Chromatic effects due to off-momentum operation for p-Pb at 4 *Z* TeV

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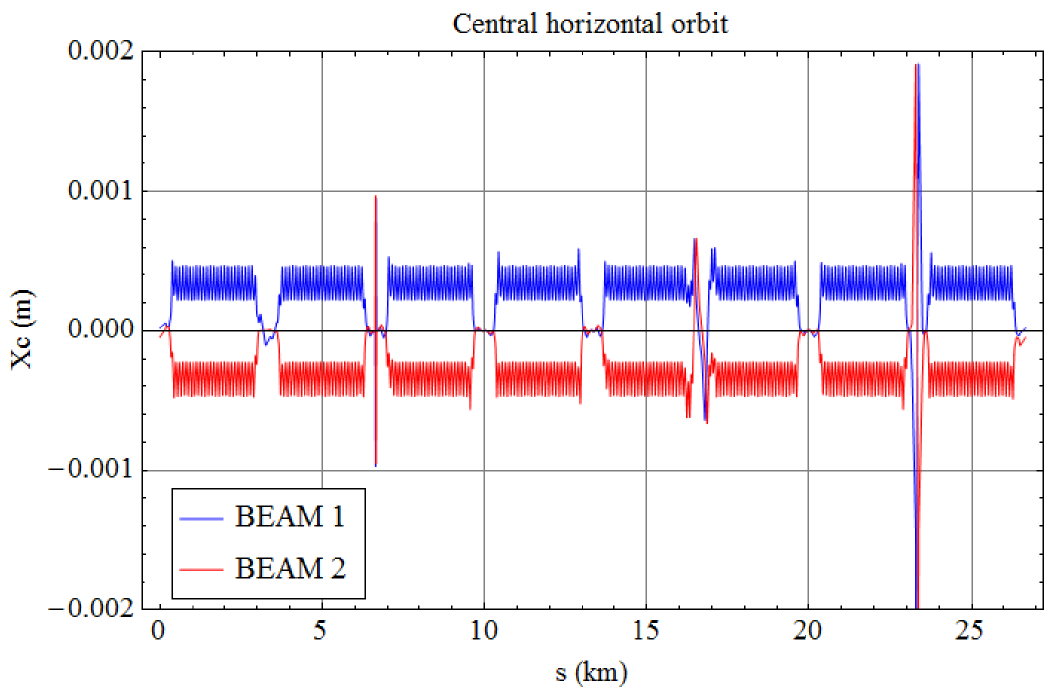
Introduction

p-Pb operation at 4 *Z* TeV implies colliding beams off-momentum because of the non equal revolution frequencies. So far equivalent and opposite shifts have been considered:

$$\delta = \pm 2.3 \times 10^{-4} \text{ at } 4\ Z \text{ TeV}$$

leading to ~ 0.5 mm maximum orbit shift in the arcs (s = 0 is IP6):



Introduction

- Most important effect of the horizontal orbit shift is the focusing errors, referred to as intrinsic beta-beating $\Delta\beta/\beta$, to be superimposed to beta-beating due to field errors and misalignments,

- Off-momentum operation also impacts on the tune Q and the chromaticity ξ.

- Outline :

