Long range beam-beam effects in the LHC

(basics, observations, understanding)

W. Herr

for LHC beam-beam working group
Why do we have long range interactions?

- High luminosity: save bet is to increase the number of bunches:

\[ L = \frac{N_1 N_2 f \cdot n_B}{4\pi \sigma_x \sigma_y} \]

- Are there obvious constraints?
Additional considerations

- Peak luminosity is not the full story
- Integrated luminosity is not the full story either
  - Total beam intensity - machine protection
  - Event pile up in detectors

(see also: session "Operational Aspects", Wednesday 20.3. 14:00)
Pile up - and long range

- High luminosity from few bunches: large spacing not good
- Pile up from different crossing: small spacing (or coasting beams) not good
- Have to take requirements (experiments, injectors, beam-beam) into account

Number of bunches (spacing !) is important

Mostly an issue with crossing angle
The long range problem

Unknowns before 2010 (for LHC):

- Effect on dynamic aperture?
- What is the required separation?
- Do we have PACMAN effects?
- Do alternating crossing schemes help?
- Can we collide with offset beams?
- Can we predict anything?

Only simulations until first experience...
The long range problem

- How to collide many bunches ??
- Must avoid unwanted collisions !!

Separation of the beams:
- Pretzel scheme (CESR, SPS, LEP, Tevatron, ..)
- Bunch trains (LEP, PEP)
- Crossing angle (Factories, ...)
- Crossing angle (ISR, LHC)
Few equidistant bunches
(6 against 6)

Beams travel in same beam pipe
(12 collision points !)

Two experimental areas

Need global separation

Horizontal pretzel around most of the circumference
Example: Pretzel in SPS

- IP 1
- IP 2
- IP 3
- IP 4 - UA 2
- IP 5 - UA 1

Electrostatic separators:
- IP 2 to IP 3
- IP 3 to IP 4
- IP 4 to IP 5
- IP 5 to IP 1

Proton orbit for operation with 6 * 6 bunches:
- IP 1 to IP 2
- IP 2 to IP 3
- IP 3 to IP 4
- IP 4 to IP 5
- IP 5 to IP 6
- IP 6 to IP 1

Antiproton orbit for operation with 6 * 6 bunches:
- IP 1 to IP 2
- IP 2 to IP 3
- IP 3 to IP 4
- IP 4 to IP 5
- IP 5 to IP 6
- IP 6 to IP 1
Separation: LHC

- Many equidistant bunches (2808 per beam)
- Same charges for both beams
- Beams separated in two beam pipes except:
  - Four experimental areas
  - Need local separation
- Two horizontal and two vertical crossing angles
Layout of LHC
Crossing angles (example LHC)

- Separation typically 8 - 12 $\sigma$
- Determined by crossing angle and beam size
What is the separation?

As standard, we use normalized separation in the drift space (for small enough $\beta^*$ and round beams):

$$d_{sep} \approx \frac{\sqrt{\beta^*} \cdot \alpha \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}}$$

- For $\beta^*$ much smaller than half bunch spacing, it is a constant
- Usually quoted for comparison
- Outside drift space depends on exact optics
Separation (beam 1) constant in drift space (nominal: round beams)

Different in triplet, requires exact calculation
For low $\beta^*$: $\Delta \mu \approx \frac{\pi}{2}$ for most of them

The effects can add up!
Crossing angles versus Pretzel scheme

Crossing angle
- Non-linearity very local, close in phase - strong effect
- Strong PACMAN effects
- Easier to control separation
- Possibility for compensation (active and/or passive) *)

Pretzel separation
- Non-linearity distributed
- More difficult to control
- Much more difficult to compensate (multipoles ?) *)

*) Local vs global compensation:

W. Herr, J. Shi, L. Jin, (EPAC 2002); J. Shi, L. Jin, Phys Rev E69 (2004)
For horizontal separation \( d \) (simplified, round beams):

\[
\Delta x'(x + d, y, r) = -\frac{2Nr_0}{\gamma} \cdot \frac{(x + d)}{r^2} \left[ 1 - \exp\left(-\frac{r^2}{2\sigma^2}\right) \right]
\]

\((\text{with: } r^2 = (x + d)^2 + y^2)\)
Footprints

Footprint from long range interactions

- Large for largest amplitudes where non-linearities are strong
- Size proportional to $\frac{1}{d^2}$
- Must expect problems at small separation
- Footprint very asymmetric
What is special about them?

