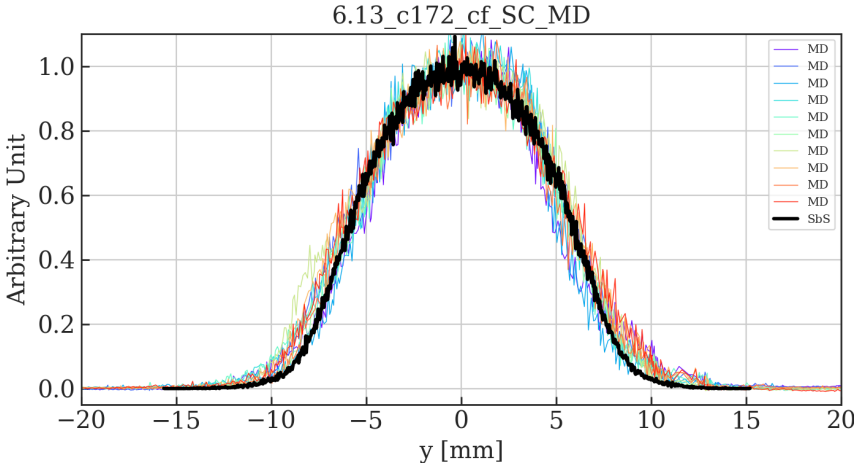
Q_y = 6.15, t = 172 ms



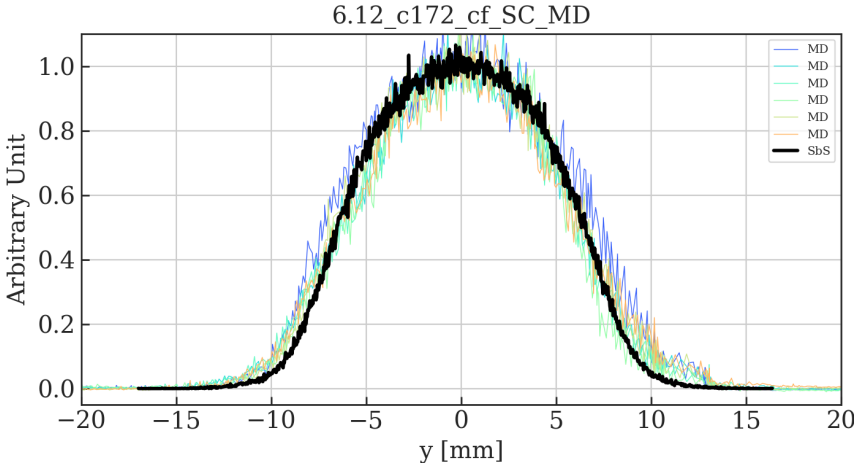
Q_y = 6.14, t = 172 ms



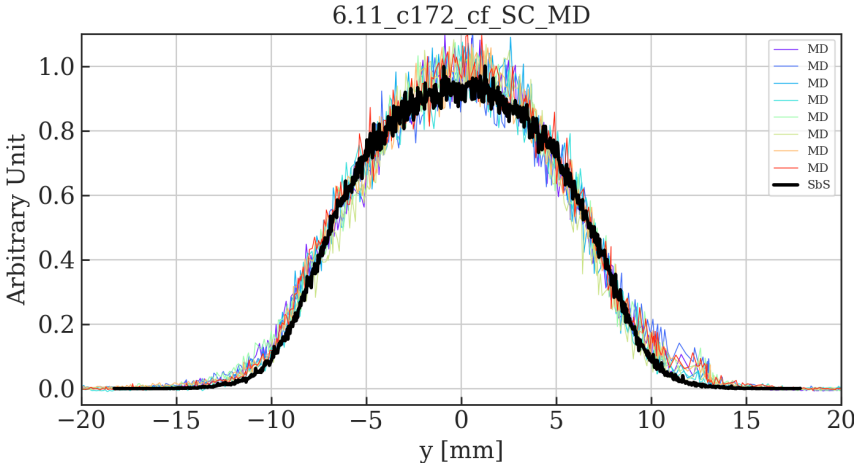
Q_y = 6.13, t = 172 ms



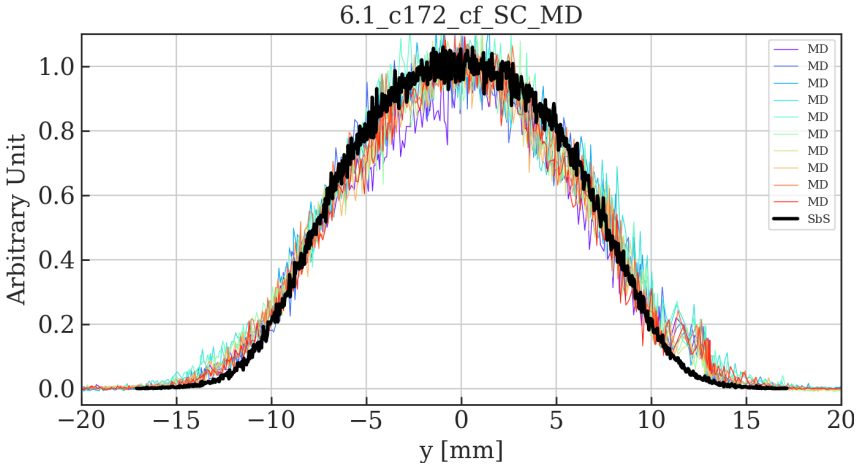
Q_y = 6.12, t = 172 ms



Q_y = 6.11, t = 172 ms



Q_y = 6.10, t = 172 ms

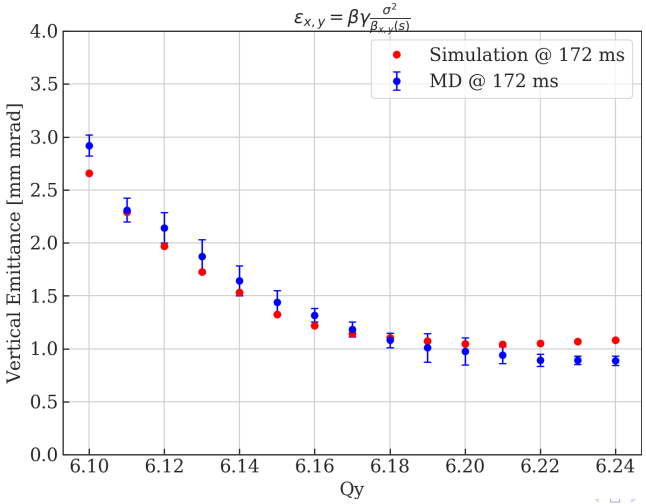


Common Profile Treatment for Wirescanner and Simulated Data

- 5 parameter Gaussian fit to find mean and σ.
- $\pm$ 6 σ cut to find slope. Remove slope.
- 3 parameter Gaussian fit to find centre.
- Use σ and optics (statistical $\beta_{x,y}$ from simulated bunch) for corresponding tune to calculate emittance. Note vertical dispersion is negligible.