I- Influence of β^* on $\Delta\beta/\beta$

II- Analytical approach for $\Delta\beta/\beta$ correction

III- Application to the squeeze

IV- Chromaticity compensation

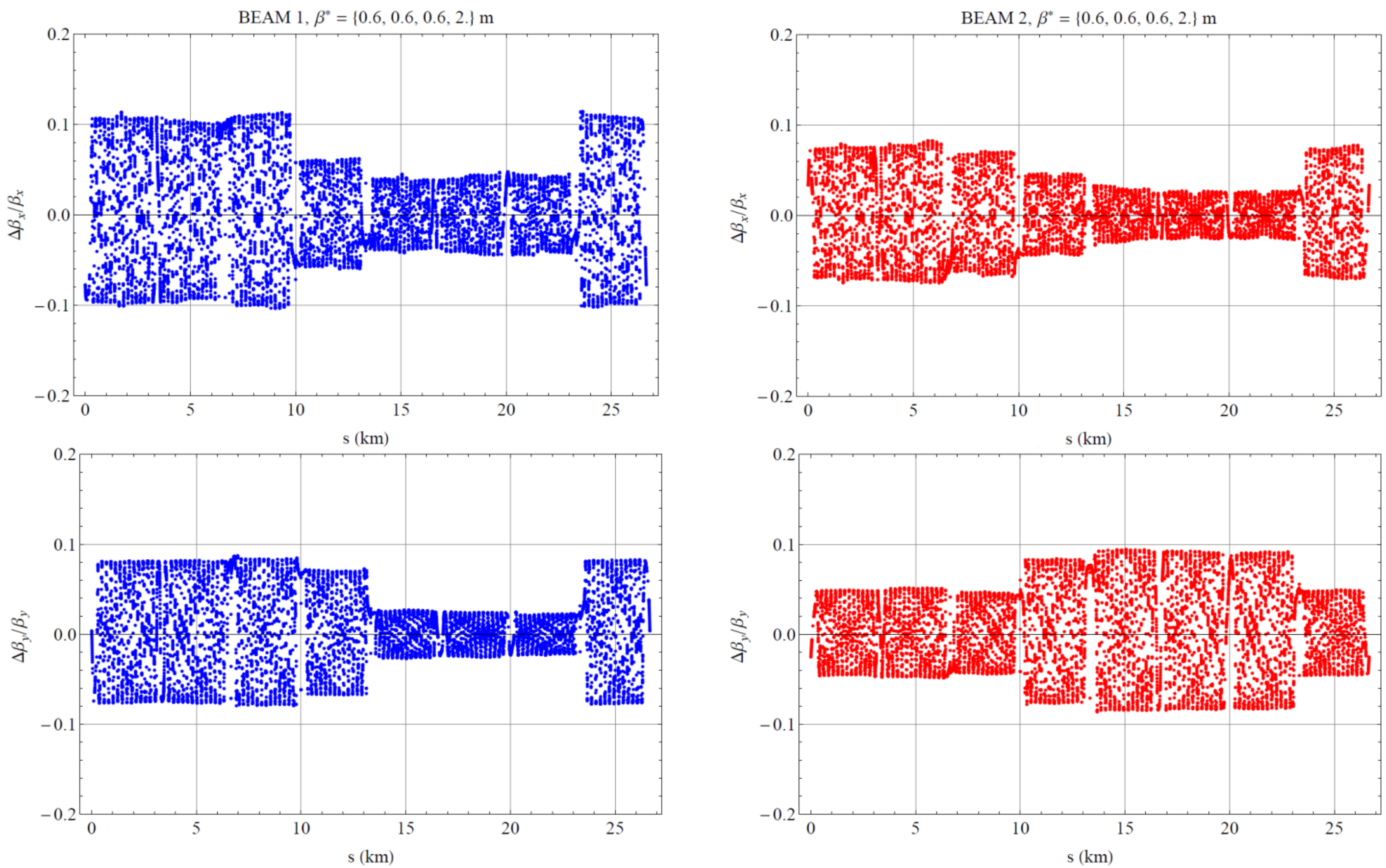
V- Effects of octupoles

I- Influence of β* on Δβ/β (1/2)

Δβ/β calculated from MADX TWISS, for

- β*(IP1, IP2, IP5, IP8) = (0.6, 0.6, 0.6, 2.0) m,
- δ = ± 2.3 x 10^{-4} depending on the beam.

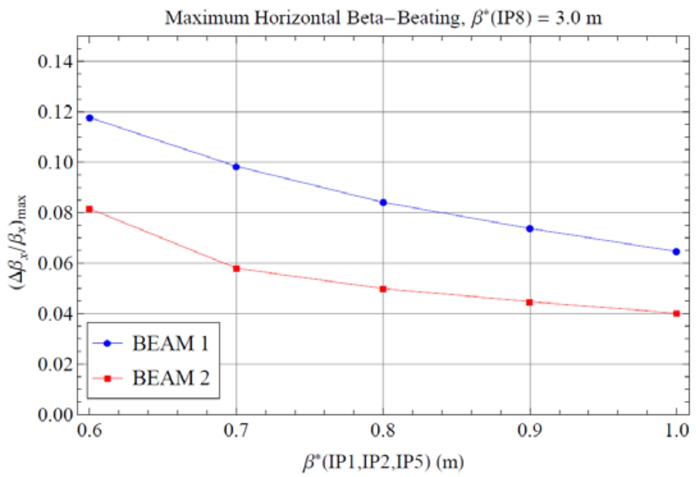
=> ~12 % max. intrinsic beta-beating

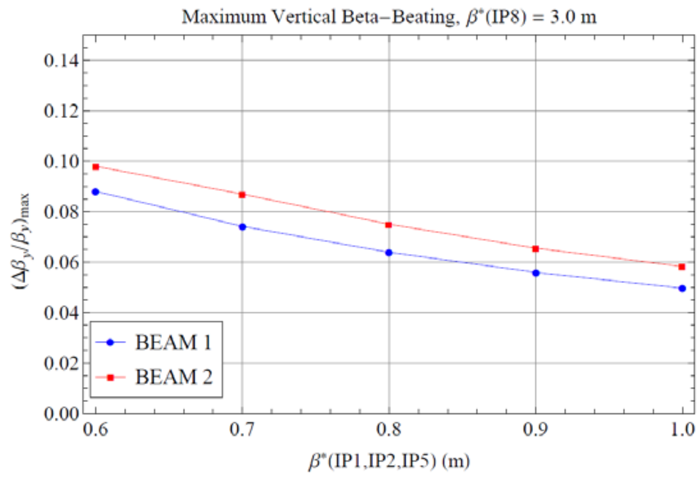


s = 0 is IP6

I- Influence of β* on Δβ/β (2/2)

- Δβ/β is reduced for higher β* at IP1, IP2, IP5, keeping the same shape:





- $(\Delta\beta/\beta)_{max}$ ratio for β* = 0.8 m vs β* = 0.6 m:
  About 30% less beta-beating at 0.8 m (av.)

B1, H	B1, V	B2, H	B2, V
0.72	0.73	0.61	0.77

- Maximum Δβ/β for β*(IP8) = 3.0 m vs 2.0 m, for β*(IP1, IP2, IP5) = 0.6 m:
  max. 0.4% for B2 V
  -> reducing β*(IP8) from
  3.0 m to 2.0 m has a
  small impact on Δβ/β.

β*(IP8) (m)	B1, H	B1, V	B2, H	B2, V
3.0	12.07 %	8.90%	8.16 %	9.81 %
2.0	12.32 %	8.93 %	8.27 %	9.43 %

II- Analytical approach for Δβ/β correction (1/4)

- Δβ/β can be calculated analytically for a momentum offset δ :

$$\frac{\Delta\beta}{\beta}(s_0) = -\frac{\delta}{2\pi \sin Q}\sum_{quads} \beta\, K1L \cos[2\,(|\varphi - \varphi(s_0)| + 2\pi Q)]$$
$$+ \frac{\delta}{2\pi \sin Q}\sum_{sextus} \beta\, K2L\, D_x \cos[2\,(|\varphi - \varphi(s_0)| + 2\pi Q)]$$

