Experimental tests for BBLR compensation with wires in the LHC

S. Fartoukh, Y. Papaphilippou, A. Poyet, A. Rossi and G. Sterbini on behalf of the BBLR wire compensation team.

Special thanks to HL-LHC WP2, WP5, WP13 and LHC MD coordinators.
Outlook

- Introduction of the wire compensation.
- Optimization of the wires settings and experimental constraints.
- Experimental results.
- Plans and summary.
Since 2018 four wires prototypes (BBCW) are installed in LHC (B2, IR1+IR5) with the aim to explore a scenario beyond the Baseline: local compensation of the beam-beam long-range (BBLR) with DC wires.
Integration of the prototype in the collimator

- The **wire-beam distance has to be of the order of few mm** (function of $\theta_c$, s-position and machine optics): LHC wires prototypes are embedded in the jaw of three operational tertiary collimators.

- During the 2018, it was performed a complete test campaign to ensure the correct functioning of the wire interlocks, the collimator motors and PUs when the wire is powered therefore to preserve the full functionality of this device as collimator.

![Image of wire-beam distance and maximum current](image_url)

**Maximum Current $I_w=350$ A**

**Courtesy of F. Carra**
Wire settings for RDT compensation

We used the RDT criterion presented and described in details in

- It is shown as a numerical evidence that by compensating 4 RDTs with 2 wires one can minimize ALL RDTs provided that the wires s-position of BBCW is conveniently chosen.
- In case of sub-optimal s-position, beam-wire distance only a subset of RDT can be compensated.
**IDEAL settings** \((\beta^* = 30 \, \text{cm}, \theta_c/2 = 150 \, \mu\text{rad})\)

**Optimal** \(I_w = 103 \, \text{A} \) for \(1.15 \times 10^{11} \, \text{pbb}\)

**Optimal s-position** = \(\pm 158.3 \, \text{m}\)

**Optimal beam-wire distance** = 5.7 mm

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**Results of the Beam-Beam Long-Range compensation experiment in LHC**
REAL s-position (II)

Optimal s-position = ± 158.3 m
⇒ It was not possible to install the wires at the optimal s-positions.

The ideal s-position of the BBCW is ±158.3 m from the IP5. The actual s-positions are -150.03 and +147.94 m.

Results of the Beam-Beam Long-Range compensation experiment in LHC

Even a small modification of the s-coordinate has an impact on the symmetry and the optimal beta ratio.
Optimal beam-wire distance = **5.7 mm**

⇒ It is not possible to operate the wires at the optimal distance wrt the beam.

### WIRE COLLIMATORS with SETUP BEAM

- **5.5 σ_{coll}**
- **3 mm**

### Table:

<table>
<thead>
<tr>
<th>Wire</th>
<th>Plane</th>
<th>Wire-beam distance [mm]</th>
<th>σ_{coll} [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>V</td>
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</tr>
<tr>
<td>L1</td>
<td>V</td>
<td>-7.41</td>
<td>0.80</td>
</tr>
<tr>
<td>R5</td>
<td>H</td>
<td>+8.24</td>
<td>0.95</td>
</tr>
<tr>
<td>L5</td>
<td>H</td>
<td>-7.15</td>
<td>0.75</td>
</tr>
</tbody>
</table>

** Courtesy of R. Bruce **
IDEAL ⇒ REAL: back to 2 RDTs compensation

Technical constraints: only two RDTs with the 2 wires at the same jaw position in $\sigma_{\text{coll}}$.

• We choose to compensate (4,0) and (0,4): first order amplitude detuning.

• Tracking studies needed for tuning the optimal position and current [See Kyriakos’s presentation].

(4,0)-(0,4) RDT Compensation
$\beta^* = 30 \text{ cm}, \theta_c/2 = 150 \mu\text{rad}$
IDEAL ⇒ REAL: asymmetric filling scheme

- To approach the wire to the beam the B2 has to be $<3\times10^{11}$ p (SETUP BEAM).
- We will mainly concentrate on the two bunches of B2 (Only HO and HO+BBLR).

