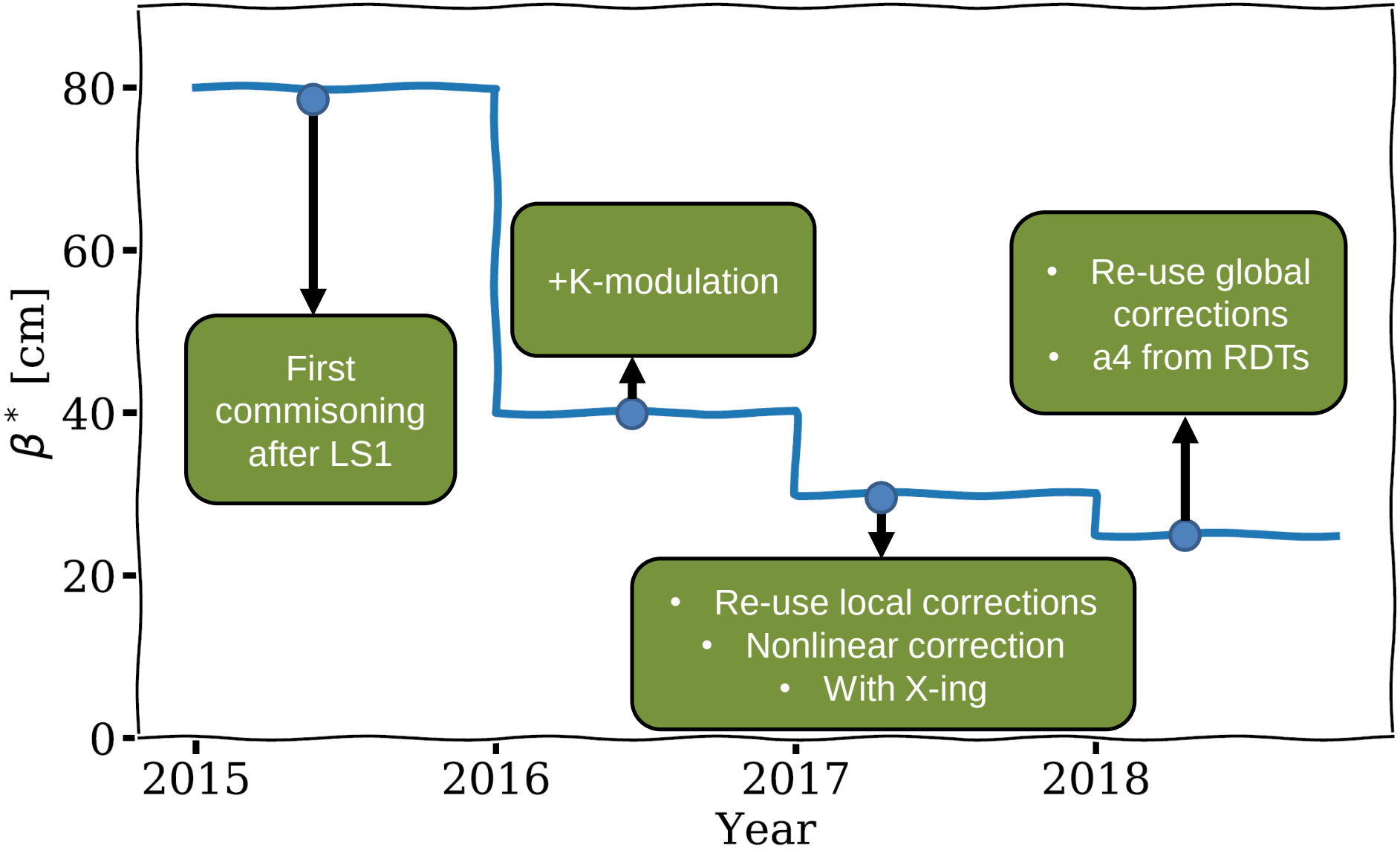
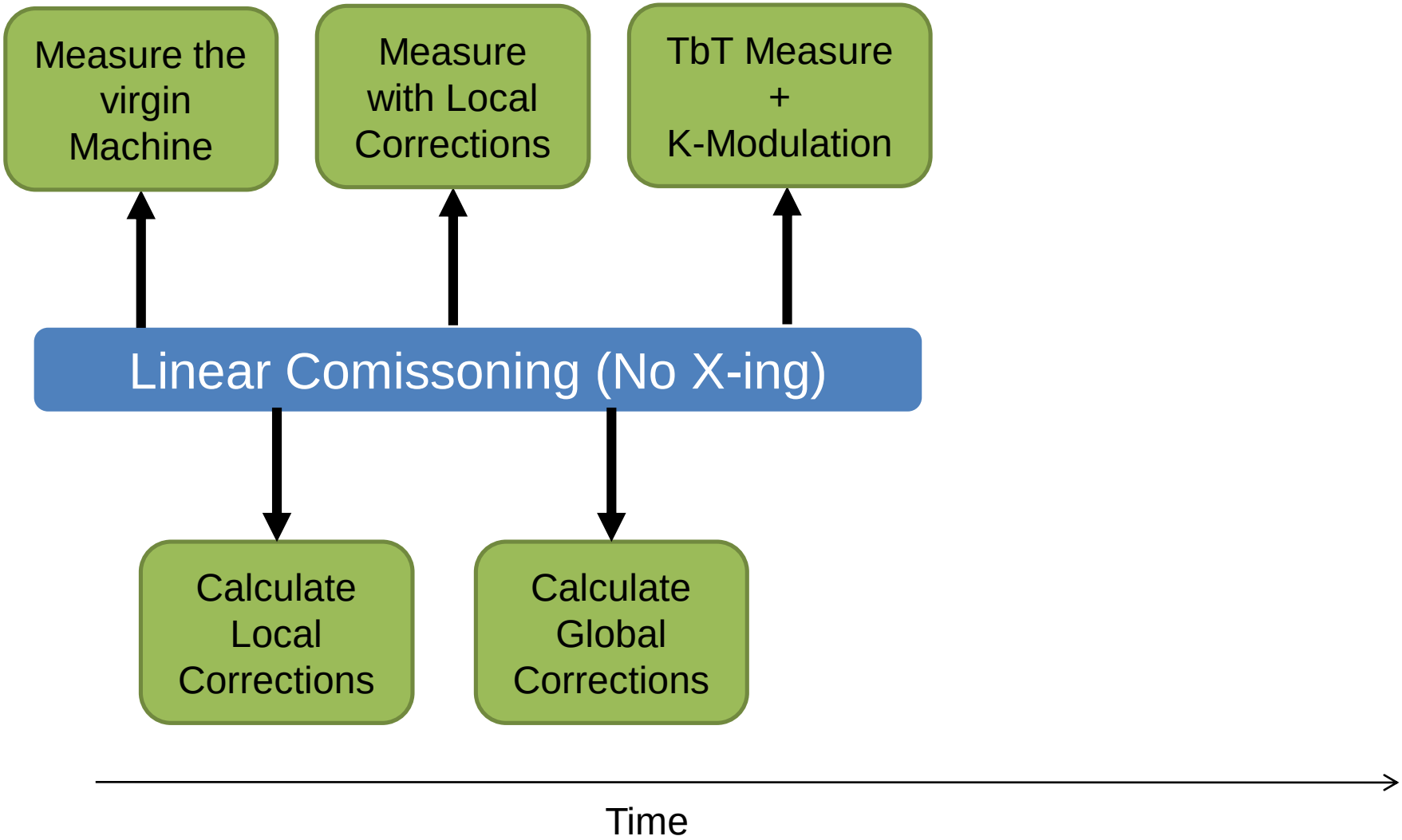
Optics and Corrections

T. Persson
On behalf of the OMC-team

Overview of the proton commisonings



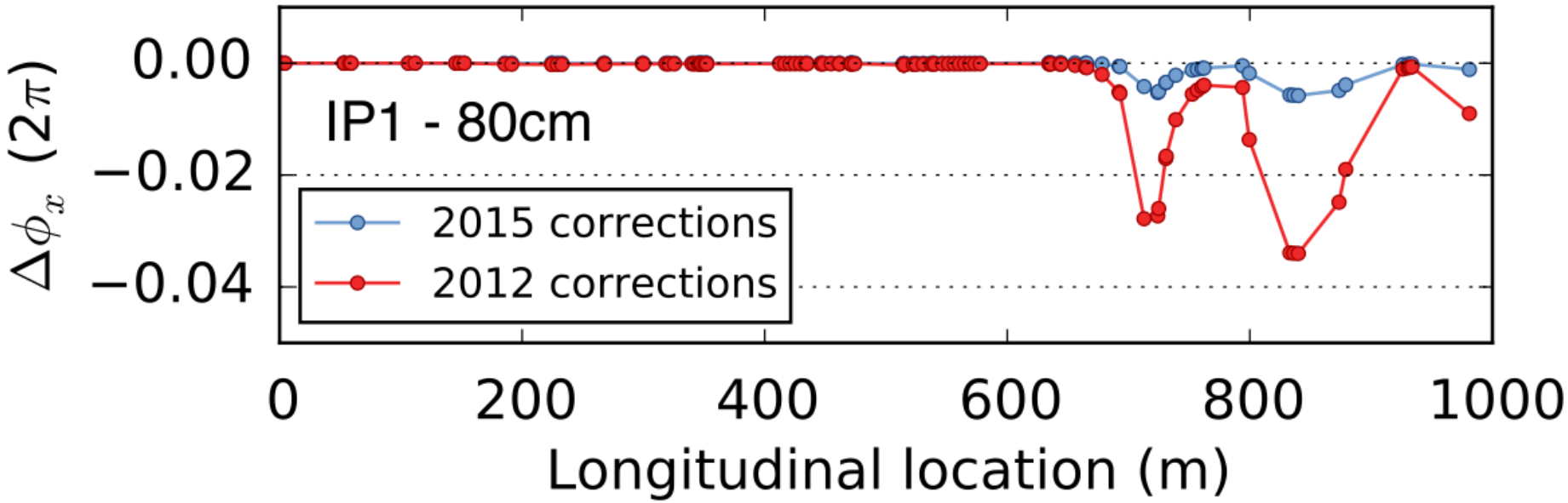
Commisiong strategy 2015



Local correction after LS1

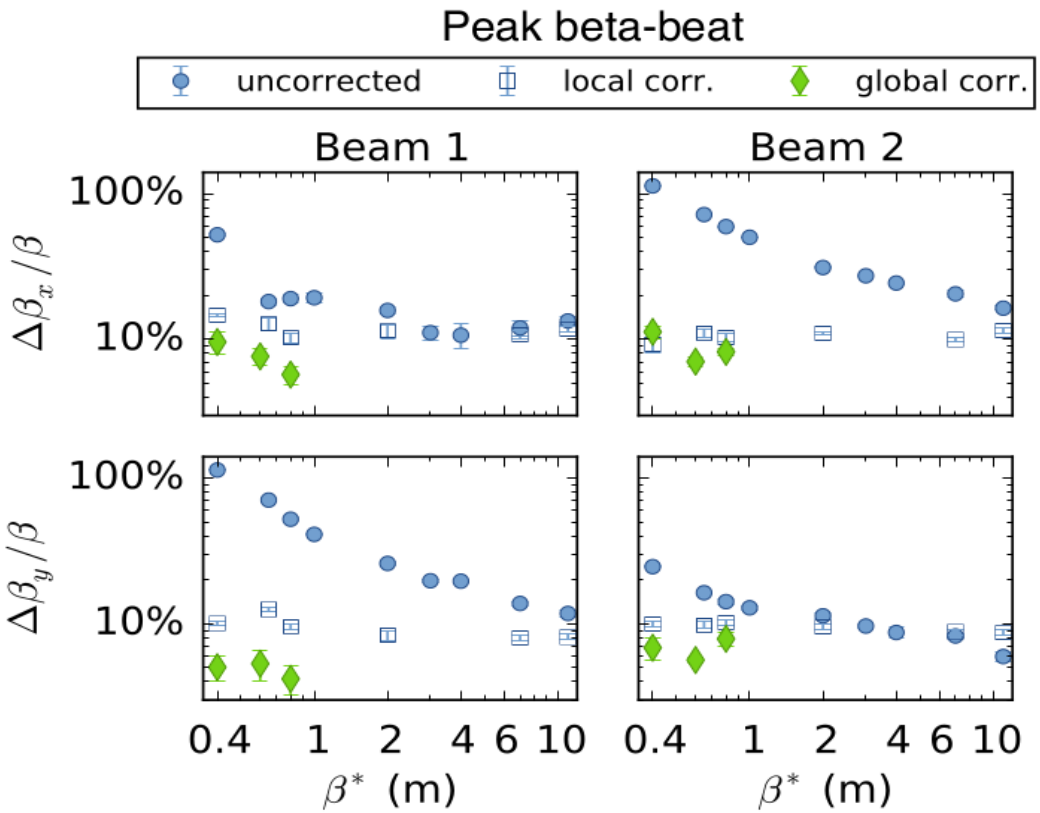
- The local corrections were very different after LS1

  → Need for new local corrections



- Not apparent where the change came from
  - Energy might have been a factor although the 2015 corrections were also valid for 2.51 TeV run!

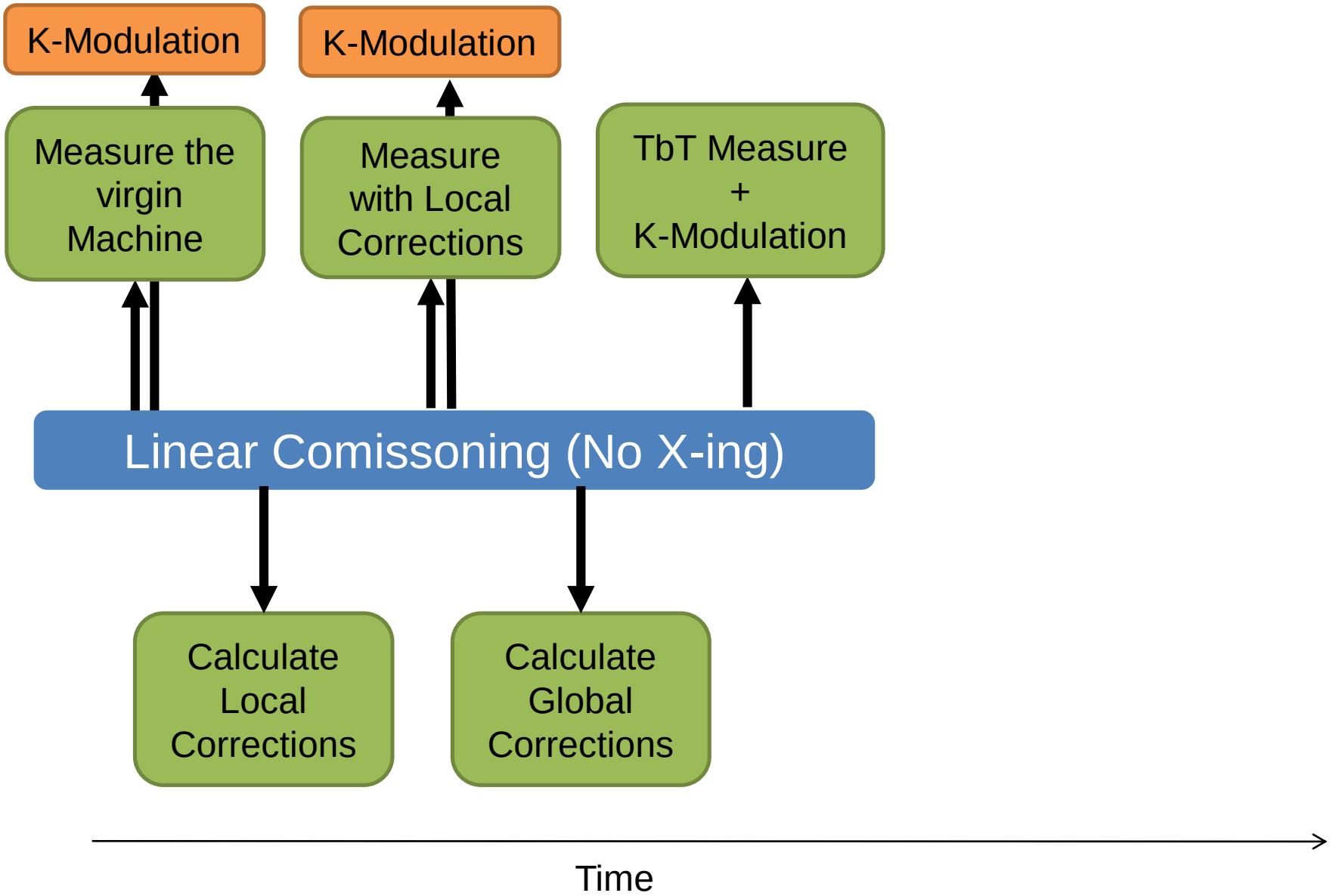
Final β-beating 2015



IP	Beam	β_x^* [cm]	β_y^* [cm]	w_x [cm]	w_y [cm]
1	1	88 ± 1	86 ± 1	25 ± 2	23 ± 1
1	2	82 ± 1	83 ± 1	18 ± 2	21 ± 1
5	1	86 ± 1	86 ± 5	22 ± 2	24 ± 9
5	2	87 ± 1	83 ± 2	24 ± 2	16 ± 5

