CERN

PS Space Charge Studies

Latest Updates: S. Albright, H. Bartosik, M. A. Fraser, A. Huschauer, A. Oeftiger, H. Rafique

haroon.rafique@cern.ch

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Motivation

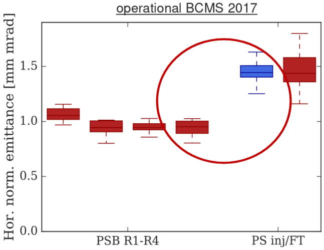


Figure: Measured horizontal emittance blow-up [1].

Measured 30-40% emittance blowup between PSB and PS:

Try to **gauge effect of space charge at PS injection** and assess possible contribution to blow-up, using beam profile measurements.

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

Motivation

Test latest models of the PS:

Benchmark models with measured data to understand beam behaviour in the PS.
Using **A. Huschauer's opdated model of the PS** and applying it with MAD-X/PTC to generate optics. Applying 3D (slice-by-slice) space charge via PTC-PyORBIT.

Predict bunch behaviour for LIU-era PS:

Use benchmarked tool to **compare analytical expectations with detailed simulation** in order to optimise machine performance.
Preparation for simulating possible issues during or after commissioning.

Ongoing Studies

Simulation Studies Relevant to the PS:

- Space charge at PS injection (MD4224).
- Transfer line dispersion mismatch.
- Longitudinal emittance study (MD211).
- LIU tunespread and emittance growth.
- Injection bump.

SC @ PS Injection: Measurement Campaign

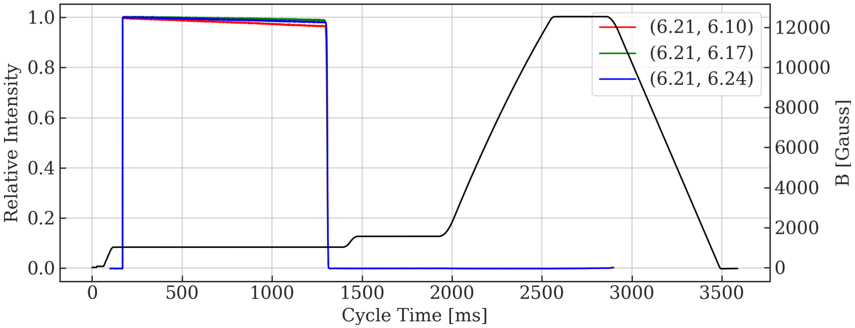


Figure: MD4224: **BCMS Low Chroma**, single injection from PSB Ring 3, no acceleration (flat bottom), internal dump @ 1350 ms. **Tunes varied using low energy quadrupoles (LEQs)**.

SC @ PS Injection: 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	0.19
Vertical maximum tune spread $\Delta Q_{y,\mathrm{max}}$	0.28	0.26
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

Table: Beam and machine parameters.

SC @ PS Injection: Measurement Campaign

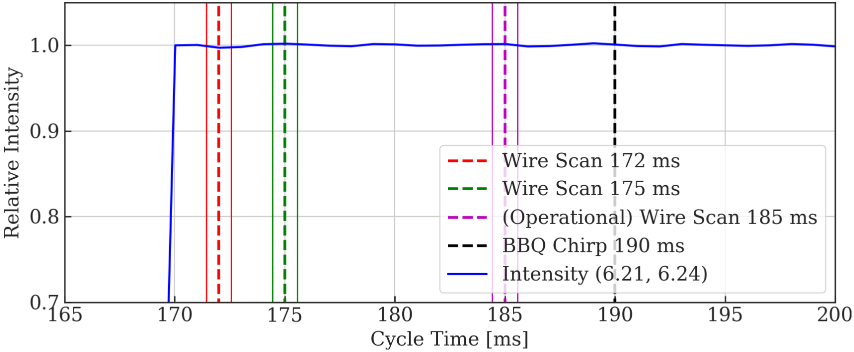


Figure: MD4224: Wire scanner **measurements at 2, 5, and 15 ms post-injection**. BBQ chirp active form 190 ms.

SC @ PS Injection: Measurement Results

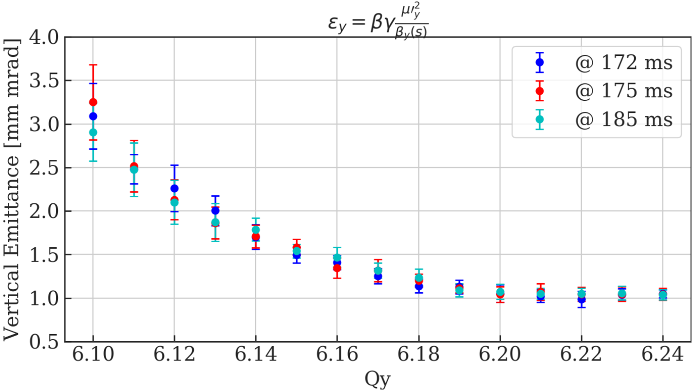


Figure: MD4224: **Measured vertical emittances constructed from beam profiles** using second moment $\mu_y' = \sqrt{\langle y \rangle}$. There is no dependence on measurement time - implying a **fast blow-up (within 2 ms). Measure with SEM grids / BGI?**

SC @ PS Injection: Measurement Campaign

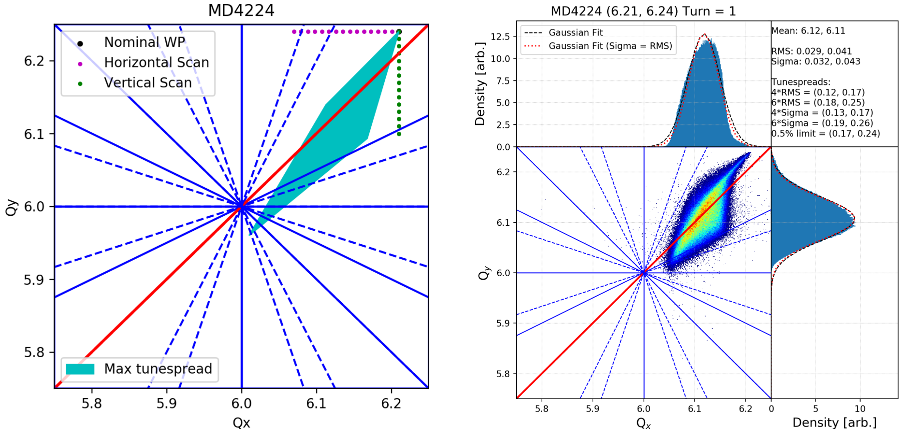


Figure: MD4224: **Predicted tune footprint and tune scan points** (left), simulated tune footprint (right) at (6.21, 6.24).

SC @ PS Injection: Measurement Campaign

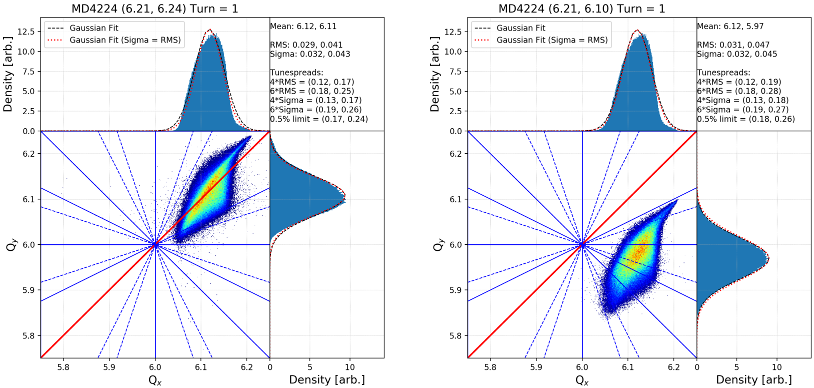


Figure: MD4224: **Simulated tune footprints** for vertical tunes 6.24 (left), and 6.10 (right). The horizontal tune is fixed at 6.21. **The bunch is expected to interact with the vertical (half-) integer resonance when the vertical working point is 6.10 (right)**, but not when it is 6.24 (left).

