
CERN

MD4224 High Brightness: Simulations

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MD4224 Parameters

Parameter	MD	Simulation
Intensity N_p [10^{10}]	$\approx$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 $\Delta Q_{x,\mathrm{max}}$	0.2	0.16
Vertical maximum tune spread $\Delta Q_{y,\mathrm{max}}$	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

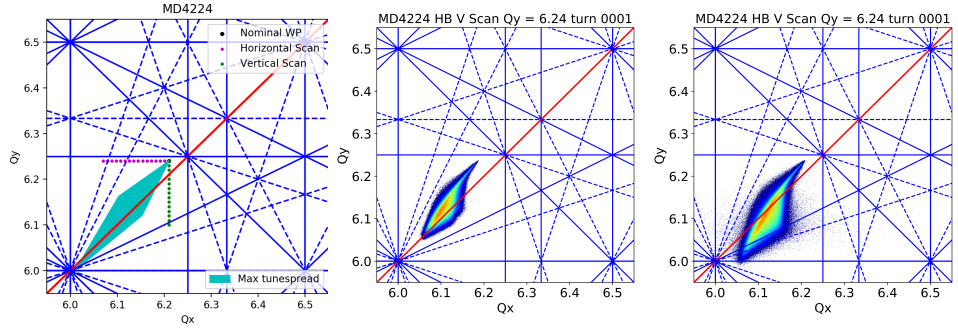
Parameter	Simulation
SC Grid x	64
SC Grid y	64
SC Grid z	32
N_{mp}	$1.5 \cdot 10^6$
Turns	2200

Table 2: Simulation parameters

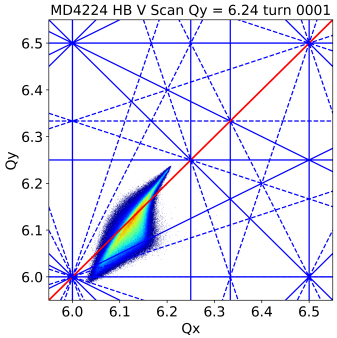
Note that Slice-by-Slice $Q_y = 6.22$ simulation did not run due to an unknown SLURM error. Re-running now (along with all other sims with larger SC grid 128x128x64).

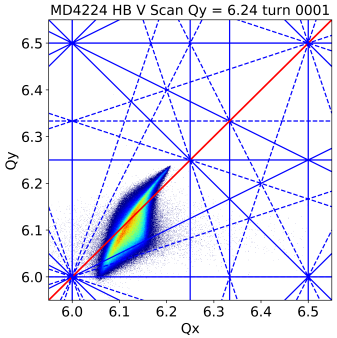
Tune Footprints: Predicted, Old, New

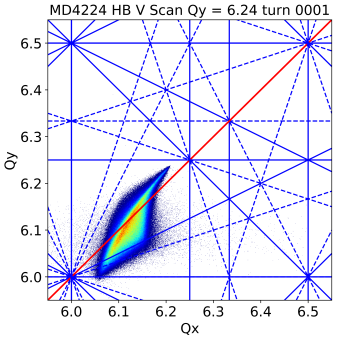
- Predicted (0.2, 0.24).
- Old WS 65H injection, 32^3 SC grid, natural chroma.
- New WS 64V injection, 64 x 64 x 32 SC grid, low chroma. $\approx (0.16, 0.24)$



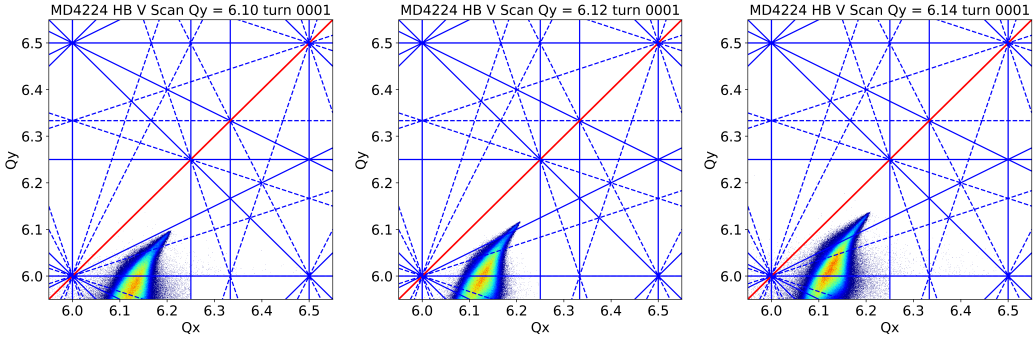
Tune Footprints: 2.5D, Slice-by-slice, Slice-by-slice with longitudinal kick



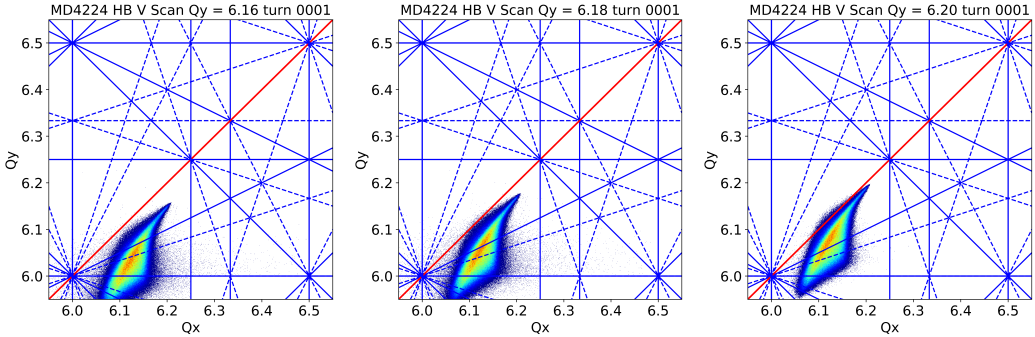




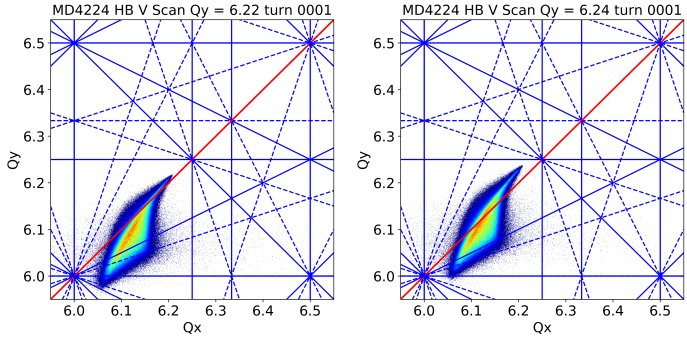
Tune Footprints: 6.10, 6.12, 6.14



Tune Footprints: 6.16, 6.18, 6.20



Tune Footprints: 6.22, 6.24



Apertures

PS_2013.aper - /home/HR/Documents/PyORBIT_Utils/MD4224/High_Brightness/Simulation/Lattice_LowChroma - Geany

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Flat_file.madx | copy_bunch_outputs.sh | plot_tunefootprint.py | Plot_All_Outpu...ltifile_Conv.py | PS_2013.aper

```
1  !-----------------------------------------------------------------------!
2  !                              Main magnets                             !
3  !-----------------------------------------------------------------------!
4  ! We define the apertures for the blocks, not for the thin virtual elements
5  APERTHAXIS = 0.073;
6  APERTVAXIS = 0.035;
7
8  !-----------------------------------------------------------------------!
9  !                              MU1                                      !
10 !-----------------------------------------------------------------------!
11 APERTHAXIS001 := APERTHAXIS;
12 APERTVAXIS001 := APERTVAXIS;
13 PR.BHT000001.FINFF1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};
14 PR.BHT000001.FINFF2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};
15 PR.BHT000001.DINDD1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};
16 PR.BHT000001.DINDD2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS001,APERTVAXIS001};
17
18 !-----------------------------------------------------------------------!
19 !                              MU2                                      !
20 !-----------------------------------------------------------------------!
21 APERTHAXIS002 := APERTHAXIS;
22 APERTVAXIS002 := APERTVAXIS;
23 PR.BHU000002.FINFF1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
24 PR.BHU000002.FINFF2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
25 PR.BHU000002.DINDD1, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
26 PR.BHU000002.DINDD2, APERTYPE=ELLIPSE, APERTURE={APERTHAXIS002,APERTVAXIS002};
```

Optics

The following section shows plots using:

- Slice-by-Slice with longitudinal kick space charge model.
- 1.5 million macro particles.
- Vertical tune scan Q_y =(6.10, 6.12, 6.14, 6.16, 6.18, 6.20, 6.22, 6.24).
- 'Effective' values = calculated in PyORBIT from the bunch distribution correlations.
- 'Real' values = calculated in PyORBIT from the bunch statistics.

PyORBIT Dispersion Calculation

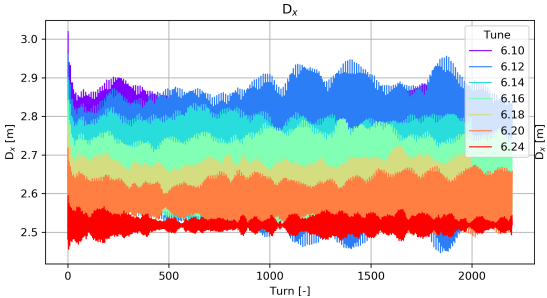
$$\texttt{BunchTwissAnalysis::getDispersion} = D = \frac{< x\ dE >}{< dE^2 >}\ P\ \beta_L \qquad (1)$$

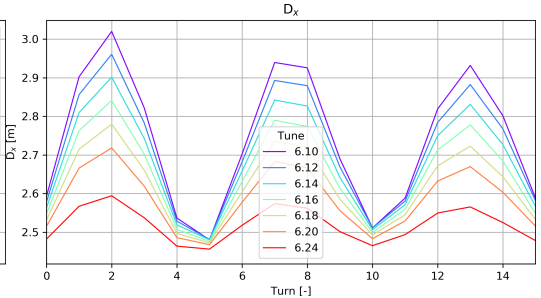
where P = bunch momentum, β_L = Lorentz Beta (of beam).

Horizontal Dispersion

2200 turns, 15 turns

Lower vertical tune -> higher horizontal dispersion. Beating of dispersion at $\approx Q$.

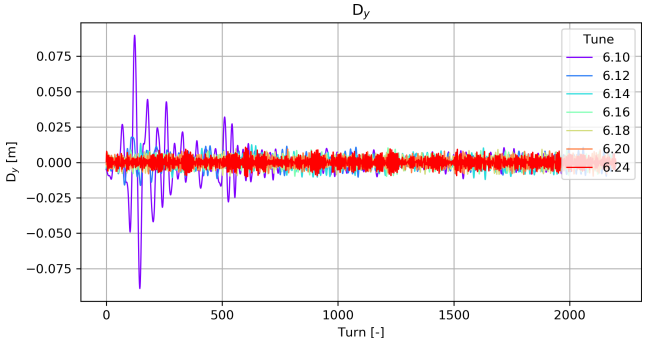




Vertical Dispersion

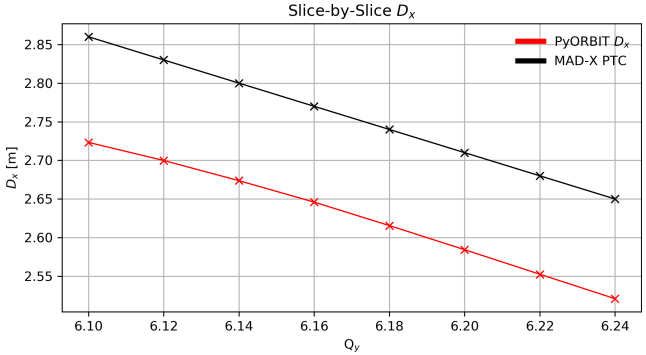
2200 turns

Small displacement at lowest vertical tunes.