$$\epsilon_{x,y} = \beta\gamma\frac{\sigma^2}{\beta_{x,y}(s)} \tag{3}$$

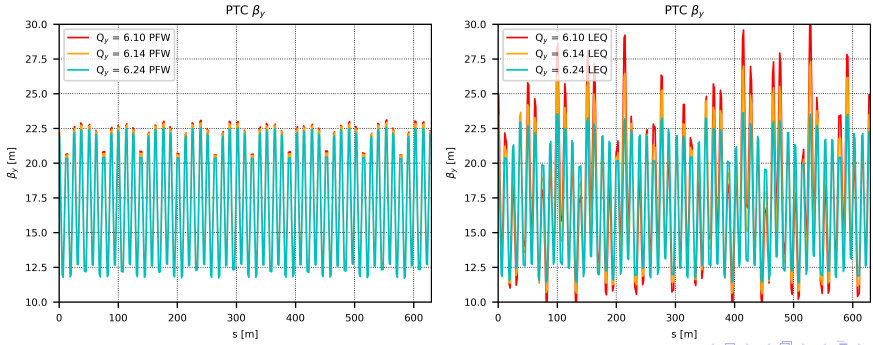
Emittance Using Simulation Optics and beam size σ



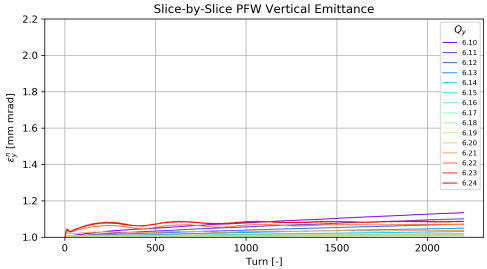
Optics Comparison

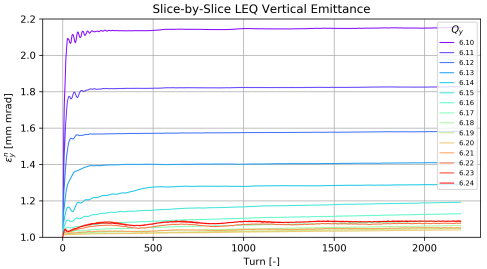
In MD4224 the LEQs were used for setting the tune, this results in irregular optics.

What happens when using the PFWs instead?

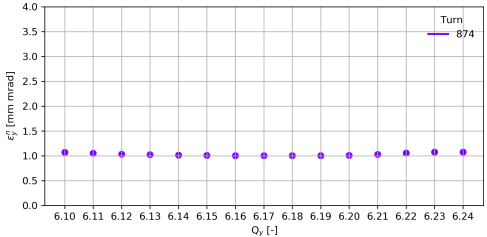


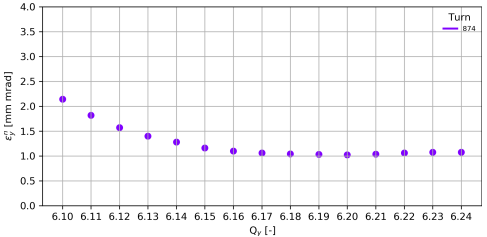
Emittance


Slice-by-Slice PFW Vertical Emittance
ϵ_y^n [mm mrad]
Turn [-]
Q_y
6.10
6.11
6.12
6.13
6.14
6.15
6.16
6.17
6.18
6.19
6.20
6.21
6.22
6.23
6.24


