# Space Charge at PS Injection

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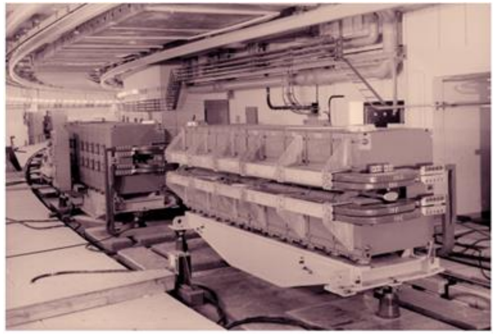
# Proton Synchrotron @ 60

- 60 years old in 2019! Still operating beyond it's original design -> provides interesting problems.

60+ years ago

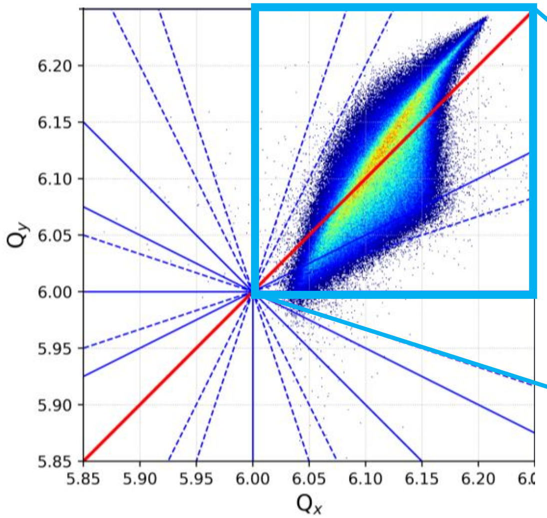


2020

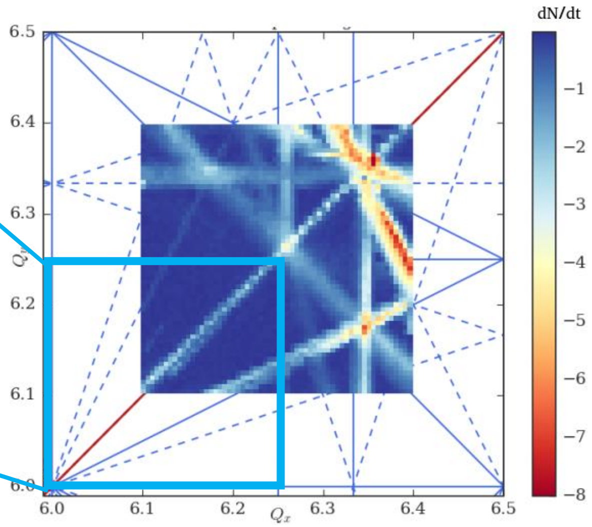
LIU project makes the PS an injector for HL-LHC -> we must understand performance limitations.

# Motivation

- The **LIU** project aims to deliver **higher <u>intensity</u>** & **higher <u>brightness</u>** (intensity/emittance) beams to the LHC for the HL-LHC upgrade.




Simulated Run2 BCMS tune spread




Run2 PS resonance measurements (M. Kaitatzi) indicating available resonance-free tune space

- In the Proton Synchrotron (PS) the <u>brightness</u> limit **is defined by:**
  - **The space charge tune spreads ($\Delta Q_x$, $\Delta Q_y$)** at injection and,
  - The available **resonance-free tune space**.

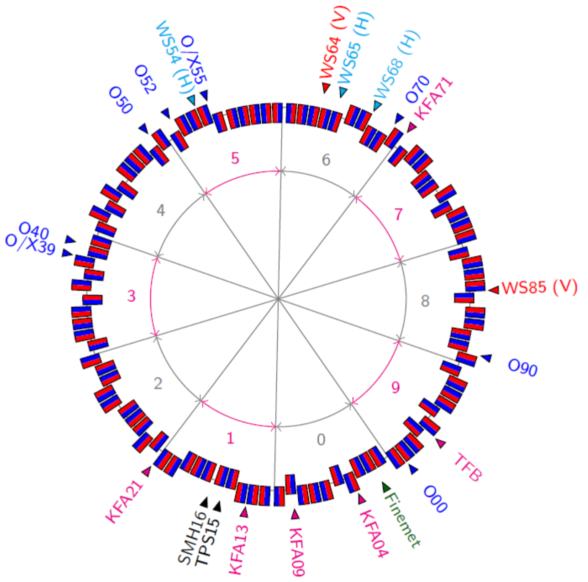
- In the PS the <u>intensity</u> reach has been demonstrated at extraction in Run 2, therefore **<u>brightness is the LIU PS priority.</u>**

In order to verify analytic calculations of space charge tune spread, and to improve our understanding of space charge effects at injection into the PS, it is essential to build a simulation based model that is benchmarked against measurements.

# Structure of the PS: Effect on working point

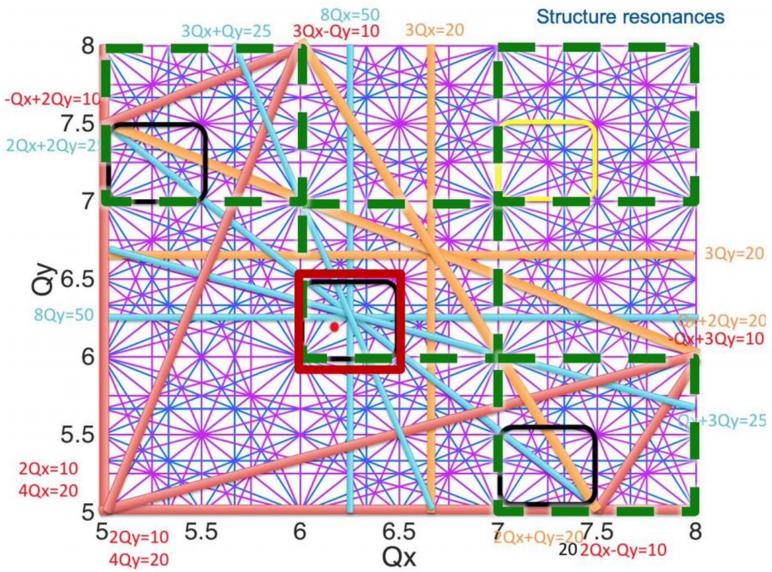
Proton Synchrotron:

- Circumference 2π * 100 m
- 100 combined function dipoles (half focussing, half defocussing gradient along length).
- Auxiliary windings on all main magnets: pole face windings (PFW) and figure-8 loop.
- 40 Low energy quadrupoles (LEQs).
- Higher order magnets for bunch manipulation and control (e.g. multi-turn extraction octupoles/sextupoles shown in diagram as O/X).
- Beam wire scanners (WS) to measure transverse profiles.



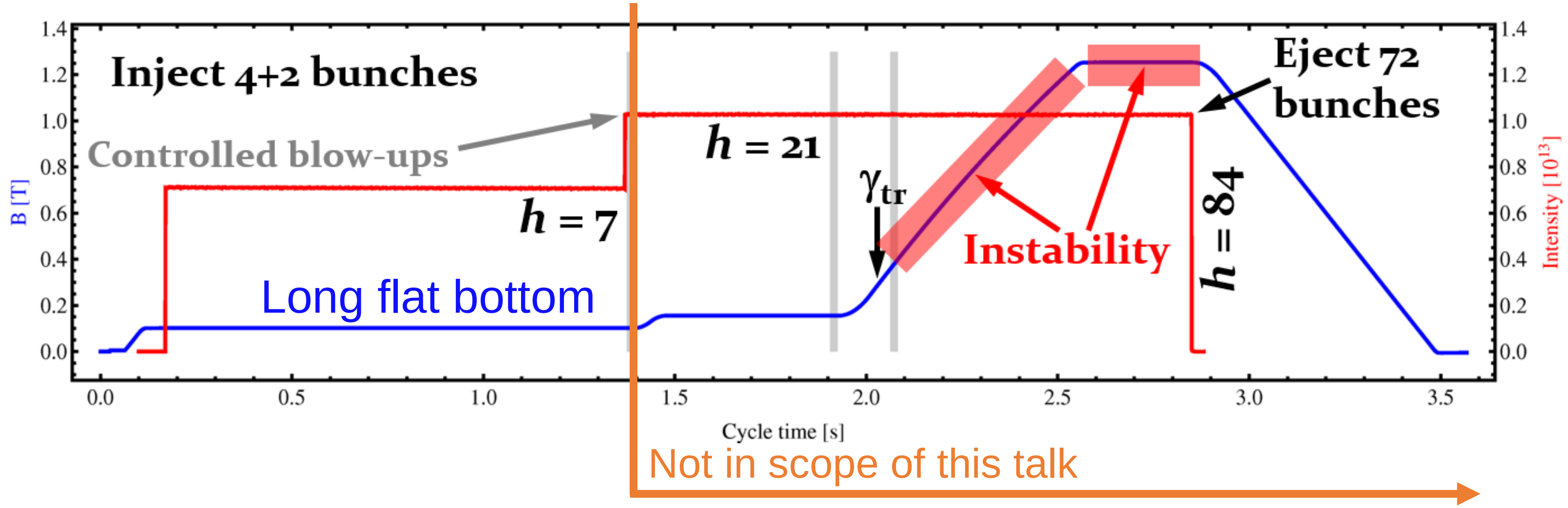

**Control of working point:**

- Due to machine symmetry the original working point was chosen in the (6., 6.) tune space to avoid structural resonances of $nQ_x + nQ_y = 10, 20, 25, 50$.
- The working point at injection can be controlled using the 40 LEQs or the PFWs present on all main magnets.



# Proton Synchrotron Cycle

- PS Booster (PSB) has 4 rings and a harmonic of 1 -> 4 bunches extracted and injected into the PS in a single PSB cycle.
- PS (single ring) operates at a harmonic of 7, 8, or 9 at injection for LHC beams. For operational scenarios the PS requires two injections from the booster (LHC Standard = 4 + 4, BCMS = 4 + 2).
- **Two PSB->PS injections require a long injection flat bottom** of ~1.2 seconds (PSB cycle time) -> first batch of protons stored for this time.




**Transverse emittance preservation at injection and on the flat bottom is <u>expected to be critical</u> for LIU brightness target** (PS limit of 5% emittance blow-up).

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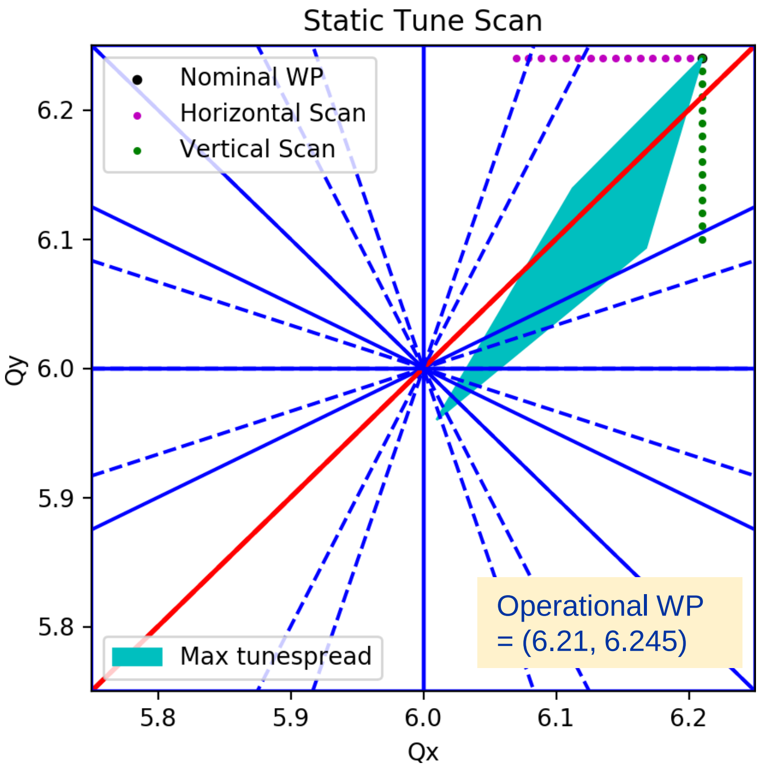
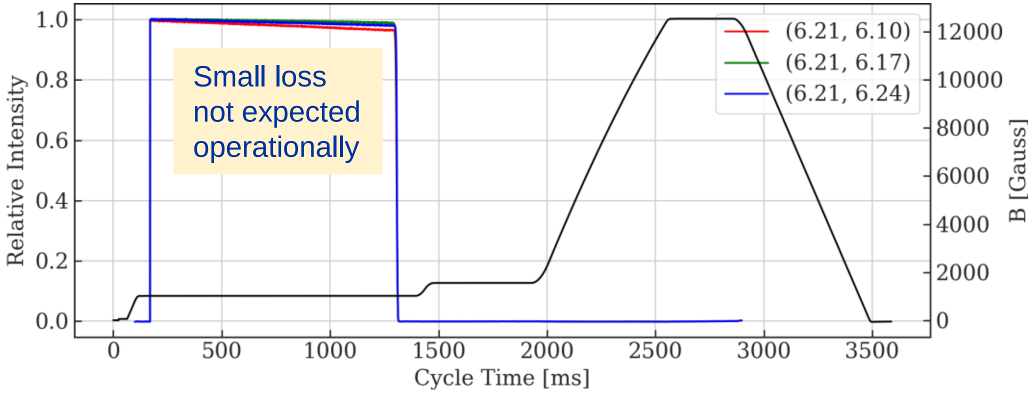
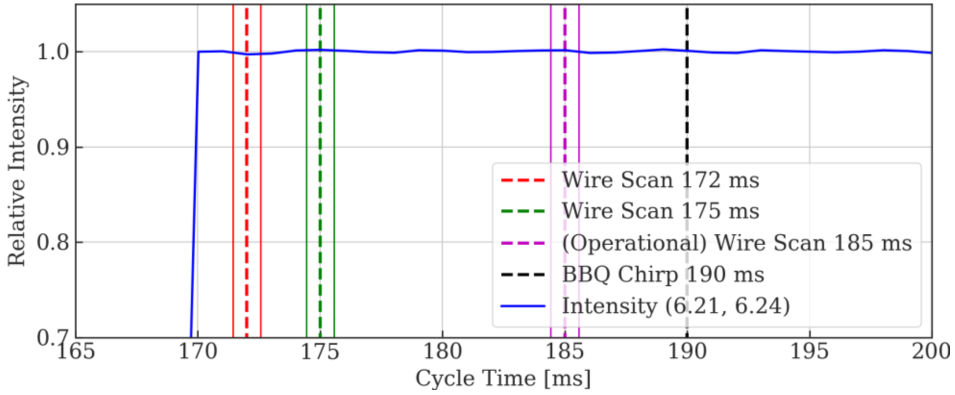
# Benchmarking the model: measurements

- Single BCMS bunch injected from PSB Ring 3.
- Used **low energy quadrupoles (LEQs)** to control the working point (WP) at injection, and perform static tune scans in each plane separately – shown on left diagram as purple points (horizontal scan), or green points (vertical scan).



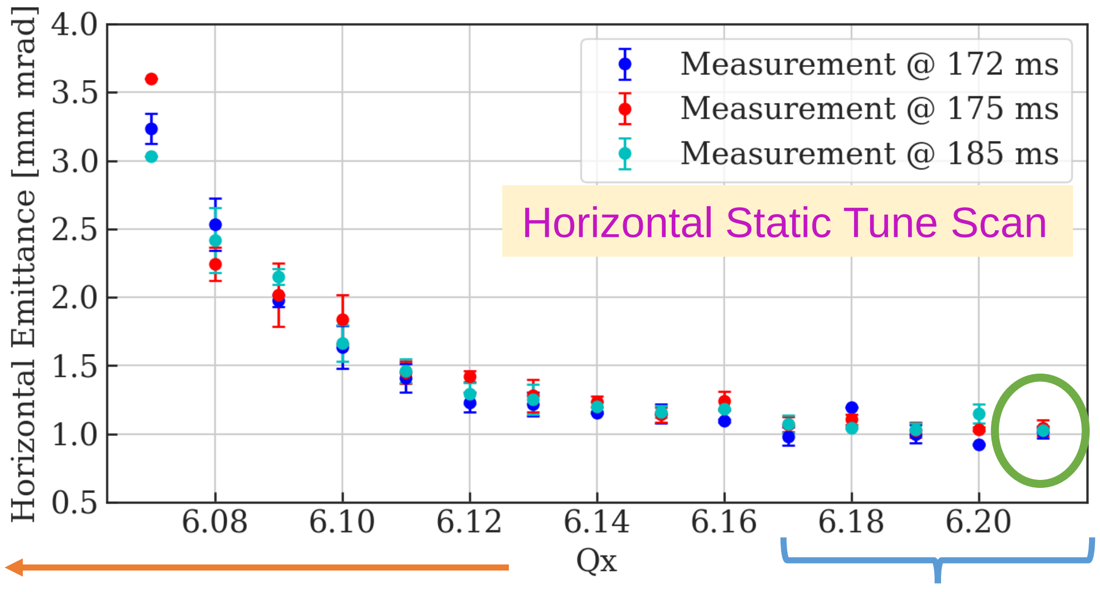

Single bunch injected and internally dumped @ 1300 ms

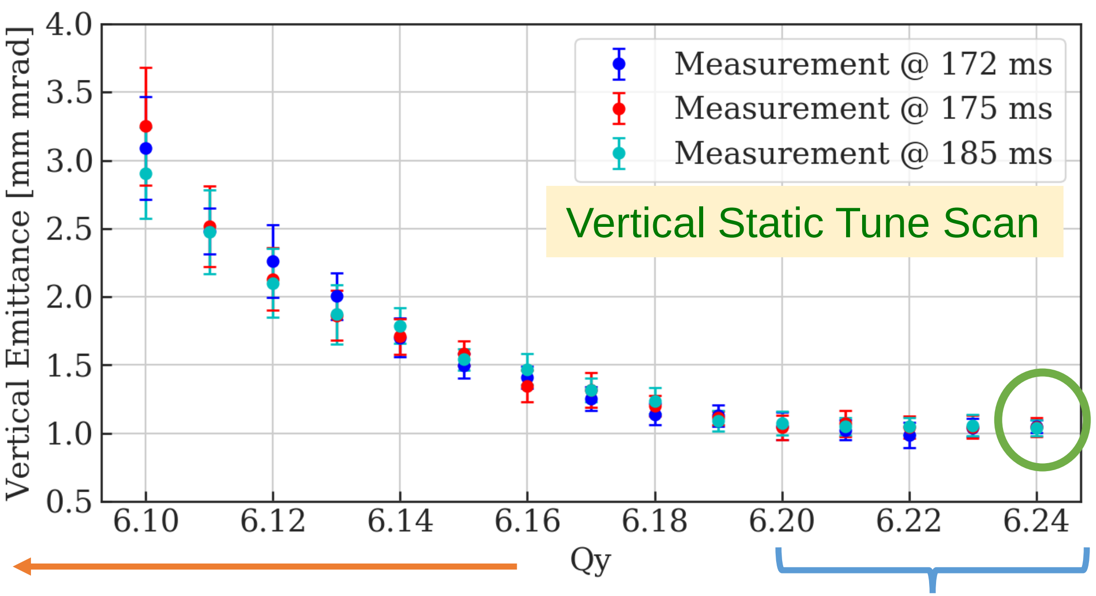
Wire scanner measurements @ 2, 5, 15 ms post-injection

BBQ chirp from 190 ms gives small loss

# Benchmarking the model: measurements

- Analysing the bunch profiles from the wire-scanner allows us to compute the beam emittance.



