Summary of the HL-LHC Wire Compensation Meeting

G. Sterbini, Y. Papaphilippou, A. Rossi
on behalf of the participants of the participants of the
WP2/WP13 HL-LHC Wire Compensation Meeting, FERMILAB, 17th October 2019

WP2 meeting, 26th November 2019

Links and Outline

INDICO link

1. Setting the scene
2. Results RUN2 and perspective RUN3
3. HL-LHC theory, simulation and potential
4. Technical aspects & TRIUMF potential contributions
5. Main conclusions

Session	Contribution	Speaker	Location	Time
1	Welcoming remarks	Oliver Bruning	Wilson Hall, One West, Fermilab	08:45 - 09:00
1	Introduction/Motivation and current wire HW	Adriana Rossi	Wilson Hall, One West, Fermilab	09:00 - 09:30
2	MD results during LHC RunII and plans for RunIII	Guido Sterbini	Wilson Hall, One West, Fermilab	09:30 - 10:00
2	Modelling of MD results and effect of crossing angles (remote presentation)	Axel Poyet	Wilson Hall, One West, Fermilab	10:00 - 10:30
	Coffee break		Wilson Hall, Atrium 1st floor, Fermilab	10:30 - 11:00
3	Simulations for HL-LHC configuration (remote presentation)	Kyriacos Skoufaris	Wilson Hall, One West, Fermilab	11:00 - 11:30
3	Correction of resonant driving terms with wires	Dobrin Kaltchev	Wilson Hall, One West, Fermilab	11:30 - 12:00
3	Lunch break		Wilson Hall, Atrium 1st floor, Fermilab	12:00 - 13:00
3	Scenarios and timeline for wire compensation in the HL-LHC	Yannis Papaphilippou	Wilson Hall, One West, Fermilab	13:00 - 13:30
4	Wire HW design for HL-LHC and integration	Alessandro Bertarelli	Wilson Hall, One West, Fermilab	13:30 - 14:00
4	TRIUMF contribution to the BBLR Compensation Project for HL-LHC	Oliver Kester	Wilson Hall, One West, Fermilab	14:00 - 14:30
5	Discussion (All)		Wilson Hall, One West, Fermilab	14:30 - 15:30

Minutes of the meeting

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HL-LHC management perspective

- The wire compensation option **is NOT in the HL-LHC baseline.**
- **HL-LHC supported the demonstrators constructions and the studies but cannot support the HL-LHC compensators.**
- It can **be envisaged only if additional resources** (in-kind contributions) could be allocated.
- The **HL-LHC management supports and recommends initiatives along this direction**. In particular a potential contribution from TRIUMF in the Beam Dynamics studies, in the wire compensator technical design and in its fabrication is welcome, desired and praised.

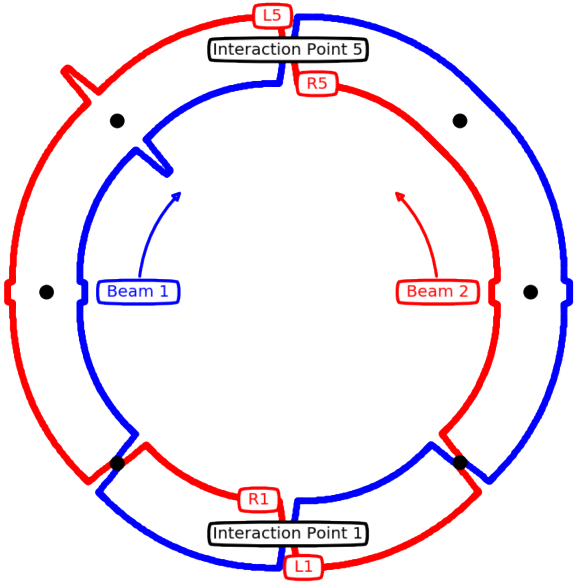
O. Brüning

The goal of the meeting

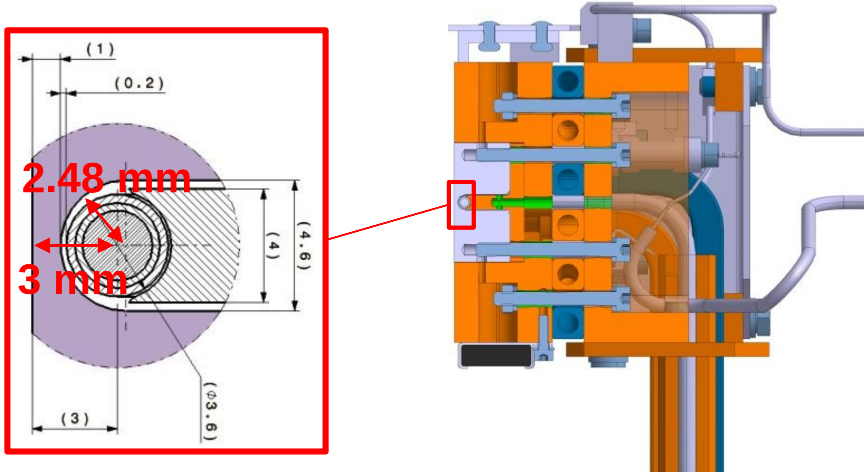
- To present/discuss **the latest experimental and simulation results at LHC** with the present demonstrator of wire for Beam-Beam Long Range Compensation.
- To present/discuss the **predictions for the HL-LHC, together with first ideas for the wire hardware design** and possible implementation.
- To build upon the existing **collaboration between TRIUMF and CERN**, look for a framework for future contributions from TRIUMF to HL-LHC for BBLR wire compensation.

A. Rossi

The LHC wire demonstrators



Layout of the wire installation, not to scale



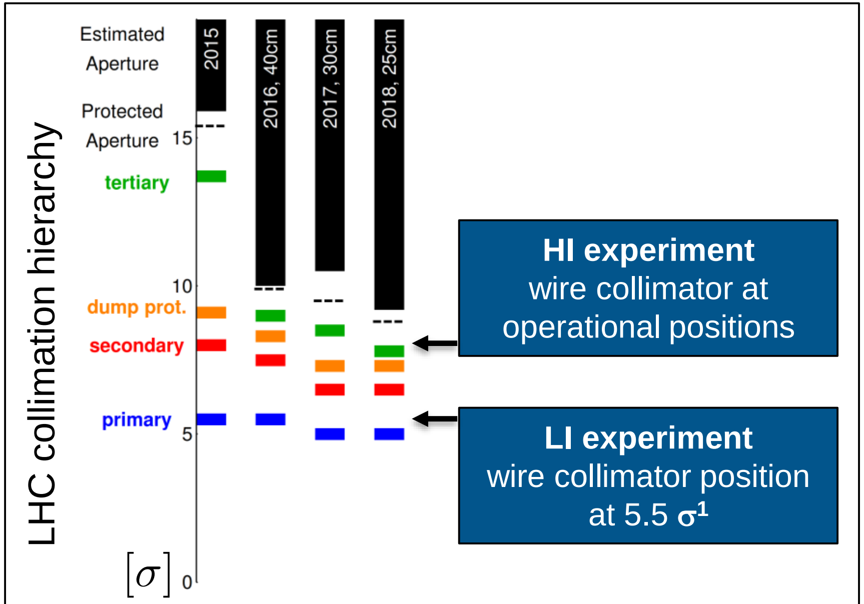
Courtesy of L. Gentini

Front view

- **Since 2018 four wire demonstrators are installed in LHC (B2, IR1+IR5)** with the aim to explore the potential of the wires in HiLumi HL-LHC PROJECT

Transverse positions of the wires

- 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 with wire-collimator just in the shadow of the primary collimators
  2. **HI**: **High-Intensity** experiment with wire-collimator at the operational position.



Courtesy of R. Bruce

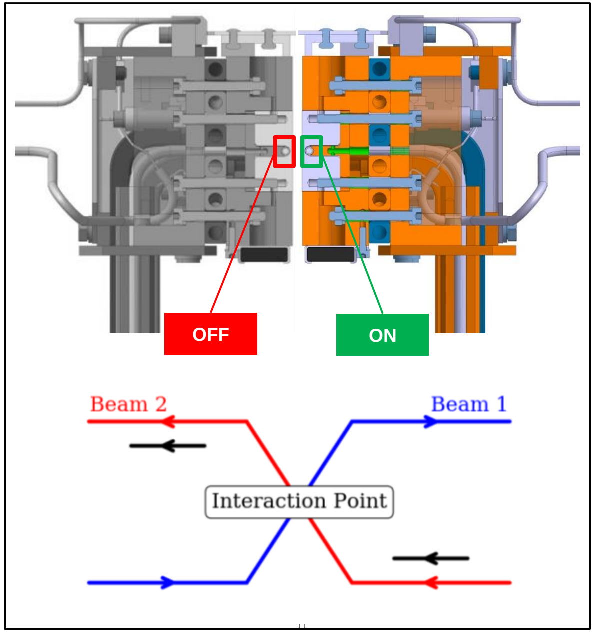
Wire demonstrator	LI experiment	HI experiment
	beam-wire distance [mm]	
L1	**-7.41**	not powered
R1	**7.42**	**9.83**
L5	**-7.15**	not powered
R5	**8.24**	**11.10**

[1] An ε_n=3.5 mm mrad assumed.

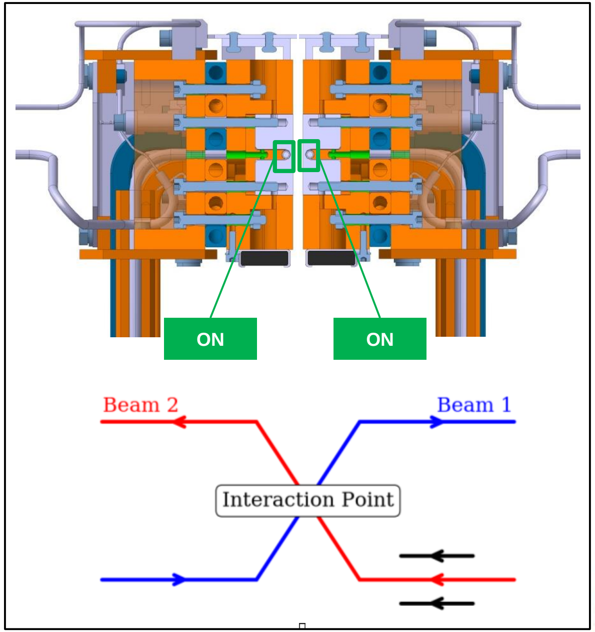
Wire current settings

- 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 where powered: this allowed to double the integrated strength of the quadrupolar, octupolar, etc., components.

