CERN

Approaching the Integer Resonance in the Proton Synchrotron

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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 baseline parameters for BCMS beams [1].

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

Observed Emittance Increase Between PSB and PS

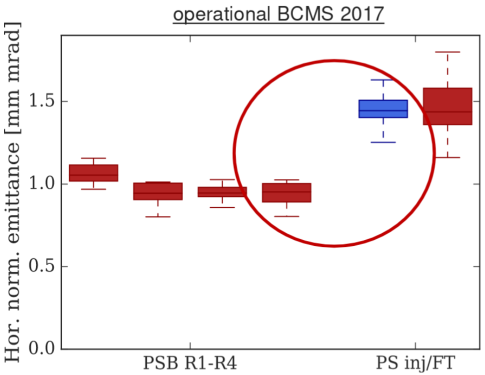

Figure: Observed emittance increase between the PSB and PS[2].

[2] 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 [3].
- Systematic errors on emittance (wire scanner) measurements in both machines of upto 25% [4].
- KFA14 (PSB extraction kicker) flat top ripple [5].
- Injection bump induced tune swing [6].
- Injection mis-steering [7].
- Space charge.

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

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

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

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

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

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.

Resonances in the PS

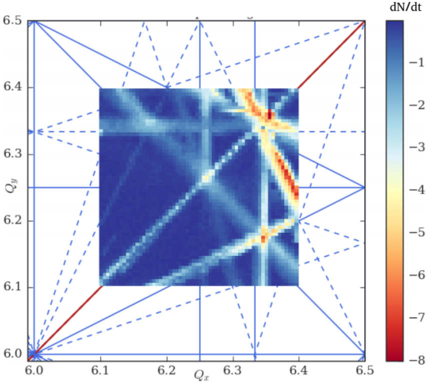


Figure: Tune scan in the CERN Proton Synchrotron indicating resonances from loss rate $\frac{dN}{dt}$ [8]

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

Where do these resonance come from?

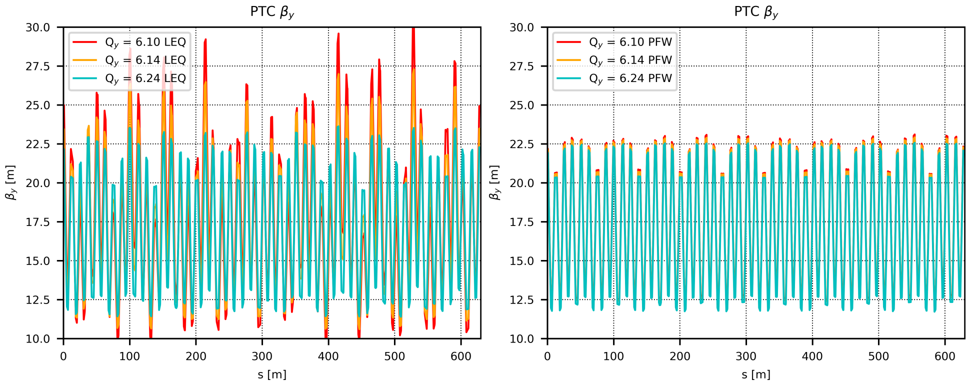
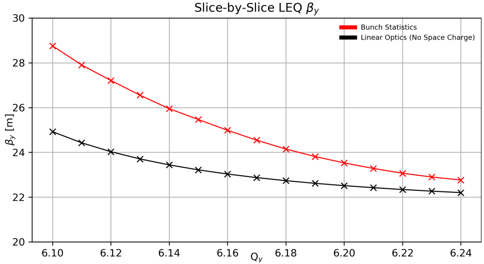


Figure: PS vertical beta function comparison. Tune modification using LEQs (left) compared to tune modification using PFWs (right).

Where do these resonance come from?



