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PS : Measurements for the Linear Optics Model

H. Bartosik, A. Huschauer, A. Wegscheider, P. Zisopoulos

Acknowledgements: Y. Papaphilippou, G. Sterbini, F. Tecker,
PSB and PS Operator Teams

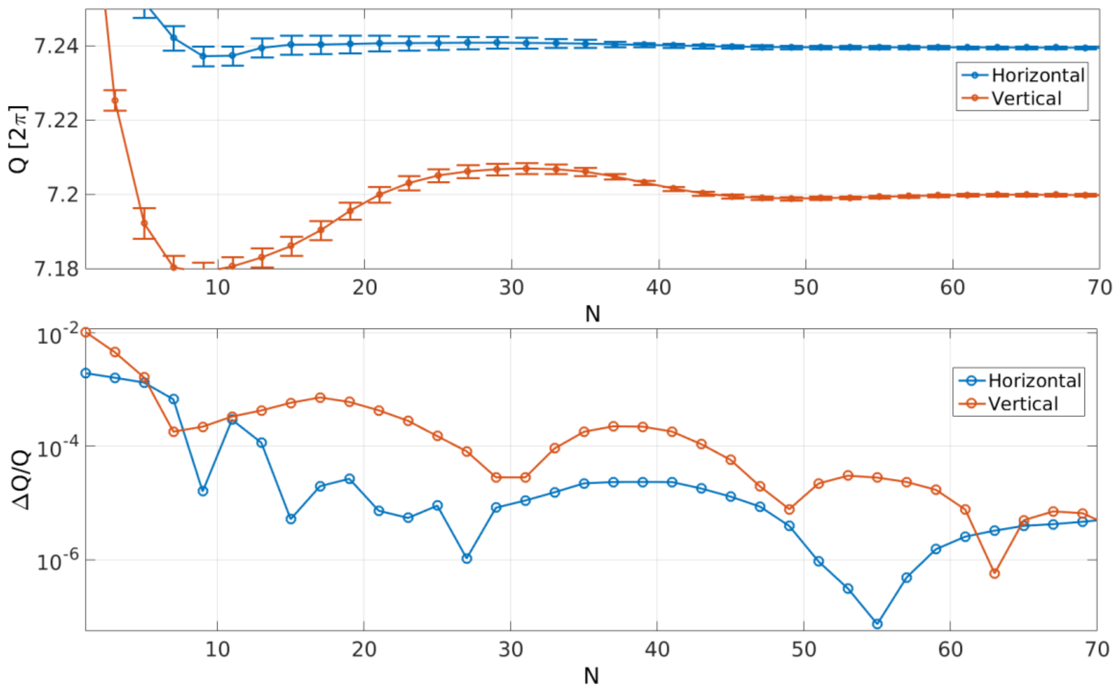
2nd Space Charge Collaboration Meeting

Outline

- Tune measurements at PS injection
  - A novel method for tune measurements.
  - Periodic Modulation of the betatron tunes at PS injection.
- Beta-beating measurement campaign at the PS
  - Motivation and Methodology.
  - The N-BPM method and a simple tool.
  - Experimental results.
- Conclusions
- Future actions

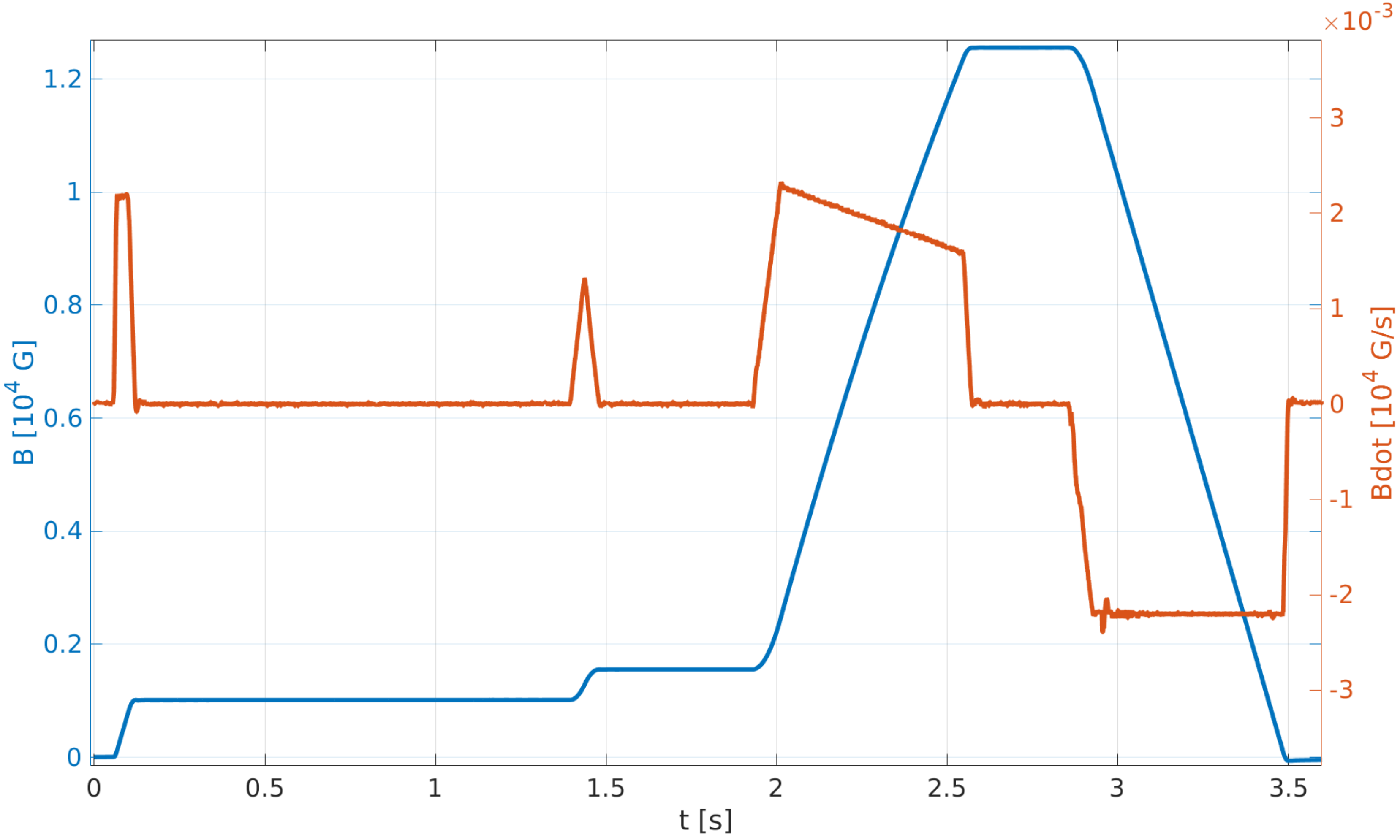
A novel method for tune measurements at the PS

- Refined Fourier analysis with NAFF **[1]** for precise tune measurements.
- Theoretical convergence of NAFF: $\Delta Q \sim 1/N^4$, N number of turns.
- Convergence of the tunes from mixing TbT data from M BPMs : $\Delta Q \sim (1/\mathbf{M}^3 N^4) + \delta(M)$, with $\delta(M)$ the sampling error.
- The integer part of the tune can be also recovered with this method.

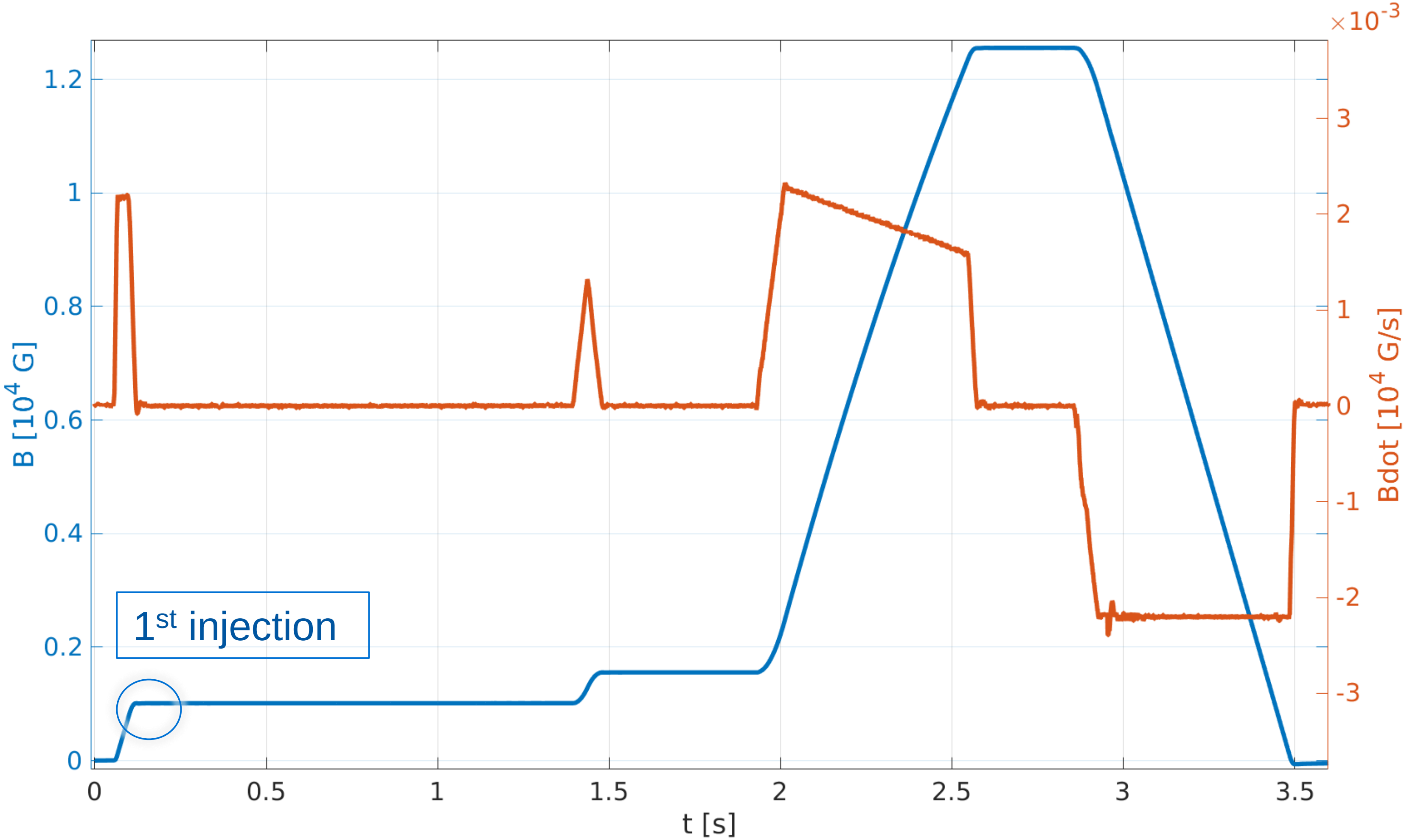


[1] J. Laskar: "Frequency Analysis for multi-dimensional systems. Global dynamics and diffusion", Physica D 67 (1993) 257-281

PS Magnetic Cycle

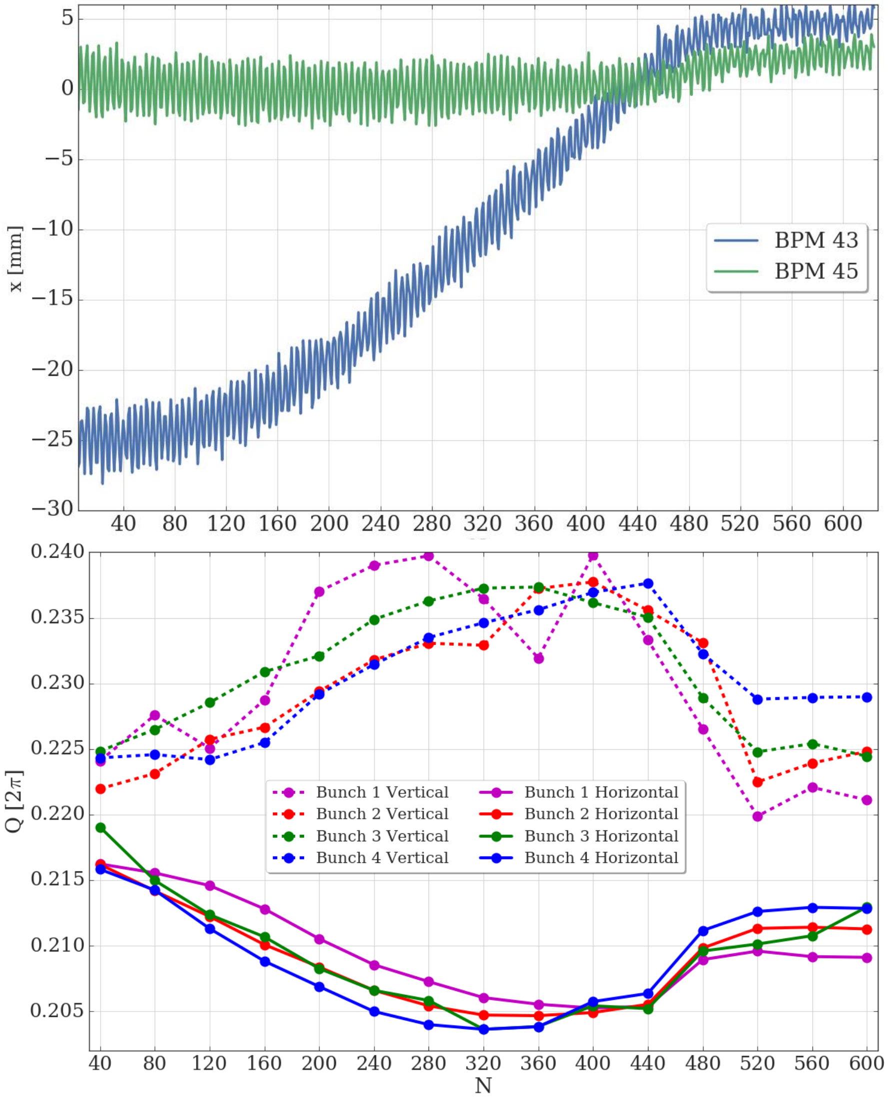


PS Magnetic Cycle



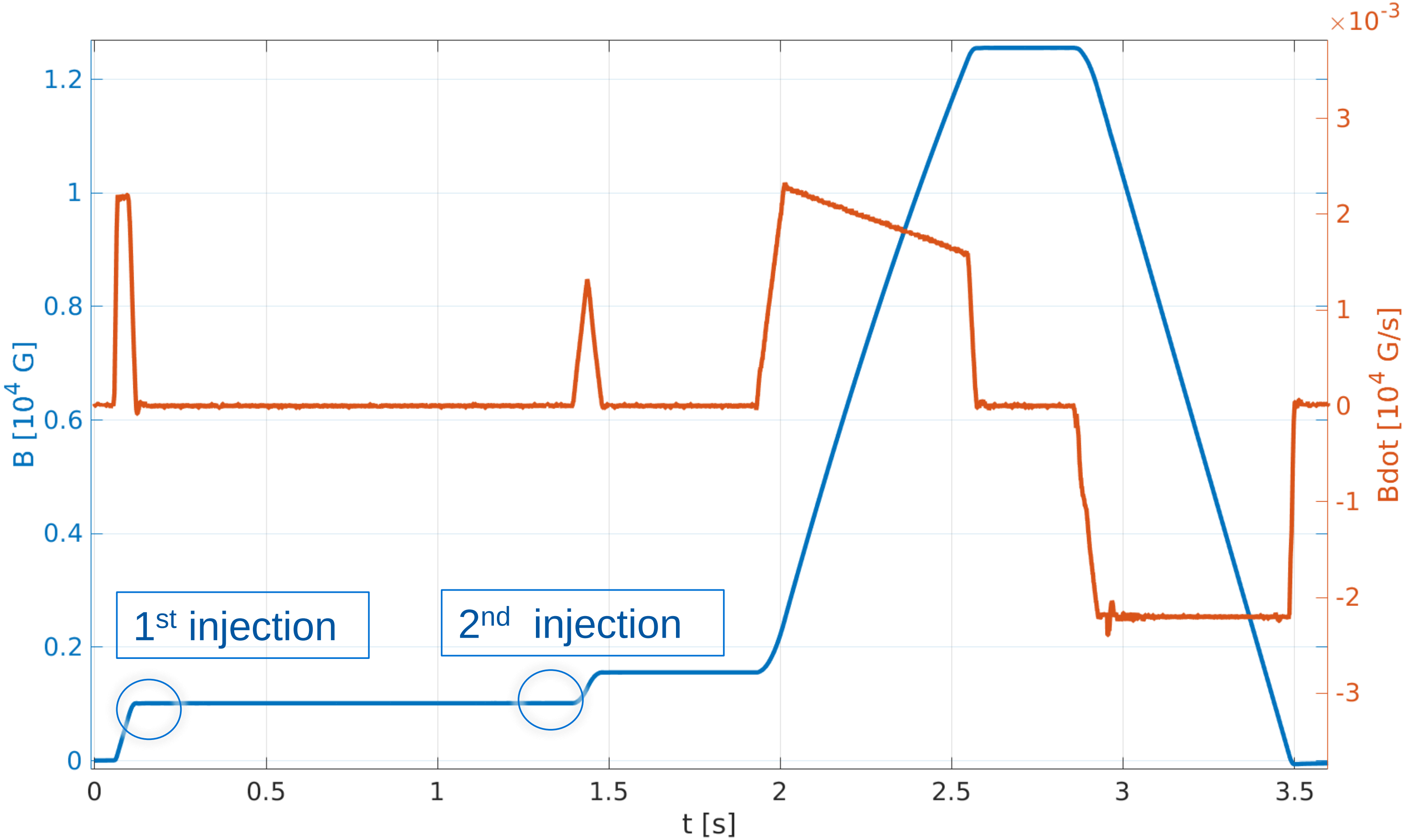
Tune Measurements after 1st injection

- Large orbit displacement at the injection region.
- A sliding window of 40 turns was used for tune estimation along the turn by turn data.
- The mixed BPM method reveals a tune modulation and tune-shift of $\mathbf{10^{-2}}$ **[2]**.
- Horizontal tune: The bunch-by-bunch response may suggest energy errors from the 4 PSB rings.
- Modulation appears to be related to the B dot through a quadrupolar feed-down. (eddy currents on the chamber)