LI experiment: 1-jaw powered

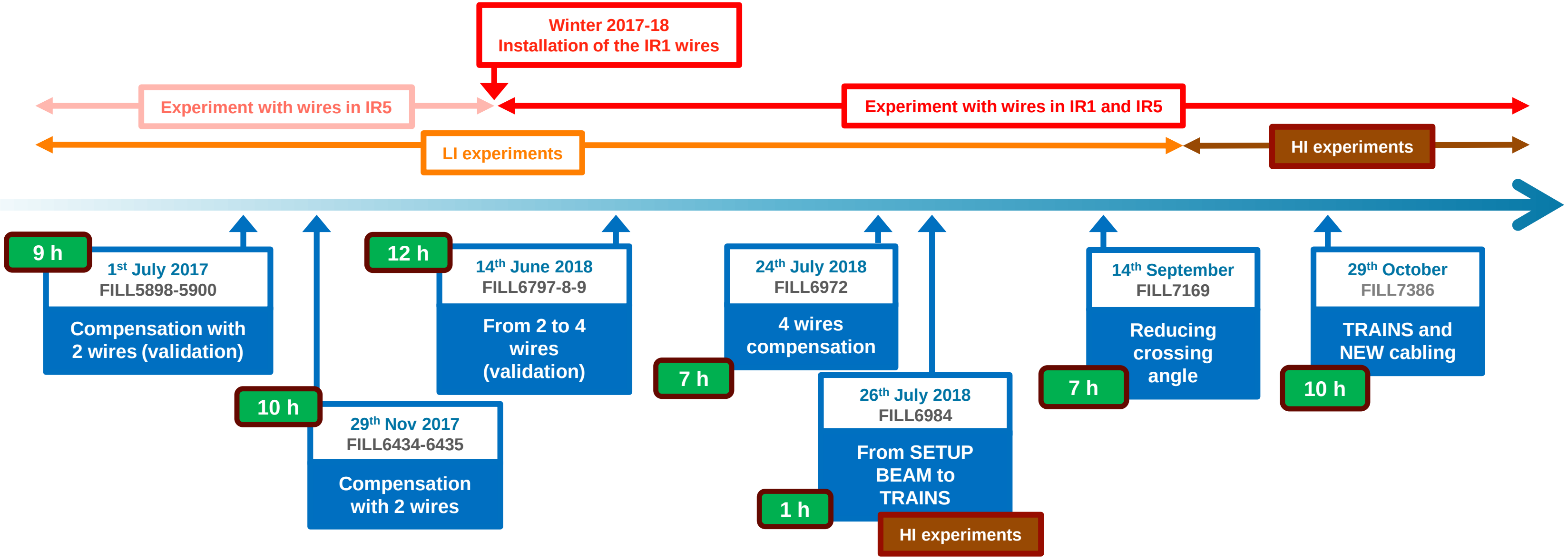


HI experiment: 2-jaws powered



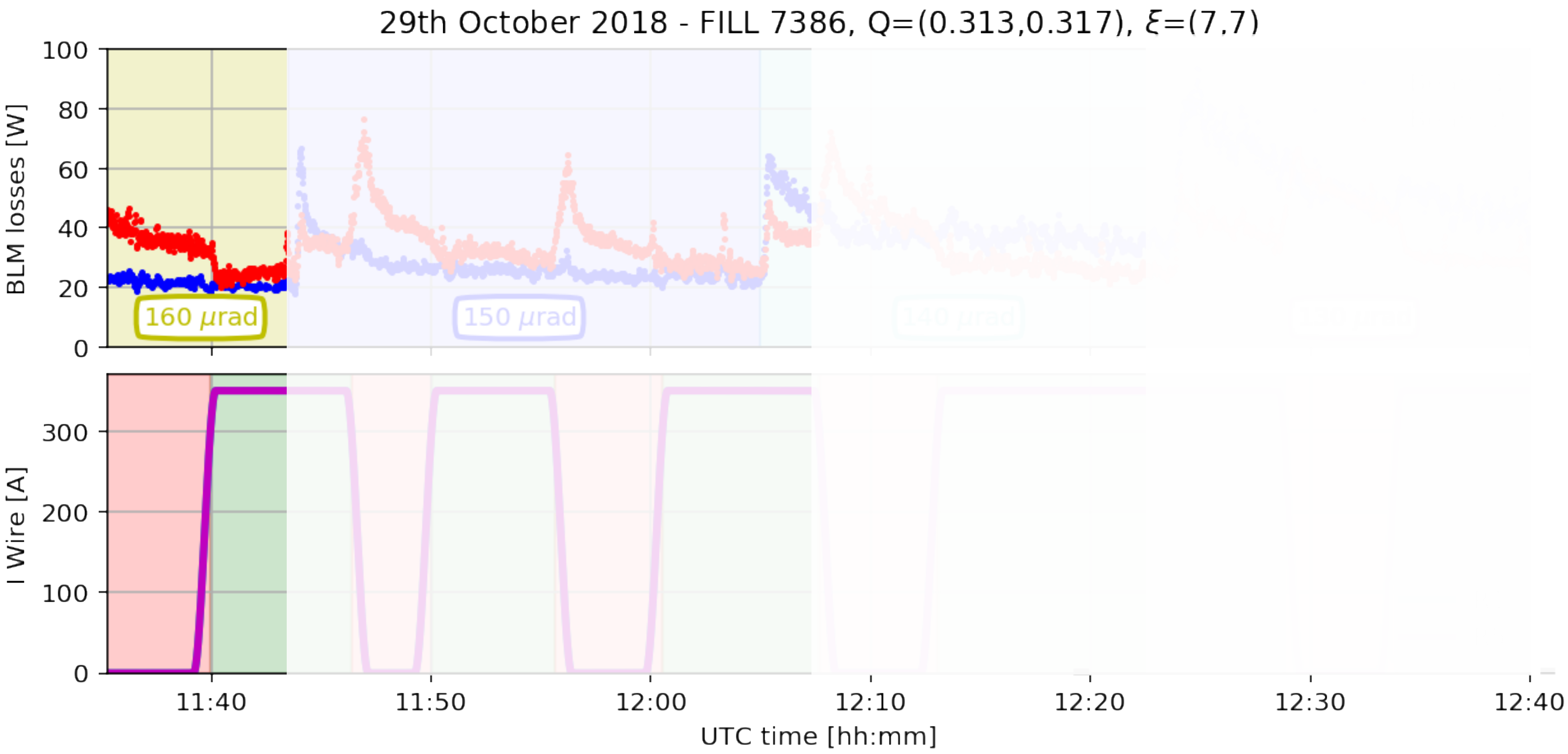
Wire demonstrator	LI experiment	HI experiment
	Current [A]	
L1	350 x 1	not powered
R1	320 x 1	350 x 2
L5	190 x 1	not powered
R5	340 x 1	350 x 2

The experimental campaign



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

HI experiment (operational conditions)



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

Simulating the HI experiment

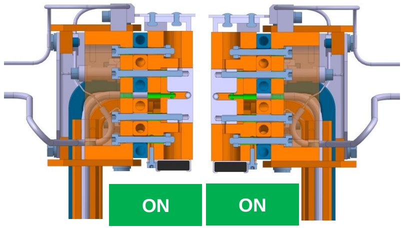
- Second experimental setup: **2-jaws powering** configuration
  - Both internal/external wires powered
  - Only 1 collimator per IP
  - Non-safe beam: **collimators opened at 8.5σ (operational settings)**
  - Wires powered up to their maximal possible currents

- From the scan, similar possible improvements (not reachable experimentally)

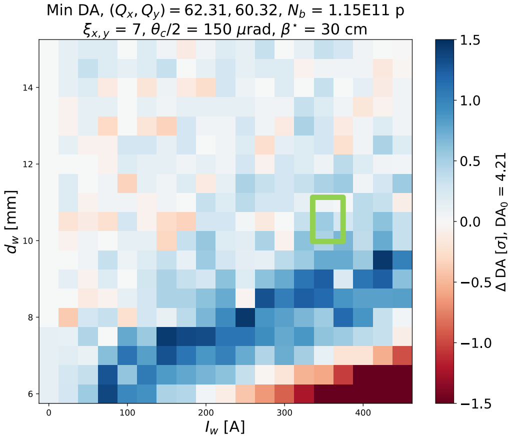
- In configuration space, effect not so visible but still ~0.8σ **gain in minimum DA**

A. Poyet

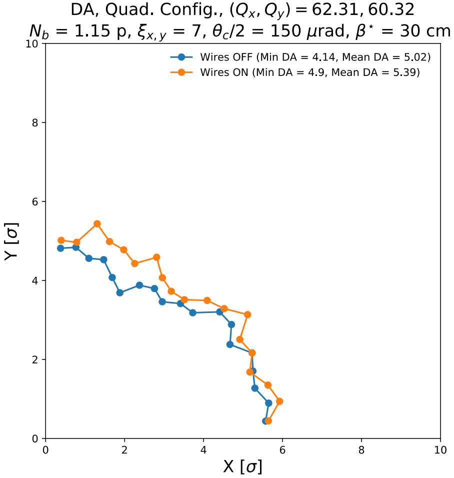
HI experiment	beam-wire distance [mm]	Wire Current [A]
L1	not powered	not powered
R1	9.83	2 x 350
L5	not powered	not powered
R5	11.10	2 x 350



DA dependency on wires current/position (2-jaws powering)

