Optics Control in the CERN Proton Sychrotron

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Many thanks to the members of the OMC team and the PS operators

Pole Face Windings settings generation & control

Zero dispersion optics

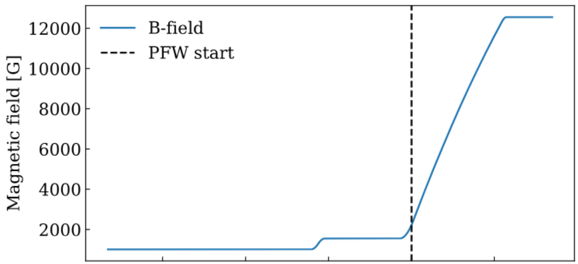
Resonance Driving Terms

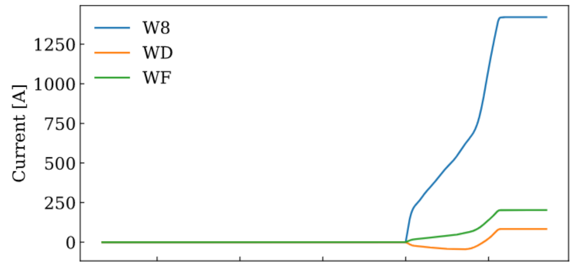
Pole Face Windings settings generation & control

The current settings generation and control of the PFW

Settings generation → Empirical basic functions

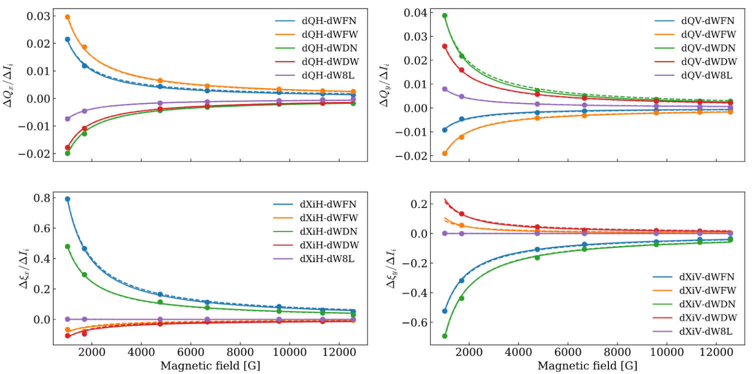
- Fitted vs the main field using polynomials functions
- Optimised for transition crossing and working point at extraction
- **Only defined when the main field exceed 2.215 GeV**





Control → empirical response matrices

- Measurements were done at different energy plateaus
- Results in a operational B-field dependent 4x5 matrix
- Performs well for tune control but not for chroma control



Goal

Make a new mapping **F** between tunes & chromas and the PFW currents that can generate settings at all energies and allows for both tune & chroma control.

- This is a suitable candidate for regression with an **Articfical Neural Network**.

$$\mathbf{F}\begin{pmatrix} B \\ Q_x \\ Q_y \\ \xi_x \\ \xi_y \end{pmatrix} = \begin{pmatrix} I_{DN} \\ I_{FN} \\ I_{DW} \\ I_{FW} \\ I_{8L} \end{pmatrix}$$

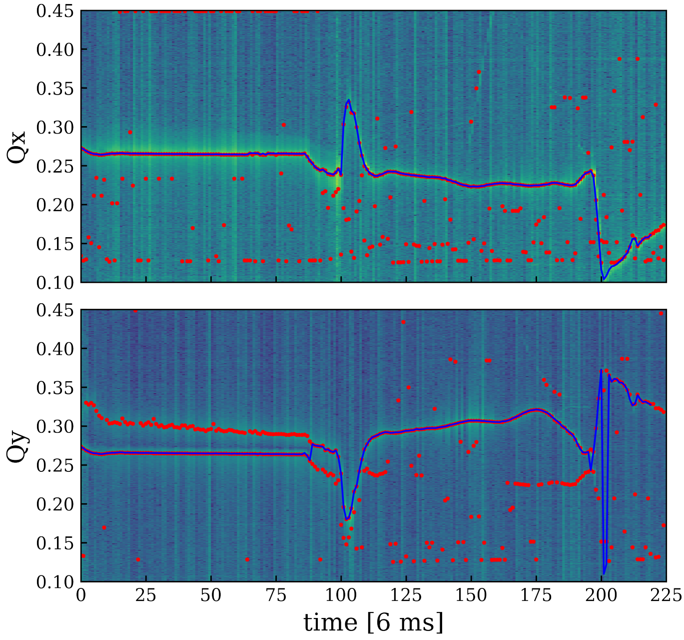
$$F^{inv}\begin{pmatrix} B \\ \frac{\delta p}{p} \\ I_{DN} \\ I_{FN} \\ I_{DW} \\ I_{FW} \\ I_{8L} \end{pmatrix} = \begin{pmatrix} Q_x \\ Q_y \\ \xi_x \\ \xi_y \end{pmatrix}$$

This is a difficult network to develop and perform tests on $\rightarrow$ a inverted network F^{inv} is developed first.

- The PFW currents are set in the machine and the tunes are measured
- The output of the network are physical concepts in tunes and chroma's instead of the abstract PFW currents
- If this inverted network succeeds in predicting the tunes and chromas, the initial network should logically succeed as well

Notable progressions

Tune cleaning Loss function Data acquisition F_0^{rev}



- Based on the **raw BBQ data**
- FFT analysis detects **multiple peaks** and selects which peak is used based on nearby neighbours
- If tunes are still similar, measurement is removed

Notable progressions

Tune cleaning | **Loss function** | Data acquisition | F_0^{rev}

A **physics based loss function** is used by the neural network

$$L = \sqrt{\left[Q_{x;meas} - (Q_{x;\beta} + \frac{dp}{p}\xi_x + \frac{dp}{p}^2 \xi_x')\right]^2 + \left[Q_{y;meas} - (Q_{y;\beta} + \frac{dp}{p}\xi_y + \frac{dp}{p}^2 \xi_y')\right]^2}$$

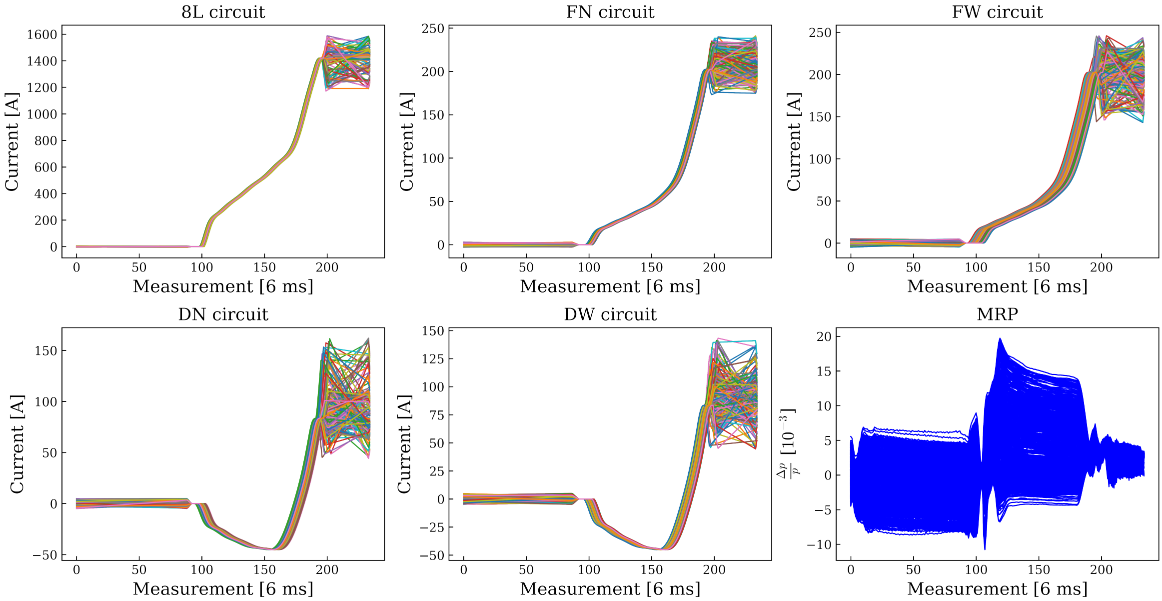
- $\frac{\delta p}{p}$ is no longer and input variable
- No need to analyse the chroma's beforehand
- The network "learns" the physics behind chromaticity

