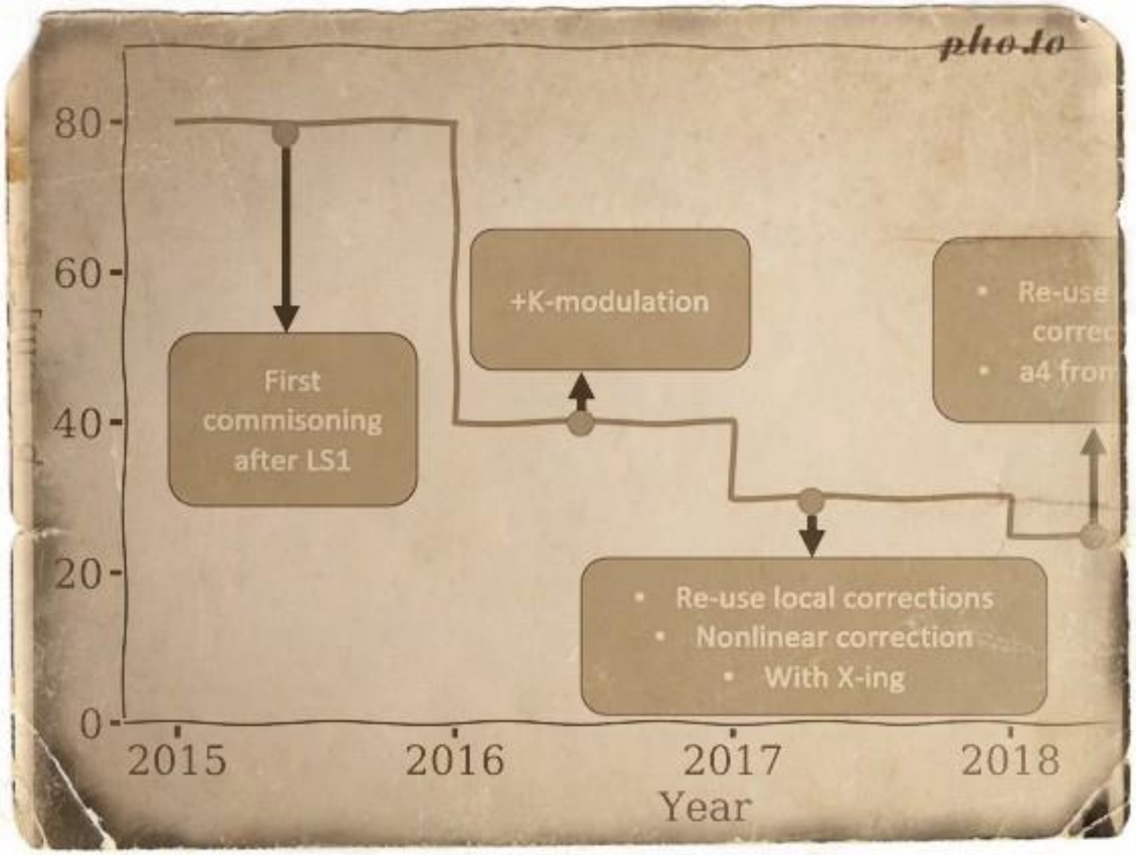
An OMC perspective on the commissioning

T. Persson
On behalf of the OMC-team

Old plot from Evian 2019..



The goal for the commissioning 2022 is to do basically all these steps!

Only possible thanks to the experience from Run 2

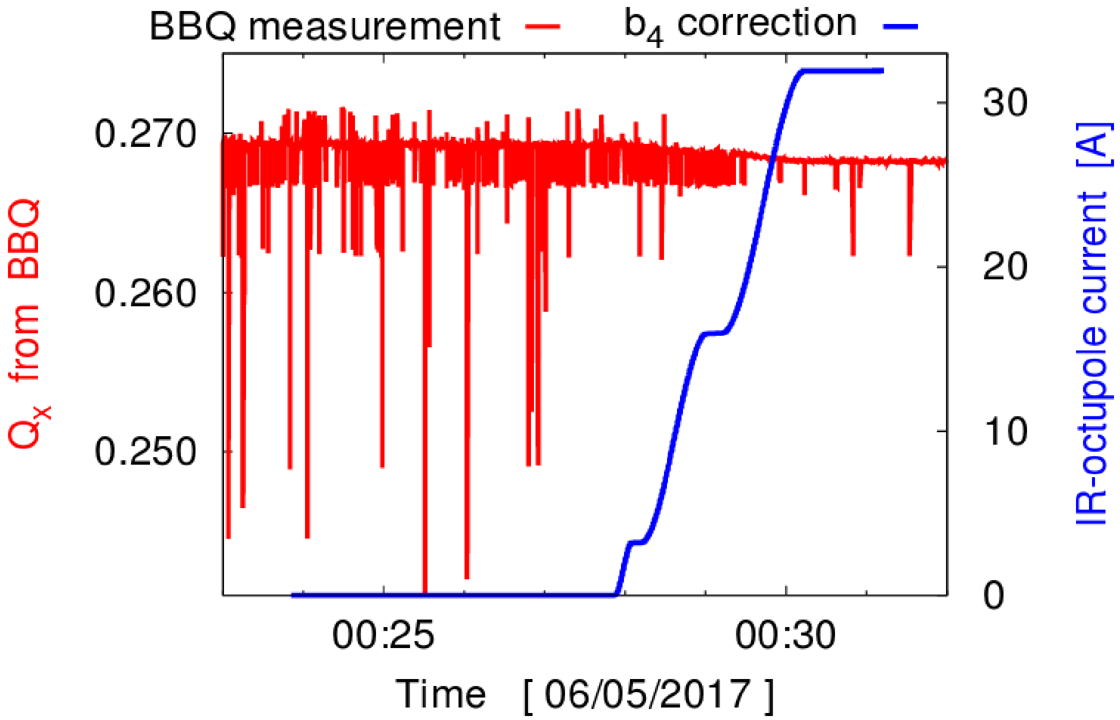
Introduction

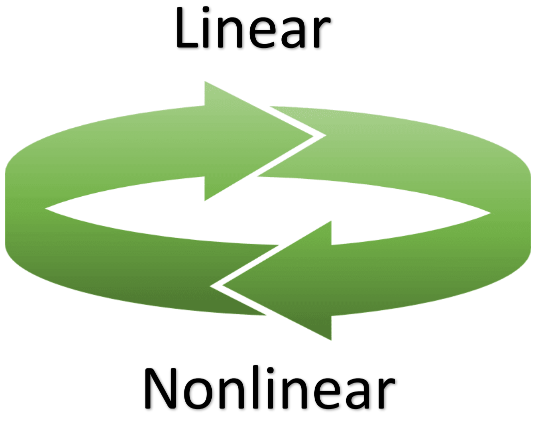
- The presentation is divided into 3 parts:
  - Injection
  - Squeezed optics + Ramp
  - Calibration optics
    - Ballistic optics
    - 60 deg phase advance optics

What do we propose to start with in terms of corrections ?

- Global β-beat correction (injection)
- Local coupling corrections
  - Very similar to Run 2 and validated during beam test
  - Possible that the MQSXs will stop working under Run 3
    - As a proof-of-principle, we propose to tilt the Q3s (or the Q2s but would have to be opposite direction) for one of the IRs to demonstrate that this could replace the MQSX corrections
- The nonlinear IR correctors settings from Run 2 sextupolar (a_3, b_3) and octupolar (b_4, a_4)

Octupole IR correction (b_4)





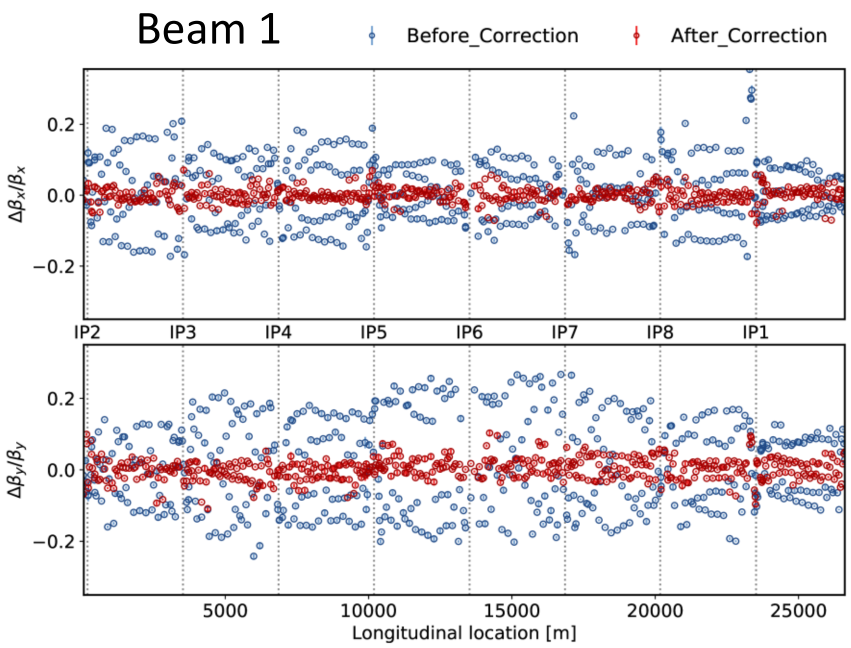
- Octupole correction based on amplitude detuning measurement in 2016
  - Improved the tune measurement from the BBQ

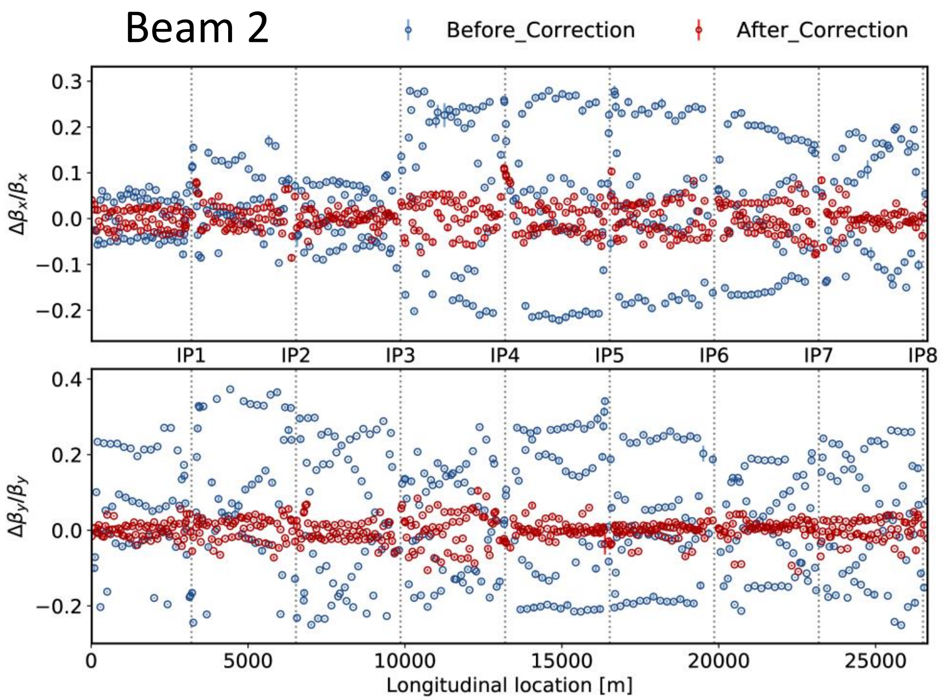
    ➔ Improved K-modulation quality

Injection

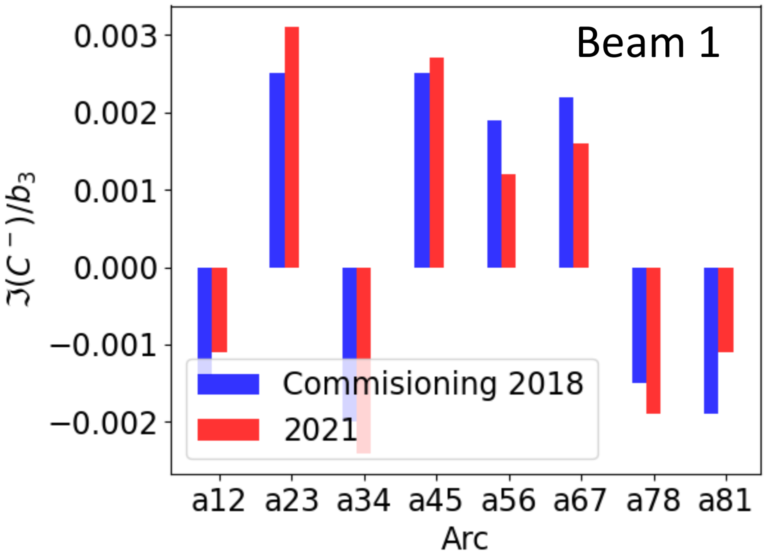
Global correction

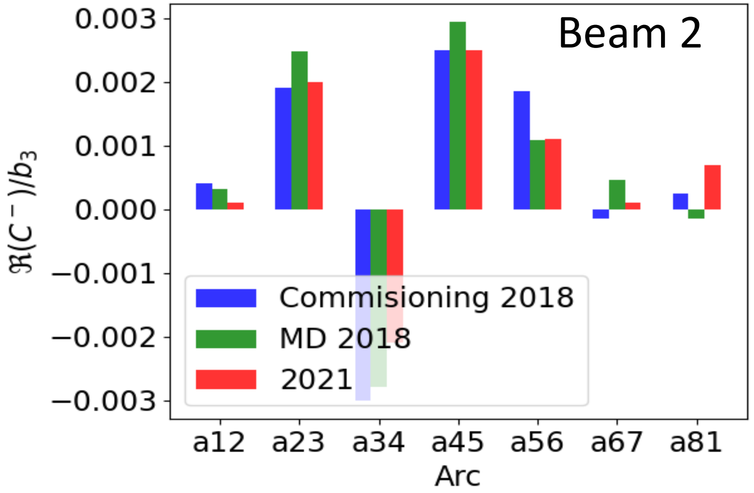
- Initial finding of the β-beat during the beam test
    - Explained by the swapped RQTL7.L3 B1/B2 and fixed (see Michi’s talk)
- The injection optics was then corrected
    - No x’ing angles and not all experimental solenoids at nominal
    - Likely we can re-use the corrections, but should re-measure to be sure