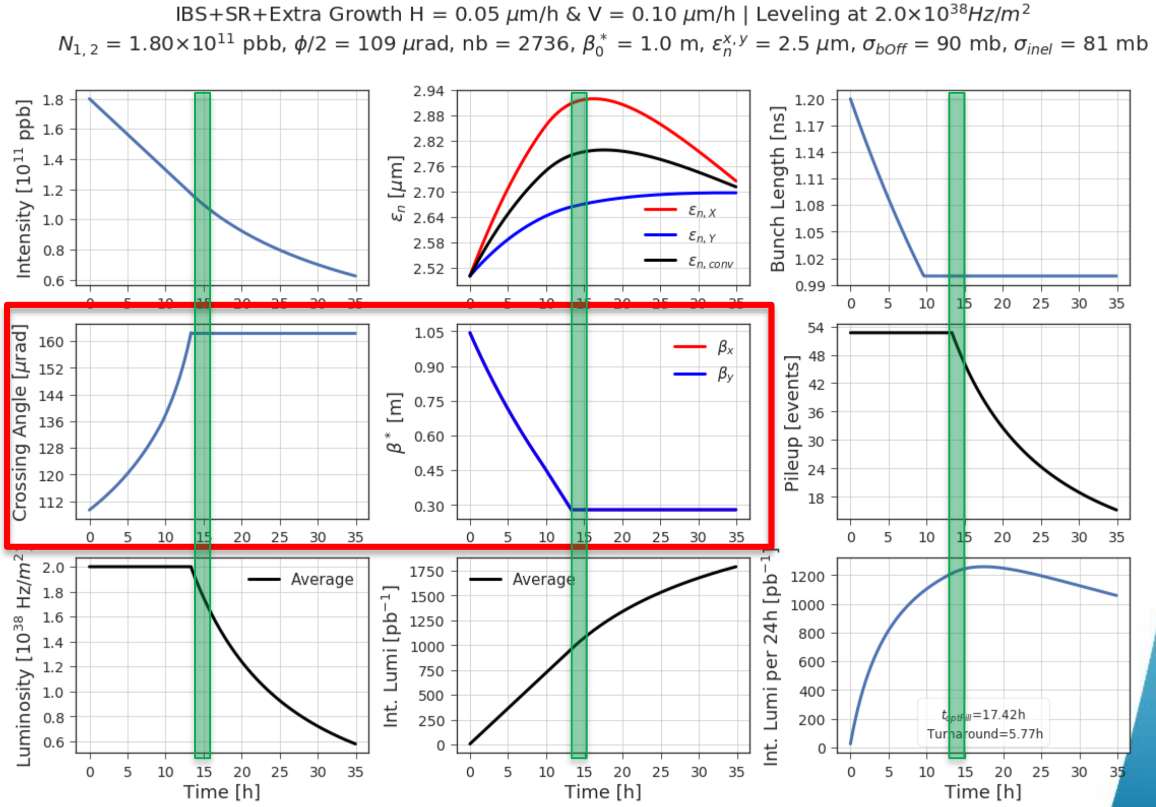


DA in configuration space for MD#4



Run-III Fill Profile (2021-23)

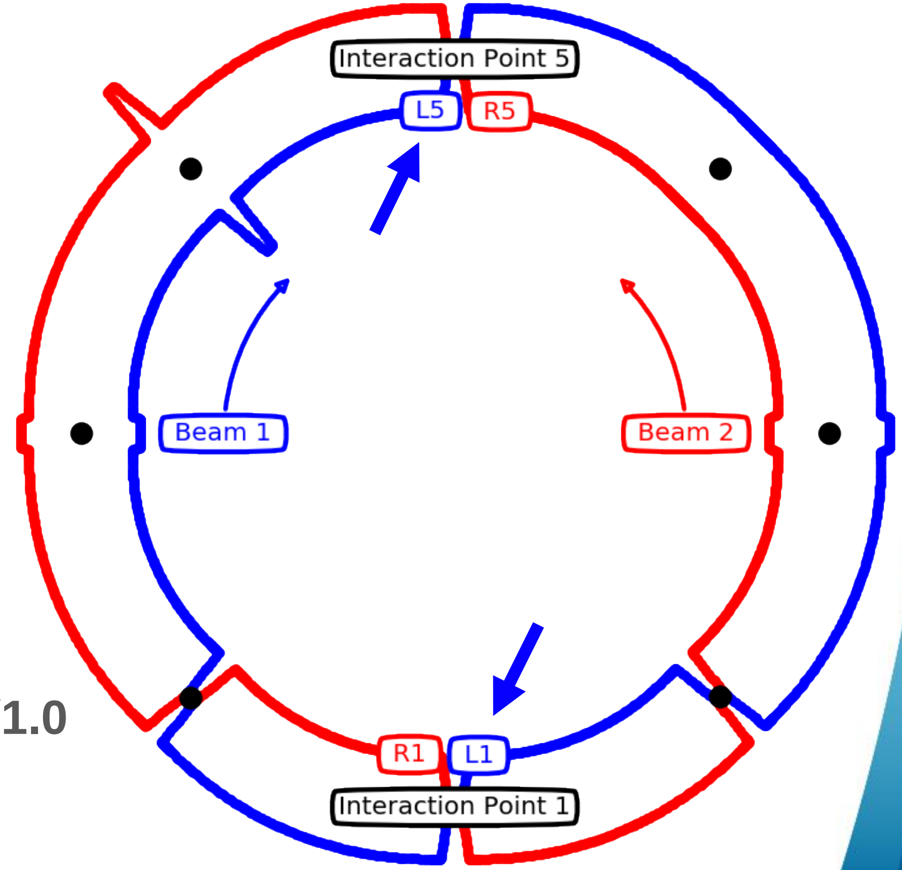
- In 2021: **round optics** with IP1 crossing in V-plane and IP5 crossing in H-plane.
- The wires could be switched on at the end of the leveling.
- We assume Run-III collimation settings similar to Run-II ones.



Courtesy of S. Fartoukh and N. Karastathis

Next steps and proposals

- 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.



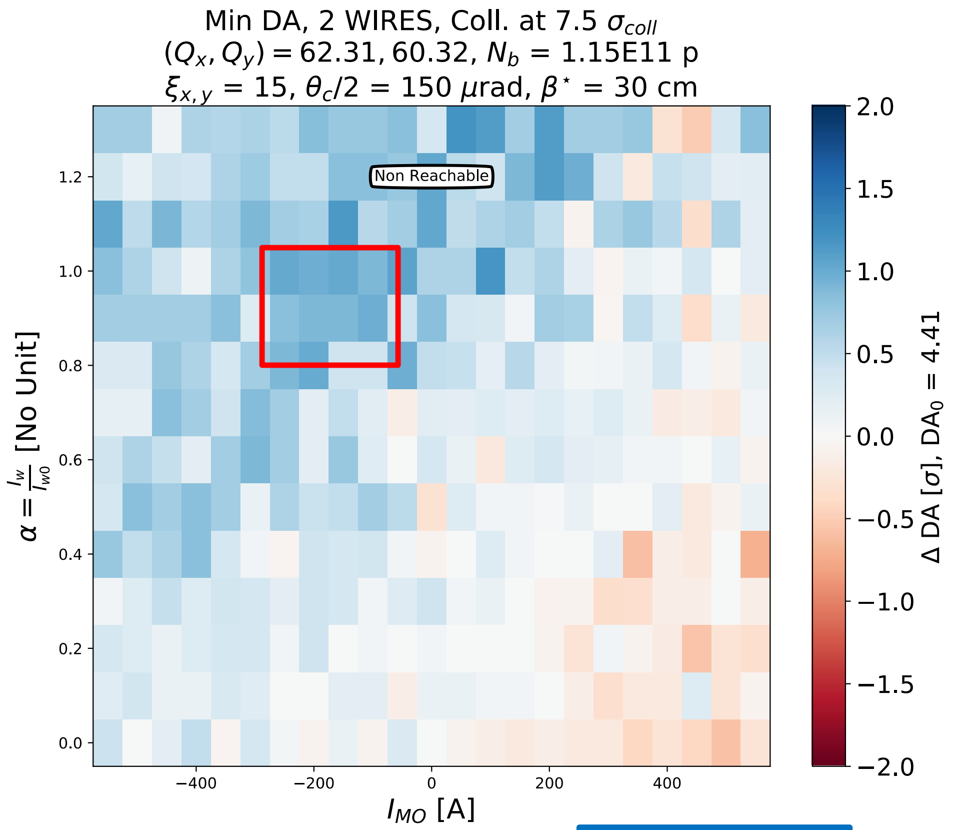
https://edms.cern.ch/document/2054712/1.0

HiLumi HL-LHC PROJECT

CERN

Towards Run III: Compromise wires/octupoles

- Experimentally, it has been shown that **octupoles can be used to mitigate BBLR** interactions (with high tele-index) [6]
- Octupoles are needed for **coherent stability**
- A **compromise** between wires and octupoles can be considered
- **Negative octupoles** could help the compensation scheme of the wires

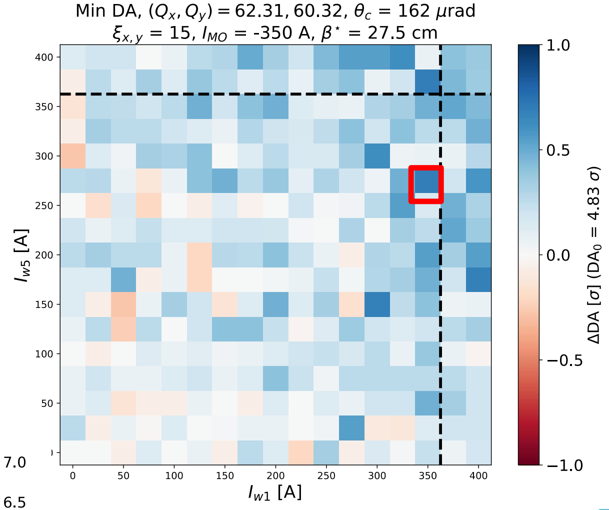


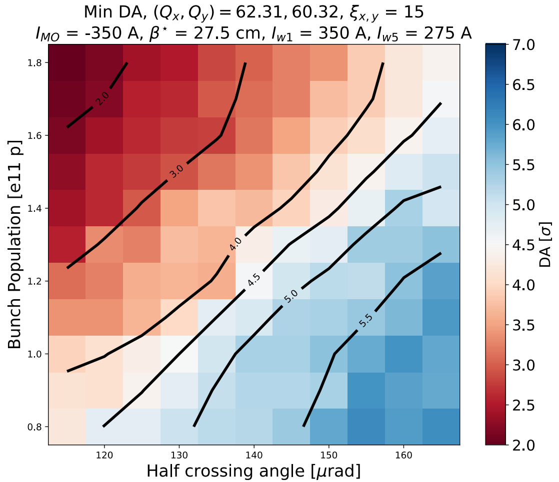
A. Poyet

Run III: Effect on the crossing angle

- Experimentally, **we observed that it is possible to reduce the crossing angle**, without increasing the losses [1]
- DA dependency on crossing angle and bunch intensity confirms this result
- Run III scenario: **crossing angle anti-levelling up to 162 μrad [7]**
- Possible use of the wires: power at the **end of the fill to reduce the crossing angle**, keeping the DA ~ 5σ
- **Clear possible gain:**
  - **1.2e11 p → 150 μrad**
  - **0.8e11 p → 135 μrad**

DA as a function of wire currents (coll. at 8.5 σ)





DA with 2 wires (coll at 8.5 σ)

A. Poyet

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THEORY

Correction of resonant driving terms with wires

- This approach is alternative to the one presented by S. Fartoukh et al. [PRST-AB 18, 121001] which was based on the kick multipolar expansion.
- The rationale is to represent the Hamiltonian associated with the long-range encounter as **a 2-D Fourier series using the 2-D generalized Bessel functions**.
- D. Kaltchev solved numerically the problem assuming horizontal crossing angle. Differently from the approach of [PRST-AB 18, 121001] he **did not constrained the left and right wires to have the same physical distance from the weak beam and allowing the wire compensation of all Fourier coefficients for any wire longitudinal positions**.
- In addition, using the recursive relation of the Fourier coefficients (1D case) D. Kaltchev showed that by **compensating the first two non linear Fourier coefficients one compensates all of them**.

