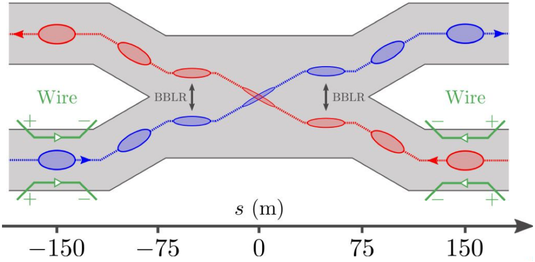
CERN

BBLR Wire Compensation in Run 4

G. Sterbini on behalf of BBCW team

We thank **HL-LHC**, **CERN** *and* **TRIUMF** *management for their support and the* **HL-LHC WP2/5/13** *and the* **LHC OP team** *for the inspiring discussions and encouragement.*



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

- The beam-beam long-range interactions (**BBLR**) act as magnetic multipolar errors[1,2]

[1] Y. Papaphilippou and F. Zimmermann, PRST AB **2** 104001 (1999)
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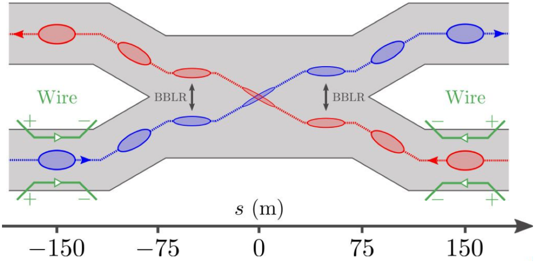
[3] S. Fartoukh et al., PRST AB **18** 121001 (2015)



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  - → limit the $\int \mathcal{L} dt$
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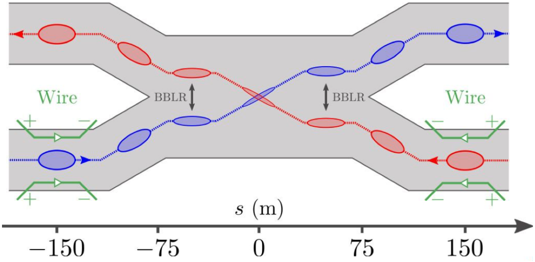

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  - $\rightarrow$ limit the $\int \mathcal{L}dt$
  - $\rightarrow$ can be corrected (e.g. by the DC wires, **BBCW**)
- in (HL)-LHC, given the symmetry of the optics and the phasing of the BBLR, we can minimize the number of BBCW.[3]

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

The BBCW experimental program supported by **HL-LHC Project**

- 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.

Run 3 Results

For the most recent Run 3 results, please refer to the comprehensive presentation of P. Bélanger. A few important elements to retain:

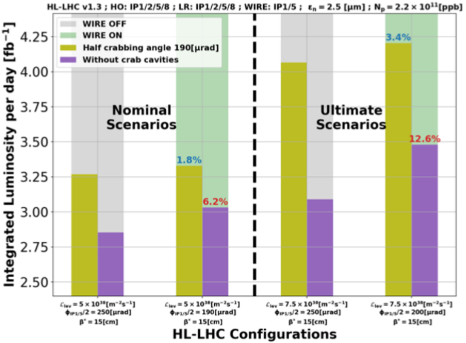
- **BBWC demonstrators** are in LHC since 2017 in MD[4] and used in **operation since 2022**.
- Beneficial effect clearly visible in MD and (less, as expected) in operation.
- 2022 and 2023 operation deployment was smooth (limited commissioning time required)
- the demonstrators (not intended to be used in operation) show a HW weakness, fixed during the last end-of-year stop for B2 (to test the proposed solution). Since then, no problem has been observed.
- We will **propose to fix the B1 wire during this end-of-year stop** and test both beams in 2024.

[4] e.g. A. Poyet et al., https://arxiv.org/abs/2203.08066, submitted for publication.

