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

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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
- $\beta$-beating
- Beam stability and dynamic aperture
- Etc.
Motivation: beam-beam effects in the LHC and HL-LHC

- Impact on performance
  - $\pm 9\% \beta^*$ change for HL-LHC
  - Direct repercussion on luminosity $\rightarrow$ luminosity imbalance between the main experiments

- Impact on protection system

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

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

- Other compensation techniques:
  - Electron beam lens
  - Current-bearing wires

- Correction of $\beta$-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 vs Measurement](image-url)
Beam-beam kick

$$\begin{align*}
\{ \Delta x', \Delta y' \} &= -\frac{2Nr_0}{\gamma} \frac{1}{r^2} \begin{pmatrix} x \\ y \end{pmatrix} \left[ 1 - \exp \left( -\frac{r^2}{2\sigma^2} \right) \right]
\end{align*}$$

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

6.5 GeV, $1.2 \times 10^{11}$ ppb

$\beta^* = 40$ cm, $\theta/2 = 140$ $\mu$rad, $\varepsilon_n = 2.5$ $\mu$rad
Example: LHC interaction region – beams

- $6.5 \text{ GeV}, \ 1.2 \times 10^{11} \text{ ppb}$
- $\beta^* = 40 \text{ cm}$,
- $\theta/2 = 140 \mu\text{rad}$,
- $\varepsilon_n = 2.5 \mu\text{rad}$

![Graph of LHC interaction region](image)
Example: LHC interaction region – matching section

6.5 GeV, $1.2 \times 10^{11}$ ppb

$\beta^* = 40$ cm, $\theta/2 = 140$ $\mu$rad, $\varepsilon_n = 2.5$ $\mu$rad
Example: LHC interaction region – dipoles

6.5 GeV, $1.2 \times 10^{11}$ ppb

$\beta^* = 40$ cm, $\theta/2 = 140$ $\mu$rad, $\varepsilon_n = 2.5$ $\mu$rad
Example: LHC interaction region – inner triplet

6.5 GeV, $1.2 \times 10^{11}$ ppb

$\beta^* = 40$ cm, $\theta/2 = 140 \mu$rad, $\varepsilon_n = 2.5 \mu$rad

Beam 1

Beam 2
Example: LHC interaction region – beam envelope

6.5 GeV, $1.2 \times 10^{11}$ ppb

$\beta^* = 40$ cm, $\theta/2 = 140$ $\mu$rad, $\varepsilon_n = 2.5$ $\mu$rad
Head-on and long-range beam-beam expansion
Head-on (HO) beam-beam

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

\[
\begin{align*}
\{ & \Delta x' |_{r \to 0} \\ & \Delta y' |_{r \to 0} \} = -\frac{N r_0}{\gamma \sigma^2} \begin{bmatrix} x \\ y \end{bmatrix}
\end{align*}
\]

- Same effect on both planes

- **Beam-beam parameter** as a measure of the induced **tune shift**:

\[
\xi_{bb} \equiv \frac{d(\Delta r')}{dr} \frac{\beta^*}{4\pi} = \frac{N r_0 \beta^*}{4\pi \gamma \sigma^2}
\]

- Horizontal and vertical
Head-on (HO) beam-beam: LHC

6.5 GeV, $1.2 \times 10^{11}$ ppb

$\beta^* = 40$ cm, $\theta/2 = 140 \mu$rad, $\varepsilon_n = 2.5 \mu$rad

Beam 1

Beam 2

HO-BB

IP5

5$\sigma$-envelope
Long-range (LR) beam-beam: LHC (16 collisions per IP side)

6.5 GeV, $1.2 \times 10^{11}$ ppb
$\beta^* = 40$ cm, $\theta/2 = 140$ $\mu$rad, $\varepsilon_n = 2.5$ $\mu$rad
• **Taylor expansions** up to second order around \((d, 0)\) (horizontal crossing):

\[
\Delta x' = K_0 + (K_1 + K_1') \Delta x + (K_2 + K_2')(\Delta x)^2 - K_2(\Delta y)^2,
\]

\[
\Delta y' = -K_1 \Delta y - 2K_2 \Delta x \Delta y,
\]

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

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

\[ \Delta x' = K_0 + (K_1 + K_1') \Delta x + (K_2 + K_2') (\Delta x)^2 - K_2 (\Delta y)^2, \]
\[ \Delta y' = -K_1 \Delta y - 2K_2 \Delta x \Delta y, \]

where \(K_i\) and \(K'_i\) are functions of

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

(See Appendix A)
• **Taylor expansions** up to second order around \((d, 0)\) (horizontal crossing):

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\Delta x' = K_0 + (K_1 + K_1')\Delta x + (K_2 + K_2')(\Delta x)^2 - K_2(\Delta y)^2,
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\[
\Delta y' = -K_1\Delta y - 2K_2\Delta x\Delta y,
\]

where \(K_i\) and \(K_i'\) are functions of

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

(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: $K_n \rightarrow (-1)^n K_n$ (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

6.5 GeV, $1.2 \times 10^{11}$ ppb

$\beta^* = 40$ cm, $\theta/2 = 140$ $\mu$rad, $\epsilon_n = 2.5$ $\mu$rad

Beam 1

Beam 2
Choice of magnets: Common sextupoles for LR

6.5 GeV, $1.2 \times 10^{11}$ ppb
$\beta^* = 40$ cm, $\theta/2 = 140$ $\mu$rad, $\epsilon_n = 2.5$ $\mu$rad
Reduction of RMS $\beta$-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 $\beta$-beating due to HO-BB and LR-BB

- Reduction of RMS $\beta$-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

![Horizontally and vertically beating before and after correction](image-url)
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 $> 5.5\sigma$ 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 strengths to the multipolar terms of the BB kick expansion.

- Successful application to the current **LHC** optics (**RMS beating** < 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 → 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