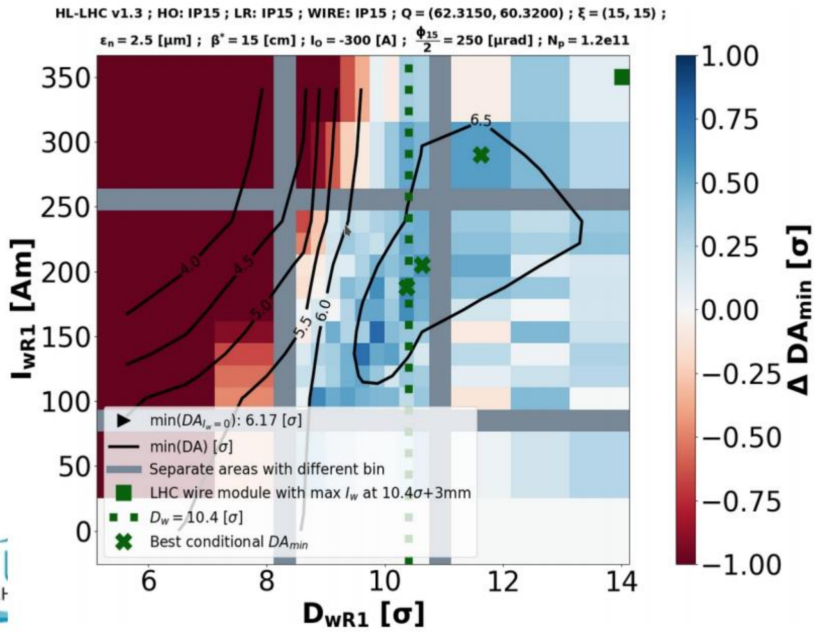
D. Kalchev

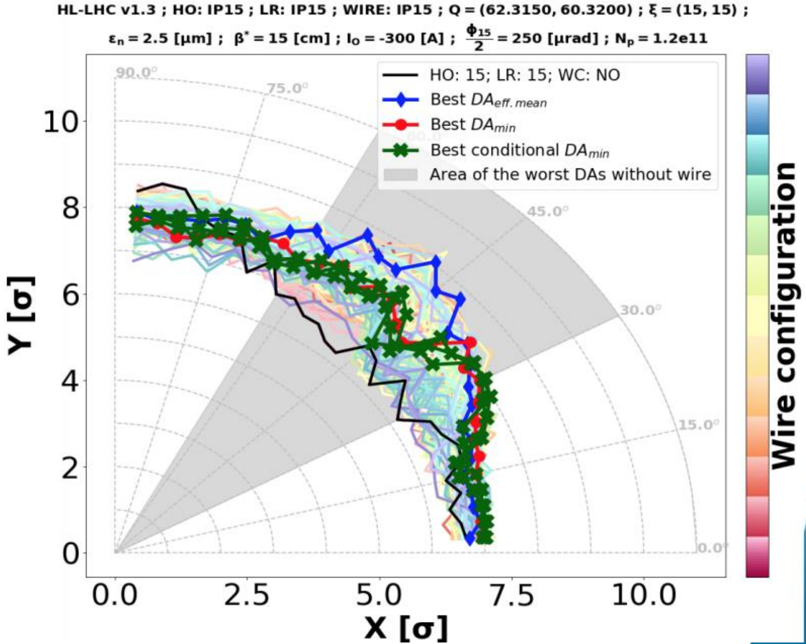
Numerical simulations - Nominal scenario

- Different **wire configurations with D_w>10.4 [σ] improve the DA_{min} up to 0.7 [σ]** on top of the well optimized nominal scenario (DA_{min} = 6.17 [σ]) - Best conditional DA_{min}.

K. Skoufaris

- The **existing LHC wire (green square) is not ideal** for the HL-LHC nominal scenario.
- The average DA gain along the different angles is even more significant.



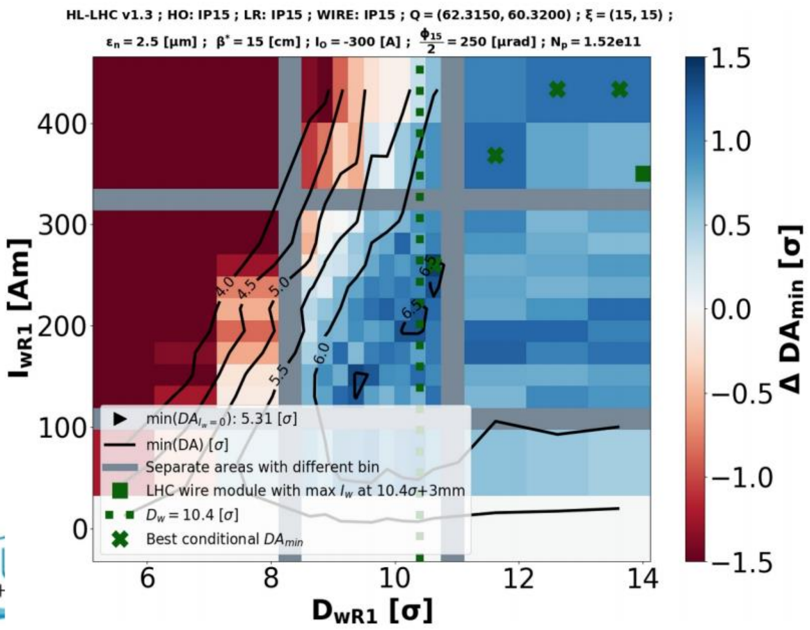


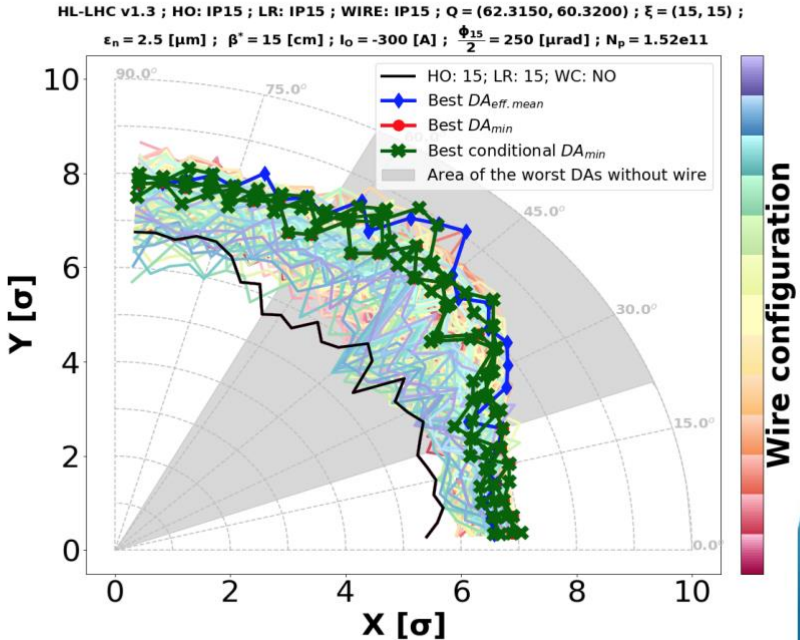
Numerical simulations - Ultimate scenario

The **wire compensators guarantee best conditional DA$_{min}$ up to 6.7 [σ]** (1.5 [σ] improvement).

K. Skoufaris

- The DA gain along the different angles is even more significant.



