
CERN

Approaching the Integer Tune 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

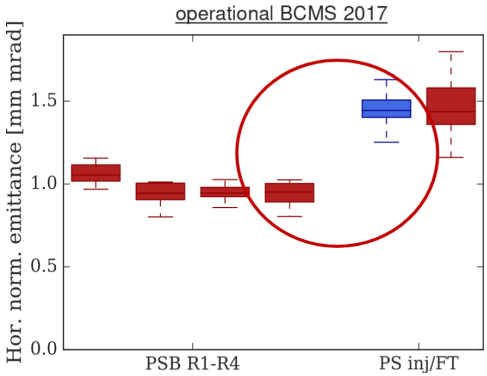


Figure: Observed emittance increase between the PSB and PS[2].

[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].
- Injection bump induced tune swing [5].
- Space charge - this talk.
- Injection mis-steering [6] - correctable.
- KFA14 (PSB extraction kicker) flat top ripple [7] - expected contribution is small.

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

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

[7] 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.

Tune Control: Effect of LEQs on Optics

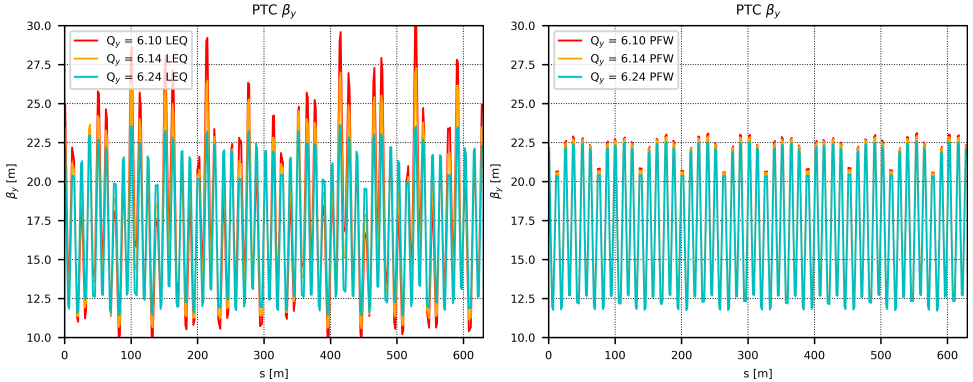


Figure: PS vertical beta function comparison. Tune modification using LEQs (left) compared to tune modification using PFWs (right).

Tune Control: Effect of LEQs on Optics

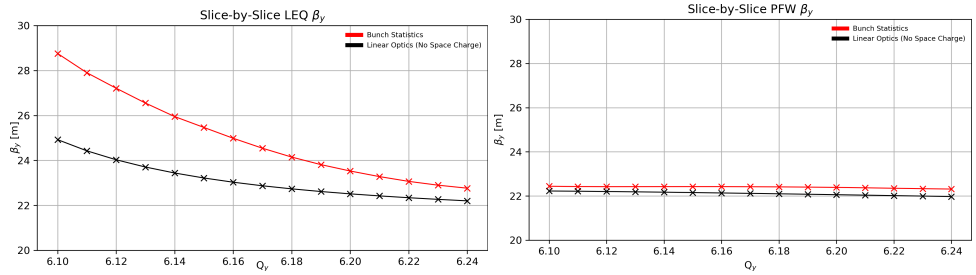


Figure: PS vertical beta function comparison at the position of the vertical wire scanner. Tune modification using LEQs (left) compared to tune modification using PFWs (right).

Resonances in the PS

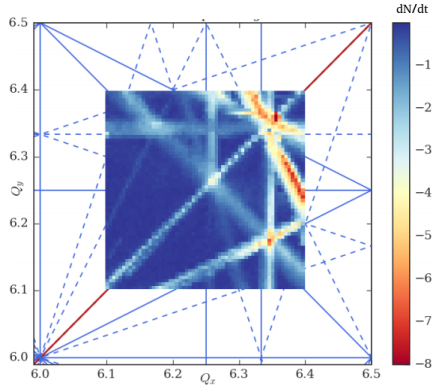


Figure: Tune scan in the CERN Proton Synchrotron indicating resonances from loss rate $\frac{dN}{dt}$ [8]

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

Tune Scan

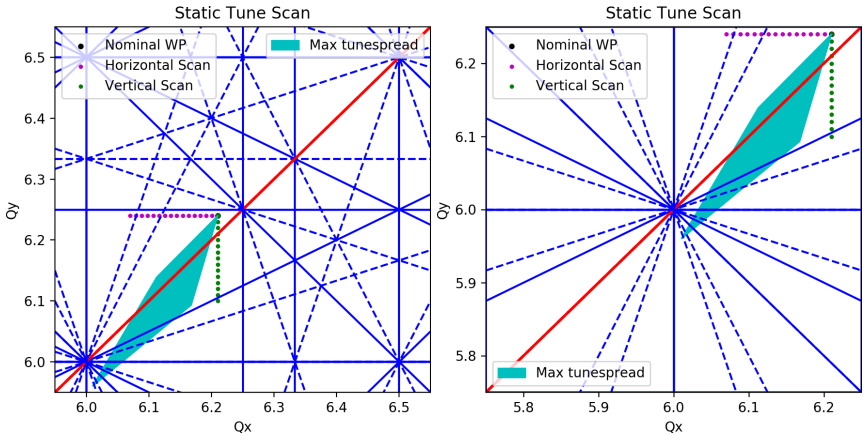


Figure: Static tune scan and estimated tune spread used in measurement campaign.

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 excitation active at flat bottom - gives small losses.
- Standard operational transfer line matching settings.

BCMS

Batch Compression Merging and Splitting

Increases the LHC peak luminosity by $\approx 20\%$

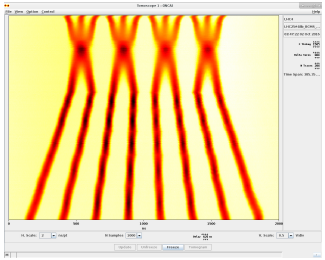


Figure: Bunch Compression Merging and Splitting (BCMS) tomogram from the PS.

Modified PS BCMS Cycle

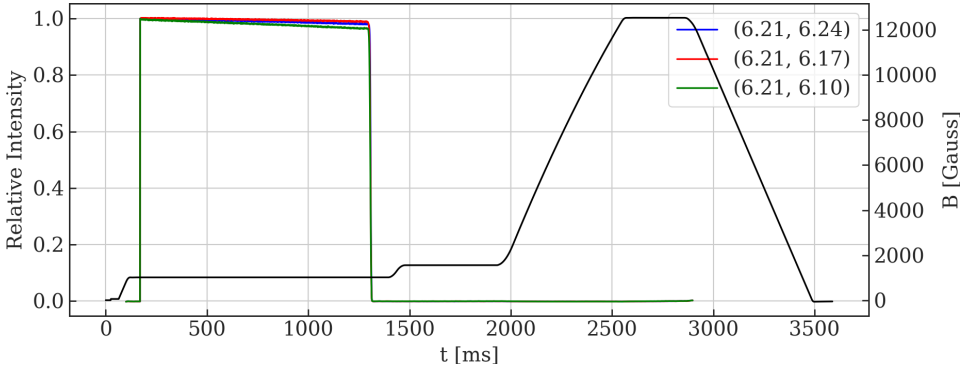


Figure: Magnetic cycle (black) and intensities (colours) for three points in the vertical tune scan. Injection takes place at 170 ms, the beam is internally dumped at 1300 ms.

Longitudinal Distribution

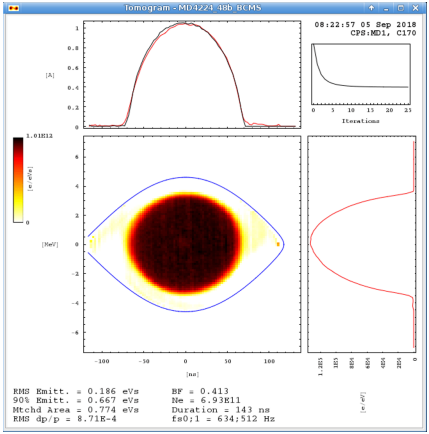


Figure: Example Tomogram from MD4224.