SC @ PS Injection: Measurement Results

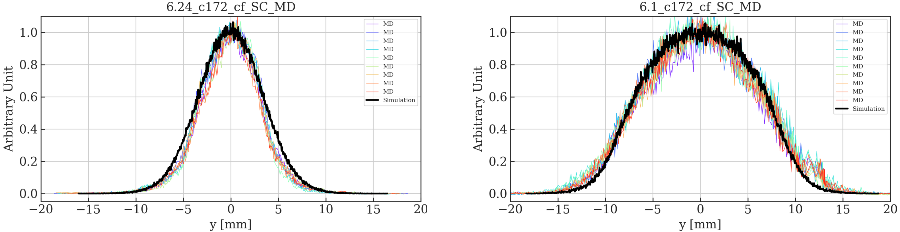


Figure: MD4224: Bunch **profile measurements compared to simulated profiles at 2 ms post-injection** for vertical tunes 6.24 (left), and 6.10 (right). The horizontal tune is fixed at 6.21. See here for animations.

SC @ PS Injection: Simulations Results

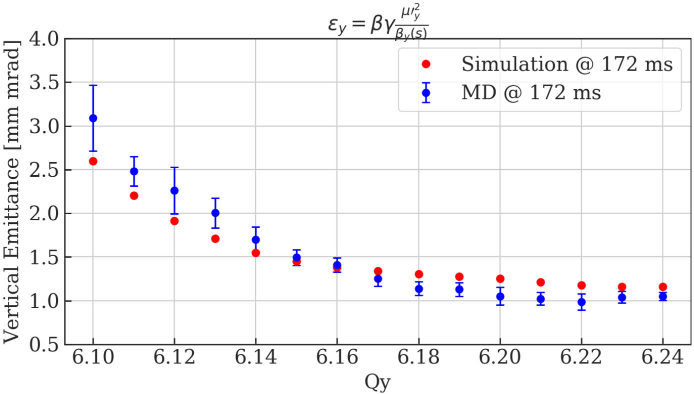


Figure: MD4224: Measured vertical emittances constructed from beam profiles using second moment $\mu_y' = \sqrt{\langle y \rangle}$.

SC @ PS Injection: Simulation Results

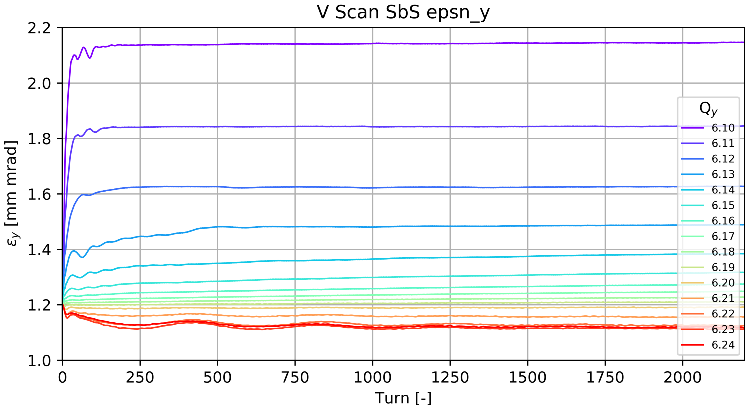


Figure: MD4224: **Simulated vertical normalised RMS. emittances from PyORBIT simulations.** Injection +2 ms ≈ 875 turns, +5 ms ≈ 2200 turns. **Blow up complete within 200 turns (< 0.5 ms).**

SC @ PS Injection: Simulation Results

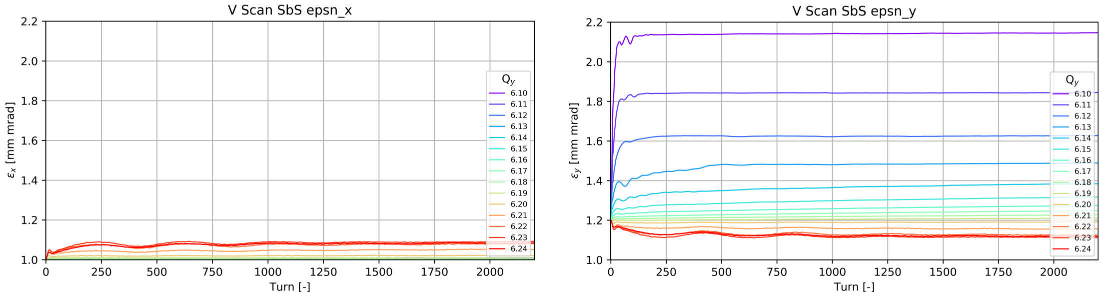


Figure: MD4224: Simulated horizontal (left) and vertical (right) normalised RMS emittances from PyORBIT simulations using LEQs to modify the tune. **Near the operational working point (6.21, 6.24)**: the Montague coupling resonance is evident, and **no space-charge blowup is observed**.

Use PFWs Instead of LEQs

Use only Pole Face Windings (PFWs) to modify the tune.

Remove sources of quadrupole error and hopefully interaction with half-integer resonances. Expect no space charge emittance growth as periodicity of the machine is maintained.

SC @ PS Injection: Probing Understanding: PFW Scan

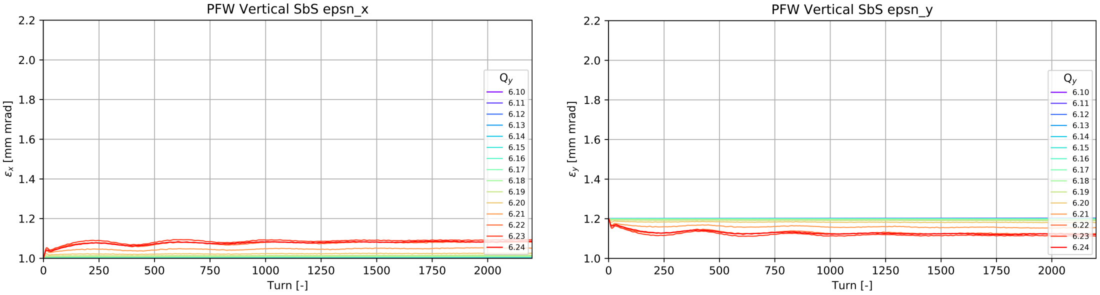


Figure: MD4224: Simulated horizontal (left) and vertical (right) normalised RMS emittances from PyORBIT simulations. **Using PFWs to modify the tune**: the Montague coupling resonance is evident, and **for all tunes no space-charge blowup is observed.**

SC @ PS Injection: Probing Understanding: LEQ vs PFW

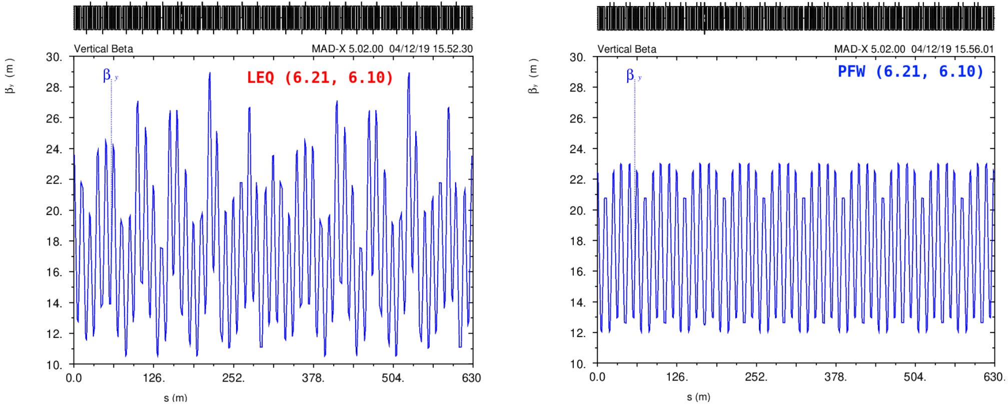


Figure: MD4224: MD4224: Simulated vertical beta functions from MAD-X simulations comparing modification of tune via LEQs (left) with PFWs (right). **Using the LEQs to modify the tune generates additional beta-beating due to violation of periodicity.**

PFW With Betatronic Error

Add betatronic error to initial distribution.

Check that the emittance blow-up is not due to a simple mismatch.