- Assuming $K1_n L_n = K1_n L_n + \Delta K1_n L_n$, for the n^{th} quadrupole, we can solve $\frac{\Delta\beta}{\beta}(s_0, \delta) = 0$ for $\Delta K1_n$,
- From $\Delta Q = \frac{1}{4\pi}\sum_{n=1}^{N_q} \beta \Delta K1L$, with N_q the number of correctors, we add a constraint to the system to minimize the impact on the tune,
- Finally we search $\Delta K1_n$ minimizing the following quantity (SVD method, Mathematica):

$$\begin{bmatrix} \Delta\beta/\beta_1 \\ \vdots \\ \Delta\beta/\beta_{N_M} \\ 0 \end{bmatrix} + \begin{bmatrix} c_{11} & \cdots & c_{1\,N_q} \\ \vdots & \ddots & \vdots \\ c_{N_M 1} & \cdots & c_{N_M N_q} \\ c_{Q1} & \cdots & c_{QN_q} \end{bmatrix} \cdot \begin{bmatrix} \Delta K1_1 \\ \vdots \\ \Delta K1_{N_q} \end{bmatrix}$$

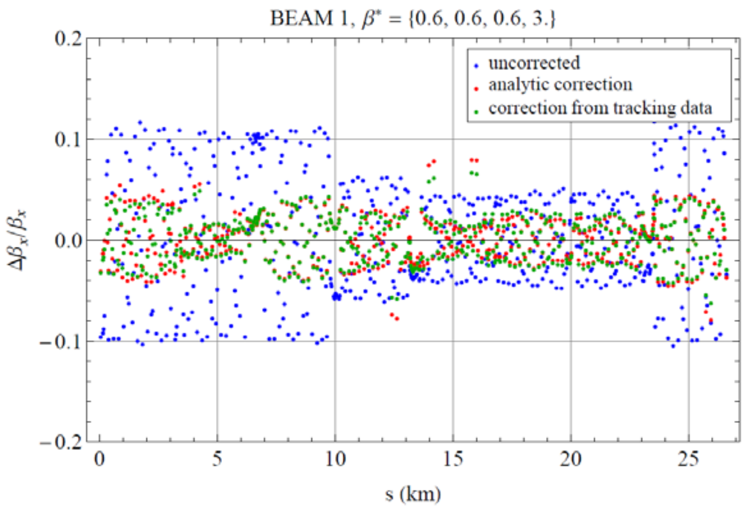
with N_M observation locations (i.e. No. of BPMs for example), and N_q matching quadrupoles.

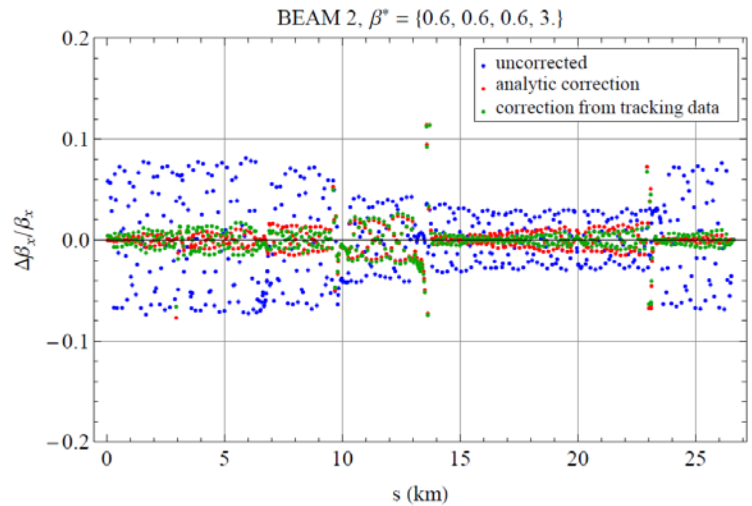
II- Analytical approach for $\Delta\beta/\beta$ correction (2/4)

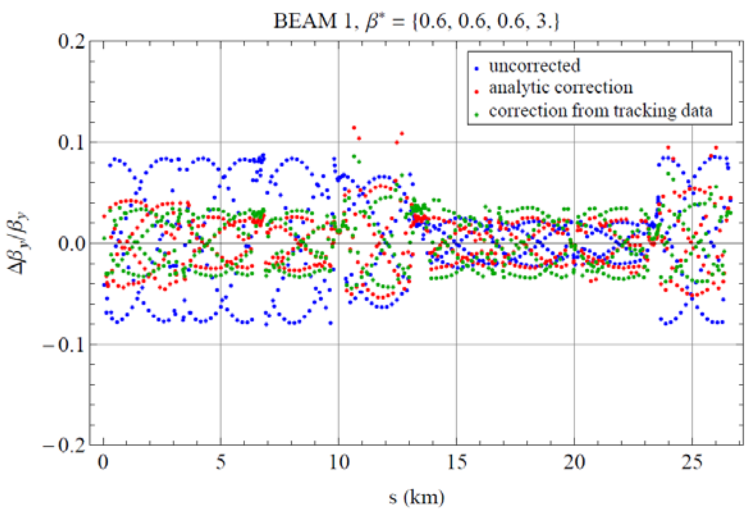
- Similar method as R. Tomás *et al.* GUI software using a PTC tracking, but :
  - $\Delta\beta/\beta$ is derived from the analytical expression => no tracking, focus on the first order,
  - Correction is calculated using of the β-function, not φ, implying the special care for the tune,
  - Chromaticity correction is implemented in the process before $\Delta\beta/\beta$ correction for off-momentum beams, and after.
- Both approaches are compared for β*(IP1, IP2, IP5, IP8) = (0.6, 0.6, 0.6, 3.0) m.
  - Only correctors with separated powering for B1 and B2 are selected: MQM, MQT, MQTL, MQY,
  - Only the non zero strengths given by the software are used in the calculation to use same correctors and limit their amount.

