Optics modelling / benchmarking through the complex

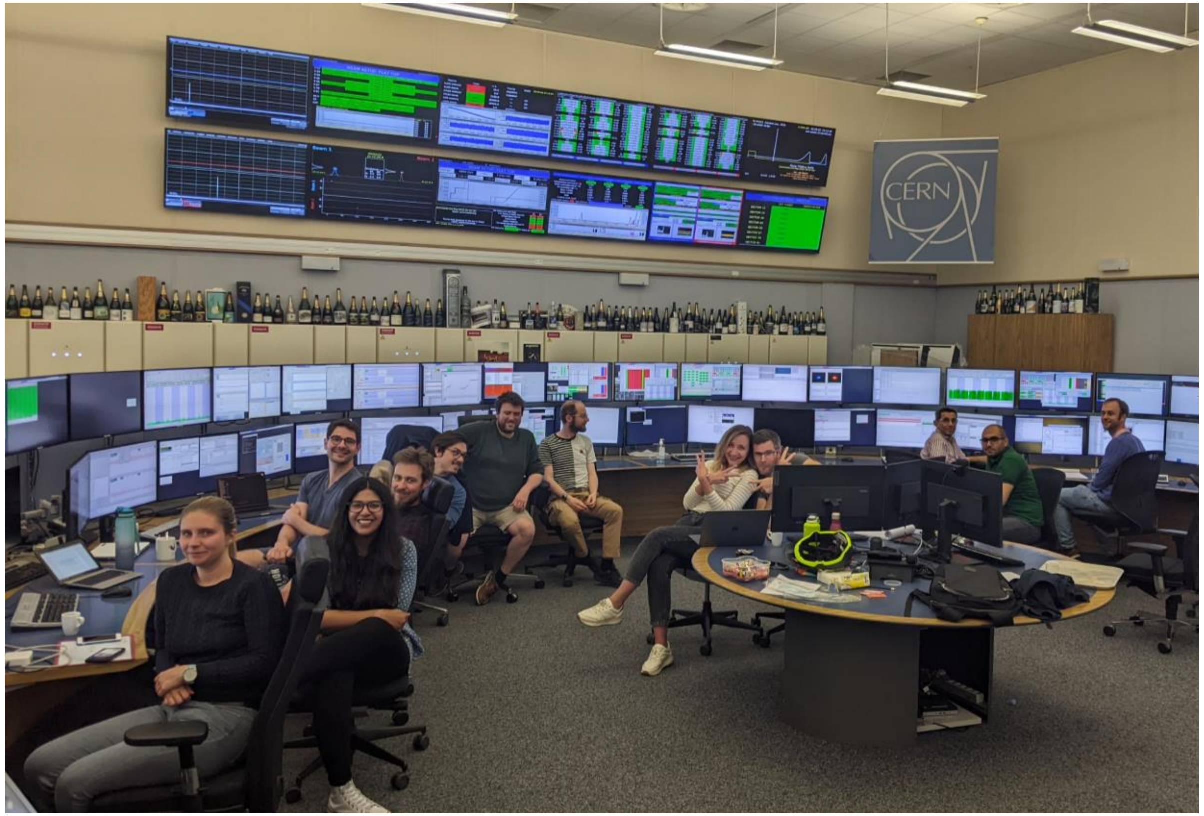
E.H. Maclean, on behalf of the OMC team:

T.H.B Persson, Y. Angelis, F. Burkhardt, J.Cardona, F. Carlier, R. De. Maria, J. Dilly, V. Ferrentino, M. Le Garrec, W. Van Goethem, S. Horney, A. Huschauer J. Keintzel, E. Kravishvili, K. Skoufaris, F. Soubelet, M. Stefanelli, R. Tomas, K. Ujani, P. Zisopoulos

Presenting activity on behalf of the OMC team

Huge thanks to very dedicated team for hard work over the last year(s)!

Many thanks to OP, collimation, optics designer, BPM, RF, ADT experts for lots of support to OMC studies!



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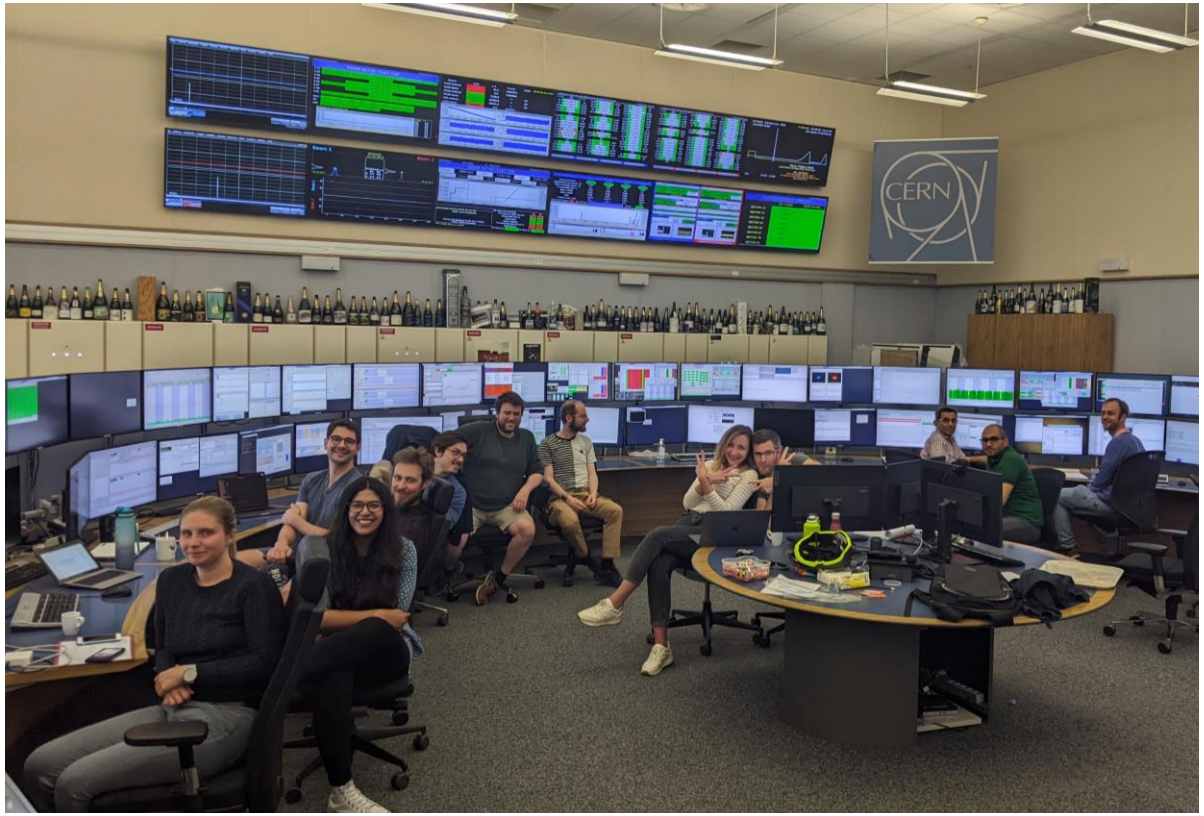
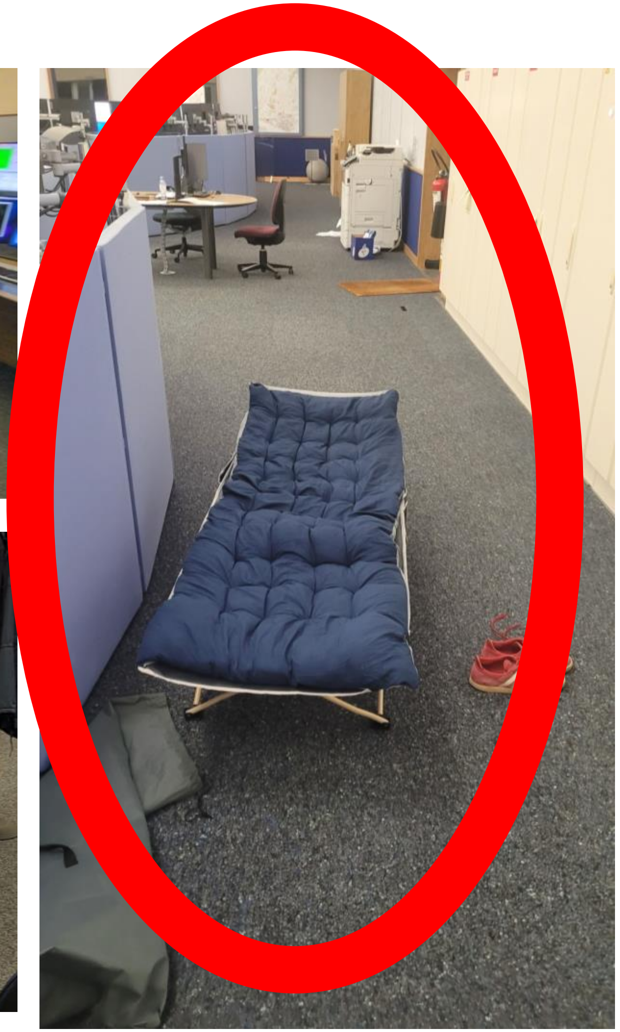




- Commissioning
- Optics corrections
- Support for emerging OP issues

(See talk by Felix in next session)

Development of methods + tools for optics measurement and correction

- Beam-based benchmarking of magnet/circuit/optics models
- Identification of HW issues, input to instrumentation, …

(this talk)

(In practice a very artificial distinction in activity)

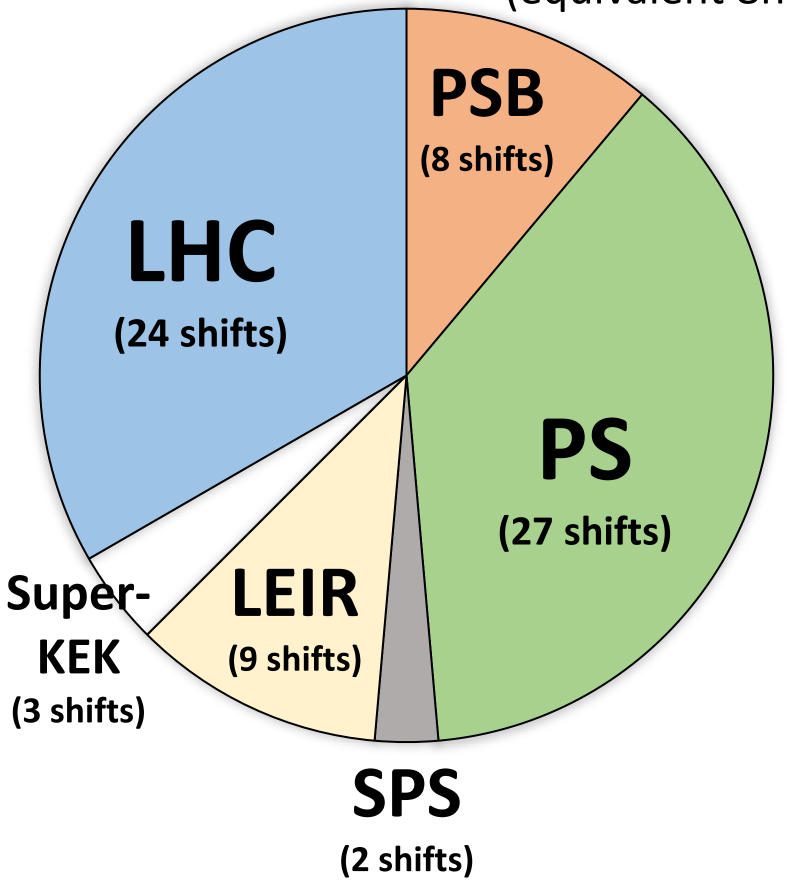
Historically OMC team only focused on LHC

➡ During Run3 expanded to also study optics in injectors

Consider status of optics benchmarking throughout the chain

- **PSB**
- **PS**
- **SPS**
- **LHC**
- **LEIR** (see talk in next session by F.Carlier)

e.g. OMC MD/commissioning in 2024
(equivalent 8h shift)

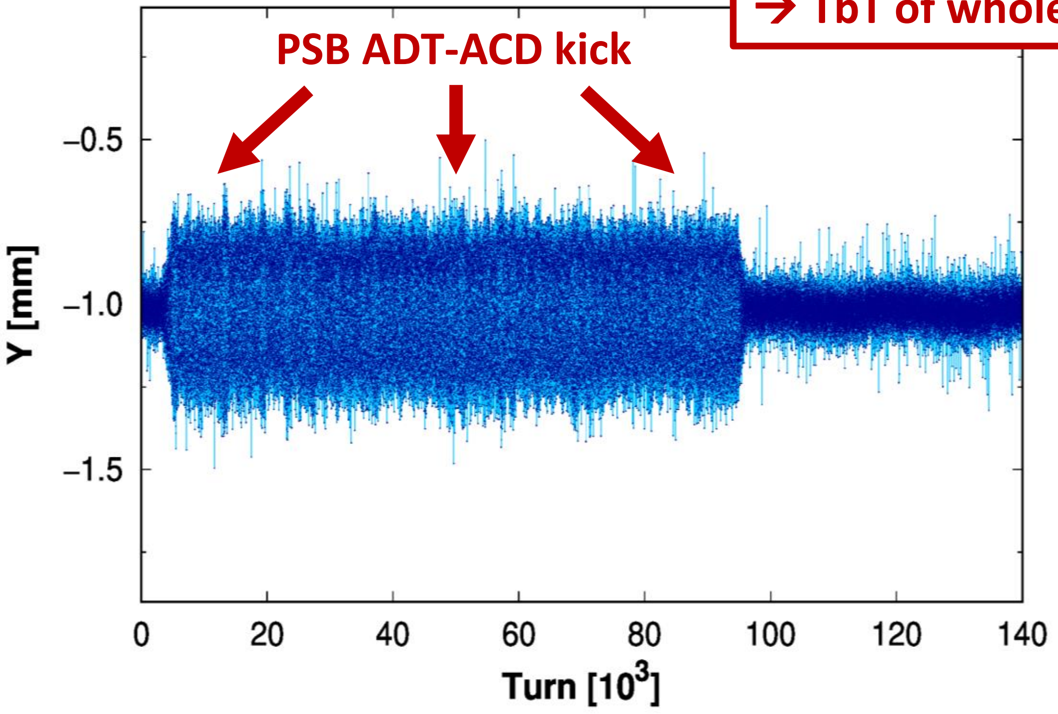


PSB

In PSB want to benchmark measured optics quality w.r.t. the design model (especially at instrumentation)

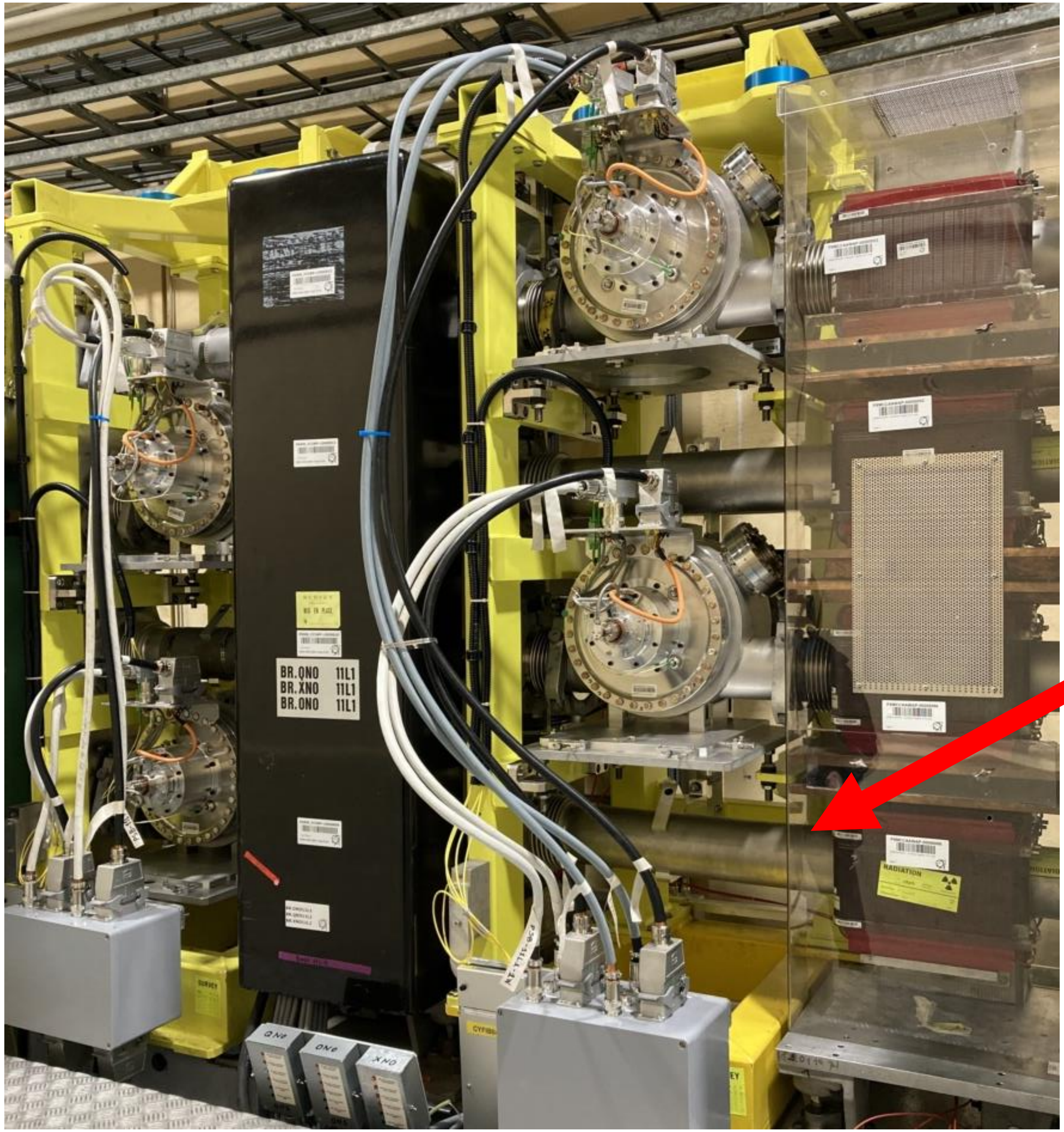
➡ **Several significant HW developments to support this during Run3**

- **Improvement to kick amplitude & implementation for ADT-AC-dipole by avoiding BBQ attenuation** (thanks: T.Levens, G.Koitzan)
- **Dramatic increase in logged turn-by-turn data in PSB and PS BPMs: 10k / 5k → 800k / 80k** (thanks M.Bozzolan & S.Bart Pedersen)
- **Single powering of QNO.11L1 to allow K-mod at vertical wirescanner**



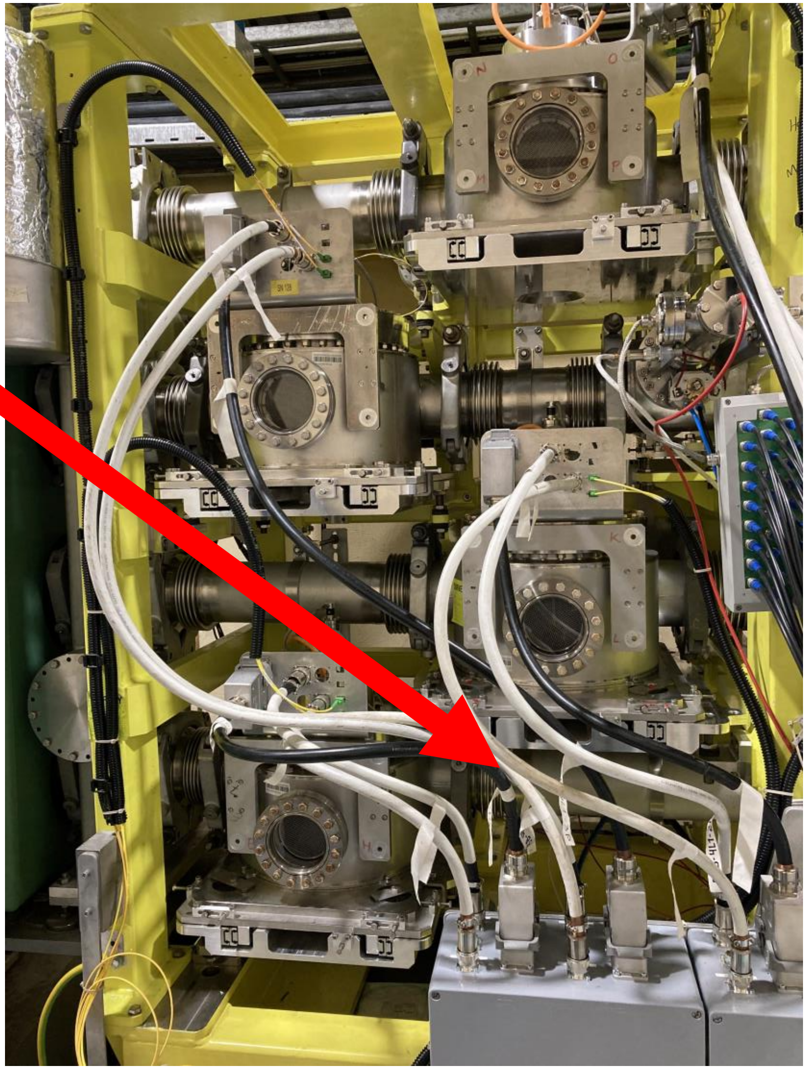
New PSB TbT GUI
→ TbT of whole cycle!

Two new BPMs installed in Ring1 at the wirescanner locations

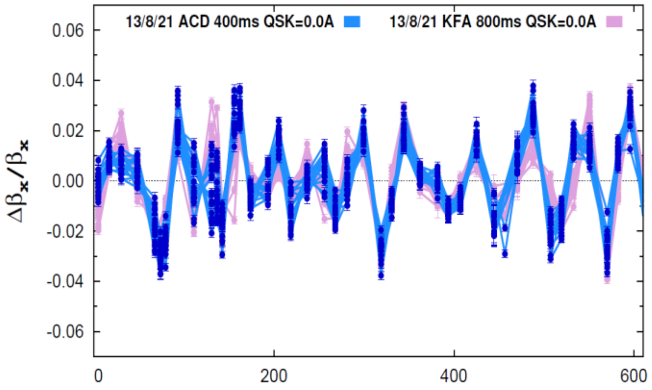


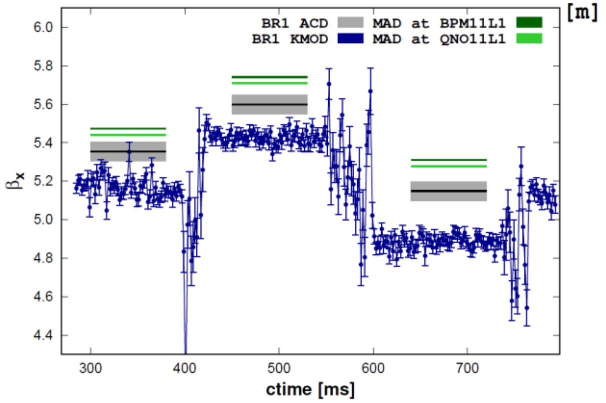
BR1.BPM4L1

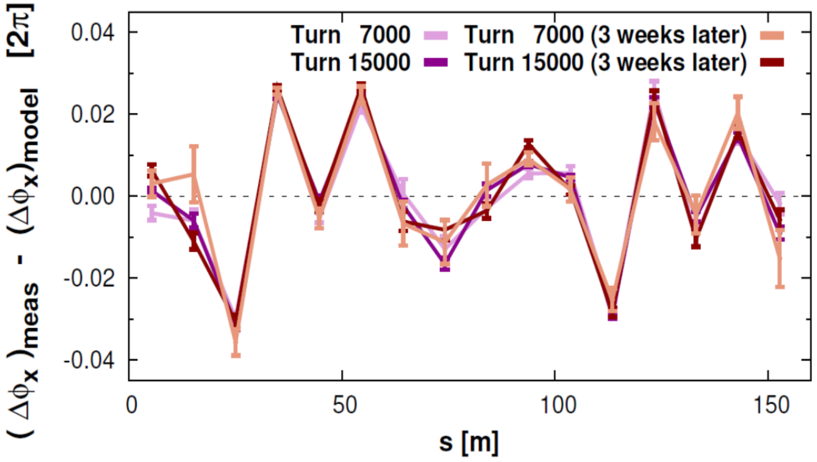
BR1.BPM11L1

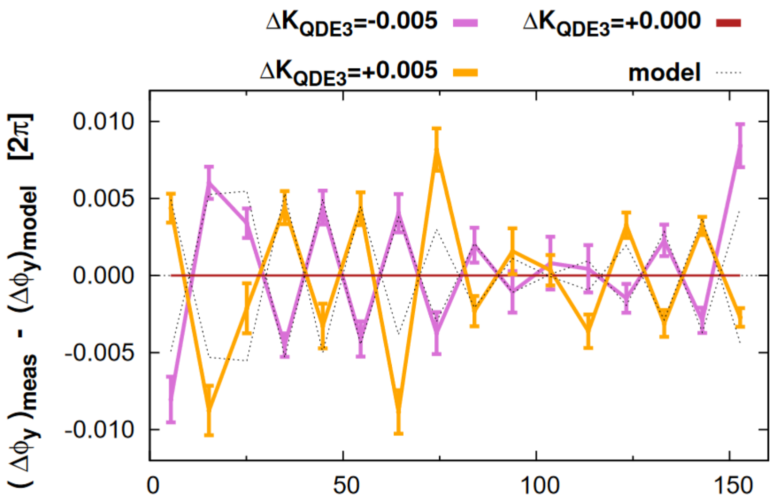


Photos before installation, courtesy M. Wendt









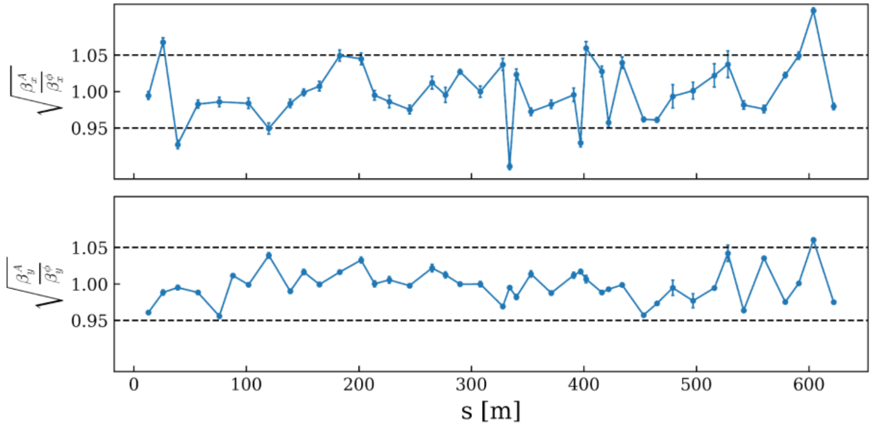
Benchmarking different techniques

Testing optics jitter/stability

BPM	$\Delta\beta_{x,model}$	$\Delta\beta_{x,meas}$
4L1 $\beta_x = 5.62\text{m}$	$+0.14\text{m}$	$+0.12\text{m}$
11L1 $\beta_x = 5.74\text{m}$	-0.03m	$+0.01\text{m}$

Beam-based checks of BPM sync, quality, calibration

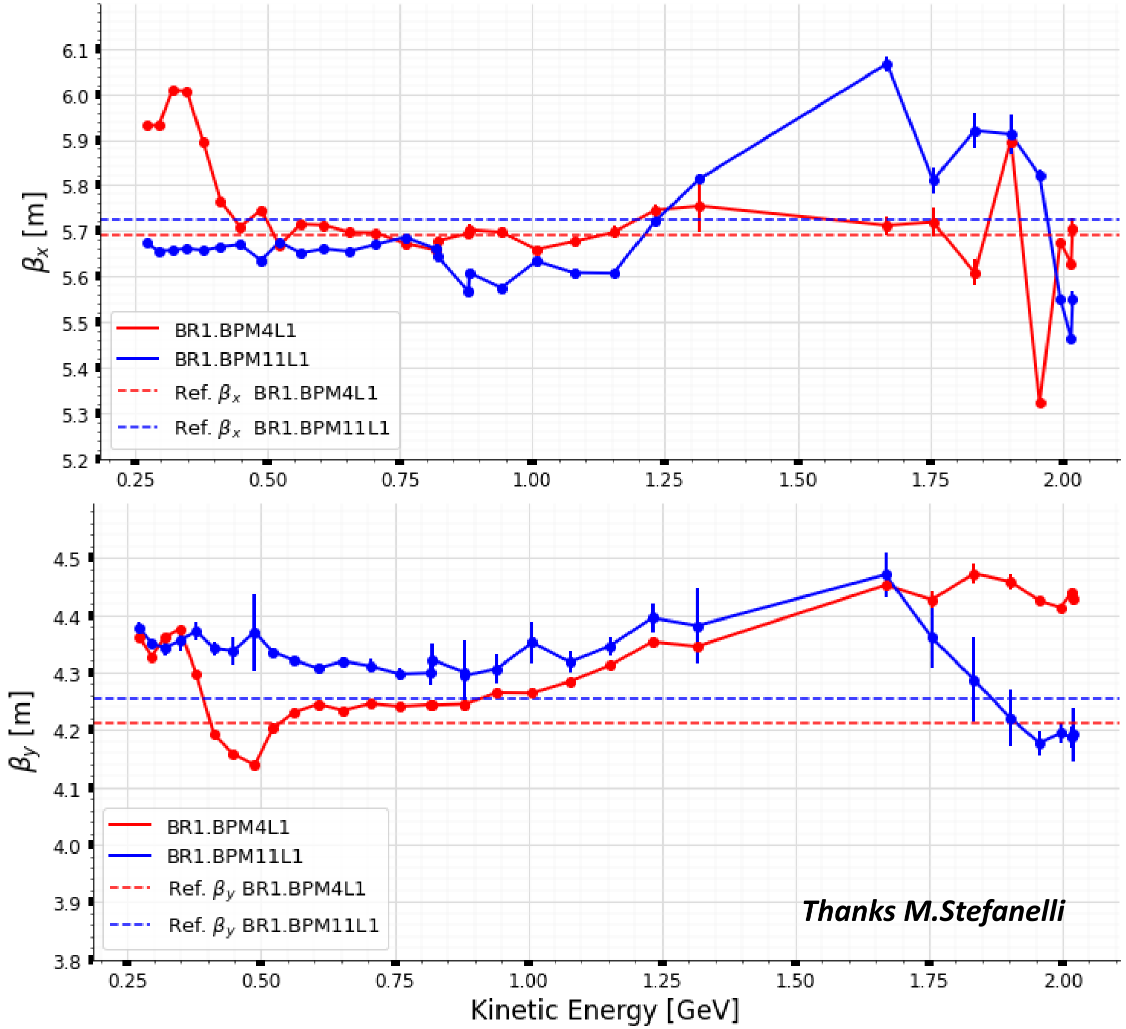
Checking precision w.r.t. known trims



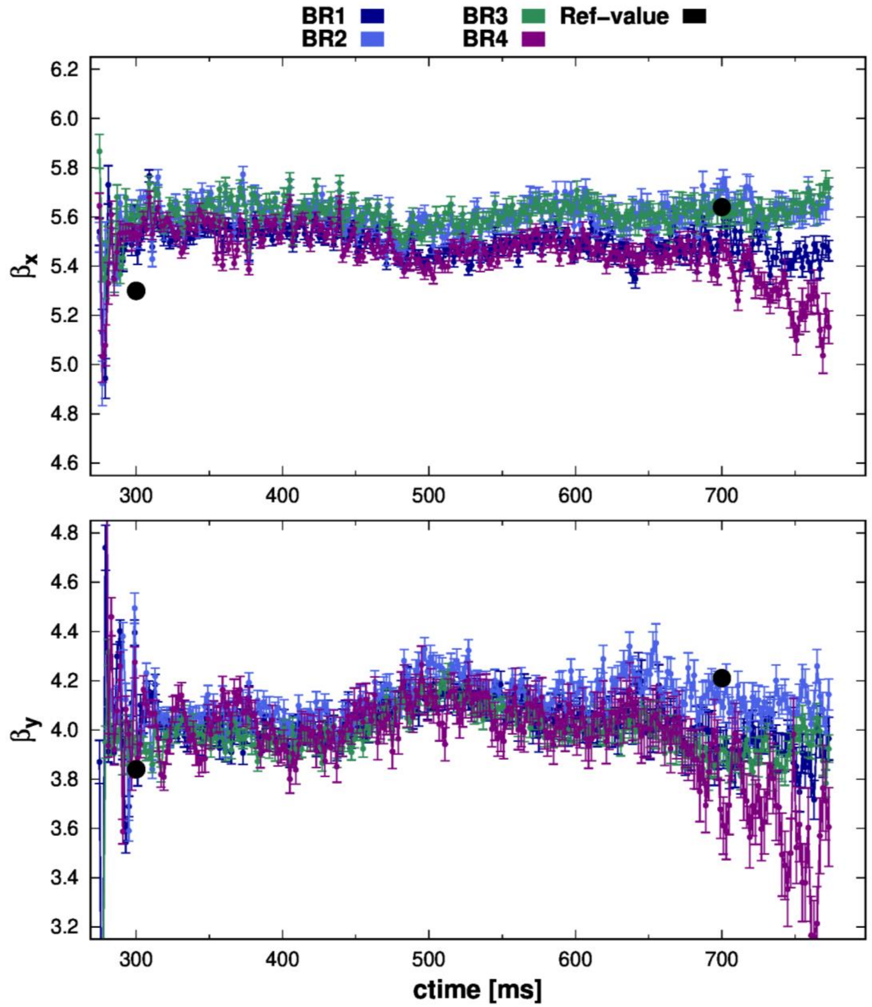
HW developments accompanied by large number of optics studies in PS/PSB testing robustness/precision of optics measurements

First direct measurements of optics at wirescanners throughout PSB cycle

➡ **So far all measurements show ≤ 20% β-beat at the wirescanners**



Thanks M.Stefanelli



PS

Historically PS simulations based on effective models (matched to beam-based measurements)

- Ideally would like a predictive optics model for PS
  - can we go directly from I in coils to correct estimate of Q,Q',optics?