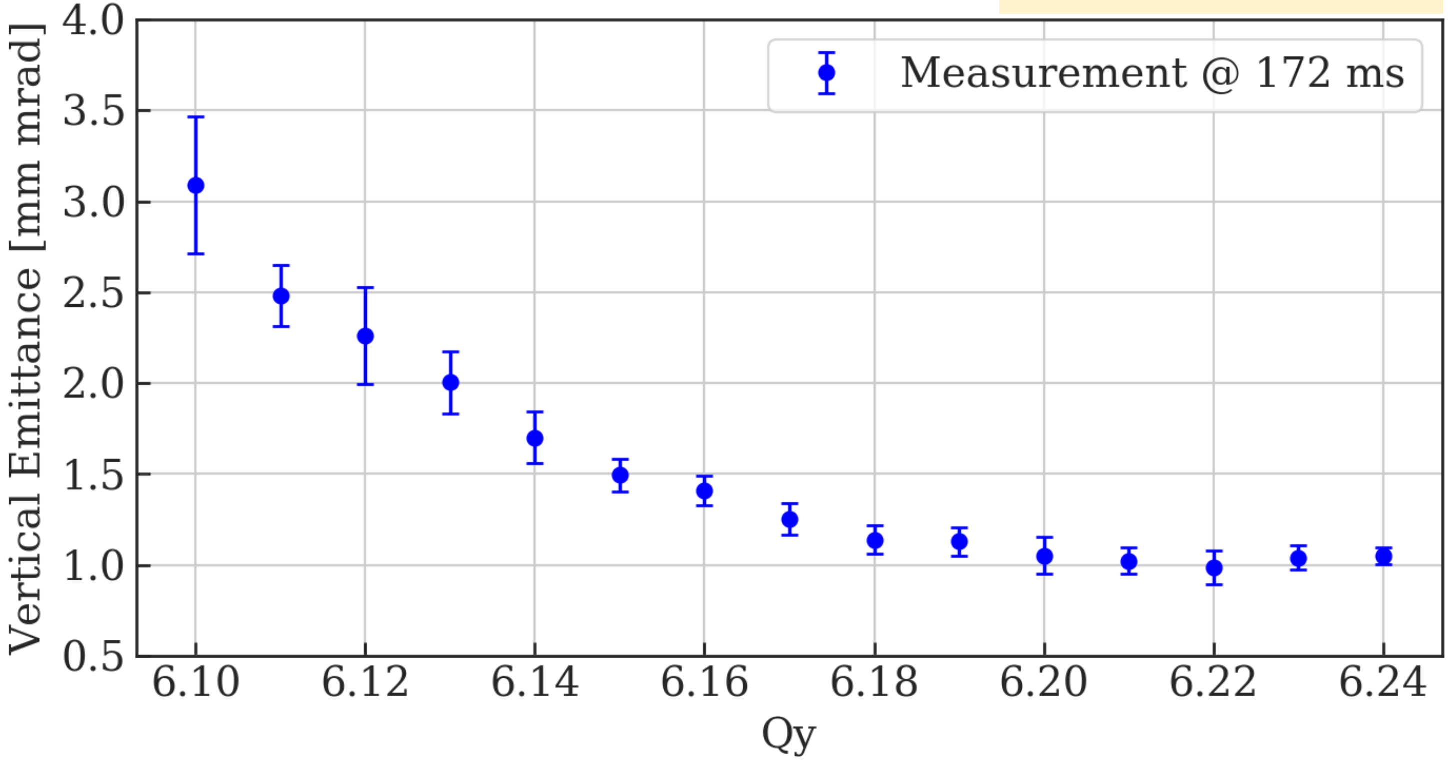




Close to the operational working point $(Q_x, Q_y) = (6.21, 6.24)$ space charge does not cause additional blow-up.
Blow-up occurs as working point gets closer to the integer tune.
No dependence on measurement time implies a fast blow-up (less than 2 ms) for working points closer to the integer.

# Benchmarking: starting point

- Use vertical measurements @ 172 ms for benchmarking our simulation model.

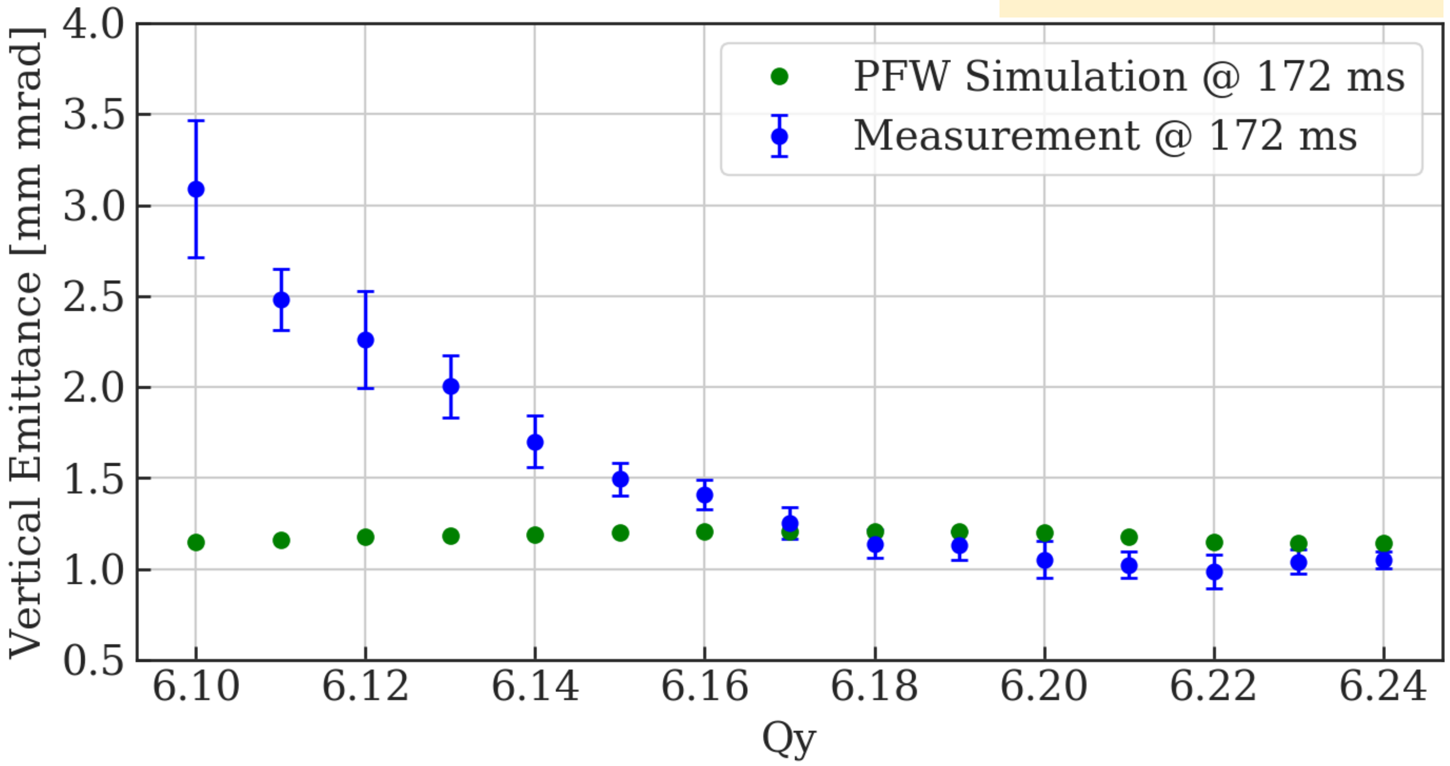
Vertical Static Tune Scan



# Benchmarking: symmetric lattice

- Controlling the working point whilst preserving lattice symmetry (with PFWs) does not produce emittance blow-up.

Vertical Static Tune Scan

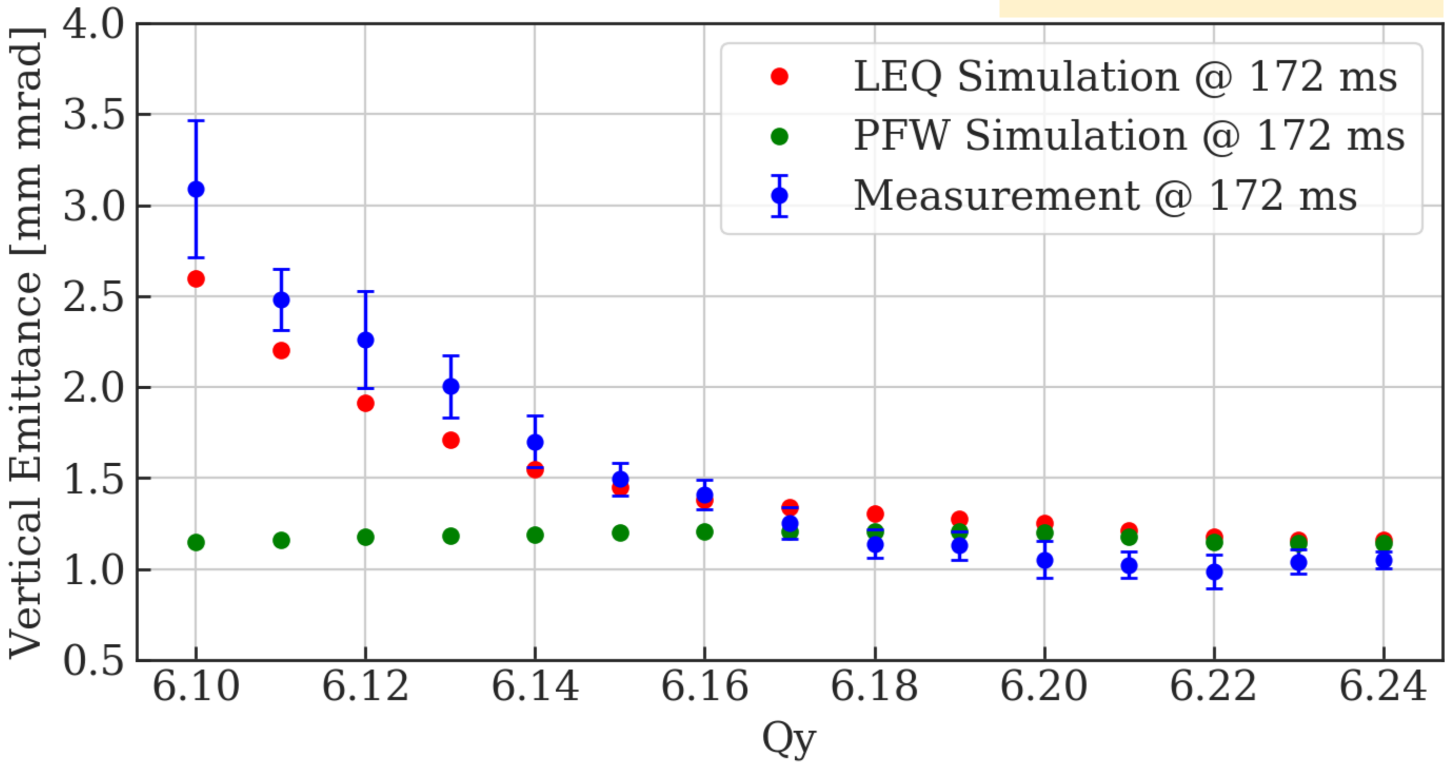



Simulated tune scan using a symmetric lattice gives no space charge blow-up.

# Benchmarking: asymmetric lattice

- Controlling the working point whilst preserving lattice symmetry (with PFWs) does not produce emittance blow-up.
- Controlling the working point with LEQs produces emittance blow-up similar to measurement.

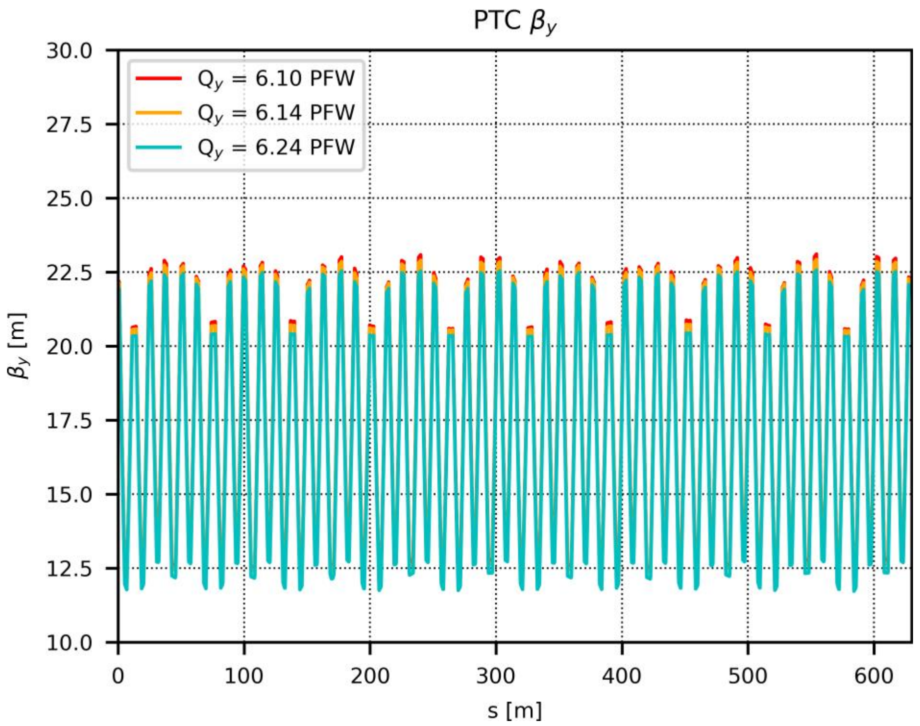
Vertical Static Tune Scan



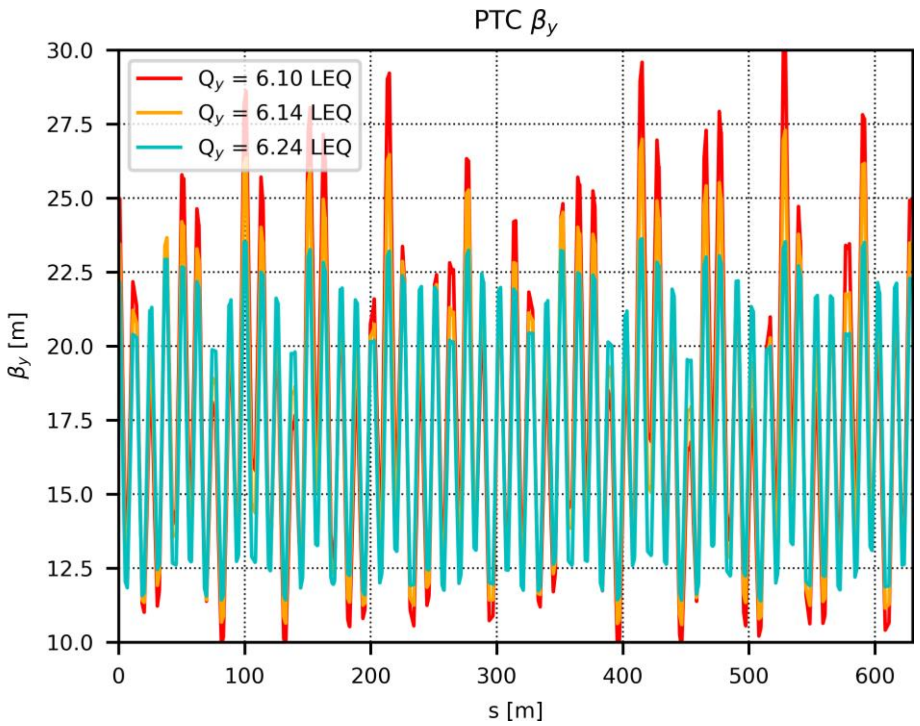

**Simulated tune scan using an asymmetric lattice gives blow-up similar to measurement. Why?**

# Benchmarking: asymmetric lattice

- Controlling the tune whilst breaking lattice symmetry (with LEQs) produces emittance blow-up similar to measurement. Why?
- Optics distorted due to asymmetric positioning of LEQs.



