Preliminary studies of beam-beam long range effects: orbit, tunes, chromaticity...

T. Pieloni, X. Barranco, D. Banfi, X. Buffat, C. Tambasco

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TRAIN CODE: some history...

**F. C. Iselin** TRAIN code for LEP: post-processor to MAD

Used by **E. Keil** for LEP studies:
“Truly Self-Consistent Treatment of the Side Effects with Bunch Trains”, CERN/SL/95-075 (AP)

**H. Grote and W. Herr** made LHC studies with bunch trains:
“Features and Implications of different LHC crossing schemes”, LHC Project Report 628 (2003) all pictures for comparison to LHC are from this note

...and much more....and still a lot to be done!
TRAIN

- Written in 1994/95 By F. C. Iselin, FORTRAN 77 around 14000 lines...
  Computes the orbit, tune, chromaticity and luminosity reductions (due to orbit offsets) for each bunch in a train self-consistently
- MADX part: 1\textsuperscript{st} and 2\textsuperscript{nd} order MAPS between collision points with BB elements and IP configurations: usual things...
  - Set-up the optics: crossing angles, separation bumps, using thin optics versions
  - Install the BB elements on LHCB2 backward “b” and LHCB1 forward beam “f”
  - Produce 2 files: 1\textsuperscript{st} “train.opt” and 2\textsuperscript{nd} order maps “train.map” for both beams

- TRAIN:
  - Reads the MADX files
  - Reads filling scheme for B1 and B2 and bbb currents: allows for random variations of bunch by bunch currents or reads from bunch current files (direct read from measurements for LEP and LHC)
  - TRAIN computes the coherent BB kicks (describes the dipolar kick a bunch as a whole will receive) at each BB element

→
- Finds the closed orbit of all bunches which circulates and collide at parasitic and main IPs (HO and LR as defined in initial MADX file) with the coherent BB kicks ON
- Computes the orbit parameters on these individual orbits for each bunch and iterates
- Computes linear ONE-TURN map of the system of all bunches (coupled by BB effects) and calculates the eigenvalues (frequencies of coherent BB modes and chromaticities)
Incoherent kick (single particle like in MADX) and Coherent kick (bunch) TRAIN calculates the coherent BB kicks at each BB element:

Bassetti-Erskine formula for the incoherent kick replacing the beam $\sigma_x^2 - \sigma_y^2$ with $2\sigma_x^2 - 2\sigma_y^2$ for $d_{\text{sep}} < 1 \sigma$

Allows for round as well as flat beams configurations

This could be eventually be improved!
The approximation of the kicks:

\[ \sum = 2\sigma^2 \]

Same approximation we use to compute the orbit deflection on VdM scans: can use MADX or analytical formula
LHC IP5 only:

- Intensity $1.15 \times 10^{11}$ ppb
- Emittance 3.75 ($16.6 \, \mu m$ at IP)
- Nominal LHC optic $\beta^*$ 0.55 collision
- 15 LR per side of IP
- IP5 only: H crossing ($285 \, \mu rad$)
- Nominal LHC filling scheme 25 ns

Figure 8: Horizontal offset in IP5 with horizontal-horizontal crossing. Details in first three batches. Indicated bunches have all the same number of long range interactions (i.e. 22), but at different positions. Leftmost and rightmost bunches miss 15 long range interactions.

LHC filling scheme:

- 38-39 empty slots for LHC injection kicker
- And 8 empty slots between trains of 72
due to SPS injection kicker

Orbit variation of 1 $\mu m$ due to long-range deflection
IP5 H&V offset

- Intensity $1.15 \times 10^{11}$ ppb
- Emittance 3.75 (16.6 µm at IP)
- Nominal LHC optic $\beta^*$ 0.55 collision
- 15 LR per side of IP
- IP5 only H crossing (285 µrad)
- Nominal LHC filling scheme 25 ns

Figure 11: Horizontal offset in IP5 with horizontal-horizontal crossing.
IP5&IP1 Collisions HV crossing: we observe in IP1

For IP1

Separation Plane: H
These effects come LR in IP5

Crossing plane: V
These effects come LR in IP1

Figure 14: Horizontal offset in IP1 with vertical-horizontal crossing.

Figure 20: Vertical offset in IP1 with vertical-horizontal crossing.
IP5&IP1 Collisions HV crossing: Observe IP5

For IP5 the opposite

Crossing plane: H
These effects come LR in IP5

Separation Plane: V
These effects come LR in IP1

Figure 17: Horizontal offset in IP5 with vertical-horizontal crossing.