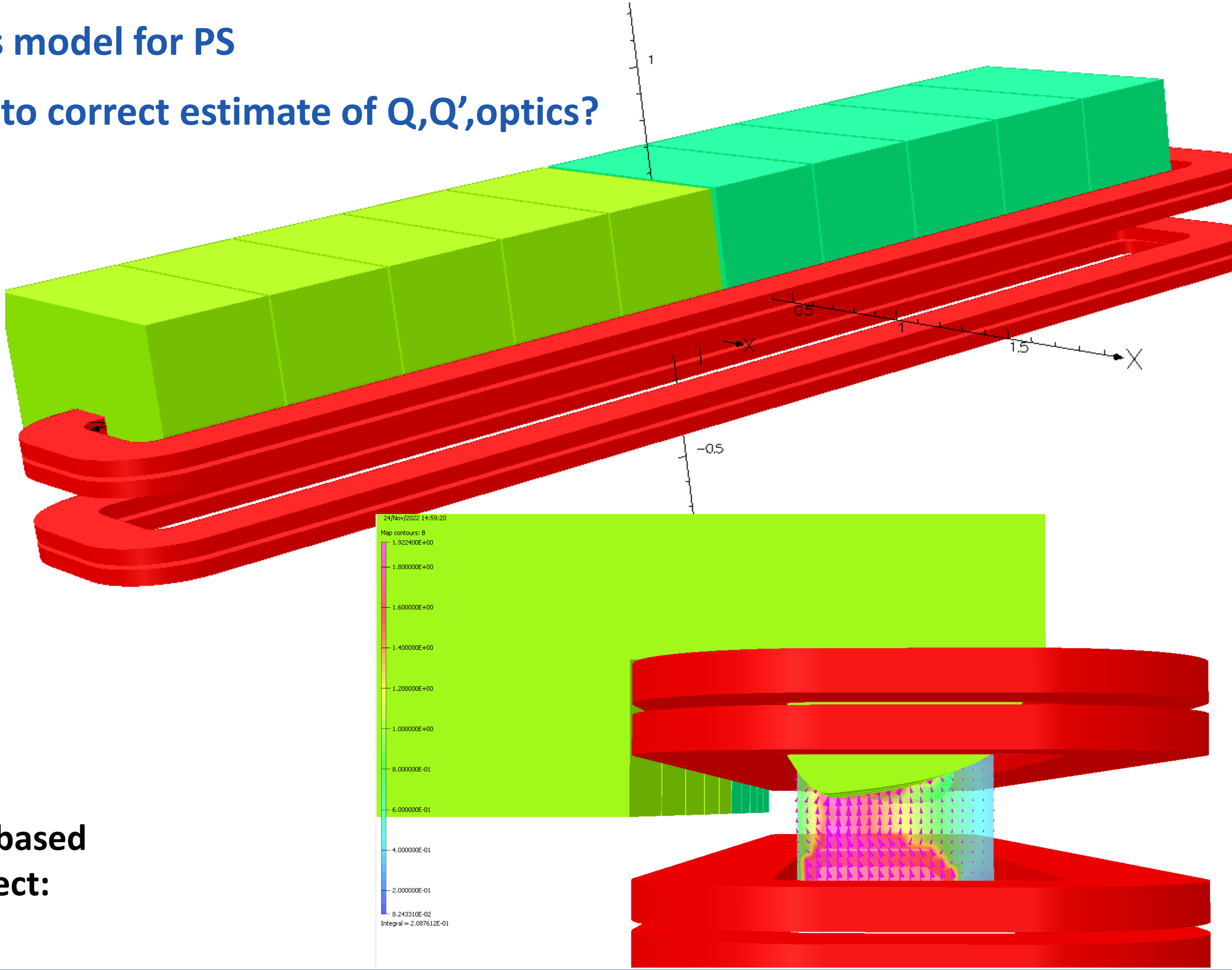
Magnetic model in OPERA

↓

MAD/optics simulations

↓

Beam-based benchmarking

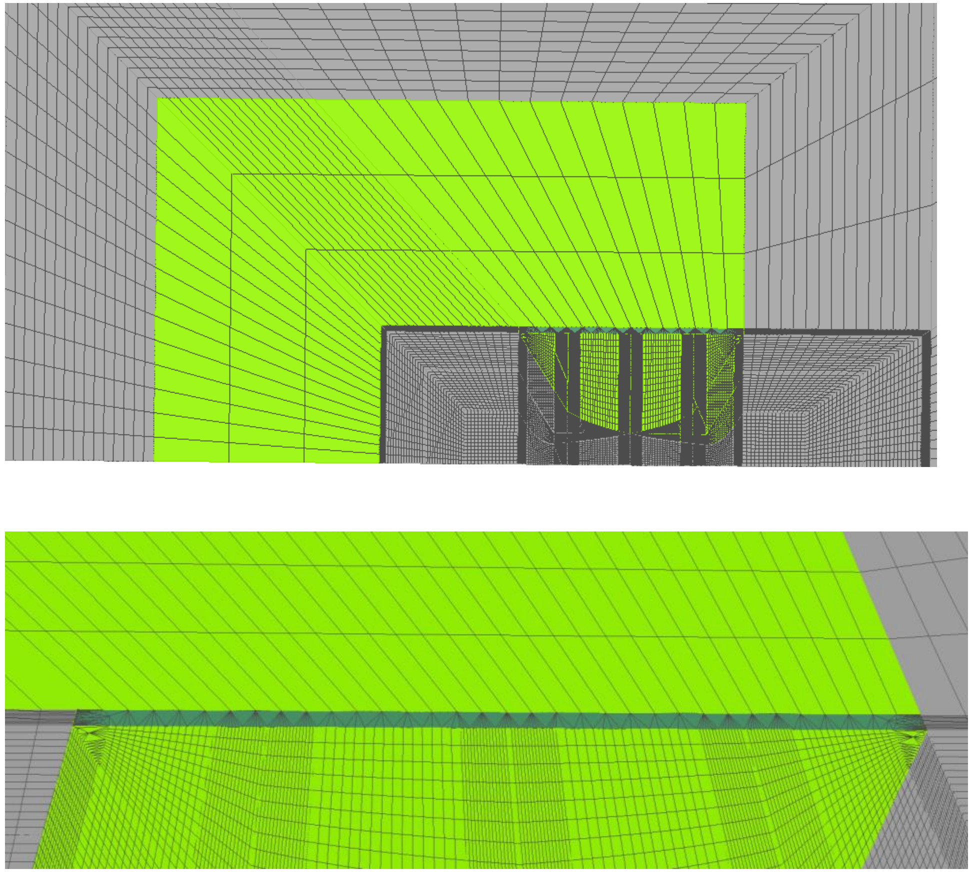


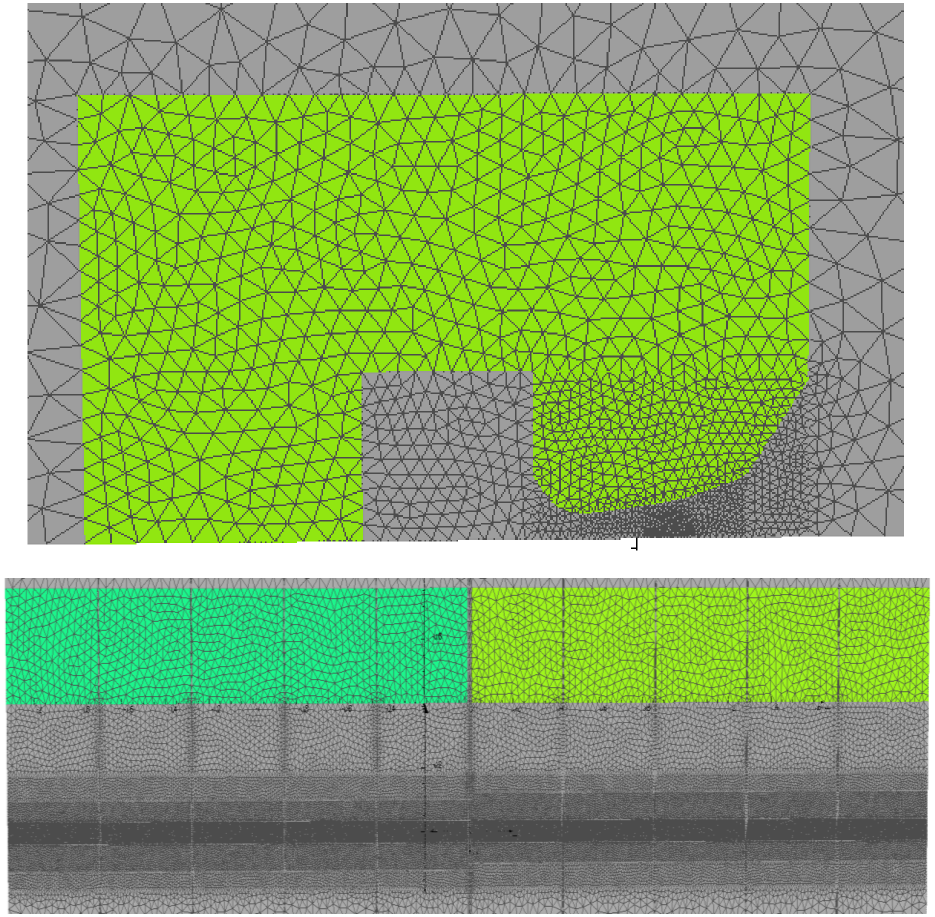
Magnetic modelling, optics modelling, beam-based benchmarking was integrated into single project:
(Ph.D. thesis of V.Ferrentino)

Previous main unit OPERA models were impractical:

- 10^1Gb per simulation
- Days needed per configuration
- Models impractical to work with online

Studies of optics sensitivity to OPERA strategy allowed reduction of simulation time from days → hours with no meaningful impact on optics fidelity

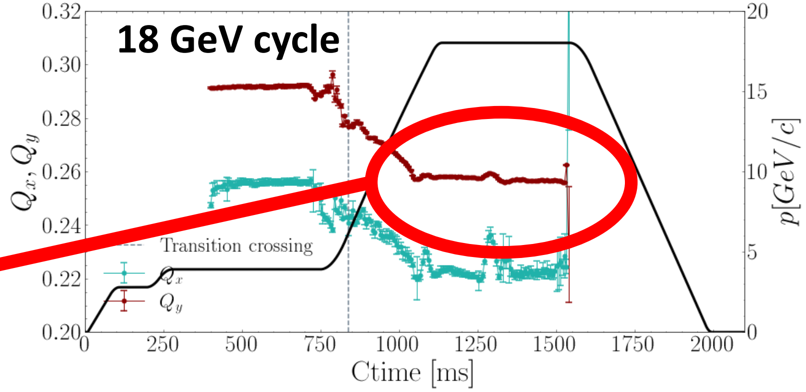


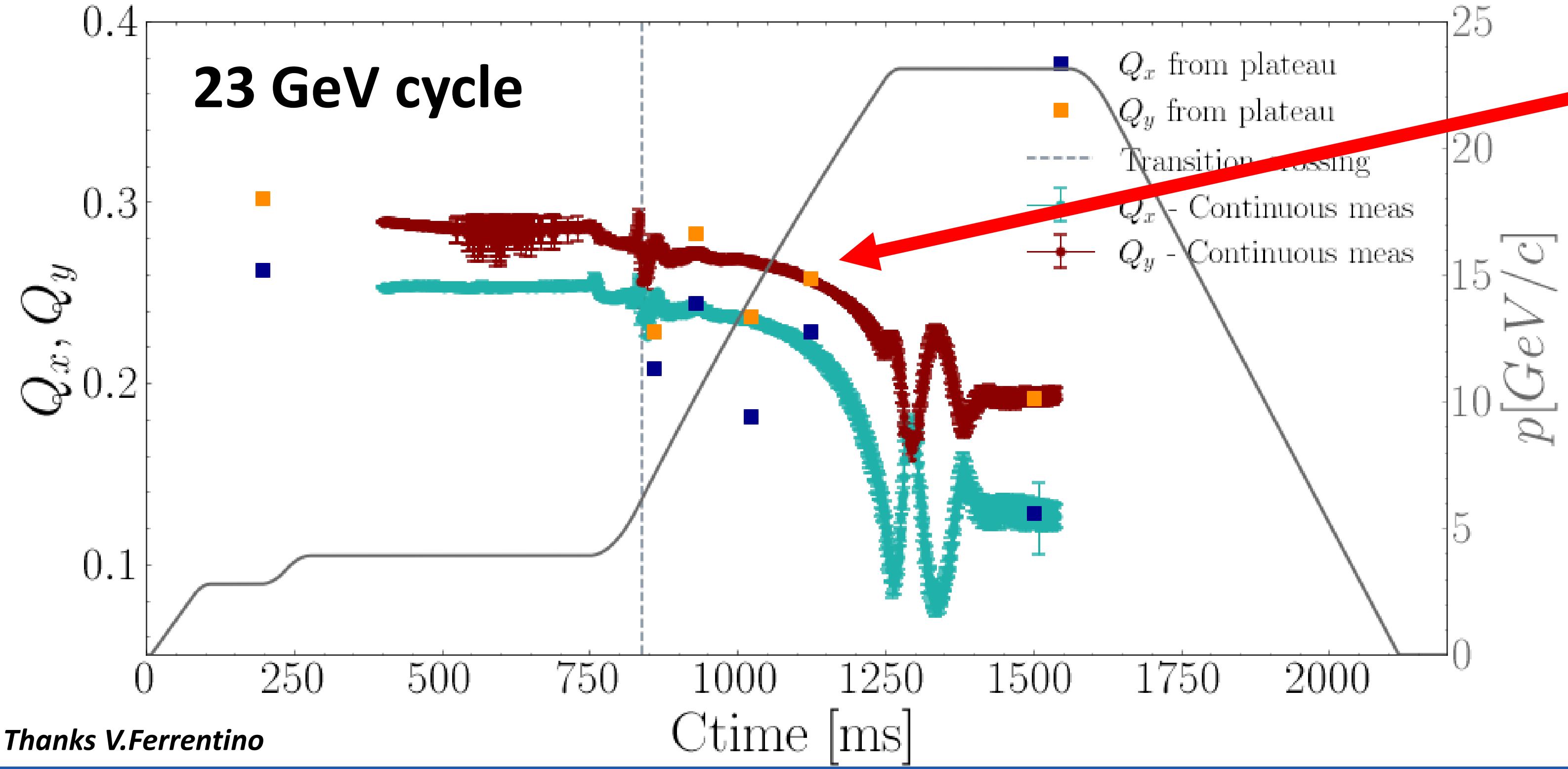


Thanks V.Ferrentino

Can the PS MU cycle be described by static OPERA-MAD simulations?

- **Large dynamic effects at start/end ramp and transition → what about rest of cycle?**
- **During main body of ramp compare continuous measurement through 23GeV bare machine cycle (only MU powered) to measurements on static platteau of lower energy cycles**





Initially looks like there is no hope…

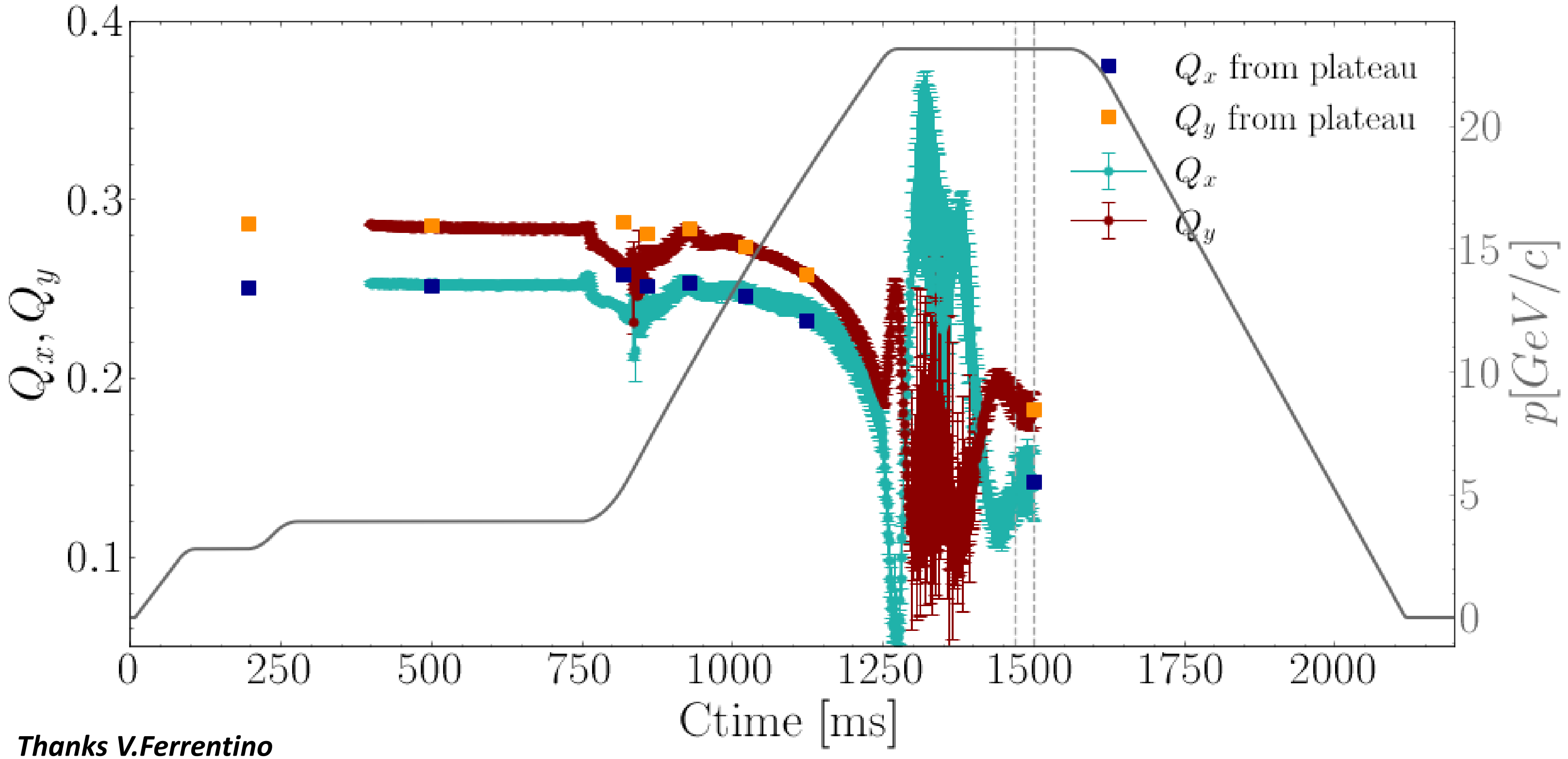
Very poor agreement between static and continuous measurements

Terrible reproducibility and super-cycle dependence

Thanks V.Ferrentino

Can the PS MU cycle be described by static OPERA-MAD simulations?

- Variability between measurements was dominated by super-cycle dependence of Mean Radial Position (MRP)
- Had been seeing feed-down effect from MU sextupole components
- After controlling MRP achieve good agreement between continuous/static measurements through main body of ramp



Controlling for MRP eliminated almost all super-cycle dependence >2GeV

Good long-term reproducibility of tune and chroma in bare-machine

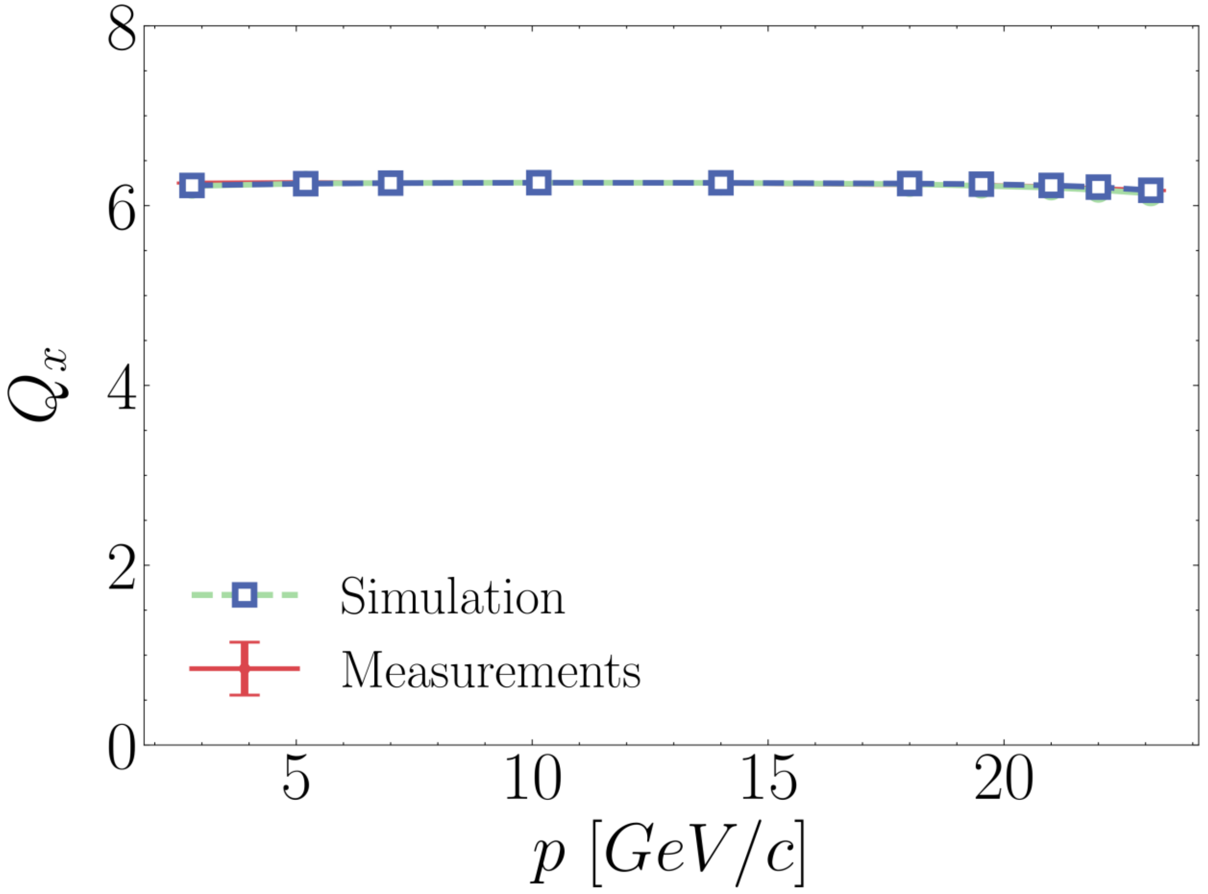
10GeV bare-machine:

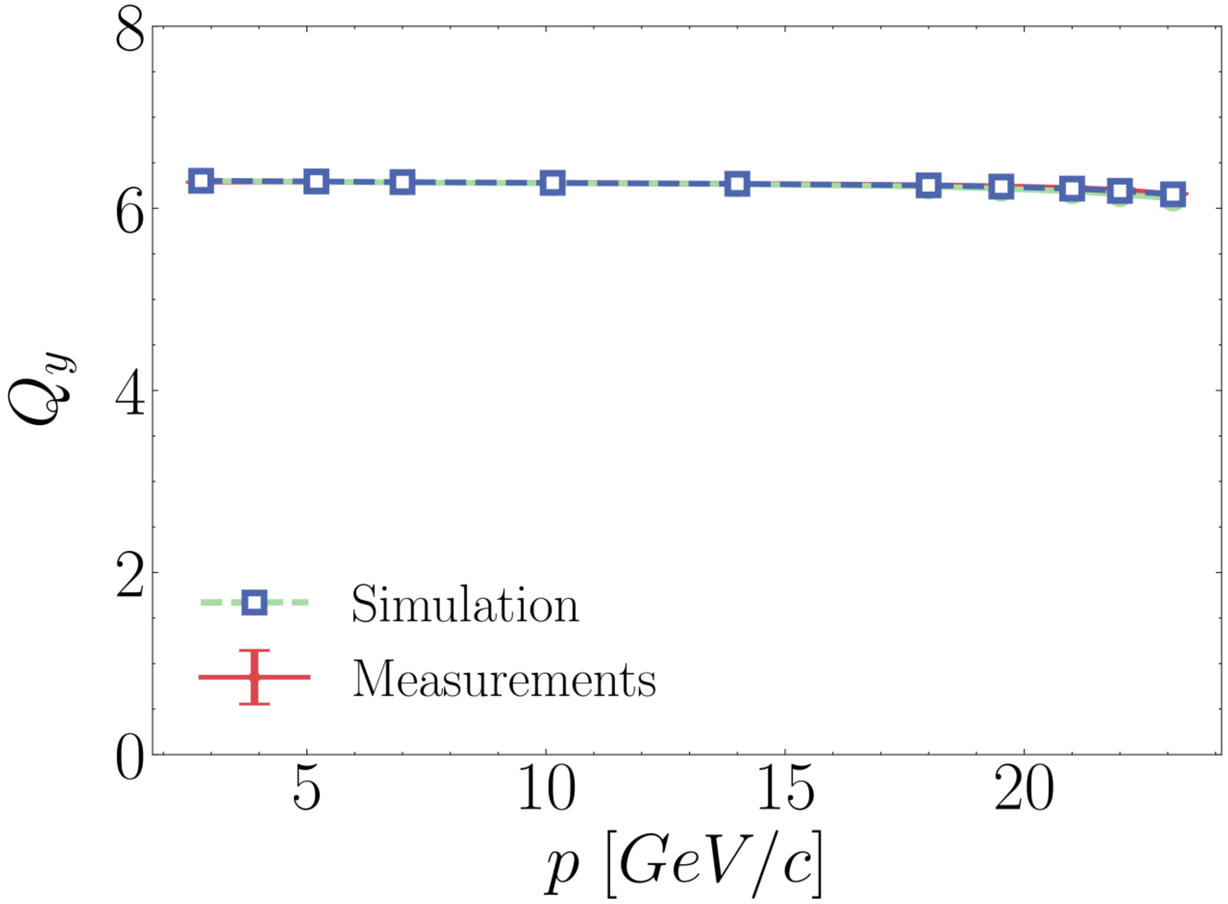
	05/2023	05/2024
Qx	.254 ± .002	.250 ± 0.002
Qy	.284 ± .002	.281 ± 0.001

Thanks V.Ferrentino

Benchmarking the OPERA-MAD model

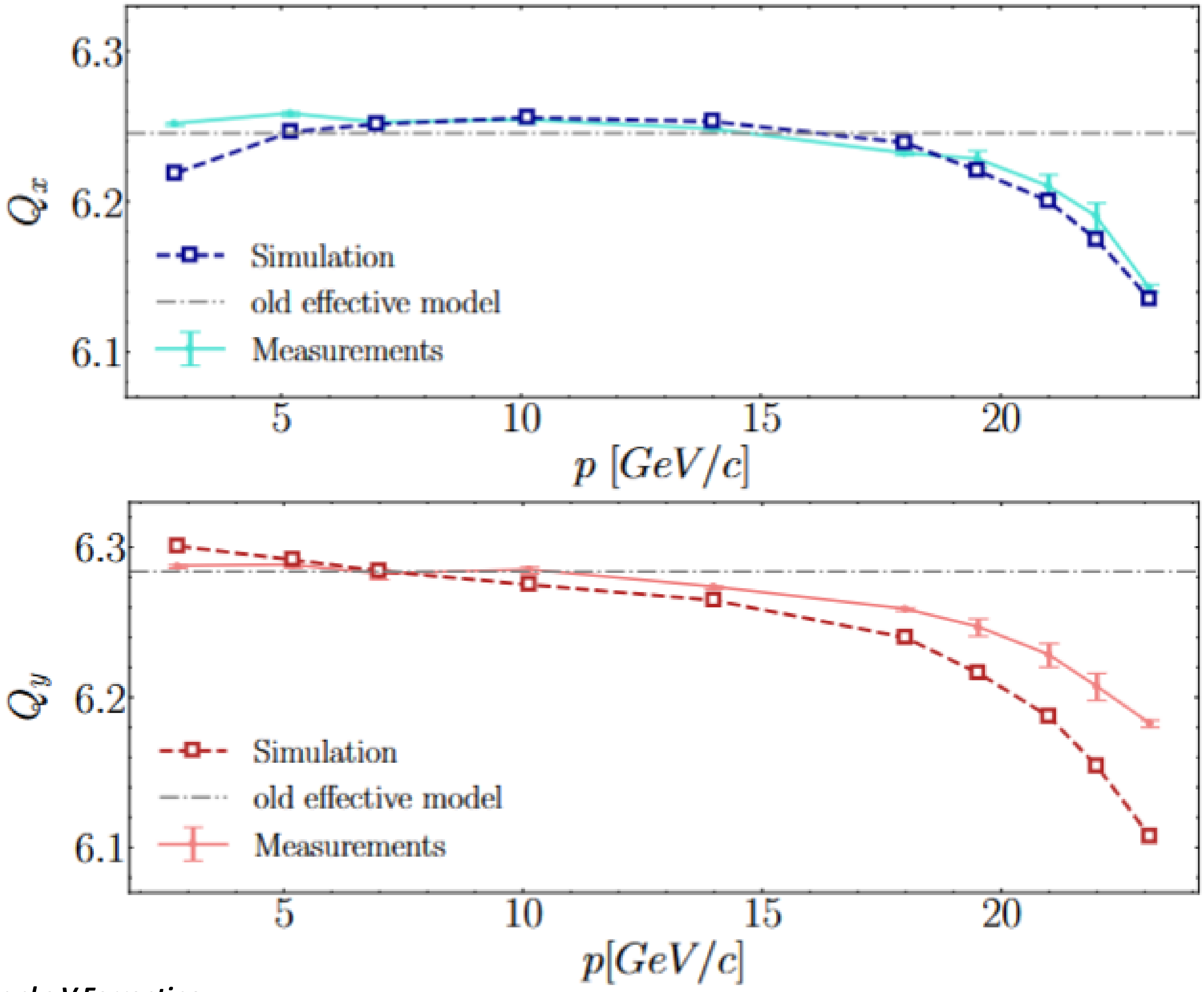
- **Global quality of quadrupole model excellent → already below 1% precision for total tune is good result**





Thanks V.Ferrentino

Benchmarking the OPERA-MAD model

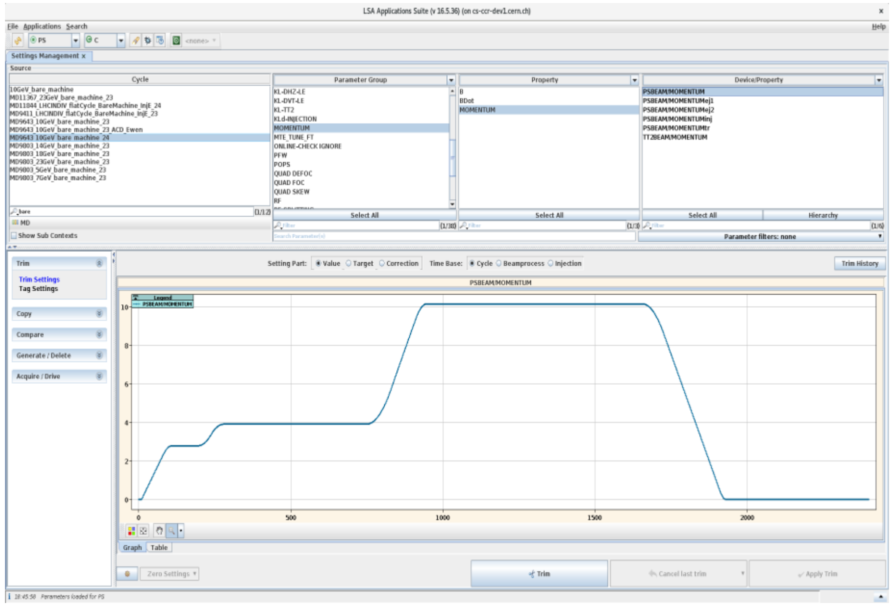


- **At 2GeV remanent field is not included in static opera model**
- **Saturation of quadrupole component is approximately reproduced**
- **Peculiar behaviour that the vertical tune agrees so much worse than the horizontal…**

