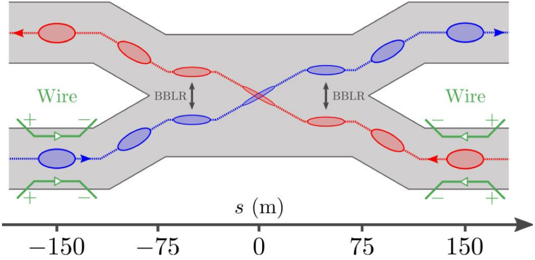
CERN

Beam-Beam Long-Range compensation, experience in 2022 & outcome of WS

G. Sterbini on behalf of BBCW team

We thank **HL-LHC** *and* **CERN** *management and the* **HL WP2/5/13 and MPP** *for the guidance, and we aknowledge BE, EN and SY groups for the technical support.*

Compensation of the Beam-Beam Long-Ranges



Courtesy of P. Bélanger.

- The beam-beam long-range (**BBLR**) is an **EM interaction between the beams** in the proximity of the IP: increases with the bunch intensity and by reducing the normalized beam distance.

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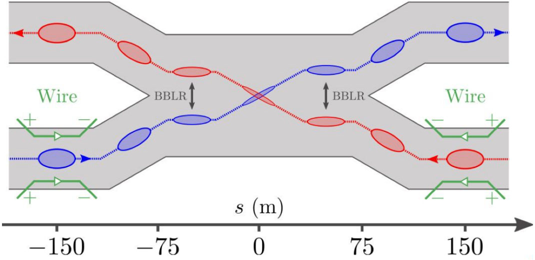

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- The beam-beam long-range (**BBLR**) is an **EM interaction between the beams** in the proximity of the IP: increases with the bunch intensity and by reducing the normalized beam distance.
- BBLRs act as **magnetic multipolar errors**:

  → **impact on lifetime, reduction of** $\int \mathcal{L} dt$,

  → **magnetic correctors (e.g., DC wires) can compensate them.**

HL-LHC wire demonstrators

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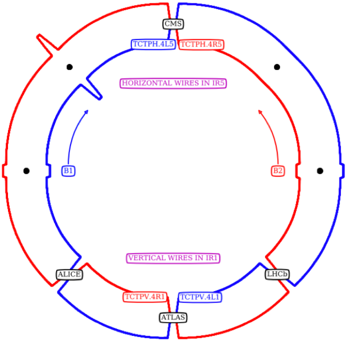
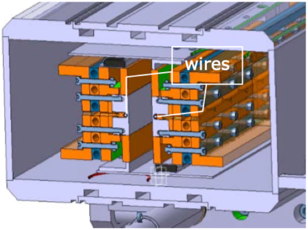
HL-LHC wire demonstrators

→ **4 demonstrators** installed in LHC since 2017 (see Run 2 MDs),
→ **embedded in operational TCTs** in IR1 (V-plane) and 5 (H-plane),
→ each TCT jaw has a **1 m** long wire carrying up to **350 A**.





Wire demonstrators configuration 2022 (**L1**, **R1**, **L5**, **R5**). From EDMS 1705791 and 2054712.

Evian 2021 proposal

$\rightarrow$ **use the compensation in LHC production fills**.

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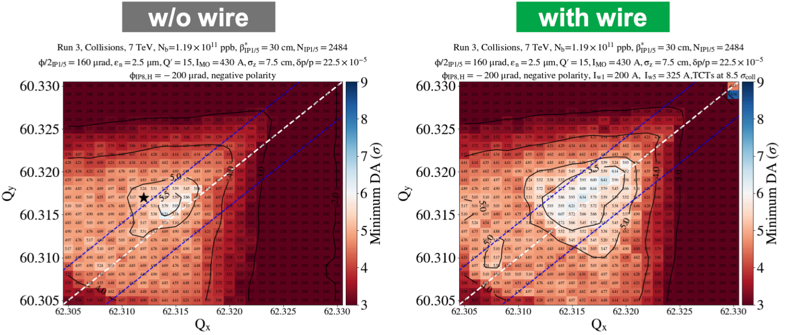

DA simulations of the wire impact in Run 3 [S. Kostoglou, Evian 2021]

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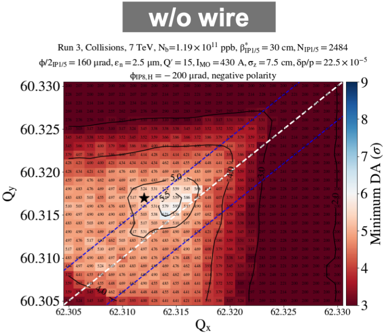

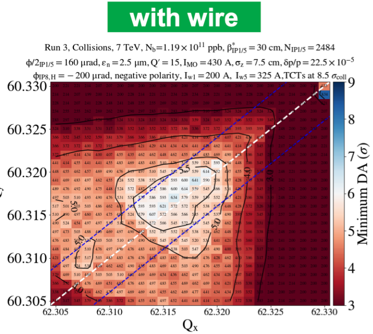

DA simulations of the wire impact in Run 3 [S. Kostoglou, Evian 2021]

→ opportunity to learn about integrating the compensation in the cycle within the MPP/collimation boundaries (critical aspect of the scheme).