Figure 23: Vertical offset in IP5 with vertical-horizontal crossing.
IP5 & IP1 Collisions HV crossing: we observe in IP1

The long-range interaction in IP5 in Vertical plane result in **displacements in IP1 of maximum 1 µm**

→ Offset at head-on collision of less than 0.1 σ

*Figure 14: Horizontal offset in IP1 with vertical-horizontal crossing.*
IP5&IP1 Collisions HV crossing: Observe IP1

The long-range interactions in IP1 in Vertical plane come back to IP1 result in symmetric displacements for the two beams in IP1 of maximum 1 µm

→ Displacement of collision centroid of 0.1 σ

Figure 20: Vertical offset in IP1 with vertical-horizontal crossing.
LHC IP5: Qx

The long-range interactions in IP5 only in V plane: **tune shifts 0.0015 in tune units**

![Figure 30: Horizontal tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.](image)
LHC IP5: Qy

The long-range interactions in IP5 only in V plane: **tune shifts 0.0015 in tune units**

Figure 31: Vertical tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.
LHC IP5:Qpx

The long-range interactions in IP5 only in V plane: $Q'$ spread of less than 1 unit

Figure 36: Horizontal chromaticity variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.
LHC IP5: Qpy

The long-range interactions in IP5 only in V plane: Q’ spread of less than 1 unit

Figure 37: Vertical chromaticity variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.
Alternating crossing

The long-range interactions in IP5 only in V and IP1 in H compensates the tune and chroma effects of long ranges plane.

Figure 30: Horizontal tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.

Similar Pictures for other plane and chroma.
Can we cross check with data? ATLAS vertex detector 2011 data

VERTICAL

Vertical centroid displacement can be measured and we can check few cases

Courtesy of R. Bartoldus and W. Kozanecki ATLAS collaboration
ATLAS data 2012 April VdM Horizontal plane

May 2011
vdM scan

Horizontal plane

Orbit drift

Courtesy of W. Kozanecki
HL-LHC case
HL-LHC: IP5 only

- Intensity 2.2 and 1.1e11 ppb
- Emittance 2.5 (7 µm at IP)
- ATS optic β* 0.15 collision
- 15 LR per side of IP
- Crossing angle 590 µrad
- Nominal LHC filling scheme 25 ns
HL-LHC: IP1 only tune shifts

- Intensity 2.2 ppb
- Emittance 2.5 (7 μm at IP)
- ATS optic β* 0.15 collision
- 15 LR per side of IP
- Crossing angle 590 μrad
- Nominal LHC filling scheme 25 ns

Due to one IP LR DQ in the range 0.0025
HL-LHC: IP1 only chroma

Int 2.2e11

- Intensity 2.2 and 1.1e11 ppb
- Emittance 2.5 (7 µm at IP)
- ATS optic $\beta^*$ 0.15 collision
- 15 LR per side of IP
- Crossing angle 590 µrad
- Nominal LHC filling scheme 25 ns

Due to one IP LR Q' spread of 2 units
HL-LHC: IP1&IP5 offsets

- Intensity $2.0 \times 10^{11}$ ppb
- Emittance 2.5 (7 $\mu$m at IP)
- ATS optic $\beta^* 0.15$ collision
- 15 LR per side of IP
- Crossing angle 590 $\mu$rad
- Nominal LHC filling scheme 25 ns

Long ranges lead to offsets in opposite IP in the plane of separation of maximum 0.3 $\sigma$ at intensities of $2.0 \times 10^{11}$ ppb
HL-LHC: IP1&IP5 offsets

- Intensity 2.0 and 2.2e11 ppb
- Emittance 2.5 (7 µm at IP)
- ATS optic $\beta^*$ 0.15 collision
- 15 LR per side of IP
- Crossing angle 590 µrad
- Nominal LHC filling scheme 25 ns

Long ranges lead to offsets in opposite IP in the plane of separation of maximum 0.3 $\sigma$ at intensities of 2.0-2.2e11 ppb
HL-LHC: IP1&IP5 IP1 observation

- Intensity 1.0e11 ppb
- Emittance 2.5 (7 µm at IP)
- ATS optic $\beta^*$ 0.15 collision
- 15 LR per side of IP
- Crossing angle 590 µrad
- Nominal LHC filling scheme 25 ns

Long ranges lead to offsets in opposite IP in the plane of separation of maximum 0.1 $\sigma$ at intensities of 1.0e11 ppb
Still on-going understanding and work....
Problems:

• Still to understood asymmetry between b1 and b2 \(\rightarrow\) on-going with Werner and Rogelio (should be easy)

• Sometime the eigenvalue routine fails finding the eigenvalues (Qs and Q’…) \(\rightarrow\) Need to check the convergency of the routine (some ideas)

• Need a careful study on the impact of different collision sets (crossing angles, separation bumps)
Beam-Beam deflection angles and orbit in the LHC: model for round and non-round beams

Deflections: \[ \theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma) \]

\[ F_0(x, y, \Sigma) = \frac{\sqrt{\pi}}{\sqrt{(\Sigma_{11} - \Sigma_{22})}} [w(\alpha_1) - w(\alpha_2) \cdot \exp\left(-\frac{1}{2}(\Sigma_{11}^{-1}x^2 + \Sigma_{22}^{-1}y^2)\right)] \]

\[ \alpha_1 = \frac{x + iy}{\sqrt{2(\Sigma_{11} - \Sigma_{22})}} \]

\[ \alpha_2 = \frac{(\Sigma_{22}x + i\Sigma_{11}y)}{\sqrt{2\Sigma_{11}\Sigma_{22}(\Sigma_{11} - \Sigma_{22})}} \]

\[ w(z) = \exp(-z^2) \text{erfc}(-iz) \]

Closed Orbit effect:

\[ Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})} \]