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

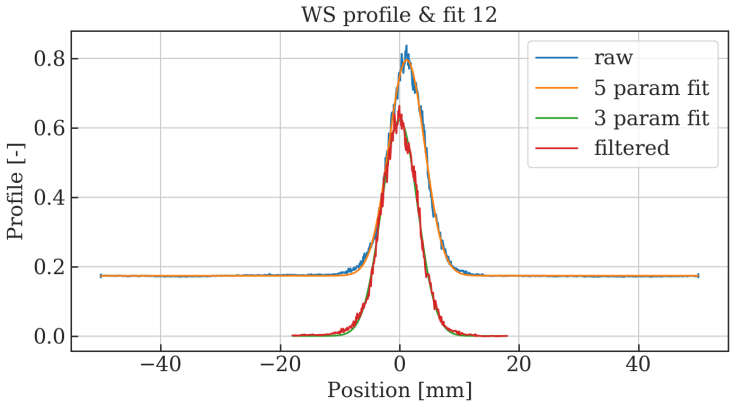


Figure: Example wire scanner profile taken at (Q_x, Q_y)=(6.21, 6.10), with multi-step fitting.

Horizontal Scan Emittance using Standard Deviation Comparison

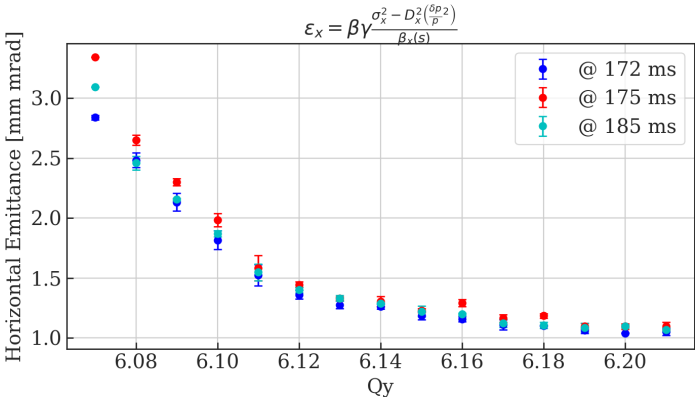


Figure: Emittances calculated using the bunch standard deviation comparing measurements with simulation using PTC optics for the horizontal tune scan.

Horizontal Scan Emittance using 2nd Moment Comparison

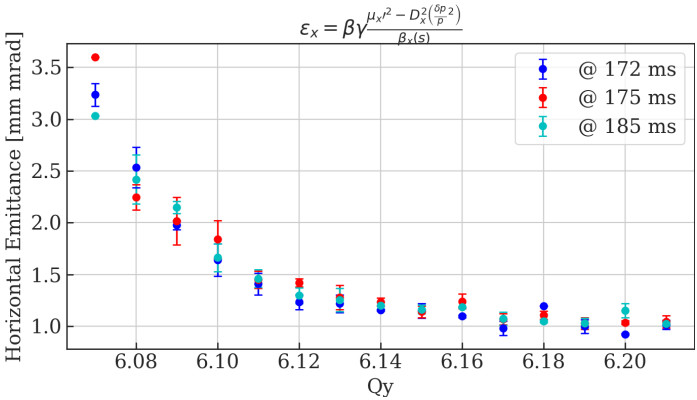


Figure: Emittances calculated using the bunch second moment comparing measurements with simulation using PTC optics for the horizontal tune scan.

Vertical Scan Emittance using Standard Deviation Comparison

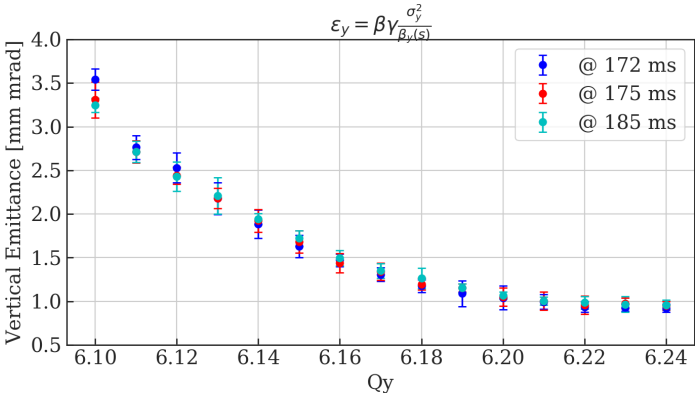


Figure: Emittances calculated using the bunch standard deviation comparing measurements with simulation using PTC optics for the vertical tune scan.

Vertical Scan Emittance using 2nd Moment Comparison

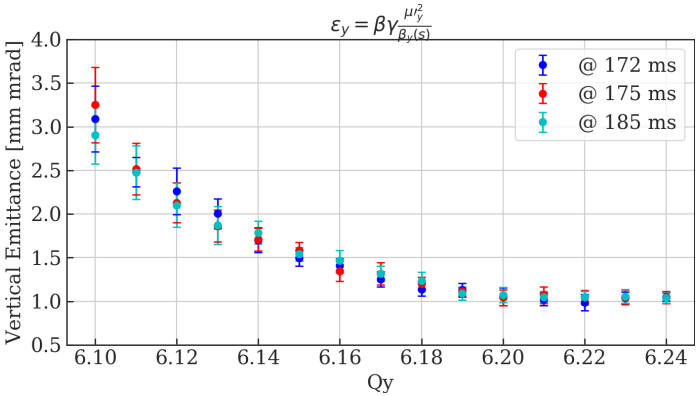


Figure: Emittances calculated using the bunch second moment comparing measurements with simulation using PTC optics for the vertical tune scan.

Emittance: Timescale of Increase

No difference in emittance with respect to measurement time.

Implies very fast beam blow-up (< 2 ms ≈ 875 turns).

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 $\Delta Q_{x,\max}$	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	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

Distribution from Tomoscope

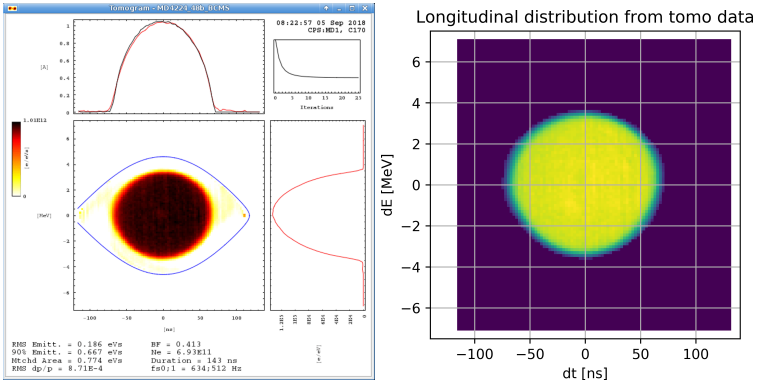


Figure: Example Tomogram from MD4224, and example PyORBIT distribution, which is a 2D Gaussian in the transverse planes.

Simulation: Vertical Scan: Vertical Emittance

First compare pure tracking with tracking + space charge.

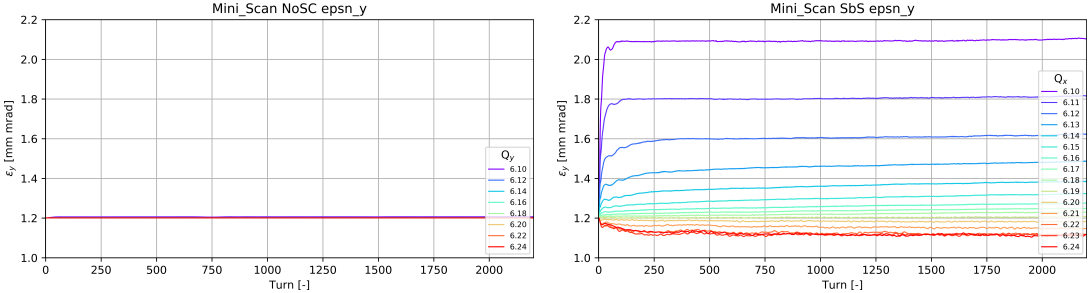


Figure: Comparison of emittances for simulations without (left) and with (right) space charge for the vertical scan. Space charge clearly affects the beam emittance, as expected.