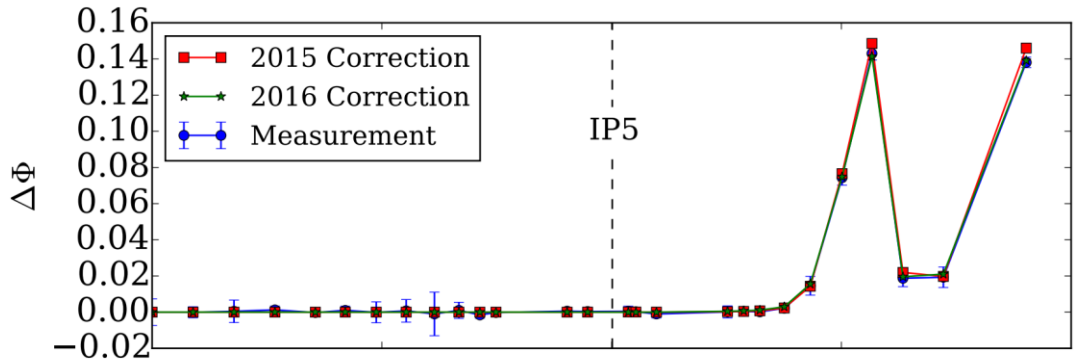
- Correction strategy the RMS and peak beta-beat down to good levels
- A waist shift was observed at the IPs
  - No imbalance but a few percent luminosity loss

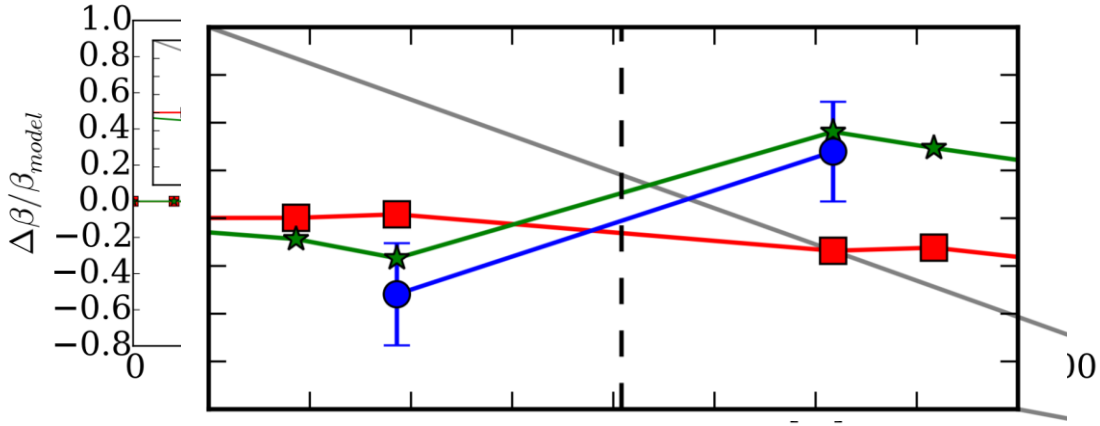
Commisiong strategy 2016

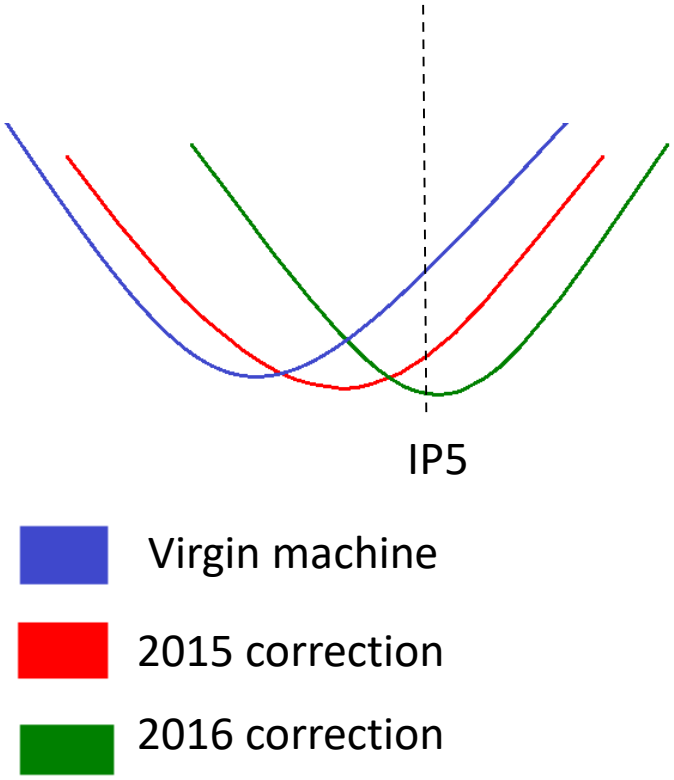


Local corrections

- The local phase corrections are degenerate. Possible to find several combinations that correct the phase
  - No guarantee that the waist or β_{IP} is well corrected



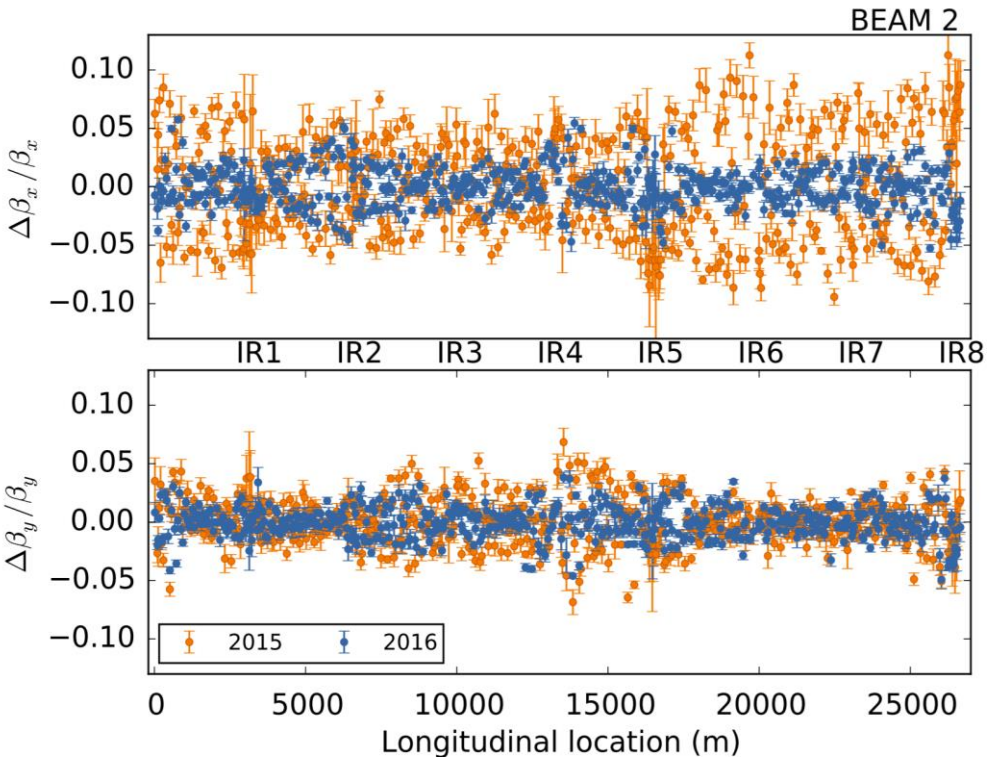




Final Corrections 2016

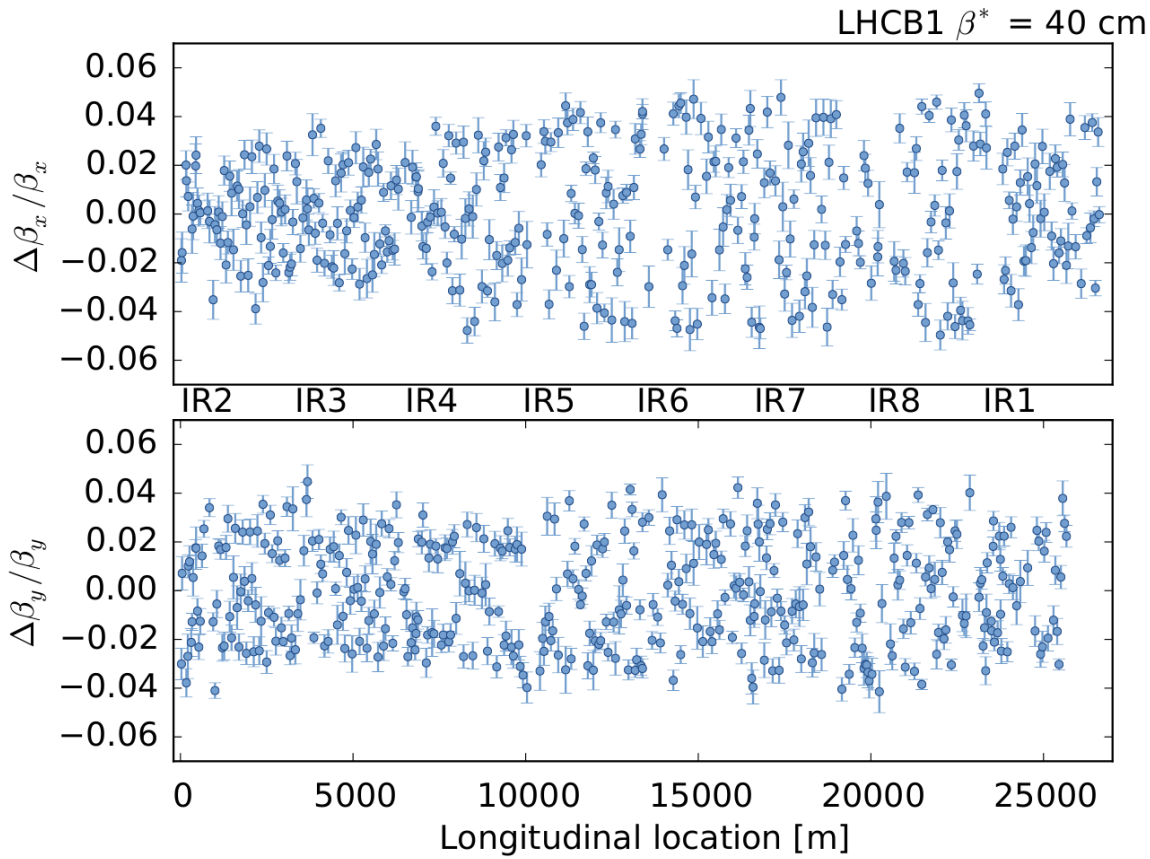
IP	β_{IP} [m]	β_{IP} err [m]	Waist [m]	waist err [m]
ip1b1.X	0.398	0.007	0.047	0.009
ip1b1.Y	0.401	0.002	-0.009	0.009
ip1b2.X	0.398	0.001	0.009	0.011
ip1b2.Y	0.402	0.001	0.072	0.010
ip5b1.X	0.399	0.003	-0.001	0.008
ip5b1.Y	0.400	0.001	-0.028	0.010
ip5b2.X	0.395	0.003	0.070	0.013
ip5b2.Y	0.396	0.004	-0.025	0.011
Average	**0.405**	**0.003**	**0.016**	**0.010**
RMS β-beat in IP %	**1%**			

No X'ing!



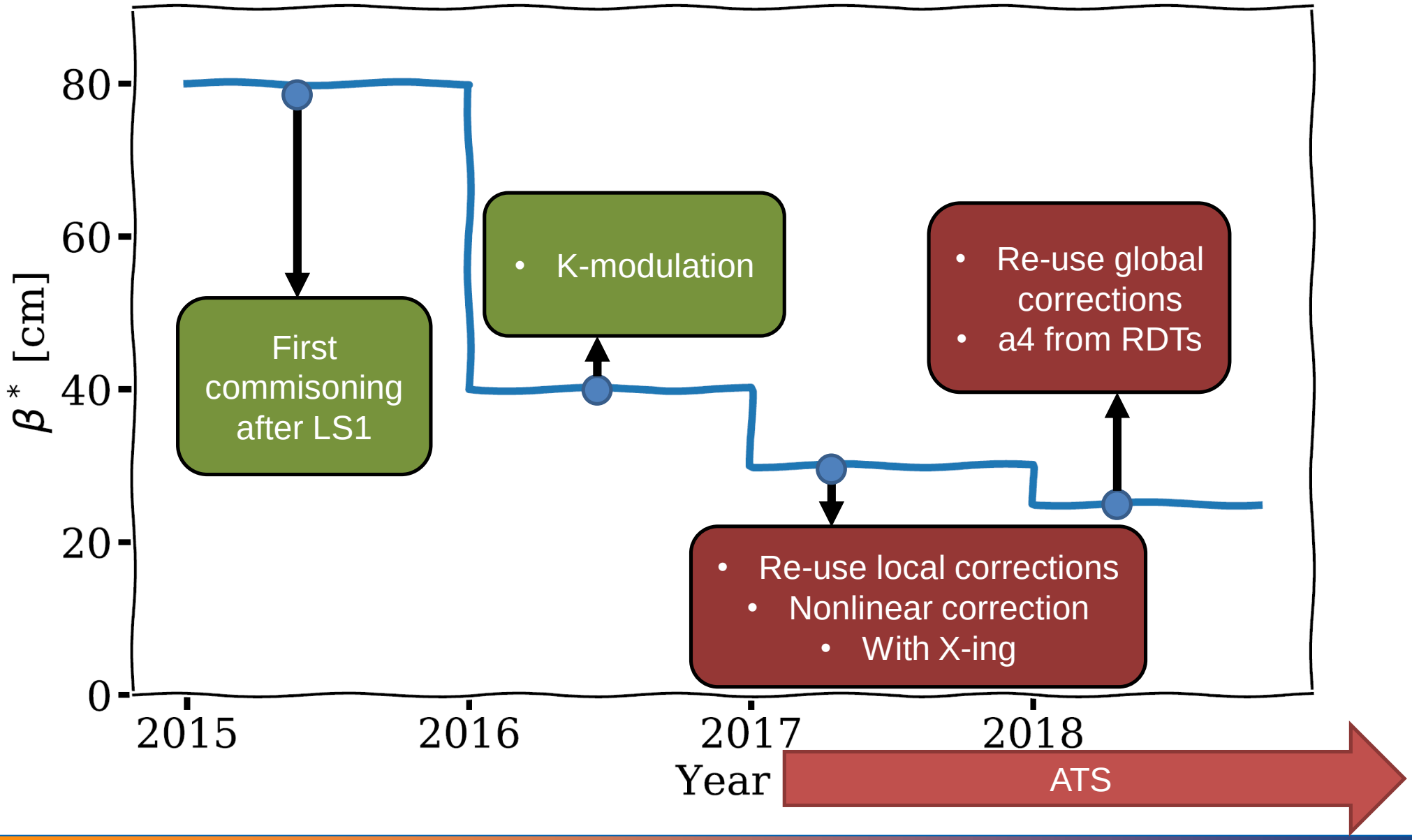
Effect of crossing angles

- Optics measured in June (commissioning without crossing angles in April)
  - **Difference between the two measurements shown in plot below**
- Consistent with simulation of the **IR sextupoles errors** + crossing angles