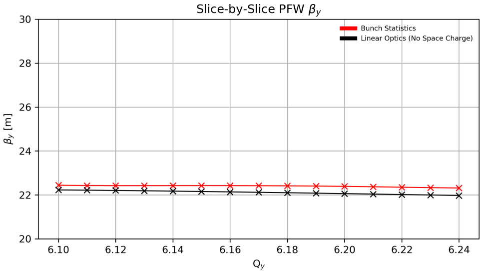


Figure: PS vertical beta function comparison at the position of the vertical wire scanner. Tune modification using LEQs (left) compared to tune modification using PFWs (right).

Integer Resonance

Integer + Half Integer etc - strongest. Large stop band?

Tune Scan

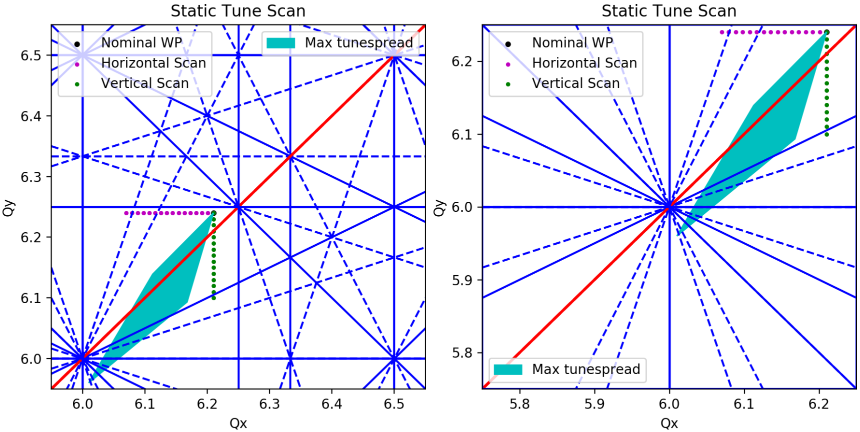


Figure: Static tune scan and estimated tune spread used in measurement campaign.

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 active at flat bottom - gives small losses.

Modified PS BCMS Cycle

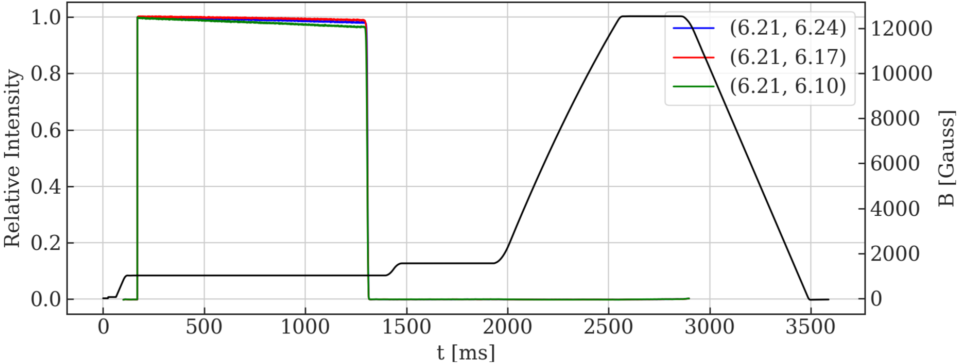


Figure: Magnetic cycle (black) and intensities (colours) for three points in the vertical tune scan. Injection takes place at 170 ms, the beam is internally dumped at 1300 ms.

To observe the 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).

Tomo Distn

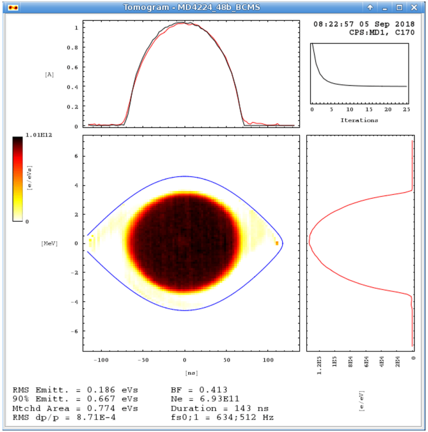


Figure: Example Tomogram from MD4224.

Emittance from Wirescanner Profile

- 5 parameter Gaussian fit to find mean and σ.
- $\pm$ 6 σ cut to find slope.
- Remove slope.
- 3 parameter Gaussian fit to find centre.
- 2nd moment calculation.

