



Pole Face Winding Scan

Simulation Updates

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Table of Contents

Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error
15% Beta-Beating Optics Comparison
Betatronic Mismatch
Conclusion

Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error
15% Beta-Beating Optics Comparison
Betatronic Mismatch
Conclusion

Previous Results

MD4224: Approaching the integer tune

High brightness beam static tune scan in Proton Synchrotron using Low Energy Quads (LEQs).

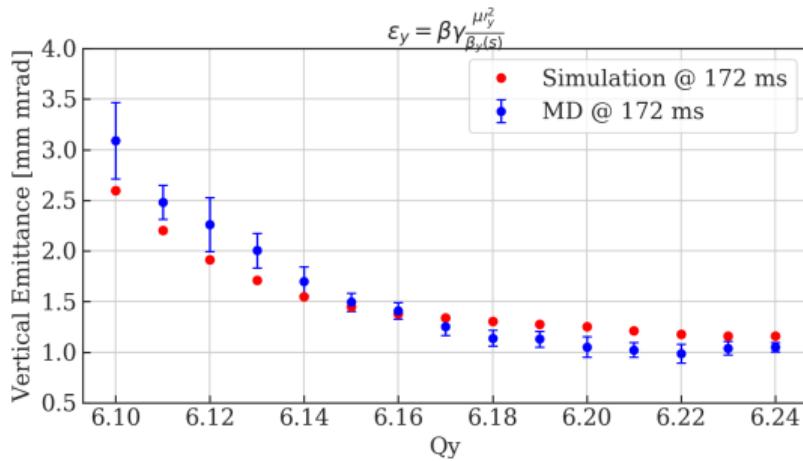


Figure: Result of MD4224 Vertical tune scan.

Motivation

Found emittance growth as tune is brought closer to the integer. Believe this to be due to the bunch interacting with the quadrupolar stop-band, which is exacerbated by the use of the LEQs to modify the tune.

- ▶ If we switch off the LEQs and modify the tune with the Pole Face Windings (PFWs), do we excite the quadrupolar stop-band?
- ▶ Can we stimulate similar emittance growth with a single quadrupolar error in the lattice?

Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error
15% Beta-Beating Optics Comparison
Betatronic Mismatch
Conclusion

Optics Comparison: Vertical Beta

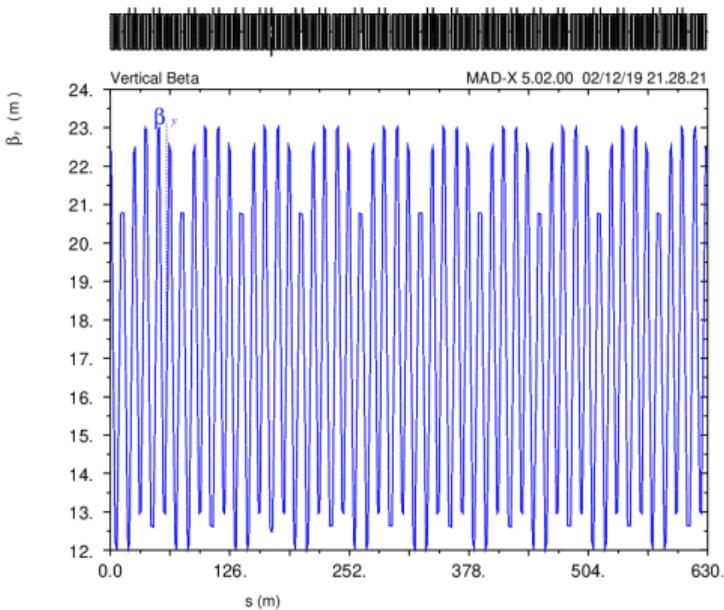
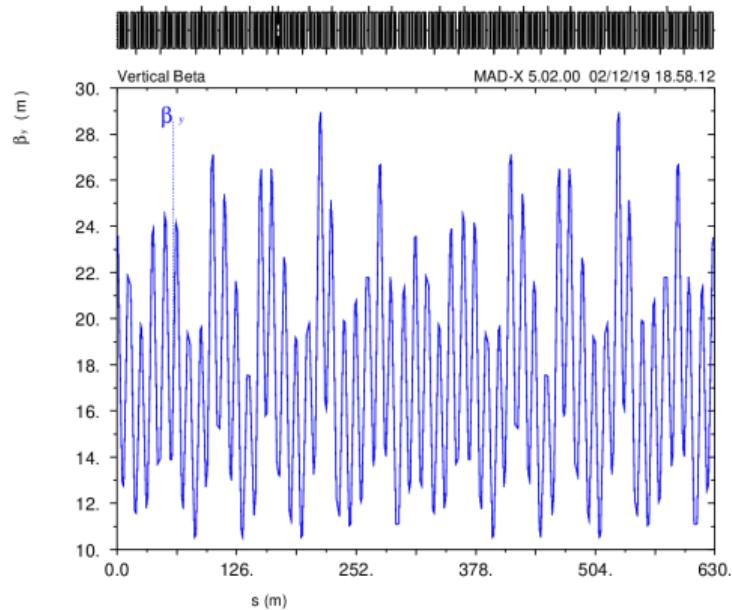


Figure: Comparison of vertical beta function when using LEQs (left) or PFWs (right) to modify the vertical tune. $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Optics Comparison: Horizontal Beta

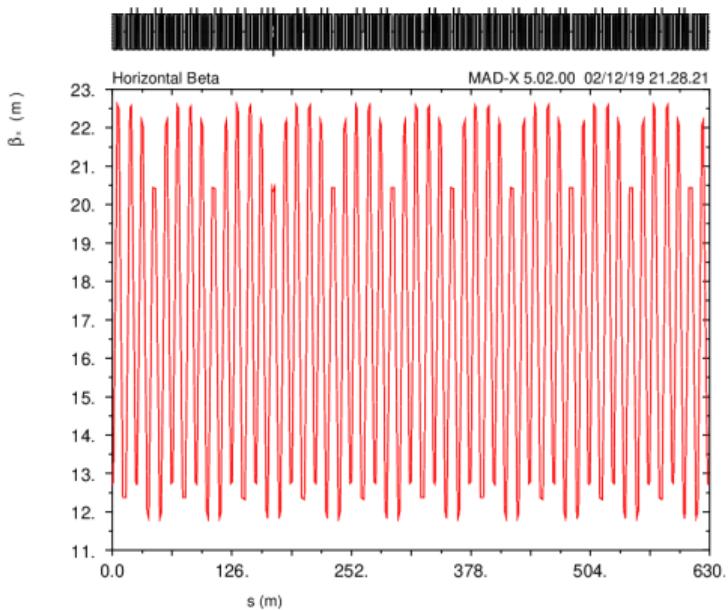
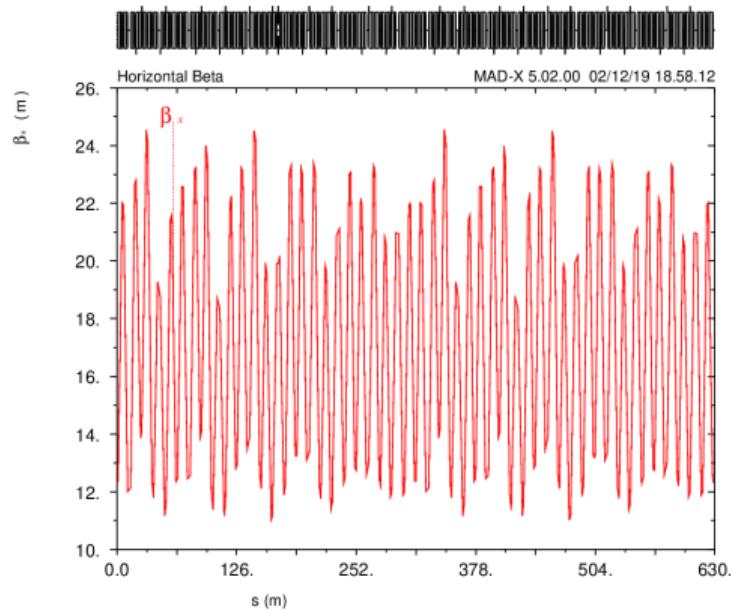


