Observations of beam-beam effects in the LHC

W. Herr

for Beam-Beam Studies Team, OP, MD crews
Glossary: what is a ”beam-beam limit” ?

- If you think about LEP:
  - Increase of vertical equilibrium emittance with increasing intensity ($\mathcal{L} \propto N, \xi \approx \text{const.}$), damping properties all important, very difficult to predict
  - Not a main issue: beam losses or tails ...

- If you think about LHC (no equilibrium emittance):
  - Forget about LEP !
  - May have slow emittance increase (over hours)
  - Will have beam losses (tails and dynamic aperture), bad life time, impossible to predict
  - More obscure: coherent beam-beam effects
Beam-beam studies in the LHC (2011)

- Relevant questions we have addressed:
  - Head-on beam-beam: are we limited?
  - Do we see long range effects?
  - Do we see ”PACMAN” effects (i.e. bunch-to-bunch differences)?
  - Are coherent beam-beam effects a problem?
  - Can we level the luminosity?

- What are the main lessons?
The LHC in 2010/2011

- Energy is 3.5 TeV instead of 7.0 TeV
- Limitations from machine protection, aperture and electron cloud:
  - Bunch spacing 50 ns (max. 1380 bunches)
  - Larger $\beta^*$ = 1.5 m (later 1.0 m)
- Emittances smaller than nominal ($\approx 1.5 - 2.5 \mu$m)
- In very first collisions at injection energy: nominal beam-beam parameter/tune shift exceeded!
- How far can we push the beam-beam parameter?
Observations: head-on beam-beam effects I

- First dedicated experiment with few bunches
- Test maximum beam-beam parameter (at injection energy) - head-on only
  - Intensity $1.9 \cdot 10^{11}$ p/bunch
  - Emittances 1.1 - 1.2 µm
Observations: head-on beam-beam effects I

- First dedicated experiment with few bunches
- Test maximum beam-beam parameter (at injection energy) - head-on only
  - Intensity $1.9 \cdot 10^{11}$ p/bunch
  - Emittances 1.1 - 1.2 μm
- Achieved:
  - $\xi = 0.017$ for single collision ($\approx 5$ times nominal !)
  - $\xi = 0.034$ for two collision points (IP1 and IP5)
- No obvious emittance increase or lifetime problems during collisions (maximum $\xi$ not yet found)
- No long range encounters present!
Observations: head-on beam-beam effects II

- Second dedicated experiment with few bunches
- Test maximum luminosity per collision (pileup) (at 3.5 TeV, \( \beta^* = 1 \text{ m} \)) - head-on, with crossing angle
  - Intensity \( \approx 2.4 \cdot 10^{11} \) p/bunch
  - Emittances 2.5 - 3.0 \( \mu \text{m} \) (blown up during injection and ramp)
  - Achieved:
    - \( \xi = 0.018 \) for two collision points (IP1 and IP5)
    - "pileup" \( \approx 35 \) per collision, lifetime above 30 hours

Allows very large head-on beam-beam tune shift!
Can we understand the large beam-beam parameter?

- "Nominal" value was conservative choice in the salad days (50% of SPS value!)

- Large value (likely) due to:
  - Low noise, vibrations etc.
  - Small tune modulation (small PC ripple, low Q’)

- Large value not due to:
  - Good field quality
  - Damping
  - Working point

→ Not really our biggest problem (as expected)
Experimental study of long range beam-beam interactions

- Test long range interactions with present machine in two dedicated experiments
- Trains of 36 bunches per beam
- Spacing 50 ns, maximum 48 parasitic encounters
- In standard operation (2011): separation is kept at \( \approx 12 \sigma \) (in drift space, normalized)
  - First study: collisions in IP1 and IP5 only
  - Second study: collisions in all IPs, but different number of collisions per train (special filling scheme)
Experimental study of long range beam-beam interactions

Procedure:
- Reduce crossing angle (separation) in one IP (IP1) in steps until effect on losses, life times or emittances
- At reduced separation in IP1: reduce crossing angle in second IP5 (crossing in other plane)

From simulations:
- Expect effect on dynamic aperture, i.e. increased losses, but little effect on emittances
- At the length truth will out
What do we expect?

