



# MD4224 High Brightness: Simulations

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# Table of Contents

**Simulation Parameters**

**Tune Footprints**

**Apertures**

**Optics**

Dispersion

Beta Function

**Results**

Beam Size

Emittance

**Beam Profiles**

**Convergence Tests**

## **Simulation Parameters**

Tune Footprints

Apertures

Optics

Dispersion

Beta Function

Results

Beam Size

Emittance

Beam Profiles

Convergence Tests

# MD4224 Parameters

Parameter	MD	Simulation
Intensity $N_p [10^{10}]$	≈72.5	72.5
Normalised horizontal RMS emittance $\epsilon_x^n [\text{mm mrad}]$	1.2	1.2
Normalised vertical RMS emittance $\epsilon_y^n [\text{mm mrad}]$	1	1
Bunch length $\sigma_t [\text{ns}]$	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 $\Delta Q_{y,\max}$	0.24	0.24
Harmonic number $h$	9	9
RF voltage $V_{rf} [\text{kV}]$	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 $\beta$	0.916	0.916
Relativistic $\gamma$	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).

Simulation Parameters

**Tune Footprints**

Apertures

Optics

Dispersion

Beta Function

Results

Beam Size

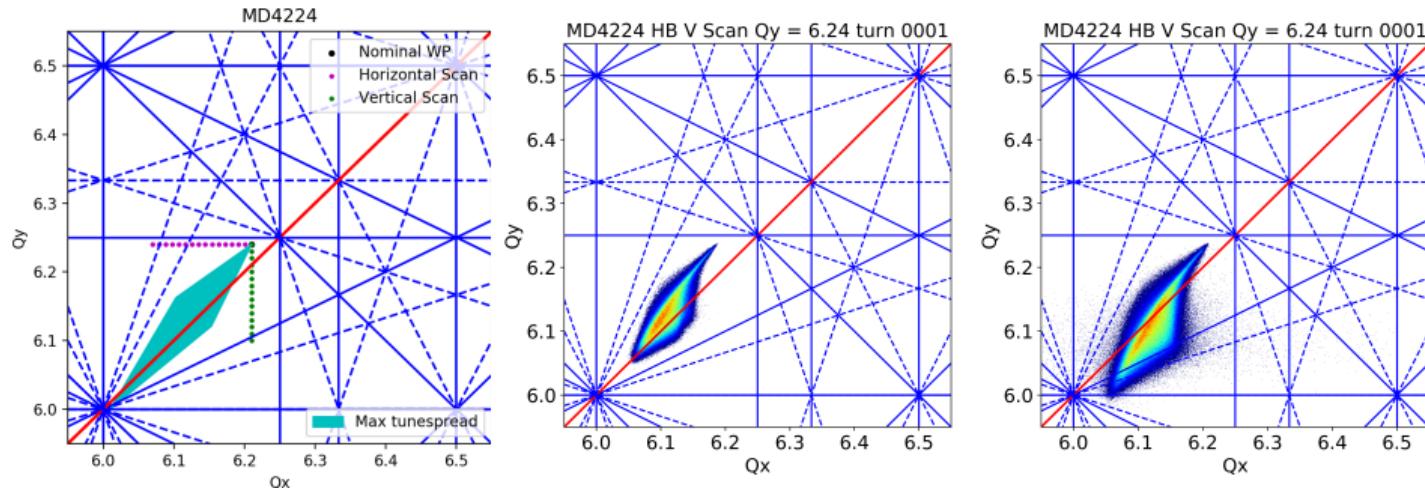
Emittance

Beam Profiles

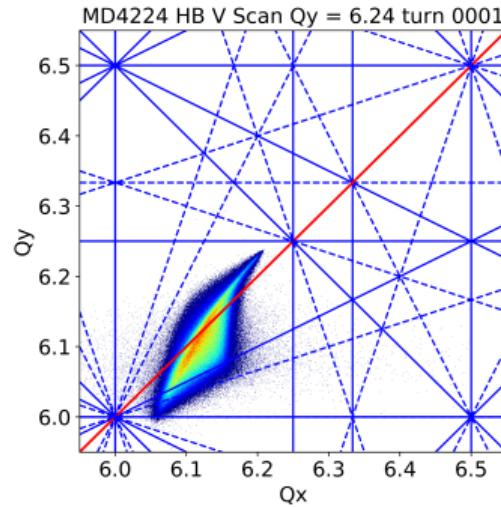
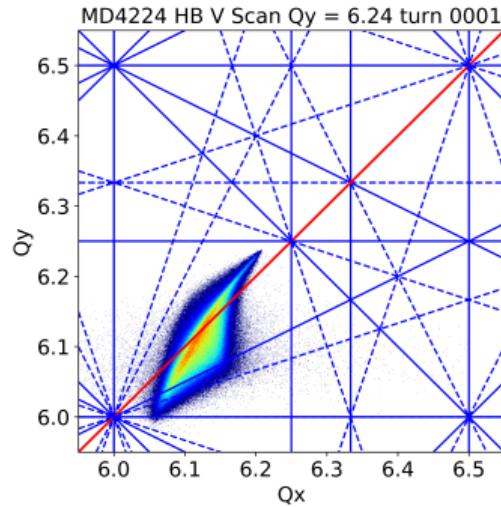
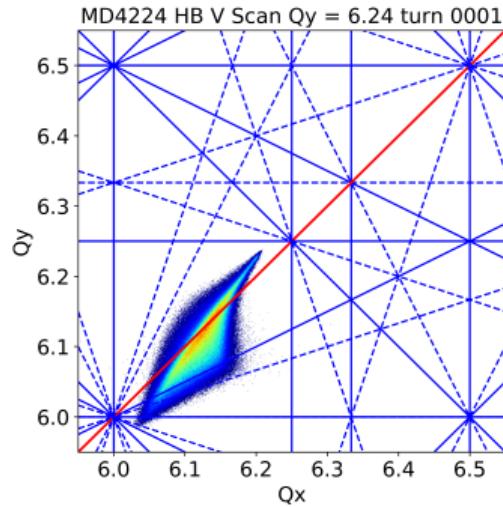
Convergence Tests

# Tune Footprints: Predicted, Old, New

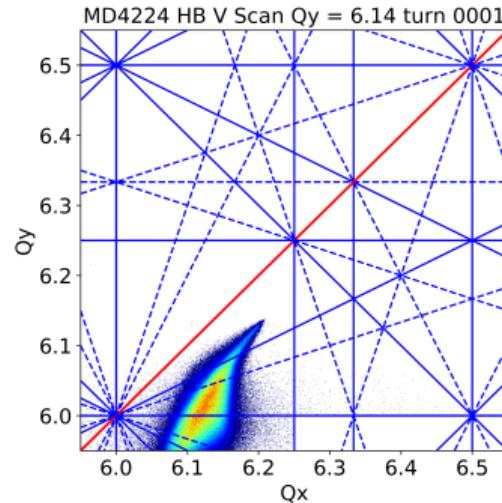
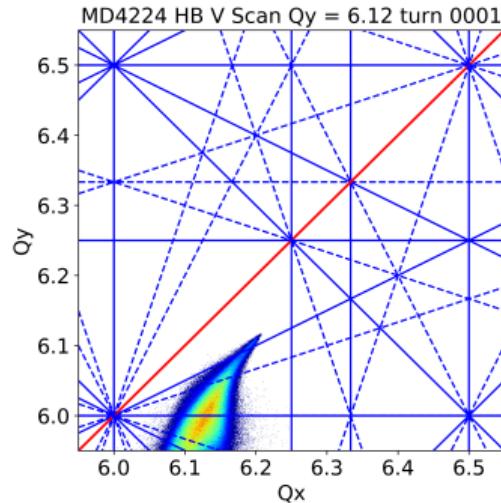
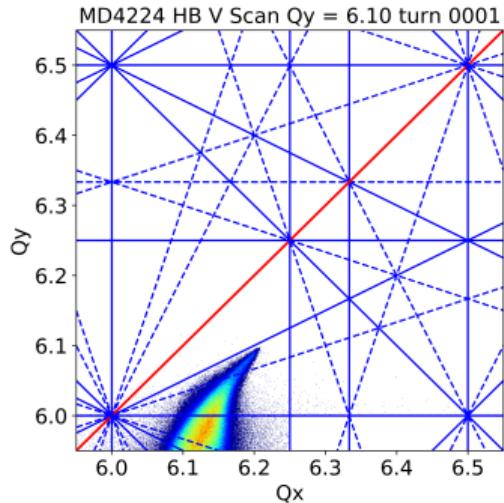
- ▶ Predicted (0.2, 0.24).
- ▶ Old WS 65H injection,  $32^3$  SC grid, natural chroma.
- ▶ New WS 64V injection,  $64 \times 64 \times 32$  SC grid, low chroma.  $\approx (0.16, 0.24)$



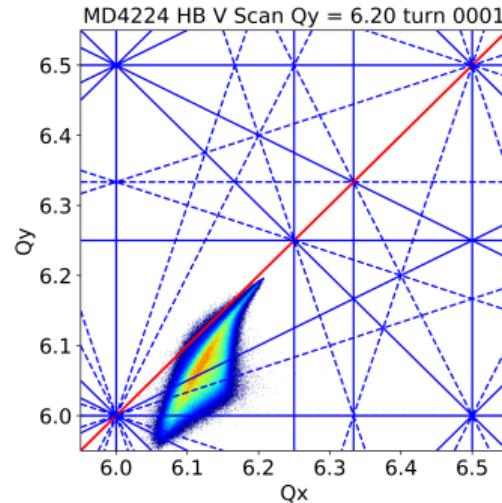
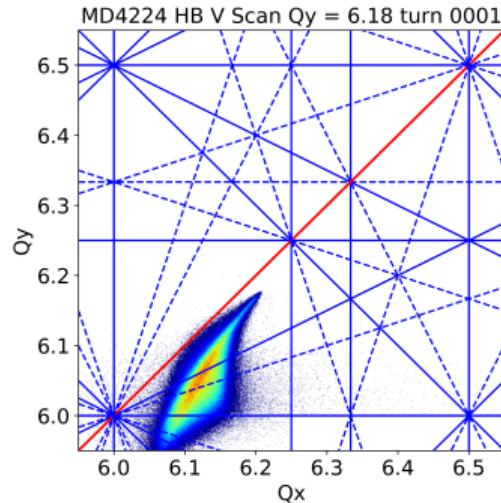
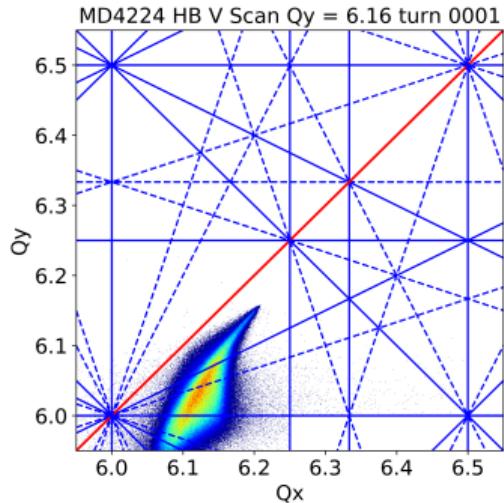
# Tune Footprints: 2.5D, Slice-by-slice, Slice-by-slice with longitudinal kick



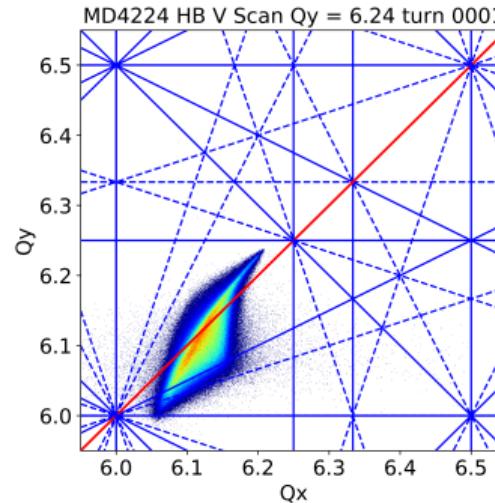
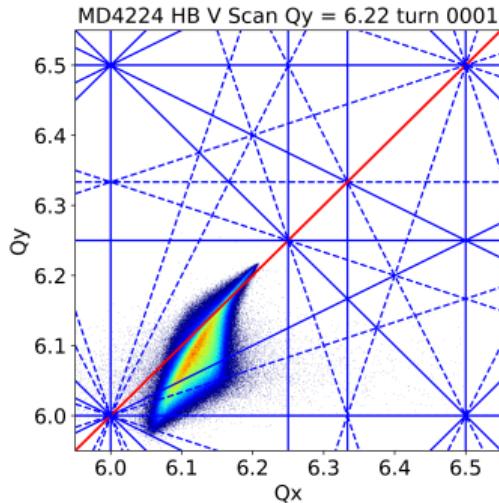
# Tune Footprints: 6.10, 6.12, 6.14



# Tune Footprints: 6.16, 6.18, 6.20



# Tune Footprints: 6.22, 6.24



**Simulation Parameters**

Tune Footprints

**Apertures**

Optics

Dispersion

Beta Function

**Results**

Beam Size

Emittance

Beam Profiles

Convergence Tests

# Apertures

PS\_2013.aper - /home/HR/Documents/PyORBIT\_Utils/MD4224/High\_Brightness/Simulation/Lattice\_LowChroma - Geany