Figure: Comparison of horizontal beta function when using LEQs (left) or PFWs (right) to modify the vertical tune. $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Optics Comparison: Horizontal Dispersion

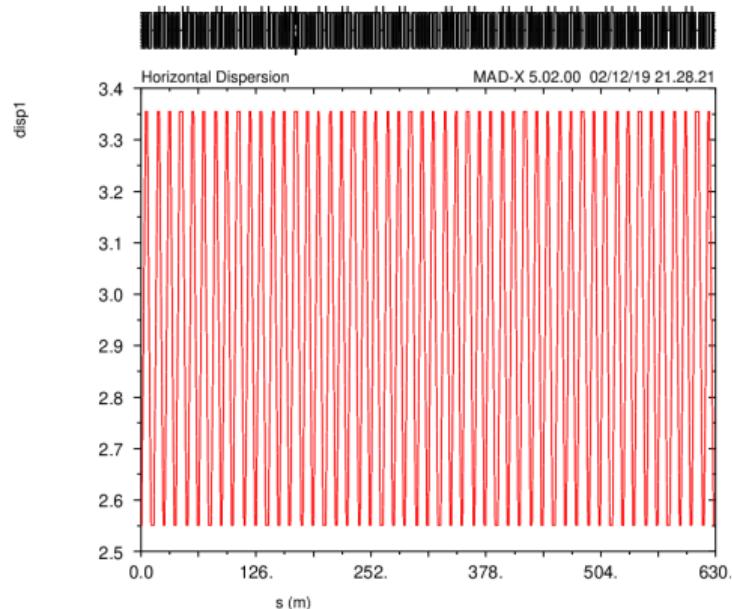
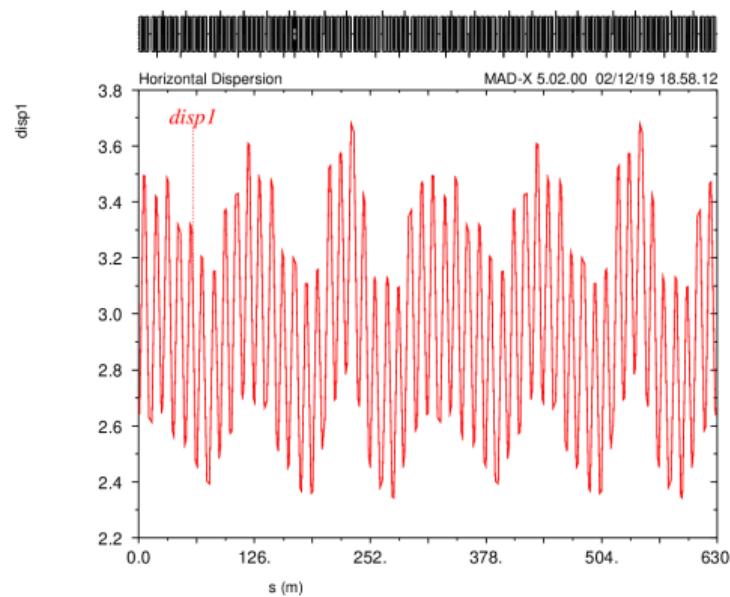


Figure: Comparison of horizontal dispersion function when using LEQs (left) or PFWs (right) to modify the vertical tune. $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Optics Comparison: Vertical Dispersion

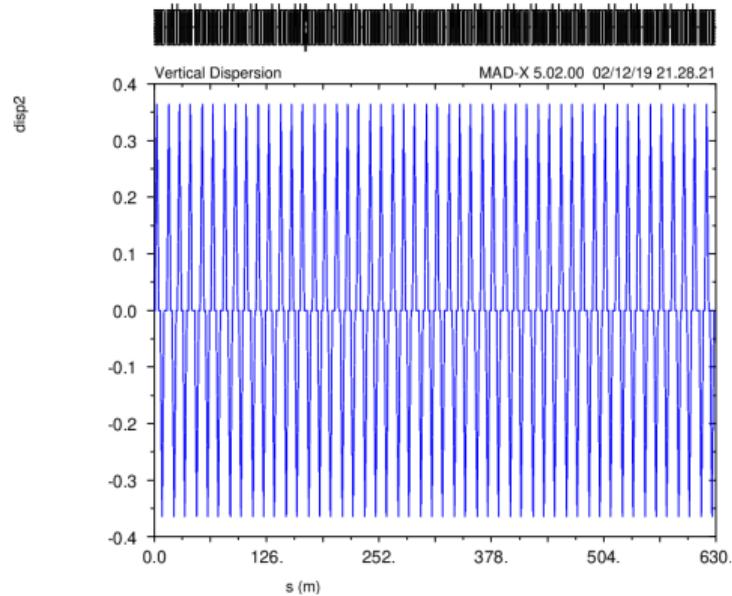
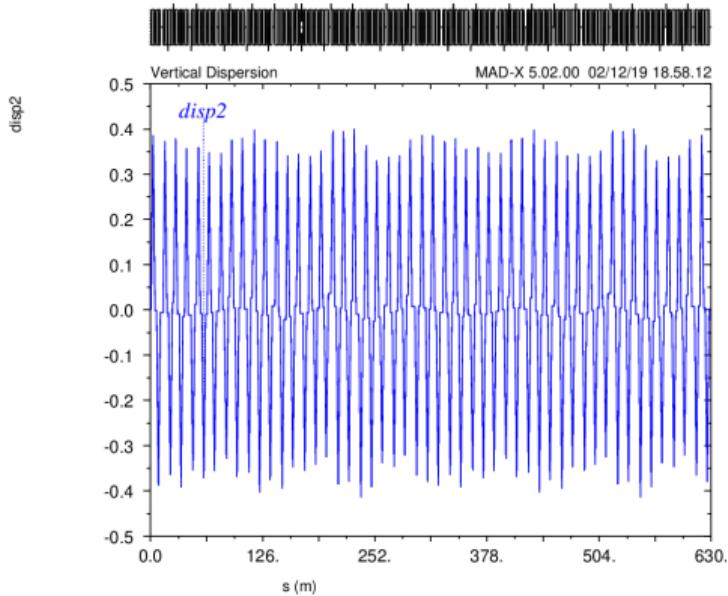


Figure: Comparison of vertical dispersion function when using LEQs (left) or PFWs (right) to modify the vertical tune. $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error
15% Beta-Beating Optics Comparison
Betatronic Mismatch
Conclusion

