Beam-Beam Long-Range Wire Compensation for Enhancing CERN LHC Performance

BE Seminar

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Outline

- Introduction and Motivations
- BBLR Compensation Using DC Wires
- Experimental Campaign in the LHC
- Towards the LHC Run 3
- Conclusions

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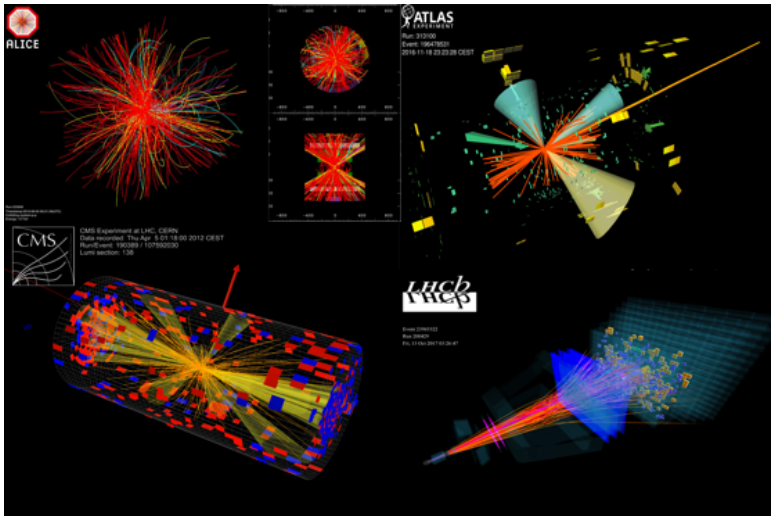
Beam-Beam Long-Range Wire Compensation for Enhancing **CERN LHC Performance**

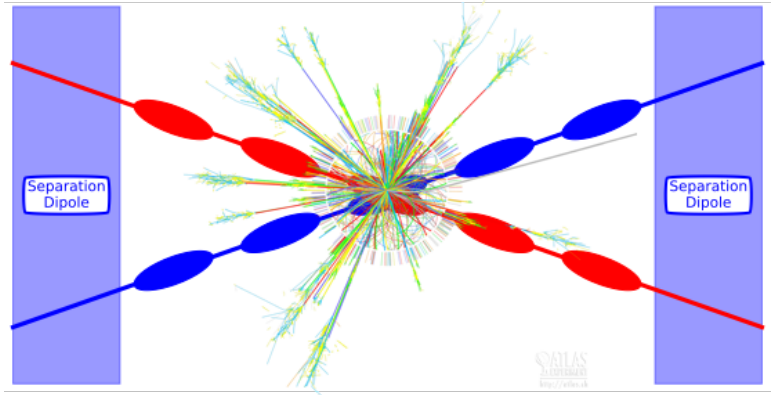
- **What is it about?**
  - The LHC and its High-Luminosity upgrade.
  - The Beam-Beam Long-Range Interactions
  - DC Wire as a compensation solution
- **What is my contribution?**
  - Experimental proof-of-concept
  - Numerical benchmark and studies
  - From prototypes to operational devices

The Two Sides of LHC

- The primary goal of the LHC is to be a **collider**:
  - **13 TeV** center of mass collisions in 4 IPs.
  - Provide as many collisions as possible to the detectors.
- Not pure Head-On collisions: use of a **crossing angle** θ_c.
- Key features: **energy** and **nb of collisions**.

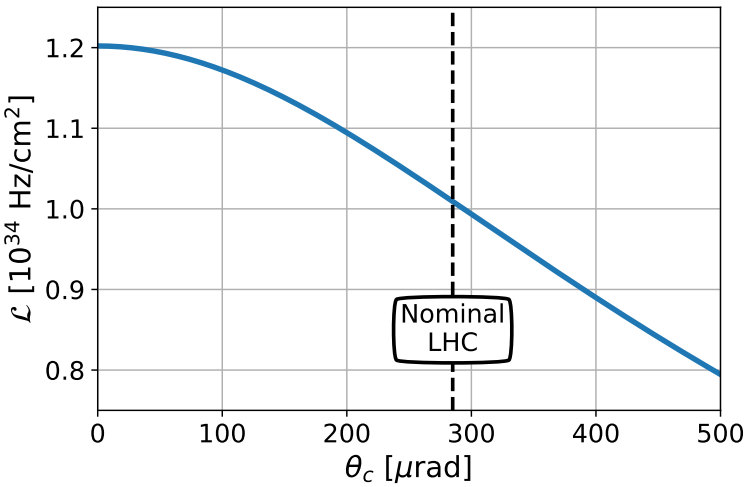
$\Rightarrow$ Nb of collisions = **luminosity** + **lifetime**