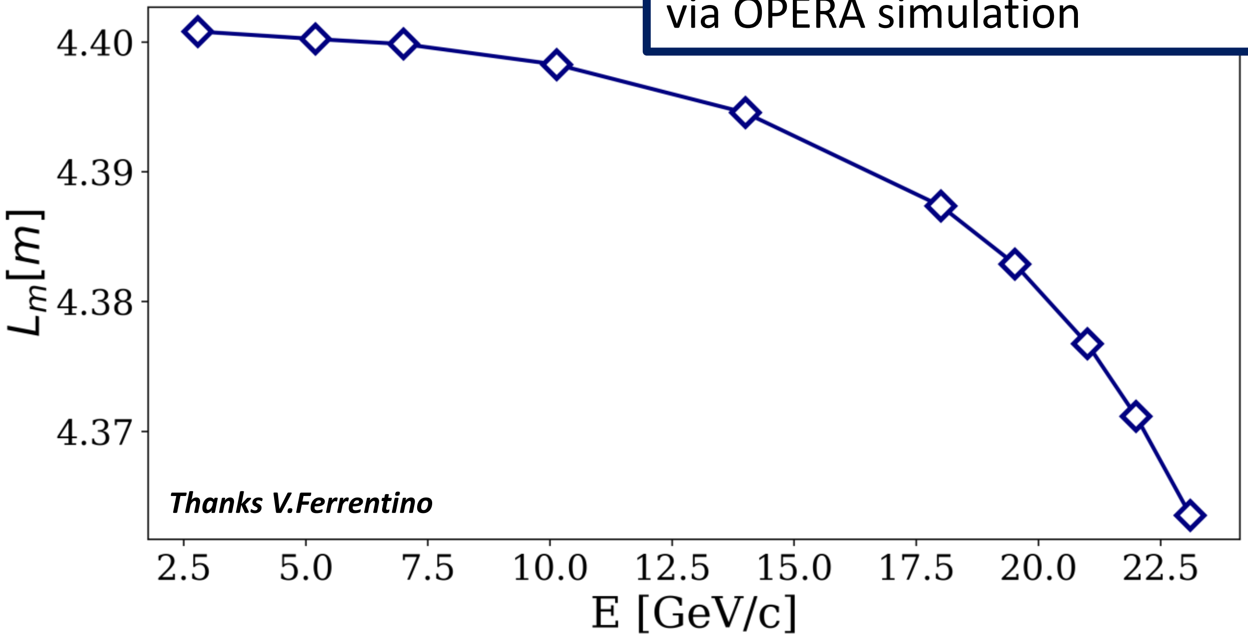
Thanks V.Ferrentino

Benchmarking the OPERA-MAD model

- **Converting from OPERA output (B) to MAD input (K) requires estimate of beam momentum or rigidity**
- **Previous simulations convert via the programmed momentum**
  → defined via programmed B field (regulated by B-train) and nominal magnetic length
  → B-train regulates to programmed field based on measurements in the magnet core
  → but saturation of the dipole field is higher at the magnet fringes



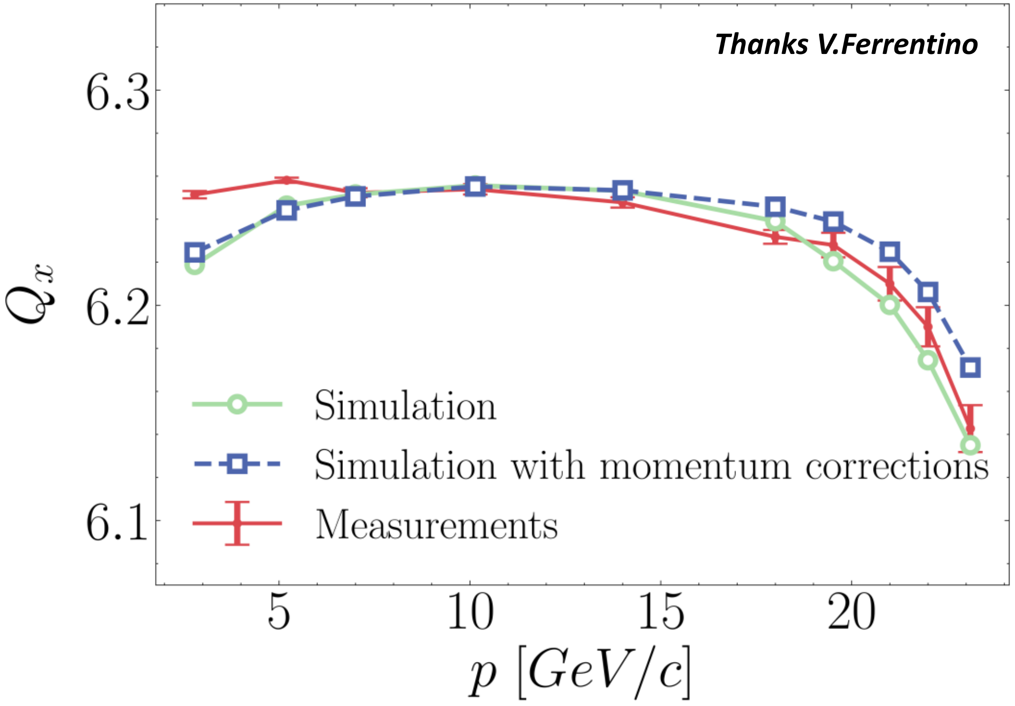
Decrease of magnetic length via OPERA simulation

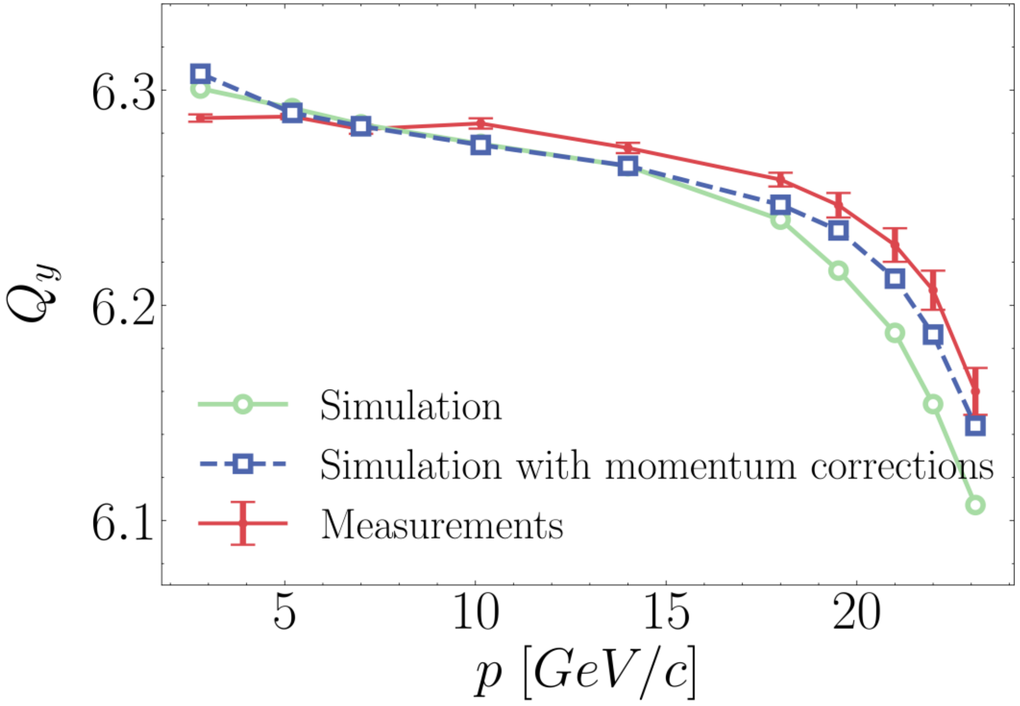


Decrease of magnetic length from saturation translates directly to error w.r.t programmed momentum/rigidity

Benchmarking the OPERA-MAD model

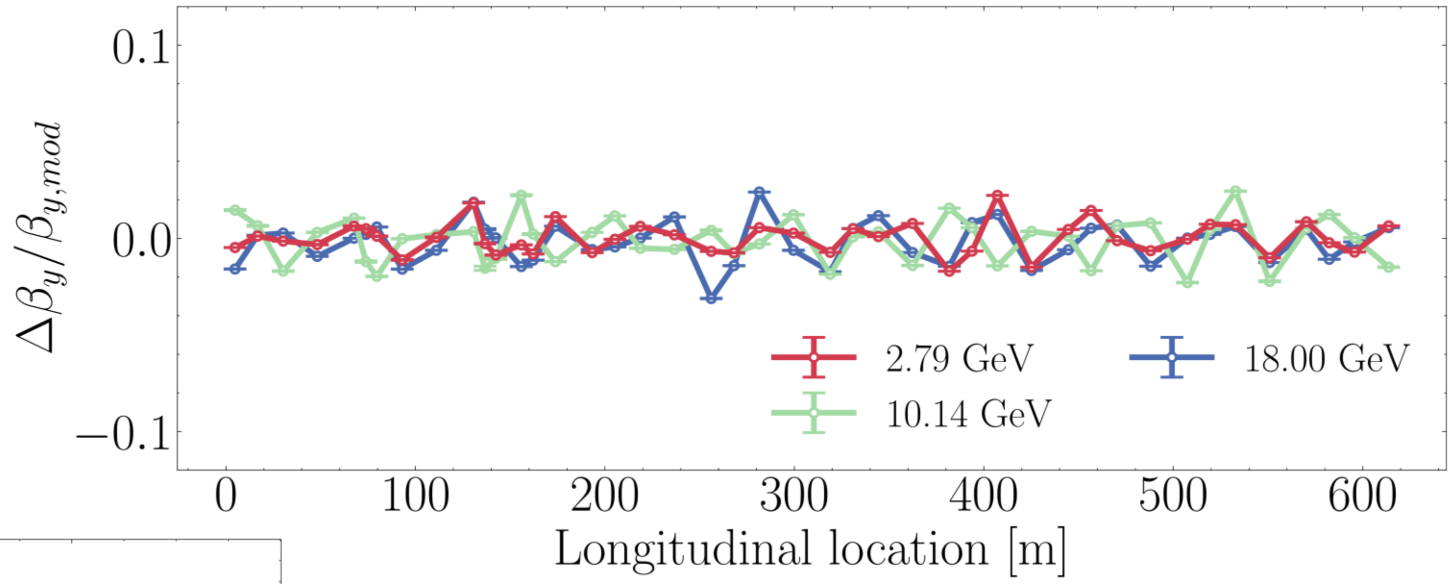
- **OPERA prediction for saturation of TF found to agree well with dedicated magnetic measurements**
- **Correct the programmed momentum/rigidity for magnetic length saturation predicted by the OPERA model when normalizing harmonics**
- **Improved normalization returns more consistent agreement between Qx and Qy**



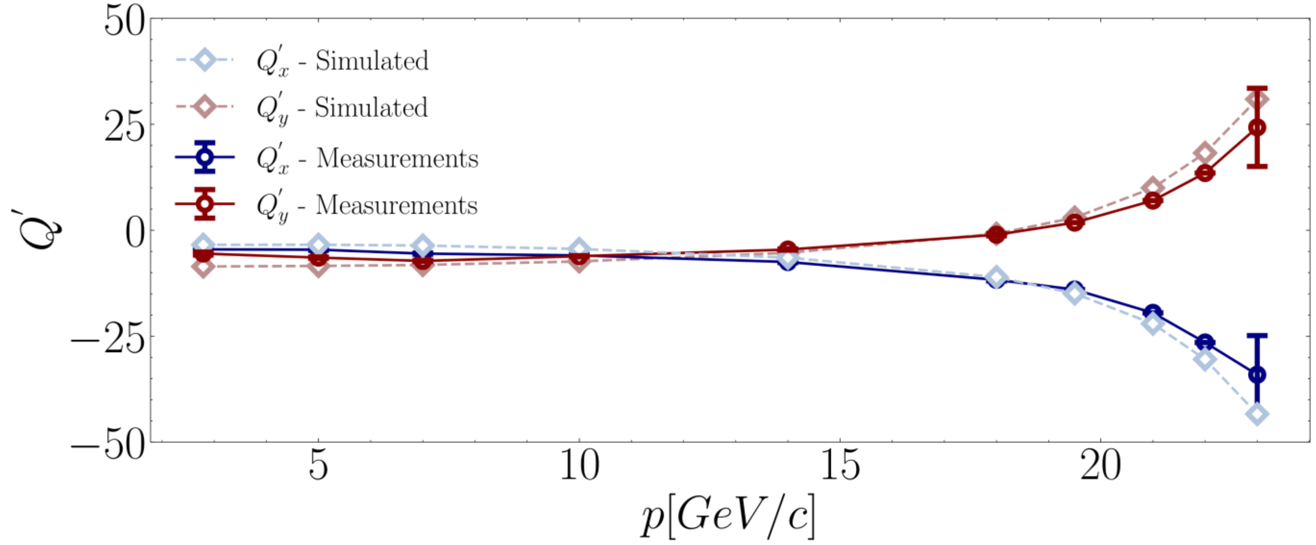


Application for model-based correction to programmed momentum/rigidity to improve I/K calibration globally in PS

Benchmarking the OPERA-MAD model



Excellent beta-beating with respect to prediction of OPERA-MAD model



Saturation of MU generates large sextupole errors:

OPERA-MAD model gives good prediction of Q' evolution

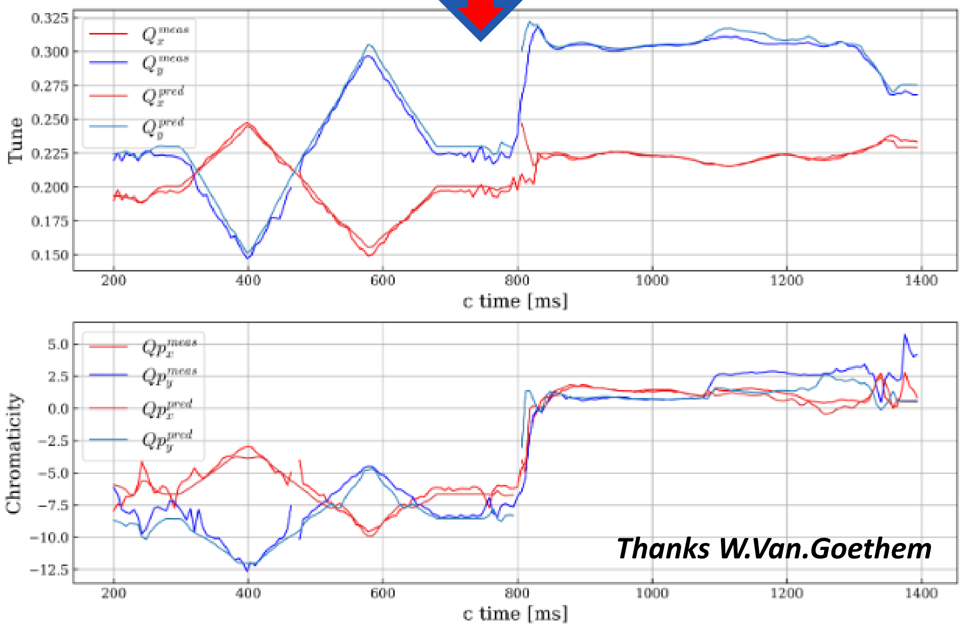
Predictions of OPERA-MAD model have been used to guide operational decisions:
e.g. choice of energy for East cycles to identify range where PFW would not be required during slow extraction

Also want to model the F8L and PFW circuits ➡ Two approaches studied

Machine Learning

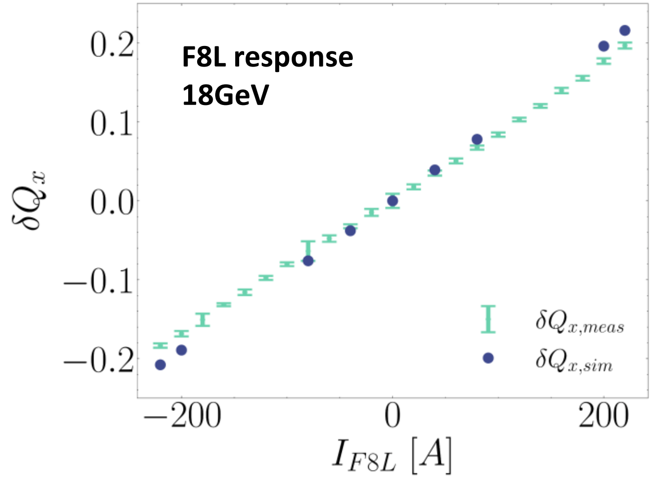
Initial attempts – simple training based on BBQ Qx/y were a disaster

Improved tune cleaning / raw BBQ analysis
Better handling of large linear coupling
Physics based loss function
Refined definition of reference Frev



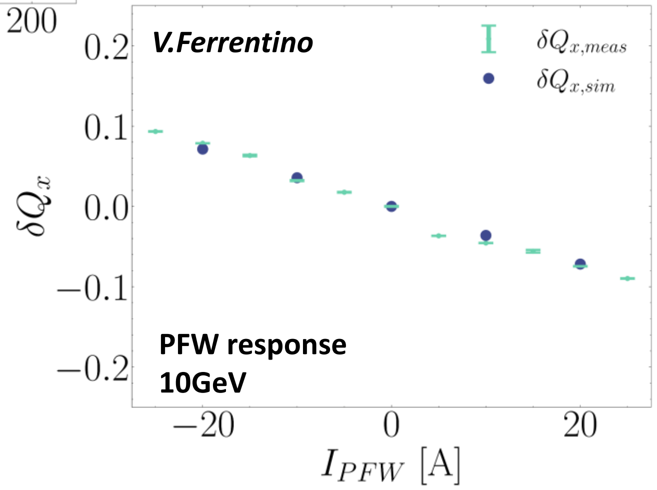
Magnetic model

ΔQ/Q' in bare machine benchmarked against OPERA/MAD models



Extremely good agreement for F8L and uniform PFW (within few %)

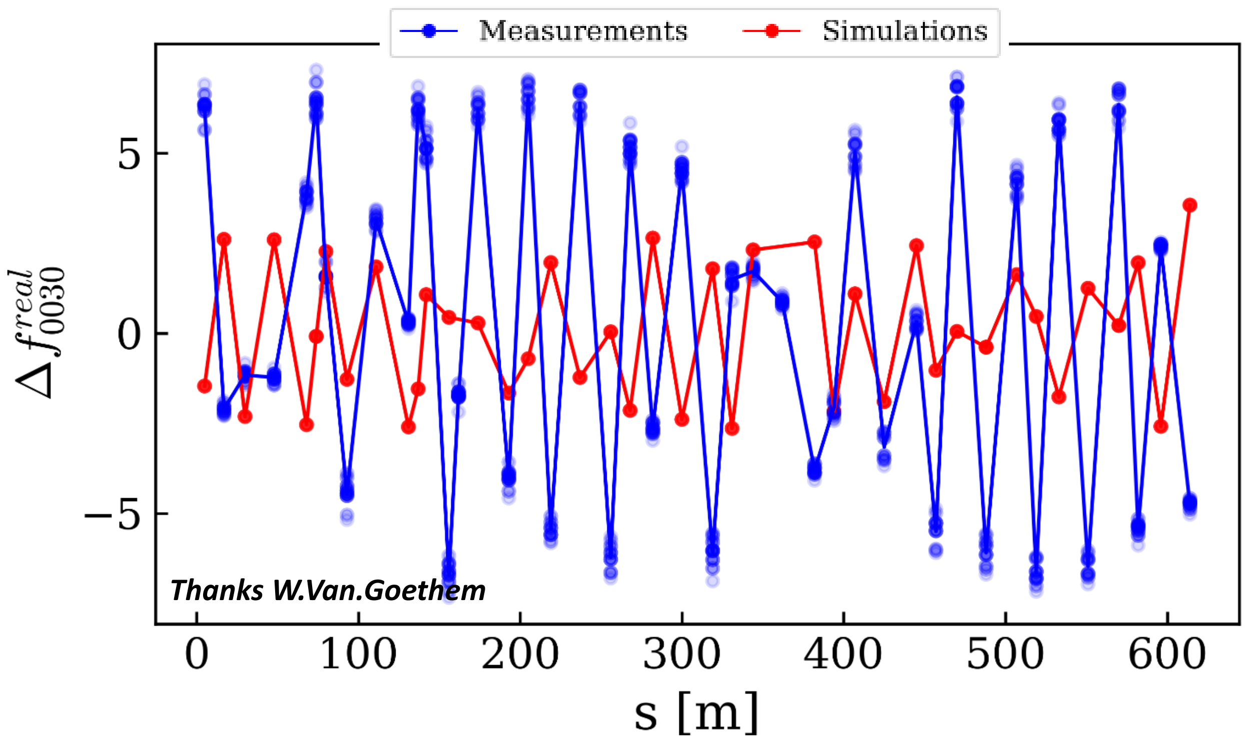
Response agrees to ≈15% for typical OP settings with F8L + non-uniform PFW



Studies ongoing to explore better tune/chroma control based on these methods

General effort to benchmark circuit responses

Initial studies of resonances generated by skew-sextupole magnets bore no relation to predictions from lattice models



Circuit by circuit RDT measurements identified large errors in I/K calibration

Circuit	Calibration factor
XSK.10	× 6.5
XSK.14	× -1.5
XSK.52	× 6.5
XSK.58	× 1.5

Bad length definition in LSA (XSK.10, XSK.52)

? (XSK.14, XSK.58)

Trying to bring machine and models better in line with each other

General effort to benchmark circuit responses

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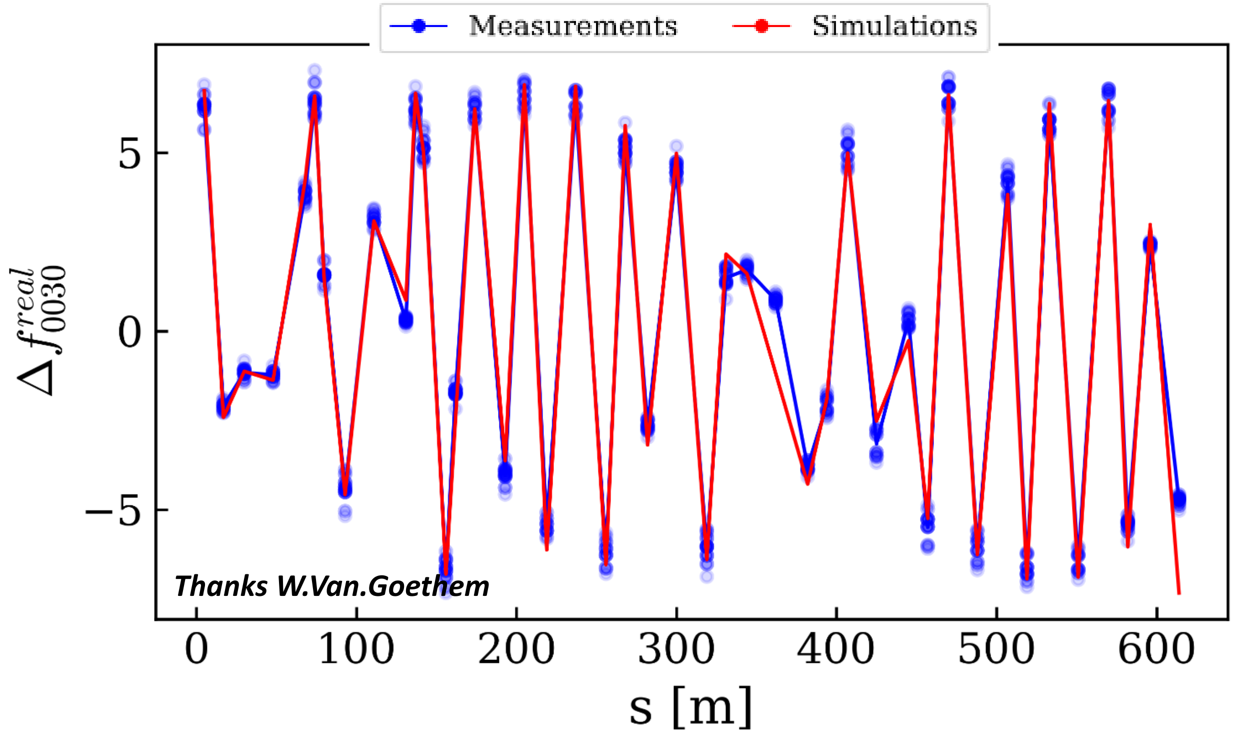

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? (XSK.14, XSK.58)

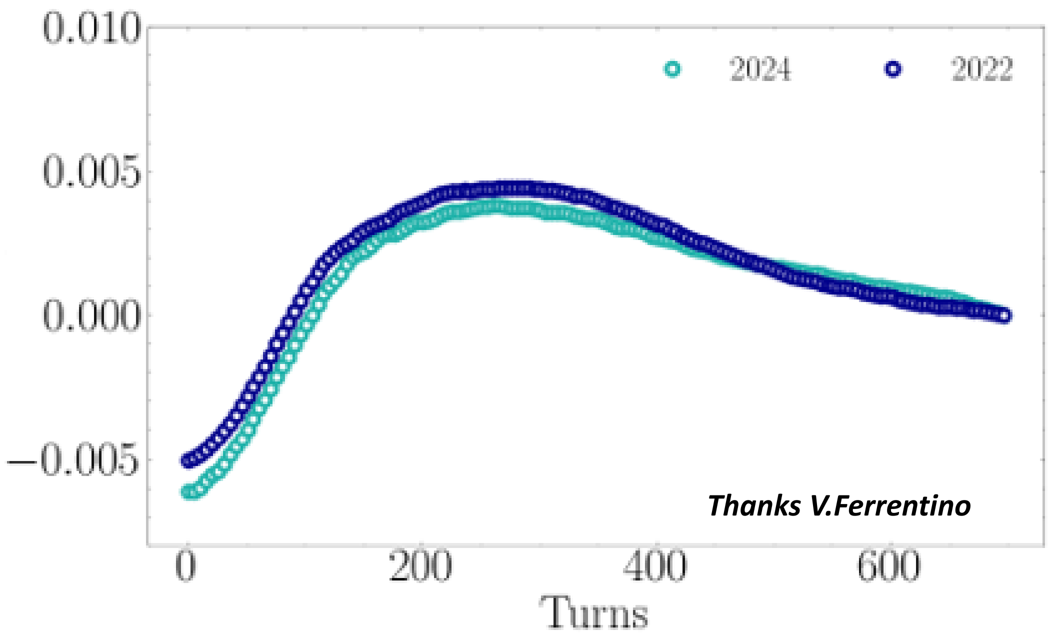
Trying to bring machine and models better in line with each other

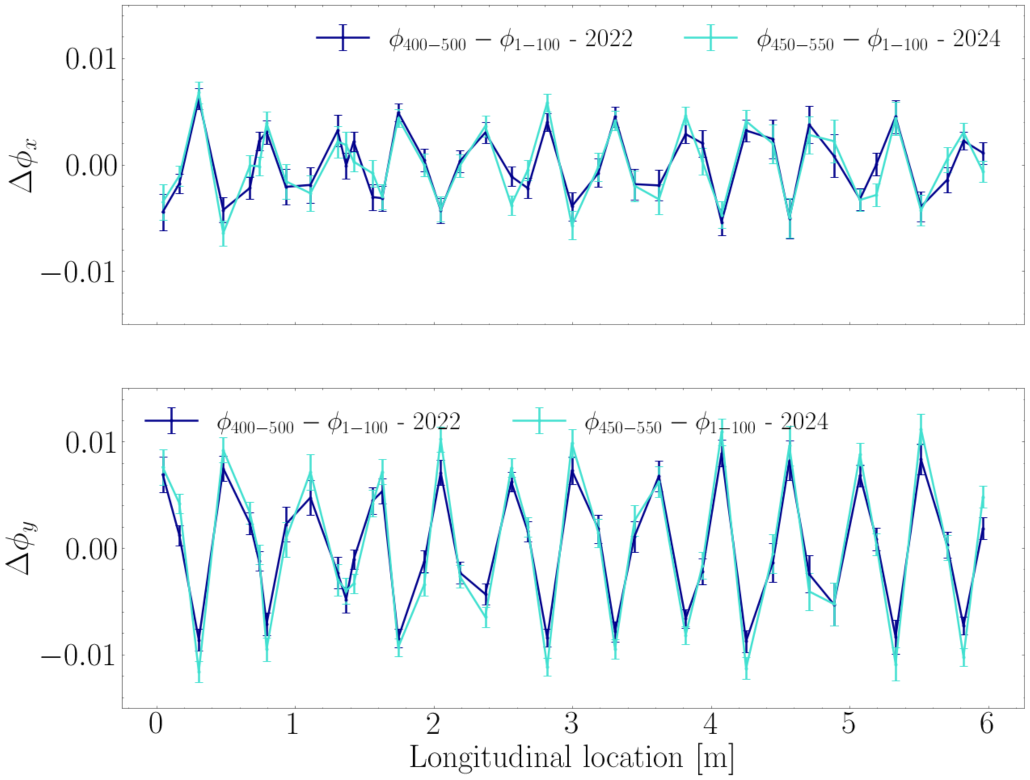
Eddy currents during PS injection

- **Large Q-shifts are observed during PS injection → historically attributed to sextupolar eddy currents from BSW**

eddy current compensation circuits were used for first time in 2024

→ Negligible change in the tune and optics perturbations





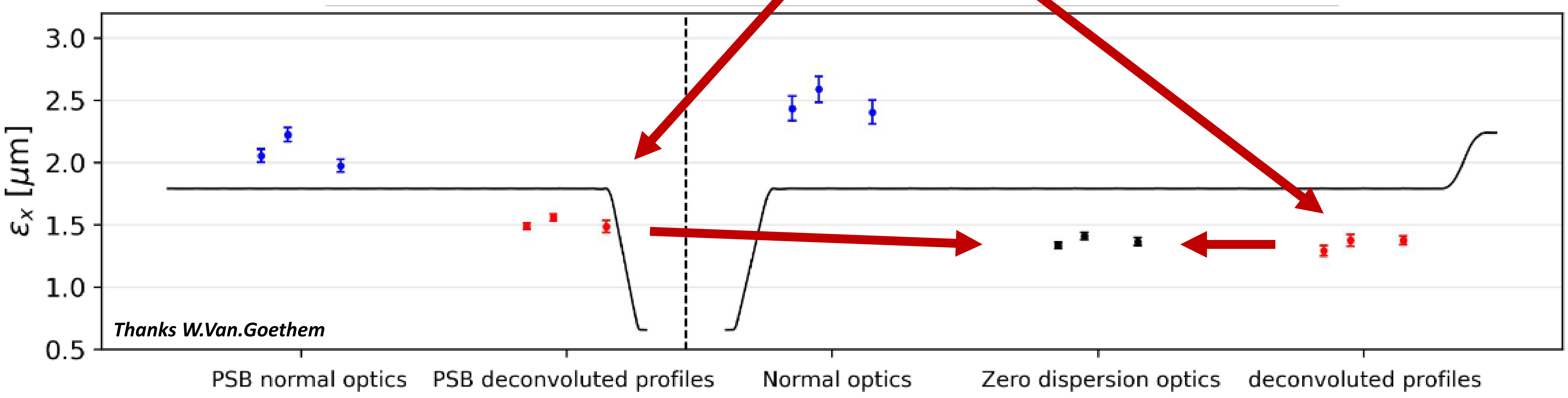
Ongoing effort to understand if these optics shifts were mis-attributed to eddy currents in the past, or results reflect a problem with compensation circuits

Dedicated optics studies for instrumentation

As in PSB, key motivation for optics studies is supporting emittance measurements

- **Special zero-dispersion optics utilized to directly benefit emittance studies** (see JAP'23, Felix' talk in next session)
  - **w.r.t. HW particularly interesting result is testing numerical deconvolution of H-emittance measurement via zero-dispersion optics**

Numerically deconvoluted profiles in PSB and PS agree well with direct measurements at zero dispersion



