Correction of β-beating due to beam-beam for the LHC and its impact on dynamic aperture

WEOAB2

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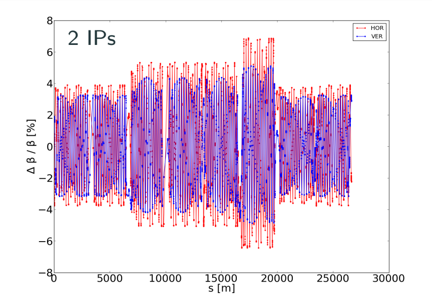
Introduction

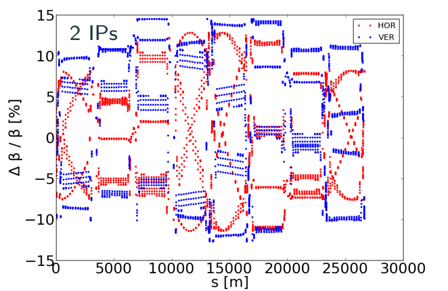
Beam-beam effects

When the bunches of two beams of a particle collider come into proximity, they interact electromagnetically and give rise to **beam-beam (BB) effects**

- Tune shift
- Tune spread
- **β-beating**
- Beam stability and dynamic aperture
- Etc.

Motivation: beam-beam effects in the LHC and HL-LHC





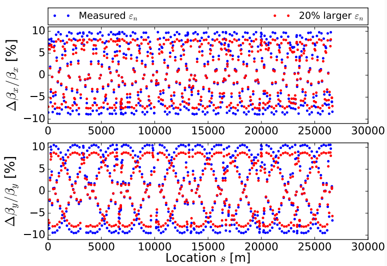
LHC: $\xi_{bb} = 0.01$ (total)
8 % β-beating

HL-LHC: $\xi_{bb} = 0.02 - 0.03$ (total)
15 % to 23 % β-beating

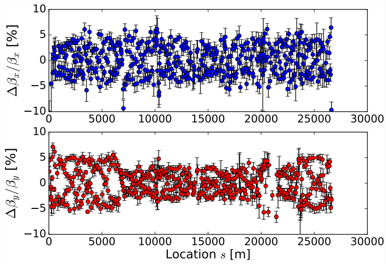
- Impact on **performance**
  - $\pm 9\,\%$ β^* change for HL-LHC
  - Direct repercussion on luminosity → **luminosity imbalance** between the main experiments
- Impact on **protection system**

Compensation techniques

- Other compensation techniques:
  - Electron beam lens
  - Current-bearing wires
- Correction of β-beating by compensation of the **BB linear kick** with local **magnets**
  - First step for a correction scheme involving higher multipoles in view of the **HL-LHC**
  - **First measurements** and **preliminary test** in the LHC (**P. Gonçalves** *et. al.*, **TUPVA030**)

