CERN

The BBWC experimental program in LHC and potential for HL era

1. Introduction
2. The BBWC experimental program in LHC
3. The BBWC performance in HL-LHC era

G. Sterbini on behalf of and indebted to many colleagues[1]

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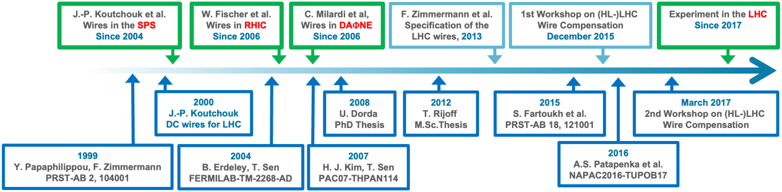
[1] See a selection of publications.

Beam-beam wire compensation in the last 25 years



J.-P. Koutchouk et al.
Wires in the SPS
Since 2004

W. Fischer et al.
Wires in RHIC
Since 2006

C. Milardi et al,
Wires in DAΦNE
Since 2006

F. Zimmermann et al.
Specification of the
LHC wires, 2013

1st Workshop on (HL-)LHC
Wire Compensation
December 2015

Experiment in the LHC
Since 2017

1999
Y. Papaphilippou, F. Zimmermann
PRST-AB 2, 104001

2000
J.-P. Koutchouk
DC wires for LHC

2004
B. Erdeley, T. Sen
FERMILAB-TM-2268-AD

2007
H. J. Kim, T. Sen
PAC07-THPAN114

2008
U. Dorda
PhD Thesis

2012
T. Rijoff
M.Sc.Thesis

2015
S. Fartoukh et al.
PRST-AB 18, 121001

2016
A.S. Patapenka et al.
NAPAC2016-TUPOB17

March 2017
2nd Workshop on (HL-)LHC
Wire Compensation

- Interest in testing experimentally the BBWC principle arose soon after the seminal papers.
- The wire excitation and compensation was tested in SPS, RHIC and made operational in DAFNE.
  (I will add few plots on SPS, RHIC and DAFNE wires)

HL-LHC wire demonstrators

→ **4 proof-of-principle demonstrators** installed in LHC since 2017 for Run 2 MDs[2],

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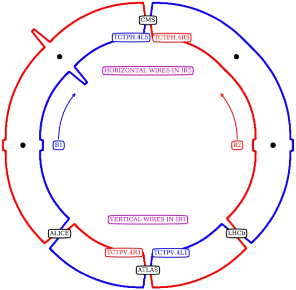
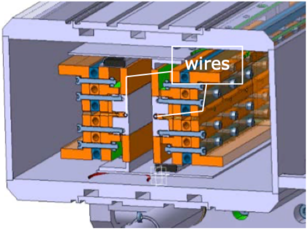
[2] A. Poyet et al., PRST AB **27** 071003 (2024)

HL-LHC wire demonstrators

- → **4 proof-of-principle demonstrators** installed in LHC since 2017 for Run 2 MDs[2],
- → **embedded in operational tertiary collimators**
  - **L1B1** and **R1B2** in IR1 (V-plane, $s_{IP} \approx 146$ m)
  - **L5B1** and **R5B2** in IR5 (H-plane, $s_{IP} \approx 148$ m)
- → each jaw has a **1 m** long, $\varnothing$=**2.48 mm** Cu wire carrying **350 A**.





Courtesy of A. Poyet and A. Rossi.

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[2] A. Poyet et al., PRST AB **27** 071003 (2024)

From Run 2 tests to Run 3 operations

→ **use the demonstrators in Run 3 production fills**.