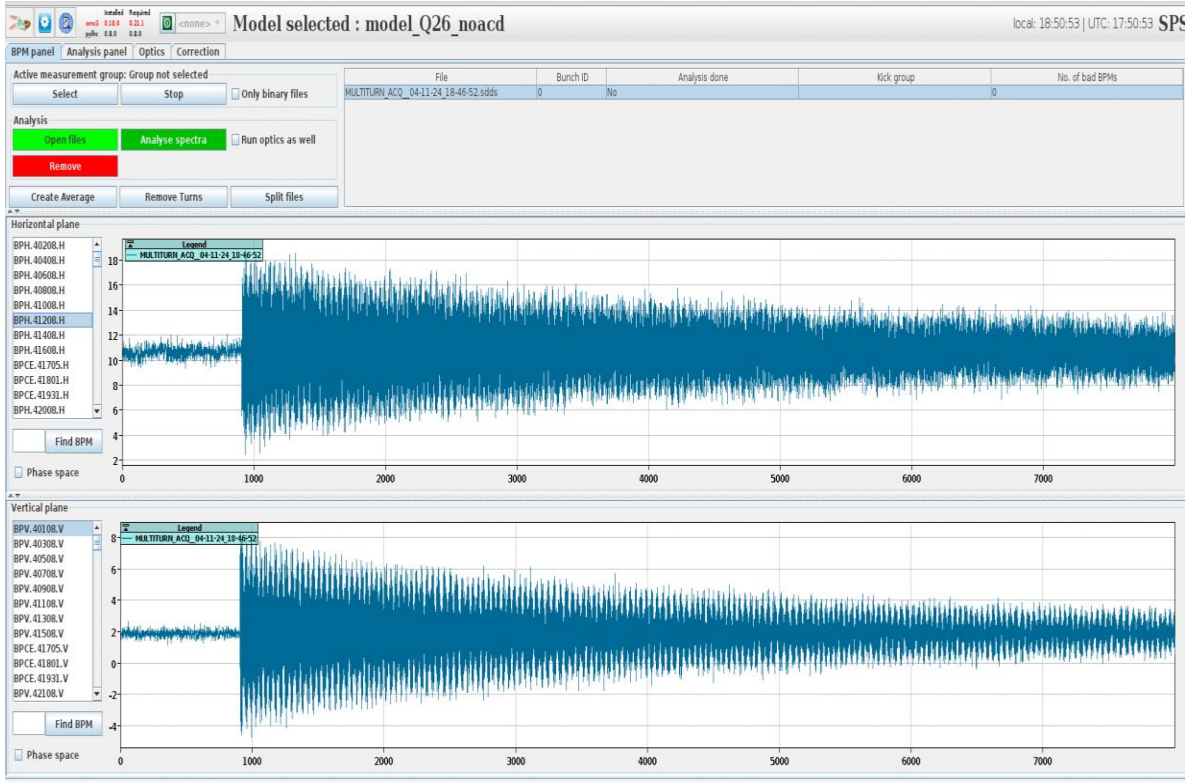
Interesting prospect to improve emittance measurements in PS and PSB

SPS

Given progress on optics studies in PSB/PS, also interest from SPS to start to utilize OMC tools to study optics

- **Together with Panos, OMC team joined several MDs in 2024 to try optics measurements in SPS with ADT-ACD and free-kicks**

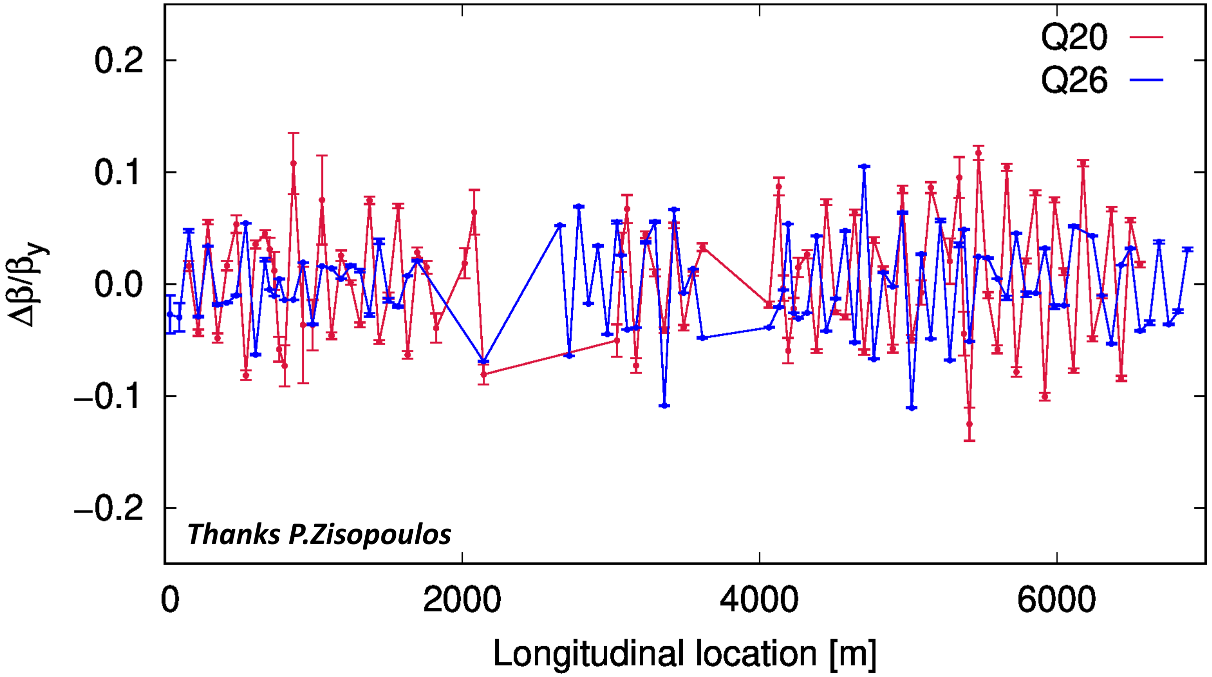
updating OMC tools/code/setting to work well for SPS



Thanks P.Zisopoulos

First tests of linear and nonlinear optics measurements with OMC tools made in 2024

e.g. very good for both Q20 and Q26 optics



Hope is to apply optics measurements in SPS, similar to PS/PSB

➡ **Still various developments/improvements desired**

- **Can period of logged TbT data in SPS be increased?**
  → currently far less than PSB/PS/LHC
- **Increase of SPS ADT-ACD kick strength**
  → reduce/remove BBQ attenuation when kicking?
- **Further updates of OMC tools required**
  → model generation tools similar to PSB/PS/LHC
  → coupling and RDT calculation updated for single -plane BPM
  → Tune-drift compensation for detuning

	Recorded turns
PSB	800,000
PS	80,000
SPS	8,000
LHC	40,000

LHC

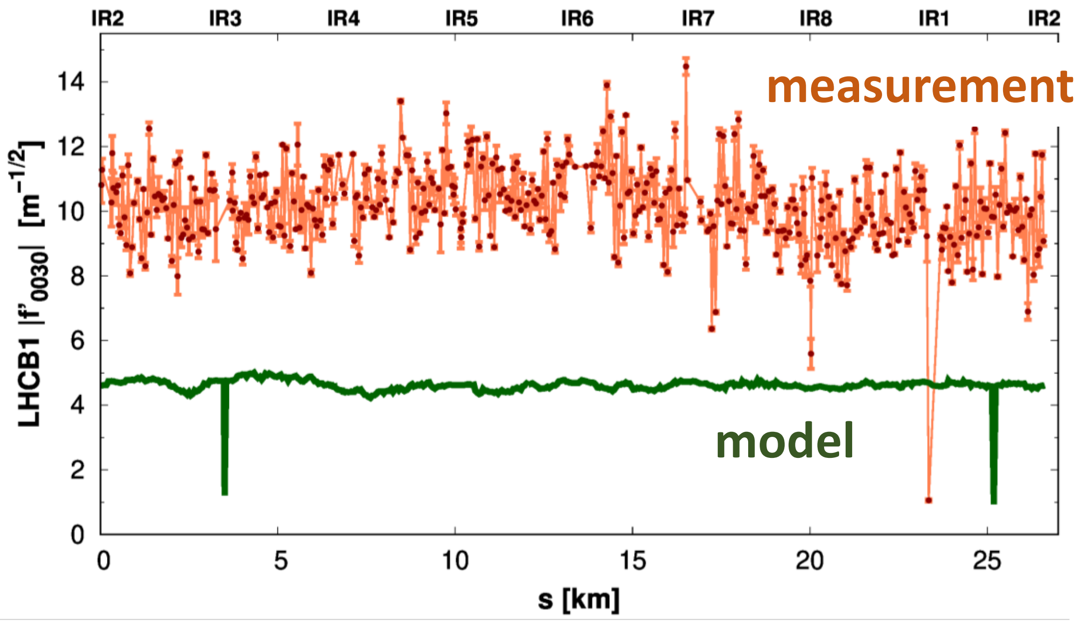
Extensive magnetic error measurements performed during construction (up to high multipole order)

- Identify & understand any discrepancies between beam-based optics measurements and best-knowledge models
  - Ongoing effort for many years: during Run3 several notable developments

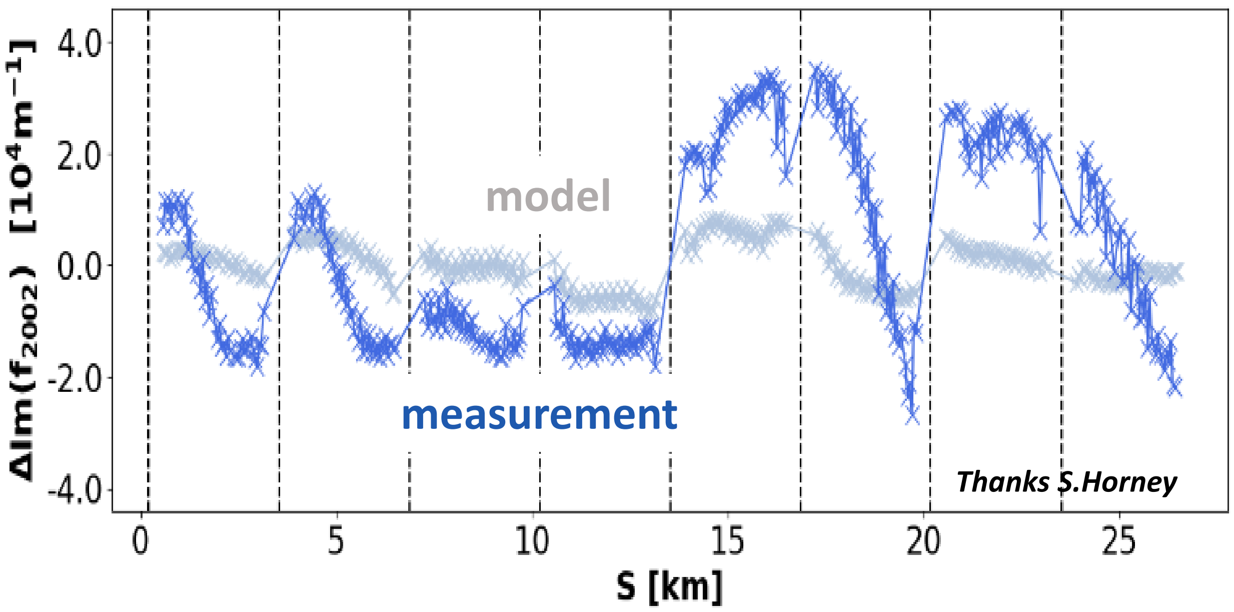
Routine application of Forced Resonance Driving Term measurements with AC-dipole

- R&D topic throughout Run1-2: now allows quantitative study of the nonlinear resonances to a level not possible before
  - Helped identify new discrepancies between best-knowledge models and real machine

3Qy resonance 2x stronger than expected

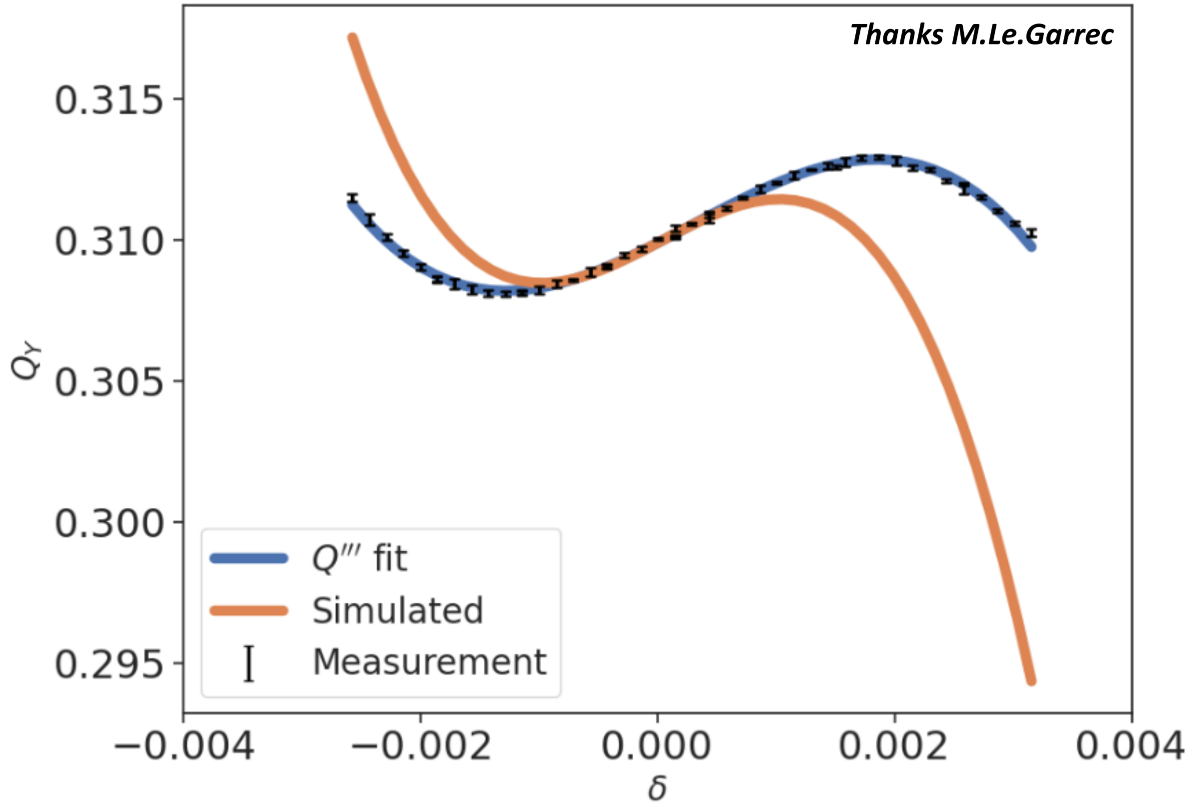


Factor 2 discrepancy in resonances generated by Landau octupole at injection → MO hysteresis?



Significant progress made during Run3 on benchmarking of very high-order multipoles

e.g. factor 2 discrepancy in Q''' with respect to best-knowledge model predictions



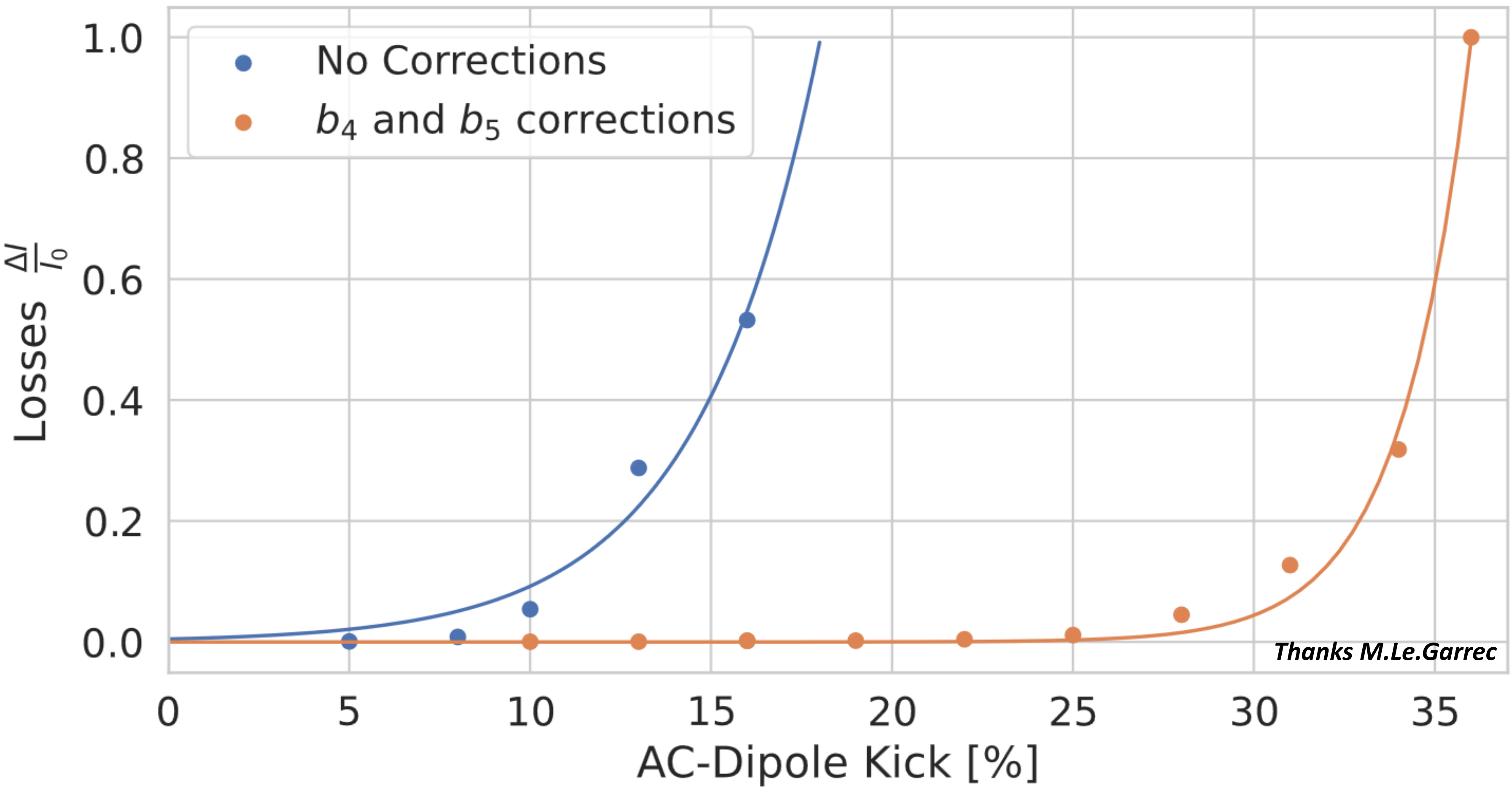
Using new types of measurement (momentum dependent detuning) clearly indicate comes from missing decapole error

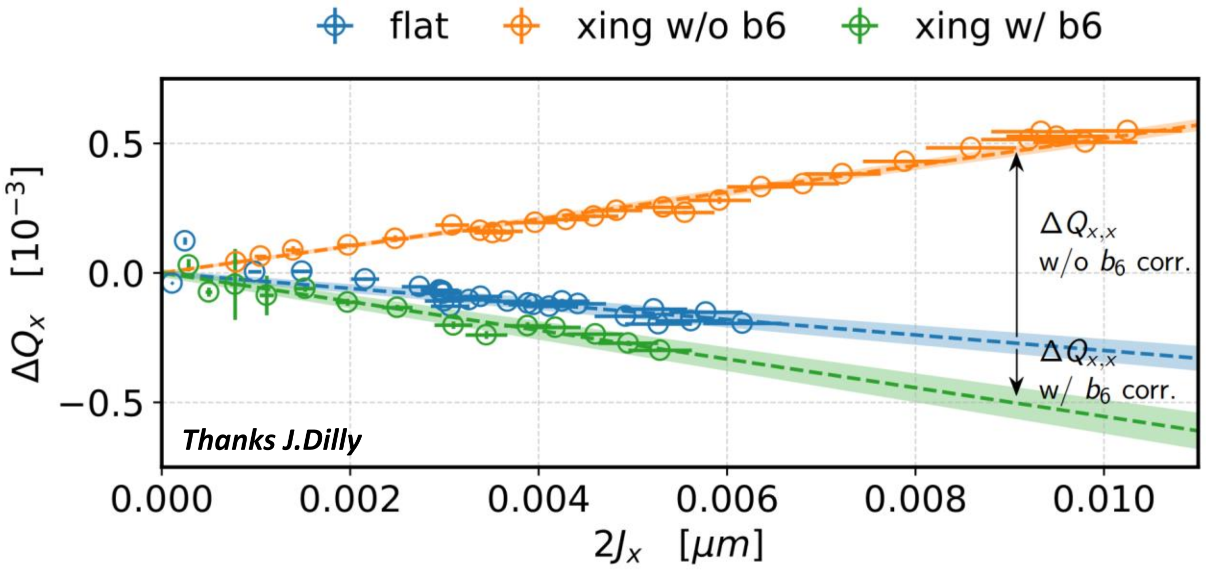
Re-visiting old magnetic measurements find that missing b5 can be explained by large b5 decay in the main dipoles

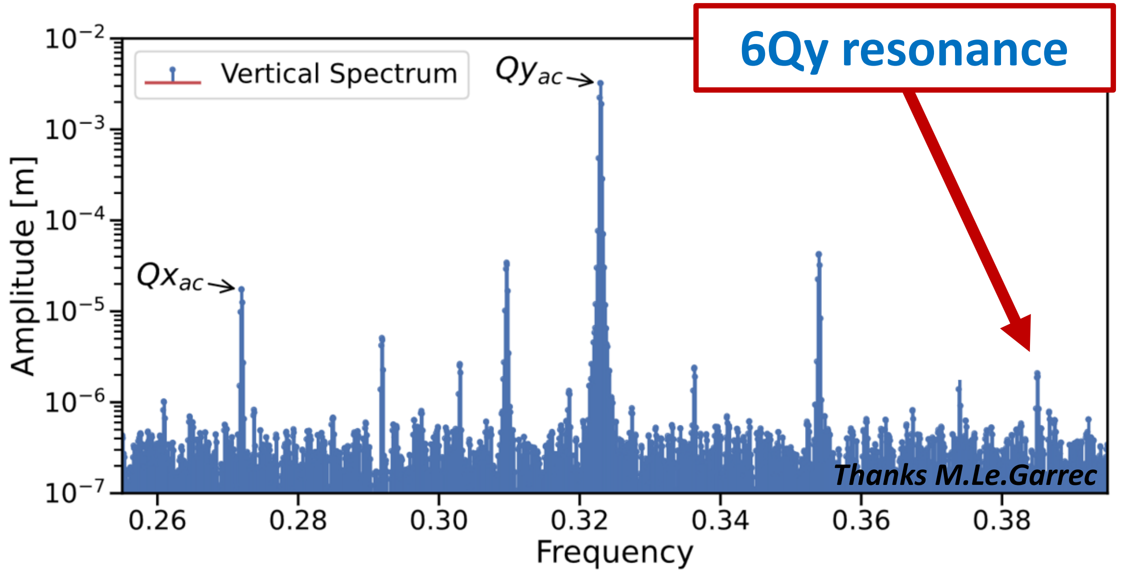
- → **b5 decay never included in OP spool settings**
- → **Standard LHC error tables generated at t=0, decay not included**

Where it has been possible to resolve discrepancies with best-knowledge model, so far has not been due to problem with magnetic model, rather extra effects (feed-down,alignment,feed-up,coupling,…) which need to be included

Better understanding of errors supports better corrections
e.g. DA improvement during AC-dipole kicks





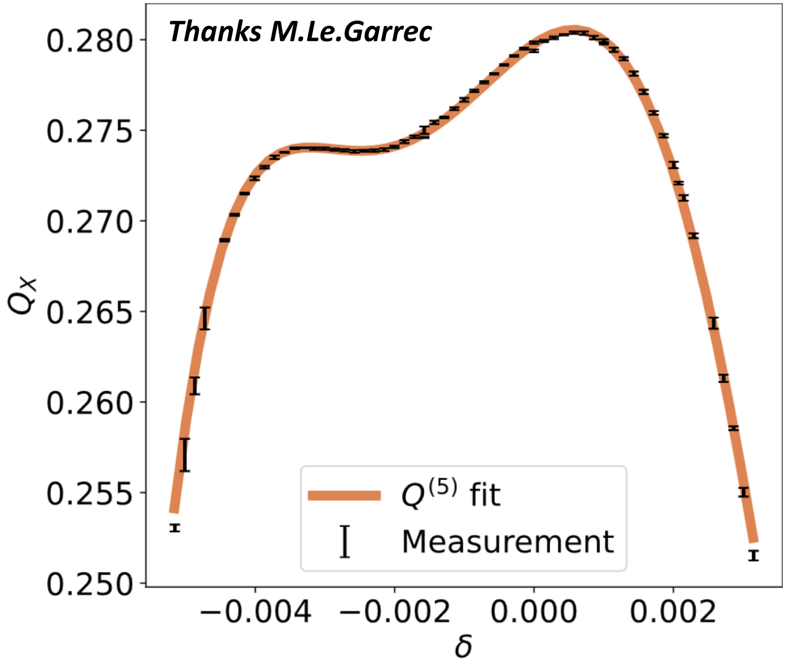


Dodecapole feed-down to detuning measured for first time at end-of-squeeze: required corrections compatible with magnetic model

Dodecapole 6Qy resonance measured for first time at 450GeV: agrees well with best-knowledge models

Better DA and measurement & setup allows us to push to extremely high-order

5th order chromaticity measured for first time: agrees within 20% of expectation from measured b7 errors

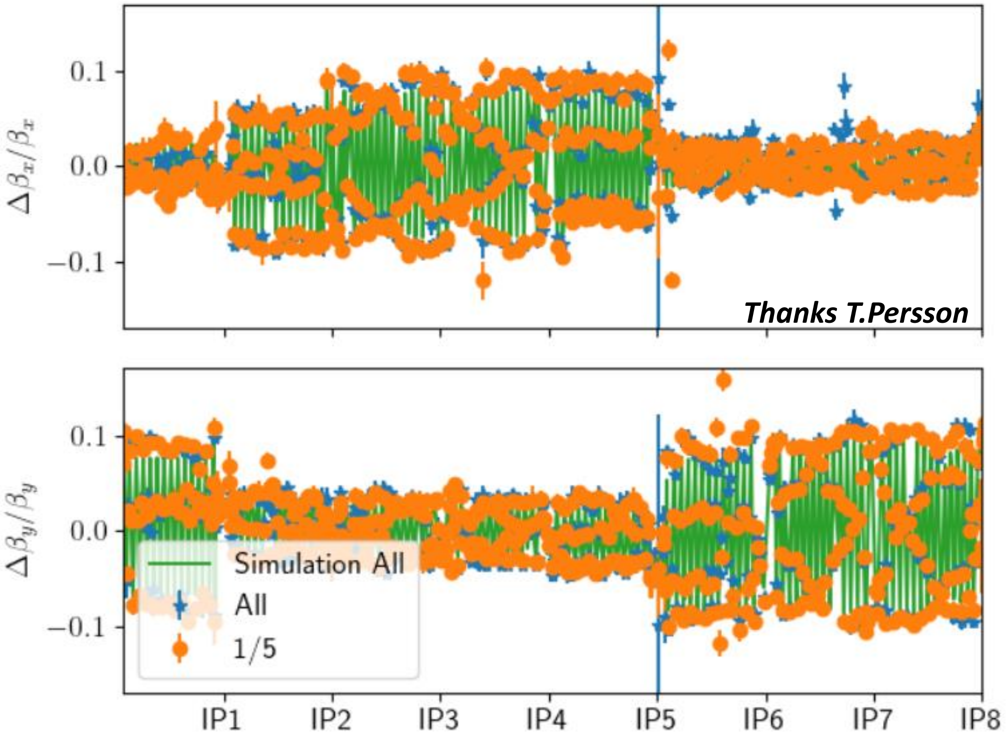


Beyond single particle! ➡ applying OMC tools to long-range beam-beam

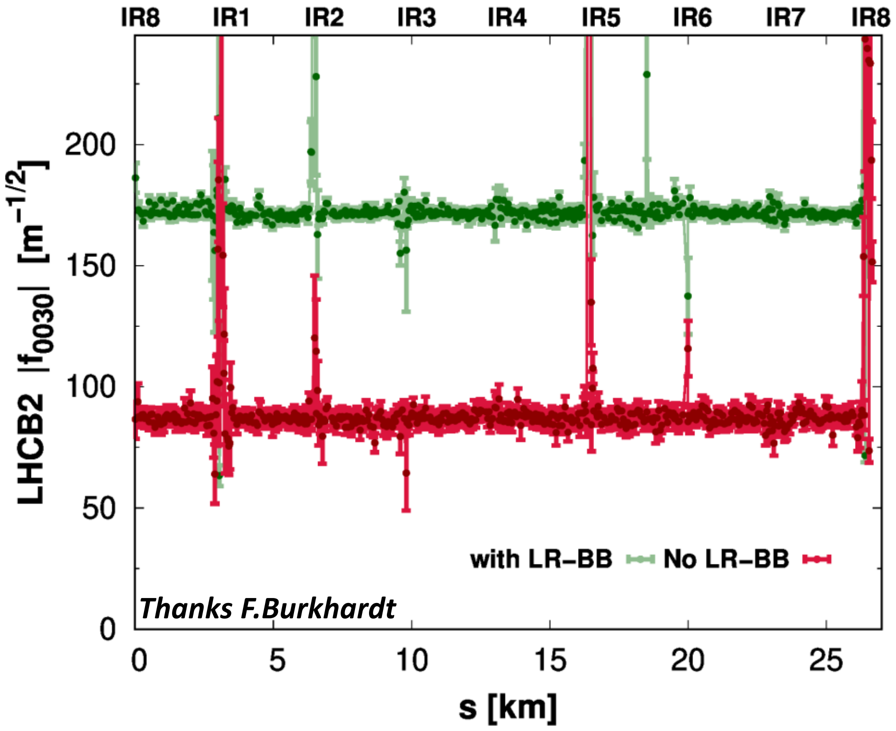
New set of OP procedures in 2024 allowed AC-dipole optics measurements of pilot beam in collision

➡ **Allowed direct benchmarking of linear and nonlinear optics perturbations from long-range beam-beam for the first time**

