
CERN

Approaching the Integer Tune in the Proton Synchrotron to Probe Space Charge at Injection

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LIU Emittance Budget

	Parameter		Achieved
Injection	Intensity per bunch (total: $2 \cdot 10^{13}$ ppp)	$1.63\ 10^{12}$ ppb ($6 \times 2.7\ 10^{11}$)	
	Injection energy, E_{kin}	2.0 GeV	1.4 GeV
	Transverse emittances	1.2 μm	
	Longitudinal emittance	1.5 eVs	
PS	Beam loss	5%	
	Transverse emittance growth	5%	
	Controlled longitudinal blow-up	~50%	
	Space charge tune shift, ΔQ_y	-0.31	
Ejection	Intensity per bunch	$2.6\ 10^{11}$ ppb	$1.7\ 10^{11}$ ppb
	Transverse emittances	1.9 μm	~2 μm
	Longitudinal emittance	0.35	
	Bunch length	4 ns	

Figure: LIU-PS baseline parameters for BCMS (Batch Compression Merging and Splitting) beams defining a 5% transverse emittance growth budget [2].

[1] H. Damerau et. al., Introduction and objectives, LIU-PS Beam Dynamics WG Meeting 1, 2017

[2] H. Damerau et. al., Introduction and objectives, LIU-PS Beam Dynamics WG Meeting 1, 2017

Observed Emittance Increase Between PSB and PS

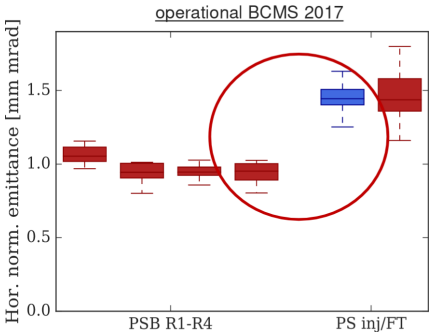


Figure: Observed emittance increase between the PSB and PS - much larger than the LIU budget[4].

[3] A. Huschauer et. al., Chamonix 2018

[4] A. Huschauer et. al., Chamonix 2018

≈ 30-40% Horizontal emittance blow-up between the PSB and PS

Possible Contributors:

- Dispersion mismatch in the transfer line [5].
- Systematic errors on emittance (wire scanner) measurements in both machines of upto 25% [6].
- Injection bump induced tune swing [7].
- Space charge - this talk.
- Injection mis-steering [8] - correctable.
- KFA14 (PSB extraction kicker) flat top ripple [9] - expected contribution is small.

[5] A. Oeftiger et. al., Dispersion vs. space charge at PS injection, LIU-PS Beam Dynamics WG Meeting 11, 2018

[6] M. A. Fraser et. al., Transverse emittance growth studies, LIU-PS Beam Dynamics WG Meeting 18, 2018

[7] E. Senes et. al., Emittance blowup studies from injection oscillations and Eddy currents in the injection bump, LIU-PS BD WG Meeting 15, 2018

[8] E. Senes et. al., Updates on emittance blowup studies from injection missteering, LIU-PS Beam Dynamics WG Meeting 17, 2018

[9] M. A. Fraser et. al., Emittance blow-up due to PSB KFA14, LIU-PS Beam Dynamics WG Meeting 29, 2019

Probe Space Charge in the PS

Perform a Machine Development Study:

Static tune scan investigating high brightness beam behaviour close to the integer tune in both planes separately. Using the low energy quadrupoles (LEQs) to vary the tune, and pole face windings (PFWs) to maintain low chromaticity.

Static Tune Scan: From (6.21, 6.24)

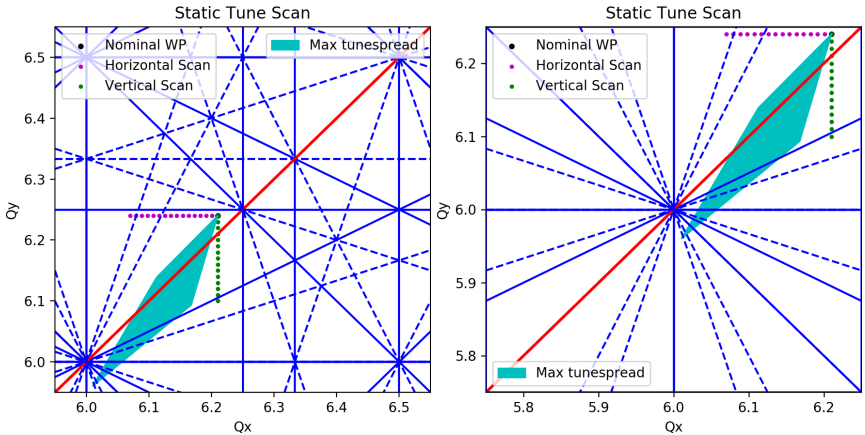


Figure: Static tune scan and estimated tune spread used in measurement campaign. The right hand plot is identical to the left, with shifted axes for clarity.

Resonances in the PS

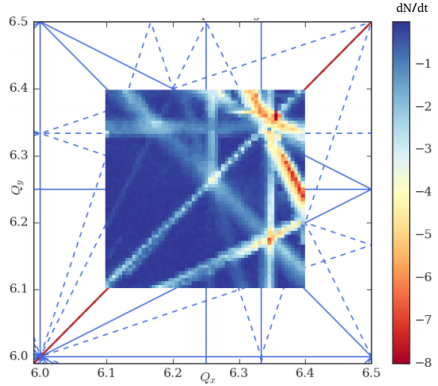


Figure: Tune scan in the CERN Proton Synchrotron indicating resonances from loss rate $\frac{dN}{dt}$ [11].

[10] M. Kaitatzi et. al., Tune Diagram Measurements in the PS, MSWG Meeting 11, 2018

[11] M. Kaitatzi et. al., Tune Diagram Measurements in the PS, MSWG Meeting 11, 2018

Tune Control: Effect of LEQs on Optics

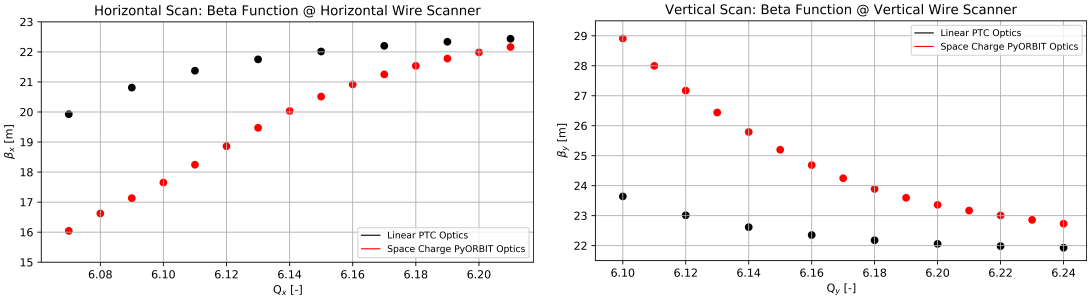


Figure: Change in beta function at the respective wire scanner position as the tune is modified with the low energy quadrupoles. Linear optics calculated using PTC are compared to space charge optics calculated from the bunch in PyORBIT simulations. The horizontal tune scan is shown on the left, the vertical tune scan on the right. These changes should be noted for emittance calculations.

MD Setup

- Low chroma BCMS cycle, single injection, no acceleration.
- Injection at 170 ms.
- Bunch dumped internally at 1300 ms.
- Tunes modified using low energy quads (LEQs).
- Orbit corrected - Injection steering was good enough for low tunes.
- Transverse feedback (set to tune of individual shot).
- RMS current on LEQs monitored (< 6 Amps).
- WS only available in same plane as scan.
- Tune measurement excitation active at flat bottom - gives small losses from 190 ms.
- Standard operational transfer line matching settings.

Modified PS BCMS Cycle

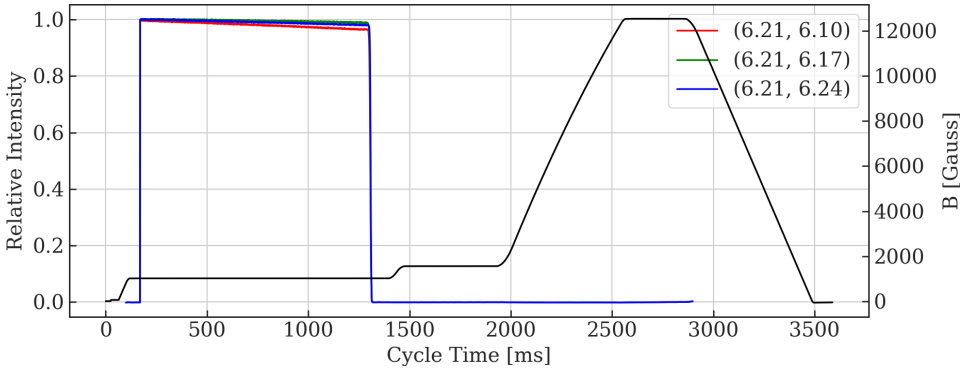


Figure: Magnetic cycle (black) and intensities (colours) for three points in the vertical tune scan. Injection takes place at 170 ms, the beam is internally dumped at 1300 ms.