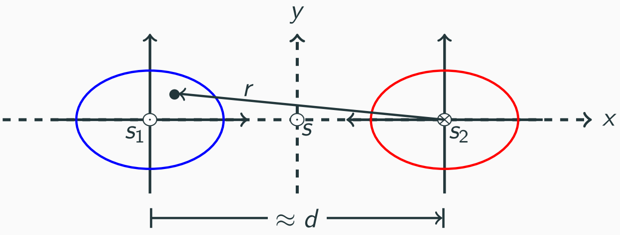


Simulation



Measurement

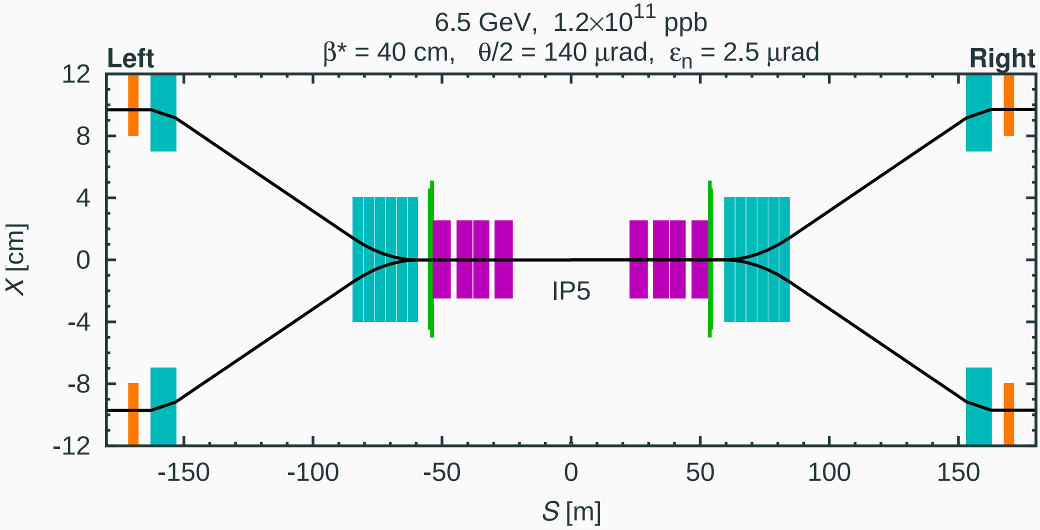
Beam-beam kick



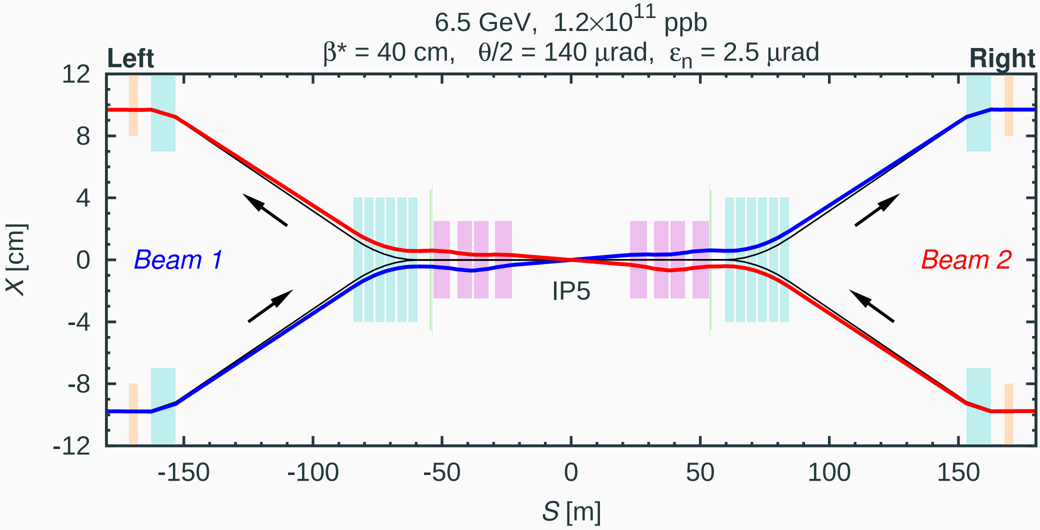
$$\left\{ \begin{array}{c} \Delta x' \\ \Delta y' \end{array} \right\} = -\frac{2Nr_0}{\gamma}\frac{1}{r^2}\left\{ \begin{array}{c} x \\ y \end{array} \right\}\left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$$

- r Radial distance from the test particle to the center of the opposite beam, $r = \sqrt{x^2 + y^2}$
- σ Beam size (assumed round)
- N Bunch population
- r_0 Classical particle radius
- γ Relativistic Lorentz factor
- d Beam separation