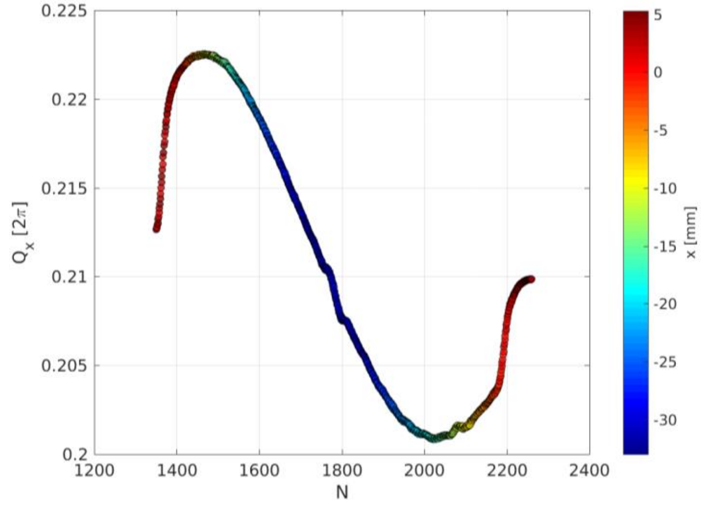


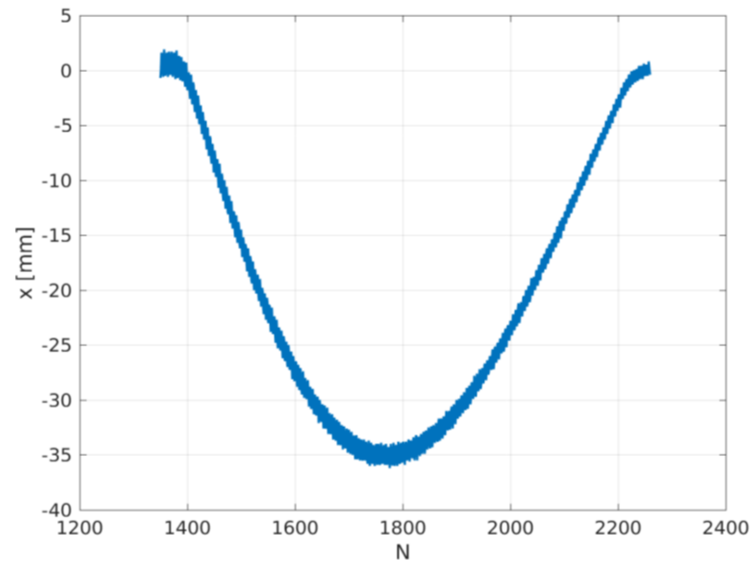
[2] "Fast bunch by bunch tune measurements at the CERN PS", Proceedings of IPAC 2017, MOPAB122, p. 415-418.

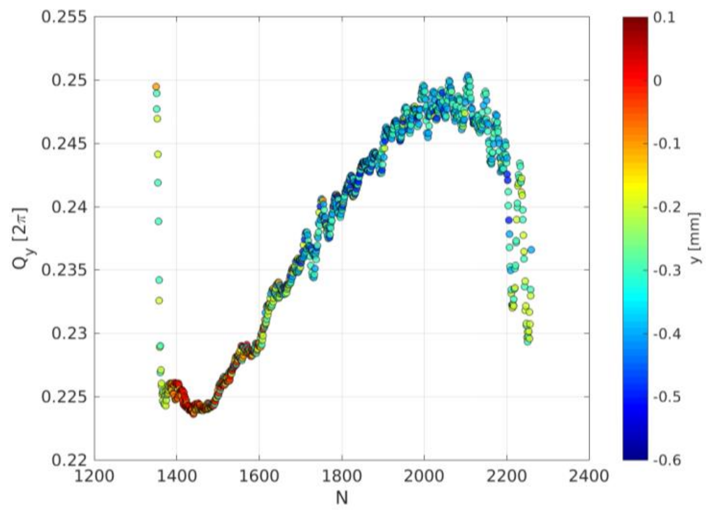
PS Magnetic Cycle



Tune measurements during bump operation

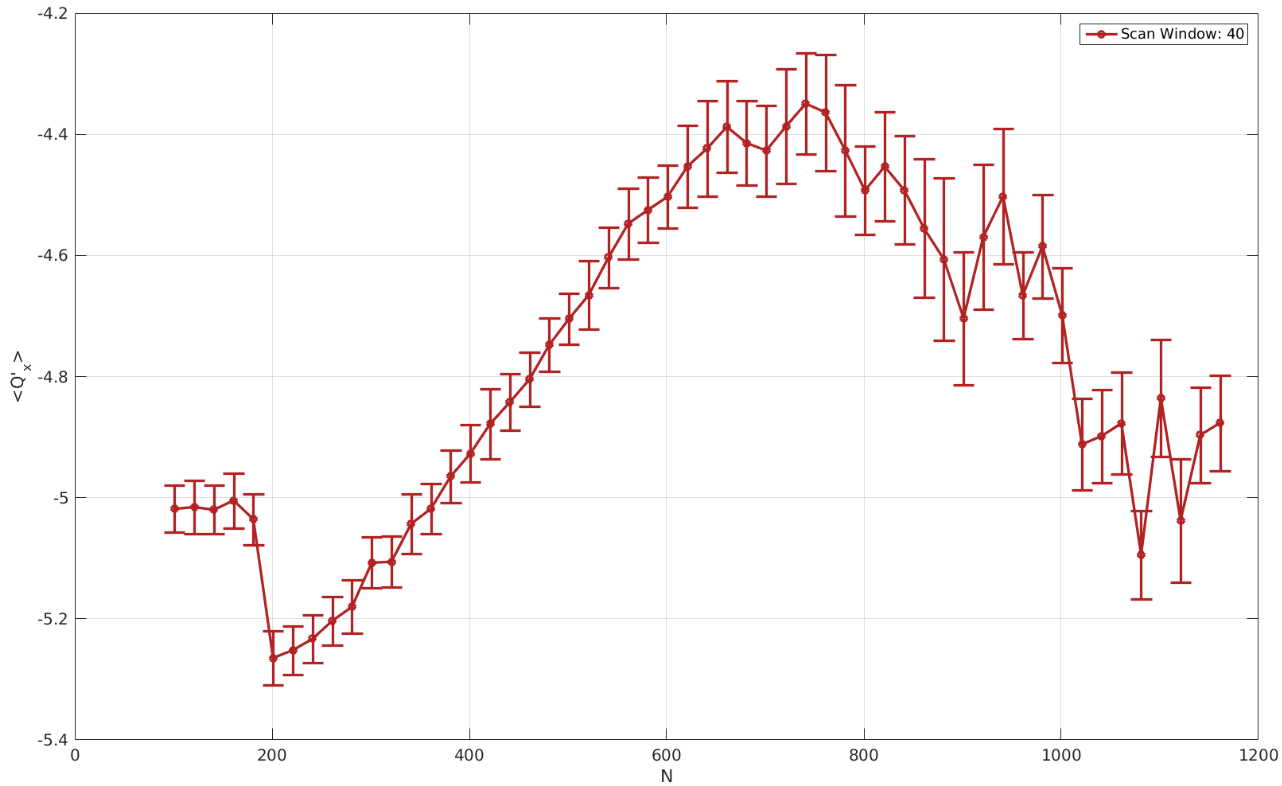






- TbT data also recorded during full duration of the bump.
- Transverse betatron tunes exhibit a periodic modulation which can be correlated to the Bdot.
- Vertical excitation through coupling so a loss of resolution is observed in the vertical tune estimation.

Modulation of the chromaticity



- Measurements of the horizontal chromaticity suggest a dynamical sextupolar component.
- Small increase by 1 unit - peak to peak - of the horizontal chromaticity during the injection bump.

Beta-beating campaign at the PS

- Motivation: Towards the LIU era of the CERN injectors, measurement and control of the optics is of paramount importance.
- Observations at the PS, suggest a dynamical change of the optics from the injection bump and a significant emittance blow-up in the PSB to PS transfer (see talk from A. Huschauer).
- In this respect, beta-beating measurements took place at the PS as to assess the validity of the current model and the quality of the PS magnets.

What is beta-beating?

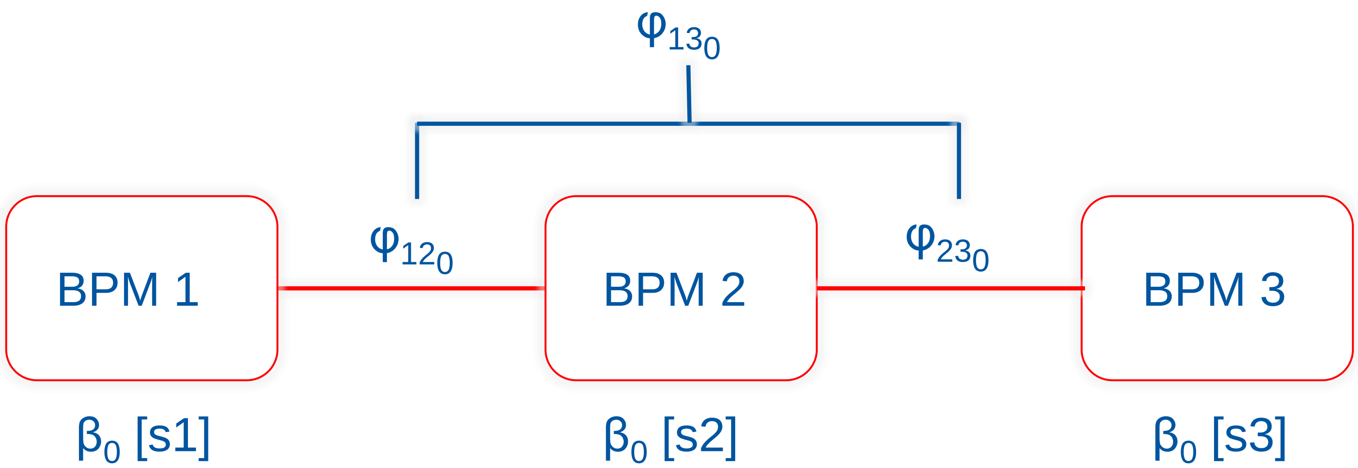
- It is simply a measurement of the difference between real and design optics.
- It is the global contribution of the quadrupolar gradient errors, which are distributed around the machine:

$$\frac{\Delta\beta(s)}{\beta(s)} = \frac{1}{\sin(2\pi Q)} \sum_{k=1}^{N} \beta(s)\beta(s_k)\Delta K(s_k)\cos(2|\Delta\Phi_k| - 2\pi Q)$$

[M. Minty, F. Zimmermann, Measurement and Control of Charged particle beams]

- Beta-beating is a spatial travelling wave with a frequency 2Q.
- Unwanted due to orbit distortions, systematics in emittance measurements etc.
- Below 5% beta beating is usually desired.

Methodology



$$\beta[s1]=\beta_0\,[s1]\,\frac{\cot[\varphi_{12}]-\cot[\varphi_{13}]}{\cot[\varphi_{12_0}]-\cot[\varphi_{13_0}]}$$

[3] P. Castro, Ph.D. thesis, Geneva, 1996

$$\beta[s2]=\beta_0\,[s2]\,\frac{\cot[\varphi_{12}]-\cot[\varphi_{23}]}{\cot[\varphi_{12_0}]-\cot[\varphi_{23_0}]}$$

$$\beta[s3]=\beta_0\,[s2]\,\frac{\cot[\varphi_{23}]-\cot[\varphi_{13}]}{\cot[\varphi_{23_0}]-\cot[\varphi_{13_0}]}$$

Methodology

- Different strategies can be implemented for the choice of the 3 BPMs.

- <u>One has to avoid n*π angles (and investigate on what is an appropriate threshold).</u>

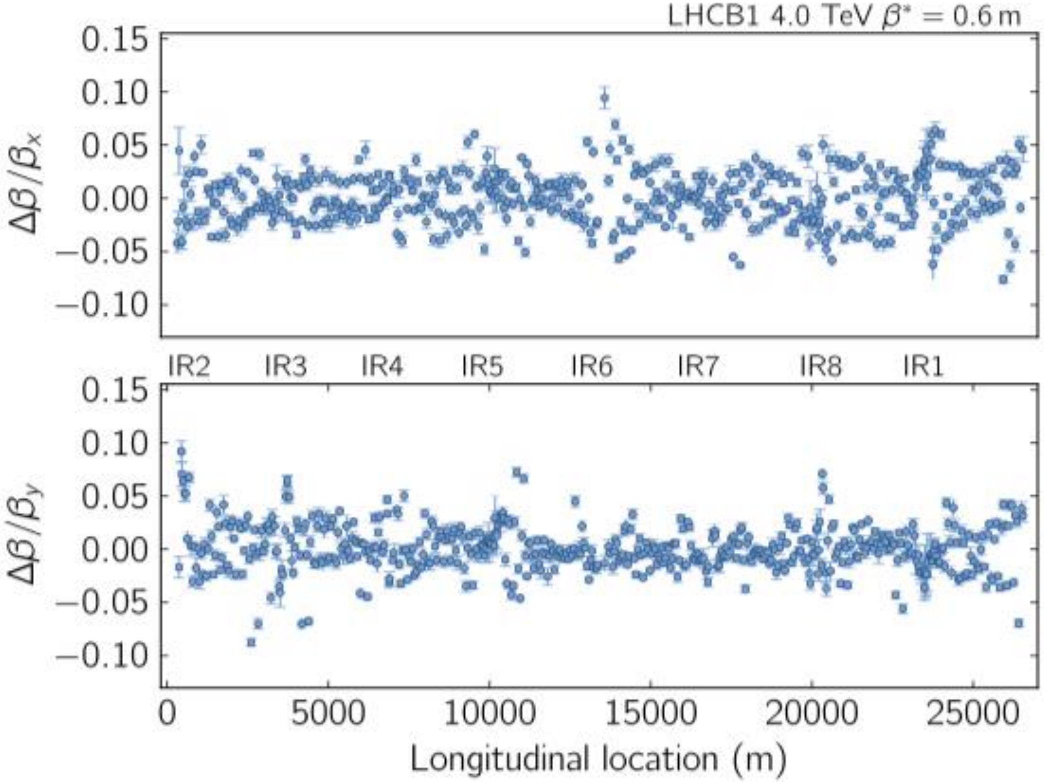
- This method makes two assumptions:
  i) <u>The machine is linear and uncoupled.</u>
  ii) <u>The model is known **exactly** i.e. error-free transfer matrices between the range of the BPMs.</u>

- Statistical Errors:
  - Fluctuations of the machine and the beam.
  - Correlations between BPMs in the triplet scheme-e.g. for phase advances $\varphi_{i,j}$, $\varphi_{i,k}$, the BPM i appears twice.

- Systematic Errors
  - Uncertainty in the multipole components of the magnets.
  - Misalignments (e.g. sextupolar Δx, BPM Δs).
  - Multipolar feed-downs.
  - BPM noise.
  - Optics stability.
  - …

The N-BPM method

Courtesy of A. Langner



- At the LHC, the beta beating is measured with the **N-BPM method [4]** where N is a range of N=10 BPMs (usually).
- This method applies a **consistent error propagation [5]** of multipolar systematic errors and has shown very good results so far, in the LHC case.
- The gradient errors have been **measured** at the LHC.
- An effort was put through to bring the experts and the method to the PS.