Simulation: Vertical Scan: Emittances

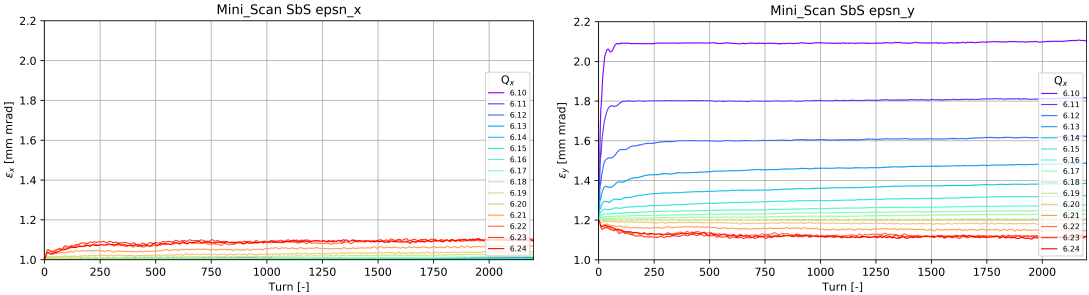
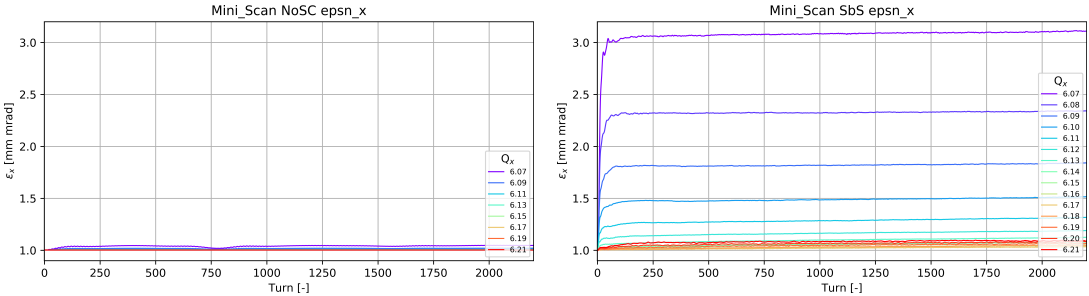


Figure: Comparison of horizontal (left) and vertical (right) simulation emittances with space charge for the vertical scan. The Montague resonance is evident around tune (6.21 , 6.21).

Simulation: Horizontal Scan: Horizontal Emittance

First compare pure tracking with tracking + space charge.



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Simulation: Horizontal Scan: Emittances

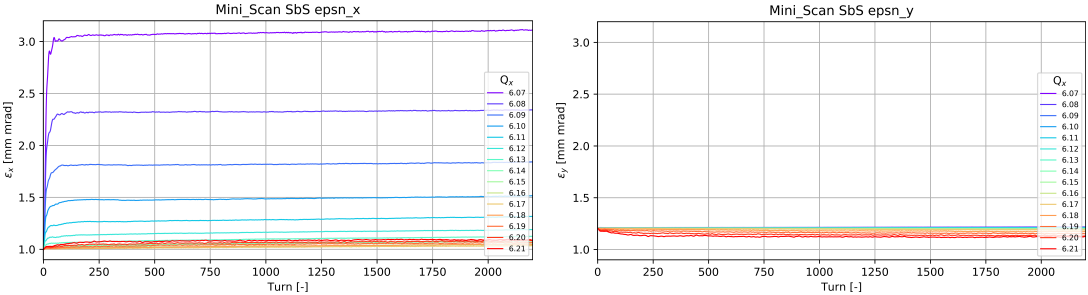


Figure: Comparison of horizontal (left) and vertical (right) simulation emittances with space charge for the horizontal scan. The Montague resonance is evident around tune (6.21 , 6.21).

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

All initial distributions matched to nominal (6.21 6.24) working point optics

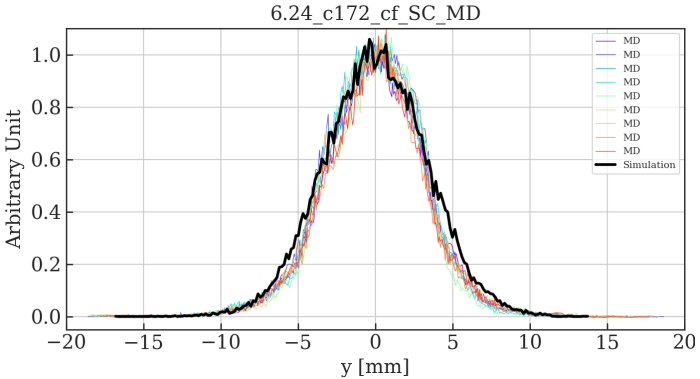


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.24) at 2 ms post injection.

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

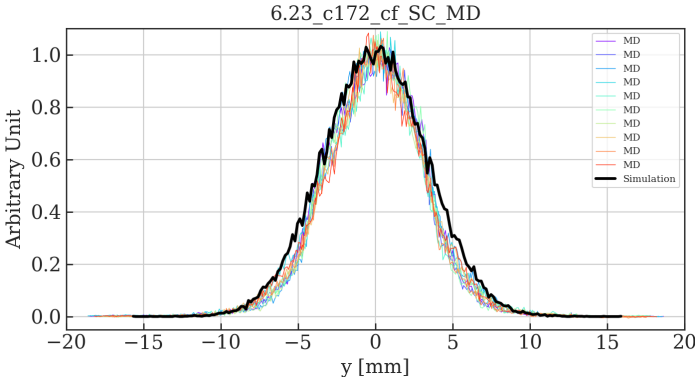


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.23) at 2 ms post injection.

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

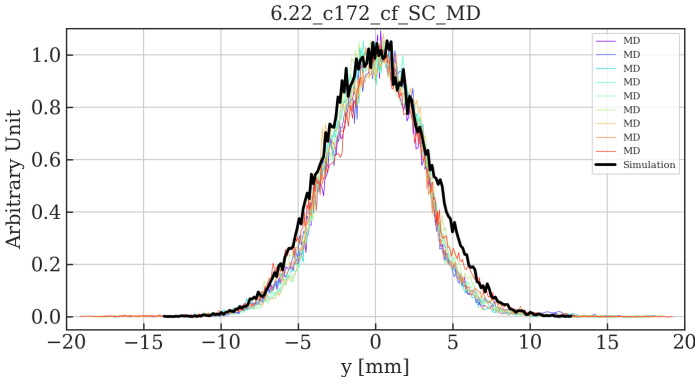


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.22) at 2 ms post injection.

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

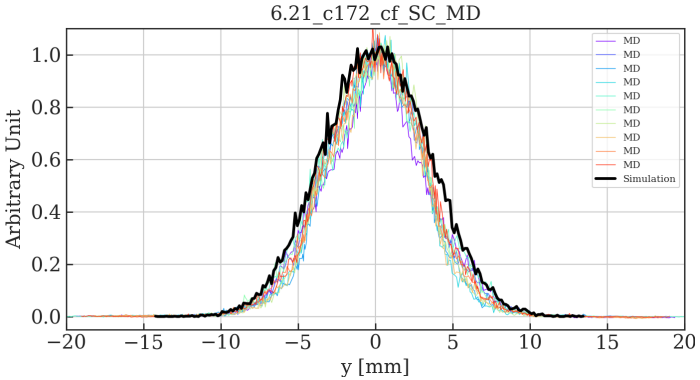


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.21, 6.21) at 2 ms post injection.