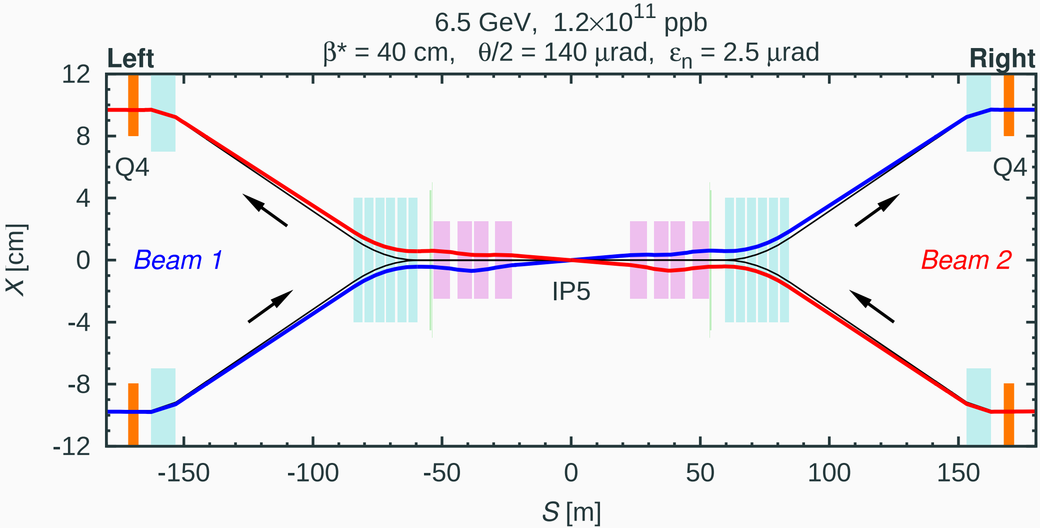
Example: LHC interaction region



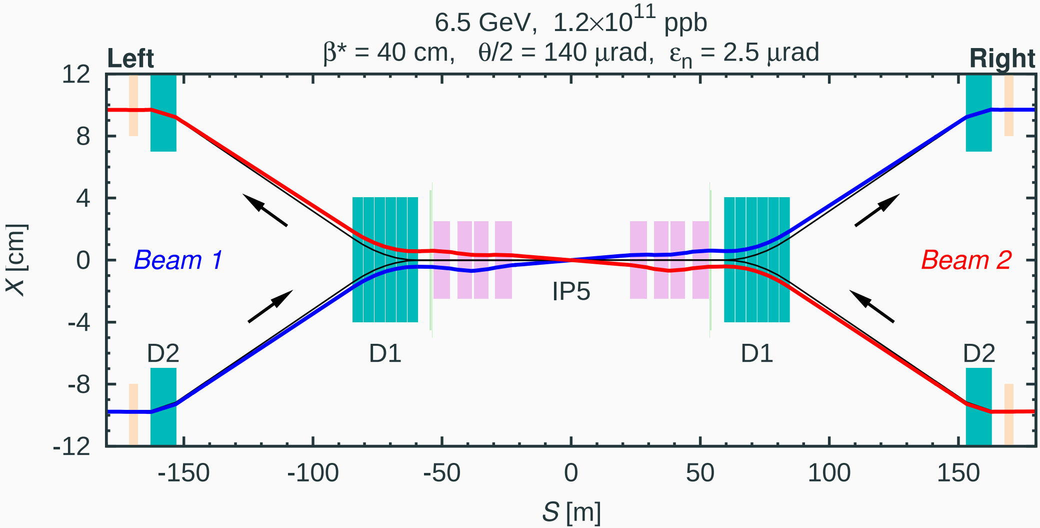
Example: LHC interaction region – beams



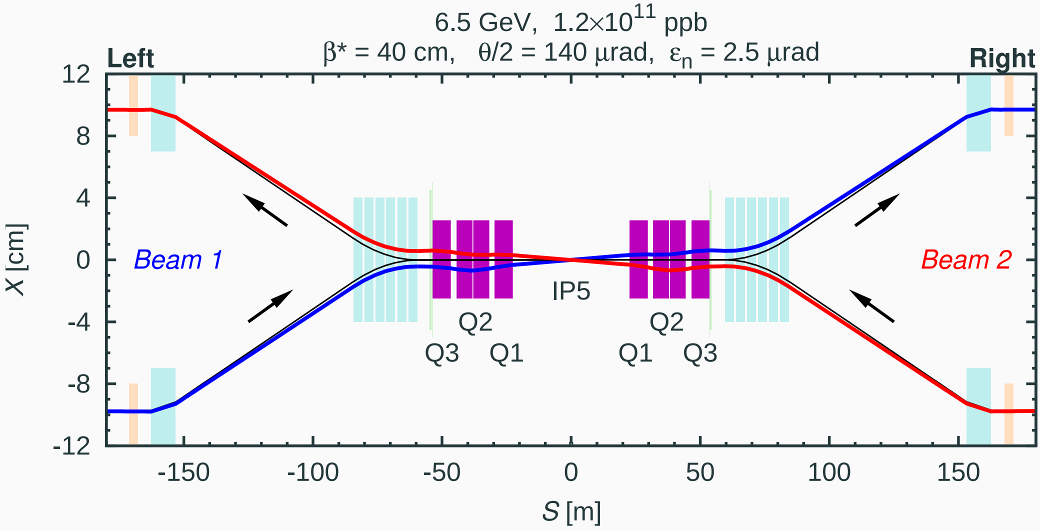
Example: LHC interaction region – matching section