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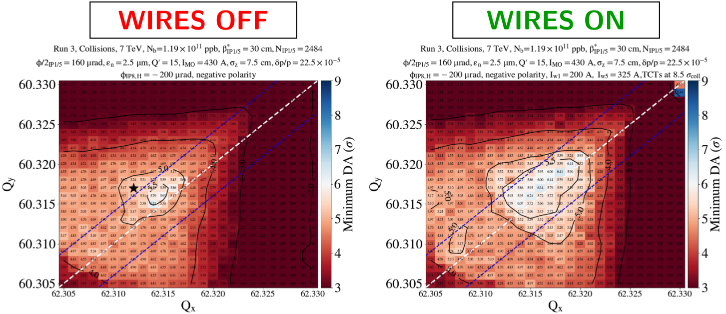

DA simulations of the wire impact in Run 3. Courtesy of S. Kostoglou.

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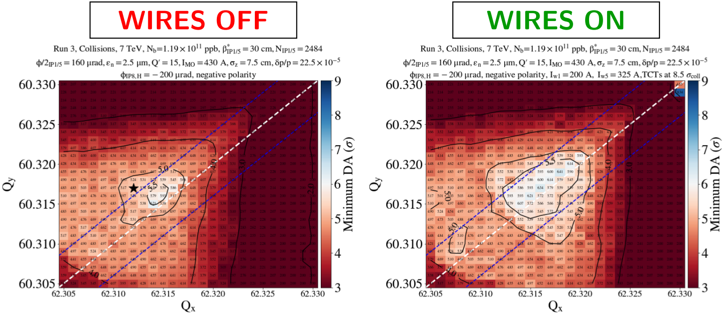

DA simulations of the wire impact in Run 3. Courtesy of S. Kostoglou.

GOAL: despite the **sub-optimal configuration**, **opportunity to integrate in the LHC cycle a moveable magnet (wire) within the machine protection and collimation boundaries**
→ **This is THE critical aspect of the scheme**

From Run 2 tests to Run 3 operations

The proposal was conceived to

→ **minimize the validation overhead** during the commissioning,

→ **be transparent** for the LHC cycle in case of wire unavailability,

→ **secure the fill integrated luminosity** before the compensation.

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In 2022, with the **invaluable support of the LHC OP team**, a beam process at **end of the $\mathcal{L}$-levelling** (β^*=30 cm, $\theta_c/2 = 160\ \mu$rad, TCT at 8.5 σ_{coll}) with **WIRES ON** was added.

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	beam-wire distance [mm]
L1B1	9.2
R1B2	9.2
L5B1	12.4
R5B2	12.4

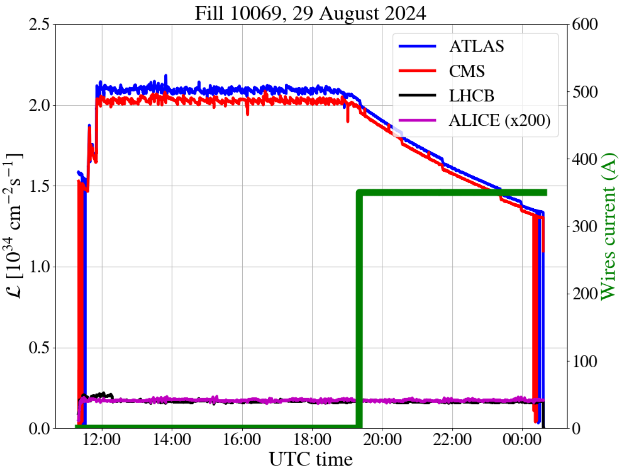
Effect of the wire and σ_{eff}

As metric to quantify the wire compensation we use the **effective cross-section**, σ_{eff}, that is beam proton losses, $\frac{dN}{dt}$, normalized to the total luminosity, $\mathcal{L}$,

$$\sigma_{eff} = -\frac{1}{\sum_{IPs} \mathcal{L}} \frac{dN}{dt}$$

IF σ_{eff} is BB-driven **THEN**, for ideal compensation, $\sigma_{eff} \approx 80$ **mb**.