MCS feed-down looks similar to in 2018





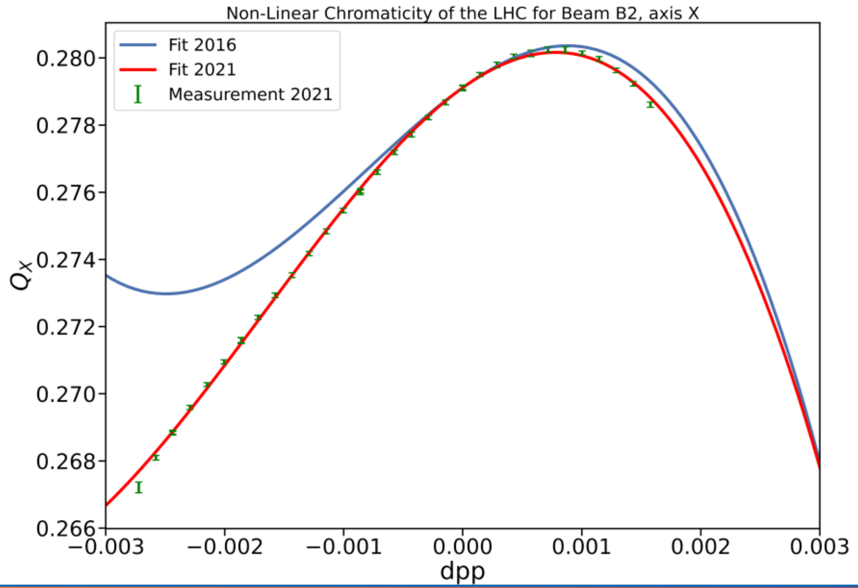
- We change the setting of each of the MCS arc-by-arc
  - Measure the change to C-
  - Stayed fairly constant between Run 2 and Run 3
- We can create a knob that changes the b_3 but still keeps the coupling constant
  - Test during commissioning

-> If successful, we could implement in Fidel

-> <u>More stable coupling at injection</u>

MCO and MCD

- We measured the Q’’ and Q’’’ during the beam test and the Q’’’ was different from the Run 2
  - Would like to repeat measurement over larger dp/p
  - Measure amplitude detuning and decoherence checks to find a good setting for both the MCO and MCD (reduced strength)



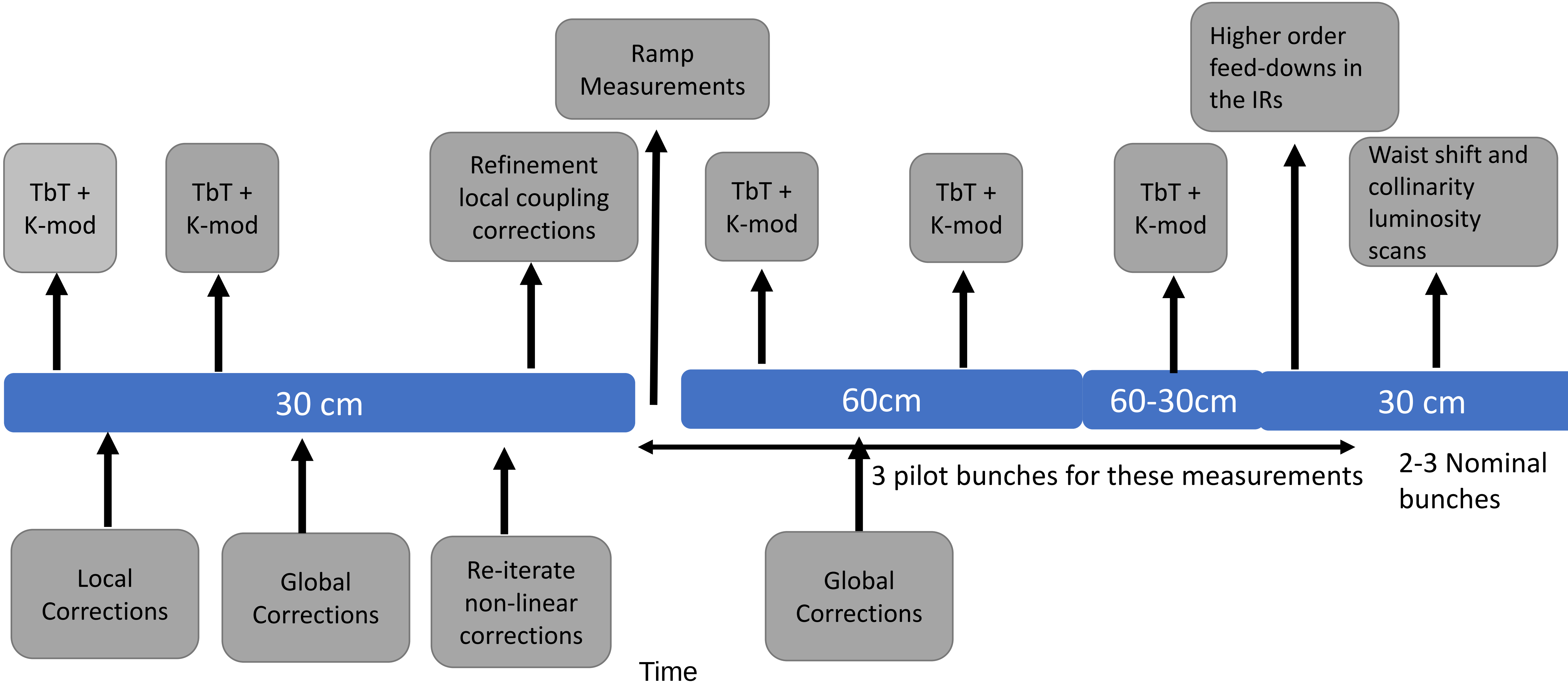
Summary injection

- The revalidation of the global corrections should be done early in the commissioning
  - Check of the new MCS “uneven” compensation is very quick so could be done at the same time
- MCD and MCO measurements can be scheduled during a quiet period

Type	Hours
Revalidate Global Correction	2 hours
MCS feed-down	1 hour
MCD and MCO correction	5 hours
Total	**8 hours**

Squeezed optics + Ramp

Optics Commissioning Strategy 2022



Ramp Measurements

Higher order feed-downs in the IRs

TbT + K-mod

TbT + K-mod

Refinement local coupling corrections

TbT + K-mod

TbT + K-mod

TbT + K-mod

Waist shift and collinarity luminosity scans

30 cm

60cm

60-30cm

30 cm

3 pilot bunches for these measurements

2-3 Nominal bunches

Local Corrections

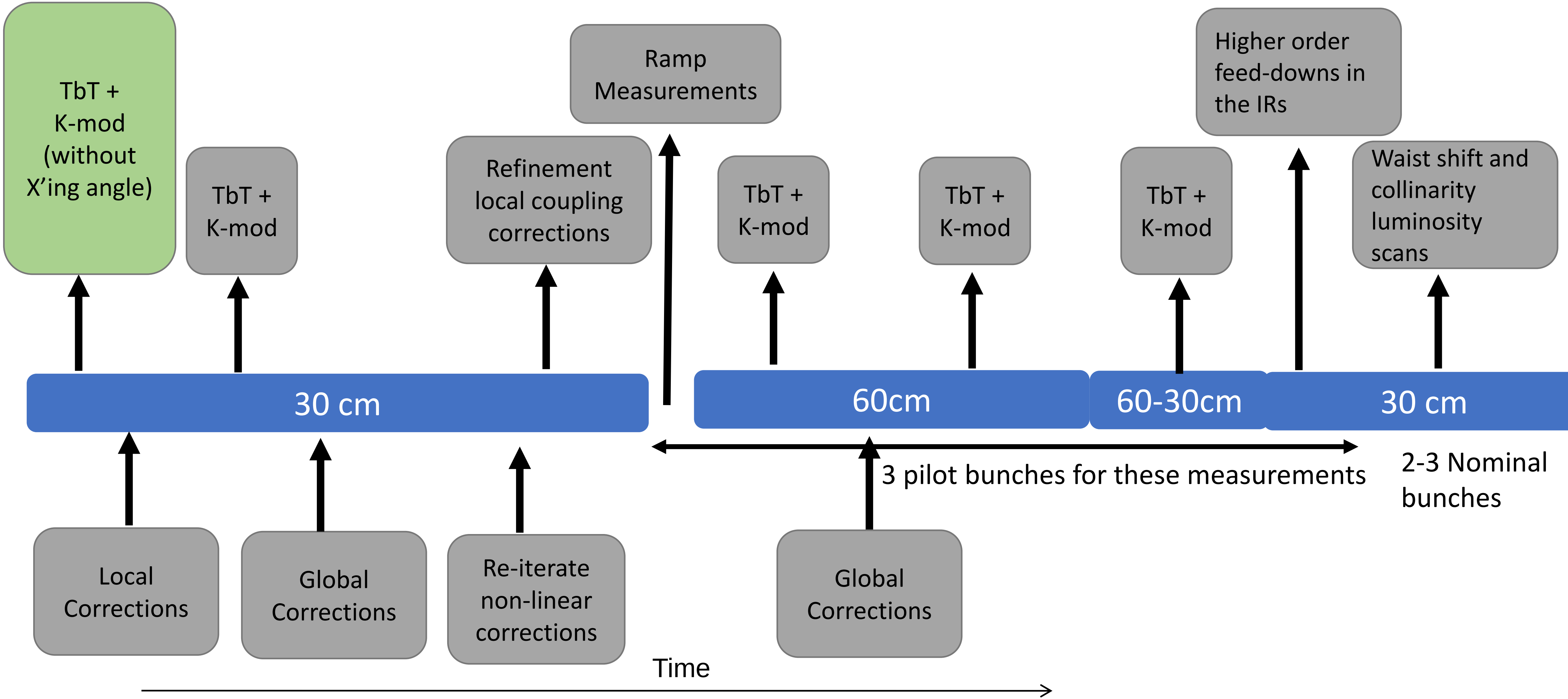
Global Corrections

Re-iterate non-linear corrections

Global Corrections

Time

Optics Commissioning Strategy 2022



TbT + K-mod (without X'ing angle)

TbT + K-mod

Refinement local coupling corrections

Ramp Measurements

TbT + K-mod

TbT + K-mod

TbT + K-mod

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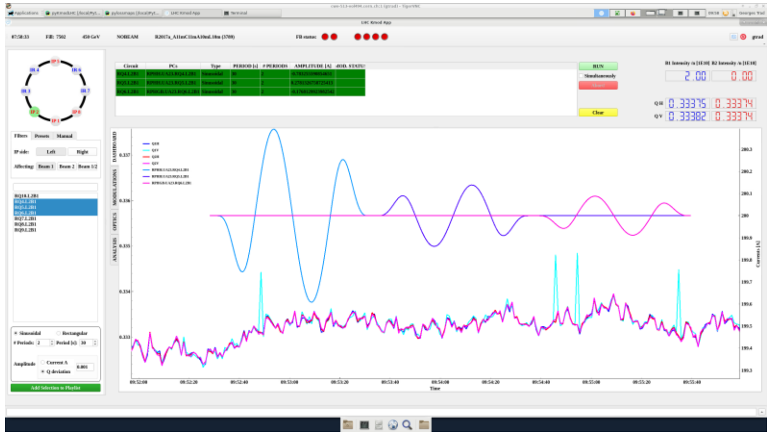
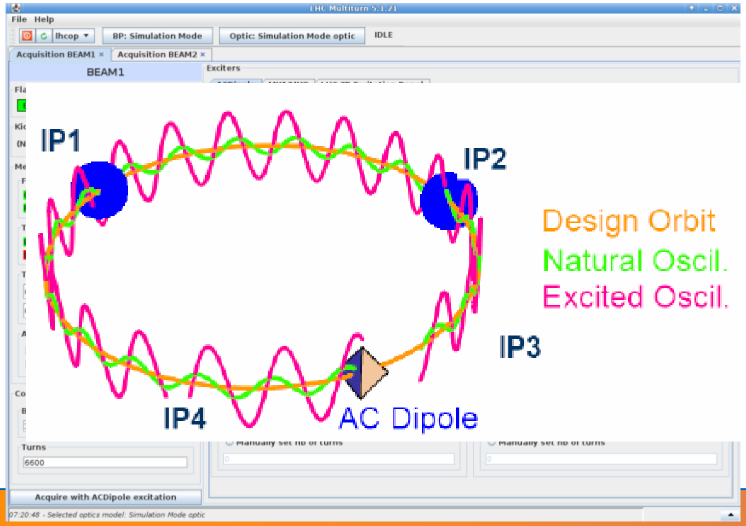
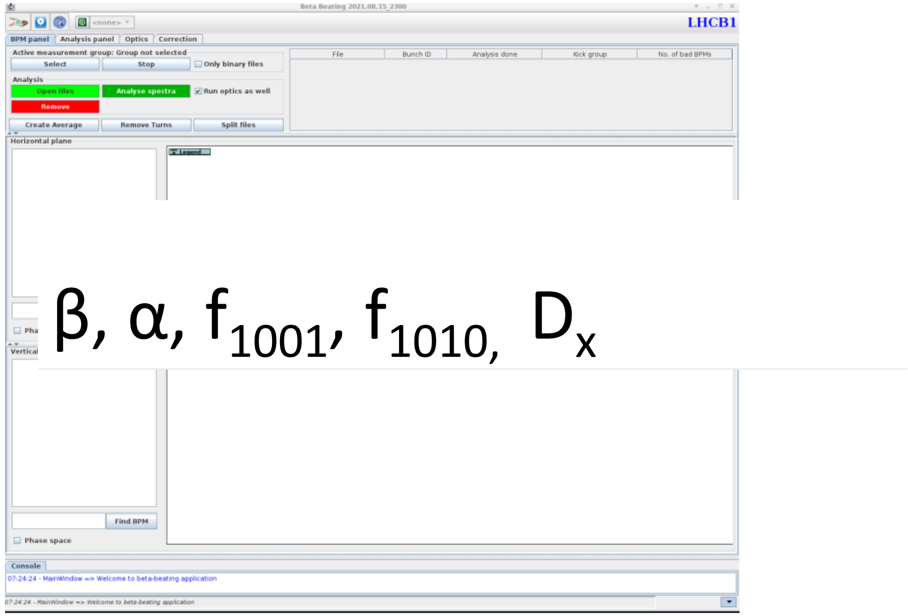
Turn-by-turn (TbT) + K-mod