Betatron Mismatch on Initial Bunch Distribution

Equation for emittance growth due to betatron mismatch taken from V. Kain's CAS 2017 lecture on emittance preservation (click for link):

$$\epsilon_{new} = \frac{\epsilon_0}{2}\left(\frac{\beta_1}{\beta_2} + \frac{\beta_2}{\beta_1}\left(\alpha_1 - \alpha_2\frac{\beta_1}{\beta_2}\right)^2 + \frac{\beta_2}{\beta_1}\right) \tag{1}$$

Define $M_\beta = \frac{\beta_2}{\beta_1}$ and $M_\alpha = \frac{\alpha_2}{\alpha_1}$, and use $M_\alpha = M_\beta$. Here we are looking at the most extreme vertical tune, so $\beta_1 = \beta_{y_0}$, $\alpha_1 = \alpha_{y_0}$.

Emittance Growth From Betatron Mismatch (No Space Charge)

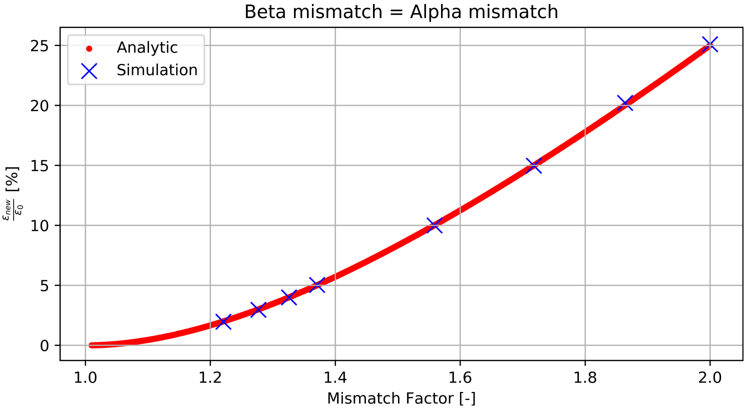
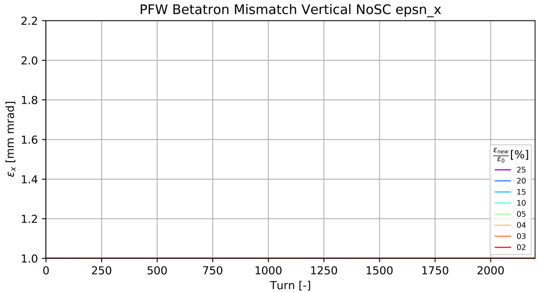


Figure: Analytical expectation for emittance growth as a function of betatron mismatch factor when using the PFW to modify tunes (red), compared to simulation data without space charge (blue), for tune (Q_x, Q_y)=(6.21, 6.10) - most extreme point in vertical scan.

SC @ PS Injection: Probing Understanding: PFW with Betatronic Error



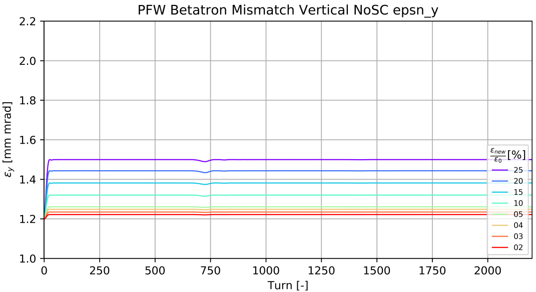


Figure: MD4224: Simulated horizontal (left) and vertical (right) normalised RMS emittances from PyORBIT simulations. **Using PFWs to modify the tune with a betatronic error**: the tune is fixed at (6.21, 6.10), results identical with space charge and **the resulting blowup is not consistent with measurements, even for a mismatch factor of 2**.

PFW With Quadrupolar Error

Add quadrupolar error to single LEQ (QDN72) to generate quadrupolar resonance.

Express error in terms of resulting beta-beating, perform simulation scan in beta-beating to obtain similar result to LEQ scan. All LEQs off except single error.

Beta Beating due to Quadrupole Error

Equations taken from H. Bartosik's JUAS 2019 lecture on linear imperfections and correction (click for link):

$$\frac{\delta\beta}{\beta_0} = -\frac{1}{2\sin(2\pi Q)} \int_{s_1}^{s_1+l} \beta(s)\delta K(s)\cos(2\psi - 2\pi Q)\,ds \tag{2}$$

Single quadrupole error ΔK, normalised quadrupole strength.

$$\Delta K = \frac{2\sin(2\pi Q)}{\beta_{max}} \left(\frac{\delta\beta}{\beta_0}\right) \tag{3}$$

Tune-shift induced by distributed quadrupole errors:

$$\delta Q = \frac{1}{4\pi} \oint \delta K(s)\beta(s)ds \tag{4}$$

SC @ PS Injection: Probing Understanding: PFW with Quad Error

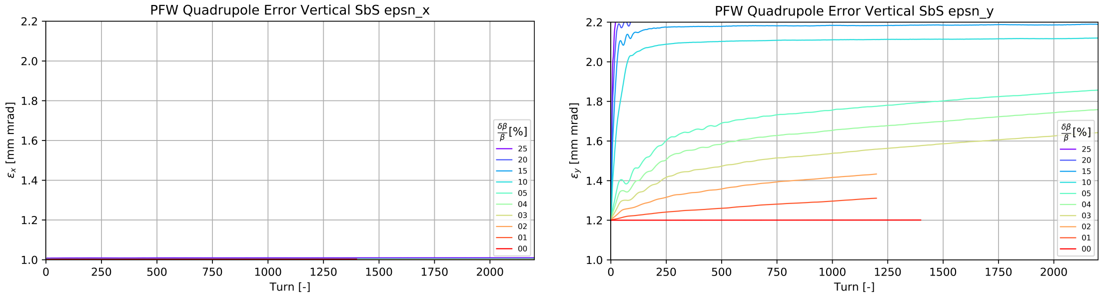


Figure: MD4224: Simulated horizontal (left) and vertical (right) normalised RMS emittances from PyORBIT simulations. **Using PFWs to modify the tune with a single quadrupolar error**: the tune is fixed to (6.21, 6.10), and $\approx$ **15% beta beating gives similar behaviour to expectation.**

SC @ PS Injection: Probing Understanding: PFW with Quad Error

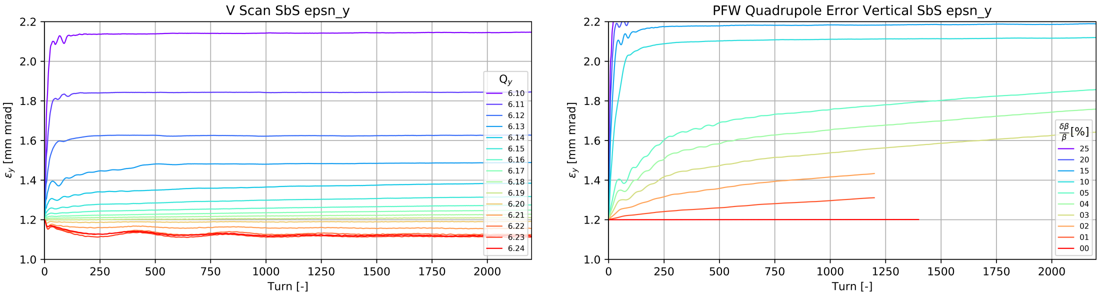


Figure: MD4224: Simulated normalised Vertical RMS emittances from PyORBIT simulations, comparing use of LEQs (left) or PFWs (right) to modify the tune. **Using PFWs to modify the tune with a single quadrupolar error (right plot)**: the tune is fixed to (6.21, 6.10), and $\approx$ **15% beta beating gives similar behaviour to expectation, shown in the left plot as a purple line.**

SC @ PS Injection: Status

- MDs performed, data analysed, **behaviour clear**.
- **Beam blows up as the working point is brought closer to the integer in each plane respectively. No dependence on measurement time (2, 5, 15 ms post injection)**.
- Unfortunately only have one plane of beam profile data.
- **Simulations agree well with measurements**. Emittances from profiles.
- PFW scan shows no blowup without LEQs active.
- PFW + single quad error gives similar emittance growth to measurement thus **confirming hypothesis**.
- Conclude **quadrupolar resonance at the (half-) integer is driving emittance growth on a very short time scale** $<$ 100 turns (1 turn = 2.287E-6 seconds $\therefore <$ 0.23 ms), **when the WP is close to the integer**.