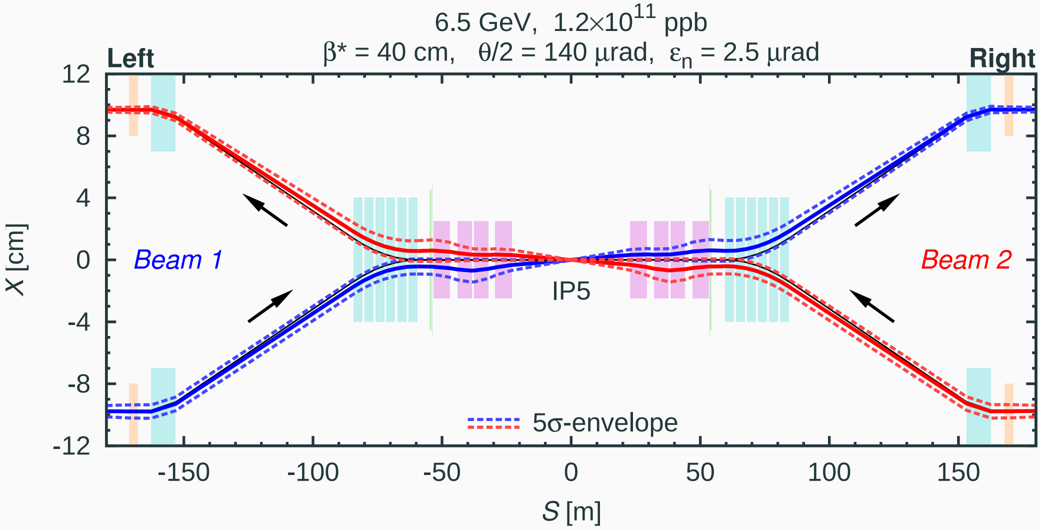
Example: LHC interaction region – dipoles



Example: LHC interaction region – inner triplet



Example: LHC interaction region – beam envelope



Head-on and long-range beam-beam expansion

Head-on (HO) beam-beam

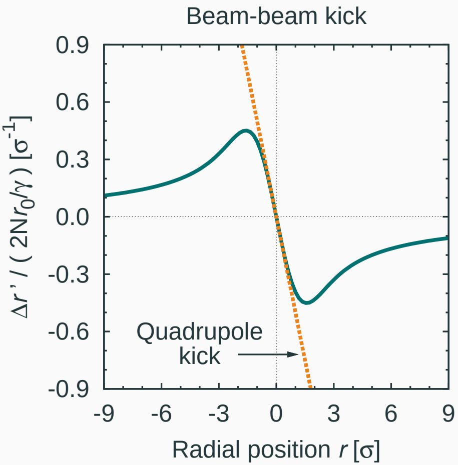
- **Linearisation** of kick for **small amplitudes**:

$$\begin{Bmatrix} \Delta x'|_{r\to 0} \\ \Delta y'|_{r\to 0} \end{Bmatrix} = -\frac{Nr_0}{\gamma\sigma^2}\begin{Bmatrix} x \\ y \end{Bmatrix}$$