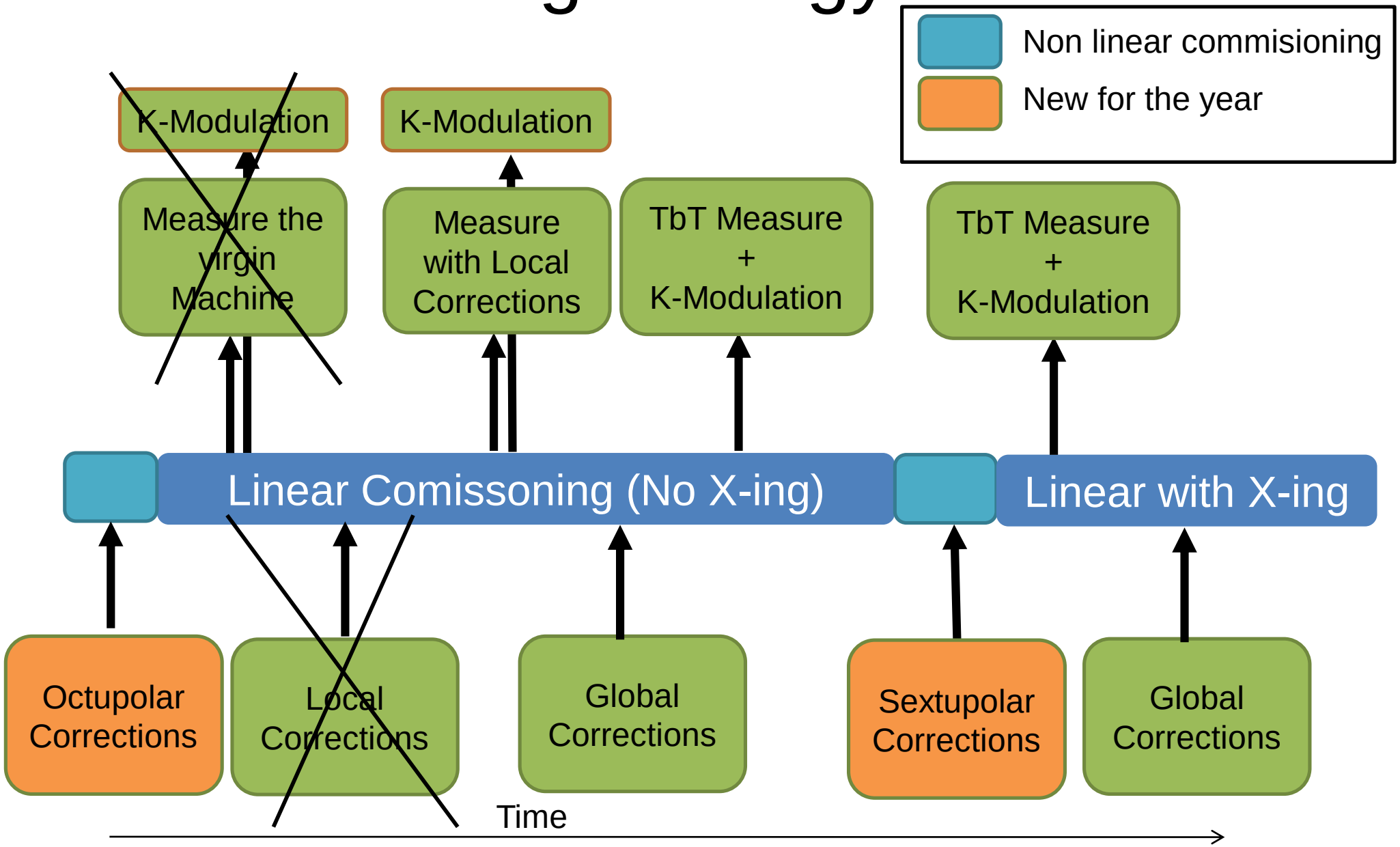


An increase of the peak β-beat in the order of **~3%** due to crossing angles + **IR sextupole errors**

Overview of the proton commisonings

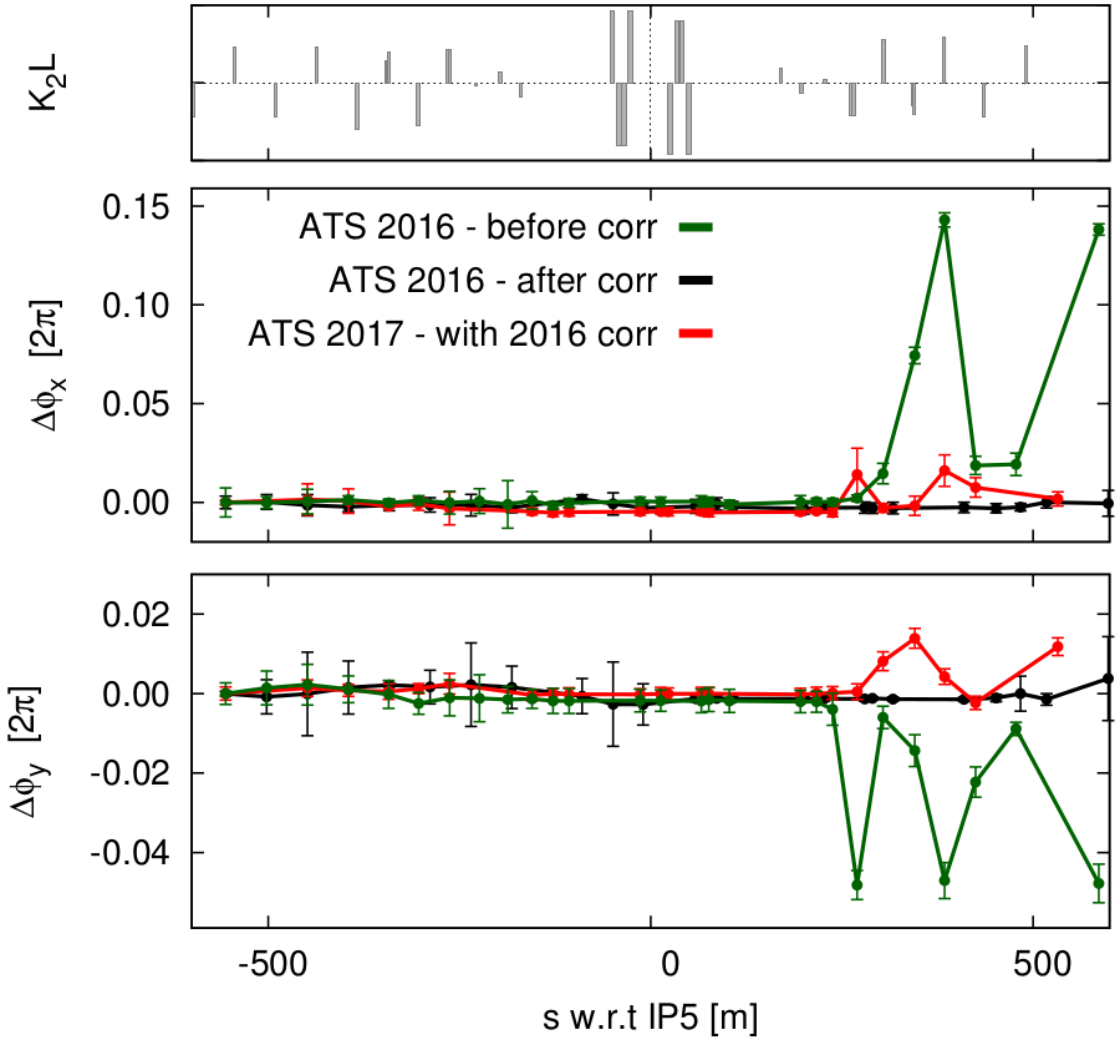


Commisiong strategy 2017

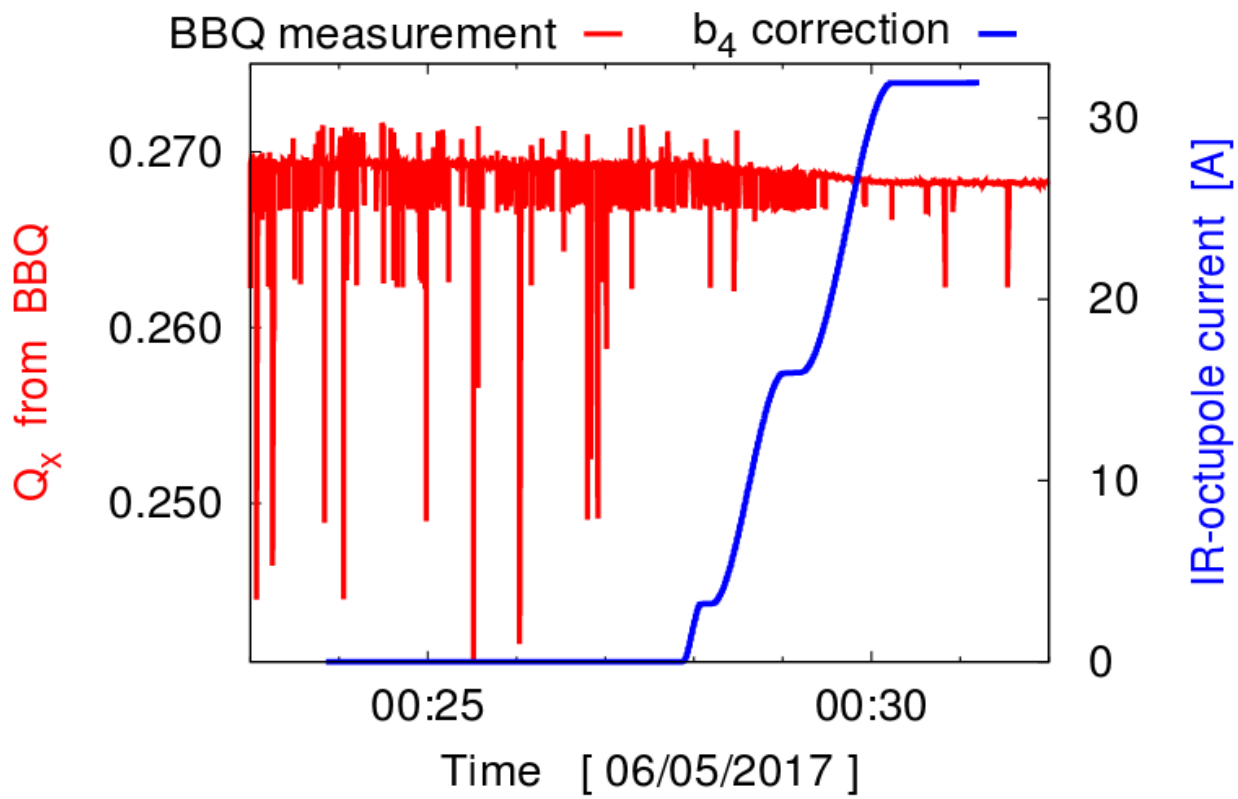


Re-Use Local correction

- Local corrections had been calculated during MD in 2016
  - Some degradation was observed but still in the range where it was considered acceptable

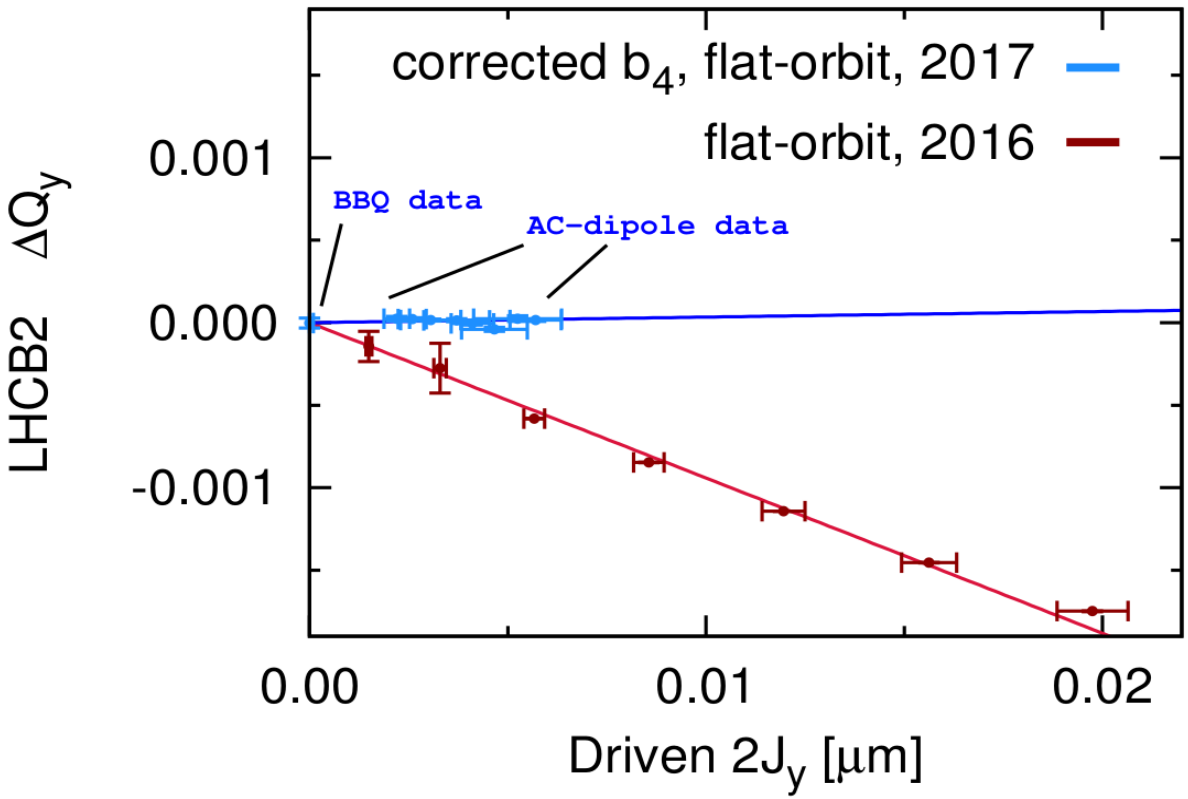


Octupole IR correction (b_4)