07:20:48 - Selected optics model: Simulation Mode optic

Analysis code and OMC GUI



β, α, f_{1001}, f_{1010}, D_x

07:24:24 - MainWindow => Welcome to beta-beating application

New K-modulation application by G. Trad. M. Hofer connecting it to our analysis

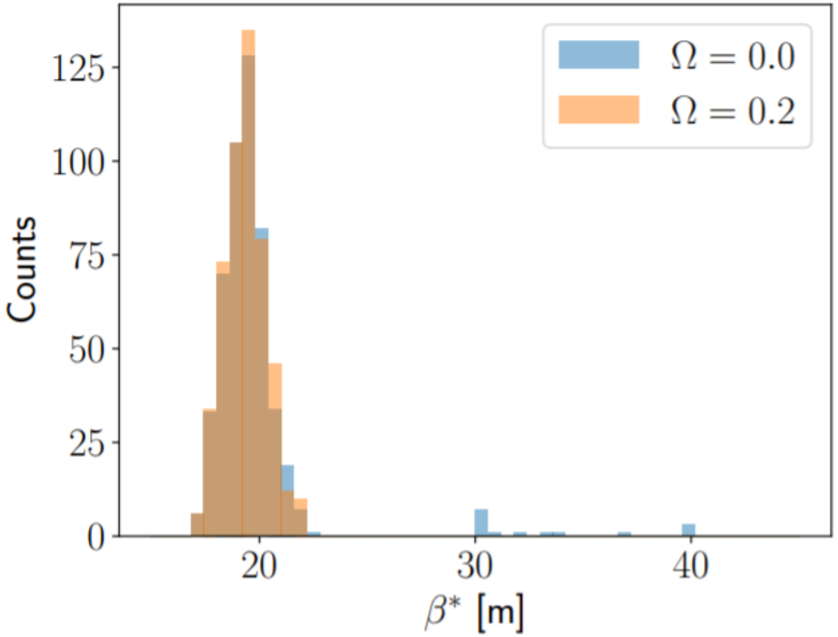
New multiturn by: D. Jacquet, A. Calia, M. Hostettler, M. Schaumann

K-modulation

New application developed to trim the magnets (G. Trad) The analysis has also been improved to incorporate the phase advance to constrain the results from k-modulation when reconstructing the β^*

Important when the distance between Q1 to the IP is close to the distance β^*

-> **Ready to precisely measure the Van der Meer Optics ($\beta^* = 19$ m)**



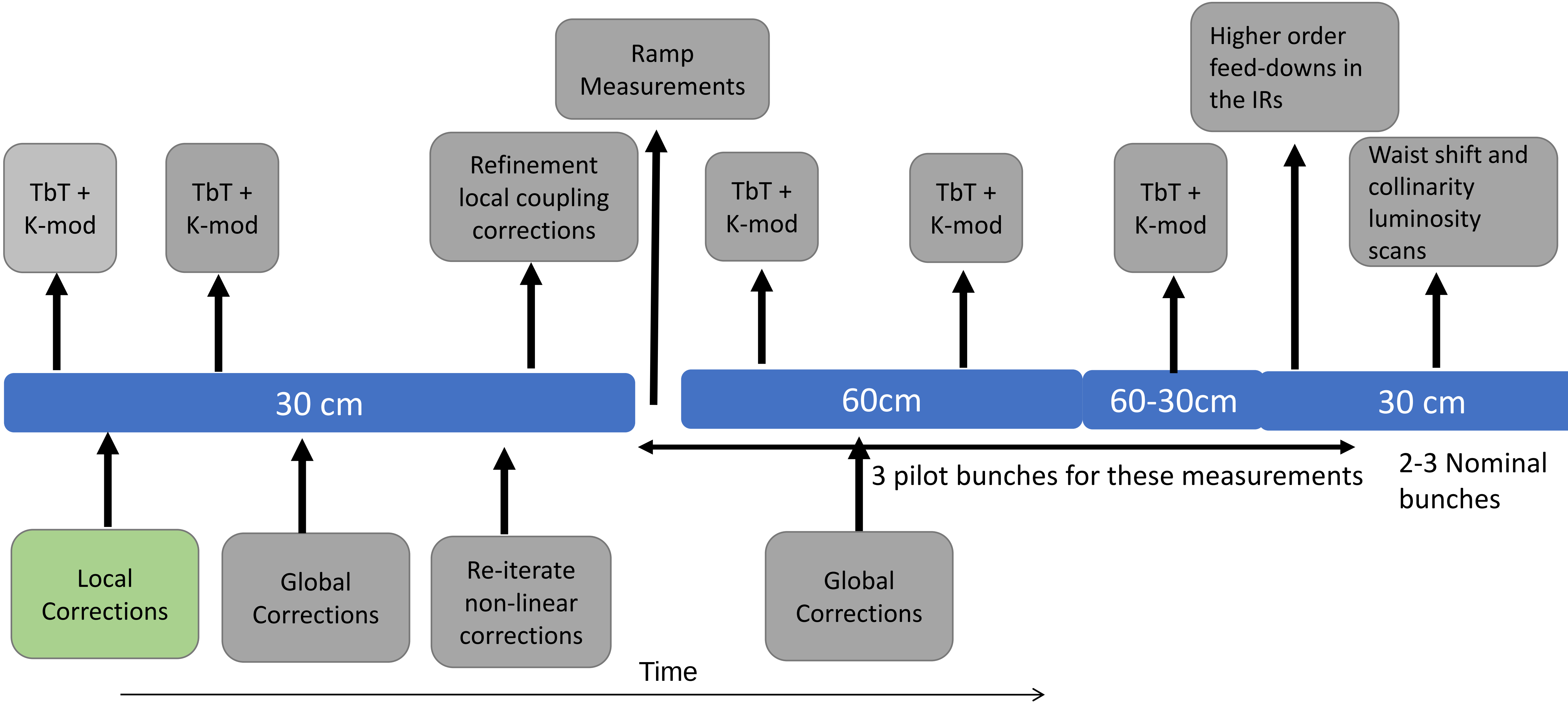
H. Garcia Morales

AC – dipole excitation

- In order to have a good measurement we need to excite the beam to around 2mm peak-to-peak in the arcs
  - Even higher for amplitude detuning
- If we excite and the collimators are too close, there is a risk of blowing up the beam
  - Worst case we need to dump and start a new cycle

    –> Hours lost
- Personal experience is that moving the collimator is complicated and time consuming
  - **<u>Define early on in the commissioning a sequence: “collimator settings for optics measurements”</u>**

Optics Commissioning strategy 2022



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Refinement local coupling corrections

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Local Corrections

Global Corrections

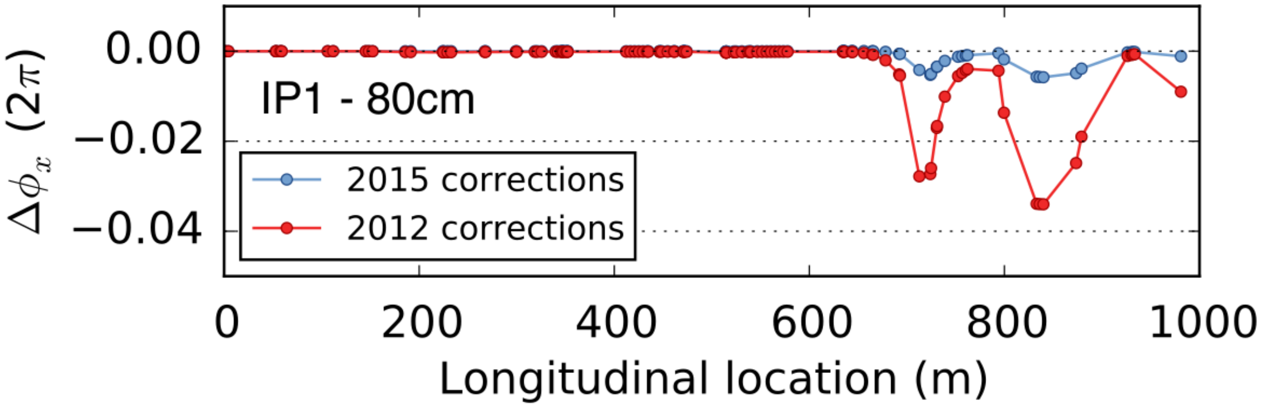
Re-iterate non-linear corrections

Global Corrections

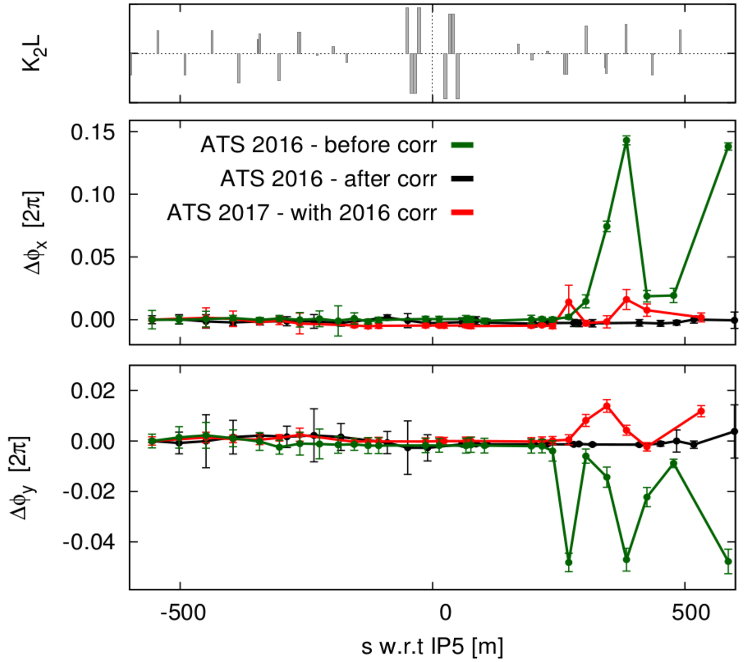
Time

Local corrections

- Squeeze the optics to 30 cm
- Measure the local errors
  - Reminder from Run 2:



Also a degradation seen during the run !



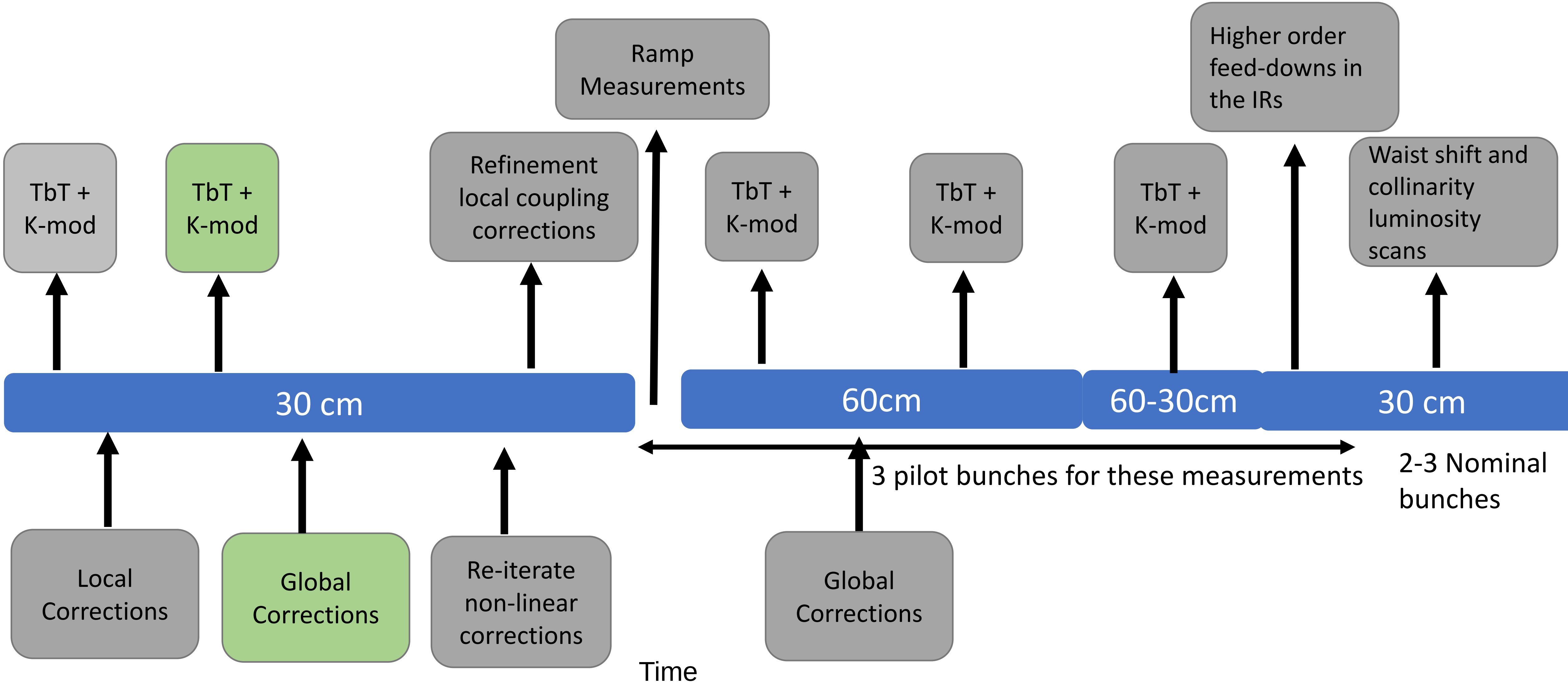
- Not apparent where the change came from
  - Energy might have been a factor although the 2015 corrections were also valid for 2.51 TeV run!

3 different methods to correct the local errors

- Segment-by-Segment
- Machine learning
- Action-phase-jump

- Ideally some time between the measurement and when we need to calculate and evaluate the correction (12h minimum)

Optics Commissioning strategy 2022



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Global Corrections

Time

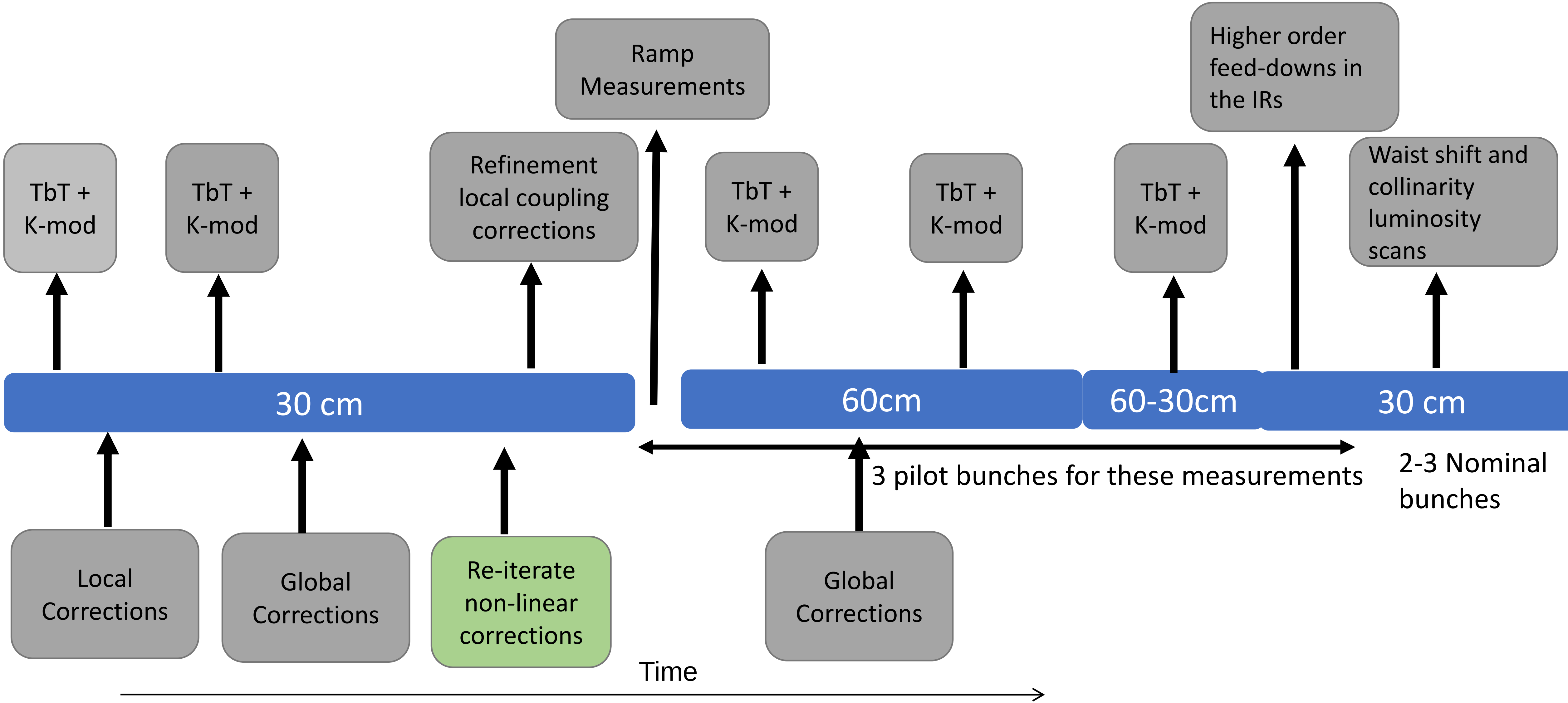
Global Corrections

- The input is:
  - Phase advance BPMs
  - Normalized dispersion
  - K-modulation results from the Q1s at IP1 and IP5
- Correction
  - Response matrix created in MAD-X
  - Correction is based on pseudo-inverse of the response matrix