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	s from IP [m]	plane	distance [mm]
BBCW.4L1.B1	-145.945	V	9.2
BBCW.4L5.B1	-147.945	H	12.4
BBCW.4R1.B2	145.945	V	9.2
BBCW.4R5.B2	147.945	H	12.4

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→ **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.

Linear effect of the wires

The proposal was endorsed by MPP provided that the linear effects of the wires were under control (orbit, Q, β-beating)

$\rightarrow$ **5-th axis alignment** of the TCTs (collimation team)

$\rightarrow$ compensation of the quad-effect by **Q4s trims** (D. Jacquet, LBOC 135).

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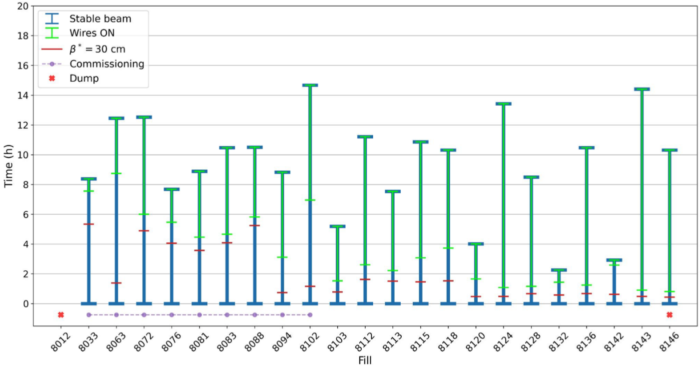
The compensation was validated in July-August 2023 with optics measurements (BE-ABP/OP), loss maps (BE-ABP/OP), asynchronous dumps (SY-ABT) and interlock tests (BE-OP, SY-EPC, TE-MPE).

→ $\approx$ 3 **shifts** exploiting synergies during the commissioning.

Experience in 2022 operation



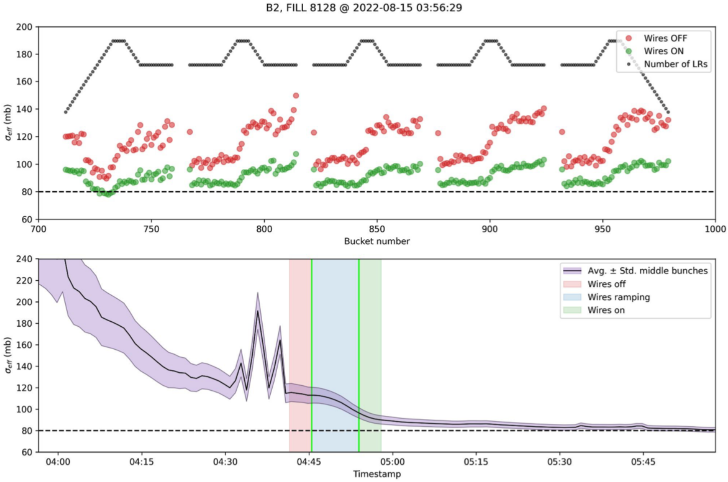
22 fills were tested with the wire compensation in the two beams (F8146 dumped on an **earth fault on L1 wire** in August, 28th). Courtesy of P. Bélanger.

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

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

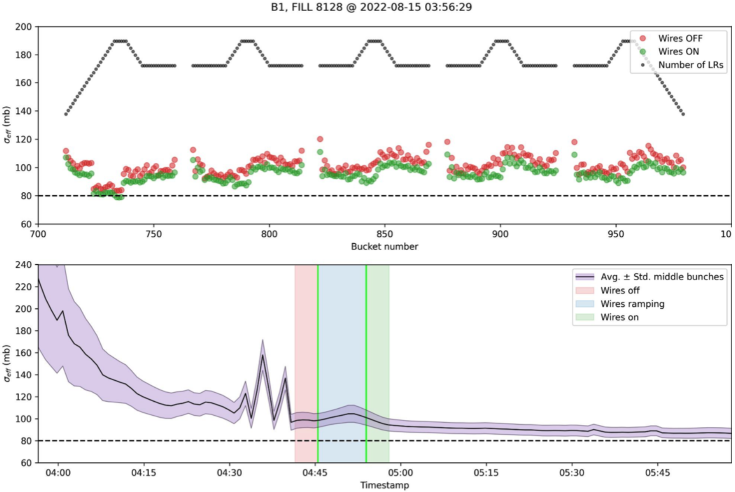
Ideal BBLR compensation $\rightarrow$ $\sigma_{eff} \approx 80$ mbarn.