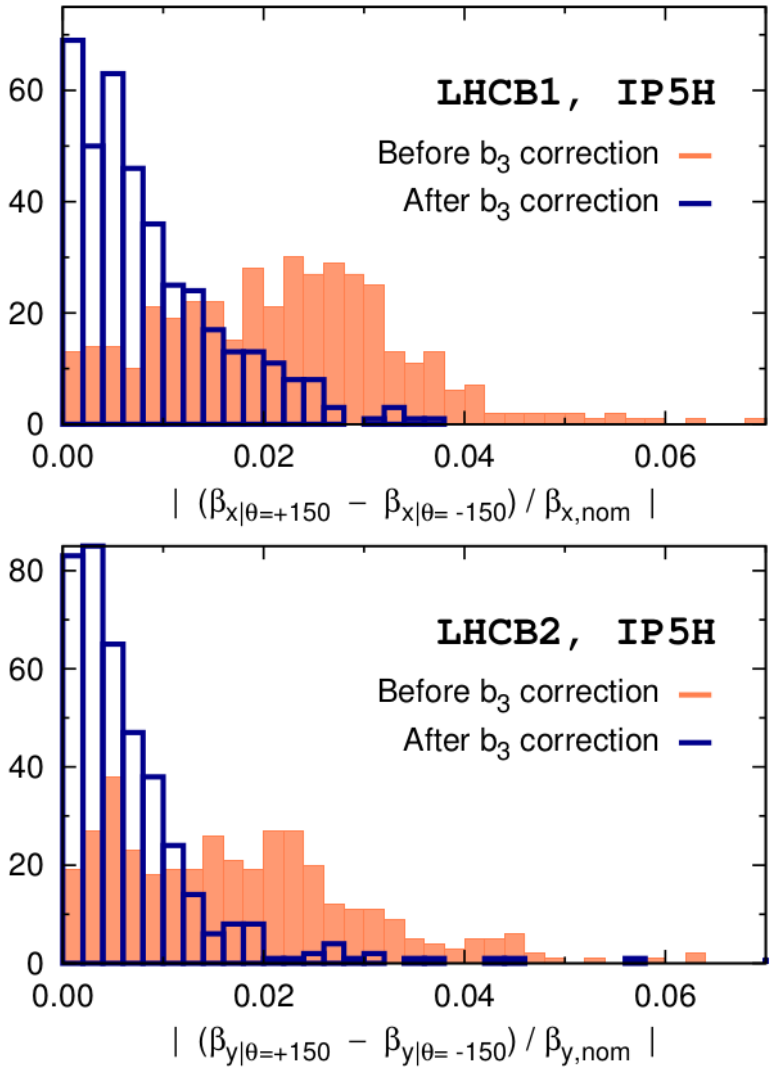
- Octupole correction based on amplitude detuning measurement in 2016
  - Improved the tune measurement from the BBQ
    ➔ Improved K-modulation quality

Octupole IR correction (b_4)



Correction removed the contribution to the footprint from octupole errors in IR1 and IR5 for flat-orbit

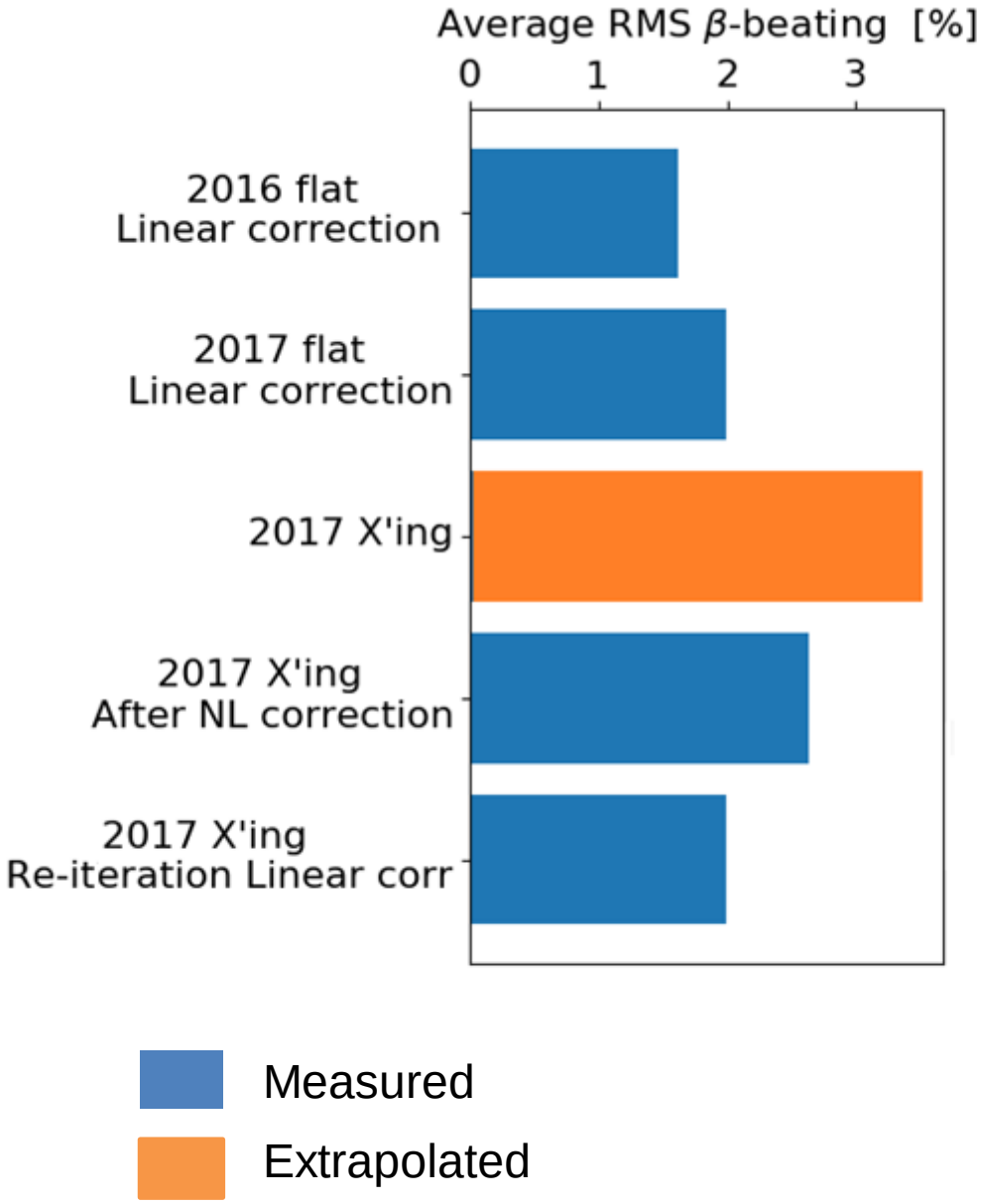
Sextupolar IR corrections



β-beating between crossing angles

- Improved the stability of the linear optics as a function of X'ing angle

Flat-orbit vs X'ing

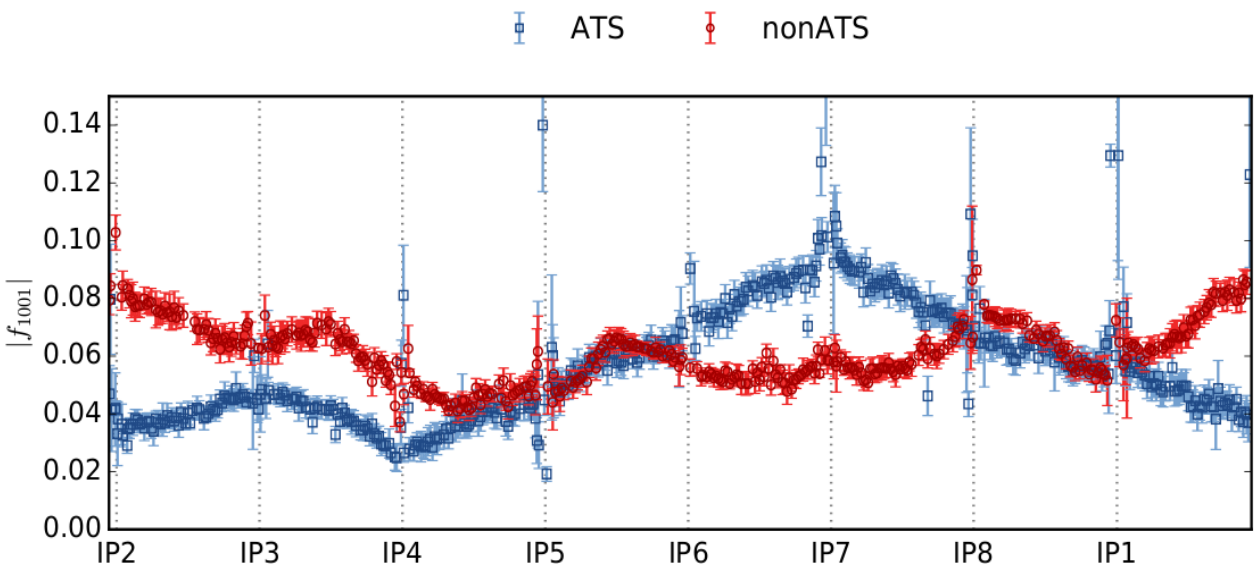


- The X'ing angles introduce β-beating
- The sextupolar correction removes most of it
- Re-iteration of the linear correction

➔ Same quality of correction as with flat orbit

Any differences with ATS?

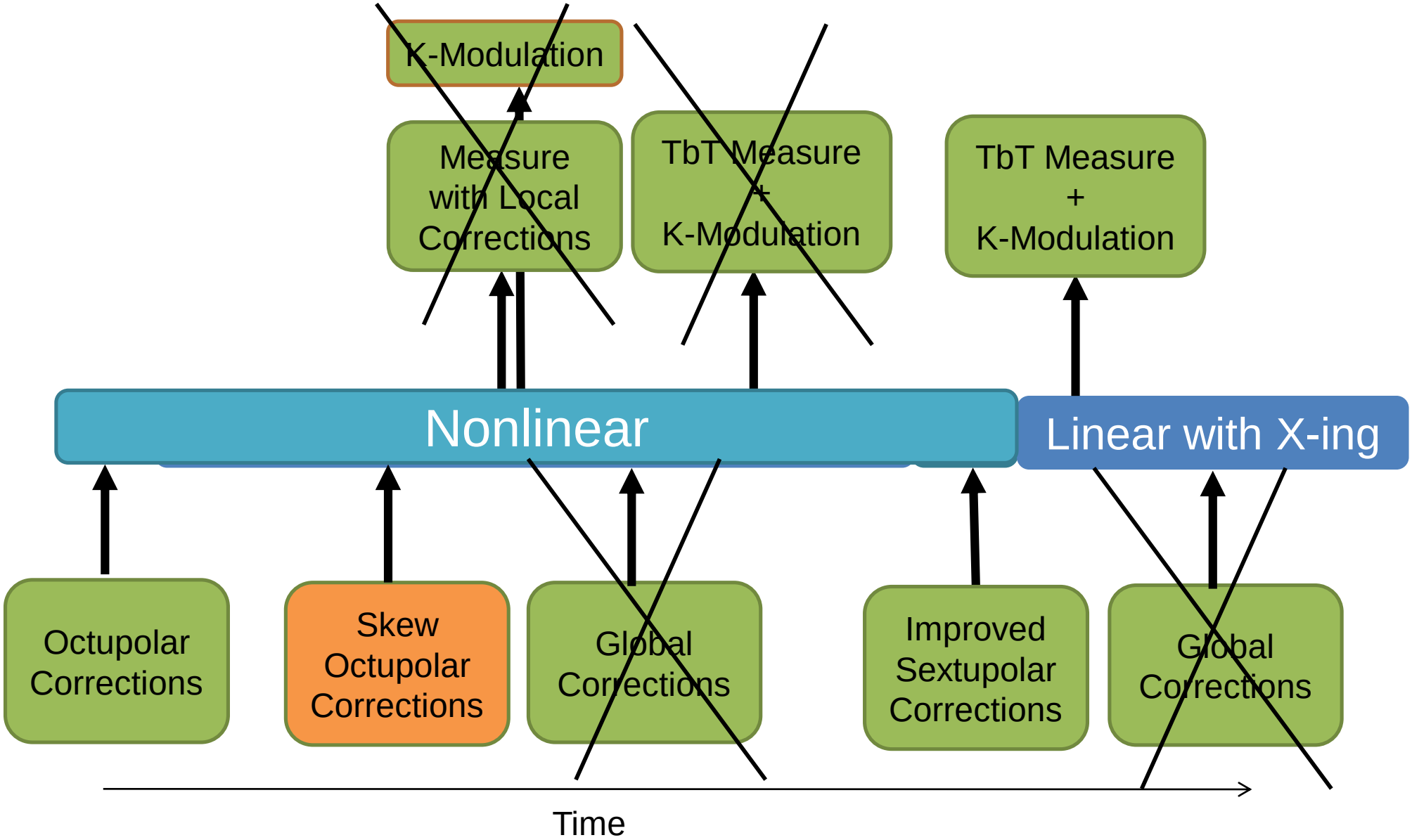
- Optics corrections were in the same level for ATS and nominal optics
- A change in the coupling structure
  - Not an issue, was easily correctable but correction created higher strength for the skew quadrupoles (only Beam 1)



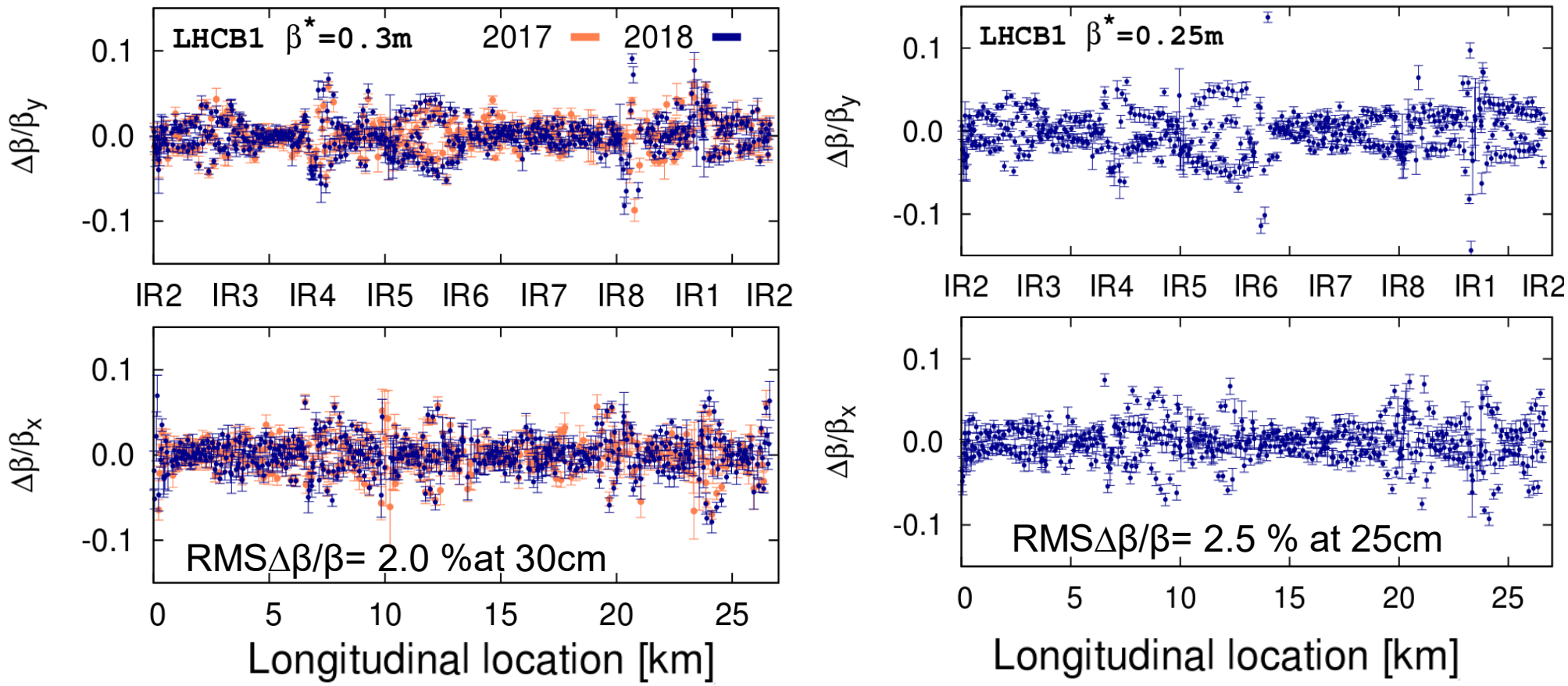
Beam 1

T. Persson, LMC 2018

Commissioning strategy 2018



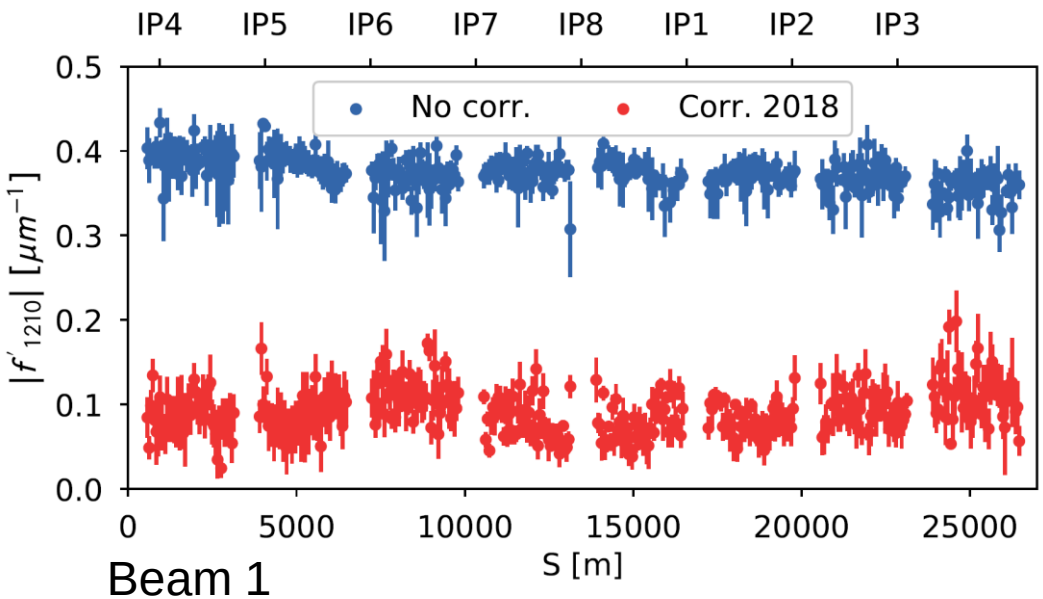
β-beating 2018 vs 2017



Re-used the correction from 2017 without any degradation in optics quality

Skew octupole Corrections (a_4)