A recent operational fill



Wires ON after the end of $\mathcal{L}$-levelling. Courtesy of S. Kostoglou.

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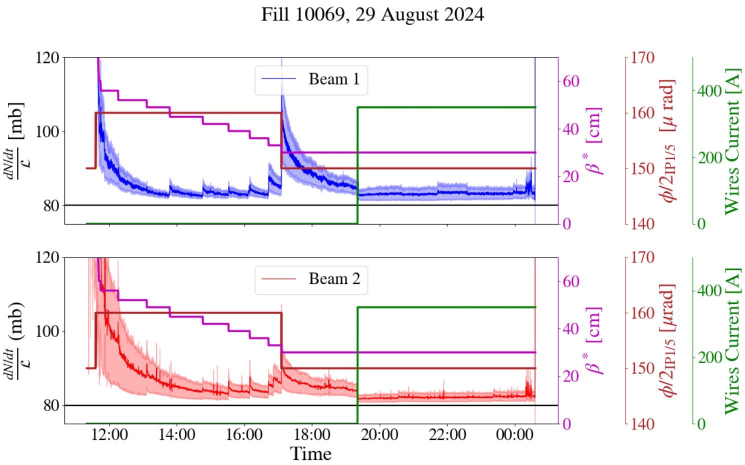

BBLR regime appears at the end of $\mathcal{L}$-levelling. Courtesy of S. Kostoglou.

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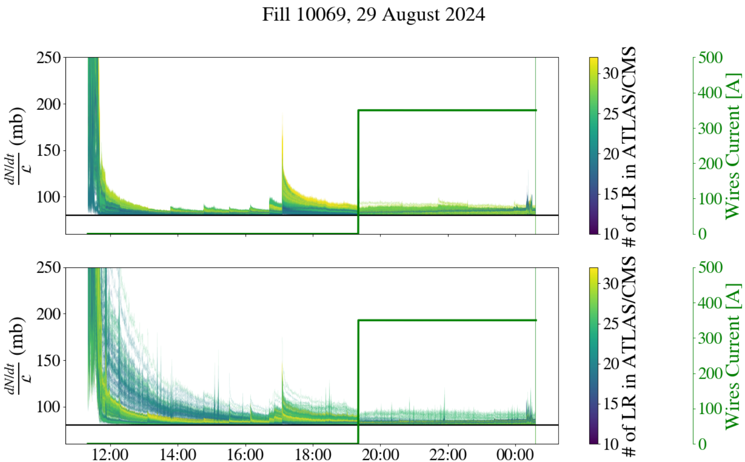

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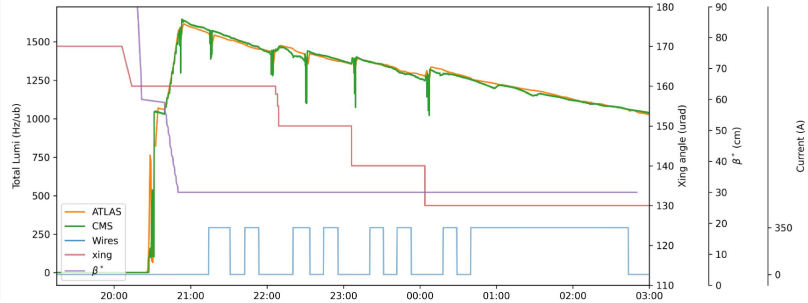
2022 MD results (I)

Before considering compensating them, we need to excite BBLRs!

→ **Explore more aggressive BBLR regimes**:



BB Compensation MD, November 5th-6th, 2022. Courtesy of P. Bélanger.