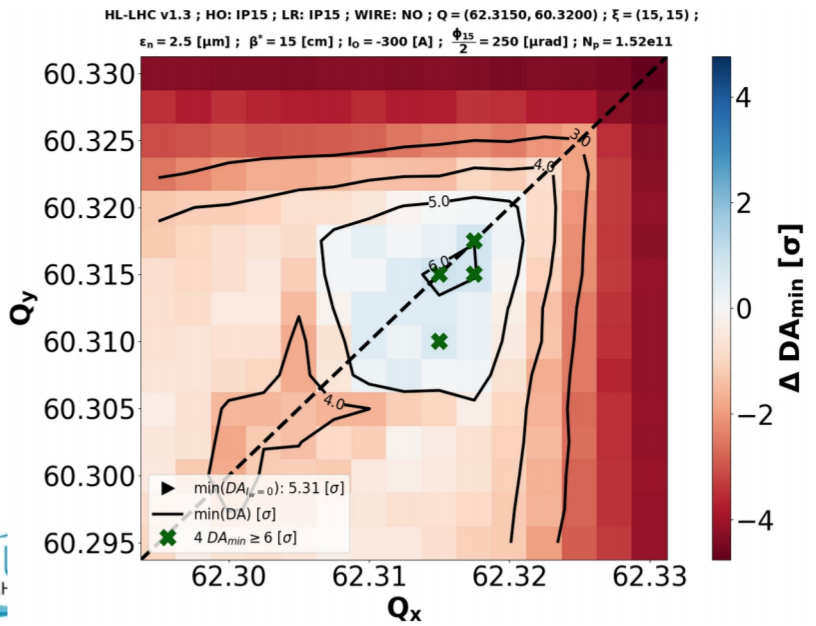


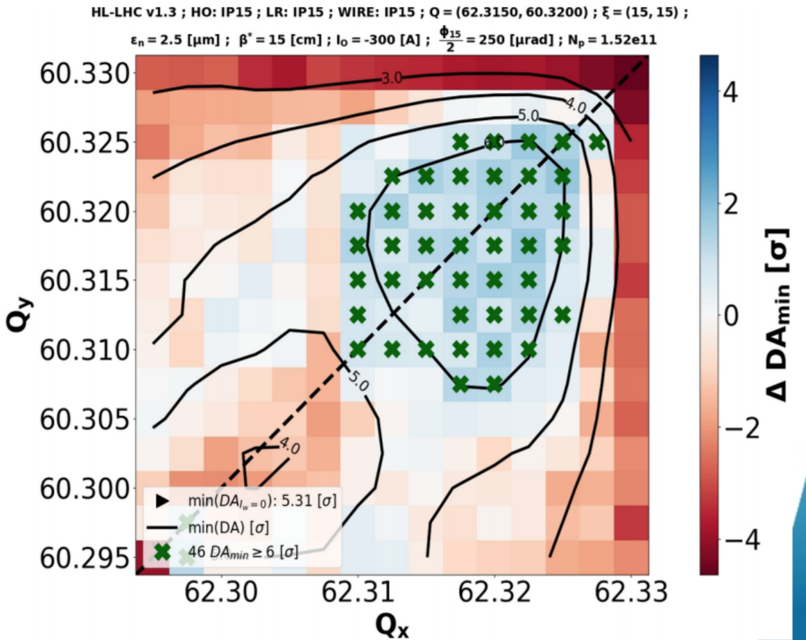
Numerical simulations - Ultimate scenario

Even with assisting octupole current (negative polarity for partial BBLR compensation) **there is not any tune configuration above the diagonal with DA_{min} ≥6 [σ].**

K. Skoufaris

Using the wire compensators (with one of the best DA configuration) **a large set of good WPs (DA_{min} ≥6 [σ]) can be used.**



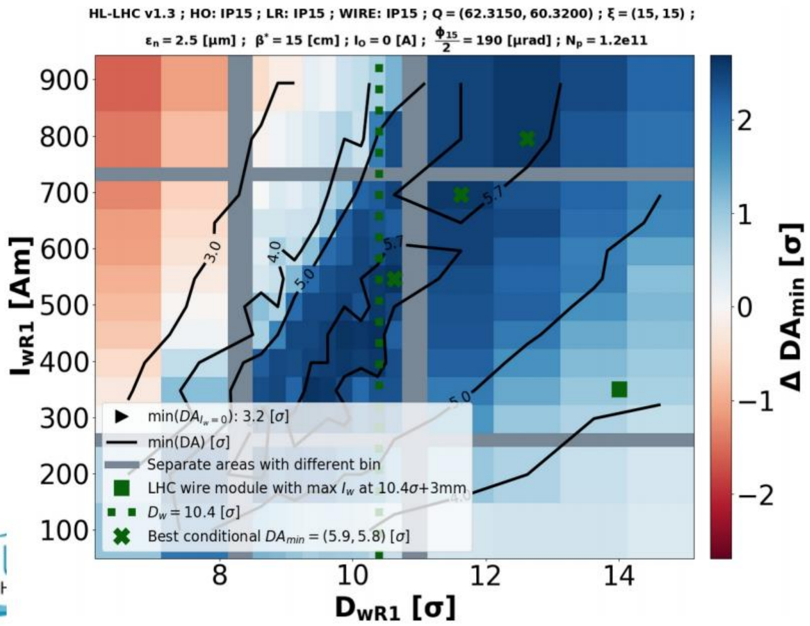


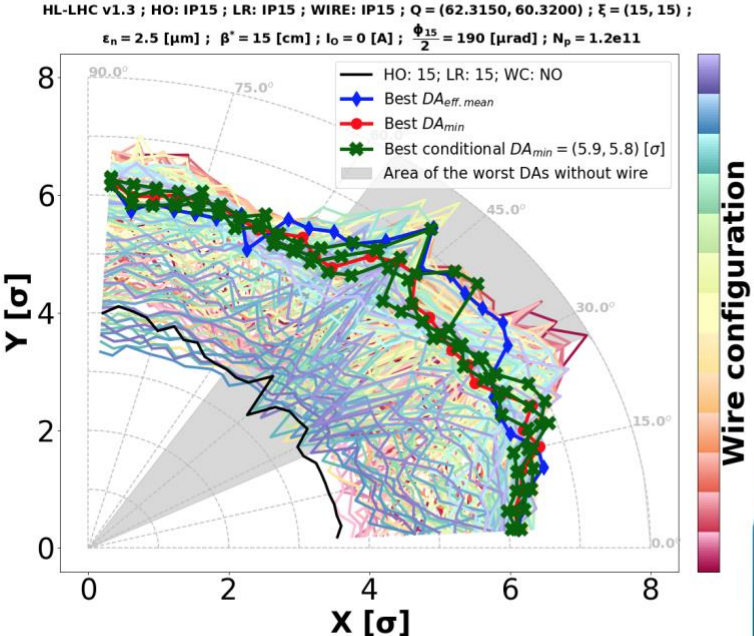
Numerical simulations - Pushed X-ing angle scenario 2

- **The DC wire can improve the DA_{min} up to 5.9 [σ] (2.7 [σ] gain) even with D_w≥10.4 [σ].**

K. Skoufaris

- For all the best conditional (wire) configurations **the DA for the different angles is very close or above 6 [σ].**



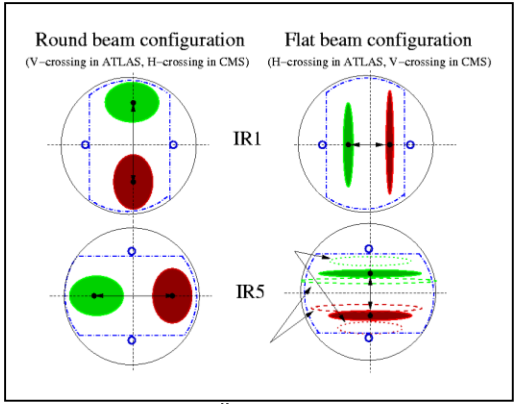


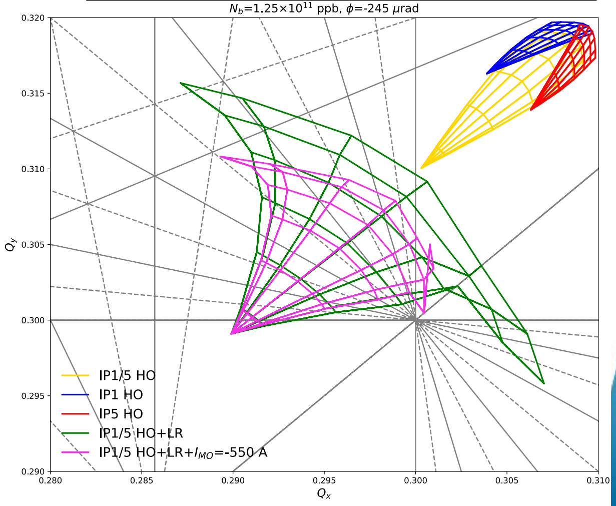
Wire and Flat Optics

Y. Papaphilippou

S. Fartoukh et al, CERN-ACC-2018-0018

- Flat Optics proposed as "**plan B**" of HL-LHC without CC, due to increased virtual luminosity performance
- Contrary to LHC case, **HL-LHC** triplet beam screens allow **beam flattening** in IP1/5 **without** crossing **plane restriction**
- By alternating crossing planes, the flat optics **reduces HO** beam-beam **tune shift** (and spread) at constant peak luminosity
- **BBLR** induced **tune shift not fully compensated** (and similar to HO)
- Feasibility of scheme strongly depends on **BBLR compensation**
- **Detailed operational scenario** to be defined, e.g. start colliding at round and then flatten β* more in the parallel plane while intensity decays.

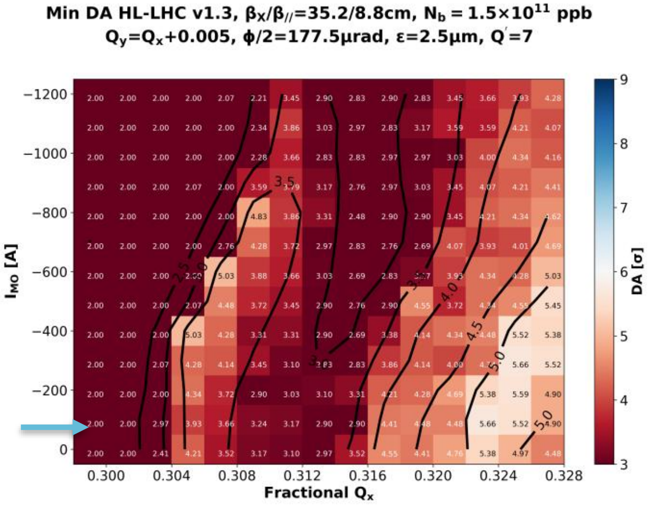




BBLR Compensation

11.5σ – No CC

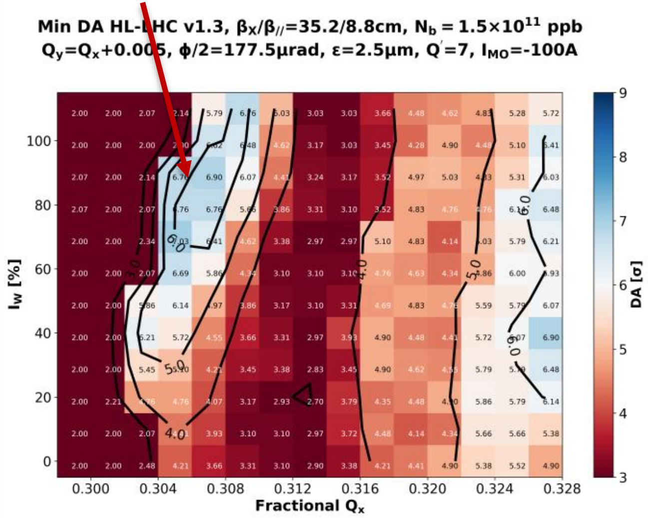
Octupoles



~7σ island

Wire [I_{MO}=-100A]