2022 Results



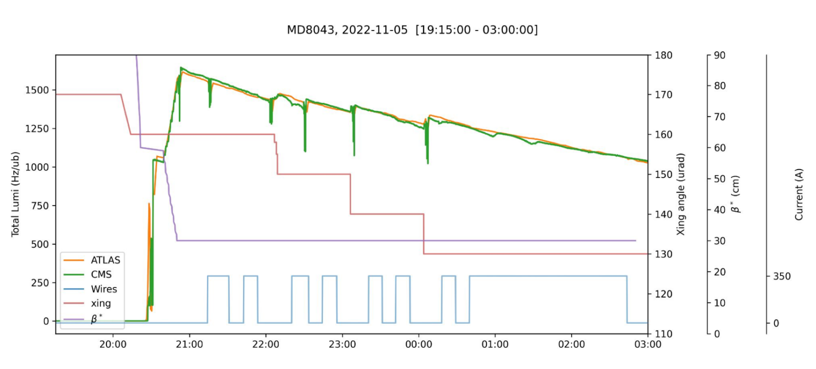
→ **clear compensation** on σ_{eff} on B2. Courtesy of P. Bélanger.

2022 Results

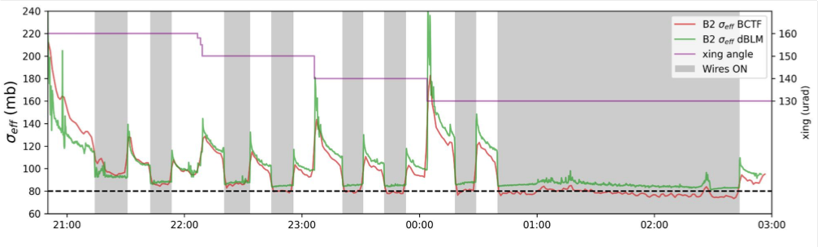


→ **compensation not visible on on B1**. Courtesy of P. Bélanger.

MD results

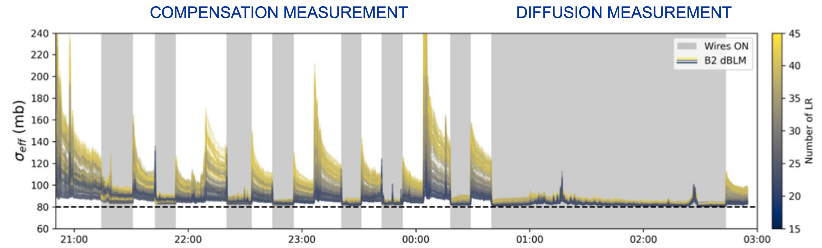

MD8043, 2022-11-05 [19:15:00 - 03:00:00]
Total Lumi (Hz/ub)
Xing angle (urad)
β* (cm)
Current (A)
ATLAS
CMS
Wires
xing
β*
0
250
500
750
1000
1250
1500
20:00
21:00
22:00
23:00
00:00
01:00
02:00
03:00
110
120
130
140
150
160
170
180
0
10
20
30
40
50
60
70
80
90
0
350

MD results



B2 σ_{eff} BCTF
B2 σ_{eff} dBLM
xing angle
Wires ON
σ_{eff} (mb)
xing (urad)
240
220
200
180
160
140
120
100
80
60
160
150
140
130
21:00
22:00
23:00
00:00
01:00
02:00
03:00

MD results

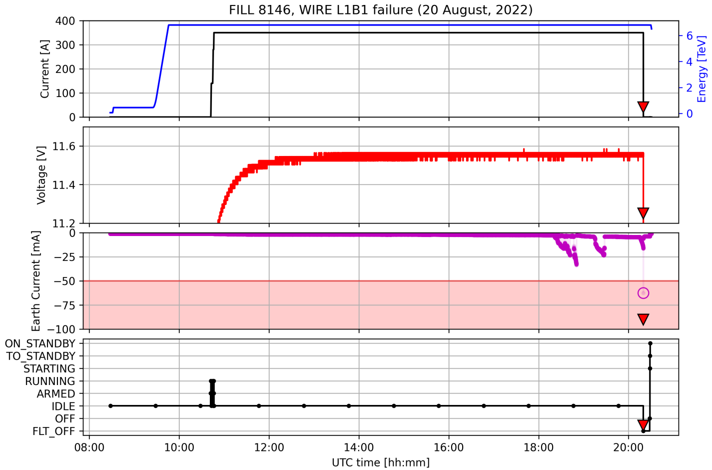


COMPENSATION MEASUREMENT
DIFFUSION MEASUREMENT
Wires ON
B2 dBLM
σ_{eff} (mb)
Number of LR
240
220
200
180
160
140
120
100
80
60
21:00
22:00
23:00
00:00
01:00
02:00
03:00
45
40
35
30
25
20
15