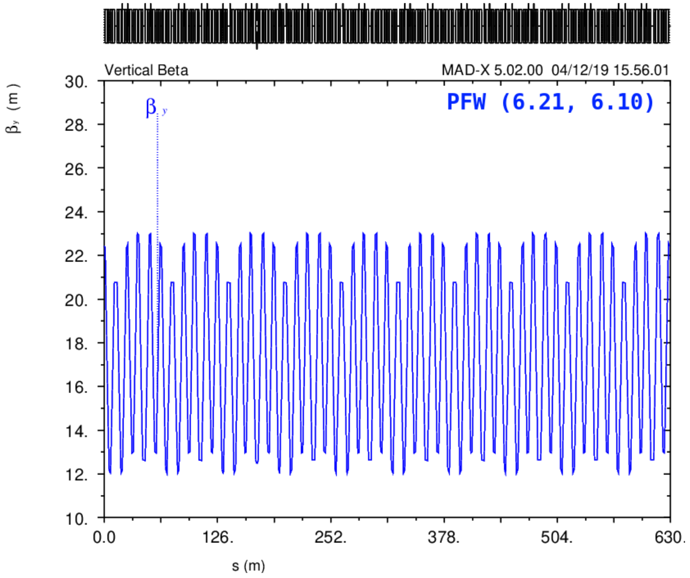

Working point control with PFWs (periodically positioned on all main magnets)



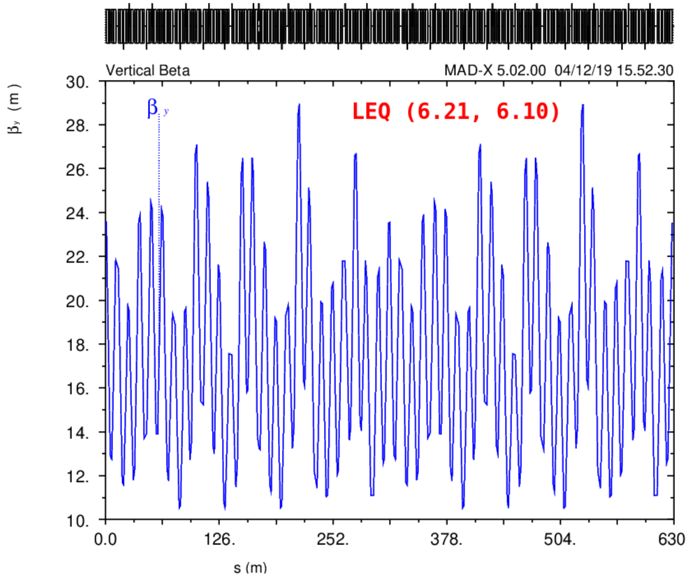

Working point control with LEQs distorts the optics due to breaking of symmetry

# Benchmarking: symmetric lattice + quadrupole error

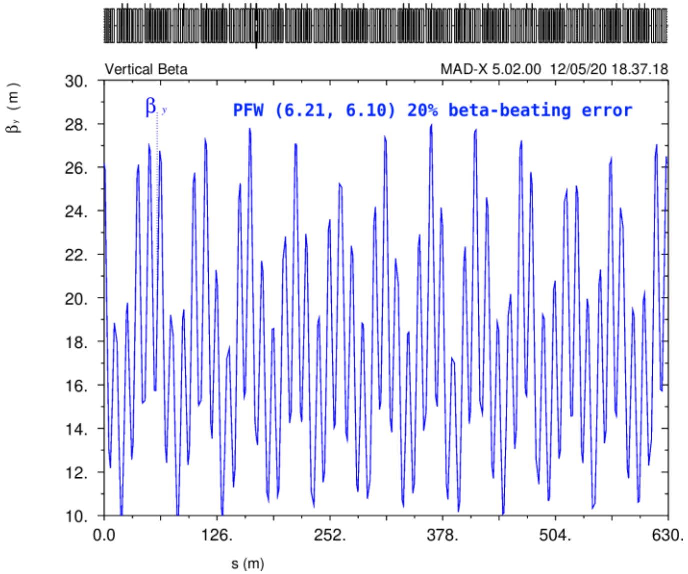
- PFW tune control maintains lattice symmetry -> periodic optics.
- LEQ tune control breaks symmetry -> results in beta-beating.
- We introduce a single quadrupole error in the symmetric lattice in order to generate similar magnitude of beta-beating -> use to confirm reason for emittance growth at a working point close to the integer (6.21, **6.10**).




Control working point with PFWs




Control working point with LEQs generates beta-beating

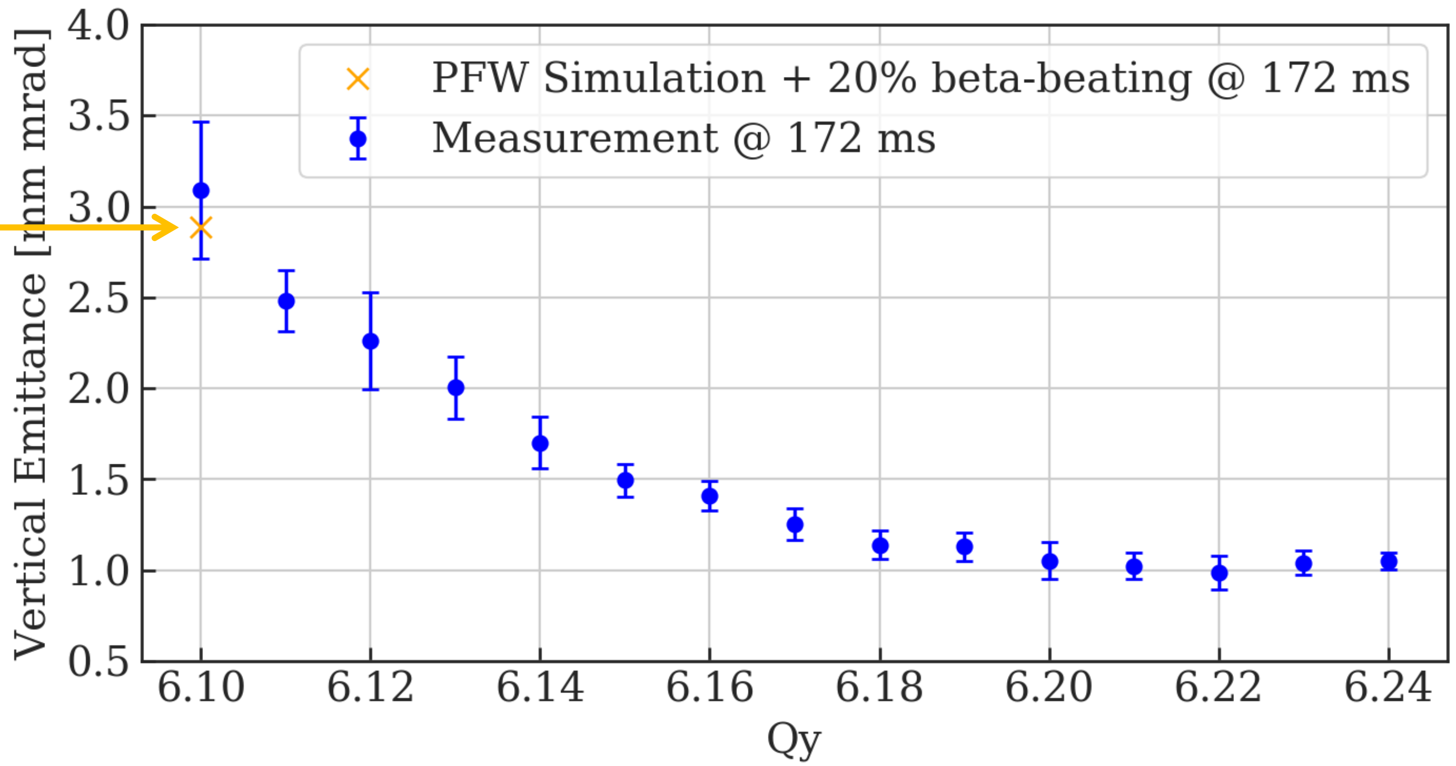



Control working point with PFWs + Single quadrupole error generating 20% beta-beating

Add Single Quadrupole Error

# Benchmarking: symmetric lattice + quadrupole error

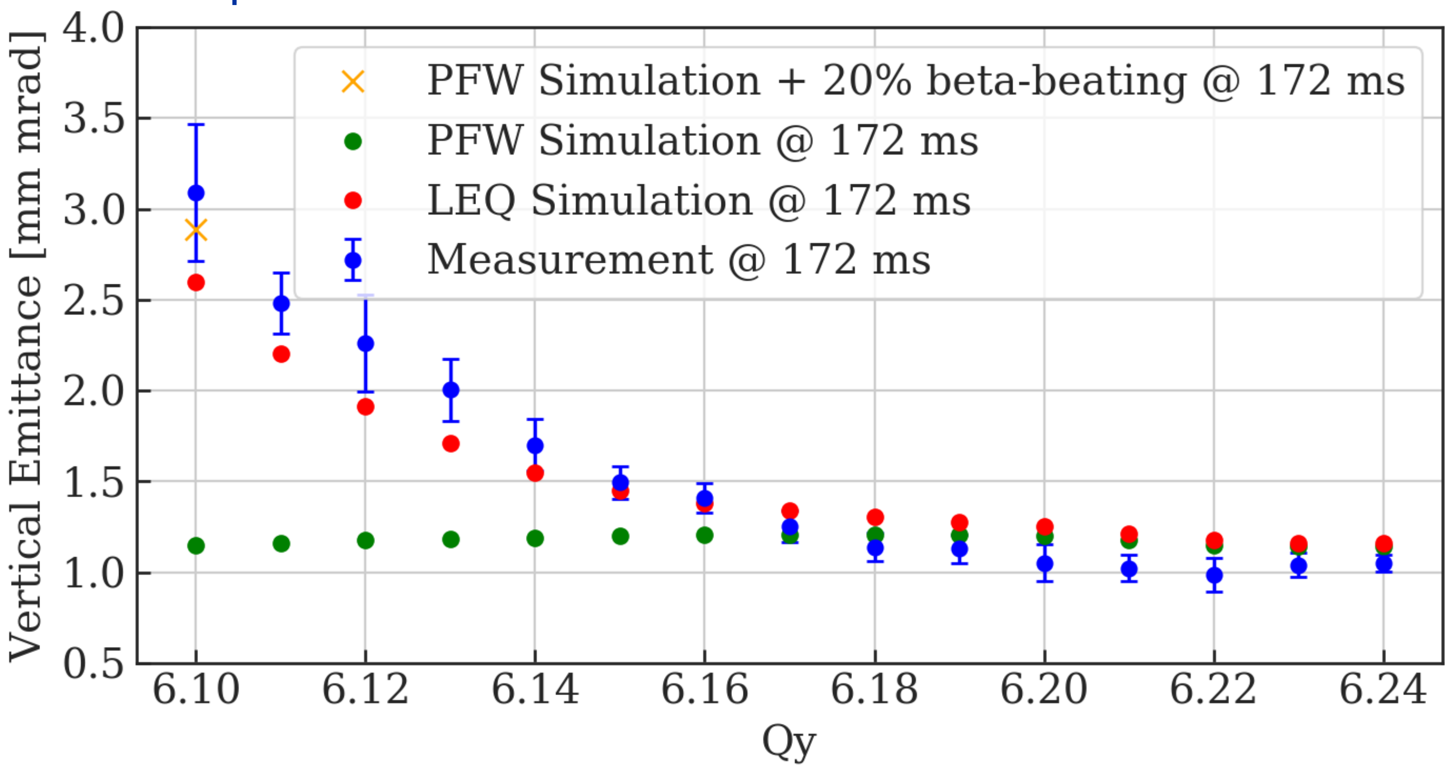
- Effect of single quadrupole error (in symmetric lattice) generating similar beta-beating to LEQ case?




**Simulation using a symmetric lattice + single quadrupole error generating 20% beta-beating gives blow-up similar to measurement.**

# Cause of blow-up

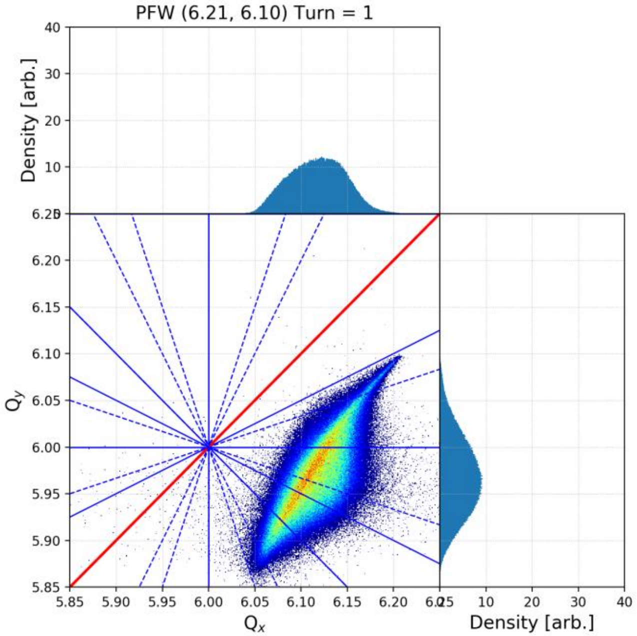
- Preserving lattice symmetry (tune control with PFWs) gives no optics distortion -> no blow-up.
- Breaking lattice symmetry (tune control with LEQs) gives beta-beating and emittance blow-up (near the integer).
- Introducing a single quadrupolar error in the symmetric lattice results in beta-beating similar to tune control with LEQs, and emittance blow-up similar to measurements.



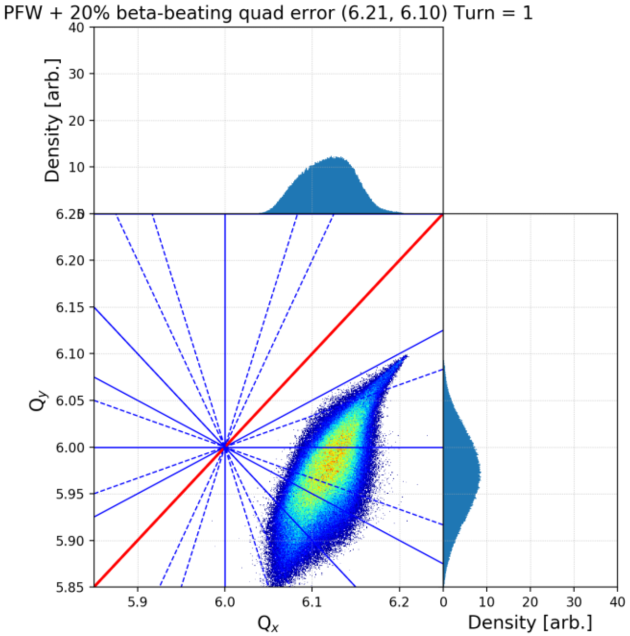

**Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune.**

# Quadrupolar resonance at the integer: turn 1

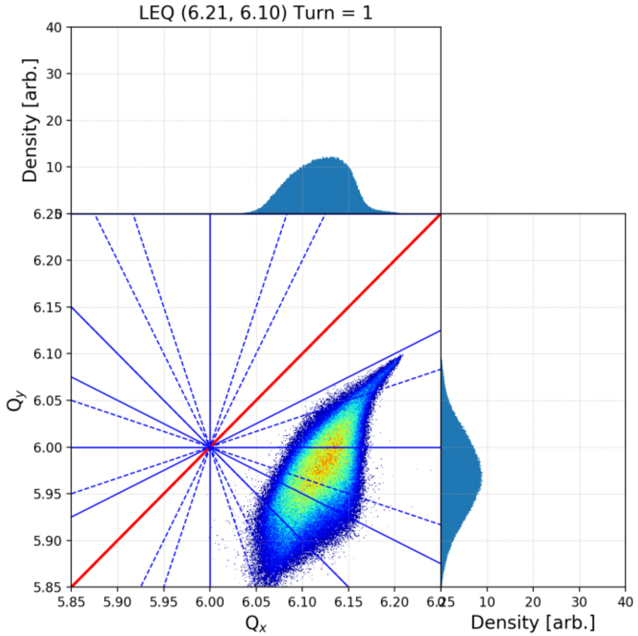
- Tune spread evolution for first 50 turns




Control working point with PFWs




Control working point with PFWs + Single quadrupole error generating 20% beta-beating

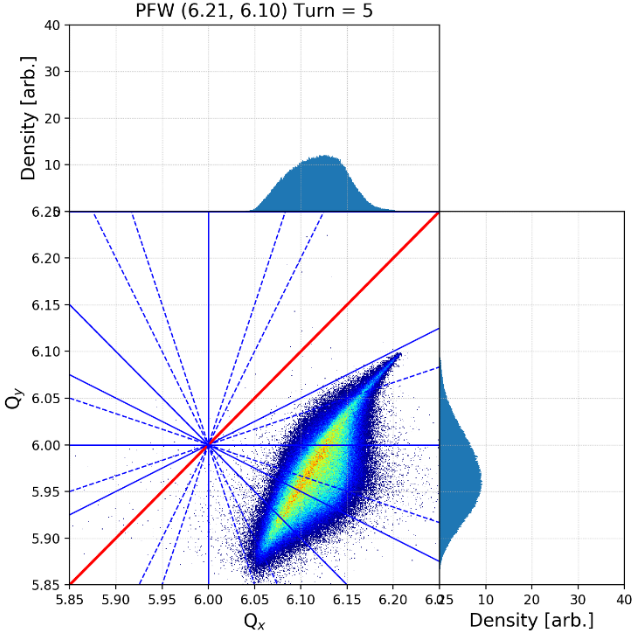



Control working point with LEQs generates beta-beating

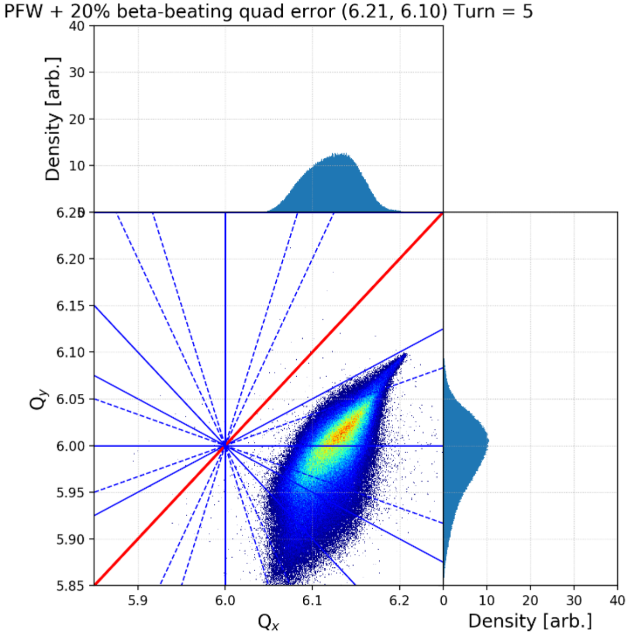
Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune. Controlling working point with PFWs could be beneficial for performance – to be studied.

