Review of instabilities with beam-beam and possible mitigations

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Outlook

• Beam-Beam interactions and instabilities
• Incoherent effects $\rightarrow$ Landau damping
  – Tune spread and Dynamic Aperture
  – Linear Coupling
• Coherent effects
  – Coherent modes
  – Orbit effects
  – Mode Coupling
  – Resonant effects
• Future studies and challenges
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Beam-beam is an effects typical of colliders
It is a very strong effect → high luminosity

It is a fundamental force in all moments of the collider (many of the studies on-going for LHC have started already in the past: Tevatron, SPPS, RHIC, LEP, DAFNE, KEKB, VEPP….)

LHC is still a very good example because:
• It shows a very large variety of instabilities since start-up
• Has very large number of beam-beam interactions of different types
• Good test-bench for new ideas maybe coming from this workshop…
Different particles will see different force

The different effects occur at different stages of the collider cycle

- Injection energy $\rightarrow$ weak long-range BB
- End of the betatron squeeze $\rightarrow$ stronger long-range
- Collision beam process $\rightarrow$ offset collisions
- Head-on collisions $\rightarrow$ crossing angle, luminosity leveling, multiple Interaction points

**Beam-Beam Force**

- **Injection energy**
  - Weak long-range BB

- **End of the betatron squeeze**
  - Stronger long-range

- **Collision beam process**
  - Offset collisions

- **Head-on collisions**
  - Crossing angle, luminosity leveling, multiple Interaction points

Second beam passing in the center

**HEAD-ON** beam-beam interaction (core particles mostly affected)

Second beam displaced offset

**LONG-RANGE** beam-beam interaction (tail particles affected)

Second beam displaced by small offset

**OFFSET** beam-beam interaction (mixed state)

**Beam-Beam force, highly non-linear**

![Graph showing beam-beam force with different interactions](image)
Beam-Beam Force

Beam-Beam force, highly non-linear

Second beam passing in the center
HEAD-ON beam-beam interaction (core particles mostly affected)

Second beam displaced offset
LONG-RANGE beam-beam interaction (tail particles affected)

Second beam displaced by small offset
OFFSET beam-beam interaction (mixed state)

Changes:
- the OPTICS (tune shifts, spread, Q', beating, resonance excitation or enhancement, particle diffusion, distribution modification, reduced dynamic aperture)
- Interplays with the other collective effects (Impedance, electron cloud)
In collider anything that matters in conventional single beam instabilities (i.e. Q’, tune spread, tune shifts, linear coupling…) will be modified by beam-beam. Depending on the operational configuration one can use some beam-beam effects to enhance stability (head-on spread for Landau damping → collision) while others might deteriorate and need to be kept under control (changes in Q’, impact to linear coupling).
Landau Octupole system used almost at full power, very high $Q'$ operation to suppress impedance driven instabilities

Many progresses in the understanding involving several aspects of beam dynamics

Better models developed thanks to experimental evidences and dedicated machine time
Better computational tools, technology made big step for multi particles models reach
Better control of important machine parameters ($Q'$, tunes, linear coupling, optical function)
Better diagnostics $\rightarrow$ head-tail monitors, BTFs, tune and $Q'$ measurements
LHC instabilities over the years

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Still not fully understood → mitigation techniques needs to be improved, be more efficient and new ones explored in all their aspects
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Instabilities occur in the presence of beam-beam → all studies need to take into account the beam-beam effects fully: incoherent and coherent
Outlook

• Beam-Beam interactions and instabilities
• Incoherent effects:
  – Tune spread and Landau damping
  – Dynamic Aperture
  – Linear Coupling
  – Noise
• Coherent effects
  – Coherent modes
  – Orbit effects
  – Mode Coupling
  – Resonant effects
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Non-linearities produce a frequency spread
Beam-Beam is the strongest non-linearity and
the particles with maximum spread are core
particles larger in number and more “reliable”
Frequency spread means Landau damping

Larger frequency spread $\rightarrow$ Stronger Landau damping

A way to quantify the Landau damping is by use of the Stability Diagram

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x, J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

Several references Prof. Vaccaro, Berg-Ruggiero
Beam-beam spread and Landau damping

Beam-beam long-ranges create a tune spread that modifies the tune spread present in the collider (mainly octupole magnets) → beam-beam can reduce the tune spread and consequently the stability area!