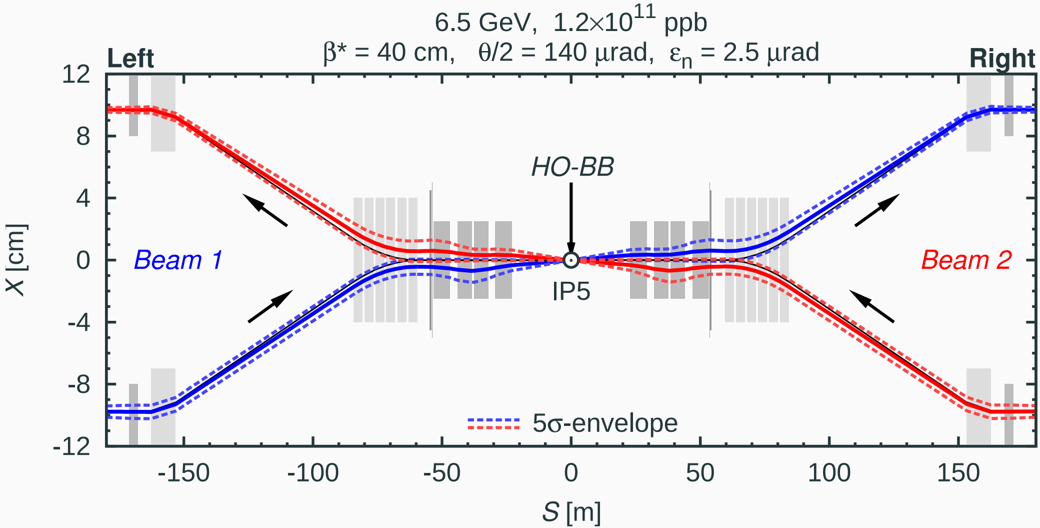
  - Same effect on both planes
- **Beam-beam parameter** as a measure of the induced **tune shift**:

$$\xi_{bb} \equiv \frac{\mathrm{d}(\Delta r')}{\mathrm{d}r}\frac{\beta^*}{4\pi} = \frac{Nr_0\beta^*}{4\pi\gamma\sigma^2}$$

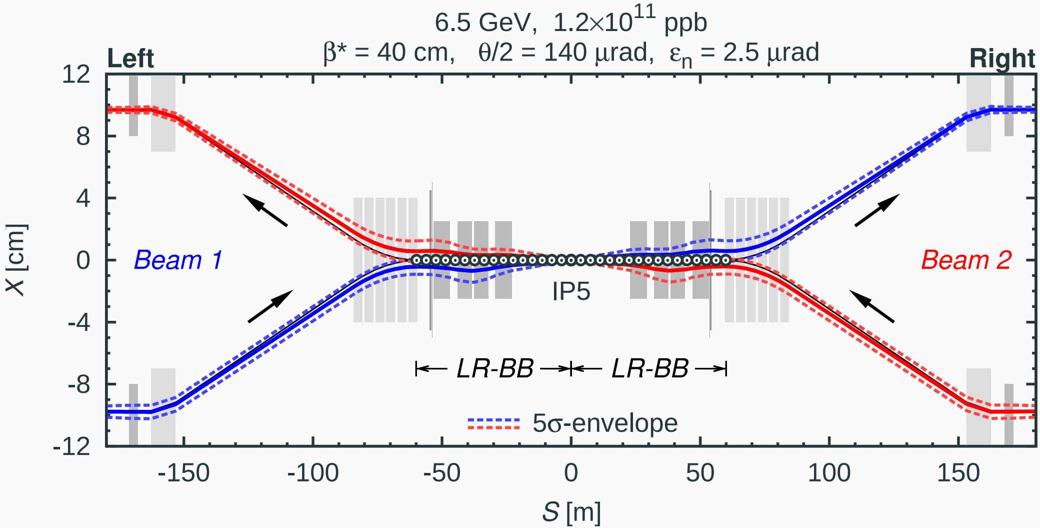
  - Horizontal and vertical



Head-on (HO) beam-beam: LHC



Long-range (LR) beam-beam: LHC (16 collisions per IP side)



