CERN

Status of the Beam-Beam Long-Range Wire Compensation Studies[1]

G. Sterbini on behalf of and indebted to many colleagues[2]

ABSTRACT: *This contribution summarizes the past years studies on Beam-Beam Long-Range Wire Compensation. After a brief introduction to the basic principles of this compensation method, the focus shifts to numerical simulations and experimental results from the LHC. The potential benefits and limitations of wire compensation for the HL-LHC are presented and discussed.*

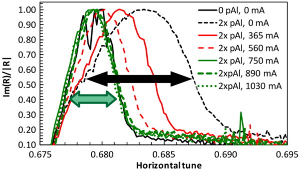
Beam-Beam Effects in Circular Colliders – EPFL, 2024

[1] See P. Bélanger's presentation for an insight of the beam dynamics.
[2] See a selection of publications.

“Do you see something?”

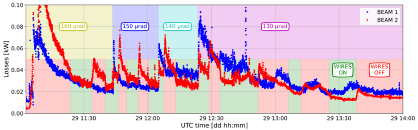
Rise of beam-beam compensation

- In the last 20 years, we observe a rise in successful compensation scheme, based on detailed understanding of side effects such as noise (e-lens), feed-down and non-linear optics control (wire, crab waist, resonance compensation)



- Tune spread reduction measured by beam transfer function with and without electron lens [Fischer17]
- Compensation of **half** the tune shift in order to maintain Landau damping
- → **Two fold increase of luminosity**

- Loss reduction with wires at the LHC (partial system deployed in operation, cf. Guido’s talk)



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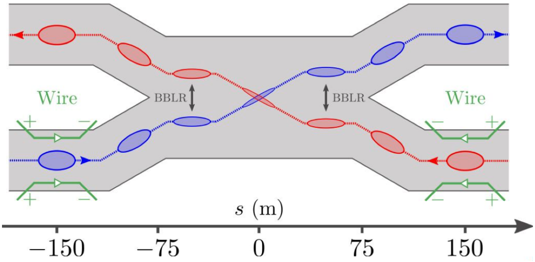
Courtesy of L. Rivkin.

Introduction

Experience in LHC in Run 3 (2022-now)

From Run 3 to HL-LHC (from 2029 to 2041)

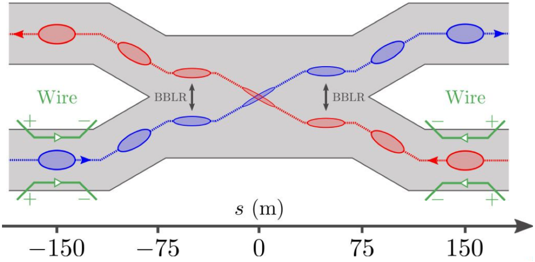
- Expected performance gain
- Integration Studies



BBLR and BBCW in LHC. Courtesy of P. Bélanger.

- The beam-beam long-range interactions (**BBLR**) act as magnetic multipolar errors[3,4]

[3] Y. Papaphilippou and F. Zimmermann, PRST AB **2** 104001 (1999)
[4] J.P. Koutchouk, LHC Project Note 223 (2000)
[5] S. Fartoukh et al., PRST AB **18** 121001 (2015)



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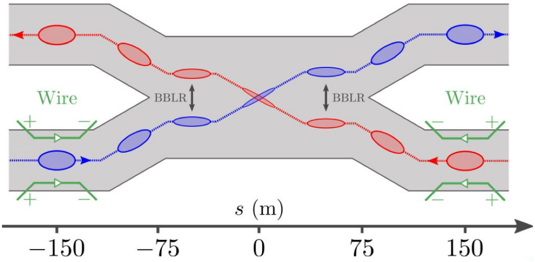

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  - → limit the $\int \mathcal{L} dt$
  - → can be corrected (e.g. by the DC wires, **BBCW**)
- in (HL)-LHC, given the symmetry of the optics and the phasing of the BBLR, we can minimize the number of BBCW.[5]