File Edit Search View Document Project Build Tools Help

Flat\_file.madx copy\_bunch\_outputs.sh plot\_tunefootprint.py Plot\_All\_Outputfile\_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};
27
```



Simulation Parameters

Tune Footprints

Apertures

**Optics**

Dispersion

Beta Function

Results

Beam Size

Emittance

Beam Profiles

Convergence Tests

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.

**Simulation Parameters**

**Tune Footprints**

**Apertures**

**Optics**

Dispersion

Beta Function

**Results**

Beam Size

Emittance

**Beam Profiles**

**Convergence Tests**



# PyORBIT Dispersion Calculation

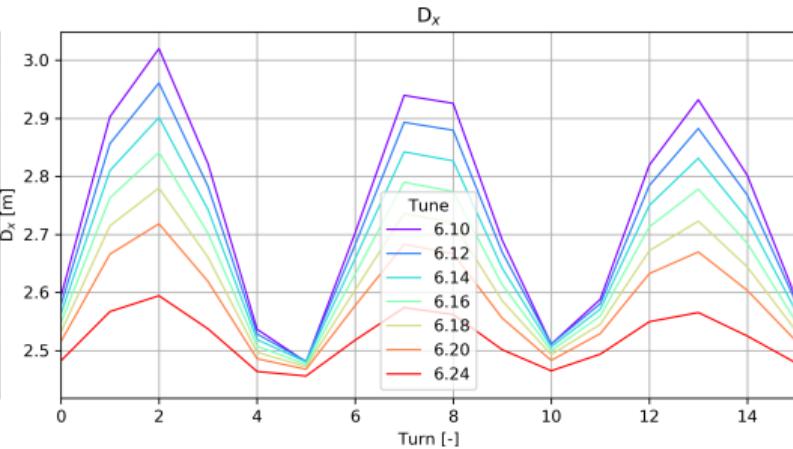
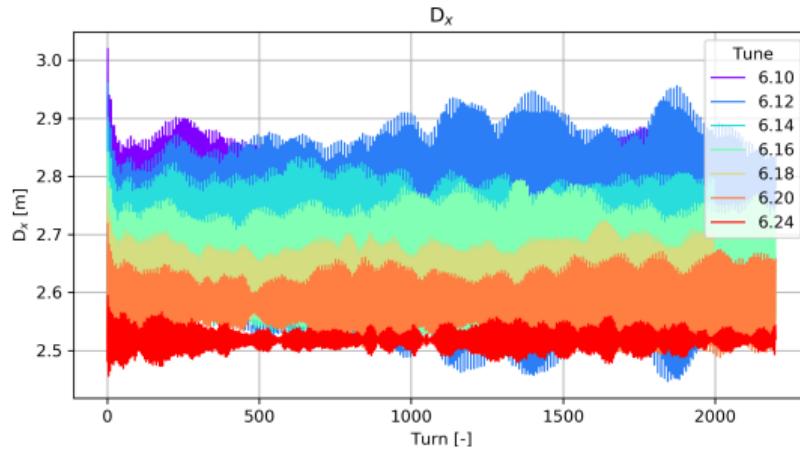
$$\text{BunchTwissAnalysis::getDispersion} = D = \frac{\langle x \frac{dE}{dx} \rangle}{\langle dE^2 \rangle} P \beta_L \quad (1)$$

where  $P$  = bunch momentum,  $\beta_L$  = Lorentz Beta (of beam).

# Horizontal Dispersion

2200 turns, 15 turns

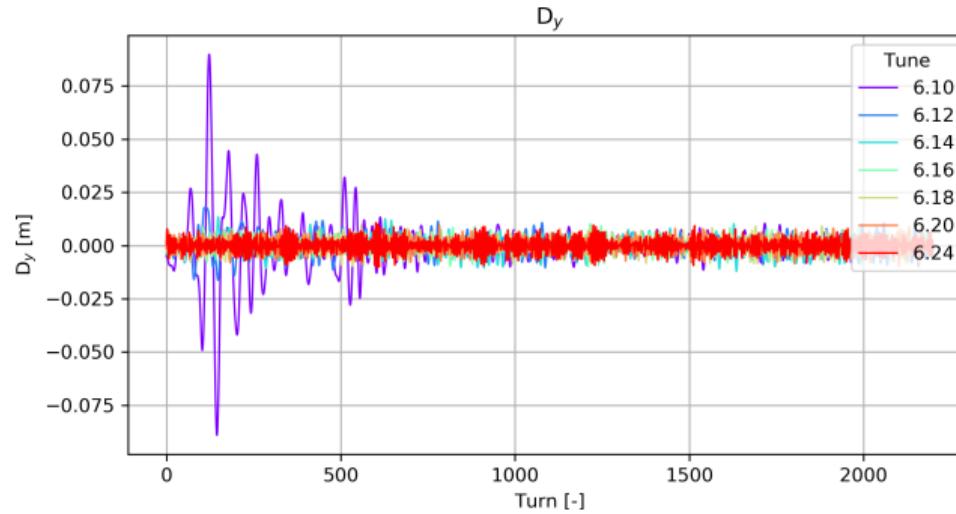
Lower vertical tune  $\rightarrow$  higher horizontal dispersion. Beating of dispersion at  $\approx Q$ .



# Vertical Dispersion

2200 turns

Small displacement at lowest vertical tunes.



**Simulation Parameters**

**Tune Footprints**

**Apertures**

**Optics**

Dispersion

**Beta Function  
Results**

Beam Size

Emittance

**Beam Profiles  
Convergence Tests**

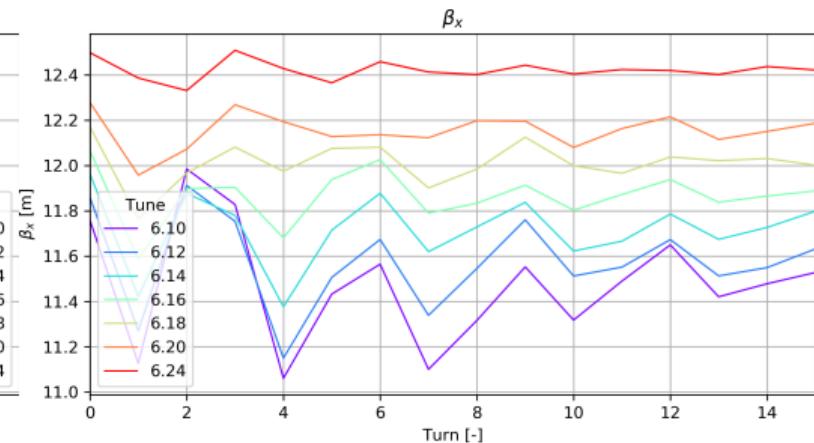
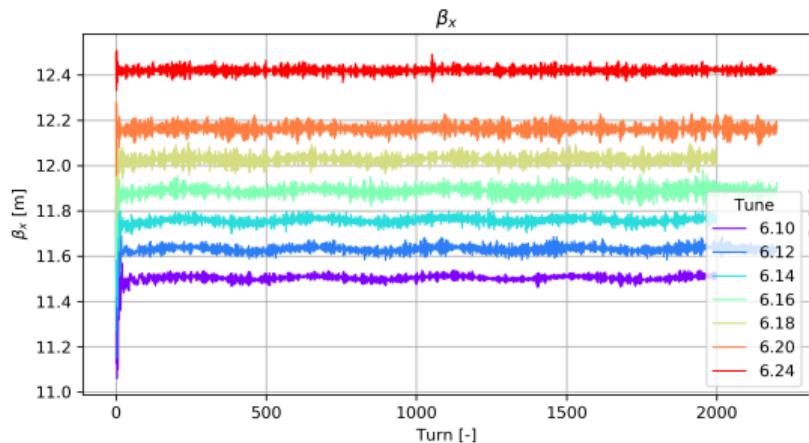