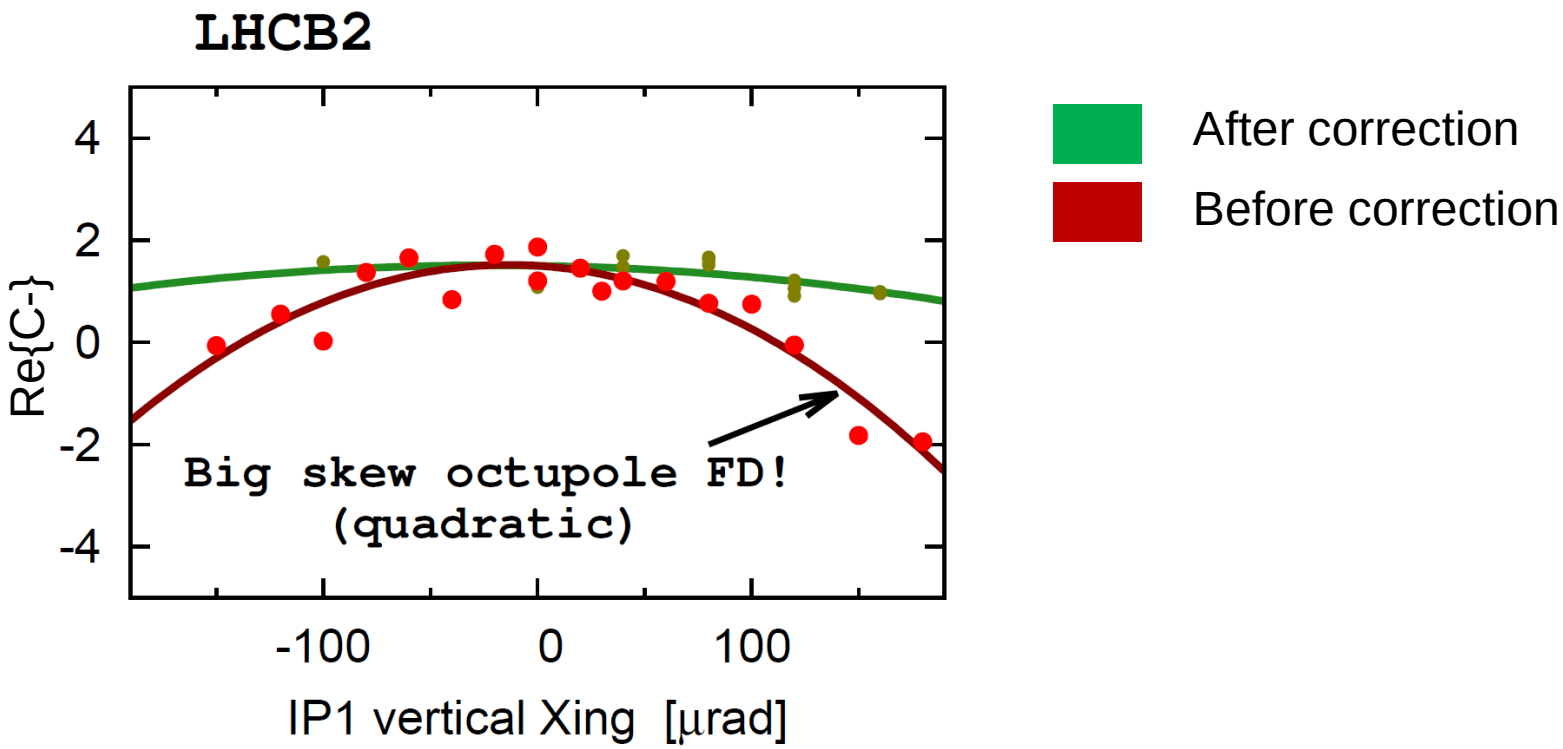
- Skew octupolar sources are known to:
  - Reduce dynamic aperture
  - Increase of octupole threshold for small tune separation (X. Buffat, 8th LHC Operations Evian Workshop)
- Reduced the a_4 RDTs for beam 1 with 75%. No change for beam 2
- 1 out of 4 a_4 correctors is not working



Beam 1

F. Carlier, LMC 2018

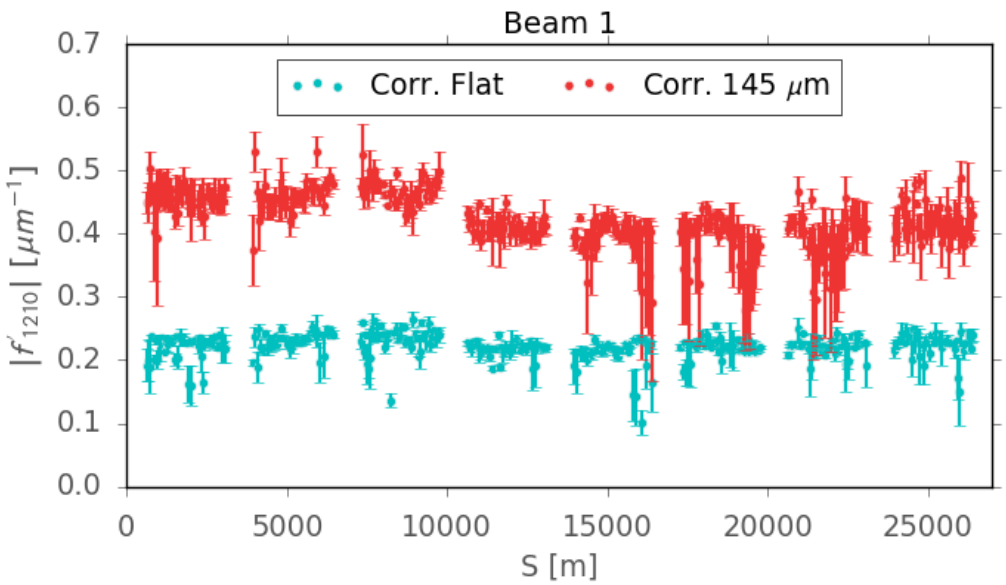
Effect of a_4 and b_3 corrections in IR1

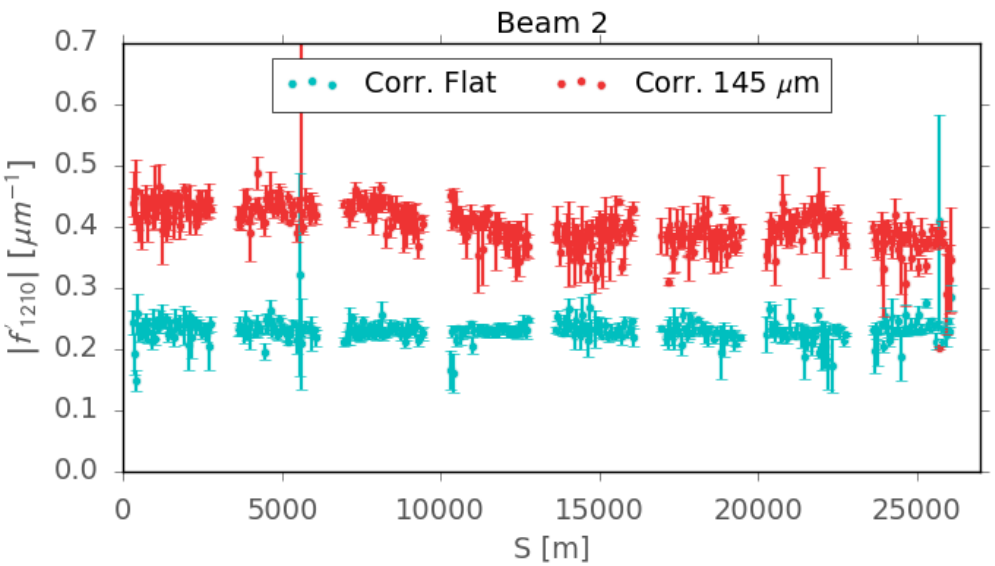


Without any nonlinear corrections the feed-down to |C-| during X'ing angle leveling would be ~2-2.5*10^{-3} at β*= 30 cm

E. H. Maclean, LMC 2018

Feed down from higher orders to the a_4 RDTs

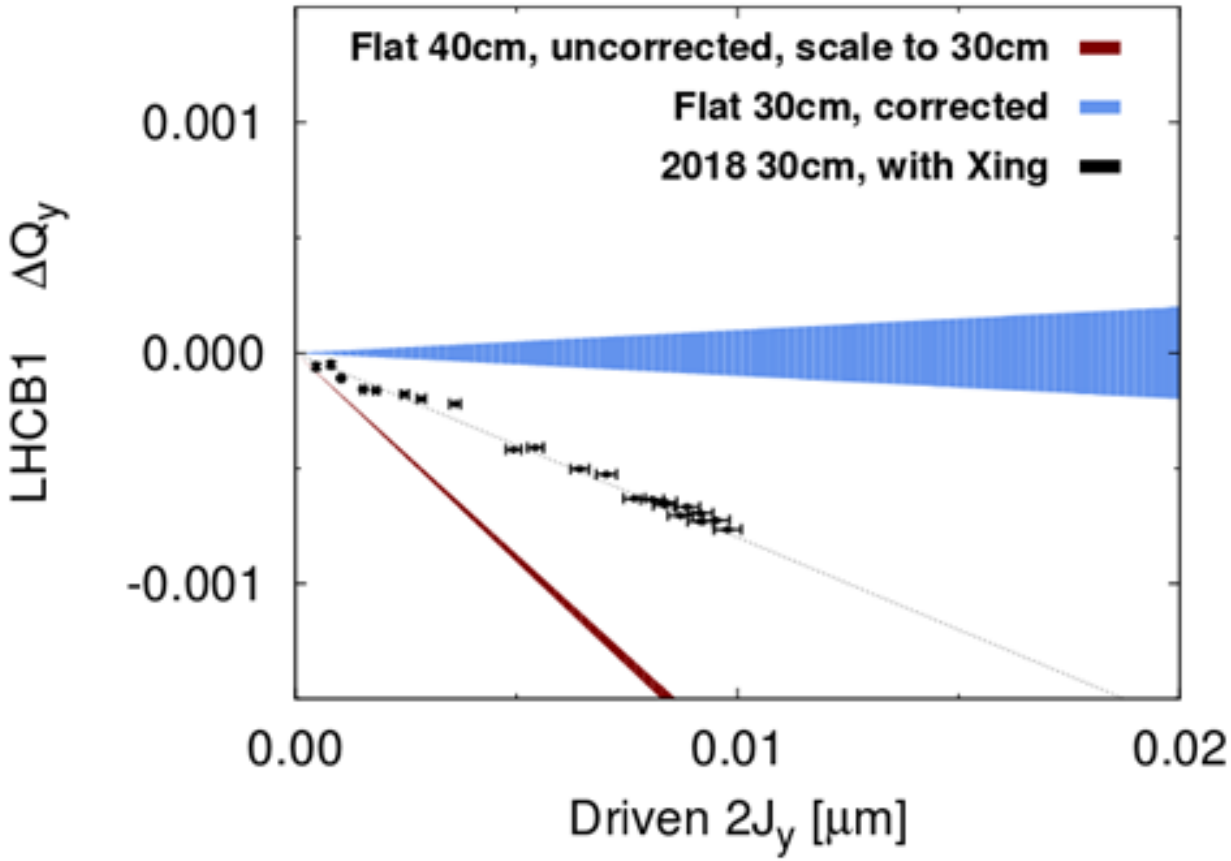




The RDTs from a_4 change with the x'ing angle

➔ Feed down from decapole and/or dodecapoles !

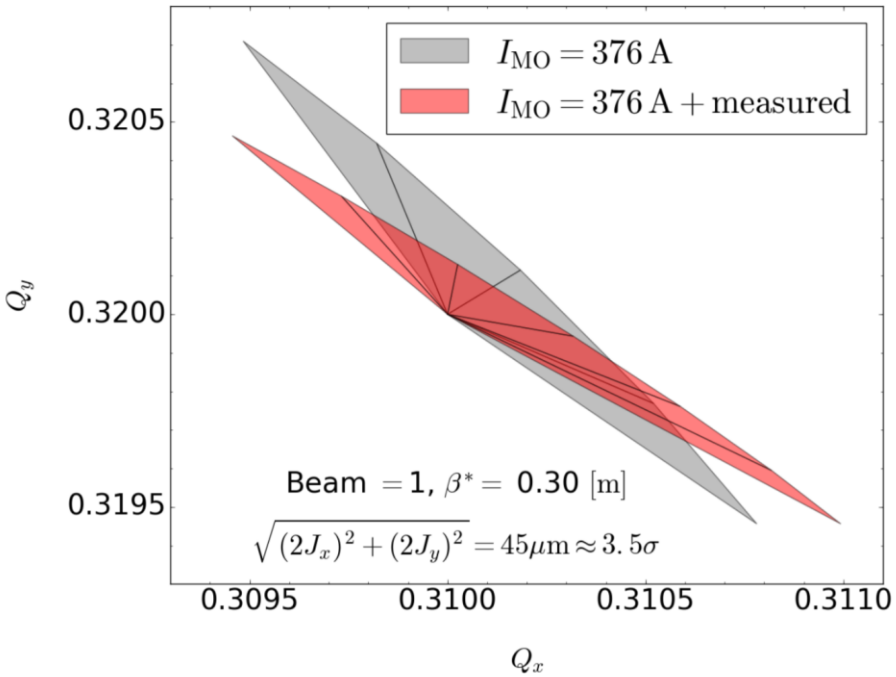
Amplitude detuning with X'ing

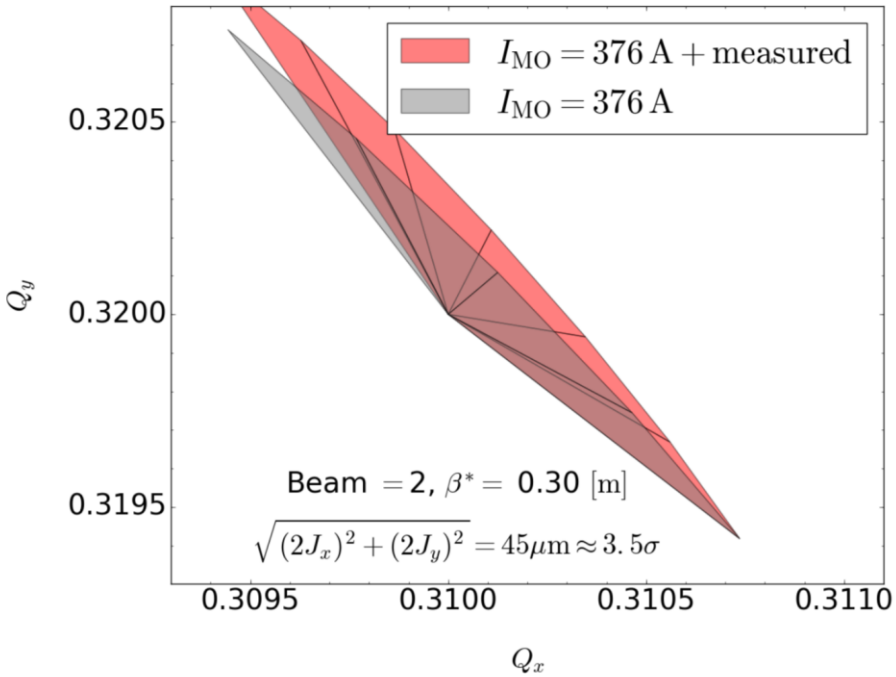


The X'ing angle causes an ampltiude detuning that is almost half of the uncorrected!