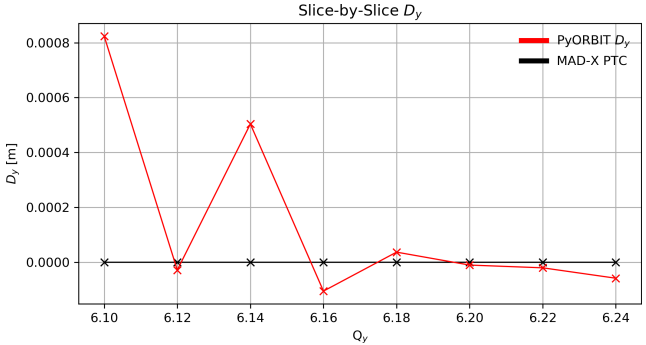
Horizontal Dispersion Comparison

PyORBIT D_x = average of D_x after 200 turns.



Vertical Dispersion Comparison

PyORBIT D_x = average of D_x after 200 turns.



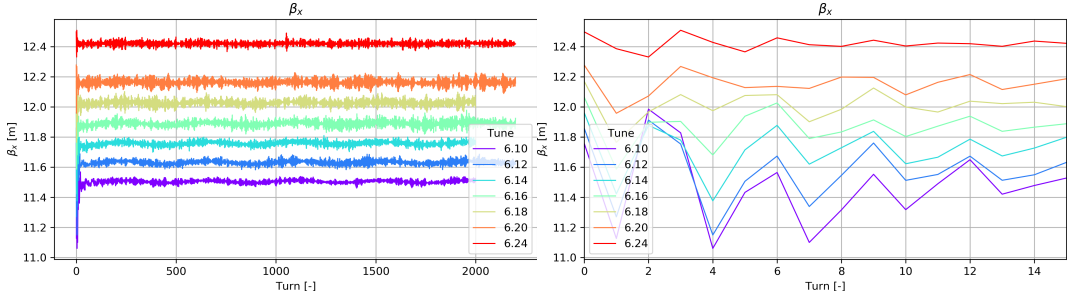
PyORBIT Beta Function Calculation

$$\texttt{getBeta()} = \beta = \frac{\left(< x^2 > - \frac{< x\ dE >^2}{< dE^2 >} \right)}{\epsilon} \tag{2}$$

$$\texttt{getEffectiveBeta()} = \beta^{eff} = \frac{< x^2 >}{\epsilon^{eff}} \tag{3}$$

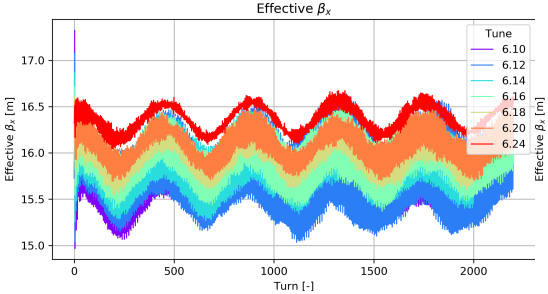
Horizontal Beta

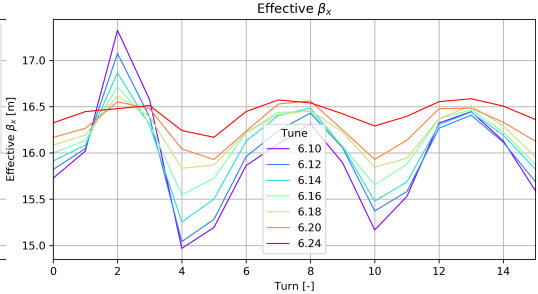
2200 turns, 15 turns



Horizontal Effective Beta

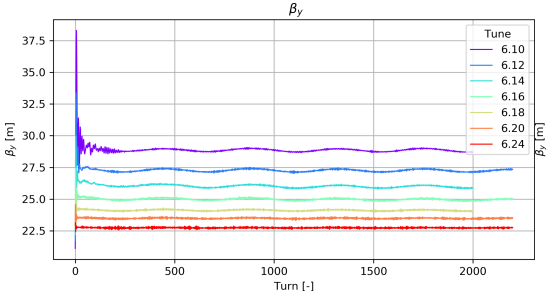
2200 turns, 15 turns

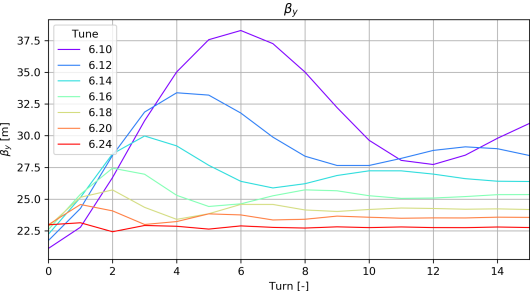




Vertical Beta

2200 turns, 15 turns

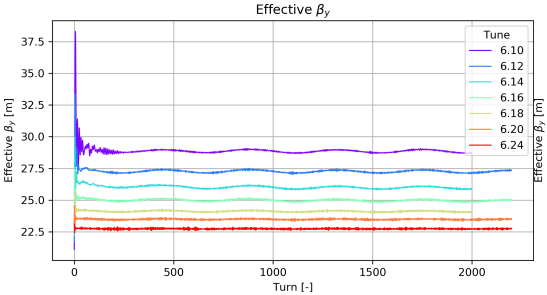


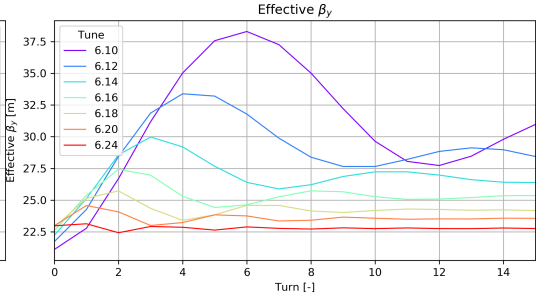


Vertical Effective Beta

2200 turns, 15 turns

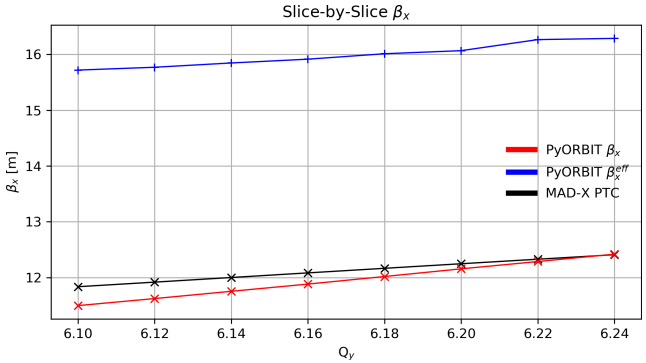
Identical to ‘real’ β_y - no vertical dispersive component.





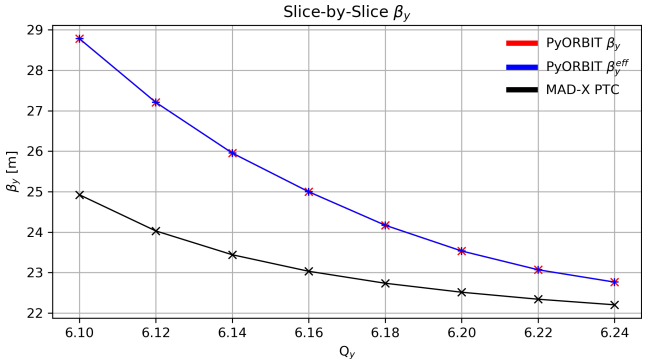
Horizontal Beta Comparison

PyORBIT β_x = average of β_x after 200 turns.



Vertical Beta Comparison

PyORBIT β_y = average of β_y after 200 turns.



Optics Summary

- No difference in real/effective vertical beta function as vertical dispersion is negligible.
- Horizontal dispersion increases in magnitude and range as Q_y is closer to the integer.
- Horizontal dispersion beating and beta beating observed.
- Clear difference between MAD-X PTC and PyORBIT optics functions. Dispersion is lower, and beta functions higher (than PTC calculated values), according to bunch statistics.

PyORBIT Emittance Calculation

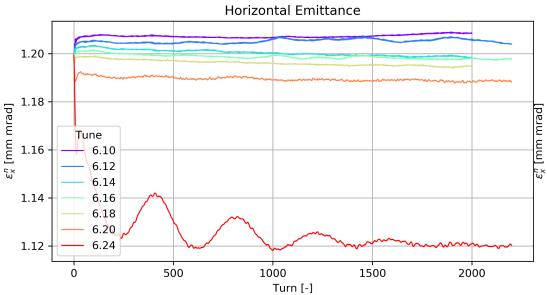
$$\epsilon = \sqrt{\left(< x^2 > - \frac{< x\ dE >^2}{< dE^2 >}\right)\left(< x'^2 > - \frac{< x'\ dE >^2}{< dE^2 >}\right) - \left(< x\ x' > - \frac{< x\ dE >< x'\ dE >}{< dE^2 >}\right)^2} \tag{4}$$

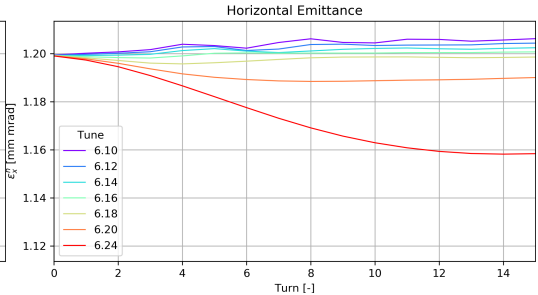
$$\epsilon^n = \epsilon \beta_L \gamma_L \tag{5}$$

$$\epsilon^{eff} = \sqrt{< x^2 >< x'^2 > - < x\ x' >^2} \tag{6}$$

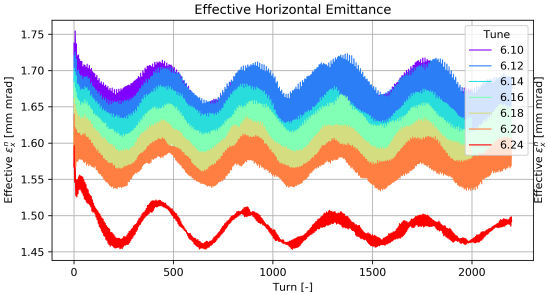
$$\epsilon^{eff\ n} = \epsilon^{eff} \beta_L \gamma_L \tag{7}$$

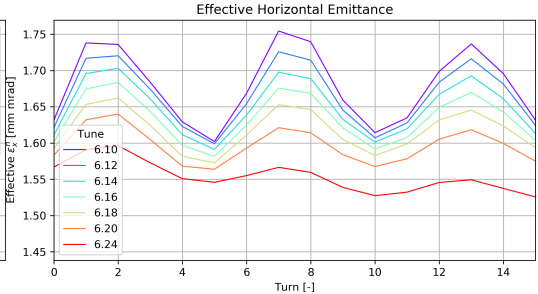
Horizontal Emittance: Slice-by-Slice



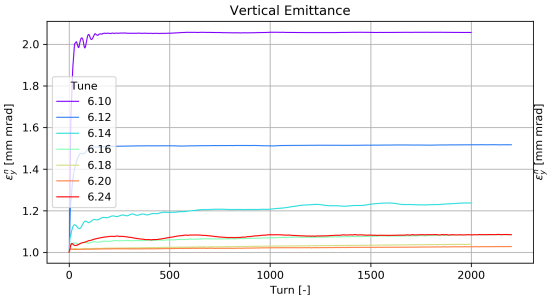


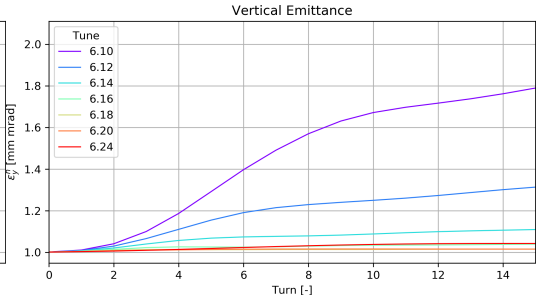
Effective Horizontal Emittance: Slice-by-Slice



