First Results of the Compensation of the Beam-Beam Effect with DC Wires in the LHC

Outlook

- Introduction on the wire compensation.
- Experimental constraints and optimization of the wires settings.
- Experimental objectives and results.
- Benchmarking with simulations.
- Next steps and summary.
Historical background

- Experimental tests of DC wires in SPS, RHIC and DAΦNE. Never tested in hadron colliders with operational configurations
- Need for direct experiments in LHC.
The wire compensation principle I

1. The electromagnetic kick of the long-range beam-beam effect is similar to the one given by a DC wire.

2. Analogy of the wire field with standard multipole magnets → Resonant Driving Terms compensation [S. Fartoukh et al., PRST-AB 18, 121001]

![Graph showing the comparison between Beam-Beam kick and Wire's kick vs. beam-beam or beam-wire distance]
Since 2018 four wire demonstrators are installed in LHC (B2, IR1+IR5) with the aim to explore the potential of the wires in (L. Rossi, MOYPLM3).
Wire-in-collimator demonstrator

- LHC wire demonstrators are embedded in the jaw of operational tertiary collimators.
- 1-m long Cu wire of 2.48 mm diameter capable to carry up to 350 A.

Maximum Current $I_W = 350$ A

Top view

Front view

Courtesy of F. Carra

Courtesy of L. Gentini
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Longitudinal position of the wires

- The longitudinal position of the wires was driven by the present position of the collimators and the integration constraints.
- Symmetric position in the IR5.

<table>
<thead>
<tr>
<th>Wire demonstrator</th>
<th>s from the Interaction Point [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1, collimator not-used in operation</td>
<td>-176.17</td>
</tr>
<tr>
<td>R1, tertiary collimator</td>
<td>145.94</td>
</tr>
<tr>
<td>L5, IP debris collimator</td>
<td>-150.03</td>
</tr>
<tr>
<td>R5, tertiary collimator</td>
<td>147.94</td>
</tr>
</tbody>
</table>
The wire are installed in the crossing plane of the Interaction Region, i.e.,
- vertical in IR1,
- horizontal in IR5.

Given the constraints of the LHC collimation hierarchy, two classes of experiments were performed

1. **LI: Low Intensity** experiment (only 2 bunches in Beam 2) with wire-collimator just in the shadow of the primary collimators

2. **HI: High-Intensity** experiment (bunch trains in Beam 2) with wire-collimator at the operational position.

<table>
<thead>
<tr>
<th>Wire demonstrator</th>
<th>LI experiment</th>
<th>HI experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>beam-wire distance [mm]</td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>-7.41</td>
<td>not powered</td>
</tr>
<tr>
<td>R1</td>
<td>7.42</td>
<td>9.83</td>
</tr>
<tr>
<td>L5</td>
<td>-7.15</td>
<td>not powered</td>
</tr>
<tr>
<td>R5</td>
<td>8.24</td>
<td>11.10</td>
</tr>
</tbody>
</table>

An $\varepsilon_n$=3.5 mm mrad assumed.
Filling schemes and beam-beam encounters

- In the **LI experiment** the first bunch of B2 see only two head-on’s (in IP1 and IP5) and the second bunch experiences head-on and long-range encounters.
- In the **HI experiment** we have a rich distribution of beam-beam interactions in IR1/5.
The experimental setup allowed to minimize only two Resonance Driving Terms.

We set the wire currents to compensate the \((4,0)\) and \((0,4)\) RDT: first order amplitude detuning.

For the HI experiment, due the larger beam-wire distance, the current for the compensation is not compatible with the standard wire configuration.
In the wire-collimator, both jaws house a wire.

In the **LI experiment** only the wire of one single jaw was powered.

For the **HI experiments** the wires of both jaws were powered: this allowed to double the integrated strength of the quadrupolar, octupolar, etc., components.

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<th>HI experiment</th>
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<tbody>
<tr>
<td></td>
<td>Current [A]</td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>350 x 1</td>
<td>not powered</td>
</tr>
<tr>
<td>R1</td>
<td>320 x 1</td>
<td>350 x 2</td>
</tr>
<tr>
<td>L5</td>
<td>190 x 1</td>
<td>not powered</td>
</tr>
<tr>
<td>R5</td>
<td>340 x 1</td>
<td>350 x 2</td>
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Objectives of the experiments

- Prove a beneficial effect of the wires demonstrators in a regime dominated by long-range beam-beam effect. The compensation should not degrade the lifetime of the head-on bunches.

- We need to guarantee the beam-wire alignment and that the linear effects of the wire (orbit and tunes) are compensated with feedforwards.

- The main observables are the beam losses, its lifetime and the bunch effective cross-section ($\sigma_{\text{eff}}$).