From Run 3 to HL

- During 2023 **pp** run, we were working in a relatively aggressive BB configuration during the $\mathcal{L}$-levelling $\rightarrow$ varying the crossing angle, at BB limit
- For HL, we are considering, thanks to the CC, constant crossing angle (low BBLR effect at **SoL**), but we are still limited at the end of **EoL**.
- 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[5] 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%

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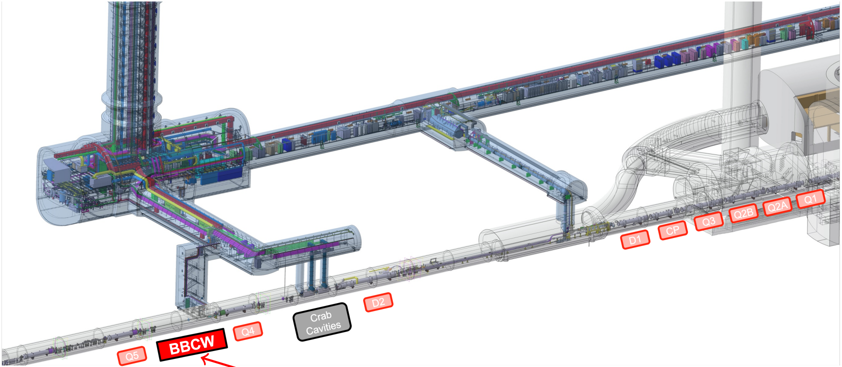
[5] K. Skoufaris et al., PRAB **24** 074001, 2021

BBWC Space Reservation Request[6]

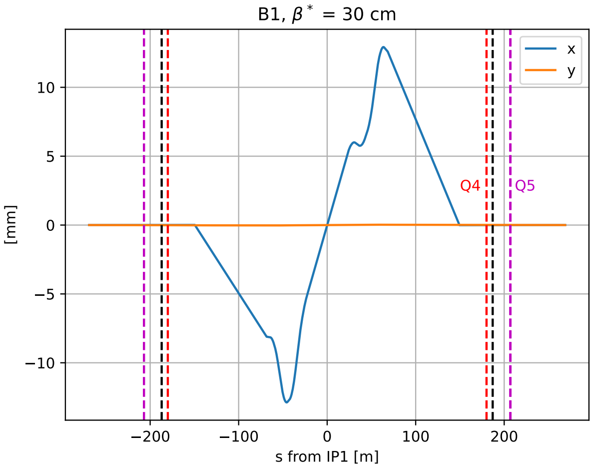


≈9 m space between Q5-Q4 reserved for HL wires for both sides of IR1/5

Courtesy of M. Modena and M. Mendes.

[6] EDMS 2037987

BBWC Space Reservation Request[7]



External to the crossing bump, close to Q4.

[7] EDMS 2037987

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 $\int I_W dl$.
- $\rightarrow$ crucial to define **collimator configuration** for a sound BBCW strategy!

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

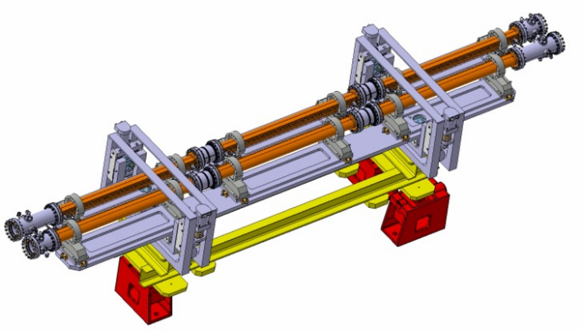
BBCW and collimation settings (II)

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**, leakage-to-experiments, but all-in-all reduced margins (robustness on losses) due to the **missing copper diamond TCTs**.