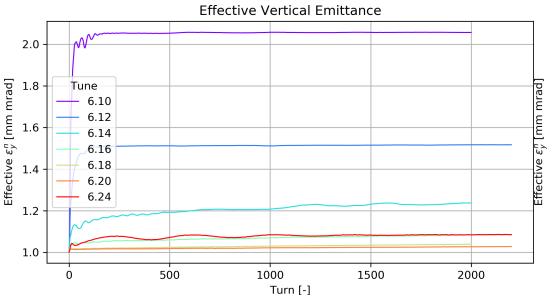


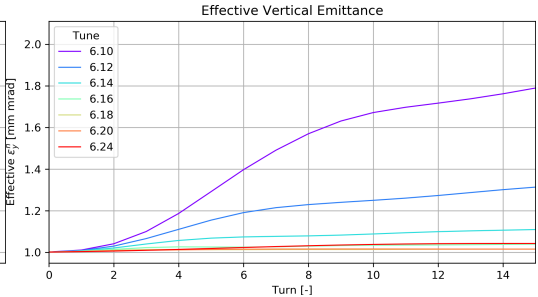
Vertical Emittance: Slice-by-Slice



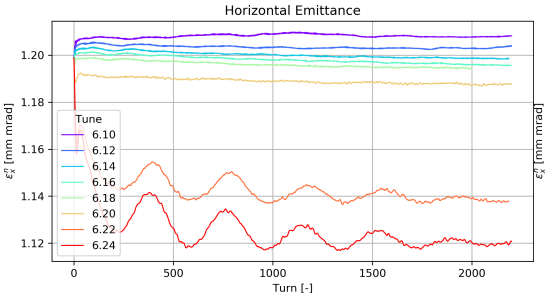


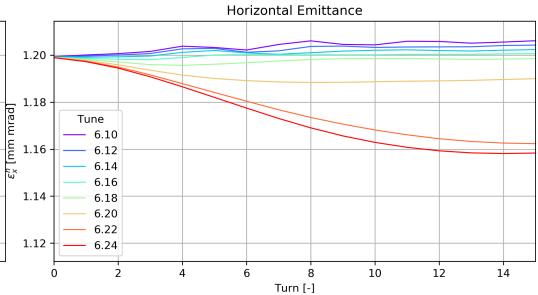
Effective Vertical Emittance: Slice-by-Slice



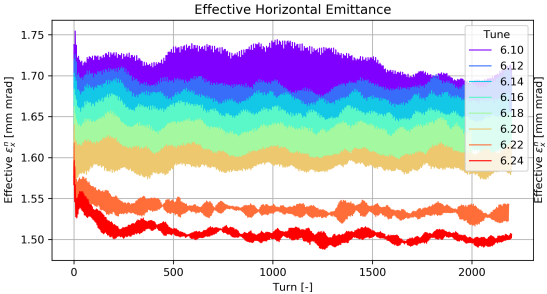


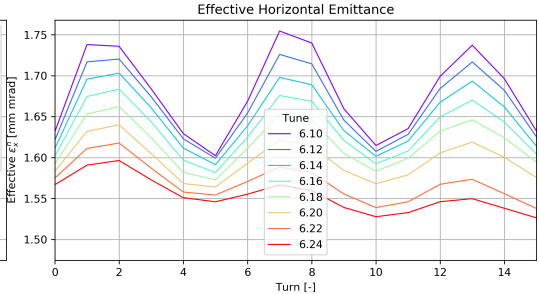
Horizontal Emittance: SbS no Longitudinal Kick



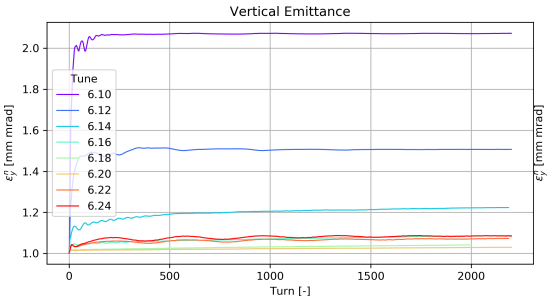


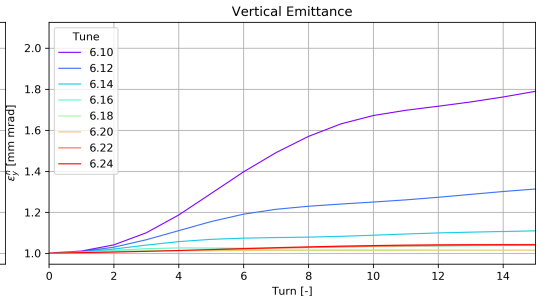
Effective Horizontal Emittance: SbS no Longitudinal Kick



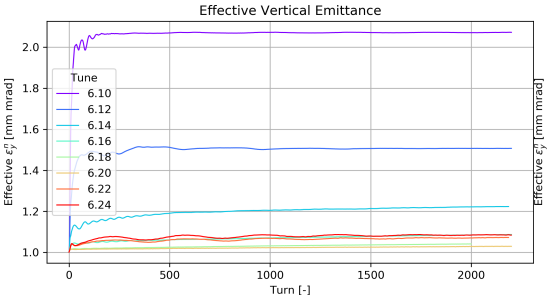


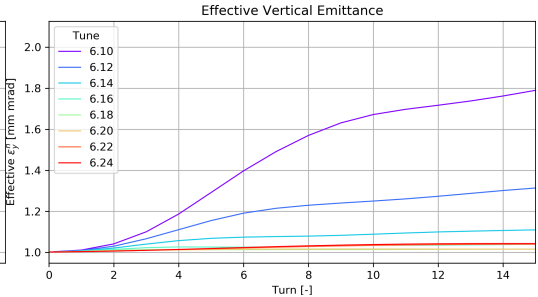
Vertical Emittance: SbS no Longitudinal Kick



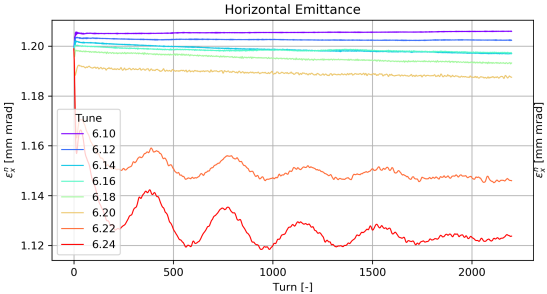


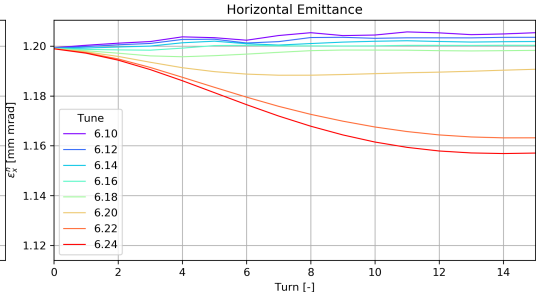
Effective Vertical Emittance: SbS no Longitudinal Kick



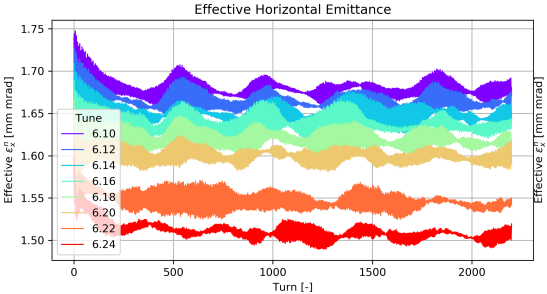


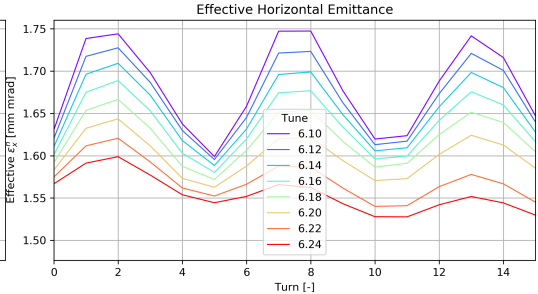
Horizontal Emittance: 2.5D



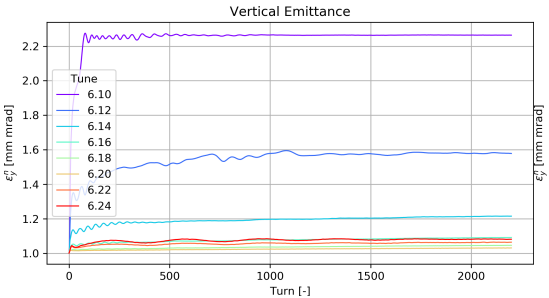


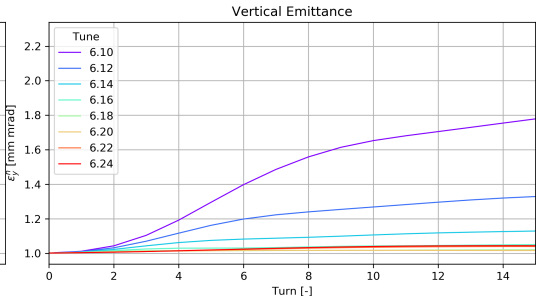
Effective Horizontal Emittance: 2.5D



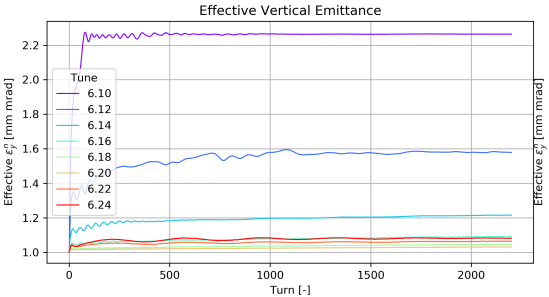


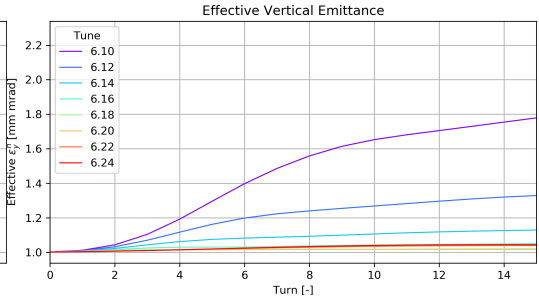
Vertical Emittance: 2.5D





Effective Vertical Emittance: 2.5D





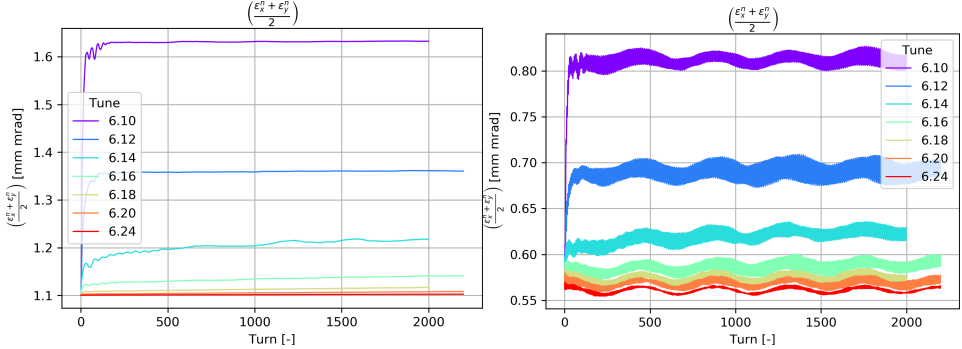
Real and Effective Emittance Summary

- Horizontal emittance growth is small.
- Vertical emittance growth is larger for smaller Q_y.
- Horizontal effective emittance beats more with Slice-bySlice models. Already observed in σ_x^{eff} and β_x^{eff}.
- Real/effective vertical emittances similar due to negligible vertical dispersion.
- Emittance growth largest in first few hundred turns.

