Beam-beam and impedance

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Thanks to N. Mounet, T. Pieloni and A. Valishev
Outline

Models

*circulant matrix, multi-particle*

Beam-beam and impedance

*head-on, long-range, offset collisions*

Stabilization techniques

*chromaticity, damper, octupoles, head-on tune shift*

Multi-bunch effects

*Preliminary results*
Models

- Two models were used to study the combined effects of beam-beam and impedance:
  
  -> **Analytical model:**
  - based on the circulant matrix approach by Perevedentsev et al., eigenvalue problem, allows to see all the modes but Landau damping not included

  -> **Macro-particles tracking:**
  - Single bunch 6D kick: based on BeamBeam3D by J. Qiang, slow but fully self-consistent field computation, includes Landau damping
  - Multi-bunch 4D kick: COMBI code by T. Pieloni and X. Buffat

- Complementary tools to understand how these effects couple

- All the following simulations were performed with the 2012 LHC impedance model (N. Mounet, PhD thesis)
Circulant matrix

- The bunch is modeled as an airbag in the longitudinal plane and sliced, each slice being characterized by its coordinates \((x,x')\). The slices are then deposited on a grid which cells are defined by their synchrotron amplitude and phase.
- The transverse motion is modeled by the 2x2 betatron transfer Matrix \(B\), and the synchrotron motion is applied by rotating \((x,x')\) on the grid using a circulant matrix \(C\) defined as:

\[
C_{ij} = \frac{\sin N \varphi_{ij}}{N \sin \varphi_{ij}} \quad \varphi_{ij} = \frac{1}{2} \left( \mu_s - (N - i + j) \frac{2\pi}{N} \right)
\]

- One turn map, one beam: \(M = C \otimes B\)
- One turn map, two beams: \(M_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \otimes M\)
- Beam-beam interaction modeled by a succession of drifts and linear kicks, here for slice 1 of bunch 1:

\[
\Delta x'_{11} = \frac{2\pi \xi}{N \beta} \left[ (x_{11} - x_{21}) + (x_{11} - x_{25}) \right]
\]

- Impedance: \(\Delta x'_{1i} = \sum W(s_{ij} - s_{ii})x_{1j}, W(s) = 0 \text{ for } s < 0\)
The modes are computed with analytical model: with beam-beam only system always stable.

For large ratio $\beta^*/\sigma_s$ – no synchro-betatron coupling introduced by beam-beam: side-bands deflected by $\sim \xi/2$ + coherent modes at Q and $Q-\xi$ (linear beam-beam kick: $Y=1$).

Small ratio $\beta^*/\sigma_s$ – the beam-beam can deflect the side bands – more complex picture.
Comparison with tracking

Three models for the beam-beam kick possible: linear, Gaussian, Poisson solver
Hollow beam + linear kick direct comparison
Used a ratio of $\beta^*/\sigma_s$ of 1 to enhance the coupling
Results qualitatively the same – reflection at +/-2$Q_s$ (in green) seen in the tracking, most likely due to linear bucket
6D Gaussian case rescale by Yokoya factor - most of the modes damped
With beam-beam only : system always stable
→ As the bunch intensity is increased the mode 0 is shifted down until it couples with mode -1 leading to the so-called TMCI (transverse mode coupling instability)

→ Benchmarking was performed using the Headtail code (G. Rumolo PRSTAB, 2002): good agreement

→ The higher TMCI threshold is due to the limited number of slices used in these cases
Comparison with matrix model

- TMCI threshold at $Q' = 0.0$:
  - The tracking is done with Gaussian distribution
  - The matrix model uses equidistant and equipopulated rings: waterbag
  - Probably explains the discrepancies. Still reasonable agreement

- Rise time as a function of $Q'$:
  - In both cases an airbag distribution was used
  - Excellent agreement
Impedance and beam-beam

→ Scan the head-on beam-beam parameters at $Q'=0.0$ and constant wake

→ The beam-beam interaction shifts the $\pi$-mode down faster: coupling between modes 0 and -1 could occur at lower intensity

→ Although the analytical model predicts also coupling between $\sigma$-mode and mode +1 it is not observed in tracking simulations
→ Look at two cases $\xi=0.003$ and $\xi=0.009$:

→ $\xi=0.009$ stable – no emittance blow up observed

→ $\xi=0.003$ unstable – strong emittance blow up leading to reduction of beam-beam parameter – once the modes are decoupled the beams are stable again

→ Instability seen on both beams – both $\sigma$ and $\pi$ modes rising
→ **Single head-on with offset:** coupling between the $\pi$-mode and mode -1 occurs at a separation between 1 and 2 $\sigma$ in this case (depends on $\xi$)

→ **Long-range interactions:** here assumed a separation of 10 $\sigma$ with all the long-range interactions lumped at a single IP. Strong instability observed around the equivalent of 10 long-range interactions for these parameters (depends on $\xi$, phase advances, tunes separation)
Impact of $\beta^*$