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HL-LHC wire demonstrators

→ **4 demonstrators** installed in LHC since 2017 for Run 2 MDs[6],

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

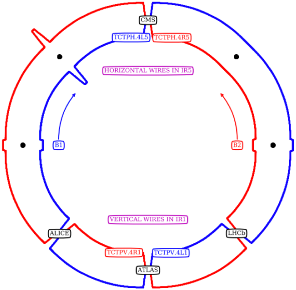
HL-LHC wire demonstrators

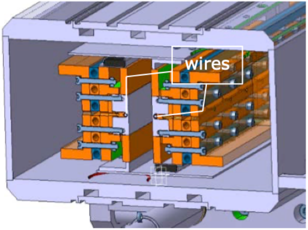
→ **4 demonstrators** installed in LHC since 2017 for Run 2 MDs[6],

→ **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, ∅=**2.48 mm** Cu wire carrying **350 A**.





Courtesy of A. Poyet and A. Rossi.

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

Plan

From Run 2 tests to Run 3 operations

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

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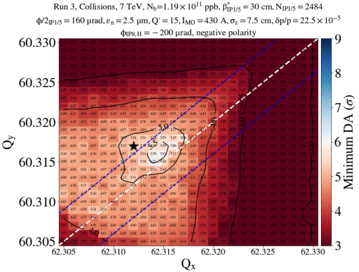

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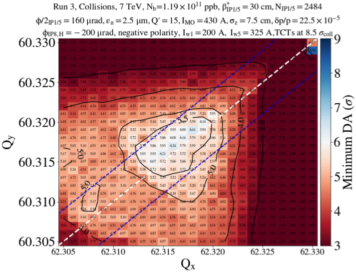

DA simulations of the wire impact in Run 3. Courtesy of S. Kostoglou.

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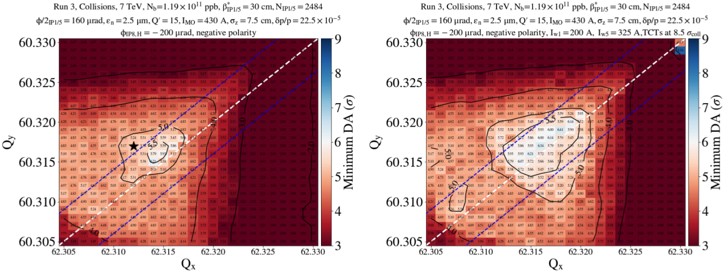

DA simulations of the wire impact in Run 3. Courtesy of S. Kostoglou.