$$F^{inv}\begin{pmatrix} B \\ \frac{\delta p}{p} \\ I_{DN} \\ I_{FN} \\ I_{DW} \\ I_{FW} \\ I_{8L} \end{pmatrix} = \begin{pmatrix} Q_x \\ Q_y \\ \xi_x \\ \xi_y \end{pmatrix} \Rightarrow F^{inv}\begin{pmatrix} B \\ I_{DN} \\ I_{FN} \\ I_{DW} \\ I_{FW} \\ I_{8L} \end{pmatrix} = \begin{pmatrix} Q_x \\ Q_y \\ \xi_x \\ \xi_y \\ \xi_x' \\ \xi_y' \end{pmatrix}$$

Notable progressions

Tune cleaning | Loss function | **Data acquisition** | F_0^{rev}

- Randomly shift the PFW currents to their extreme values that do not induce losses to fully explore the training space
- During the ramp, shift in time instead to not lose the beam during transition



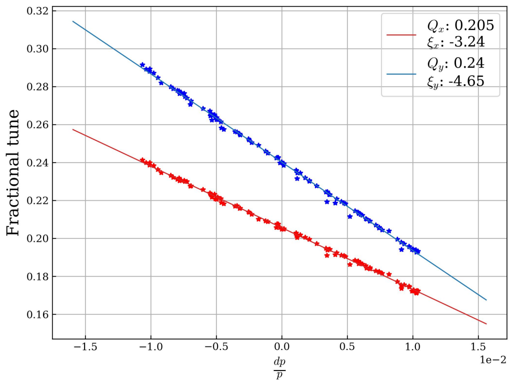
Notable progressions

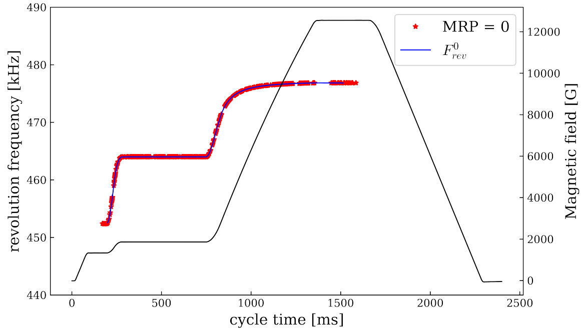
Tune cleaning　　Loss function　　Data acquisition　　F_0^{rev}

- F_0^{rev} is needed for the $\frac{\Delta p}{p}$ calculation:

$$\frac{\Delta p}{p} = \frac{1}{\eta} \frac{\Delta F_{rev}}{F^0_{rev}}$$

- If ill-defined, the final tune will be inconsistent

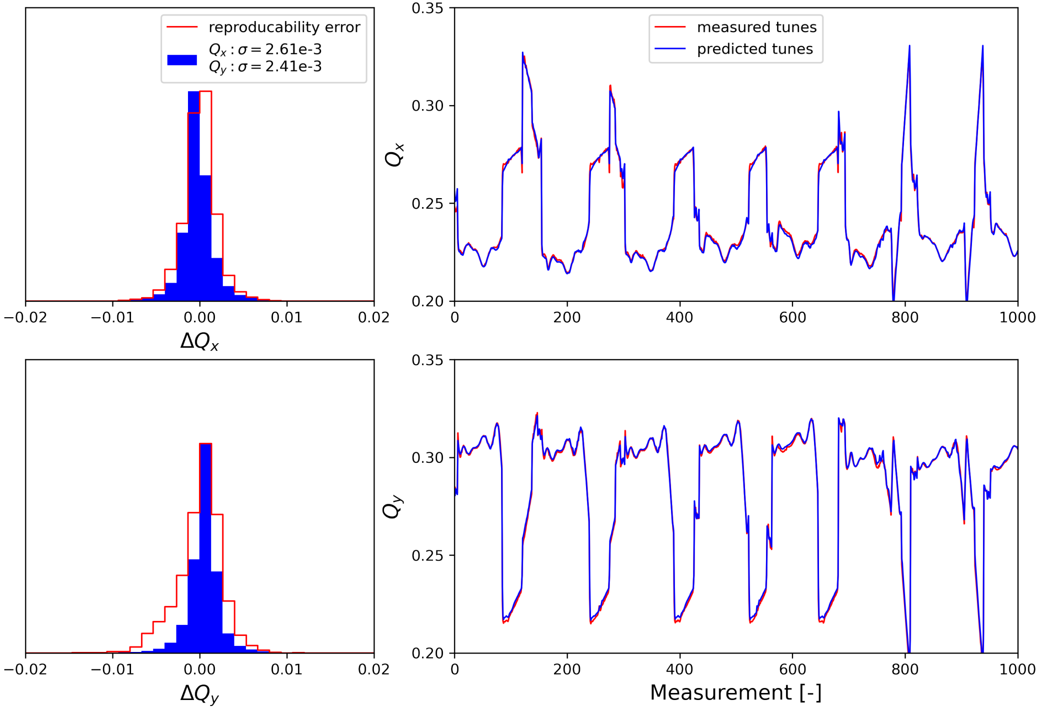




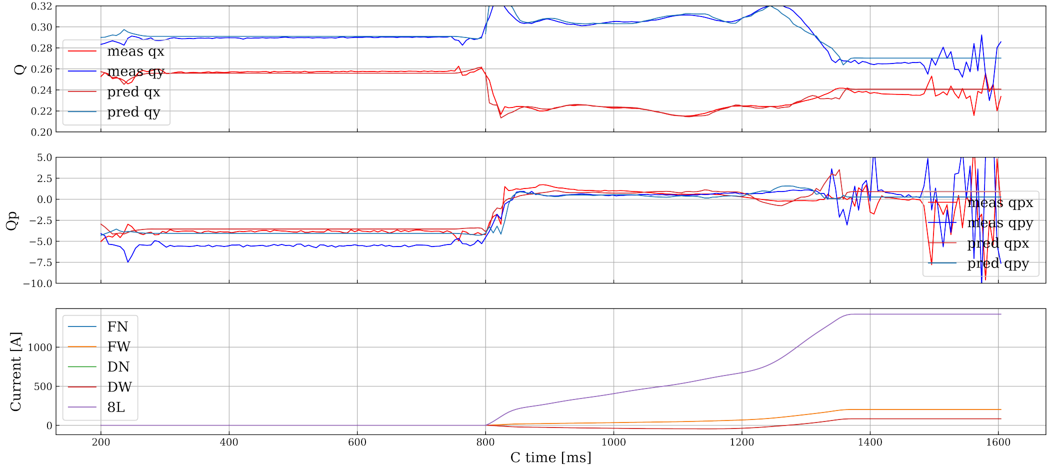
- F_0^{rev} is based on where the **mean radial position is zero**
- Most impactful development for the accuracy of the neural network

F^{inv} network result

Predictions on the training data:



F^{inv} network result



The successful prediction network F^{inv} is used to analyse the tunes and chroma inputs for network F **but there is a problem**:

- PFW current ranges:
  - Low energy: $[-10A, 10A]$ High energy: $[600A, 1800A]$ (8L)