Wire Scanner Measurements

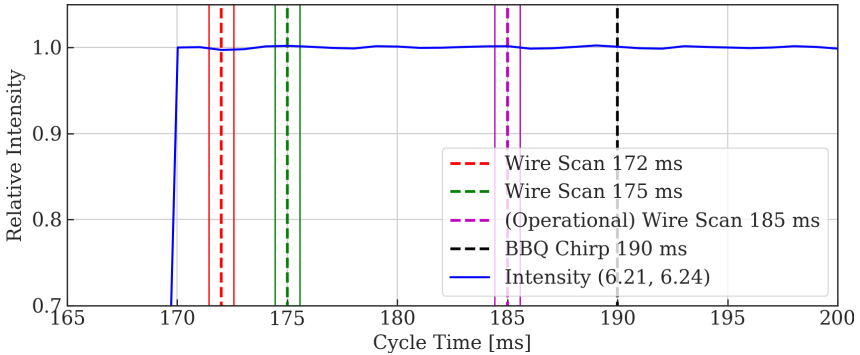


Figure: To observe the expected emittance increase we chose to measure beam profiles at three intervals post-injection. These were 2, 5, and 15 ms after injection (in cycle time 172, 175, 185 ms). The wirescanner takes $\approx$ 500 turns $\approx$ 1.144 ms, as indicated by the solid lines.

Longitudinal Distribution

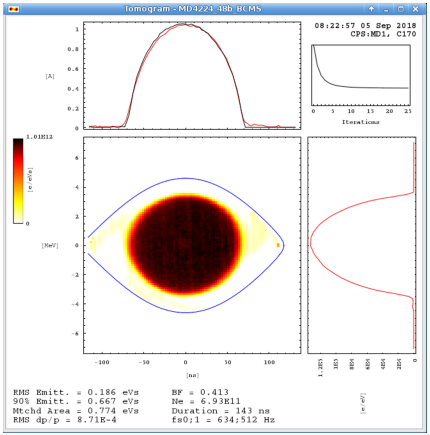


Figure: Example Tomogram from MD4224 illustrating the typical longitudinal bunch structure.

Emittance from Wire Scanner Profile

The following process was used on both measured and simulated bunch profiles:

- 5 parameter Gaussian fit to find mean and standard deviation σ.
- $\pm$ 6 σ cut to find slope.
- Remove slope.
- 3 parameter Gaussian fit to find centre.
- Second moment μ' calculation.

In the following slides we use linear optics values from PTC matched each working point in the scan, as shown on slide 9.

Example Wire Scanner Treatment

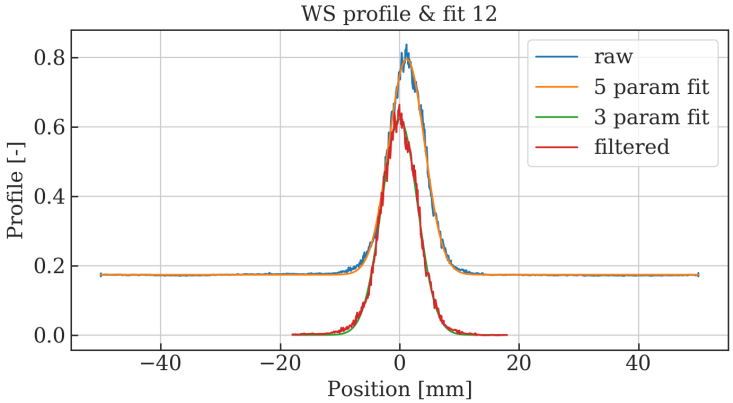


Figure: Example wire scanner profile taken at (Q_x, Q_y)=(6.21, 6.10), with multi-step fitting.

Vertical Scan Emittance using Standard Deviation

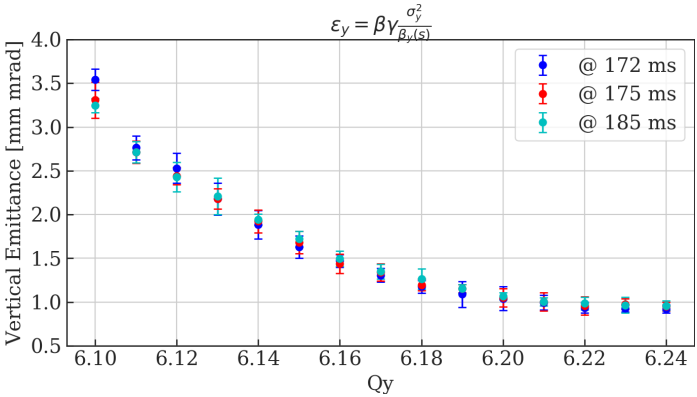


Figure: Emittances calculated using the bunch standard deviation comparing measurements with simulation using linear PTC optics for the vertical tune scan.

Vertical Scan Emittance using 2nd Moment

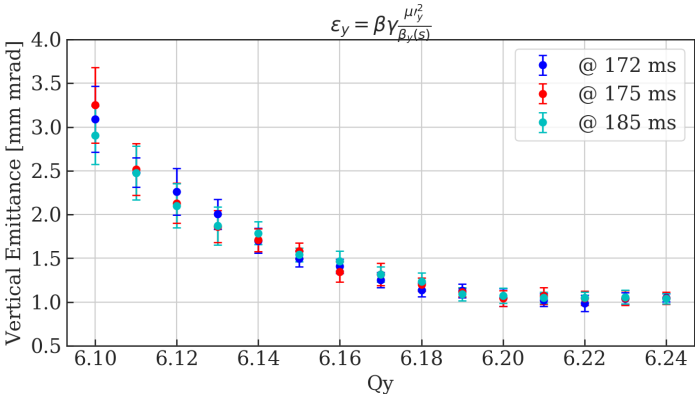


Figure: Emittances calculated using the bunch second moment comparing measurements with simulation using linear PTC optics for the vertical tune scan.

Horizontal Scan Emittance using Standard Deviation

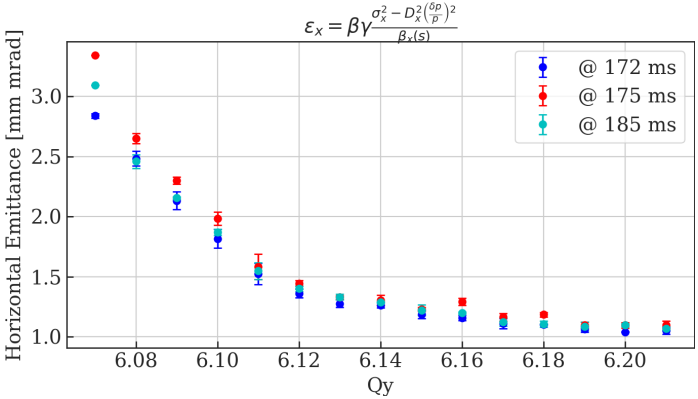


Figure: Emittances calculated using the bunch standard deviation comparing measurements with simulation using linear PTC optics for the horizontal tune scan.

Horizontal Scan Emittance using 2nd Moment

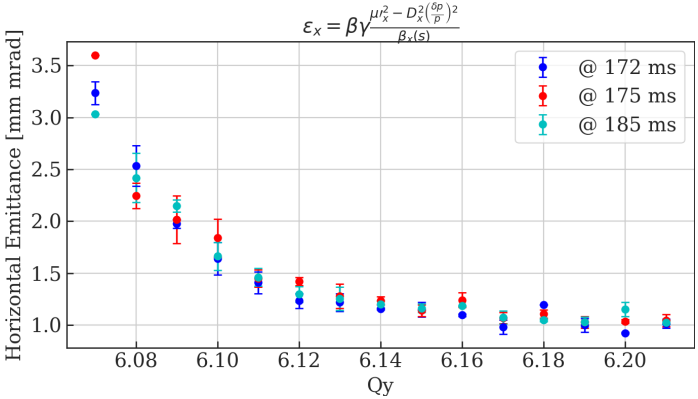


Figure: Emittances calculated using the bunch second moment comparing measurements with simulation using linear PTC optics for the horizontal tune scan.

Emittance: Timescale of Increase

No difference in emittance with respect to measurement time.

Implies very fast beam blow-up (< 2 ms $\approx$ 875 turns).

Wirescanner measurement times / turns (1 turn $\approx$ 2.287 μs):

- Injection + 2 ms = 172 ms $\approx$ 875 turns.
- Injection + 5 ms = 175 ms $\approx$ 2187 turns.
- Injection + 15 ms = 185 ms $\approx$ 6559 turns.

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	0.78
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: Beam and machine parameters

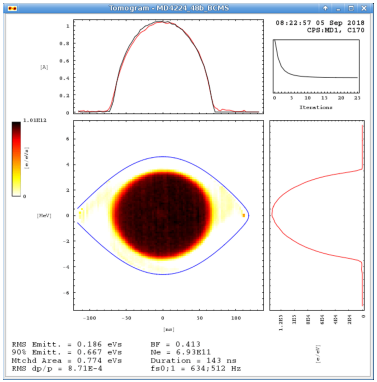
Simulation Parameters

Parameter	Full Simulation	Mini Simulation
Space Charge Grid x	128	64
Space Charge Grid y	128	64
Space Charge Grid z	64	32
N_{mp}	$5 \cdot 10^5$	$5 \cdot 10^4$
Turns	2200	2200
Approximate Simulation Time (on 4 HPC-Batch nodes)	$\approx$ 4 days	$\approx$ 12 hours

Table: Simulation parameters

Using slice-by-slice with longitudinal kick space charge in PyORBIT. Most plots shown are from full simulations (currently running to be ready for SC workshop). We expect the difference between mini and full simulation results to be small.