# PyORBIT Beta Function Calculation

$$\text{getBeta}() = \beta = \frac{\left( \langle x^2 \rangle - \frac{\langle x \rangle \langle dE \rangle^2}{\langle dE^2 \rangle} \right)}{\epsilon} \quad (2)$$

$$\text{getEffectiveBeta}() = \beta^{\text{eff}} = \frac{\langle x^2 \rangle}{\epsilon^{\text{eff}}} \quad (3)$$

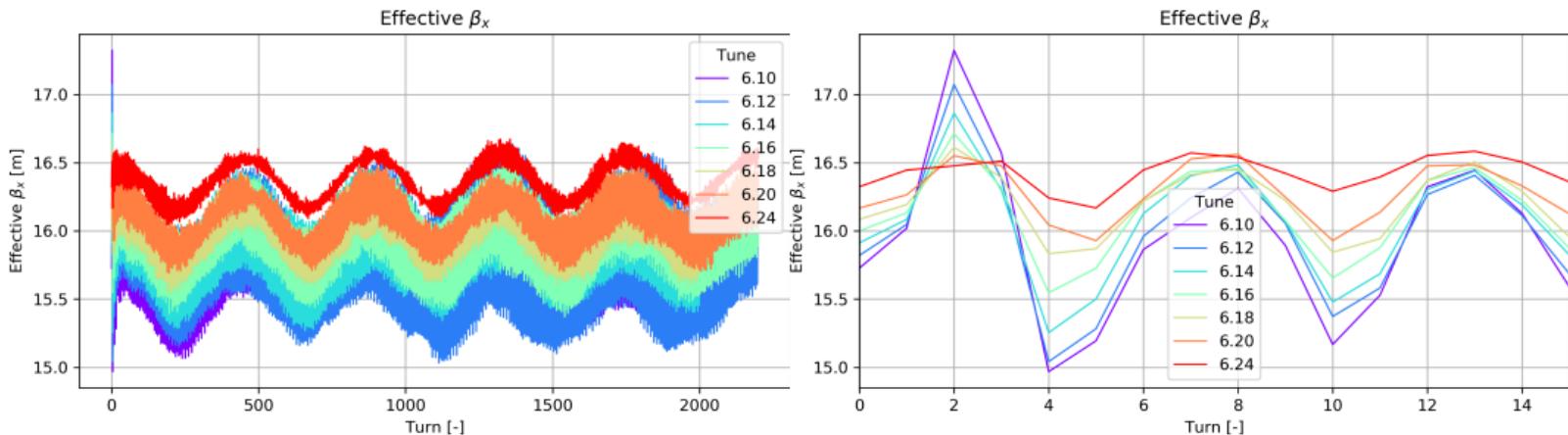
# Horizontal Beta

2200 turns, 15 turns



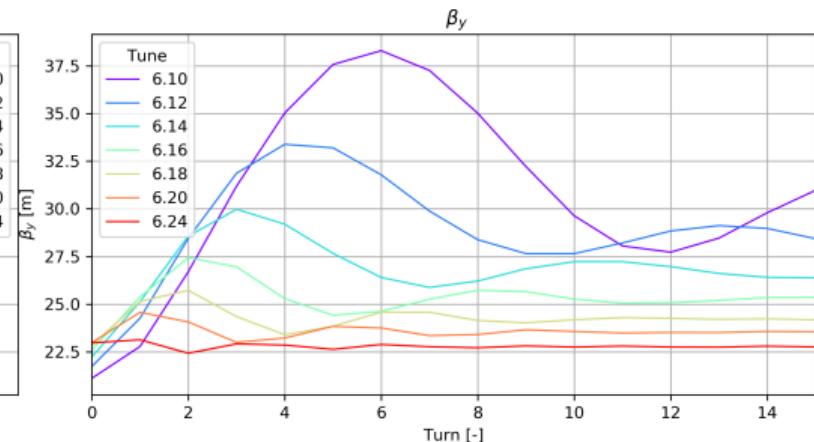
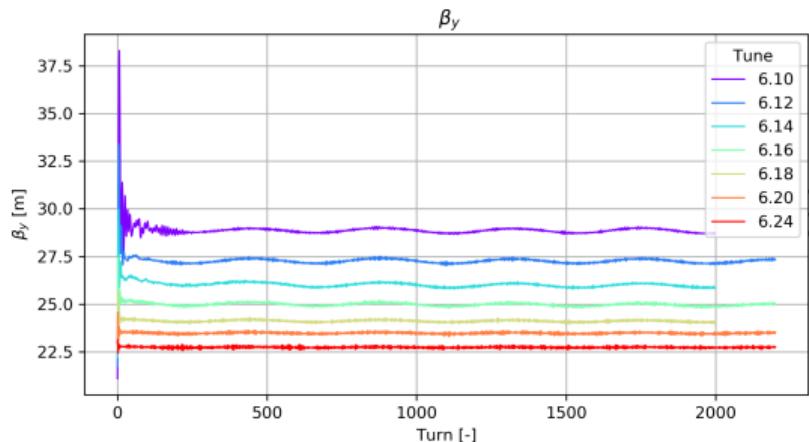
# Horizontal Effective Beta

2200 turns, 15 turns



# Vertical Beta

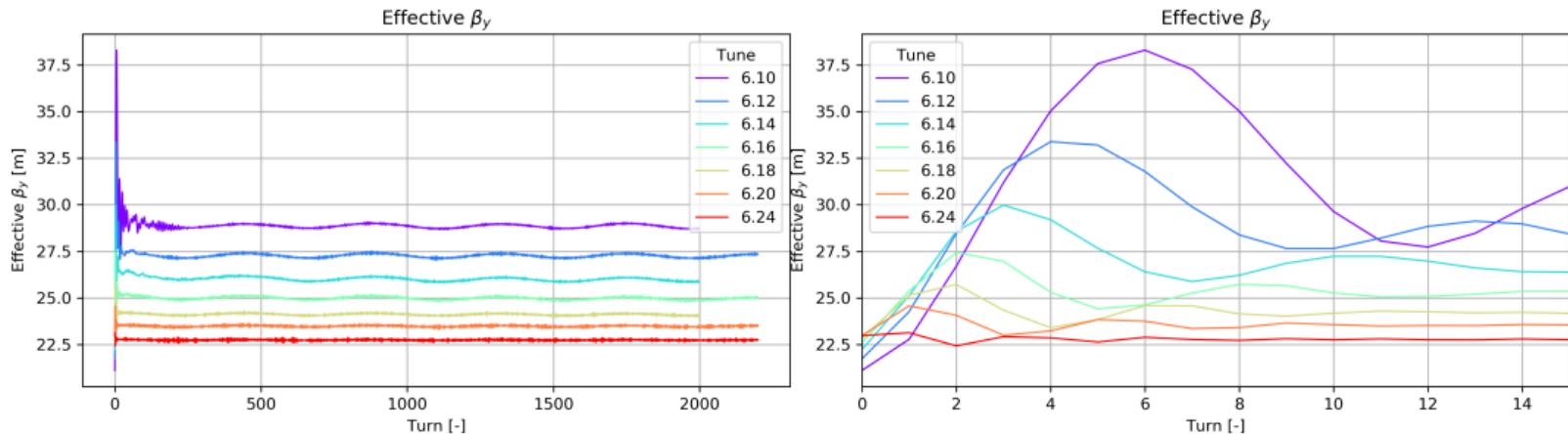
2200 turns, 15 turns



# Vertical Effective Beta

2200 turns, 15 turns

Identical to ‘real’  $\beta_y$  - no vertical dispersive component.



# 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 observed - expected due to transfer mismatch - period of  $\approx Q_y$  turns (5).
- ▶ Horizontal beta beating observed with a period  $\approx \frac{Q_y}{2}$  turns (3).
- ▶ Effective horizontal beta beating observed with a period  $\approx Q_y$  turns (6).

Simulation Parameters

Tune Footprints

Apertures

Optics

Dispersion

Beta Function

## Results

Beam Size

Emittance

Beam Profiles

Convergence Tests

**Simulation Parameters**

**Tune Footprints**

**Apertures**

**Optics**

Dispersion

Beta Function

**Results**

Beam Size

Emittance

**Beam Profiles**

**Convergence Tests**

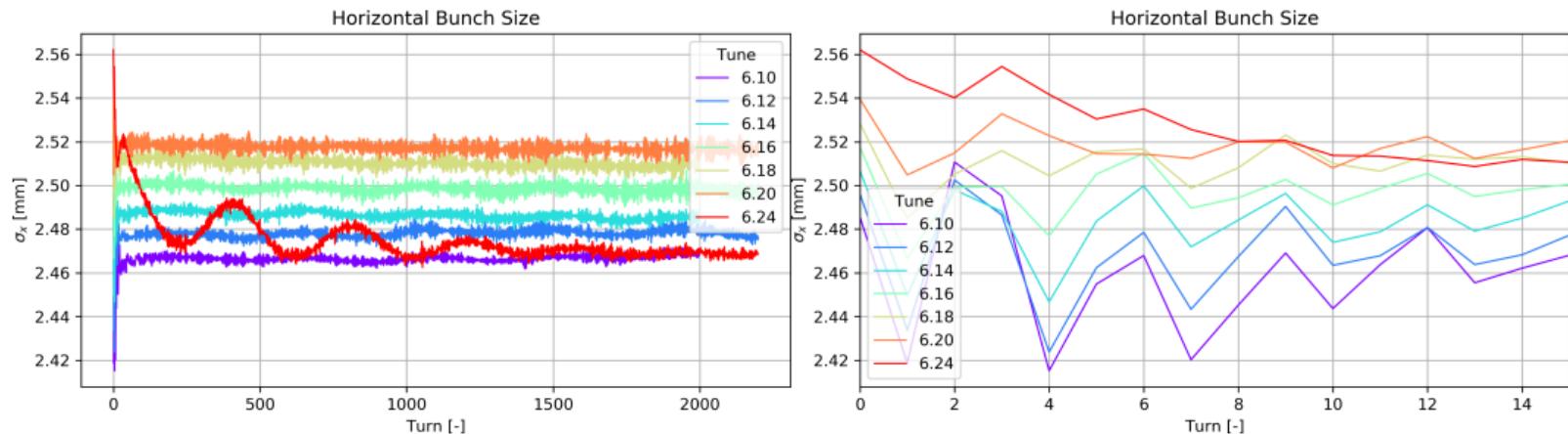
# Sigma Calculation

$$\sigma = \sqrt{\beta \frac{\epsilon^n}{\beta_L \gamma_L}} \quad (4)$$

$$\sigma^{eff} = \sqrt{\beta^{eff} \epsilon^{eff}} \quad (5)$$

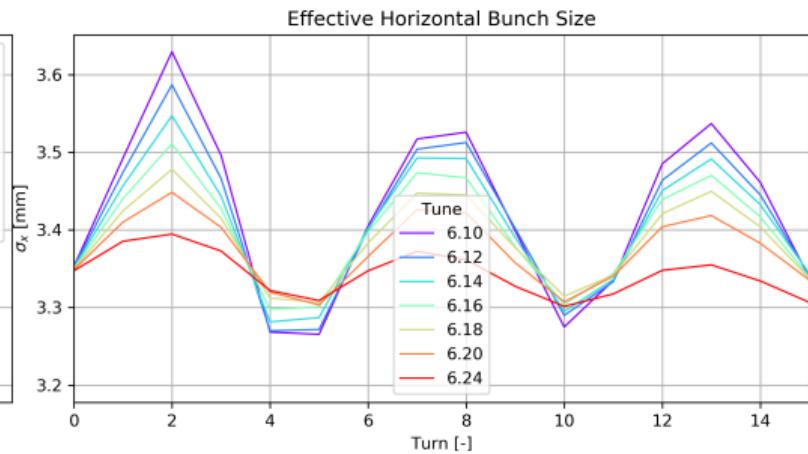