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

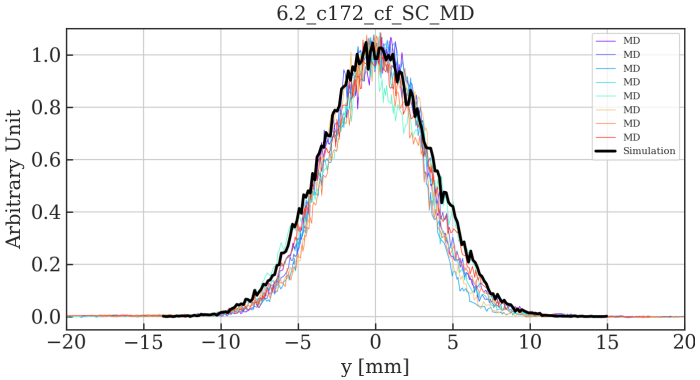


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.20, 6.21) at 2 ms post injection.

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

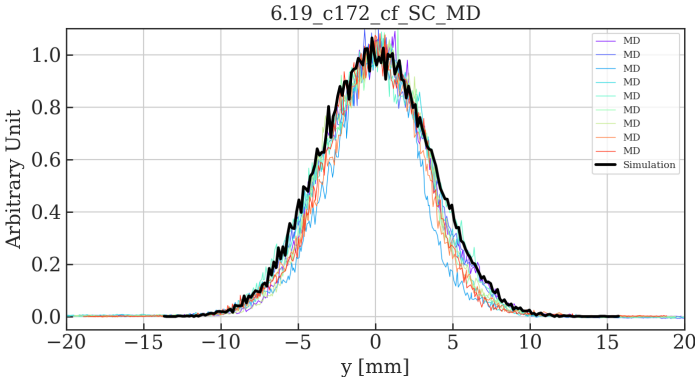


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.19, 6.21) at 2 ms post injection.

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

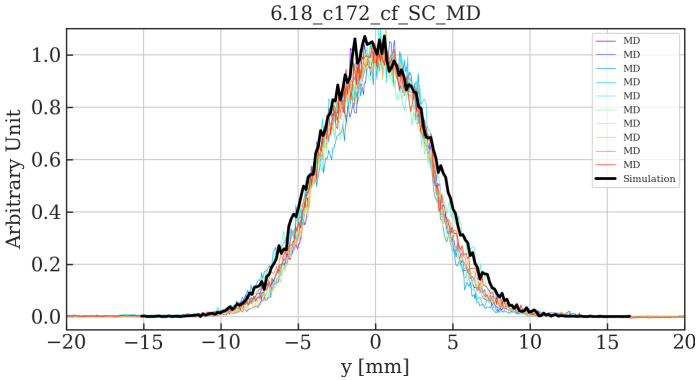


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.18, 6.21) at 2 ms post injection.

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

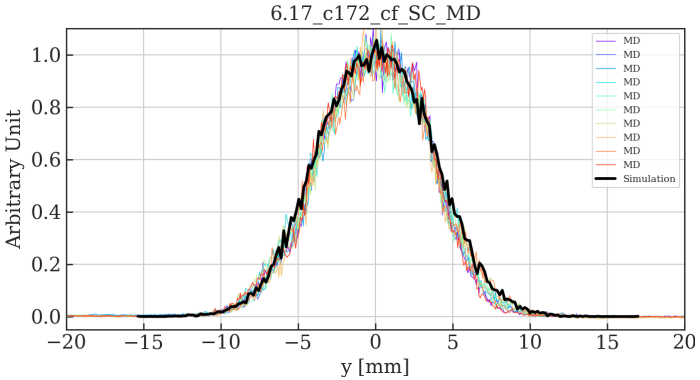


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.17, 6.21) at 2 ms post injection.

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

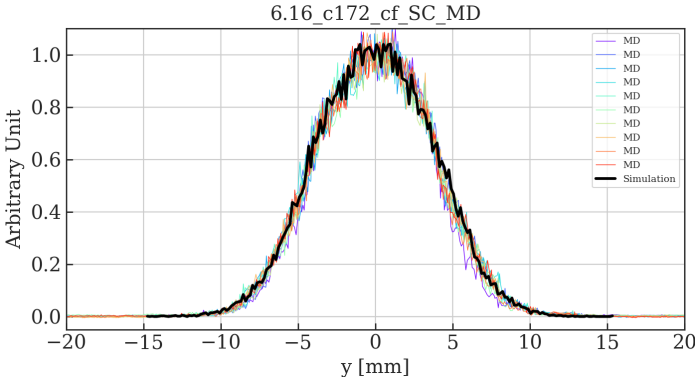


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.16, 6.21) at 2 ms post injection.

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

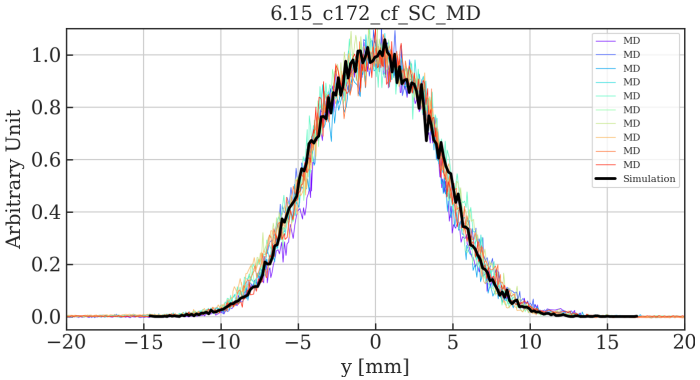


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.15, 6.21) at 2 ms post injection.

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

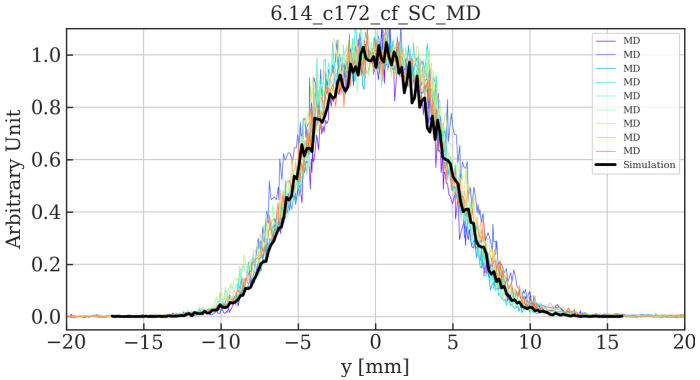


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.14, 6.21) at 2 ms post injection.

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

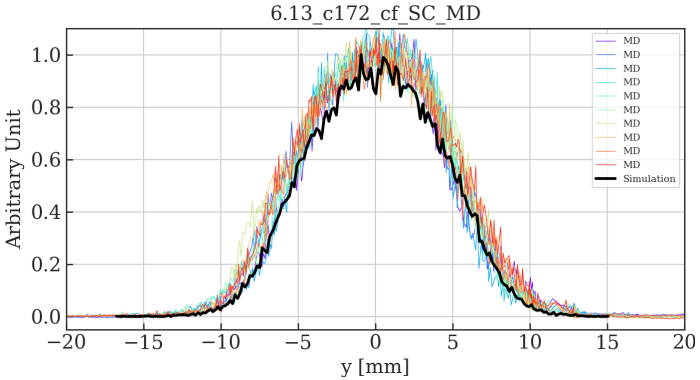


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.13, 6.21) at 2 ms post injection.

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

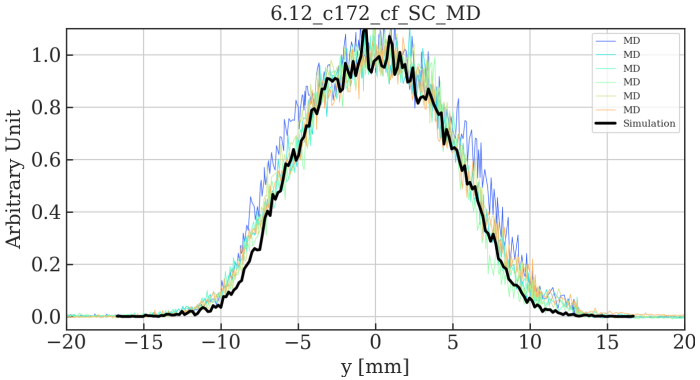


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.12, 6.21) at 2 ms post injection.