![Graph showing filled and empty bunch slots](image)

**Missing head-on:** stability issues.

**Limited statistics**
Objectives of the experiments

- Prove the beneficial effect of the WIRES in a regime dominated by long-range beam-beam effect, ensuring in the mean time that the linear effects of the wire (orbit and tunes) are compensated with feedforwards. Our privileged observable is the bunch “effective cross-section”:

\[
\sigma_{EFF} = \frac{1}{\sum_{IP} L_{IP}} \frac{dN}{dt}
\]

- Intensity loss-rate

- Instantaneous luminosity

Results of the Beam-Beam Long-Range compensation experiment in LHC
- Introduction of the wire compensation.
- Optimization of the wires settings and experimental constraints.
- Experimental results.
- Plans and summary.
Getting from 6 to 5.5 $\sigma_{\text{coll}}$ (only 2 wires)

Positive effect of the wires visible on beam lifetime.

Results of the Beam-Beam Long-Range compensation experiment in LHC
Positive effect of the wires visible on the bunch affected by the beam-beam long-range. Super-PACMAN unaffected.

Results of the Beam-Beam Long-Range compensation experiment in LHC
First tests with the 4 wires

- Results of the MD jeopardized by the strong beam instability after SQUEEZE. Mainly used for checking the alignment and the feedforwards.
Alignment of the TCTPV

The 5th axis “manual” alignment performed during TS1.

Credit to N. Fuster, S. Redaelli, A. Poyet, A. Rossi, I. Lamas Garcia
The 4 wires where powered to check the Q-feedforwards. As expected the R1 feedforward was less efficient (solved with the 5th axis manual alignment in TS1).
Compensation with 4 wires. The effect of the IR1 wires is less evident if compared with the effect of the IR5 wires.
Test with standard B2 emittance (no BU). A marginal effect of the wires is still visible.
- Very clear effect of the compensation even at reduced crossing (130 μrad).
As an end-of-MD test the right wires were switched ON ($\beta^*=30$ cm and $\theta_c/2=150$ mrad). Signals from dBLM are compatible with reduction of losses on the bunches suffering beam-beam long-range.
Can we use trains of bunches?

- During TS2 the wires were re-cabled in series.
- In this way (only for the “even” multipoles) one double the available $I_w$ and could see an effect also at nominal position.
- ⇒ End-of-Fill MDs requested and dedicated MD allocated for that purpose.
- The goals is to explore the potential of this setup in operational conditions.
Summary and next steps

- During the last year a rich measurements program to explore the potential of the wire compensation in HL-LHC was performed. A positive effect of the compensation was systematically observed even within the constraints of a sub-optimal setup.

- All the measurement were conducted with round optics and almost the totality with SETUP beam.

- A new cabling of the wires was realized during the TS2: this open the way to test the wires in nominal condition (EoF requested and MD4 slot probably available).

- Next step is the study optimal technical implementation of wires in the HL-LHC layout (⇒next 2 talks).
Thank you for the attention!

On behalf of the BBLR wire compensation team

BACK-UP SLIDES
**Vertical alignment of beam-wires**

- Important vertical offset (up to 5 mm) to be corrected with the vertical alignment procedure. Not trivial due to lack of V PUs.
Pushing B2 to the BBLR regime

To increase the BBLR effect:

1. **B2 H-emittance blown-up** to 5-6 mm mrad [credit to D. Valuch, S. Papadopoulou and M. Fitterer].

2. The tunes were set to a **sub-optimal working point** (0.31, 0.32).
IDEAL BBCW settings ($\beta^* = 30$ cm, $\theta_c/2 = 150$ $\mu$rad)

Optimal $I_w=103$ A for $1.15\times10^{11}$ pbb
Optimal s position = $\pm 158.3$ m
Optimal beam-wire distance = 5.7 mm

![RDT compensation map]

The green boxes are the 4 RDTs used to set $N_w$ and $d_w$

'0' means FULL compensation

Results of the Beam-Beam Long-Range compensation experiment in LHC
Local correction in Q4/5. Motivation and implication.

β-beating corrected using the Q4 and Q5 (350 A at 5.5 $\sigma_{\text{coll}}$). Provided that **PC interlock settings** on these 8 quads is relaxed during the MD.