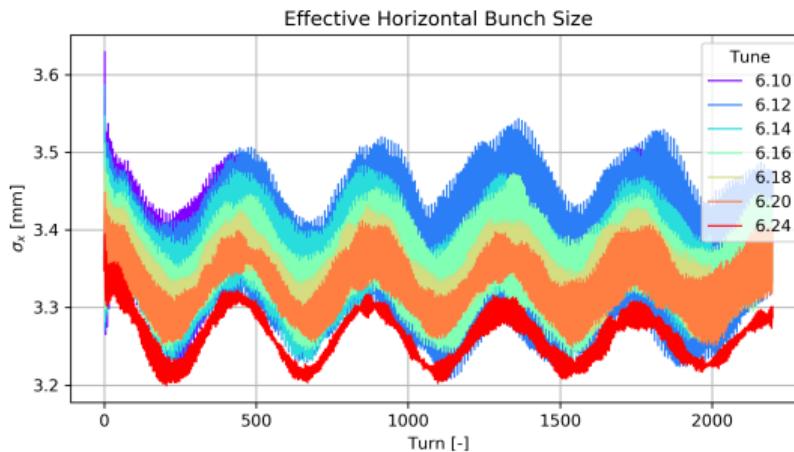
# Horizontal Beam Size: Slice-by-Slice

2200 turns, 15 turns



# Effective Horizontal Beam Size: Slice-by-Slice

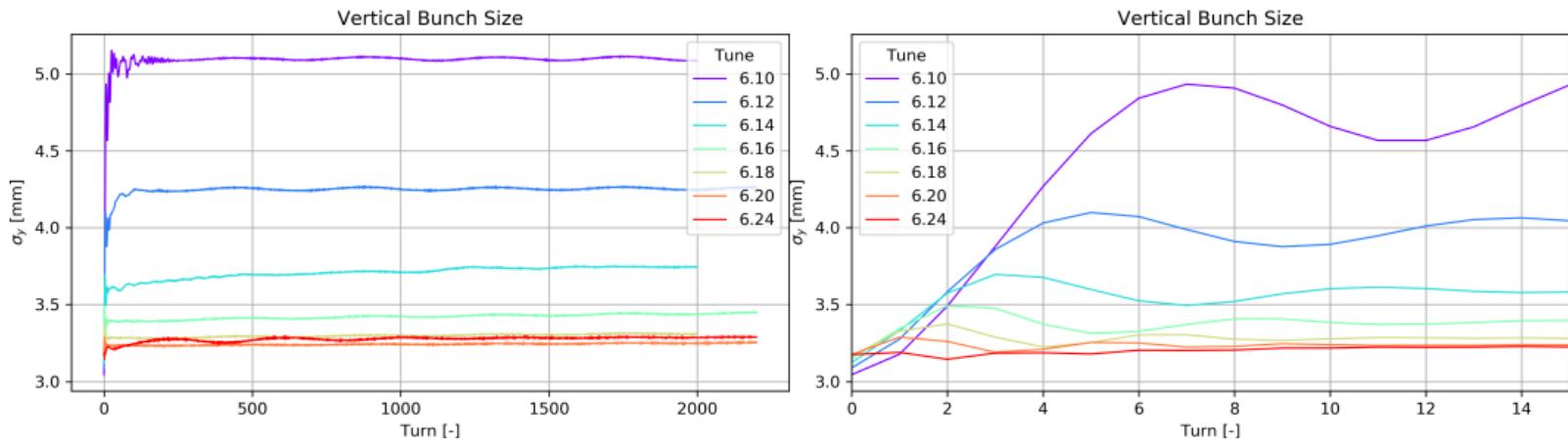
2200 turns, 15 turns



# Vertical Beam Size: Slice-by-Slice

2200 turns, 15 turns

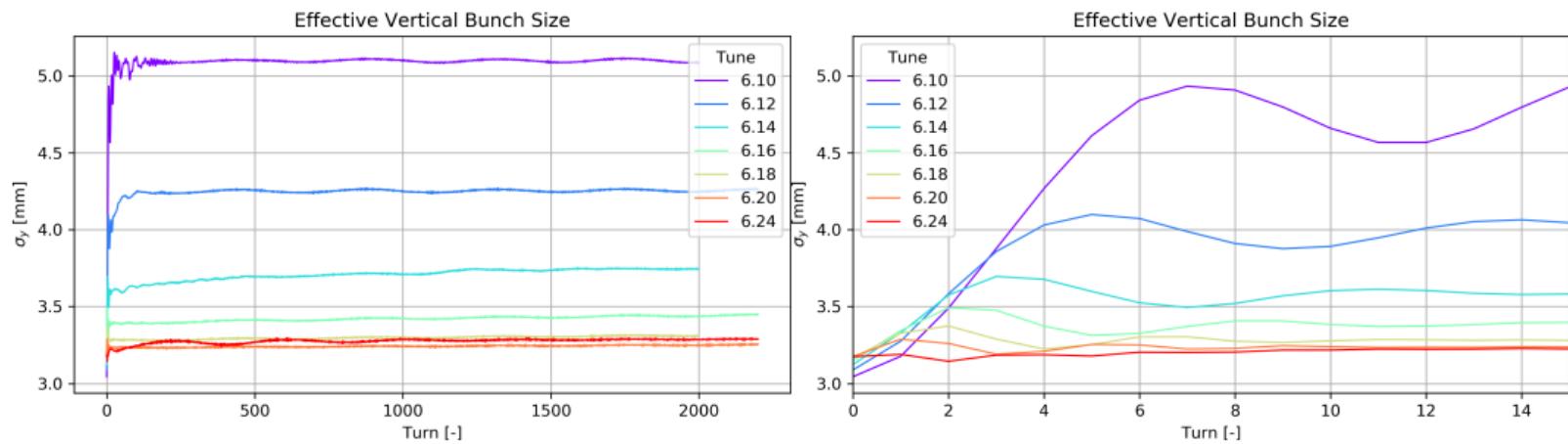
Beam size growth within first few hundred turns. Growth  $\propto Q_y$ .



# Effective Vertical Beam Size: Slice-by-Slice

2200 turns, 15 turns

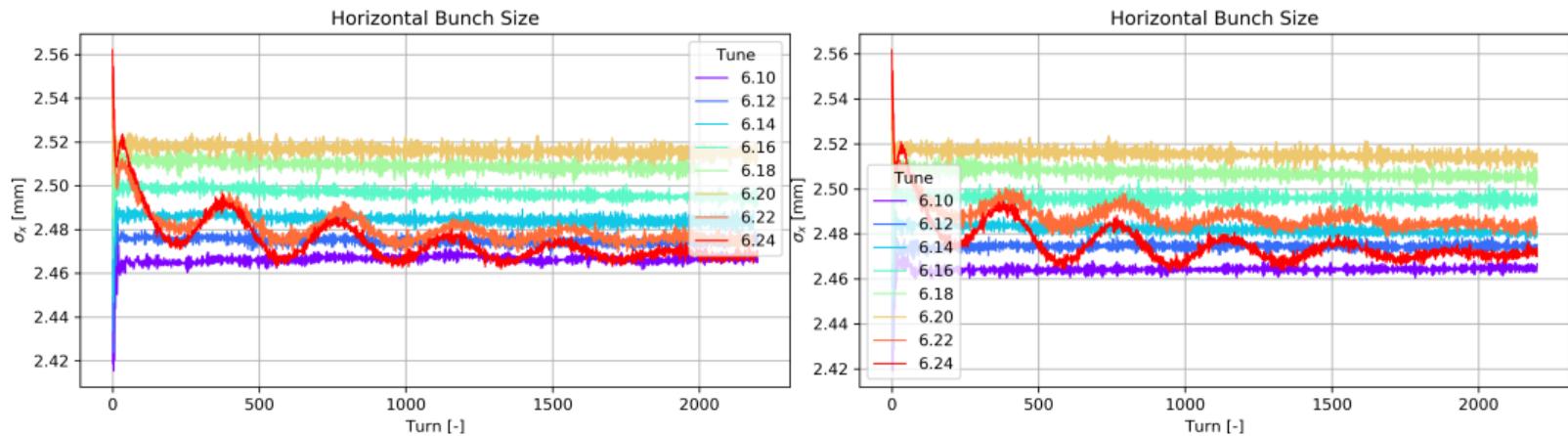
Beam size growth within first few hundred turns. Growth  $\propto Q_y$ .



# 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  $\beta_x^{eff}$ .
- ▶ Vertical beam size growth plateaus after  $\approx 250$  turns ( $\approx 0.57$  ms).

**Simulation Parameters**

**Tune Footprints**

**Apertures**

**Optics**

Dispersion

Beta Function

**Results**

Beam Size

Emittance

**Beam Profiles**

**Convergence Tests**

# PyORBIT Emittance Calculation

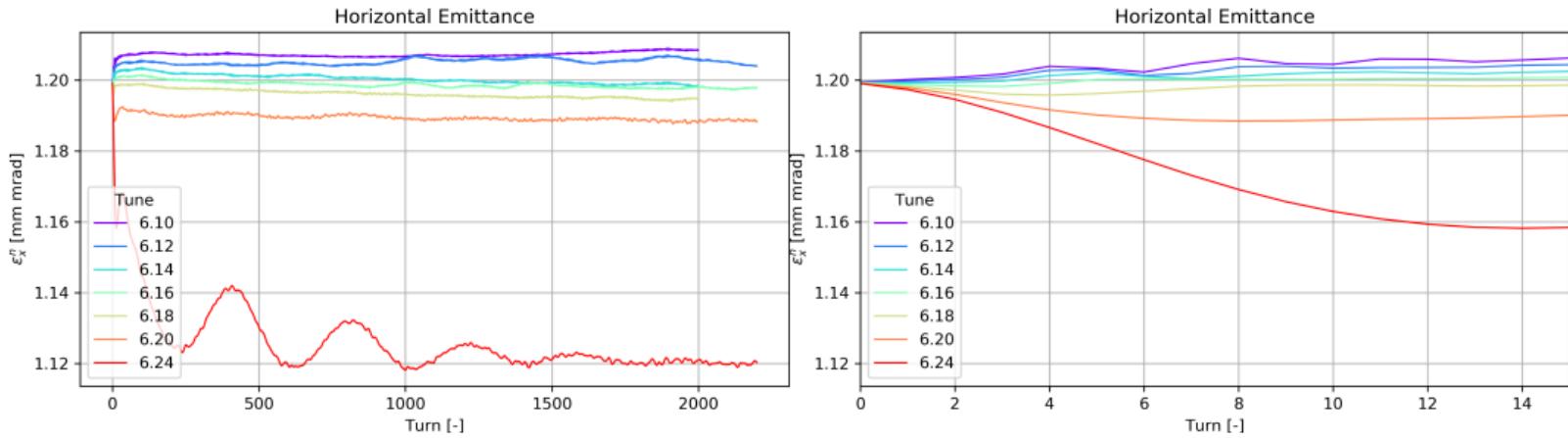
$$\epsilon = \sqrt{\left( \langle x^2 \rangle - \frac{\langle x \, dE \rangle^2}{\langle dE^2 \rangle} \right) \left( \langle x'^2 \rangle - \frac{\langle x' \, dE \rangle^2}{\langle dE^2 \rangle} \right) - \left( \langle x \, x' \rangle - \frac{\langle x \, dE \rangle \langle x' \, dE \rangle}{\langle dE^2 \rangle} \right)^2} \quad (6)$$

$$\epsilon^n = \epsilon \beta_L \gamma_L \quad (7)$$

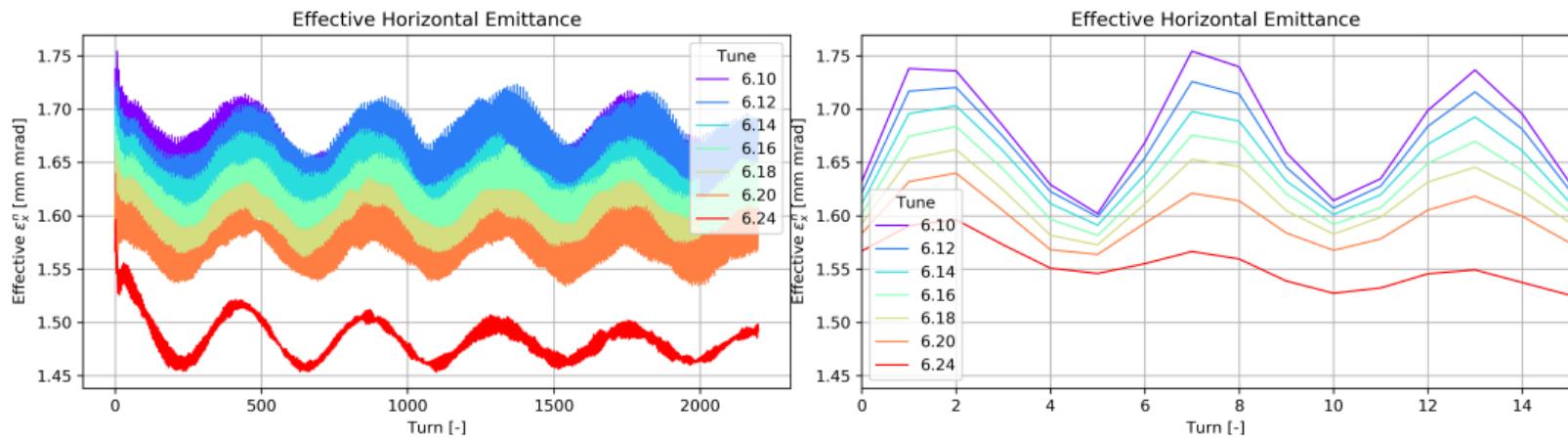
$$\epsilon^{eff} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x \, x' \rangle^2} \quad (8)$$