Vertical Scan: Vertical Beta Function

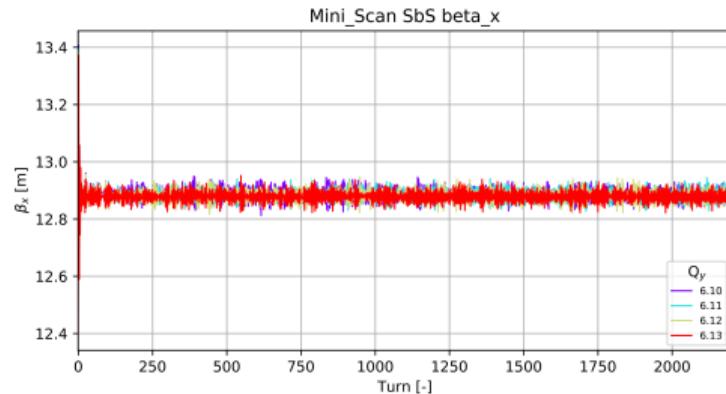
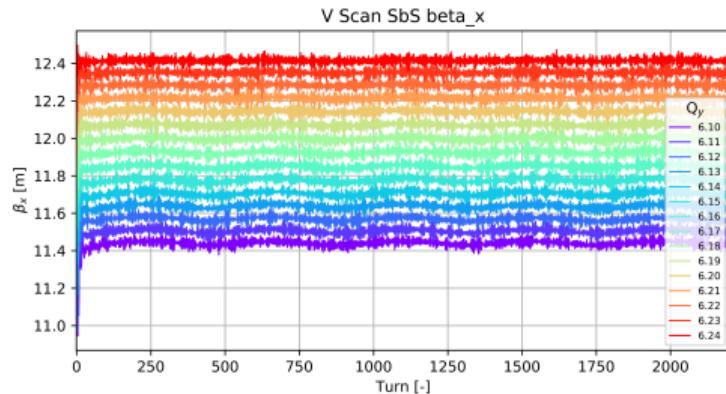


Figure: Comparison of vertical beta function at the position of the vertical wire scanner (BWSV64) when using LEQs (left) or PFWs (right) to modify the vertical tune.

Vertical Scan: Vertical Beam Size

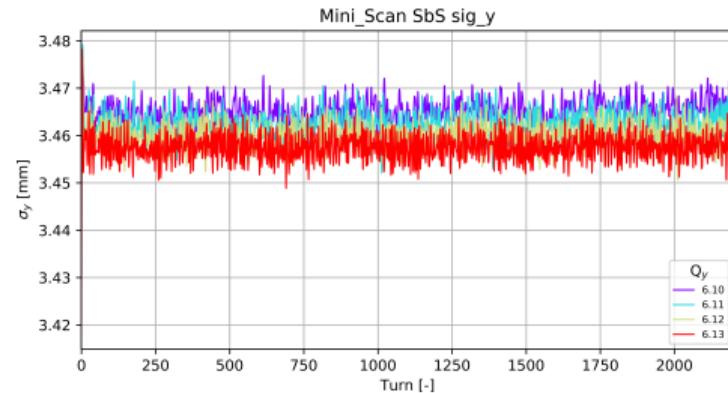
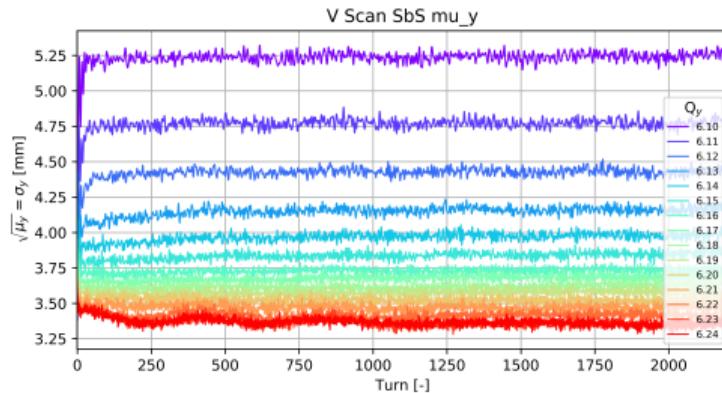


Figure: Comparison of vertical beam size at the position of the vertical wire scanner (BWSV64) when using LEQs (left) or PFWs (right) to modify the vertical tune.

Vertical Scan: Vertical Emittance

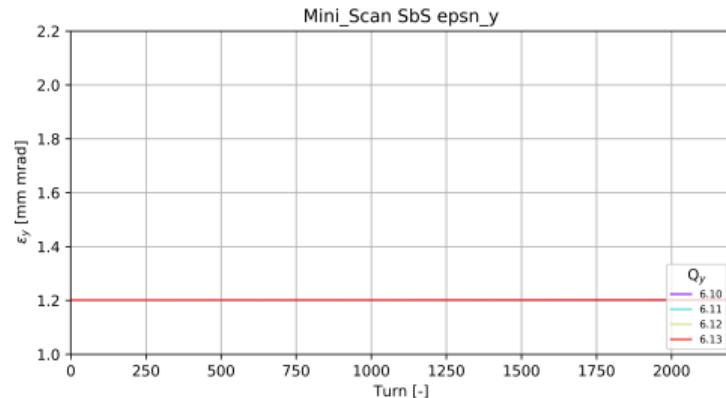
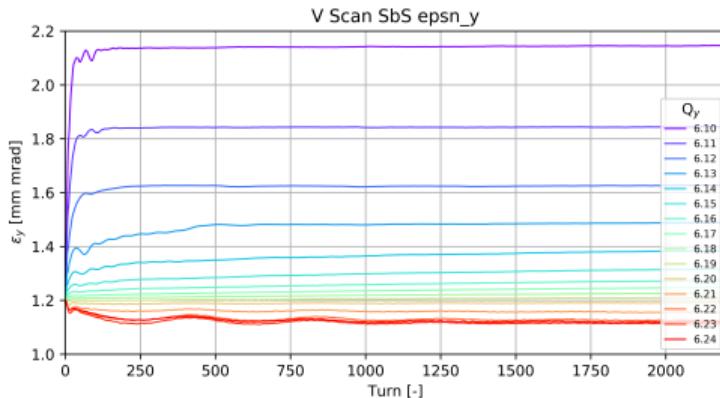


Figure: Comparison of vertical emittance at the position of the vertical wire scanner (BWSV64) when using LEQs (left) or PFWs (right) to modify the vertical tune.

Conclusion: PFWs do not excite the quadrupolar stop-band.