Distribution from Tomoscope



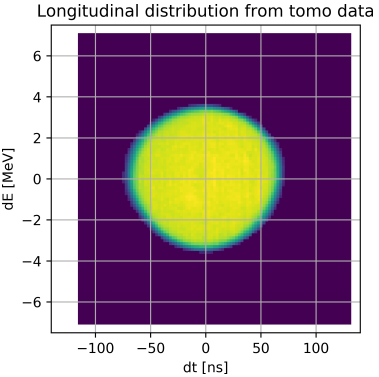


Figure: Example Tomogram from measurements (left), and PyORBIT distribution (right), which is a 2D Gaussian in the transverse planes, and uses a tomoscope measurement to populate the longitudinal distribution. Note that all simulations use an identical initial distribution, matched to the nominal working point (6.21, 6.24).

Simulation: Vertical Scan: Vertical Emittance

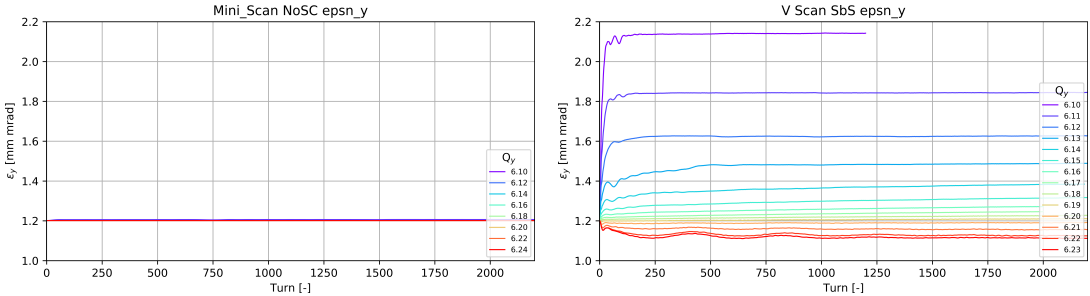


Figure: Comparison of emittances for simulations without (left) and with (right) space charge for the vertical scan. Space charge clearly affects the beam emittance, as expected.

Simulation: Vertical Scan: Emittances

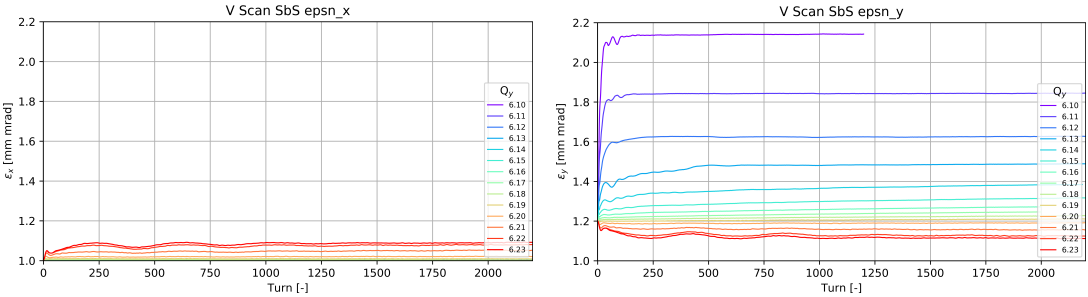


Figure: Comparison of horizontal (left) and vertical (right) simulation emittances with space charge for the vertical scan. The Montague resonance (a space charge induced emittance coupling) is evident around tune (6.21 , 6.21).

Simulation: Horizontal Scan: Horizontal Emittance

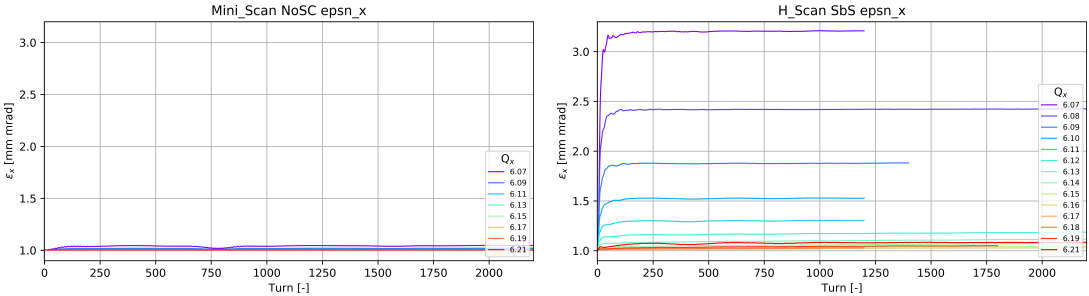


Figure: Comparison of emittances for simulations without (left) and with (right) space charge for the horizontal scan. Space charge clearly affects the beam emittance, as expected.

Simulation: Horizontal Scan: Emittances

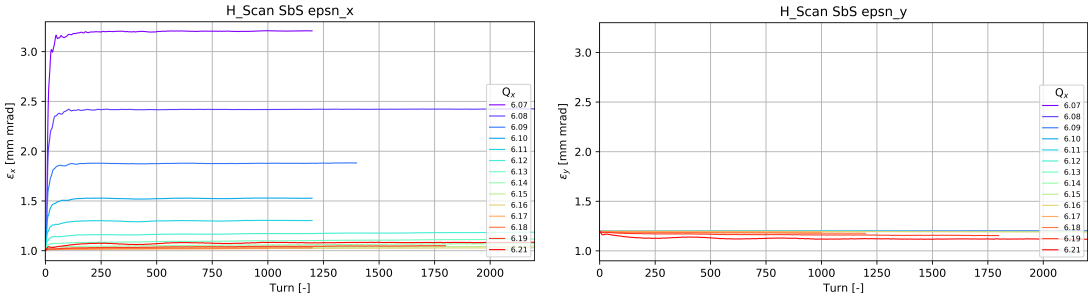


Figure: Comparison of horizontal (left) and vertical (right) simulation emittances with space charge for the horizontal scan. The Montague resonance is evident around tune (6.21 , 6.21).

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.24)

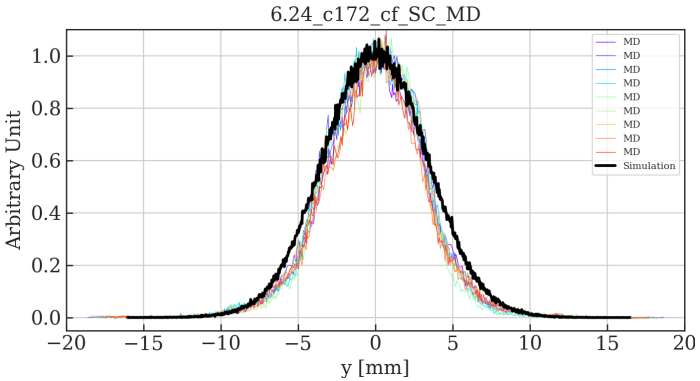


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.24) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.23)

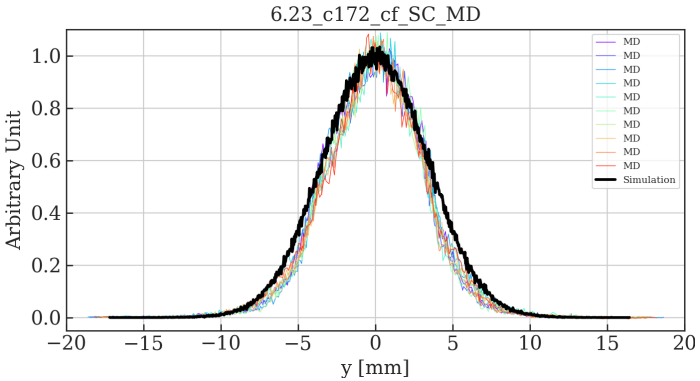


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.23) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.22)

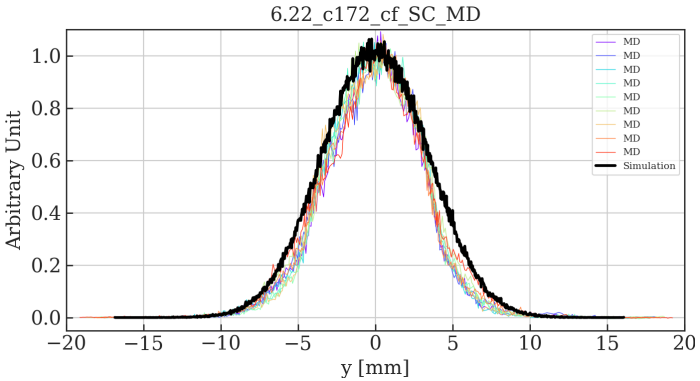


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.22) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.21)

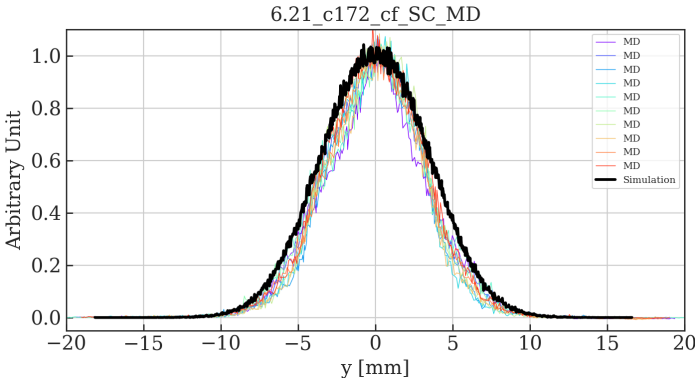


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.20)