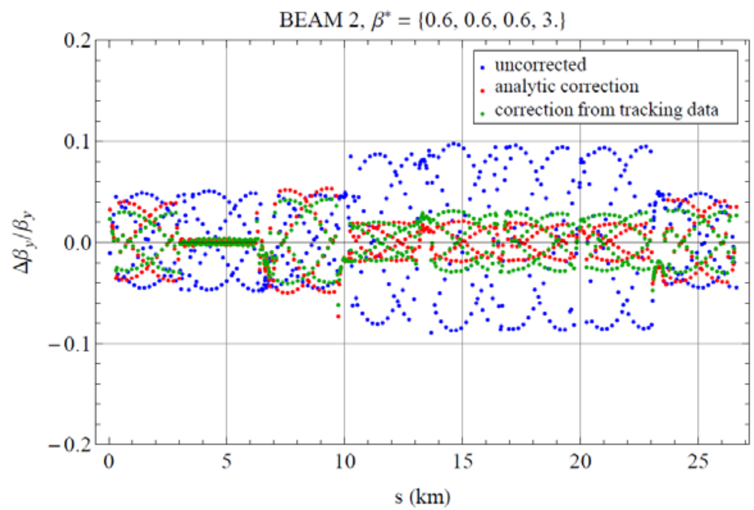
II- Analytical approach for Δβ/β correction (3/4)

- Results, Δβ/β at the BPMs as calculated by MADX (s = 0 is IP6)

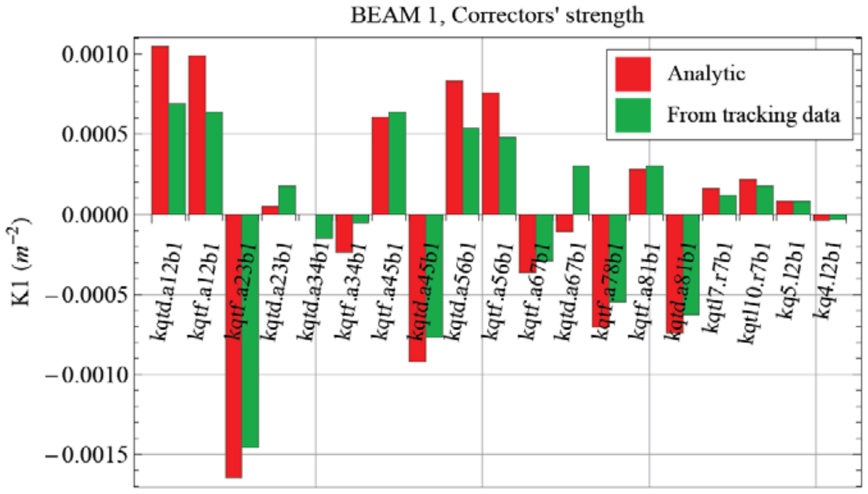


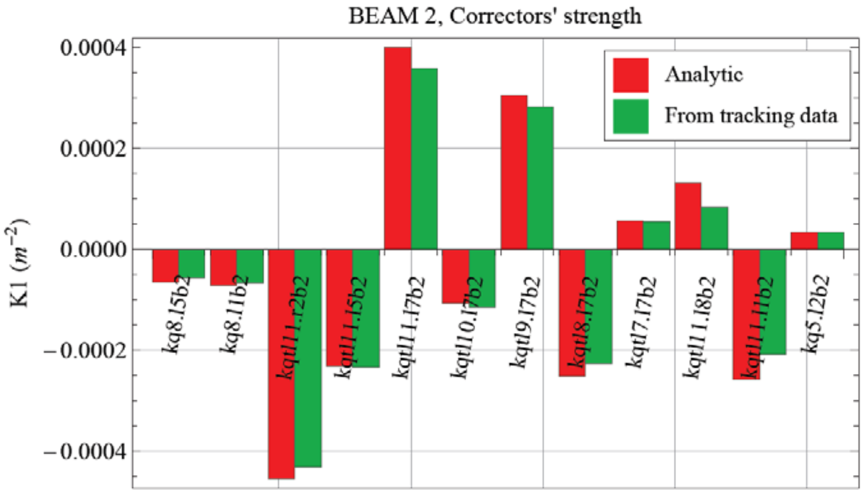






II- Analytical approach for Δβ/β correction (4/4)