SC @ PS Injection: What have we gained?

- Excellent benchmark of simulation and measurement. **Powerful Tool**
- Confirmation that space charge (alone) is not expected to be a major contributor to the 30-40% observed blowup.

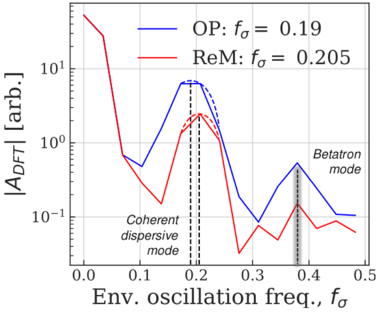
PS D Mismatch: Motivation

Unknown 30-40% emittance blowup between PSB and PS:

Try to **gauge effect of dispersion mismatch with space charge at PS injection** and assess possible contribution. Using SEM grid measurements.
Understand behaviour by **benchmarking measured data with simulations**.
Already presented by M. A. Fraser at Montreaux 2020 [link to talk]

PS D Mismatch: Envelope Oscillation Depression

Measurement:
(q_x = 0.216)
Hanning window function:



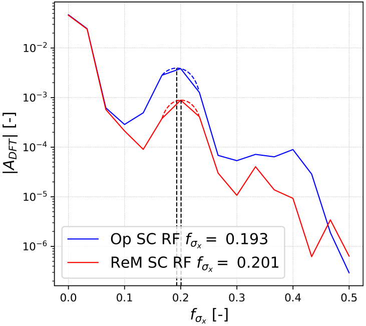


Figure: Measured (left) and simulated (right) envelope oscillation frequencies for various dispersion mismatch cases.

PS D Mismatch: Emittance with space charge

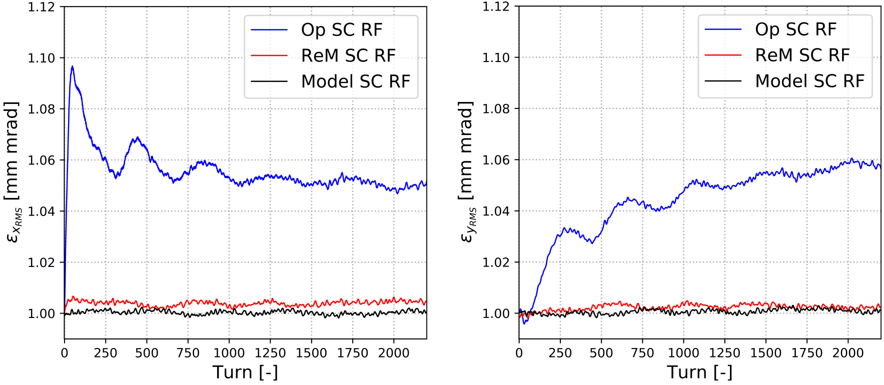


Figure: Emittances for various dispersion mismatch cases.

PS D Mismatch: What have we gained?

- Again, excellent benchmark of simulation and measurement.
- Looks like envelope oscillation frequency is dependent on mismatch amplitude.
- Confirmation that dispersion mismatch results in emittance growth. **Space charge causes this blowup to be within first 100 turns, and drives emittance exchange via the Montague resonance**.

Longitudinal Emittance Dependence: Motivation

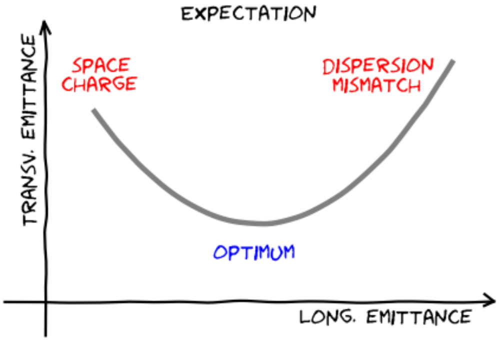


Figure: MD211 (performed by A. Oeftiger and S. Albright) Initial Hypothesis.

Longitudinal Emittance Dependence: Motivation

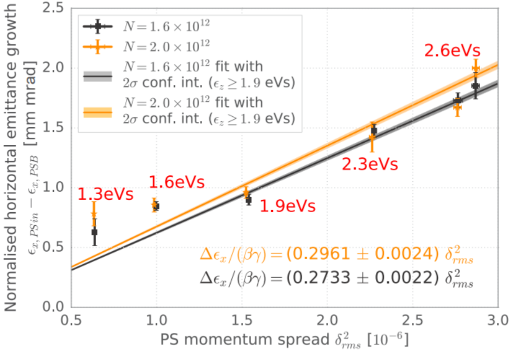


Figure: MD211 Measurement results.

Longitudinal Emittance Dependence: Summary

- Current priority (IPAC Paper).
- Longitudinal distributions need some work - combine with other efforts.
- Model: bare machine, will use LEQs to match tune. Possible issues with coupling (2017 skew quads were used to enhance natural linear coupling).

LIU Tunespread: Motivation

August 25, 2017 – Beam parameters at injection of each accelerator

		PS (Standard: 4b+2b – BCMS: 2× 4b)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$ (10^{-3})	$\Delta Q_{x,y}$
Achieved	Standard	16.84	2.25	1.4	1.2	180	0.9	(0.25, 0.30)
	BCMS	8.05	1.20	1.4	0.9	150	0.8	(0.24, 0.31)
LIU target	Standard	32.50	1.80	2.0	3.00	205	1.5	(0.18, 0.30)
	BCMS	16.25	1.43	2.0	1.48	135	1.1	(0.20, 0.31)

Figure: LIU PS Parameters: Analytical expectation for tunespreads $\Delta Q_{x,y}$ for Standard and BCMS beams - **can we confirm tunespreads and emittance blow-up expectations with newly-benchmarked tool?** [https://edms.cern.ch/ui/file/1296306/2/LIU-table-protons_v3.pdf]

Simulation Parameters and Results

Scenario	Case	N $\left[10^{11}\,\frac{p}{b}\right]$	ϵ_x $[\mu m]$	ϵ_y $[\mu m]$	E $[GeV]$	ϵ_z $[\frac{eVs}{b}]$	B_l $[nS]$	$\frac{\delta p}{p_0}$ $[10^{-3}]$	$\Delta Q_{x,y}$
PreLIU	Standard	16.84	2.25	2.25	1.4	1.01	180	0.9	(.20, .28)
PreLIU	BCMS	8.05	1.20	1.20	1.4	0.72	150	0.8	(.19, .28)
LIU	Standard	32.5	1.80	1.80	2.0	1.00	205	1.5	(.13, .25)
LIU	BCMS	16.25	1.43	1.43	2.0	0.75	135	1.1	(.16, .27)
LIU	Standard								
	2021	32.5	1.88	1.88	2.0	1.25	135	1.1	(.27, .44)
	2022	32.5	1.88	1.88	2.0	1.90	170	1.3	(.18, .32)
	2023	32.5	1.88	1.88	2.0	2.60	205	1.5	(.13, .24)

Table: PS LIU tunespread simulation injection parameters and results using a 6 RMS value for tunespreads from simulation data.

PreLIU (Achieved) Standard Tunespreads

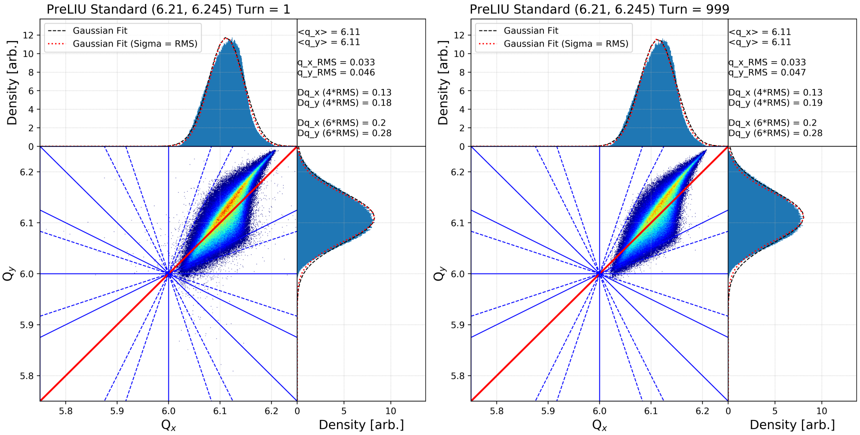


Figure: PS tunespread for PreLIU (Achieved) Standard beams from PyORBIT simulation. For turns 1 (left) and 999 (right) $\approx$ 2.3 ms post injection. $\Delta Q_{x,y}$ in the top right box.