Measured β-beat agrees well with pytrain



Measured 3Qy resonance strength
→ Comparable contribution from LRBB/lattice



Beyond single particle! ➡ applying OMC tools to long-range beam-beam

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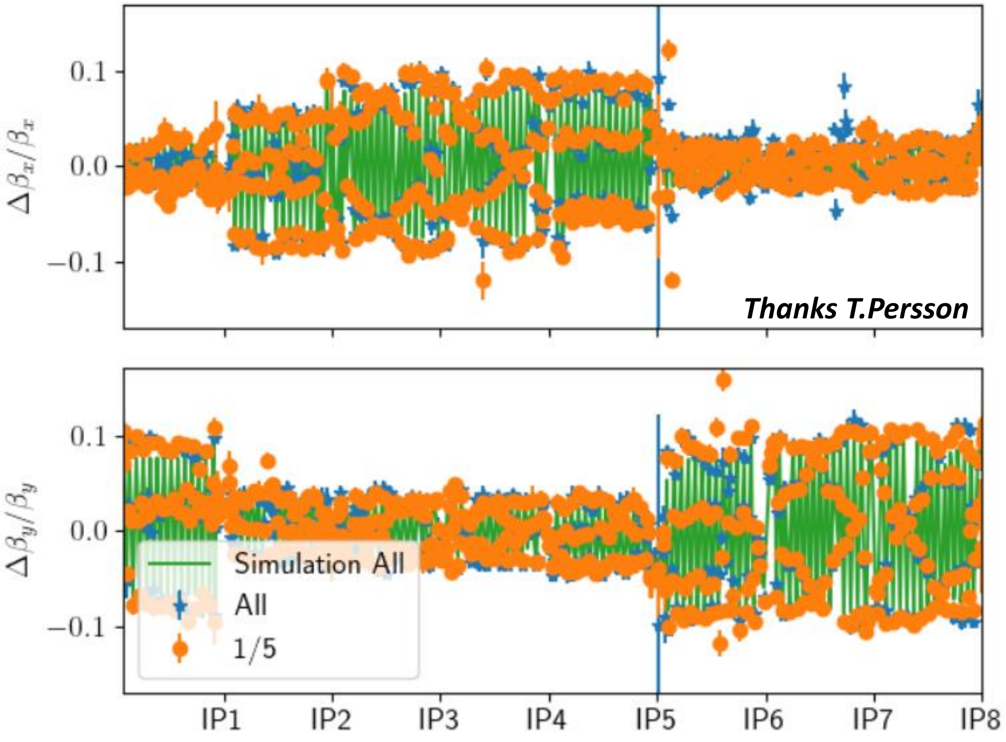
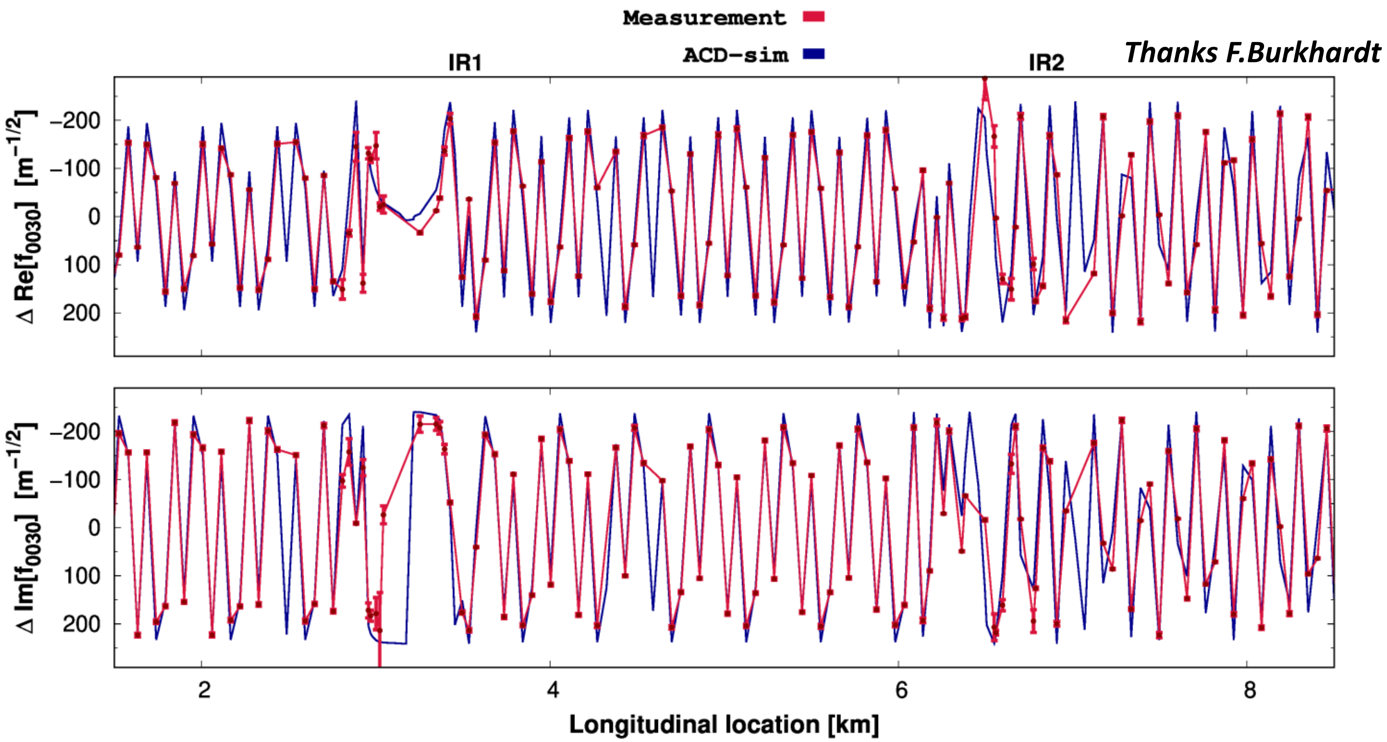
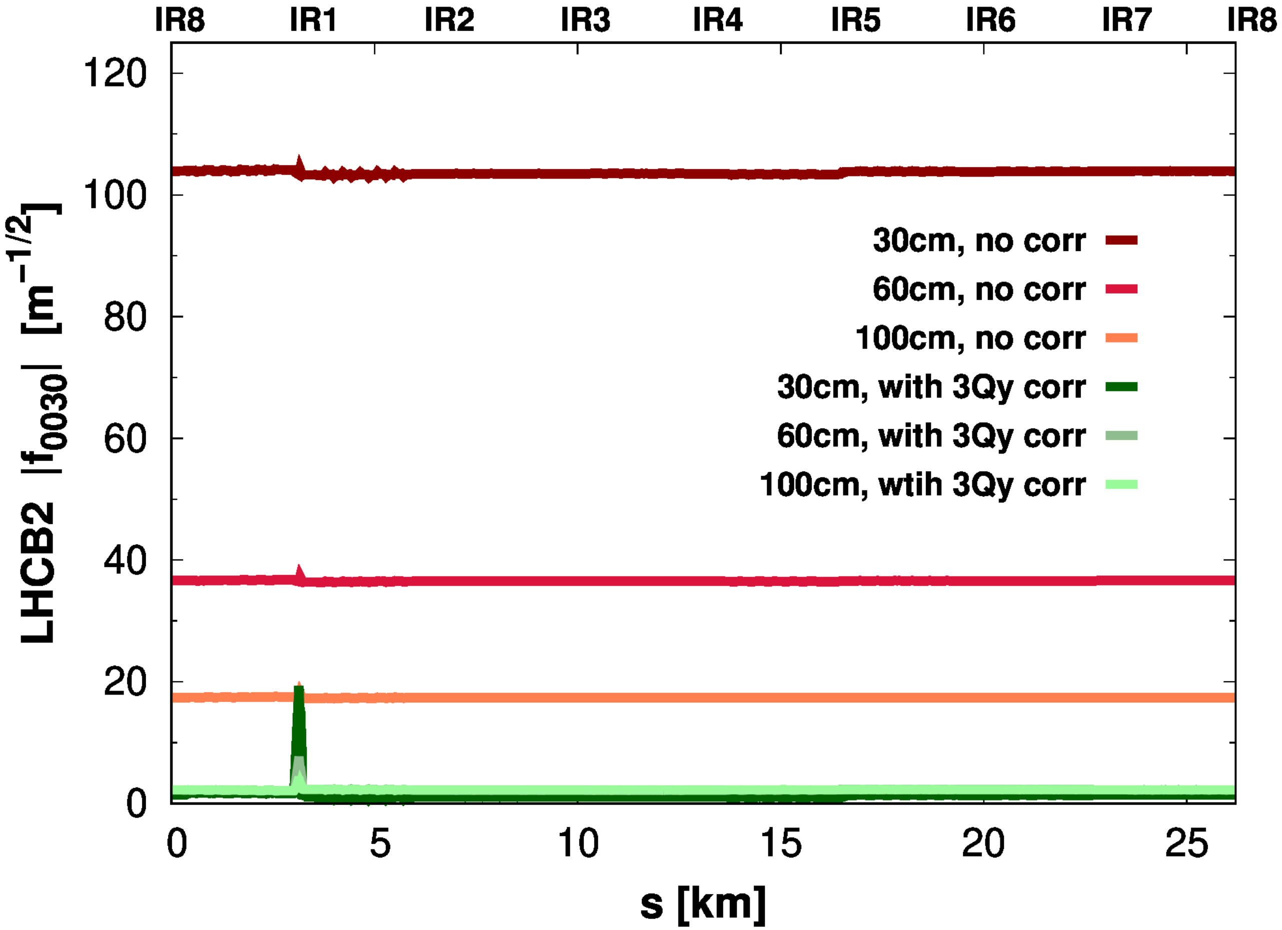


3Qy from beam-beam agreed well with MAD



Predicted optics perturbations from LRBB agree very well with optics measurements



Used **MAD-NG** to calculate corrections for main sextupole resonances driven by long-range beam-beam using the existing IR-corrector package: **3Qy, 3Qx, Qx-2Qy**

Now want to try in the real machine!

→ **2025 commissioning?**

→ To be studied if this is possible with 2025 optics

Conclusions:

- **PSB**

  → First direct measurements of optics at wirescanners show good β-beat (<20%)

- **PS**

  → good progress on development of predictive model for PS optics
  → fully integrating effort on magnetic+optics model and beam-benchmarking has been quite productive
  → planned to try similar approach in other machines e.g. LEIR
  → interesting progress on dedicated studies for emittance measurement

- **SPS**

  → hope to undertake similar optics studies as PSB and PS, initial tests promising
  → various HW improvements would be beneficial → can we increase of number of turns logged in BPM data?

- **LHC**

  → very significant progress in Run3 on benchmarking magnetic error model to high-order
  → promising applications of OMC tools/methods to also study beam-beam

Many members of the OMC team don't work full time on optics

Anyone interested in joining OMC commissioning/MDs is welcome!

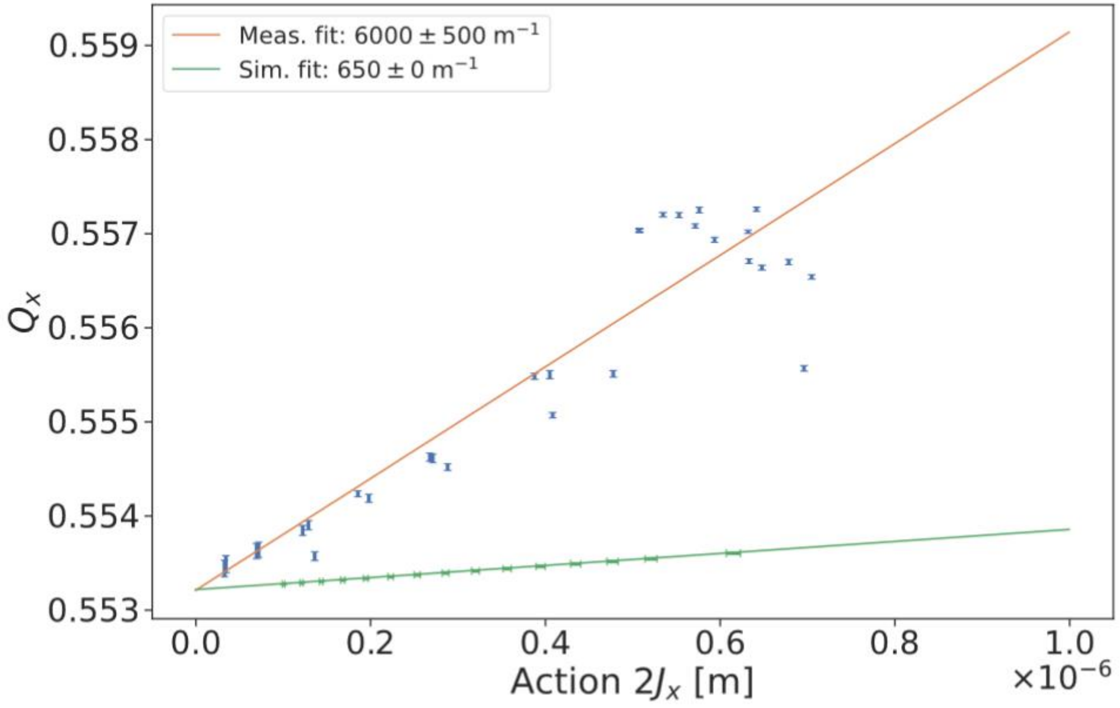
Super-KEK

With view to FCC also trying to study application of OMC methods also to superKEK

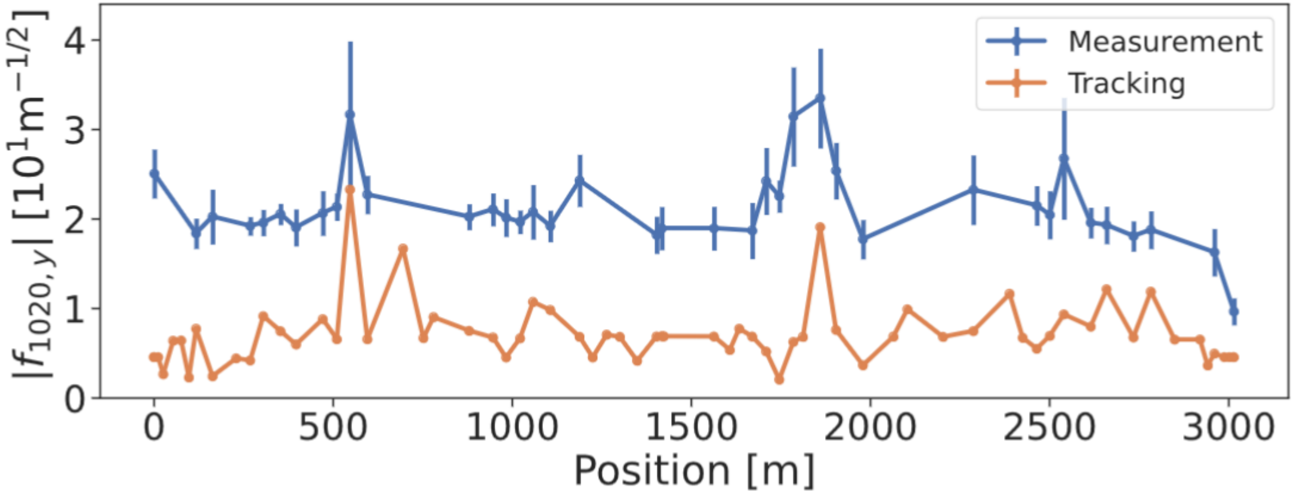
→ First tests of detuning and RDT measurements / model benchmarking undertaken in 2024

→ Point to some large discrepancies with nonlinear optics model

Order of magnitude discrepancy in amplitude detuning of LER ring



Factor >2 in Qx+2Qy sextupole resonance strength of HER ring



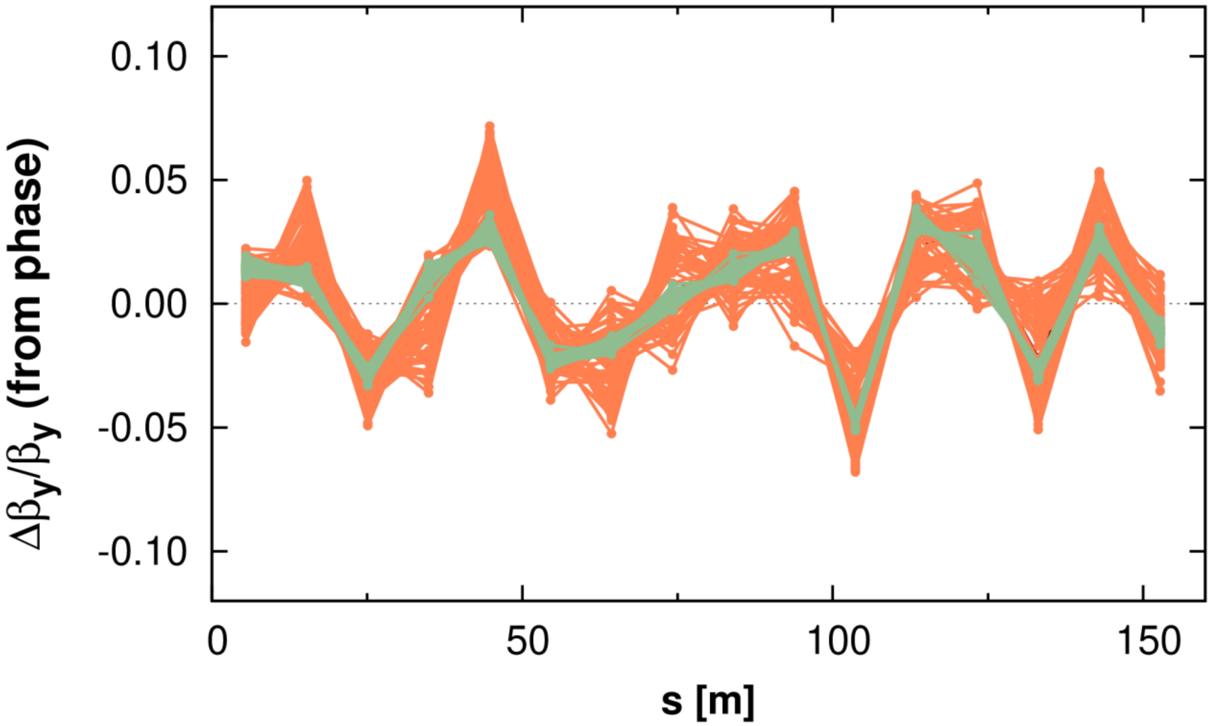
Reserve - PSB

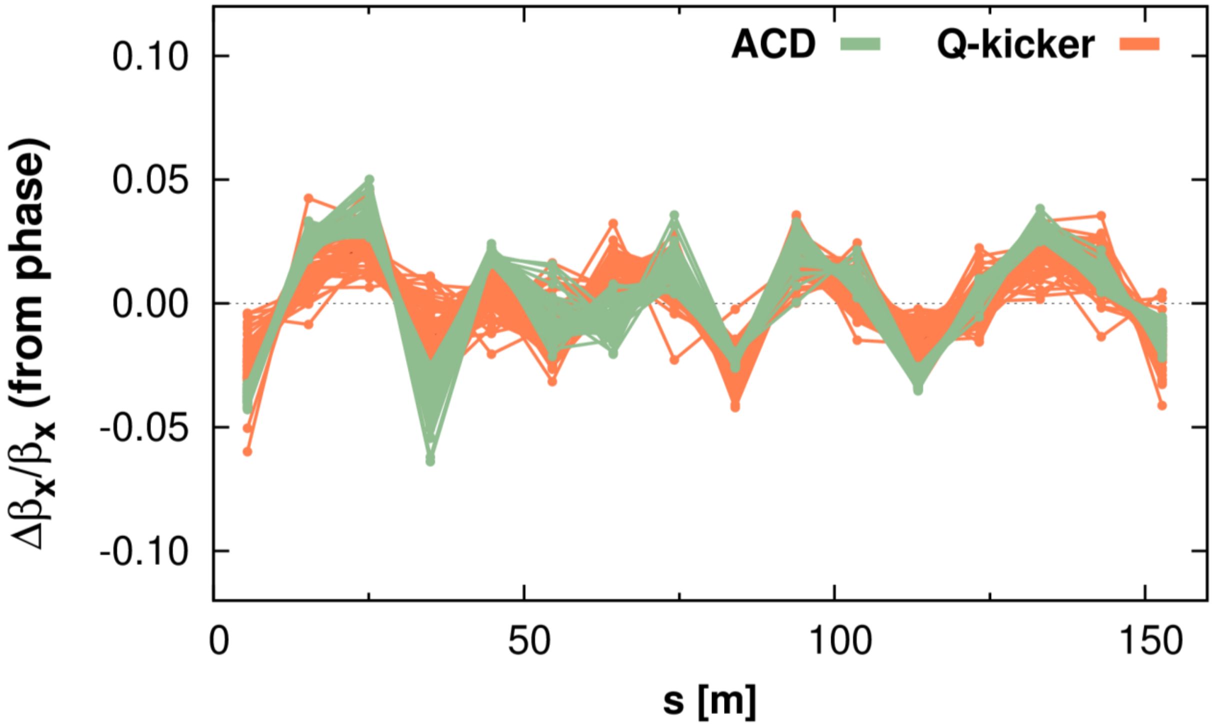
In PSB want to assess measured optics quality w.r.t. the design model

- **compare measured phase- & beta-beat to predictions from nominal sequences / strengths defined for given WP**
  → confirm lattice behaves as expected, confirm optics parameters at wirescanners

- **PSB has very few BPMs, all at $\Delta\varphi = 90^{\circ}$ for Q4Q4 optics** → challenging to measure β-functions

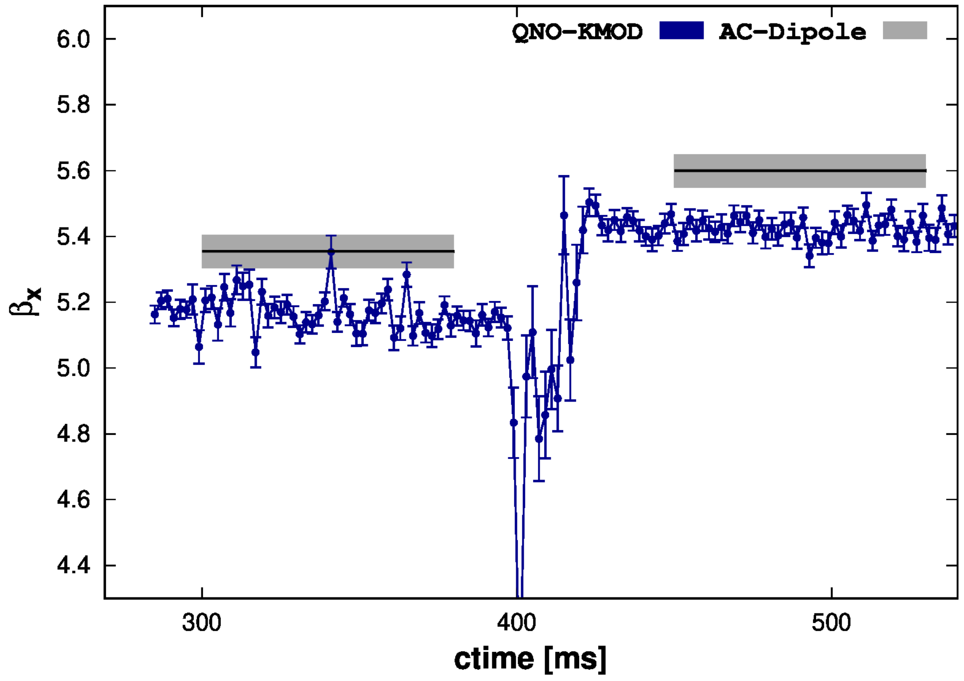
- **At low-energy use special Q3Q5 optics →** **good beta-beat at measured at BPMs (e.g. Ring3 below)**
  → limited extrapolation to BWS in nominal cycles

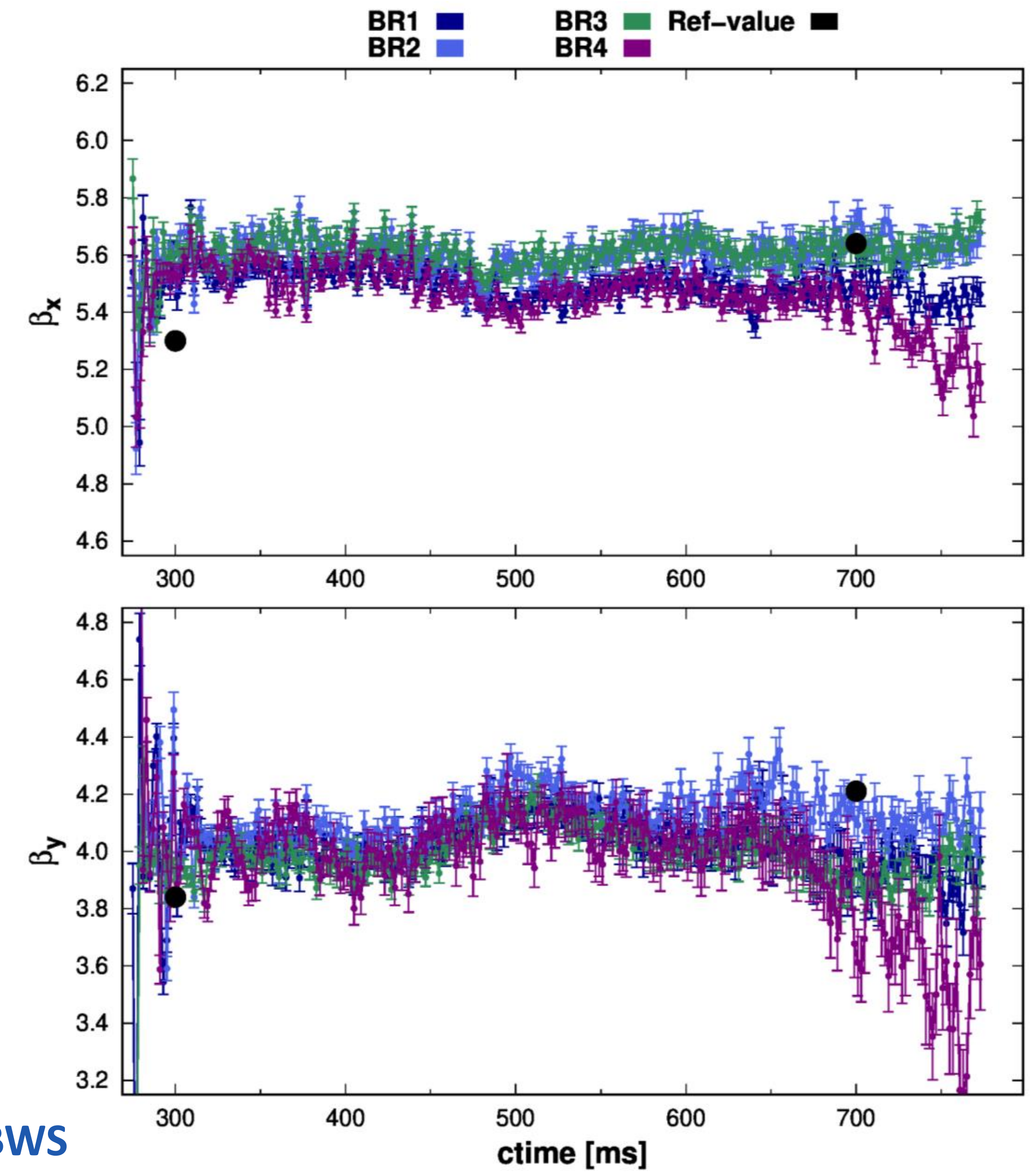




Use new BPMs to test alternative techniques to apply to other rings

K-mod at neighbouring QNO returns β within 5% of ACD:



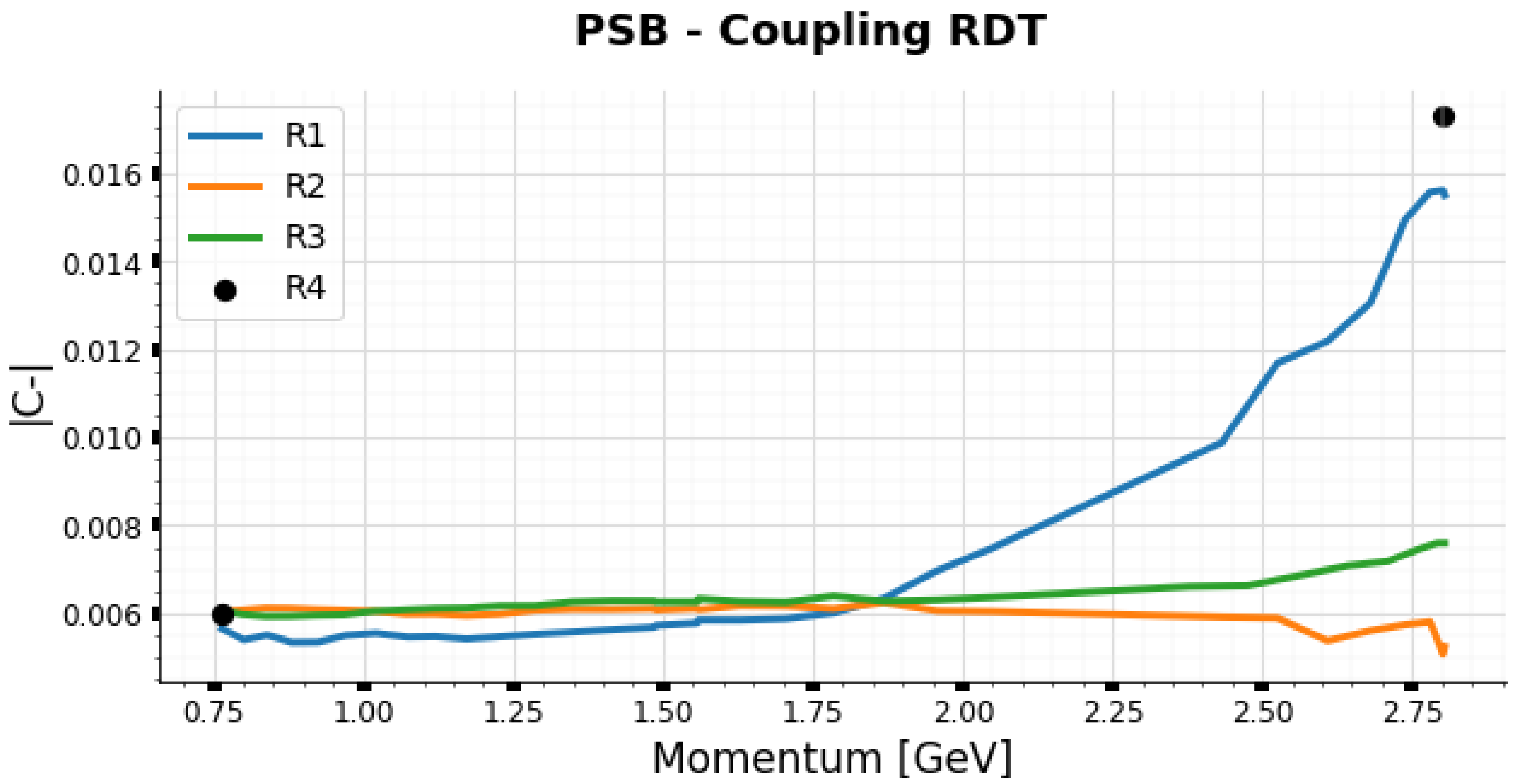


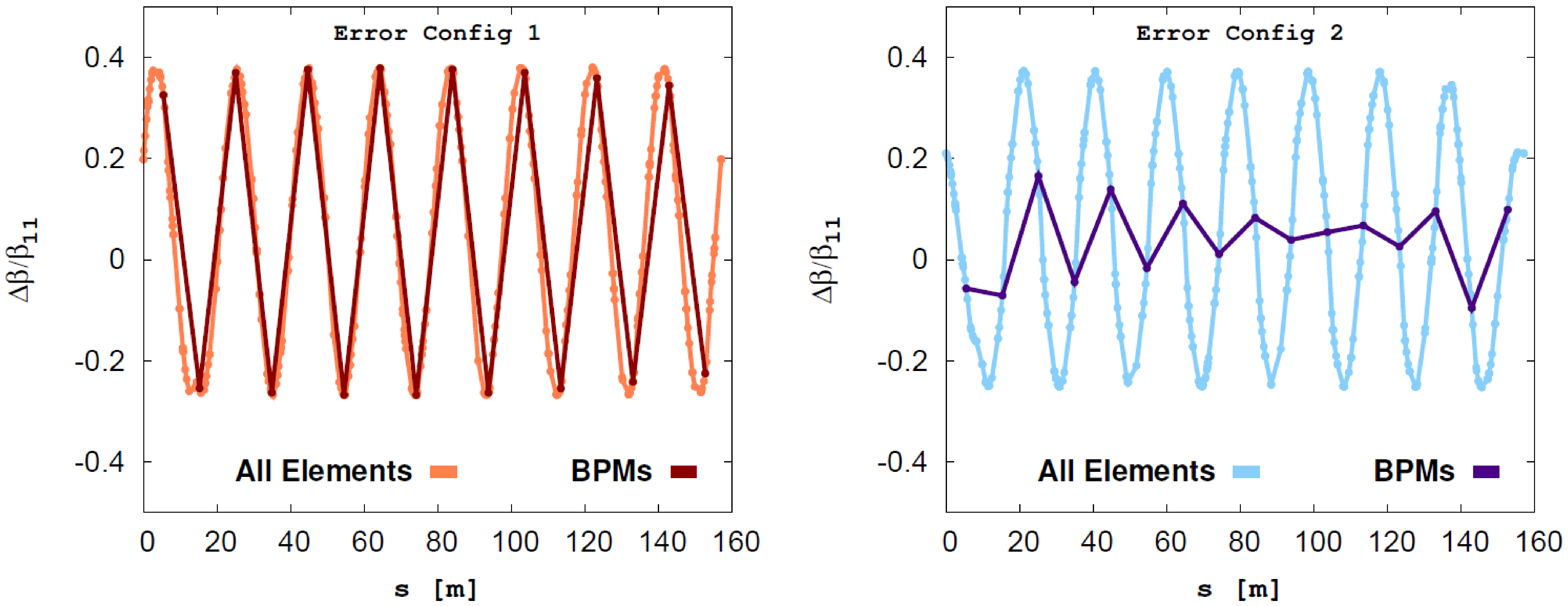
Only small potential I/K calibration error:

→ Assuming similar QNO quality in all rings see $\frac{\Delta\beta}{\beta} \leq 15\%$ at V-BWS