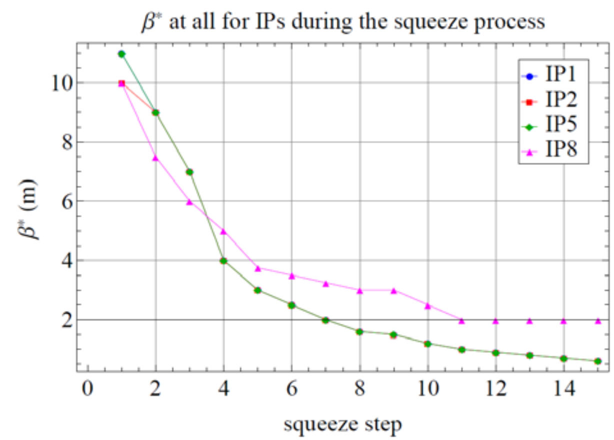


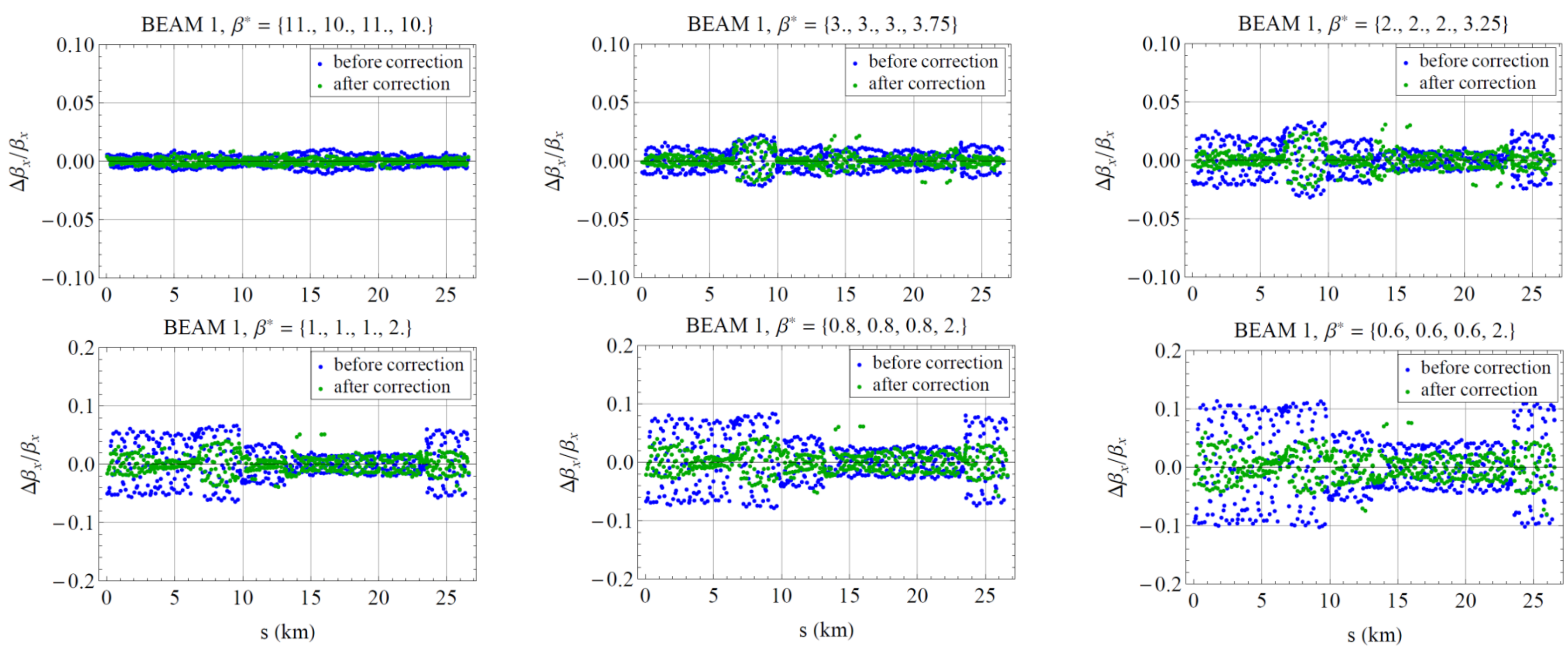


- More correctors are needed for B1 as there was more beta-beating in x-plane,
- Results are very similar for both methods, validating the analytical approach,
- $\Delta Q < 1 \times 10^{-3}$,
- Correction can be even better without the constraint on the tune, but then $\Delta Q \sim 10^{-2}$ while the tolerance is 2.5×10^{-3} .

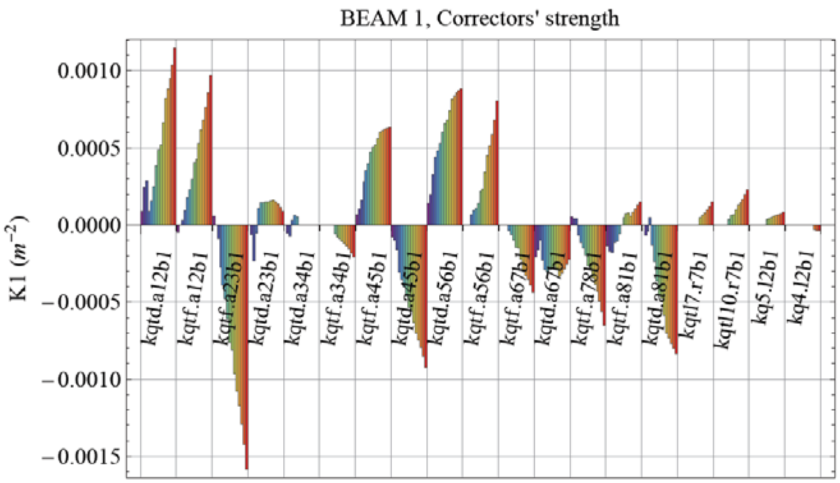
III- Application to the squeeze (1/2)

- New squeeze procedure : β* is decreased down to 0.6 m at IP1/2/5 and to 2.0 m at IP8 simultaneously,
- Δβ/β correction is calculated and applied at each step, limiting the tune perturbation and adjusting the chromaticity to ∼(2,2),
- Correction may not be required for the first steps, but could ease the procedure from about step no. 7 ($\beta^* = (2, 2, 2, 3.25)$).

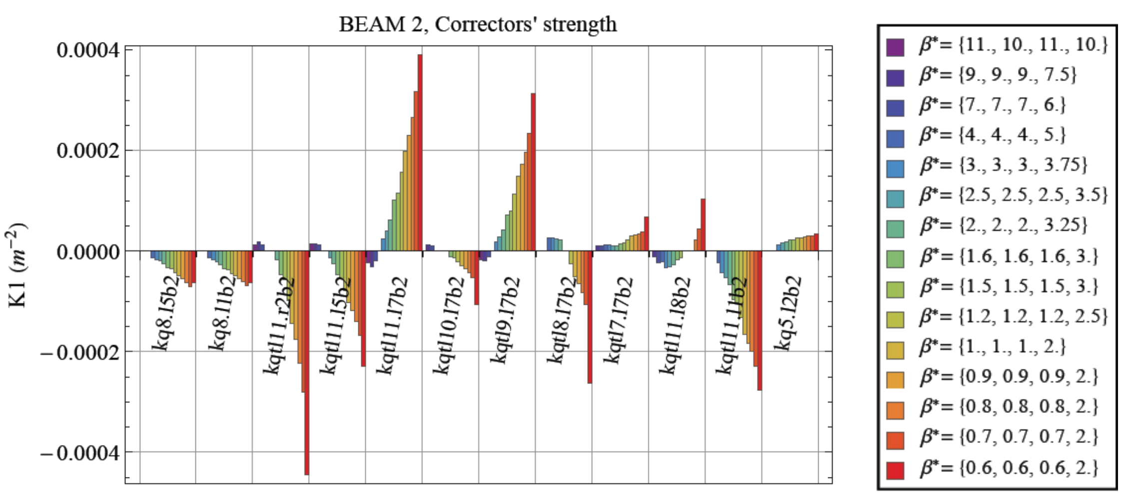




III- Application to the squeeze (2/2)