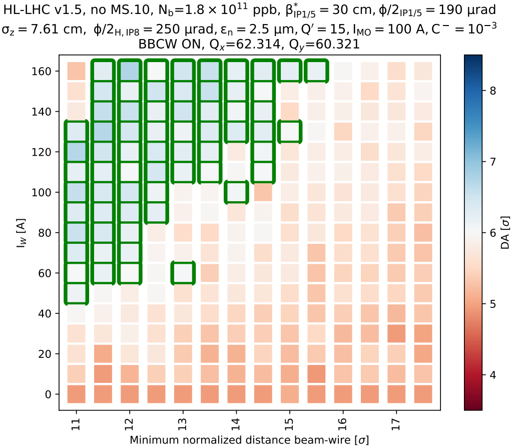
HL proposed wires' assembly



Courtesy of A. Bertarelli.

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

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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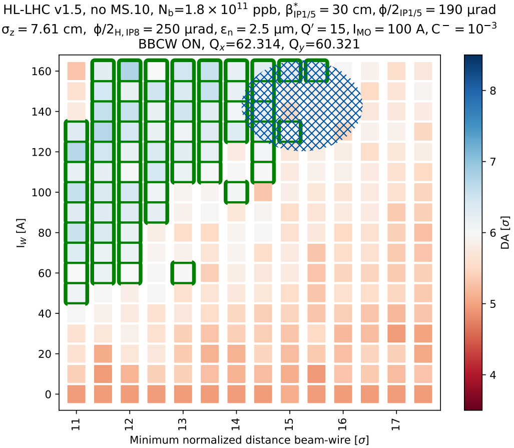

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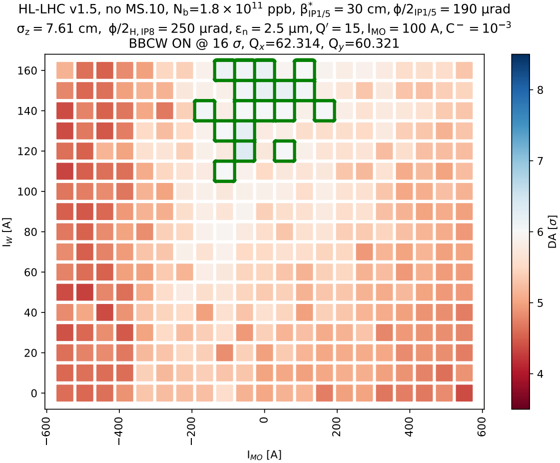
Interplay with arc octupoles



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

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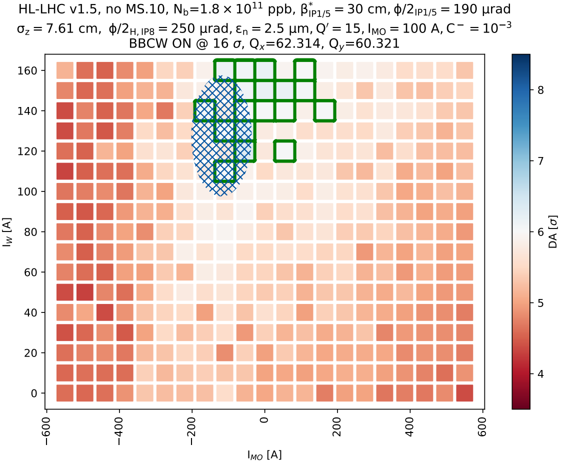

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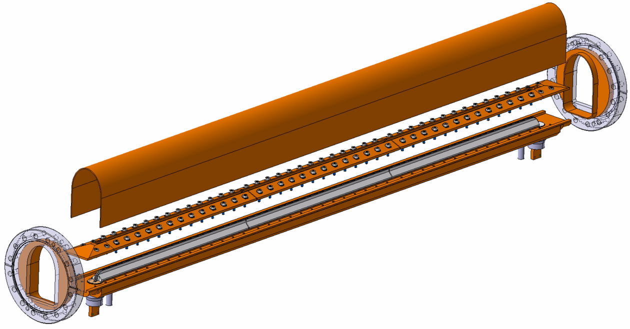
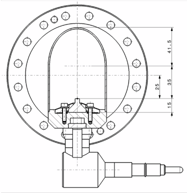
Wire module design proposal