Long-range (LR) beam-beam

- **Taylor expansions** up to second order around $(d, 0)$ (horizontal crossing):

$$\begin{aligned}\Delta x' &= K_0 + (K_1 + K_1')\Delta x + (K_2 + K_2')(\Delta x)^2 - K_2(\Delta y)^2,\\ \Delta y' &= -K_1\Delta y - 2K_2\Delta x\Delta y,\end{aligned}$$

where K_i and K_i' are functions of

$$E_d \equiv \exp\left(-\frac{d^2}{2\sigma^2}\right)$$

(See Appendix A)

LR-BB for large separation

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LR-BB for large separation: pure quadrupolar/sextupolar terms

- **Taylor expansions** up to second order around $(d, 0)$ (horizontal crossing):

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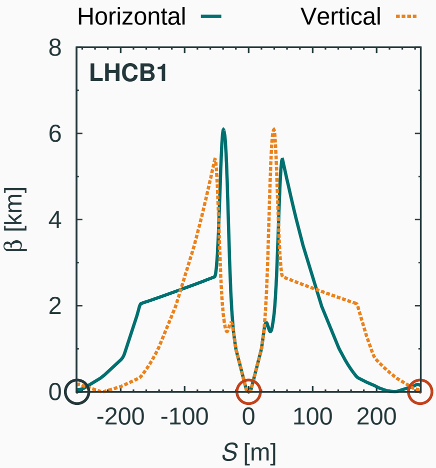
(See Appendix A)

Procedure and results

Procedure

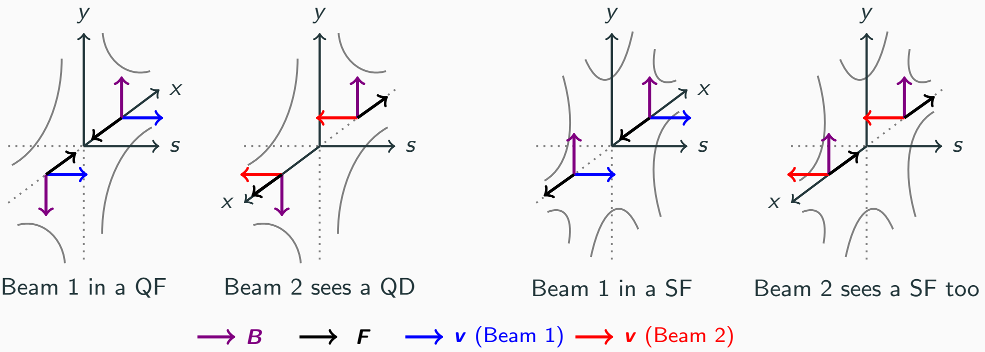
- **Re-matching** of optics ($\beta_{x,y}$, $\alpha_{x,y}$) at the start / IP / end of each IR (separately)
  - **Eight degrees of freedom** per beam per IP
  - Eight variables: **4 left-right pairs of magnets**
- Re-matching of