PreLIU (Achieved) BCMS Tunespreads

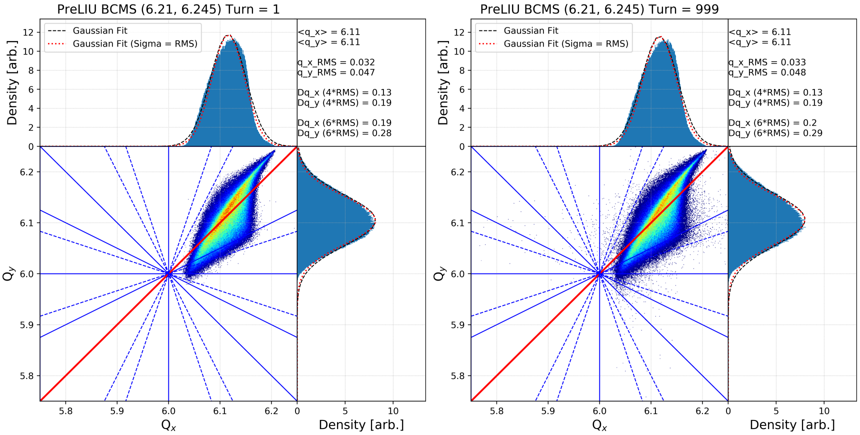


Figure: PS tunespread for PreLIU (Achieved) BCMS beams from PyORBIT simulation. For turns 1 (left) and 999 (right) ≈ 2.3 ms post injection. $\Delta Q_{x,y}$ in the top right box.

LIU Standard Tunespreads

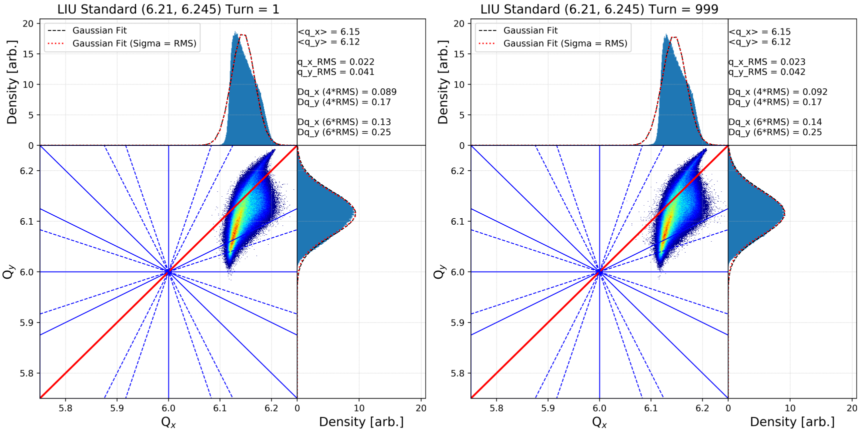


Figure: PS tunespread for LIU Standard beams from PyORBIT simulation. For turns 1 (left) and 999 (right) ≈ 2.3 ms post injection. $\Delta Q_{x,y}$ in the top right box.

LIU BCMS Tunespreads

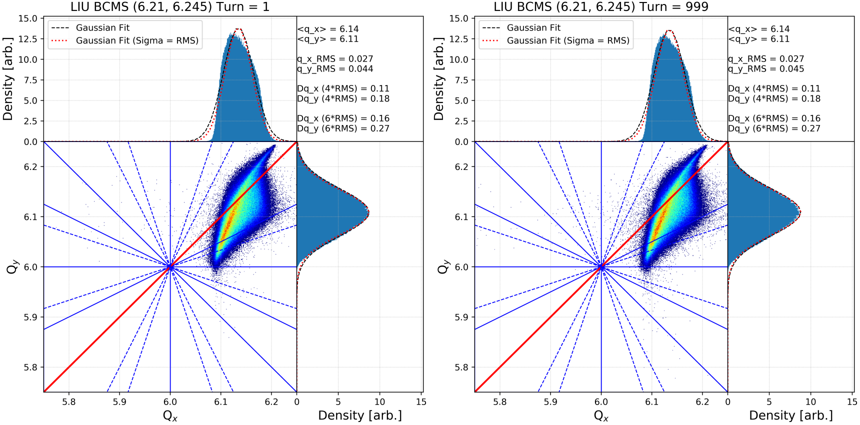


Figure: PS tunespread for LIU BCMS beams from PyORBIT simulation. For turns 1 (left) and 999 (right) ≈ 2.3 ms post injection. $\Delta Q_{x,y}$ in the top right box.

LIU Standard 2023 Tunespreads

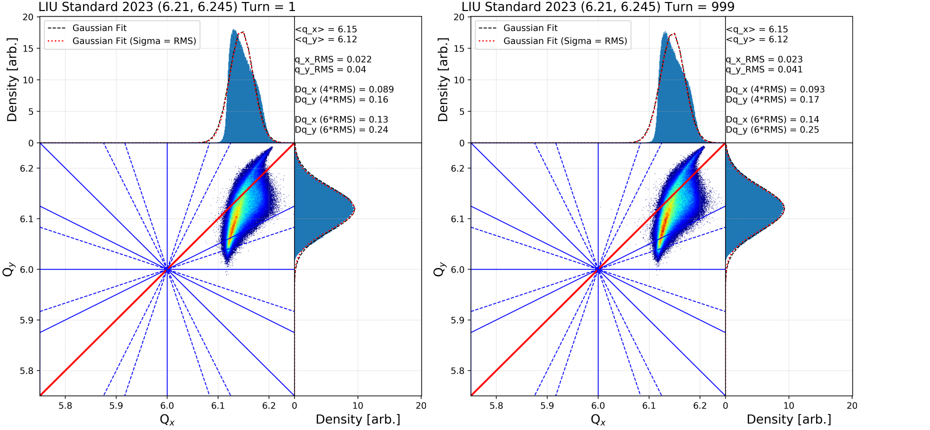


Figure: PS tunespread for LIU Standard 2023 beams from PyORBIT simulation. For turns 1 (left) and 999 (right) ≈ 2.3 ms post injection. $\Delta Q_{x,y}$ in the top right box.

LIU Standard 2022 Tunespreads

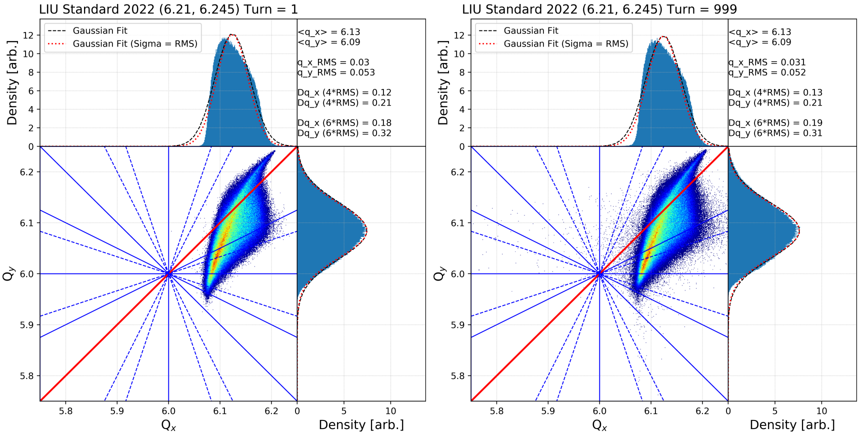


Figure: PS tunespread for LIU Standard 2022 beams from PyORBIT simulation. For turns 1 (left) and 999 (right) ≈ 2.3 ms post injection. $\Delta Q_{x,y}$ in the top right box.