Y. Papaphilippou



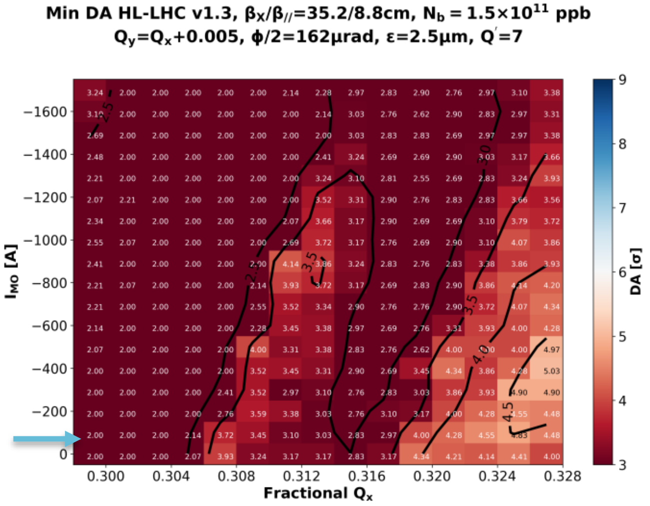
- The addition of the wire increases **DA** by **~1.5σ** DA at constant normalized crossing angle

BBLR Compensation

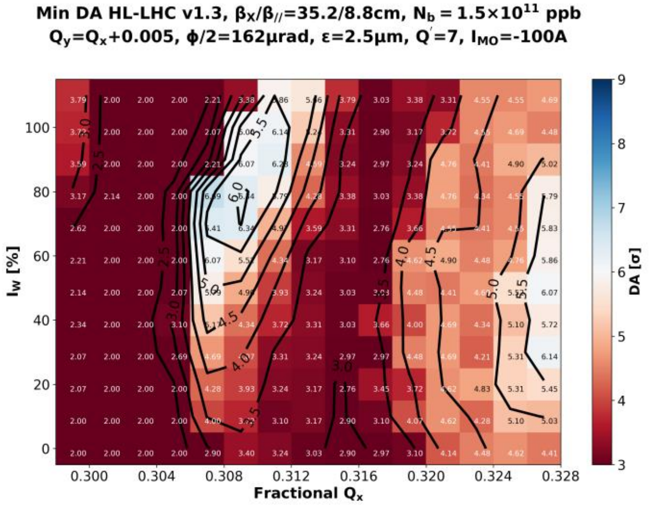
10.5σ – No CC

Y. Papaphilippou

Octupoles



Wire [I_{MO}=-100A]



- Field of wire can create all possible multipoles making it feasible to target all the RDTs
- The octupoles only target the b4 component → can be washed out if other multipoles are dominating.

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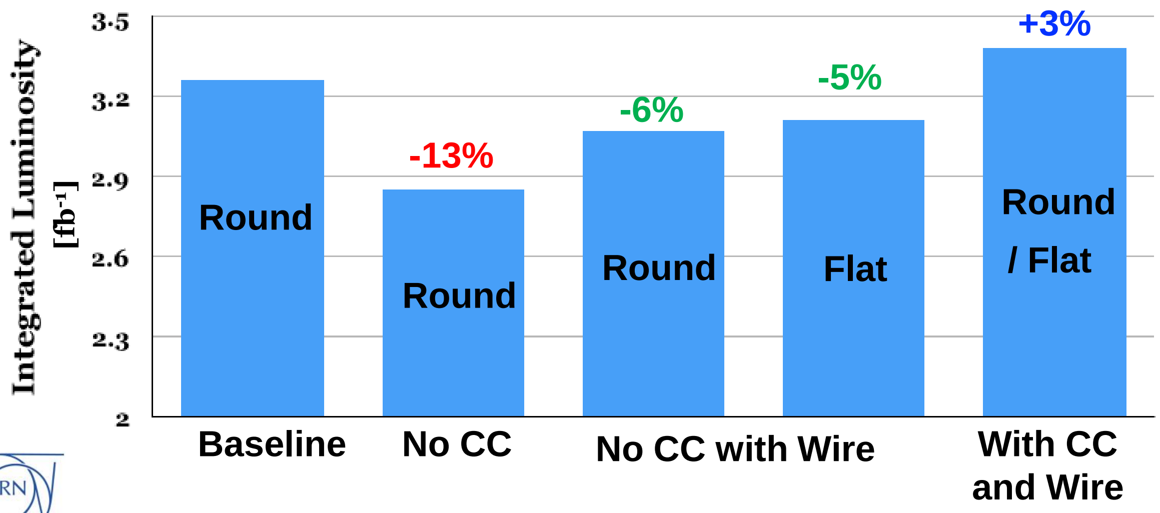
Wire impact on luminosity

- Without CC, integrated luminosity (per day) is reduced by **13 %**
- Wires **partially restore** lost **performance**
- In the presence of CC and wire a slight **increase** of **integrated luminosity** is **guaranteed**



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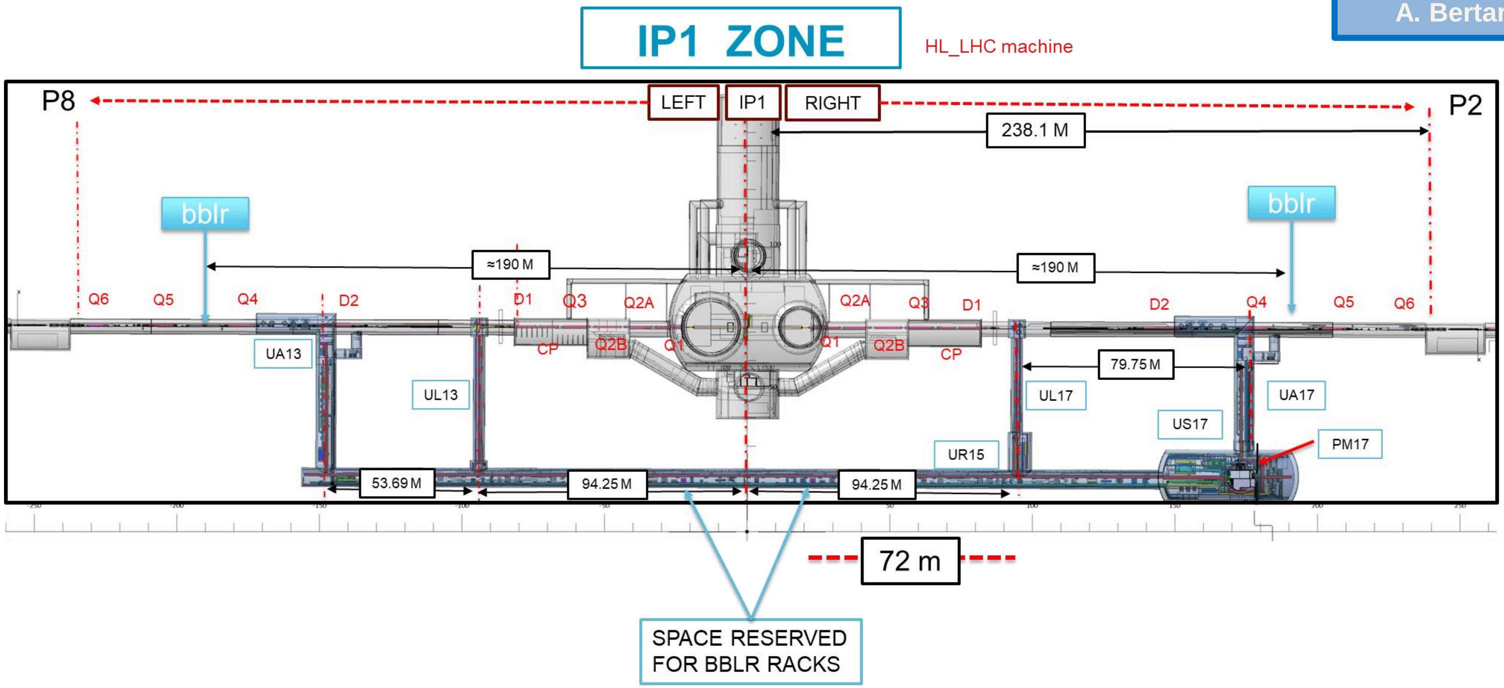
Space Reservation Request HL-LHC IP1/5