Using twiss values from PTC matched to correct optics for each working point in the scan.

Wirescanner Profiles

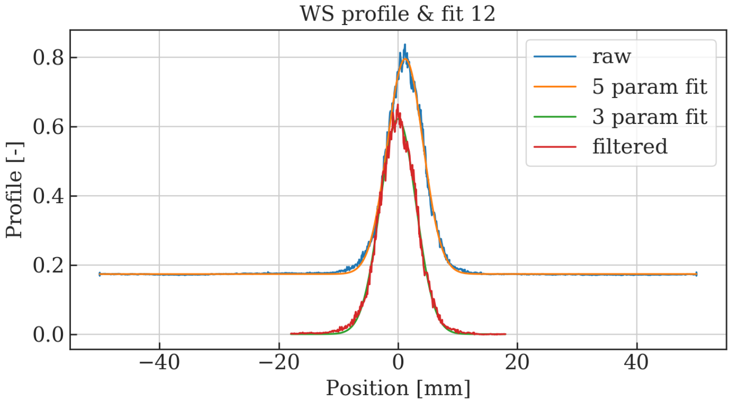
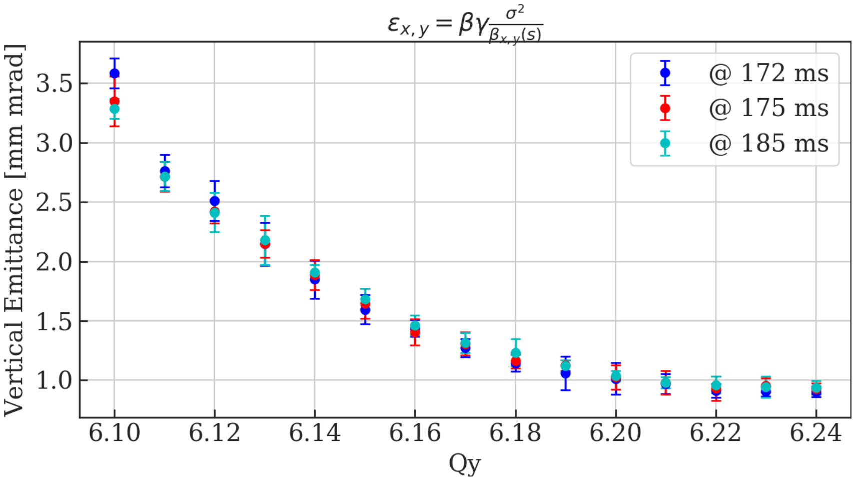
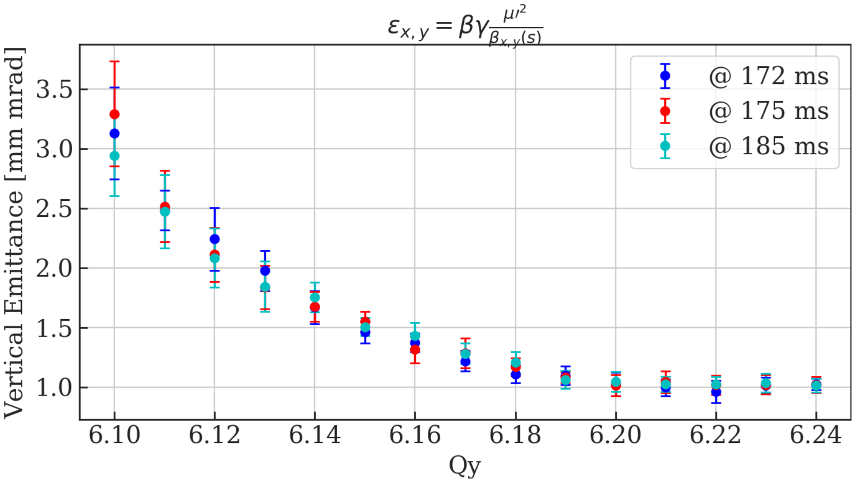


Figure: Example wire scanner profile taken at (Q_x, Q_y)=(6.21, 6.10), with multi-step fitting.