$$\epsilon^{eff \, n} = \epsilon^{eff} \beta_L \gamma_L \quad (9)$$

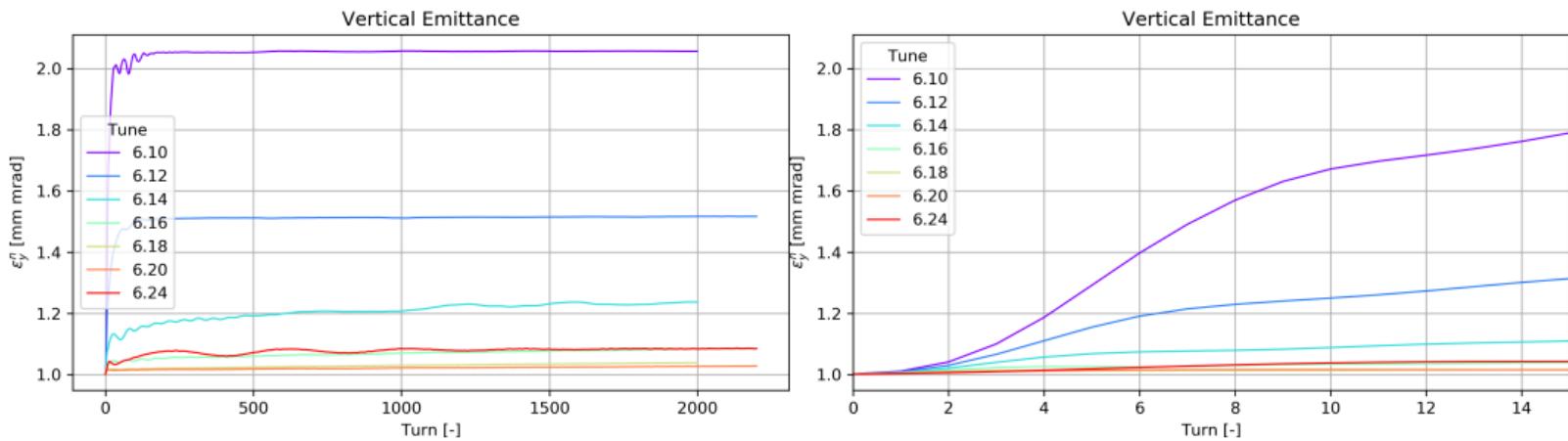
# Horizontal Emittance: Slice-by-Slice



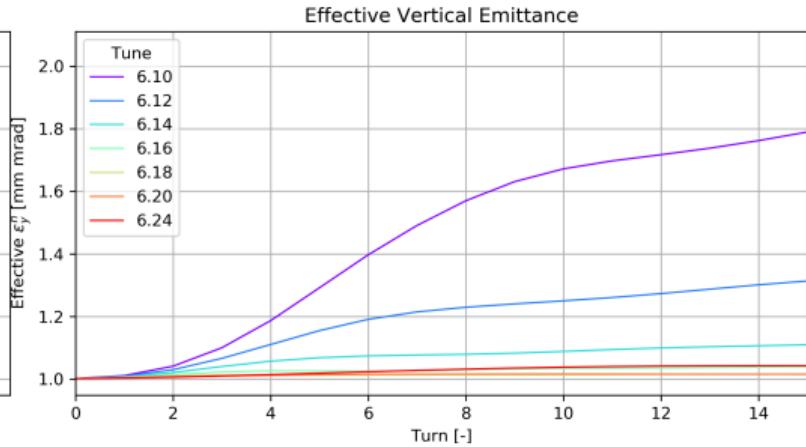
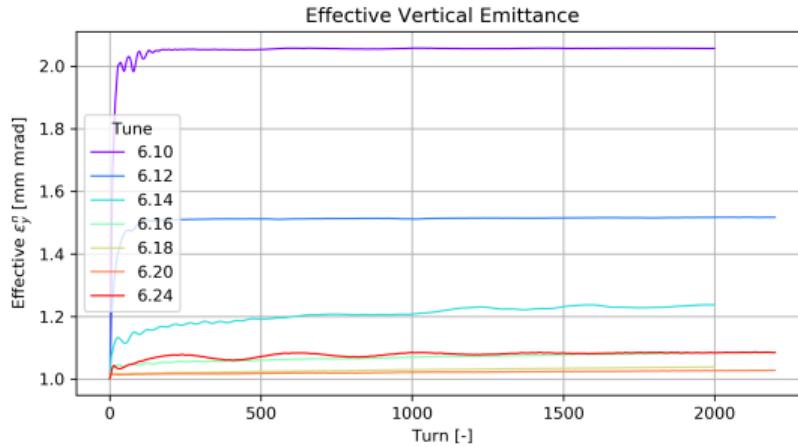
# Effective Horizontal Emittance: Slice-by-Slice



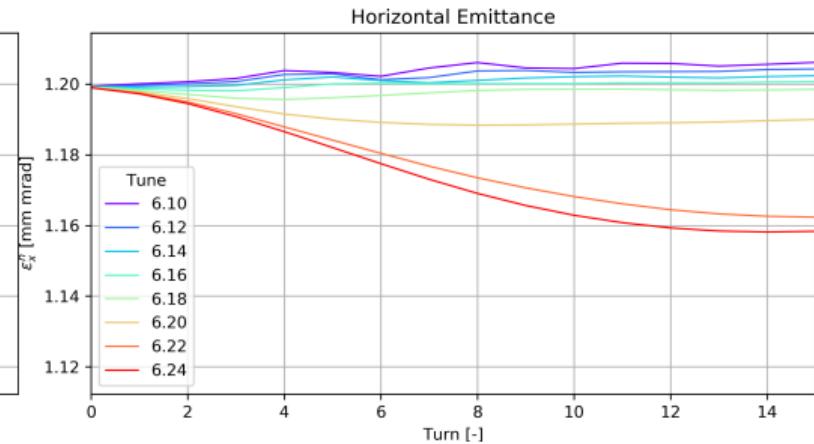
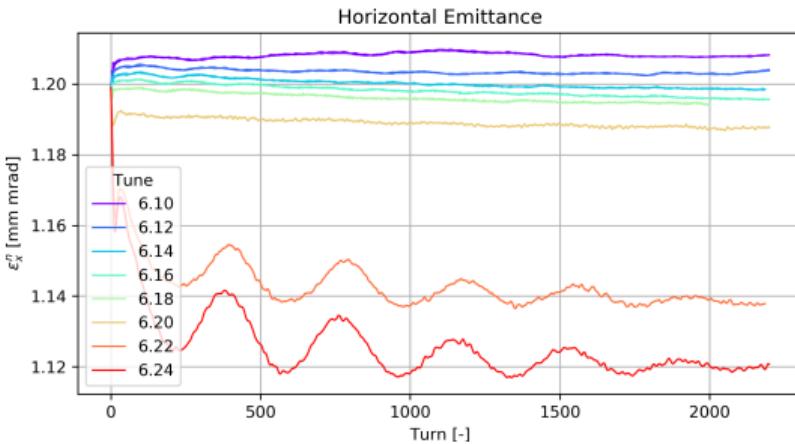
# Vertical Emittance: Slice-by-Slice



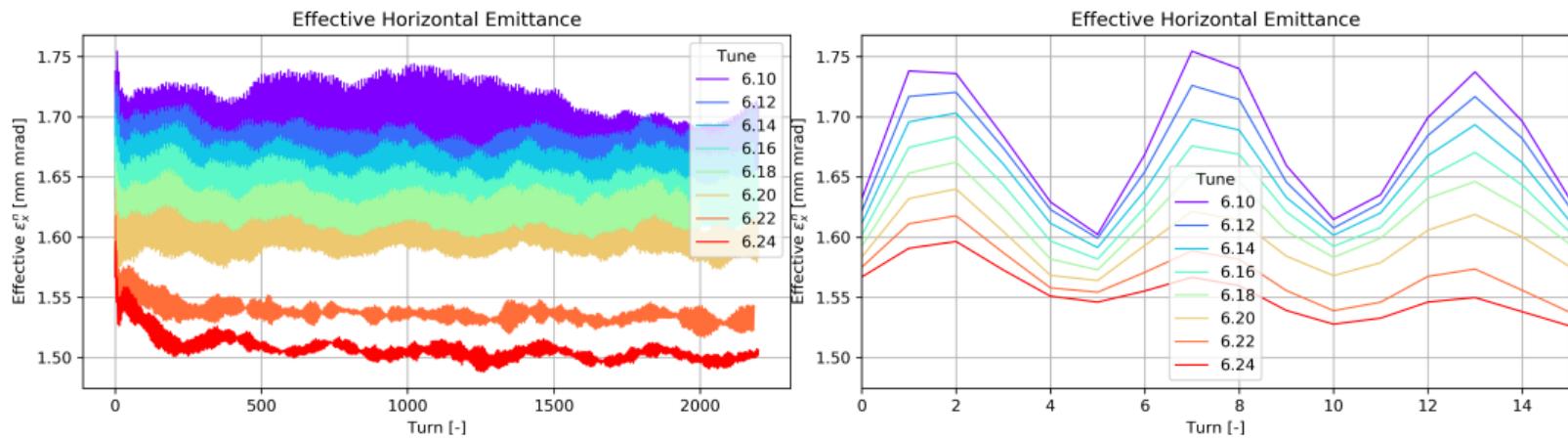
# Effective Vertical Emittance: Slice-by-Slice



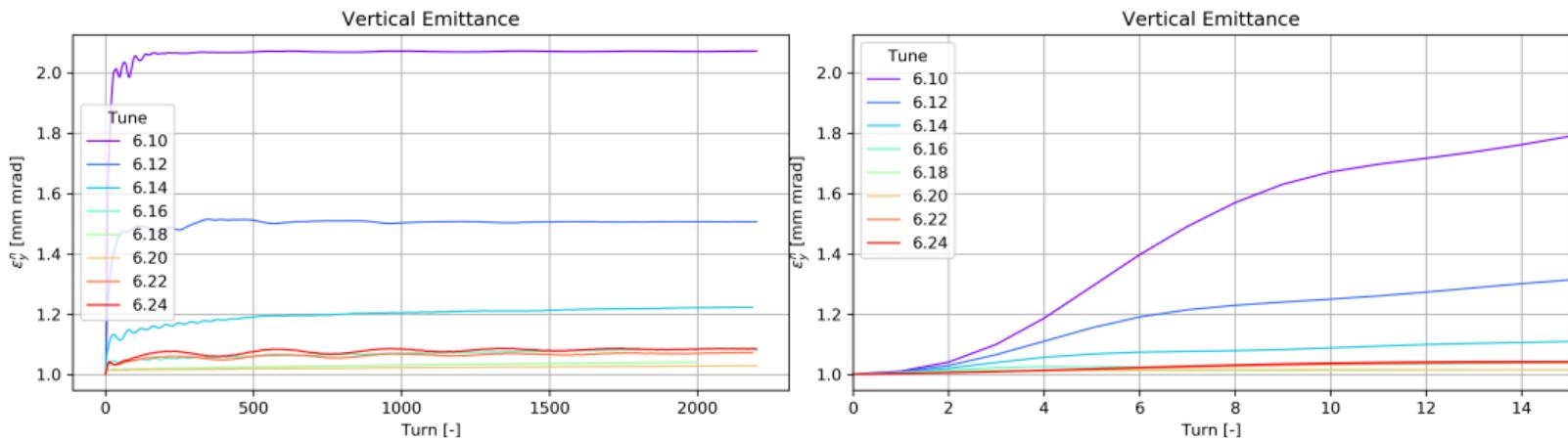
# Horizontal Emittance: SbS no Longitudinal Kick



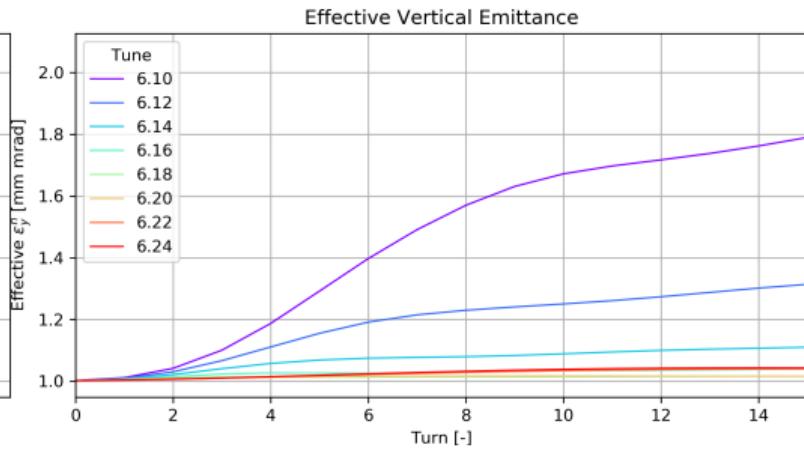
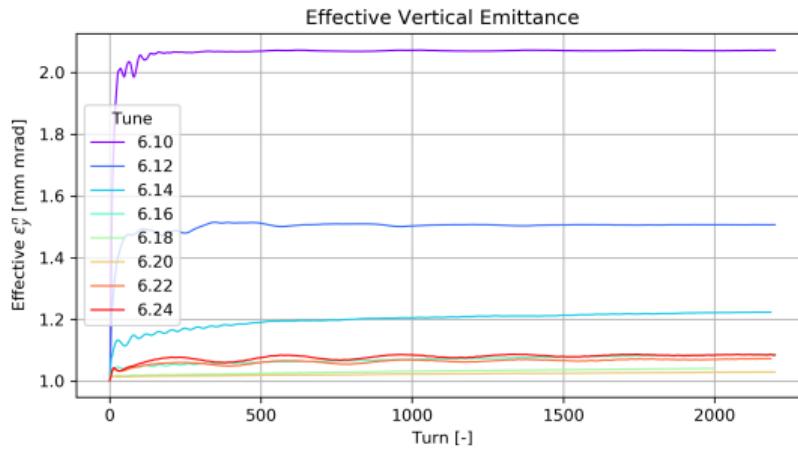
# Effective Horizontal Emittance: SbS no Longitudinal Kick



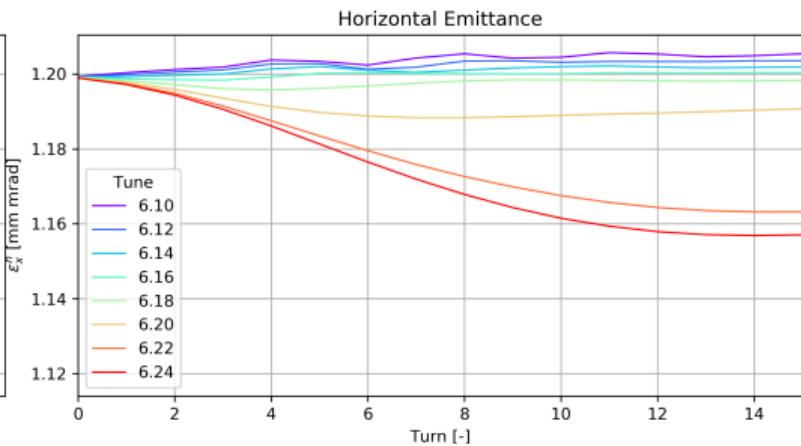
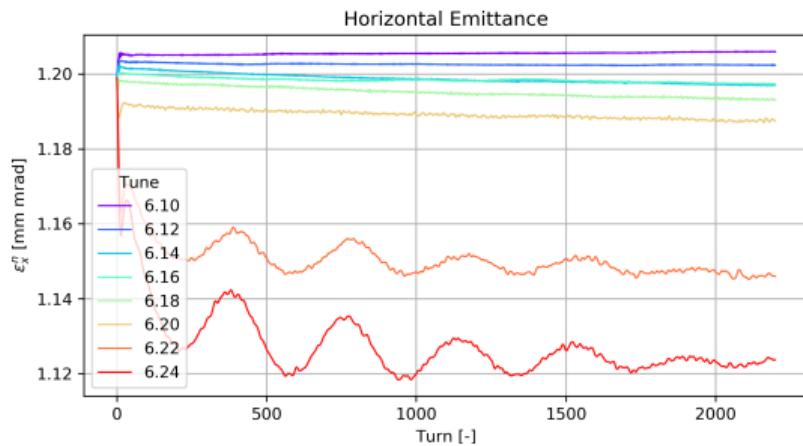
# Vertical Emittance: SbS no Longitudinal Kick



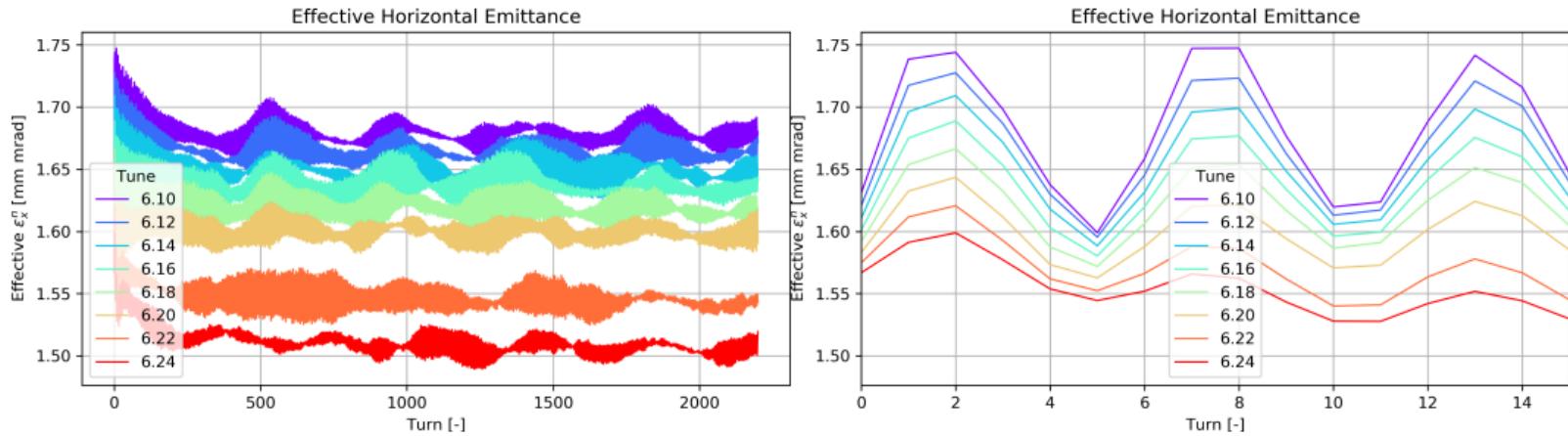
# Effective Vertical Emittance: SbS no Longitudinal Kick



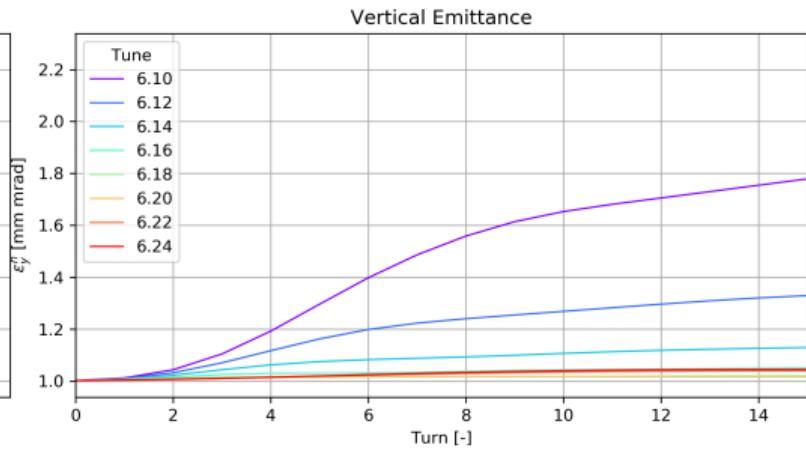
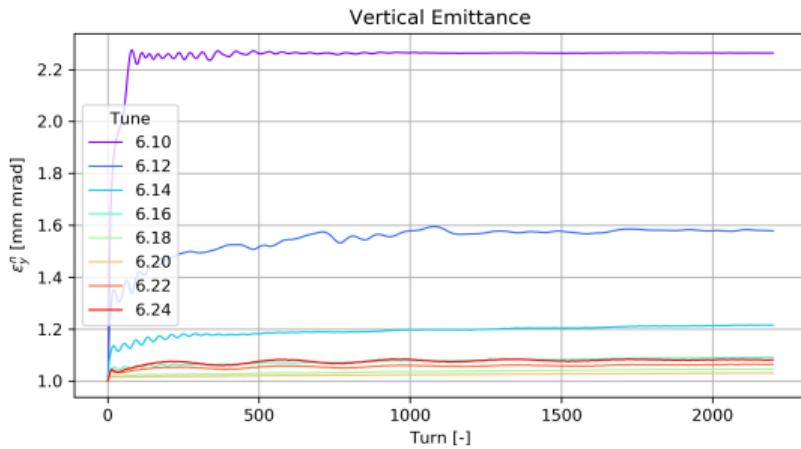
# Horizontal Emittance: 2.5D



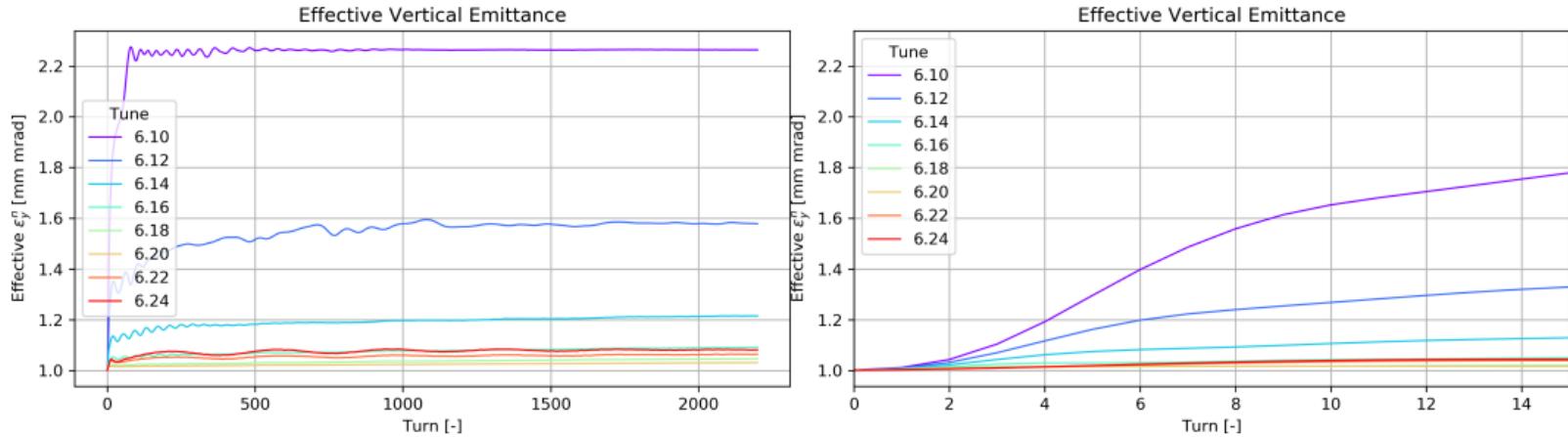
# Effective Horizontal Emittance: 2.5D



# Vertical Emittance: 2.5D



# Effective Vertical Emittance: 2.5D



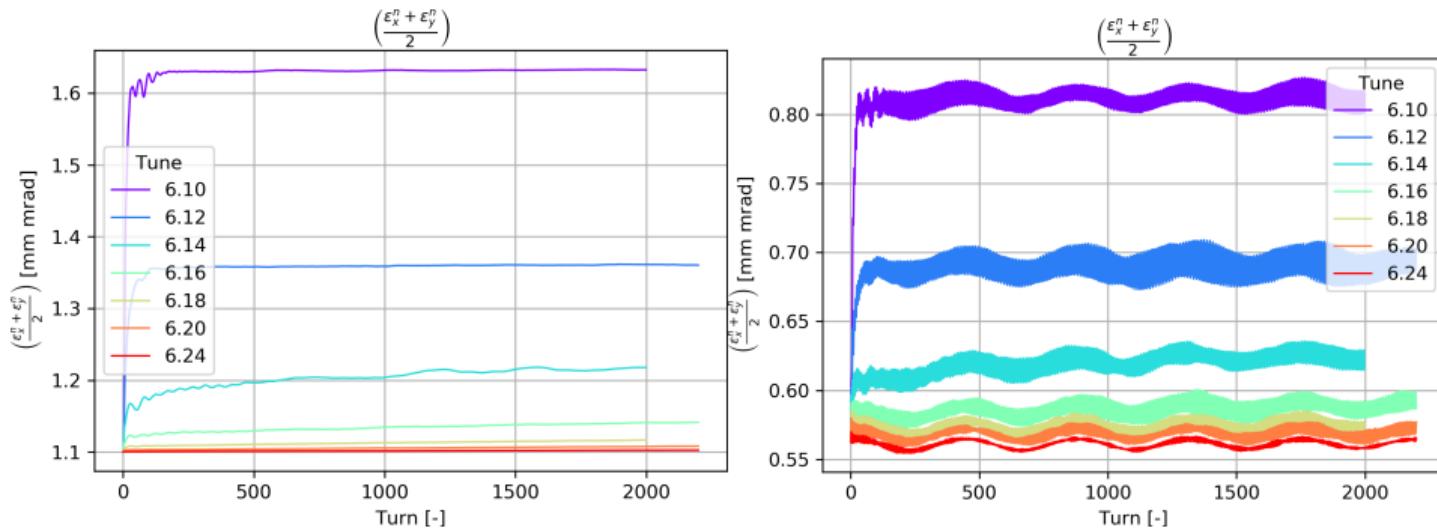
# Real and Effective Emittance Summary

- ▶ 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  $\sigma_x^{eff}$  and  $\beta_x^{eff}$ .
- ▶ Real/effective vertical emittances similar due to negligible vertical dispersion.