Vertical Scan: Longitudinal Motion

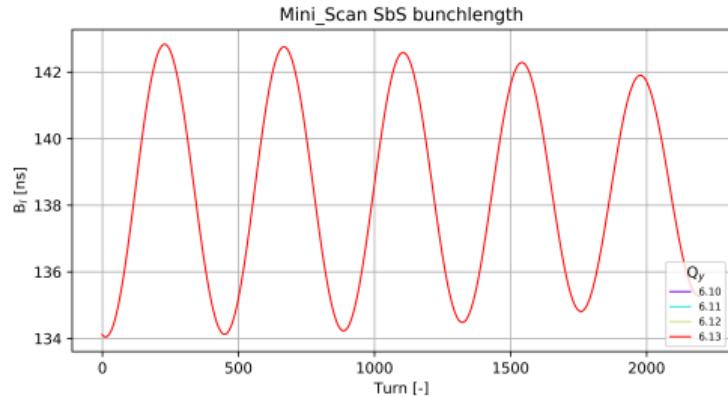
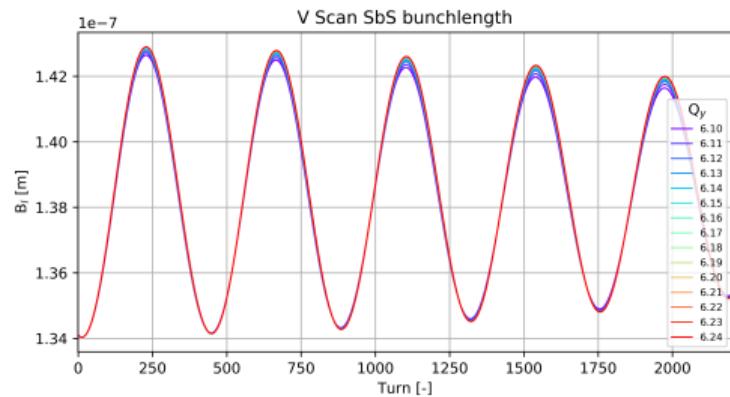


Figure: Comparison of bunch length at the position of the vertical wire scanner (BWSV64) when using LEQs (left) or PFWs (right) to modify the vertical tune.

Vertical Scan: Longitudinal Motion

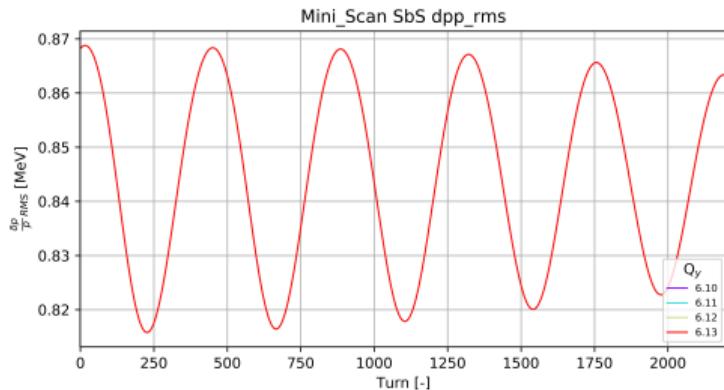
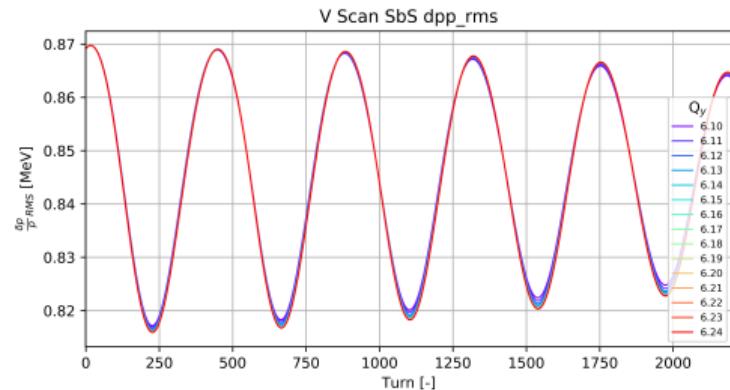


Figure: Comparison of momentum offset $\frac{\delta p}{p} \text{ RMS}$ at the position of the vertical wire scanner (BWSV64) when using LEQs (left) or PFWs (right) to modify the vertical tune.

Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error

15% Beta-Beating Optics Comparison

Betatronic Mismatch

Conclusion

PFW With Quadrupolar Error

Add quadrupolar error to single LEQ (QDN72)

Perform scan in beta-beating. All LEQs off except single error.

Beta Beating

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

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

Single quadrupole error ΔK , normalised quadrupole strength.

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

Tune-shift induced by distributed quadrupole errors:

$$\delta Q = \frac{1}{4\pi} \oint \delta K(s) \beta(s) ds \quad (3)$$

Scan in Beta-Beating

$$Q_y = 6.10, \beta_{max} = 23.01757, \beta_0 = 23.0095$$

$$\Delta K = 0.0510425 \left(\frac{\delta\beta}{\beta_0} \right) \quad (4)$$

$\frac{\delta\beta}{\beta}$ estimated [%]	ΔK	β_{max}	$\delta\beta$	$\frac{\delta\beta}{\beta}$ out [%]
1	0.000510425	23.24475	0.22718	0.987
10	0.00510425	23.3844	2.36683	10.283
20	0.0102085	27.9566	4.93903	21.46
25	0.0127606	29.3158	6.29823	27.4

Table: Quadrupole error ΔK and corresponding $\frac{\delta\beta}{\beta}$ out.

Expected Beta-Beating From Quadrupole Error

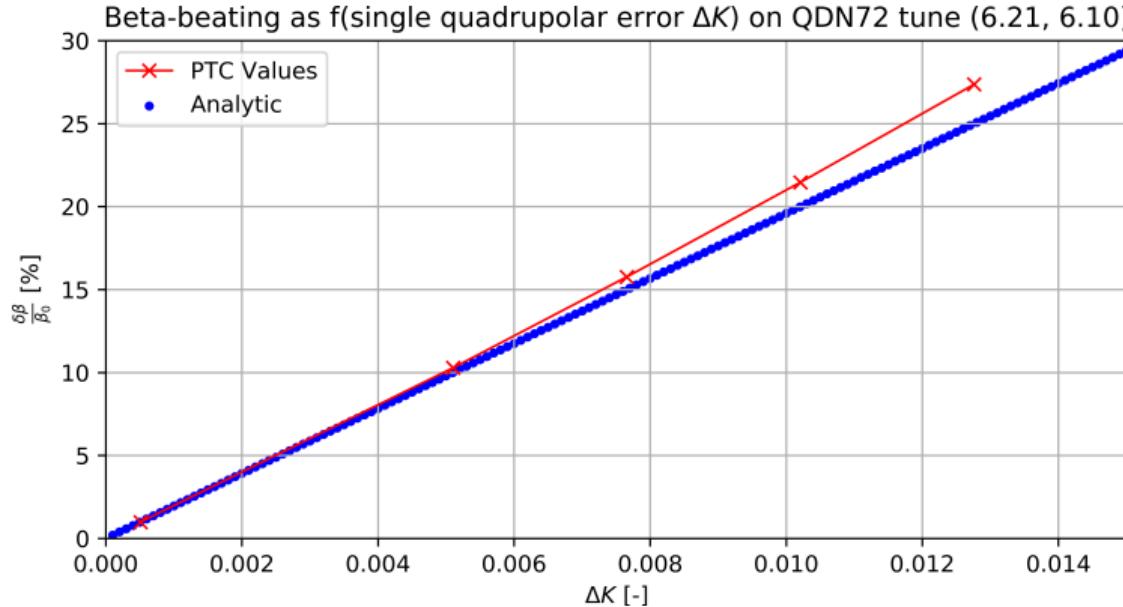


Figure: Analytical expectation for beta-beating as a function of quadrupolar error when using the PFW to modify tunes, for tune $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Expected Tune Shift From Betatron Mismatch