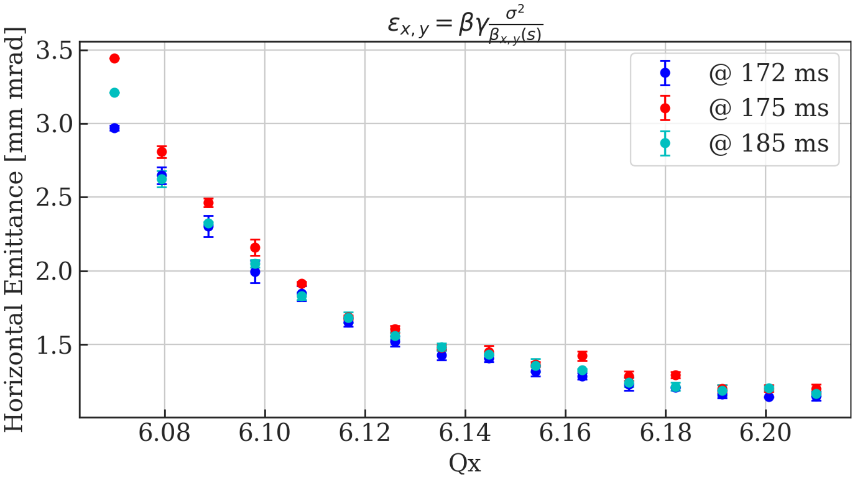
Vertical Scan Emittances using Standard Deviation



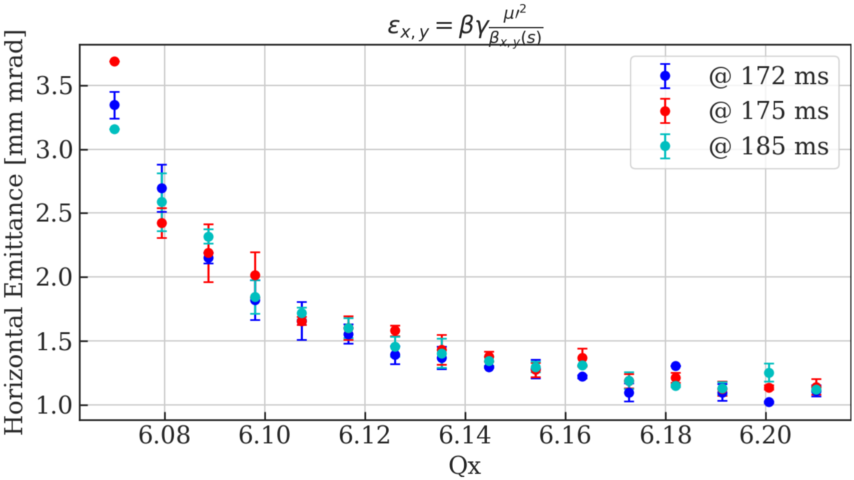
Vertical Scan Emittances using 2nd Moment



Horizontal Scan Emittances using Standard Deviation



Horizontal Scan Emittances using 2nd Moment



Emittance: Timescale of Increase

We observe no difference in emittances calculated from measured beam profiles at the three measurement times. This implies that the emittance growth is rapid, and takes less than 2 ms, which is equivalent to 875 turns. This prompted the choice of simulation turns. 2200 turns correspond to the second time measurement at 5ms post injection, and offers a reasonable simulation time.
Note all values calculated using linear optics (not including space charge).

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

Table: Simulation parameters

References for space charge model being used?