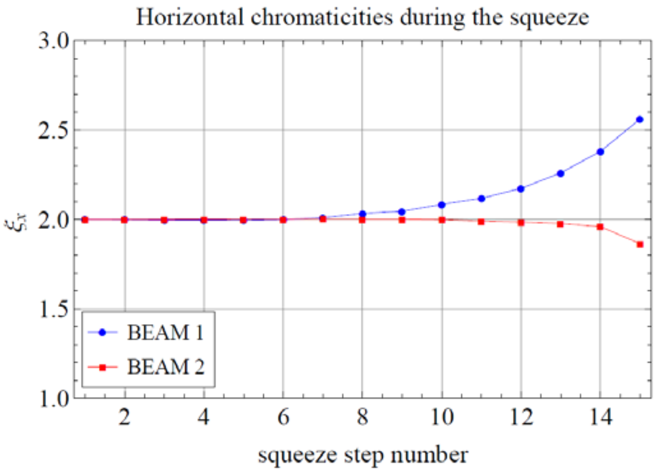


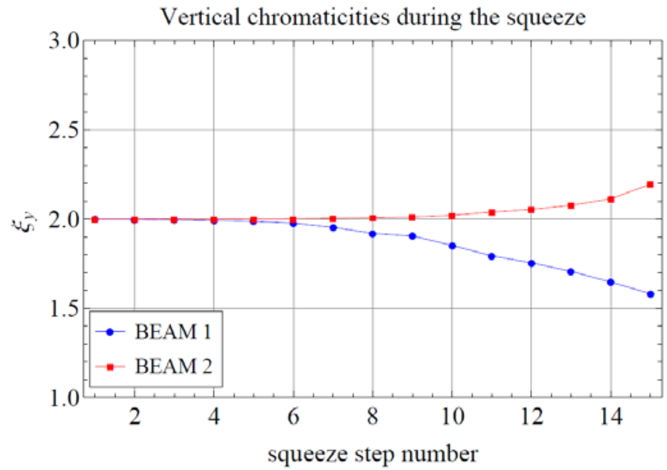
Correction could be implemented in the squeezing procedure as a knob.



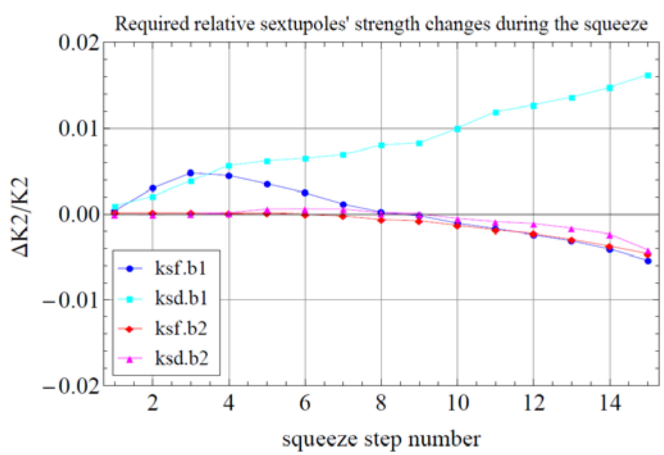
IV- Chromaticity compensation (1/1)

- ξ is matched on-momentum in MADX -> adjusted to ξ(-δ) to get ~2 at +δ and vice-versa, Error gets bigger as intrinsic Δβ/β increases, but still $1.5 < \xi < 2.6$ for β* = 0.6 m (after Δβ/β correction)





- ΔK2 needed after Δβ/β correction is about the opposite of ΔK2 needed off momentum before correction, leading a total relative difference with respect to on-momentum values of ΔK2 /K2 < 2% (would be 0 for perfect correction).



V- Effects of octupoles (1/2)

- Horizontal non zero orbit $\delta.D_x$ in the octupoles leads to ξ and Q shifts and additional $\Delta\beta/\beta$

$$\Delta\xi = \pm\frac{\delta}{4\pi}\sum_{octus}\beta\, K3L\, {D_x}^2$$

$$\Delta Q = \pm\frac{\delta^2}{8\pi}\sum_{octus}\beta\, K3L\, {D_x}^2$$

$$\frac{\Delta\beta}{\beta}(s_0) = \pm\frac{\delta^2}{4\pi\sin Q}\sum_{octus}\beta\, K3L\, {D_x}^2\cos[2\,(|\varphi-\varphi(s_0)|+2\pi Q)]$$

- Given the p-intensity ~$1.1\text{x}10^{10}$ charges, I_{oct} = 50 A or K3 = 2.5 m^{-4} was used, and, depending on the beam

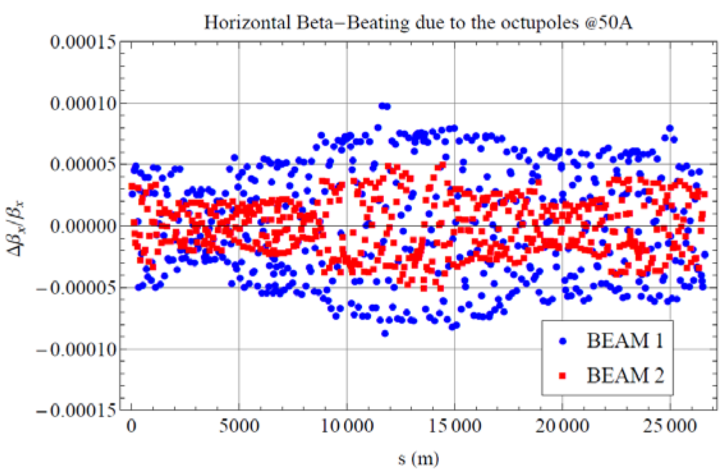
$$\Delta\xi_x \approx \pm 0.84, \qquad \Delta\xi_y \approx \pm 0.045$$