Dynamic aperture versus separation

Dynamic aperture as function of normalized separation in drift space (W. Herr, D. Kaltchev, LPN 416, 2008)

Simulations for 50 ns (x) and 25 ns (+)

”Visible” losses expected for dynamic aperture below 3 \( \sigma \)
Experiment 1: scan of crossing angle - losses

Integrated losses during scan in IP1

- Bunch by bunch loss as function of crossing angle in IP1
- Different behaviour of the bunches in the train
Experiment 2: scan of crossing angle - losses

Bunch-by-bunch losses for train 2, fill 2055-B2

- Losses, beam 2, train 2 with collisions in IP1, IP5
- All losses dominated by long range interactions in IP1 and IP5!

Courtesy M. Schaumann
**Experiment 2: scan of crossing angle - emittances**

- Bunch-by-bunch vertical normalised emittance for train 2, fill 2055-B2

- Emittances during scan, vertical, beam 2, train 2

- No emittance increase ➡️ reduced dynamic aperture

*Courtesy M. Schaumann*
Comparison with our expectations

Data estimated from separation scan (50 ns, 3.5 TeV, 1.25 $10^{11}$ p)

Dynamic aperture as function of normalized separation in drift space (W.Herr, D.Kaltchev, LPN 416)

(though this be madness yet there’s method in it)
Summary: scan of crossing angle

Observations:

- Losses start after some threshold (4 - 5 $\sigma$ separation)
  remember: 48 parasitic encounters (nominal 120 !)
- Smaller separation leads to increased losses (dynamic aperture !) as predicted
- No effect on emittances
- Different bunches have different threshold !
- Strong evidence for PACMAN effects
Integrated losses and number of long range interactions

Losses directly related to number of long range interactions

So-called ’PACMAN’ bunches have **better** life time!

’PACMAN’ effects clearly visible

(Courtesy G. Papotti)
Can we understand the observations?

- Try an analytical model (allows to study parametric dependences)
- Based on computation of beam-beam invariants and smear (W. Herr, D. Kaltchev; IPAC09) ➔ backup slides
- Can compute invariants for individual long range encounters
  - Derive scaling laws for dynamic aperture (losses) etc.
  - Estimate PACMAN effects (loss pattern)
  - Find the ”critical” long range encounters
Expected scaling laws: tune shift

Scaling laws for long range tune shift $\Delta Q_{lr}$

- $\Delta Q_{lr} \propto N$ (Intensity)
- $\Delta Q_{lr} \propto n_b$ (number of bunches)
- $\Delta Q_{lr} \propto \epsilon$
- $\Delta Q_{lr} \propto \frac{1}{d_{sep}^2} \propto \frac{1}{\alpha^2}$
- $\Delta Q_{lr} \propto \frac{1}{d_{sep}^2} \propto \frac{1}{\beta^*}$
Expected scaling laws: dynamic aperture

Scaling laws for long-range dynamic aperture $DA$

$$DA \propto \frac{1}{n_b} \quad \text{(number of bunches)}$$

$$DA \propto \frac{1}{\sqrt{\epsilon}}$$

$$DA \propto d_{sep} \propto \alpha$$

$$DA \propto d_{sep} \propto \sqrt{\beta^*}$$

$$DA \propto \frac{1}{N} \quad \text{(Intensity, still to be checked)}$$
Coherent beam-beam modes have been observed colliding few bunches

Provide high degree of symmetry

- Demonstrated by analysis of sum and difference signals between bunches (X. Buffat, IPAC11)
- Symmetry breaking suppresses modes as expected

But not (yet) a problem for operation
Coherent beam-beam modes

Signal without beam-beam collisions
Coherent beam-beam modes

Sum and difference signals

Clearly observed and identified coherent beam-beam modes
Beam-beam Orbit effects

- Strong beam-beam interaction with static offset produces dipole kick
  - Orbit changes due to beam-beam kick
  - Used for LEP: deflection scan
  - Expect strong effect for reduced separation