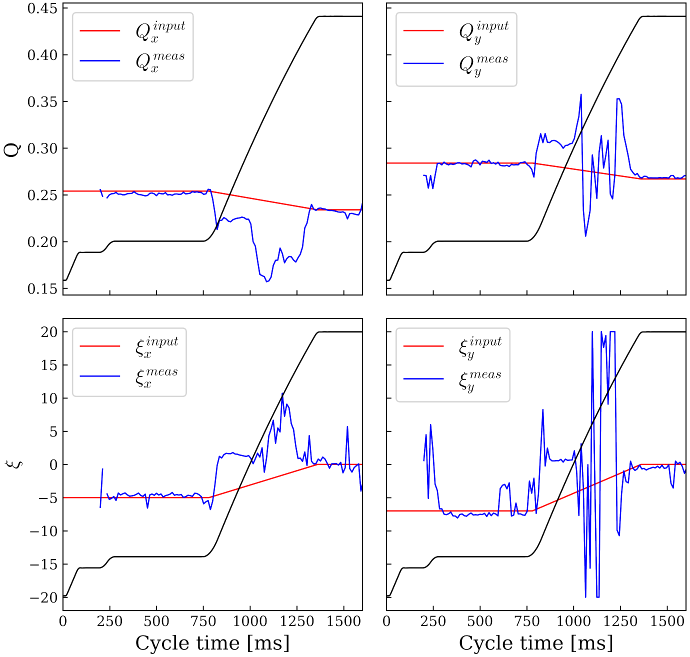
  → Only the high energy section will **hold weight** in training
- Even if beam rigidity is used to normalise the PFW currents, the difference are still too large

⇒ **A Low energy network, below transition, and high energy network, above transition, will be trained separately**

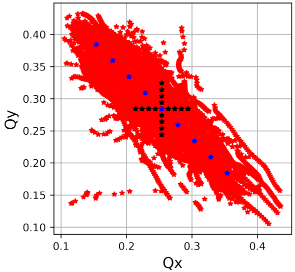
F network result

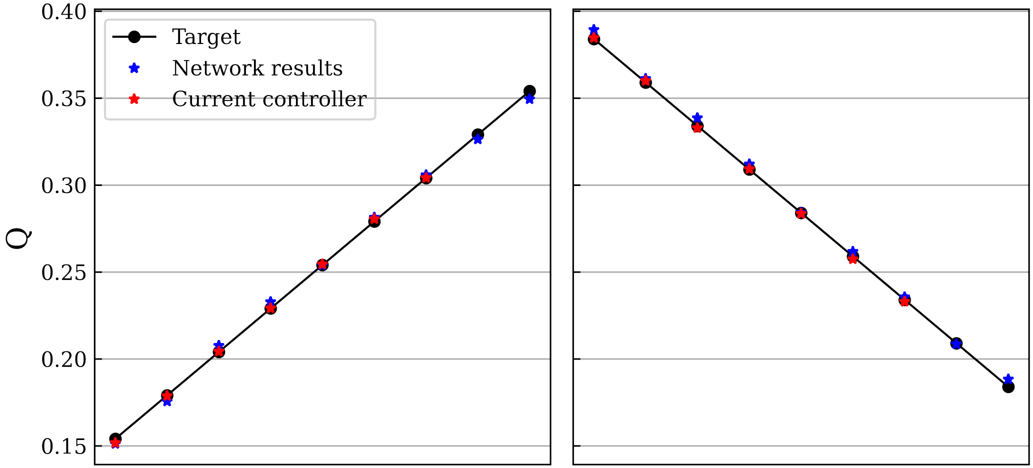
$$\mathbf{F}\begin{pmatrix} B \\ Q_x \\ Q_y \\ \xi_x \\ \xi_y \end{pmatrix} = \begin{pmatrix} I_{DN} \\ I_{FN} \\ I_{DW} \\ I_{FW} \\ I_{8L} \end{pmatrix}$$

- Setting the tunes and chromas performs well **below transition and at flat top**
- The tunes and chromas along the ramp is not set correctly
  - Due to the PFW current ranges
- Compare the performance below transition and at top energy to the current control system



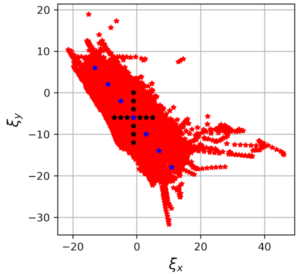
Low energy (Tune)

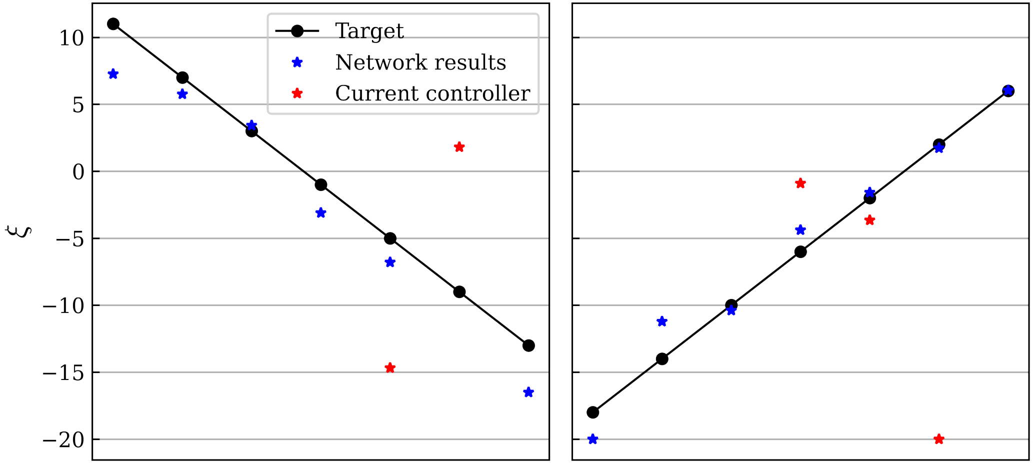




⇒ Network performs very well but not better than current PFW controller

Low energy (Chroma)

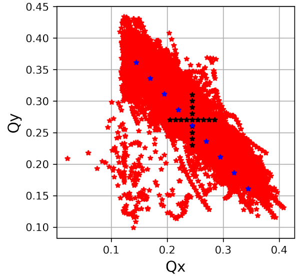


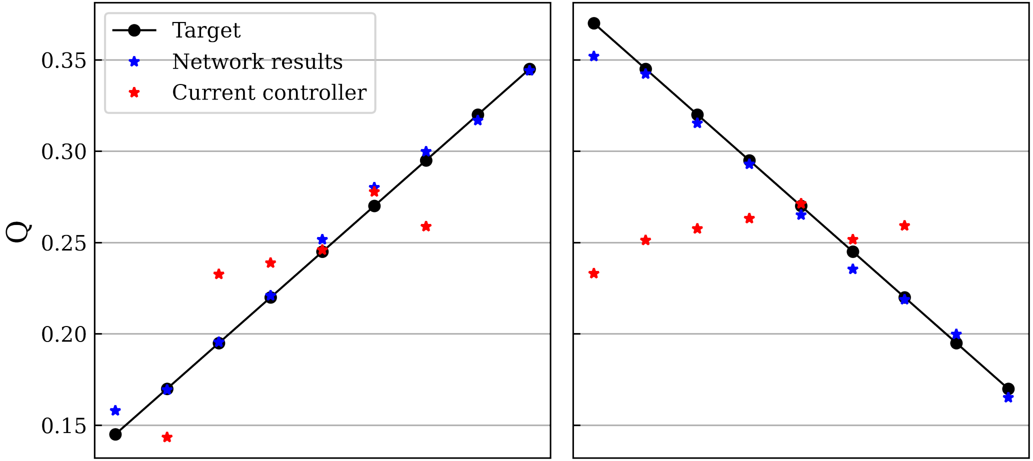


⇒ For chromas, the network performs **a lot better**

- Note: missing data points are due to beam losses or coupled data

High energy (Tune)