A. Bertarelli



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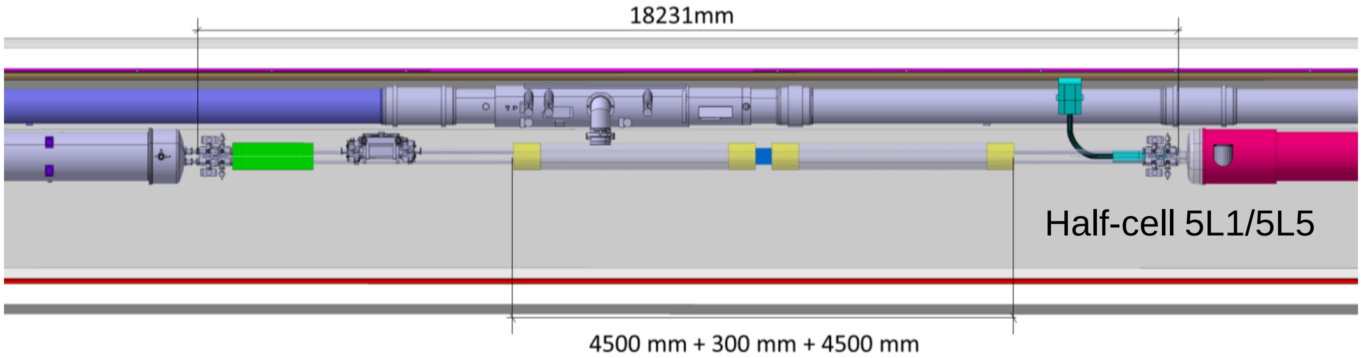
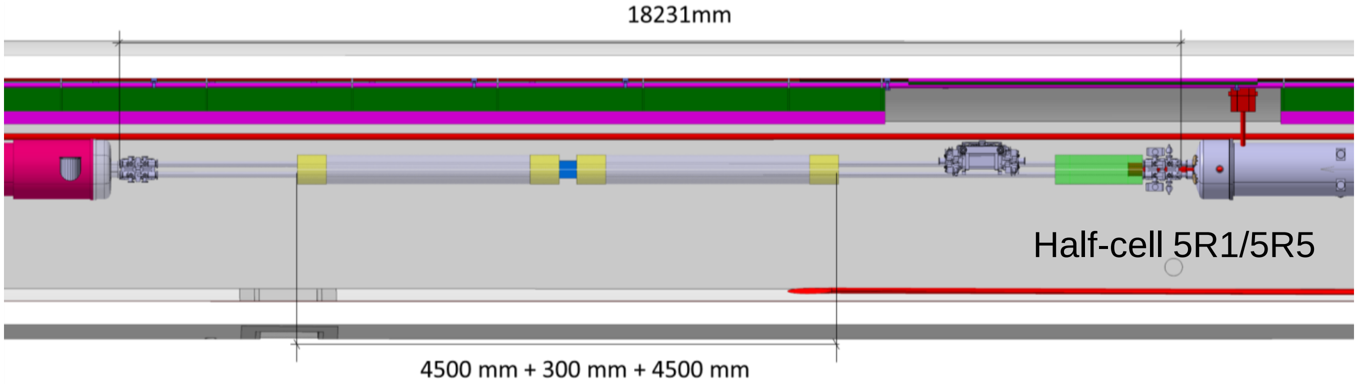
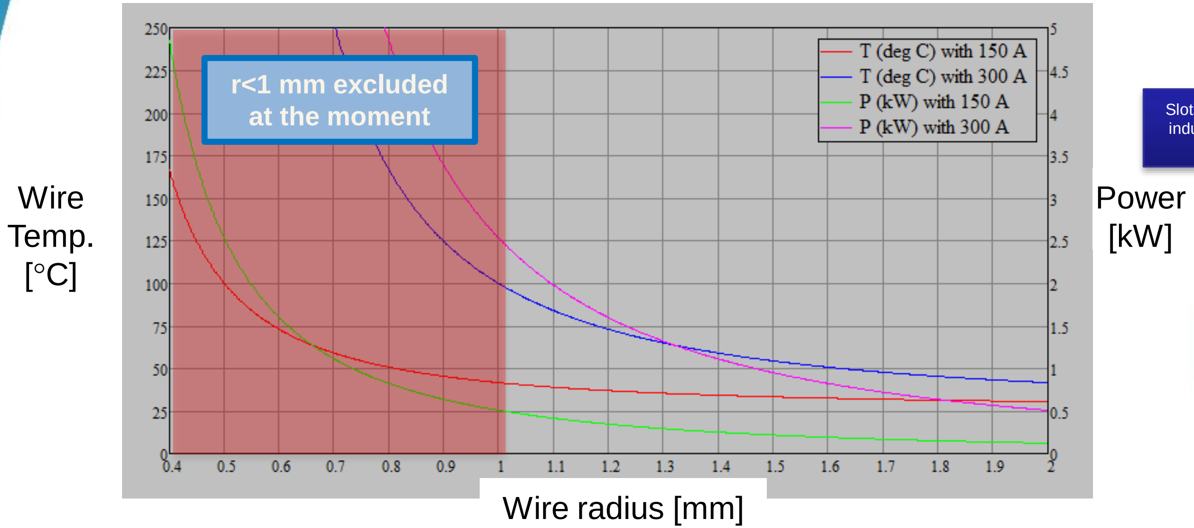
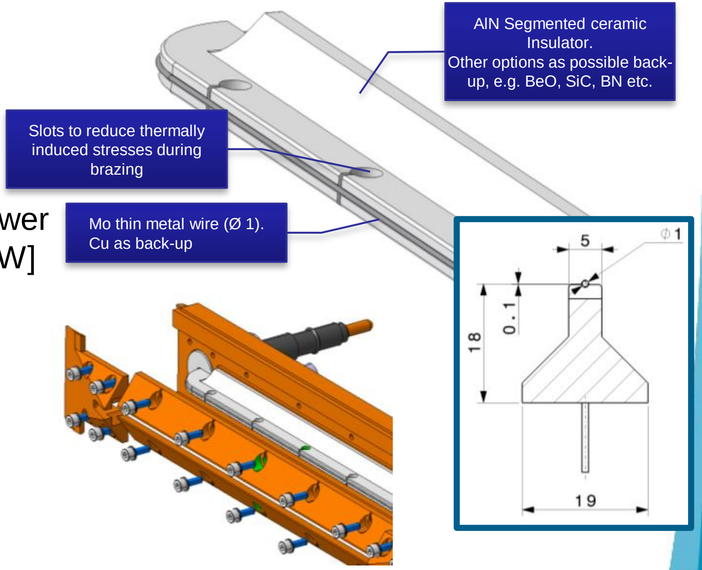




https://edms.cern.ch/document/2037987/1.0

Wire radius vs temperature/power





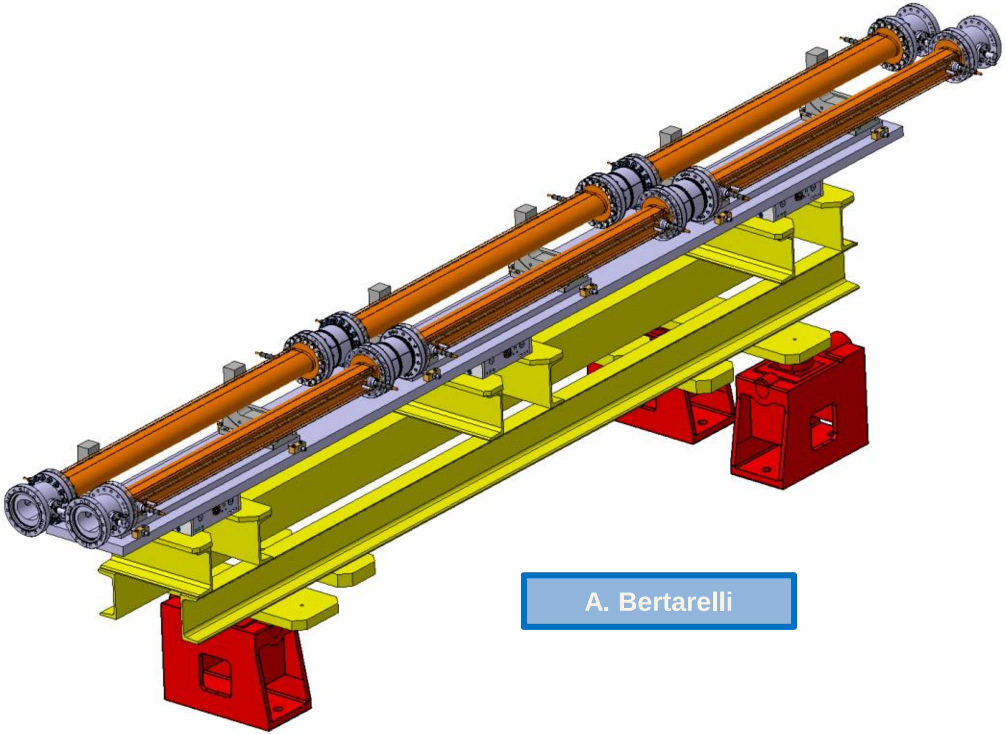
- To start, we assume a **∅1 mm 1 m-long Mo** wire with **150 A** current (Vacuum brazed)
- **Mo wire** has higher electrical resistivity compared to **Cu** (back-up), but is **better matching** ceramic **CTE** and is refractory (higher robustness)
- Diameter **can hardly be smaller than 1 mm** for **technological reasons**

HiLumi HL-LHC PROJECT CERN

A. Bertarelli

Possible Assembly Layout

- Conceptual layout with two parallel assemblies. For discussion only, many details missing, e.g. actuation system …



A. Bertarelli

Proof of Concept of the wire design

- Vacuum Brazing is the most critical step in the process (a few mm gap between wire and cooler may induce a thermal runaway of hundreds degrees …) → **proof of concept proposed**
- **AlN + Mo (and Cu as back-up) wire specimens ordered, to be brazed to verify feasibility and optimize brazing parameters.** Specimens to be delivered in 6 weeks
- If results are ok a **short demonstrator (290 mm long)** will be built, brazed and assembles early 2020, to validate the process and check residual deformations …

Canadian interest to contribute via TRIUMF to the wire compensation project

Canada contributes via TRIUMF beam physics support including the wire compensation activities in the LHC.

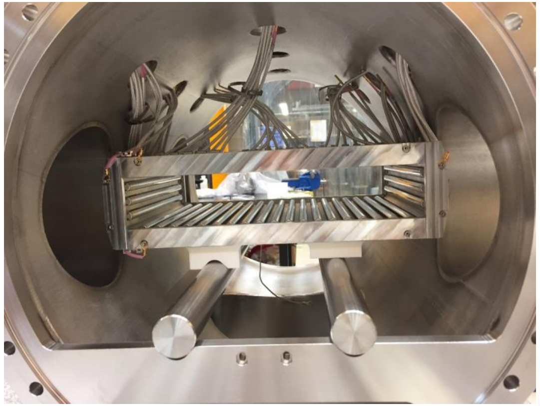
1. **Dobrin work on wire optimization with H driving terms** – extension into 2D Short-term tracking test with MadX and the BB Invariant.
2. Testing wire on sixtrack (long term track and DA tune-scans) Support for Yannis, Kyriacos and Nikos who are **running DA calculations** with wire
3. In the long term → **moving to flat-beam optics scenario for both 1. and 2. above**.

Work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC)

TRIUMF

Canadian interest to contribute via TRIUMF to the wire compensation project

- First beam tests with DC wire prototypes in LHC have been run successfully and **TRIUMF would like to participate in future beam tests.**
- **Canadian community via TRIUMF could contribute to the construction and realization of a wire compensation system for HL-LHC via technical expert groups.**
- Will need to go through (1) TRIUMF's Policy and Planning Advisory Committee (**PPAC**) before we apply for funds from (2) Canadian Foundation for Innovation (**CFI**) for instance.