Creating large tune spread will provide larger stability area!
Beam-beam long-ranges create a tune spread that can increase consequently the stability area!
But too large tune spread gives unwanted side effects that can deteriorate stability → not all spread gives Landau damping but particles are diffused faster and eventually lost ....
Low Dynamic Aperture reduces Landau damping

\[ \beta = 60 \text{cm} \quad \text{Beam Charge} = 1.8 \cdot 10^{11} \text{p/bunch} \]

Too Large tune spread (by strong non-linearities and high chromaticity) gives resonance excitation, particle distribution modification and reduced dynamic aperture. Do we have more Landau damping?

\[ d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}} \]

- High brightness
- Chromaticity
- Octupoles
Reduced stability for low dynamic aperture

Reduced dynamic aperture $\rightarrow$ acts like a scraper on tails

$\rightarrow$ Stability area is reduced if not optimized at all phases of the collider

Dynamic aperture is sensitive to several-all optical and physics parameter $\rightarrow$
Fundamental a stable and relaxed set of parameter to avoid loss of Landau damping due to low DA

$\rightarrow$ Tune shifts (stabilize at few $10^{-4}$ level any known impact IP2-IP8)
$\rightarrow$ Change in chromaticity (relaxed long-ranges)
$\rightarrow$ Change in linear coupling term not present in this example

**Dynamic Aperture scraps away particles that provide Landau damping**
First attempt to reproduce Stability Diagram

First attempt to characterize experimentally the stability area.
Very challenging already in simple cases, but powerful tool → octupole, chroma scans, BB

**Amplitude Response**

**Phase Response**

Need to develop diagnostic methods for Landau damping!
BTF is one but is it representative of the stability?
Reduced stability with strong beam-beam and linear coupling

- Unexpected behavior w.r.t. models
- Larger stability measured in horizontal plane (3 times larger than expectations)
- Vertical plane sensitive to the tune value (not expected) → other mechanisms plays a role

Ref: L. Carven et al.
C. Tambasco et al.
Reduced stability with strong beam-beam and linear coupling

Creating more spread in not useful if particle distribution is modified strongly
New measurement devices and experimental studies help in guiding models and understanding of the impact of beam-beam on stability
Head-on interaction is the strongest part of the force and can provide the largest stability area and core particles are involved → collision is the most stable moment.
Q’ at zero and Octupoles reduced to zero current
Colliding bunches rock stable - Non-colliding bunches unstable.
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Coherent Modes

Two bunches are “locked” in a coherent oscillation like two coupled oscillators!

- 0-mode is stable (mode with NO tune shift)
- $\pi$-mode can become unstable (mode with largest tune shift)

BB mode is always out of the incoherent spectrum \(\rightarrow\) is not Landau damped

Mathematical Formula:

$$\Delta Q = Y \cdot \xi$$

Ref: Hirata, Alexahin, Herr
Coherent beam-beam modes
Coherent beam-beam modes

Well known: observed and reproduced with models are stable if not excited by some external force.
Asymmetries will break the coherent motion: tune split, intensity un-balance (60%), many long-range interaction (i.e. in LHC).