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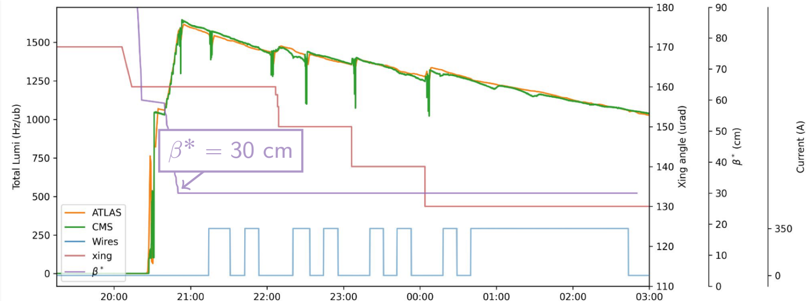

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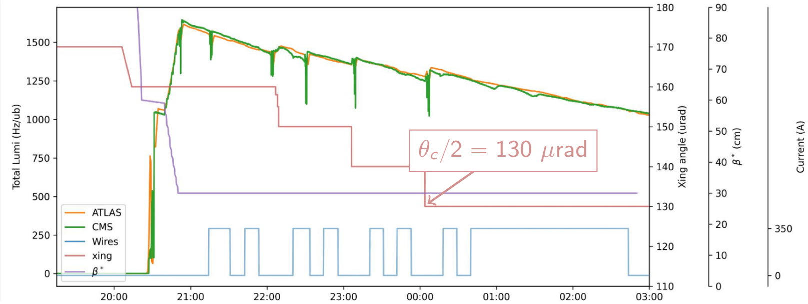

$\theta_c/2 = 130\ \mu$rad

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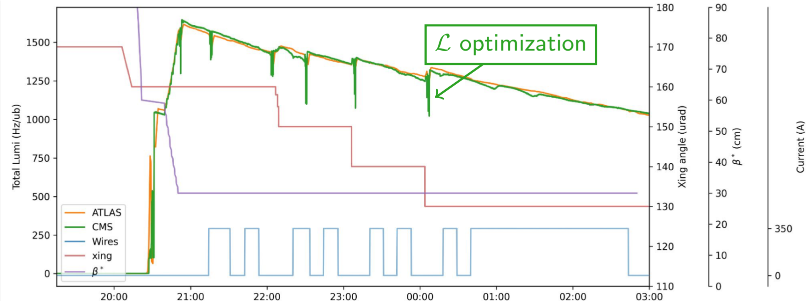

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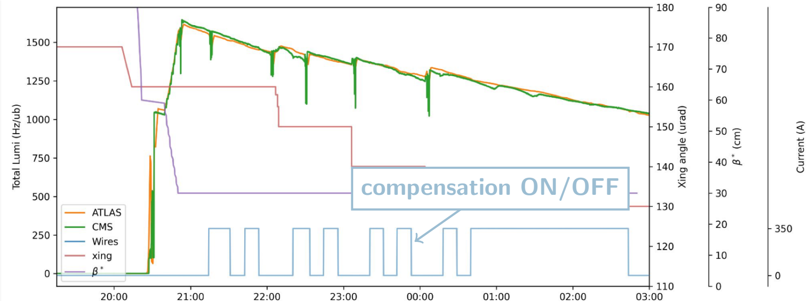
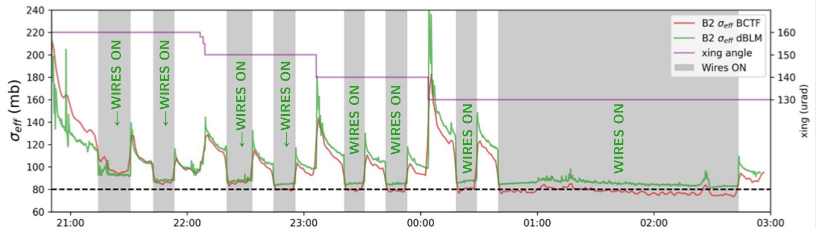
- $\mathcal{L}$ + tunes optimization before switching wires ON,
- Switching ON/OFF the compensation, **only B2 wires available.**