Average Emittances: Slice-by-Slice

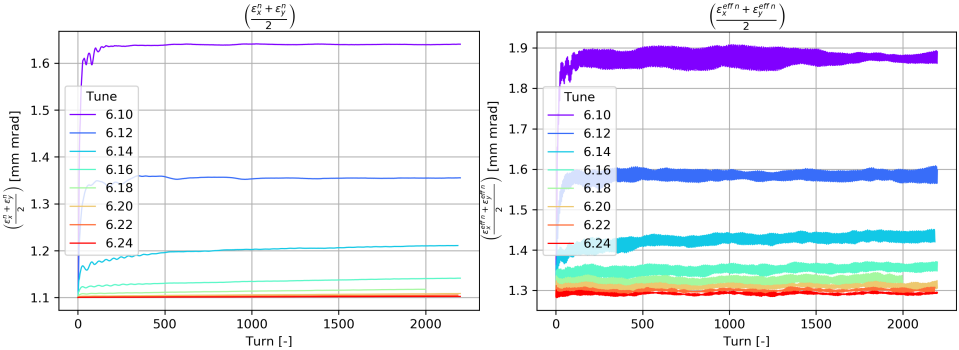
Mean of normalised emittance, mean of effective emittance.

Note effective plot is incorrect (no $\beta_L \gamma_L$ normalisation and incorrect label).



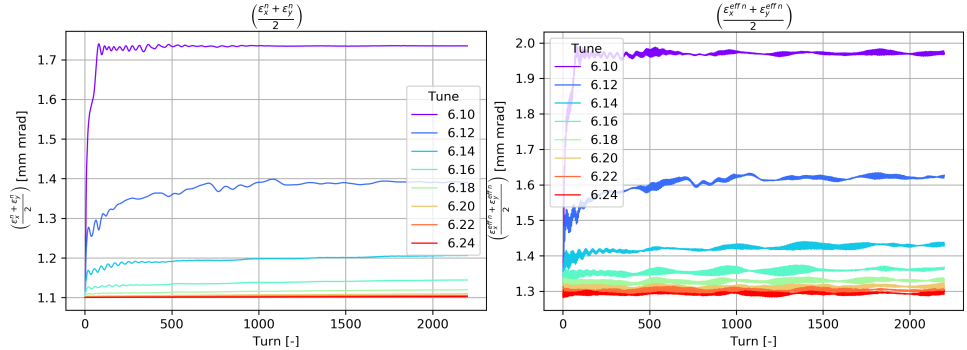
Average Emittances: Slice-by-Slice no Long Kick

Mean of normalised emittance, mean of normalised effective emittance.

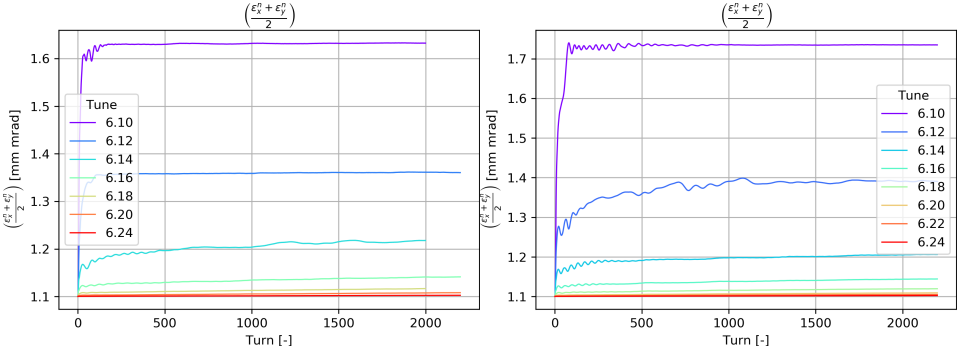


Average Emittances: 2.5D

Mean of normalised emittance, mean of normalised effective emittance.



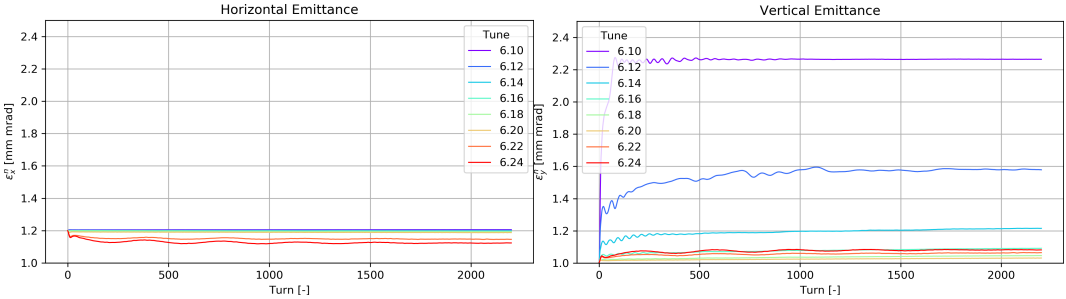
Average Emittances: SbS & 2.5D



Emittance Exchange: Same Scale 2.5D

Observing Q_y = 6.22 and 6.24

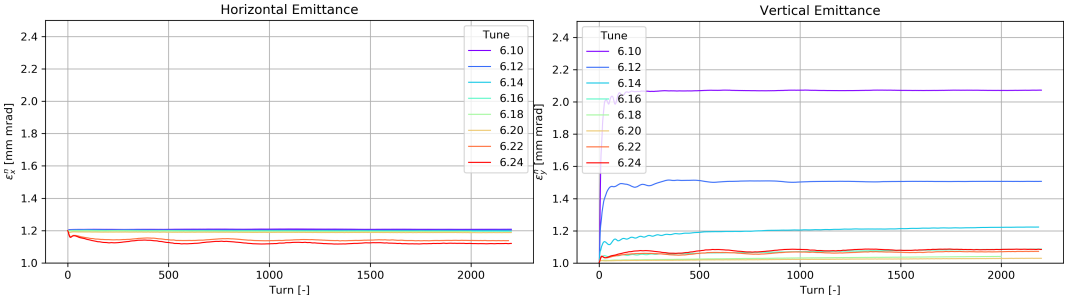
Obvious emittance exchange



Emittance Exchange: Same Scale nLK

Observing Q_y = 6.22 and 6.24

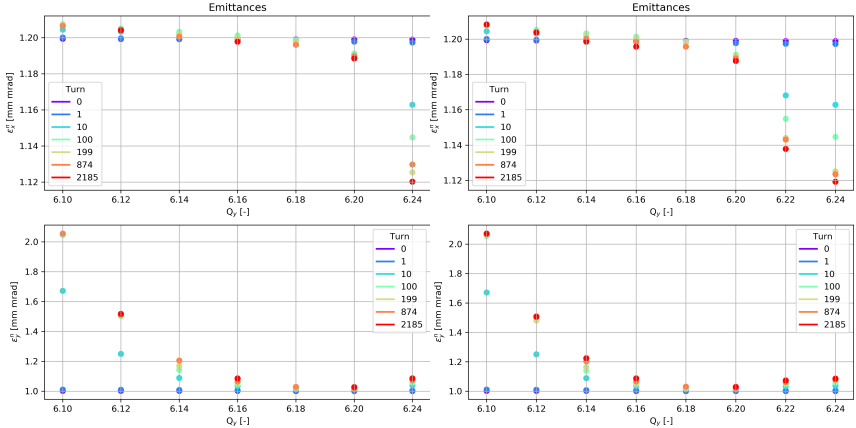
Obvious emittance exchange



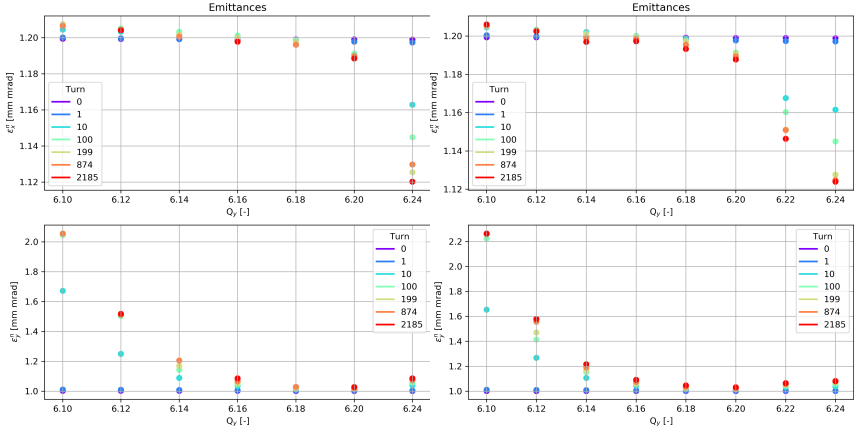
Average Emittance & Emittance Exchange Summary

- Both Slice-by-Slice (SbS) and Slice-by-Slice with no Longitudinal Kick (nLK) show similar average emittance behaviour.
- 2.5D space charge model gives a slightly higher overall emittance increase.
- At $Q_y = 6.22$ and 6.24 there is an obvious emittance exchange, due to the Montague resonance at $(Q_x, Q_y) = (6.21, 6.21)$.