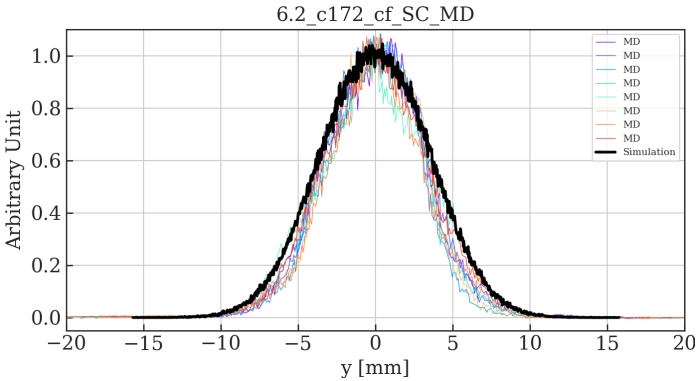


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.20, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.19)

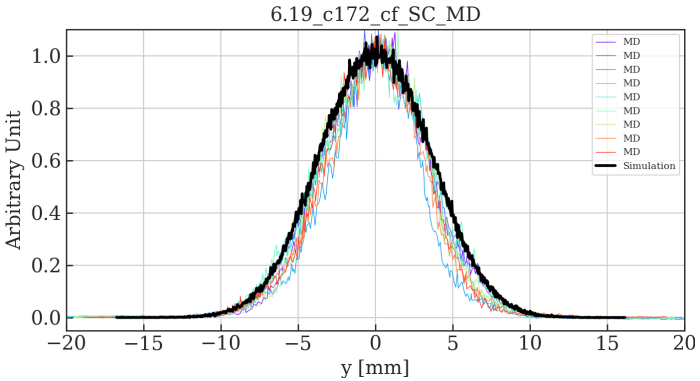


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.19, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.18)

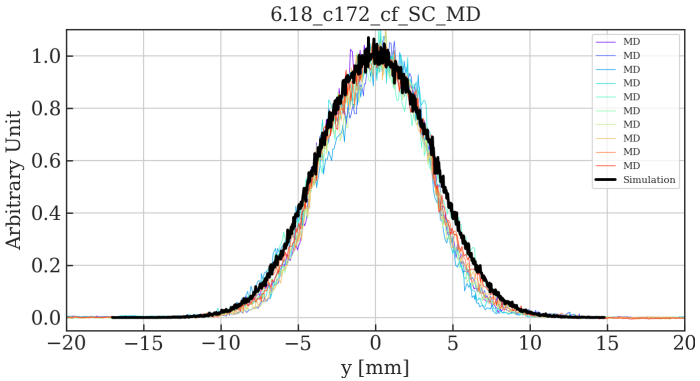


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.18, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.17)

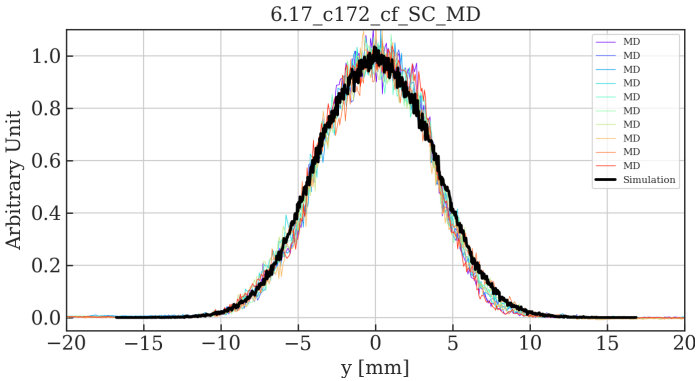


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.17, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.16)

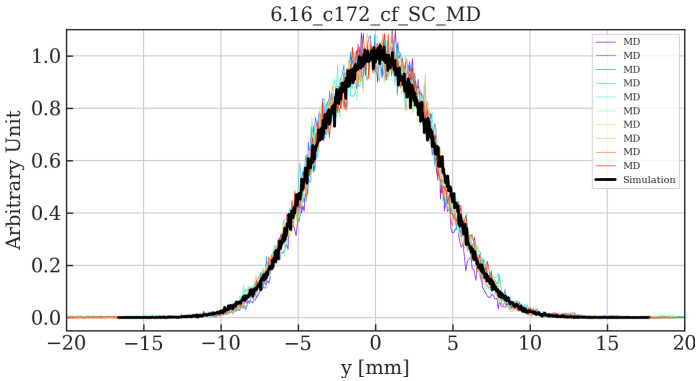


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.16, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.15)

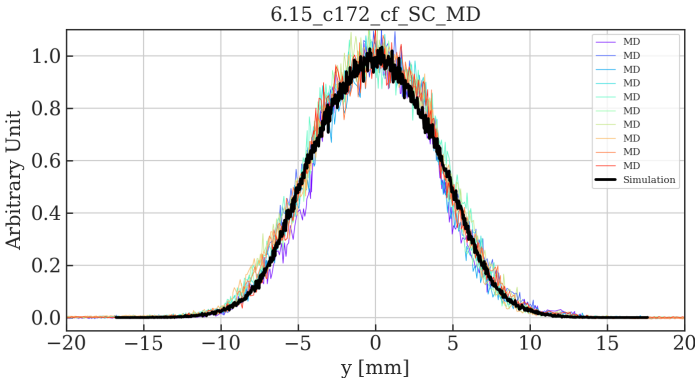


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.15, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.14)

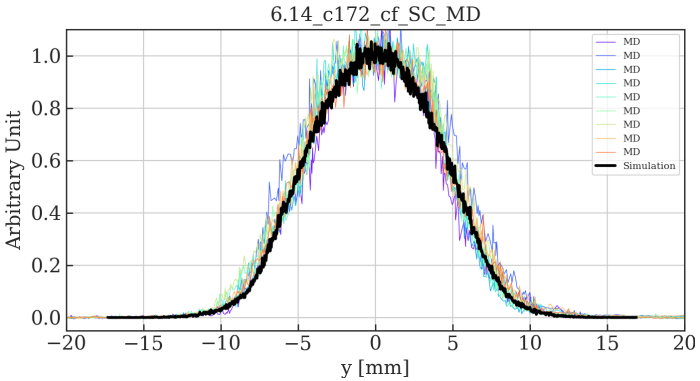


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.14, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.13)

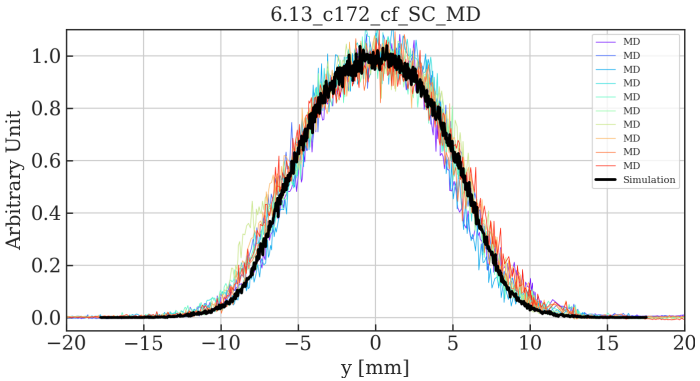


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.13, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.12)

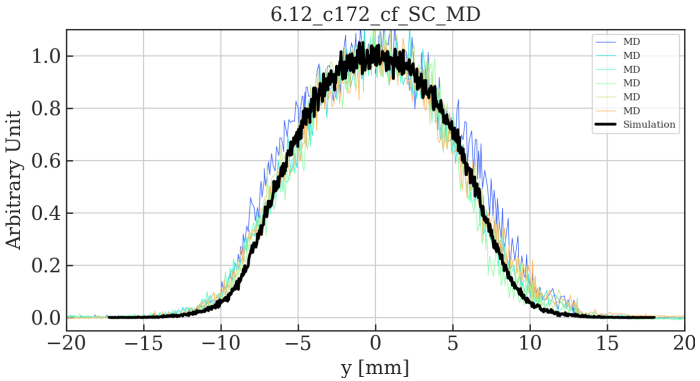


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.12, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.11)

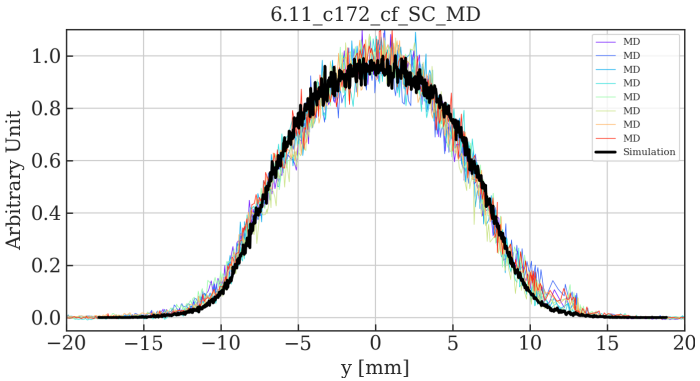


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.11, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Vertical Scan: (6.21, 6.10)