- ▶ Emittance growth largest in first few hundred turns.

# Average Emittances: Slice-by-Slice

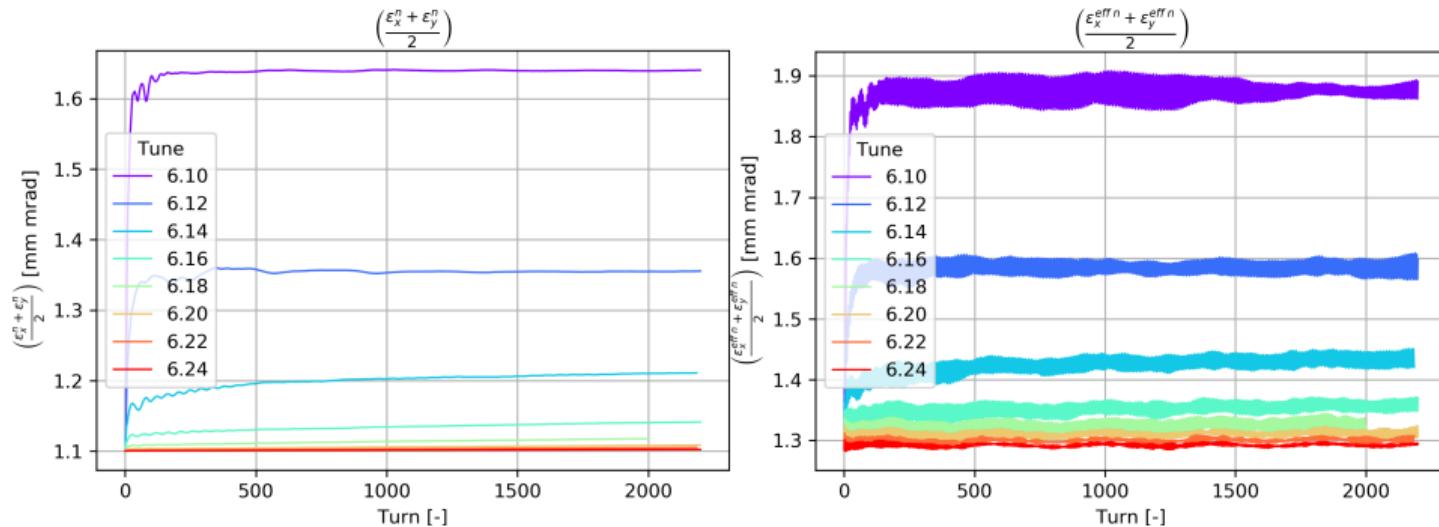
Mean of normalised emittance, mean of effective emittance.

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



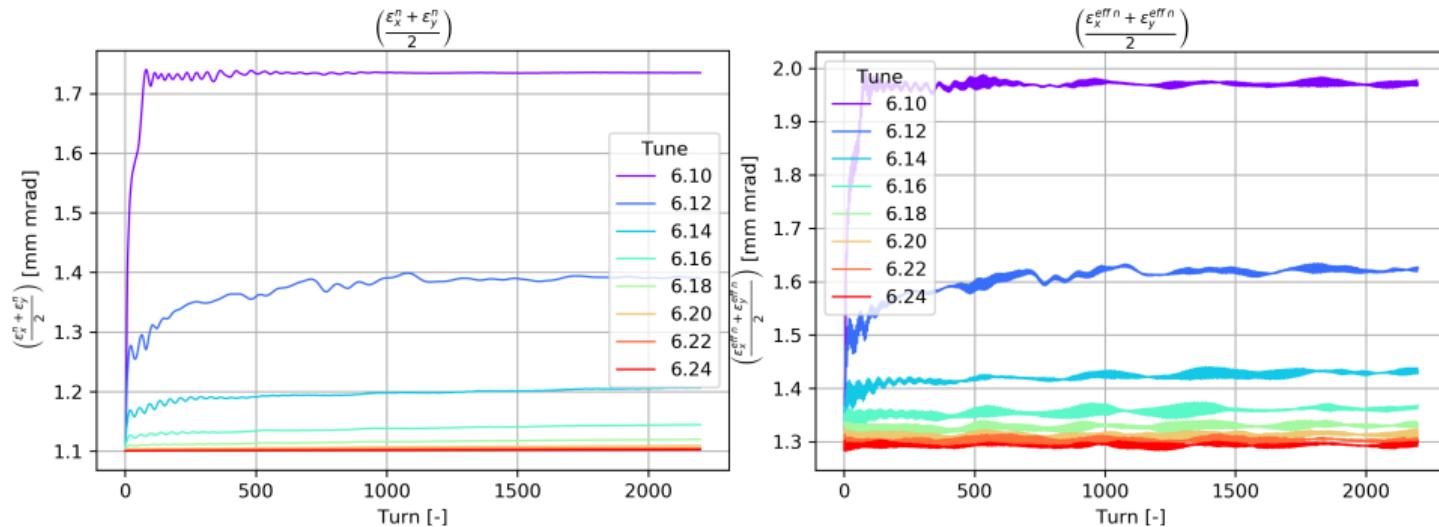
# Average Emittances: Slice-by-Slice no Long Kick

Mean of normalised emittance, mean of normalised effective emittance.

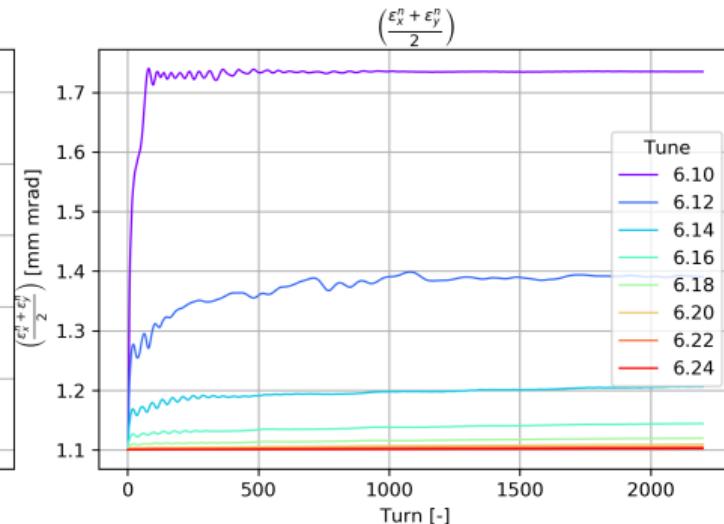
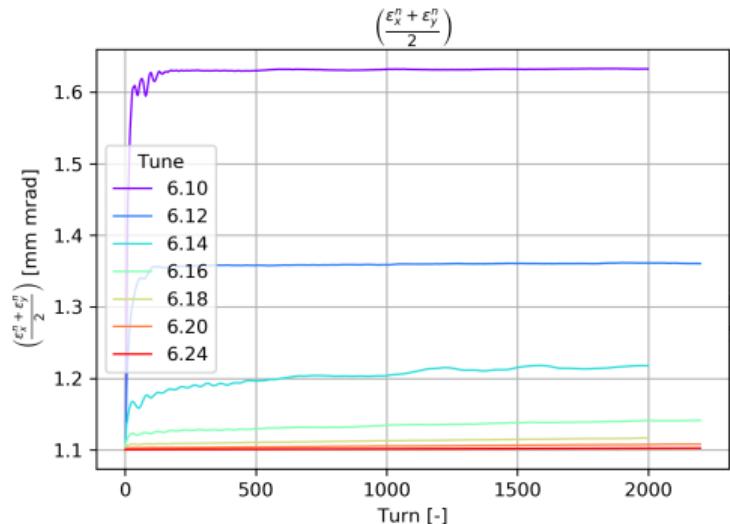


# Average Emittances: 2.5D

Mean of normalised emittance, mean of normalised effective emittance.



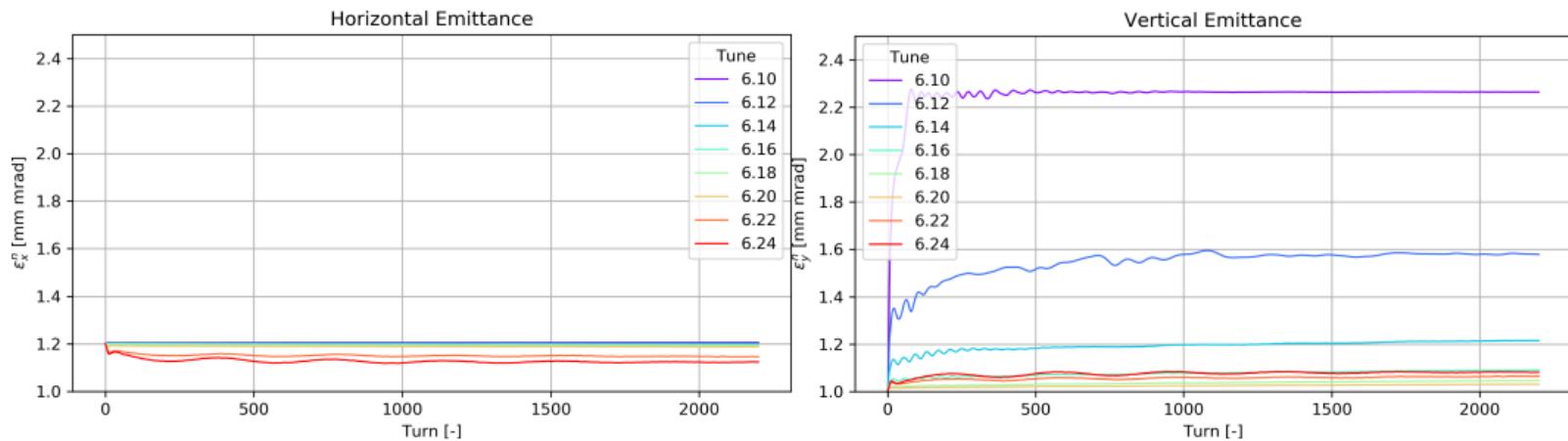
# Average Emittances: SbS & 2.5D



# Emittance Exchange: Same Scale 2.5D

Observing  $Q_y = 6.22$  and  $6.24$

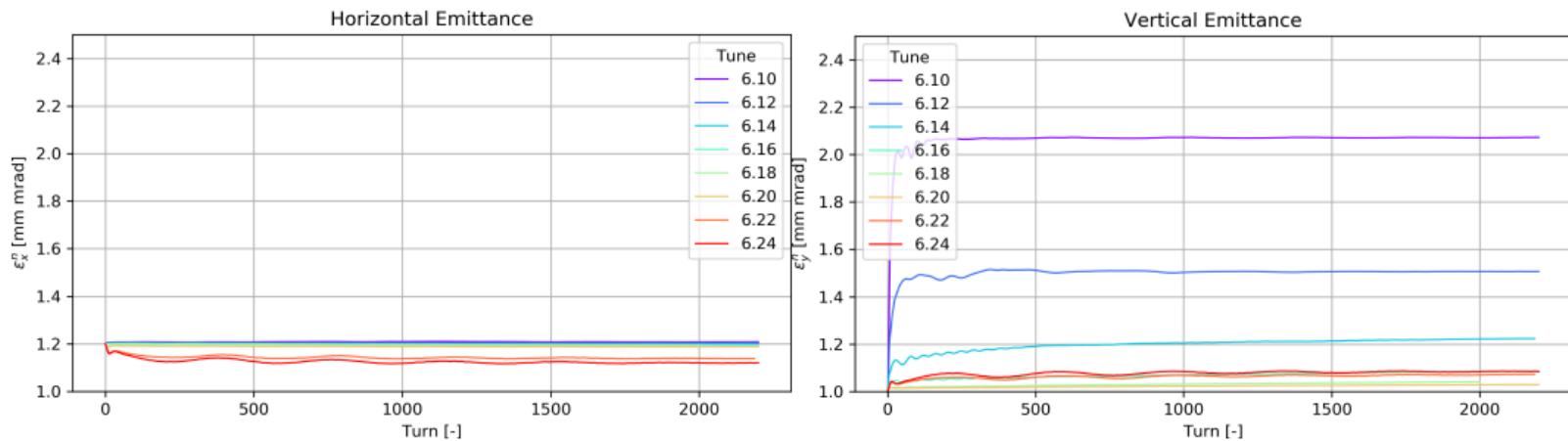
Obvious emittance exchange



# Emittance Exchange: Same Scale nLK

Observing  $Q_y = 6.22$  and  $6.24$

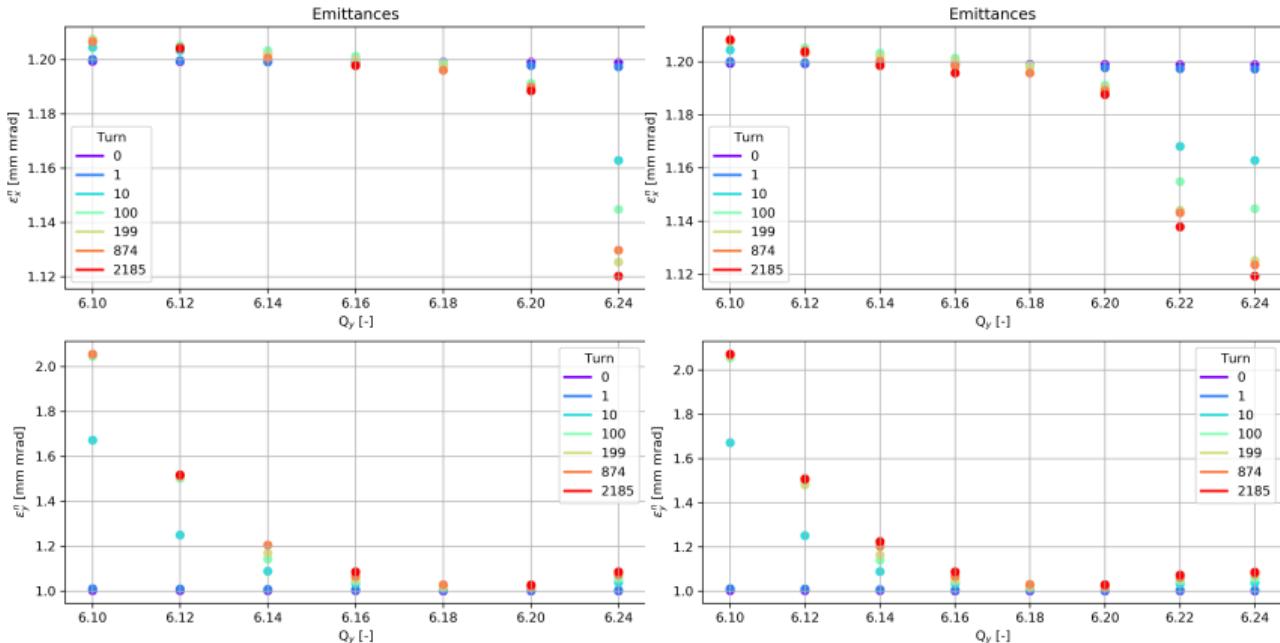
Obvious emittance exchange



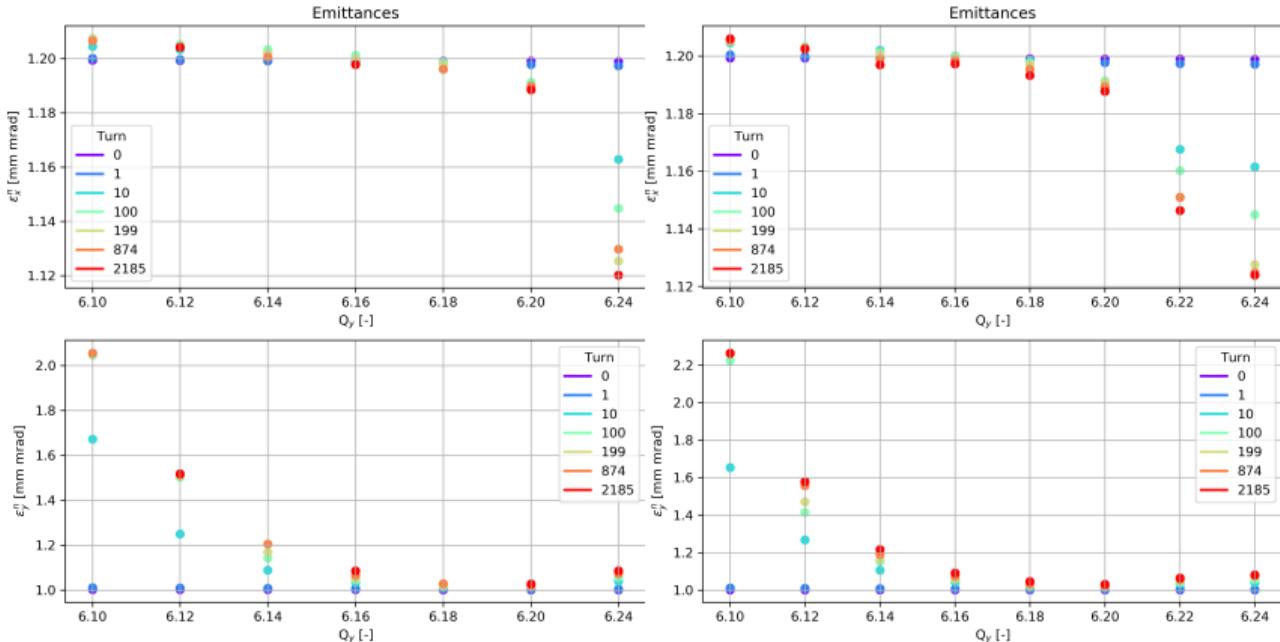
# Average Emittance & Emittance Exchange Summary

- ▶ 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  $(Q_x, Q_y) = (6.21, 6.21)$ .

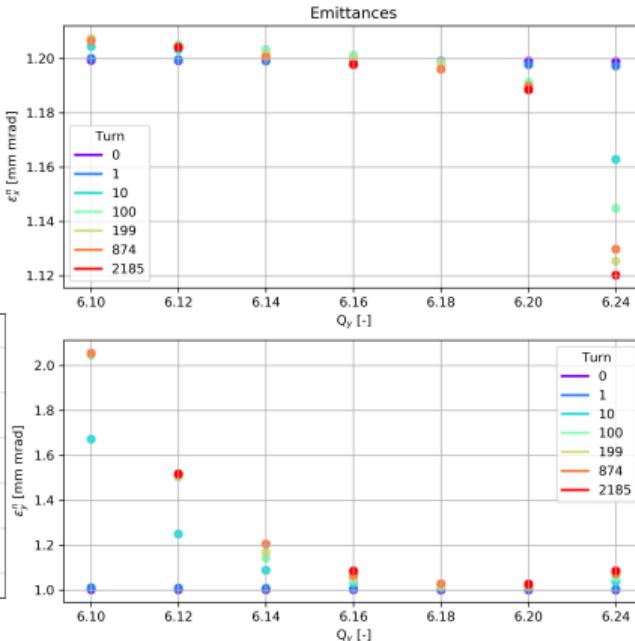
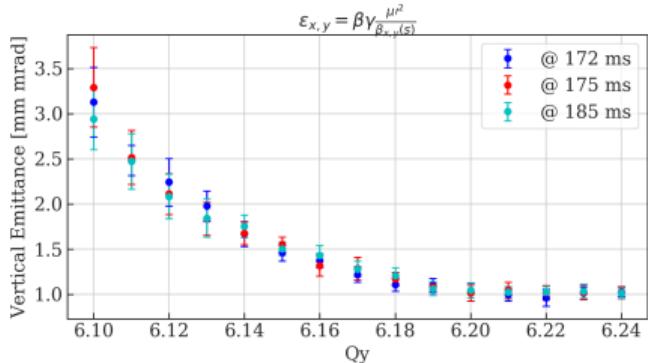
# Final Emittances: SbS & nLK



# 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 wiresscanner (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  $\approx 1.5$ .

Simulation Parameters

Tune Footprints

Apertures

Optics

Dispersion

Beta Function

Results

Beam Size

Emittance

**Beam Profiles**

Convergence Tests