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

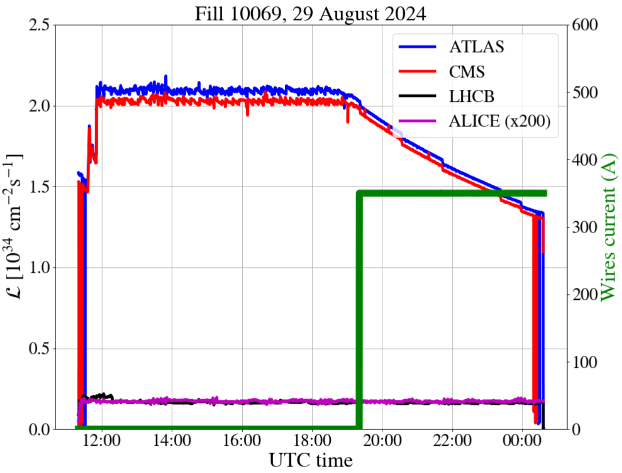
Effect of the wire and σ_{eff}

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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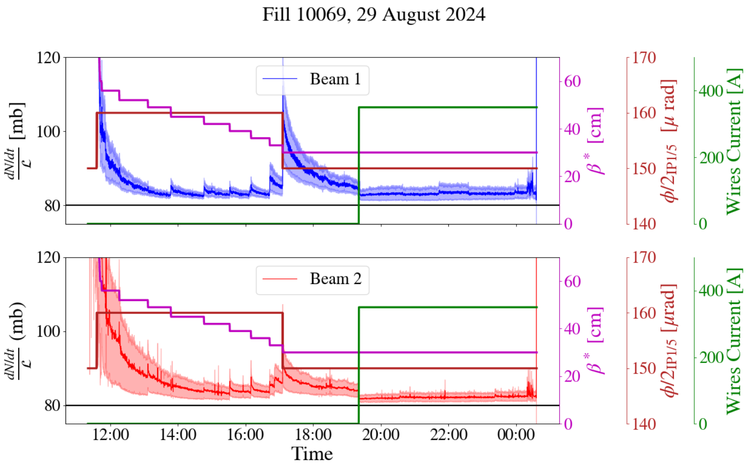

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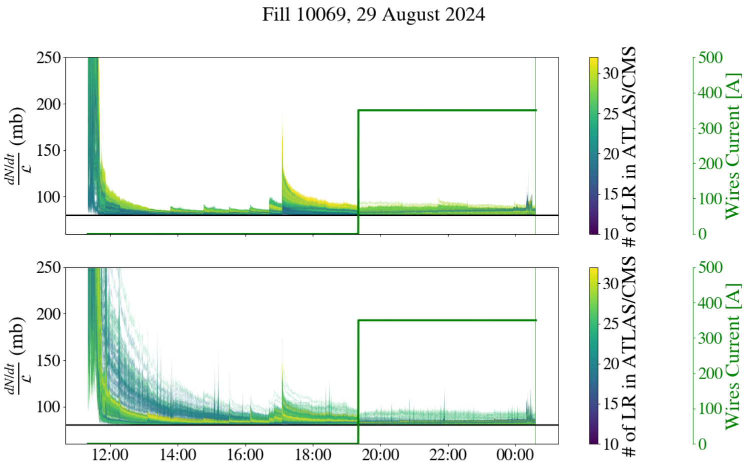

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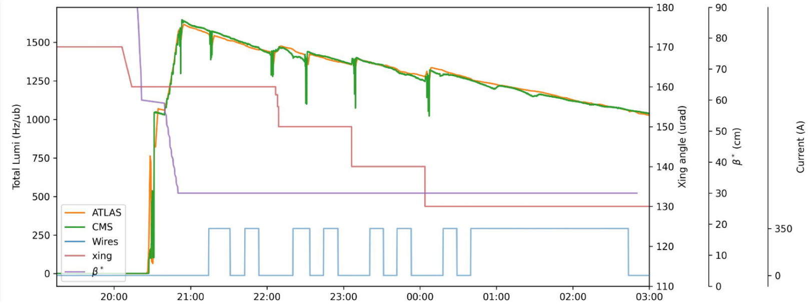
2022 MD results (I)

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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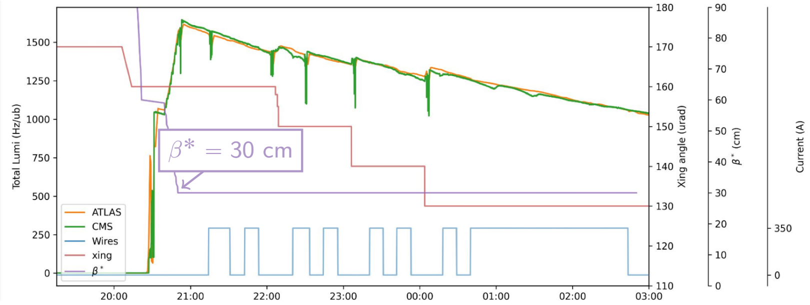

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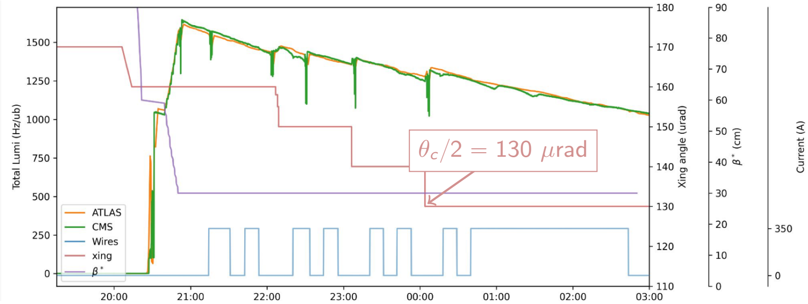