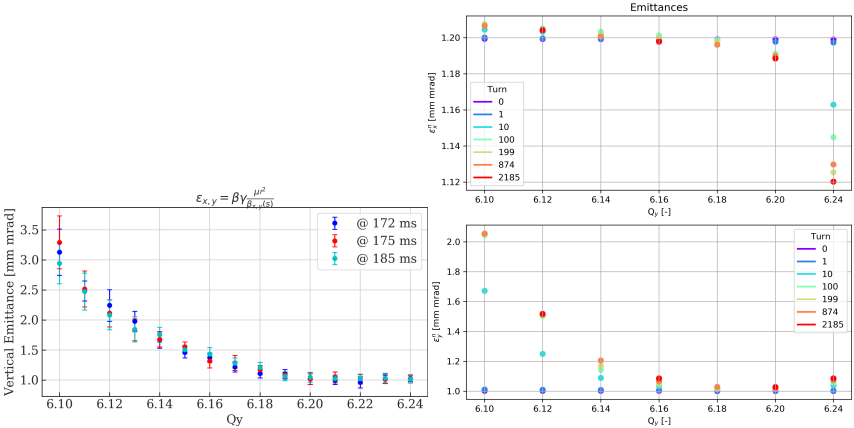
Final Emittances: SbS & nLK



Final Emittances: SbS & 2.5D



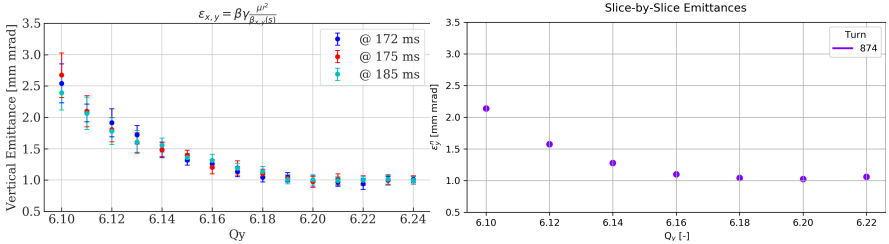
Final Emittances: MD data & SbS



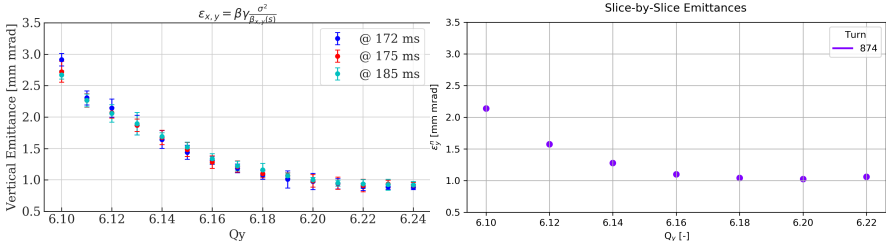
Final Emittance Summary

- We observe that the simulation emittances at turns 874 and 2185 are similar. These turns correspond to wirescanner (WS) measurement times of 172 ms and 175 ms respectively. Thus the lack of difference in measured emittance (for the same Q_y at different measurement times) is explained. The emittance growth is fast - less than 1000 turns (2.3 ms).
- Unfortunately we have no horizontal emittance measurement so cannot compare to the simulation.
- The vertical emittance growth shows similar behaviour in simulations and measurements with respect to Q_y, however in simulations we observe a minimum at $Q_y = 6.20$, in measurements it is difficult to observe the exact minimum between 6.20 - 6.24.
- The maximum vertical emittance growth is also larger in measurements by a factor ≈ 1.5.

Emittance Using Sim Optics and 2nd Moment μ'



Emittance Using Sim Optics and beam size σ



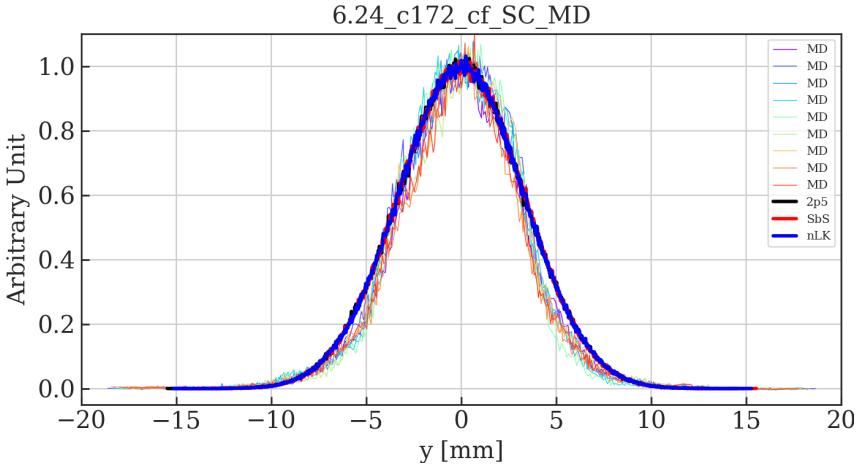
Beam Profiles

Measured and simulated beam profiles.

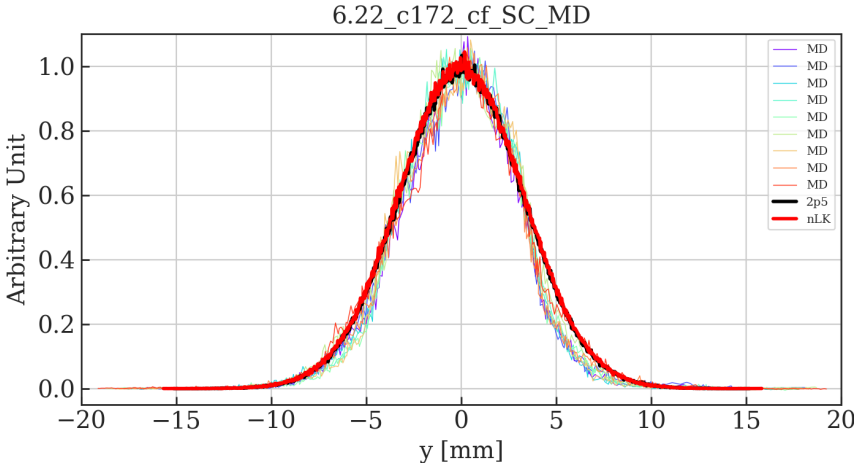
PS turn $\approx$ 2.287 μs. Using maximum of each data set to normalise to 1.

- c172 = 172 ms = 875 turns
- c175 = 175 ms = 2186 turns
- c185 = 185 ms = 6559 turns (not plotted)
- note the python start index is 0, thus plotted turns are 874 and 2185.