  Tunes to **(64.31, 59.32)**
  Chromaticities to **2**



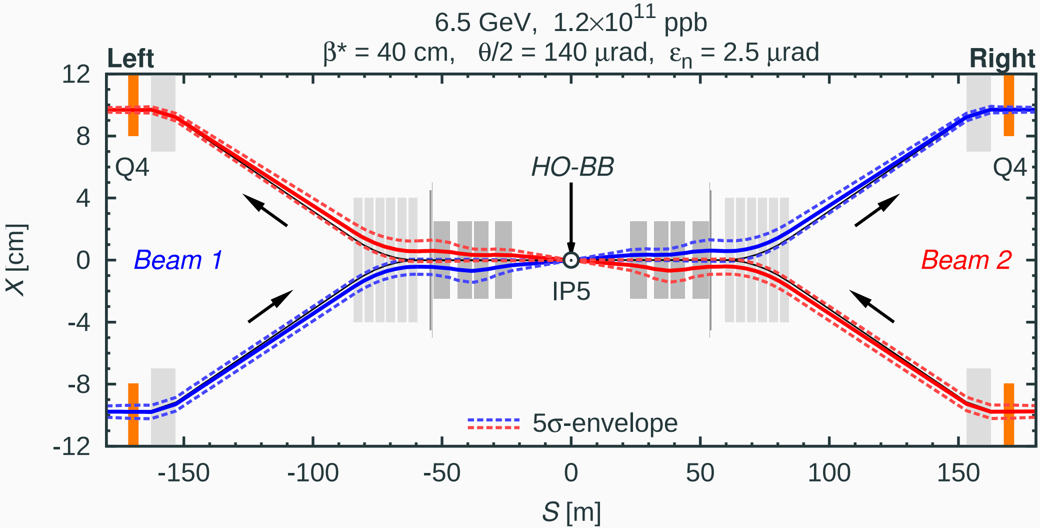
Choice of magnets

- Correction in **both beams**
- Magnet strengths for counter-rotating beams: $K_n \to (-1)^n K_n$ (0: dipole, 1: quad, etc.)

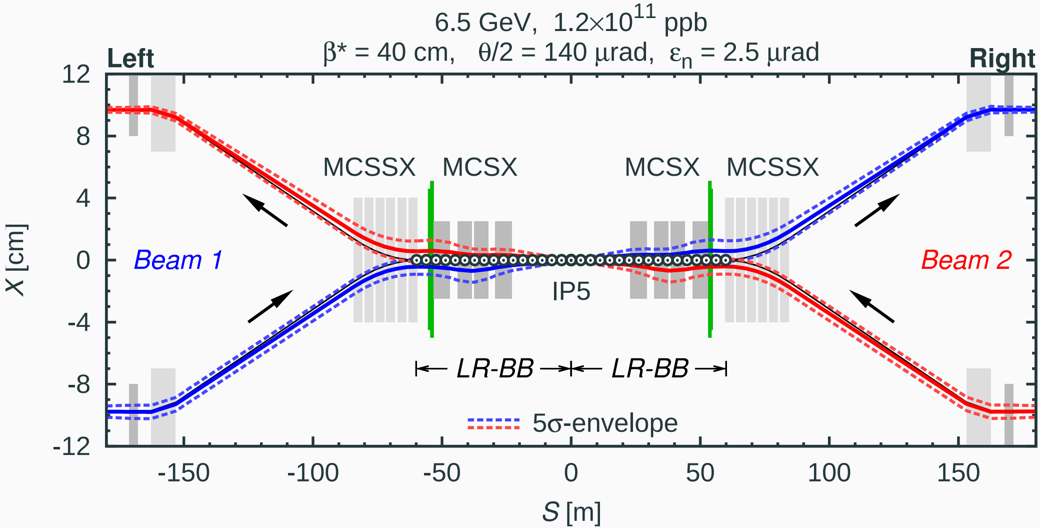


- **Quadrupole**, **octupole**, etc. components of the BB **cannot** be directly compensated for both beams using **common magnets**.

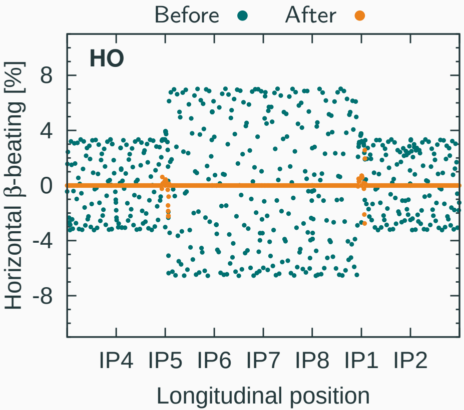
Choice of magnets: Matching quadrupoles for HO