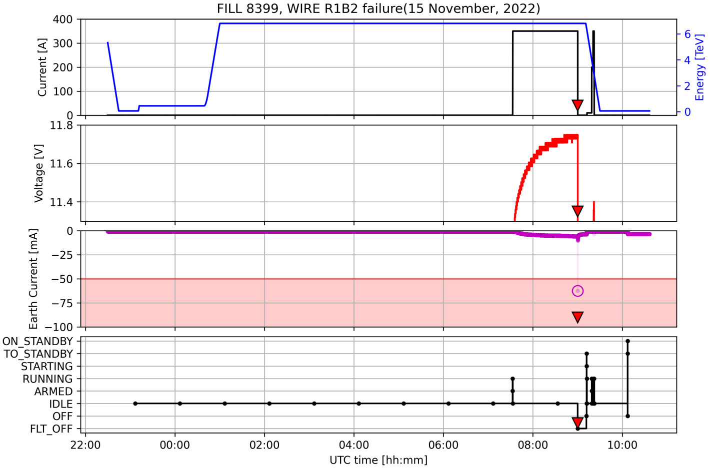
Dumps

In 2022 run, 6 dumps related to the BBLR:

1. FILL 8012 @ 6.8 TeV (p^+, R1B2 PC fault/**WIC**)
2. FILL 8146 @ 6.8 TeV (p^+, L1B1 earth fault → PC fault/**WIC**)
3. FILL 8320 @ 6.8 TeV (p^+, BBLR_ON@β^*=32 cm → **PCInterlock**)
4. FILL 8399 @ 6.8 TeV (p^+, R1B2 earth fault → PC fault/**WIC**)
5. **FILL 8405 @ 2.5 TeV (Pb, R1B2 earth fault → PC fault/WIC)**
6. **FILL 8407 @ 2.0 TeV (Pb, R1B2 earth fault → PC fault/WIC)**



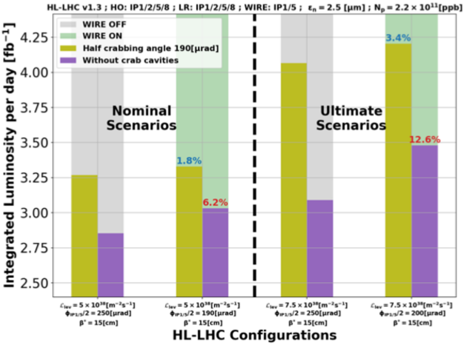
L1B1 failed on August 20th, 2022.



R1B2 failed on November 15th, 2022.

Run4 Constraints & Potentials

From Run3 to HL[1]



Performance gain 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%

[1] PRAB **24** 074001, 2021

EYETS scenario to fix intensity limitation (HEL, dilution kickers, RF?)

*under review

Year	ppb $[10^{11}]$	Virtual lumi. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Days in physics	θ $[\mu\mathrm{rad}]$	β^*_{start} [cm]	β^*_{end} [cm]	CC	Max. PU
2029	1.8	4.4	90	380*	70	30	exp	116
2030	1.8	9.0	120	500	100	20	on	132
EYETS (≈5 months) HEL , dilution kickers?								
2031	2.2	13.5	90	500	100	20	on	132
2032	2.2	13.5	160	500	100	20	on	132
2033-34	Long shutdown 4							
2035	2.2	13.5	140	500	100	20	on	132
2036	2.2	16.9	170	500	100	15	on	132
2036	2.2	16.9	200	500	100	15	on	200

HEL cryo connections for efficient installation in EYETS (and avoiding sector warm-up) is extra scope.

R. Tomas in LHC performance workshop, January 2022 23

- Focus on the first period of Run 4 (**BBCW-leverage while commissioning the CC**) → potential to use BBCWs before the end-of-levelling (further increase gain).
- Crucial to define **collimator configuration** for BBCW strategy!

Run 4 collimation settings (I)

The ideal BBWC setting requests a **beam-BBCW distance in σ_n "close" to the one between the two beams**. Experimental results and simulations show that we can still trade-off, i.e. increase the beam-BBCW distance at the cost of a higher $\int I_W dl$.

⇓

TCT endpoint setting [σ]	BBLR IR1L pos [mm]	BBLR IR1R pos [mm]	BBLR IR5L pos [mm]	BBLR IR5R pos [mm]
12.0 tight	8.9	7.0	6.3	9.4
13.2 relaxed	9.7	7.6	6.9	10.3

Two scenarios considered here (β^*=**20 cm**): **tight** and **relaxed** as trade-off between impedance minimization and minimum beam-wire distance. **Retraction from the TCTs** to be defined. Courtesy of B. Lindström.