- In a separate correction step, but based on the same input data, we will also calculate a correction for the chromatic coupling as was done in Run 2

T. Persson et al. , “LHC optics commissioning: A journey towards 1% optics control”

Optics Commissioning strategy 2022



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Refinement local coupling corrections

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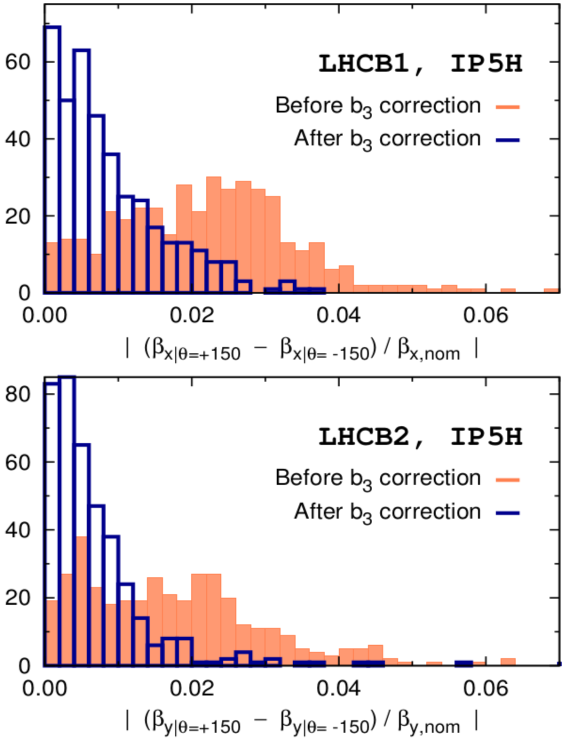
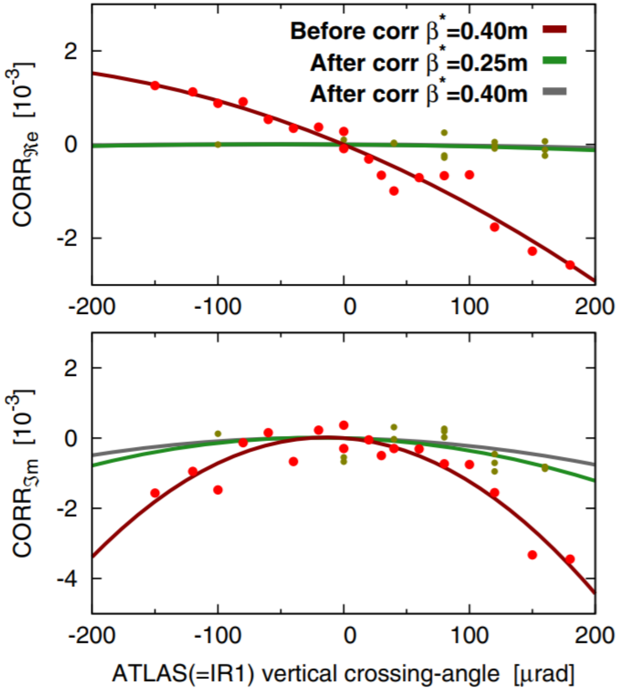
Global Corrections

Time

Sextupolar IR corrections

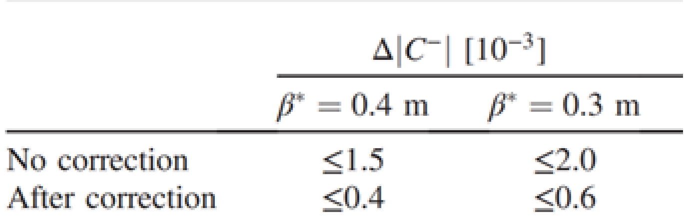
β-beating between crossing angles





If the sextupole correctors fail we will need to correct the coupling and β-beat (depending on crossing plane and if it is a skew or normal sextupole) as a function of crossing angle and β*

150 µrad → 100 µrad

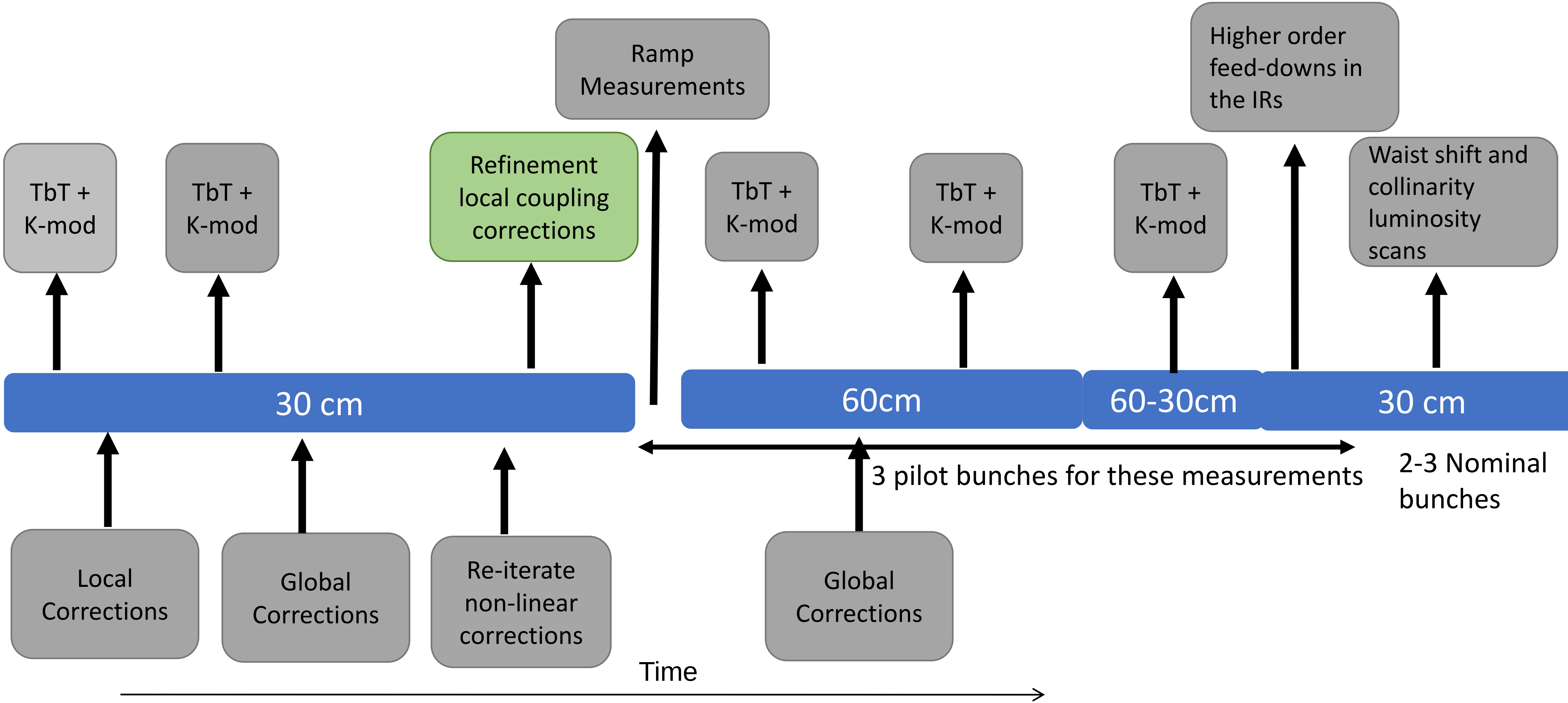


	$\Delta\|C^-\|$ $[10^{-3}]$	
	$\beta^* = 0.4$ m	$\beta^* = 0.3$ m
No correction	$\lesssim 1.5$	$\lesssim 2.0$
After correction	$\lesssim 0.4$	$\lesssim 0.6$

- The sextupolar error in the IR feed-down to beta-beat and coupling
- Possible that the Run 2 correction is not valid anymore

E.H. Maclean et al, New approach to LHC optics commissioning for the nonlinear era

Optics Commissioning strategy 2022



TbT + K-mod

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30 cm

Local Corrections

Global Corrections

Re-iterate non-linear corrections

Global Corrections

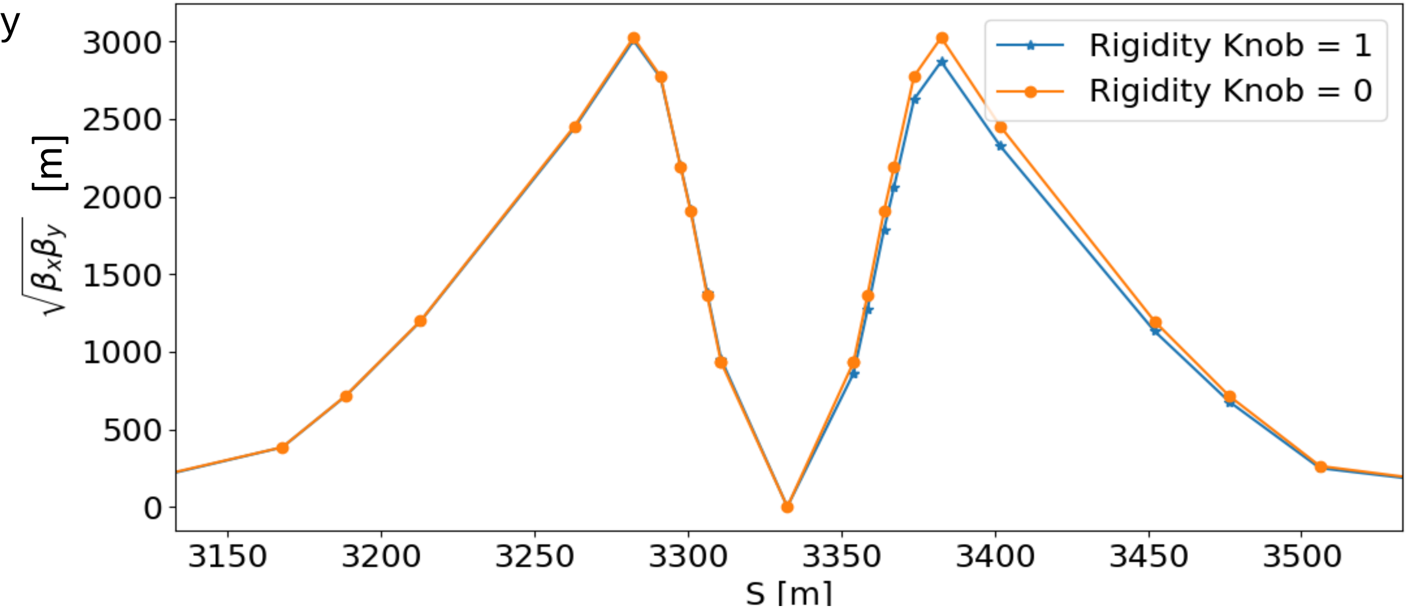
3 pilot bunches for these measurements

2-3 Nominal bunches

Time

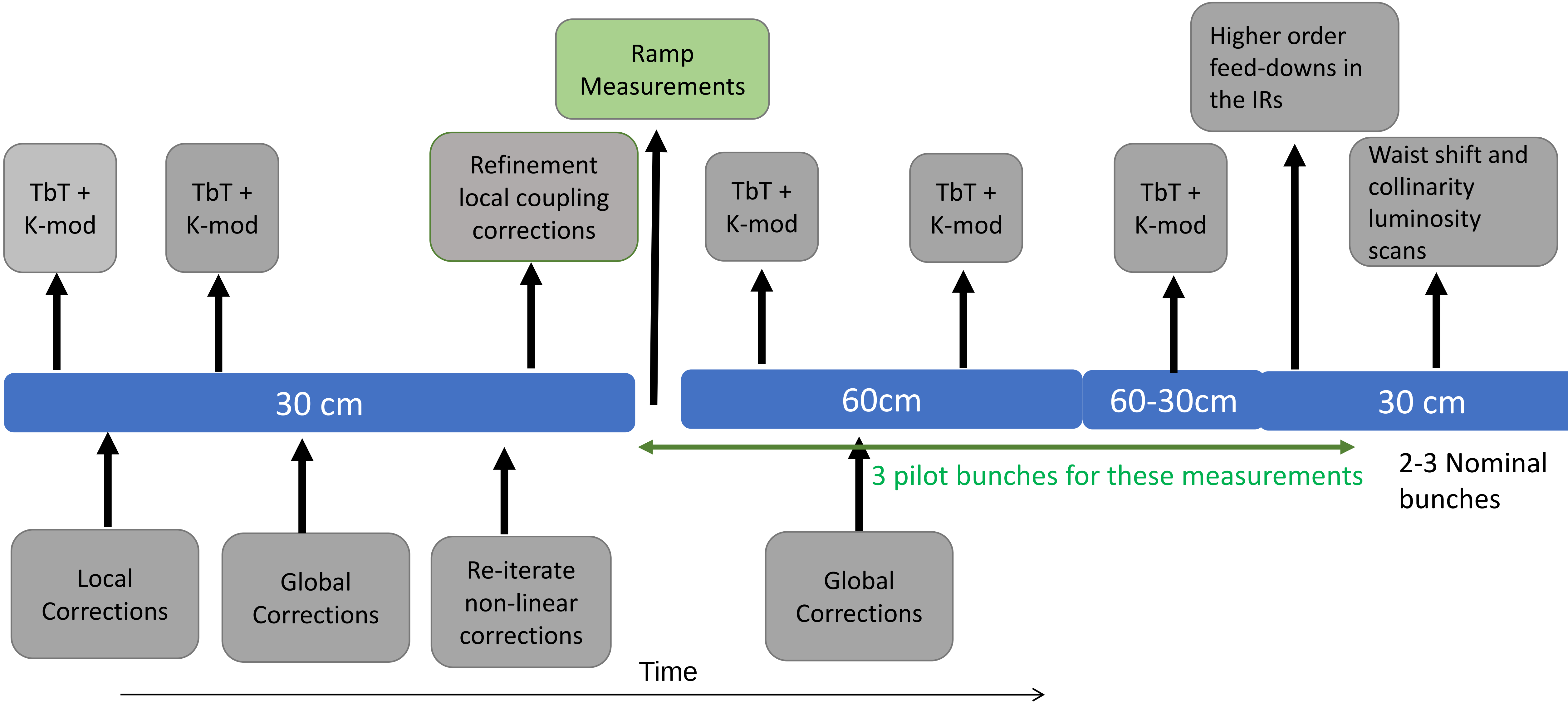
New method to measure the local coupling