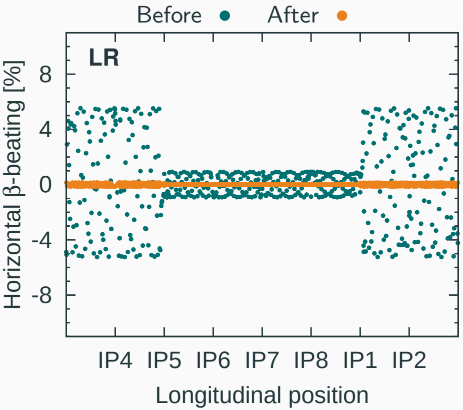


Choice of magnets: Common sextupoles for LR



Reduction of RMS β-beating due to HO-BB or LR-BB



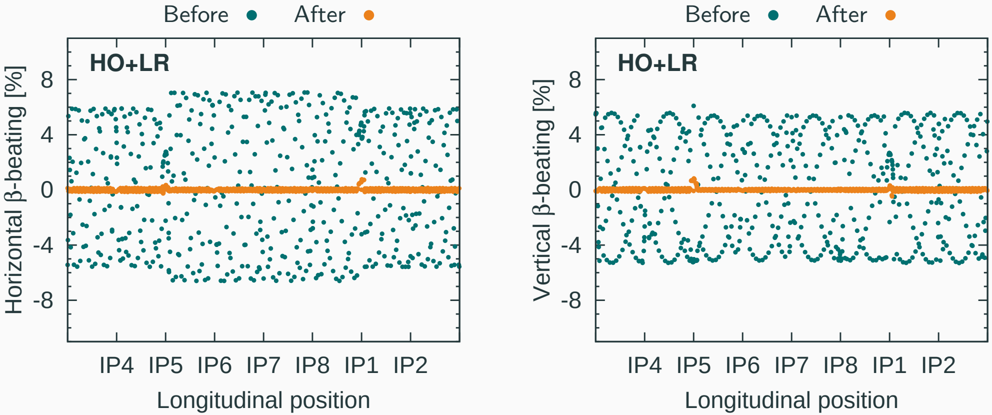


HO: from 3.67 % / 1.91 % (Hor./Ver.)
to **0.30 % / 0.15 %**

LR: from 2.69 % / 3.84 %
to **0.04 % / 0.04 %**

Reduction of RMS β-beating due to HO-BB <u>and</u> LR-BB

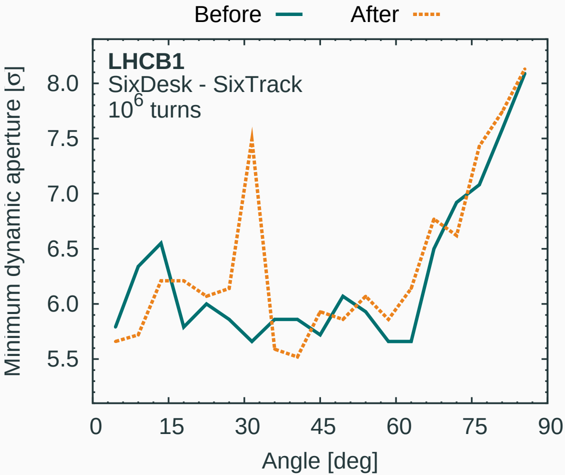
- Reduction of **RMS β-beating to $< 0.15\,\%$**
- Tunes reduced by 0.01, chromaticities increased by 2 units $\rightarrow$ Re-matched to nominal
- Correction with an identical process for the **opposite beam** $\rightarrow$ **Similar results**



Stability of the HO-BB and LR-BB correction

- Correcting sextupole strengths have opposite sign to the sextupolar term of the BB kick.
- **Non-linear** elements
  - **Long-term stability**?
- Dynamic aperture (DA), via single-particle tracking.
- Little impact on DA $> \mathbf{5.5\sigma}$ for all angles

$I_{\text{oct}} = 0\,\text{A}$
2 units of chromaticity



Conclusions and outlook

Conclusions and Outlook

- **Beam-beam** interactions can limit the machine **performance**.
  - Luminosity imbalance, machine protection
- Induced β-**beating** can be corrected, at least partially, by matching local magnet strenghts to the multipolar terms of the BB kick expansion.
- Successful application to the current **LHC** optics (**RMS beating** $< \mathbf{1\,\%}$)
  - Linear HO corrected with matching quadrupoles
  - LR quadrupolar term corrected via sextupole feed-down
- Compensation scheme involving common sextupoles has **negligible impact on DA**.
- **First measurements** and **test** of correction in LHC $\rightarrow$ anyalsis on-going
- Extension to higher orders, and to the **HL-LHC**:
  - Compensation of beam-beam octupolar component via feed-down from decapoles (not present in the LHC)

Thank you