An example of β-beating induced by a wire (R5, 350 A at 5.5 $\sigma_{\text{coll}}$)
From the formalism to the experiment

We will consider the LHC optics used in the second part of 2017 (ATS with $\beta^*=30\text{ cm}$, $\theta_c/2=150\mu\text{rad}$). It corresponds to the condition of the second experiment (we will consider only IP5).

A. Poyet

We consider 25 encounter per side of the IP.
The wires were switched ON-OFF for several powering cycles.

During the powering of the wires, the tunes of the beam (and its position) has to be controlled with high precision: dipolar and quadrupolar contributions of the wires were compensated with feed-forward trims [credit to M. Solfaroli and G.-H. Hemelsoet].
Results of the Beam-Beam Long-Range compensation experiment in LHC

From 2 to 4 wires (validation)

No BBLR signature!

HO behaves better if we switch of IR1 wires

Very rapid scan

Credit to A. Poyet
The **TCLVW.A5L1.B2** is NOT an operational collimator.
Compensation studies: from LHC to HL-LHC

- In the beam-beam team, significant efforts are put on the wire compensation tracking studies with the two-fold aim to benchmark the LHC results and optimize the HL-LHC scenario with the wires.

- For HL-LHC, preliminary results without a full optimization of the longitudinal and transverse wire position, are showing an additional gain of the order of 30 µrad for the half-crossing angle.

Distance Beam-Wire [σ, εᵣ=2.5 μm]

8.4  12.6  16.8  21

Distance Beam-Wire [mm]

4.5  6.16  7.82  9.48  11.14  12.8

Wire Current [A]

0  100  150  200  250

Xing/2 [µrad]

4.0  6.0  8.0  10.0

Results of the Beam-Beam Long-Range compensation experiment in LHC

Preliminary HL-LHC start of the levelling

Courtesy of D. Pellegrini
Analysis of the BBCW compensation

- Given the constraint on the minimal beam-wire distance, it was not possible to compensate all the resonances excited by the B1.

- We used the maximum current of the wires (350 A) to attack as much as possible the BBLR octupolar term.

- The octupolar terms induced by the BBLR in IR5 was reduced by 75%.
- 10 h MD.
- The FILL5898 was dumped (RF on B1, not clear the reason, RF experts suggest a glitch on the interlock). Half-RF detuning.
- The observations we report concern the FILL5900. Full-RF detuning.
**IDEAL CASE: 2 BBCW for IP at s_{opt}=+-159 m**

As expected (under the mentioned assumptions) the compensation is covering many more RDTs than the 4 used to set the BBCWs (green boxes). The p+q=1 and p+q=2 could be addressed by using “local” linear magnets (Q4s and the Q4 correctors).
The observed effect of the BBCW can be related to a partial compensation of the detuning terms.
IDEAL CASE: considering the phase advance.

One can quantify a posteriori the effect of the phase advance. The compensation of the RDT does degrade. The compensation of detuning terms (Q-footprint compression) is not affected.
DA simulations with Wire in MD-like conditions

- MD-like conditions: $d_w = 8$ mm. LR in IR1/5 but wire only in IR1, real aspect ratio at wire position, phase advances.
- A modest gain of DA is observed for 8 mm wire-beam distance.
- Optimal DA for 800 A.
- With no rematch of the chromaticity (as in the MD), the gain of DA is improved.

- Good agreement between footprints from MADX and Sixtrack.
- Improvement observed but no clear identification of the optimum.

K. Skoufaris

First results from LLRB MD
DA simulations with Wire in MD-like conditions II

- Push $d_w$ to 6 mm
- Still not ideal conditions: LR in IR1/5 but wire only in IR1, aspect ratio at wire position, phase advances.
- $1\sigma$ (@2.5 μm) DA gained for an optimal wire current of ~400 A.
- Clear improvement over all the angles.