⇒ Network performs better for tune control at flat top

Summary PFW controller

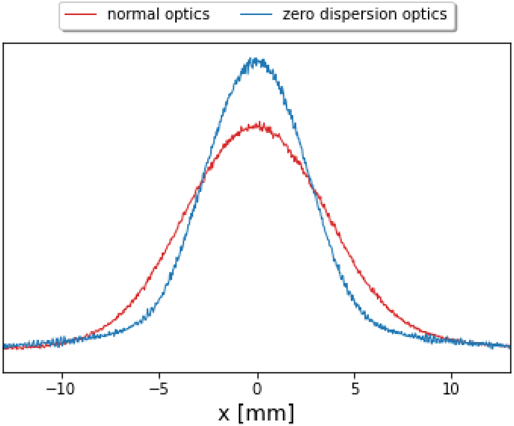
- A prediction network connecting the PFW currents to the PS tunes and chromas was developed
- A lot of good progress has been made in developing a new neural network based PFW control system
- The network performs a lot better for chromaticity at low energy and tune at high energy, while performing good for the tune at low energy
- The network does not yet work over the ramp of beam

Zero dispersion optics

Emittance measurement improvement

Recap

- Emittance measurements in the PS are limited by a dispersive contribution
- Using the LeQs, zero dispersion optics can be achieved at any location
- Significant improvement on the precision and accuracy of the emittance measurements



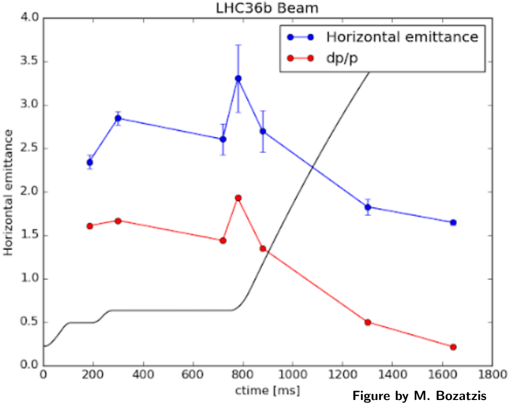
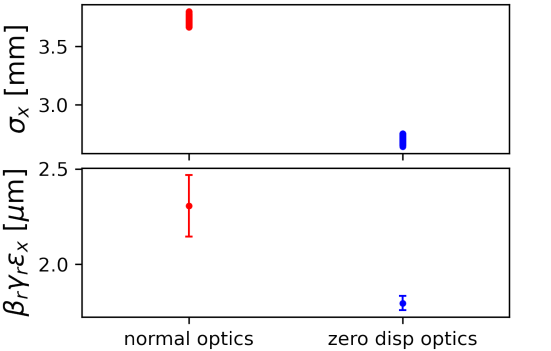
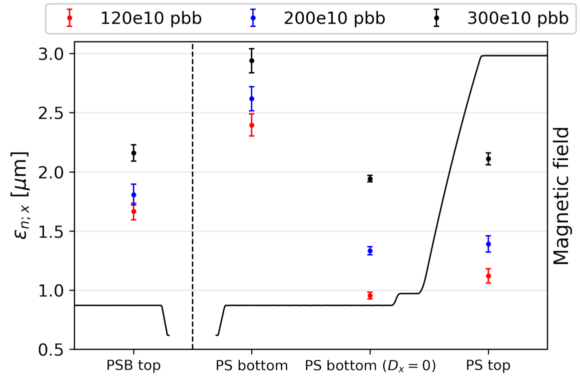


Figure by M. Bozatzis

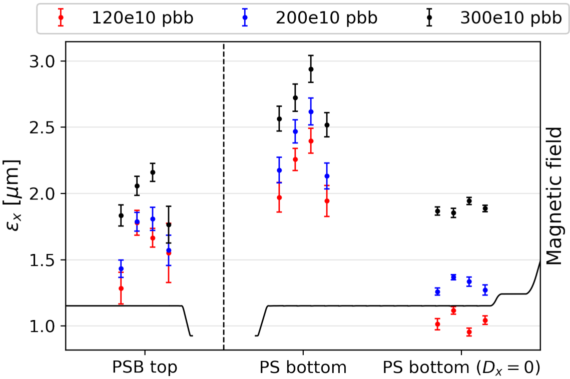


Emittances between PSB top energy and PS top energy

- The emittance shows a small increase between between the zero dispersion measurement and the top energy measurement
  - This could be due to emittance blow-up at transition crossing or the small dispersive contribution to the emittance at top energy
- The higher the intensity, the larger the betatronic contribution to the emittance and the closer all the emittances are to eachother



Comparison between the 4 PSB rings

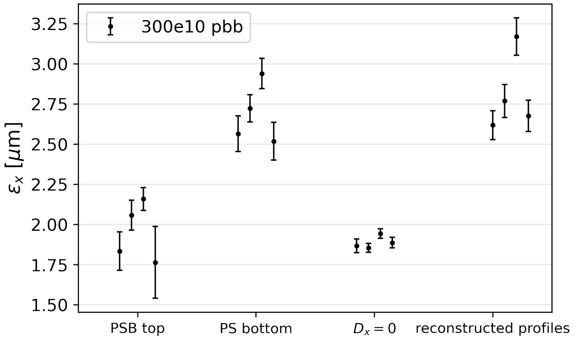


- There is an emittance trend between the PSB rings, with the outer rings having a consistently lower emittance than the inner rings
- This trend disappears when going to zero dispersion optics

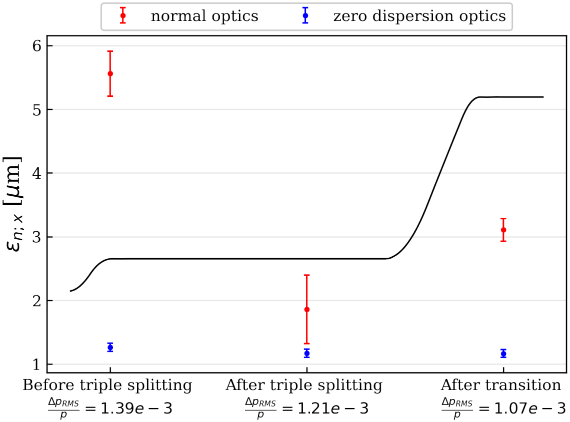
$\rightarrow$ The longitudinal distribution from the four rings is different rather than the transverse distribution

beam profile reconstruction

- If the deconvoluted beam profile is reconvoluted with the longitudinal distribution, does the same pattern emerge?
- **Yes!** The longitudinal distribution causes the emittance to be different for the inner and outer PSB rings