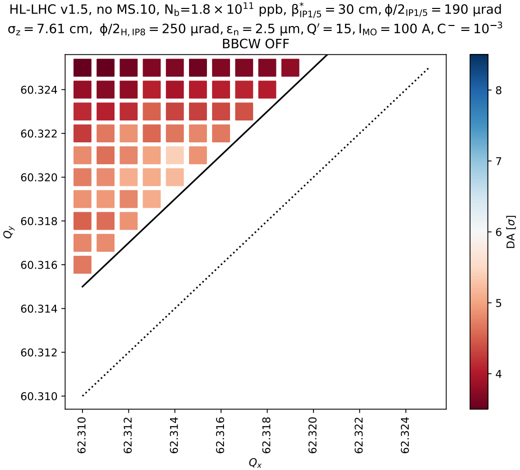
Run 4 collimation settings (II)

Several scenarios were presented to minimize the beam-BBCW distance

1. **Keep TCTs at constant sigma settings from FT**: **to be operational already in 2023**
2. Use tighter TCT settings
3. Use tighter TCP/S/T settings throughout cycle
4. Close collimators (including TCP) during collisions as bunch intensity drops
5. Keep TCPs at tight settings from FT and then close TCS/TCT during levelling
6. (Put wire closer to beam than TCTs, option excluded)

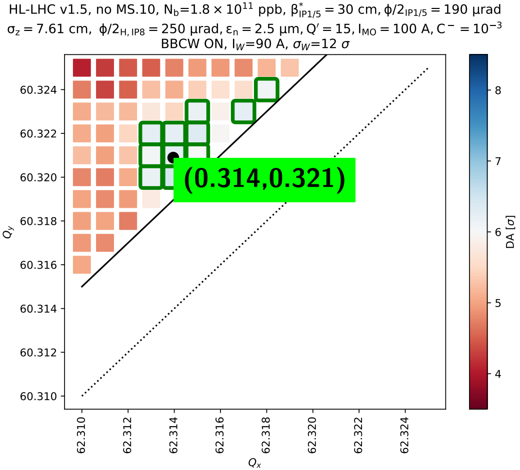
Some flexibility with the **cells 4/6 TCTs optimization** (leakage-to-experiments) but less margins (robustness on losses) due to the **missing copper diamond TCTs**.

Run 4 performance's gain



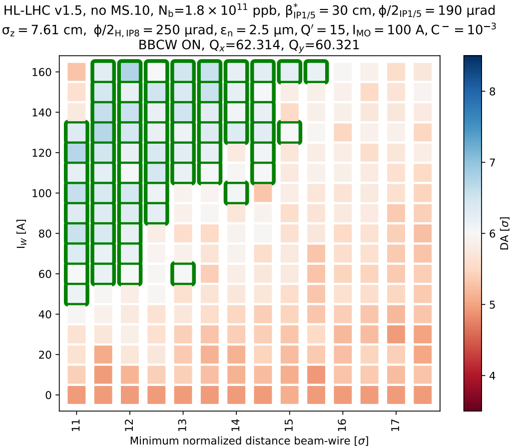
BBCW OFF with $\beta^* = 0.30$ m, $N_b = 1.8\ 10^{11}$ ppb, $\theta_c/2 = 190\ \mu$**rad**.

Run 4 performance's gain



BBCW ON at 90 A and 12 σ.

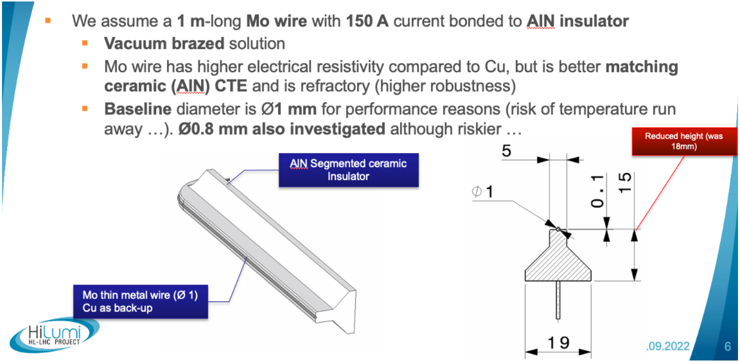
Run 4 performance's gain



Distance vs I_w scan at Q=(0.314, 0.321): **up to 2 σ of DA gain**

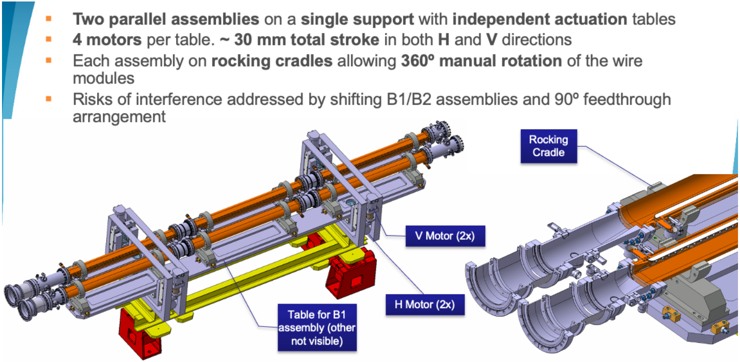
Design Concept & Challenges

Design of the BBCW



Use a slim, light design with a thin, bare, metal wire, allowing to move as close as necessary to the beam, while minimizing interactions with beam particles. Courtesy of A. Bertarelli.