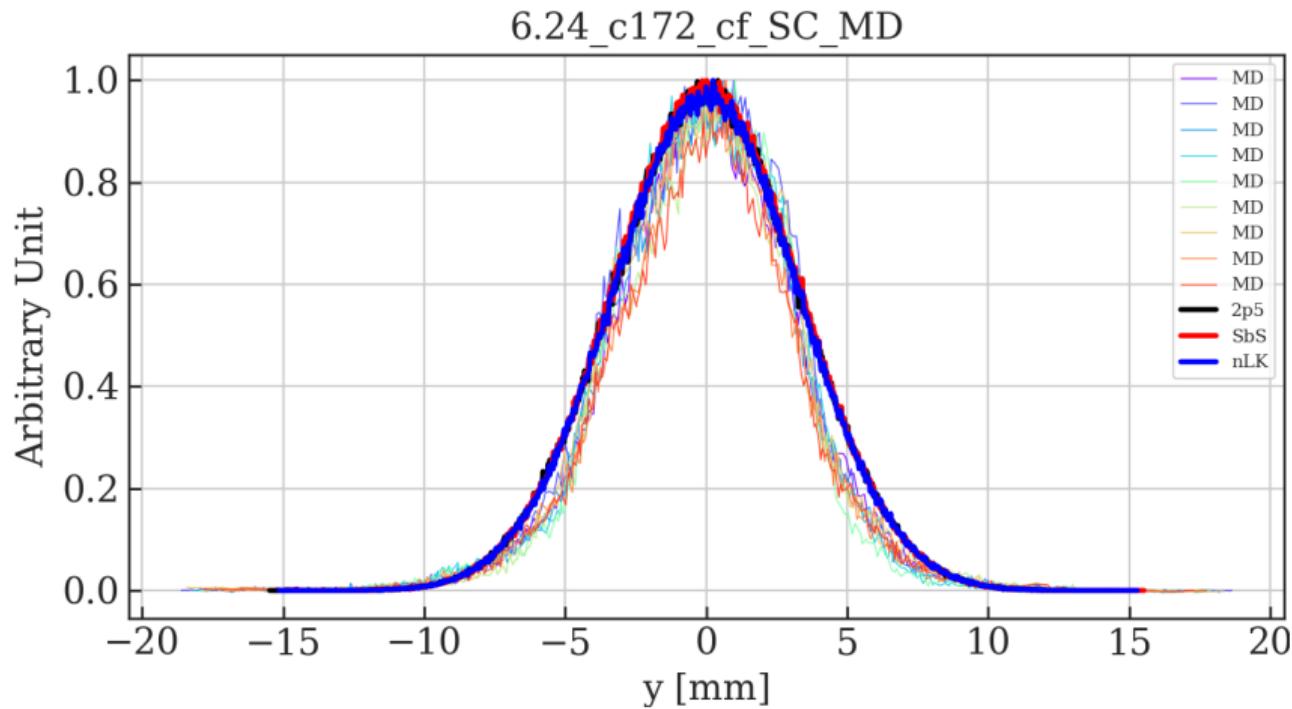


## Measured and simulated beam profiles.

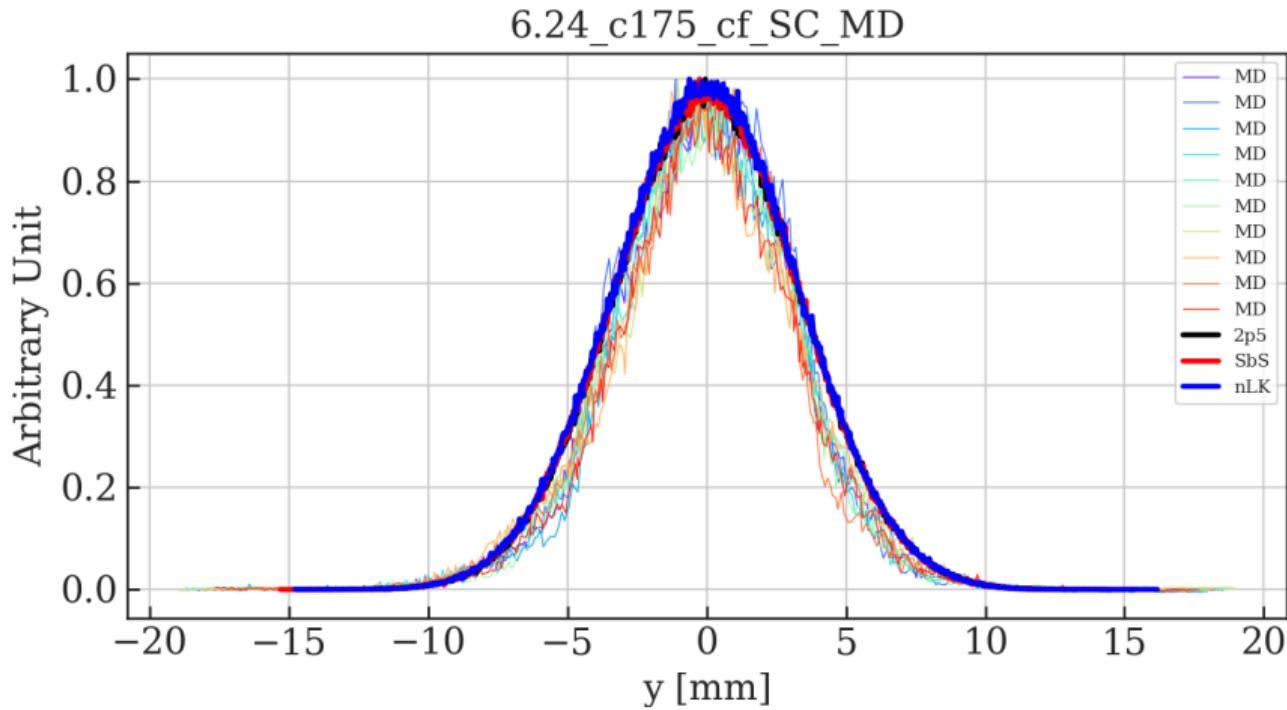
PS turn  $\approx 2.287 \mu\text{s}$ . Using maximum of each data set to normalise to 1.

- ▶ 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.

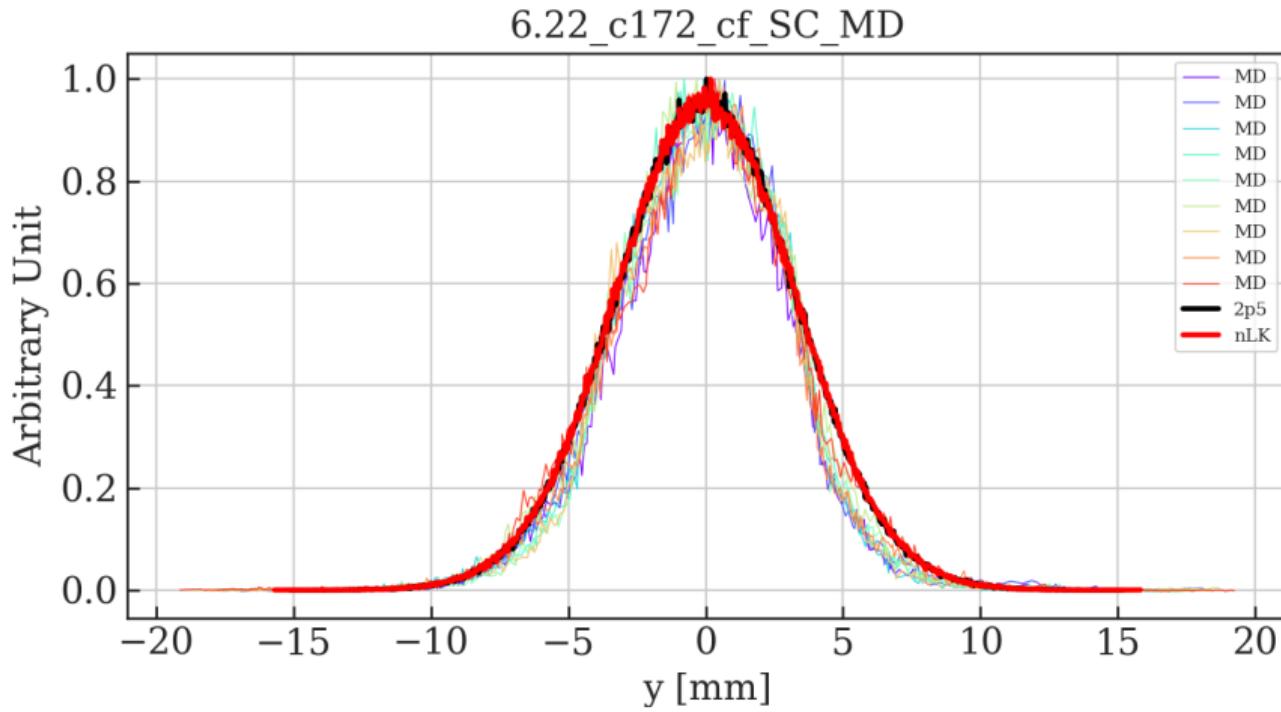
$Q_y = 6.24$ ,  $t = 172$  ms



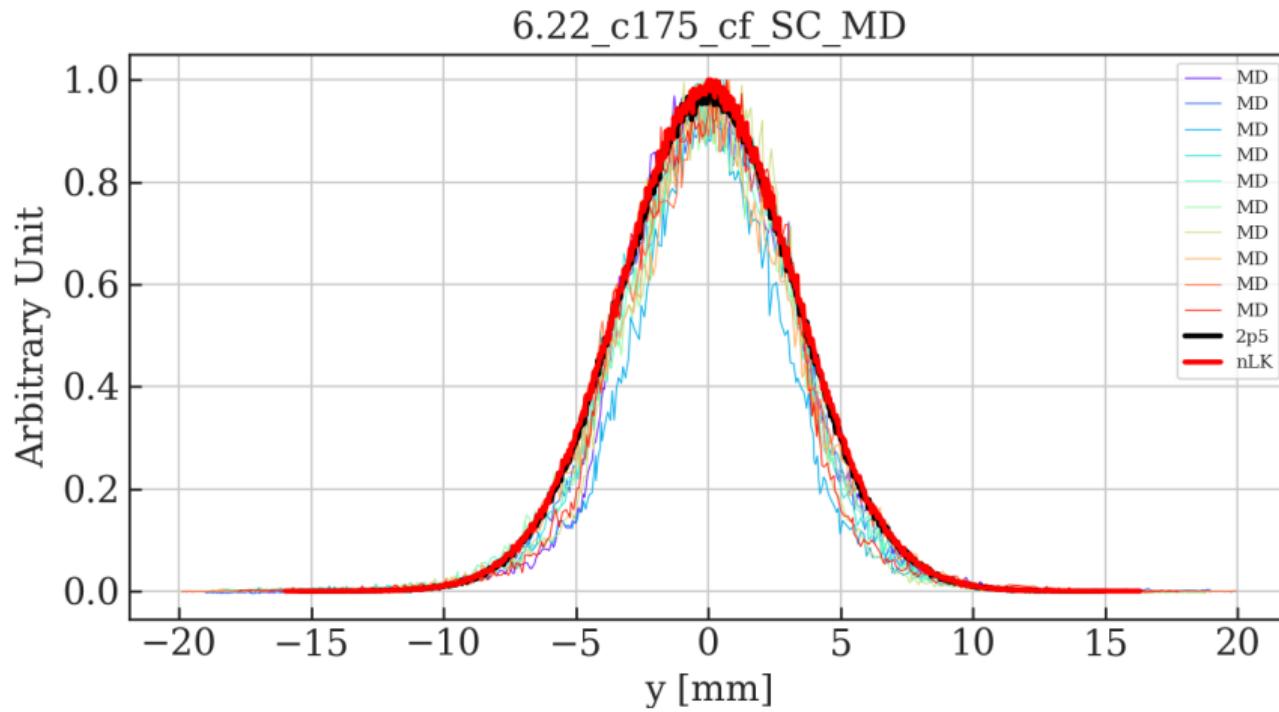
$Q_y = 6.24$ ,  $t = 175$  ms



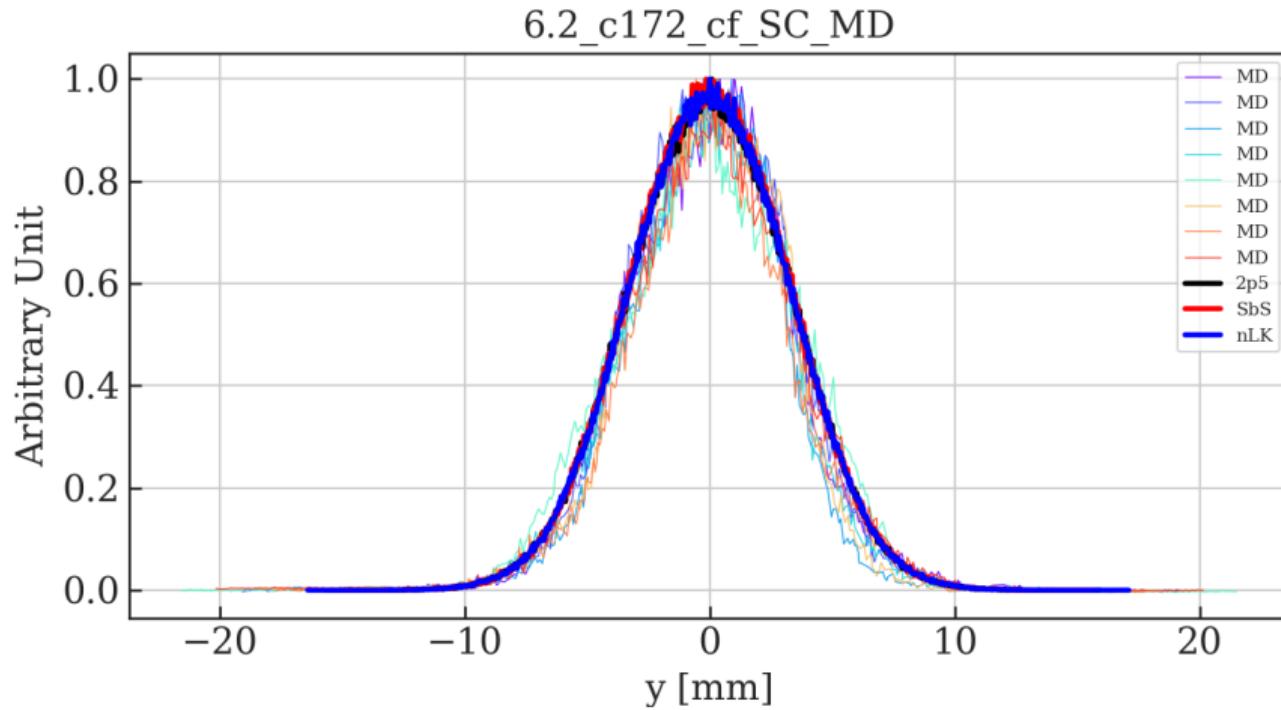
$Q_y = 6.22$ ,  $t = 172$  ms



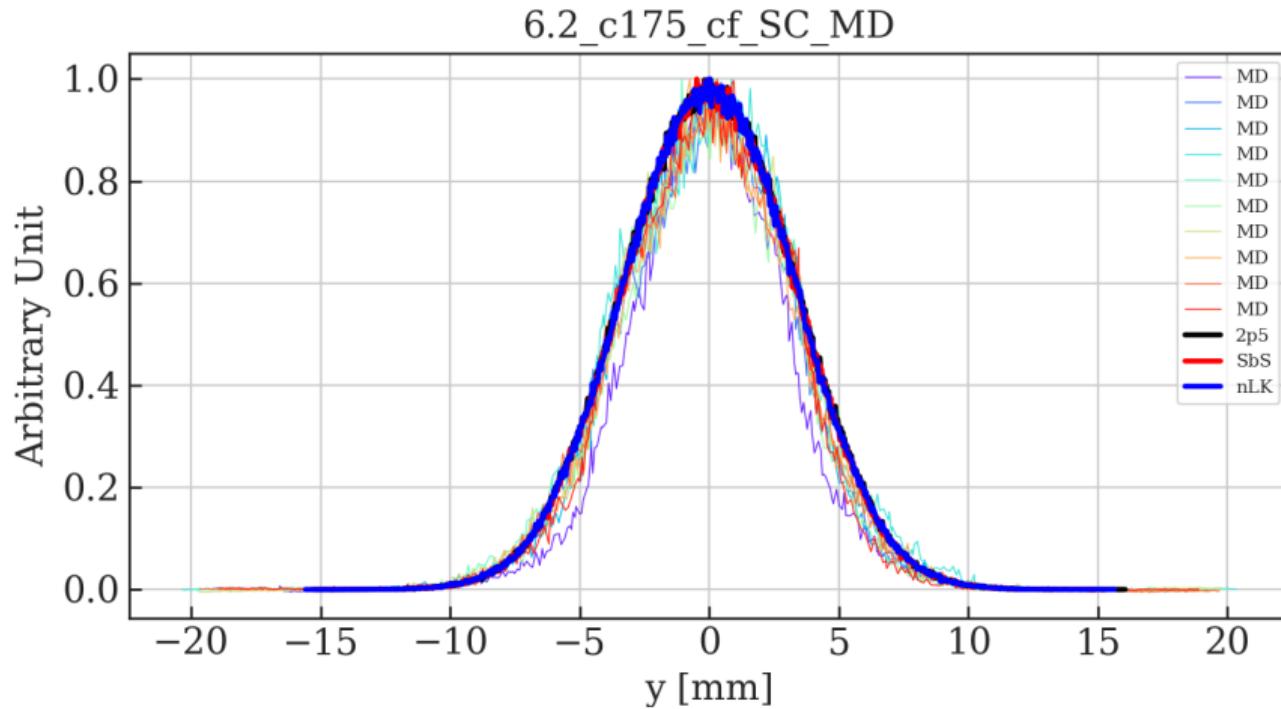
$Q_y = 6.22, t = 175 \text{ ms}$



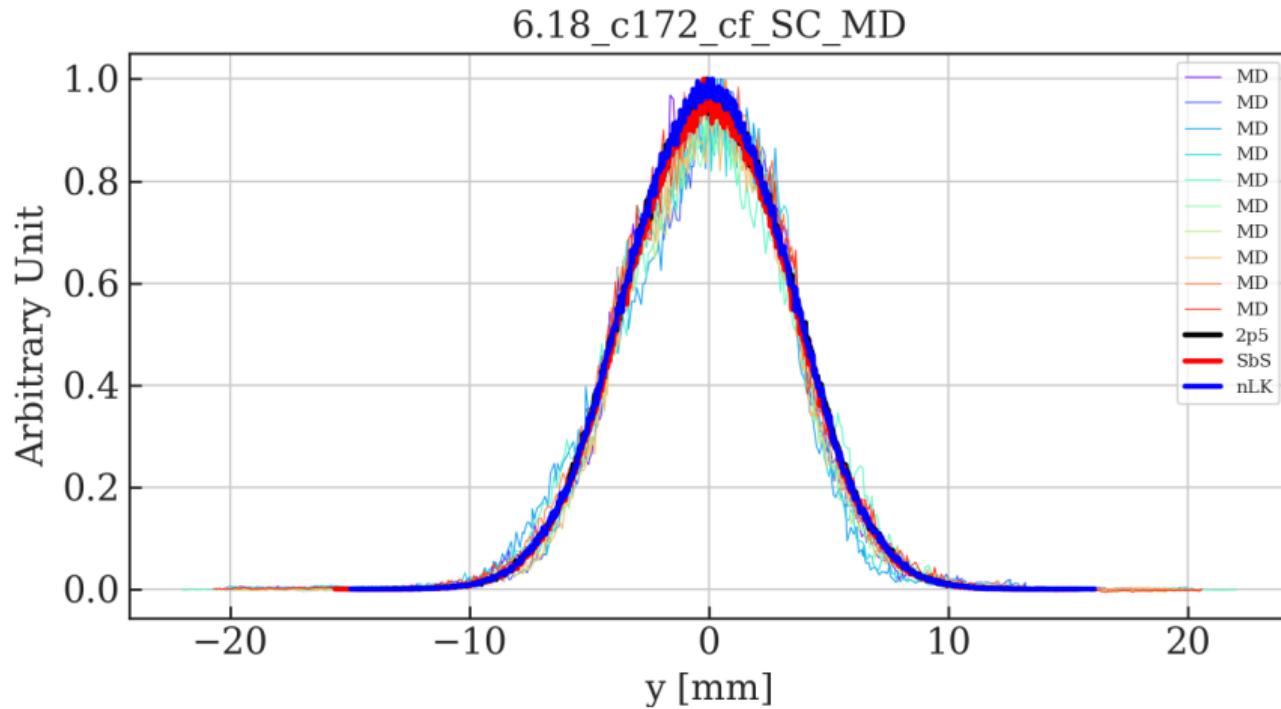
$Q_y = 6.20$ ,  $t = 172$  ms



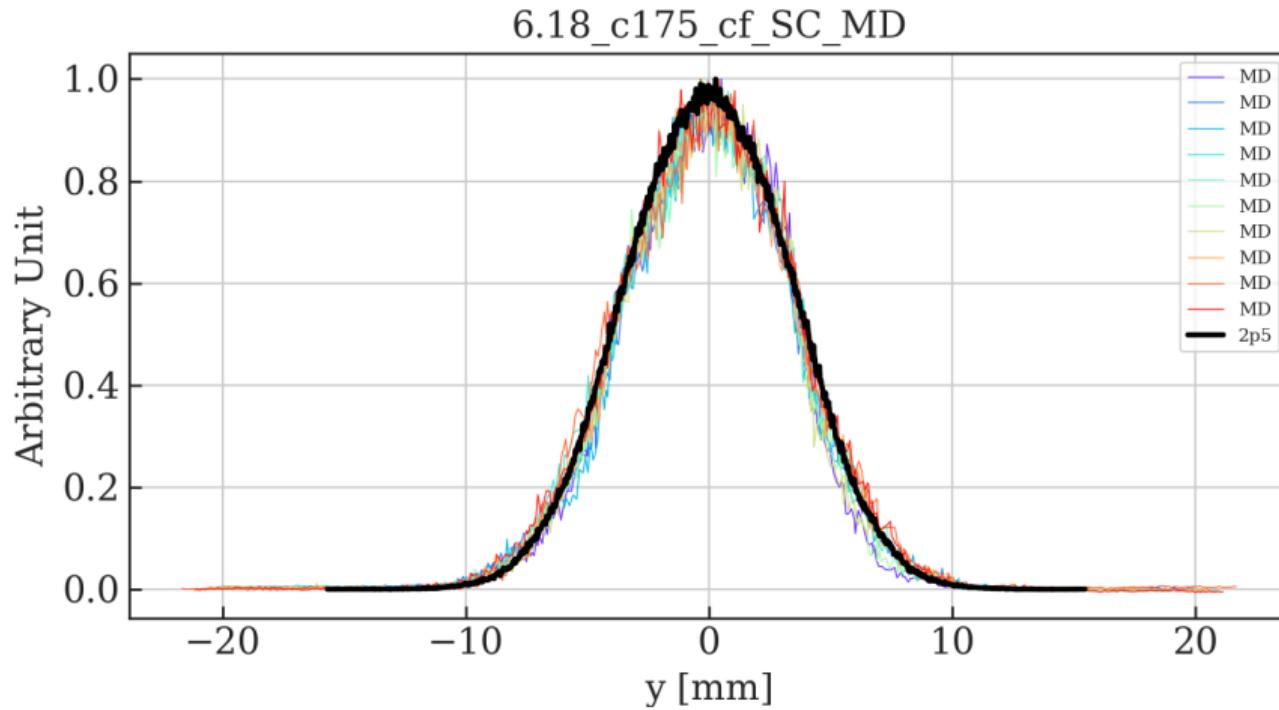
$Q_y = 6.20$ ,  $t = 175$  ms



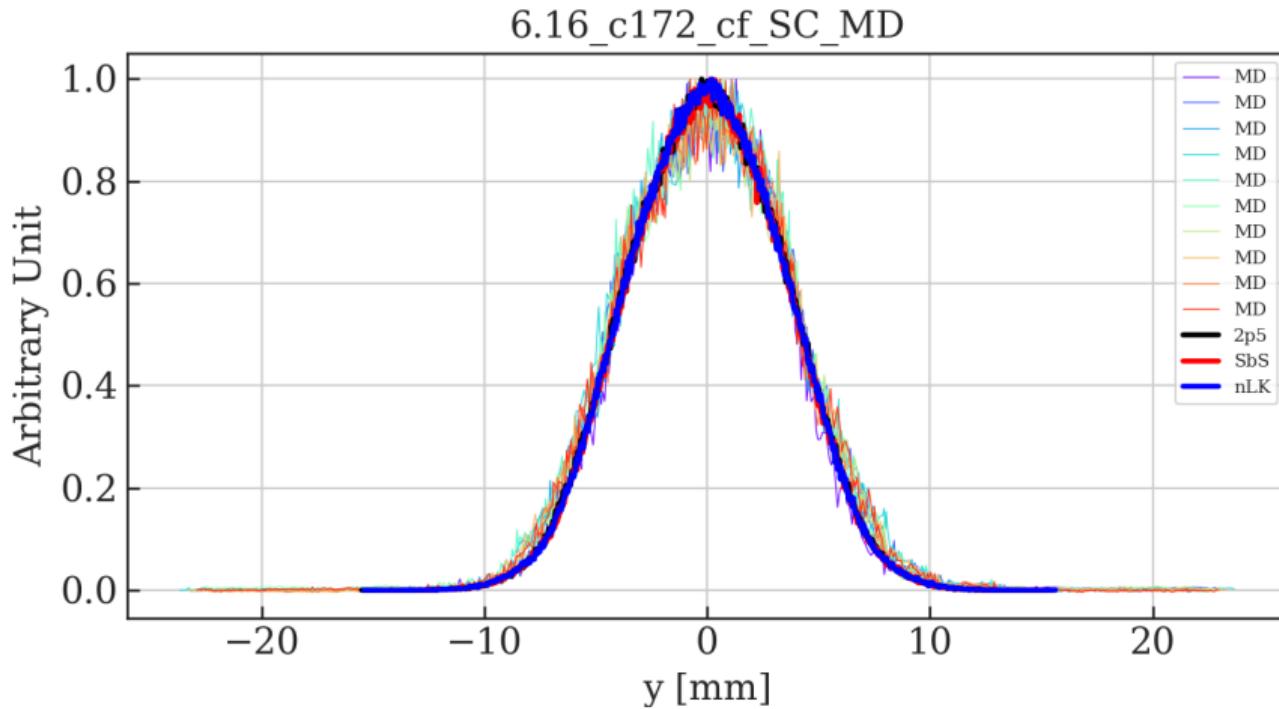
$Q_y = 6.18$ ,  $t = 172$  ms



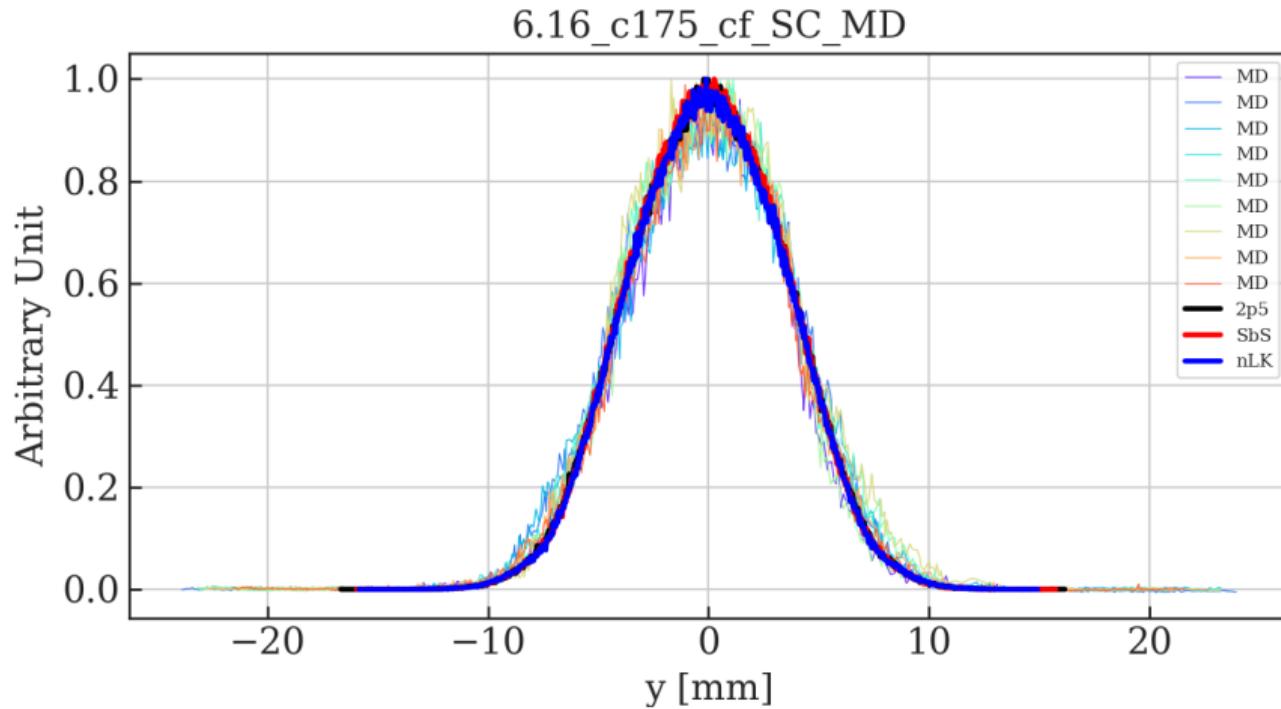
$Q_y = 6.18$ ,  $t = 175$  ms



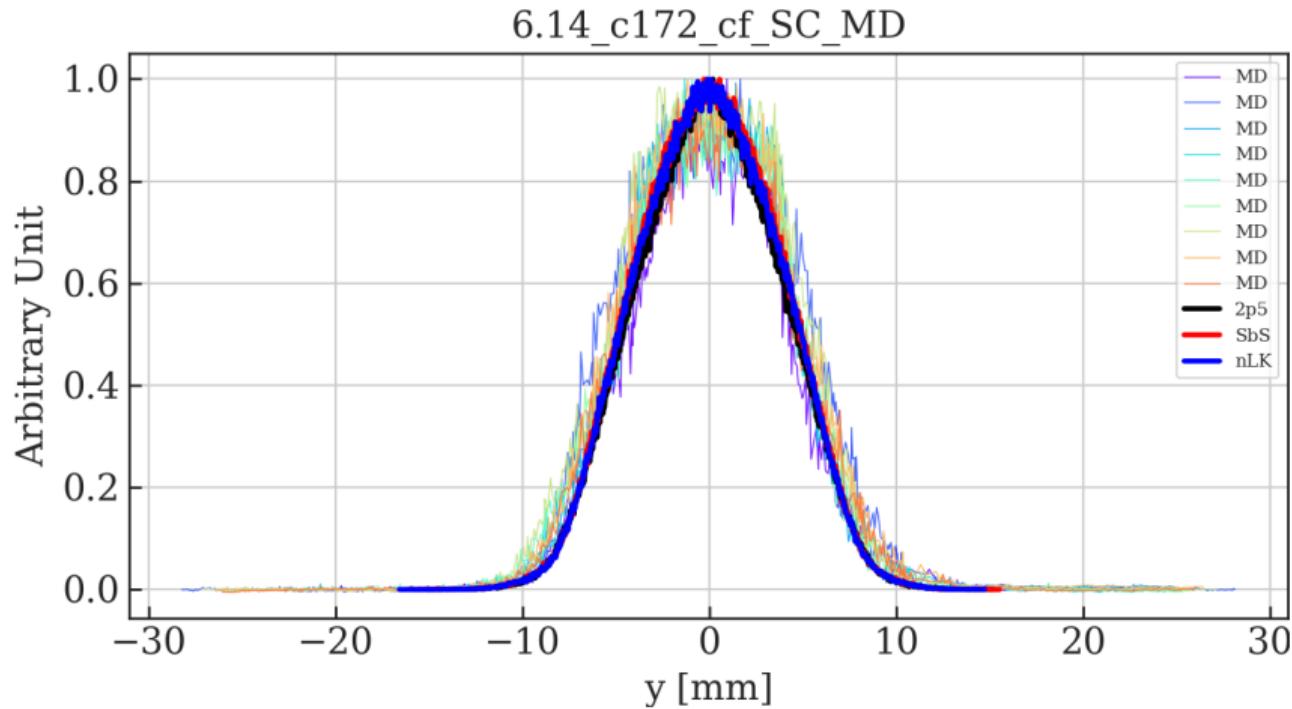
$Q_y = 6.16$ ,  $t = 172$  ms



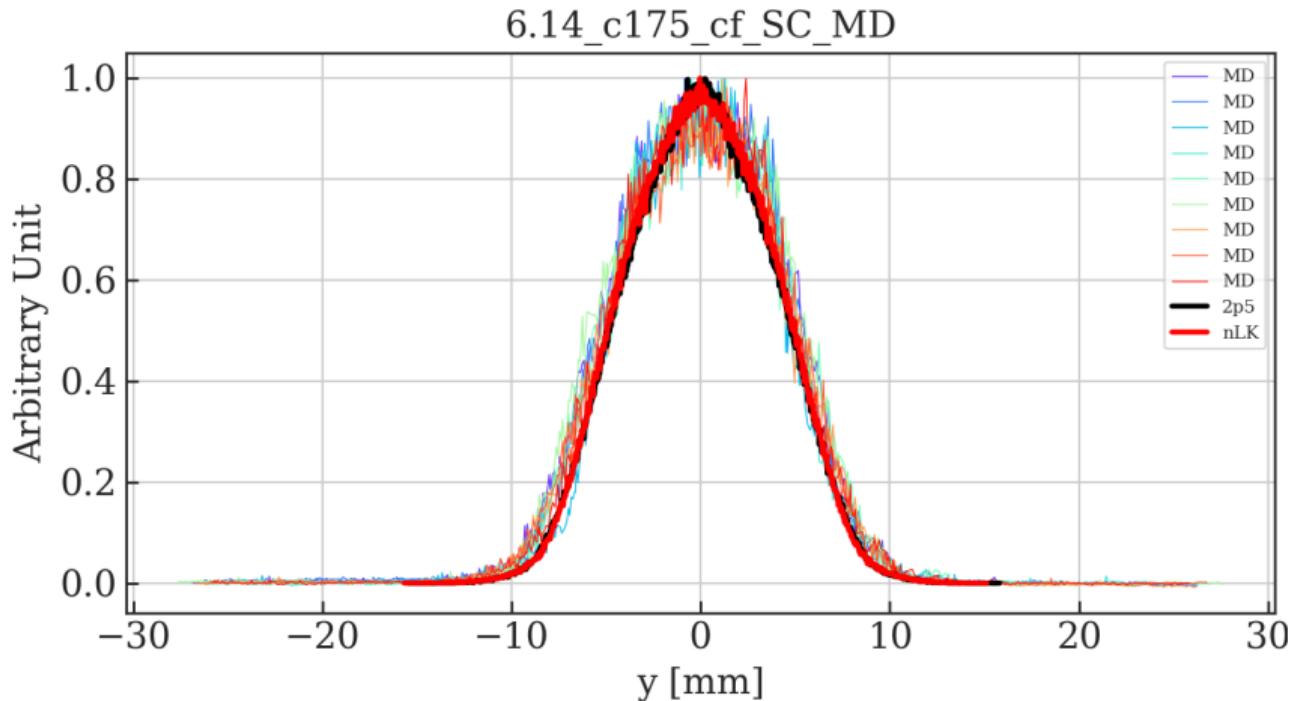
**$Q_y = 6.16$ ,  $t = 175$  ms**



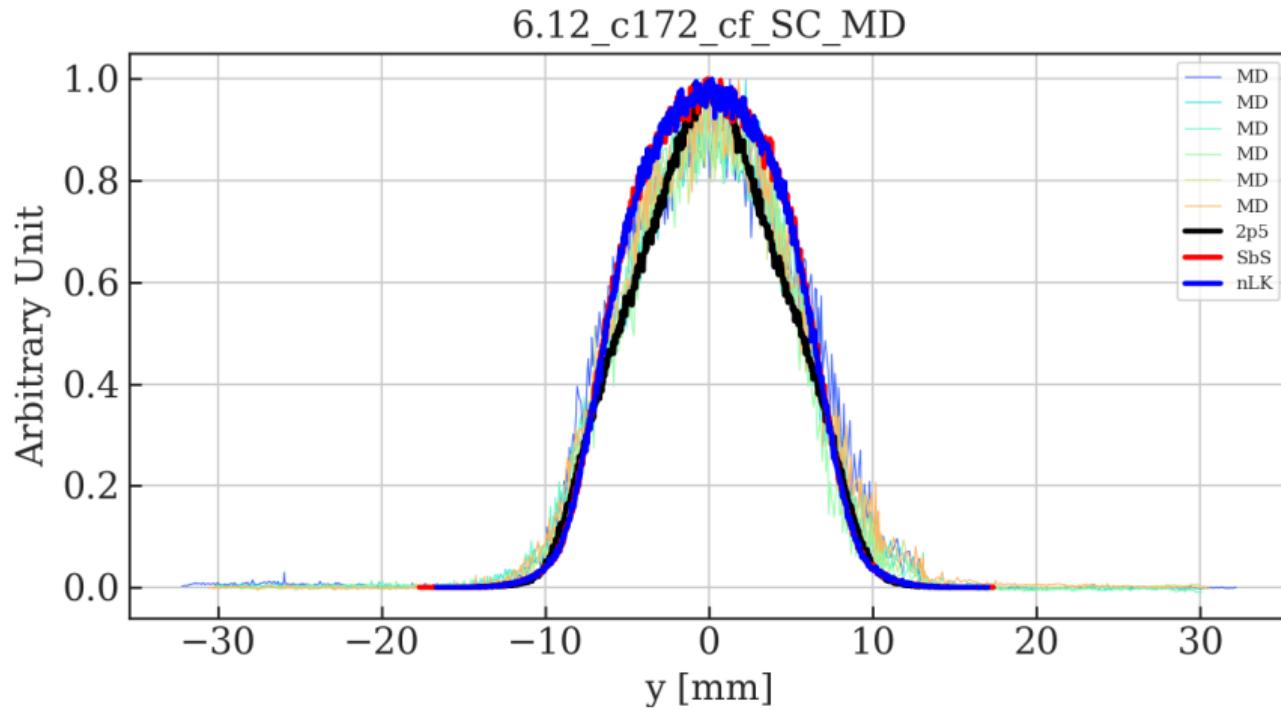
$Q_y = 6.14$ ,  $t = 172$  ms



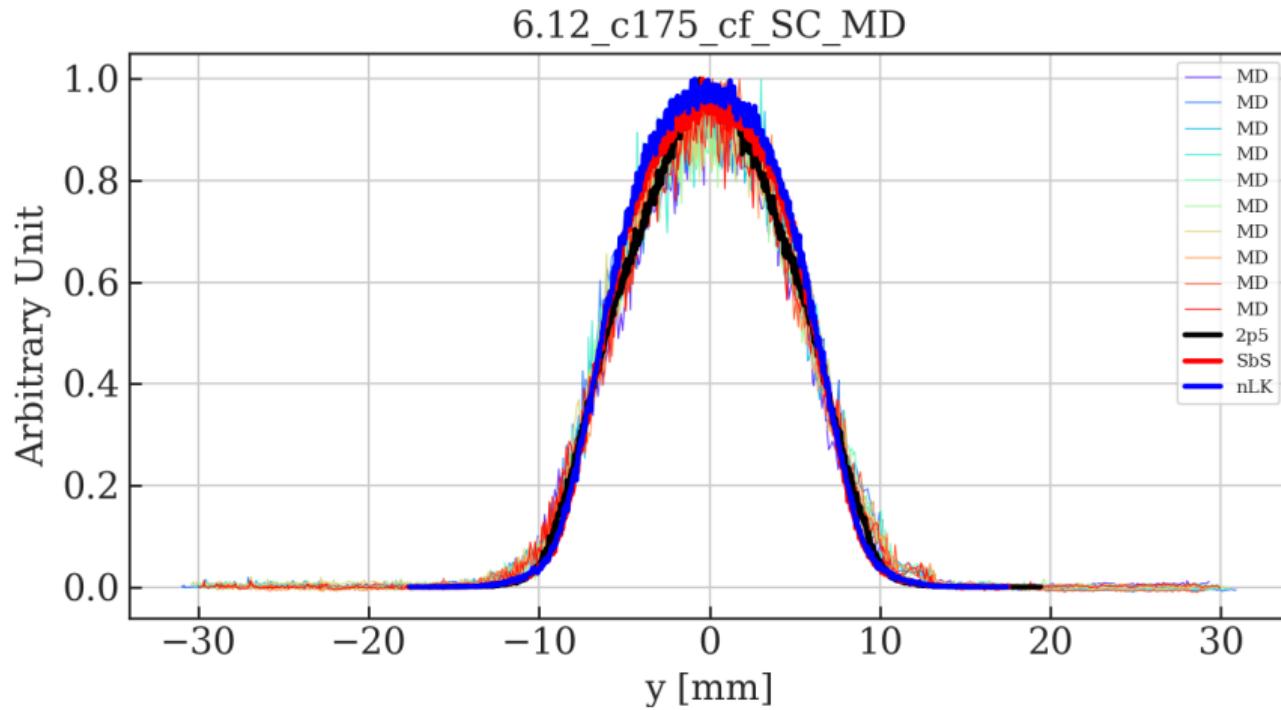
$Q_y = 6.14$ ,  $t = 175$  ms



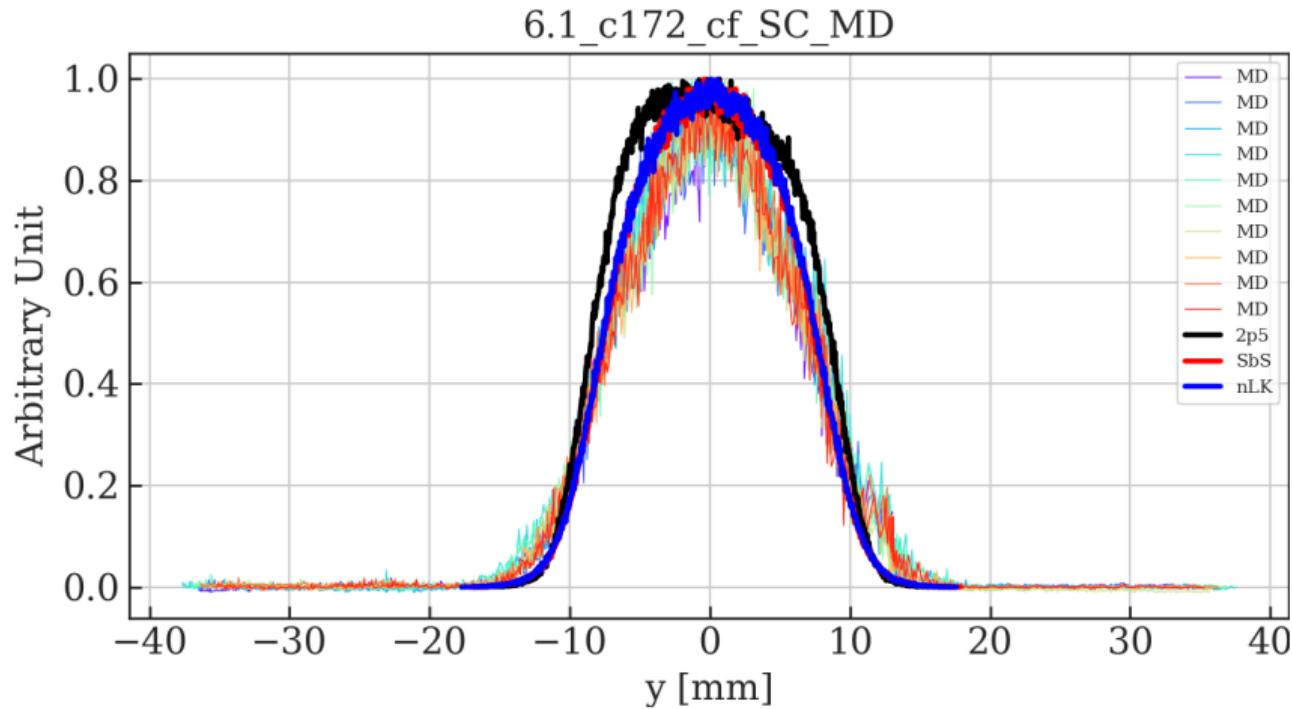
$Q_y = 6.12$ ,  $t = 172$  ms



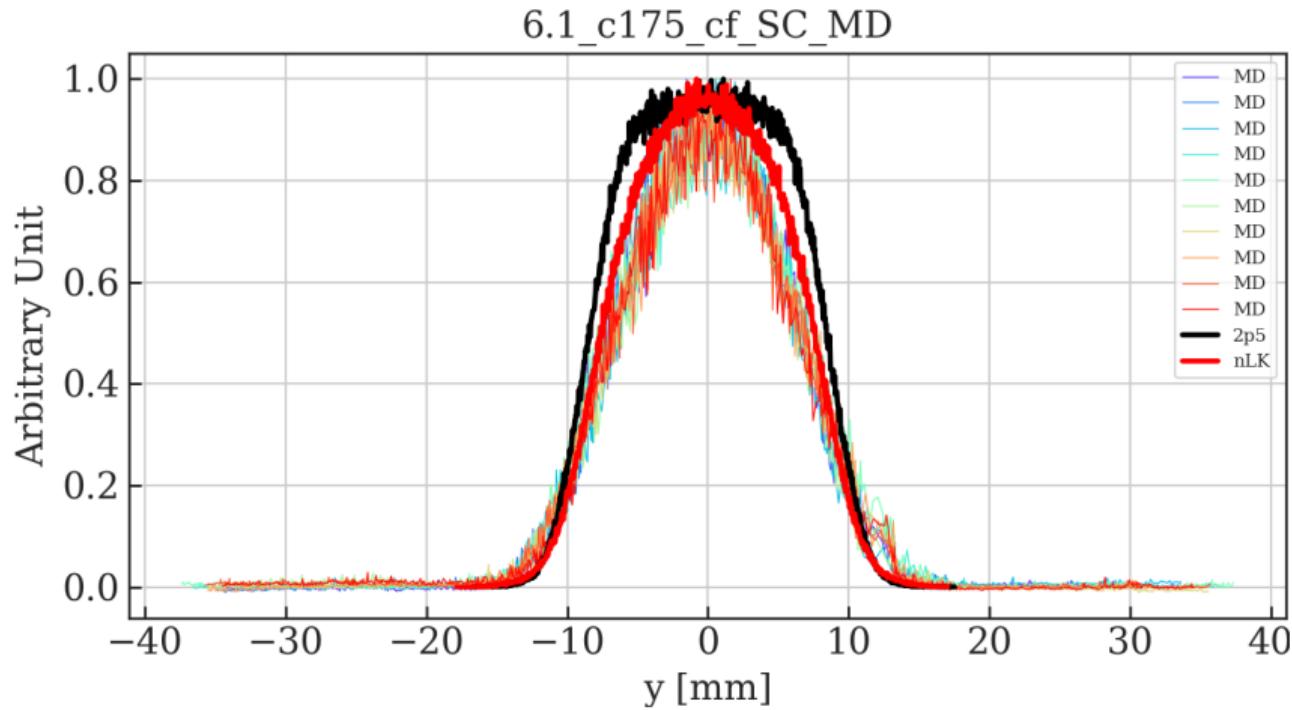
$Q_y = 6.12$ ,  $t = 175$  ms



$Q_y = 6.10$ ,  $t = 172$  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 each other.
- ▶ 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.

**Simulation Parameters**

**Tune Footprints**

**Apertures**

**Optics**

Dispersion