Ref: Yokoya, Alexahin
Coherent modes

Beam Transfer Function Measurement

Beams Separated

Beams Colliding

<table>
<thead>
<tr>
<th></th>
<th>$I$ $[10^{11}$ p/b$]$</th>
<th>$\epsilon_x[\mu$m rad$]$</th>
<th>$\epsilon_y[\mu$m rad$]$</th>
<th>$\Delta Q = 2 \cdot Y \cdot \xi_{bb}$</th>
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<tr>
<td>B1b1</td>
<td>1.09</td>
<td>2.11</td>
<td>2.05</td>
<td>$1.33 \cdot 10^{-2}$</td>
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<tr>
<td>B2b1</td>
<td>0.891</td>
<td>1.92</td>
<td>2.01</td>
<td>$1.56 \cdot 10^{-2}$</td>
</tr>
</tbody>
</table>
Coherent beam-beam modes are present and many because of the very complex collision schemes in the collider but are not unstable. Also the presence of a transverse feedback helps in reducing their amplitude.
Coherent synchrobetatron beam-beam modes were predicted based on the circulant matrix model and demonstrated experimentally at VEPP-2000.

The same model including the impedance showed a TMCI-like instability due to beam-beam interaction (BBMCI).

Ref: Perevedentsev, Valishev et al.

Ref: S. White, X Buffat
- Instability observed for intermediate separations
- Stability ensured by the transverse feedback
- In agreement with the models
If coherent BB mode couples to impedance mode then instability occurs on both beams. Transverse Feedback efficiently dumps mode coupling instability. Need to keep feedback noise level low to avoid impact to particle distributions.
Instabilities during Adjust Beam Process

Reduced Landau damping and Mode coupling due to offset:

- Impedance and beam-beam Mode coupling fully suppressed by transverse feedback

- Beam-beam changes chromaticity $Q'$ variations (2-3 units) → high chromaticity operation needed

- To avoid minimum of Landau damping to in collision (full head-on damping) faster than rise time of instability
Suppression of coherent beam-beam modes

Several methods of suppression of discreet modes in LHC proposed:

- Splitting bare lattice tunes (A. Hoffman)
- Redistribution of phase advances between IPs (A. Temnykh, J. Welch)
- Different parity of integer parts of the tunes in separate rings (W. Herr)

- Transverse dampers (pickup noise <1 μm required)
- Head-tail damping of dipole oscillations by positive chromaticity
- Landau damping by overlapping synchro-betatron sidebands

Coherent beam-beam modes alone do not represent a limitation but they can couple to impedance and other collective instability

Y. Alexahin 2007
Summary

- **Beam-beam effects** have an important impact on **Landau damping** and the **coherent motion** can enhance instabilities.

- BB interactions **affects the optics** and **the optics changes beam-beam effects** → **all has to be taken into account** because has an impact to stability.
  - Collider optimization (Q’, tunes, linear coupling, beating, phase advance) → hope for more automatized optimizations (**Self consistent treatment of optics and beam-beam**) technology allows larger computations.
  - Problem becomes very complex **multi-parameter optimization** (LHC has learn on-line) → Machine learning can help in optimization of parameters.
  - Such **global optimization** should be endorsed at a design stage in new projects.
  - **Better control** of machine parameters improves knowledge and understanding.
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Nothing new but more pronounced and complex: many IPs, many bunches, pushed parameters and impedances more computing power and techniques
Many of present observations were there in the past …

New design studies should make the effort to boost new development and think differently for the future!
Preliminary results

- Evaluated various machine learning models for the best performance with Gradient Boosted Decision Trees.

- Promising study:
  - Model predicts the optimum working point (red) in agreement with MD data.
  - Trends in beam lifetime vs. time predicted correctly.

- Collective effects are relevant: impedance, electron-cloud, etc. to be taken into account.

Similar idea for simulations!
Thank you!
(1) Observations of beam-beam modes


W. Fisher, et al, Observation of coherent beam-beam modes in RHIC, Proceedings of the Particle Accelerator Conference 2003, Portland, USA


D.B. Shwartz, Recent beam-beam effect at VEPP-2000 and VEPP-4M, Workshop on beam-beam effects in hadron colliders, Geneva, Switzerland, 2013


(8) L. Barraud, Mode Coupling Instability of Colliding beams in the HL-LHC, master thesis, UPMC, Paris

(9) W. Herr, et al., Landau damping of coherent beam-beam modes by overlap with synchrotron sidebands, *LHC Project Note* 304