# Quadrupolar resonance at the integer: turn 5

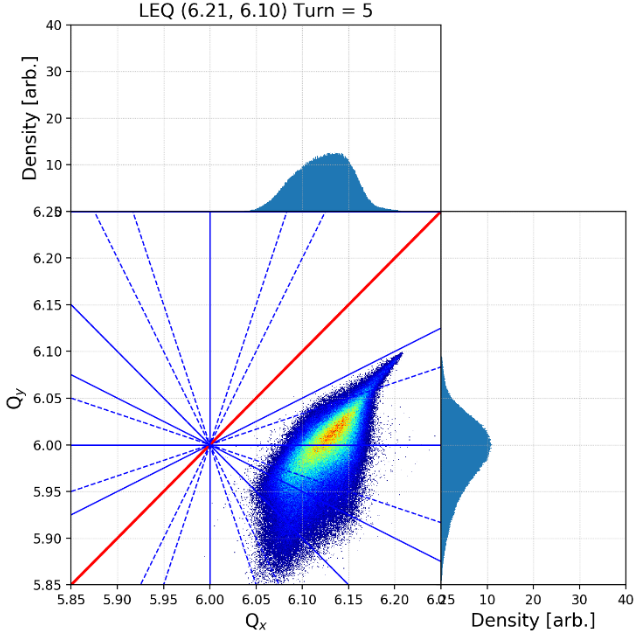
- Tune spread evolution for first 50 turns




Control working point with PFWs




Control working point with PFWs + Single quadrupole error generating 20% beta-beating

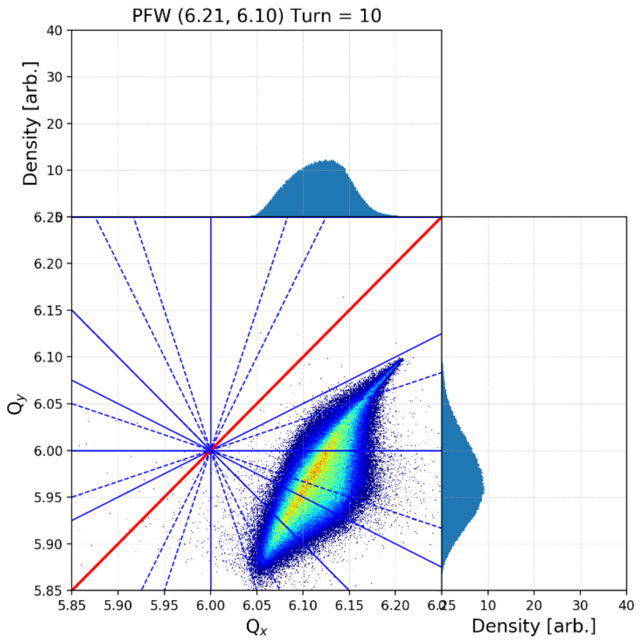



Control working point with LEQs generates beta-beating

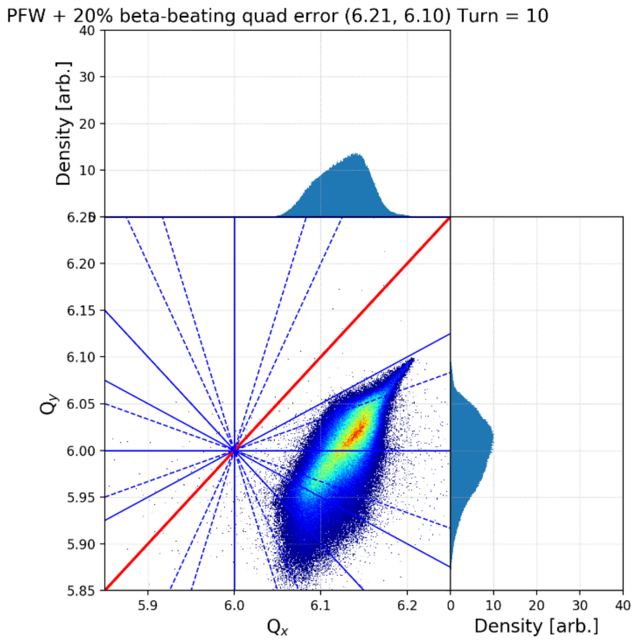
Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune. Controlling working point with PFWs could be beneficial for performance – to be studied.

# Quadrupolar resonance at the integer: turn 10

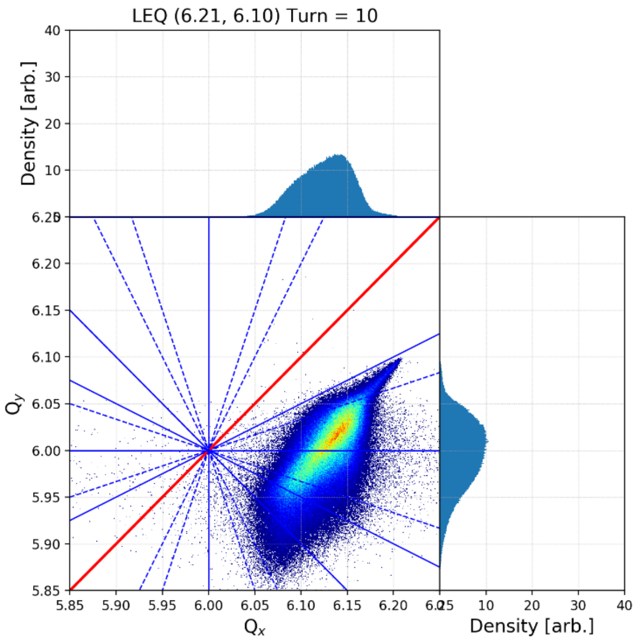
- Tune spread evolution for first 50 turns




Control working point with PFWs




Control working point with PFWs + Single quadrupole error generating 20% beta-beating

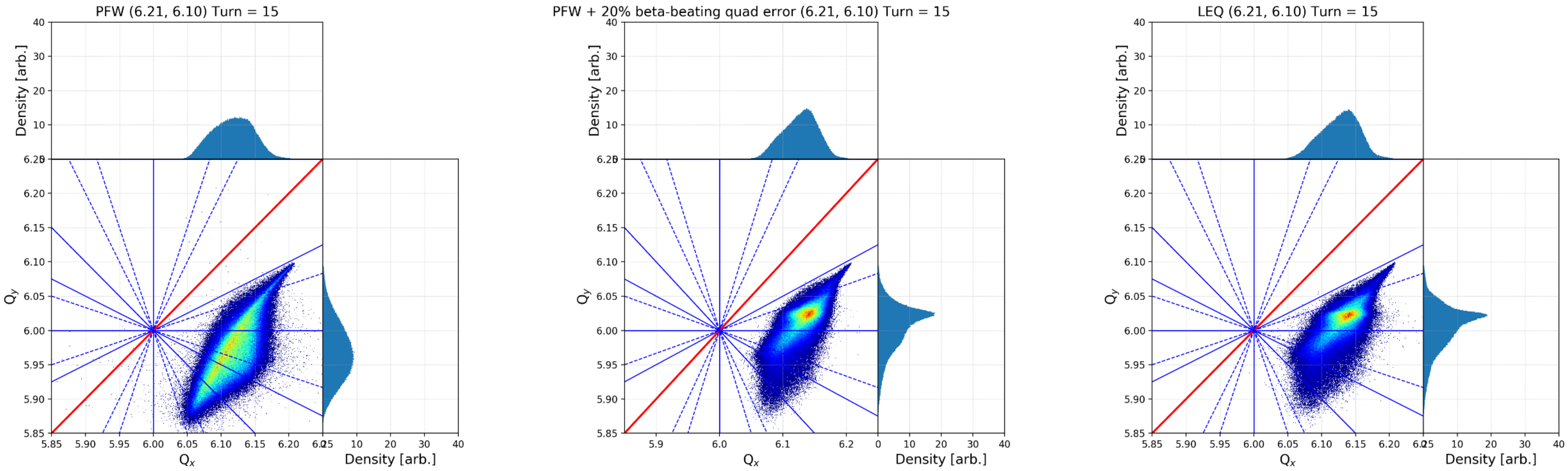



Control working point with LEQs generates beta-beating

Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune.
Controlling working point with PFWs could be beneficial for performance – to be studied.

# Quadrupolar resonance at the integer: turn 15

- Tune spread evolution for first 50 turns




Control working point with PFWs

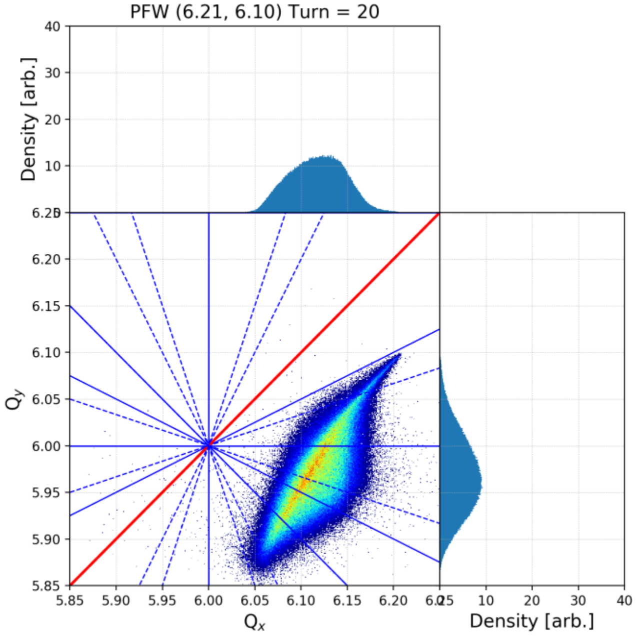
Control working point with PFWs + Single quadrupole error generating 20% beta-beating

Control working point with LEQs generates beta-beating

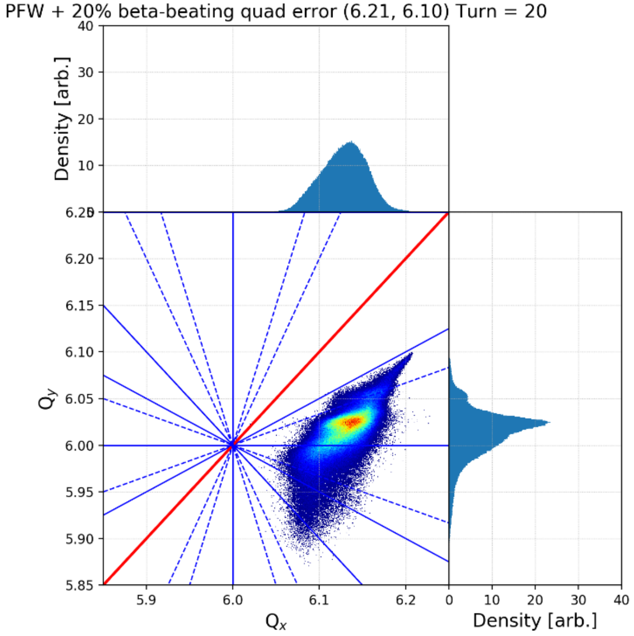
Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune. Controlling working point with PFWs could be beneficial for performance – to be studied.

# Quadrupolar resonance at the integer: turn 20

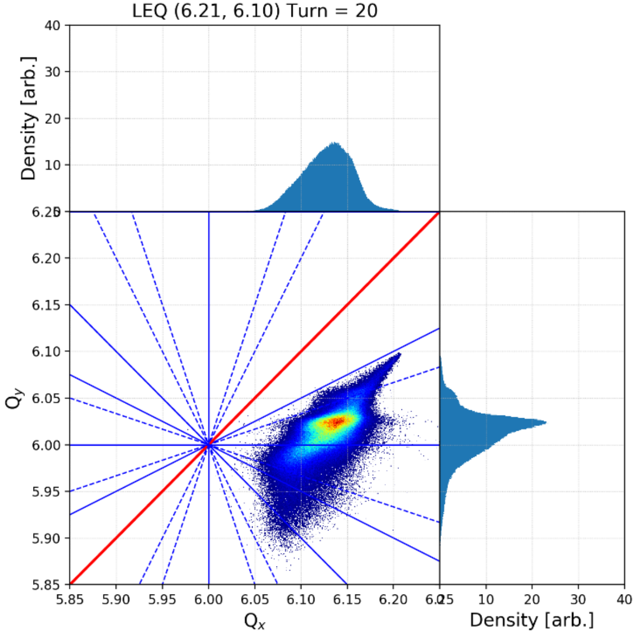
- Tune spread evolution for first 50 turns




Control working point with PFWs




Control working point with PFWs + Single quadrupole error generating 20% beta-beating

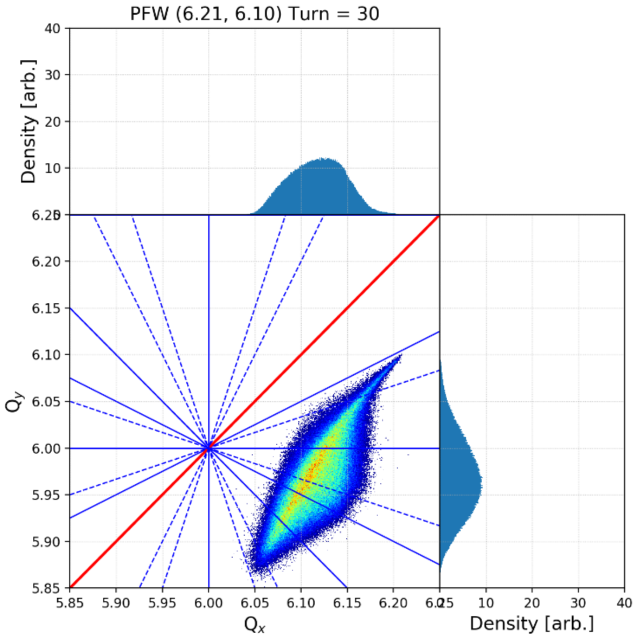



Control working point with LEQs generates beta-beating

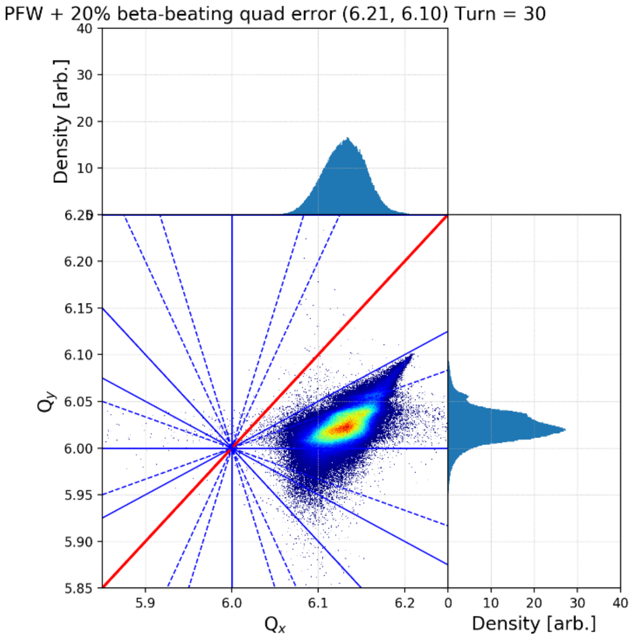
Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune. Controlling working point with PFWs could be beneficial for performance – to be studied.