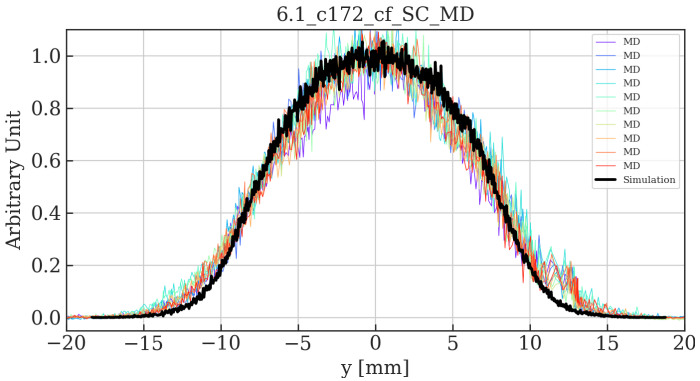


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.10, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.21, 6.24)

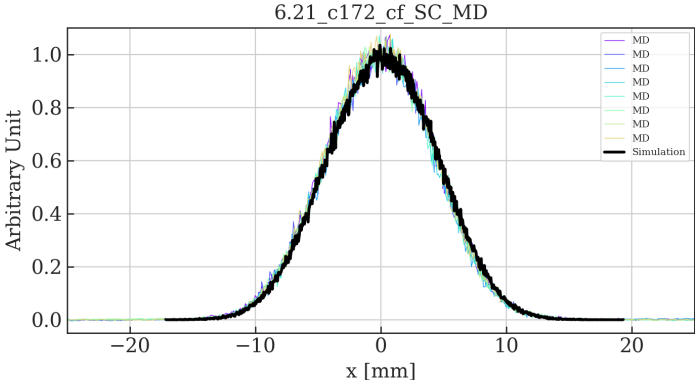


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.21, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.20, 6.24)

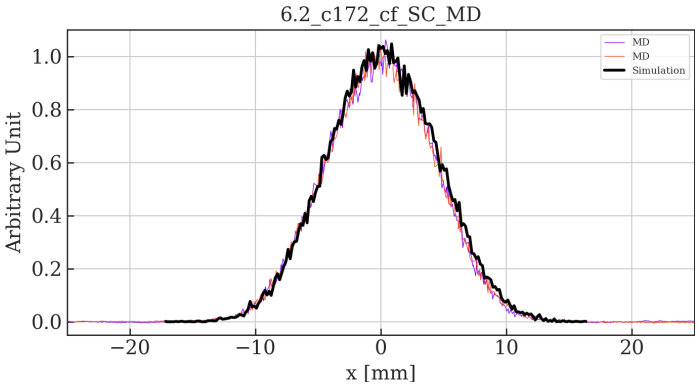


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.20, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.19, 6.24)

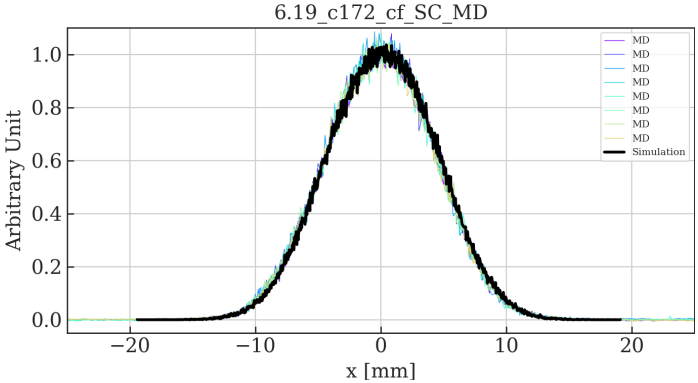


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.19, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.18, 6.24)

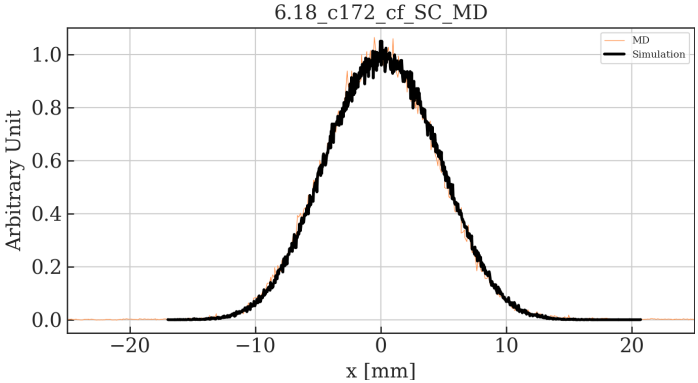


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.18, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.17, 6.24)

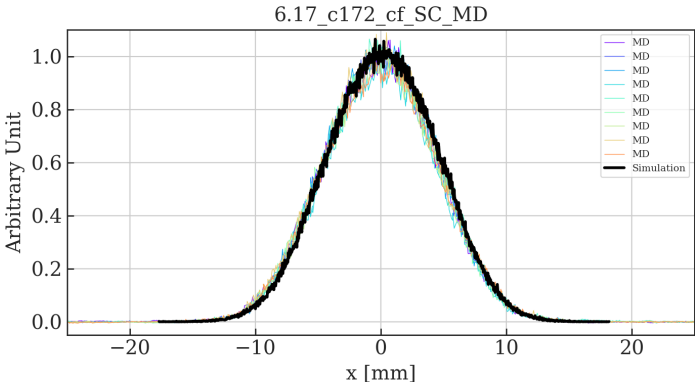


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.17, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.16, 6.24)

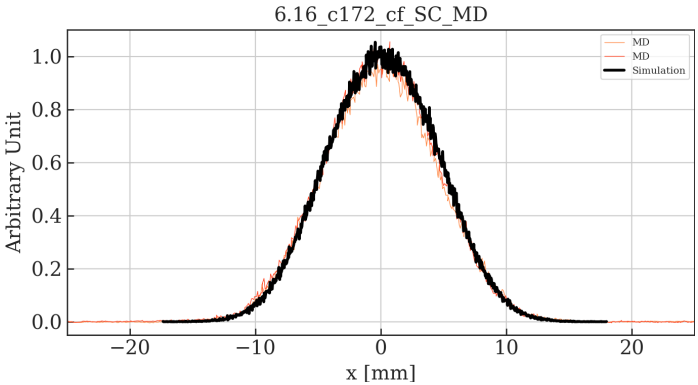


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.16, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.15, 6.24)

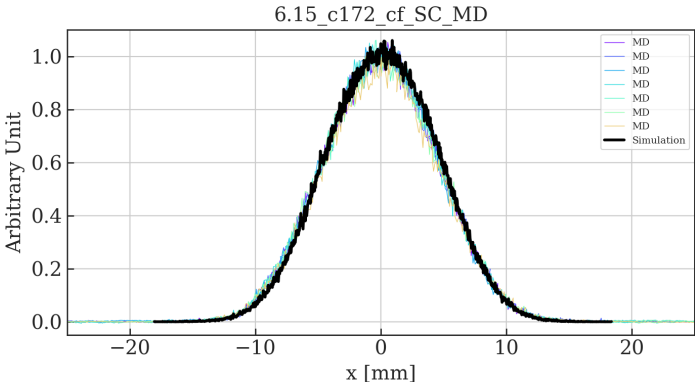


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.15, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.14, 6.24)

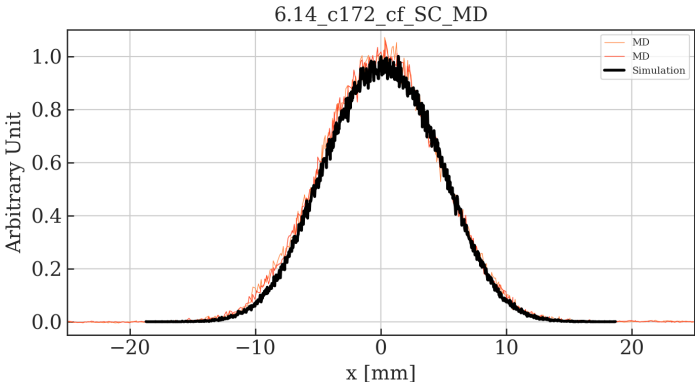


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.14, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.13, 6.24)

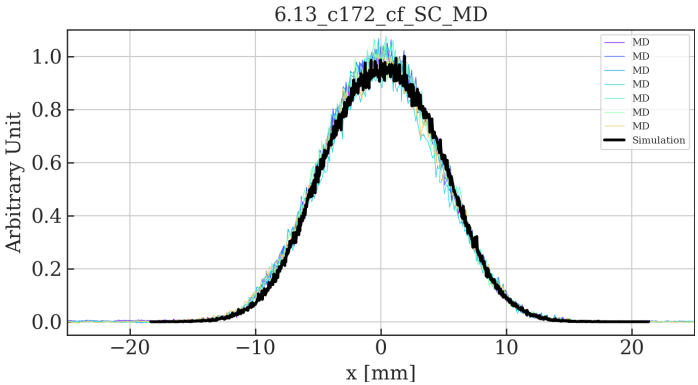


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.13, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.12, 6.24)

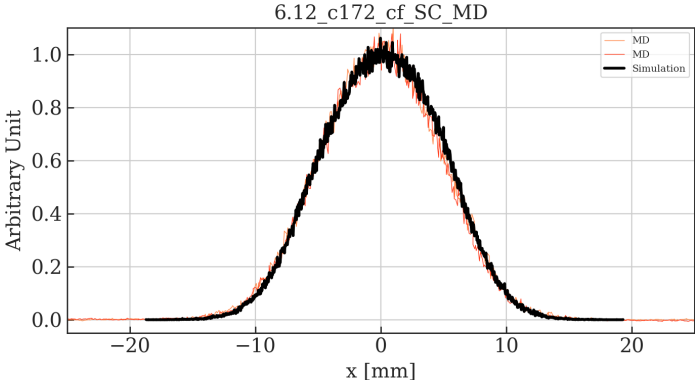


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.12, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.11, 6.24)