Slice-by-Slice LEQ Vertical Emittance
ϵ_y^n [mm mrad]
Turn [-]
Q_y
6.10
6.11
6.12
6.13
6.14
6.15
6.16
6.17
6.18
6.19
6.20
6.21
6.22
6.23
6.24

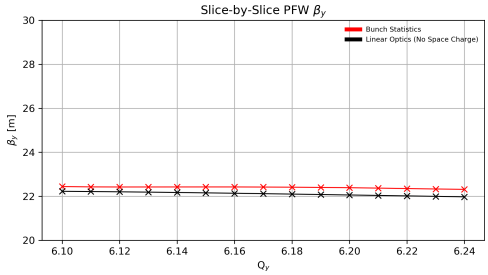
Emittances PFW & LEQ

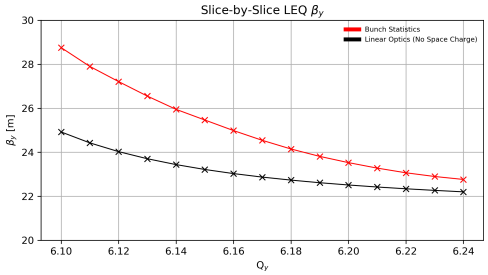




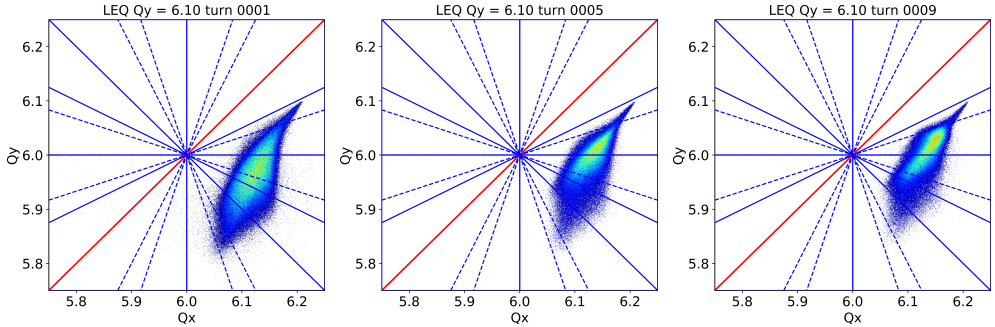
Optics Comparison

Compare Linear Optics and Statistical Bunch Optics @ WS 64 V

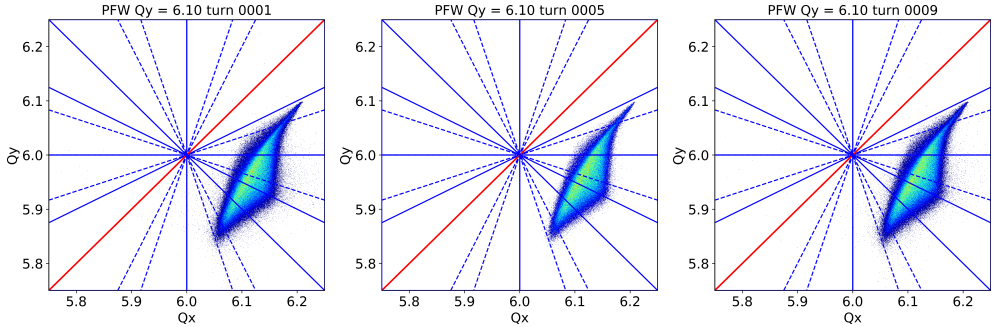




Footprint Evolution: LEQs



Footprint Evolution: PFWs



Next Steps

- Simulate collapse of the injection bump - induces a tune swing and a β function distortion.
- Add single quadrupole error to gauge strength that results in the same blowup as when using the LEQs to set the tune.
- Possibly investigate what drives emittance growth in the case using PFWs.
- **Horizontal Scan.**

Conclusion

Vertical Tune Scan

- Vertical beam size observed to increase closer to integer tune.
- Measured beam profiles and simulated beam profiles agree well.
- Emittances from MD and simulation profiles, when applying the same treatment agree well.
- Vertical emittance growth is fast (< 200 turns). Horizontal emittance growth is negligible.
- Montague resonance causes emittance exchange near tune (6.21, 6.21).
- Comparison of setting tune using PFWs and LEQs shows optics distortion for LEQs resulting in fast emittance blow-up.

Acknowledgements

- F. Asvesta, M. Kaitatzi: MD assistance, discussions, etc.
- PSB & PS Operators: MD setup and assistance.
- S. Albright, A. Santamaria Garcia, E. K. Platia: Assistance with tomoscope -> PyORBIT tomo distribution.
- A. Oeftiger: Tunespread tool, low brightness MDs, general assistance.
- G. Sterbini: MD analysis SWAN/python Toolbox.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