- What about orbits for PACMAN bunches?
  - Different kicks - different orbits
  - Cannot be fully compensated by alternating crossing schemes (but minimized and made symmetric)!
Orbit effects measured in 2nd MD

Absolute amount of the change in position w.r.t. to bunch 100 at BPM.6L1.B1, B1-HOR

- Time 0
- Time 1
- Time 2
- Time 3
- Time 4

- Orbit changes for different steps in separation
- Measurement at on BPM
- Changes only for bunches colliding in IP1 and IP5
In regular operation: offsets expected at collision point

Predicted orbits from self-consistent computation, here vertical IP1 (H. Grote, W. Herr, 2001)

Cannot be resolved with beam position measurement, but ..
PACMAN Orbit effects: observation

Measurement of vertex centroid by ATLAS (IP1)
Qualitatively: follows exactly predicted behaviour
Must be kept under control (sufficient separation)!
Luminosity levelling

LHC has 4 experiments:
2 require highest luminosity,
2 require lower luminosity (up to factor $10^{-4}$)

Luminosity levelling required already in 2011 (reduce luminosity and keep constant)

- Achieved by transversely offset collisions
  (simple to do, very large range)
- When proposed (Evian Dec. 2010), considered a wild goose chase ..
- Separation $\approx 4 \sigma$ (IP2) and $\approx 0.5 - 1.5 \sigma$ (IP8)
- Routinely done without detrimental effects
Luminosity levelling - all’s well that ends well

Luminosity in LHC experiments during levelling

→ Luminosity very constant in IP8, no effect on other IPs
Other options for levelling

- Must be independent for all experiments
- Transverse offset works without problems (so far), large range
  - can only reduce luminosity!
- Crossing angle and $\beta^*$
  - change long range behaviour, $\rightarrow$ limited range
- Crab crossing (only for HL-LHC)
  - limited range but can recover geometric factor
Summary of observations

- Obtained large head-on tune shifts above nominal
  In daily operation: twice ”nominal” value is standard

- Effect of long range interactions clearly visible (losses, dynamic aperture), no data yet on 25 ns spacing ..

- Number of head-on and/or long range interactions important for losses, strong PACMAN effects !

- All observations in excellent agreement with expectations and well understood (so far)

- Beam-beam effects should allow higher than nominal luminosity (at 7 TeV)
Beam-beam is a **critical issue** in LHC, but (so far) under control, well understood and **no surprises**

For higher luminosities:

- **Aim at high head-on beam-beam parameter:**
  - high brightness, avoid noise or modulations
  - very unlikely to be the limit for high luminosities

- **Avoid any increase of long range beam-beam effects:**
  - provide **sufficient separation** (large crossing angle - don’t touch it !), avoid **larger** number of long range

- **Minimize PACMAN effects** and bunch-to-bunch fluctuations (source of noise !)
- BACKUP SLIDES -
Observations: Losses due to long range

(Courtesy G. Papotti)

- First attempt with $\beta^* = 1$ m, reduced (!) crossing angle
- Bunches colliding in IP1 and IP5: too small separation
- Bunches colliding in IP2 and/or IP8: sufficient separation
Second study: more trains and more head-on collisions

Bunch-by-bunch losses for train 3, fill 2055-B2

- Losses, beam 2, collisions in IP2, IP8
- All losses dominated by long range interactions in IP1 and IP5!