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

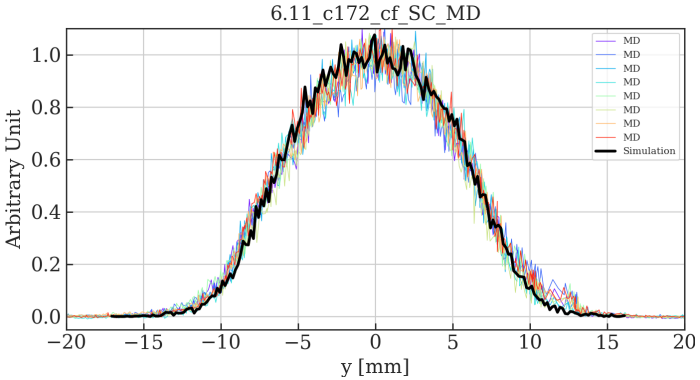


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.11, 6.21) at 2 ms post injection.

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

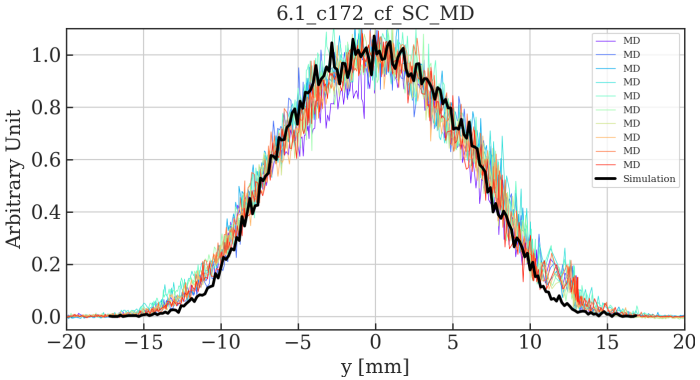


Figure: Wirescanner measurements compared to simulation profile for Vertical scan working point (6.10, 6.21) at 2 ms post injection.

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

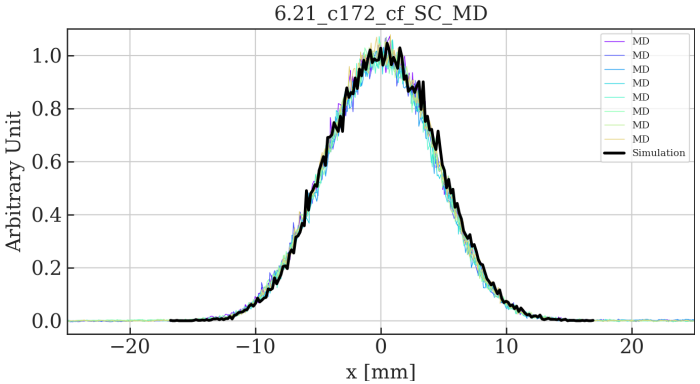


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.21, 6.21) at 2 ms post injection.

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

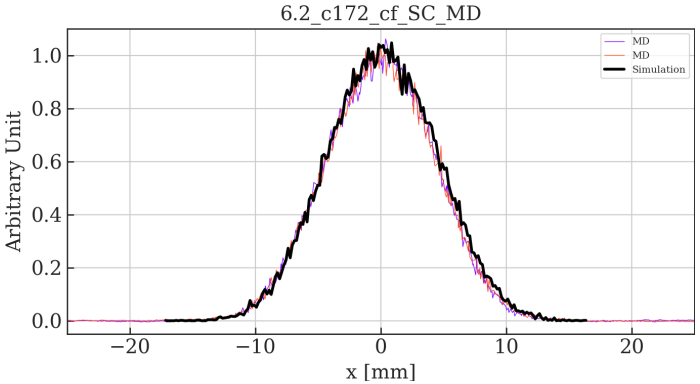


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.20, 6.21) at 2 ms post injection.

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

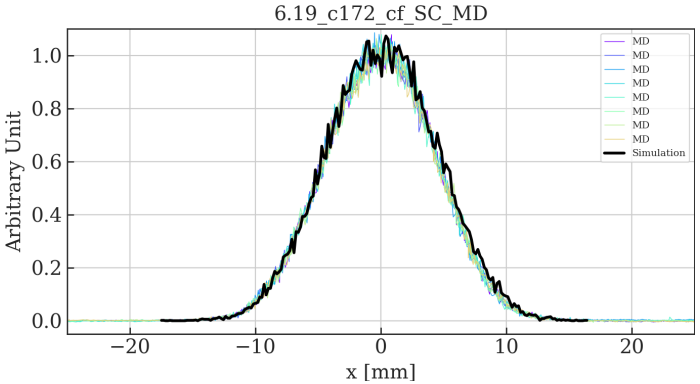


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.19, 6.21) at 2 ms post injection.

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

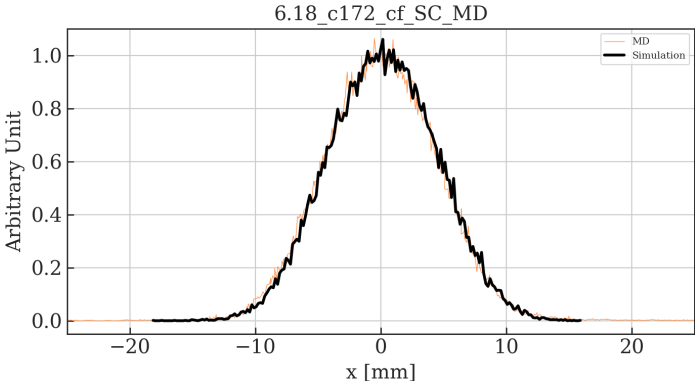


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.18, 6.21) at 2 ms post injection.

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

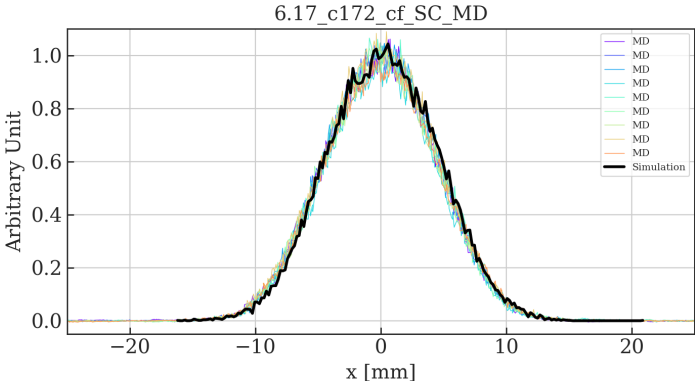


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.17, 6.21) at 2 ms post injection.

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

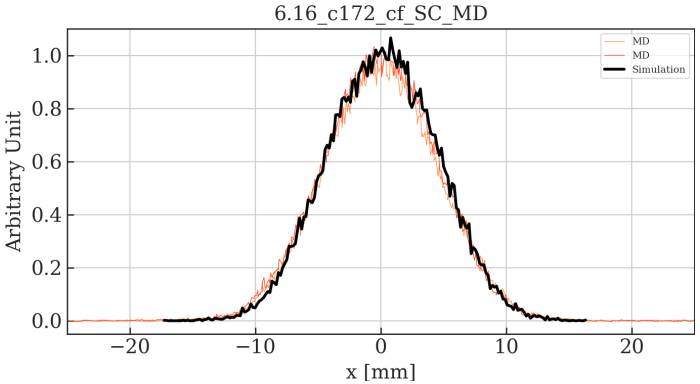


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.16, 6.21) at 2 ms post injection.

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

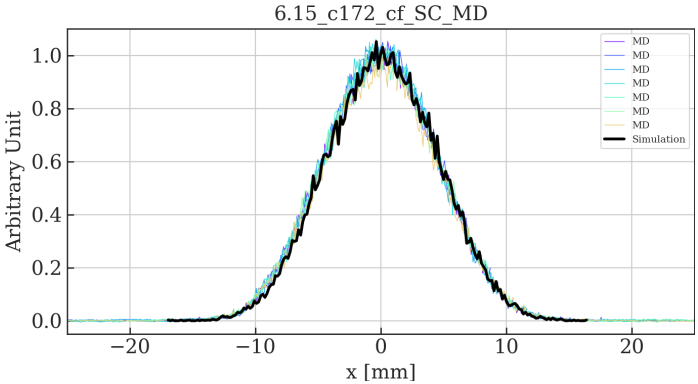


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.15, 6.21) at 2 ms post injection.