[4] A. Langner, R. Tomas, PhysRevSTAB 18, 0031002

[5] A. Franchi, A. Wegscheider, PhysRevAB 20, 111002, (2017)

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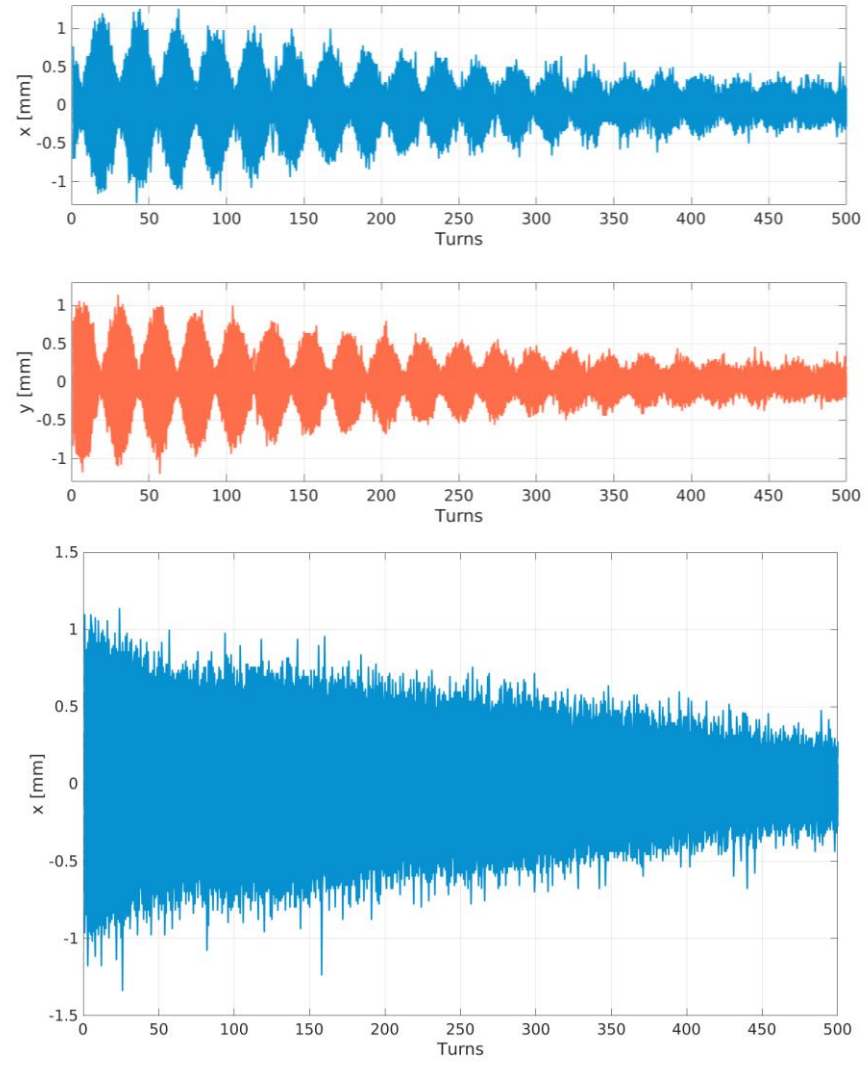
In parallel: A simple tool to measure beta-beating

- While applying the N-BPM method at the PS for the first time, a more simple method was also used for benchmarking and understanding the N-BPM method.
- The simple method consists of a range of **5 BPMs** and the final result is the weighted average of all the BPM combinations.
- The measurement errors are the propagated errors coming from the statistical fluctuations of the phases.
- No implementation of systematic error correction in this tool.

Experimental set-up

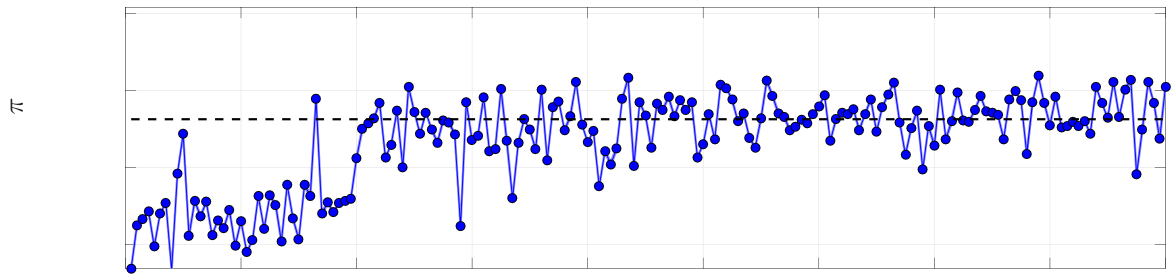
- Case 1: Low Energy Quadrupole (LEQ) ON with coupling.
- Case 2: LEQ ON with coupling | Qx close to the integer.
- Case 3: LEQ ON with coupling corrected.
- Case 4: LEQ OFF with coupling (Bare machine).
- Case 5: LEQ ON with coupling | Intensity scan.

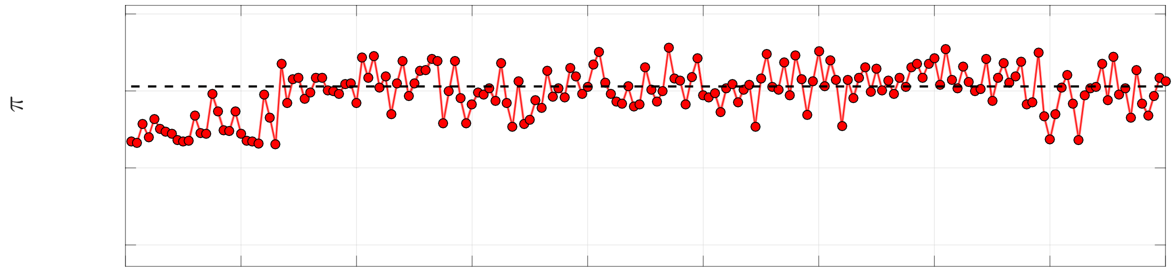


Experimental set-up

- Overall, the tune is stable along the cycle at the 10^{-3} level.

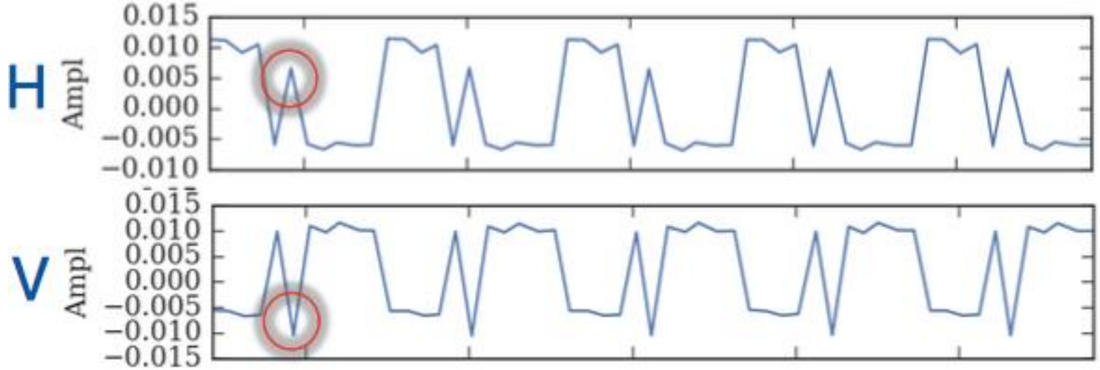
- To reduce various statistical errors the strategy to be followed is:
  - Samples outside ±2σ are excluded
  - Noise levels are reduced with SVD analysis.





Yet another surprise !

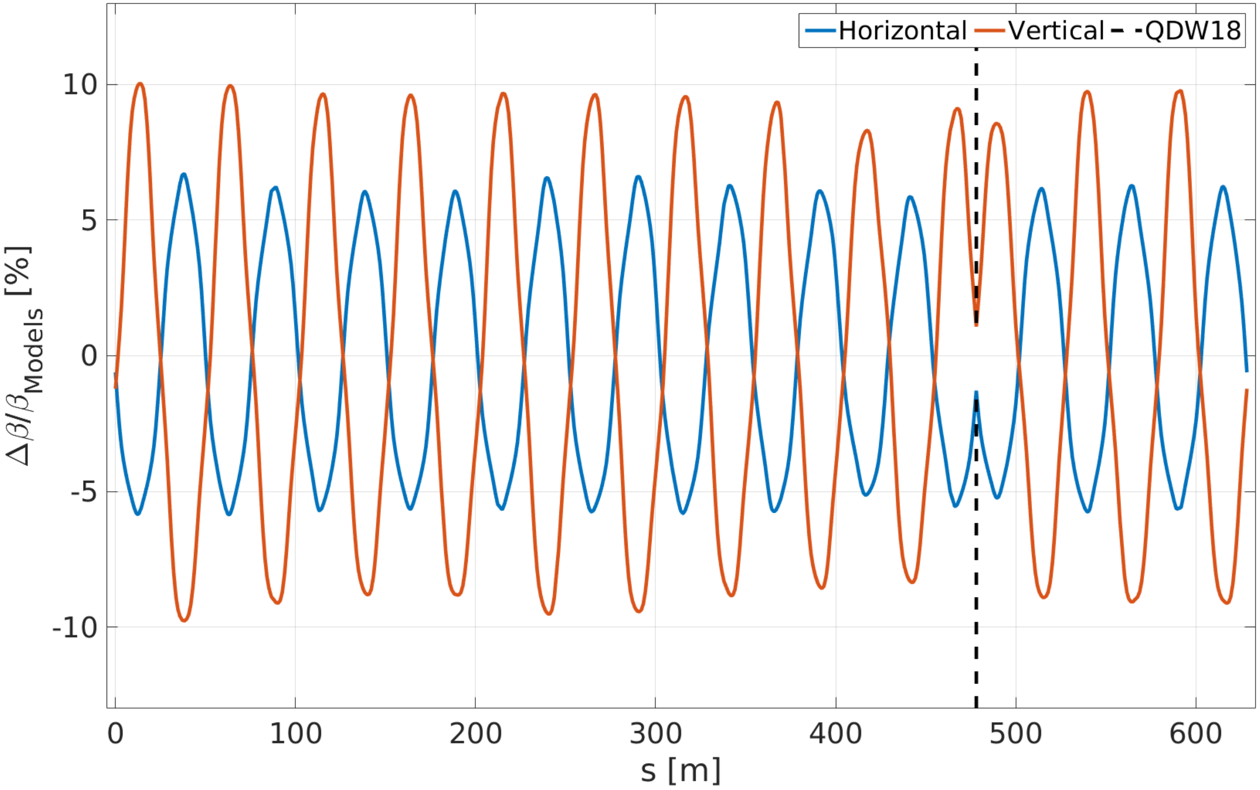
Fit amplitude



Courtesy of F. Tecker.

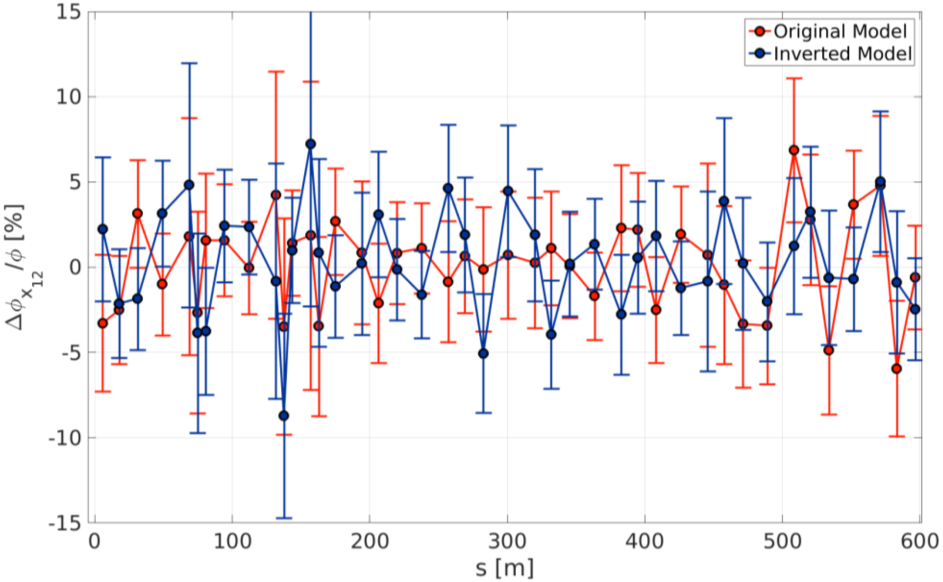
- In parallel, beta function was measured with K-Modulation.
- The analysis revealed a discrepancy in the polarity of LEQ **QDW18**, which is a <u>defocusing</u> quadrupole.
- In order to estimate the contribution of this discrepancy to the beta-beating results, the analysis included both models:
  - Original Model **(**QDW18 with **initial polarity)**
  - Inverted Model (QDW18 with **inverted polarity**)

Case 1 LEQ ON with coupling: Model Comparison (Qx,Qy)~(6.20,6.24)



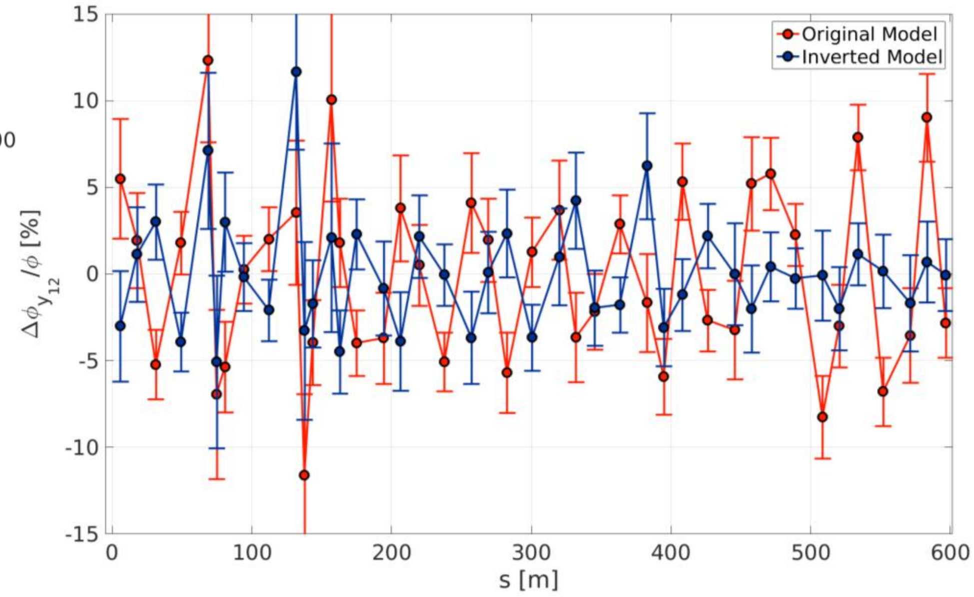
- $\Delta\beta/\beta=(\beta_{orig}-\beta_{inv})/\beta_{inv}$
- Vertical beating almost twice as the horizontal.
- Symmetry breaking at the location of QDW18.
- Since it is a defocusing quadrupole a phase shift of $\Delta\beta/\beta$ towards positive values is expected after the perturbation.