Impact on footprint

- Distortion of the footprint
- Coming from decapole and/or dodecapoles (under investigation)
- Asymmetric between Beam 1 & Beam 2
  → Can not correct with IR-correctors, need to use MO
  - Would need to change the powering of MOD by +142 A and MOF -108A to get back to the unperturbed (grey) footprint





Ion Commissioning 2018

Ion Commissioning 2018

- A big step in β* for IP2
- Re-did local (normal quadrupolar) correction at IP1 and IP2
- A new automatic local coupling matching was used:
  - Unfortunately, the corrections were trimmed in with a swap between MQSX3.L and MQSX3.R
  - If trimmed in correctly we would have been close to what was found optimal with luminosity
  - This was fixed by re-balancing the strength of MQSX3 left and right using the colinearity knob (S. Fartoukh)

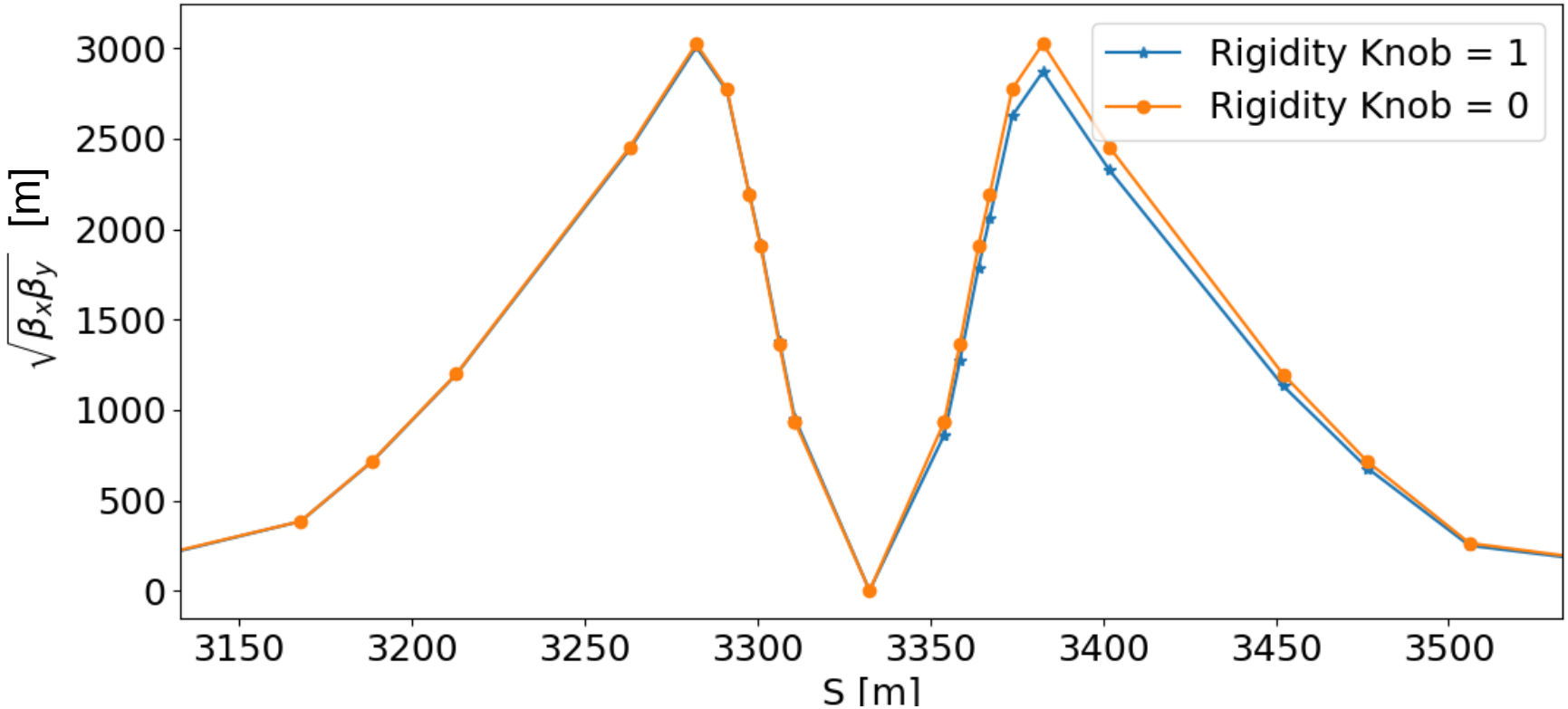
Why is the local coupling hard to measure?

- Because of the phase advance and symmetry an increase of MQSX3.L and decrease of MSQX3.R (colinearity knob is doing this) by the same amount has almost no effect outside the IR.
  - Difficult to have good measurements inside the IR due to the phase advances
  - If we break the symmetry by increasing the strength of the left triplet and decrease the right

    ➔A non optimal MQSX setting gives a change of the global |C-|

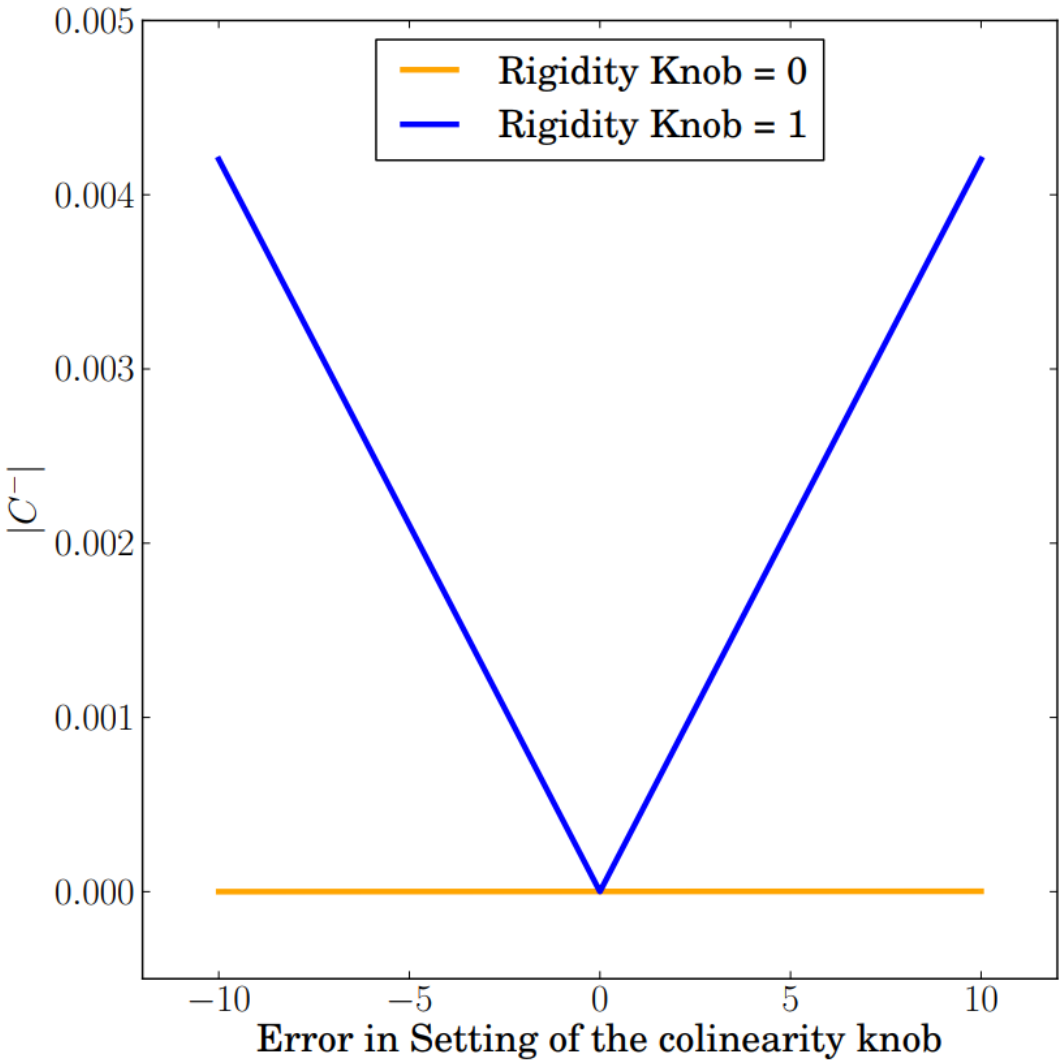
New method to measure the local coupling

- Tested during the last MD period
- Principle of the rigid waist shift:
  - Unbalance the strength of the left and the right triplet
    - Breaks the left-right symmetry



Rigidity waist shift knob

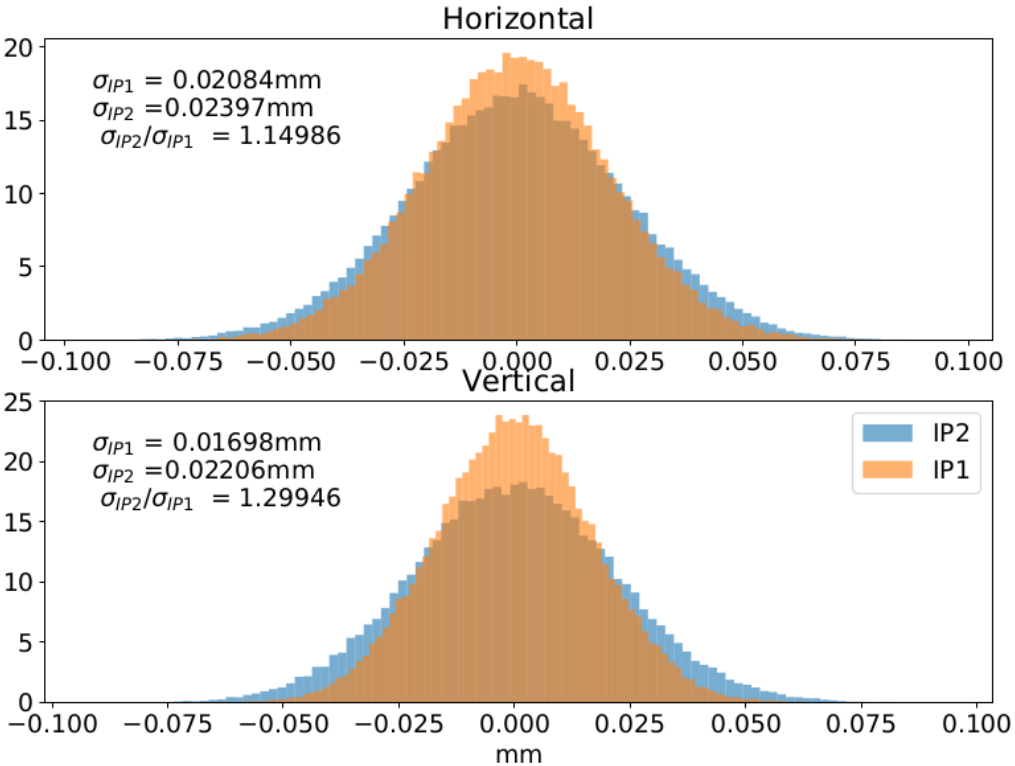
- The colinearity knob gives no contribution to the global observable |C-|
  - After applying the rigidity knob there is a dependency

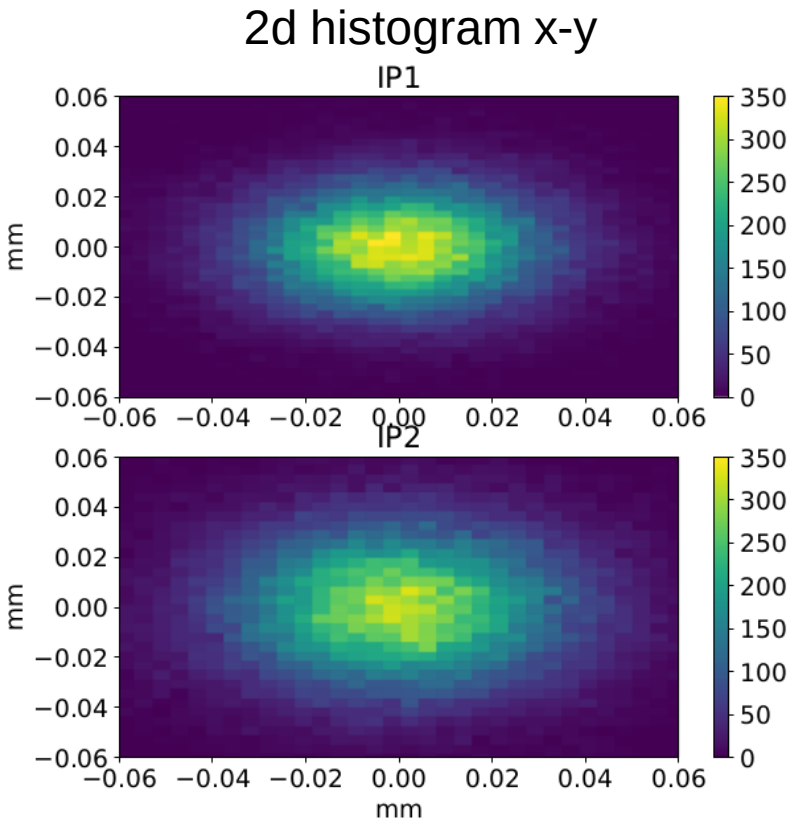


Simulation of.....