compensation ON/OFF

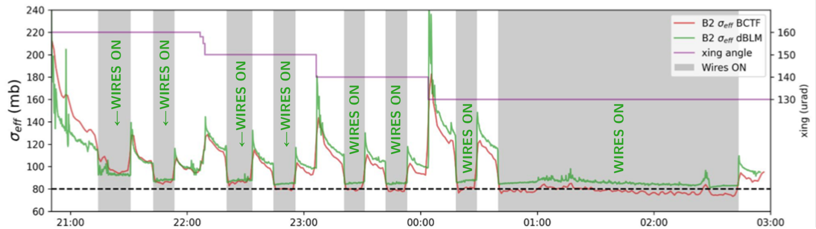
BB Compensation MD, November 5th-6th, 2022. Courtesy of P. Bélanger.

2022 MD results (II)



Courtesy of P. Bélanger.

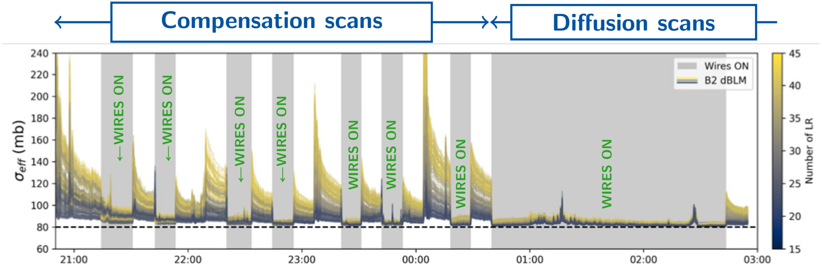
2022 MD results (II)



Courtesy of P. Bélanger.

- **Clear compensation** effect on the average σ_{eff} of Beam 2.
- With compensation ON **reaching almost 80 mb** in a systematic and reproducible way.
- **For reduced crossing angle (BB dominated regime), wire compensation effect even more evident.**

2022 MD results (III)



Courtesy of P. Bélanger.

- Using **dBLM** signals, clear BB signature visible.
- **The compensation reduce significantly the bunch-by-bunch σ_{eff} spread.**
- **The PACMAN bunches (with lower parasitic encounter) are not degraded.**

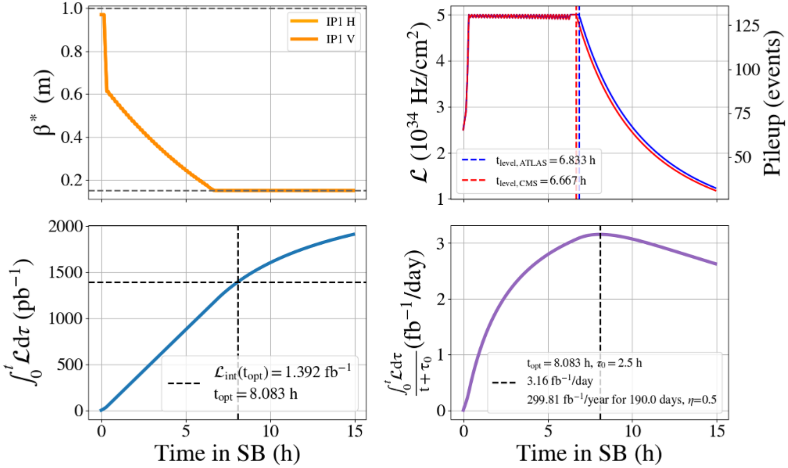
Plan

Introduction

Experiments in LHC during Run 3 (2017-2024)

From Run 3 to HL-LHC
- Expected performance gain

HL-LHC Baseline $\mathcal{L}$-production



Full-crossing angle of 500 μrad in IP1/5. Courtesy of S. Kostoglou.

Two **synergistic** lines of defence against BBLR

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- **HL baseline**: set a large crossing angle to remove/alleviate the problem at the source (→ **aperture and CC kick limit**)

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- **post-LS3 option**: BBCW to compensate/alleviate the (residual) BBLR effects.