Design of the BBCW



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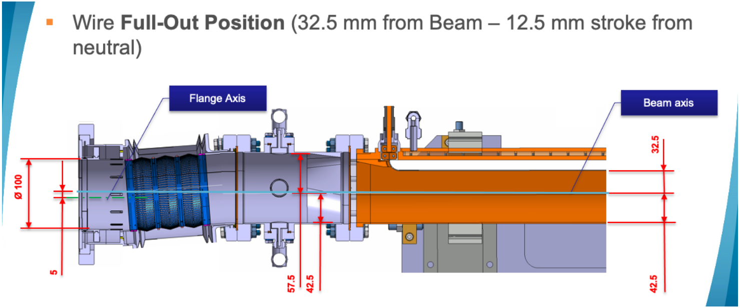

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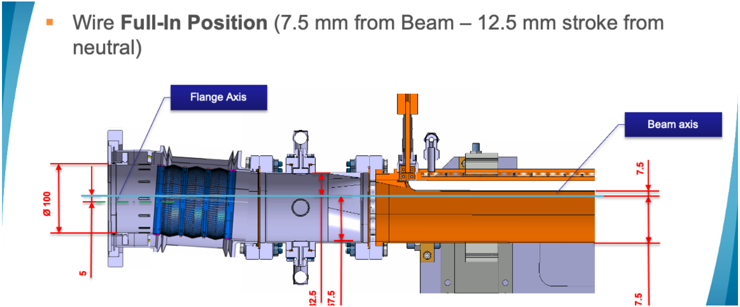

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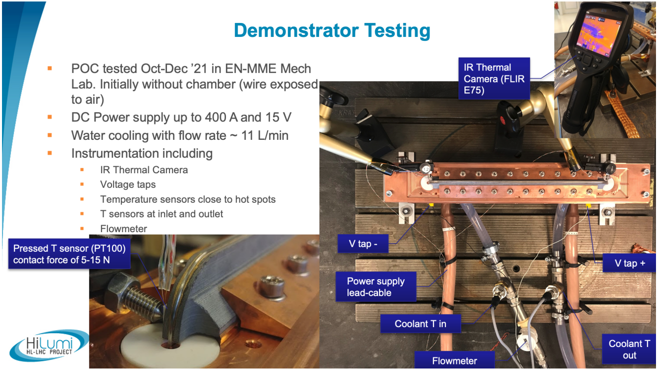
Proof of Concept test



A low-cost short demonstrator (290 mm long) was built and tested to validate the concept and perform online measurements. Courtesy of A. Bertarelli.

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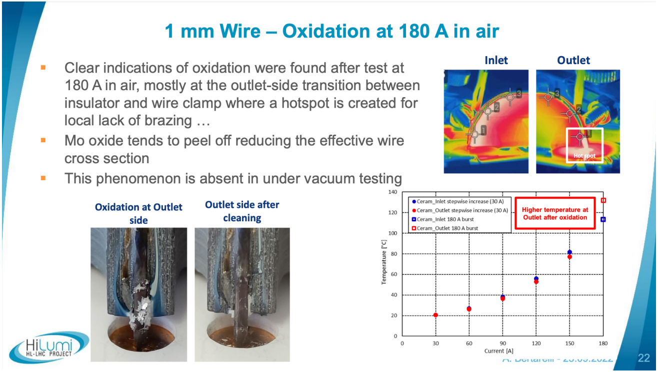

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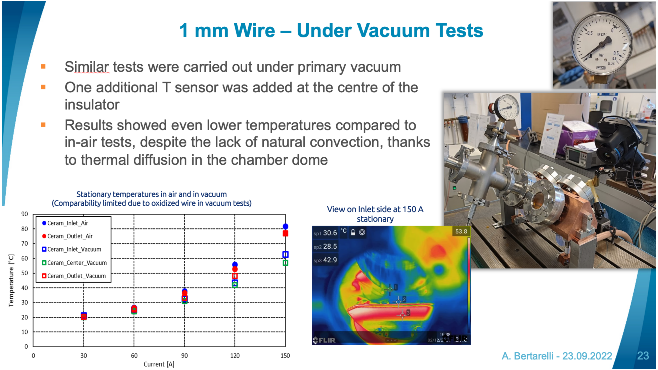

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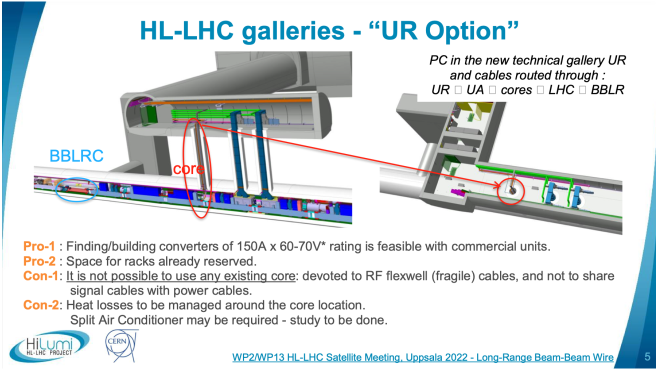
Infrastructure/Integration constraints



Two options considered for the integration: **UR** and **RR** options. **Presently there are criticalities**. Courtesy of A. Rossi.