- Difficult to measure the local coupling in the IR due to the phase advance
- New method tested during the last MD period in 2018
  - Gave promising results
- Principle of the rigid waist shift:
  - Unbalance the strength of the left and the right triplet
    - Breaks the left-right symmetry



[F. Soubelet et al, Prospect for Interaction Region Local Coupling Correction in Run 3]()

Optics Commissioning strategy 2022



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Global Corrections

Time

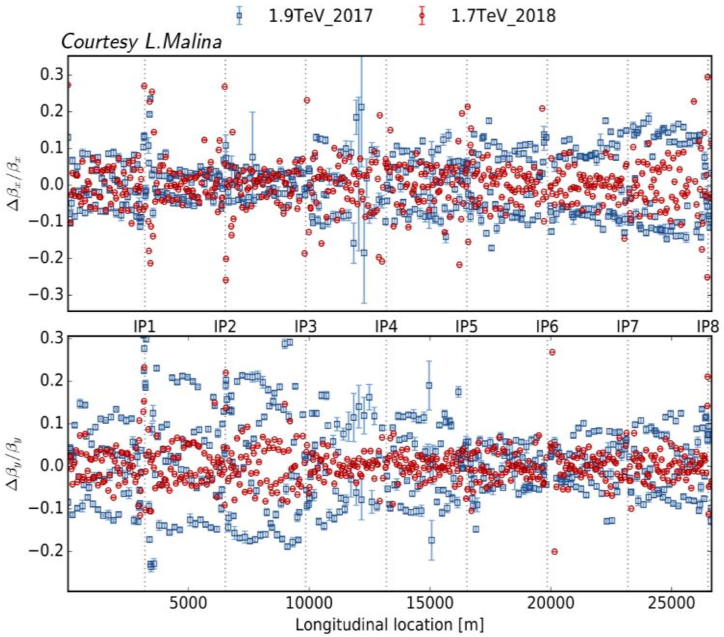
3 bunches

- Enables faster measurement and/or more data leading to better statistics
- At this stage we have validated that the optics is well under control
  - β-beat < 20 %
- Simulated failure scenarios with 3 bunches, roughly equally spaced around the ring
  - BLM triggers on total losses from 3 bunches sooner than it triggers on 1 bunch in the simulated cases!
  - Discussed with the MPP and agreed to be used when the beta-beat is below 20%

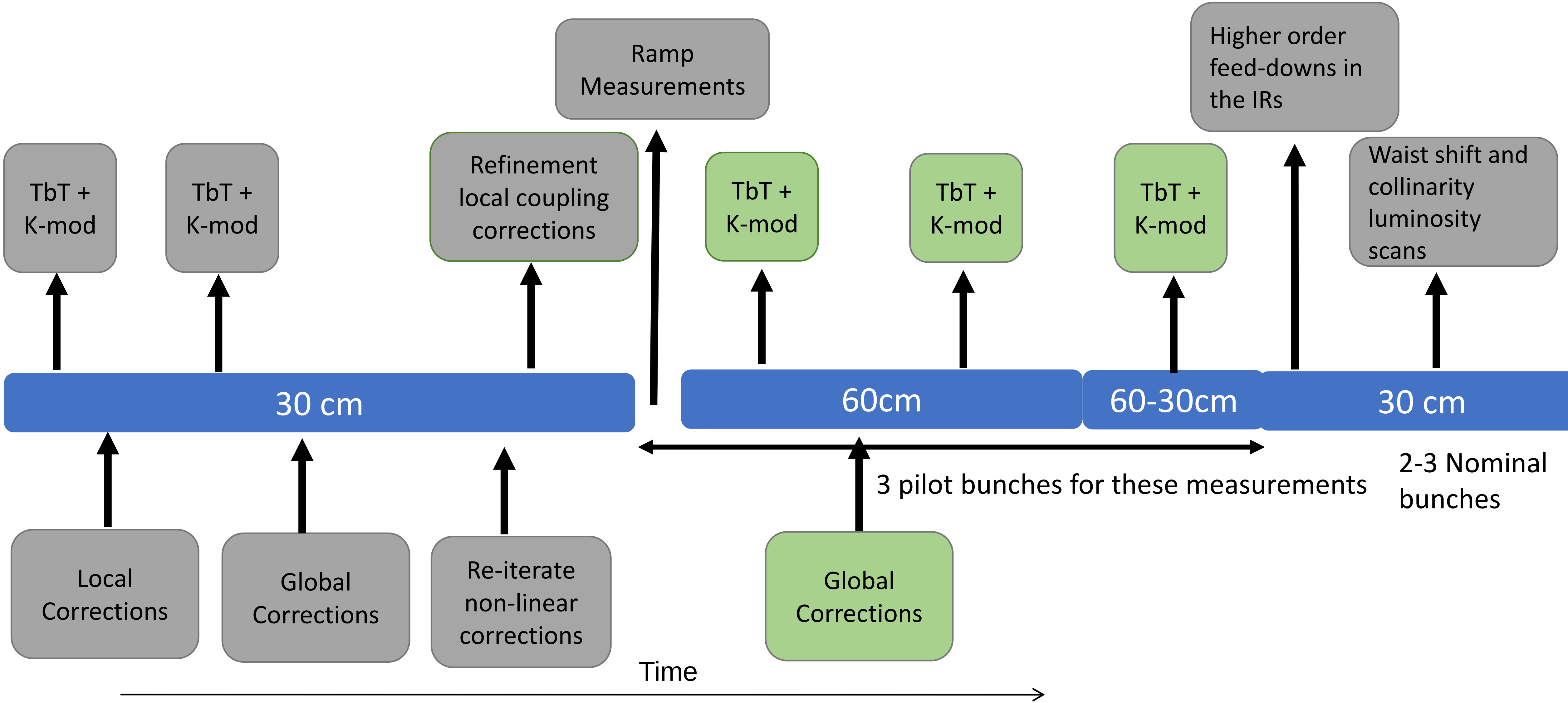
L. Malina

Ramp

- Would like to measure the ramp with 3 bunches for better statistics
  - Better measurement of the β-functions
  - No systematic uncertainty from the timing of the kicks
- Trimming out of the injection corrections similar to what was done in 2018



Optics Commissioning strategy 2022



Ramp Measurements

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2-3 Nominal bunches

Local Corrections

Global Corrections

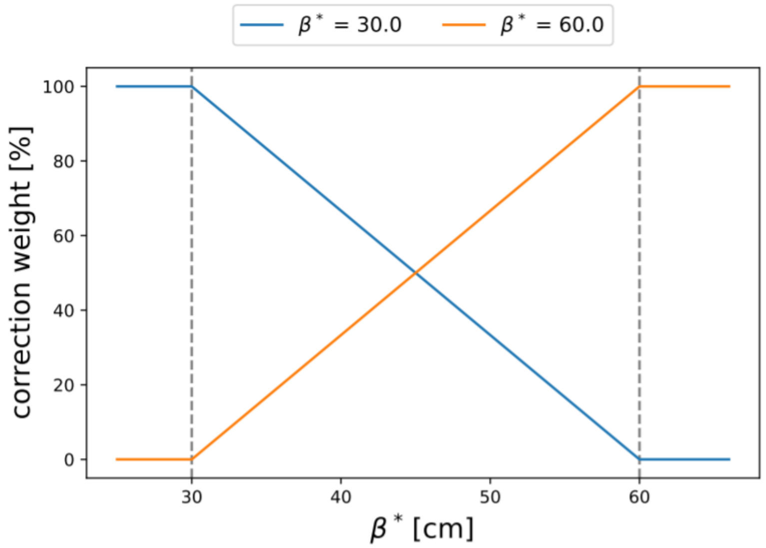
Re-iterate non-linear corrections

Global Corrections

Time

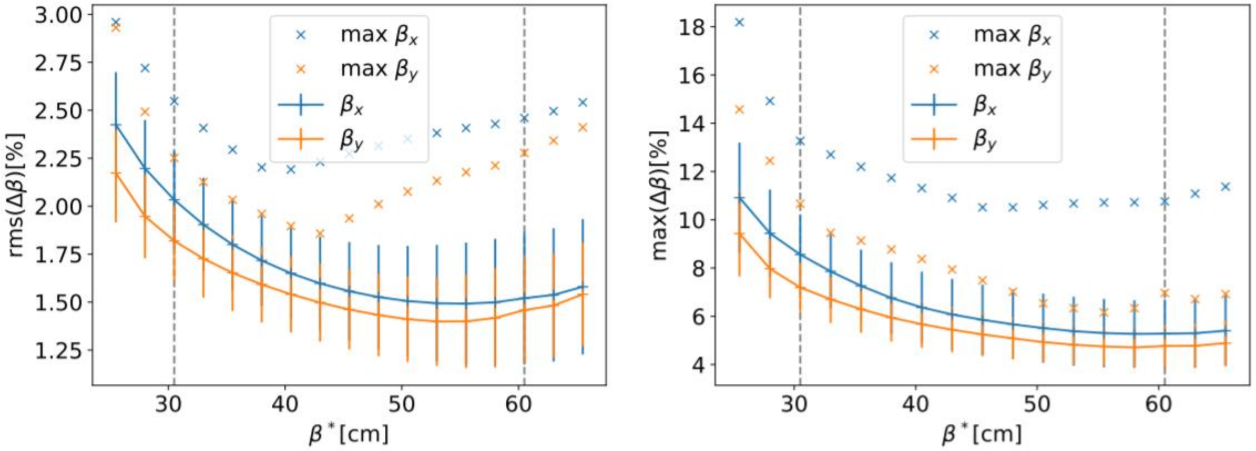
Optics corrections from 60 cm to 30 cm

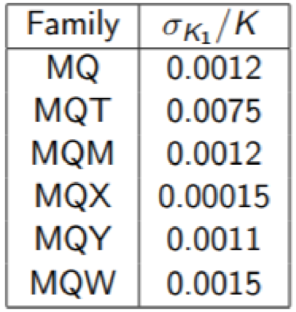
- We need 60cm-30cm be well corrected for
  - Machine protection
  - Deliver design luminosity to ATLAS and CMS
- Simulations showed that only correcting 1 optics is not sufficient
  - Propose to correct at 60 cm and 30 cm



60cm-30cm (Simulation)

- 50 seeds with errors corresponding to what we expect after local corrections





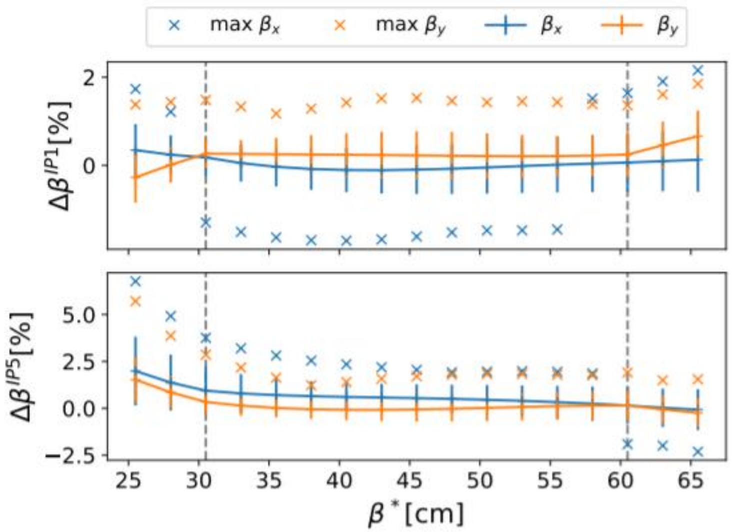
Family	σ_{K_1}/K
MQ	0.0012
MQT	0.0075
MQM	0.0012
MQX	0.00015
MQY	0.0011
MQW	0.0015

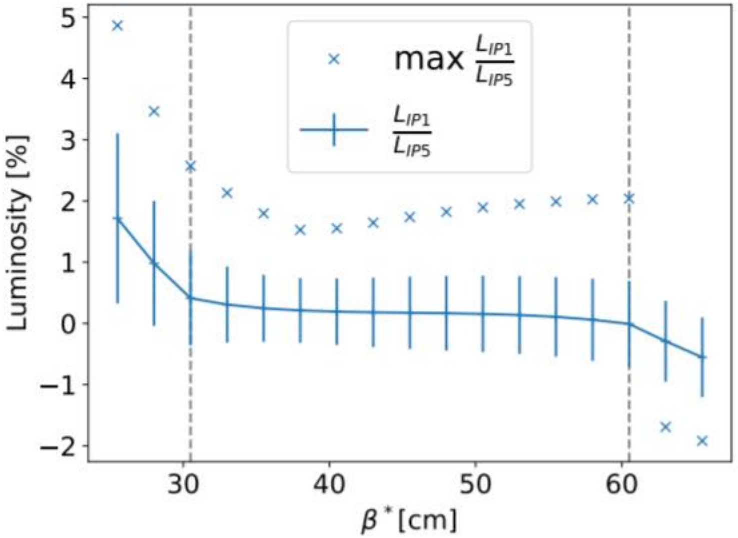
- All of the seeds are corrected within machine protection tolerance between 60 cm and 30 cm
- A few seeds are too large at 25cm assuming no additional corrections
  - In Run 2 we didn't recorrect at 25 cm and still well within machine protection requirements

E. Høydalsvik

60cm-30cm (Simulation)