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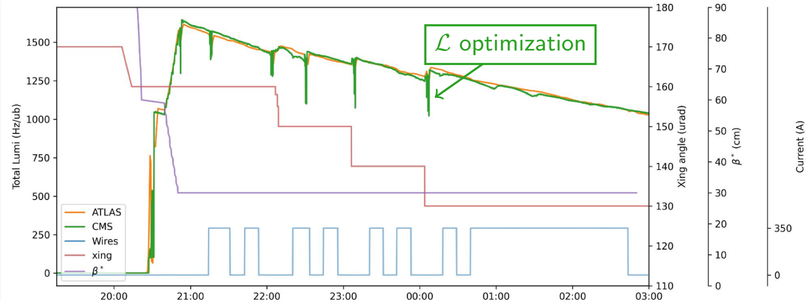

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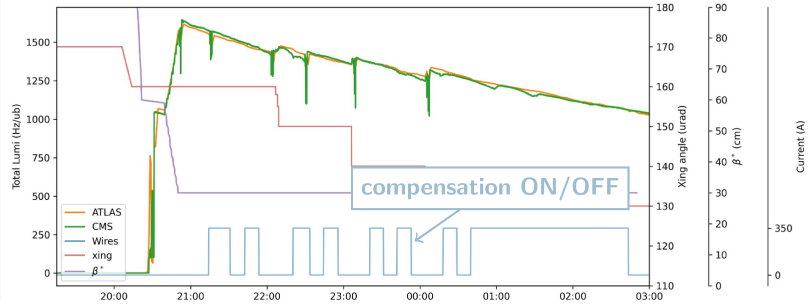
- Switching ON/OFF the compensation, **only B2 wires available.**



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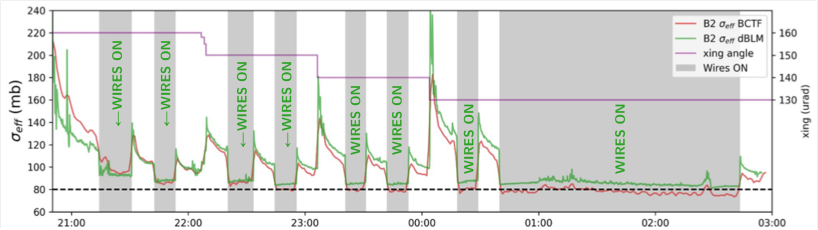

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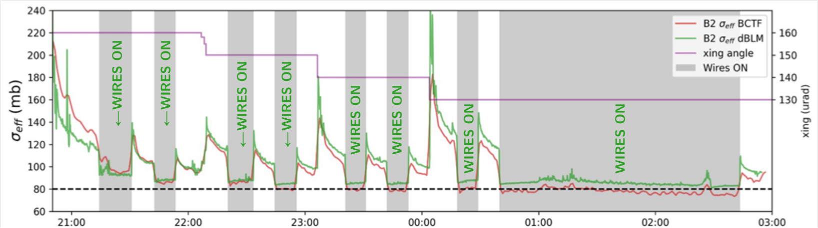
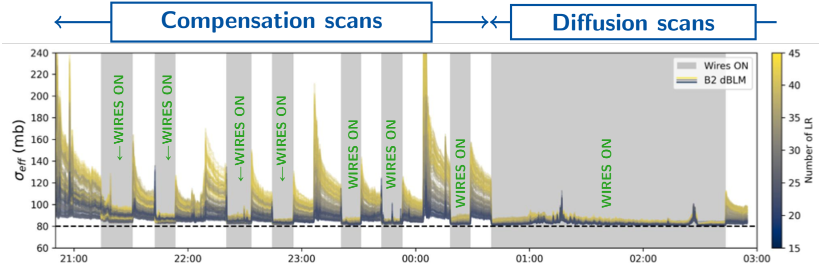


Courtesy of P. Bélanger.