Distribution from Tomoscope

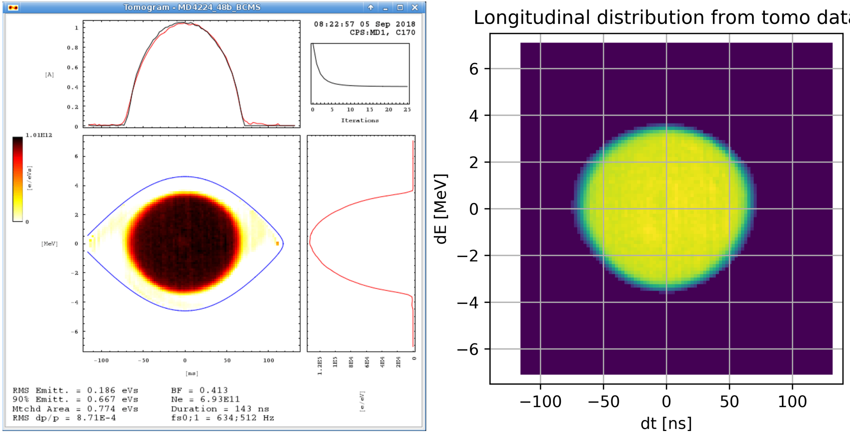


Figure: Example Tomogram from MD4224, and example PyORBIT distribution.

Injection Bump

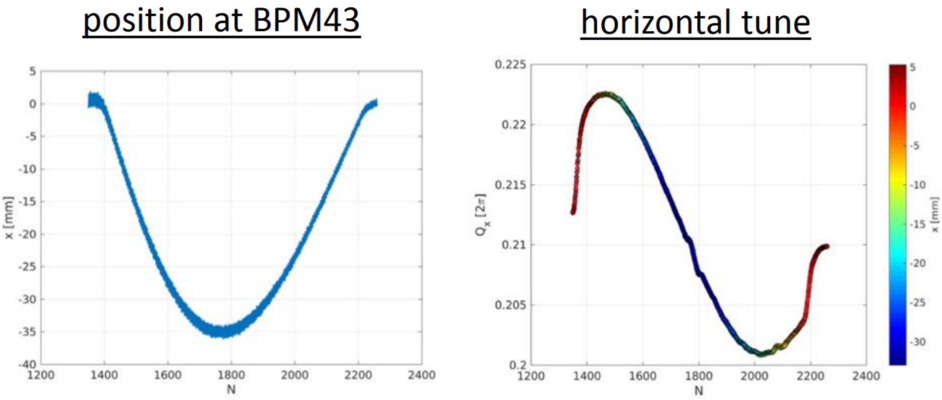


Figure: Measured horizontal offset (left) and tune swing (right) during injection into the PS [9]

[9] Motivation for PSB-PS tranfer studies and PS observations, A. Huschauer et. al., LIU-PS Beam Dynamics WG Meeting 3, 2017.

Injection Bump

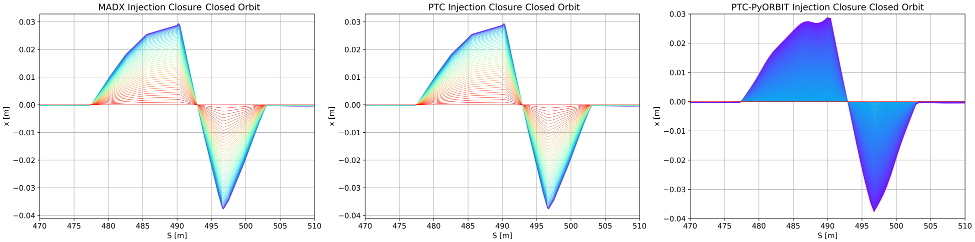


Figure: Closed Orbit comparisons for the closure of the injection bump in MAD-X (left), PTC (middle), and PyORBIT (right).

Injection Bump Tune Swing

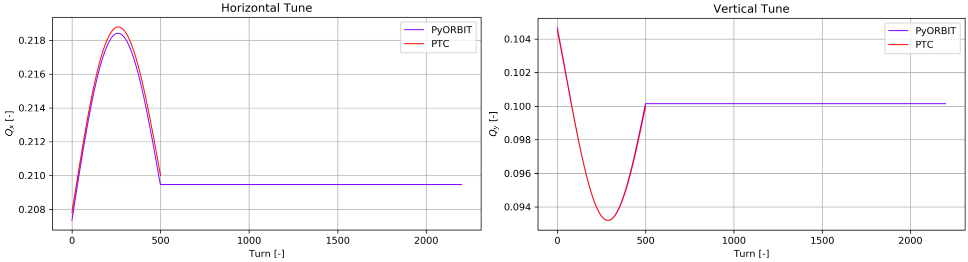


Figure: Horizontal (left) and vertical (right) tunes in PTC and PyORBIT modelling the injection bump tune swing for the closure of the bump.