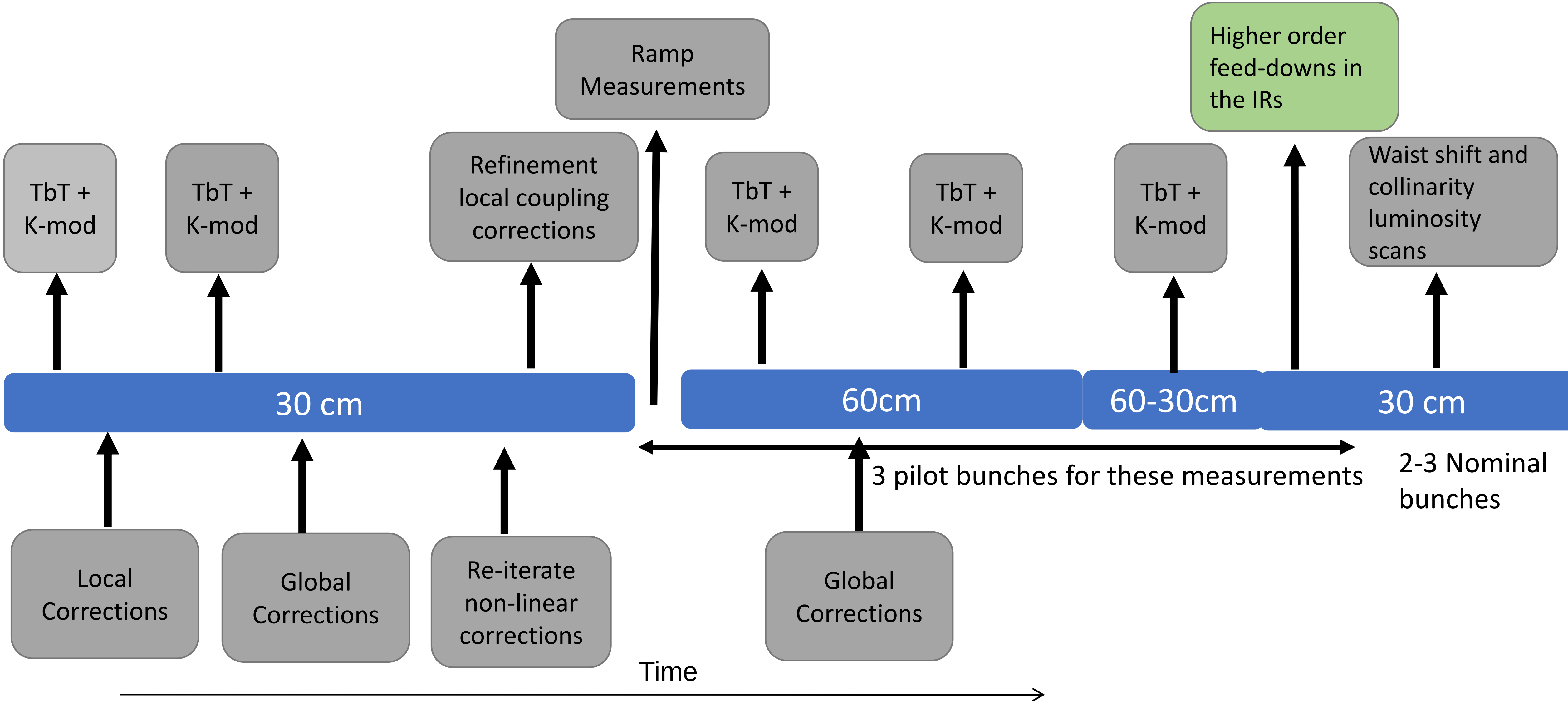
- Luminosity imbalance between ATLAS and CMS < 1 % for most seeds
  - Around 2 % for the worst seed



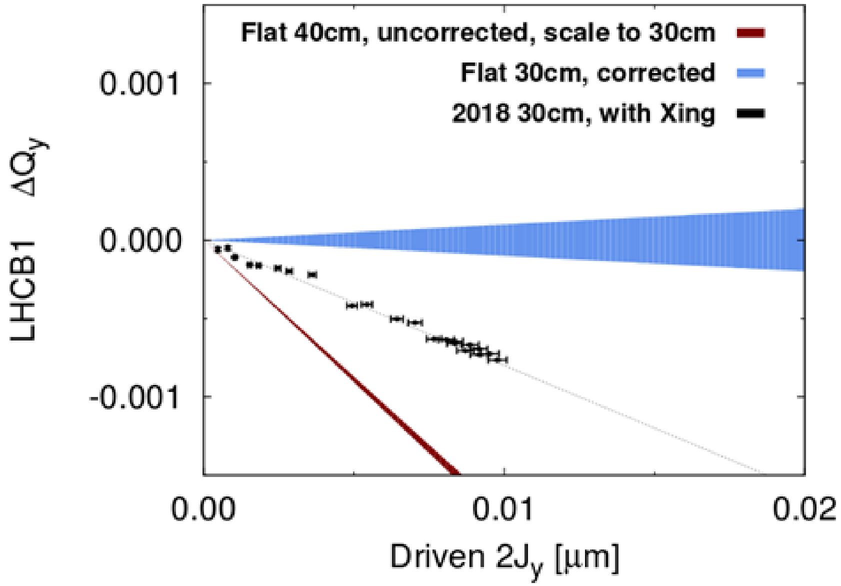


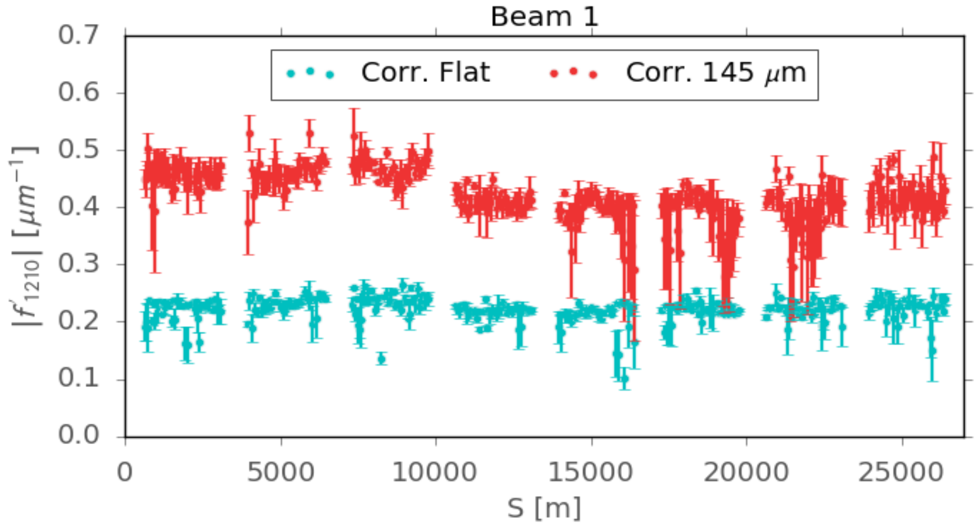
E. Høydalsvik

Optics Commissioning strategy 2022



Amplitude detuning with X’ing





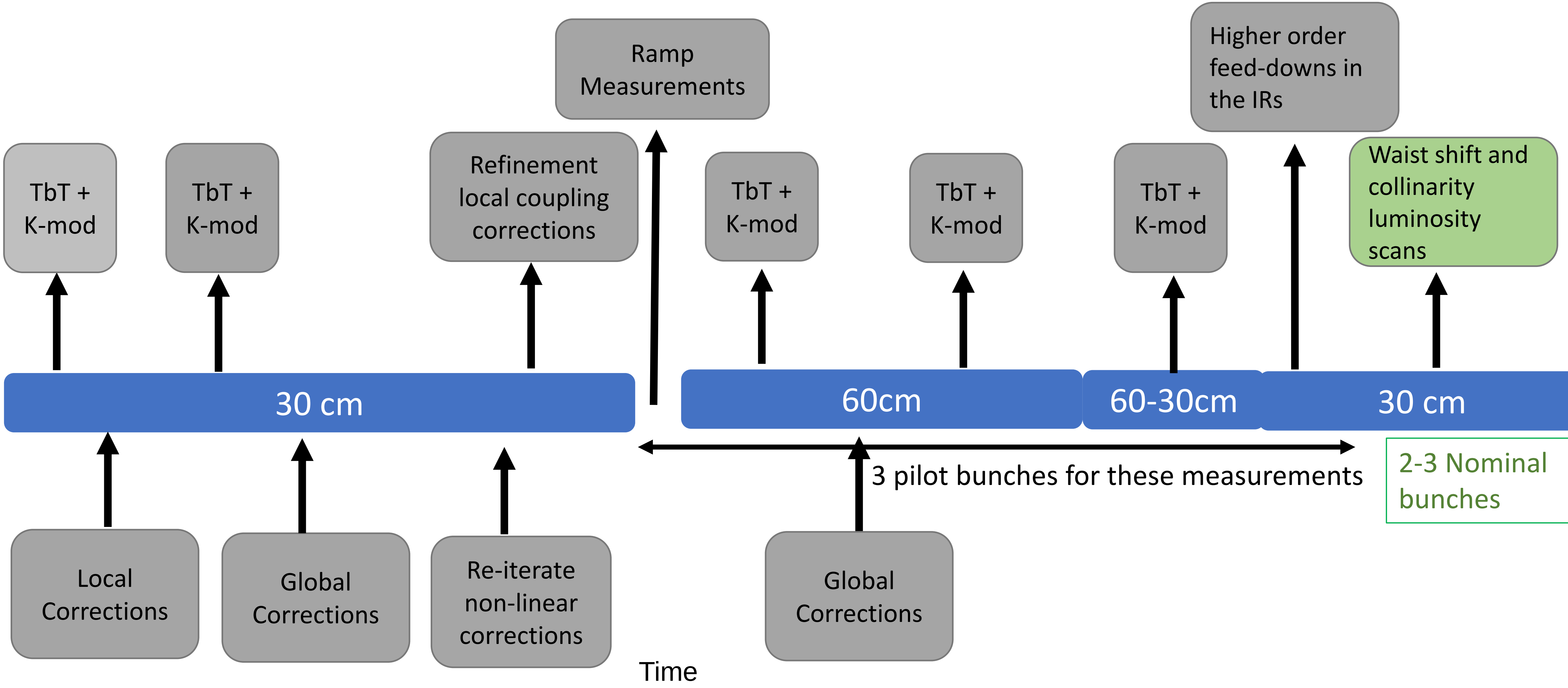
F. Carlier

- The amplitude detuning and the RDTs from a_4 change with the x’ing angle

➔Feed down from decapole and/or dodecapoles!

- Crucial to correct in HL-LHC:
- Getting expereience now would be very valuable for the future!

Optics Commissioning strategy 2022



TbT +
K-mod

TbT +
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Refinement
local coupling
corrections

Ramp
Measurements

TbT +
K-mod

TbT +
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TbT +
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Higher order
feed-downs in
the IRs

Waist shift and
collinarity
luminosity
scans

30 cm

60cm

60-30cm

30 cm

3 pilot bunches for these measurements

2-3 Nominal
bunches

Local
Corrections

Global
Corrections

Re-iterate
non-linear
corrections

Global
Corrections

Time

Scans with luminosity

- Nominal bunches colliding in IP1 and IP5
  - Scanning dedicated waist shifts knobs
  - Tested in MD, but time-consuming
    - -> Only planes and beams where we have suspicion something could be wrong
  - Scan the collinearity knob in IR1 and IR5 for validation of the local coupling corrections

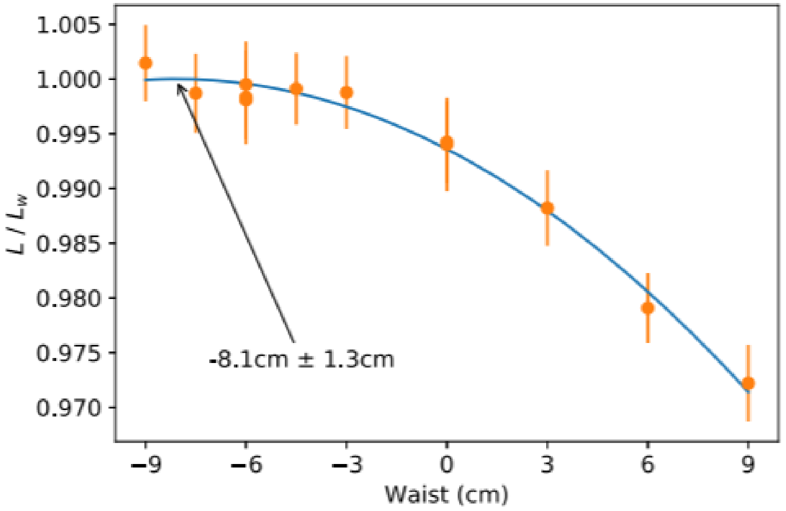


FIG. 14. Luminosity scan of Beam 1 on the vertical plane.