- **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.**

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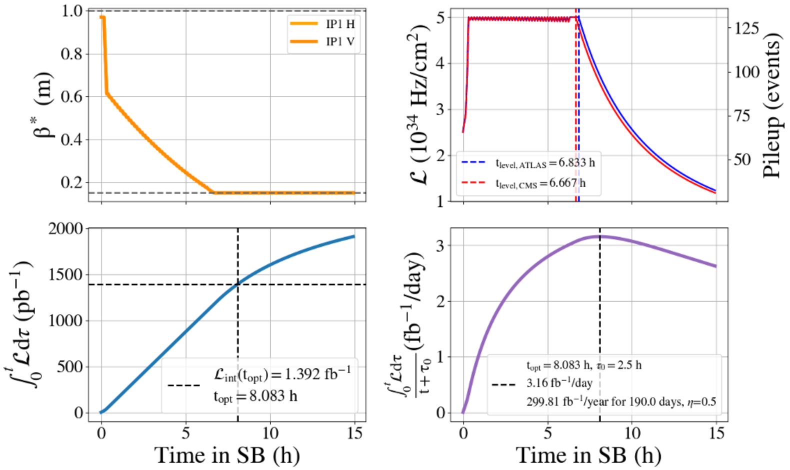
HL-LHC Baseline $\mathcal{L}$-production



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

Two **synergistic** lines of defence against BBLR

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

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- **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,
- 13^{th} 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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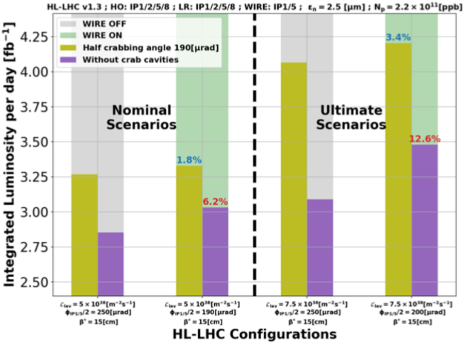
- BBWC could be used to gain flexibility, e.g.:
  - w/o CC (CC commissioning, only at the start of Run 4), to improve (marginally) performance
  - w/ CC (during Run 4), toward the EoL, by extending the luminosity levelling time (crossing-angle anti-levelling + aperture gain)
  - if we cannot reach nominal 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[7] by extending the levelling reach/time:

$\rightarrow$ w/ CC, BBCWs push $\int \mathcal{L} dt$ by **1.8-3.4%**

$\rightarrow$ w/o CC, BBCWs push $\int \mathcal{L} dt$ by **6.2-12.6%**

[7] 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**[8] 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!

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

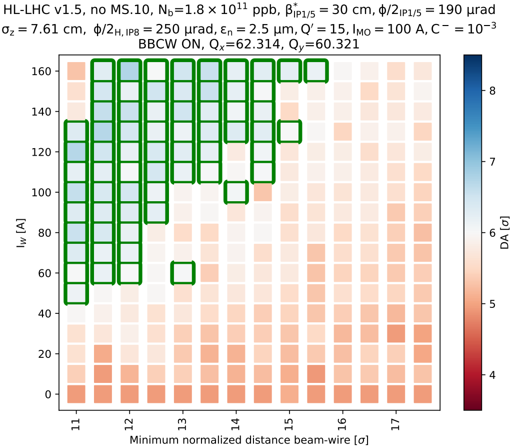
BBCW and collimation settings (II)

TCT setting	wire L1	wire R1	wire L5	wire R5
tight $\rightarrow$12.0 σ at $\beta^* = 20$ cm	8.9 mm	7.0 mm	6.3 mm	9.4 mm
relaxed $\rightarrow$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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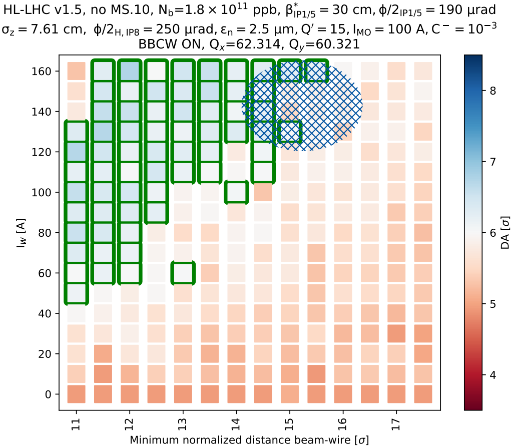