- Break symmetry between planes, stronger resonance excitation
- Mostly affect particles at large amplitudes
- Cause effects on closed orbit
- PACMAN effects
- Tune shift has opposite sign in plane of separation
Long range tune shift

Beam-beam potential for central collision:

\[ U(x, y, \sigma_x, \sigma_y) = C \int \frac{\exp\left(-\frac{x^2}{2\sigma_x^2+t} - \frac{y^2}{2\sigma_y^2+t}\right)}{\sqrt{(2\sigma_x^2 + t)(2\sigma_y^2 + t)}} dt \]

and (horizontally) separated beams:

\[ U(x, y, \sigma_x, \sigma_y, d) = C \int \frac{\exp\left(-\frac{(x-d)^2}{2\sigma_x^2+t} - \frac{y^2}{2\sigma_y^2+t}\right)}{\sqrt{(2\sigma_x^2 + t)(2\sigma_y^2 + t)}} dt \]

\[ \Delta x' = \frac{\partial U}{\partial x} = C \cdot (x - d) \int \frac{\exp\left(-\frac{(x-d)^2}{2\sigma_x^2+t} - \frac{y^2}{2\sigma_y^2+t}\right)}{(2\sigma_x^2 + t)^{3/2}(2\sigma_y^2 + t)^{1/2}} dt \]
Long range tune shift

For zero amplitude particles (on orbit) it becomes:

\[ \Delta x' = \frac{\partial U}{\partial x} = C \cdot d \int \frac{\exp(-\frac{(d)^2}{2\sigma_x^2 + t})}{(2\sigma_x^2 + t)^{3/2}(2\sigma_y^2 + t)^{1/2}} dt \]

This is merely an orbit kick, cannot change tune

No equivalent in the head-on case

Particles now oscillate with the same betatron tune, but around a new closed orbit (watch out in a simulation !!)

For the tune change \( \Delta Q \):

\[ \Delta Q \propto \frac{1}{f} \propto \frac{\partial (\Delta x')}{\partial x} \quad \text{and NOT} \quad \frac{\Delta x'}{x} \]
Long range tune shift

\[ \Delta Q \propto \frac{\partial}{\partial x} \left[ C \cdot (x - d) \int \frac{\exp(-\frac{(x-d)^2}{2\sigma_x^2 + t} - \frac{y^2}{2\sigma_y^2 + t})}{(2\sigma_x^2 + t)^{3/2}(2\sigma_y^2 + t)^{1/2}} \, dt \right] \]

\[ \Delta Q \propto C \int \frac{\exp(-\frac{(x-d)^2}{2\sigma_x^2 + t} - \frac{y^2}{2\sigma_y^2 + t})}{(2\sigma_x^2 + t)^{3/2}(2\sigma_y^2 + t)^{1/2}} \, dt - 2C(x - d)^2 \int \frac{\exp(-\frac{(x-d)^2}{2\sigma_x^2 + t} - \frac{y^2}{2\sigma_y^2 + t})}{(2\sigma_x^2 + t)^{5/2}(2\sigma_y^2 + t)^{1/2}} \, dt \]
Long range tune shift

We get:

\[ \Delta Q \propto C \int \frac{\exp(-\frac{(x-d)^2}{2\sigma_x^2+t} - \frac{y^2}{2\sigma_y^2+t})}{(2\sigma_x^2 + t)^{3/2}(2\sigma_y^2 + t)^{1/2}} dt - 2C(x - d)^2 \int \frac{\exp(-\frac{(x-d)^2}{2\sigma_x^2+t} - \frac{y^2}{2\sigma_y^2+t})}{(2\sigma_x^2 + t)^{5/2}(2\sigma_y^2 + t)^{1/2}} dt \]

👉 First part is classical (head-on) part

👉 Second makes it negative after some separation \( d \)
Complication: orbit effects

We have seen an orbit effect from:

\[
\Delta x' = \frac{\partial U}{\partial x} = C \cdot d \int \frac{\exp\left(-\frac{(d)^2}{2\sigma_x^2 + t}\right)}{(2\sigma_x^2 + t)^{3/2}(2\sigma_y^2 + t)^{1/2}} dt
\]

- If separation \(d\) is changed ➔ kick \(\Delta x'\) is changed
- This changes separation \(d\)
- Requires self-consistent calculation
Long range effects

Self-consistent computations required to find modified orbit

Due to configuration: contributions from many long range interactions ($\approx 120$)

All optical calculation on new orbit

Can be tedious for 2808 bunches ....

Is that all ???

Not yet!