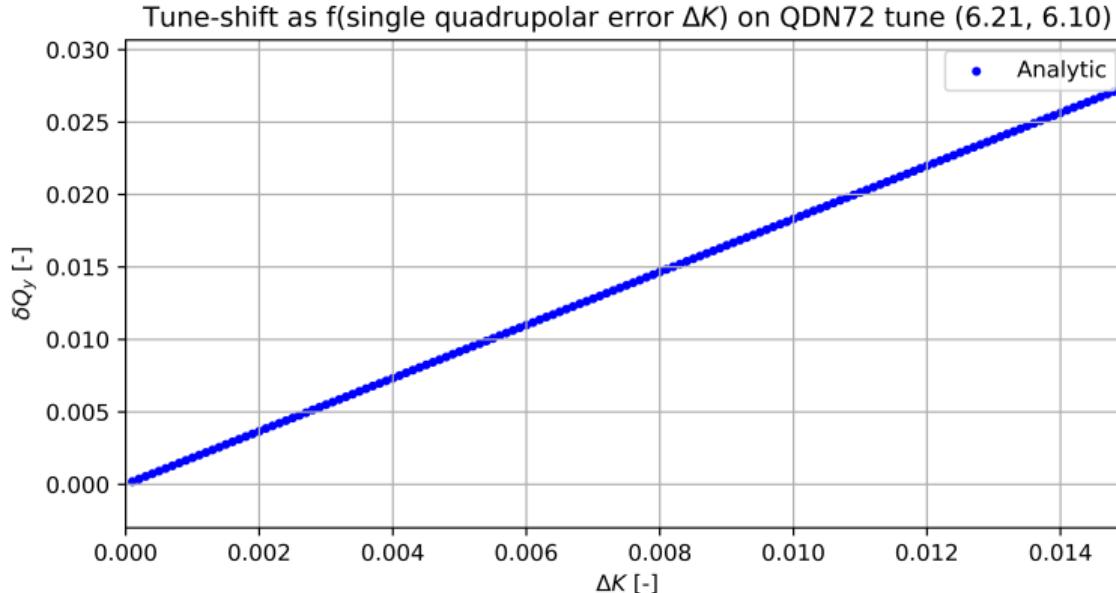


Figure: Analytical expectation for tune shift as a function of betatron mismatch factor when using the PFW to modify tunes, for tune $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

PFW with Quadrupolar Error: Longitudinal Motion

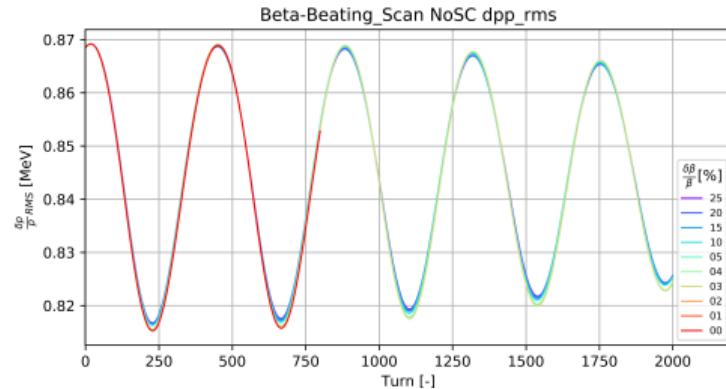
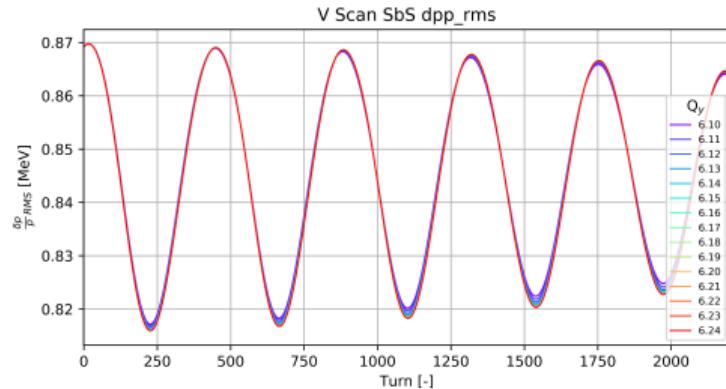


Figure: Comparison of momentum offset $\frac{\delta p}{p_{RMS}}$ at the position of the vertical wire scanner (BWSV64). The left plot shows a static tune scan using LEQs to modify the tune. The right plot shows a fixed tune of (6.21, 6.10) with a beta-beating error (indicated in legend) applied via a single quadrupolar error on the LEQ QND72.

PFW with Quadrupolar Error: Horizontal Beam Size

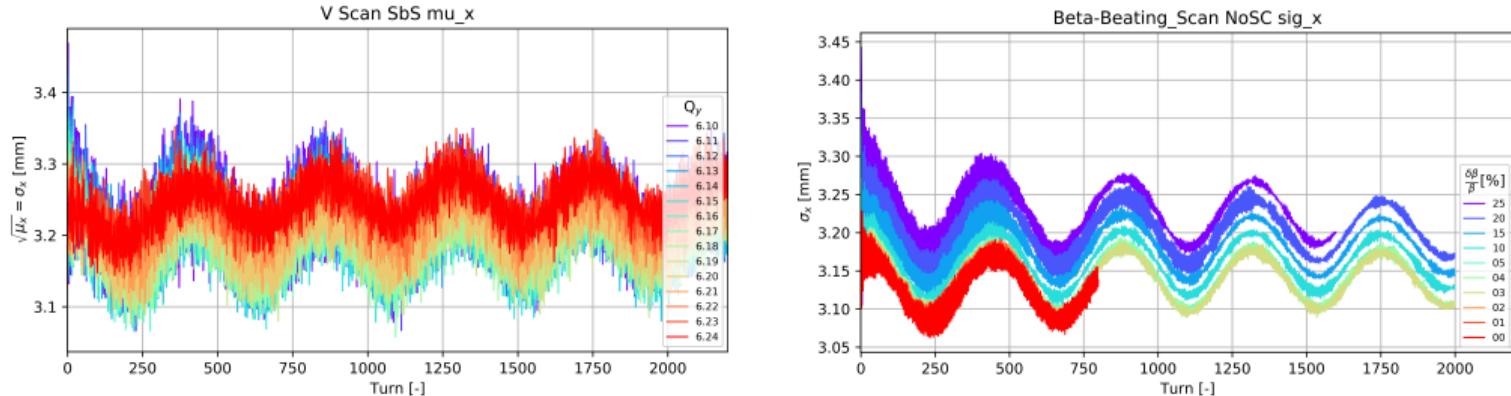


Figure: Comparison of vertical beam size at the position of the vertical wire scanner (BWSV64). The left plot shows a static tune scan using LEQs to modify the tune. The right plot shows a fixed tune of (6.21, 6.10) with a beta-beating error (indicated in legend) applied via a single quadrupolar error on the LEQ QND72.