# Quadrupolar resonance at the integer: turn 30

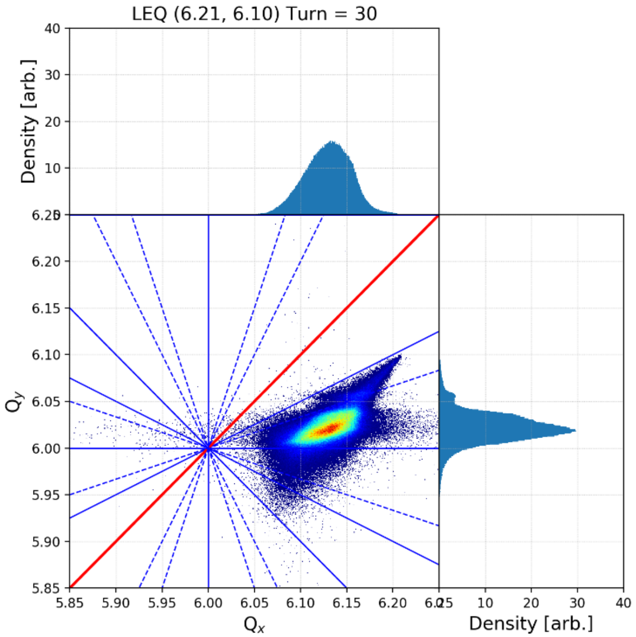
- Tune spread evolution for first 50 turns




Control working point with PFWs




Control working point with PFWs + Single quadrupole error generating 20% beta-beating

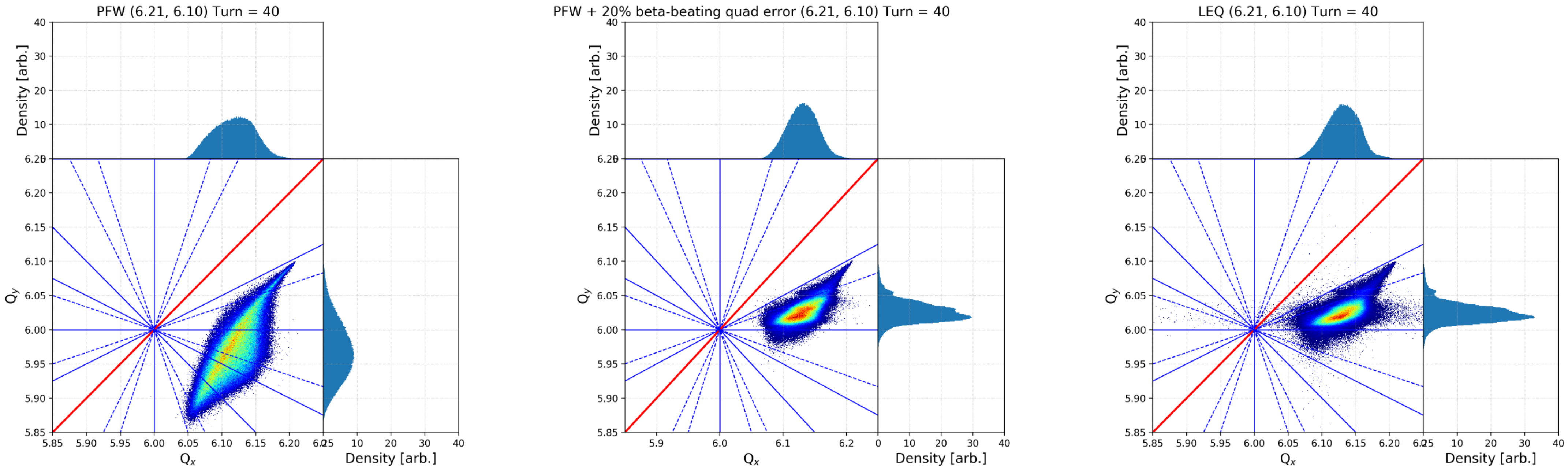



Control working point with LEQs generates beta-beating

Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune. Controlling working point with PFWs could be beneficial for performance – to be studied.

# Quadrupolar resonance at the integer: turn 40

- Tune spread evolution for first 50 turns




Control working point with PFWs

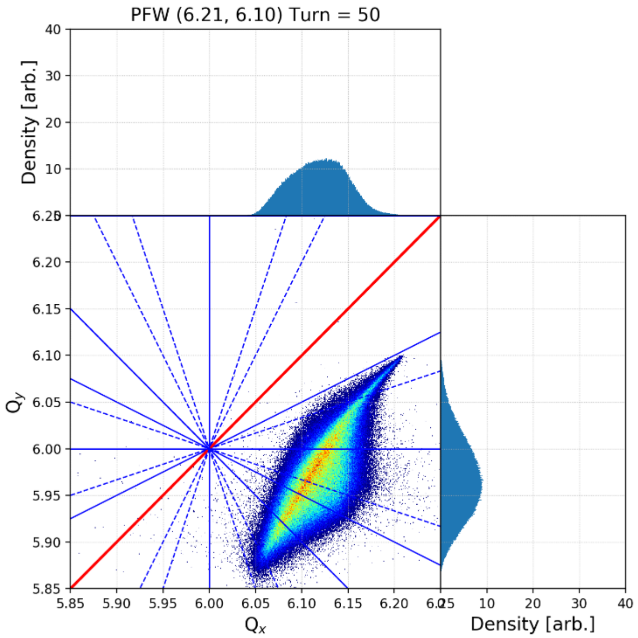
Control working point with PFWs + Single quadrupole error generating 20% beta-beating

Control working point with LEQs generates beta-beating

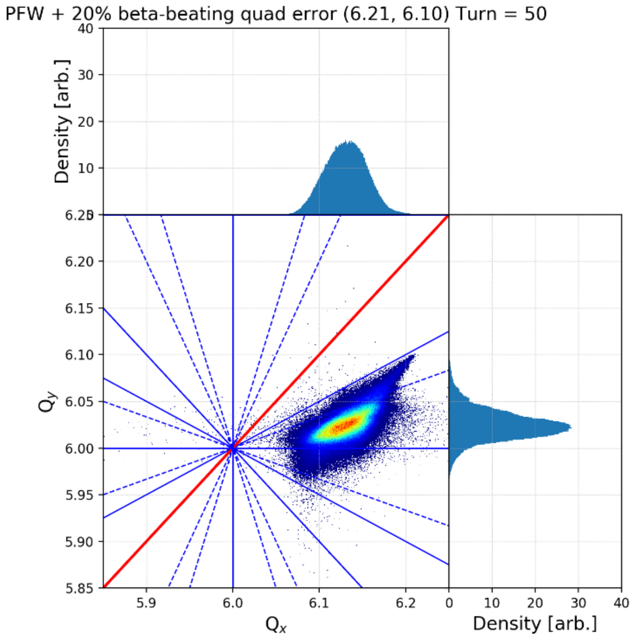
Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune. Controlling working point with PFWs could be beneficial for performance – to be studied.

# Quadrupolar resonance at the integer: turn 50

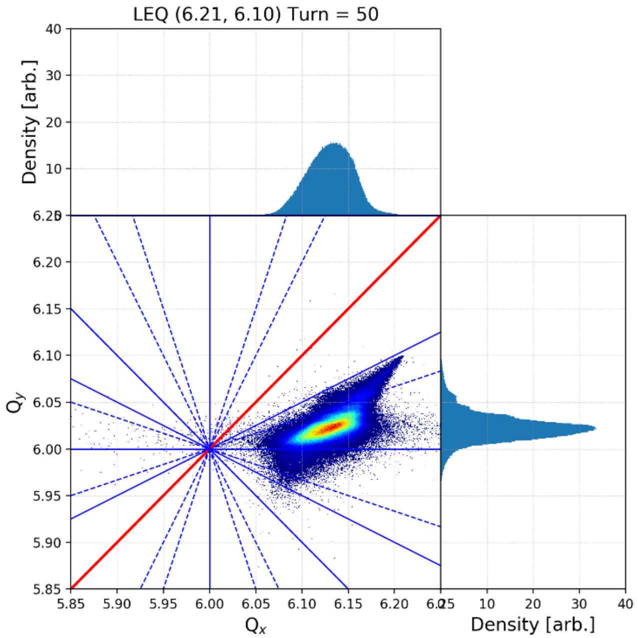
- Tune spread evolution for first 50 turns ~ 0.11 ms




Control working point with PFWs




Control working point with PFWs + Single quadrupole error generating 20% beta-beating

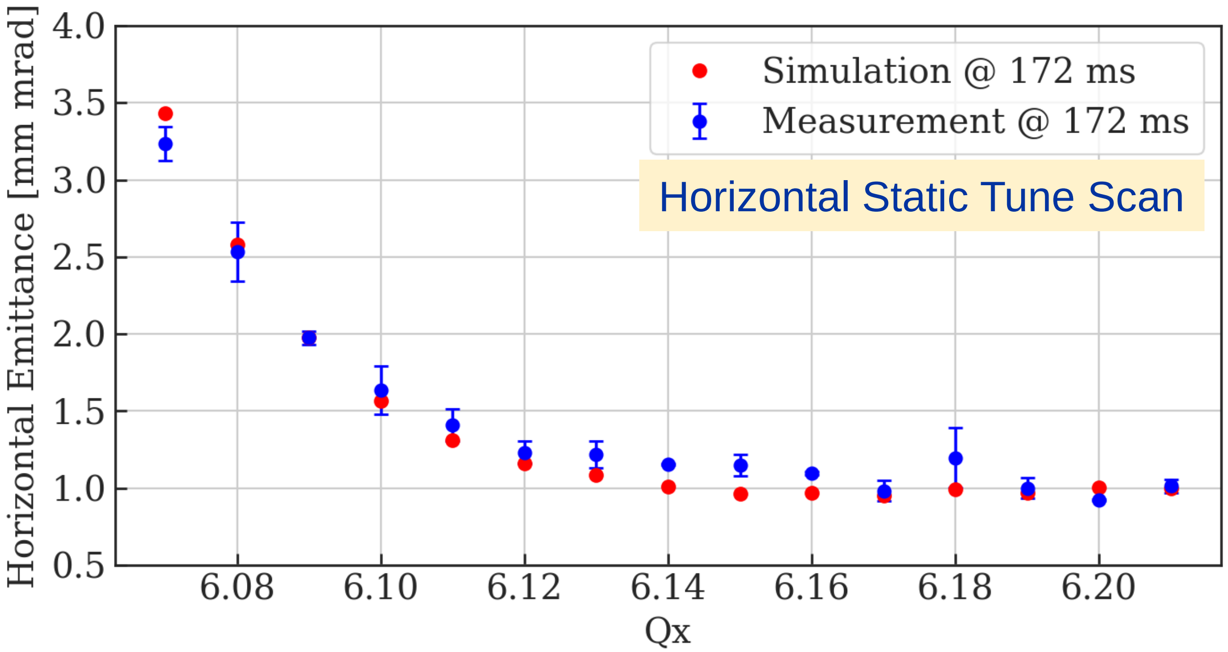



Control working point with LEQs generates beta-beating

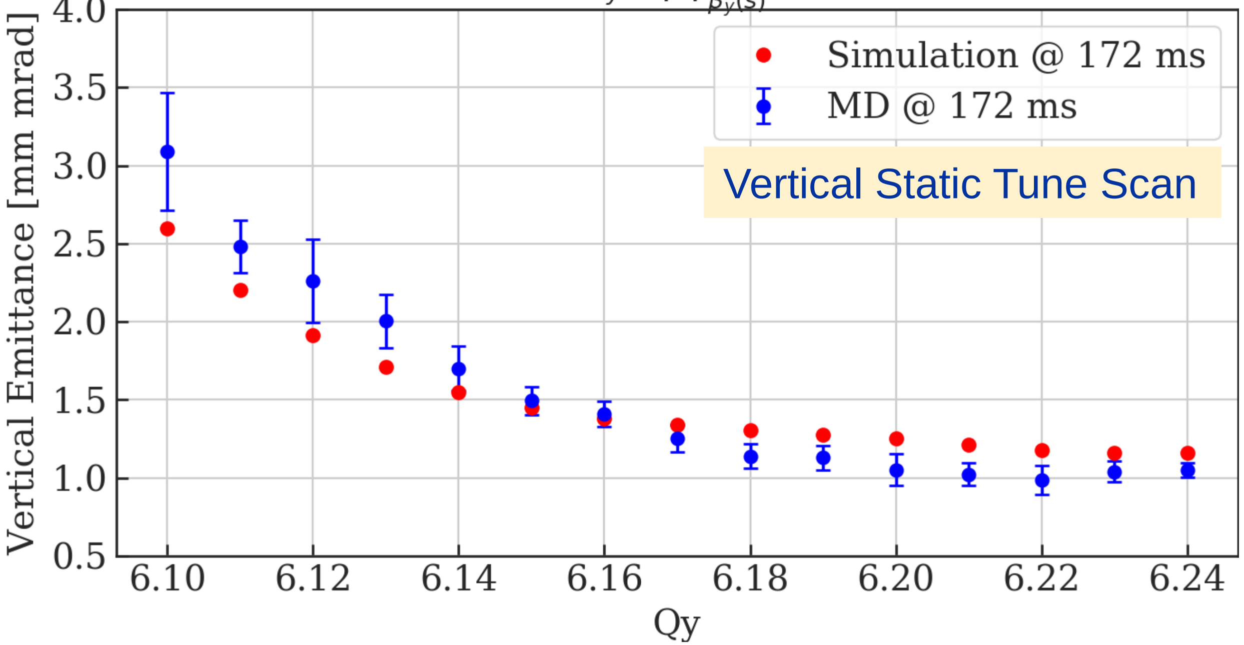
Emittance blow-up at working points close to the integer is caused by the quadrupolar resonance at the integer tune. Controlling working point with PFWs could be beneficial for performance – to be studied.

# PS space charge model benchmarked

- Calculating the emittance using identical methods on measured and simulated bunch data gives good agreement of model with measurements.




$$\epsilon_y = \beta\gamma\frac{\mu{\prime}_y^2}{\beta_y(s)}$$




**Agreement of simulation with measurements in both planes -> model is benchmarked.**

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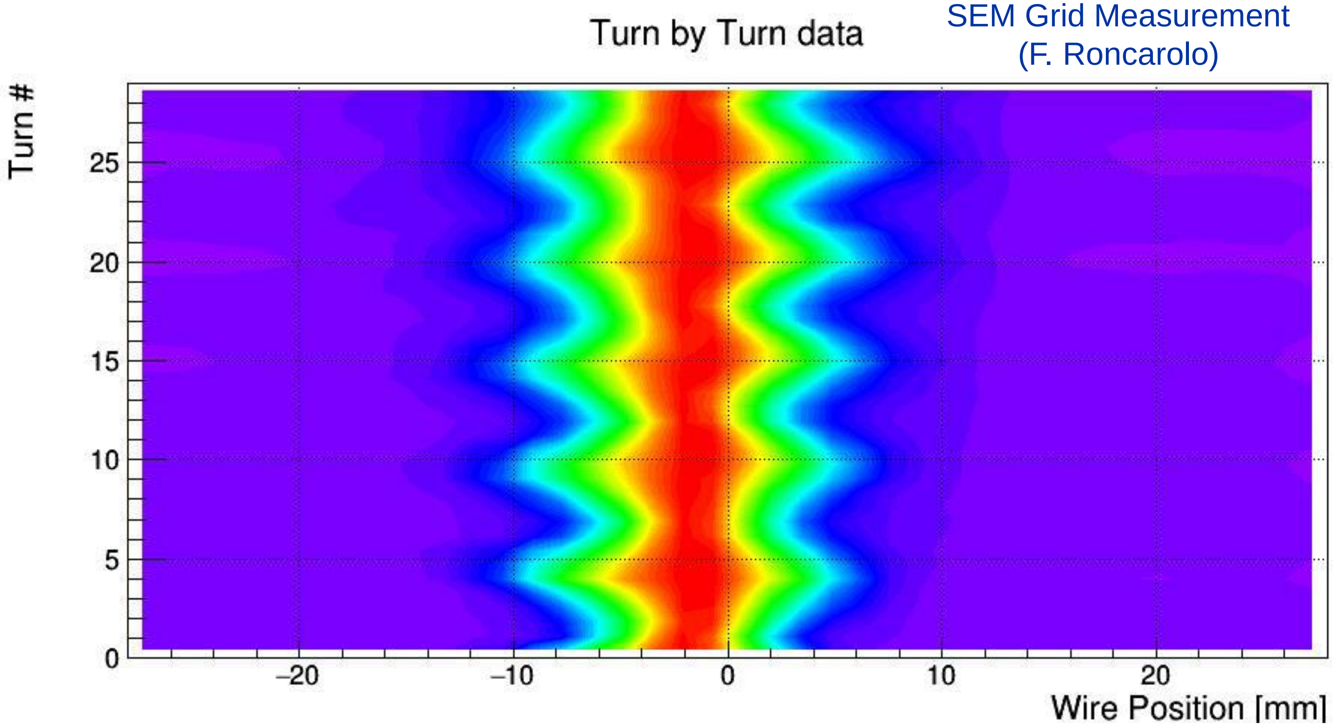
# Dispersion mismatch @ PS injection

- The PS operated with a known mismatched dispersion between PSB – PS in Run 2.
- Dispersion mismatch @ PS injection is expected to be a major contributor to the observed emittance blow-up in 2016 – 2018 measurements.
- MD efforts ongoing to study benefits of re-matched (ReM) optics.

SEM Grid Measurement
(F. Roncarolo)




Horizontal beam envelope oscillation as a function of turn – SEM grid measurement

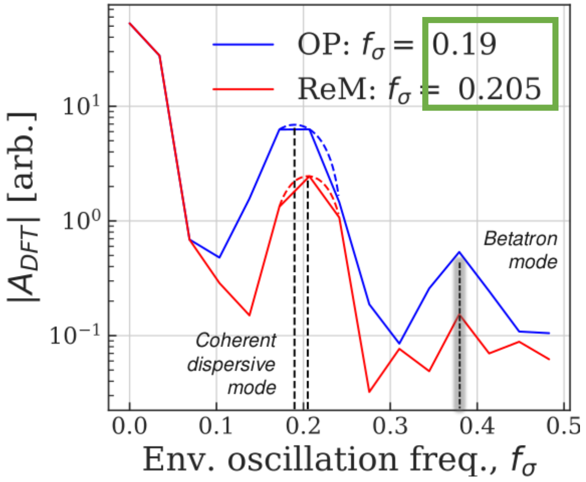
# Dispersion mismatch: envelope oscillation

- Turn-by-turn SEM grid measurements in 2018 show horizontal envelope oscillation dependent on the dispersion mismatch.