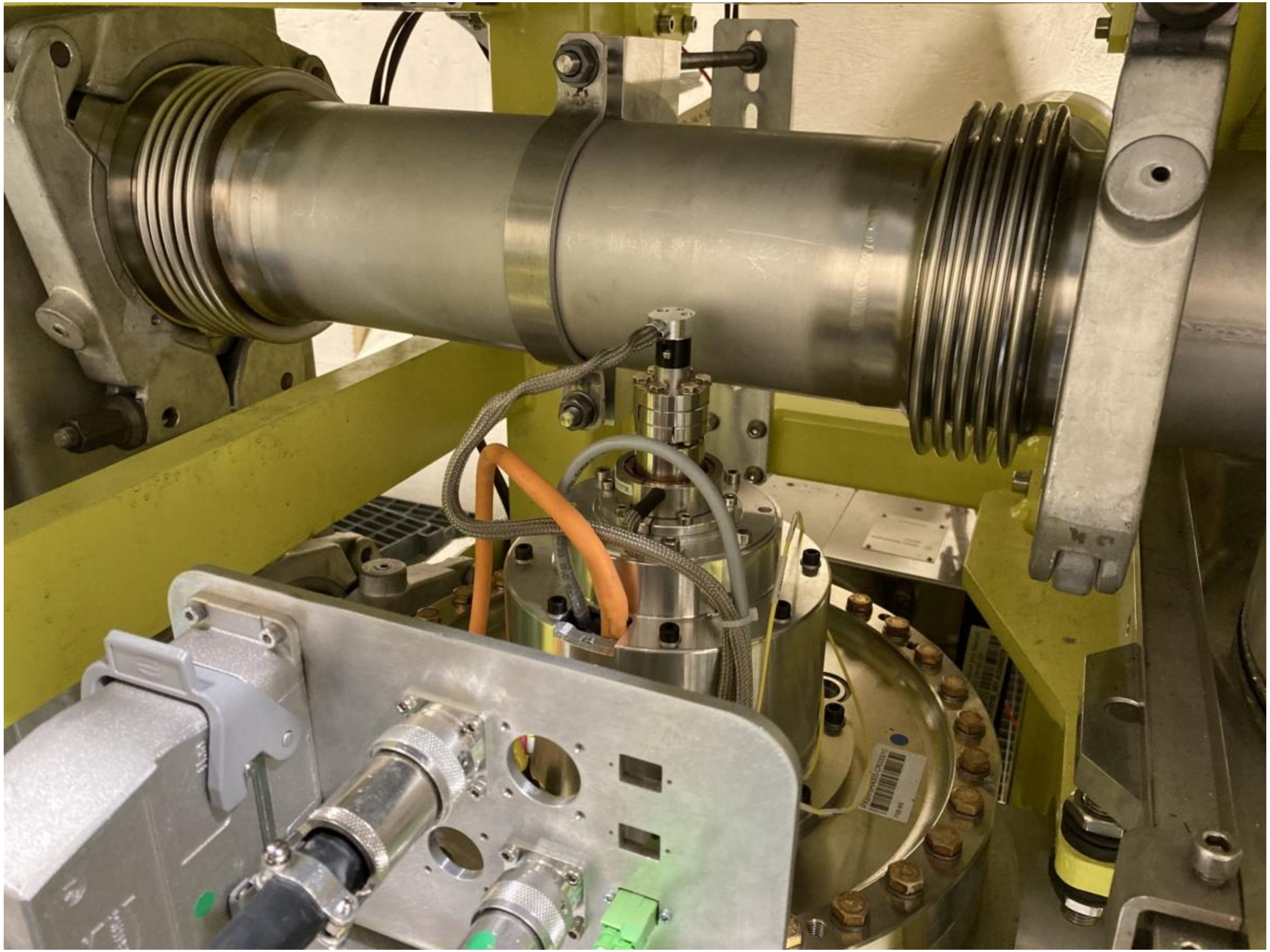
So far, linear optics in PSB looks relatively consistent with design model

- No obvious issue for emittance measurement from beta-beating seen so far → study of BWS-H R2-3 ongoing
- Quite consistent linear optics between different rings
- Systematic difference in linear coupling between inner/outer rings

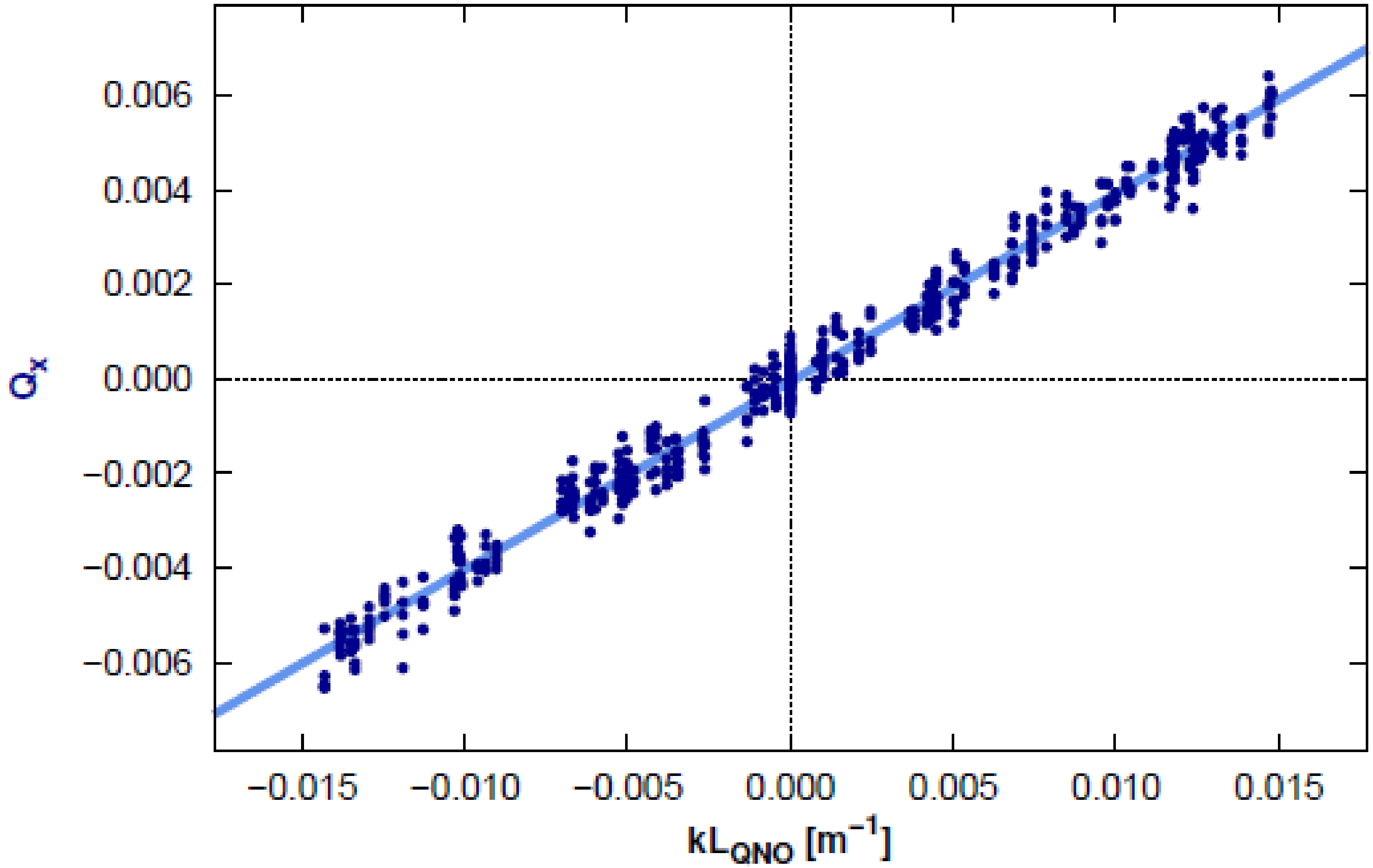




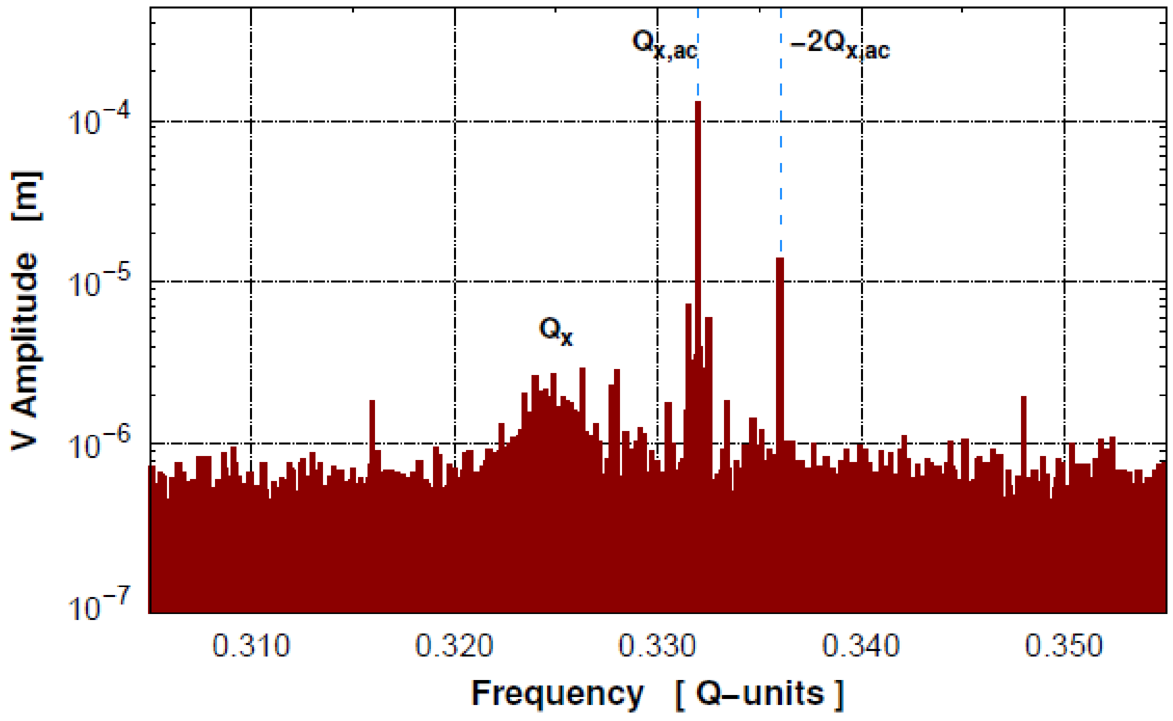
Error Config 1
0.4
0.2
0
-0.2
-0.4
Δβ/β11
All Elements
BPMs
0
20
40
60
80
100
120
140
160
s [m]
Error Config 2
0.4
0.2
0
-0.2
-0.4
Δβ/β11
All Elements
BPMs
0
20
40
60
80
100
120
140
160
s [m]



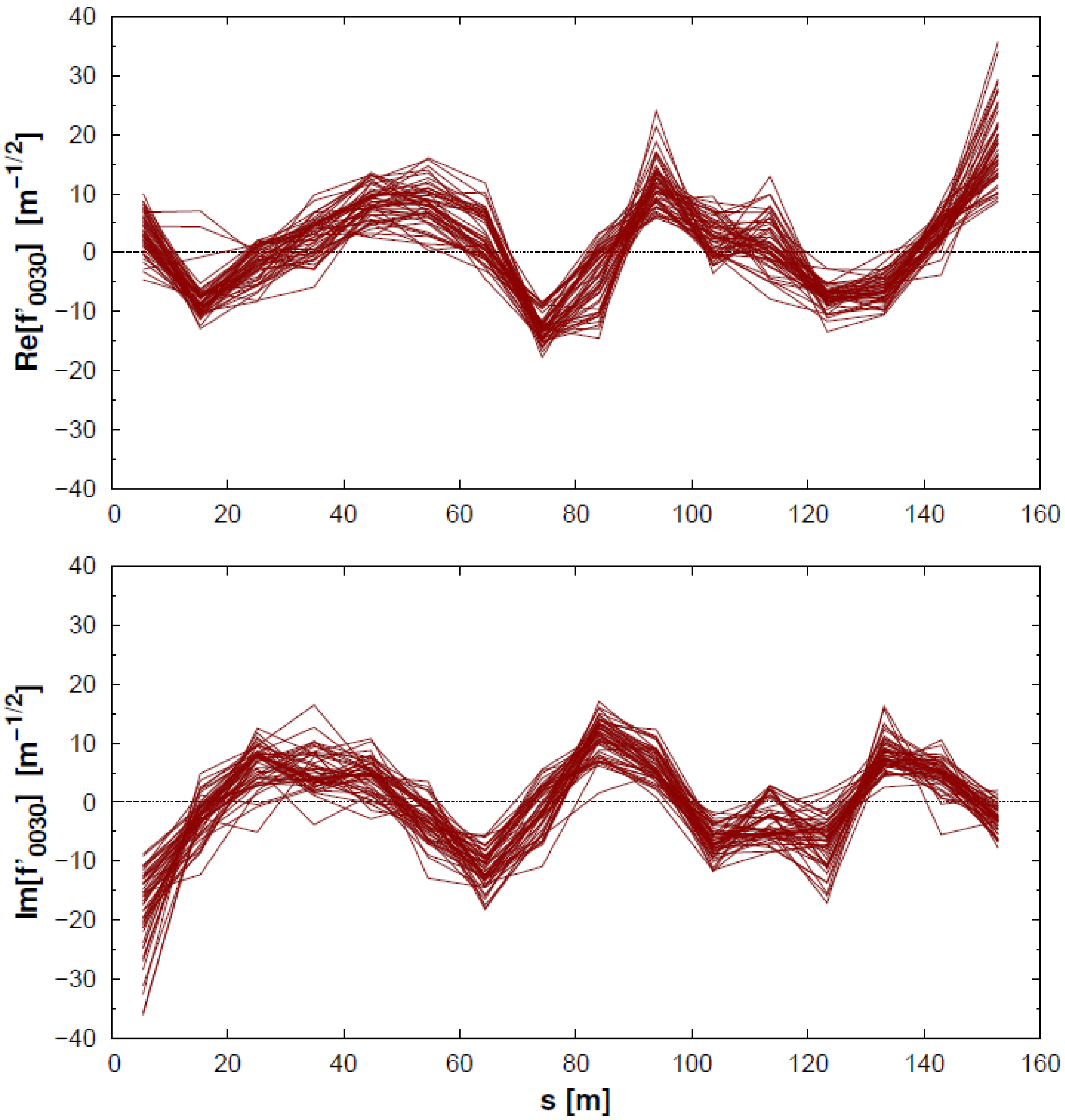
QNO 311L1 Kmod



RDT in PSB



$Q_{x,ac}$
$-2Q_{x,ac}$
Q_x
10^{-4}
10^{-5}
10^{-6}
10^{-7}
V Amplitude [m]
0.310
0.320
0.330
0.340
0.350
Frequency [Q–units]

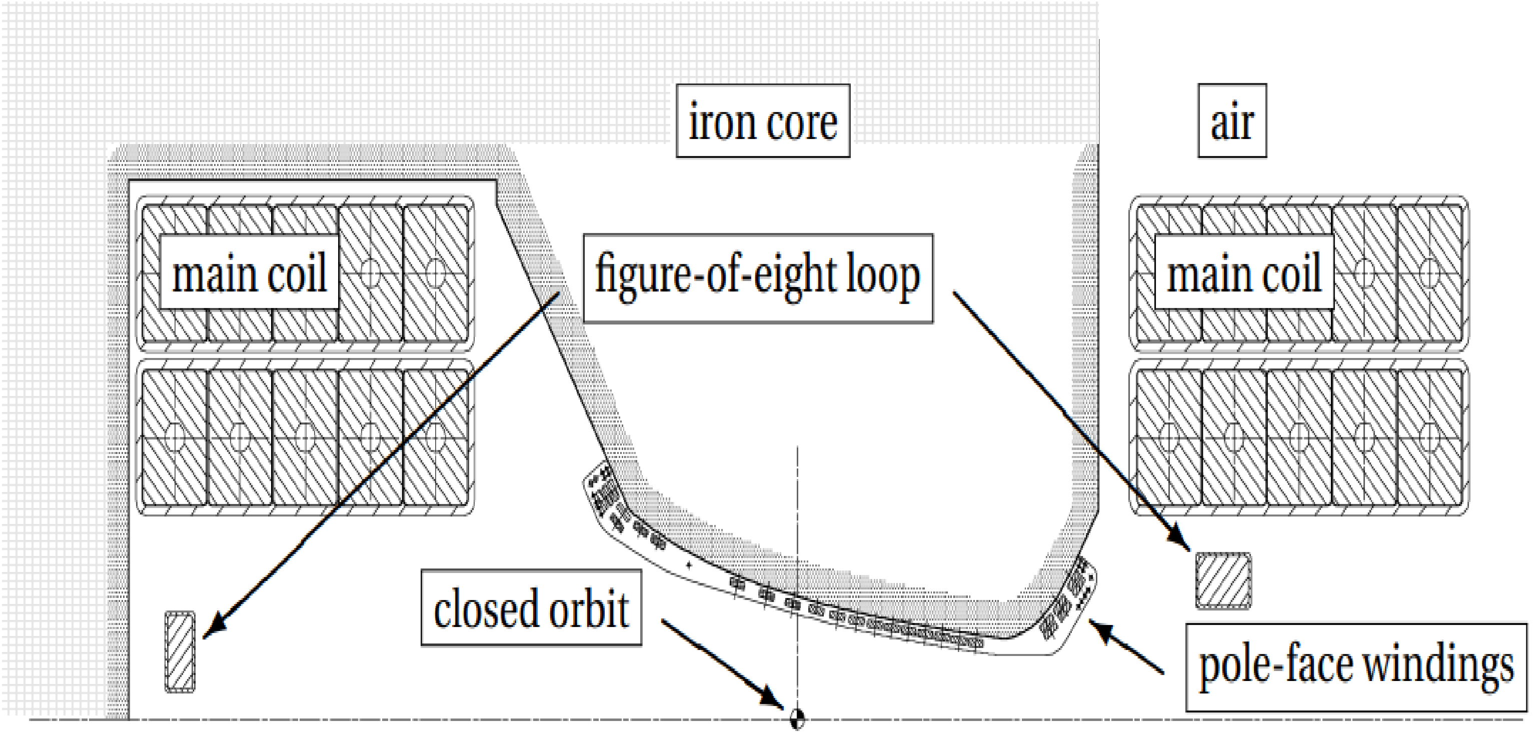


Re[f'$_{0030}$] [m$^{-1/2}$]
Im[f'$_{0030}$] [m$^{-1/2}$]
40
30
20
10
0
−10
−20
−30
−40
0
20
40
60
80
100
120
140
160
s [m]

Reserve - PS

Optics modelling/studies for PS have taken a very different approach

- PS optics (mostly) defined by combined function Main Unit (MU) magnets. Exhibit strong saturation over OP cycles.
- Tune & Chroma control handled (mostly) via complicated set of auxiliary pole-face-windings (PFW) and figure-8-loop (F8L) which perturb the MU-field



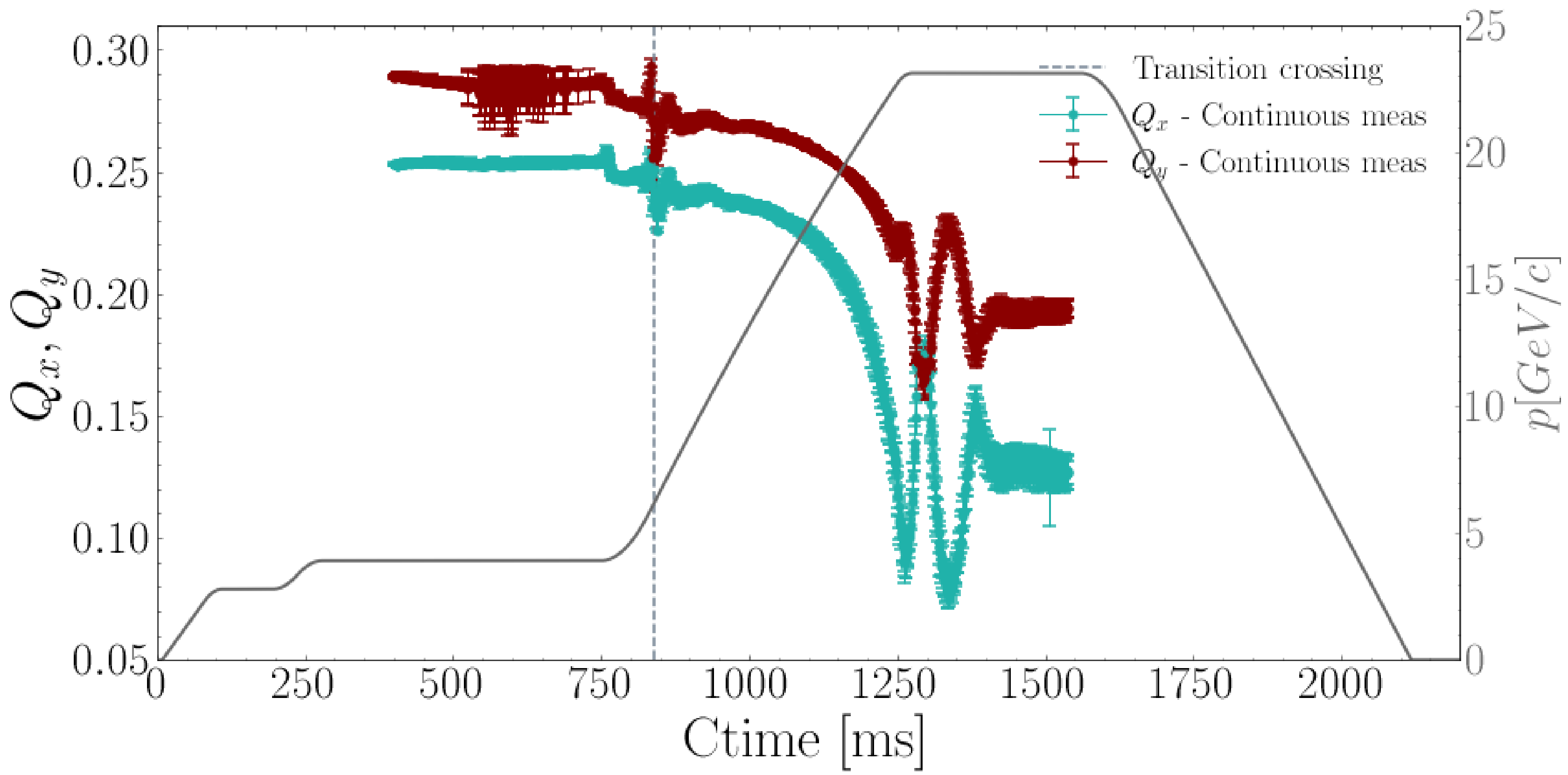
- PS optics simulations generally based on effective models
  → produced by matching to beam-based measurements
- Tune and chroma control based on empirical settings and measured responses of the PFW / F8L

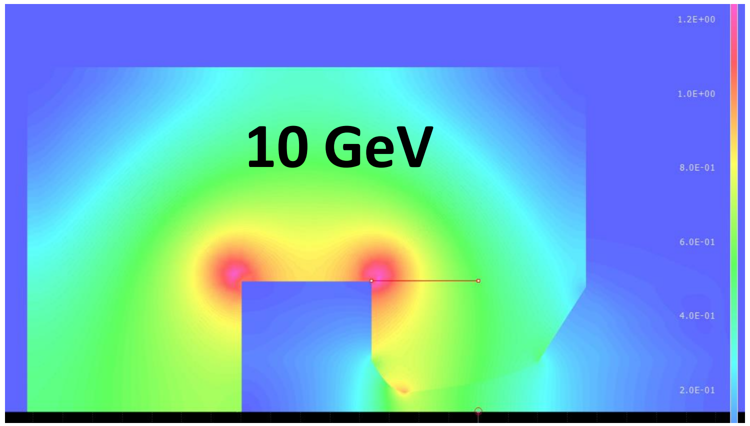
To benchmark OPERA-MAD models tested dedicated bare-machine cycles with only MU

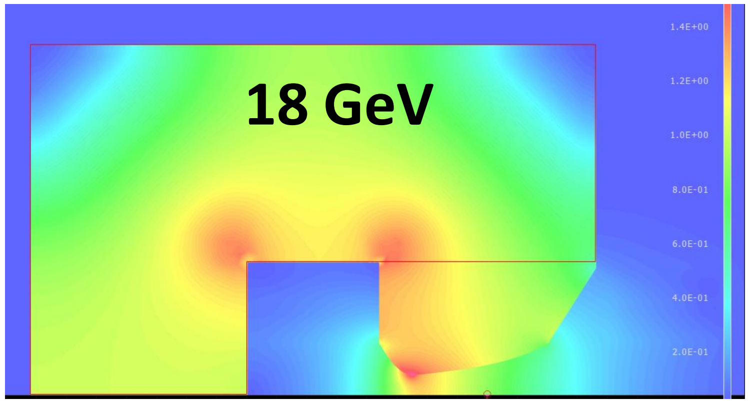
→ **lots of support from PS-OP to create large number of bare machine cycles**

Rapid tune drop with momentum → **faster saturation of quadrupole harmonic compared to dipole**

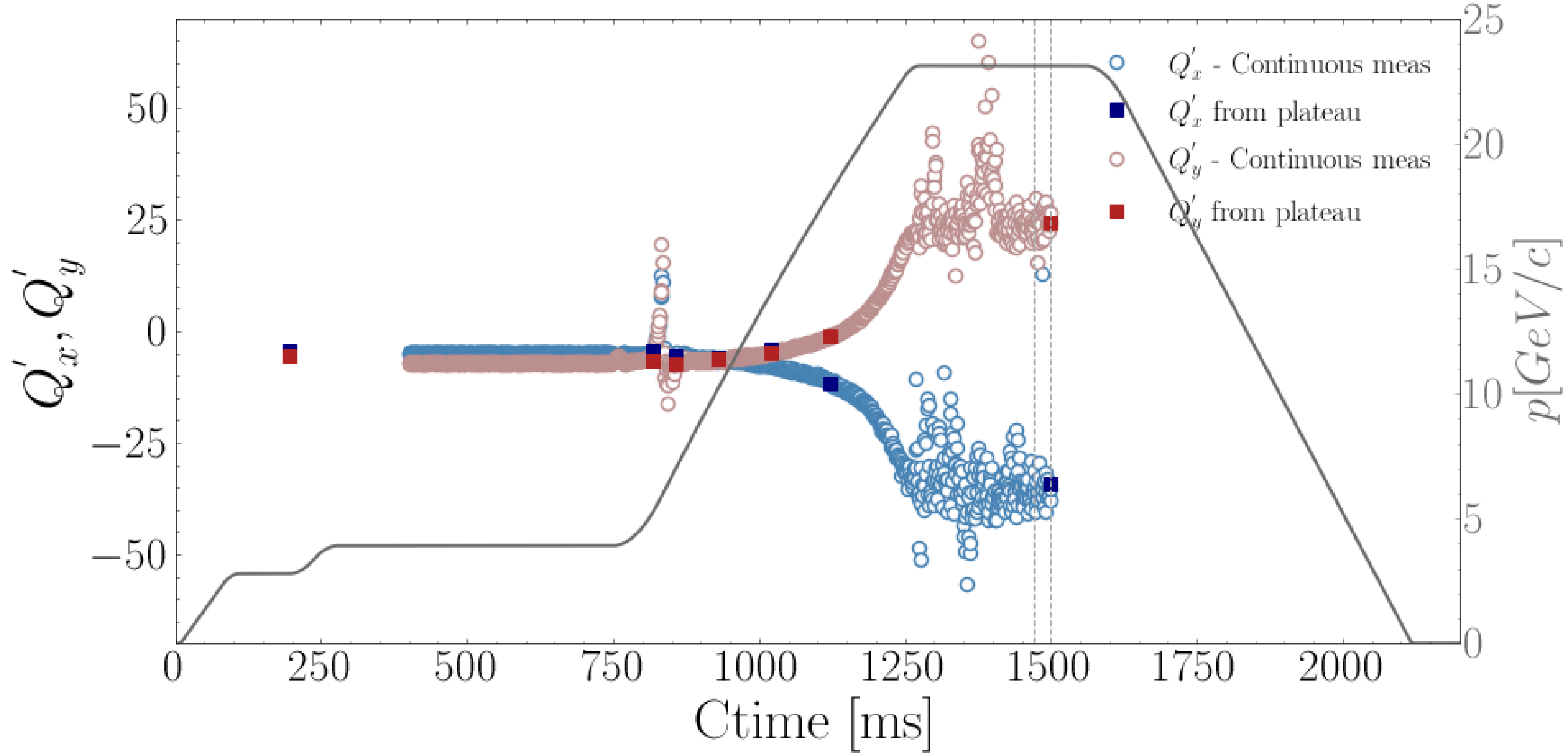
→ **also expected from magnetic model**



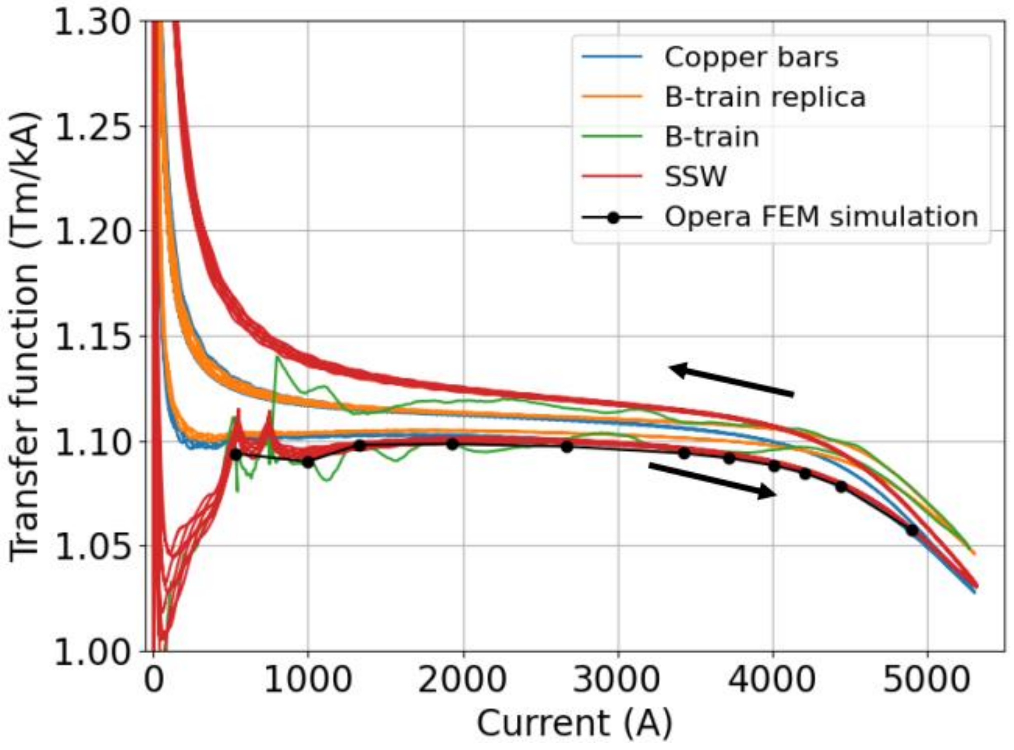




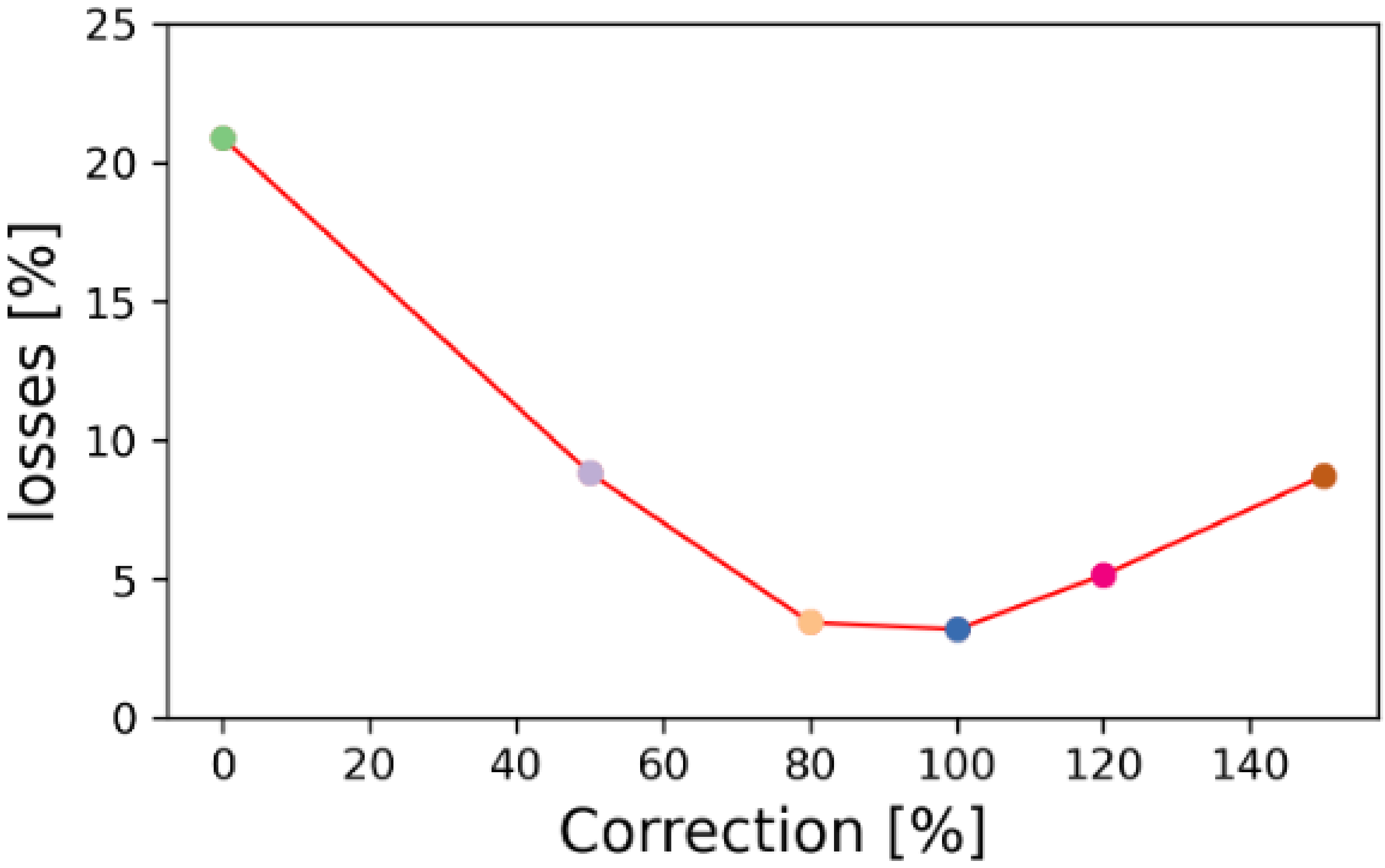
Energy [GeV/c]	I_{MC} [A]	B_{meas} [T]	B_{sim} [T]	ΔB [mT]	$\Delta B/B_{meas}$ [%]
2.79	**531.6**	0.1329	0.1320	0.9	0.67
5.25	**998.5**	0.2500	0.2487	1.3	0.52
7.00	**1329.5**	0.3332	0.3314	1.8	0.54
10.14	**1925.3**	0.4827	0.4803	2.4	0.50
14.04	**2668.5**	0.6684	0.6655	2.9	0.43
18.00	**3428.0**	0.8570	0.8537	3.3	0.39
23.11	**4443.6**	1.1000	1.0965	3.5	0.32



