Long-Range Beam-Beam Compensation with Wires

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Abstract

The wire compensation is one of the possible LHC upgrade plans to overcome the beam-beam limit. We present weak-strong simulation results for the effect of long-range beam-beam interaction (LR-BBI) in LHC. In particular, we discuss the effectiveness of compensation, the difference between nominal and PACMAN bunches for the LHC, and wire tolerances.

INTRODUCTION

The short bunch spacing in the LHC of 25ns causes 15 LR-BBI to occur at each side of each IP. The design crossing angle $\theta = 300\mu rad$ was chosen as trade off between beam-losses due to long range beam beam interaction and geometric luminosity losses and triplet aperture. Still the nonlinear forces will cause beam blow up and beam loss. As this distortion is proportional to the bunch population, the bunch spacing and the crossing angle, any upgrade scenario, aiming to tighten one of these parameters, will make the situation even worse.

The nonlinear field due to an opposing bunch (e.g: round Gaussian beam shape: $\Delta x' \propto 1/r(1 - e^{-r^2/\sigma^2})$) is - within limits - comparable to the one of a current carrying wire ($\Delta x' \propto 1/r$). Therefore we studied the idea of installing wires into the beam pipes at both sides of the IP at locations where the two beams are already separated (Fig:1). In the nominal case a current of 81A for a 1m long wire at a distance of 9.5$\sigma$ from the beam-center would be ideal. The wire current can be adapted to compensate for a higher bunch population or a higher number of bunches.

The compensation will not be perfect for a number of reasons: there remains a small discrepancy in the field shapes, there is a finite phase advance between the LR-IPs and the wire (on average 2.6°), there is a variation of the beam-beam spacing between the different long range beam beam encounters (LR-IPs, min: 7$\sigma$, max: 13$\sigma$), and the actual beam might deviate from a perfect Gaussian shape. Furthermore there it might be necessary to offset the wire from its optimal position (the wire must be positioned in the shadow of the collimators instead of at the optimal distance (9.5$\sigma$)).

Weak strong simulations were performed using BBTrack [1]. In order to find the dynamical aperture (DA) particle distributions (off-momentum by $\delta p = 2.7 \times 10^{-4}$) were tracked for 300,000 turns and the stability evaluated using the criterion of nonzero Lyapunov exponent. In addition to the beam-beam interactions triplet errors and their correctors were included in the simulation model.

NOMINAL

Bunches in the center of a bunch train are affected by all LR-BBI at both sides of the IP and are referred to as nominal ones. The significant tune spread can be seen in Figure 2. The DA is found at 6.2$\sigma$

![Figure 2: LRBBI affecting a nominal bunch](image)

**Optimal compensation**

The tune shift due to a wire alone is in the opposite direction and is depicted in Figure 3 a. The optimal compensation is given for 81A at 9.5 sigma from the beam center. This improves the DA by $1\sigma$ and eliminates the tune spread due to the LR-BBI almost completely (fig: 3 b).

![Figure 3: The optimal wire compensation](image)
**Larger Wire Separation**

In the introduction it was mentioned that it might not be possible to position the wire compensator at 9.5σ but it might have to be positioned further out. The difference in distance might be partially compensated for by increasing the wire current, but the mismatch in field pattern reduces the effectiveness slightly. Figure 4 shows the compensation of a nominal LHC bunch by wires at 11σ. The border of stability is found at 6.7 σ, still improving by 0.5 σ compared to the uncompensated case.

![Figure 4: Footprint of a nominal LHC bunch with compensation at 11σ](image)

**ULTIMATE**

The most straightforward upgrade scenario, increasing the bunch population, was chosen as an example, to study the benefit of the wire compensator for an LHC luminosity upgrade. The wire current is adapted to fit the new requirements. An increase from 1.15E11/bunch to 1.725E11/bunch would reduce the DA to 4.5σ. In this case the wire compensation could recover 2 σ. The dynamical apertures for the different cases are summarized in table 1.

<table>
<thead>
<tr>
<th>protons/bunch</th>
<th>DA uncompensated</th>
<th>DA compensated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15E11</td>
<td>6.2</td>
<td>7.2</td>
</tr>
<tr>
<td>1.725E11</td>
<td>4.5</td>
<td>6.5</td>
</tr>
<tr>
<td>2.3E11</td>
<td>3.8</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 1: Comparison between the uncompensated and the optimal (9.5σ) compensated case

The nominal compensation will overcompensate these bunches. The uncompensated DA is found at 6.7 σ. The nominal compensation reduces this slightly to 6.4σ.

![Figure 5: 1.715E11 protons/bunch](image)

**Adapted compensation**

It would be of interest to adapt the wire current to the specific bunches. In a first approach one can try to find a trade off in performance of a DC wire between nominal and Pacman bunches (Fig:8). Individually adapting the wire current poses severe technological problems as this would require switching times of the order of 400ns on a inductive load. Furthermore any turn-to-turn jitter would cause emittance blow up. From figure 7b) one can find that a turn to turn jitter of 4mA (=0.02ns assuming for a linear ramp) results in a 10 % emittance increase within 20 h.

![Figure 6: Tune footprints of the uncompensated and nominally compensated Pacman bunches](image)

**PACMAN BUNCHES**

Pacman bunches are bunches at the start and end of a bunch train which will experience a reduced number of LRBBI. In the following we show simulation results for the very last ones (the extreme Pacman bunches), which encounter no LRBBI at one side of the IP. The nominal compensation will overcompensate these bunches. The uncompensated DA is found at 6.7 σ. The nominal compensation reduces this slightly to 6.4σ.

![Figure 7: A pulsed compensation scheme compensates also the Pacman bunches perfectly but poses severe technological challenges](image)

\[ \Delta \varepsilon = 4E - 9 \Delta \tau^2 \]
SUMMARY & OUTLOOK

In simulation the wire compensation proves to an effective remedy for the LRBBI of nominal and Pacman bunches. A pulsed device is a desirable upgrade option, promising even better performance, but faces significant technological problems. In the future, it will be studied whether the transverse feedback can be used to relax the requirements.

REFERENCES