PACMAN bunches ....
Bunches in one beam can see holes in the second beam
Also the case for head-on collisions (see later)
Implies different kicks, i.e. different orbits for all bunches
Oops: self-consistent calculation required for 2*2808 orbits
PACMAN effects

- Due to different number of long range and head-on collisions expected:
  - Systematic tune differences between nominal and PACMAN bunches
  - Systematic orbit differences between nominal and PACMAN bunches
  - Significant difference in tune spread (missing head-on)

- In LHC: alternating crossing scheme (horizontal and vertical crossing planes) removes tune difference by compensation for collisions in IP1 and IP5
Passive compensation

- Opposite sign tune shift can be used for passive compensation

- Low $\beta$ insertions in IP1 and IP5
  - Exactly opposite in azimuth
  - Same bunch pairs colliding !!

- Alternating crossing plane:
  - Vertical crossing angle in IP1
  - Horizontal crossing angle in IP5
Why alternating crossing?

To resolve some recurrent confusion:

What is NOT the reason:

- Compensate or reduce tune spread (footprint) from long range (but becomes symmetric)

What is the reason:

- Avoid PACMAN effects on tune, chromaticity
- Minimize PACMAN effects on orbit, crossing angle

No detrimental effects observed (dynamic aperture, ..)

(see also: session ”Operational Aspects”, Wednesday 20.3. 14:00)
Alternating crossing

Tune footprint, head-on and long range

Tune footprint, combined head-on and long range

Tune footprint becomes symmetric

ICFA Beam-Beam Workshop 2013, CERN, 18.-22.3.2013
PACMAN tune effects: calculation

Horizontal tune along bunch trains with and without alternating crossing (IP1 and IP5)

Predicted tunes from self-consistent computation (see e.g. beam-beam workshop, Fermilab 2001)
Predicted orbits from self-consistent computation (2003)

Vertical offset computed for collision point in IP1

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

→ Predicted orbits at IP1 for beam 1 and beam 2
→ Vertical crossing in IP1 and IP5
→ Optimization will always cause offset collisions
PACMAN Orbit effects: calculation

- Predicted orbits at IP1 for beam 1 and beam 2
- Alternating crossing in IP1 (V) and IP5 (H)
- Optimization will make overlap, but not on central vertex
Measurement of vertex centroid by LHC experiments (ATLAS)

Qualitatively: follows exactly predicted behaviour
Active long range compensation

- At large separation ($\geq 8\sigma$): same force as a wire

- See session on "Beam-beam Compensation", Wednesday 20.3. 8:30

- Compensation with multipoles:
  - Studied for LHC:
    J. Shi et al., Phys Rev. E 69, 036502 (2004)
  - Increases dynamic aperture, but cannot act on PACMAN behaviour (pulsed wire might do it)
  - Beware: do not increase long range non-linearities with multipoles !!
Don’t we have 4 experiments?

- Two experiments IP1 and IP5 opposite in azimuth
- What about IP2 and IP8 ???
  - Nominal LHC:
    - IP1 and IP5: $\beta^* = 0.55\text{m}$
    - IP2 and IP8: $\beta^* = 10.0\text{m}$
  - Larger normalized separation, long range (should be) dominated by IP1 and IP5
  - No compensation, horizontal and vertical crossing planes for other reasons
Implications from long-range beam-beam:

- Long-range beam-beam reduces **dynamic aperture**, i.e. losses and lower lifetime

- Scaling of the losses (parameters we can control):
  - Separation \((\alpha, \beta^*, \epsilon)\)
  - Number of long-range encounters
  - Bunch intensity
  - Usually computed by single particle tracking

- For estimates: extrapolate from 2011 and 2012 experience and model
Which crossing angle do we need?

For comparison → always use normalized separation in the drift space:

\[ d_{sep} \approx \frac{\sqrt{\beta^*} \cdot \alpha \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \]

- Proposed (minimum) separation \( \approx 12 \sigma \)
- Smaller emittance \( \epsilon_n \) allows smaller crossing angle \( \alpha \)
- Crossing angle \( \alpha \) depends on \( \beta^* \) (in crossing plane)!
- Smaller \( \beta^* \) requires increased crossing angle \( \alpha \)
What can happen?

$\beta^*$ was reduced (from 1.5 m to 1.0 m) but crossing angle not increased (IPs 1 and 5)

- Losses at end of squeeze, no collisions yet ...
- Separation for bunches colliding in IP1 and IP5 became too small, strong losses
Scaling laws for long range tune shift $\Delta Q_{lr}$

\[
\begin{align*}
\Delta Q_{lr} & \propto N \quad \text{(Intensity)} \\
\Delta Q_{lr} & \propto n_b \quad \text{(number of bunches)} \\
\Delta Q_{lr} & \propto \epsilon \\
\Delta Q_{lr} & \propto \frac{1}{d_{sep}^2} \propto \frac{1}{\alpha^2} \\
\Delta Q_{lr} & \propto \frac{1}{d_{sep}^2} \propto \frac{1}{\beta^*}
\end{align*}
\]

For dynamic aperture: see following and Dobrin Kaltchev
Test long range interactions with present machine in dedicated experiments

- Trains of 36 bunches per beam
- Spacing 50 ns, maximum 48 parasitic encounters
- Study collisions in IP1 and IP5 (small $\beta^*$ → strong long range), procedure:
  - Reduce crossing angle (separation in small steps)
  - Observe losses bunch by bunch
What do we expect?