Q'_x - Continuous meas
Q'_x from plateau
Q'_y - Continuous meas
Q'_y from plateau
Q'_x, Q'_y
$p[GeV/c]$
Ctime [ms]
0
250
500
750
1000
1250
1500
1750
2000
50
25
0
−25
−50
25
20
15
10
5
0

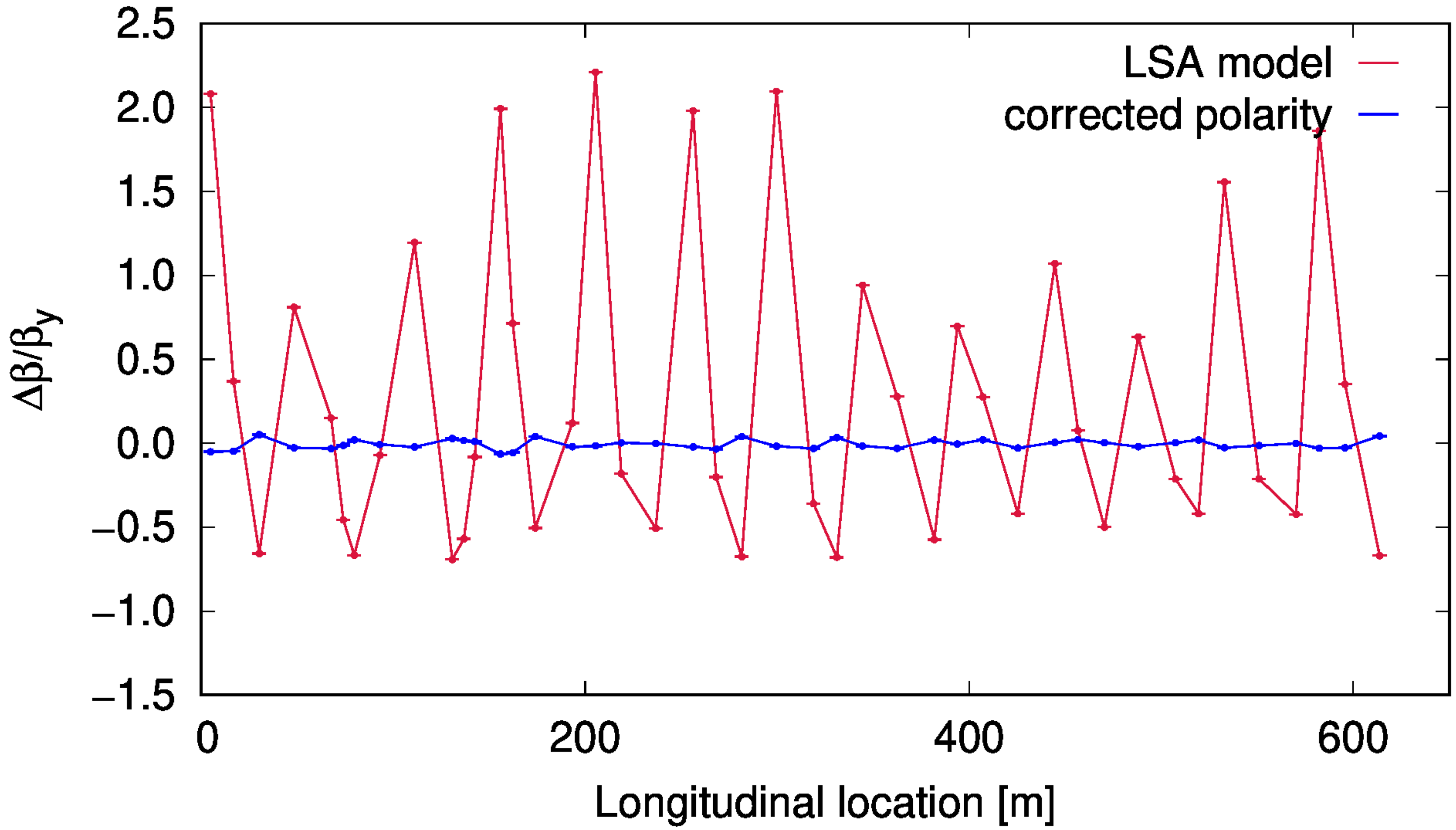

1.30
1.25
1.20
1.15
1.10
1.05
1.00
Transfer function (Tm/kA)
0
1000
2000
3000
4000
5000
Current (A)
Copper bars
B-train replica
B-train
SSW
Opera FEM simulation

Reduced losses crossing the 2Qx+Qy resonance following direct correction of the forced RDT



General effort to benchmark circuit responses

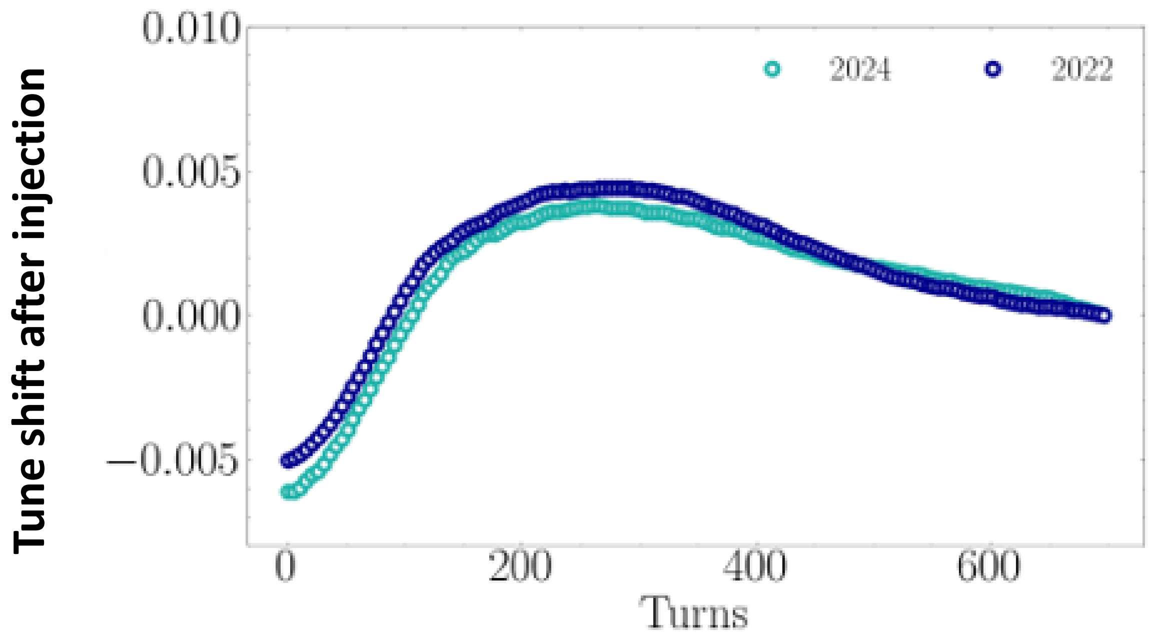
e.g: <u>fake</u> 200% beta-beat during PS extraction → caused by inconsistent polarity definition in model vs LSA

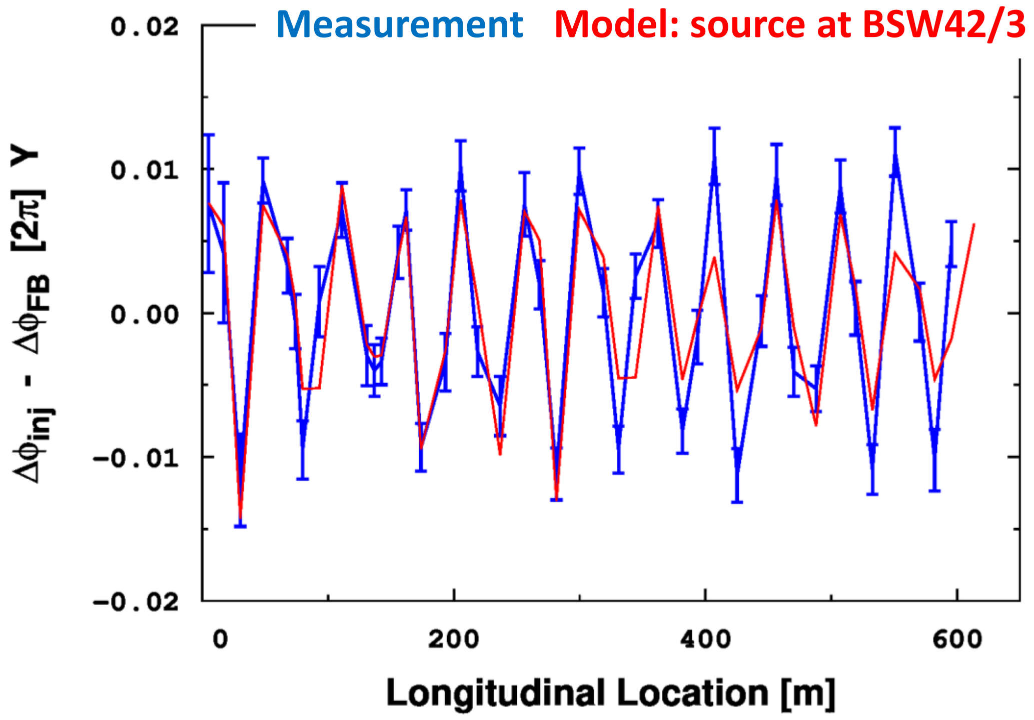


Eddy currents during PS injection

- Large Q-shifts are observed during PS injection ➡ historically attributed to sextupolar eddy currents from BSW

Looking at phase and beta-beat during injection, optics error agrees well with source at BSW42 and BSW43 (as would expect for eddy current feed-down)



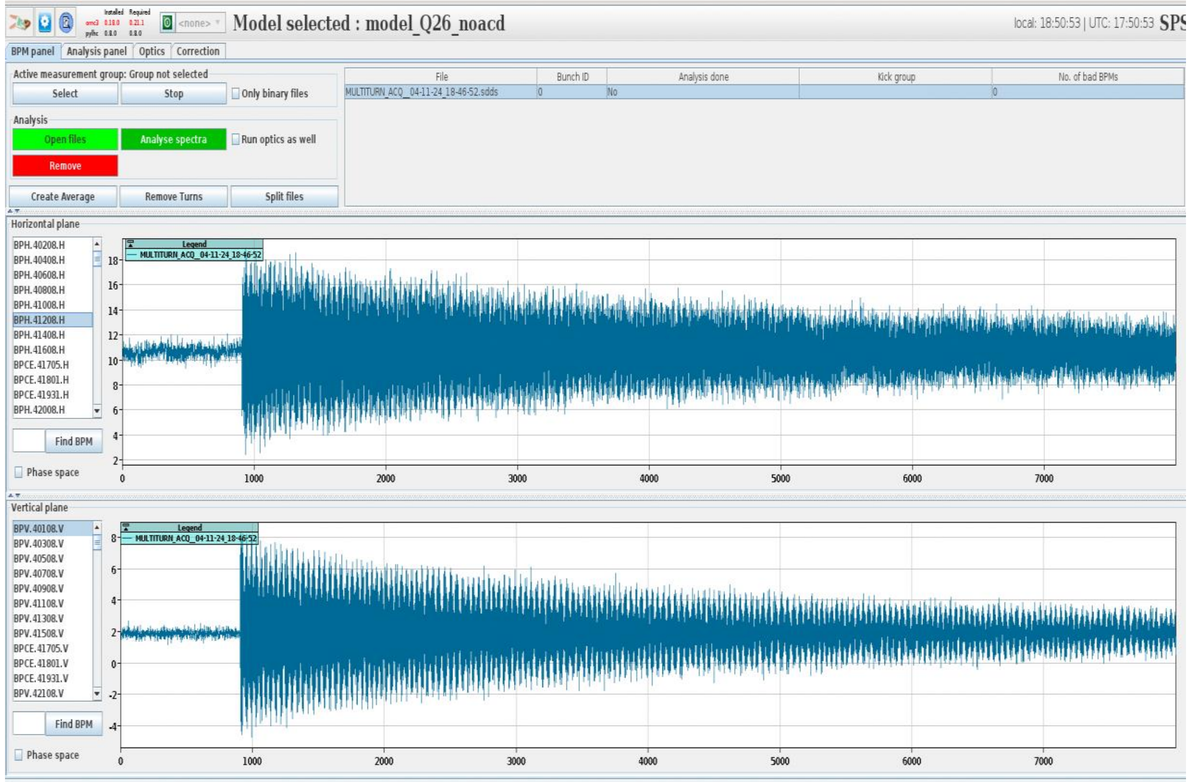


Reserve - SPS

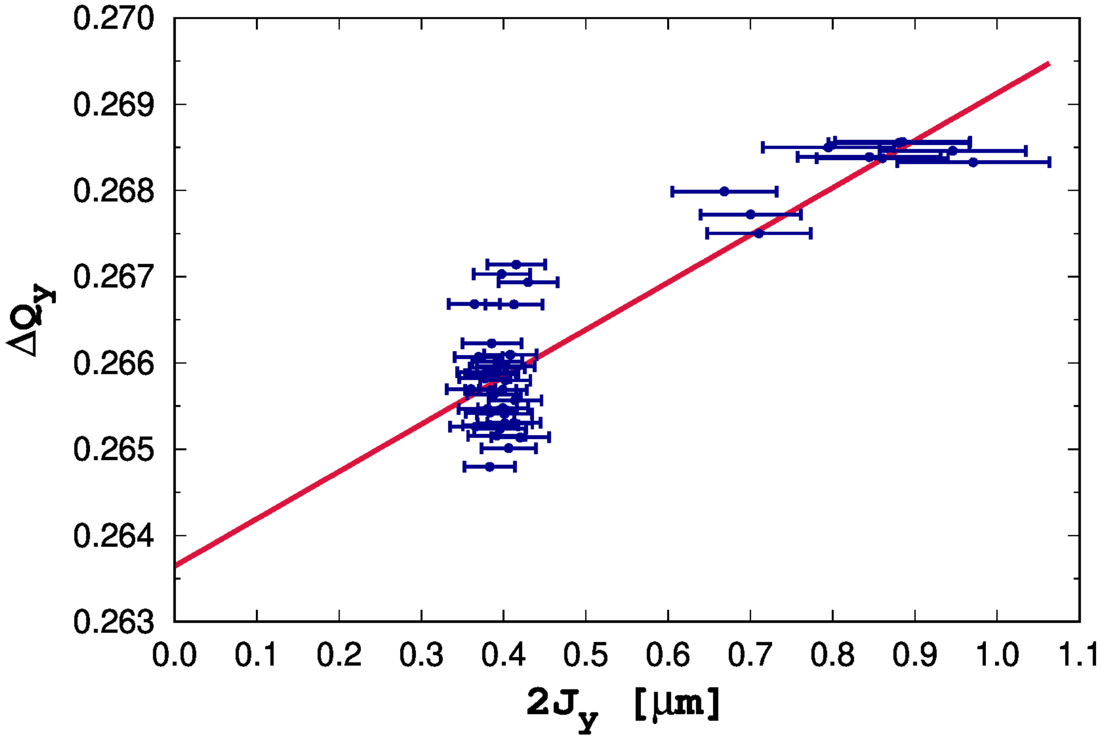
Given progress on optics studies in PSB/PS, also interest from SPS to start to utilize OMC tools to study optics

- **Optics studies in SPS aren't new, but not a machine OMC team has generally supported (for many years)**
- **Several parallel MDs in 2024 to try optics measurements in SPS with ADT-ACD and free-kicks**

updating OMC tools/code/setting to work well for SPS



First tests of SPS amplitude detuning measurements
→ Needs LHC-like correction for shot-to-shot drift

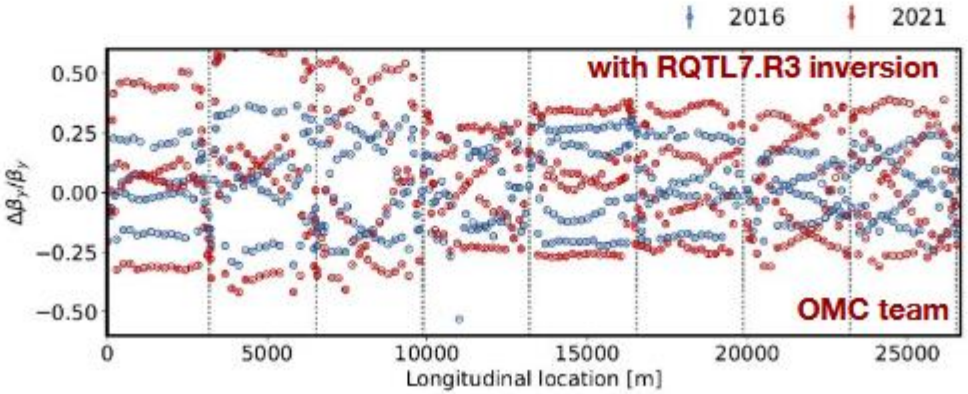


Reserve - LHC

LHC has very large linear optics errors with respect to design model

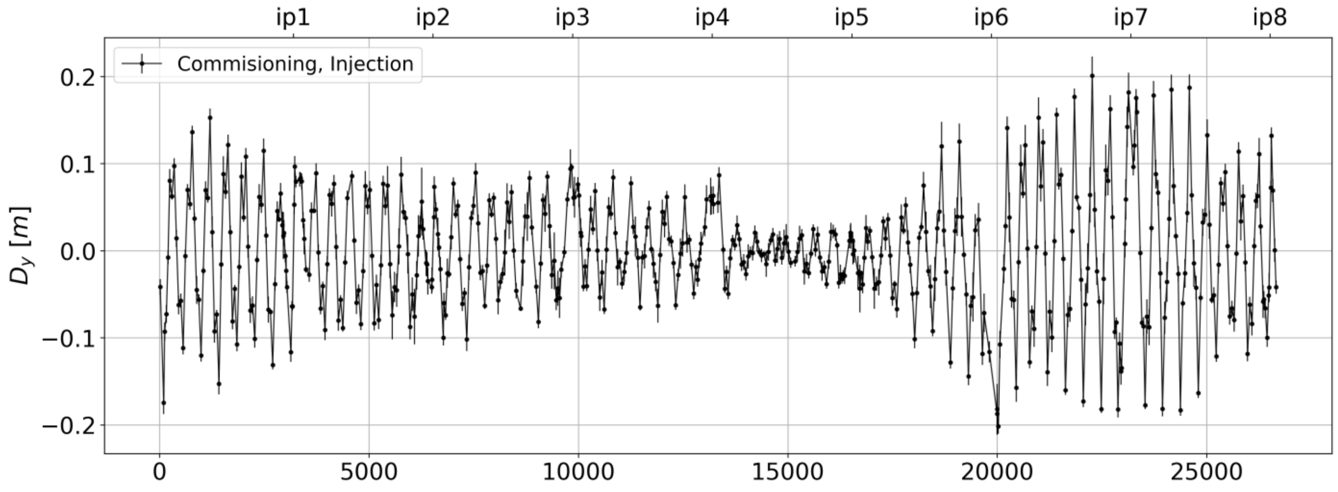
- addressed each year in commissioning with beam-based corrections (see Felix's talk)
  - w.r.t. hardware models: a key focus is identification of significant non-conformities

Classic example is identification of cable swap in RQTL7.R3 B1/B2 at start of Run1/3



Fitting the optics perturbation in the model allows the offending quad to be identified

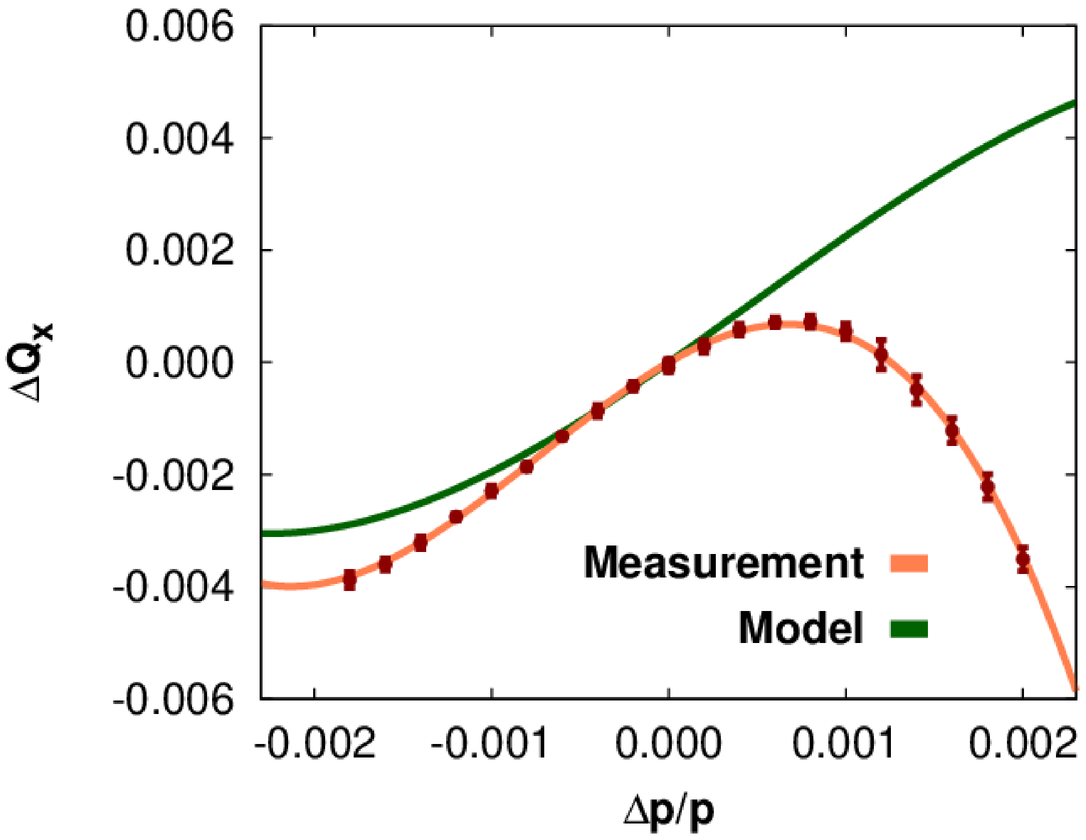
Particular focus in 2024 has been large vertical dispersion wave consistently measured over many years/optics



Best fit in model points to very out-of-spec roll error in MQ.29R5.B2 ($\Delta\theta \approx 10\text{mrad}$)

Concerning the magnetic model LHC is fortunate compared to injectors

- Very extensive magnetic measurements of main magnets performed during construction up to high multipole order
- want to benchmark against real machine & understand any discrepancies
- Process ongoing for many years

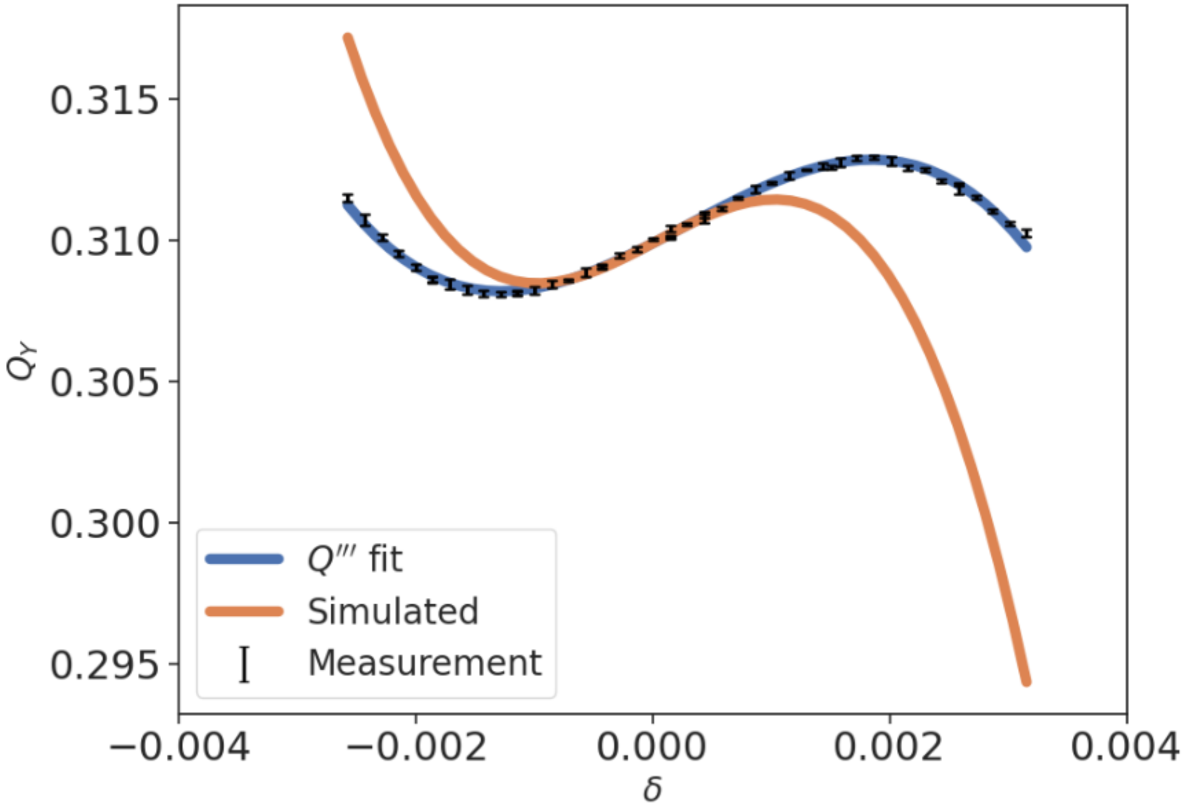


e.g.

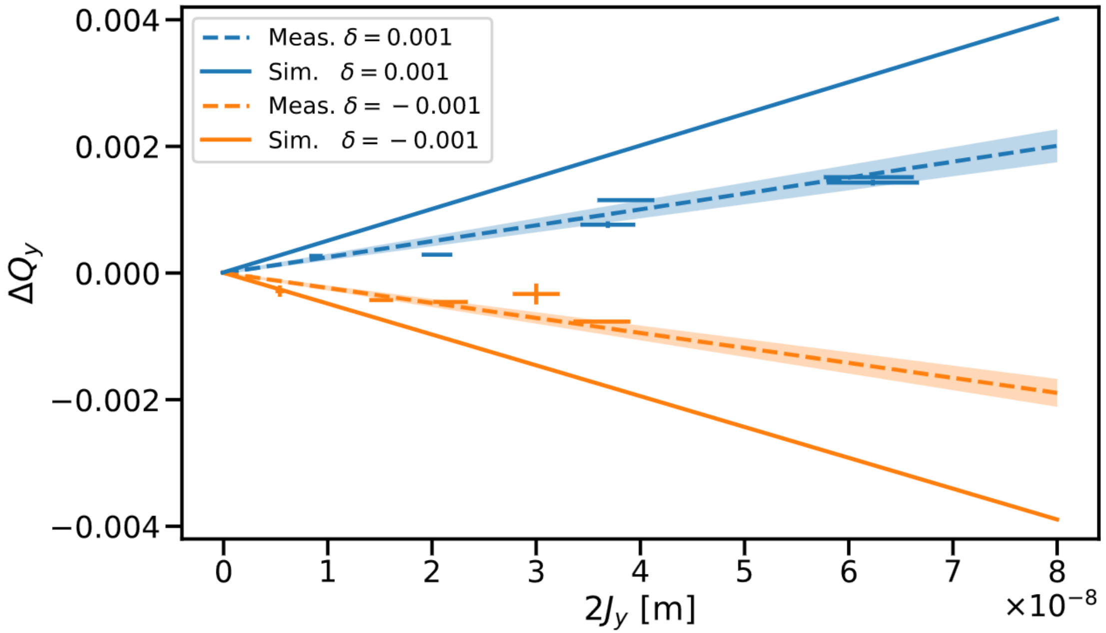
Observed Q'' at injection is $10 \times$ higher than predicted from magnetic measurements of the octupole errors

➡ **Beam-based studies identified source as additional octupole component generated by decapole spool pieces** (feed-down or cross talk)

Significant progress made during Run3 on benchmarking of very high-order multipoles



Factor 2 discrepancy in Q''' with magnetic model predictions



New types of measurement (momentum dependent detuning) clearly indicate comes from missing decapole

$$\Delta Q(J_x, J_y, \delta) = \frac{\partial^2 Q}{\partial J_x \partial \delta} J_x \delta + \frac{\partial^2 Q}{\partial J_y \partial \delta} J_y \delta + \frac{1}{3!} \frac{\partial^3 Q}{\partial \delta^3} \delta^3$$

Re-visiting old magnetic measurements (thanks L.Deniau) large b5 decay was measured

→ Not something included in errors tables used for optics studies, or used for OP-spool piece settings