Two **synergistic** lines of defence against BBLR

- **HL baseline**: set a large crossing angle to remove/alleviate the problem at the source (→ **aperture and CC kick limit**)
- **post-LS3 option**: BBCW to compensate/alleviate the (residual) BBLR effects.

The BBCW program supported by **HL-LHC Project** but not in the baseline.

- Simulations and Measurements of Long Range Beam-Beam Effects in the LHC, Lyon (FR), 2015,
- Second Workshop on Wire Experiment for Long Range Beam-Beam Compensation, Divonne (FR), 2017,
- WP2/WP13 HL-LHC Satellite Meeting – Wire Compensation, Fermilab (US), 2019,
- WP2/WP13 HL-LHC Satellite Meeting – Wire Compensation, Uppsala (SE), 2022,
- 13th HL-LHC Collaboration Meeting, Vancouver (CA), 2023.

From Run 3 to HL

- For HL, we are considering, thanks to the crab cavities (CC), full crossing angle of 500 μrad (low BBLR effect at **Start of $\mathcal{L}$-levelling**, SoL, but we are still limited at the end of **End of $\mathcal{L}$-levelling**, EoL.

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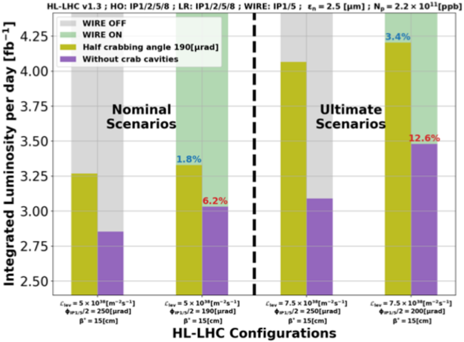
- BBWC could be used to gain flexibility, e.g.:
  - w/o CC (CC commissioning, only at the start of Run 4), to improve (marginally) performance
  - w/ CC (during Run 4), toward the EoL, by extending the luminosity levelling time (crossing-angle anti-levelling + aperture gain)
  - if we cannot reach nominal N_b, to gain aperture by reducing the crossing-angle (to lower β^* and recover geometrical $\mathcal{L}$ loss)
  - if we can go beyond nominal N_b, to cope with BBLR effect.

From Run 3 to HL



Performance gain[3] by extending the levelling reach/time:
→ w/ CC, BBCWs push $\int \mathcal{L} dt$ by **1.8-3.4%**
→ w/o CC, BBCWs push $\int \mathcal{L} dt$ by **6.2-12.6%**

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[3] K. Skoufaris et al., PRAB **24** 074001, 2021

BBCW and collimation settings (I)

- Even if not housed in a collimator (as for the LHC demonstrator), we are assuming that, as all the other machine elements, the BBCW has to be in the shadow of the tertiary collimators
- the **ideal**[4] BBWC setting requests a **beam-BBCW distance in σ_n "close" to the one between the two beams**
- Simulation and experimental results show that we can still trade-off, i.e. increase, the beam-BBCW distance at the cost of a higher $\int I_W dl$.
- → crucial to define **collimator configuration** for a sounded BBCW strategy!

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[4] S. Fartoukh et al., PRST AB **18** 121001 (2015)

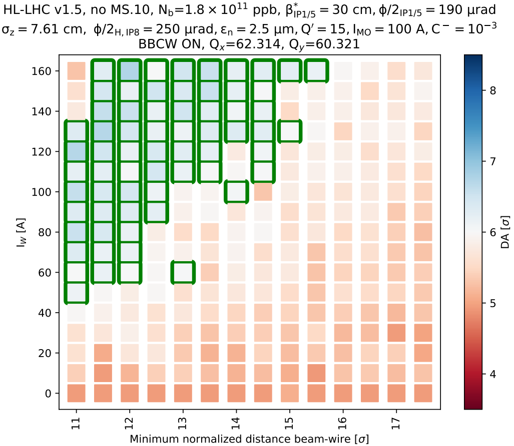
BBCW and collimation settings (II)