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

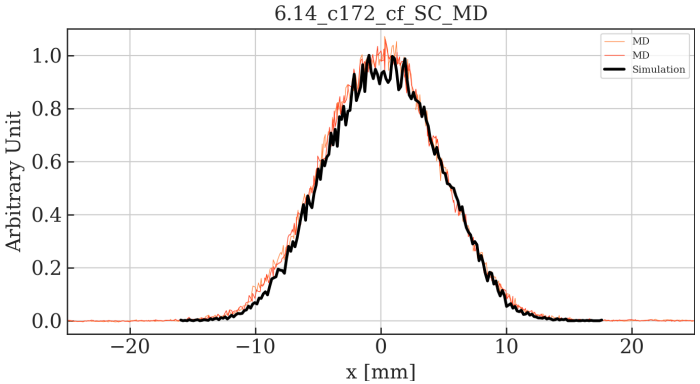


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.14, 6.21) at 2 ms post injection.

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

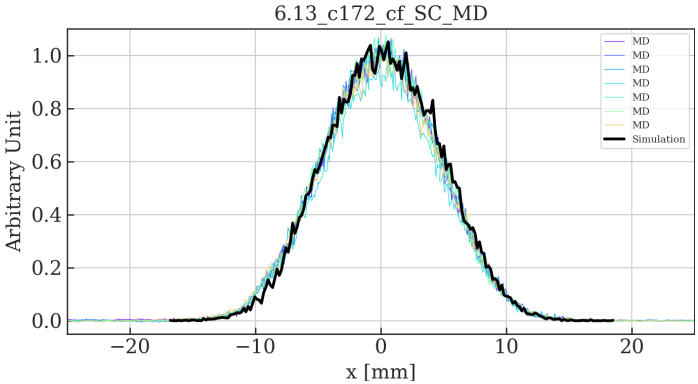


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.13, 6.21) at 2 ms post injection.

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

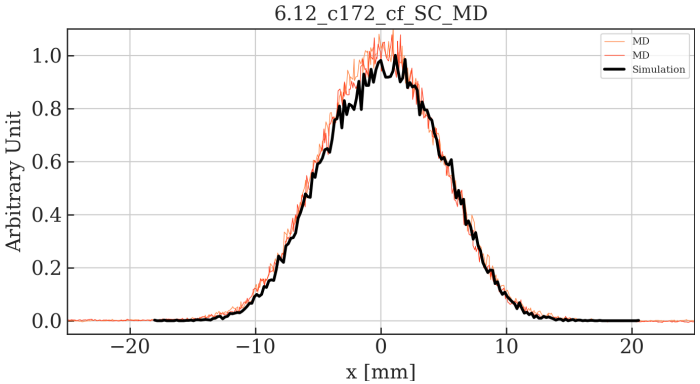


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.12, 6.21) at 2 ms post injection.

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

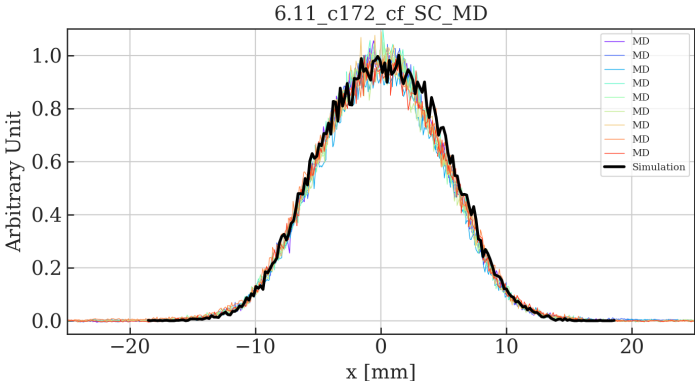


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.11, 6.21) at 2 ms post injection.

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

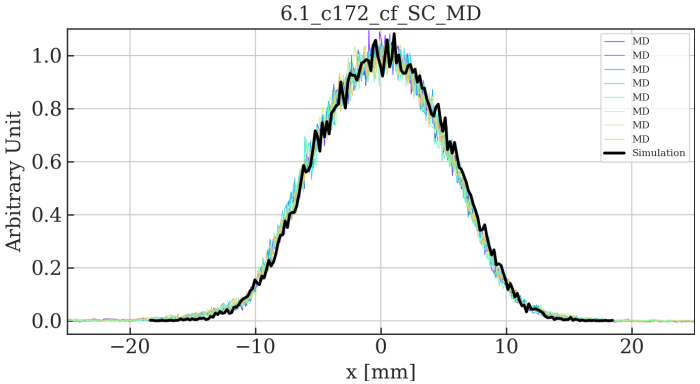


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.10, 6.21) at 2 ms post injection.

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

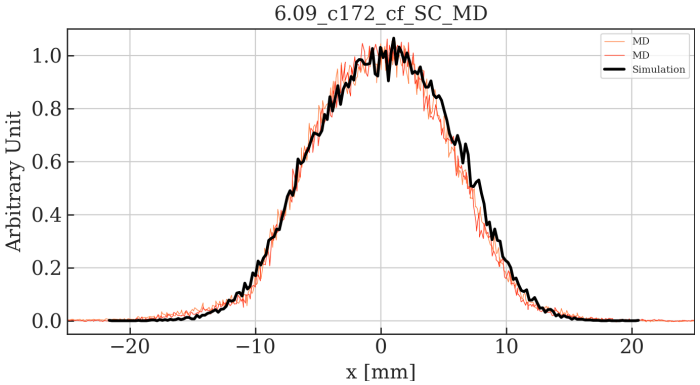


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.09, 6.21) at 2 ms post injection.

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

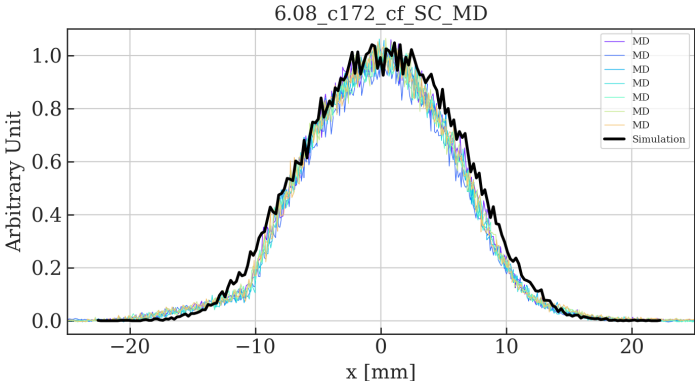


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.08, 6.21) at 2 ms post injection.

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

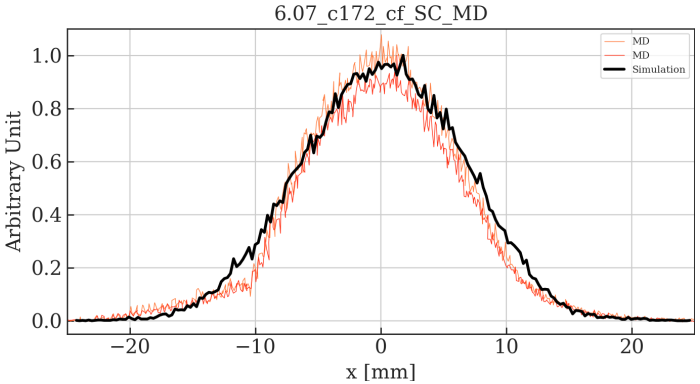


Figure: Wirescanner measurements compared to simulation profile for Horizontal scan working point (6.07, 6.21) at 2 ms post injection.

Tune Footprints: Vertical Extreme

Tunes move to stable area within first 50 turns.