→ Incorporating into optics simulation explains most of the missing b5

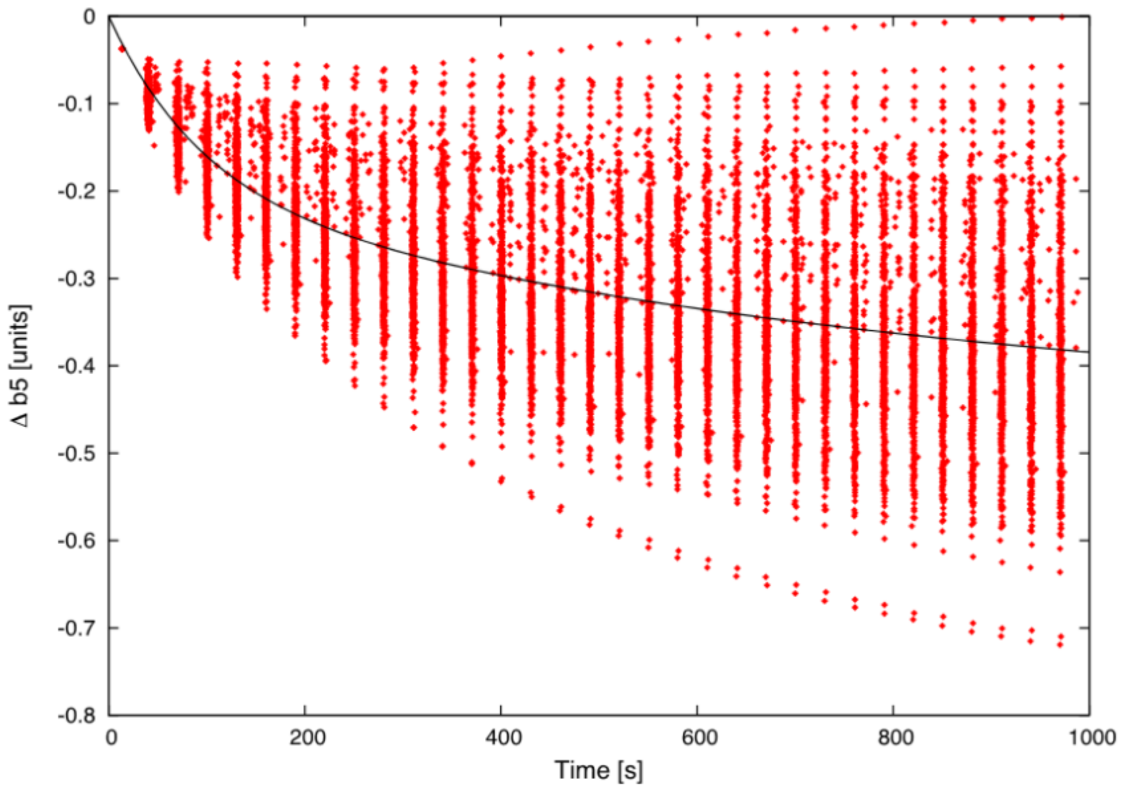
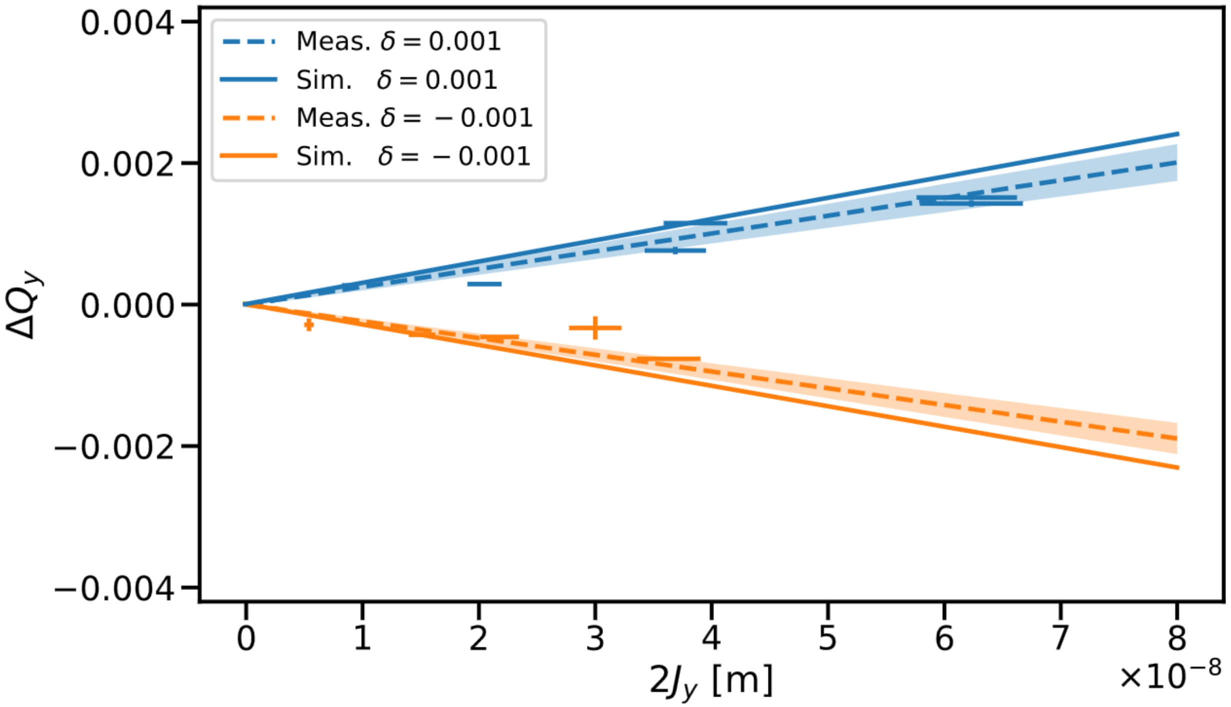
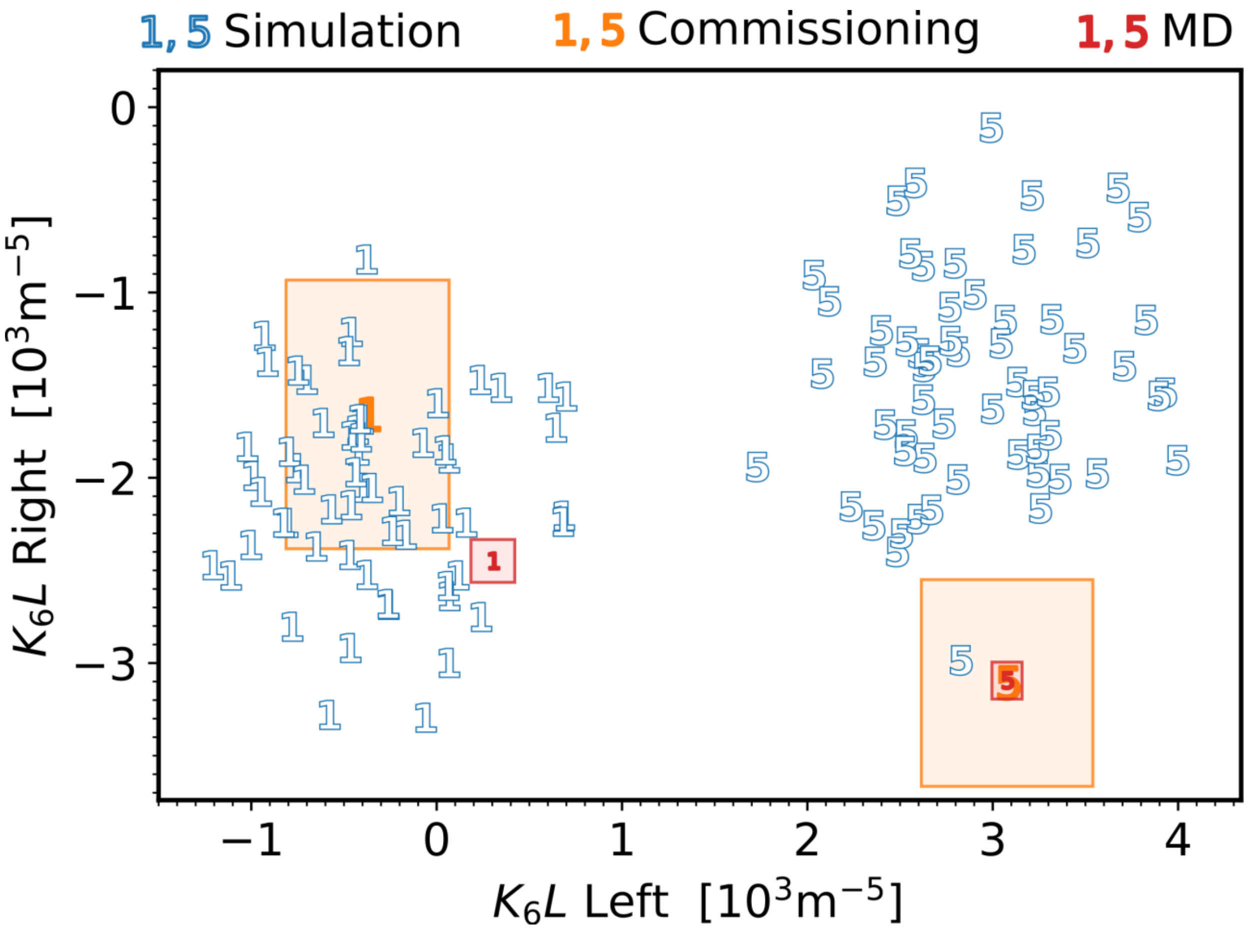
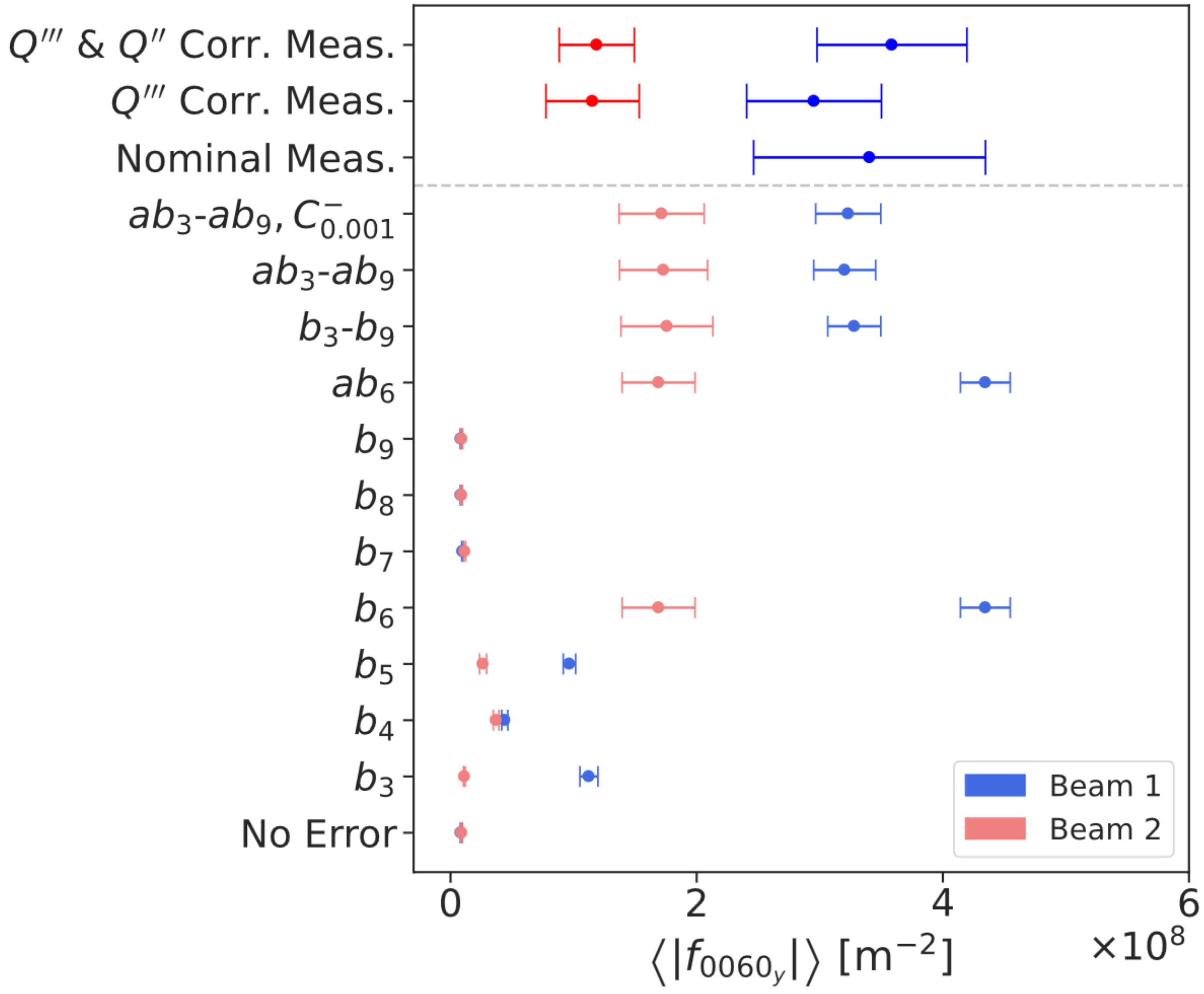


Figure 31: Decay of integrated b_5 at injection (430 apertures) and the decay fit (black line).



B6: model vs measurement





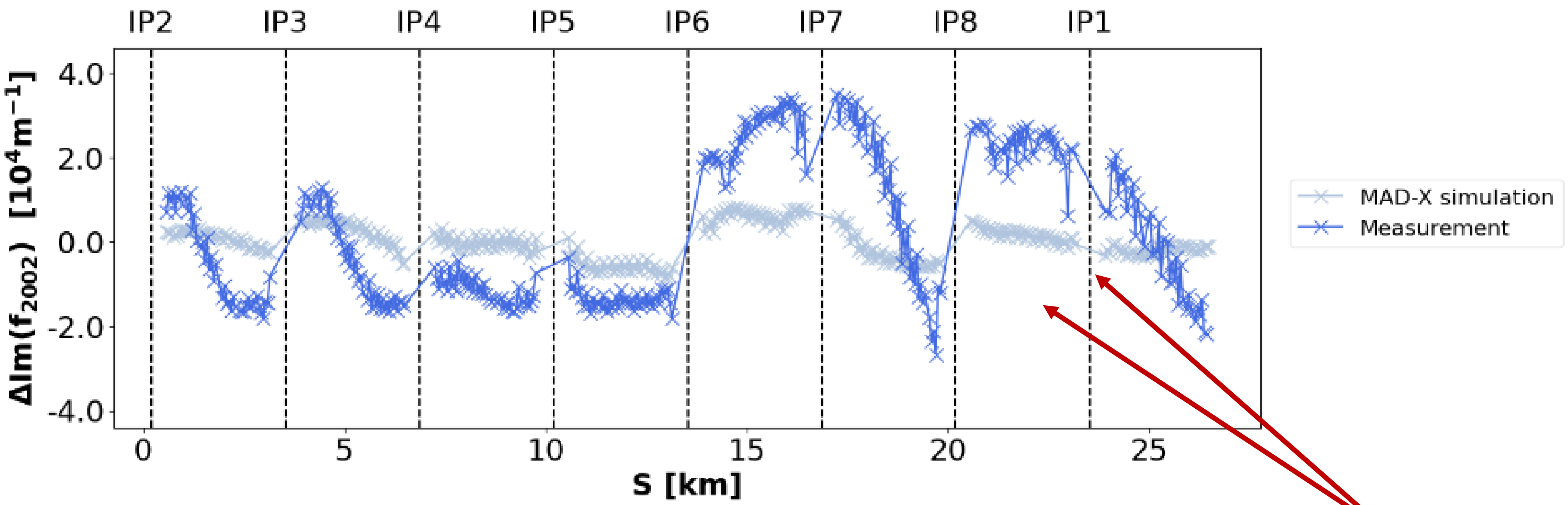
Where significant discrepancies with magnetic model have been resolved, haven't represent "errors" in magnetic measurements → rather additional complications (alignment errors, feed-down, feed-up, decays, phase, coupling) which would need to be included to achieve a good prediction

observables	
Normal sextupole (arc)	Good agreement. RDT = MS dominated
Normal sextupole (IR)	Good agreement (cold D1), or FD dominated
Skew sextupole (arc)	3Qy resonance factor 2 stronger than model
Skew sextupole (IR)	Large FD contribution from badly corrected a4
Normal octupole (arc)	FD from decapole spool piece
Landau octupole	MO RDT response @ 450 off by factor 2 – hysteresis?
Normal octupole (IR)	Discrepancy in required b4 correction ~40%
Skew octupole (arc)	RDT are feed-up dominated (coupling+MO)
Skew octupole (IR)	Comparable magnitude
Normal decapole (arc)	Good agreement after including B5 decay / B5 RDT feed-up dominated (b3+b4)
Normal dodecapole (arc)	Good agreement
Normal dodecapole (IR)	Good agreement
Normal decatetrapole (arc)	Good agreement (within 20%)

A few larger discrepancies (factor ~ 2) remain to be understood

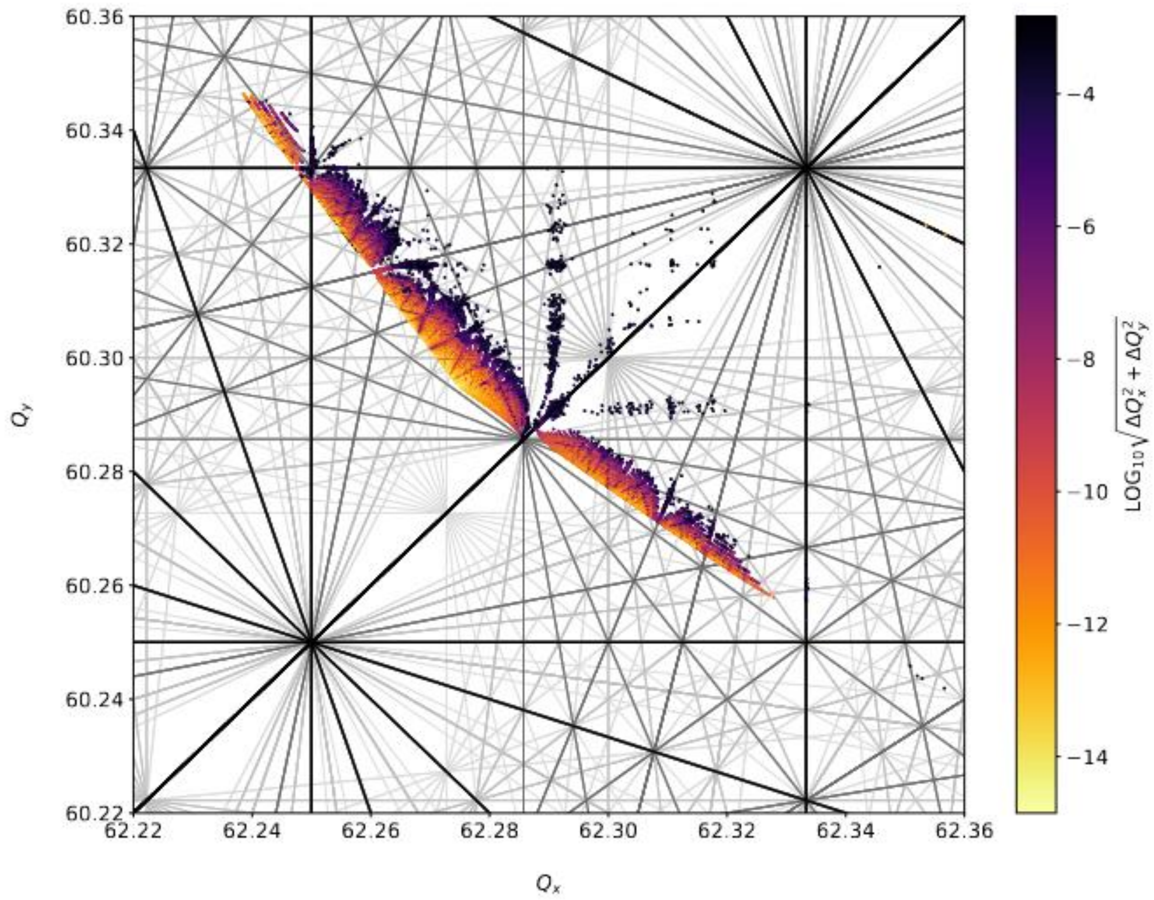
Key development during Run3 has been routine use of forced-RDT measurement

- **Helped resolve some discrepancies with LHC model, but revealed others**
- **3Qy resonance, and MO driven octupole resonances show up to factor 2 discrepancy with model: still not understood**

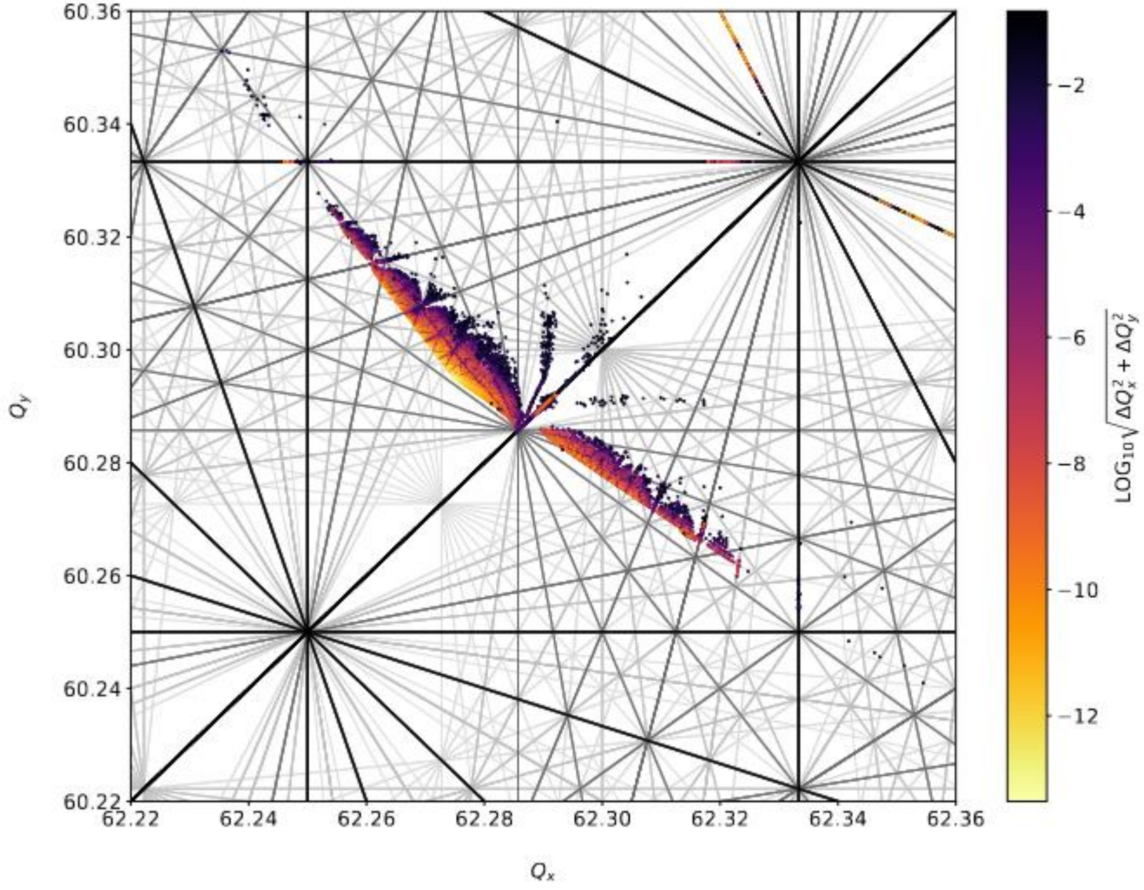


2Qx-2Qy resonance generated by Landau Octupoles considerably worse than expected (with phase knob)

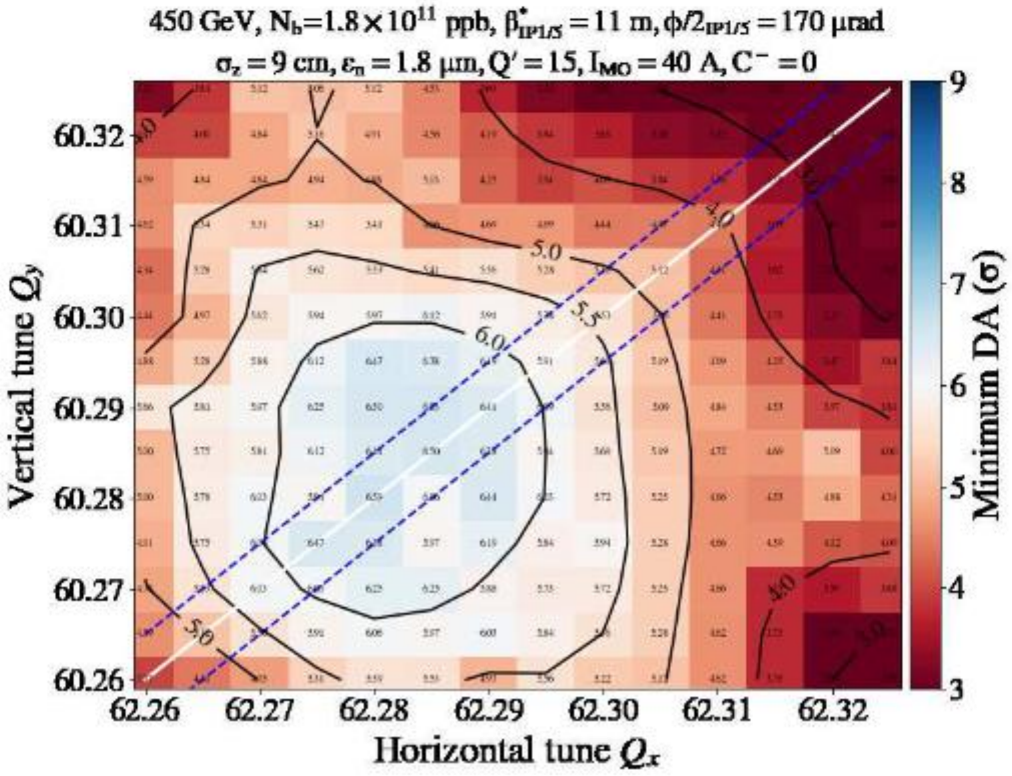
No errors



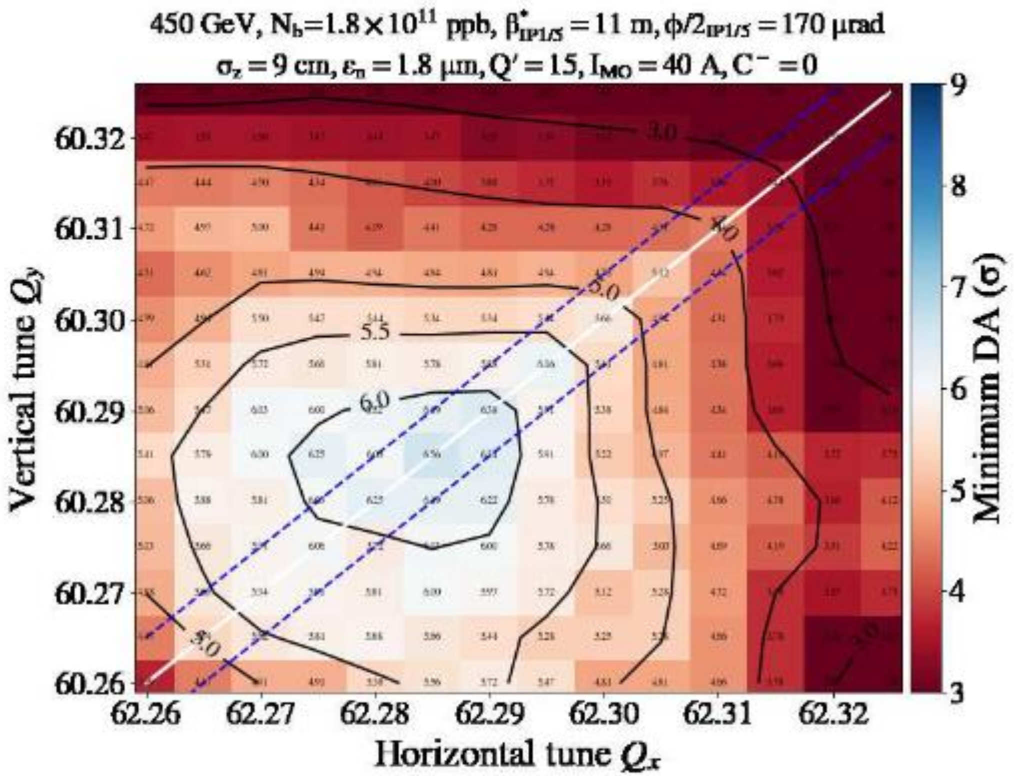
Effective 3QY

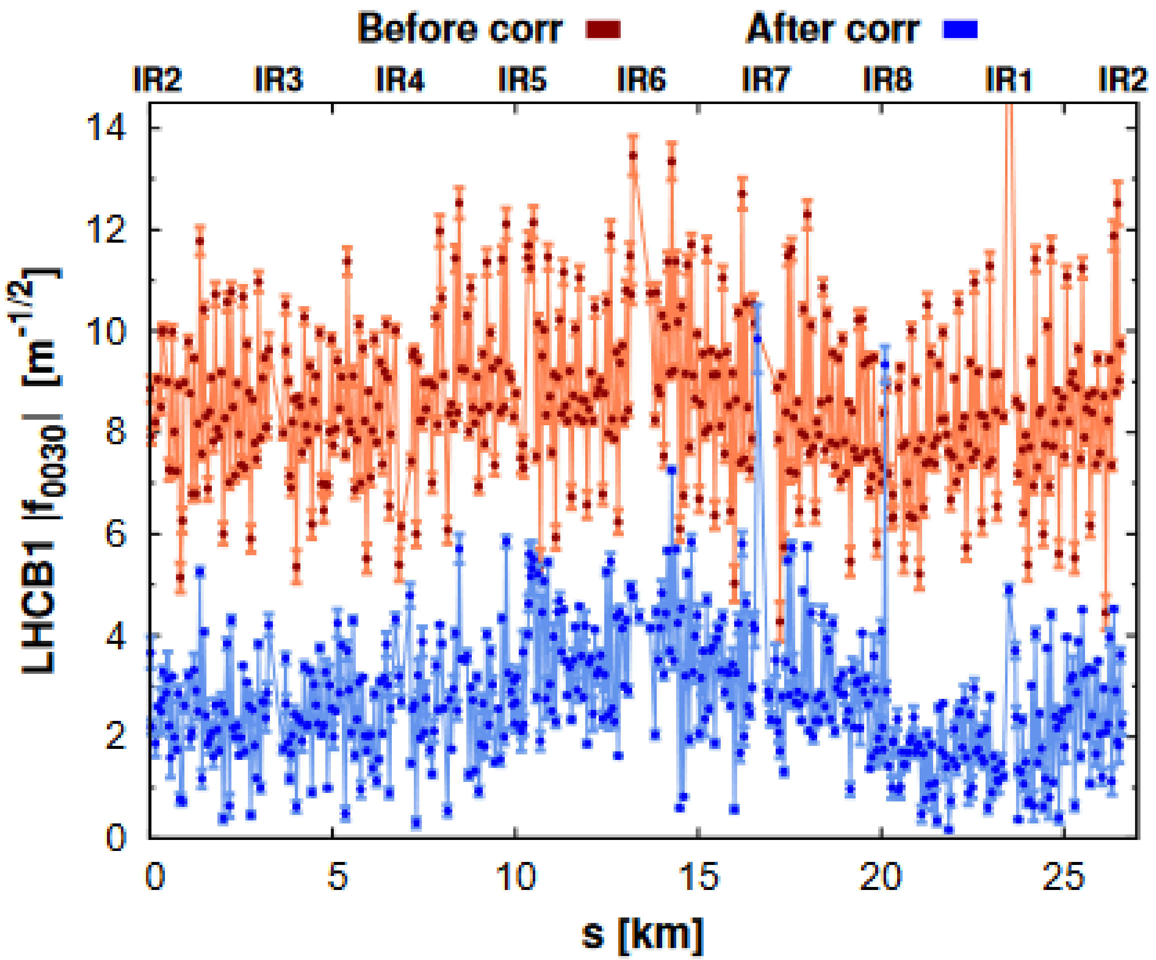


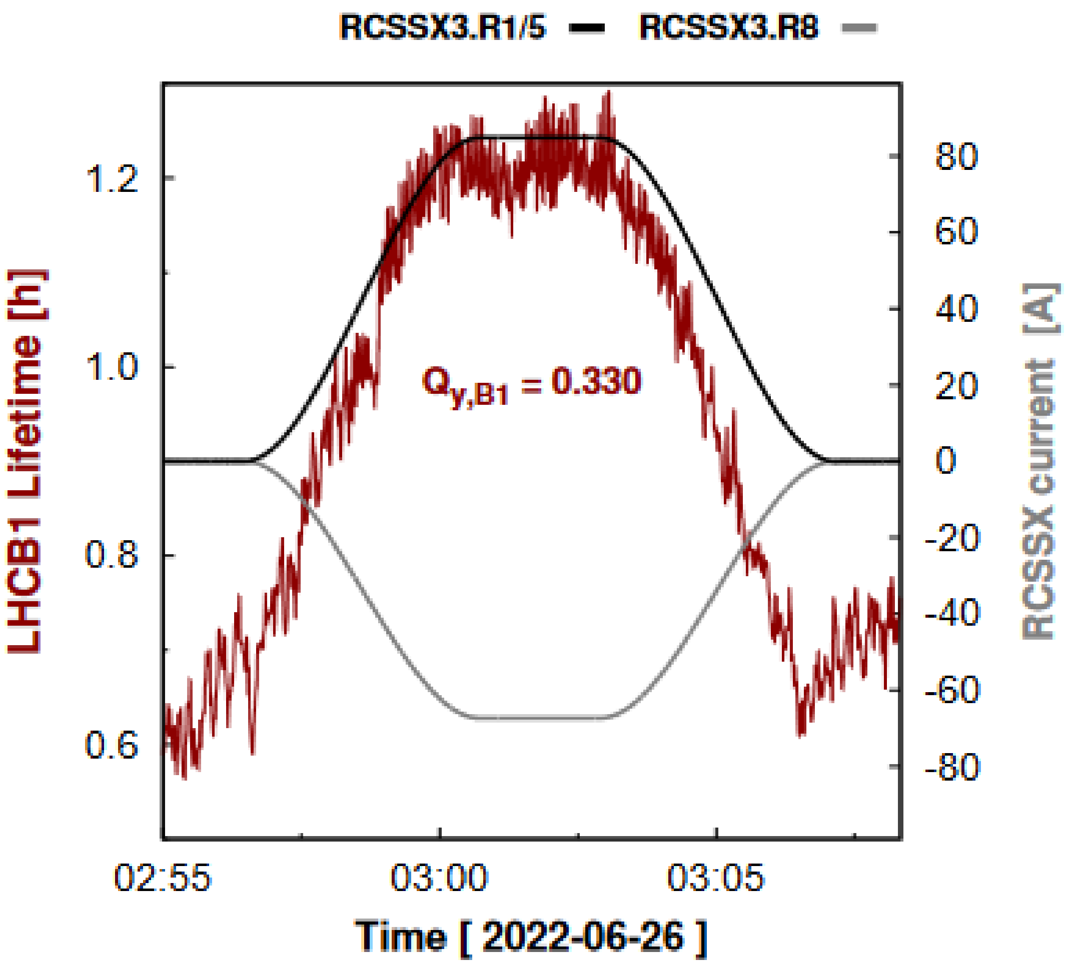
Nominal DA simulation



Adding effective 3Qy




Before corr
After corr
IR2 IR3 IR4 IR5 IR6 IR7 IR8 IR1 IR2
LHCB1 |f0030| [m^-1/2]
s [km]
0 2 4 6 8 10 12 14
0 5 10 15 20 25


RCSSX3.R1/5
RCSSX3.R8
LHCB1 Lifetime [h]
RCSSX current [A]
Q$_{y,B1}$ = 0.330
Time [2022-06-26]
02:55 03:00 03:05
0.6 0.8 1.0 1.2
80 60 40 20 0 -20 -40 -60 -80