TCT setting	**wire L1**	**wire R1**	**wire L5**	**wire R5**
tight →12.0 σ at $\beta^* = 20$ cm	8.9 mm	7.0 mm	6.3 mm	9.4 mm
relaxed →13.2 σ at $\beta^* = 20$ cm	9.7 mm	7.6 mm	6.9 mm	10.3 mm

Courtesy of B. Lindström.

- 2 collimation settings considered: **tight** and **relaxed** (to reduce impedance),
- **retraction wire-TCT** to be defined (some flexibility with the **cells 4/6 TCTs optimization** but the background to the experiment need to be taken into account).

Run 4 performance's gain



Distance vs I_w scan with $\beta^* = 0.30$ m, $N_b = 1.8\ 10^{11}$ ppb,
$\theta_c/2 = 190\ \mu$**rad**, Q=(0.314, 0.321): **up to 2 σ of DA gain**

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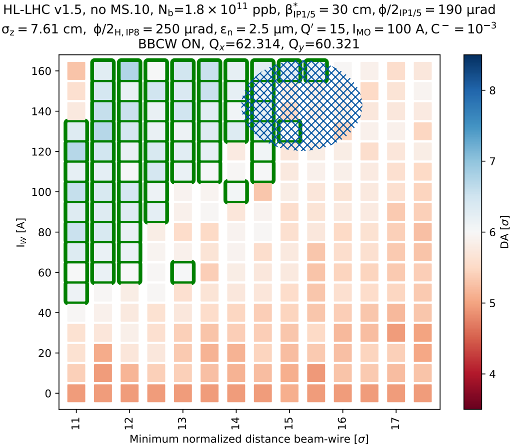

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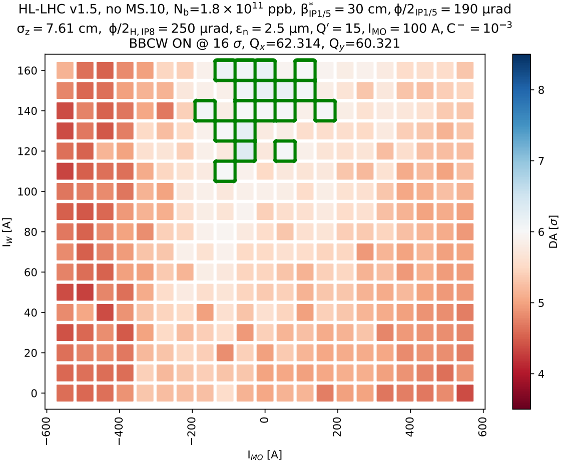
Interplay with arc octupoles



With a wire at 16 σ, can the arc octupole help? **Marginally**.

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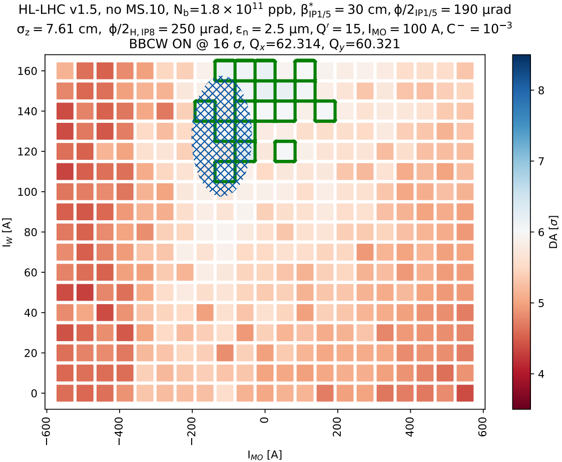

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Summary

Thank you for your attention.

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