J. Coello et al, ``New local optics measurements and correction techniques for the LHC and its luminosity upgrade''

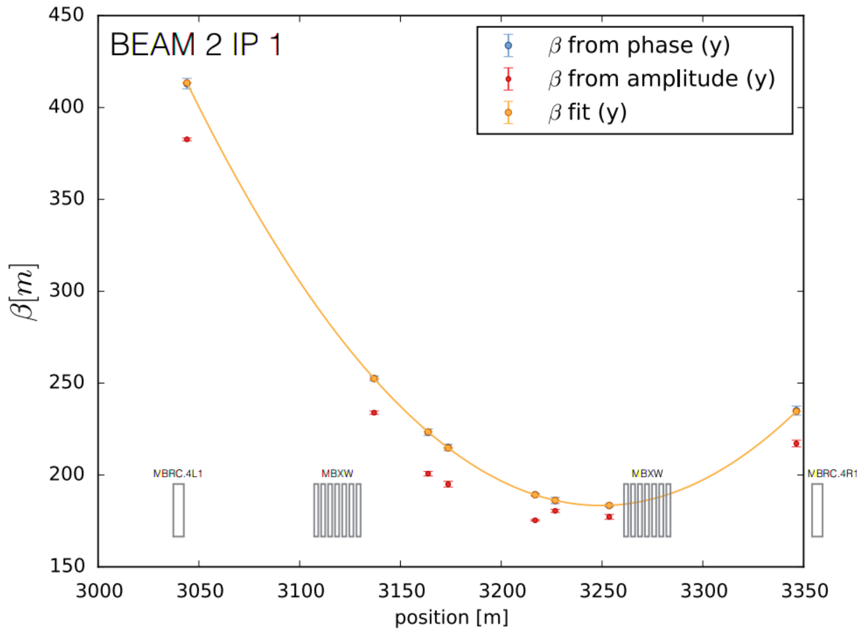
Summary Ramp + Squeezed

Shift	Activities	Time
Local correction	1. Measuring the local errors in the IR	6h
Global Corrections	1. Global corrections 2. Refine Local coupling 3. Refine non-linear	20h
Ramp + 60-30 cm	1. Measure the ramp 2. Correct at 60cm 3. Measure down to 30 cm	8h
Higher order Feed-down	1. X’ing angle scans with amplitude detuning	8h
Luminosity scans	1. Vary the collinearity knob and waist shift and optimize the luminosity	8 h
Total		**50h**

Calibration optics

Ballistic Optics

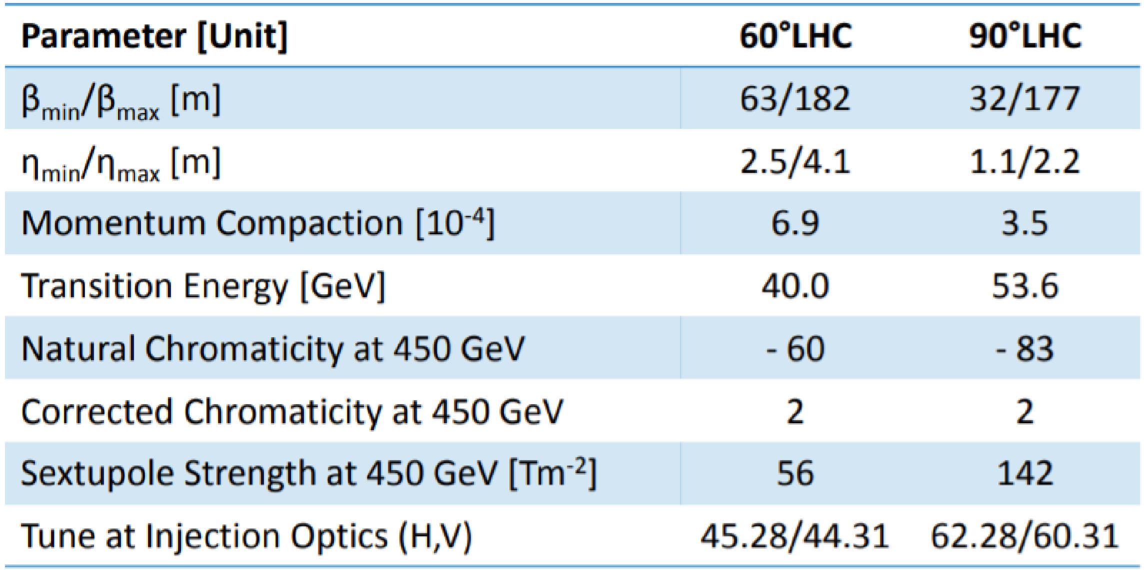
- Can reconstruct the β at a BPM and propagate it to the IP
  - Needs very precise calibration of the BPMs
- We can use the β reconstruction from phase to compare with what we get from β from amplitude, and then use this to calibrate BPMs relative to the arc BPMs
- Also ballistic for IR4
  - Turning off Q5 there which could help calibration of in instruments in that area



A. García-Tabarés Valdivieso

60 deg phase advance optics

- Would be a different optics with different settings
  - Helps in identifying underlying alignment and magnetic errors
  - In particular, the momentum compaction factor is different



Parameter [Unit]	**60°LHC**	**90°LHC**
β_{min}/β_{max} [m]	63/182	32/177
η_{min}/η_{max} [m]	2.5/4.1	1.1/2.2
Momentum Compaction [10^{-4}]	6.9	3.5
Transition Energy [GeV]	40.0	53.6
Natural Chromaticity at 450 GeV	- 60	- 83
Corrected Chromaticity at 450 GeV	2	2
Sextupole Strength at 450 GeV [Tm^{-2}]	56	142
Tune at Injection Optics (H,V)	45.28/44.31	62.28/60.31

J. Keintzel

Mom. Comp. Factor Measurements

- Fit of relative energy (momentum) offset over frequency
- Problem: no device in LHC to measure energy → Use TbT measurements

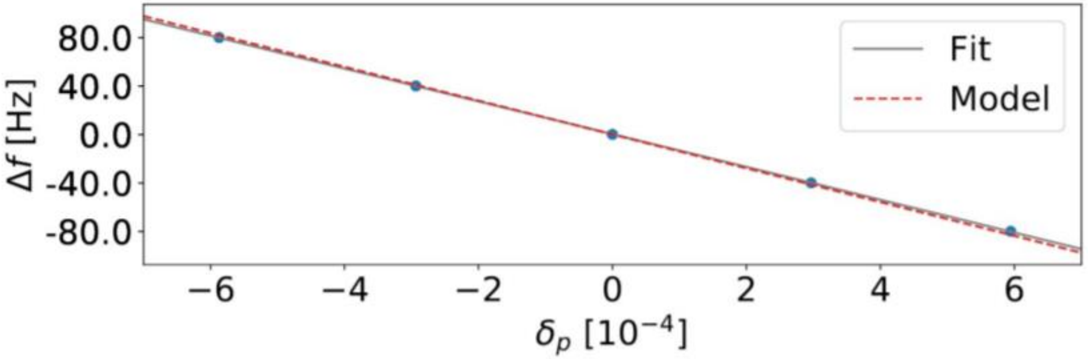
$$\delta_p = \frac{\langle \eta_x^{\mathrm{mdl}} CO_x \rangle}{\langle (\eta_x^{\mathrm{mdl}})^2 \rangle}$$

Measured closed orbit and model dispersion at arc BPMs

- Fit using

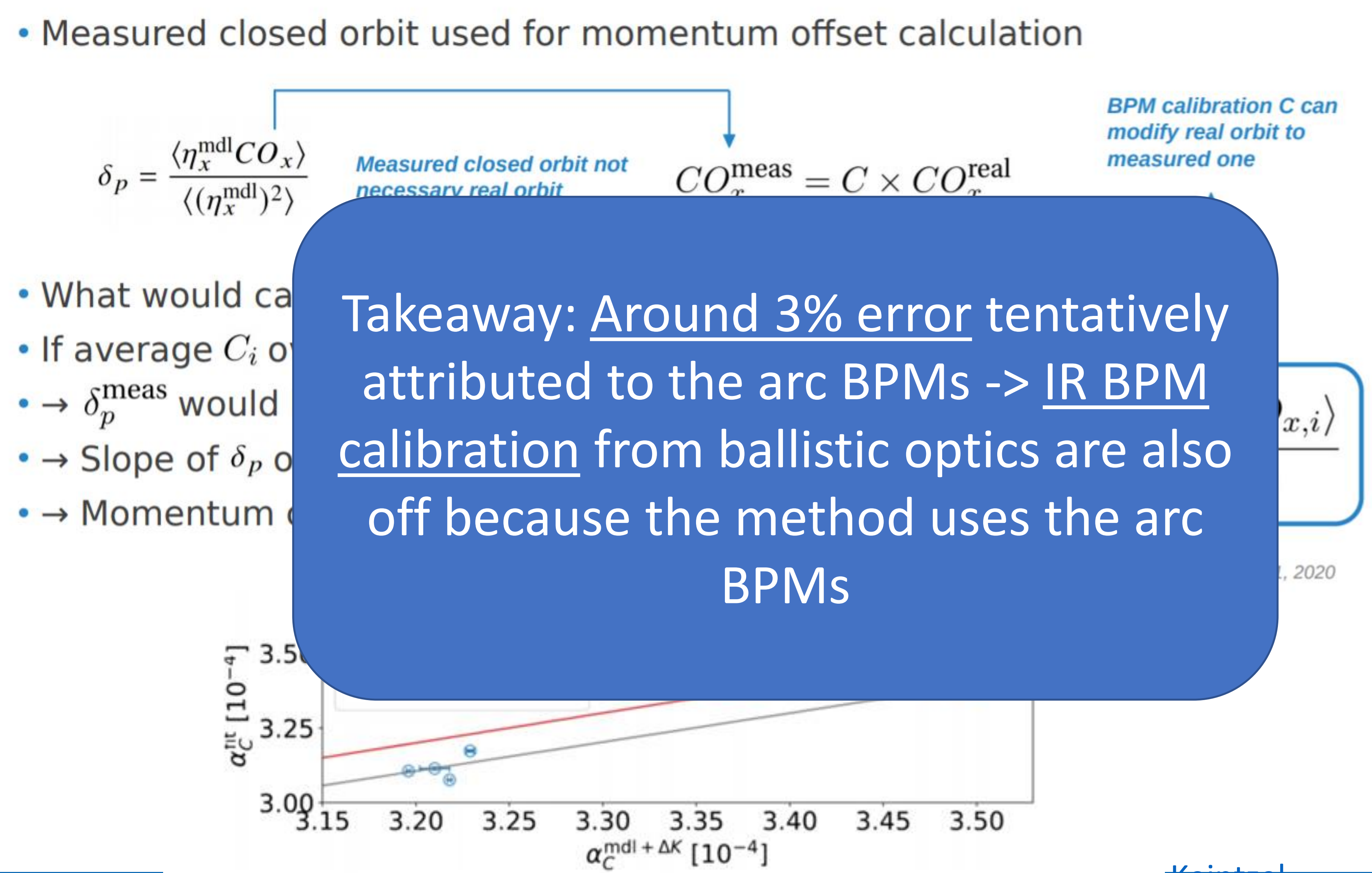
$$\delta_p = -\left(\frac{1}{\gamma_{\mathrm{rel}}^{-2} + \alpha_C}\right)\frac{\Delta f}{f}$$

E = 6.5 TeV and therefore the relativistic gamma is negligible



Relative error between measurement and model about ***-3 %***

Beam Position Monitor Errors



- Measured closed orbit used for momentum offset calculation

$$\delta_p = \frac{\langle \eta_x^{\text{mdl}} CO_x \rangle}{\langle (\eta_x^{\text{mdl}})^2 \rangle}$$

Measured closed orbit not necessary real orbit

$$CO_x^{\text{meas}} = C \times CO_x^{\text{real}}$$

BPM calibration C can modify real orbit to measured one

- What would ca
- If average C_i o
- → δ_p^{meas} would
- → Slope of δ_p o
- → Momentum

$x,i\rangle$

, 2020

Takeaway: Around 3% error tentatively attributed to the arc BPMs -> IR BPM calibration from ballistic optics are also off because the method uses the arc BPMs

Keintzel

Summary: calibration optics

- Measuring these optics would provide insight in BPM calibrations and offsets in the IR
  - Indirectly provide an additional measurement of the β-functions at the IP

Type	Hours
Ballistic optics	8 hours
60 deg phase advance	12 hour
Total	**20 hours**

Total time estimates

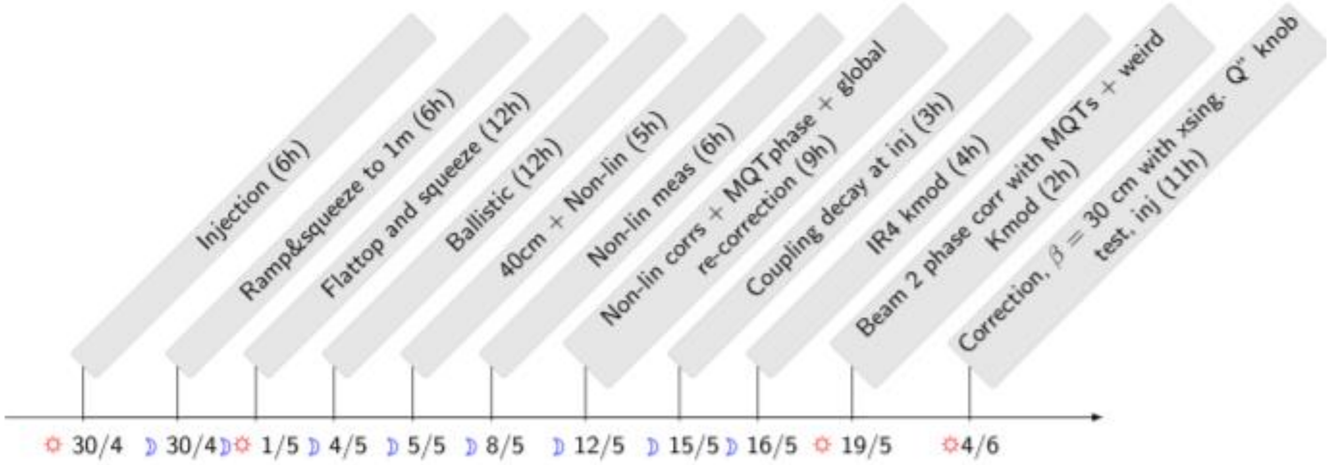
Type	Hours
Injection	8 hours
Squeezed	48 hours
Calibration optics	20 hours
Total	**76 hours**

- Comparable in terms of time to a normal commissioning in Run 2 (2017 was 76 hours!)
    - The time estimates are based on the assumption that all systems are functional

Conclusion

- The beam tested provided valuable input and enabled us to identify the swapped RQTL7.L3 B1/B2
- The validity of the linear and non-linear corrections used in Run 2 remains to be tested
  - The more surprises the more challenging and time consuming calculating corrections will be
- Measuring the ballistic and the 60 deg phase advance optics would be important for understanding the calibration of the BPMs
- A very challenging but also very interesting time ahead for the Optics Measurements and Corrections in the LHC!