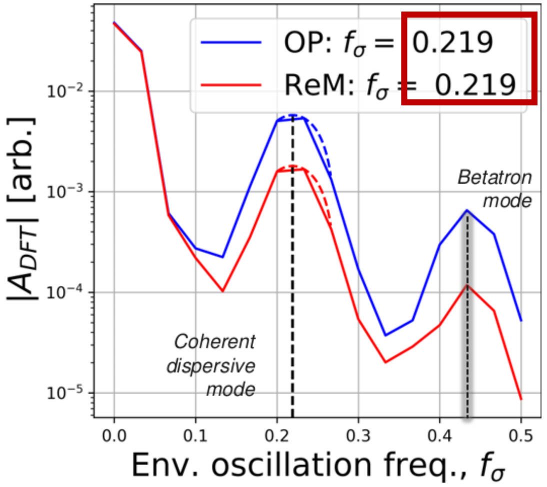
Op = operational optics
ReM = Re-Matched (reduced dispersion mismatch) optics

5D simulations without space charge do not reproduce measurement

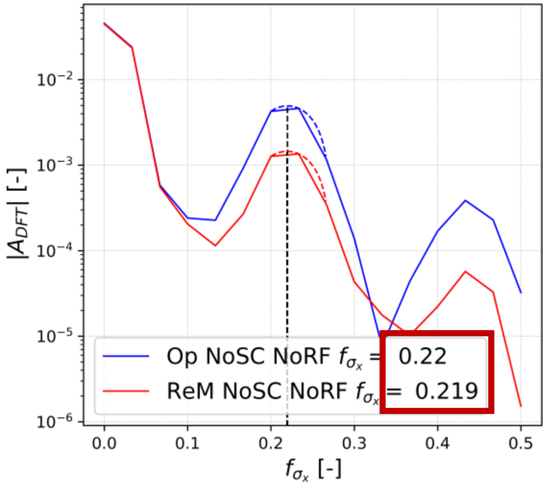
SEM Grid Measurement (M. Fraser)



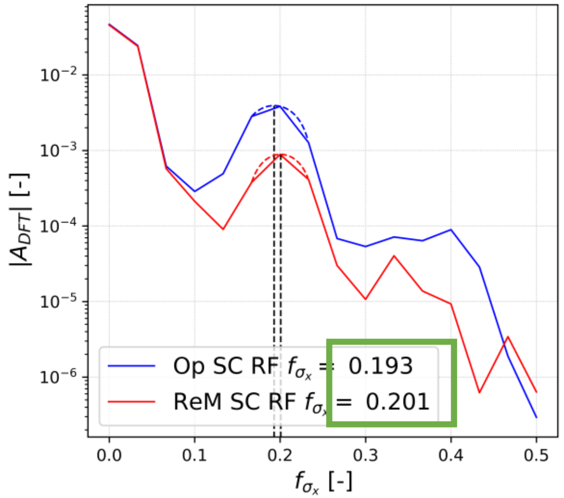

5D No Space Charge simulation (M. Fraser)




PTC-PyORBIT
5D No Space Charge simulation




PTC-PyORBIT
6D Space Charge simulation

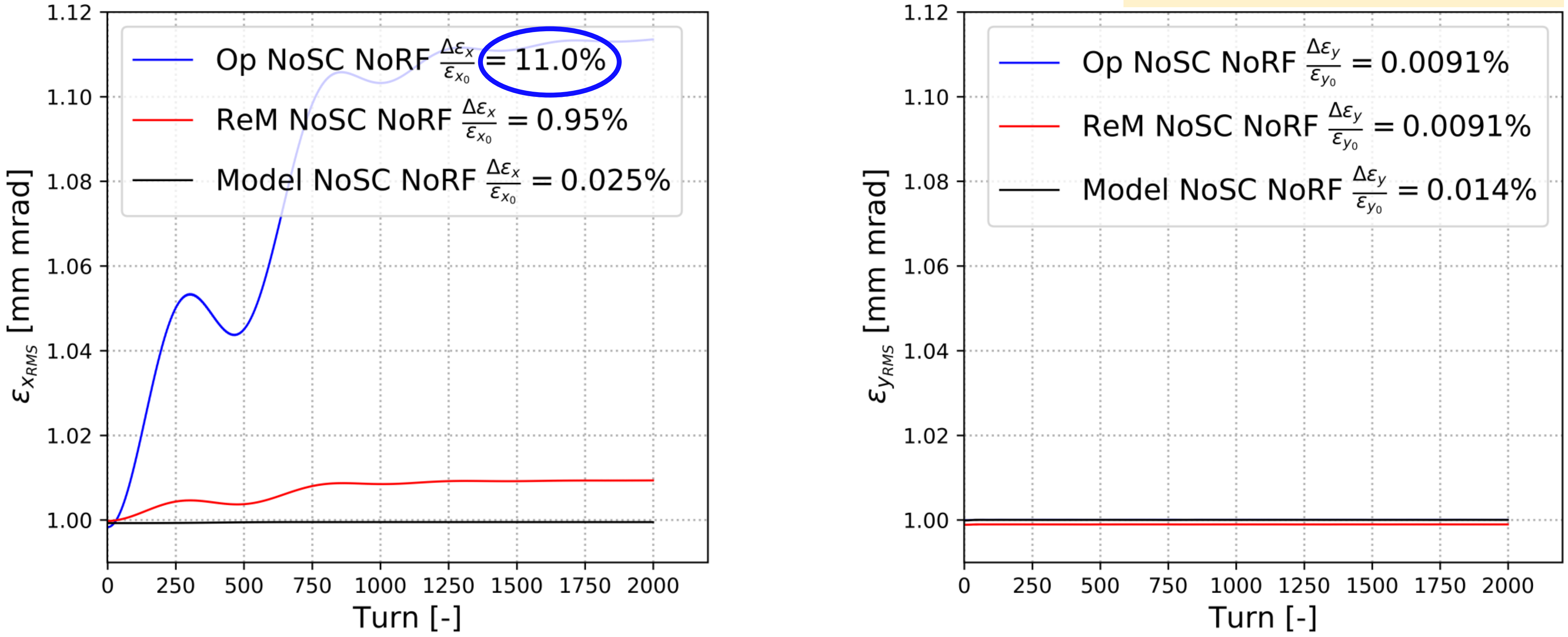



Including space charge is required to reproduce measurements.
Space charge shifts the frequency of (dispersion mismatch generated) horizontal envelope oscillation.

# Emittance blow-up without space charge

- Expected horizontal emittance blow-up from analytic calculation (without space charge) ~ 10%.

Op = operational optics
ReM = Re-Matched (reduced dispersion mismatch) optics

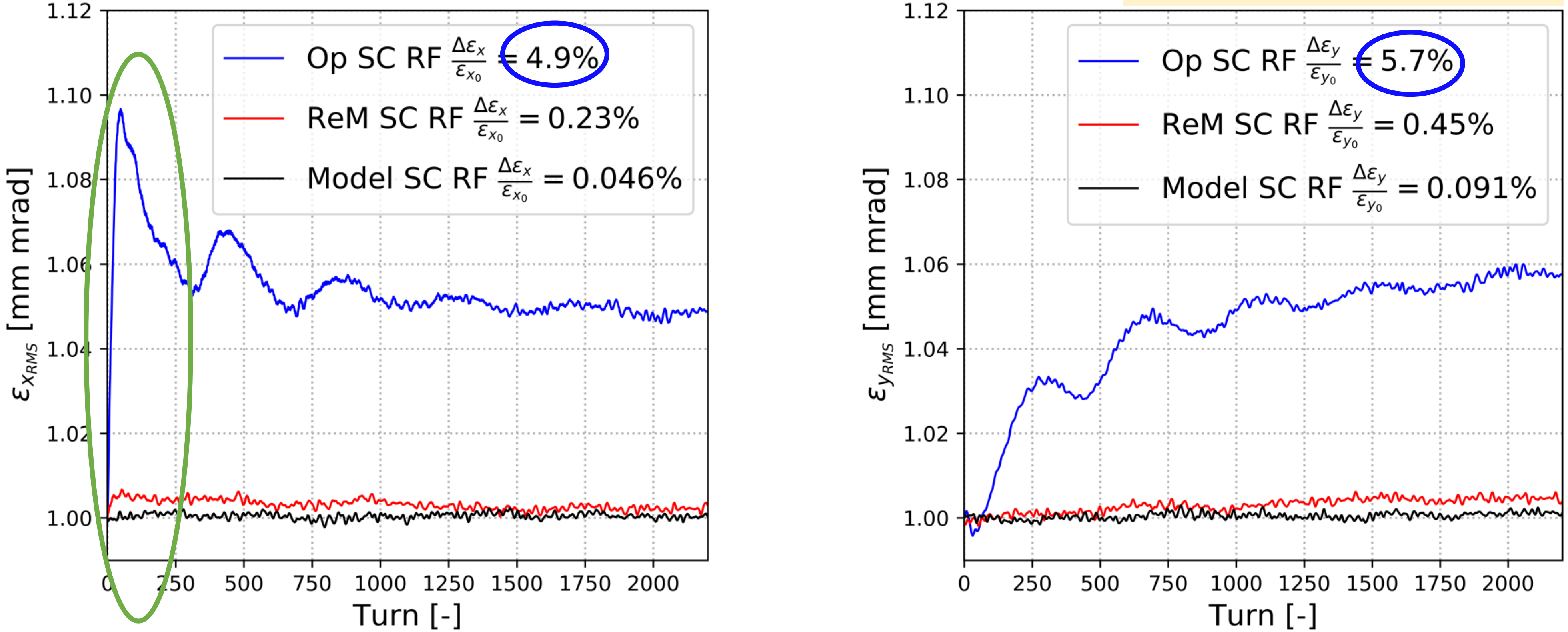



Simulations without space charge show ~ 10% <u>horizontal</u> emittance growth from dispersion mismatch alone.

# Emittance blow-up with space charge

- How does space charge influence the emittance evolution?

Op = operational optics
ReM = Re-Matched (reduced dispersion mismatch) optics




Much faster initial horizontal blow-up to 10% (peaks at 50 turns ~ 0.11 ms).
The emittance growth is shared in the transverse planes via the Montague coupling resonance.
Simulations with space charge show ~ 10% <u>total</u> emittance growth from dispersion mismatch.
**<u>No additional blow-up due to space charge.</u>**

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# Twice brightness: space charge mitigation

- Increased injection energy and longitudinal parameters to mitigate space charge for twice bright LIU beams.
- Analytic calculations of space charge tune spread have been used to define LIU bunch parameters.
- Use model to check analytic with simulated tune spreads.
- First compare operational Run 2 scenarios (labelled Achieved in the table).

| **PS** (Standard: 4b+2b – BCMS: 2× 4b) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $N$ ($10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $E$ (GeV) | $\epsilon_z$ (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) |

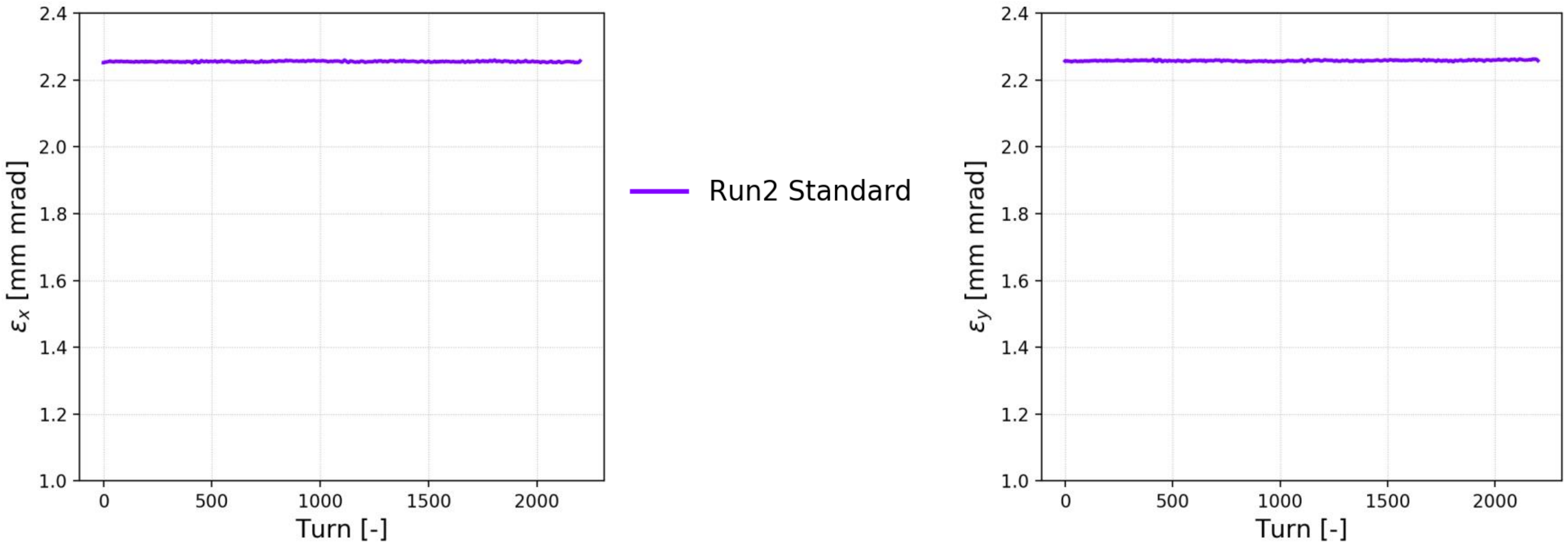
Run 2 and LIU PS beam parameters for LHC-type beams https://edms.cern.ch/ui/file/1296306/2/LIU-table-protons_v3.pdf

# Run 2 Standard

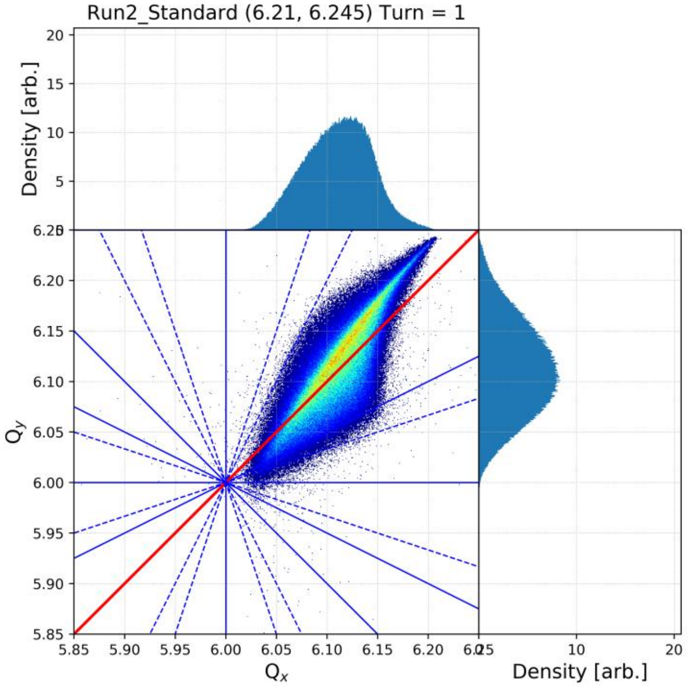
| **PS** (Standard: 4b+2b – BCMS: 2× 4b) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $N$ $(10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $E$ (GeV) | $\epsilon_z$ (eVs/b) | $B_l$ (ns) | $\delta p/p_0$ $(10^{-3})$ | $\Delta Q_{x,y}$ |
| Achieved | Standard | 16.84 | 2.25 | 1.4 | 1.2 | 180 | 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) |

$(\Delta Q_x, \Delta Q_y)_{\text{simulation}}$

**(0.18, 0.24)**




No space charge emittance growth.