Expertise in

- Design of multipole corrector
- OPERA® Tosca calculation for magnetic field
- High manufacturing tolerances (less than 10 μm)

O. Karsten

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Links and Outline

INDICO link

1. Setting the scene

2. Results RUN2 and perspective RUN3

3. HL-LHC theory, simulation and potential

4. Technical aspects & TRIUMF potential contributions

5. Main conclusions

Contribution	Speaker / Location	Time
Welcoming remarks	Oliver Bruning	
Wilson Hall, One West, Fermilab		08:45 - 09:00
Introduction/Motivation and current wire HW	Adriana Rossi	
Wilson Hall, One West, Fermilab		09:00 - 09:30
MD results during LHC RunII and plans for RunIII	Guido Sterbini	
Wilson Hall, One West, Fermilab		09:30 - 10:00
Modelling of MD results and effect of crossing angles (remote presentation)	Axel Poyet	
Wilson Hall, One West, Fermilab		10:00 - 10:30
Coffee break		
Wilson Hall, Atrium 1st floor, Fermilab		10:30 - 11:00
Simulations for HL-LHC configuration (remote presentation)	Kyriacos Skoufaris	
Wilson Hall, One West, Fermilab		11:00 - 11:30
Correction of resonant driving terms with wires	Dobrin Kaltchev	
Wilson Hall, One West, Fermilab		11:30 - 12:00
Lunch break		
Wilson Hall, Atrium 1st floor, Fermilab		12:00 - 13:00
Scenarios and timeline for wire compensation in the HL-LHC	Yannis Papaphilippou	
Wilson Hall, One West, Fermilab		13:00 - 13:30
Wire HW design for HL-LHC and integration	Alessandro Bertarelli	
Wilson Hall, One West, Fermilab		13:30 - 14:00
TRIUMF contribution to the BBLR Compensation Project for HL-LHC	Oliver Kester	
Wilson Hall, One West, Fermilab		14:00 - 14:30
Discussion (All)		
Wilson Hall, One West, Fermilab		14:30 - 15:30

Minutes of the meeting

Summary of wire impact

- **DC solid wires** at distances compatible with collimation hierarchy are able to partially **restore integrated luminosity** in the absence of CC
- Slightly **increase luminosity** in the baseline scenario
- Wires provide a series of **positive side effects,** e.g.,
  - Relax **WP choice** through levelling
  - Recover **6 σ DA** for **ultimate scenario** (round optics)
  - Enhance **β* reach**
  - **Reduce triplet radiation**, increasing significantly (up to 20%) triplet lifetime
  - Increase luminous region leading to **peak pile-up density reduction**
  - **Enable** running with **full crabbing** through levelling, or reduce impact of limited crab voltage.

Y. Papaphilippou

Timeline

- **Experimental verification** achieved with demonstrator (2016-2018)
- **Simulations** proved potential at present LHC but also for HL-LHC, with a **solid DC wire solution** (2017-2019)
  - Refining flat optics operational scenario (2020)
- **Wire operation** during **Run3** will clarify operational and machine protection issues (2021-2023)
- **Hardware design** and short prototype HW tests for HL-LHC (2020)
- **Technical review** (including budget) for using wire compensation in the HL-LHC era (2020)
- Prepare **locations** for integration (during LS3)
- Wire **installation** and **operation for HL-LHC** (during Run4)

Main outcome of the discussion

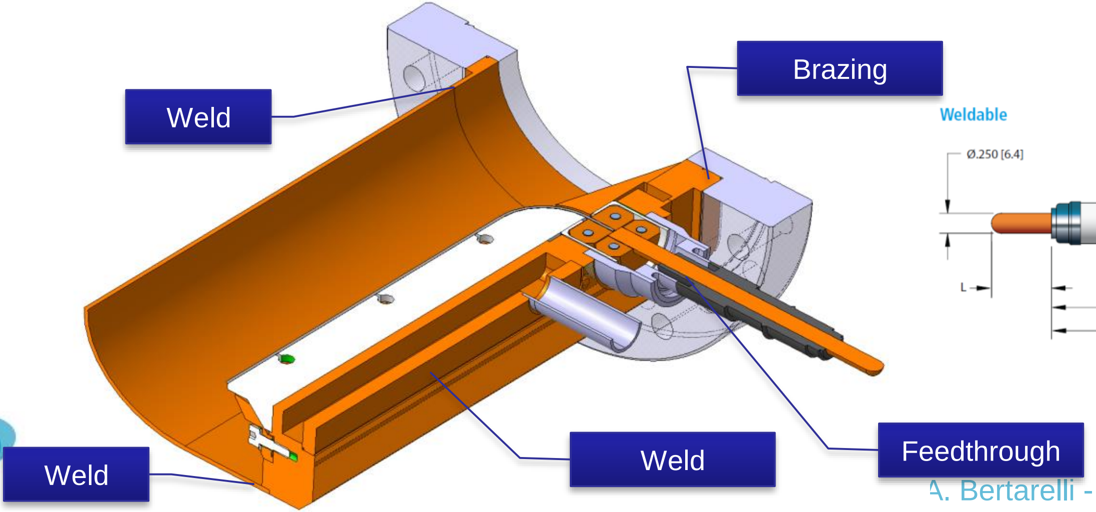
- TRIUMF wish of a strong connection with CERN, and to start collaboration asap, including participation to the beam tests during Run3 in 2021.
- Target by end of 2020 an external review to support to the preparation of the TRIUMF proposal for funds where we:
  - Present detailed plans for Run-III.
  - Show the clear impact of the wire on lifetime (particle diffusion in the beam core) and in presence of the HEL w/ and w/o CC.
  - Give an estimate of irradiation reduction to the triplets as a function of Xing angles.
  - Review thermo-mechanical design including all thermal loads (wire current, heating via RF coupling or losses).
  - Check compliance of the HW design with impedance, vacuum, …
  - Review instrumentation for the wire and alignment.
  - Verify that the position proposed for wire operations is compatible with Machine Protection (in case of asynch dump), and irradiation (also caused by the wire) to elements downstream the wires (collimation studies + FLUKA simulation).
  - Present strategy of interlock on the wire for Machine Protection.
  - Review machine integration and staging of installation.
  - Discuss a budget envelop.
  - Present preliminary results on flat optics if additional manpower is allocated.

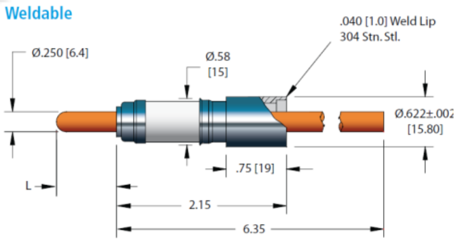
Thank you for the attention!

BACKUP SLIDES

Main Design Features: Vacuum Chamber

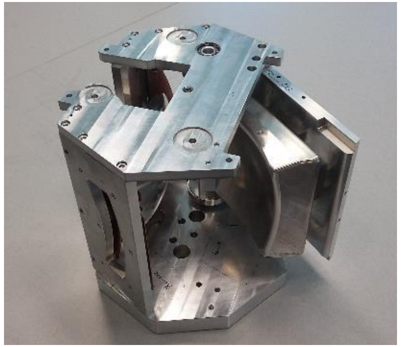
- Water cooling channel obtained by housing machining and cover welding.
- **Commercial feedthrough** connection carrying up to 185 A. If more current is needed, liquid-cooled feedthroughs should be adopted
- Cu half-shell welded to the housing
- Stainless steel flange brazed to copper and then welded to vacuum chamber.





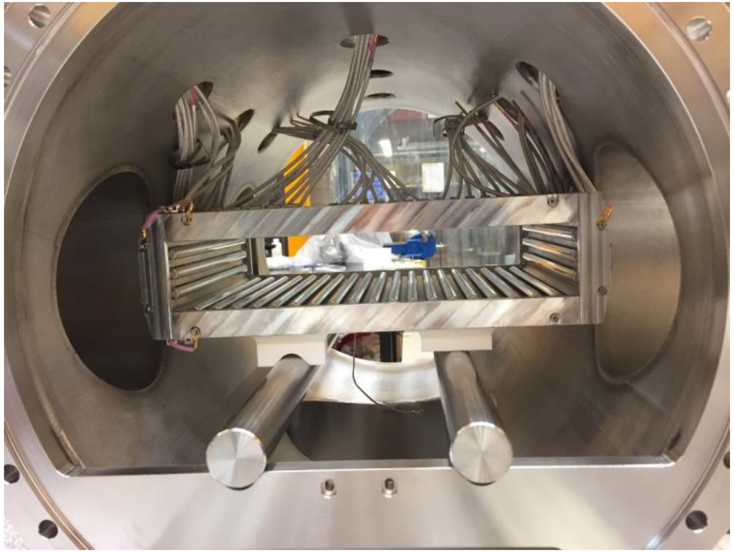
Expertise in beam transport and accelerator systems
Beam line engineering physics group (M. Marchetto)

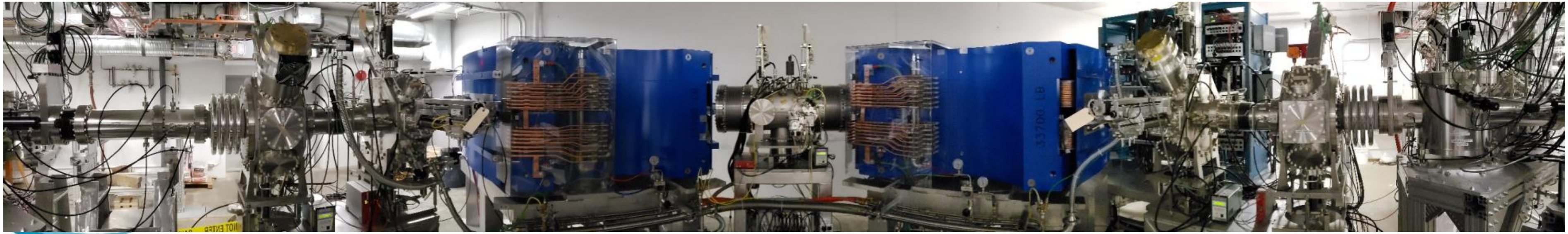
- Beam optics design
- Hardware design, engineering and installation of electrostatic and magnetic beam line systems
- OPERA® Elektra calculation for electric field
- Custom feedthrough developed in collaboration with vender
- UHV assembly procedure



Expertise in special element’s design and construction

- Ion source design and engineering
- Optics and magnetic dipole design of the high resolution mass separator system (20,000 resolving power for 3 μm transmitted emittance)
- Design of multipole corrector
- OPERA® Tosca calculation for magnetic field
- High manufacturing tolerances (less than 10 μm)





Numerical simulations

- Estimated deflection of the vacuum chamber in operating conditions is ~ 30 μm