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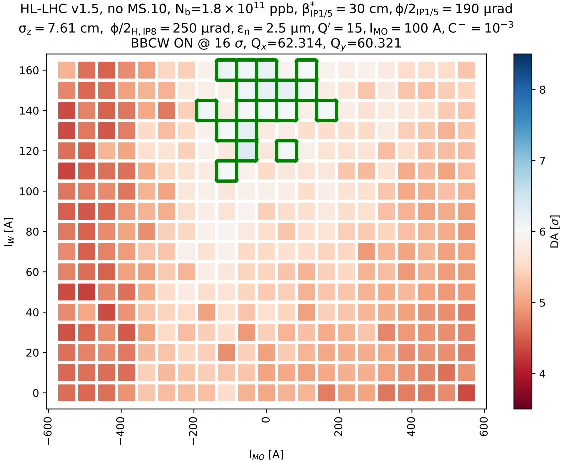
Interplay with arc octupoles



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

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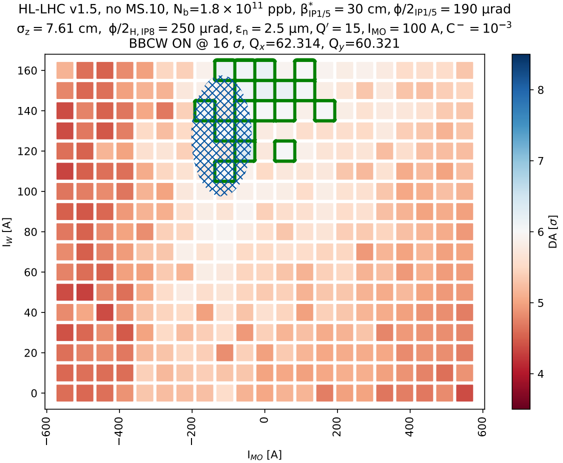

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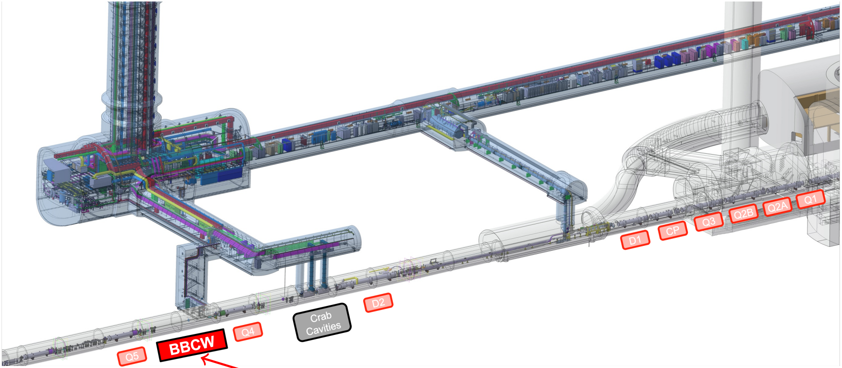
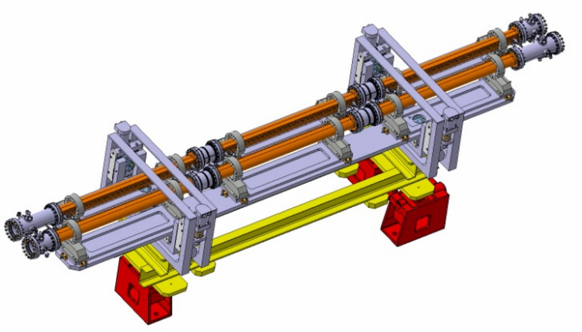
BBWC Space Reservation



≈9 m space between Q5-Q4 reserved for HL wires for both sides of IR1/5

Courtesy of M. Modena and M. Mendes.