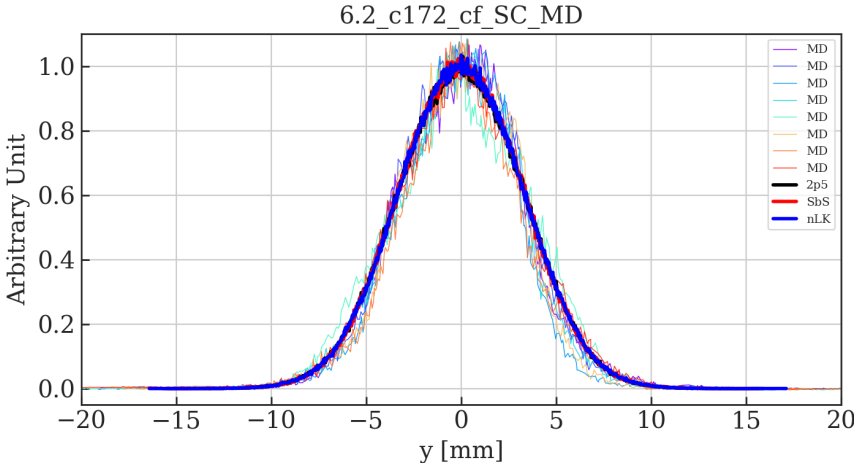
Q_y = 6.24, t = 172 ms



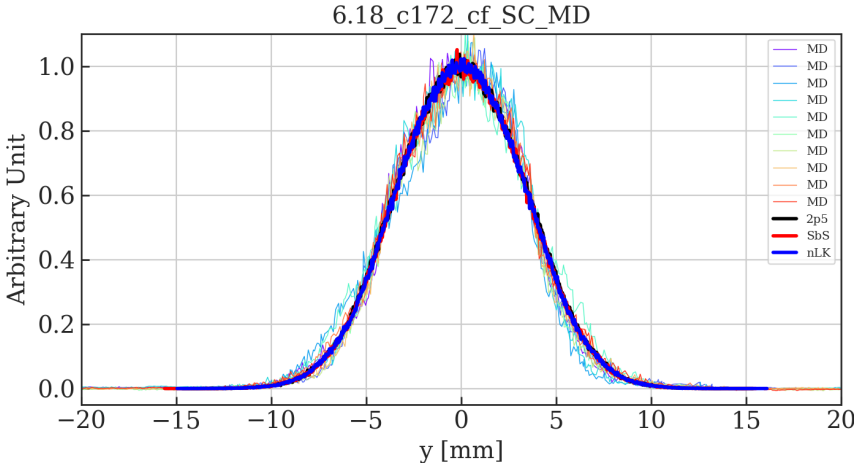
Q_y = 6.22, t = 172 ms



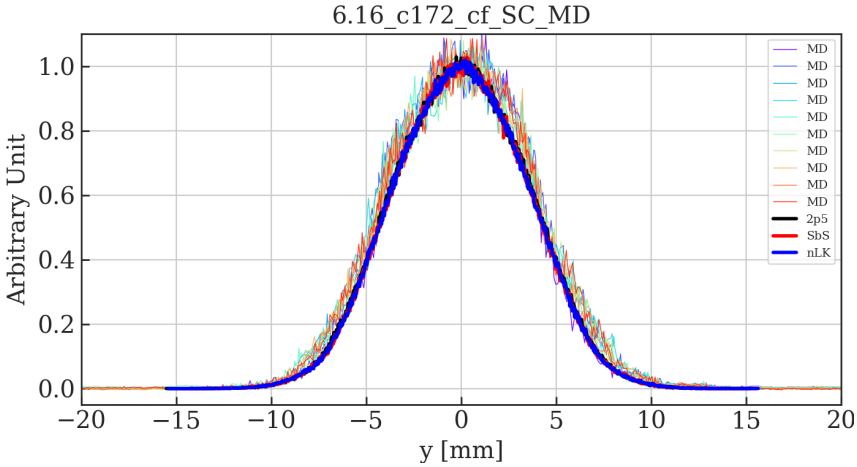
Q_y = 6.20, t = 172 ms



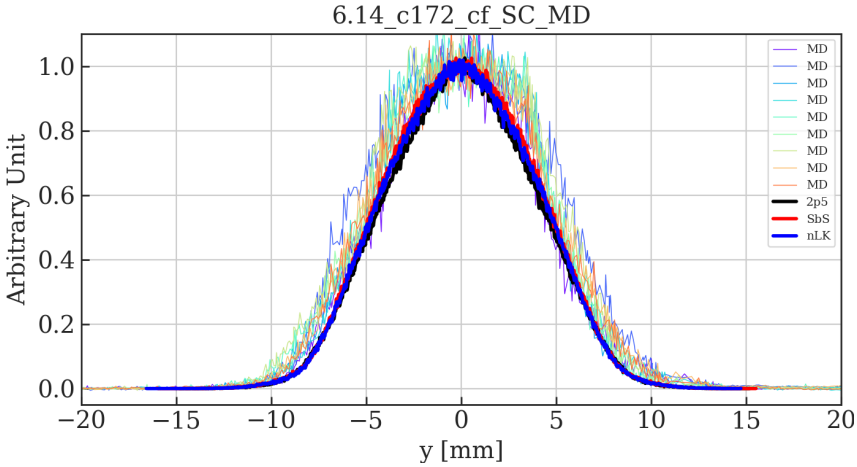
Q_y = 6.18, t = 172 ms



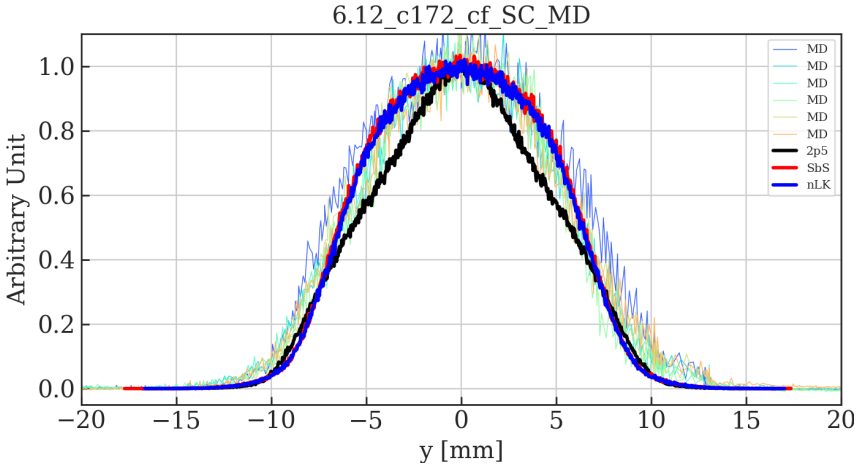
Q_y = 6.16, t = 172 ms



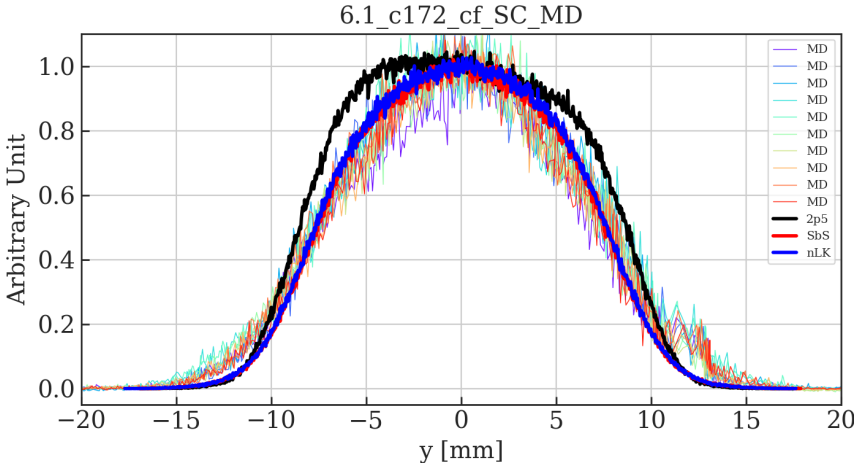
Q_y = 6.14, t = 172 ms



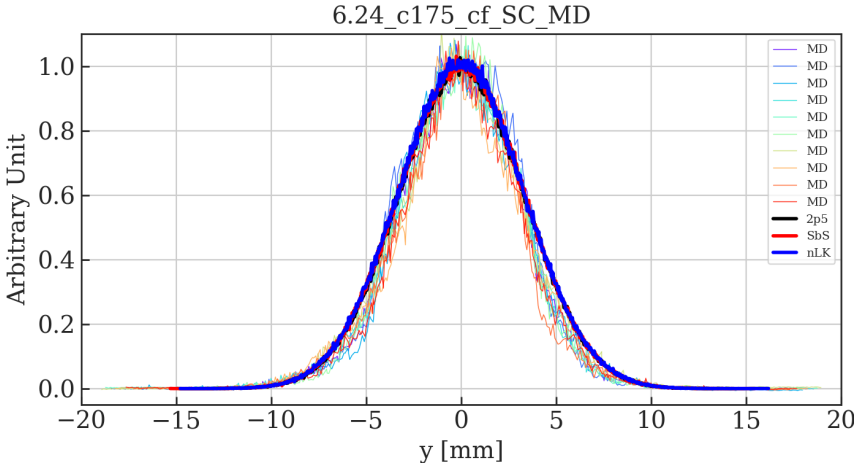
Q_y = 6.12, t = 172 ms



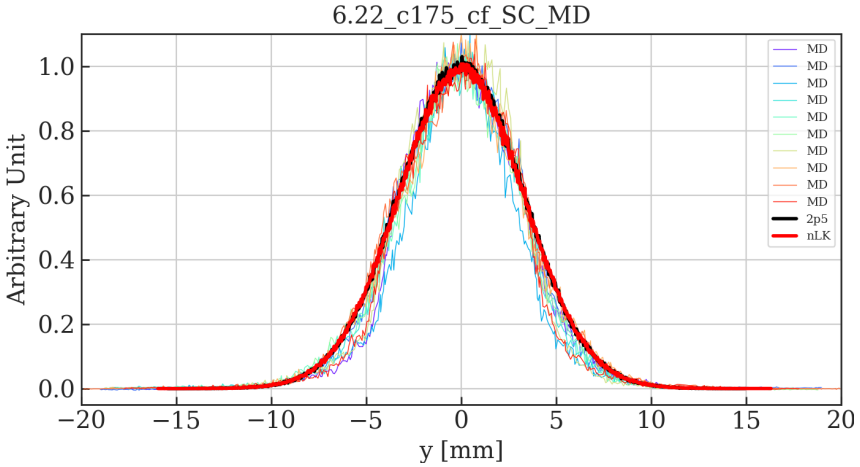
Q_y = 6.10, t = 172 ms



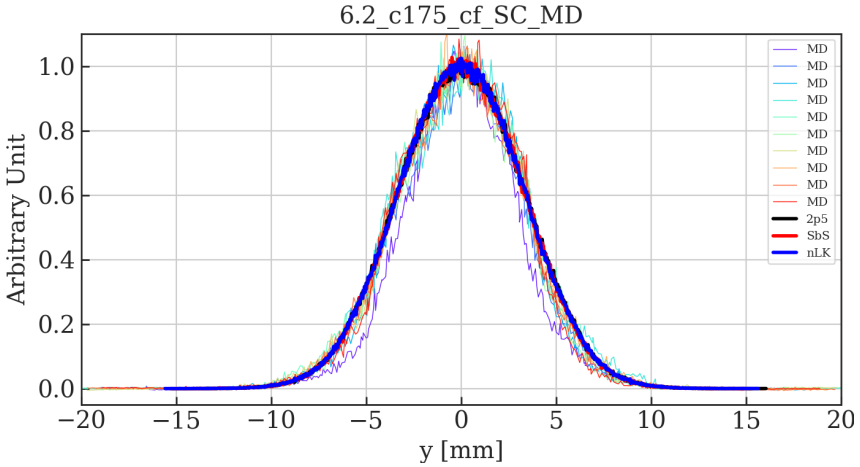
Q_y = 6.24, t = 175 ms



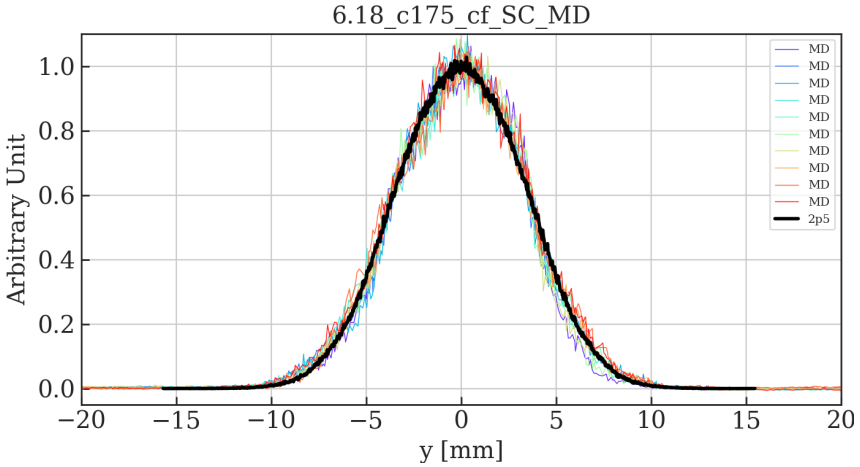
Q_y = 6.22, t = 175 ms



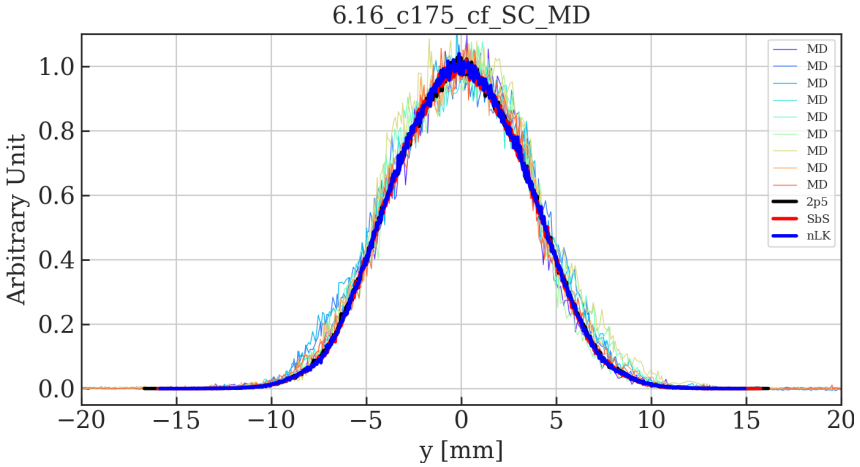
Q_y = 6.20, t = 175 ms



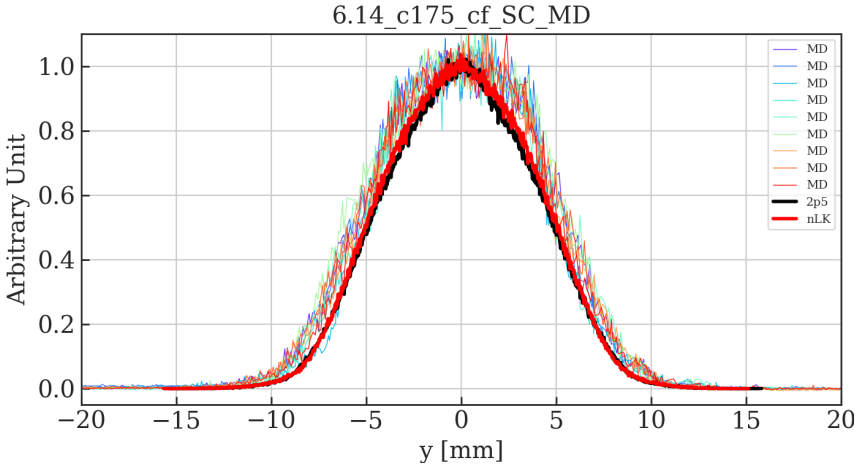
Q_y = 6.18, t = 175 ms



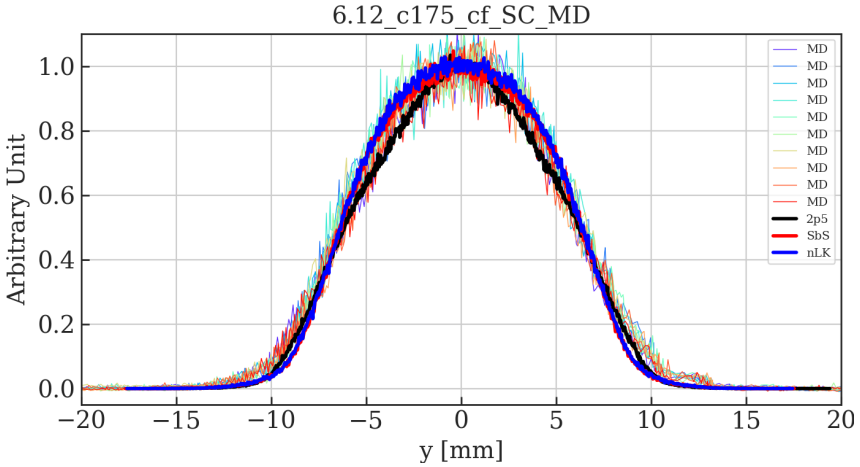
Q_y = 6.16, t = 175 ms



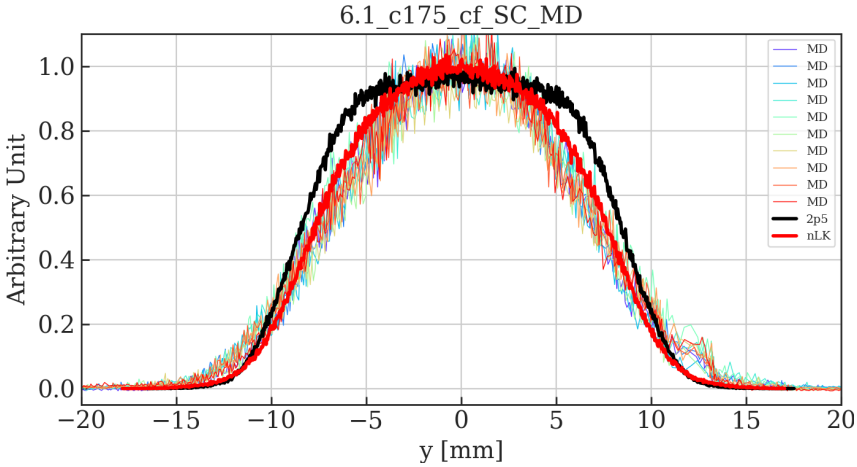
Q_y = 6.14, t = 175 ms



Q_y = 6.12, t = 175 ms



Q_y = 6.10, t = 175 ms



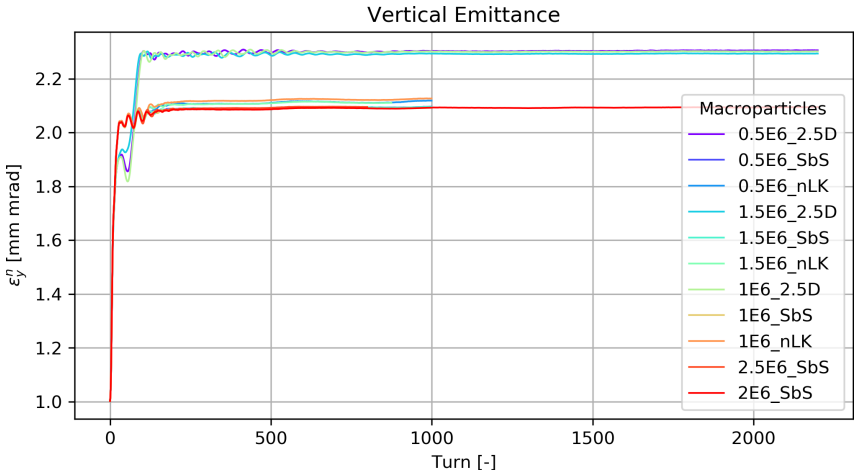
Beam Profile Summary

- For tunes closer to the nominal $(Q_x, Q_y) = (6.21, 6.24)$ space charge models agree well with eachother.
- Space charge models diverge at $Q_y = 6.12$ with slice-by-slice models giving a more parabolic distribution than 2.5D.
- At $Q_y = 6.10$ the 2.5D model gives an asymmetric profile with greater peak-width than the slice-by-slice models.
- MD data shows the same trend as simulations; Gaussian-like profile moves towards a parabola as the vertical tune is closer to the integer, though MD data is less Gaussian than simulations.