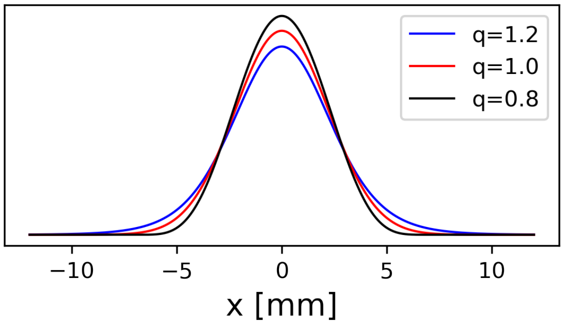
Transition Crossing

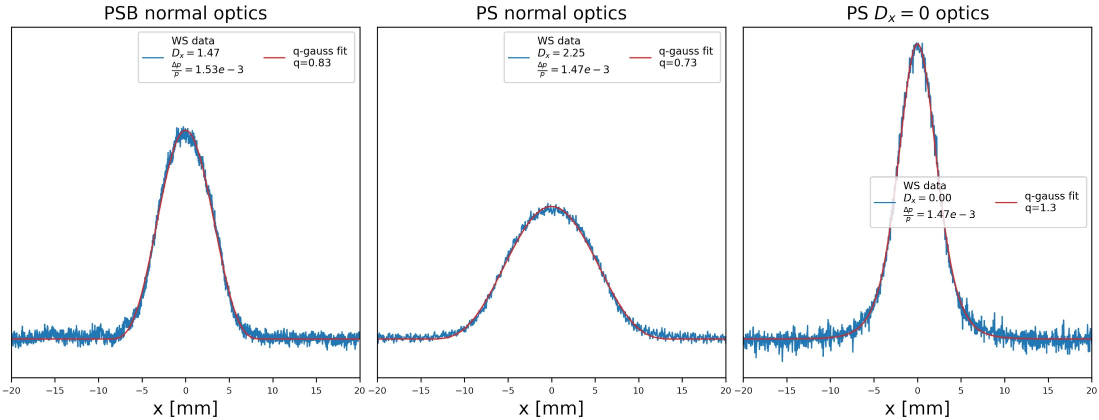


- Custom magnetic cycle right below **(1860 Gauss)** and above **(4500 Gauss)** Transition energy **(2000 to 3000 Gauss)**
- **No difference** between the zero dispersion emittance measurements
  - small intensity loss at triple splitting results in an equally neglictible emittance reduction
- The emittance increase at flat top was possibly due to the dispersive contribution that's still present

Beam tail evolution

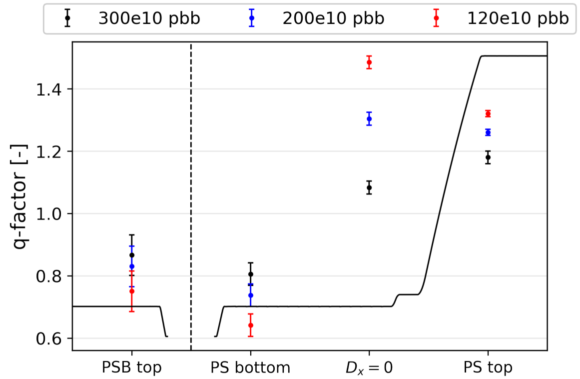
- A q-Gaussian fit is used to look at tail population
- The q-parameter is a measure of how heavily the tails are populated:
  - $q = 1 \rightarrow$ Gaussian distribution
  - $q < 1 \rightarrow$ underpopulated tails
  - $q > 1 \rightarrow$ overpopulated tails





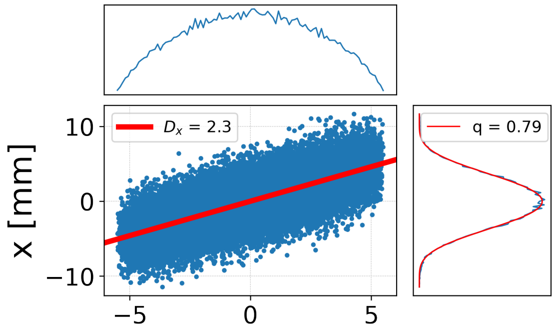
Tails between PSB top energy and PS top energy

- The beam tails for profiles with a dispersive contribution are underpopulated and those without (or with less) dispersive contribution have overpopulated tails
- The higher the intensity, the more Gaussian the distribution in all cases
- Does the zero dispersion optics cause a blow-up in the tails?

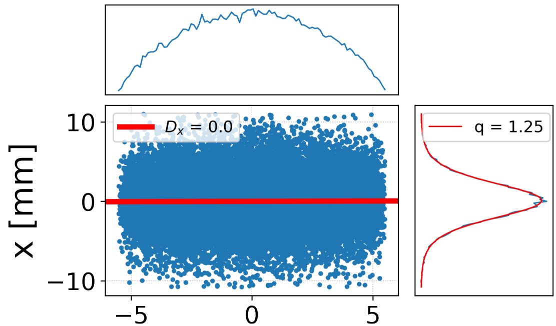


Multi-particle tracking result

- q-Gaussian beams $q = 1.25$ are generated and the beam distributions at zero and normal dispersions are shown

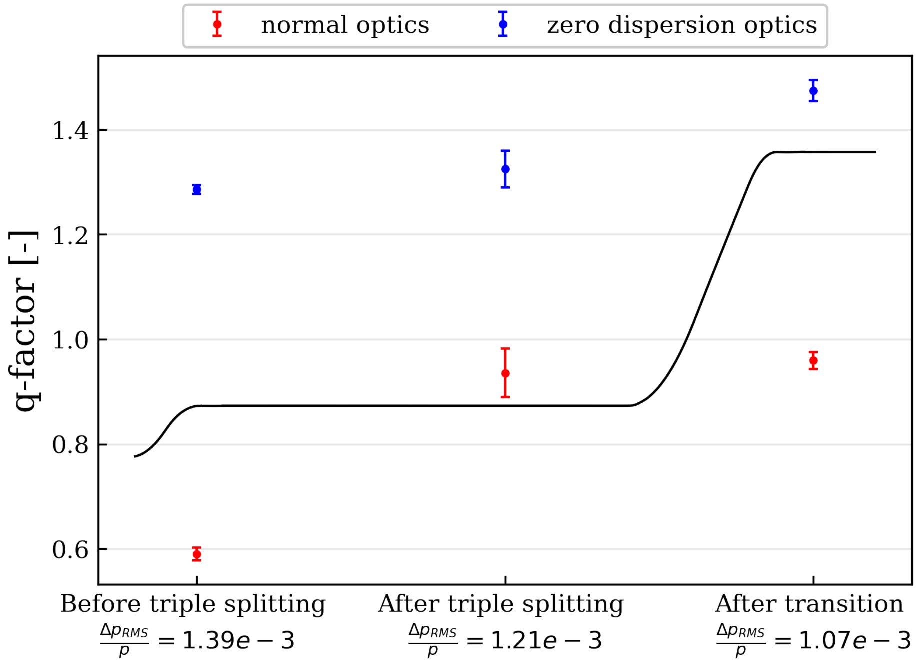


- **The "true" tails of the distribution are revealed**



Tails over transition crossing

- The tails are already overpopulated before transition crossing
- There is still an increase in the beam tails over transition crossing



Summary Zero dispersion optics

- Zero dispersion optics can be achieved for **any location in the PS ring** at low energy
- The emittance and tail progression has been studied for PSB-PS injection and transition crossing effects
- **The "true" tails of the transverse distribution** are revealed when the dispersive contribution is small
- There is a discrepancy in the longitudinal distribution between the outer and inner rings of the PSB
- There is no emittance blow-up over transition crossing however there is an increase in tail population

Resonance Driving Terms

Loss map

The effect of these resonances can be visualised by how much intensity is lost when the tunes are scanned over the resonance lines, this is called **a loss map**