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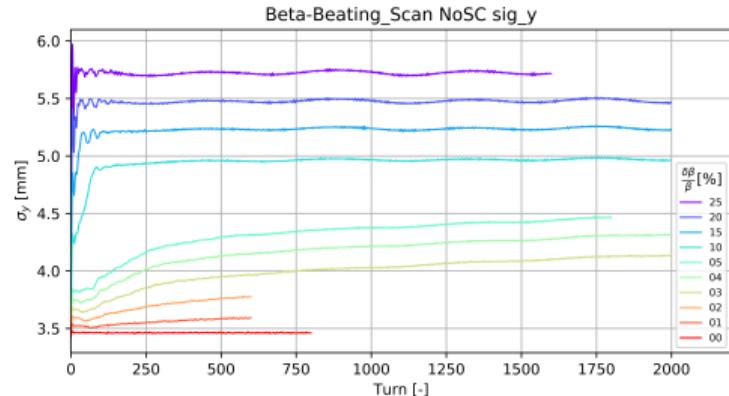
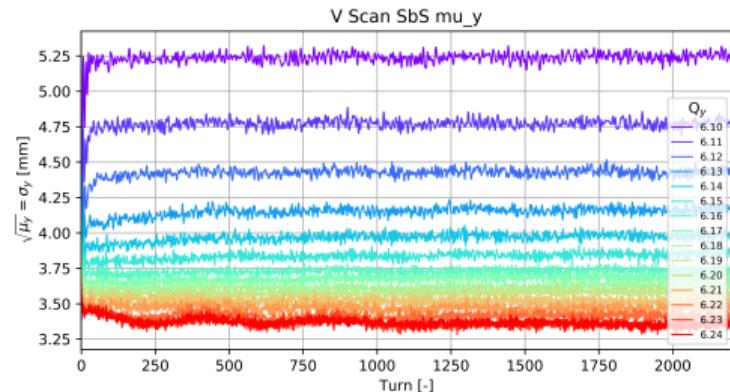


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PFW with Quadrupolar Error: Horizontal Emittance

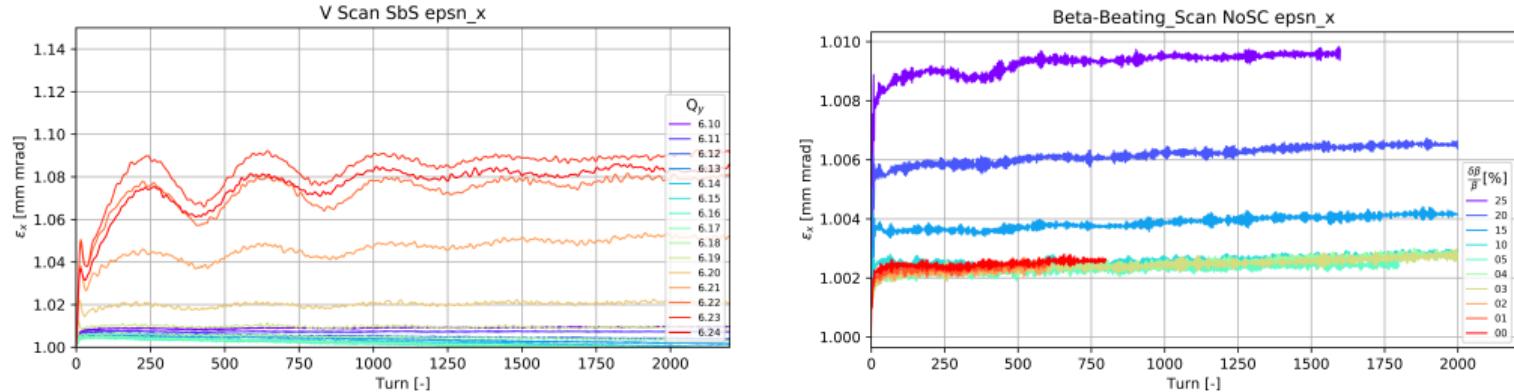


Figure: Comparison of horizontal emittance at the position of the vertical wire scanner (BWSV64). The left plot shows a static tune scan using LEQs to modify the tune. The right plot shows a fixed tune of (6.21, 6.10) with a beta-beating error (indicated in legend) applied via a single quadrupolar error on the LEQ QND72.

PFW with Quadrupolar Error: Vertical Emittance

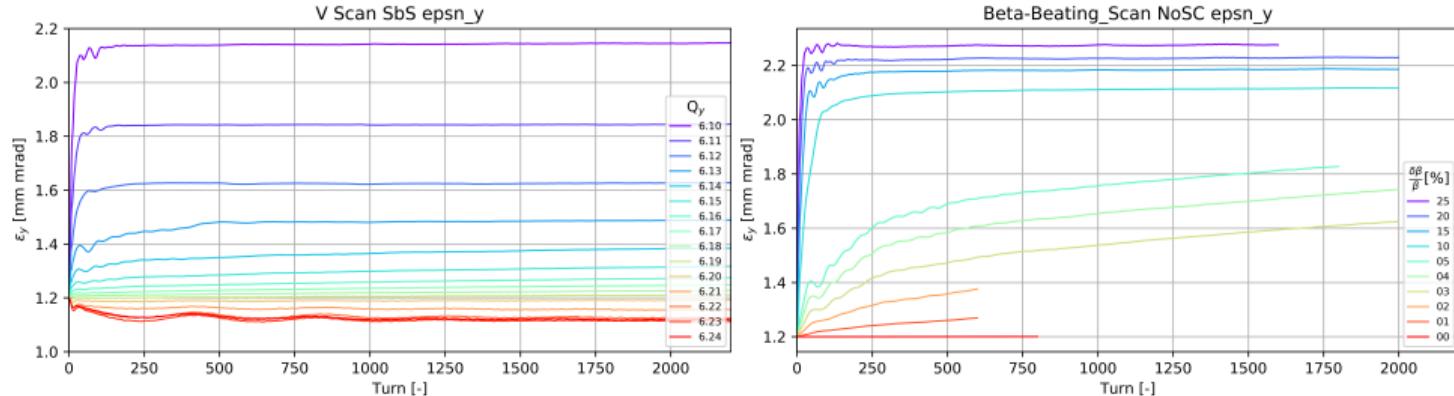


Figure: Comparison of vertical emittance at the position of the vertical wire scanner (BWSV64). The left plot shows a static tune scan using LEQs to modify the tune. The right plot shows a fixed tune of (6.21, 6.10) with a beta-beating error (indicated in legend) applied via a single quadrupolar error on the LEQ QND72.

Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error
15% Beta-Beating Optics Comparison
Betatronic Mismatch
Conclusion