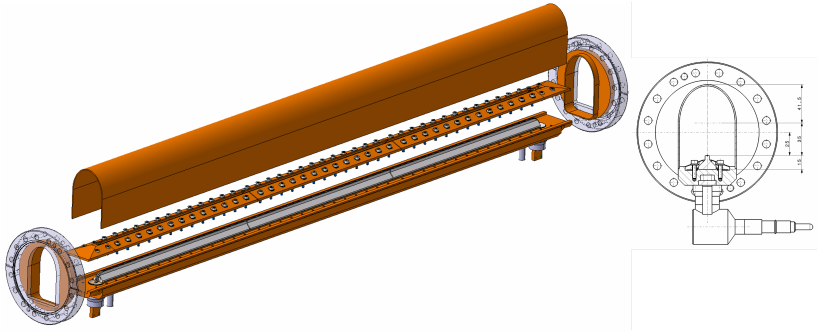
HL proposed wires' assembly



Courtesy of A. Bertarelli.

- $\times 4$ **assemblies** needed.
- **1 assembly → 3 × 1-m wire modules/beam**
- **1 wire module can carry 150 A → 450 Am per beam/side/IP**
- Wire moveable from 32.5 → 7.5 mm from the beam, assembly capable to rotate (roll) for crossing angle polarity switch.

Wire module design proposal



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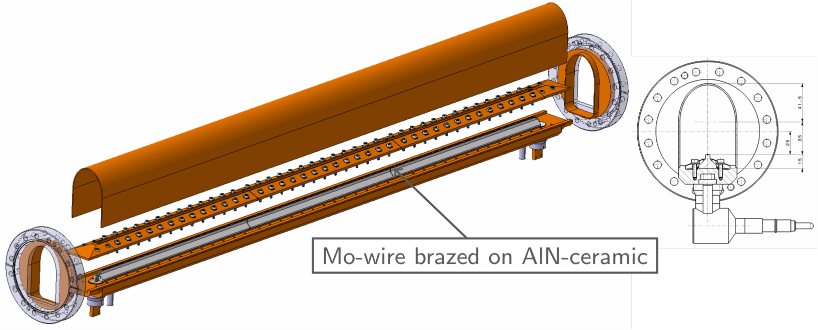

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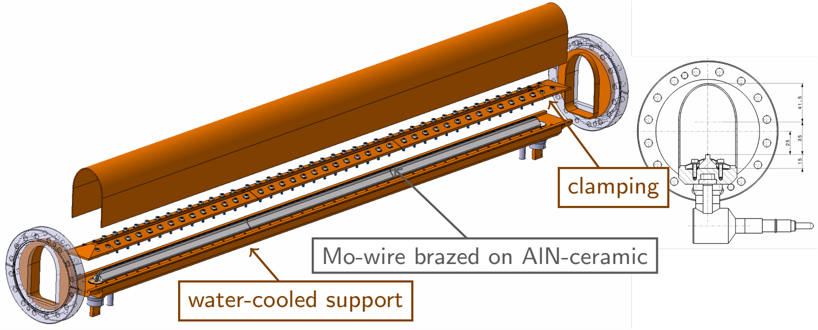

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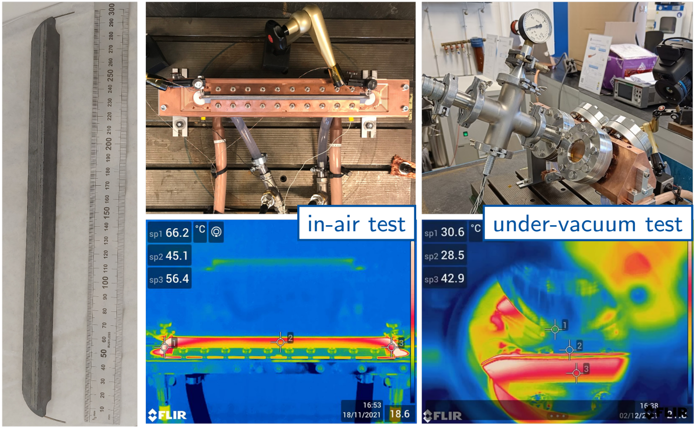
- the ceramic is clamped on a **water-cooled support**.