Case1: Phase Beating

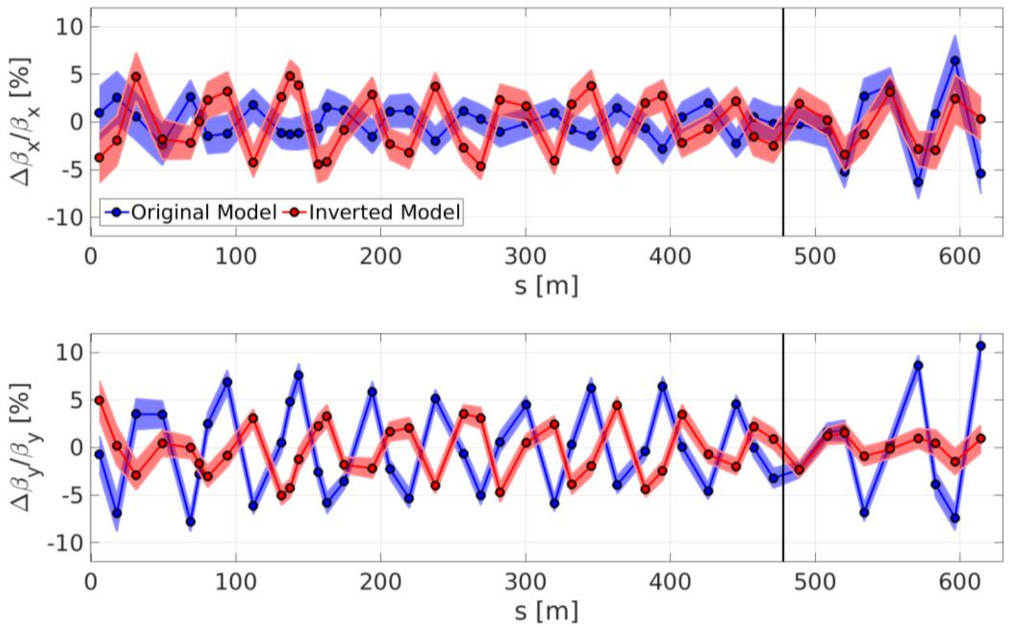


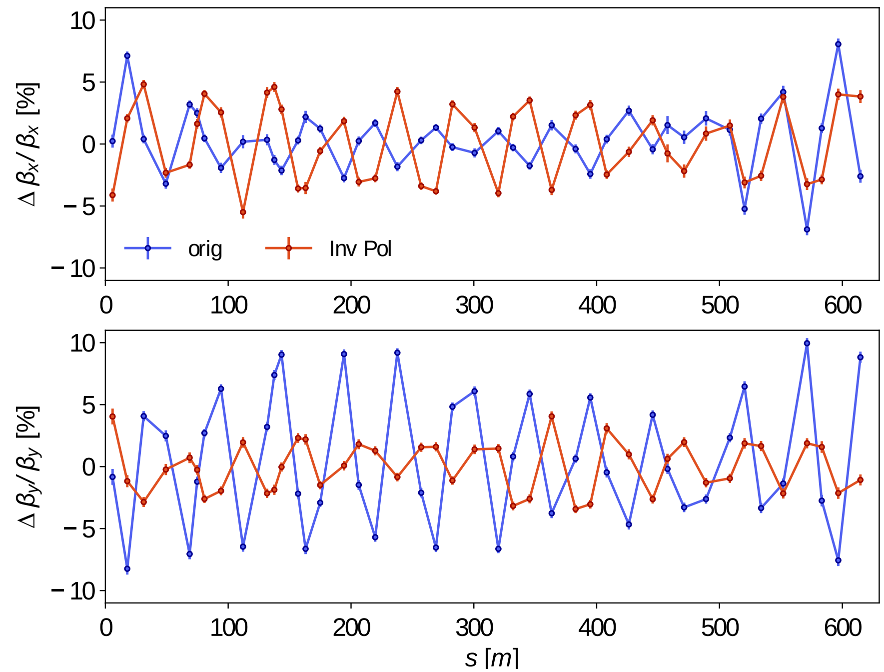
- Horizontal phase beating: For the original model very close to 0% at some cases but blows up to **5%** towards the end of the sequence.
- Less agreement in some case for the inverted model.

- Vertical phase beating : **10%** maximum beating with the original model which decreases in the case of the inverted model.



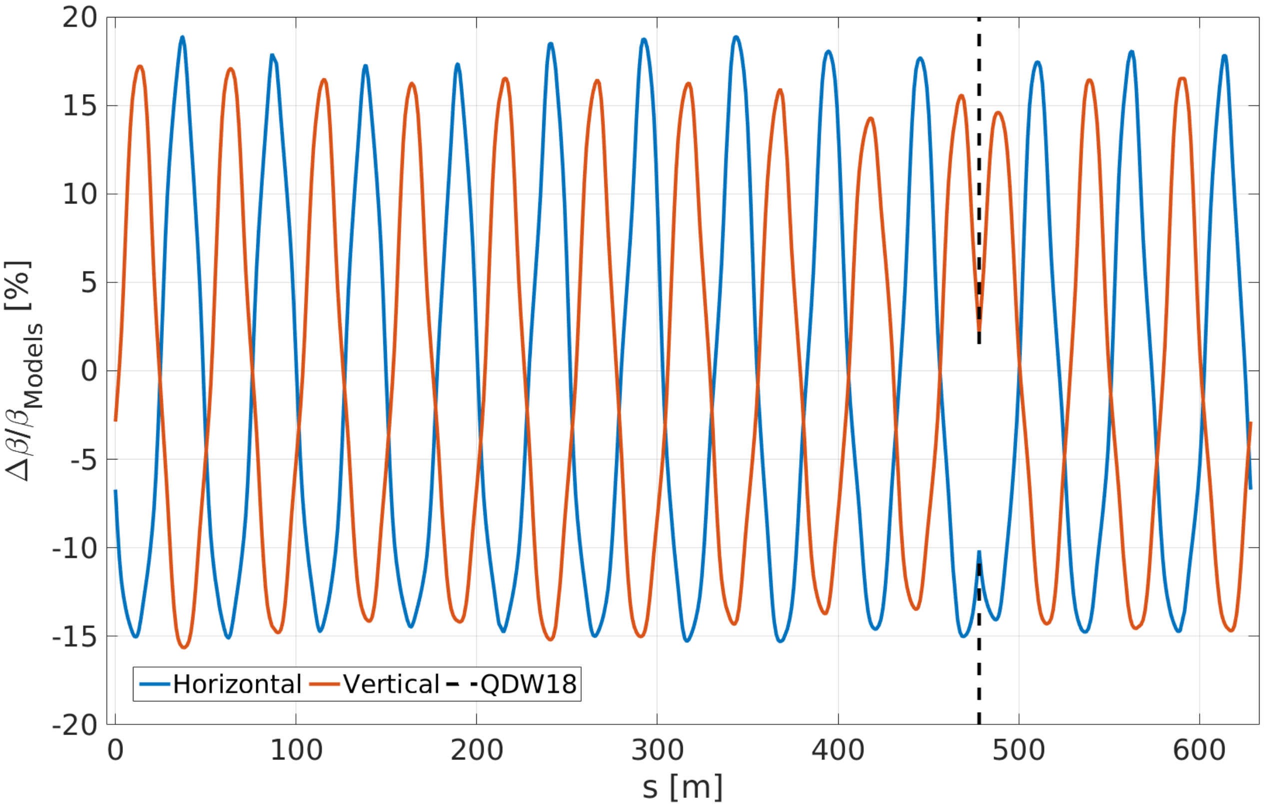
Case 1 Beta Beating





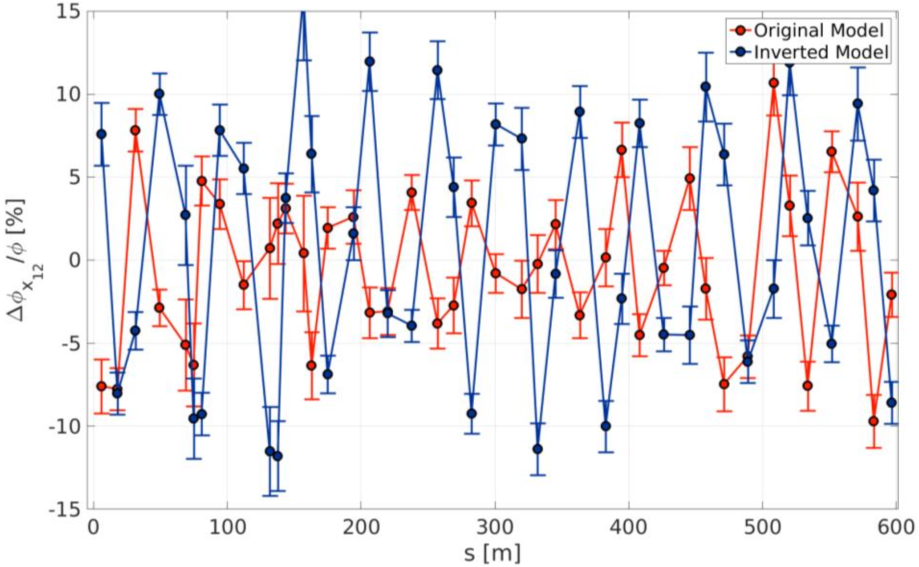
- Errorbars for the 5-BPM method: One standard deviation of the statistical uncertainty.
- Note how the vertical beta-beating reduces drastically in the case of the inverted model.
- Errorbar for the N-BPM method: Standard error of the mean and 0.1% systematic quadrupole gradient errors included.
- The phase of the beta-beating flips between the two models.

Case 2 Integer Qx: Model Comparison (Qx,Qy)~(6.11,6.24)

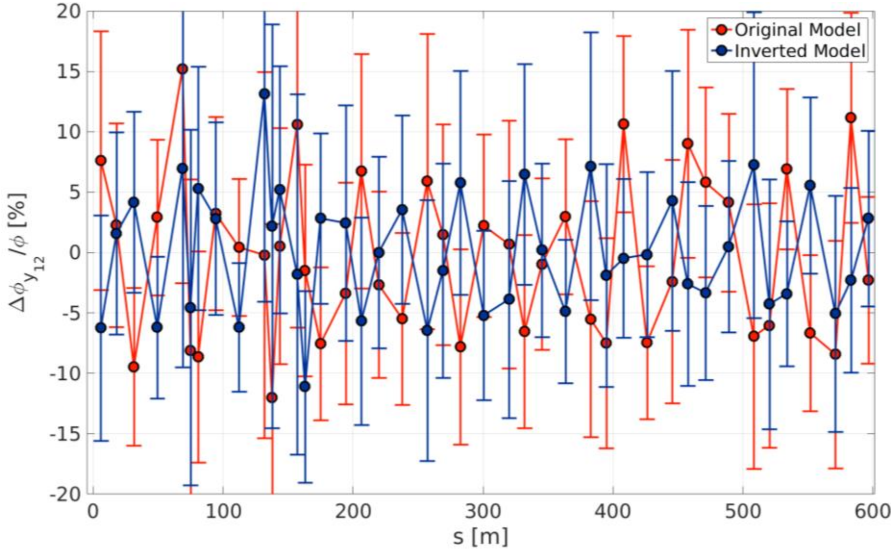


- As we approach the integer resonance beta-beating increases.
- Vertical exhibits substantial increase as well.

Case 2: Phase Beating

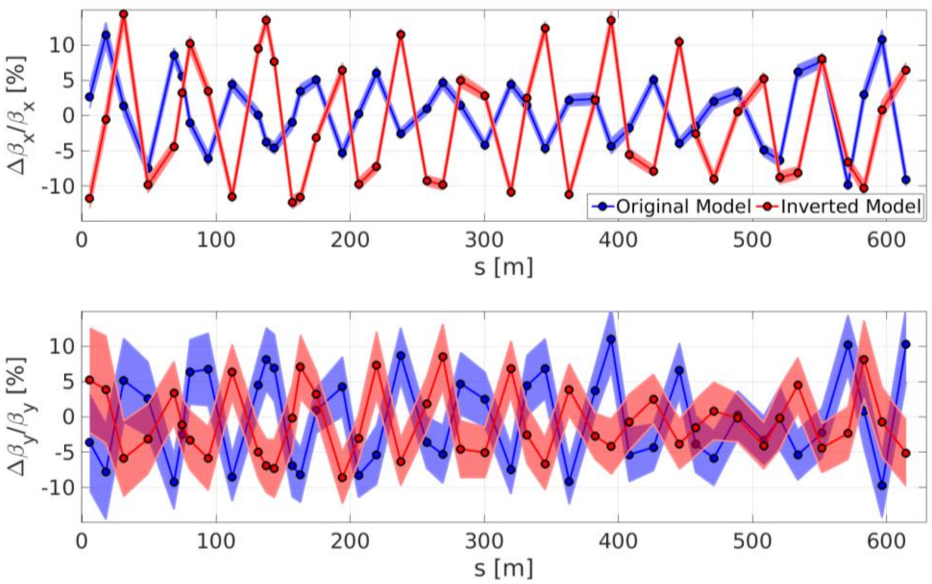


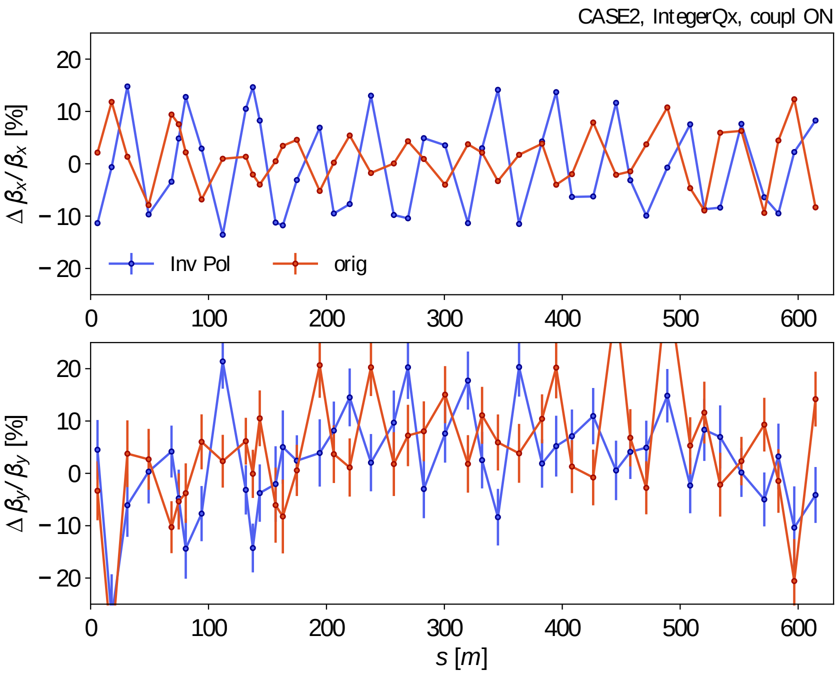
- Larger phase beating maximum at with these optics. In the original model beating increases again towards the end of the sequence.
- The inverted model produces larger phase beating !
- Very good reproducibility of the phases for these optics.



- Reproducibility of the phases is not as good due to moving away from the coupling resonance.

Case 2 Beta Beating

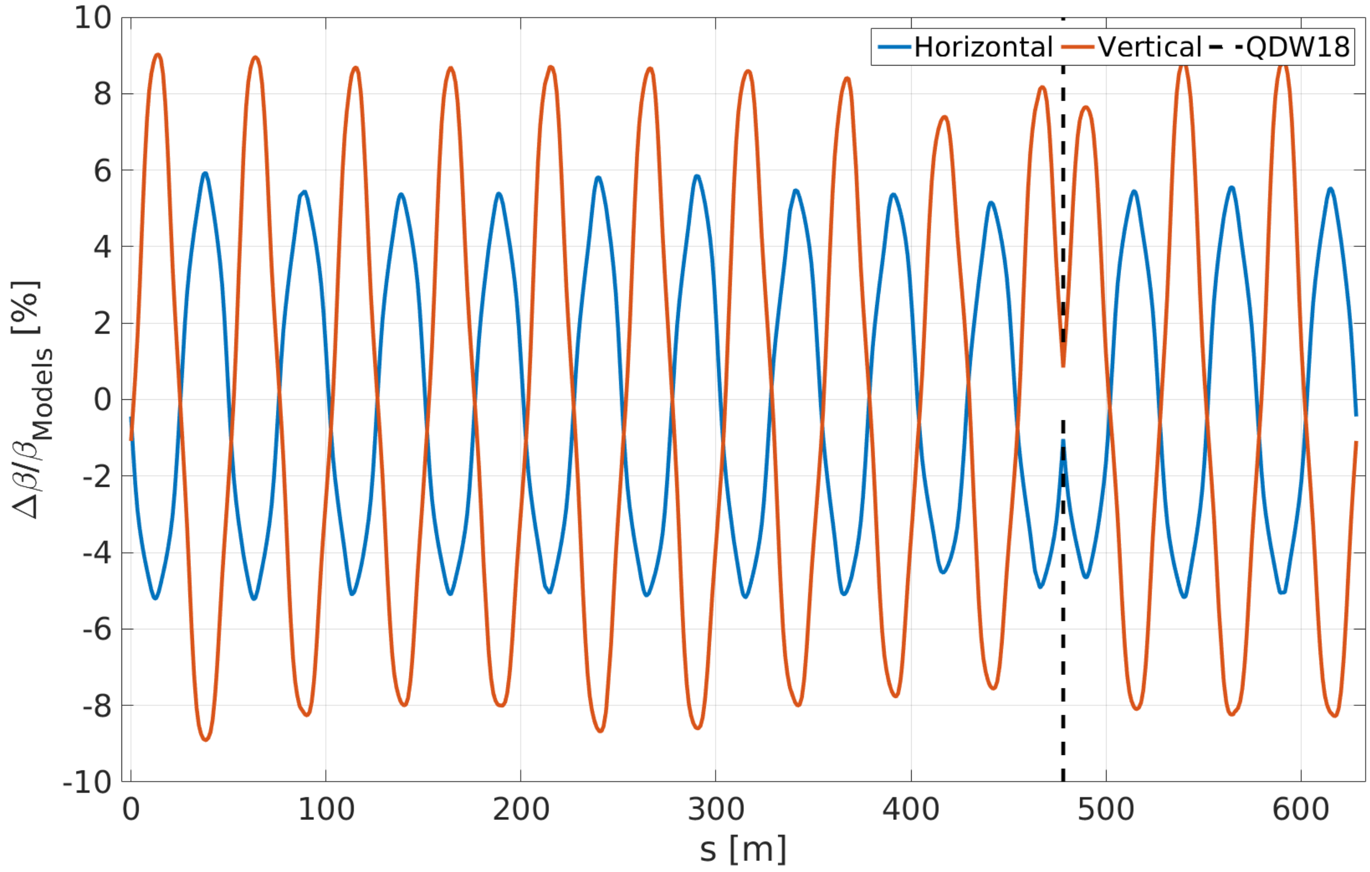




- Small statistical uncertainty for the horizontal plane and loss of precision in the vertical.
- For the original model around 5% and for the inverted around 10%.