Optics Comparison: Vertical Beta

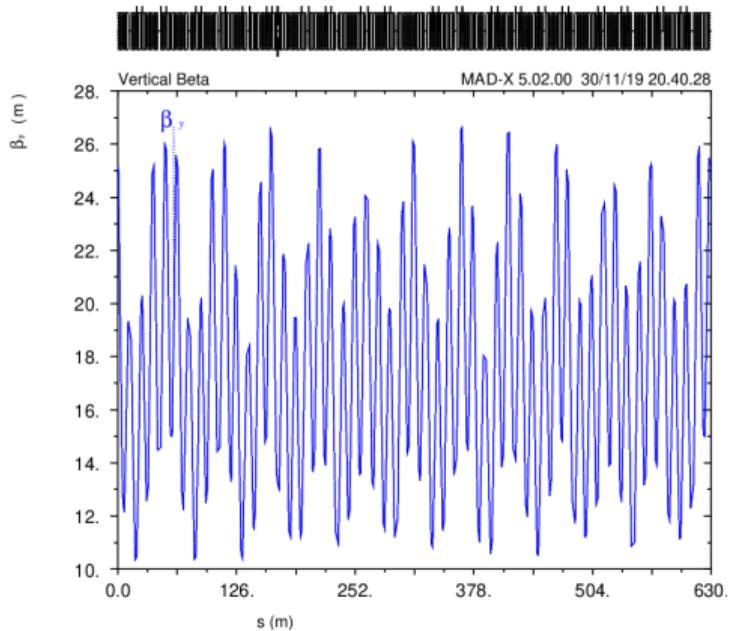
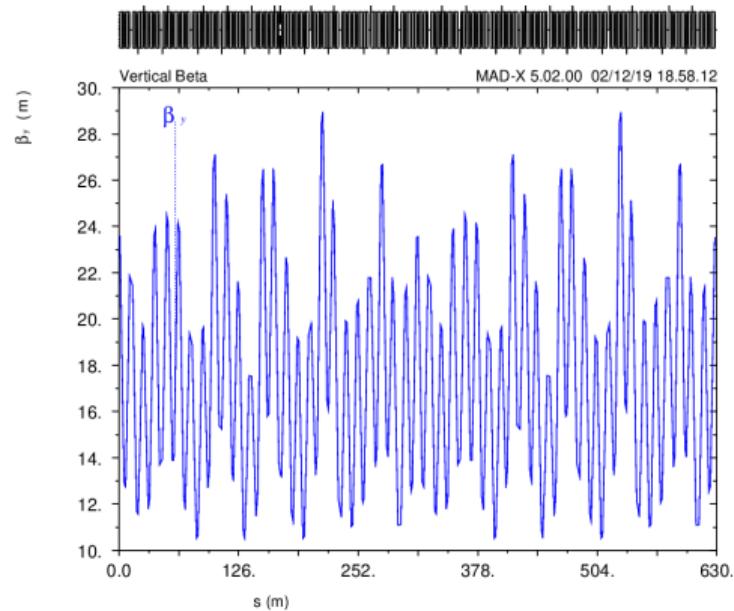


Figure: Comparison of vertical beta function when using LEQs (left) or PFWs with single $\frac{\delta\beta}{\beta} = 15\%$ quadrupole error (right) to modify the vertical tune. $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Optics Comparison: Horizontal Beta

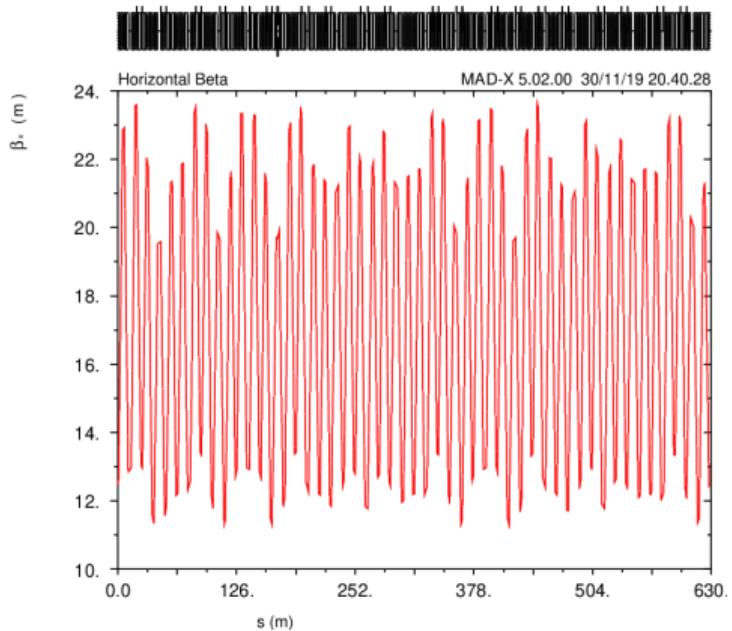
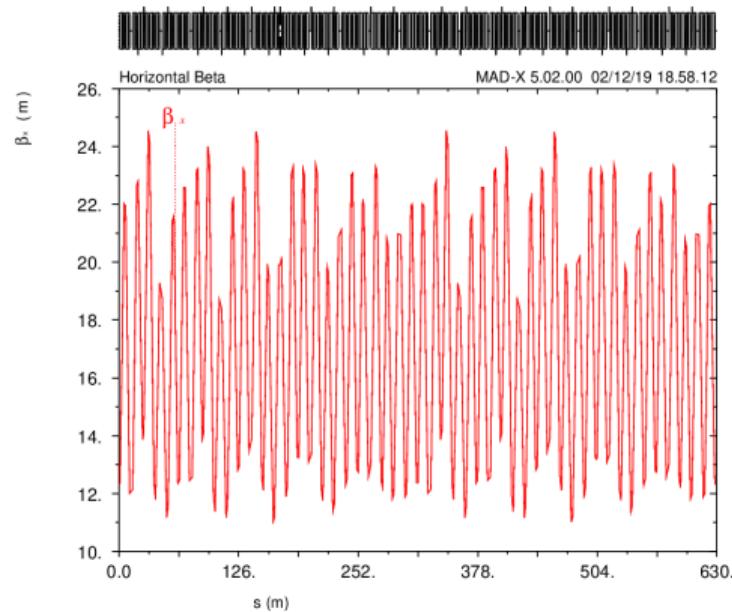


Figure: Comparison of horizontal beta function when using LEQs (left) or PFWs with single $\frac{\delta\beta}{\beta} = 15\%$ quadrupole error (right) to modify the vertical tune. $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Optics Comparison: Horizontal Dispersion

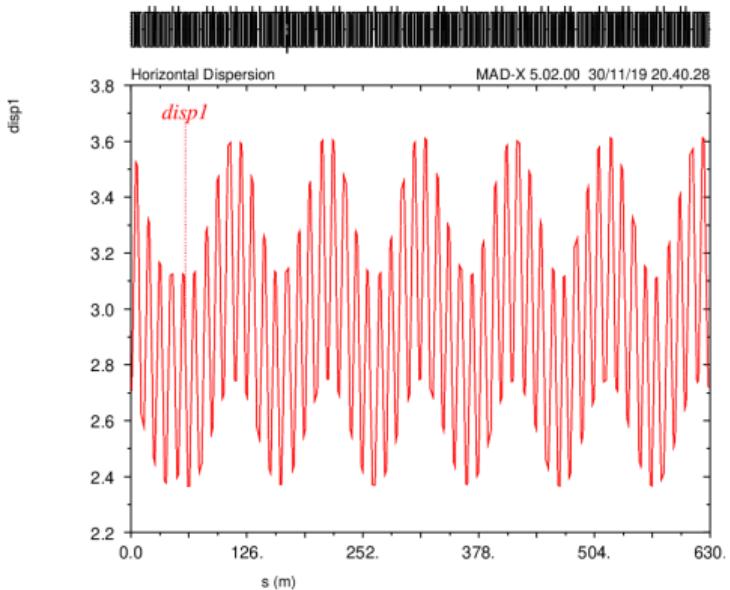
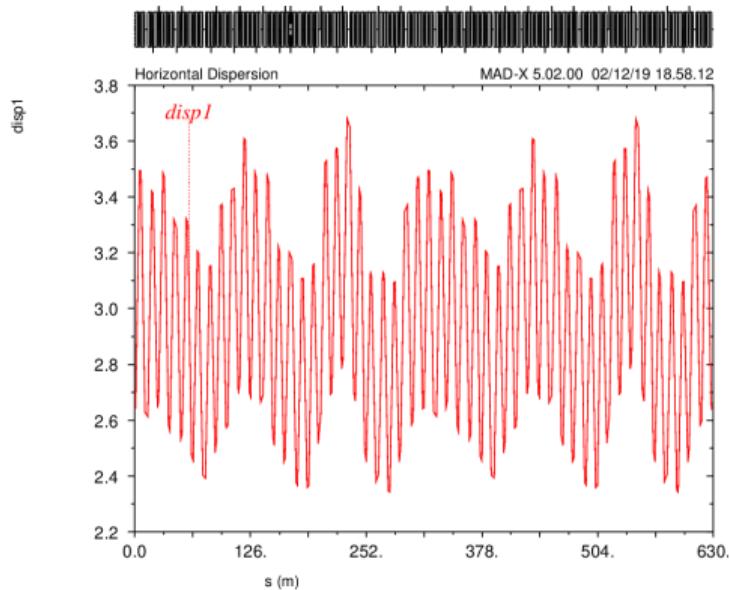