$\beta^*/\sigma_s = 90$

$\beta^*/\sigma_s = 1$

→ Decreasing the ratio $\beta^*/\sigma_s$ take the mode apart and the strong instability observed when the modes couple is removed

→ A decrease of the amplitude of the $\sigma$ and $\pi$-mode is also observed when $\xi > Q_s$

→ Additional Landau damping provided by synchro-betatron coupling
Chromaticity

- Chromaticity scan done for $\beta^*/\sigma_s = 70$:
  - $Q' = 0.0$: strong coupling and instabilities
  - $Q' = 2.0$: weaker coupling, the rise time is slower
  - $Q' = 10.0$: modes fully decoupled

→ Chromaticity should help mitigating the coupling instability, the higher $\beta^*/\sigma_s$ the higher the stabilizing chromaticity
Assume an ideal damper (G[1/turn]), Q'=0.0 and $\beta*/\sigma_s = 8$:

→ Mode 0, which is involved in the instability, is strongly damped, so is the instability

→ If Landau damping is sufficient the beam should be stable even at small gain

→ True for head-on interactions, maybe not the case for long-range
Head-on interactions

\[ \beta^* = 0.6 - \xi = 0.003 \]

\[ \beta^* = 0.6 - \xi = 0.003 - Q' = 0.0 \]

→ High chromaticity helps stabilizing although much less efficient at higher \( \beta^* \)

→ Transverse damper very efficient, should be able to cure these instabilities

→ Comments: octupoles have no impact on stability in this case
Long-range interactions

→ Octupoles have a stabilizing effect. For 2x impedance not possible to fully stabilize even at full current

→ Combination of high damper gain and chromaticity should cure instabilities

→ Single bunch simulations, in reality we have as many modes as bunches and things may well be more complicated
→ Track 2x2 bunches such that each bunch has 10 long-range (lumped) + 1 head-on. Each bunch couples with a different counter rotating bunch for the long-range and the head-on

→ Octupoles, damper gain and chromaticity set to 0, both planes look stable over 400000 turns

→ Full head-on has a clear stabilizing effect even without octupoles or damper
Summary of single bunch simulations

- Models fully benchmarked and in good agreement

- When combined coherent beam-beam effects and impedance can give rise to strong mode coupling instabilities similar to the classical TMCI

- Head-on interactions, small $\xi$:
  - Chromaticity alone can stabilize the beams when $\beta*/\sigma_s$ is sufficiently small
  - When $\beta*/\sigma_s$ approaches 1 the instability disappears even at $Q'=0.0$
  - The transverse damper is very efficient
  - Also occurs for offset collisions (going into collision may be critical without damper and large $\beta*/\sigma_s$)

- Long-range interaction $\beta*>>\sigma_s$, lumped interactions:
  - Chromaticity or damper alone is not enough to damp the instability
  - A combined strong damper gain and high chromaticity is effective, optimum balance between the two can be found

- In general, high chromaticity and damper gain are preferable. A full head-on provide a lot of Landau damping and cures all instabilities
Multi-bunch effects

→ At the LHC many bunches will couple together through the long-range interactions and the train structure will introduce PACMAN effects (missing collision)

→ Bunches will also couple through the wake field

→ The complexity of the LHC collision pattern and the train structure makes the single bunch approximation a very poor representation of the reality

• In order to study the multi-bunch effects two models were used:

  → The circulant matrix approach was extended to multi-bunch correctly taking into account the coupling between the different bunches through long-range interactions and wake field

  → Impedance was implemented in the existing COMBI code which is a multi-bunch tracking code
Multi-bunch simulations with circulant matrix:

→ 2x2 no PACMAN effects: 1 long-range per bunch. Similar to single bunch, difference comes from coupled bunch impedance

→ 3x3 no PACMAN effects: 2 long-range per bunch. Coupling instability observed in few places

→ 8x8 with PACMAN effects: all bunches have different number of long-range, very complex picture, coupling instabilities in many places
Benchmarking

→ Comparison with the COMBI code for 36x36 bunches colliding in one IP:

→ Good agreement – instabilities in COMBI around 0.32 due to the other plane. Some discrepancies may be explained by the Yokoya factor (1 for linear model)

→ Done for $Q_s \sim 0.002$ – using the nominal 0.002342 could move the instabilities towards lower separation – to be checked
→ High chromaticity helps

→ Cannot cure all instabilities – consistent with single bunch: for long-range interactions $\beta^* \gg \sigma_s$
Summary

- Numerical tools were developed to study multi-bunch configurations as relevant for the LHC

- Preliminary results, but the codes were benchmarked and are in good agreement

Observations:

- Including multiple bunches drastically increases the complexity of the picture, mode coupling instabilities occur for many tune shifts depending on which bunch/mode is involved
- The effects of chromaticity was tested. High chromaticity helps but cannot cure all the instabilities, consistent with single bunch results

- More studies are required to draw final conclusions (the effect of the damper was not looked at) but preliminary results indicate that the problem cannot simply be reduced to single bunch

- Only the case of a single airbag in the circulant matrix approach was considered: importance of radial modes? This may become relevant when including the transverse damper
Thank you for your attention!