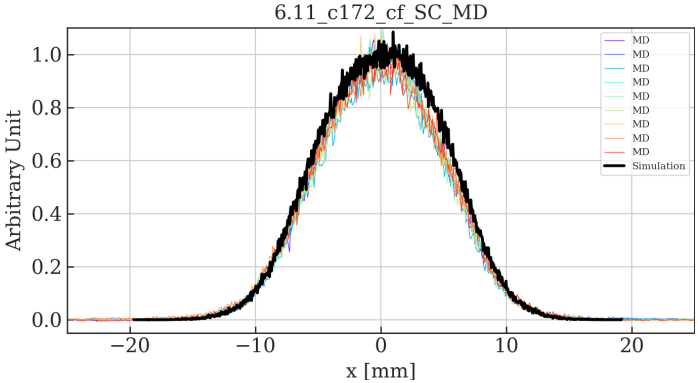


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.11, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.10, 6.24)

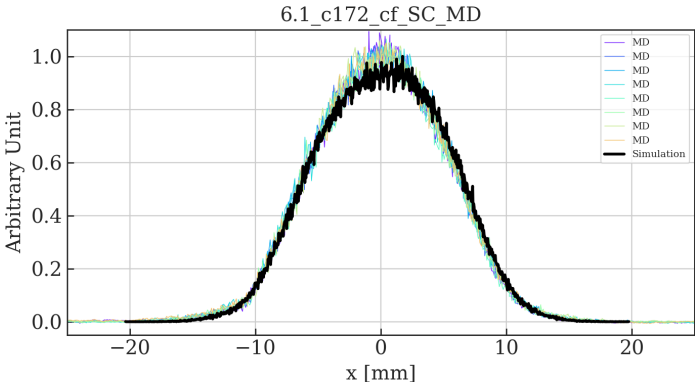


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.10, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.09, 6.24)

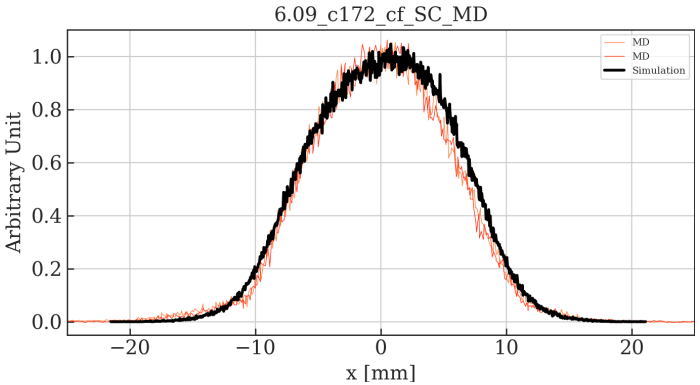


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.09, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.08, 6.24)

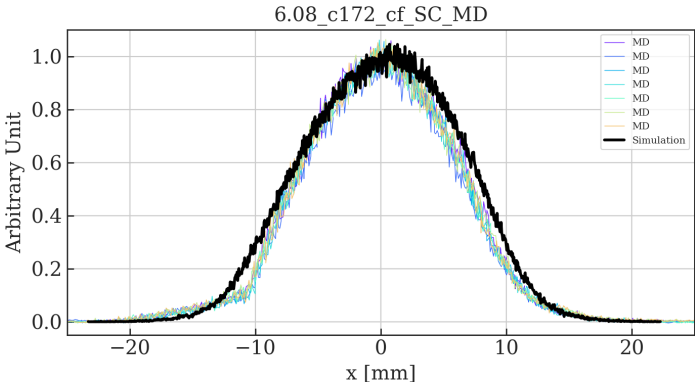


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.08, 6.21) at 2 ms post injection.

Wirescanner Profile Comparison: Horizontal Scan: (6.07, 6.24)

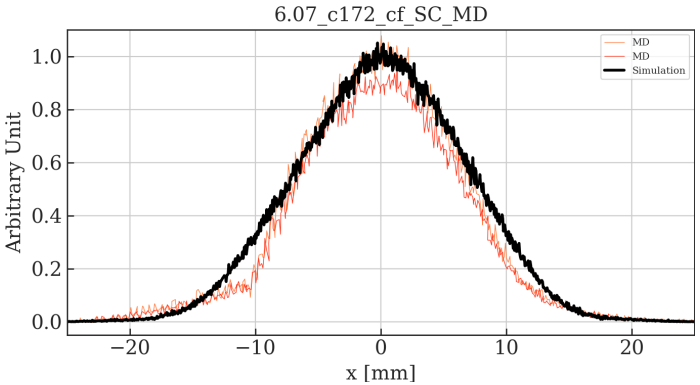


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.07, 6.21) at 2 ms post injection.