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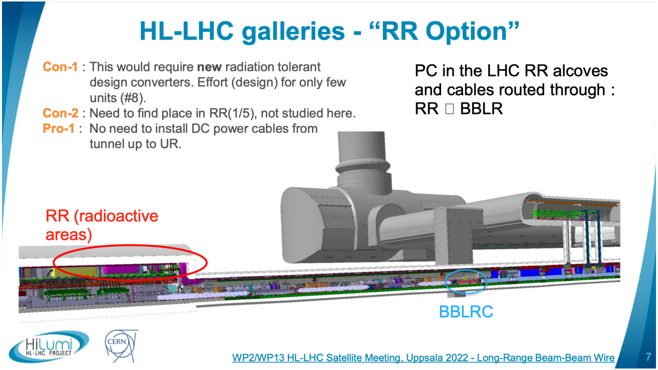

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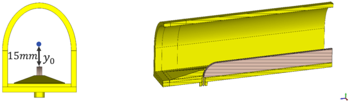
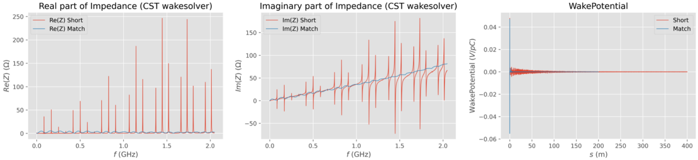
Preliminary Impedance Studies

Longitudinal Beam Coupling Impedance

From an Impedance point of view the situation changes drastically if the Coaxial termination is closed on a load.





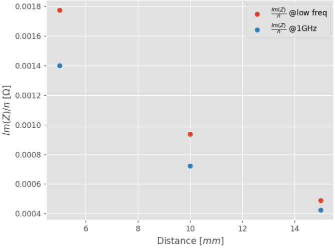
Impedance contributions are **significant but no showstopper was identified, reduced when matched load is applied at wire termination**. A shielding (e.g. foil, grid) between the wire and the beam would strongly reduce impedance. Negligible EM thermal load. Courtesy of B. Salvant.

Preliminary Impedance Studies

Effective Longitudinal Impedance

Impact of the beam position on the Longitudinal Effective Impedance: $\frac{Im\,(Z)}{n}$, $n = \frac{f}{f_{rev}}$

LHC Effective Impedance ~90 $m\Omega$



Note: the Impedance value refers only to one module, each beam will interact with 12 modules.

→ Significant contribution of 5 to 17 $m\Omega$ for the total system

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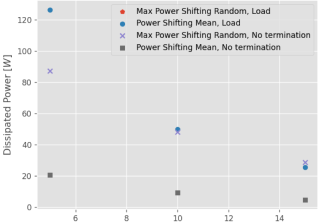
Preliminary Impedance Studies

Dissipated Power

The dissipated power is growing when going closer to the wire.



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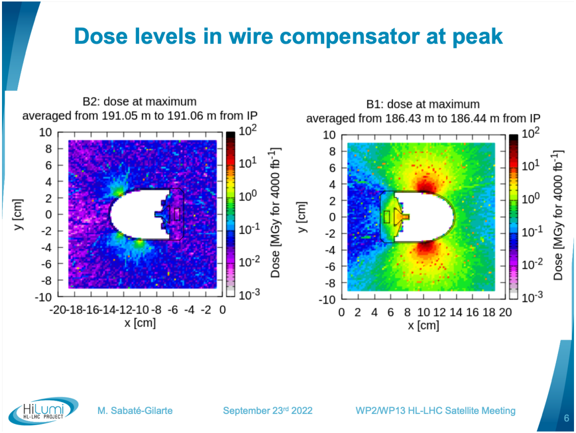
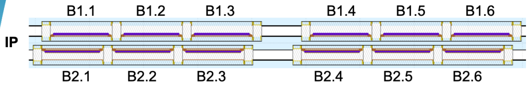
Preliminary energy deposition studies



Up to 100 MGy per 4000 fb^{-1}, negligible thermal load on the BBCW due to $\mathcal{L}$.
Courtesy of M. Sabaté-Gilarte.

Preliminary energy deposition studies

Energy deposition in the wire compensator



Total power in the Mo wire (**W**) for 7.5 Lo	.1	.2	.3	.4	.5	.6
B1	0.6×10^{-3}	0.4×10^{-3}	0.3×10^{-3}	1.2×10^{-3}	0.4×10^{-3}	0.4×10^{-3}
B2	24×10^{-4}	14×10^{-6}	6×10^{-6}	23×10^{-6}	15×10^{-6}	24×10^{-6}

Total power in the full compensator (**W**) for 7.5 Lo	.1	.2	.3	.4	.5	.6
B1	0.4	0.2	0.2	0.3	0.2	0.3
B2	0.04	0.02	0.01	0.02	0.02	0.02