LIU Emittance Stability

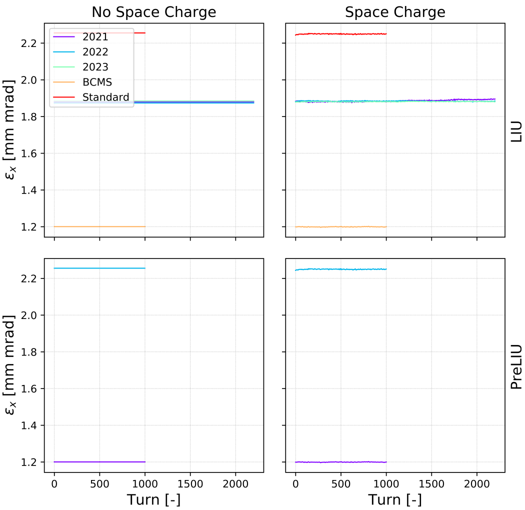


Figure: Horizontal emittance from PyORBIT simulations comparing all simulated cases.

All cases are stable under space charge.

LIU Emittance Stability

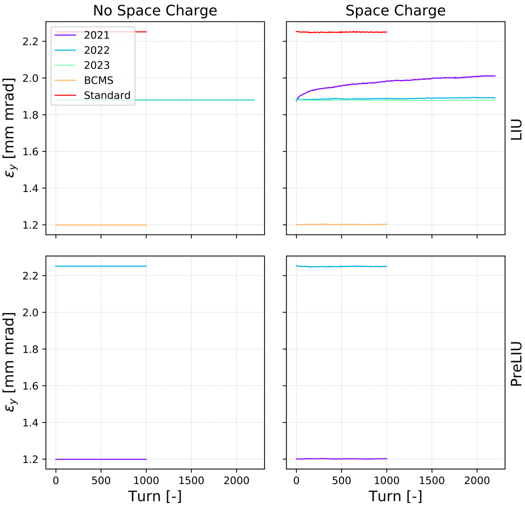


Figure: Vertical emittance from PyORBIT simulations comparing all simulated cases.

All cases are stable under space charge except the 2021 LIU Standard which shows vertical emittance growth.

LIU Standard 2021 Tunespreads

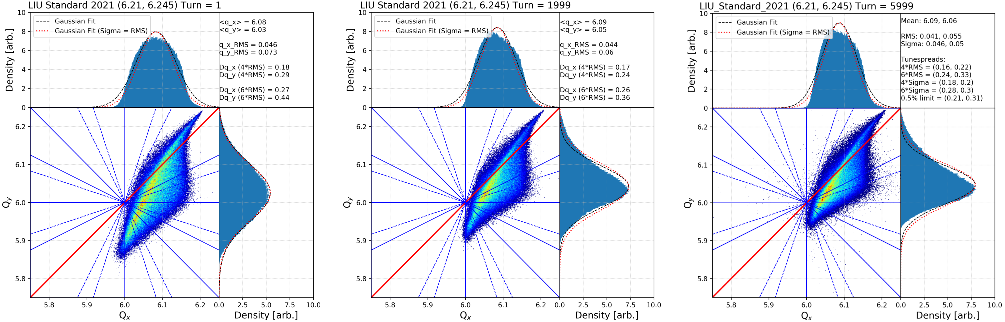


Figure: PS tunespread for LIU Standard 2021 beams from PyORBIT simulation. For turns 1 (left), 1999 (middle), and 5999 (right). **The bunch appears still to interact with the (half-) integer vertical resonance after 6000 turns (≈ 13.7 ms).** Simulations ongoing.

LIU Standard 2021: Beta-Beating

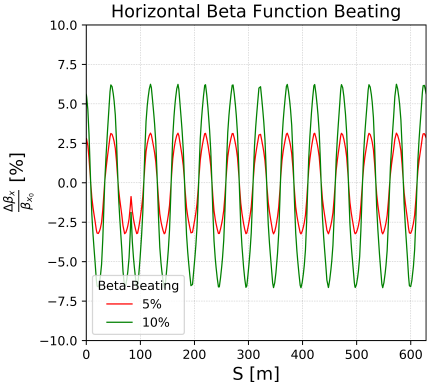


Figure: Vertical beta-beating induced in the PS lattice using a single quadrupolar error. **Use a similar approach as previously demonstrated to induce faster emittance growth and gauge final emittance.**

LIU Standard 2021: Emittance Growth with Beta-Beating

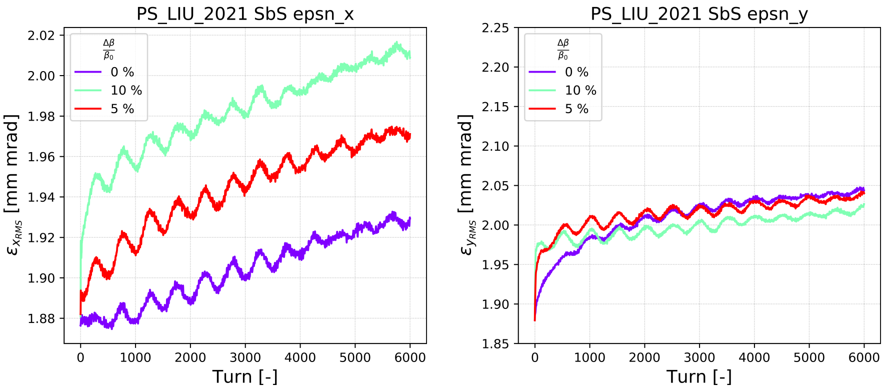


Figure: Horizontal (left) and Vertical (right) emittance with beta-beating generated using a single quadrupolar error. **Vertical emittance growth has not plateaued after 6000 turns - simulations running.**

LIU Standard 2021: Oscillations due to Longitudinal Mismatch

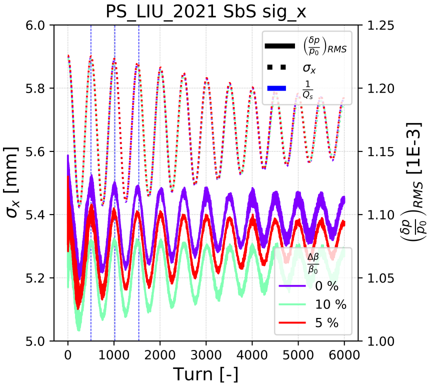


Figure: Horizontal beam size σ_x and momentum offset $\frac{\delta p}{p_0}$ illustrating longitudinal mismatch.
Aim to consolidate longitudinal distributions using S. Albright's new tomo code, should not have major effect on blow-up.

LIU tunespread: Summary

- Longitudinal distributions generated with help from A. Lasheen.
- Transverse parameters provided from LIU table.
- Perfect machine, settings as defined by A. Huschauer.
- Pre-LIU, and LIU Standard and BCMS type beams simulated.
- **All cases stable except 2021 Standard - large tunespread crosses vertical (half-) integer - drives emittance growth**.
- 2021 emittance growth ($\approx 2.05\mu m$) **doesn't meet expectation** ($\approx 3.5\mu m$). Plateau not reached after 6000 turns but still far from expectation.
- **Long term simulations running** with 0%, 5%, 10% $\frac{\Delta\beta}{\beta_0}$.

LIU tunespread: Next Steps

- Consolidate longitudinal distribution generation methods to reduce mismatch in PTC.
- Estimate final emittance for LIU Standard 2021 parameters, understand difference with analytical expectation.

Injection Bump: Motivation

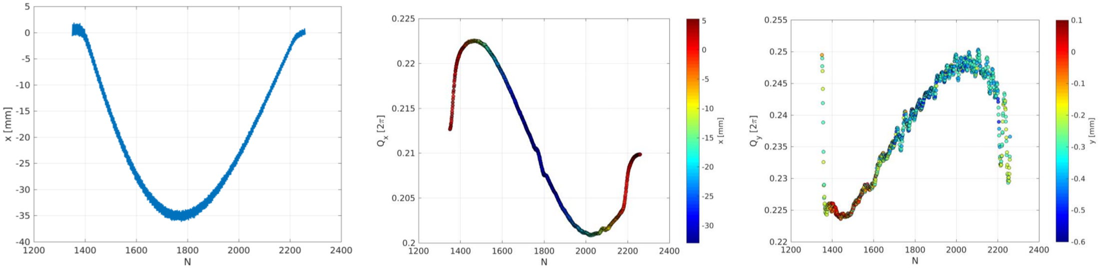


Figure: Measured closed orbit horizontal bump (left), horizontal tune (middle), and vertical tune (right), in 2018. **Measurements show tune swing caused by sextupolar components in BSW magnets**. Implement in MAD-X/PTC and thus create tables for PTC in PyORBIT.