images/Screenshot from 2023-11-1

The $3Q_y$ and the $2Q_x + 1Q_y$ are interesting

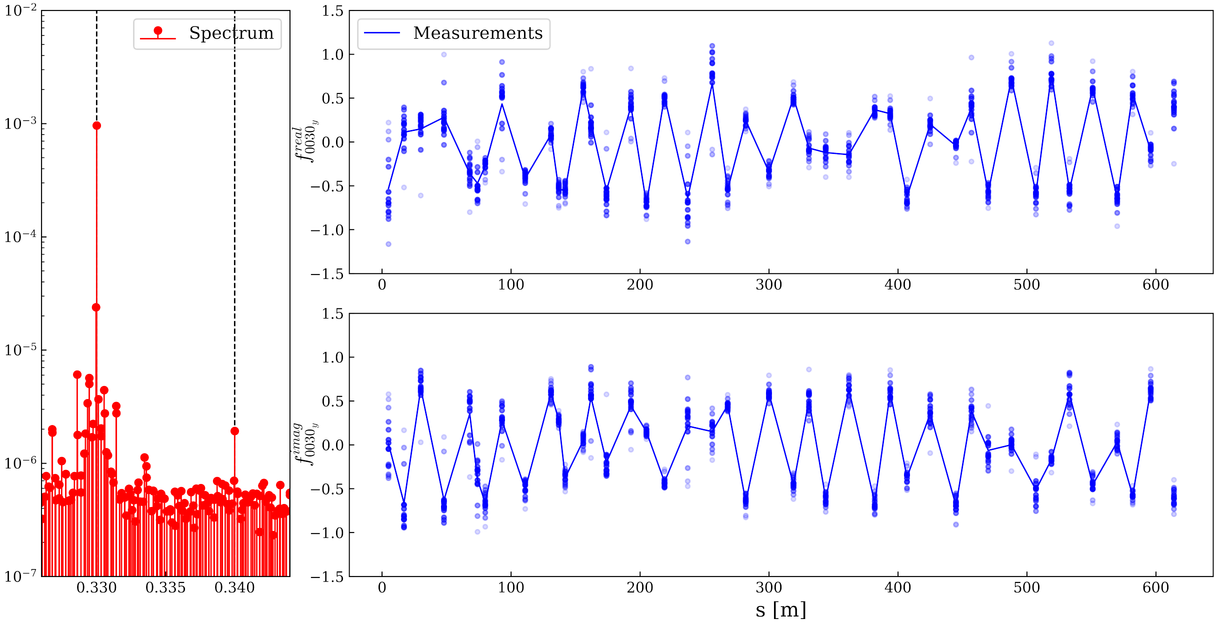
- They are both skew sextupole resonances
- The $2Q_x + 1Q_y$ resonance causes the most losses in this loss map

Resonance driving terms (RDTs)

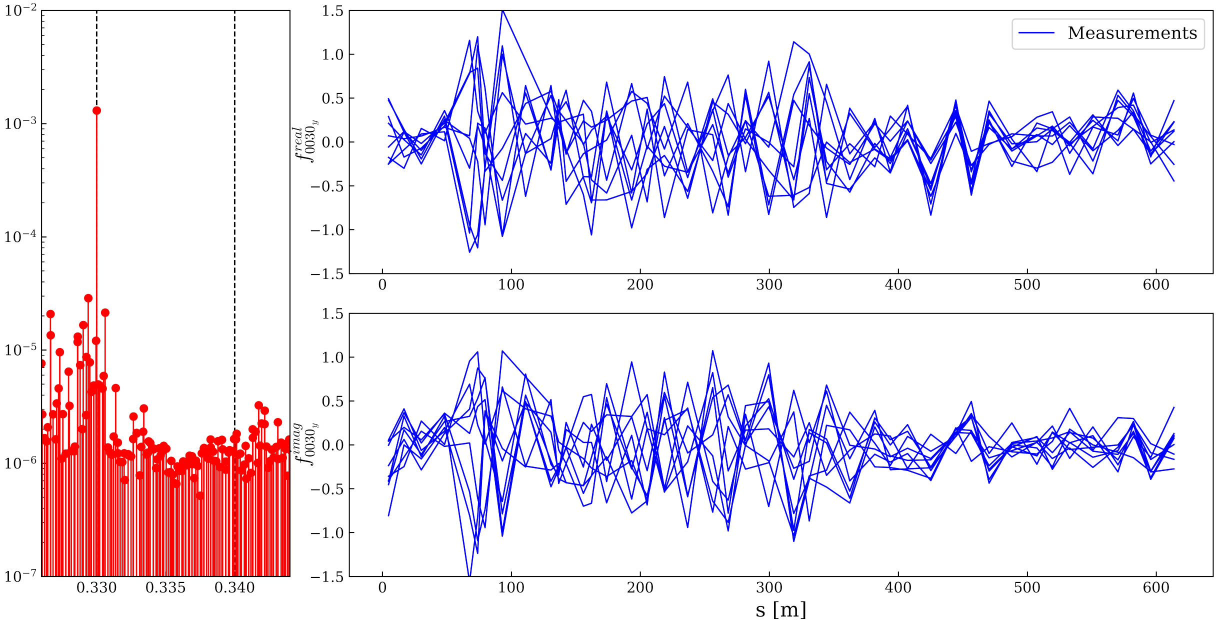
- The frequency spectrum produced by the transverse position of the beam has its largest peaks **at the fractional tunes**
- An AC-dipole can be used to kick the beam with a certain frequency to change the tune of the machine and **increase the amplitude** of this peak
- When the tunes are approaching a resonance, a new spectral line becomes visible called a **resonance driving term (RDT)**
- Using non-linear mechanics the relations between the resonance and the location, amplitude and phase of an RDT can be found:

Resonance	(j-k)Q_x + (l-m)Q_y	3Q_y	2Q_x +1Q_y
RDT	f_{jklm}	f_{0030}	f_{2010}
Location (H)	H(1-j+k, m-l)	/	H(-1,-1)
Location (V)	V(k-j, 1-l+m)	V(0,-2)	V(-2,0)

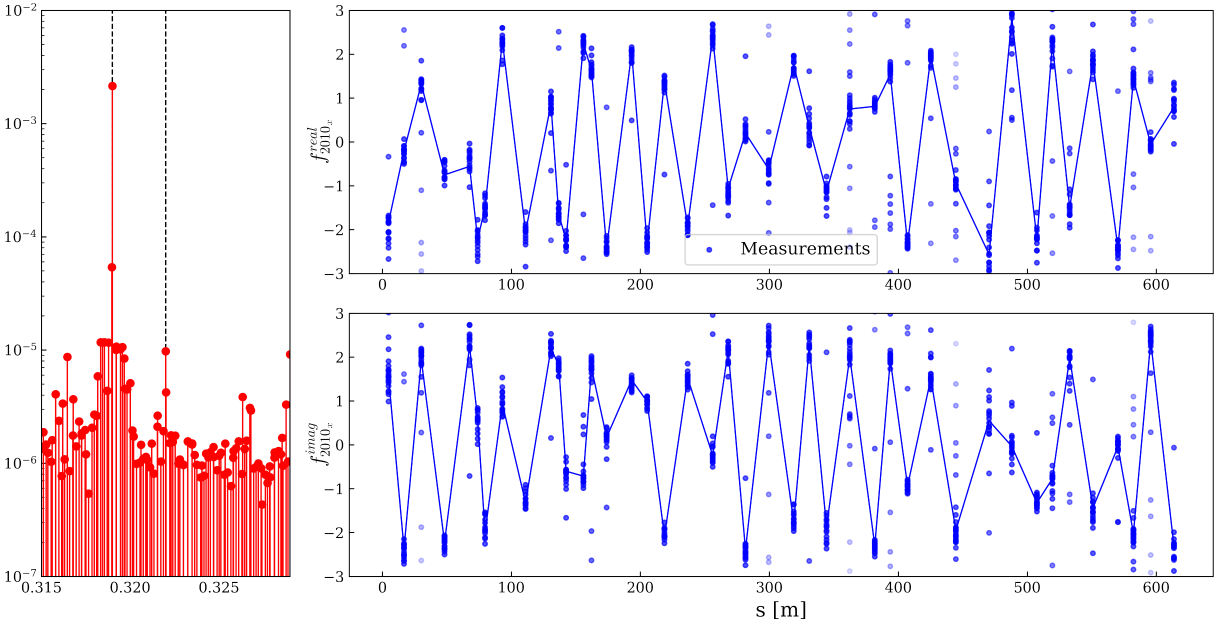
$3Q_y$ V(0,-2) (f_{0030})