Tune Footprints: Vertical Extreme

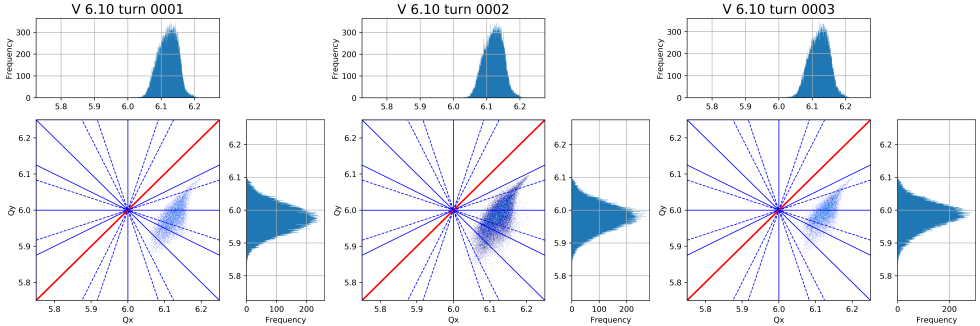


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

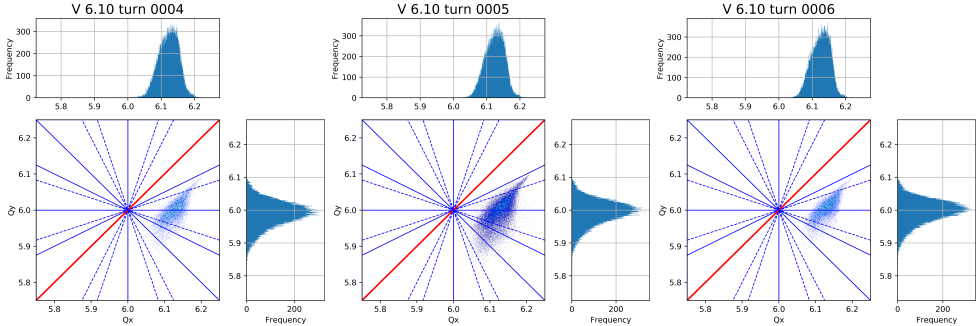


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

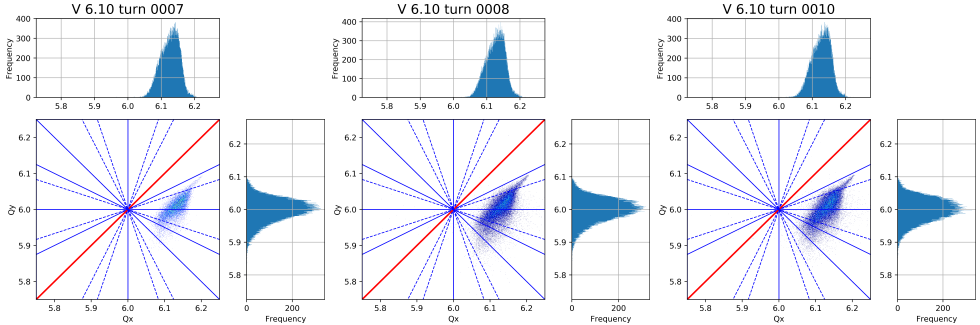


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

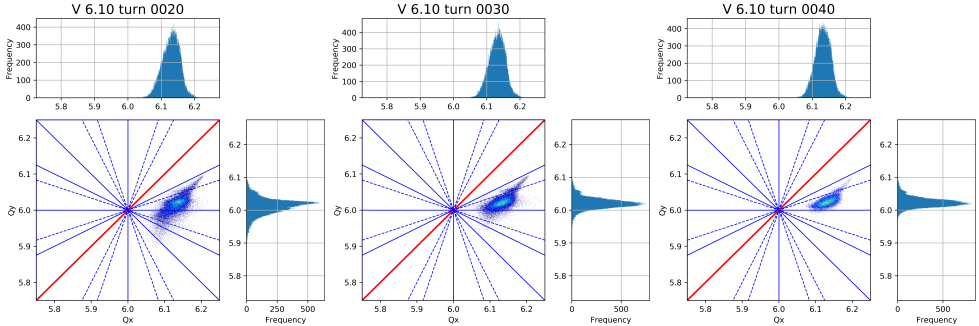


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

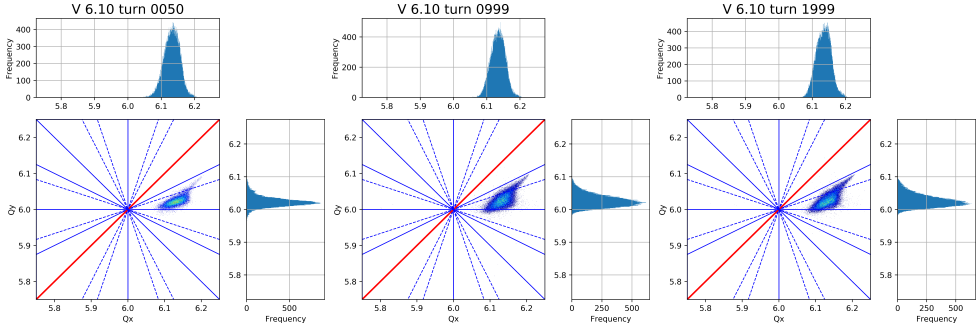


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Horizontal Extreme

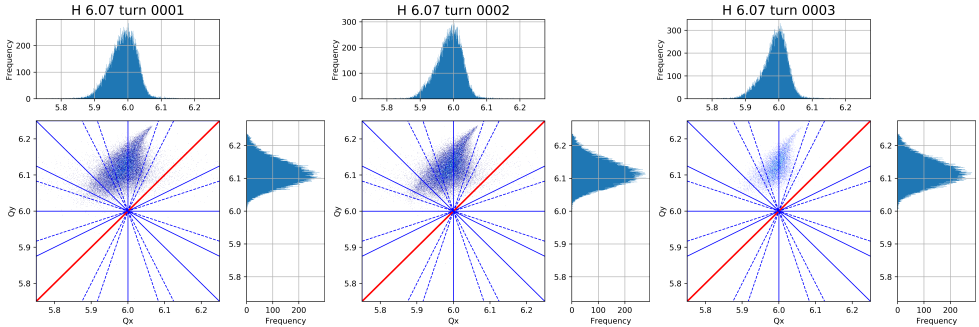


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Tune Footprints: Horizontal Extreme

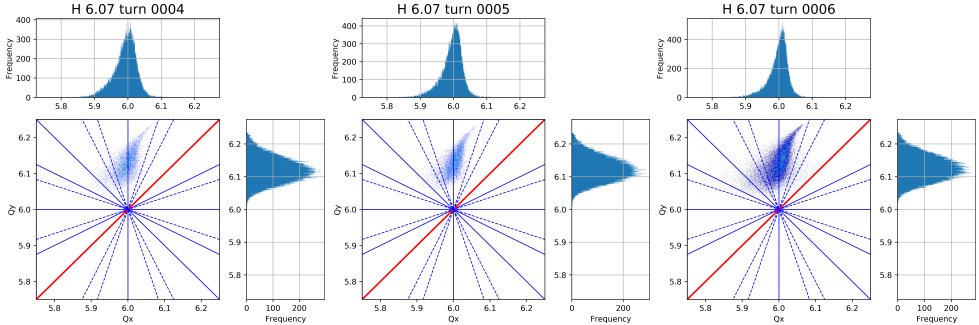
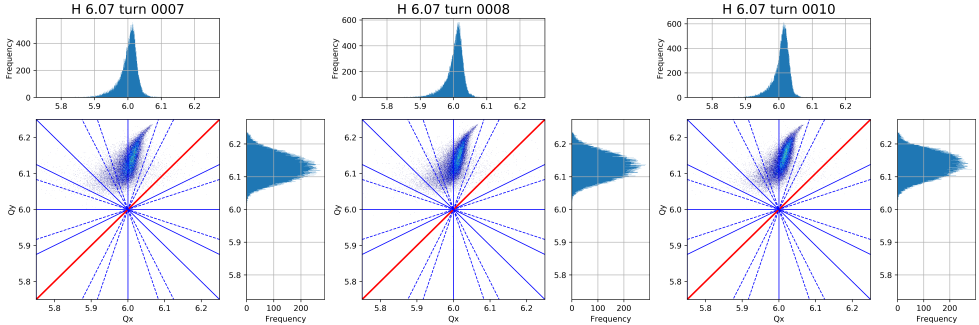


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Tune Footprints: Horizontal Extreme



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Tune Footprints: Horizontal Extreme

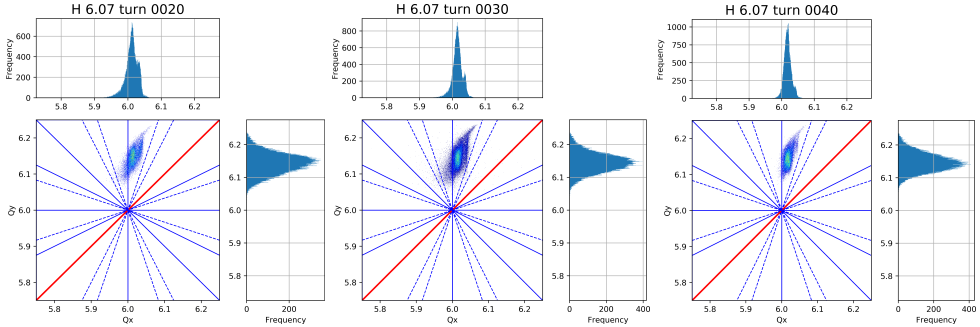


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Tune Footprints: Horizontal Extreme

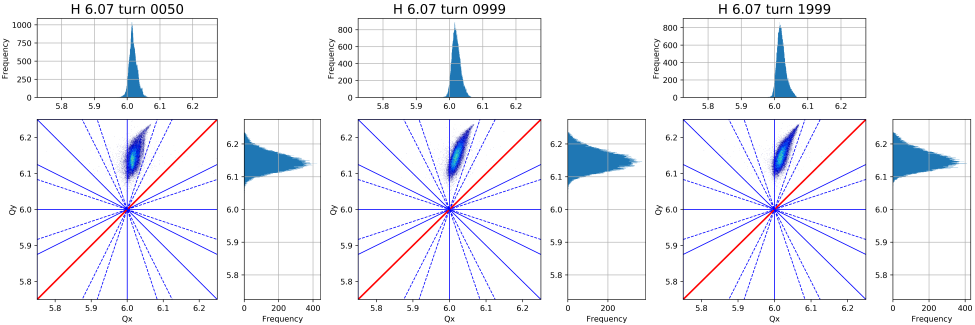


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Vertical Scan Emittance using Standard Deviation Comparison

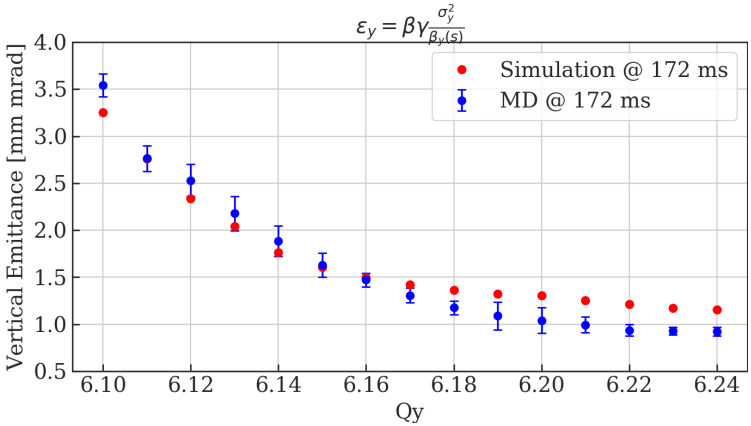


Figure: Emittances comparing measurements with simulation using PTC optics for the vertical tune scan.

Vertical Scan Emittance using 2nd Moment Comparison

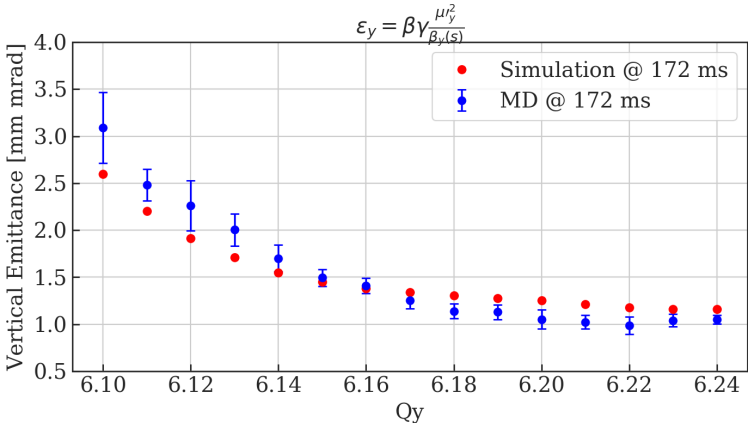


Figure: Emittances comparing measurements with simulation using PTC optics for the vertical tune scan.

Horizontal Scan Emittance using Standard Deviation Comparison

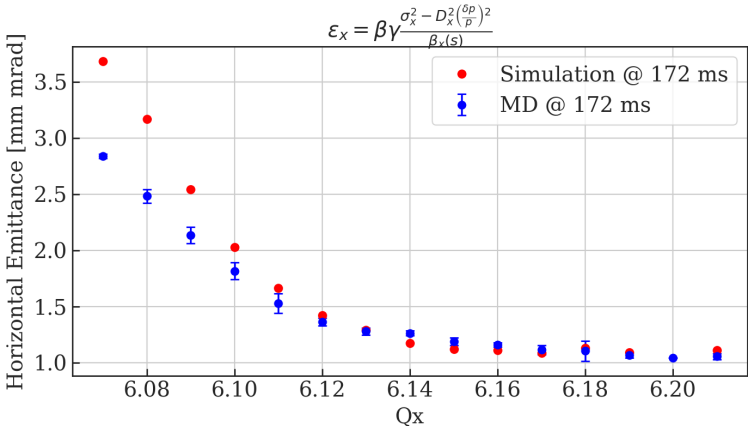


Figure: Emittances comparing measurements with simulation using PTC optics for the horizontal tune scan.