Injection Bump Tune Swing

Need to switch the direction of the tune swing...

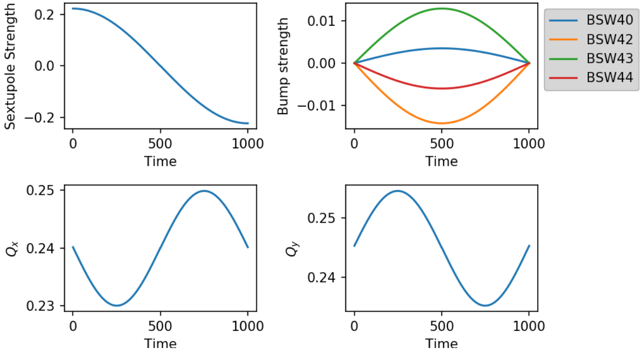


Figure: Tune swing settings from Eugenio.

Wirescanner Profile Comparison: Vertical Scan: No Injection Bump

Initial distribution matched to nominal working point optics

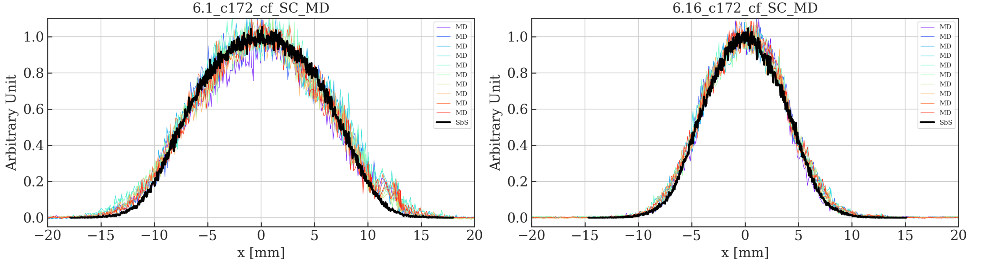


Figure: Wirescanner measurements compared to simulation profile for two points in vertical tune scan.

Tune Footprints

Tunes move to stable area within first 50 turns.

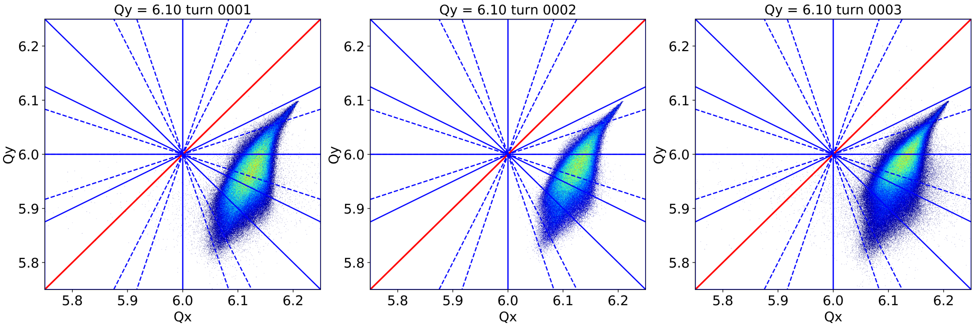
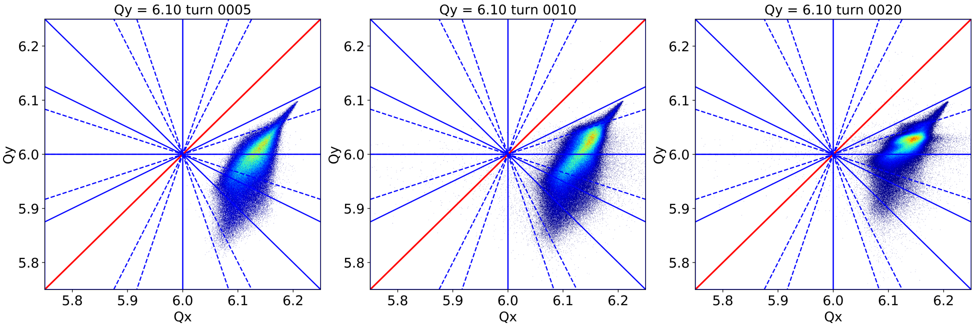


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turn.