- From $Q_y = 6.14$ to $Q_y = 6.10$ MD data shows larger tail populations than simulations, and a small peak in the positive tail.

Macroparticle Scan

- 64 x 64 x 32 space charge grid
- 0.5, 1, 1.5, 2, 2.5, 3 million macro particles (larger simulations still queued).
- for **S**lice-**b**y-**s**lice with longitudinal kick (**SbS**), Slice-by-slice with **n**o **l**ongitudinal **k**ick (**nLK**), and 2.5D (**2.5D**) space charge models.
- No obvious convergence - 3 groups (in next slide plot) depend on space charge model, not number of macro particles.

Macroparticle Scan



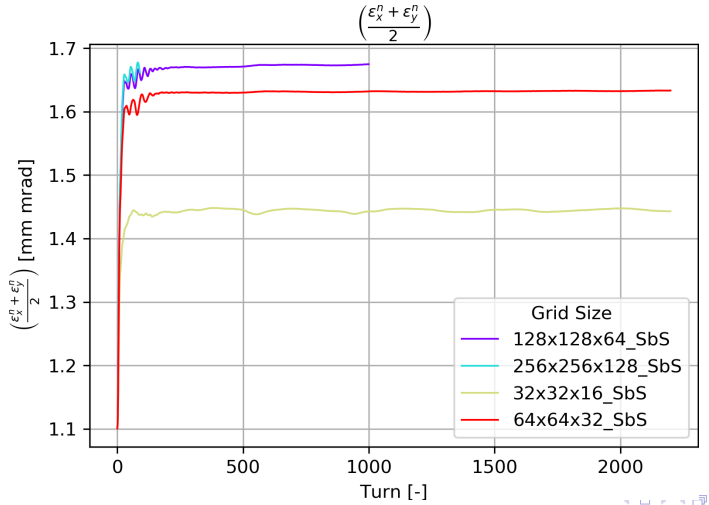
Space Charge Grid Size Scan

- 1.5 million macro particles. Grids sizes shown in Table 84.
- for **S**lice-**b**y-**s**lice with longitudinal kick (**SbS**), Slice-by-slice with **n**o **l**ongitudinal **k**ick (**nLK**), and 2.5D (**2.5D**) space charge models.
- Converging around 128x128x64 - 256x256x128. 512x512x256 simulations launched.
- Note difference in turns - some simulations are computationally demanding and reach 2 day time limit.

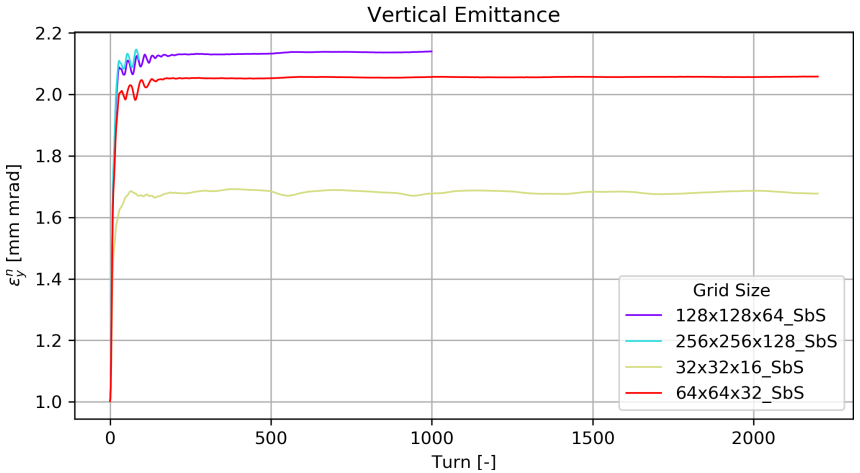
x	y	z	SLURM Nodes
32	32	16	4
64	64	32	4
128	128	64	6
256	256	128	8
512	512	256	16

Table 3: Space charge grid sizes.

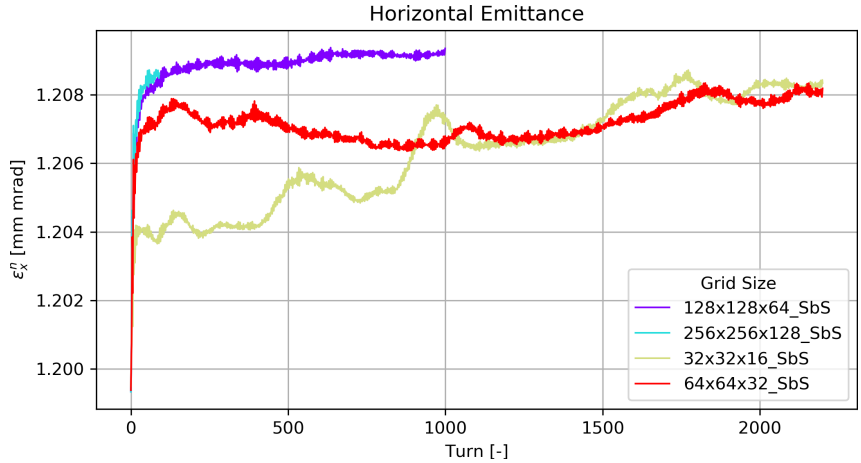
Space Charge Grid Size Scan: Slice-by-Slice: Average Emittance



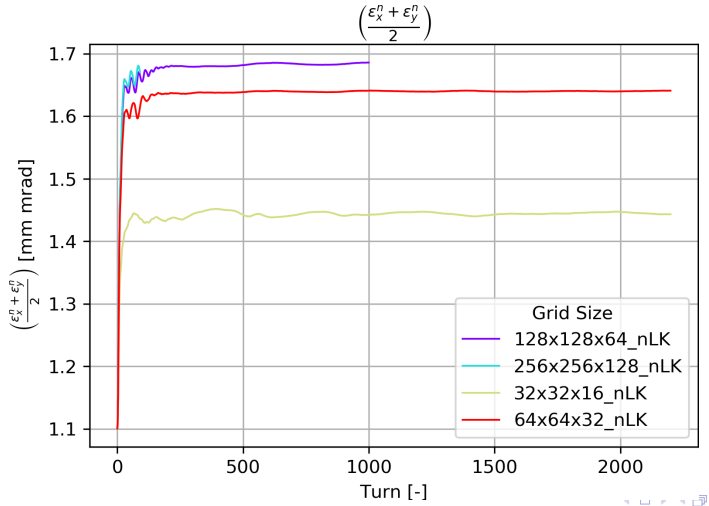
Space Charge Grid Size Scan: Slice-by-Slice: Vertical Emittance



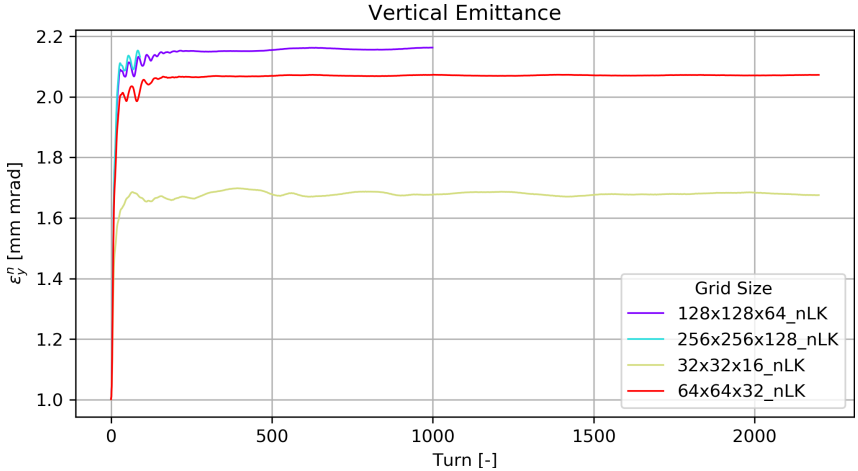
Space Charge Grid Size Scan: Slice-by-Slice: Horizontal Emittance



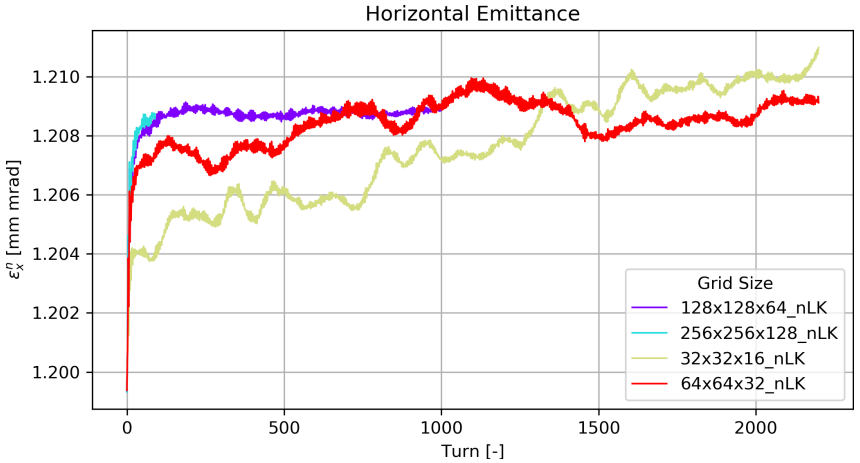
Space Charge Grid Size Scan: No Long Kick: Average Emittance