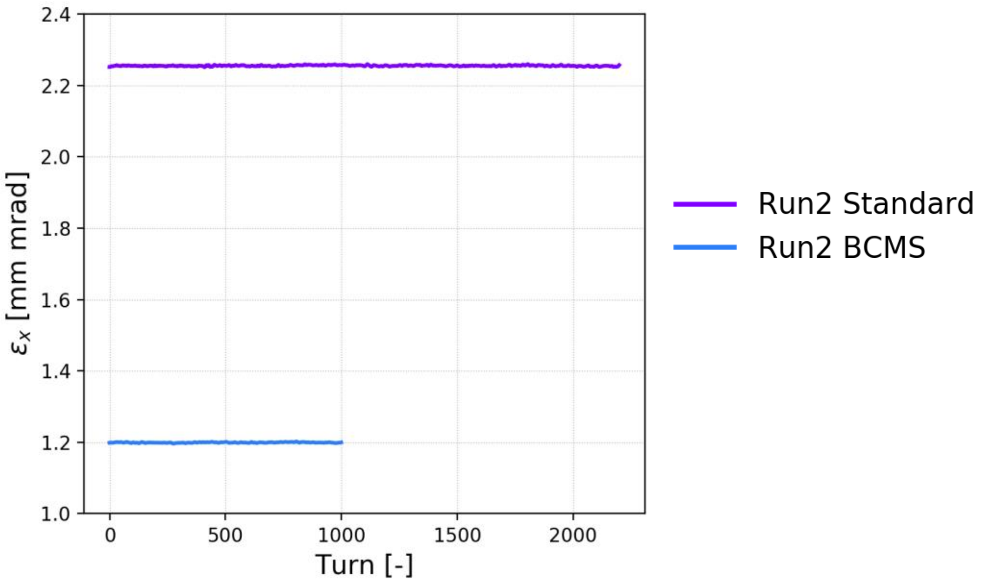

Tune spread from PTC-PyORBIT simulation using parameters shown

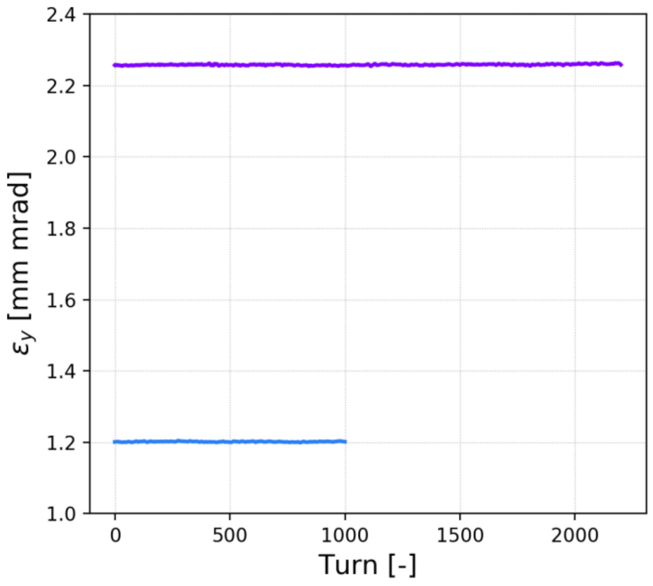
# Run 2 BCMS

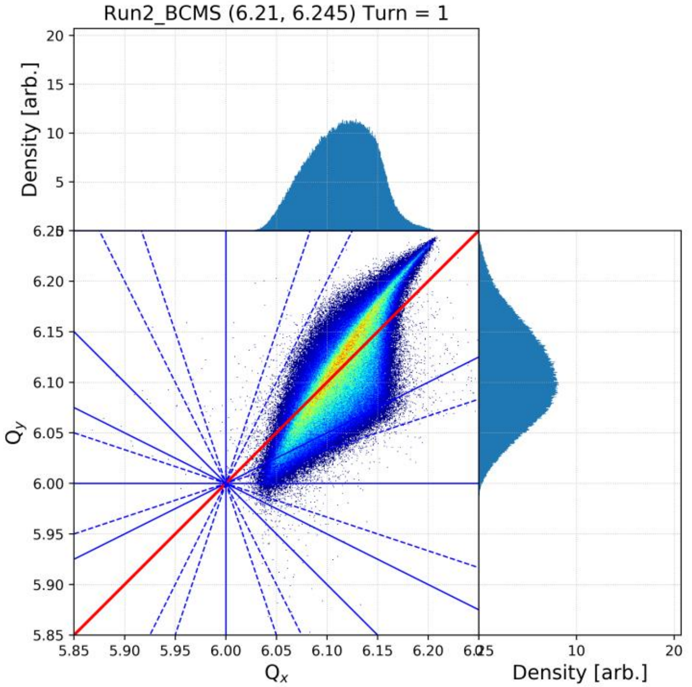
| | | **PS** (Standard: 4b+2b – BCMS: 2× 4b) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $N$ $(10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $E$ (GeV) | $\epsilon_z$ (eVs/b) | $B_l$ (ns) | $\delta p/p_0$ $(10^{-3})$ | $\Delta Q_{x,y}$ |
| Achieved | Standard | 16.84 | 2.25 | 1.4 | 1.2 | 180 | 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) |

$(\Delta Q_x, \Delta Q_y)_{\text{simulation}}$

(0.18, 0.24)
**(0.17, 0.25)**




No space charge emittance growth.

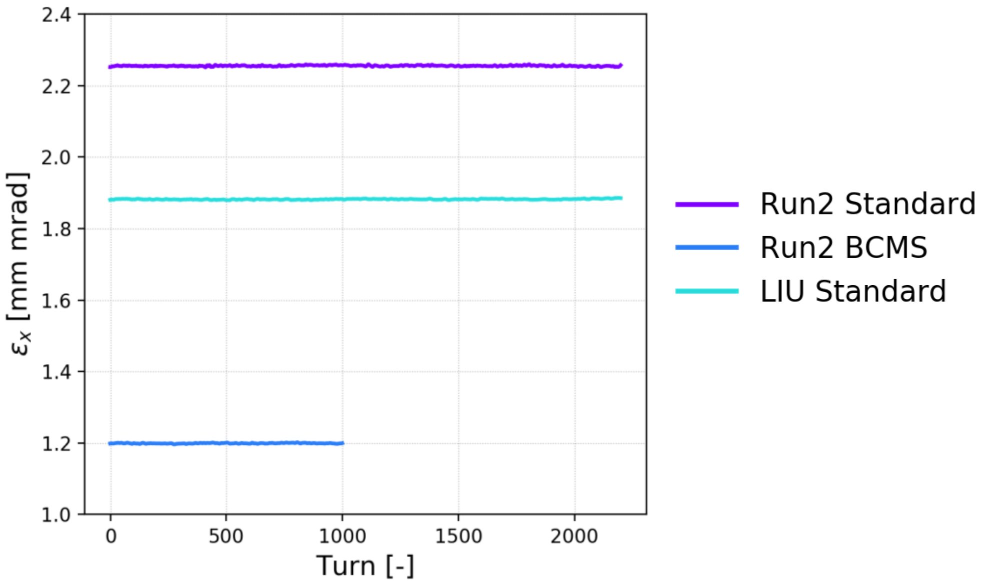
Tune spread from PTC-PyORBIT simulation using parameters shown

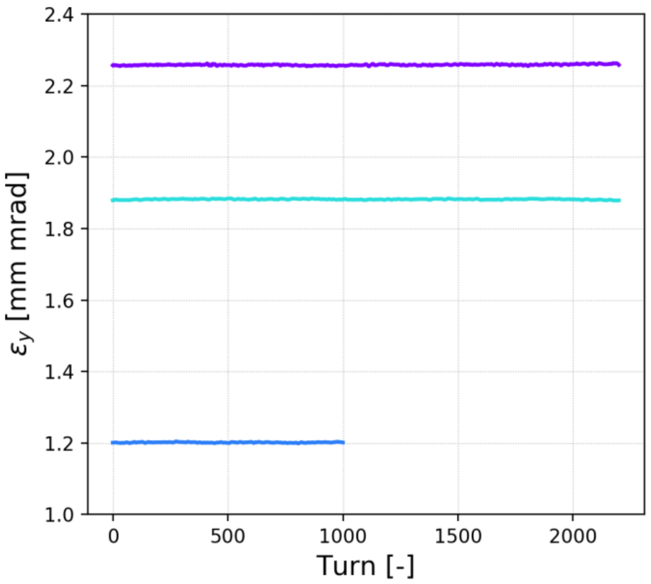
# LIU Standard

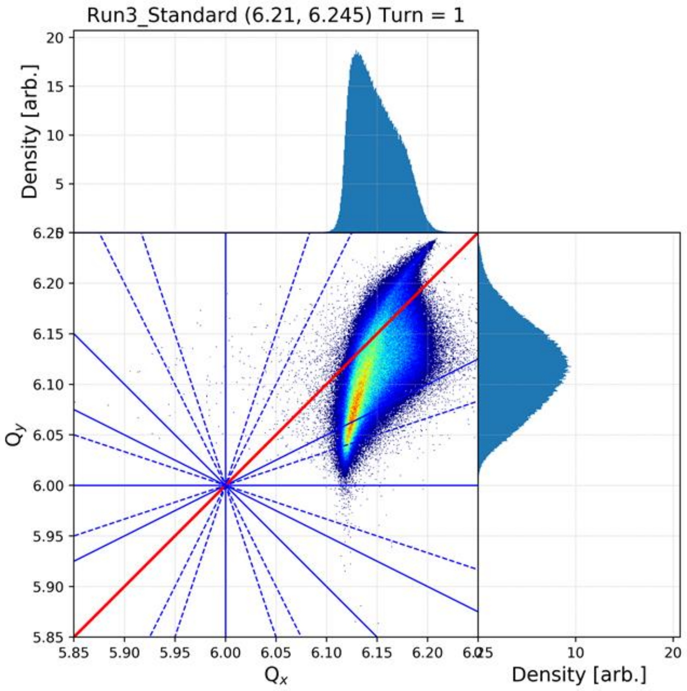
| | | PS (Standard: 4b+2b – BCMS: 2× 4b) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $N$ ($10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $E$ (GeV) | $\epsilon_z$ (eVs/b) | $B_l$ (ns) | $\delta p/p_0$ ($10^{-3}$) | $\Delta Q_{x,y}$ |
| Achieved | Standard | 16.84 | 2.25 | 1.4 | 1.2 | 180 | 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) |

$(\Delta Q_x, \Delta Q_y)_{simulation}$

(0.18, 0.24)
(0.17, 0.25)
**(0.10, 0.23)**



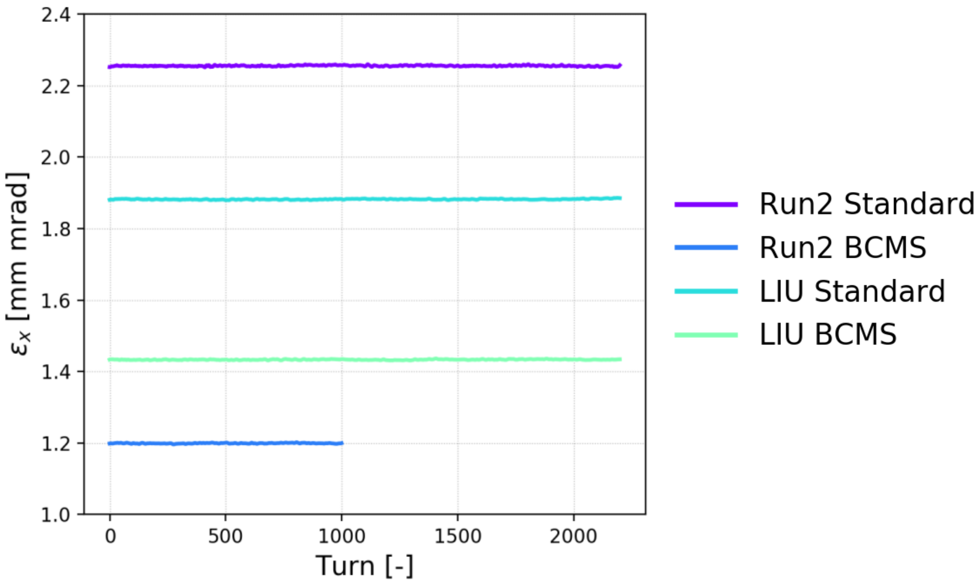



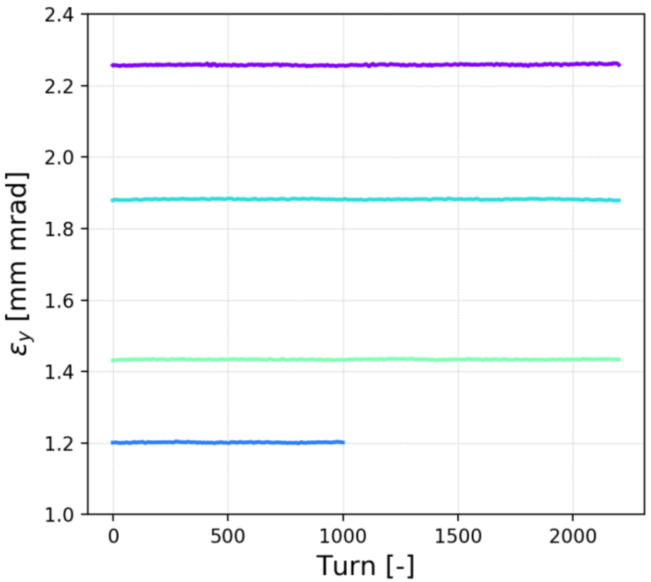

No space charge emittance growth.

Tune spread from PTC-PyORBIT simulation using parameters shown

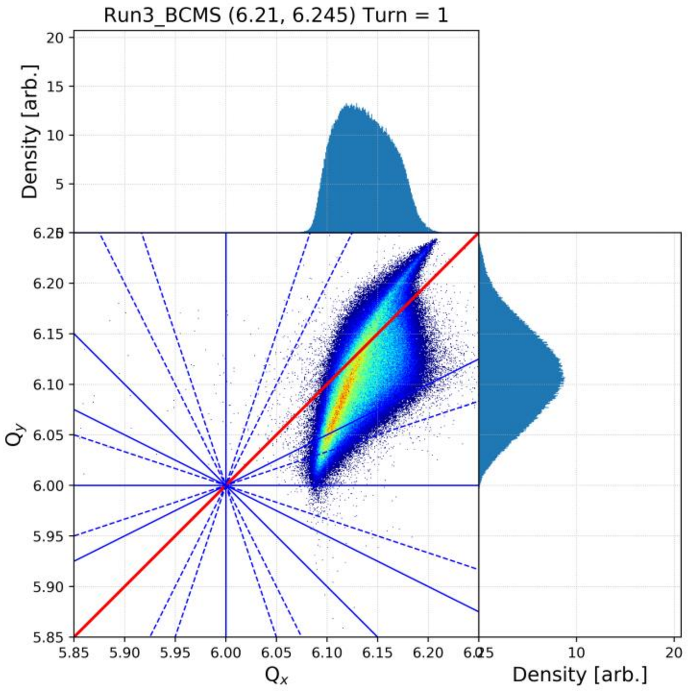
# LIU BCMS

| PS (Standard: 4b+2b – BCMS: 2× 4b) | | | | | | | | | $(\Delta Q_x, \Delta Q_y)_{\text{simulation}}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | $N$ ($10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $E$ (GeV) | $\epsilon_z$ (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) | (0.18, 0.24) |
| | BCMS | 8.05 | 1.20 | 1.4 | 0.9 | 150 | 0.8 | (0.24, 0.31) | (0.17, 0.25) |
| LIU target | Standard | 32.50 | 1.80 | 2.0 | 3.00 | 205 | 1.5 | (0.18, 0.30) | (0.10, 0.23) |
| | BCMS | 16.25 | 1.43 | 2.0 | 1.48 | 135 | 1.1 | (0.20, 0.31) | **(0.13, 0.24)** |




No space charge emittance growth.




Tune spread from PTC-PyORBIT simulation using parameters shown

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# Brightness Ramp-Up

- LIU aims to use large longitudinal emittance bunches as a remedy for space charge tune spread at injection.
- Steady brightness ramp-up in the PS defined by evolution of longitudinal parameters at PS injection to increase performance in stages as proposed in the LIU Montreux workshop 2020 [link].

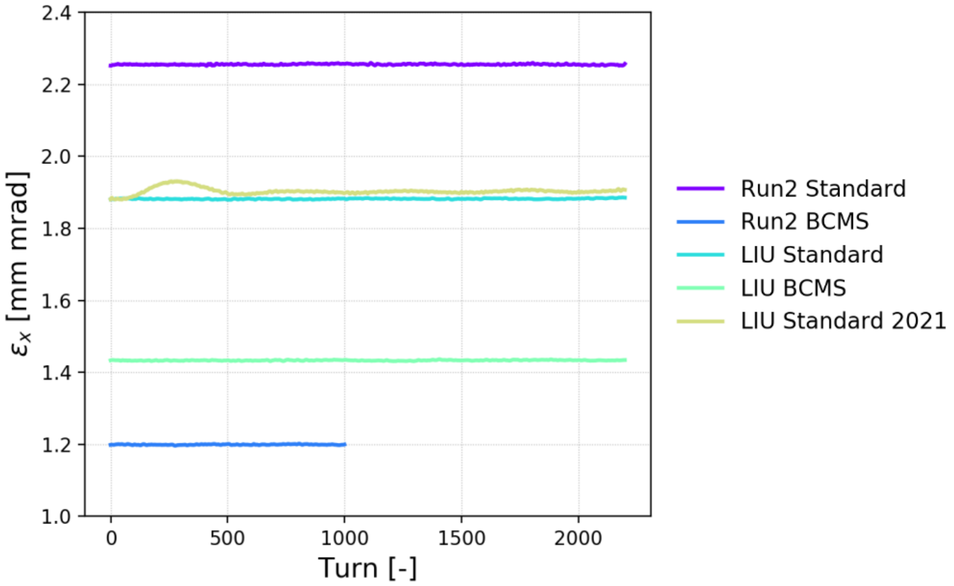
| Scenario | Case | N $\left(10^{11}\frac{p}{b}\right)$ | $\epsilon_{x,y}$ $(\mu m)$ | E $(GeV)$ | $\epsilon_z$ $\left(\frac{eVs}{b}\right)$ | $B_l$ $(ns)$ | $\frac{\delta p}{p_0}$ $(10^{-3})$ |
|---|---|---|---|---|---|---|---|
| Run2 | Std | 16.84 | 2.25 | 1.4 | 1.01 | 180 | 0.9 |
| Run2 | BCMS | 8.05 | 1.20 | 1.4 | 0.72 | 150 | 0.8 |
| LIU | Std | 32.5 | 1.80 | 2.0 | 3.00 | 205 | 1.5 |
| LIU | BCMS | 16.25 | 1.43 | 2.0 | 1.48 | 135 | 1.1 |
| LIU | Std | | | | | | |
| | 2021 | 32.5 | 1.88 | 2.0 | 1.50 | 135 | 1.1 |
| | 2022 | 32.5 | 1.88 | 2.0 | 2.25 | 170 | 1.3 |
| | 2023 | 32.5 | 1.88 | 2.0 | 3.00 | 205 | 1.5 |