Courtesy M. Schaumann
Experiment 2: scan of crossing angle - losses

Bunch-by-bunch losses for train 2, fill 2055-B2

- Losses, beam 2, collisions in IP1, IP5
- All losses dominated by long range interactions in IP1 and IP5!
## Second study: more trains and more head-on collisions

### Bunch-by-bunch losses for train 2, fill 2055-B1

<table>
<thead>
<tr>
<th>Train</th>
<th>Bunches</th>
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</table>

Losses, beam 1, train 2, all losses dominated by long range interactions in IP1 and IP5!
PACMAN effects

Due to different number of long range collisions expected:

- Systematic tune differences between nominal and PACMAN bunches
- Could have reduced lifetimes when machine is optimized for nominal bunches
- Bunches at head and tail of train would be lost first (origin of the name)
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In LHC: alternating crossing scheme (horizontal and vertical crossing planes) removes tune difference by compensation
Horizontal tune along bunch trains with and without alternating crossing

Predicted tunes from self-consistent computation
Luminosity versus $\beta^*$

Luminosity versus beta$^*$ for constant separation
Luminosity versus $\beta^*$ for constant separation
Strength of beam-beam interactions in the LHC

or: why do bunches behave differently?

W. Herr

With material from:

Beam-beam strength

In LHC a bunch can have many beam-beam interactions: head-on (4) and long-range (120).

Which are important and which are not?

Which ones need special "care"?

Look at individual contributions

Technique [1] extended to long range encounters [2]

Compute contribution of smear for each encounter
Beam-beam kicks (weak-strong)

Study effect of beam-beam encounters in weak-strong model, using (non-linear) transfer maps [3, 4]

\[ M = \prod_{k=1}^{N_{IP}} e^{iF^{(k)}} e^{iF_2^{(k)}} = e^{iH} \]

- \( N_{IP} \) number of collision points (head-on and long-range)
- \( e^{iF^{(k)}} e^{iF_2^{(k)}} \): operators associated with \((k\text{-th})\) beam-beam kick and linear matrix (between \(k\) and \(k+1\))
- \( e^{iH} \): is the non-linear one turn map, (eff. Hamiltonian, invariant)
Beam-beam kicks

Beam-beam potential $F^{(k)}(x)$ re-written from force $f(x)$ [4]:

$$f(x) = \lambda \cdot \frac{2(x + d_x)}{(x + d_x)^2 + d_y^2} \cdot \exp\left[-\frac{(x + d_x)^2 + d_y^2}{2\sigma^2}\right]$$

\[\Rightarrow\] With $\lambda = \frac{N_b r_0}{\gamma}$ we write $F^{(k)}(x)$ as [4]:

$$F^{(k)}(x) = \int_0^x f^{(k)}(x')dx'$$

\[\Rightarrow\] $f^{(k)}(x)$ denote k-th encounter, $\lambda^{(k)}, d_{x,y}^{(k)}$ and $\sigma_{x,y}^{(k)}$

from now: using $d_{x,y}^{(k)}$ normalized to beam size $\sigma_{x,y}^{(k)}$

$$d_{x,y}^{(k)} \rightarrow d_{x,y}^{(k)} / \sigma_{x,y}^{(k)}$$
Beam-beam kicks

Going to action angle variables, the integral $F^{(k)}(A, \Phi)$ becomes:

$$F^{(k)}(A, \Phi) = \int_0^1 \frac{dt}{t} \left( 1 - e^{-t} \left[ \left( \sqrt{A} \sin(\Phi) + \frac{d_{x}^{(k)}}{\sqrt{2}} \right)^2 - \frac{d_{y}^{(k)^2}}{2} \right] \right)$$

we can expand as Fourier series (for later use):

$$F^{(k)}(A, \Phi) = \sum_{n=-\infty}^{\infty} c_n^{(k)}(A) e^{in\Phi}$$

Can be solved numerically:

1. **Head-on** ($d_{x,y}^{(k)} = 0$): with Bessel functions (see: e.g. Chao, and [1])

2. **Long-range** ($d_{x,y}^{(k)} \neq 0$): through incomplete $\Gamma$ function (see: Herr, Kaltchev, PAC09 [2])
Interlude (I):

What about the constant part of the kick (dipole, orbit kick) ? 

In tracking, subtract constant part \( (x = 0) \):

\[
f^{(k)}(x) \quad \Rightarrow \quad f^{(k)}(x) - f^{(k)}(0)
\]

we need now to compute the coefficients \( c_n^{(k)} \) from modified potentials:

\[
F^{(k)} \quad \Rightarrow \quad F^{(k)} - F_1^{(k)}
\]

where \( F_1^{(k)} \) is the linear part of \( F^{(k)} \).