Tune Footprints

Tunes move to stable area within first 50 turns.



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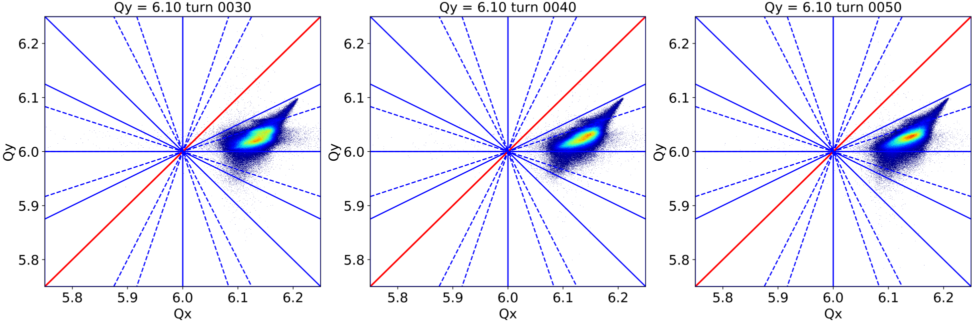

Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turn.

Emittance Blow-Up

Plot emittance vs turn: Start with no space charge.

Emittance Blow-Up

Plot emittance vs turn: Add space charge.

Vertical Scan Emittance using Standard Deviation Comparison

Initial distribution fixed to one matched to nominal working point (6.21, 6.24) optics.

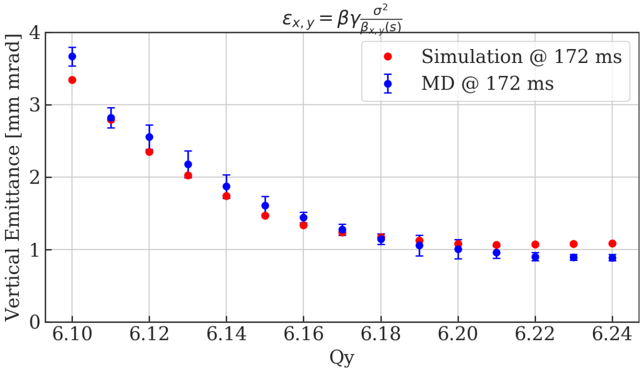

Figure: Emittances comparing measurements with simulation using space charge optics for the vertical tune scan.

Vertical Scan Emittance using 2nd Moment Comparison

Initial distribution matched to individual working point optics

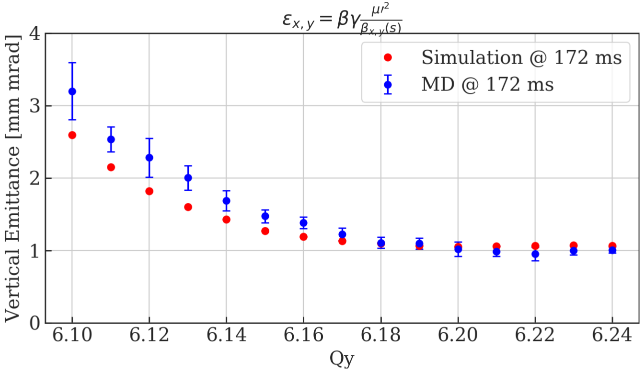

Figure: Emittances comparing measurements with simulation using space charge optics for the vertical tune scan.

Conclusion

- Clear beam blow-up as the beam is brought closer to the integer tune.
- Blow-up is evident from 2ms post injection - very fast.
- Simulations agree so far.
- Look at injection bump data.
- Check horizontal scan behaviour at (6.07, 6.21) before scan.

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.
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- G. Sterbini: MD Analysis SWAN Toolbox.