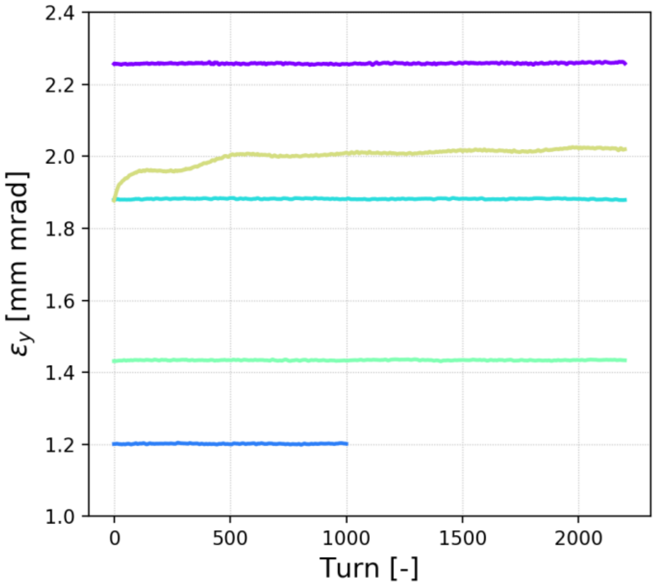
# LIU Standard brightness ramp-up: 2021

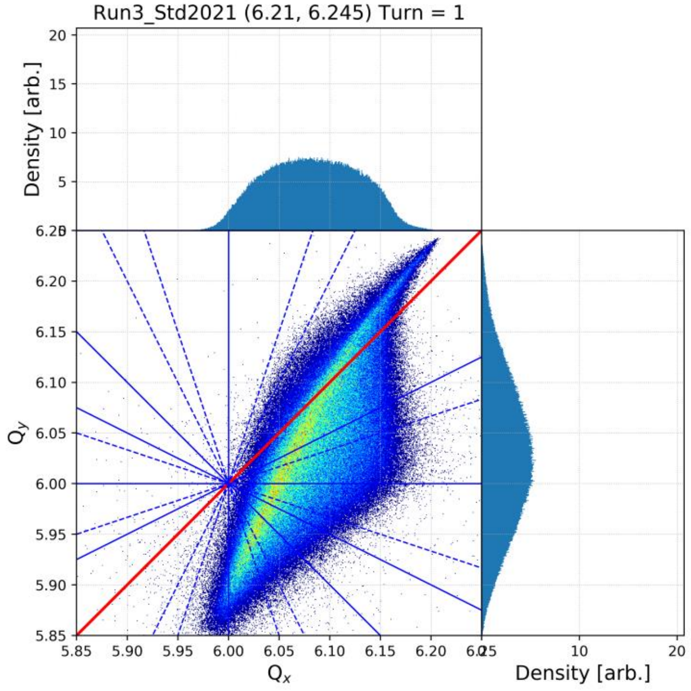
| Scenario | Case | N | $\epsilon_{x,y}$ | E | $\epsilon_z$ | $B_l$ | $\frac{\delta p}{p_0}$ |
|---|---|---|---|---|---|---|---|
| | | $(10^{11}\frac{p}{b})$ | $(\mu m)$ | $(GeV)$ | $(\frac{eVs}{b})$ | $(ns)$ | $(10^{-3})$ |
| LIU | Std | | | | | | |
| | 2021 | 32.5 | 1.88 | 2.0 | 1.50 | 135 | 1.1 |
| | 2022 | 32.5 | 1.88 | 2.0 | 2.25 | 170 | 1.3 |
| | 2023 | 32.5 | 1.88 | 2.0 | 3.00 | 205 | 1.5 |

$(\Delta Q_x, \Delta Q_y)_{simulation}$

**(0.24, 0.37)**




**Large tune spread crossing the integer tune causes emittance growth.**
**1.2% horizontal, 7.6% vertical** growth in 2200 turns ~ 5 ms (Run 2), 4.85 ms (LIU).

Tune spread from PTC-PyORBIT simulation using parameters shown

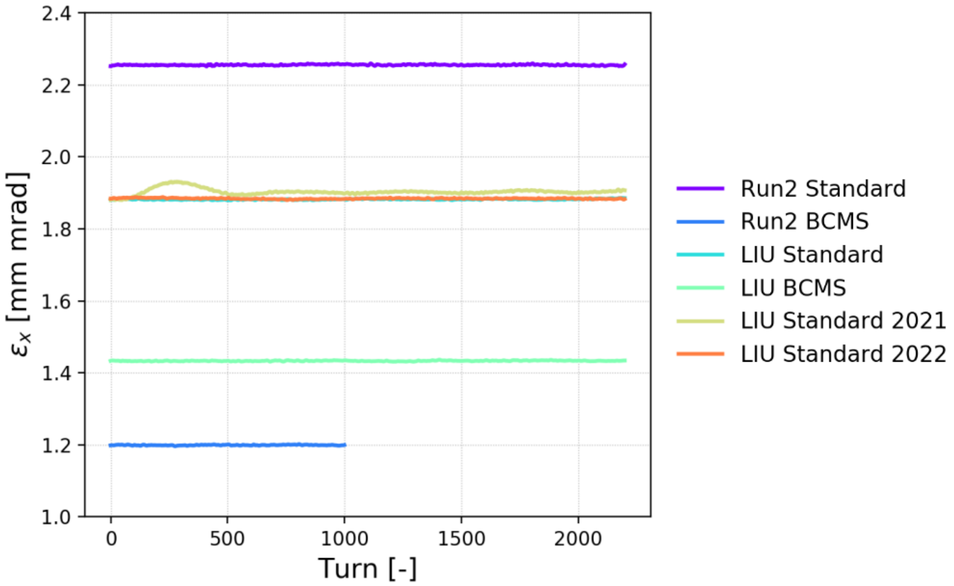
# LIU Standard brightness ramp-up: 2022

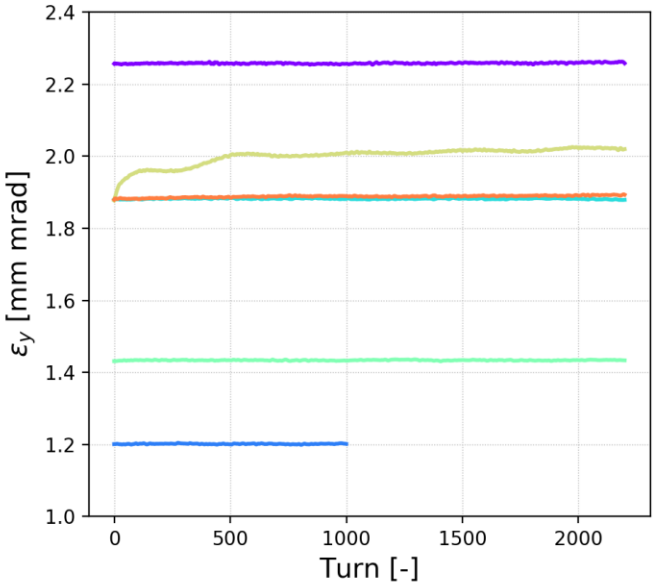
| Scenario | Case | N $(10^{11}\frac{p}{b})$ | $\epsilon_{x,y}$ $(\mu m)$ | E $(GeV)$ | $\epsilon_z$ $(\frac{eVs}{b})$ | $B_l$ $(ns)$ | $\frac{\delta p}{p_0}$ $(10^{-3})$ |
|---|---|---|---|---|---|---|---|
| LIU | Std | | | | | | |
| | 2021 | 32.5 | 1.88 | 2.0 | 1.50 | 135 | 1.1 |
| | 2022 | 32.5 | 1.88 | 2.0 | 2.25 | 170 | 1.3 |
| | 2023 | 32.5 | 1.88 | 2.0 | 3.00 | 205 | 1.5 |

$(\Delta Q_x, \Delta Q_y)_{simulation}$

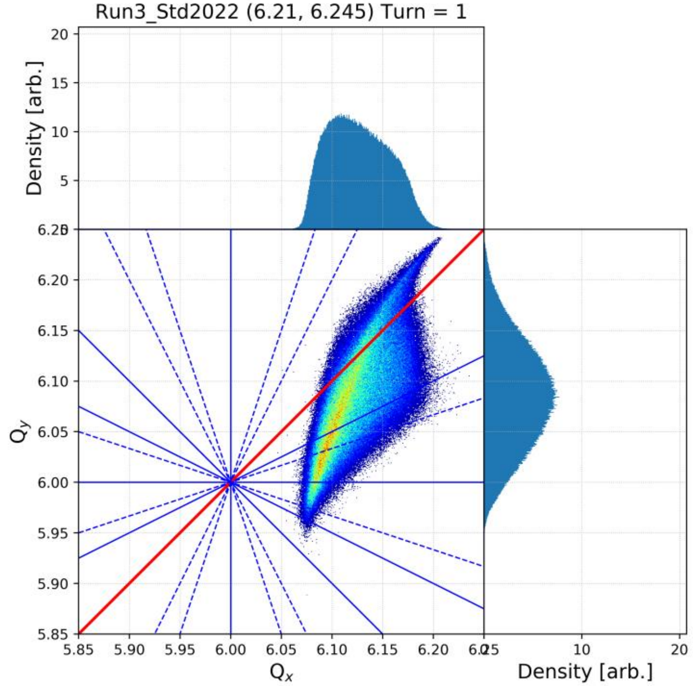
(0.24, 0.37)

**(0.14, 0.28)**




No space charge emittance growth.



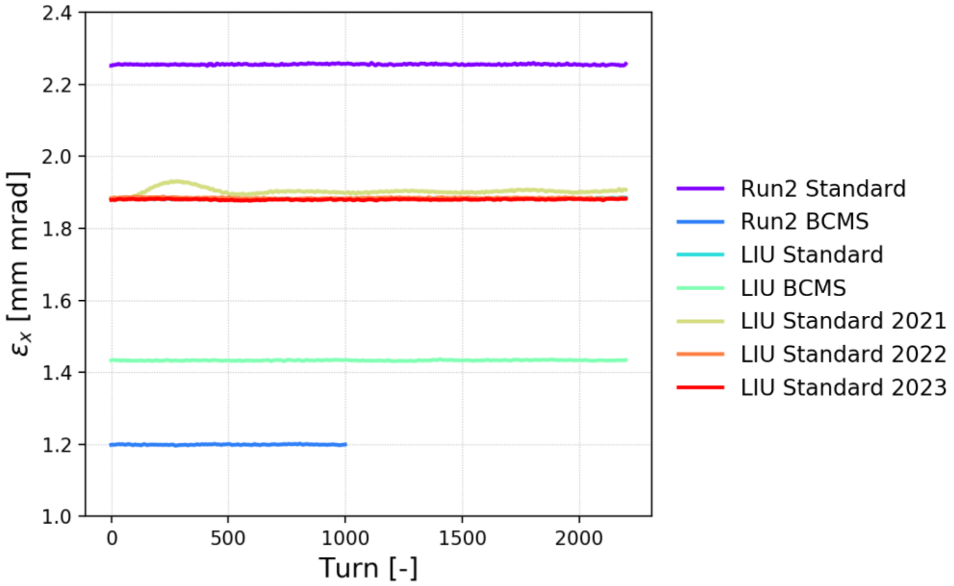

Tune spread from PTC-PyORBIT simulation using parameters shown

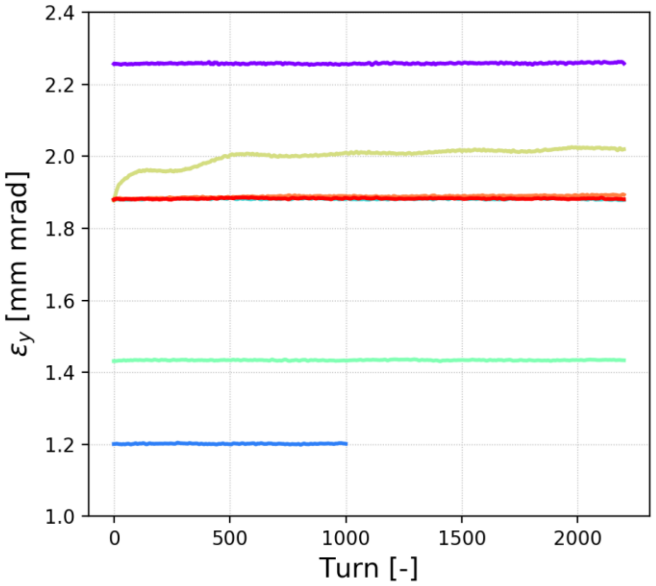
# LIU Standard brightness ramp-up: 2023

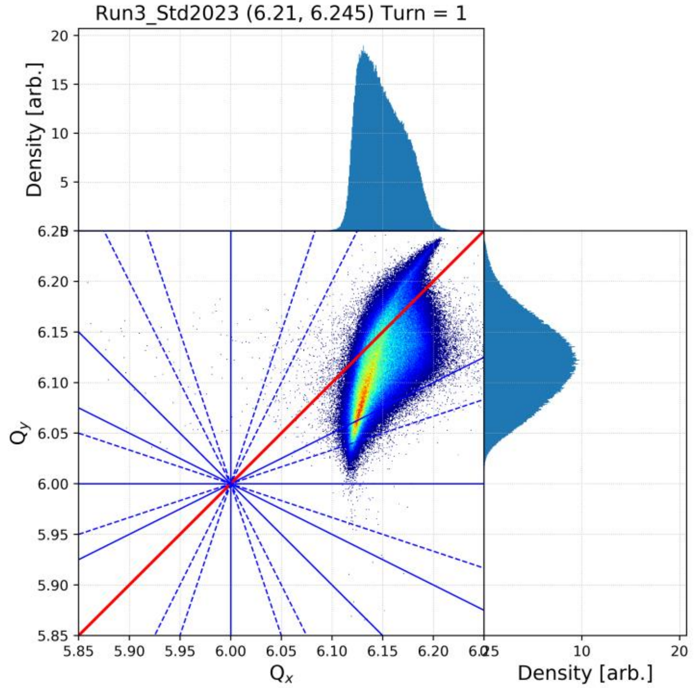
| Scenario | Case | N | $\epsilon_{x,y}$ | E | $\epsilon_z$ | $B_l$ | $\frac{\delta p}{p_0}$ |
|---|---|---|---|---|---|---|---|
| | | $(10^{11}\frac{p}{b})$ | $(\mu m)$ | $(GeV)$ | $(\frac{eVs}{b})$ | $(ns)$ | $(10^{-3})$ |
| LIU | Std | | | | | | |
| | 2021 | 32.5 | 1.88 | 2.0 | 1.50 | 135 | 1.1 |
| | 2022 | 32.5 | 1.88 | 2.0 | 2.25 | 170 | 1.3 |
| | 2023 | 32.5 | 1.88 | 2.0 | 3.00 | 205 | 1.5 |

$(\Delta Q_x, \Delta Q_y)_{simulation}$

(0.24, 0.37)
(0.14, 0.28)
**(0.10, 0.23)**




No space charge emittance growth.

Tune spread from PTC-PyORBIT simulation using parameters shown

# Tune spread confirmation

| Scenario | Case | N $(10^{11}\frac{p}{b})$ | $\epsilon_{x,y}$ $(\mu m)$ | E $(GeV)$ | $\epsilon_z$ $(\frac{eVs}{b})$ | $B_l$ $(ns)$ | $\frac{\delta p}{p_0}$ $(10^{-3})$ | $\Delta Q_{x,y}$ Simulation | $\Delta Q_{x,y}$ Analytic |
|---|---|---|---|---|---|---|---|---|---|
| Run2 | Std | 16.84 | 2.25 | 1.4 | 1.01 | 180 | 0.9 | (.18, .24) | (.25, .30) |
| Run2 | BCMS | 8.05 | 1.20 | 1.4 | 0.72 | 150 | 0.8 | (.17, .25) | (.24, .31) |
| LIU | Std | 32.5 | 1.80 | 2.0 | 3.00 | 205 | 1.5 | (.10, .23) | (.18, .30) |
| LIU | BCMS | 16.25 | 1.43 | 2.0 | 1.48 | 135 | 1.1 | (.13, .24) | (.20, .31) |
| LIU | Std | | | | | | | | |
| | 2021 | 32.5 | 1.88 | 2.0 | 1.50 | 135 | 1.1 | (.24, .37) | |
| | 2022 | 32.5 | 1.88 | 2.0 | 2.25 | 170 | 1.3 | (.14, .28) | |
| | 2023 | 32.5 | 1.88 | 2.0 | 3.00 | 205 | 1.5 | (.10, .23) | |

**Table:** PS LIU tune spread at injection: parameters and results using simulation data.

Comparing simulation values with analytic:

- **Preservation of tune spreads for double brightness** with LIU parameters as expected.
- Simulations indicate the tune spread in both planes is slightly smaller than the analytical expectation.
- **Fast emittance blow-up only expected for LIU Standard 2021** parameters due to large space charge tune spread (long-term flat bottom effects are out of capabilities of simulation model due to numerical noise).

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# Conclusions & Outlook

- **Benchmarked PS injection model with space charge** against measurements – required for greater understanding of bunch behaviour at PS injection.
- Demonstrated that **use of the low energy quadrupoles in the PS induces (beta-beating via) a quadrupolar half-integer resonance** (at the integer tune) as the 40 low energy quadrupoles break the periodicity of the PS lattice.
- Showed **overall emittance blow-up from measured dispersion mismatch at injection is unchanged when including space charge** (however emittance blow-up can be shared between two transverse planes due to Montague coupling resonance). No additional blow-up due to space charge when considering the dispersion mismatch.
- **Confirmed space charge tune spreads** for Run 2, and expected tune spreads for the double brightness of LIU beams. Results consistent with proposed brightness ramp-up.
- **Outlook:** Space charge simulations to understand interplay of longitudinal emittance with dispersion mismatch and space charge at injection (comparison with measurements in 2017 [link]).

# Acknowledgements

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

- **H. Bartosik, M. Fraser, A. Huschauer:** Leadership & guidance.
- **F. Asvesta, M. Kaitatzi:** MD/simulation assistance & discussions.
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- **E. Senes, P. Zisopoulos:** Injection bump tune swing measurements and initial work.
- **CERN IT-CM:** HPC-Batch, AFS, & LXPlus support.
- **G. Sterbini:** MD Analysis SWAN Toolbox.

- **You:** for your time and attention.

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