We have:

\[
F_1 = \frac{2\sqrt{2} A \sin \Phi}{d^2} \cdot d_x \cdot (1 - e^{-\frac{d^2}{2}})
\]

with \( d^2 = d_x^2 + d_y^2 \)
Interlude (II):

If you get bored:

What happens when we subtract the quadratic parts of the potential as well?

\[ F^{(k)} \implies F^{(k)} - F_1^{(k)} - F_2^{(k)} \]

with:

\[ F_2 = \frac{2A \cdot \sin^2 \Phi}{d^4} \cdot \left[ -d_x^2 + d_y^2 + (d_x^2 + d_x^4 - d_y^2 + d_x^2d_y^2) \cdot \exp \frac{-d^2}{2} \right] \]

Would that be useful?

Good luck ..


**Beam-beam invariant**

The invariant $h$ we get with the CBH formula:

$$h(A, \Phi) = -\mu A + \mu \sum_{k=1}^{N_{IP}} \frac{\lambda^{(k)}}{\epsilon} \tilde{h}^{(k)}(A)$$

for the individual contributions $\tilde{h}^{(k)}$ of encounters:

$$\tilde{h}^{(k)}(A) = c^{(k)}_0(A) + \sum_{n=1}^{m} \frac{(-1)^n n}{2\sin(n\mu/2)} \left[ c^{(k)}_n(A) e^{in\left(\frac{1}{2}\mu - \mu^{(k)} - \Phi\right)} + c.c. \right]$$

and the coefficients $c^{(k)}_n(A)$ (remember the Fourier expansion):

$$c^{(k)}_n(A) = \frac{1}{2\pi} \int_{0}^{2\pi} e^{-in\Phi} F^{(k)}(A, \Phi) d\Phi$$

Remarks:

- Invariant away from resonances
  
  (because $\frac{(-1)^n n}{2 \sin(n \mu/2)} \rightarrow "exit \ invariant"")

- Use individual $\lambda^{(k)}$

  Could model "poor men’s simulation" with lumped interactions (not done here)
From the invariant to the smear

- The $\tilde{h}^{(k)}$ are the contributions of the k-th collision (head-on or long range)

- Use $h(A, \Phi)$ to express $A$ as a function of $\Phi$

  With $(A_0, \Phi_0) = \left(\frac{n^2}{2}, \frac{\pi}{2}\right)$ and $h(A, \Phi) = h(A_0, \Phi_0)$ since invariant: \[ A(A_0, \Phi, \Phi_0) \]

- The smear is the r.m.s. deviation of $A$ from the mean

- Can compare the individual contribution of $\tilde{h}^{(k)}$ to the overall smear
Comparison: model and tracking

\[ n_0 = 9 \quad \text{x-smear} = 0.76 \% \]

Invariant, model and tracking
Comparison: model and tracking

\[ x\text{-smear} \% \]

- Lie algebra
- model
- Sixtrack

Smear: model and tracking (SIXTRACK)
Contribution of long range encounters

Individual contributions, 50 ns spacing
Contribution of long range encounters

Individual contributions, 25 ns spacing
Comparison with tracking

Comparison: Lie-model vs SIXTRACK

Comparison: model versus tracking (SIXRACK)
Dependence on spacing

Smear vs spacing

25 ns, nominal intensity
50 ns, nominal intensity

Strength of non-linearity for 25 ns and 50 ns spacing
Dependence on intensity (25 ns)

Smear vs Intensity

25 ns, nominal intensity
25 ns, half intensity

Strength of non-linearity for different intensity (nominal and half nominal)
Strength of non-linearity for different intensity (nominal and half nominal)

Less sensitive for 50 ns than for 25 ns (see backup slides)
A conundrum to guess ...

What have these techniques in common?

- Electron lenses
- Large Piwinski angle
- Long range wire compensation
- Crabbed waist scheme