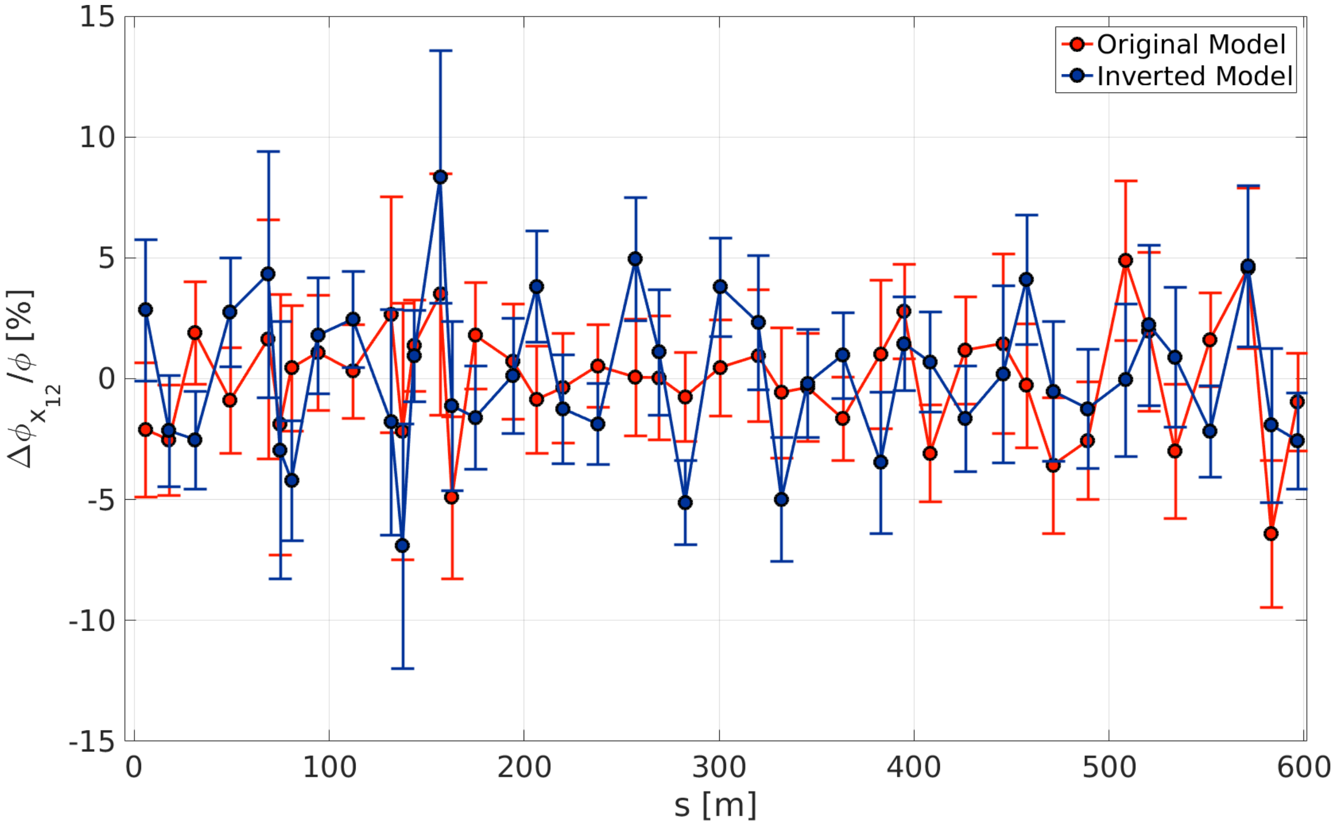
- Similar results for the N-BPM method and the large uncertainty in the vertical plane is evident.
- Note the color legend is inverted in this case!

Case 3 LEQ ON coupling corrected: Model Comparison (Qx,Qy)~(6.21,6.24)

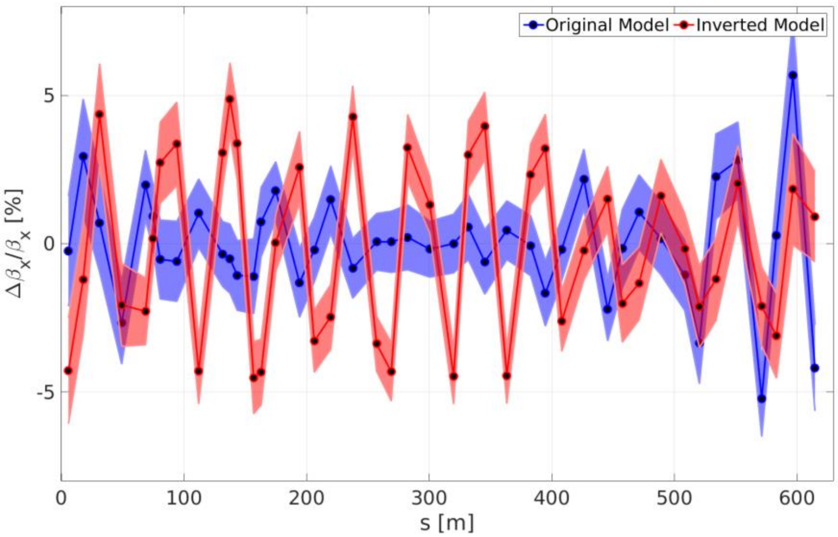


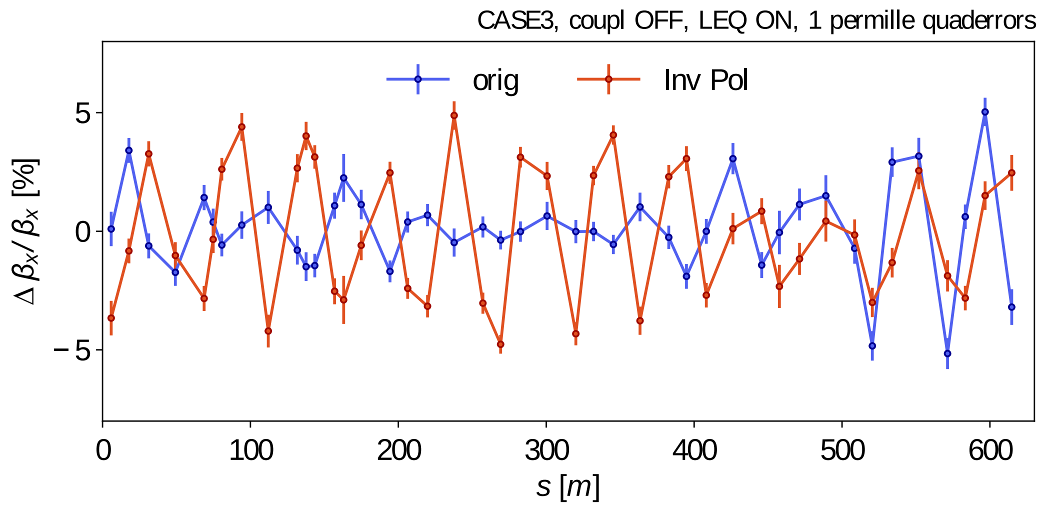
Case 3: Phase Beating

- Again phase beating with the original model is larger dowstream QDW18.
- The phase beating in the inverted model is larger upstream QDW18.
- Overall **5%** phase beating



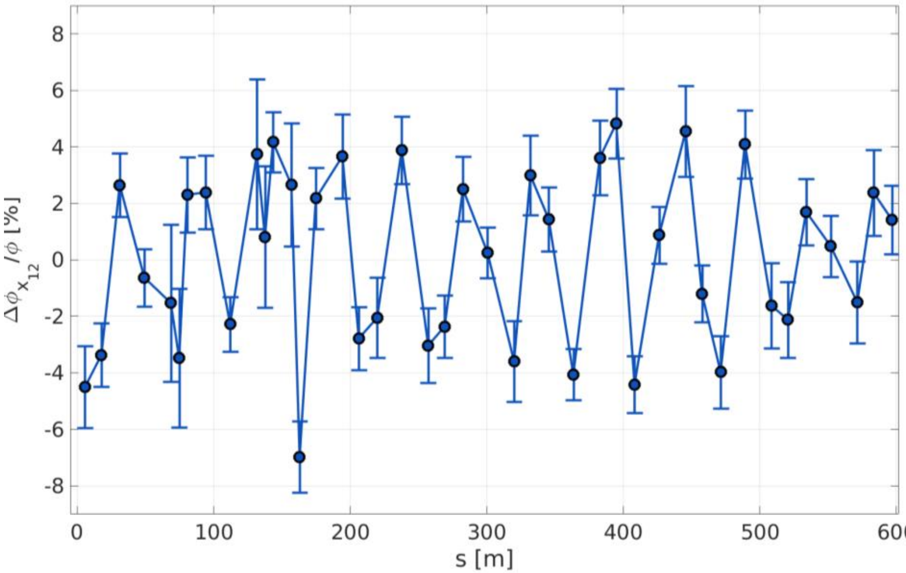
Case 3 Beta Beating





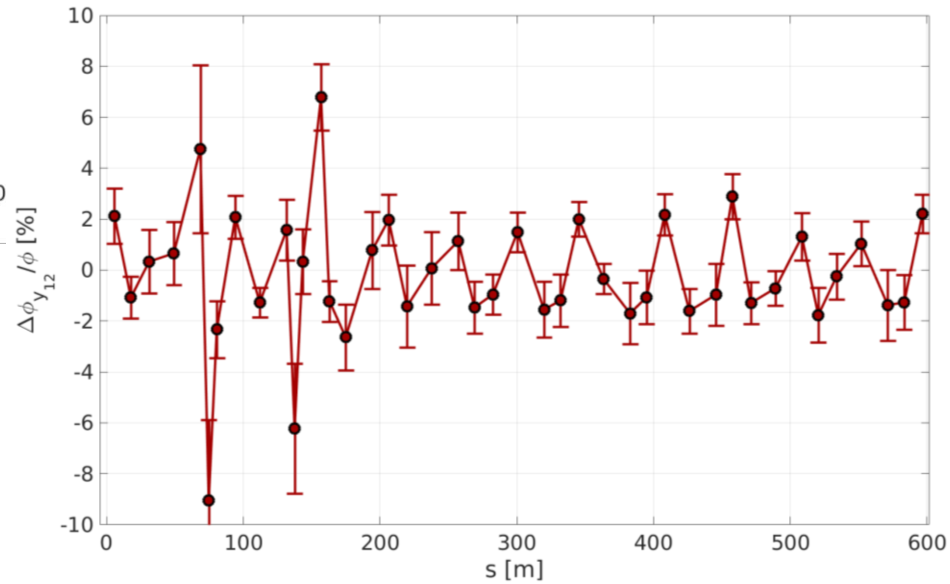
- For these optics and measurements around 1% statistical uncertainty.
- Beta-beat for the original model around 5% and for the inverted around 10%.
- Once again similar results for N-BPM with increased standard error of the mean due to small number of measurements.
- Towards the end of the sequence beating increases.

Case 4: Bare machine phase advance (Qx,Qy)~(6.24,6.29)

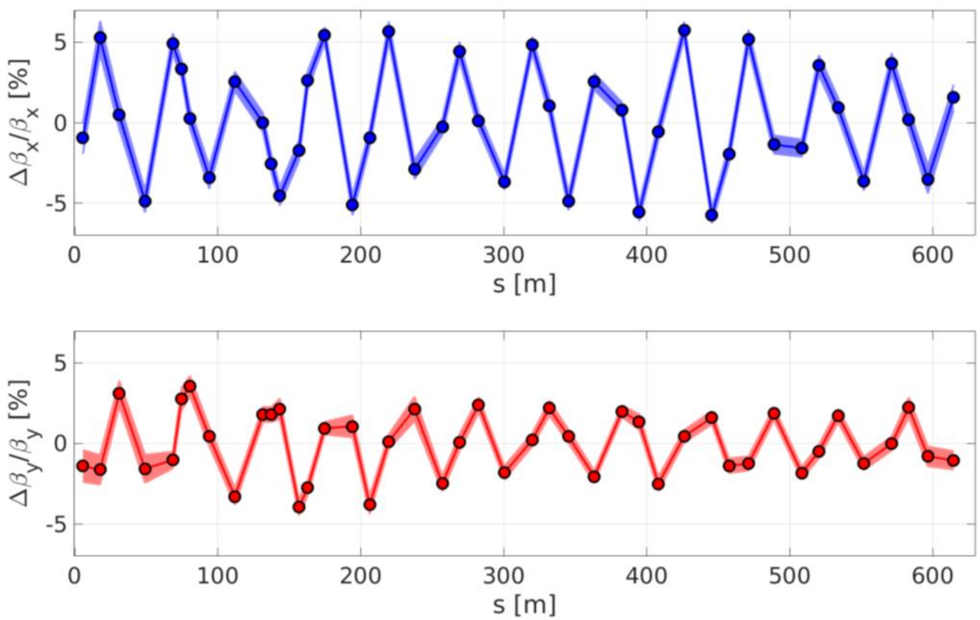


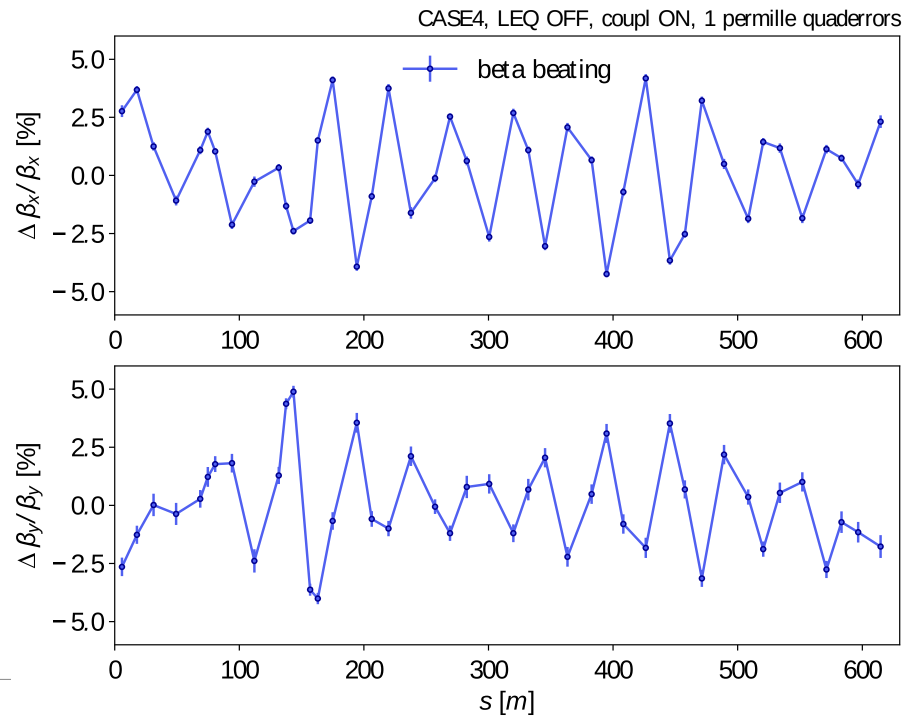
- Maximum horizontal phase beating around **4 %**
- For these optics the reproducibility is good

- Smaller beating for the vertical plane almost half the horizontal.
- The reproducibility is quite good as well.