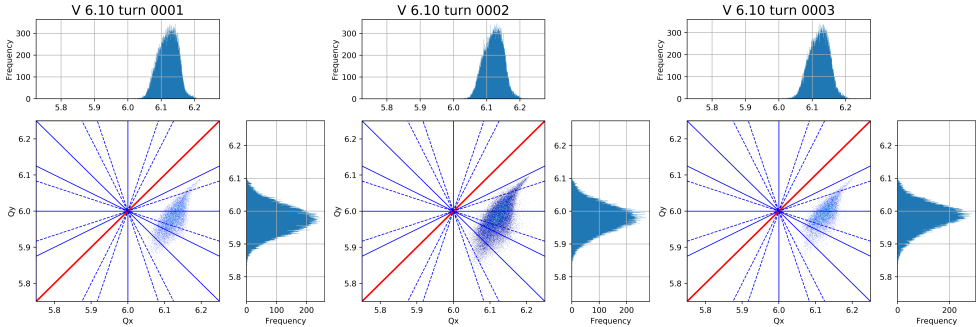


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

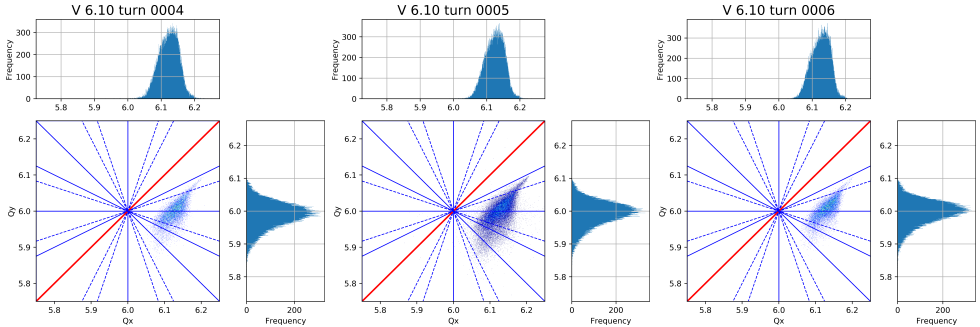


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

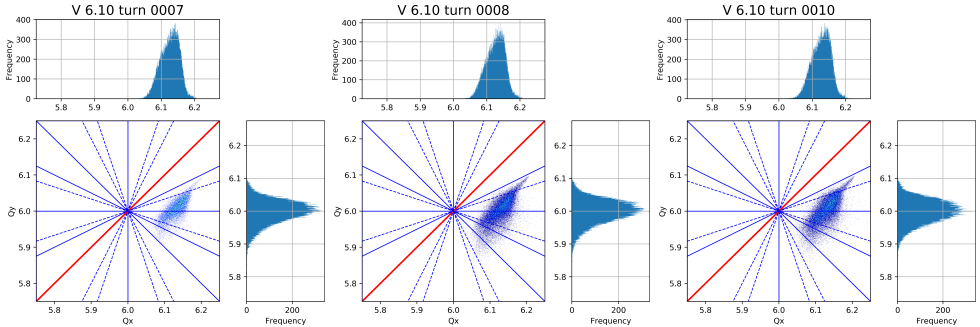


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

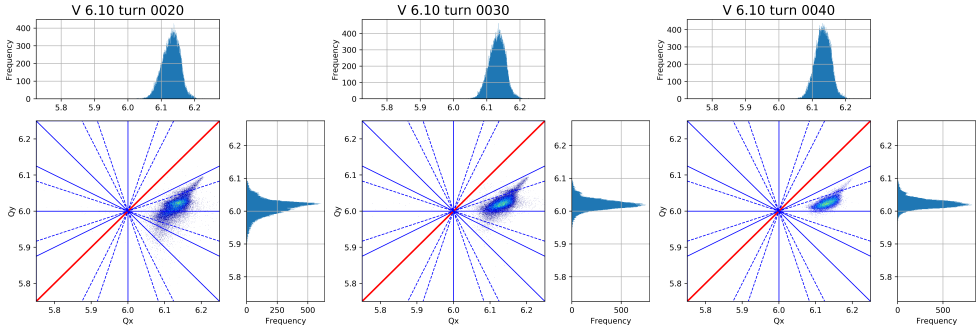


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Vertical Extreme

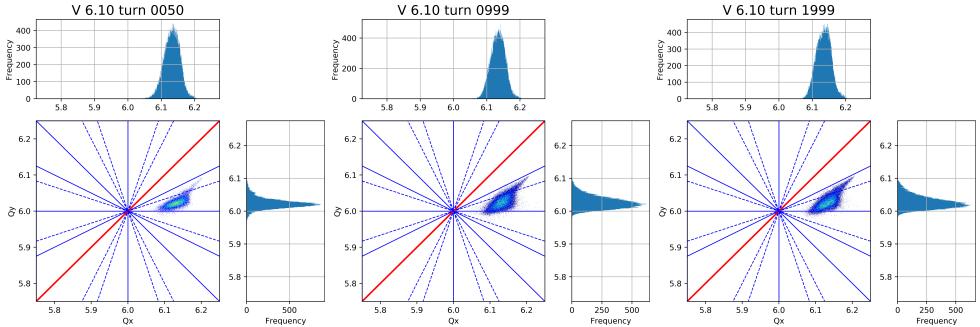


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.21, 6.10) for indicated turns.

Tune Footprints: Horizontal Extreme

Tunes move to stable area within first 50 turns.

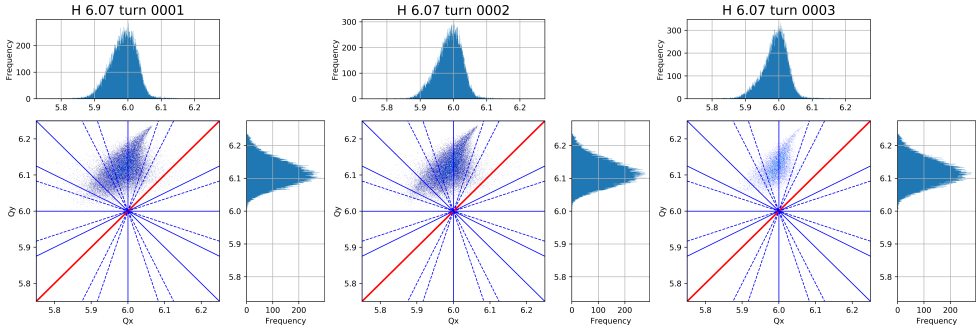


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Tune Footprints: Horizontal Extreme

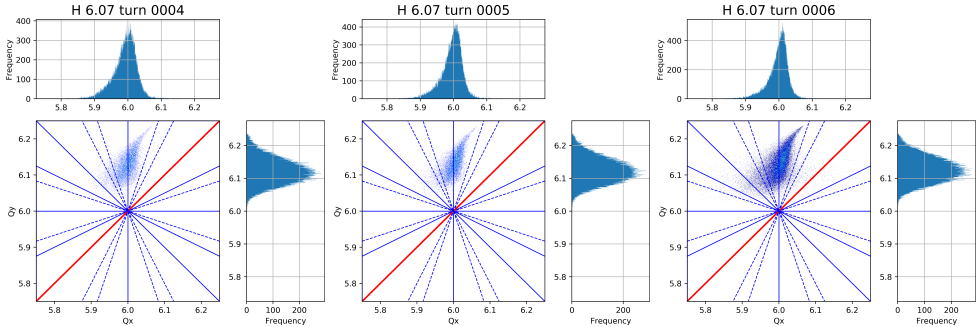


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Tune Footprints: Horizontal Extreme

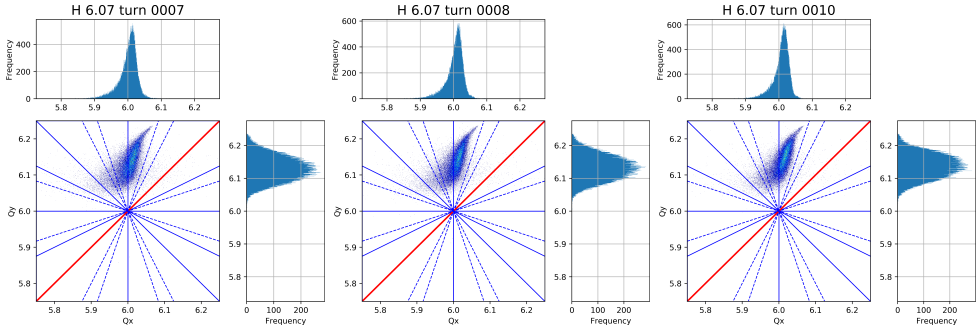


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Tune Footprints: Horizontal Extreme