Figure: Comparison of horizontal dispersion function when using LEQs (left) or PFWs with single $\frac{\delta\beta}{\beta} = 15\%$ quadrupole error (right) to modify the vertical tune. $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Optics Comparison: Vertical Dispersion

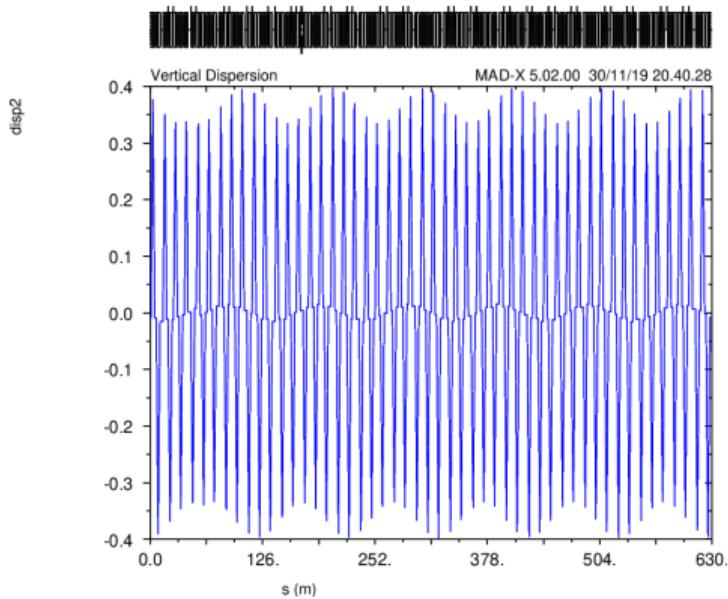
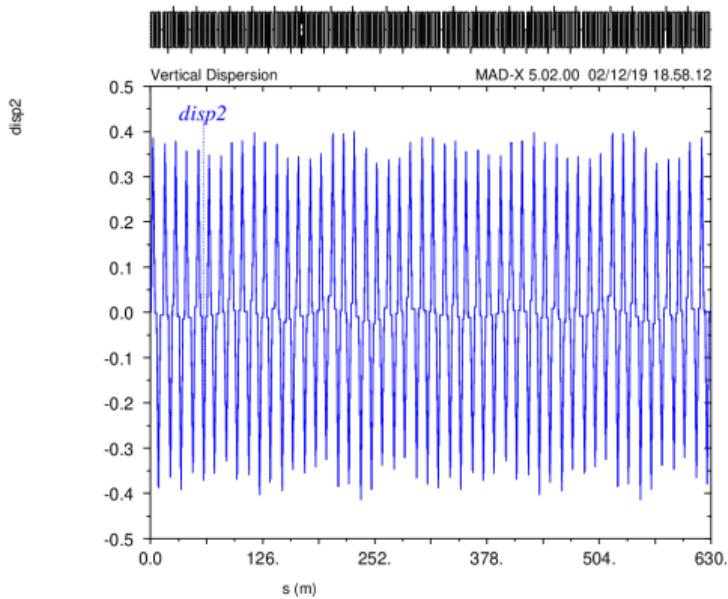


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Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error
15% Beta-Beating Optics Comparison
Betatronic Mismatch
Conclusion

Betatron Mismatch

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

$$\epsilon_{new} = \frac{\epsilon_0}{2} \left(\frac{\beta_1}{\beta_2} + \frac{\beta_2}{\beta_1} \left(\alpha_1 - \alpha_2 \frac{\beta_1}{\beta_2} \right)^2 + \frac{\beta_2}{\beta_1} \right) \quad (5)$$

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 $\beta_1 = \beta_{y_0}$, $\alpha_1 = \alpha_{y_0}$.

Expected Emittance Growth From Betatron Mismatch

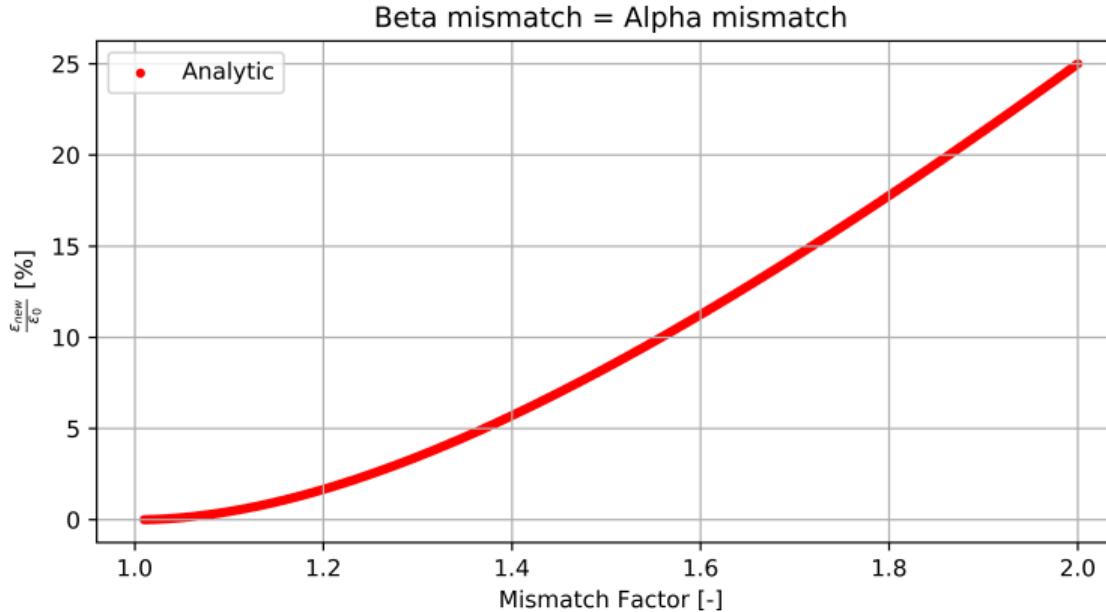


Figure: Analytical expectation for emittance growth as a function of betatron mismatch factor when using the PFW to modify tunes, for tune $(Q_x, Q_y) = (6.21, 6.10)$ - most extreme point in vertical scan.

Introduction

Optics Comparison

PFW vs LEQ Scan Comparison

PFW Scan with Quadrupolar Error
15% Beta-Beating Optics Comparison
Betatronic Mismatch
Conclusion

Conclusions

- ▶ PFW static tune scan shows no emittance growth with tune change - PFWs don't excite the quadrupolar stop-band at the (half) integer.
- ▶ Single quadrupolar error on QDN72 gives beta-beating - defined a scan in beta-beating from 1 - 25%.
- ▶ $\approx 15\%$ beta-beating on top of PFW scan gives similar emittance growth as LEQ scan.



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