Case 4: Beta Beating

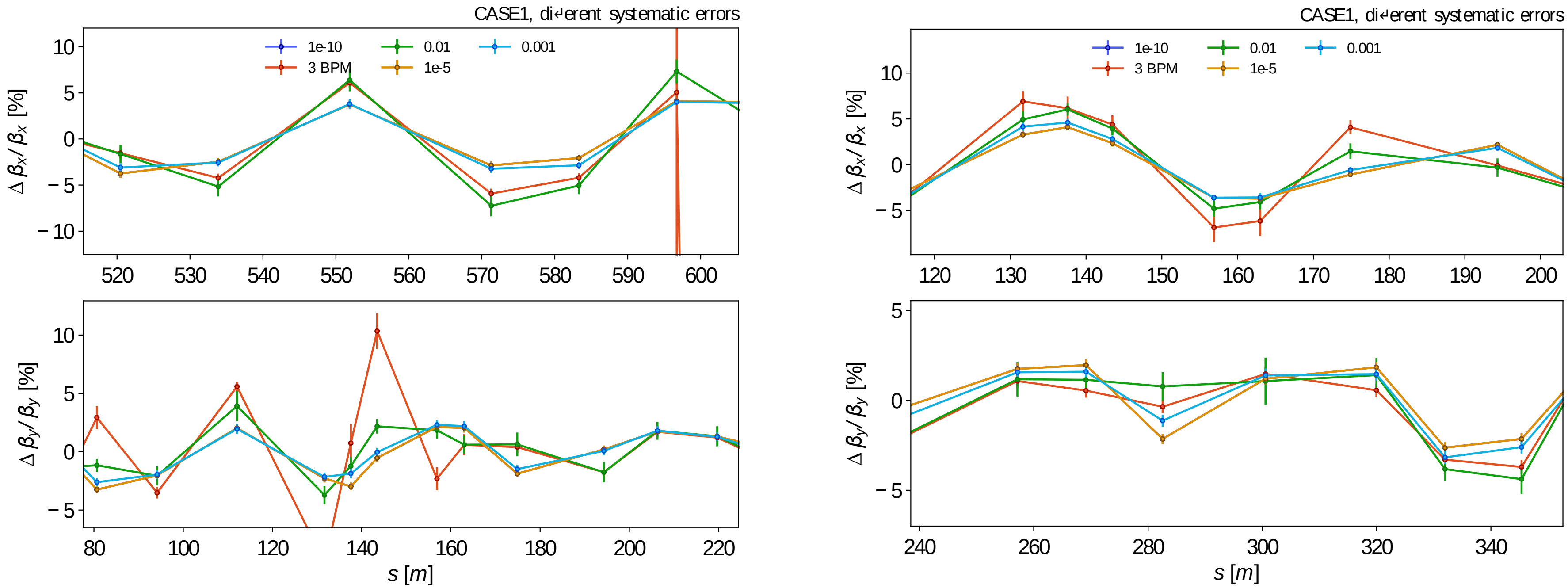




- 5 BPM method: 5 % horizontal beta-beating and smaller for the vertical plane.
- The bare machine optics exhibit a very small error in the measurements.

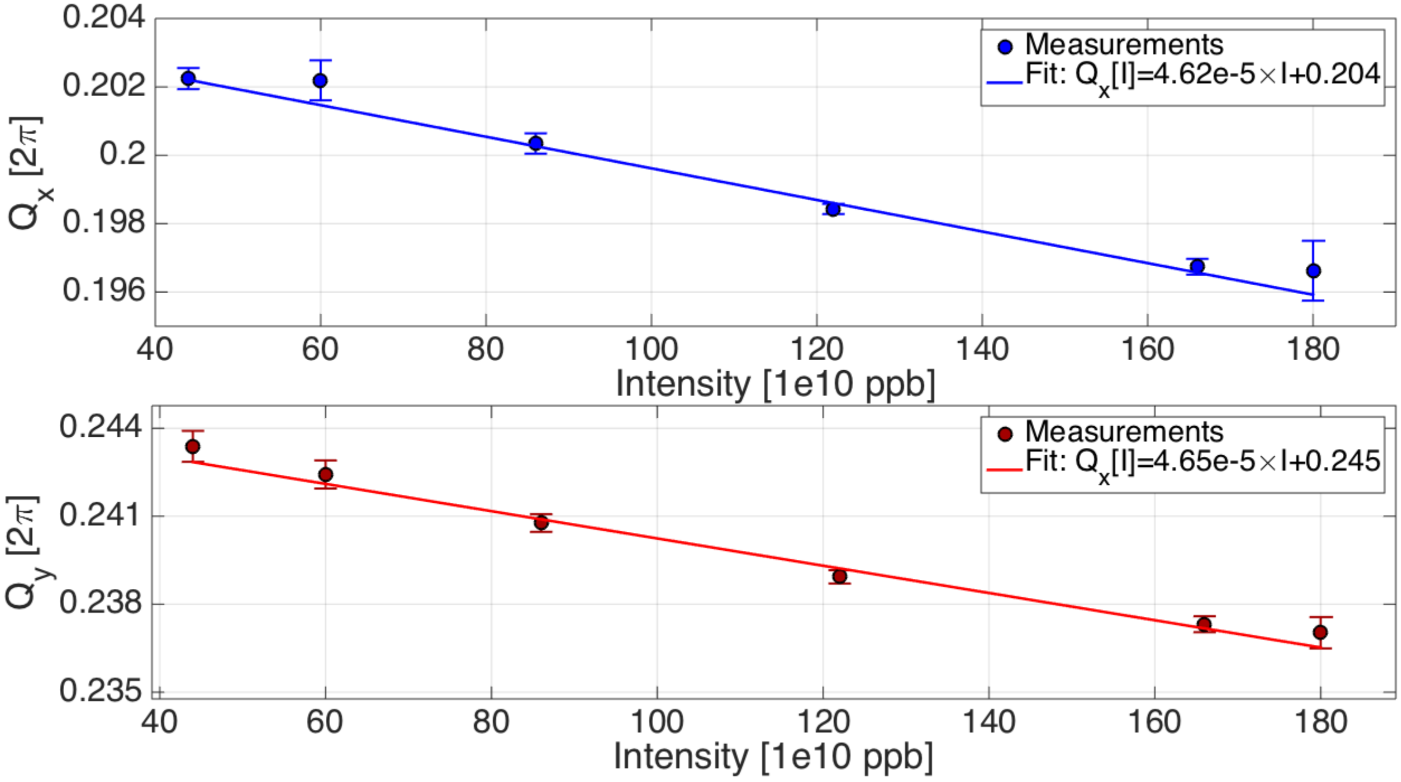
- The N-BPM method exhibits smaller beta-beating in the beginning and the end of the sequence.
- The role of the systematic errors should be properly considered.

The impact of the systematic errors in the N-BPM method



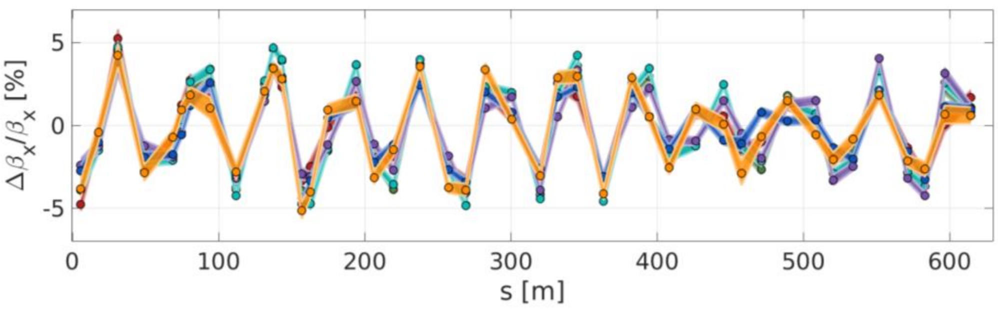
- Case 1: Measurements with 3 BPMs to be used as a reference-Less systematic errors with this configuration.
- Then use N=10 BPMs and measure Δβ/β with different quadrupolar gradient errors.
- The 1% error case seems systematically closer to the 3 BPM measurement.
- This may suggest that the initial 0.1% error may be an under-estimation.

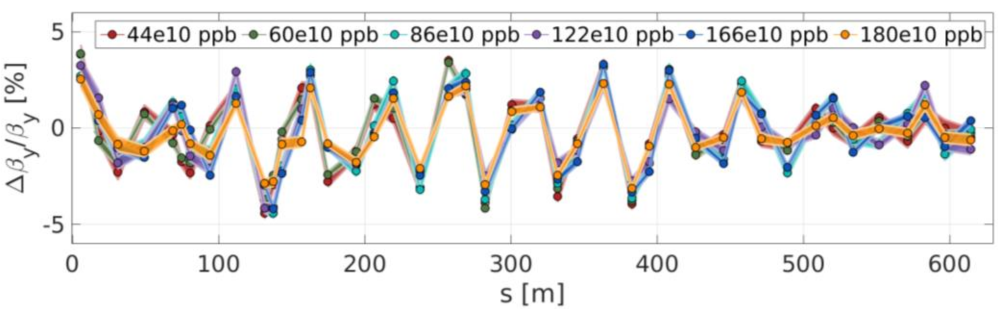
Case 5: Intensity Variation

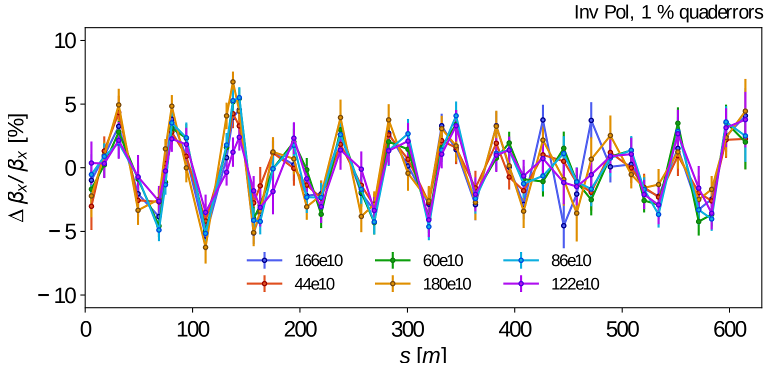


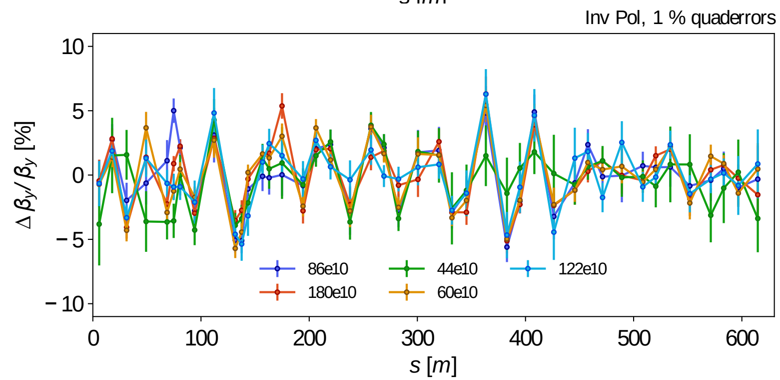
- For both planes the linear tune-shift is about: ΔQ [%]~ $4.6*10^{-3}$ [$2\pi/10^{10}$ ppb]
- Each intensity exhibits different reproducibility of the measurements.
- Frequency analysis revealed that **coupling** becomes more dominant in the Fourier spectra as intensity increases.

Case 5: Beta Beating









- All measurements bounded to the level of 5% beating.
- Largest uncertainty for the highest intensity but still less than 1%.
- In this method coupling was excluded by locking on higher harmonics.

- The N-BPM method utilizes 1% quadrupolar gradient errors in this case.
- Coupling was not treated in this method, hence the large uncertainties in both planes.
- Model for both methods: Inverted Polarity.

Conclusions

- Linear optics measurements were initiated at the PS and (thankfully!) provided us with a lot of surprises.
- A novel method for tune measurements was applied and revealed a tune modulation at the level of 10^{-2} along the bump which can be linked to time-varying multipolar fields induced by eddy-currents.
- Beta-beating analysis has been also performed by applying for the first time the standard LHC tool for optics measurement and comparing results with a simple beta-beating measurement method.
- Two models were tested and indeed inverting the polarity of the QDW18 LEQ appears to reduce the vertical beta-beating and slightly enhances horizontal beta-beating.
- With ”normal” optics a maximum 5% beta-beating is measured, which almost doubles if one approaches the integer tune.
- The effect on accuracy and precision, from the quadrupolar gradient errors in the N-BPM method, as well as from the optics , has been highlighted.
- Intensity scan revealed nothing dramatic in the distribution of beta-beating in the PS.

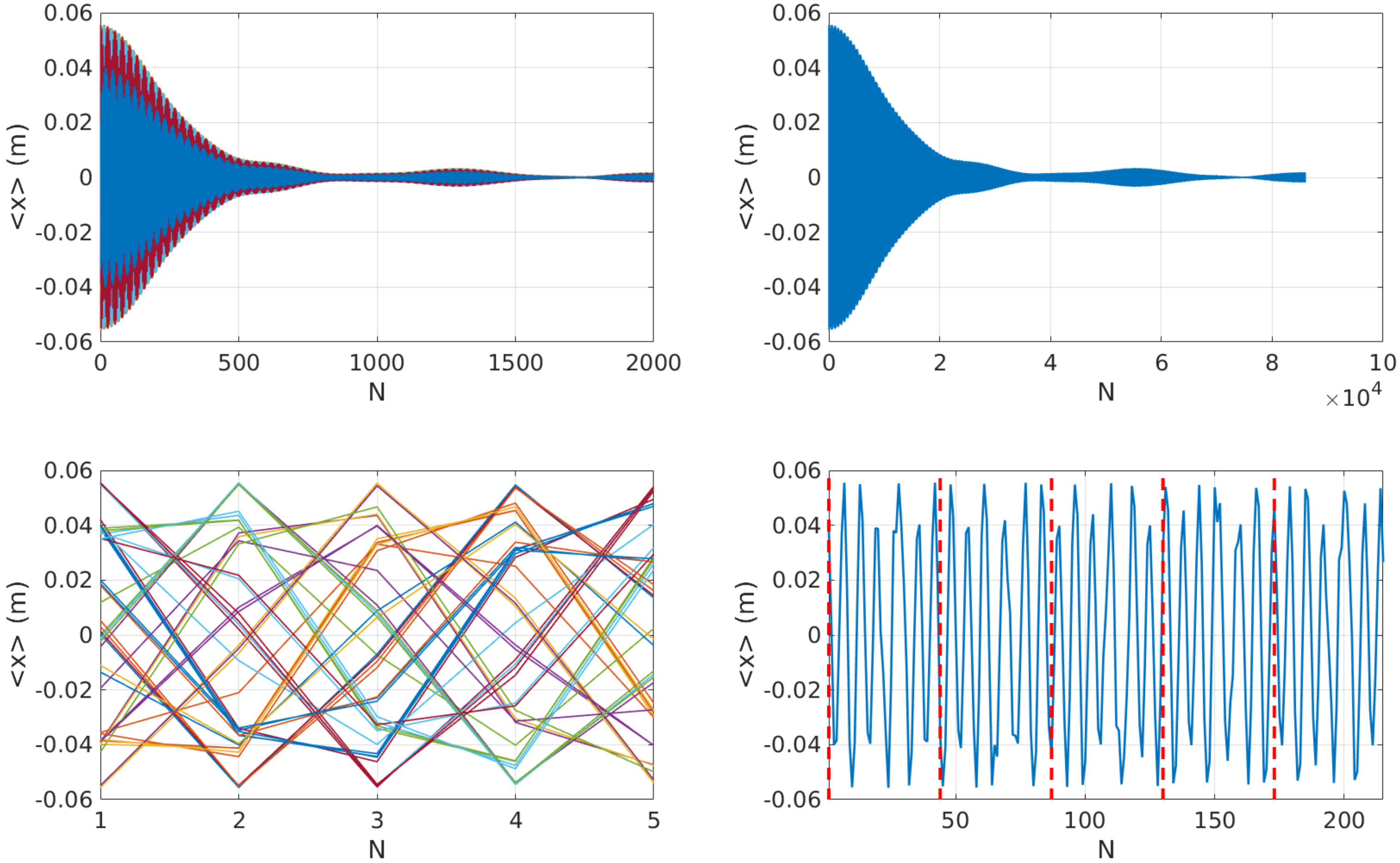
Future actions

- Produce the observed tune modulation in simulations at injection including the effect of space-charge.
- Estimate the impact of this effect on beam quality.
- Integrate the N-BPM method in the PS control room for on-line measurements.
- Run simulations for the actual contribution of the systematic errors in the measurements.
- Combine the two measurements: Beta-beating measurement during the injection bump!

Thank you for your attention !