CMS & ATLAS: HO + LRBB; $Q'=(15,15)$; $Q=(62.31,60.32)$; $I_{MO}=510.7\,A$; $\beta^*=40\,cm$; Xing=120μrad; wire_dist = 6mm

K. Skoufaris
“Strong beam”-wire equivalence: tracking

- The zero-emittance-LR strong beam does not show a better DA.
- Effect of phase advance? Plans to test with the wire at ~70 m for better phases.
“Strong beam”-wire equivalence

- For $\beta_x \neq \beta_y$ the “strong beam”-wire equivalence is not valid anymore
- We compare the strong beam field and the wire field in terms of multipoles
- Case 1: $\beta_x = \beta_y$, perfect equivalence
- Case 2: $\beta_x = 4 \beta_y$, see plot below
- Case 2: $\beta_y = 4 \beta_x$, plot below
- We assume bi-Gaussian density ($4\sigma$ cut)
First attempts of BBCW in HLLHC1.3

- B1 tracking with operational settings for emittance, tunes, chroma, octupoles.
- 4 wires (L/R IP1/5) installed in the crossing plane.
- The wires are arbitrarily placed at +/-150m from the IPs.
- The distance is tuned so that the beam-wire normalised separation is the same as the normalised crossing.
- Likely a suboptimal configuration to be further refined.

<table>
<thead>
<tr>
<th>β* = 60 cm</th>
<th>H Beta [m]</th>
<th>V Beta [m]</th>
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<tbody>
<tr>
<td>wire_l1.b1</td>
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<td>wire_r1.b1</td>
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<table>
<thead>
<tr>
<th>β* = 20 cm</th>
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<tr>
<td>wire_r5.b1</td>
<td>3636</td>
<td>3003</td>
</tr>
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</table>
The H-position of the beam is well under control.

The V-position and correctors behaviour confirm a very good V-alignment of the BBCW.
The Q-trims are mostly due to the feedforward.
BBCW MD: dipolar trims

The correctors trims are mostly due to the crossing angle settings.
BBCW MD: optimizing HO collision
BBCW MD: wires H-positioning

The hectic activity on the BBCW positioning.
During next MD we will use stronger octupole settings to avoid the instability of the non-colliding bunches in B1.
ATS 2017 optics

<table>
<thead>
<tr>
<th>NAME</th>
<th>X</th>
<th>PX</th>
<th>Y</th>
<th>PY</th>
<th>BETX</th>
<th>BETY</th>
<th>sigma_x at 3.5 um at 6.5 TeV [mm]</th>
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<td>0.825659</td>
</tr>
</tbody>
</table>

Physical separation of BBLRs

Normalized separation of BBLRs
By plotting the $N_w(s)$ and $d_w(s)$ for different RDT minimization strategy, one sees there are specific $s$-positions, $s_{\text{opt}}$, that minimizes more than the usual 4 RDTs.

The BBCW is positioned $\sim 10$ m apart with respect to the optimal position.
### $s_{\text{opt}}$, $N_w$ and $d_w$ on crossing angle

- There is no dependence of $s_{\text{opt}}$ on the crossing angle.
- $N_w$ dependence on the crossing angle is marginal (smaller crossing angle, smaller $N_w$).
- $d_w$ is linearly dependent on the crossing angle.
The $s_{\text{opt}}$ depends on the PACMAN pattern.
BBCW impact of the beam profiles (I)

- A very detailed presentation by Miriam and Stefania at https://indico.cern.ch/event/658908/
BBCW impact of the beam profiles (II)

- A very detailed presentation by Miriam and Stefania at https://indico.cern.ch/event/658908/

Beam size change is consistent with beta-beat (decrease of beta) + the profile changes observed
Results on the compensation (I)

- Compensation seen from the $\sigma_{eff}$ [credit to N. Karastathis].
- Clear effect on the BBCW when switching-off: signal compatible with a contraction of the dynamic aperture of the machine.

![Graph showing results of the Beam-Beam Long-Range compensation experiment in LHC](image-url)
Result on the compensation (II)

- Using dBLM signals to compute the cross-section [credit to A. Poyet, A. Gorzawski]: **improved time resolution.**
- A constant calibration factor was adopted to rescale the BLM reading to the FBCT losses.
Result on the compensation (III)

- From the bunch-by-bunch intensity signals we can measure the effectiveness of the compensation on the losses [credit to M. Hostettler].
- Clear effect of the BBCW.