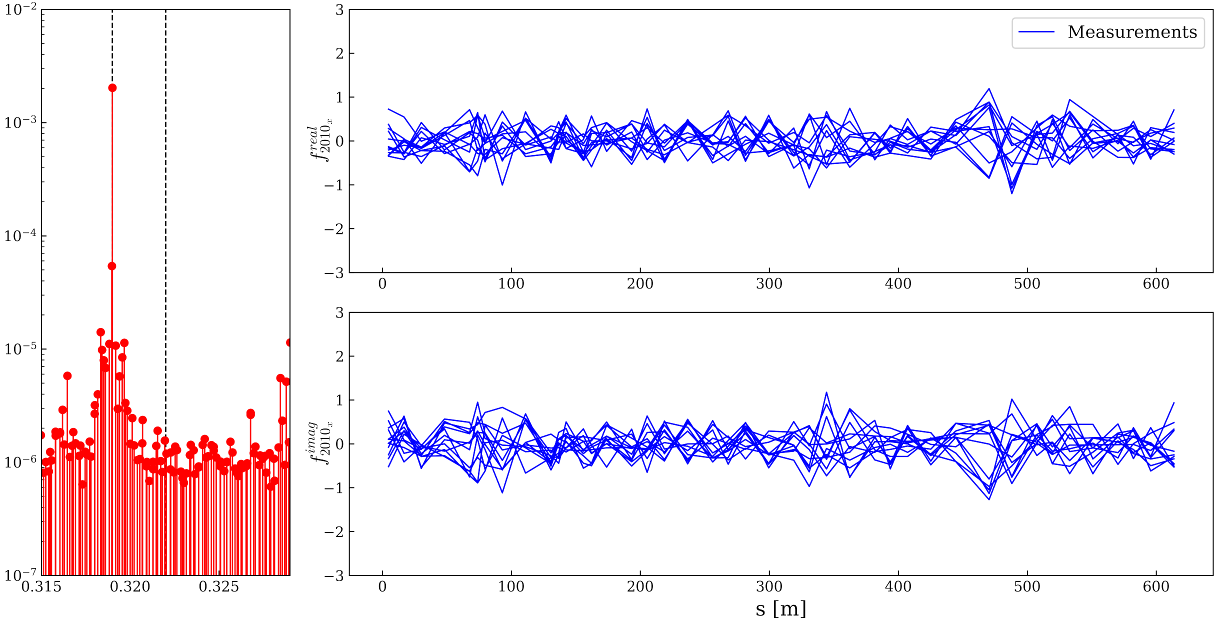
$3Q_y$ V(0,-2) (f_{0030})



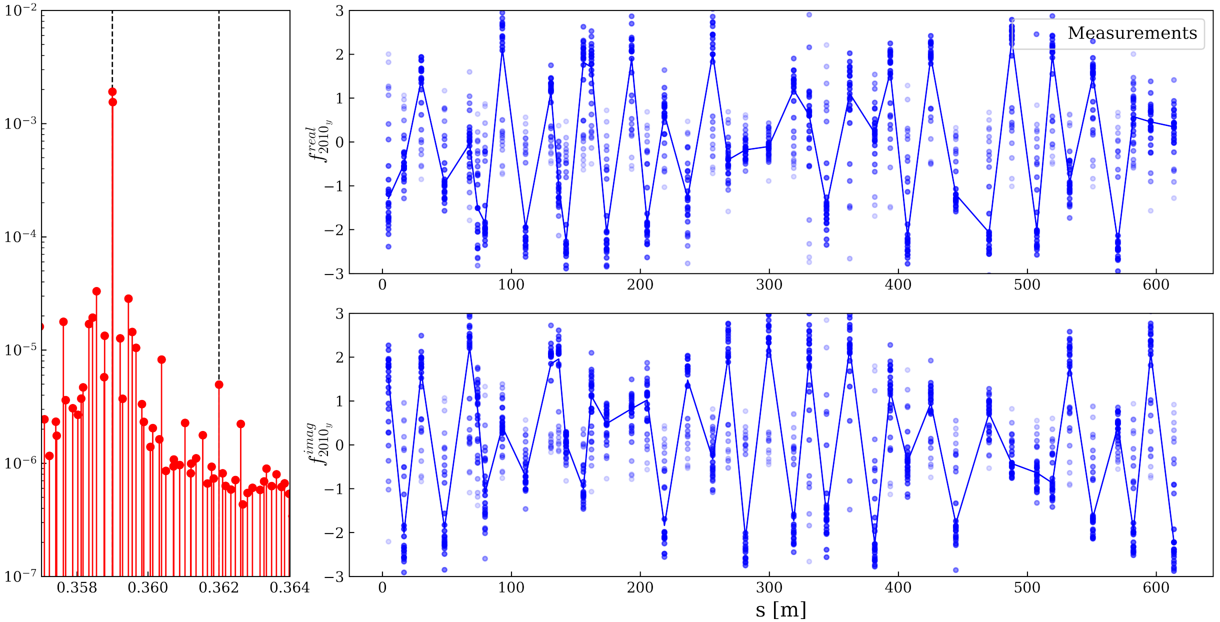
$2Q_x + 1Q_y$ H(-1,-1) (f_{2010})



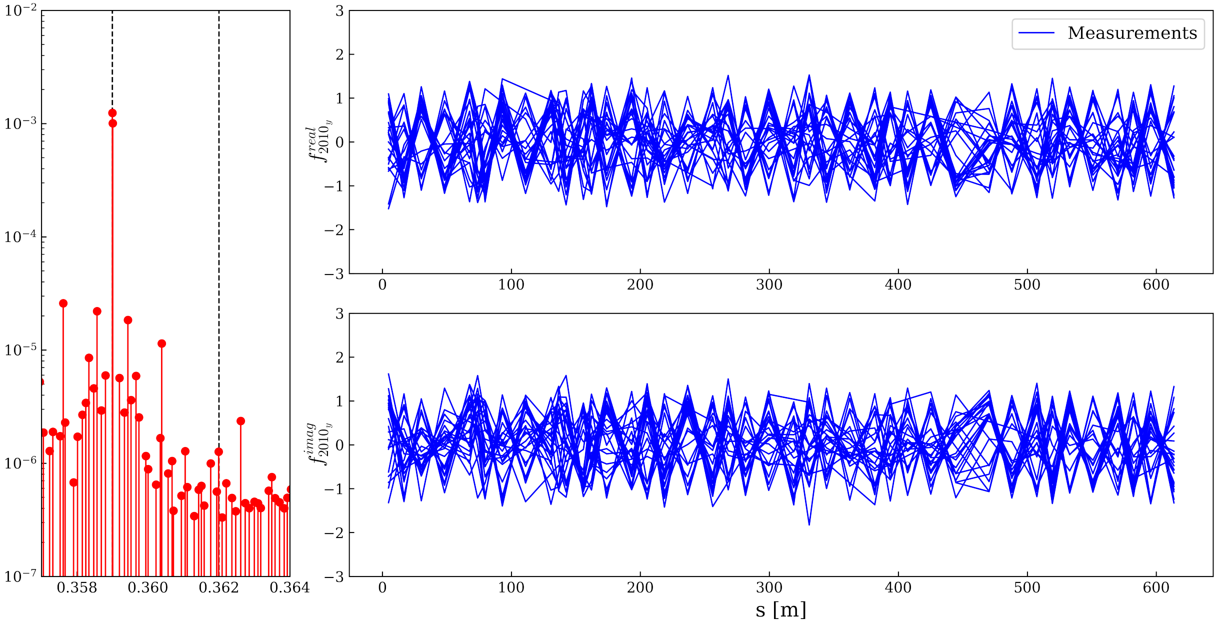
$2Q_x + 1Q_y$ H(-1,-1) (f_{2010})