PS: Measurements for the Linear Optics Model, P. Zisopoulos et. al., 2nd Space Charge Collaboration Meeting, 12.03.18.

Injection Bump Closure: Implementation

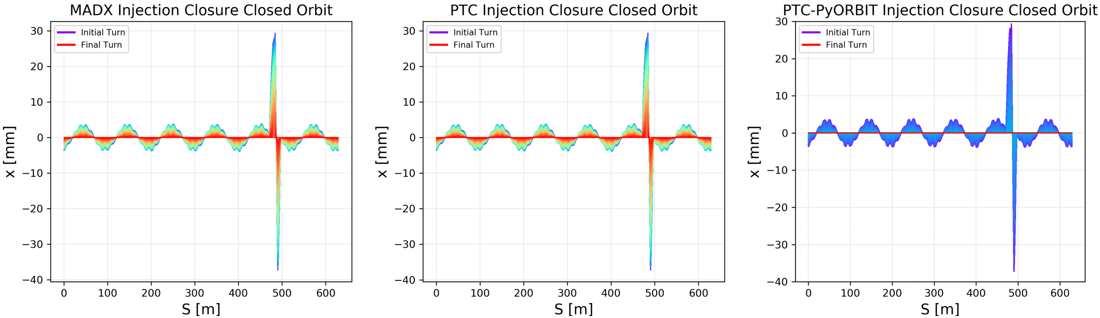


Figure: Closed orbit for injection bump closure comparing MAD-X (left), PTC (middle), and PTC-PyORBIT (right).

Injection Bump Closure: Implementation

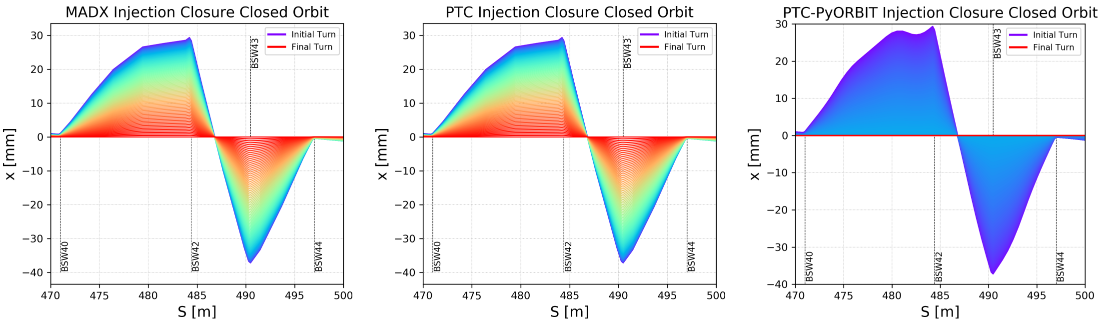


Figure: Closed orbit for injection bump closure comparing MAD-X (left), PTC (middle), and PTC-PyORBIT (right).

Injection Bump Closure: Implementation

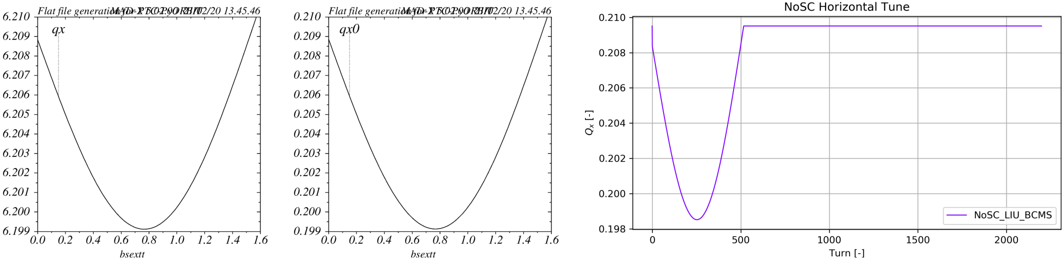


Figure: Horizontal tune Q_x for injection bump closure comparing MAD-X (left), PTC (middle), and PTC-PyORBIT (right).

Injection Bump Closure: Implementation

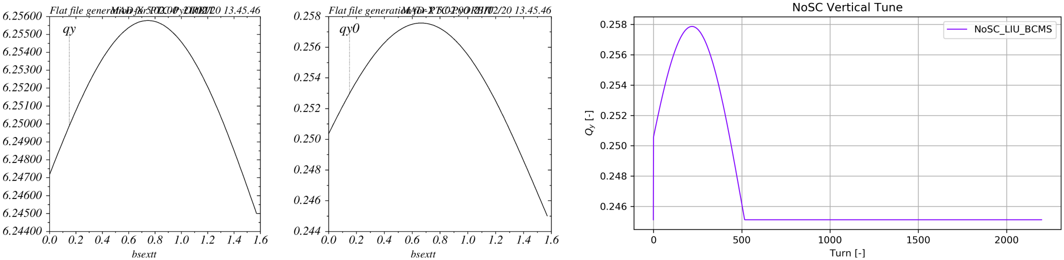


Figure: Vertical tune Q_y for injection bump closure comparing MAD-X (left), PTC (middle), and PTC-PyORBIT (right).

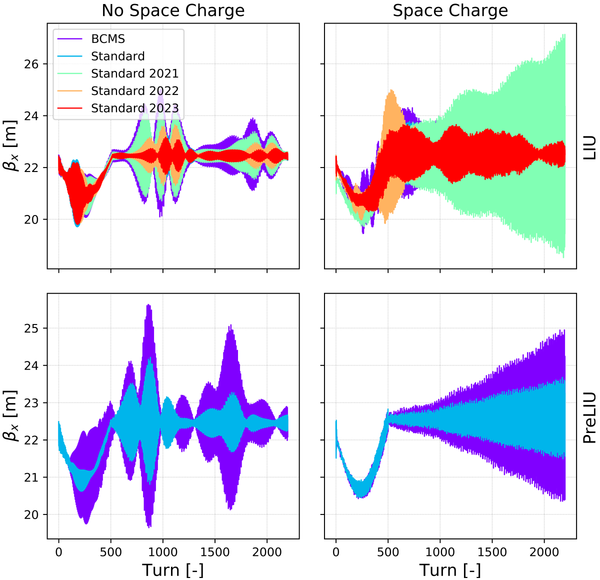
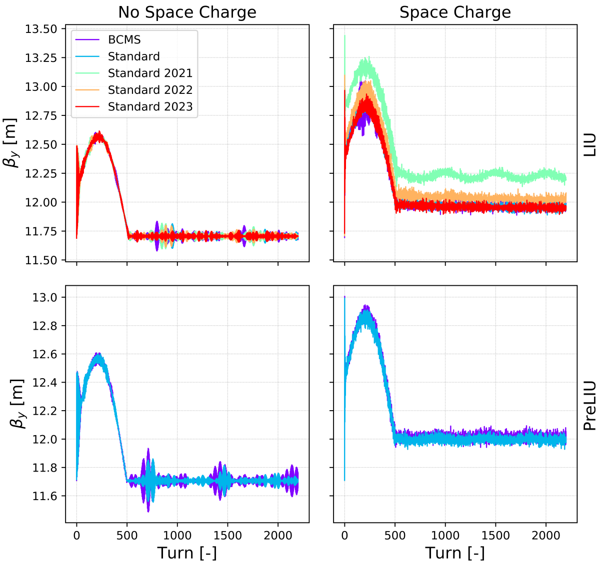


Figure: Horizontal beta function β_x as calculated from the bunch in PyORBIT.

Left column using no space charge, right column using slice-by-slice PIC space charge. Top row for LIU beams, bottom row for PreLIU beams.

The effect of the injection bump is evident from turn 0 - 500.