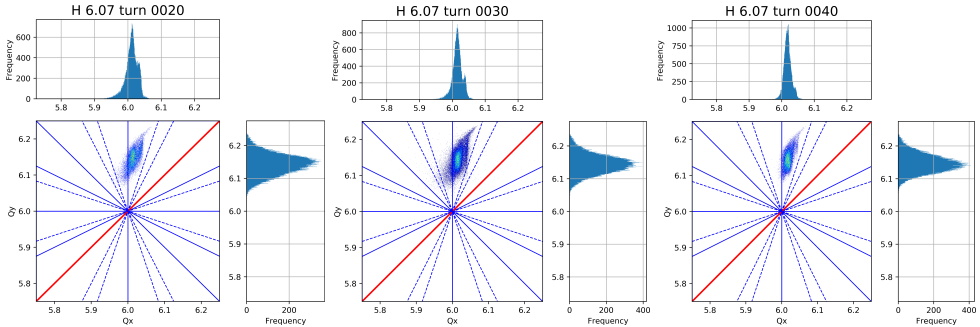


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Tune Footprints: Horizontal Extreme

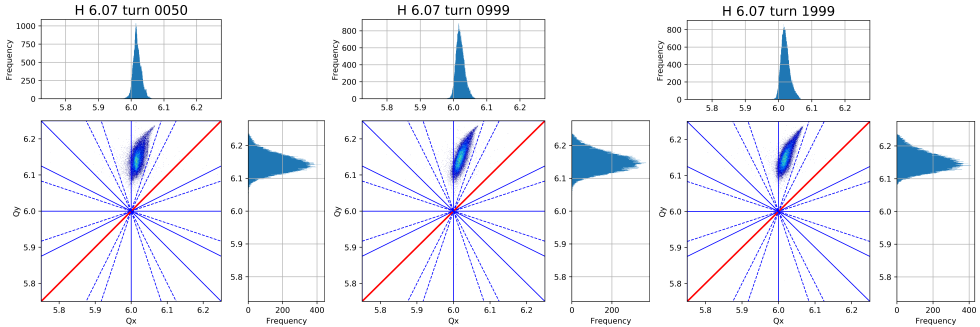


Figure: Tune footprints from PyORBIT simulations for vertical scan WP (6.07, 6.24) for indicated turns.

Vertical Scan Emittance using Standard Deviation Comparison

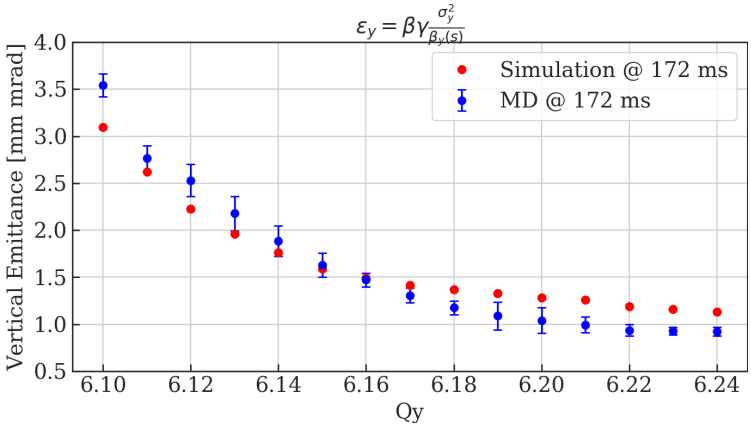


Figure: Emittances comparing measurements with simulation using PTC optics for the vertical tune scan.

Vertical Scan Emittance using 2nd Moment Comparison

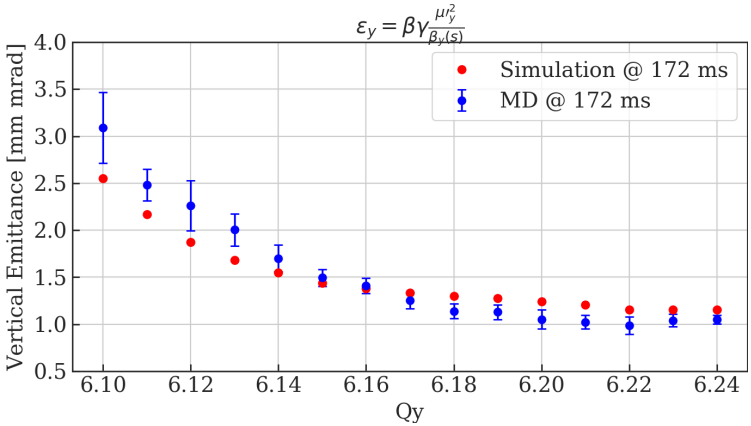


Figure: Emittances comparing measurements with simulation using PTC optics for the vertical tune scan.

Horizontal Scan Emittance using Standard Deviation Comparison

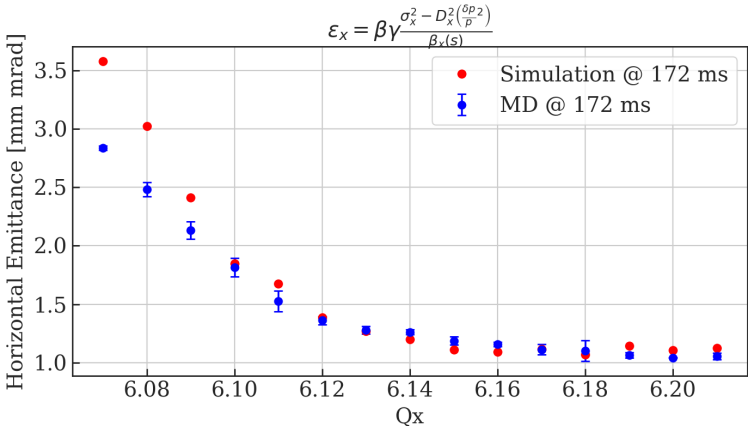


Figure: Emittances comparing measurements with simulation using PTC optics for the horizontal tune scan.

Horizontal Scan Emittance using 2nd Moment Comparison

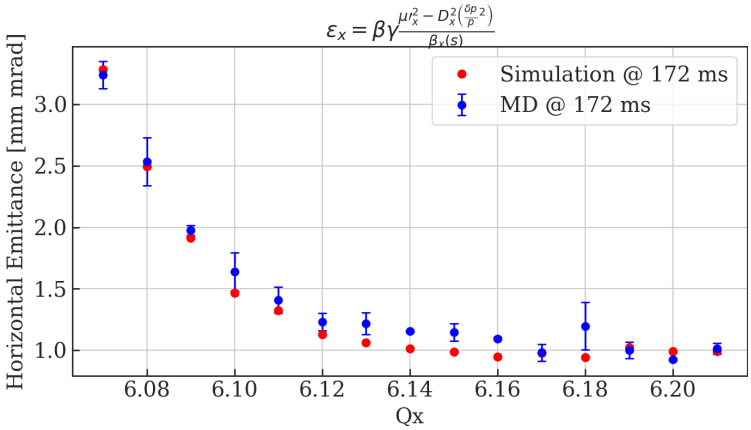


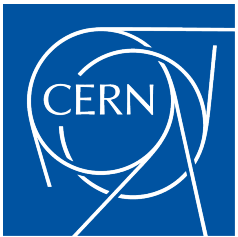
Figure: Emittances comparing measurements with simulation using PTC optics for the horizontal tune scan.

Conclusions

- Measurements show clear beam blow-up as the beam is brought closer to the integer tune, where the half-integer resonance sits.
- The emittance blow-up is evident from 2 ms post injection - very fast.
- Simulated agree well with measurements.
- From simulations, beam blow up in first $\approx$ 50 turns $\approx$ 0.11 ms.
- 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.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