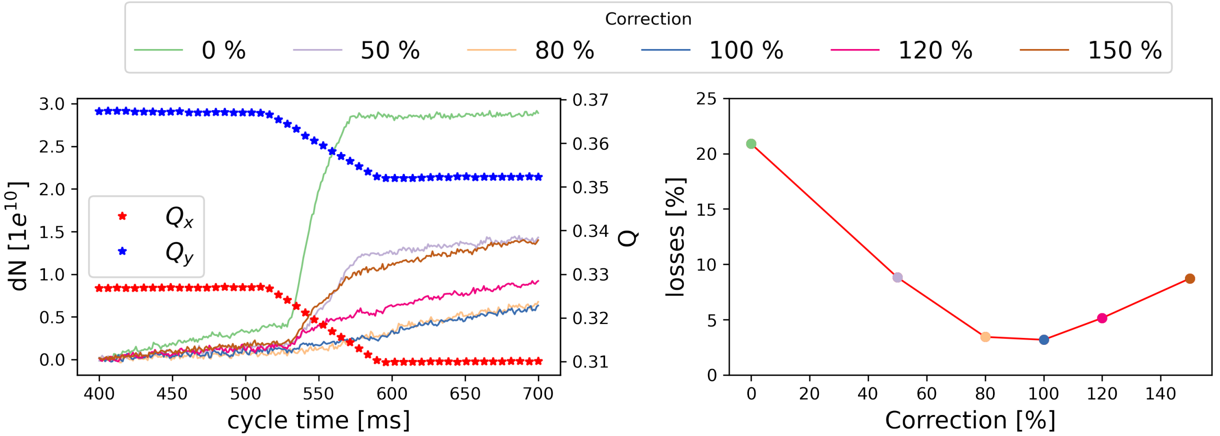
$2Q_x + 1Q_y$ V(-2,0) (f_{2010})



$2Q_x + 1Q_y$ V(-2,0) (f_{2010})



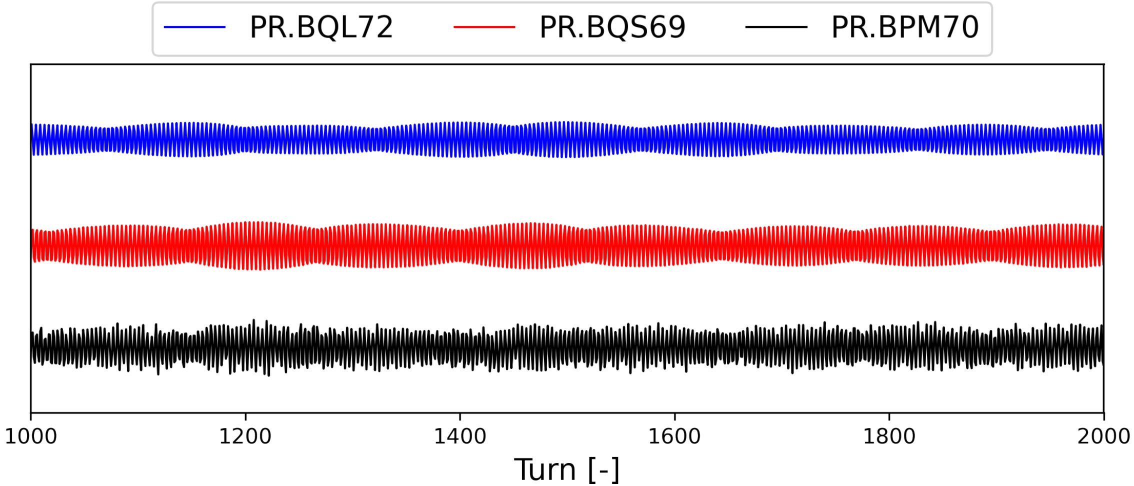
losses



Correction
0 %
50 %
80 %
100 %
120 %
150 %
dN [1e10]
Q
Q_x
Q_y
cycle time [ms]
losses [%]
Correction [%]

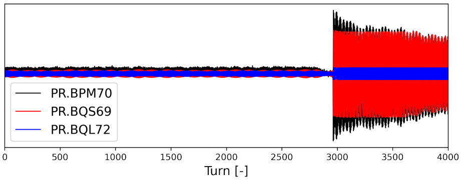
Noise reduction

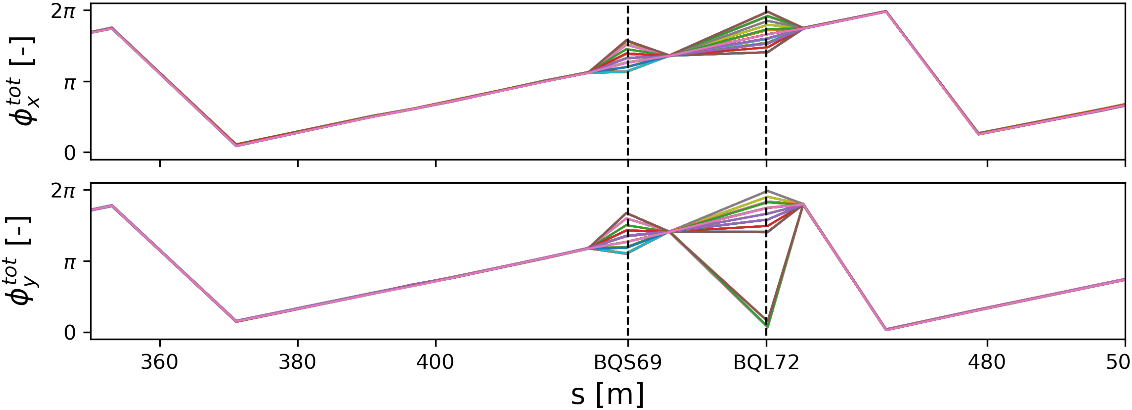
- The pickup instrumentation for tune measurement also takes turn-by-turn data of the transverse position
- They could serve as **high precision BPMs** in our analysis



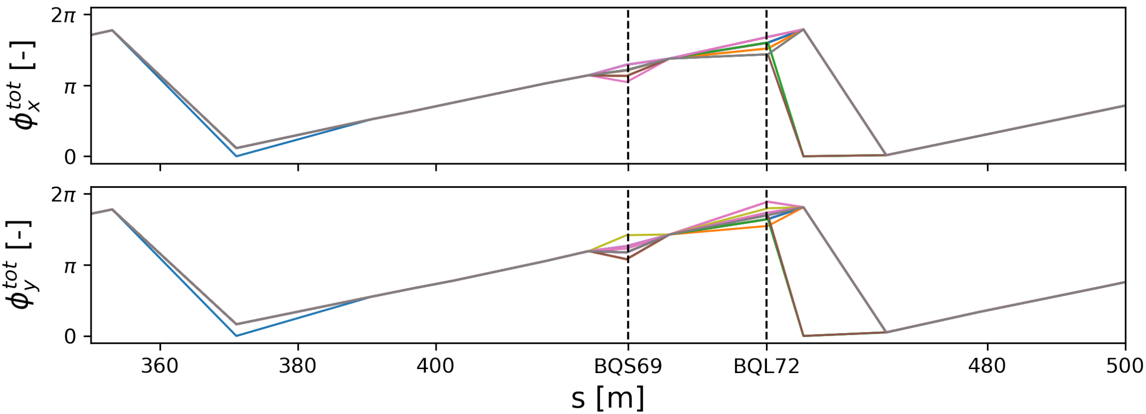
Noise reduction

- The action and phase of the pickups can be synchronised by 1-turn kick after the measurement
  - However we can only synchronise the phase of the pickups up to 1 turn ($\Delta\varphi = Q$) but the timing of the BBQ is randomly within 1/7 of the RF clock so it isn't perfectly synchronised $\rightarrow$ Should be solved by next year





2024 phase mismatch



Summary RDTs

Conclusion

- **Non-linear study**
  - The f_{0030} and f_{2010} H(-1,-1) lines have been corrected to noise level
  - The f_{2010} V(-2,0) line is been reduced in amplitude
  - Using the tune measurment pick-ups as high precision BPMs can lead to even better corrections
- **Linear study**
  - Zero dispersion optics results in more precise and more accurate emittance measurements
  - Tracking simulations will be done to learn more about beam width behaviour that i didn't expect to see
- **PFW control study**
  - Good progress has been made to make a new PFW control system
  - Once the FREV analysis is complete, the backwards network can be tested

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