Dynamic aperture versus separation

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

Simulations for 50 ns (x) and 25 ns (+)
What do we expect?

Separation changed by:

- Variation of crossing angle
- Variation of $\beta^*$

Suggests strong scaling with separation

"Visible" losses expected for dynamic aperture below $3 \sigma$

corresponding to $\approx 5 \sigma$ separation
First test (2011) with $\beta^* = 1.50 \text{ m}$, intensity: $1.2 \times 10^{11} \text{ p/b}$, emittance: $2.0 - 2.5 \text{ \mu m}$

- 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 - emittances

- Emittances during scan, vertical, beam 2, train 2
- No emittance increase → reduced dynamic aperture

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

Courtesy M. Schaumann
Comparison with our expectations

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

Dynamic aperture as function of normalized separation
(W.Herr, D.Kaltchev, LPN 416, (2008))
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, and exactly reproducible !!

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

- Try an analytical model (allows to study parametric dependencies)

- Based on computation of beam-beam invariants and smear (W.Herr, D.Kaltchev; IPAC09) → D. Kaltchev, this session

- Can compute invariants for individual long range encounters
  - Derive scaling laws for dynamic aperture (losses) etc.
  - Find the ”critical” long range encounters
  - Estimate effects for future machine (in finite time, i.e. without tracking) HL-LHC, HE-LHC
Test of parametric dependence (separation, intensity)

| experiment     | emittance       | $\beta^*$ | Intensity   |
|----------------|-----------------|-----------|-------------|
| 2011 (50 ns)   | 2.0 - 2.5 $\mu$m | 1.5 m     | 1.2 $10^{11}$ |
| 2012 (50 ns)   | 2.0 - 2.5 $\mu$m | 0.6 m     | 1.2 $10^{11}$ |
| 2012 (50 ns)   | 2.0 - 2.5 $\mu$m | 0.6 m     | 1.6 $10^{11}$ |
| 2012 (25 ns)   | 3.5 - 4.0 $\mu$m | 1.0 m     | 1.2 $10^{11}$ |

- Combination of parameters allows parametric studies
- Normalized separation adjusted with $\beta^*$ and crossing angle: $\sqrt{\beta^*} \cdot \alpha = \text{const.}$
- For detailed analysis: see Dobrin Kaltchev, this session
Recent test (2012) with $\beta^* = 0.60\text{m}$, intensity: $1.6 \times 10^{11} \text{ p/b}$

Initial separation $\approx 9 - 9.5 \sigma$

Losses start $\approx 6 \sigma$ separation
Recent test (2012) with $\beta^* = 0.60\text{m}$, intensity: $1.2 \times 10^{11} \text{ p/b}$

Initial separation $\approx 9 - 9.5 \sigma$

Losses start $\approx 5 \sigma$ separation
Scaling laws for long-range dynamic aperture $DA$

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

\[
DA \propto \frac{1}{\sqrt{\epsilon}}
\]

\[
DA \propto d_{sep} \propto \alpha
\]

\[
DA \propto d_{sep} \propto \sqrt{\beta^*}
\]

\[
DA \propto \frac{1}{N} \quad \text{(Intensity)}
\]
Summary - long range beam-beam in the LHC

- Plenty of experience in two years and significant progress understanding
- Long range interactions main source of dynamic aperture
- PACMAN effects very visible - require attention
- Scaling laws have been established, can serve for extrapolation for new configurations
The long range problem

After 2012 (for LHC):

- Effect on dynamic aperture? Yes
- What is the required separation? $\geq 10 \, \sigma$
- Do we have PACMAN effects? Yes
- Do alternating crossing schemes help? Yes
- Can we collide with offset beams? Yes
- Can we predict anything? Yes
The long range problem

After 2012 (for LHC):

- Effect on dynamic aperture? Yes
- What is the required separation? $\geq 10\ \sigma$
- Do we have PACMAN effects? Yes
- Do alternating crossing schemes help? Yes
- Can we collide with offset beams? Yes
- Can we predict anything? Yes
- Do they help for Landau damping? No