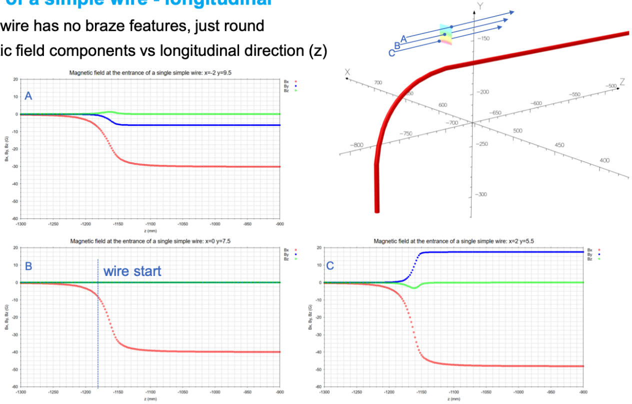
HiLumi HL-LHC PROJECT   M. Sabaté-Gilarte   September 23rd 2022   WP2/WP13 HL-LHC Satellite Meeting   8

Up to 100 MGy per 4000 fb^{-1}, negligible thermal load on the BBCW due to $\mathcal{L}$. Courtesy of M. Sabaté-Gilarte.

Magnetic model of the wires

Entrance of a simple wire - longitudinal

- Simple wire has no braze features, just round
- Magnetic field components vs longitudinal direction (z)



3D magnetic map available to simulate edge effect and non-idealities (brazing errors, cabling effect). Courtesy of M. Marchetto.

TRIUMF Contribution & Next Steps Proposal

TRIUMF contributions

Outlook to future involvement of TRIUMF beam physics in HL-LHC

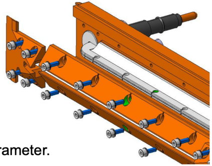
- Preparing the tools for comprehensive simulation to prepare material for the review.
  - Analytic calculation will allow for faster systematic parameter scans.
  - Benchmarking with other codes need to be completed.
- Supporting LHC machine development with simulation and data analysis.
  - Data analysis to quantify the effect of the wires on the luminosity production, effective cross section and beam lifetime.
  - Run octupole studies, also called "wire-as-octupole".
  - Demonstrate that the wires allow a reduction of the diffusion of beam particles from the core into the halo!
- Need to update and extend the Addendum 1 to the CERN-TRIUMF MoU on beam physics!

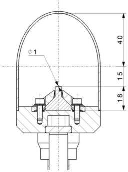
Strong collaboration with TRIUMF on several directions of the studies. **Proposal of a full scale prototype and to target fall 2023 for the CFI proposal**. Courtesy of O. Kester.

TRIUMF contributions

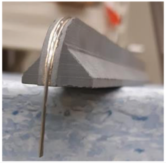
Plans for a full-scale prototype at TRIUMF

- Proposal to produce a test system addressing some engineering aspects
  - Thermo-mechanical characterization of AIN to ascertain its properties as a function of temperature.
  - Current feedthrough and operational parameter.





- Vacuum chamber addressing pumping, UHV cleaning, baking, access to the wire etc.)
- Want to explore a simple, low-cost, modular design, allowing a certain scalability to the complete module



Strong collaboration with TRIUMF on several directions of the studies. **Proposal of a full scale prototype and to target fall 2023 for the CFI proposal**. Courtesy of O. Kester.

TRIUMF contributions

TRIUMF

Project proposal to CFI typical timeline

HiLumi HL-LHC PROJECT

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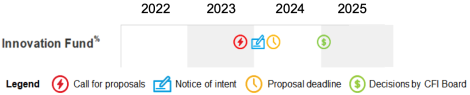
- The next call from the Canada Foundation for Innovation (CFI) Innovation Fund (IF) competition is expected in fall 2023.
- The typical timeline could be:
  Letter of intent (LOI) deadline in early 2024, the full proposal submission deadline in the spring or summer of 2024, and a decision by the CFI Board in early 2025.



- The TRIUMF internal project is already defined (P530).
- For the LOI the stakeholders – the involved Canadian Universities – need to be informed and fully included in the planning. A project description has to be provided to the lead university. We will again ask Alain Bellerive from Carlton University to be the PI of the wire project.

Strong collaboration with TRIUMF on several directions of the studies. **Proposal of a full scale prototype and to target fall 2023 for the CFI proposal**. Courtesy of O. Kester.

Outline

- **BBCW demonstrators operational in 2022**. Beneficial effects observed.
- **In the first period of Run4 there could be a substantial leveraging of the BBCW compensation effect** (CC commissioning). This is compatible with tight collimation scenarios (to be tested in 2023).
- A simple, low-cost, modular design was explored. **No showstoppers identified**.
- The UR integration solution is compatible with **off-the-shelf PCs** but **cabling integration still outstanding**.
- Preliminary studies on impedance and energy deposition show no show-stopper. Both can be improved by adequate matching, shielding. . .
- **If endorsed by TCC**, we will target the Review 2023 (budgets and schedule as additional topic) and, depending on the results and following decision, TRIUMF will apply for the CFI funds.

Thank you for your attention.

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