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

Intensity loss-rate

Instantaneous luminosity

Ideal experiment

- WIRES OFF Long-range dominated
- WIRES ON Long-range compensated

Burn-off efficiency [%]

$\sigma_{\text{eff}}$ [mbarn]

t1 time

IPAC19, G. Sterbini
The experimental campaign

- A rich experimental campaign was performed during the last 2 years: the compensation effect was systematically observed.

Winter 2017-18
Installation of the IR1 wires

Experiment with wires in IR1 and IR5

Experiment with wires in IR1

LI experiments

HI experiments

From SETUP BEAM to TRAINS

26th July 2018
FILL6984

24th July 2018
FILL6972

4 wires compensation

14th September
FILL7169

Reducing crossing angle

29th October
FILL7386

29th November 2017
FILL6434-6435

Compensation with 2 wires

29th November 2017
FILL6434-6435

Compensation with 2 wires (validation)

1st July 2017
FILL5898-5900

Compensation with 2 wires (validation)

1st July 2017
FILL5898-5900

From 2 to 4 wires (validation)

14th June 2018
FILL6797-8-9

HI experiments

HI experiments

15th IPAC19, G. Sterbini
Low-Intensity experiment

Almost full compensation, even at reduced crossing angle, for regular bunch whereas head-on bunch not degraded.
Hi experiment (operational conditions)

29th October 2018 - FILL 7386, $Q=(0.313,0.317)$, $\xi=(7,7)$

- Compensation provides a reduction of B2 losses of $\sim 20\%$. 
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Simulations of the LHC experiments

- The experimental configuration was simulated using Dynamic Aperture (DA) tracking.

- Correlation between DA and beam lifetime was studied in D. Pellegrini et al., Incoherent beam-beam effects and lifetime optimization, 8th LHC Operation Evian Workshop, 2018.

- Simulations show a large compensation area corresponding to the (4,0)-(0,4) RDT minimization. A clear effect on the compensation is also visible by parametric studies on the tunes plane.
Simulations of the LHC experiments

- The configuration of the LI experiment was simulated with numerical tracking and the machine Dynamic Aperture (DA) was observed.

- Simulations show a large compensation area corresponding to the (4,0)-(0,4) RDT minimization.

- A clear effect on the compensation is also visible by parametric studies on the tunes plane.
Simulations of the HL-LHC case

- A systematic numerical study was performed for the HL-LHC scenarios (focusing on round optics).

- In the HL-LHC (round optics), up to 2 $\sigma_{\text{beam}}$ in DA can be gained with the wire compensation. The results suggest the possibility to trade-off beam-wire distance with wire current.

- A significant improvement in the tunes plane was observed also in this case.
Simulations of the HL-LHC case

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Introduction on the wire compensation.

Experimental constraints and optimization of the wires settings.

Experimental objectives and results.

Benchmarking with simulations.

Next steps and summary.
Following these encouraging results, it was proposed:

- **to use the wires routinely** during the next LHC operation period in the High-Intensity configuration.
- **to equip also the Beam 1** with wires by moving two wire demonstrators (L1 and L5) from Beam 2 to Beam 1.

First iterations for a **HL-LHC wire design** are on-going.
Next steps and proposals

- Following these encouraging results, it was proposed
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Summary

- In 2017-18 a rich measurements campaign was performed to explore the potential of the wire compensation for HL-LHC. For the first time in a hadron collider, the positive effect of the compensation was systematically observed in operational-like conditions. Following this results we proposed to use the wire demonstrators operationally for the next LHC run.

- Simulations results are consistent with measurement and the explored scenarios confirm the wire potential for HL-LHC. It can relax the HL-LHC operation in several directions (crossing angle reach, triplet irradiation and available tune space).

- First iterations for a HL-LHC wire design are on-going. Our next objective is to prepare a proposal for a technical review.
Thank you for the attention.

On behalf of the HL-LHC wire compensation team


and all participants to the design, production and commissioning of the wire compensator demonstrators.
BACKUP SLIDES
Low-Intensity experiment

- ~80 mb Wire alignment
- Transverse blow-up and BBLR signature
- Current scan example

14th September 2018 - FILL 7169, Q=(0.31, 0.32), ξ=(15,15)

- Reduction of crossing angle

- Almost full compensation, even at reduced crossing angle, for regular bunch whereas head-on bunch not degraded.
HI experiment (operational conditions)

- Compensation provides a reduction of B2 losses of ~20%.

Reduction of crossing angle

COMPENSATION ON

COMPENSATION OFF

29th October 2018 - FILL 7386, Q=(0.313,0.317), $\xi=(7.7)$

Very good reproducibility