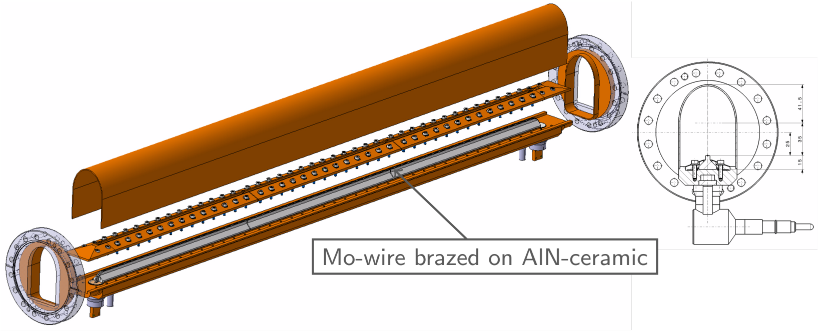




Courtesy of A. Bertarelli.

- **Use a slim, light design with a thin, bare, metal wire** to minimizing interactions with beam particles,

Wire module design proposal



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- **Use a slim, light design with a thin, bare, metal wire** to minimizing interactions with beam particles,
- **1 m long, $\varnothing = 1$ mm Mo-wire brazed on AlN-ceramic**,

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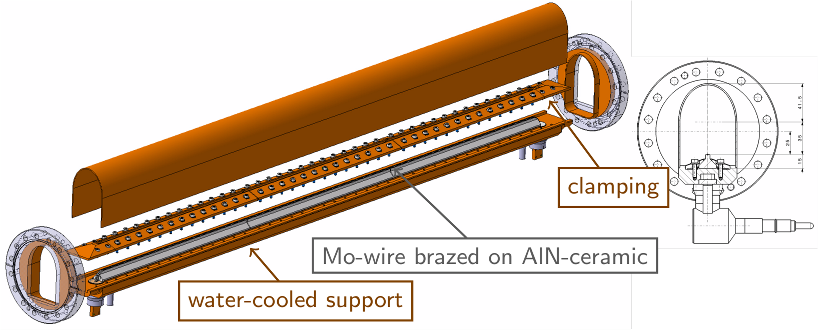

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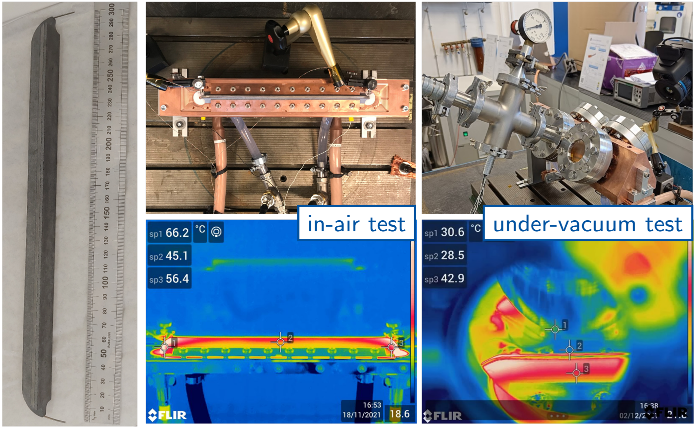
- **Use a slim, light design with a thin, bare, metal wire** to minimizing interactions with beam particles,
- **1 m long, $\varnothing = 1$ mm Mo-wire brazed on AlN-ceramic**,
- the ceramic is clamped on a **water-cooled support**.