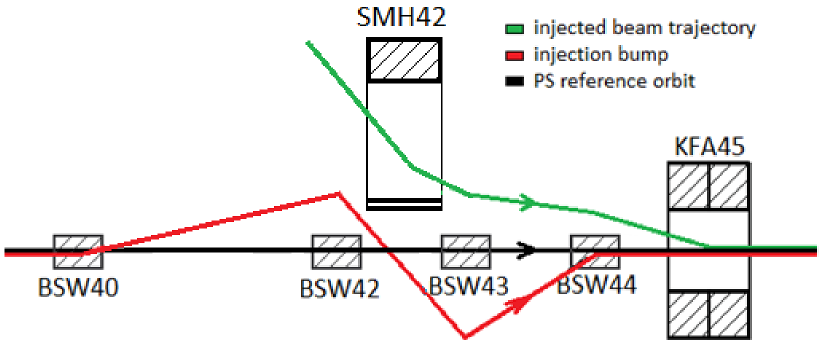
Back-up Slides

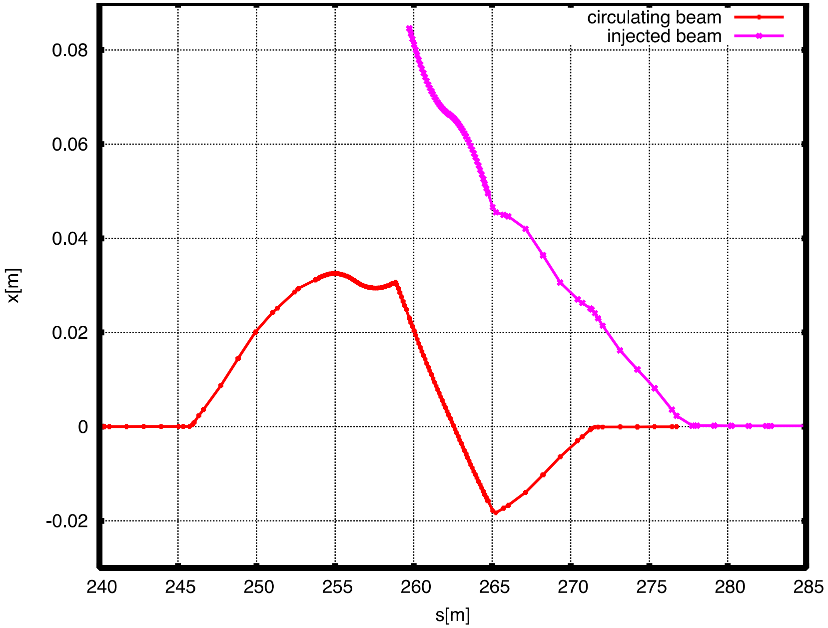
Mixing BPM scheme



PS Injection Scheme

- Single turn, bunch-to-bucket injection.
- BSW43 and BSW44 ensure zero displacement and small angle at KFA45 for the injected beam.
- In addition the bump reduces the losses at the septum blade.
- Currently injection at 1.4 GeV, will be upgraded to 2 GeV after LS2, with a faster bump.





The pictures are taken from the LIU-PS EDMS Document: **PS-M-ES-0002, EDMS No: **1557577***

And if it is a feed-down effect?

- Analytical formulae available for the sextupolar field due to eddy currents on vacuum pipes. E.g: From Syphers “An Introduction to the Physics of High Energy Accelerators”, p. 113:

$b_3=2\mu_0\sigma_c\,(\tau/g)\,(dB/dt)/(B\rho)$

σ_c : Conductivity

τ : Thickness

g : Gap

dB/dt : Bdot

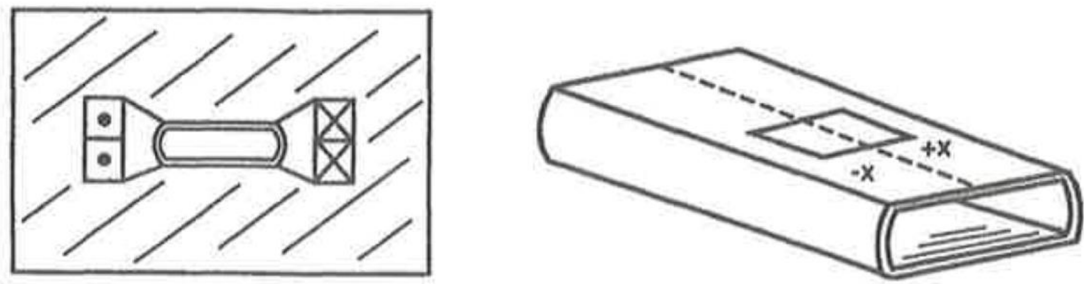


Figure 4.3. Dipole magnet with steel vacuum chamber.

Rough analytical estimation for the PS, give an effect of **10^{-2}** which is consistent to the experimental observations.

Corrections for systematic errors in the N-BPM Method

- In the presence of systematic multipole uncertainties and BPM misalignments, corrections have been derived from A.Franchi and A. Wegscheider [***PhysRevAB 20, 111002, (2017)]:***

$$\beta[s_i] = (\beta_0[s_i] - 2\alpha_0[s_i]\delta s_i)\,\frac{\cot[\varphi_{ij}] - \cot[\varphi_{ik}]}{\cot[\varphi_{ij0}] - \cot[\varphi_{ik0}] - h_{ij} - hik}$$

$$h_{ij} = sgn(i-j)\,\frac{\Delta + \sum_{i<w<j} \beta_{w0}\,\delta K_w\,\sin^2\varphi_{wj0}}{\sin^2\varphi_{ij0}}$$

$$\Delta = \frac{\delta s_j}{\beta 0[s_j]} - \frac{\delta s_k}{\beta 0[s_k]}$$

with w the elements between BPMs i,j,k, δK gradient errors, δs BPM longitudinal misalignments.

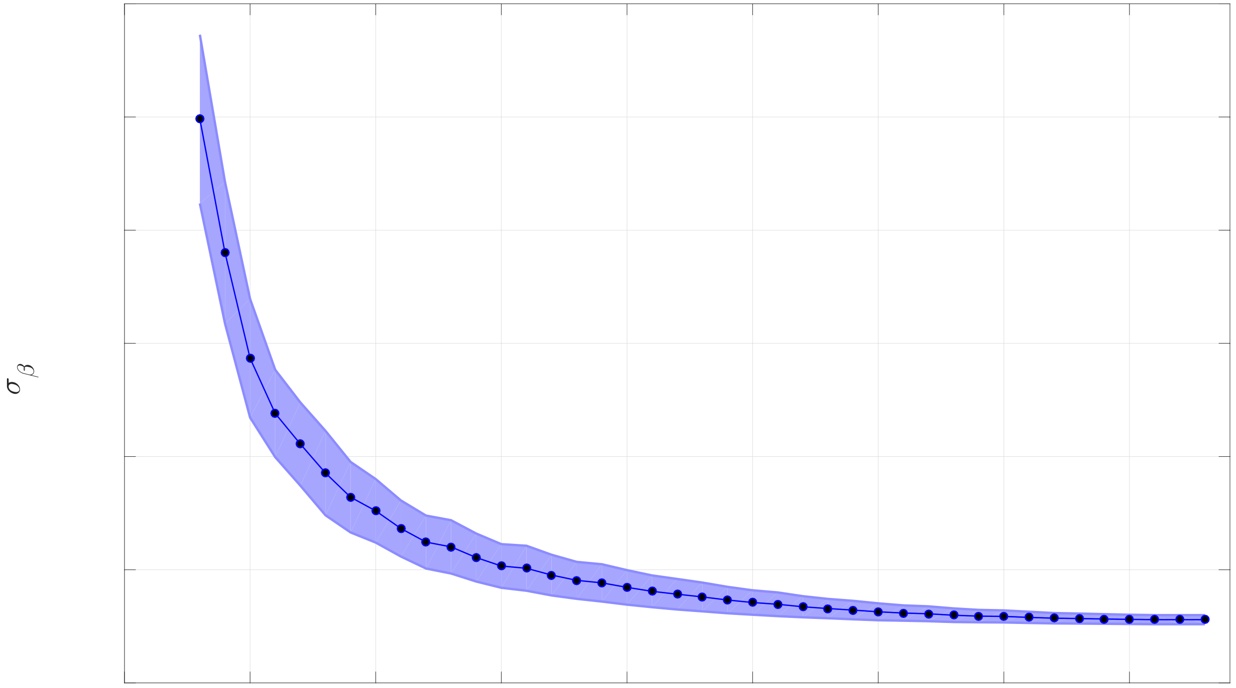
- These corrections are implemented in the N-BPM method. In the case of unknown errors one can include a normal distribution of errors on the magnets between the range of BPMs.

- For the LHC the sigma of the error distribution is 0.1% (ΔK/K).

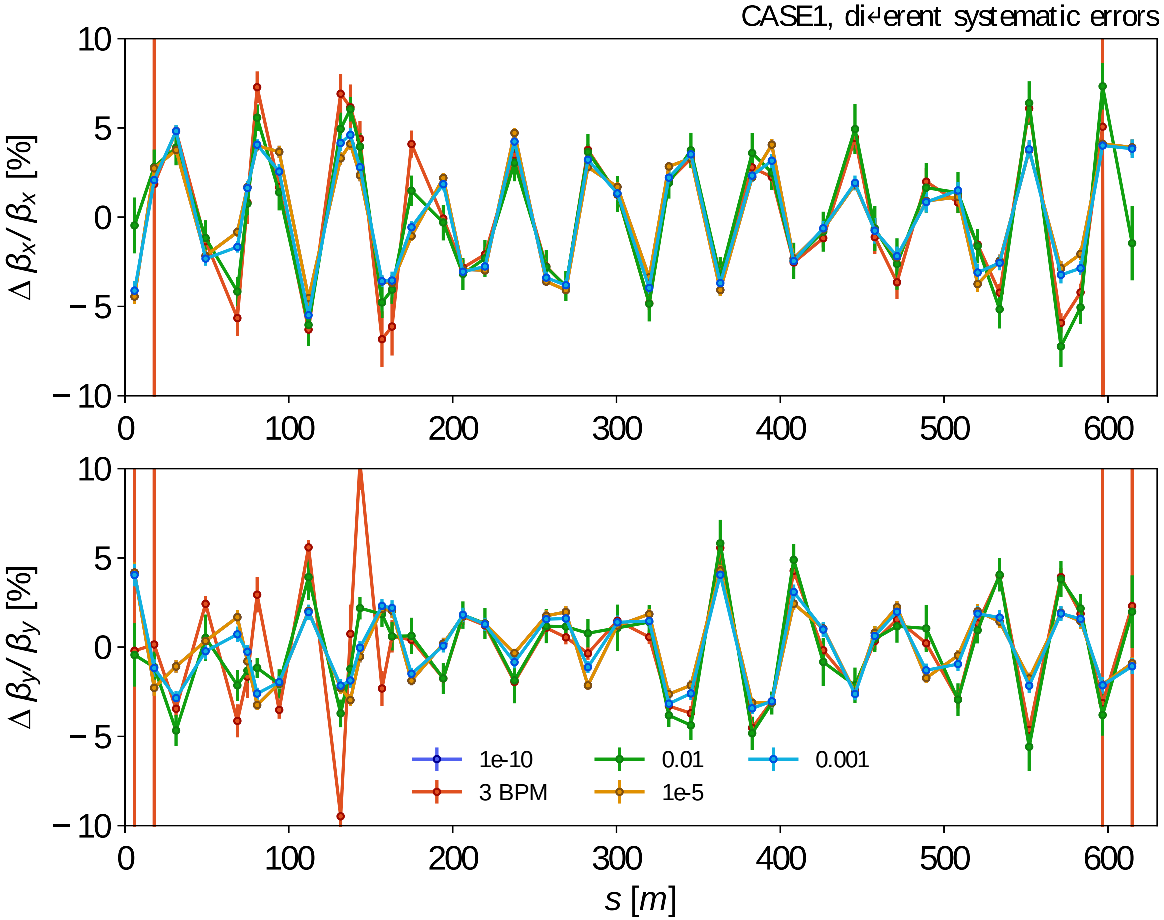
Why not all the BPMs?

- By increasing the range of BPMs, the average beta-function measurement error decreases, i.e. our statistic increases which ensures more **precise** results.

- However by increasing the range of BPMs that is used, quadrupolar gradient errors are accumulated which result in a loss of **accuracy.**

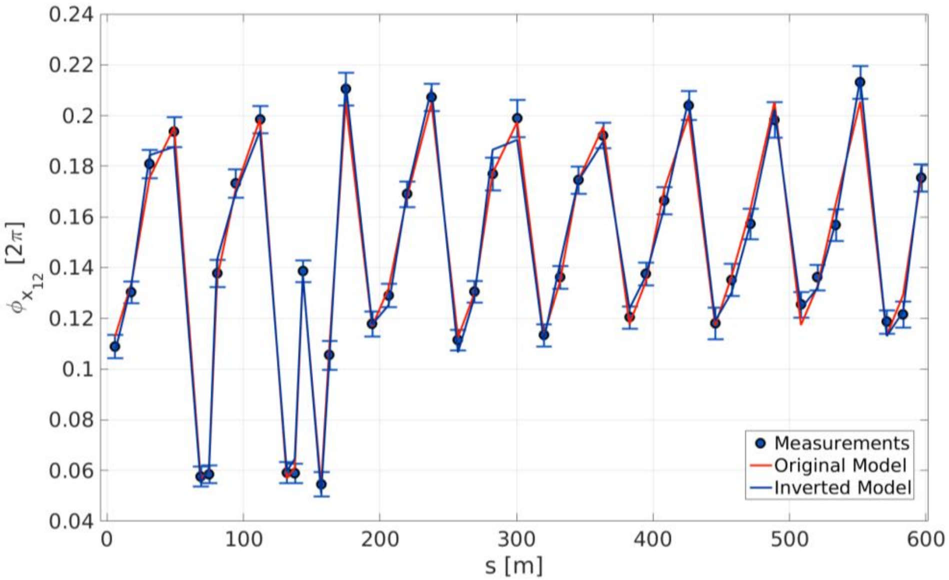


The impact of the systematic errors in the N-BPM method

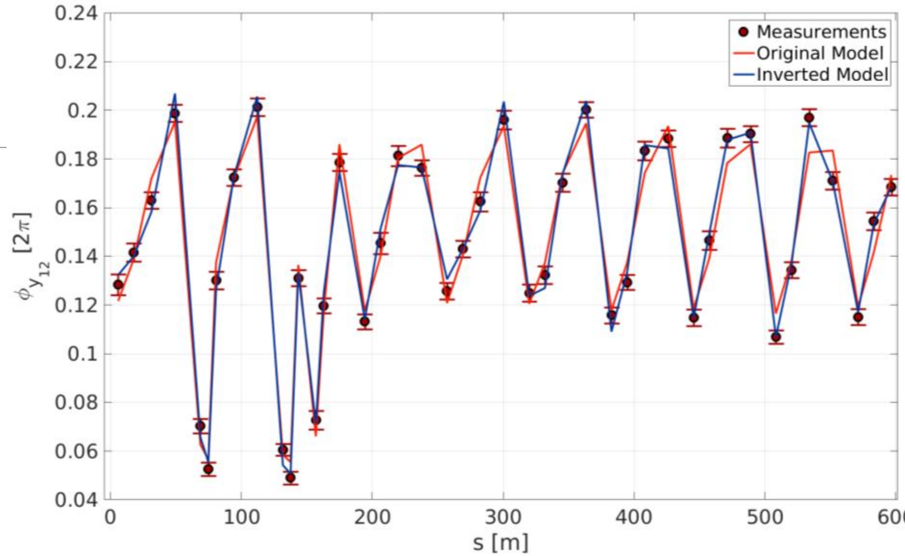


- Until now 0.1 % systematic errors were used in the N-BPM method.
- A scan however revealed their impact on the final results.
- Some BPMs show larger dispersion in the measurements due to the distribution of the quadrupoles in the PS.
- The configuration with the smallest contribution of errors from the magnets is the 3 BPM range and it can be used as a reference, although dangerous angles can be met!