Commissioning 2017…



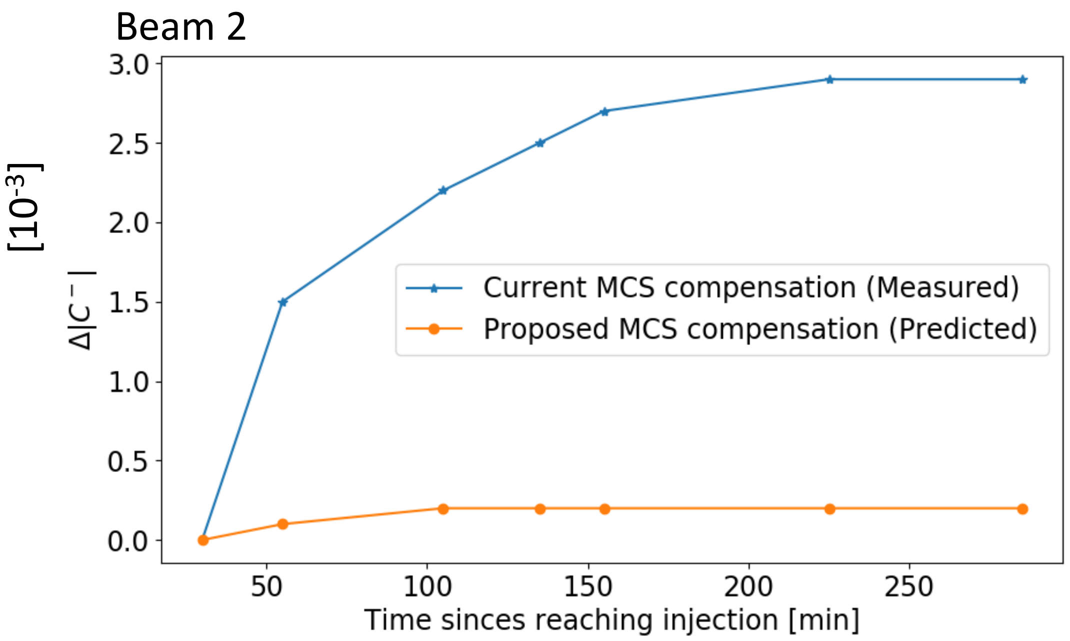
- **3 new optics commissioned**
- **11 shifts (3-days 8-nights)**
- **76 hours of measurements**

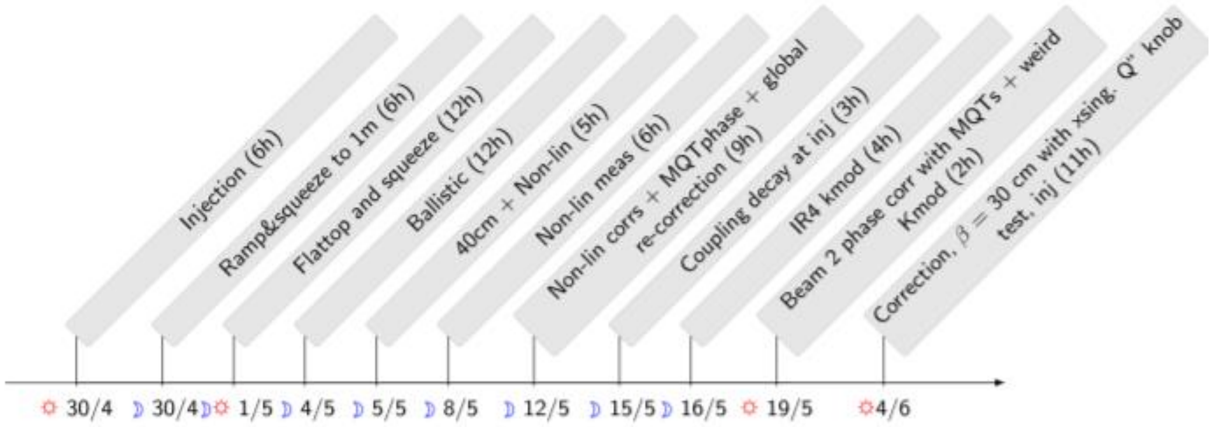
So the OMC-team is ready for both day and night shifts in 2022!

Backup

Counteracting the coupling decay at injection

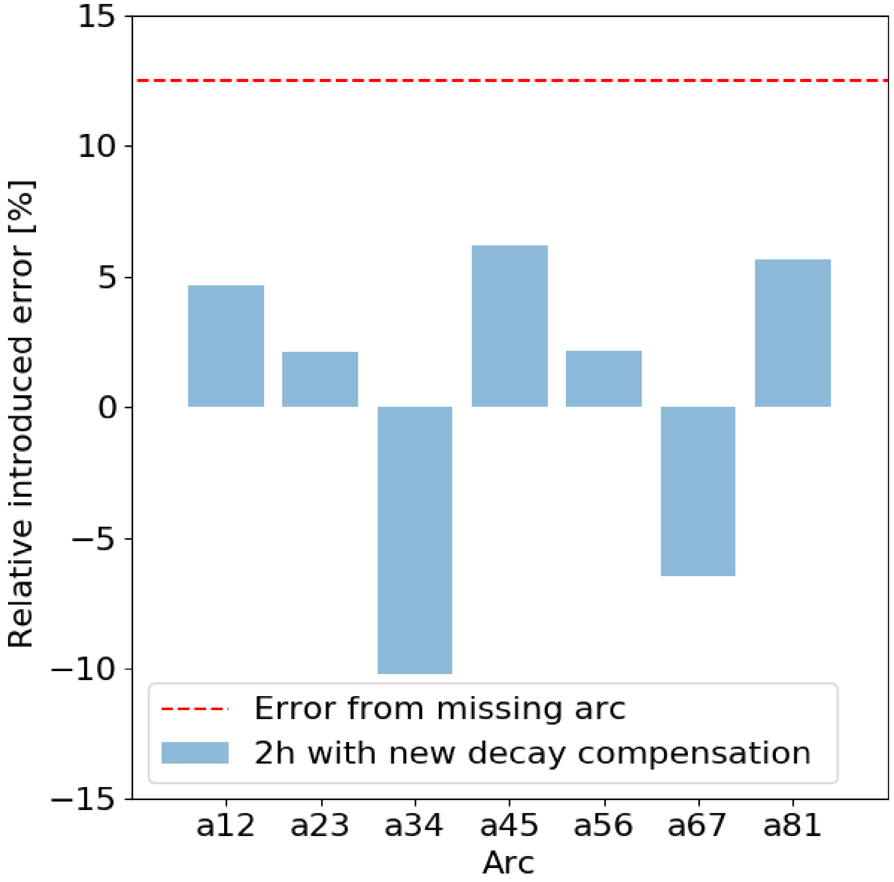
- The coupling decay is linked to the powering of the MCS (b3-spool pieces)
  - By powering them differently (dynamic part)
    - Mitigate the coupling decay
    - Still compensating the chromaticity decay



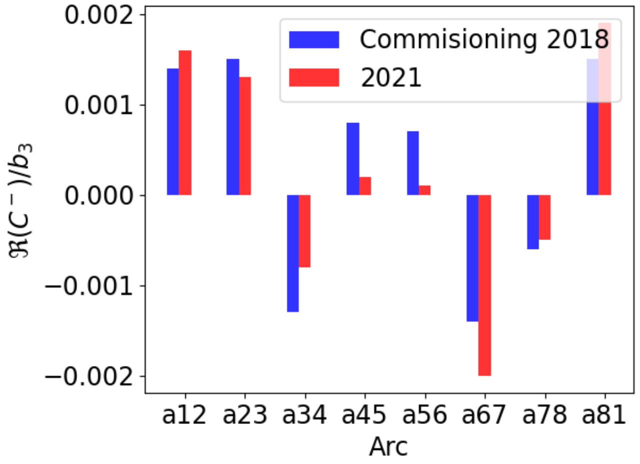


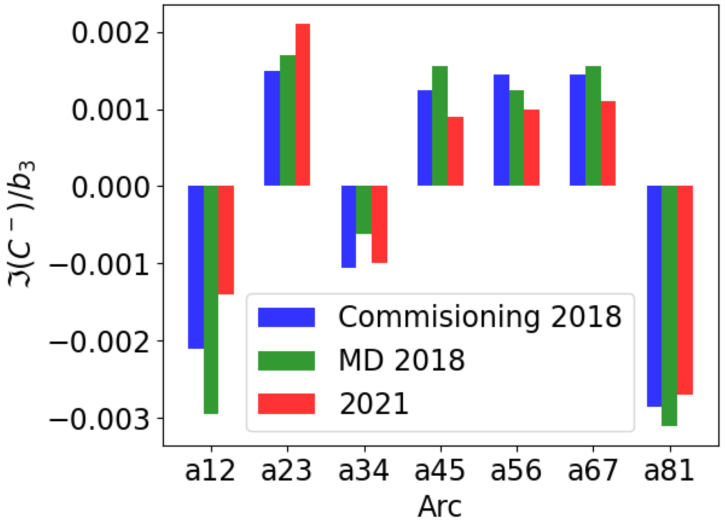
- **3 new optics commissioned**
- **11 shifts (3-days, 8-nights)**
- **76 hours of measurements**

Proposed MCS correction

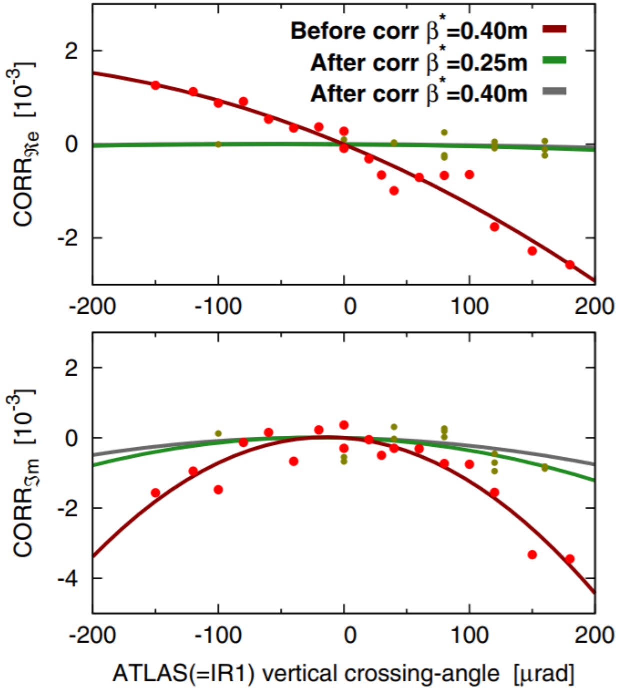


- What is the impact of this ”non local” decay compensation
  - Neglible effect on the Q’’
  - Chromatic β-beating almost identical
  - Smaller difference than the missing arc (a78) in Run II


0.002
0.001
0.000
−0.001
−0.002
$\Re(C^-)/b_3$
Commisioning 2018
2021
a12
a23
a34
a45
a56
a67
a78
a81
Arc

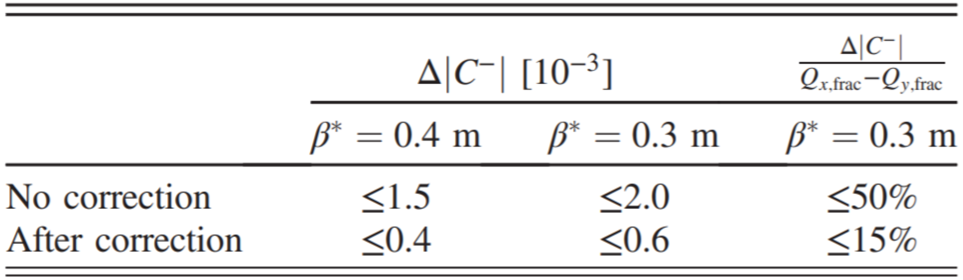

0.002
0.001
0.000
−0.001
−0.002
−0.003
$\Im(C^-)/b_3$
Commisioning 2018
MD 2018
2021
a12
a23
a34
a45
a56
a67
a81
Arc

Can we change the crossing angles to equalize the luminosity? (coupling)



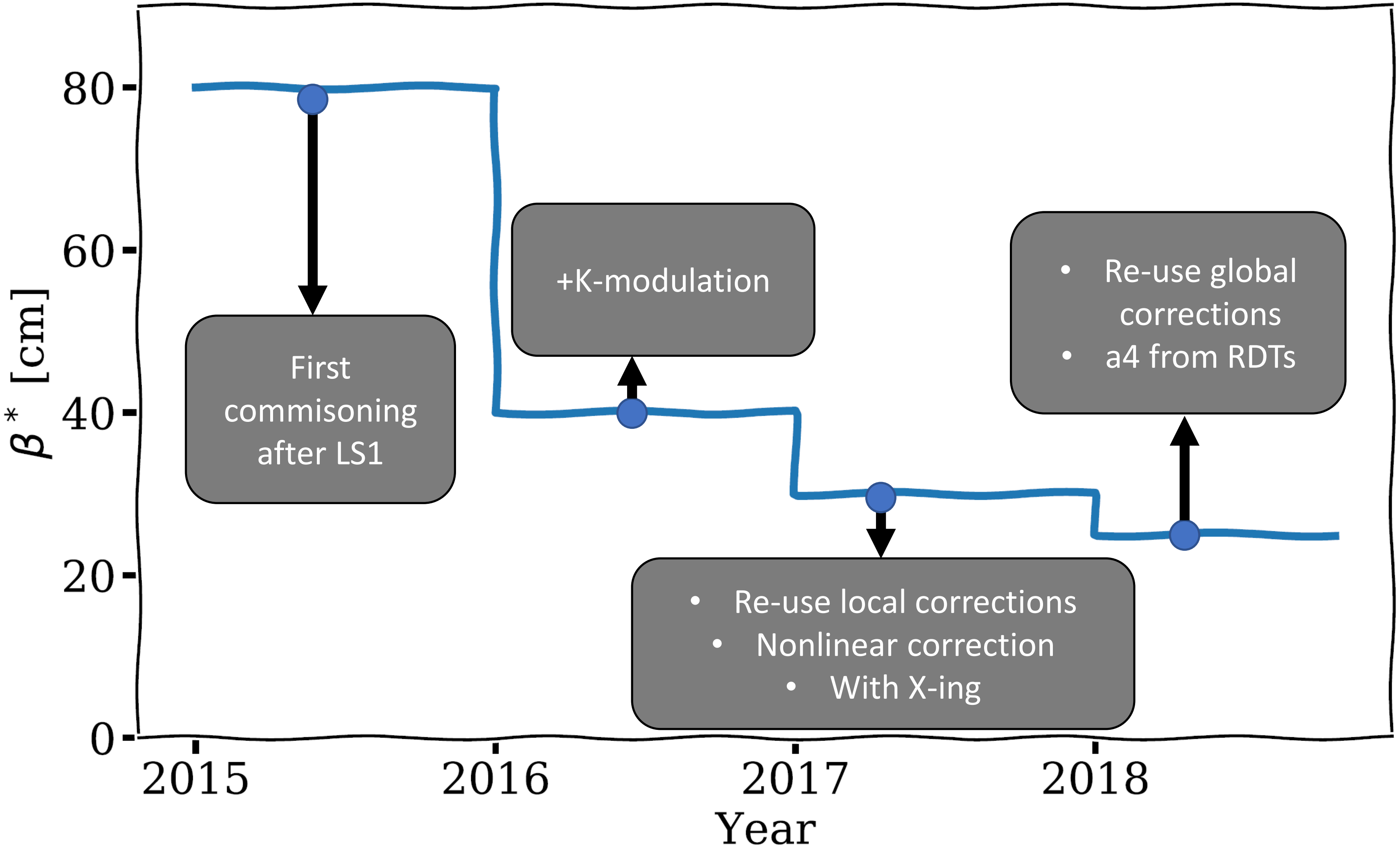
- Even after sextupole correction the feed-down to coupling is still noticeable. For changes in 10 μrad the effect is small.
- A global correction could be applied for every crossing angle to correct if a problem

150 μrad → 100 μrad



	$\Delta\lvert C^-\rvert$ [10^{-3}]		$\frac{\Delta\lvert C^-\rvert}{Q_{x,\mathrm{frac}}-Q_{y,\mathrm{frac}}}$
	$\beta^* = 0.4$ m	$\beta^* = 0.3$ m	$\beta^* = 0.3$ m
No correction	≤ 1.5	≤ 2.0	$\leq 50\%$
After correction	≤ 0.4	≤ 0.6	$\leq 15\%$

Overview of the proton commisoning in Run 2



First commisoning after LS1

+K-modulation

- Re-use local corrections
- Nonlinear correction
- With X-ing

- Re-use global corrections
- a4 from RDTs