(Local coupling at IP2)

Simulation of the local coupling error





Tracking simulation: Ideal machine (beam 1) + trim of the **colinearity knob = 10** (MQSX.3L2 = 10^{-3} m^{-2} and MQSX.3R2 = -10^{-3} m^{-2})

Start with 50% larger emittance in horizontal compared to vertical

→ **Beam size is 15% larger in horizontal and 30%** in vertical in IP2 compared to IP1

→ **33% lower luminosity** (neglecting effect from crossing angles) compared to the 50% that was observed in the machine

→ Almost identical beam size increase for beam 2 (less than 1% difference)

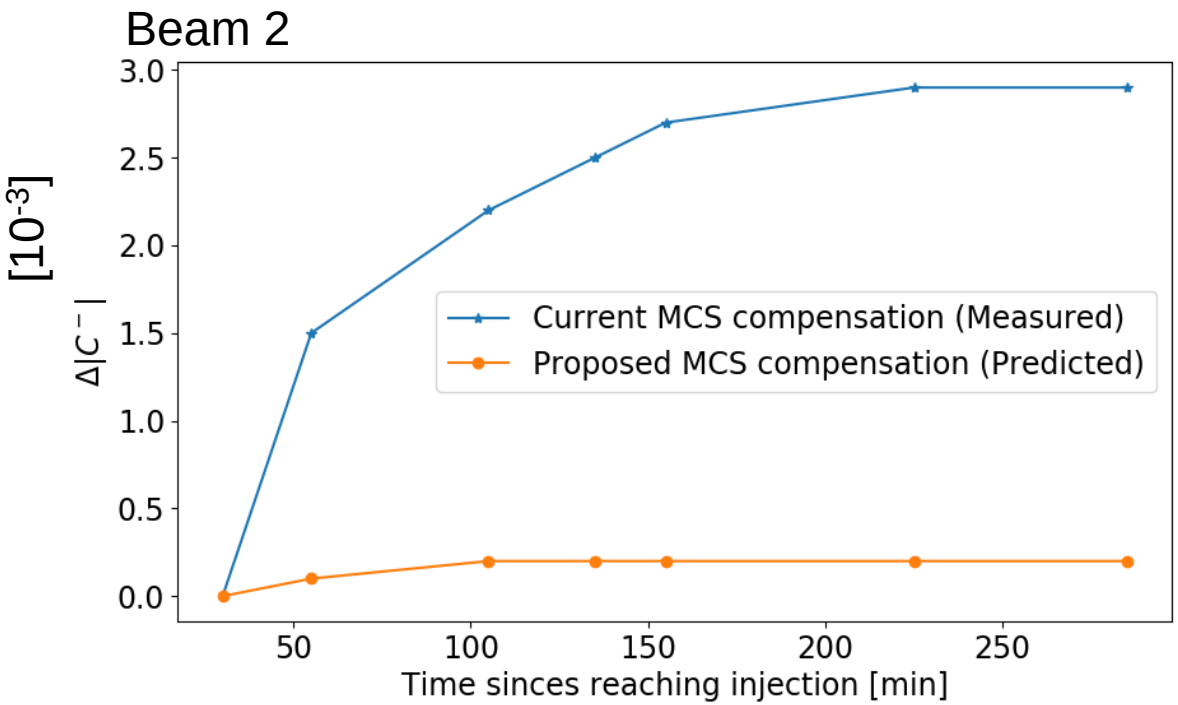
Transverse Global Coupling (C-)

Automatic coupling correction tool

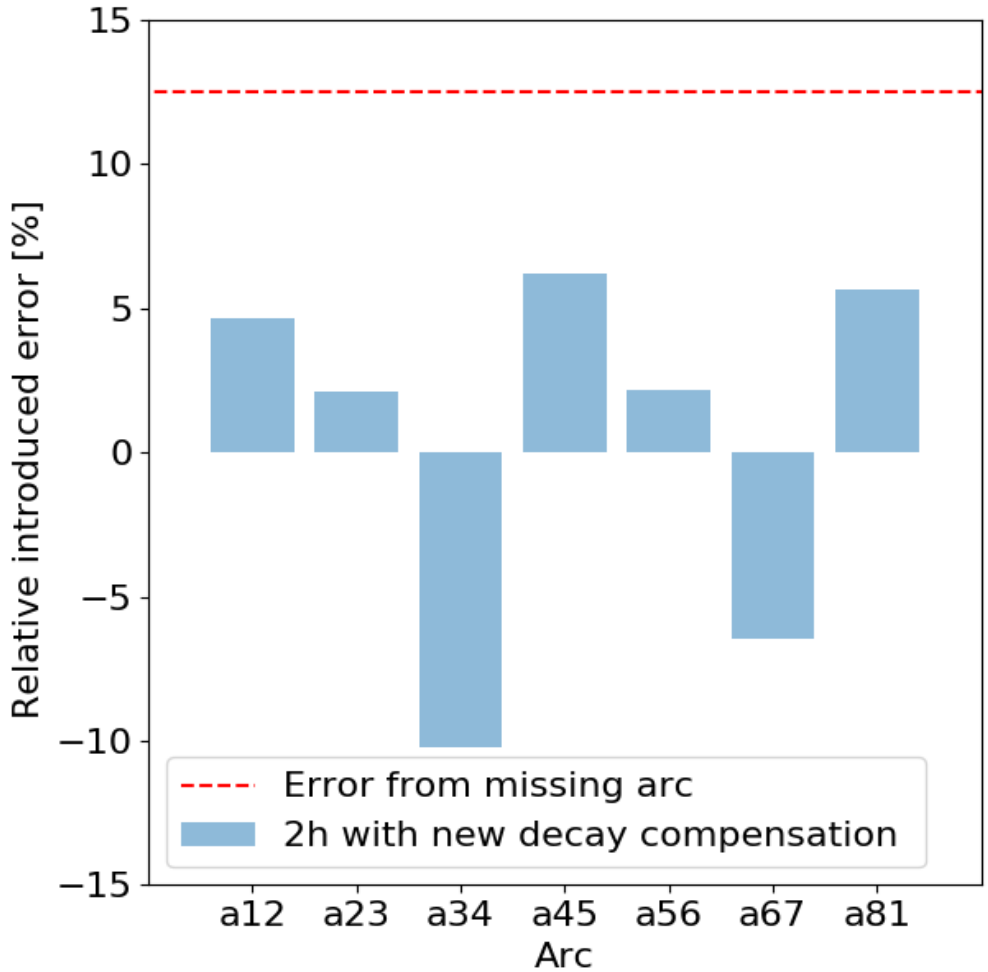
- The studies to make an automatic coupling tool started already in Run I
  - Attracted additional focus due to the link between coupling and instabilities (L.R. Carver et al. Phys. Rev. Accel. Beams **21**, 044401)
- In 2017 a collaborative effort was made to turn it into an operational tool (OP, ABP, RF, CO, BI)
  - Plans for a similar tool for tune measurement
  - Code parallelized in 2018
  - More than 2000 measurements since August 2018
    - Most of them at injection where we observe a drift

Counteracting the coupling decay at injection

- The coupling decay is linked to the powering of the MCS (b3-spool pieces)
  - By powering them differently (dynamic part)
    - Mitigate the coupling decay
    - Still compensating the chromaticity decay



Proposed MCS correction



- What is the impact of this ”non local” decay compensation
  - Neglible effect on the Q”
  - Chromatic β-beating almost identical
  - Smaller difference than the missing arc (a78) in Run II

Collaborations and Codes

- The automatic coupling correction tool is an example of a successful collaboration
  - Developed in a team ➔ Several people are able to maintain the software and make modifications
- Other examples of codes are the K-modulation and the multi-turn software
  - Developed by individuals and then new features have been added by others
  - People leave or change roles (both in the OMC-team and OP)
- Plan to have a mini workshop to discuss common codes and needs with OP
  - Also discuss how to optimize commissioning tasks between OP and the OMC-team

Conclusion

- We have learned something new evey commissioning:
  - 2015: New energy
  - 2016: K-modulation to correct the waist
  - 2017: Correct with X-ing + sextupolar and octupolar corrections
  - 2018: Use RDTs to correct skew octupolar error (a_4)
- Reproducibility:
  - After LS1 the errors were very different
  - Possible that it will be the same after LS2
  - β-beating within a few percent when re-measured during the same year
- The automatic coupling correction tool is heavily used in operation and in MDs:
  - Proposal to change the powering of the b_3-spool pieces to mitigate the coupling decay at injection

A look into the past and into the future...

Slide for 2021 ?

Slide from

from 2017

Thank you for your attention!

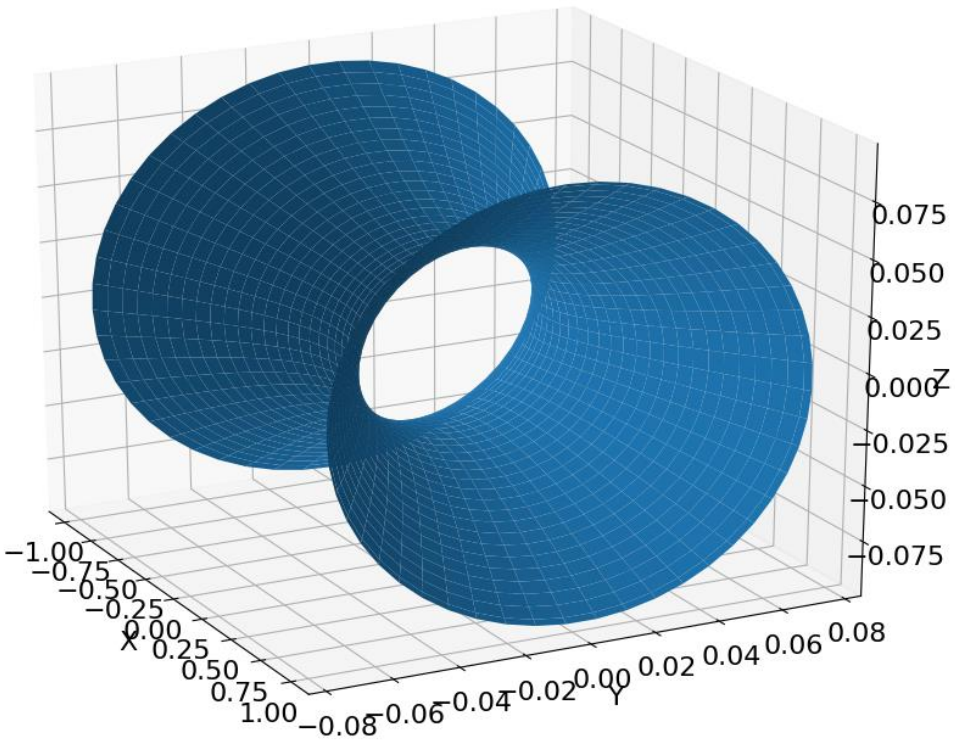
Many thanks to OP, BI, CO, RF for all the support and collaborations throughout the years!!

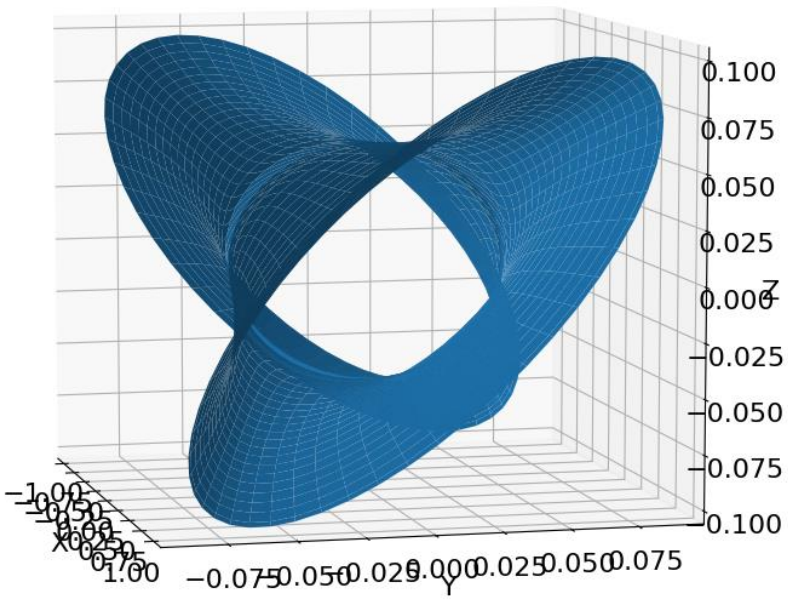
It is a privilege to work with all of you!

Back up slides

Does the coupling change the beam size?

- Normally we think of coupling as a rotation in phase space
  - But also have a direct impact on the beam size