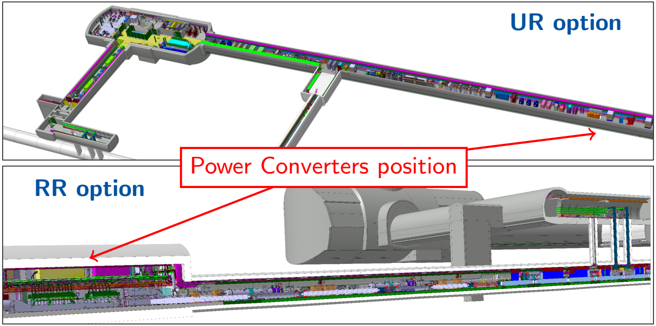
Proof of Concept tests



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.

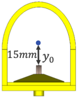
Infrastructure/Integration constraints

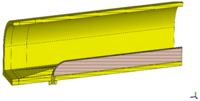


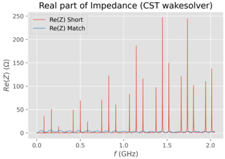
Courtesy of A. Rossi.

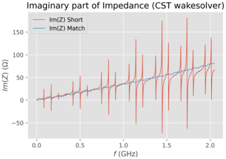
- **8 power converters** (200 A×60 V),
- 2 options for the power converters location:
  - **UR**: commercial PCs possible but limits with cabling in the HL cores,
  - **RR**: RR PCs not available at the moment,
- **the cabling of the wires (power+signals) is outstanding**.

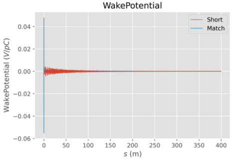
Preliminary Impedance Studies







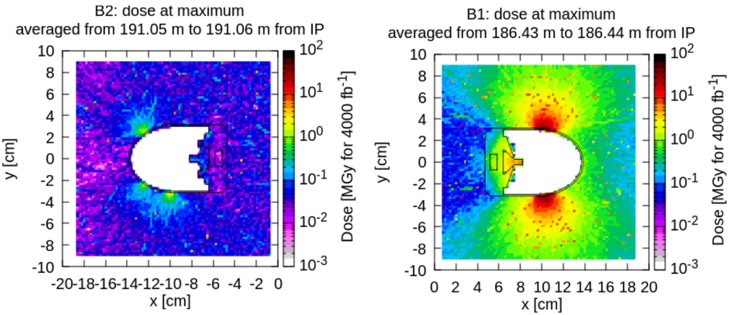




Courtesy of B. Salvant.

- 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,
- **negligible EM thermal load**,
- **vacuum and e-cloud** compliance should be investigated.

Preliminary energy deposition studies



Courtesy of M. Sabaté-Gilarte.

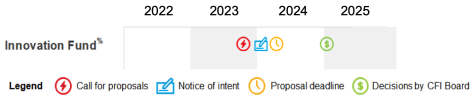
- **Up to 100 MGy per 4000 fb^{-1}**,
- **negligible $\mathcal{L}$-driven thermal load on the wire**,
- **the BBCW impact on the Forward Physics (in IP5) is still outstanding.**

TRIUMF contributions

TRIUMF — Project proposal to CFI typical timeline

10

- 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.

Courtesy of O. Kester.

- **Strong TRIUMF collaboration on the compensation studies**,
- proposal to build a full scale prototype at TRIUMF,
- **pending CERN-TRIUMF agreement**, submit a **proposal to the Canada Foundation for Innovation**.

Summary

- **Wire demonstrators used in operational fills since 2022**.

- 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 organized (**budgets and schedule** will be addressed) and, depending on the outcome and following decisions, TRIUMF could apply for a CFI Innovation Fund.

Thank you for your attention.

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Review of BB Wire Compensation (I)

Charge:
Review the need for beam-beam wire compensation in the HL-LHC era, looking at the benefits, technical feasibility, cost, and schedule for implementation.

Charge Questions:
Is beam-beam wire compensation worth implementing in the HL-LHC era, taking into account the benefits obtained for the resources invested?