Beta Function

**Results**

Beam Size

Emittance

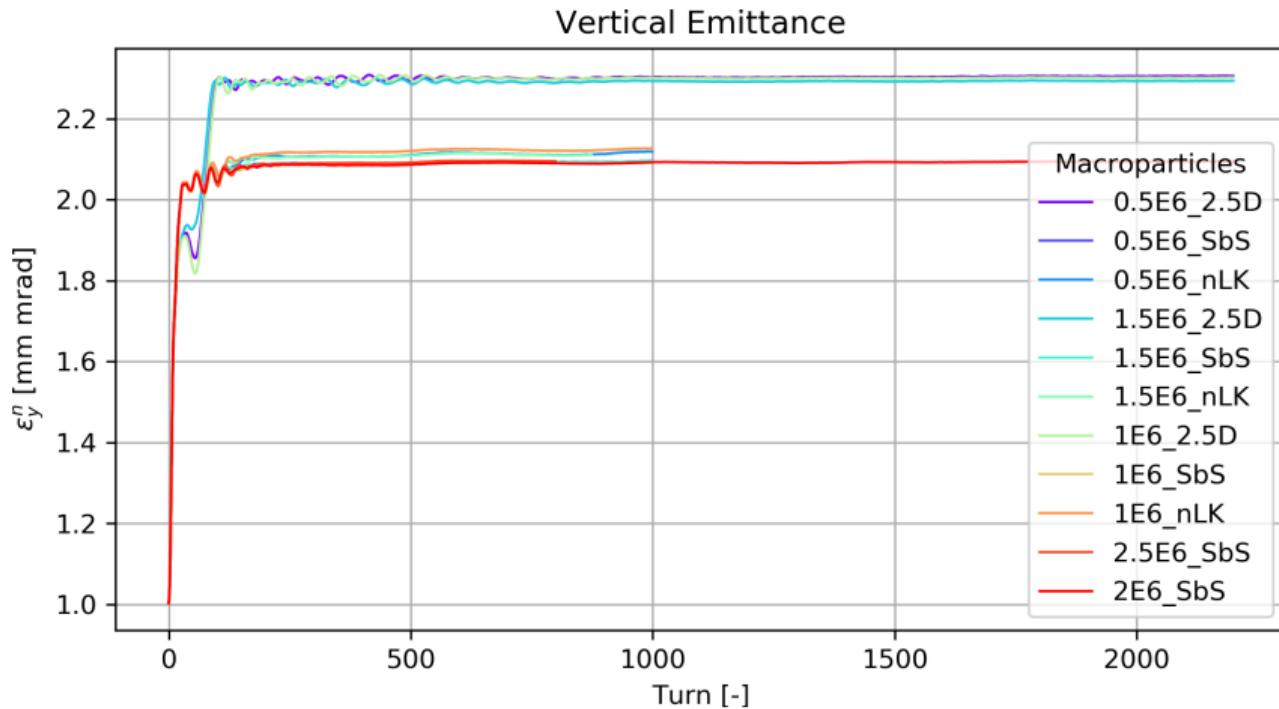
Beam Profiles

**Convergence Tests**

# 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 **Slice-by-slice** with longitudinal kick (**SbS**), Slice-by-slice with **no** longitudinal kick (**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



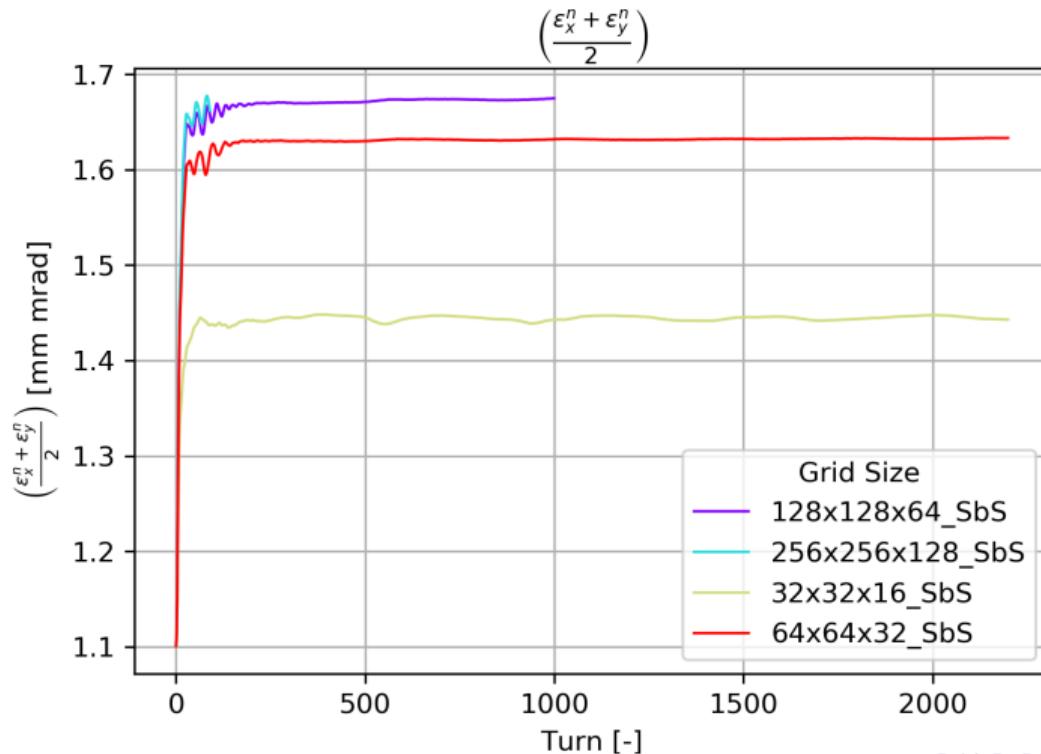
# Space Charge Grid Size Scan

- ▶ 1.5 million macro particles. Grids sizes shown in Table 83.
- ▶ for **Slice-by-slice** with longitudinal kick (**SbS**), Slice-by-slice with **no** longitudinal kick (**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.

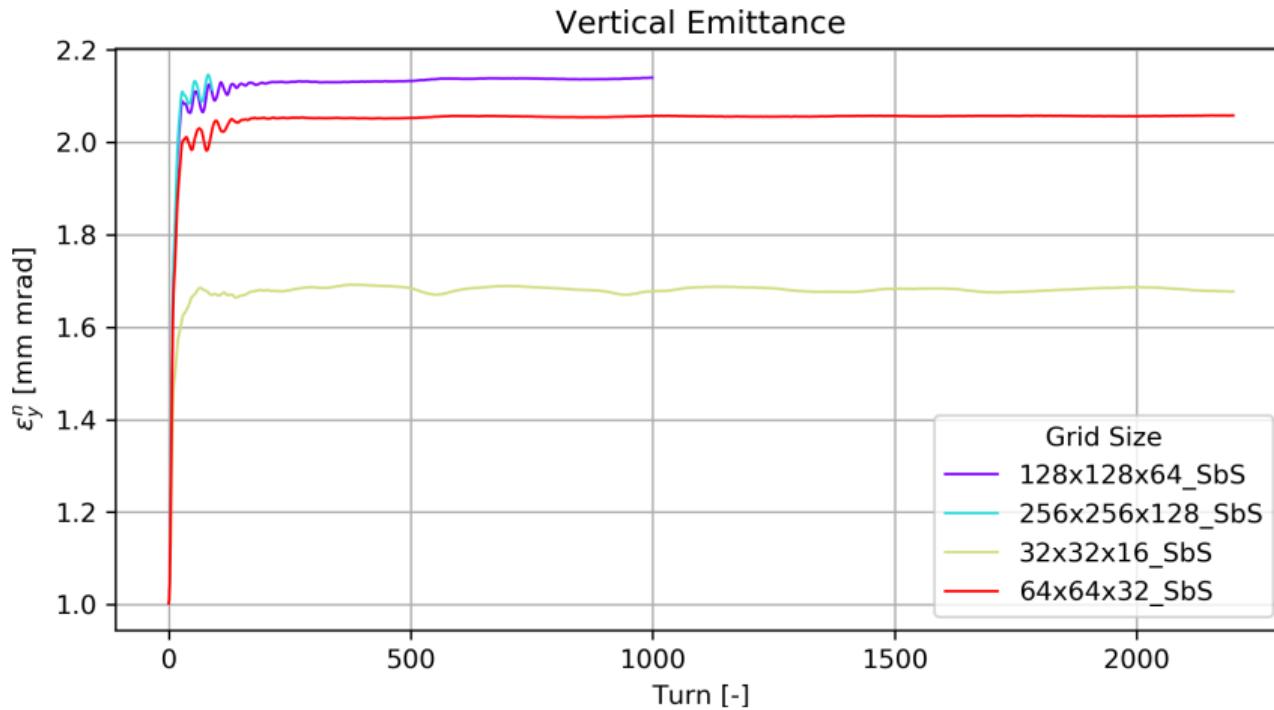
x	y	z	SLURM Nodes
32	32	16	4
64	64	32	4
128	128	64	6
256	256	128	8
512	512	256	16

**Table 3:** Space charge grid sizes.

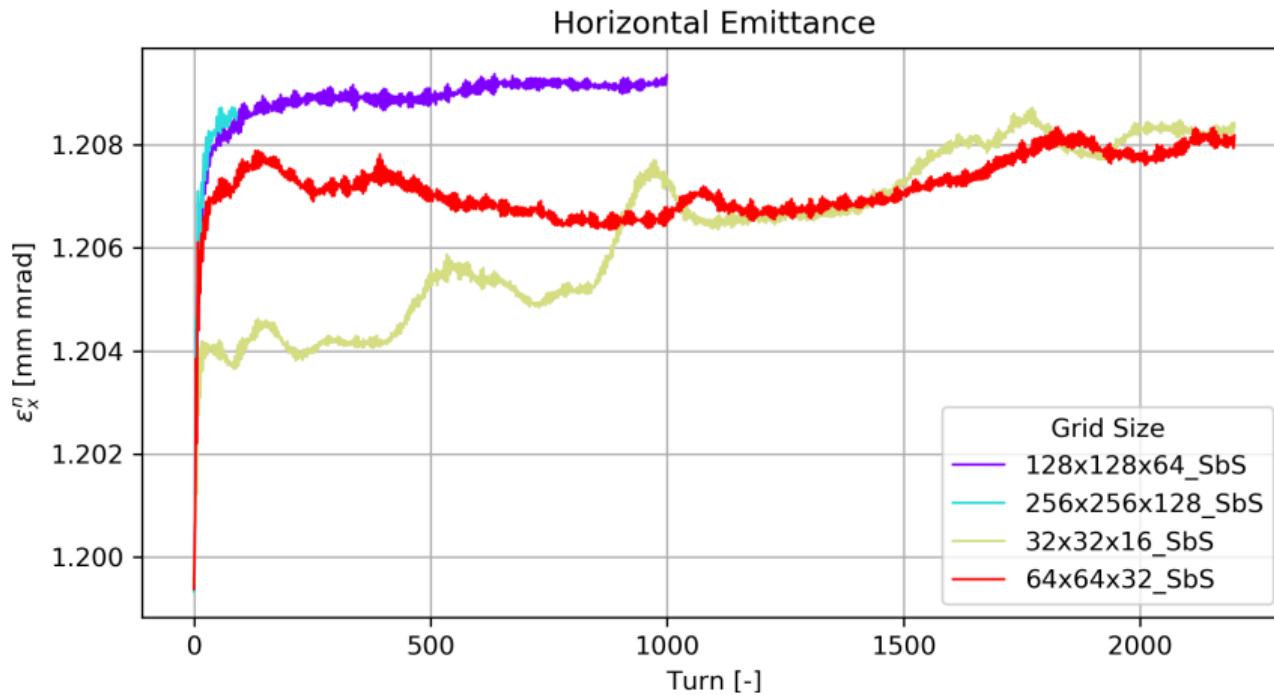
# Space Charge Grid Size Scan: Slice-by-Slice: Average Emittance



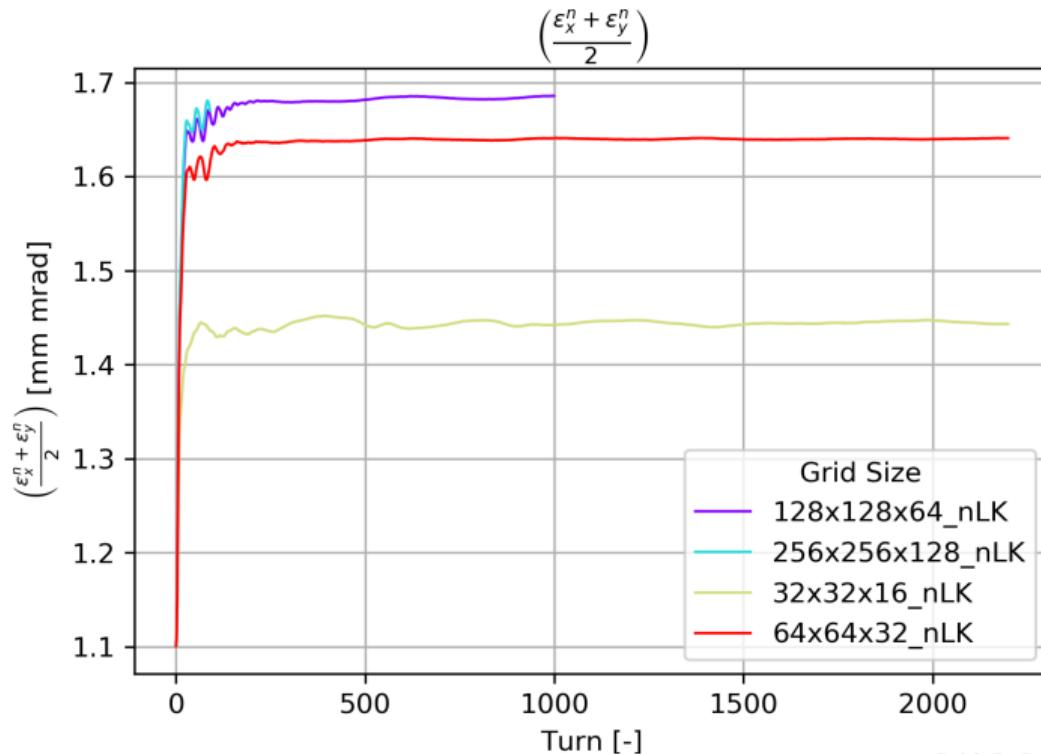
# Space Charge Grid Size Scan: Slice-by-Slice: Vertical Emittance



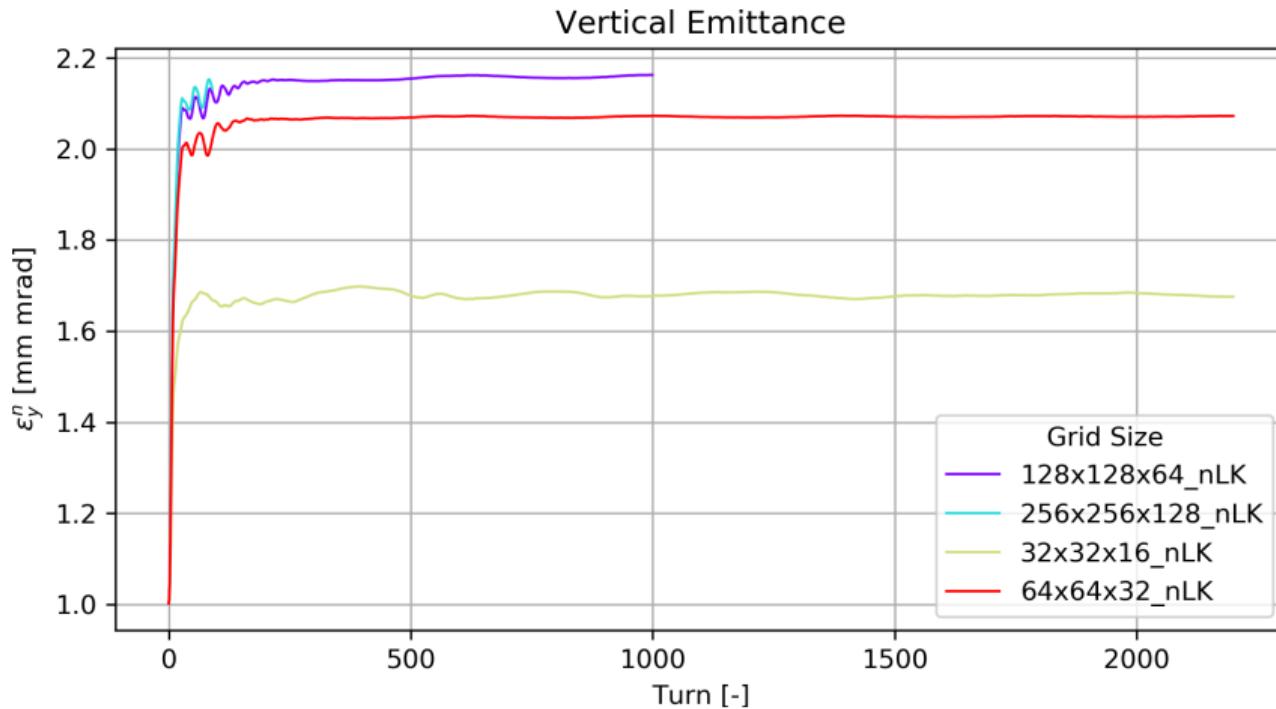
# Space Charge Grid Size Scan: Slice-by-Slice: Horizontal Emittance



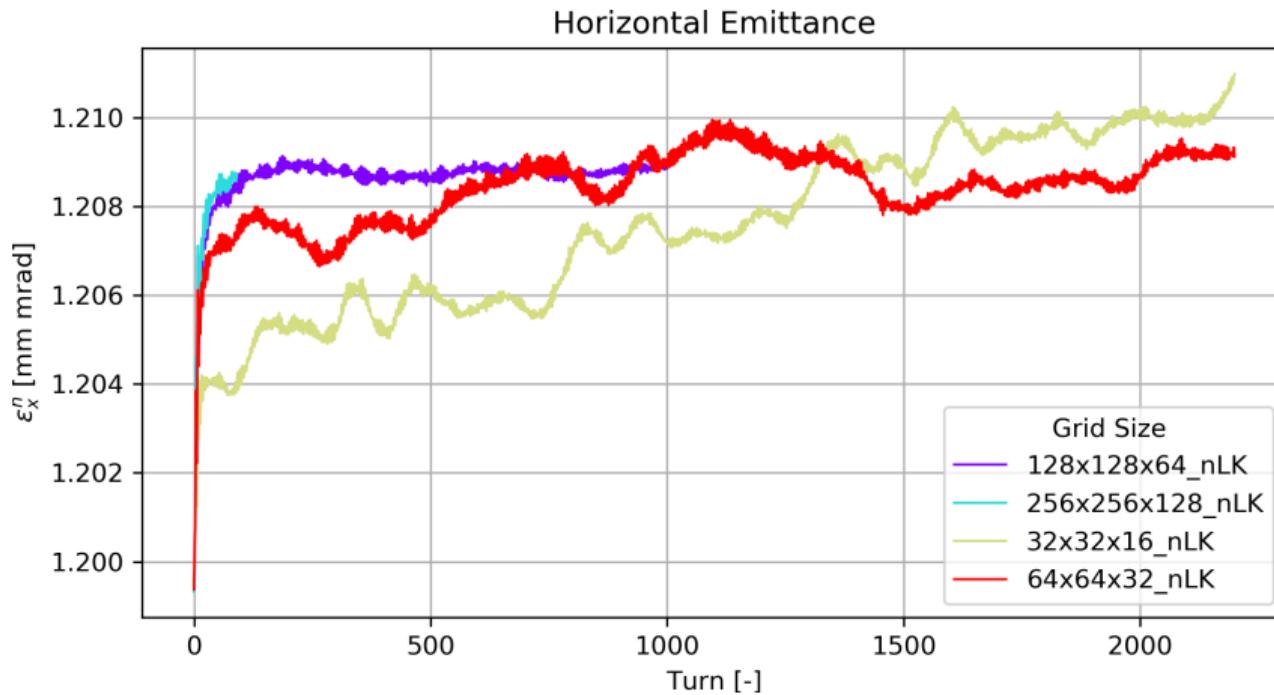
# Space Charge Grid Size Scan: No Long Kick: Average Emittance



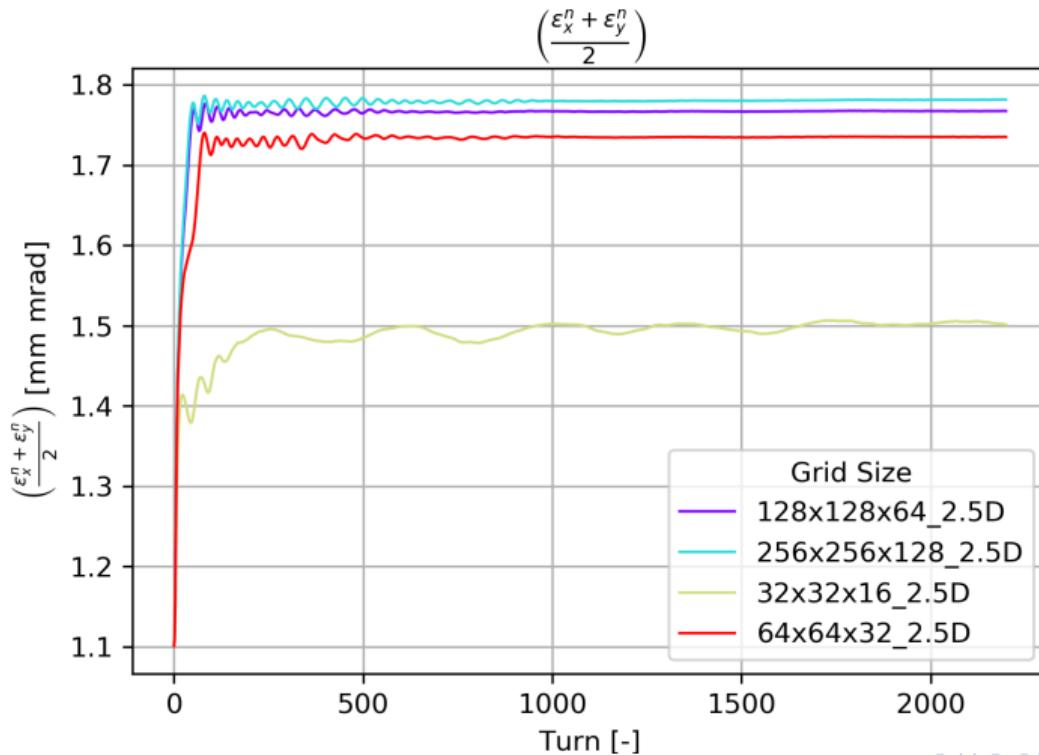
# Space Charge Grid Size Scan: No Long Kick: Vertical Emittance



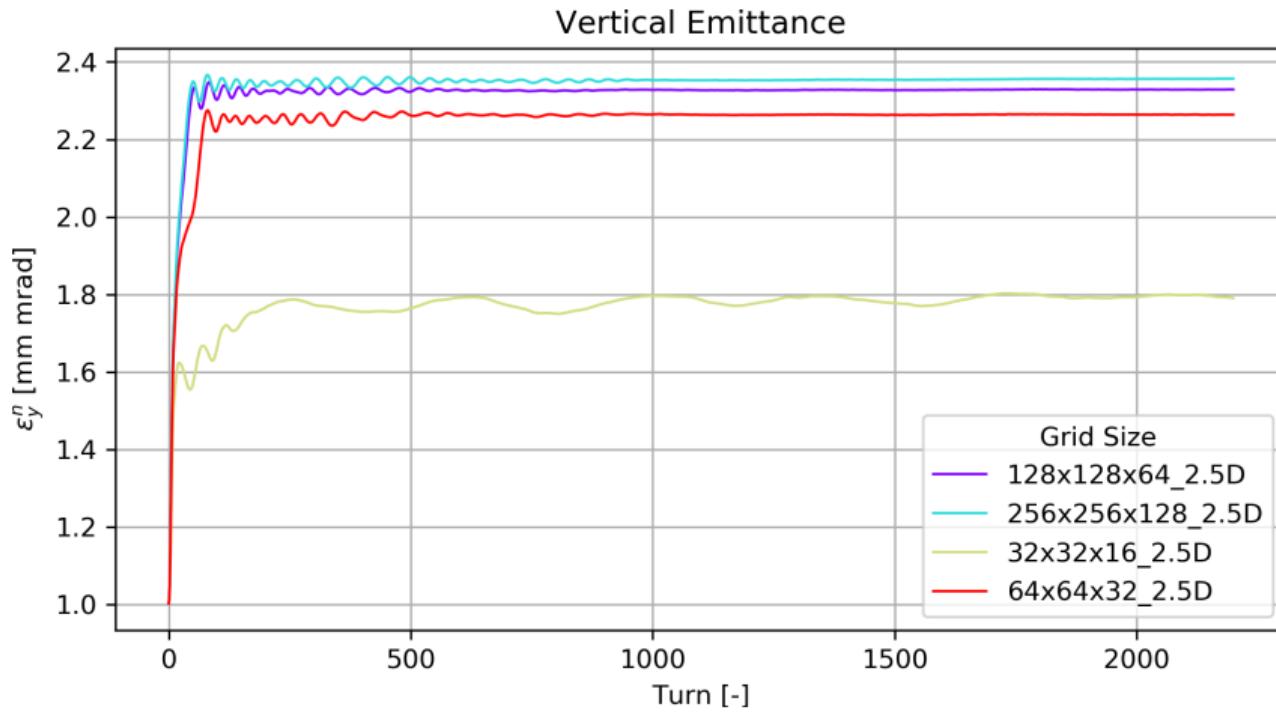
# Space Charge Grid Size Scan: No Long Kick: Horizontal Emittance



# 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