Horizontal Scan Emittance using 2nd Moment Comparison

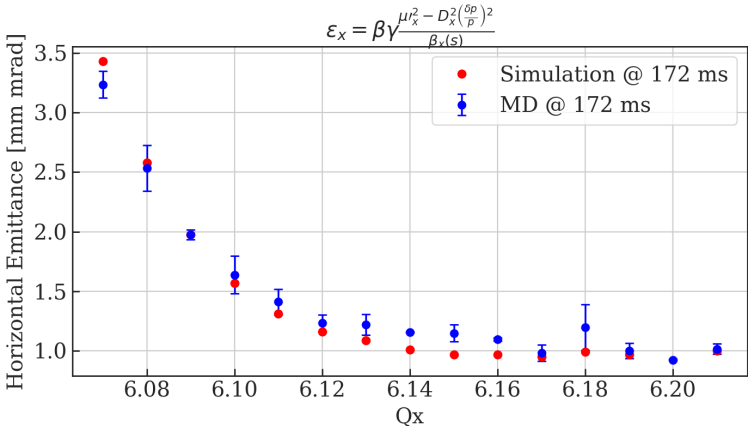


Figure: Emittances comparing measurements with simulation using PTC optics for the horizontal tune scan.

Tune Control: Effect of PFWs on Optics

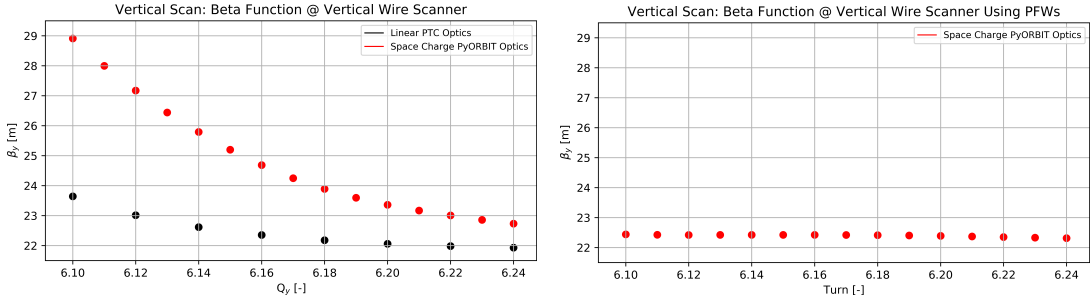


Figure: Change in beta function at the respective wire scanner position as the tune is modified with the low energy quadrupoles (LEQs, left) or pole face windings (PFWs, right). Linear optics calculated using PTC are compared to space charge optics calculated from the bunch in PyORBIT simulations in the left plot, in the right only space charge optics calculated from the bunch in PyORBIT simulations are shown.

Vertical Scan Simulation Emittance: PFW Comparison

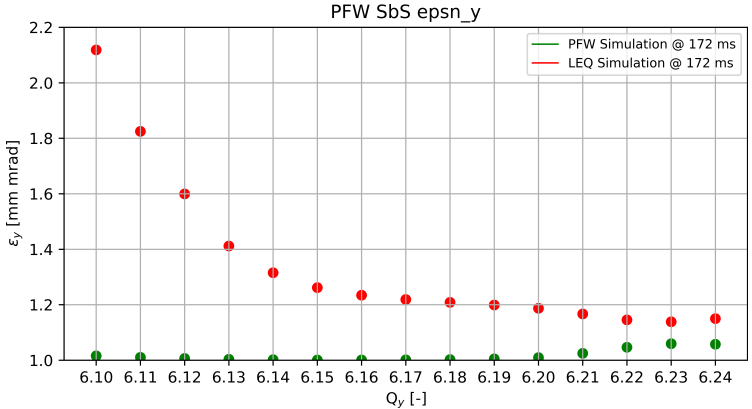


Figure: Comparison of PyORBIT simulation vertical emittance values for the vertical scan, comparing tune modification with LEQs (red) or PFWs (green). Note that the PFW simulation uses an older optics version, and the initial emittance $\epsilon_{y0} = 1$ mm mrad instead of 1.2.

Conclusions

- Measurements show clear beam blow-up as the beam is brought closer to the integer tune, where the quadrupole resonance sits.
- The emittance blow-up is evident from 2 ms post injection - very fast.
- Use of LEQs (rather than PFWs) to modify the tune clearly increases space charge effect due to contribution to resonances.
- From simulations, beam blow up in first $\approx$ 50 turns $\approx$ 0.11 ms - not possible to see with wire scanner - perhaps with BGI?
- Emittances calculated using measured and simulated bunch profiles agree well.
- Model of PS benchmarked with space charge for this case.

Acknowledgements

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

Tune Control: Effect of LEQs on Optics

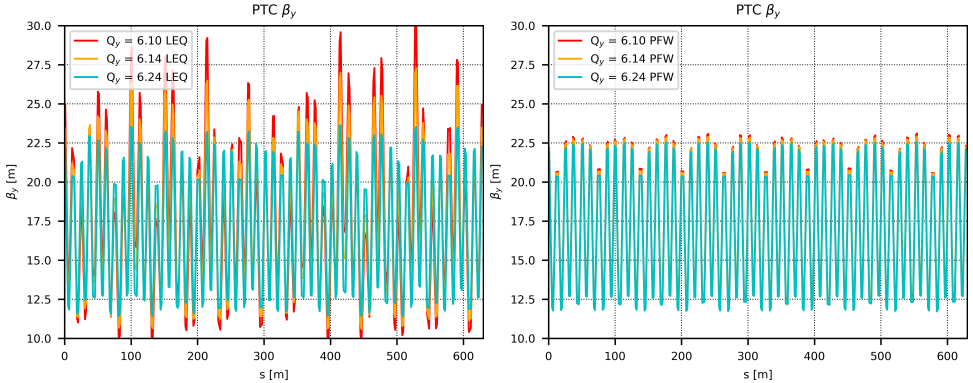


Figure: PS vertical beta function comparison. Tune modification using LEQs (left) compared to tune modification using PFWs (right). Plots from old simulations.

Tune Control: Effect of LEQs on Optics

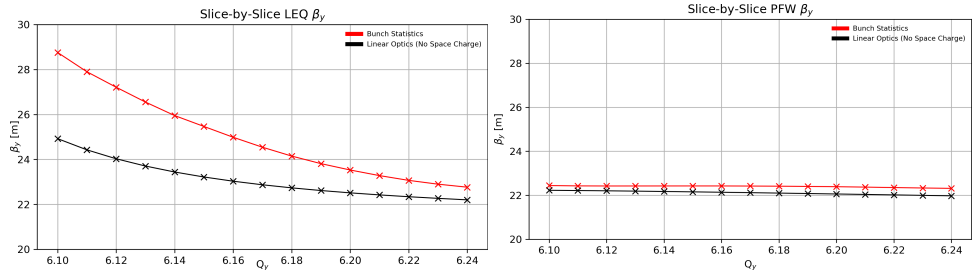


Figure: PS vertical beta function comparison at the position of the vertical wire scanner. Tune modification using LEQs (left) compared to tune modification using PFWs (right). Plots from old simulations.

Simulation: Vertical Scan with PFWS: Emittances

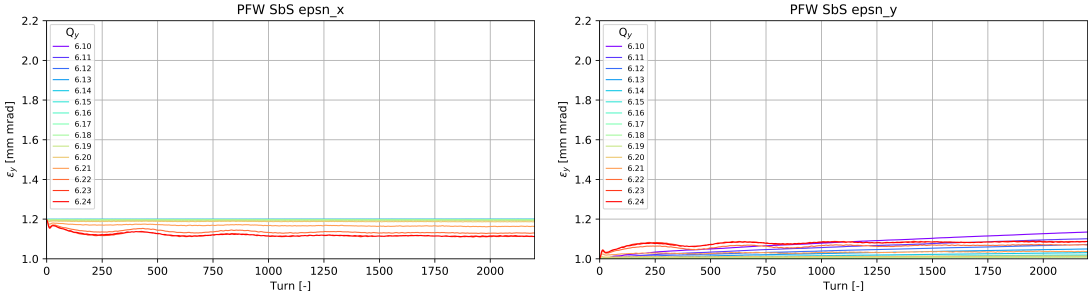
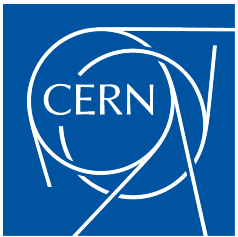


Figure: Comparison of horizontal (left) and vertical (right) simulation emittances with space charge for the vertical scan when using Pole Face Windings (PFWs) to modify the tune instead of the Low Energy Quadrupoles (LEQs). The Montague resonance is evident around tune (6.21, 6.21). Note the incorrect initial emittances (should be $\epsilon_x 0 = 1, \epsilon_y 0 = 1.2$).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