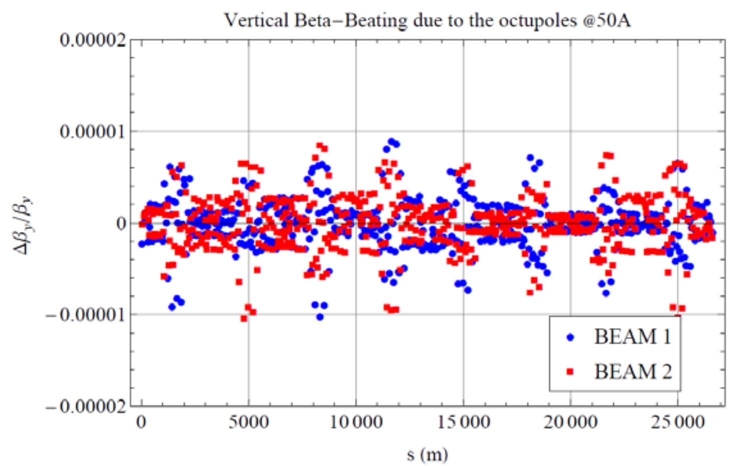
which is compensated by additional $\Delta K2/K2 \sim 0.4$ % maximum => same order of magnitude than the resulting variation after $\Delta\beta/\beta$ correction.

- Doubling the intensity would imply doubling this effect if the octupoles are needed.

V- Effects of octupoles (2/2)

- Second order effects in Δx are very small:
  - o tune shifts: $\Delta Q_x \approx 1.10^{-4}$, $\Delta Q_y \approx -5.10^{-6}$
  - o beta-beating (IP6 is at s = 0):





=> Tune shift is less than one order of magnitude smaller than the tolerance and Δβ/β is less than 0.2 % of the remaining beating after correction.

Conclusion (1/2)

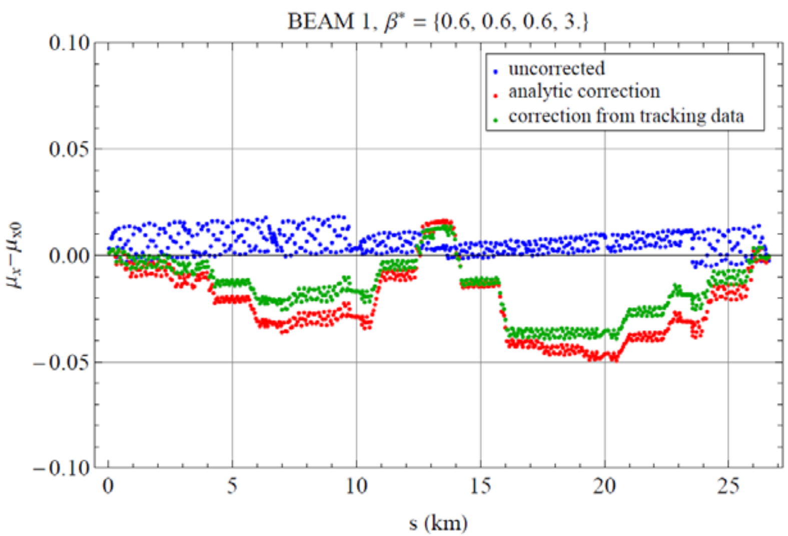
- Operating with β* = 0.6 m would increase the intrinsic beta-beating of about 30% av. compared to β* = 0.8 m,
- Going down to β* = 2 m at IP8 would have negligible impact on beta-beating,
- Intrinsic beta-beating can be corrected offline for any set of β* without requiring a particle tracking, but only the on-momentum Twiss tables from MADX,
- Application to the squeeze procedure shows that correcting beta-beating could ease the operation by reducing intrinsic errors, especially from about the middle of the sequence (β*~2 m at IP1/2/5),
- Matching quadrupoles' strength could be implemented in the squeezing procedure as a knob.

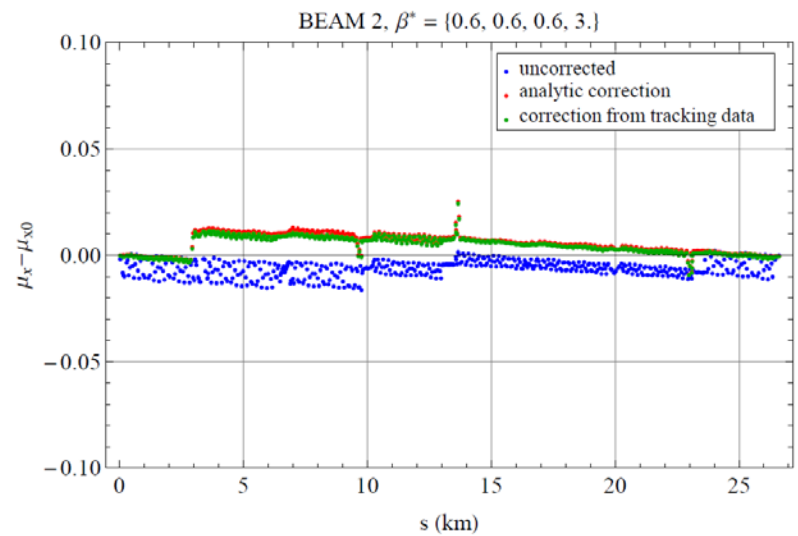
Conclusion (2/2)