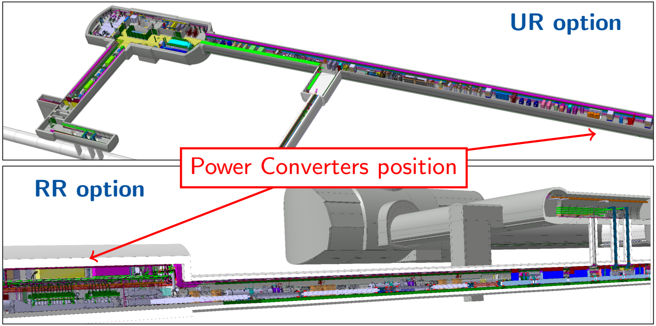
Proof of Concept tests



Courtesy of A. Bertarelli.

- 290 mm demonstrator built to validate the brazing and the concept,
- **in-air** and **under-vacuum** thermo-mechanical tests performed,
- **no showstoppers identified** for $\varnothing = 1$ mm.

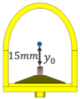
Infrastructure/Integration constraints

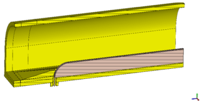


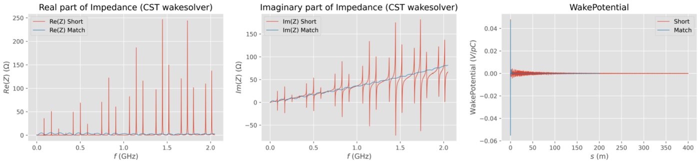
Courtesy of A. Rossi.

- **8 power converters** (200 A×60 V),
- commercial PCs possible but limits with cabling in the HL cores,
- **the cabling of the wires (power+signals) is outstanding**.

Preliminary Impedance Studies



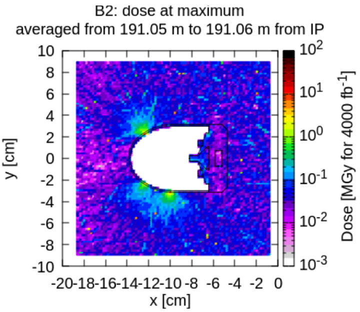


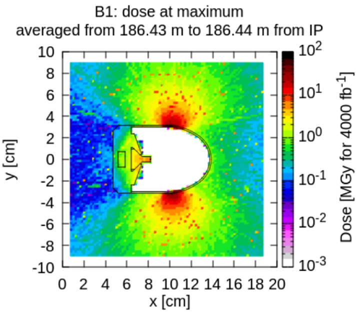


Courtesy of B. Salvant.

- Impedance contribution is **significant but no showstopper was identified, matched load should be applied at wire termination**,
- an **RF shielding** (e.g. foil, grid) between the wire and the beam would strongly reduce impedance,
- **vacuum and e-cloud** compliance should be investigated.

Preliminary energy deposition studies





Courtesy of M. Sabaté-Gilarte and F. Cerutti.

- **Up to 100 MGy per 4000 fb^{-1}**,
- **negligible $\mathcal{L}$-driven thermal load on the wire**,
- **the BBCW impact on the Forward Physics (in IP5) is still outstanding.**

Summary

- **Wire demonstrators used in operational fills** since 2022, and, in BBLR dominated regime, they showed their **positive effect.**

- Wire compensation could contribute to HL performance by adding **margin and flexibility**.
- **Wire retraction from TCTs** to be defined.
- A simple, low-cost, modular HL design was explored: **no showstoppers identified** but **a complete integration proposal is still outstanding**.

- An **External Review** will be taken place on 14-15 October 2024. Depending on its outcome, a full wire prototype could be designed and build by our **TRIUMF** colleagues.

Thank you for your attention.

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