Case1: Phase Advance Measurements

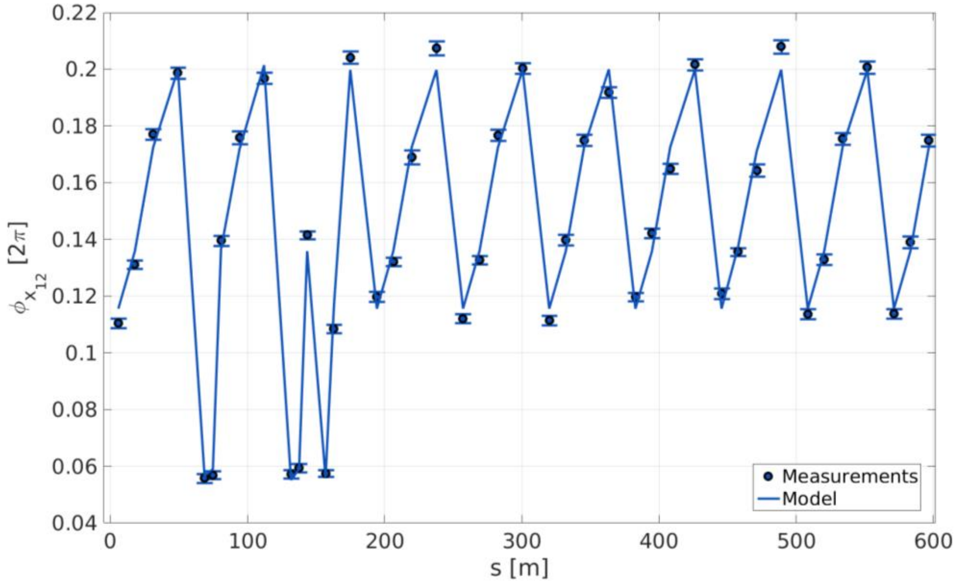


- Horizontal phase advance agrees more with the original model.
- Around 5% beating with the inverted model.
- Slightly worse reproducibility of the phase advance.



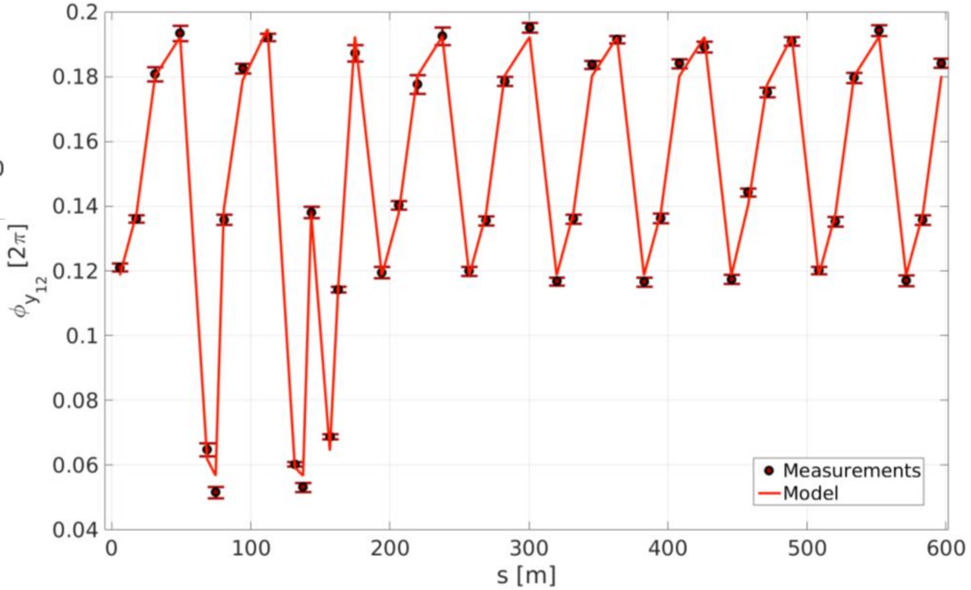
- Vertical phase advance agrees more with the inverted model.
- Around 10% beating with the original model.
- Reproducibility is better for the vertical case.

Case 4: Bare machine phase advance (Qx,Qy)~(6.24,6.29)

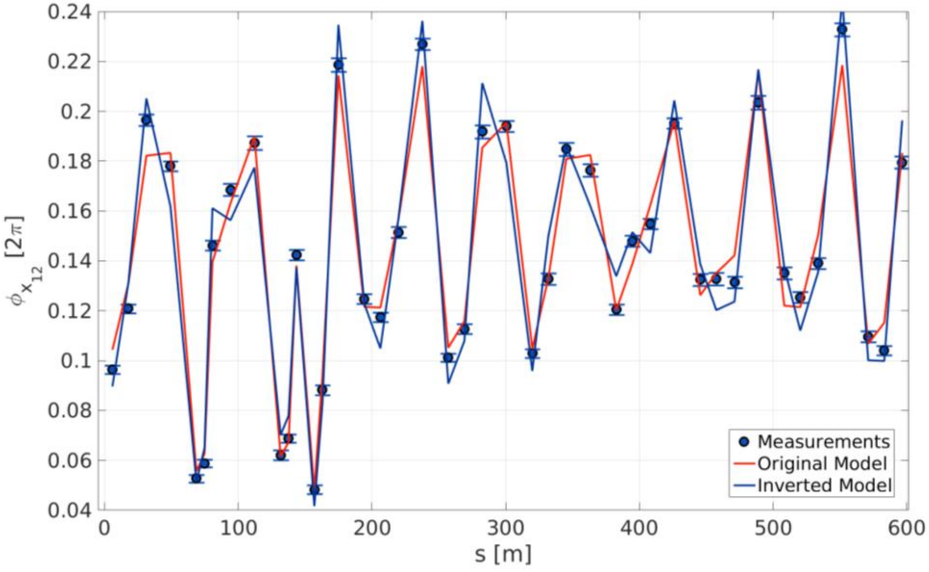


- The models of horizontal and vertical phase advance are more symmetrical for these optics
- Maximum horizontal beating around 5 %

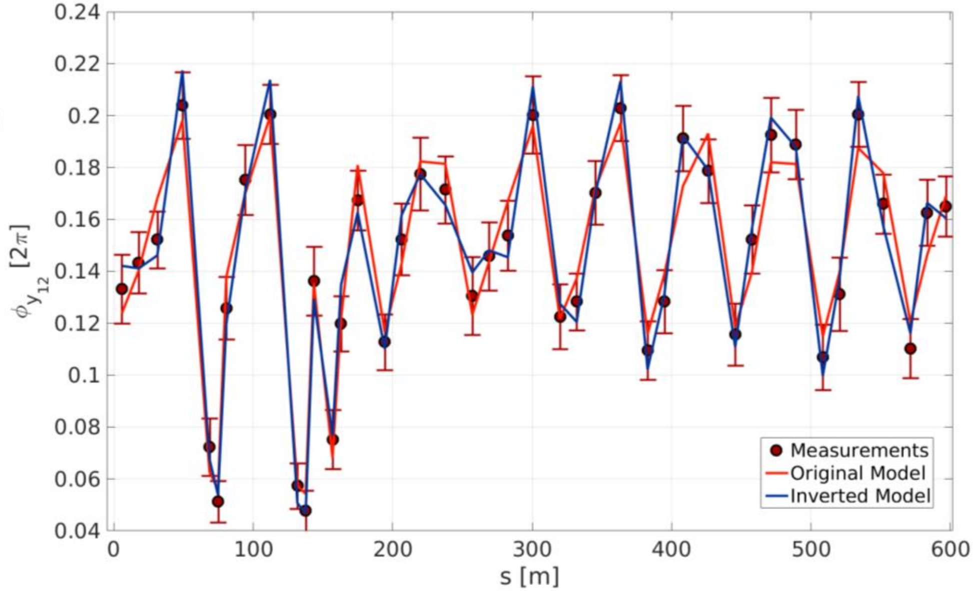
- Smaller beating for the vertical plane almost half the horizontal.
- The statistical uncertainty is remarkably low for both planes.



Case 2: Phase Advance Measurements

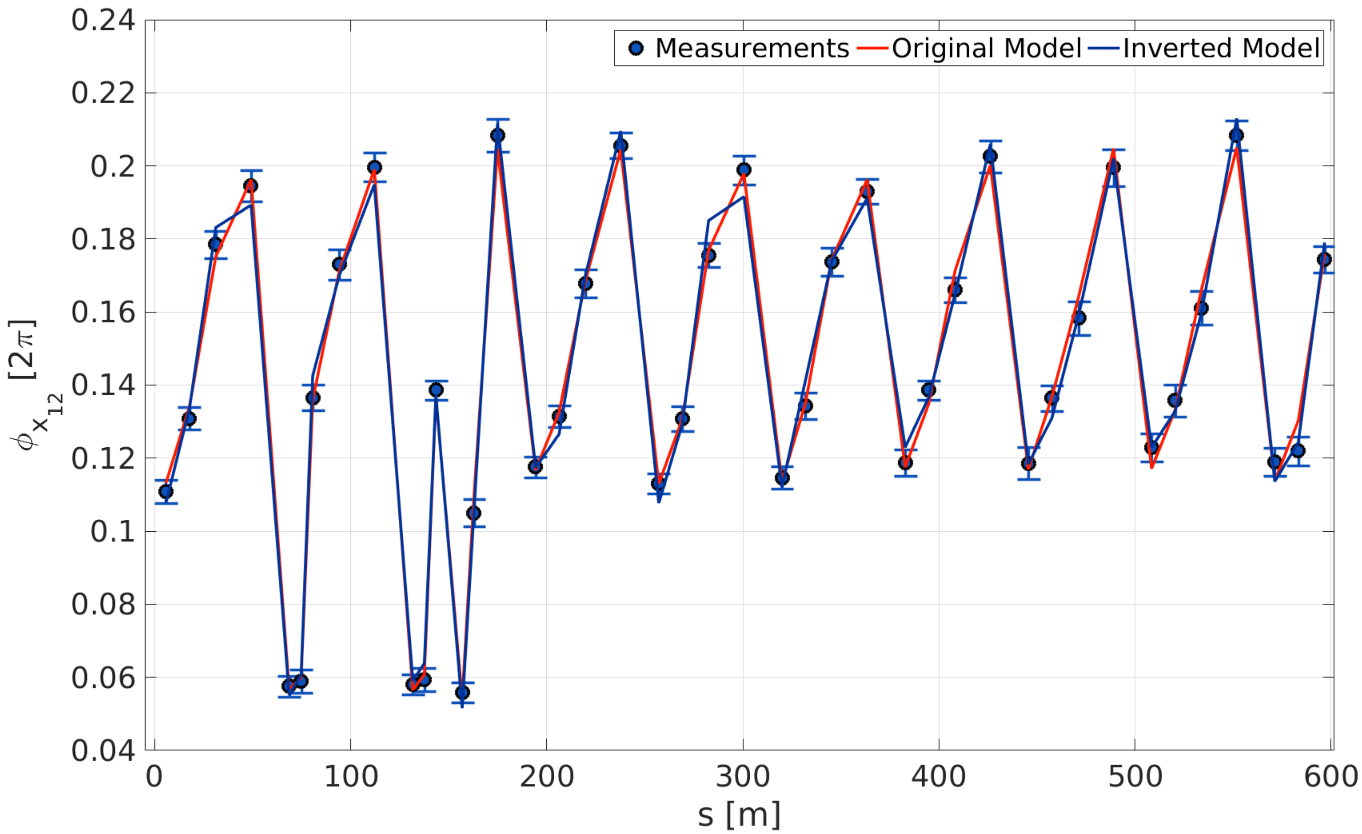


- Overall less horizontal phase beating for the original case.
- Very good reproducibility of the phases for these optics.

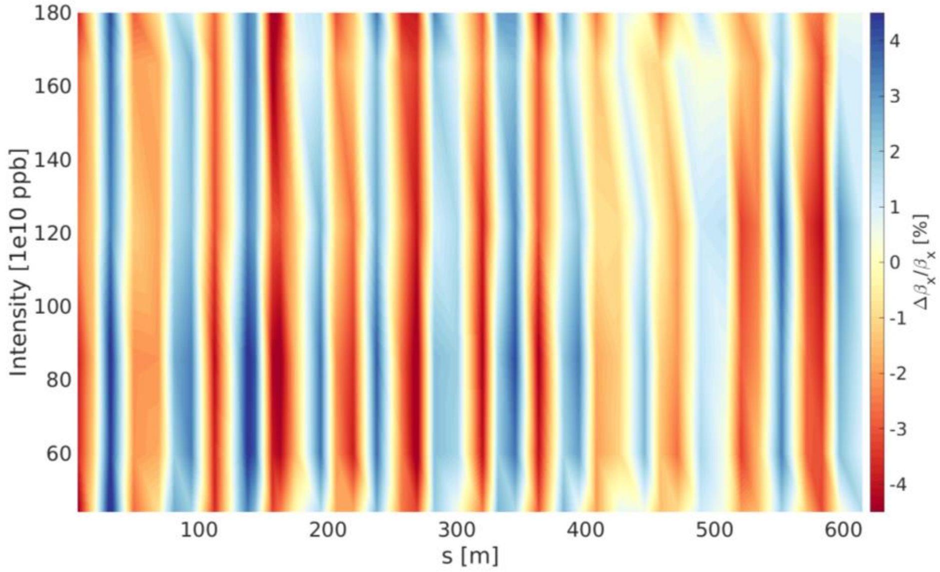


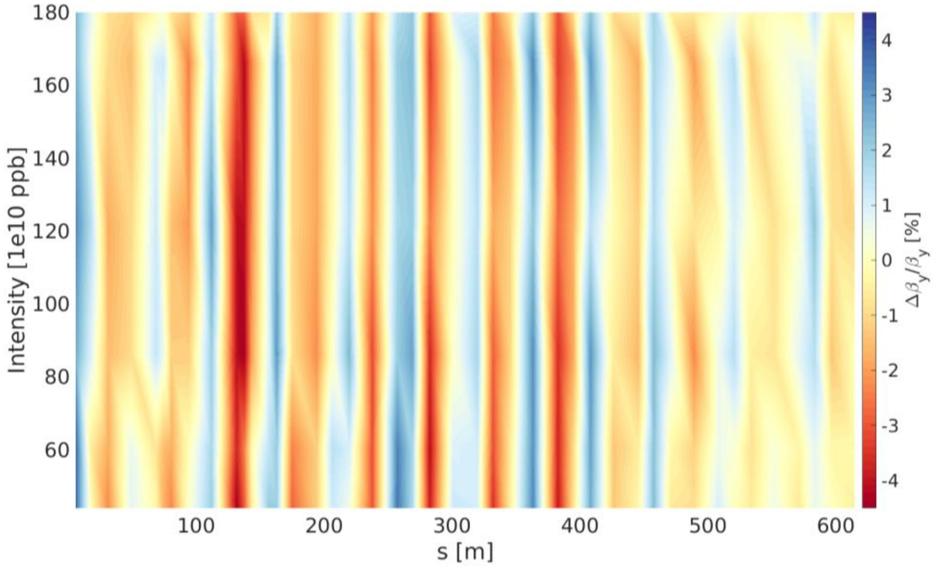
- Vertical phase advance agrees more with the original model.
- Reproducibility of the phases is not as good due to moving away from the coupling resonance.

Case 3: Phases Measurements



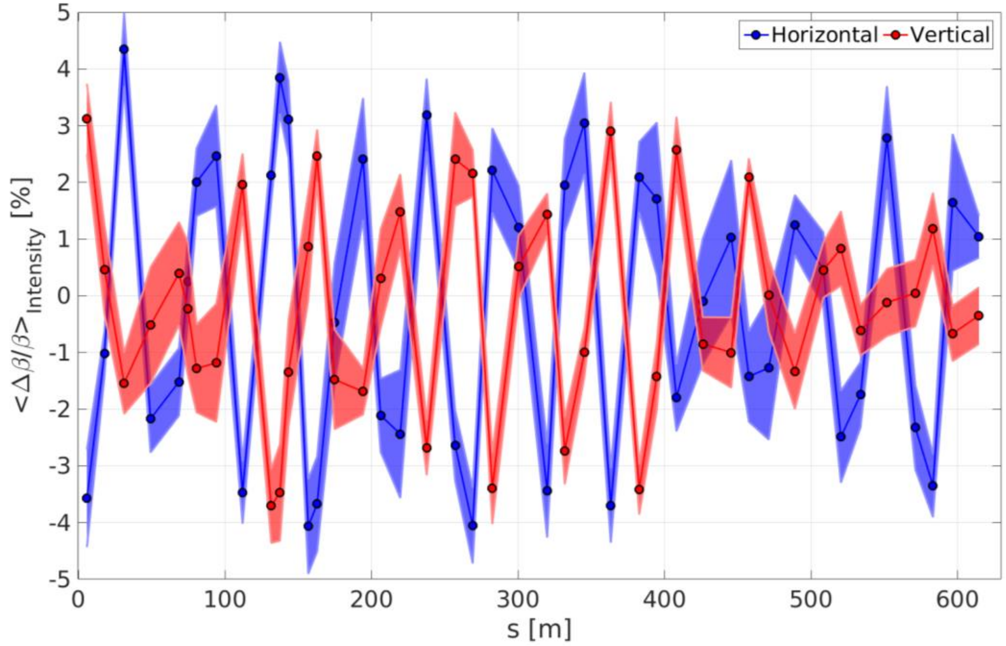
Case 5: Beta Beating





- Measurements from the 5 BPM method.
- Intensity contribution to beta-beating does not seem to be important.
- Regions where beta-beating is low seem to fluctuate more with respect to intensity.

Intensity variation Beta-beat



- Average Δβ/β with respect to the different intensities