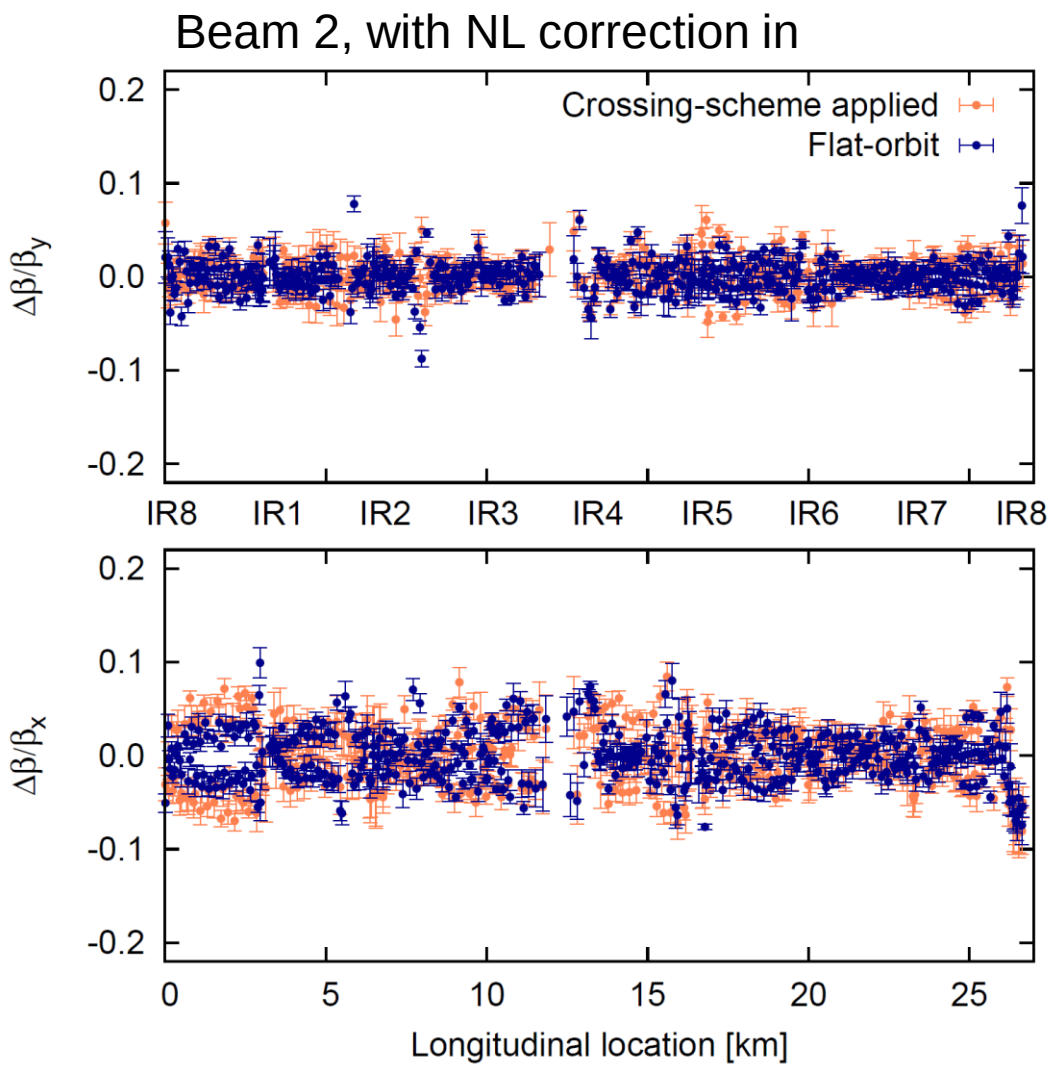




Local coupling correction strategy for Run III

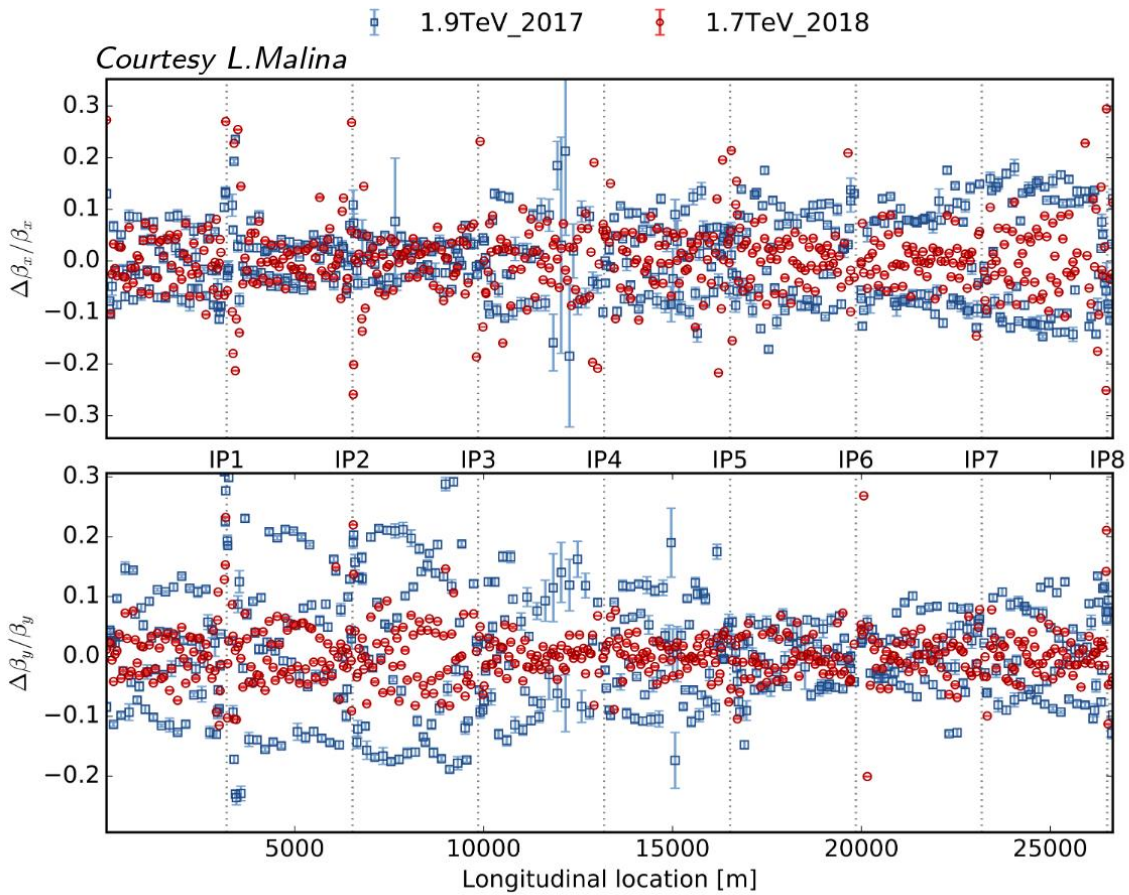
- Main problem was due to the swap between the right and left MQSX when implementing the correction
  - Automatic conversion from MAD-X to LSA
  - **Include the check of the local coupling corrections in our validation procedures**
- The MD after the ion run, provided us with new crucial measurements to evaluate if we can correct the local coupling to required level
  - **New method** was tested

Flat-orbit vs X'ing



- Still a slight degradation from the X'ing

  ➔ A linear optics correction with X'ing in



2018: 6shifts, 51hours2017: 11shifts, 76hours

Collaboration between many groups

Beams Department | Accelerators and Beam Physics

J. Coello de Portugal
E. Fol
L. Malina
T. Persson
P. Skowronski
R. Tomas

Beams Department | Radio-Frequency

Valuch, Daniel

Beams Department | Operation

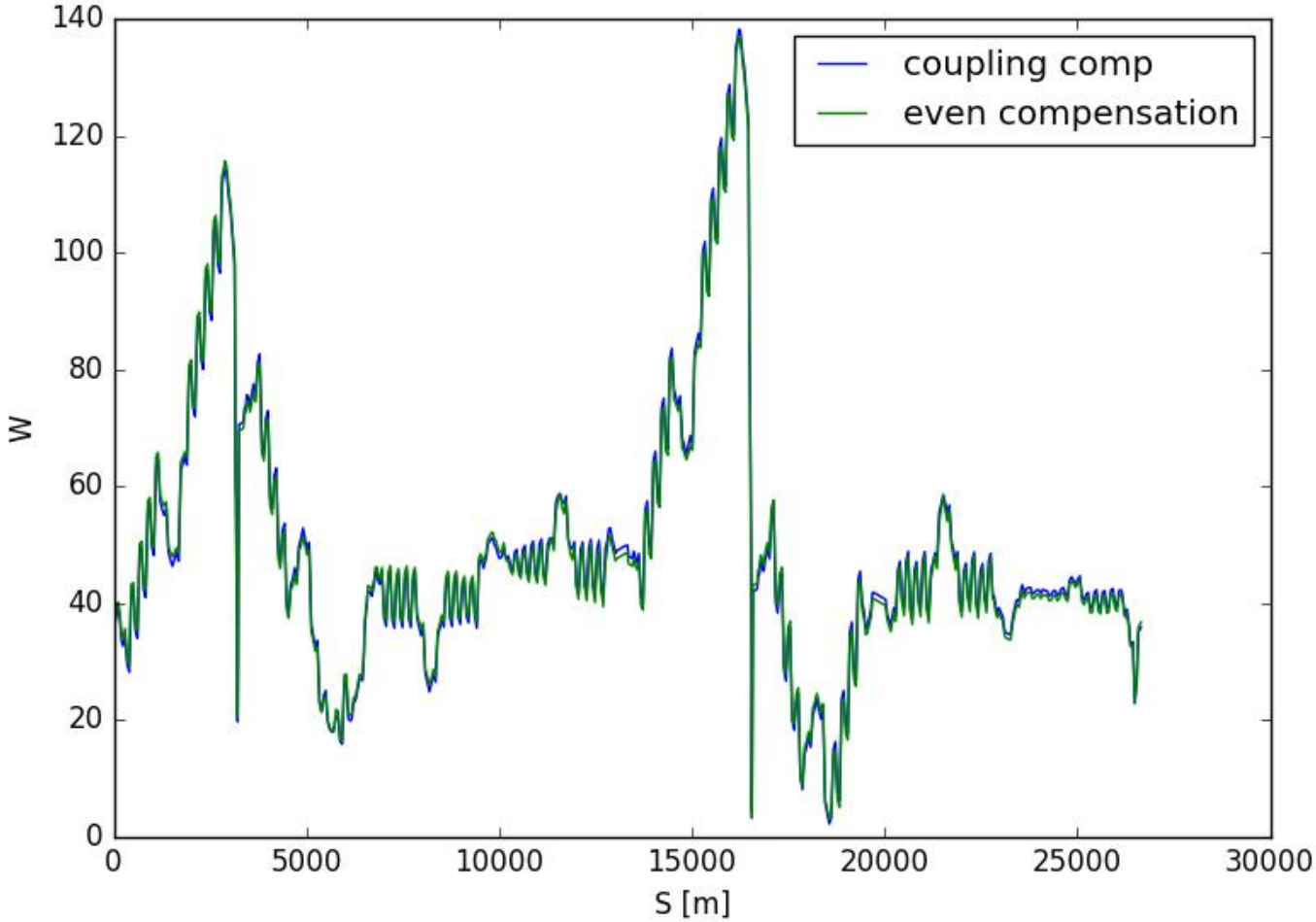
M. Hostettler, A. Calia, K. Fuchsberger, . H. Hemelsoet

Söderén, Martin

Beams Department | Controls

Hruska, Marek

Gabriel,Mathieu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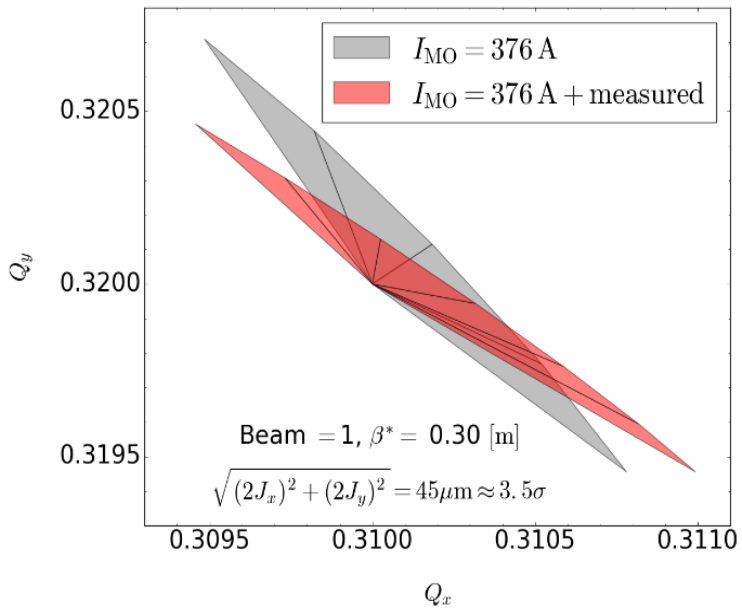
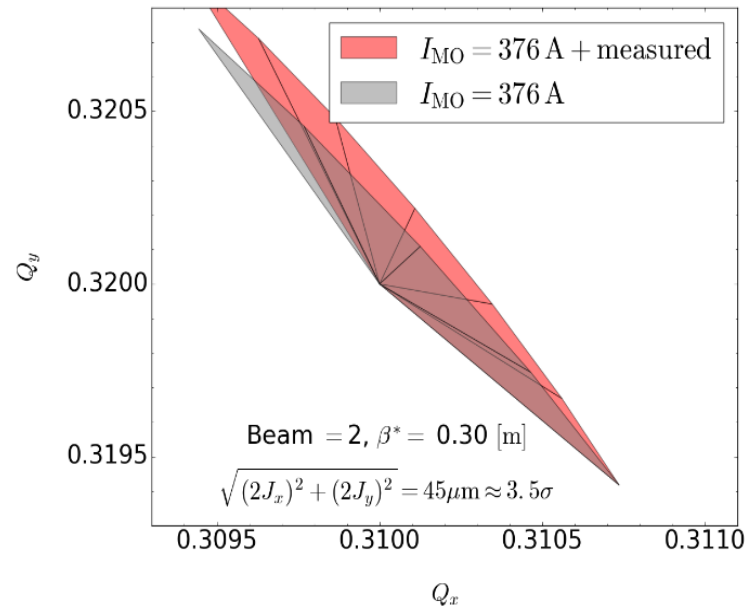
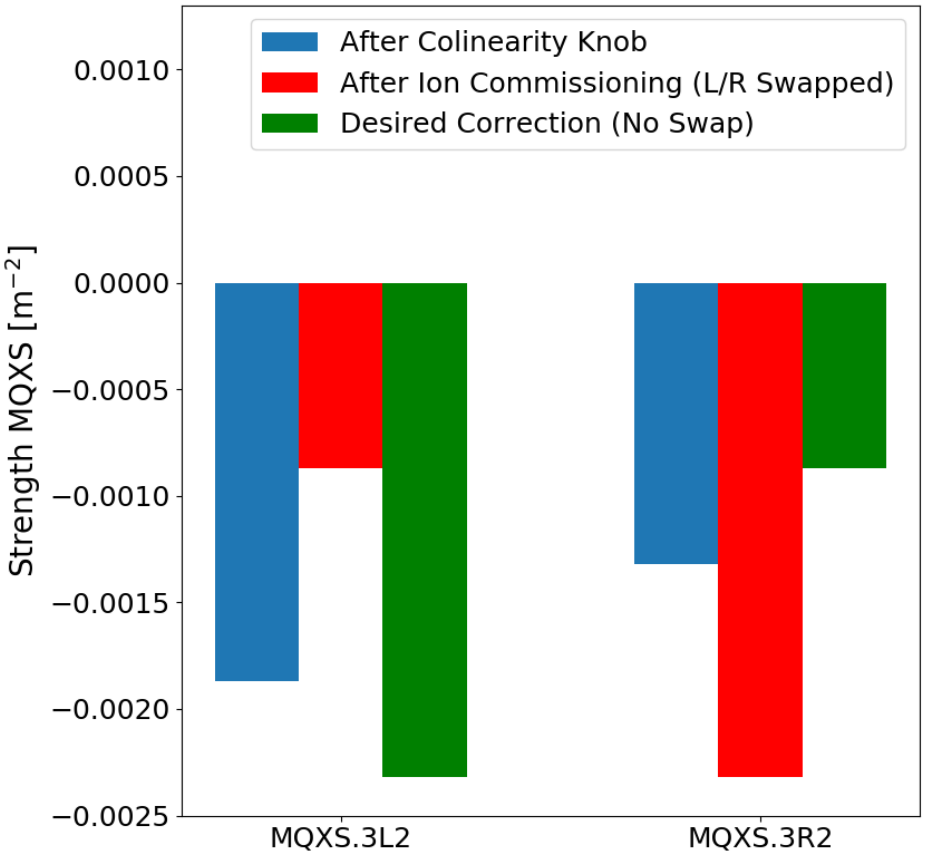




	LHCB1		LHCB2	
	Value	$\lvert I_{MO}\rvert$ correction	Value	$\lvert I_{MO}\rvert$ correction
$\partial Q_x/\partial 2J_x$	$+32$	$\Delta\lvert I_{MOF}\rvert = -108$	0	
$\partial Q_y/\partial 2J_x$	0		0	
$\partial Q_y/\partial 2J_y$	-40	$\Delta\lvert I_{MOD}\rvert = +142$	$+20$	$\Delta\lvert I_{MOD}\rvert = -70$

Investigation of the lower luminosity in IP2

- When the cogging measurement was repeated, it was concluded that no waist shift was present (November 18th)
  - Our focus turned to coupling
  - Plan to remeasure and check the coupling
  - The test of the colinearity knob with luminosity
  - fixed the issue (November 19th)
- The Colinearity knob (S. Fartoukh) :
  - Trimmed on top of the previous corrections
  - **Δ**MQXS.3L2 = +knobStrength* 10^{-4} m^{-2}
  - **Δ**MQXS.3R2 = -knobStrength* 10^{-4} m^{-2}
  - Optimal was found to be knobStrength=-10
  - (knobStrength=-12 for opposite polarity)



If no left/right swap
→ Corrections much closer to what was found with the colinearity knob

	Circuit	Δk (10^{-5} m^{-2}) 2012	2015	2016	Polarity LSA
IR1	**ktqx1.l1**			1.23	−
	ktqx1.r1	1.0		−1.23	+
	ktqx2.l1	1.0	0.35	0.65	+
	ktqx2.r1	−1.4	−0.7	−1.0	−
	ktqx3.l1			1.22	−
	ktqx3.r1			−1.22	+
	kq9.l1b1	1.5			−
IR5	**ktqx1.l5**		2.0	2.0	−
	ktqx1.r5		−2.0	−2.0	+
	ktqx2.l5	0.7	1.9	0.27	+
	ktqx2.r5	1.05	1.9	1.48	−
	ktqx3.l5			1.49	−
	ktqx3.r5			−1.49	+
	kq4.l5b2	3.80			−

Results from k-modulation taken during the MD (Beam 2)

	β* Horizontal [m]	β* Vertical [m]	Waist Shift Horizontal [m]	Waist Shift Vertical [m]
Colinearity -12 (operational setting of the machine for opposite polarity)	0.514	0.502	-0.08	-0.01
Colinearity -5	0.5084	0.5051	-0.049	0.025

Small change in the measured horizontal and vertical β* and waist shift as a function of the setting of the colinearity knob

The results are consistent with simulation → k-modulation is measuring β_x and β_y,
→ For a situation with strong coupling beam size is **not** equal to $\sqrt{\beta_x \epsilon_x}$

Pro:

- Measurement insensitive to local coupling errors
  → Can be used for our normal quadrupolar corrections