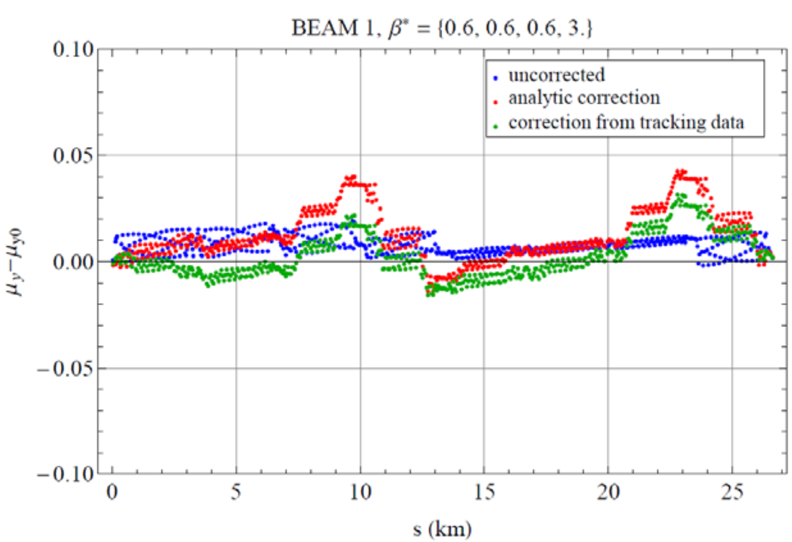
- Correction scheme does not affect the tune more than $\pm 1\times10^{-3}$ while the tolerance is $\Delta Q = 2.5\times10^{-3}$,
- Adjustments of sextupoles' strength to maintain chromaticity close to 2 units are less than 2 % maximum of the values required on-momentum.
- Orbit offset in octupoles generates chromaticity of the order of 1 unit in x-plane for $I_{octu} = 50A$. Would double if we double the p beam intensity with octupoles ON,
- Tune shift and beta-beating due to octupoles are negligible,
- Correction should be calculated for reversed beams, Pb in B1 ($-\delta$) and p in B2 ($+\delta$).

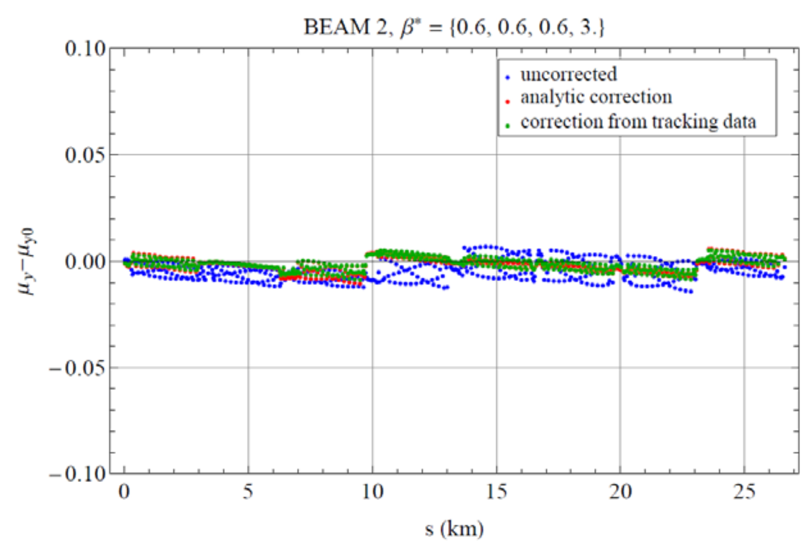
Back up

$\Delta\mu = \mu_\delta - \mu_0$

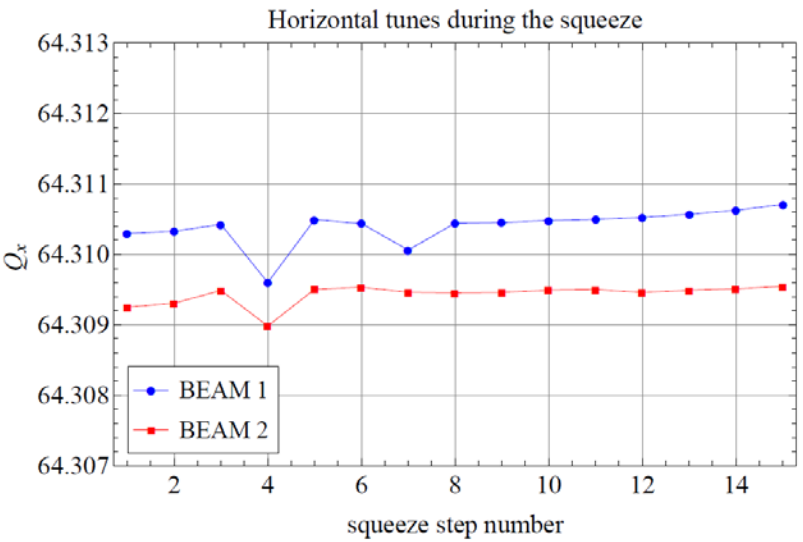


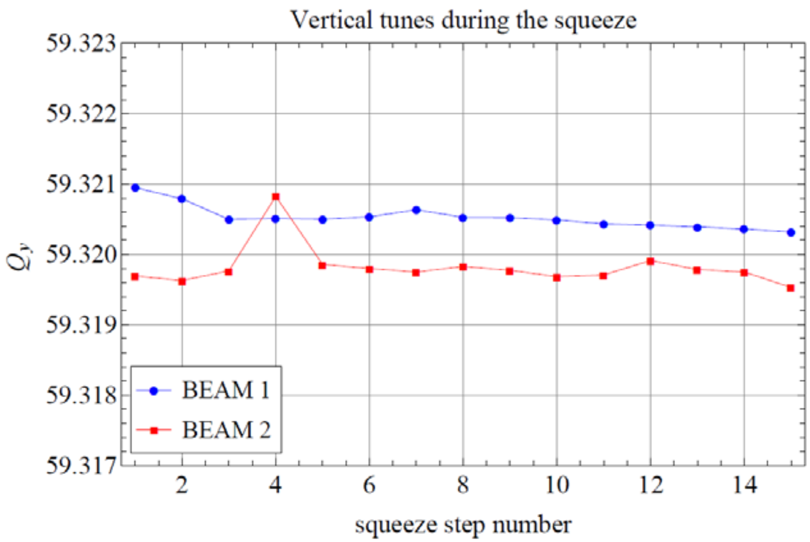






Tunes after analytic Δβ/β correction in the squeeze





Iterations on K2