Review of BB Wire Compensation (II)

Beam Physics and Operational Aspects

1. Is the case for the use of beam-beam compensating wires sound, with clear benefits demonstrated with the compensation scheme proposed for the HL-LHC era?
2. Has the possible beam performance gain been adequately demonstrated through simulation?
3. Has the interplay between the wire with tune, chromaticity and octupole settings been optimised?
4. Has the operational feasibility been demonstrated, taking into account machine and equipment protection, and the compatibility with Forward Physics requirements?

Review of BB Wire Compensation (III)

Design Aspects:

1. Is the presented thermo-mechanical design sound and have all possible mechanical constraints been studied?
2. Have all effects impacting the interaction of the wire with the beam been considered?
3. Are the pre-alignment and active alignment strategies proposed adequate to maintain the required beam-wire distance?
4. Has the feasibility of integrating the wire and its auxiliary equipment in the tunnel been demonstrated with the necessary infrastructure requirements identified?

Review of BB Wire Compensation (IV)

Resource Aspects:

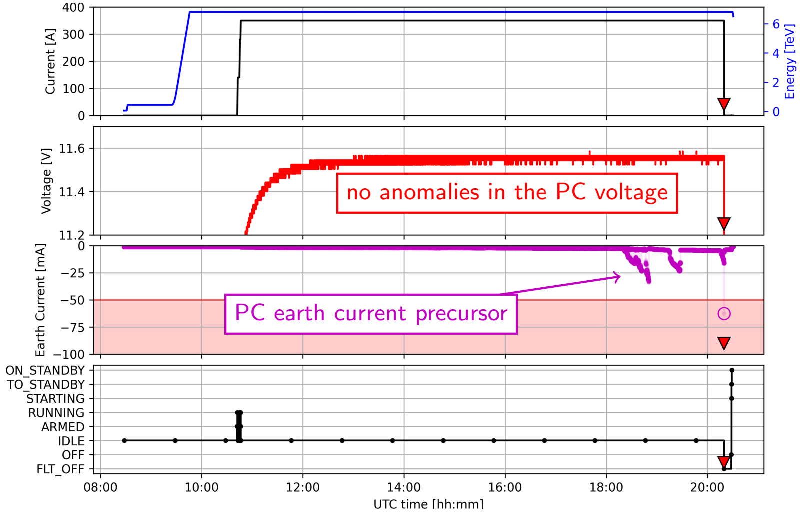
1. Is the resource estimate in terms of both material cost and workforce realistic?
2. Are the possible in-kind contributions credible?
3. Does the proposed schedule for implementation fit with the estimated resource needs?

Beam dumps related to the wires

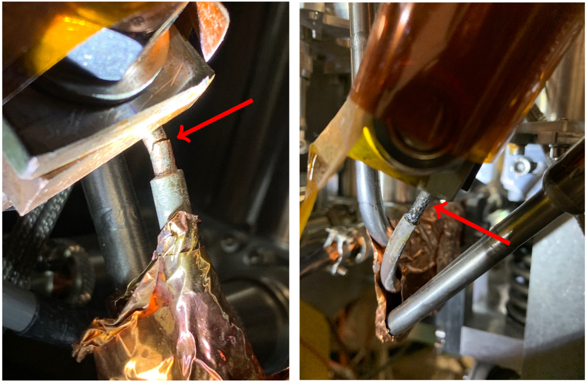
2022 dumps related **directly** or indirectly to the use of demonstrators:

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^+, 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)**

4 dumps due to earth faults of the IR1 wires.



L1B1 earth fault on August 20th, 2022 (fill 8146).



Courtesy of A. Rossi.

Cracks and evident signs of oxidation on the wire feed-through ($\varnothing$=3.45 mm, outside the TCT) close to the 95 mm^2 power cable.

→ **root cause due to the mechanical constrains of the power cables**: lab tests ongoing to evaluate the **technical feasibility + risks of an in situ repair and consolidation** (SY-BI/STI and EN-MME).