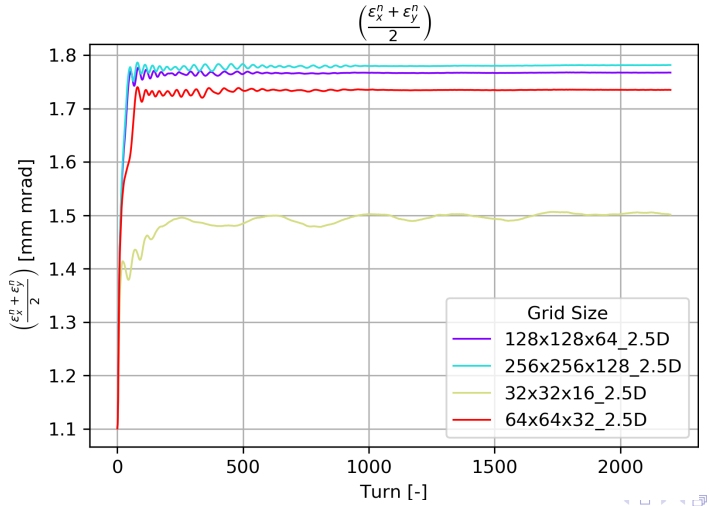
Space Charge Grid Size Scan: No Long Kick: Vertical Emittance



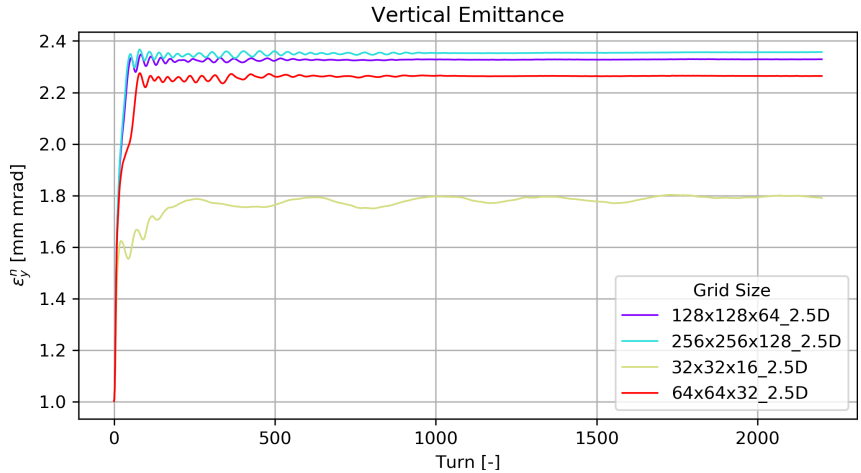
Space Charge Grid Size Scan: No Long Kick: Horizontal Emittance



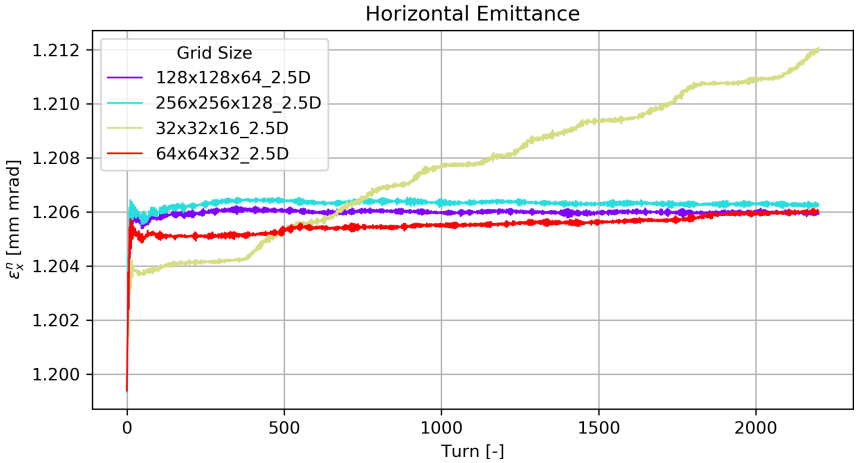
Space Charge Grid Size Scan: 2.5D: Average Emittance



Space Charge Grid Size Scan: 2.5D: Vertical Emittance



Space Charge Grid Size Scan: 2.5D: Horizontal Emittance



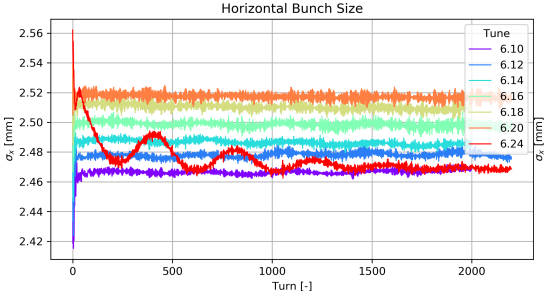
Sigma Calculation

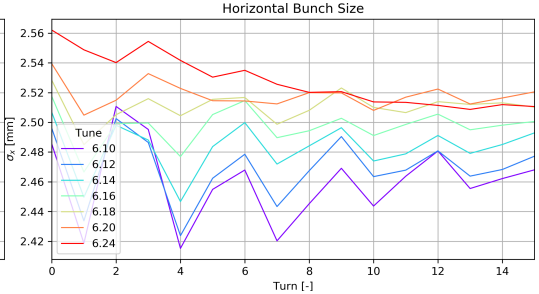
$$\sigma = \sqrt{\beta \frac{\epsilon^n}{\beta_L \gamma_L}} \tag{8}$$

$$\sigma^{eff} = \sqrt{\beta^{eff} \epsilon^{eff}} \tag{9}$$

Horizontal Beam Size: Slice-by-Slice

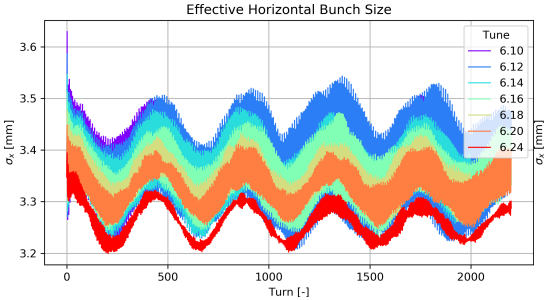
2200 turns, 15 turns

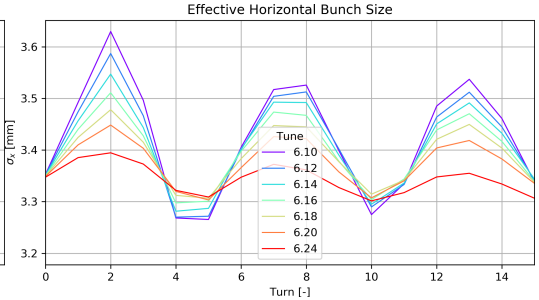




Effective Horizontal Beam Size: Slice-by-Slice

2200 turns, 15 turns

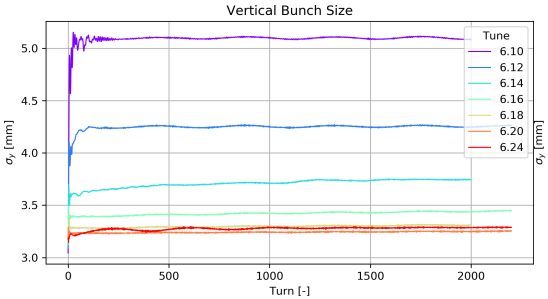


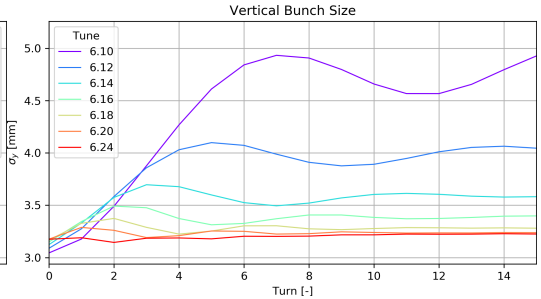


Vertical Beam Size: Slice-by-Slice

2200 turns, 15 turns

Beam size growth within first few hundred turns. Growth $\propto Q_y$.

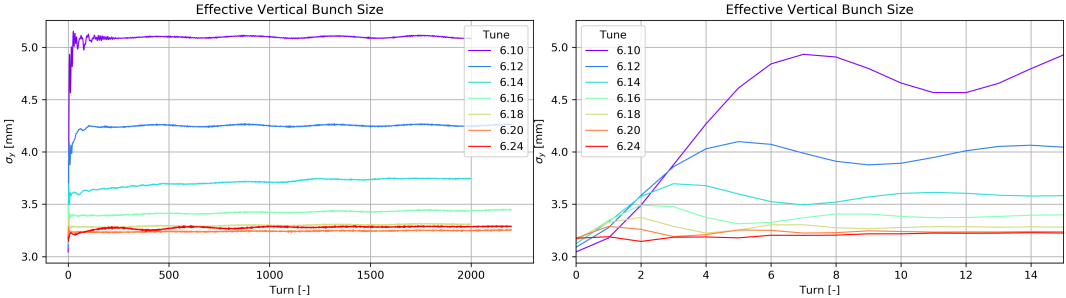




Effective Vertical Beam Size: Slice-by-Slice

2200 turns, 15 turns

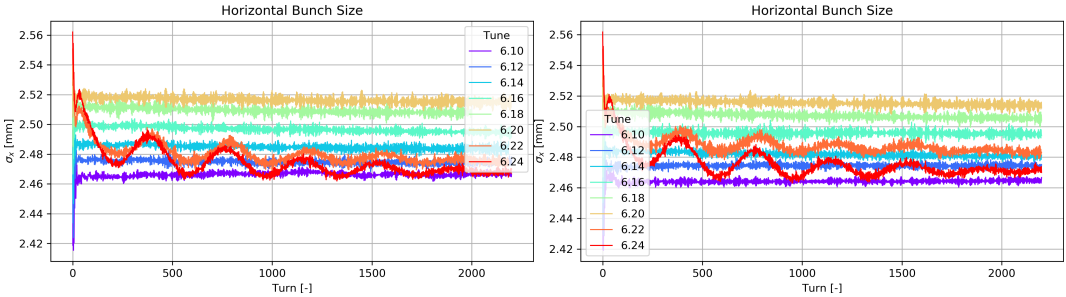
Beam size growth within first few hundred turns. Growth $\propto Q_y$.



Horizontal Beam Size: nLK & 2.5D

SbS no Long Kick, 2.5D

Possible emittance exchange at Montague resonance at Q_y = 6.22 and 6.24



Beam Size Summary

- Horizontal beam size smaller as Q_y is closer to the integer, remains constant after $\approx$ 50 turns with the exception of oscillating decrease for Q_y = 6.22 and 6.24.
- Q_y = 6.22 and 6.24 cases likely due to emittance exchange due to Montague resonance - shown later.
- Effective horizontal beam size beats with β_x^{eff}.
- Vertical beam size growth plateaus after $\approx$ 250 turns ($\approx$ 0.57 ms).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