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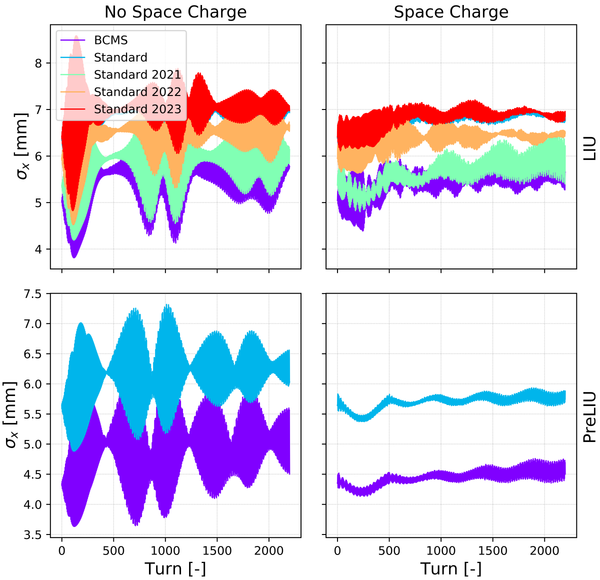
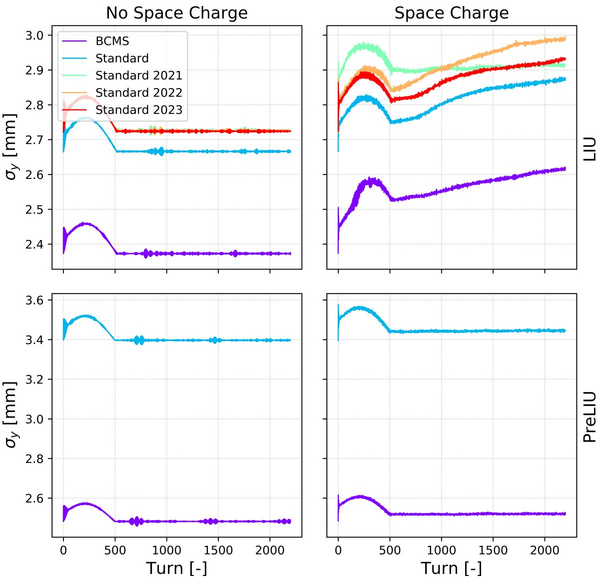


Figure: Horizontal Beam size σ_x as calculated from the bunch in PyORBIT.

Left column using no space charge, right column using slice-by-slice PIC space charge. Top row for LIU beams, bottom row for PreLIU beams.

Including space charge shows the beam size behaves like the tune swing.



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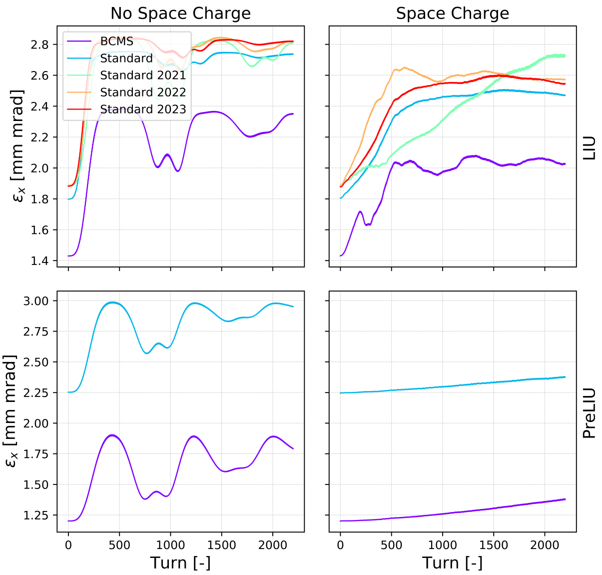

Figure: Horizontal normalised RMS emittance ϵ_x as calculated from the bunch in PyORBIT.

Left column using no space charge, right column using slice-by-slice PIC space charge. Top row for LIU beams, bottom row for PreLIU beams.

The injection bump tune swing causes horizontal emittance growth in all cases.

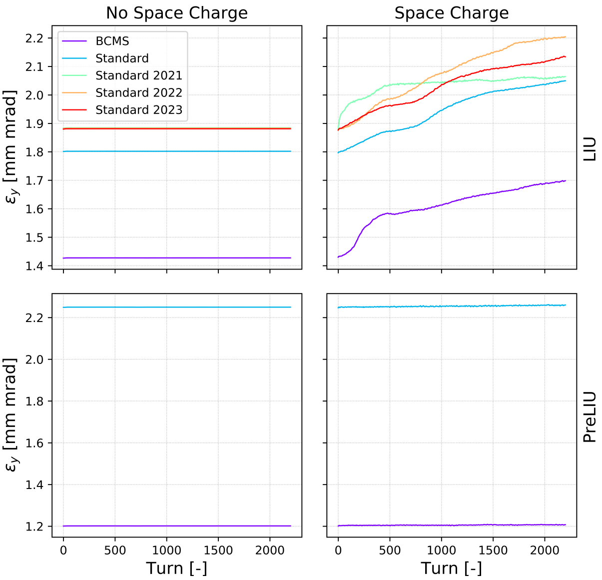

Figure: Vertical normalised RMS emittance ϵ_y as calculated from the bunch in PyORBIT.

Left column using no space charge, right column using slice-by-slice PIC space charge. Top row for LIU beams, bottom row for PreLIU beams.

The injection bump tune swing causes vertical emittance growth in only LIU cases with space charge.

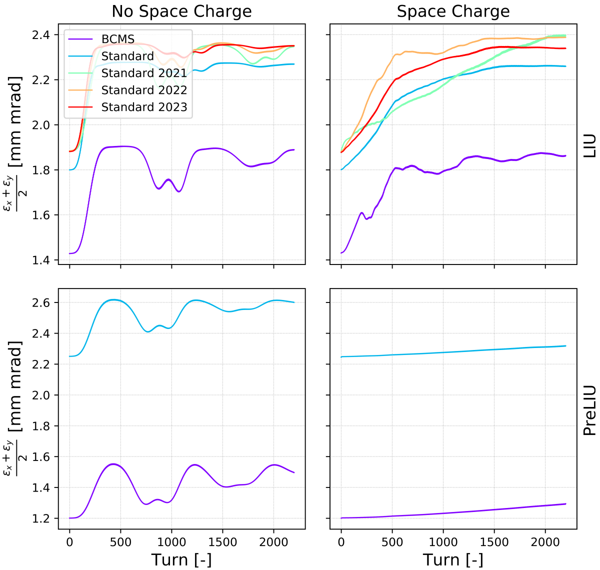

Figure: Average normalised RMS emittance $\frac{\epsilon_y+\epsilon_x}{2}$ as calculated from the bunch in PyORBIT.

Left column using no space charge, right column using slice-by-slice PIC space charge. Top row for LIU beams, bottom row for PreLIU beams.

The injection bump tune swing causes average emittance growth in all cases.

Conclusion

What have we learnt?

- Measurements of bunch profiles at PS Injection (MD4224) well understood - use of LEQs causing half-integer resonance due to violation of lattice periodicity. The beam interacts with this resonance only at working points near the integer, resulting in emittance blow-up.
- **Conclude that at the nominal working point we expect no blow-up due to space charge alone.**
- Benchmarking of PS model, simulation methods, PyORBIT space charge for the PS, to provide us with a powerful tool for space charge dominated scenarios in commissioning and operation.
- Dispersion mismatch: SEM grid measurements agree well with 6D space charge simulations. **Emittance growth due to dispersion mismatch as expected ($\approx$ 10%) but shared due to Montague coupling resonance.**

Conclusion

What have we learnt?

- Longitudinal emittance dependence MD211 currently in simulation setup stages.
- **Used new tools to predict LIU-era tunespread, mostly agreeing with expectations and observing emittance stability for predicted parameters**.
- LIU 2021 emittance growth not yet meeting expectations. Further investigation needed.
- Injection bump preliminary results appear interesting - to be discussed.

Acknowledgements

“If I have seen further it is by standing on the shoulders of Giants” - Newton

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- A. Lasheen for BLONDE longitudinal distributions setup.
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