The Two Sides of LHC: Luminosity

Assuming two equal Gaussian bunches in all dimensions, colliding with a crossing angle θ_c:



$$\mathcal{L} = \frac{N_1 N_2 f_{rev} N_b}{4\pi\sigma_x\sigma_y} \times \left[\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\left(\frac{\theta_c}{2}\right)\right)^2}\right]^{-1}$$

Symbol	Meaning [Unit]	LHC Value
$N_{1,2}$	Bunch Intensity [10^{11} p]	1.15
N_b	Nb. of HO collisions at the IP	2808
f_{rev}	Revolution Frequency [Hz]	11245
$\sigma_{x,y}$	RMS Transverse Beam Size [m]	$1.7{\cdot}10^{-5}$
σ_z	RMS Bunch Length [cm]	7.55

The Two Sides of LHC: Lifetime

- The LHC is made of **2 storage rings**:
  - **27 km long**, ∼100 m underground
  - Protons are **stored for about 10 h**
- **Challenge:** storage of protons for such periods of time, **in presence of non-linear effects** such as beam-beam interactions

Luminosity/Lifetime Trade-Off

How can we increase the luminosity?

- Increase the **bunch intensity**
- Decrease the **beam size** at the IP (emittance, β^*)
- Decrease the **crossing angle**

By decreasing the crossing angle, the interactions between the two beams (BBLR) are **enhanced**.

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How to relax the trade-off?
$\Rightarrow$**Compensate the BBLR!**

Goals and Motivations

Through this presentation, we try to answer three questions:

⇒ **How can we compensate the BBLR interactions in the LHC using DC wires?**

⇒ **What are the limitations of the current hardware?**

⇒ **What are the perpespectives to be drawn from the LHC experience, in view of the HL-LHC era?**

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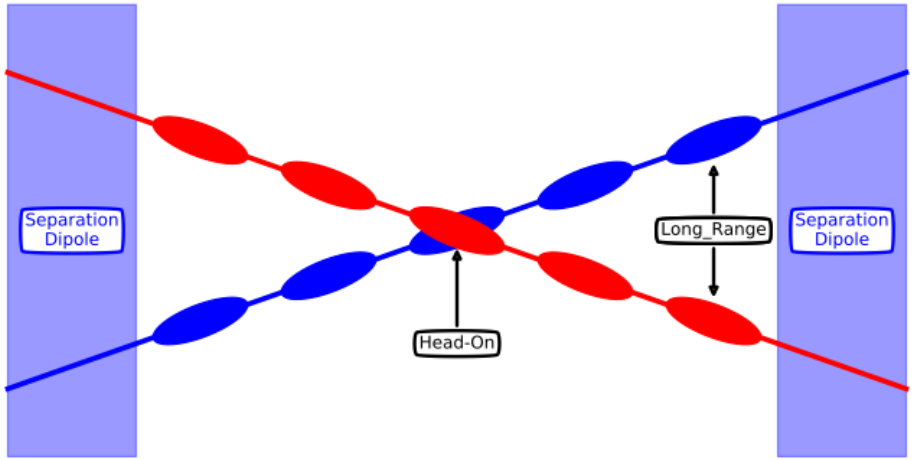
Dealing with BBLR Interactions

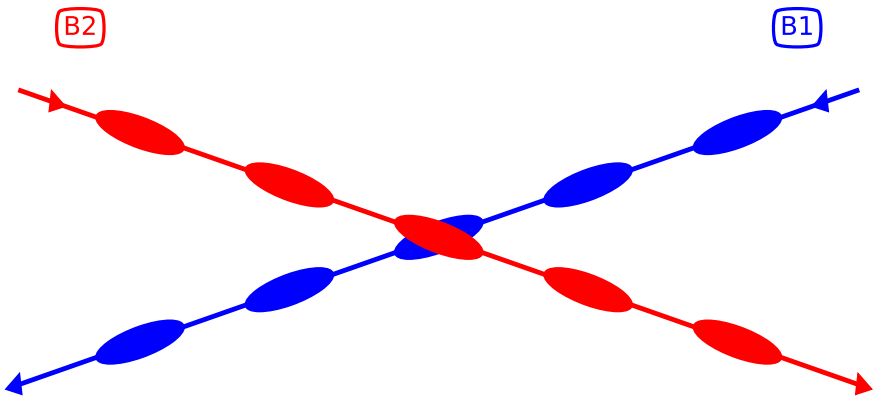
- The goal of a collider is to maximize **nuclear interactions** $\Rightarrow$ optimize HO collisions.
- BBLR occur between the two beams, **with a longitudinal offset with respect to the IP**.
- Luminosity due to BBLR is negligible, but not **electromagnetic interactions**.



How do we deal with BBLR interactions?

Single Encounter

Let us first simplify the problem and **consider only one BBLR interaction**.



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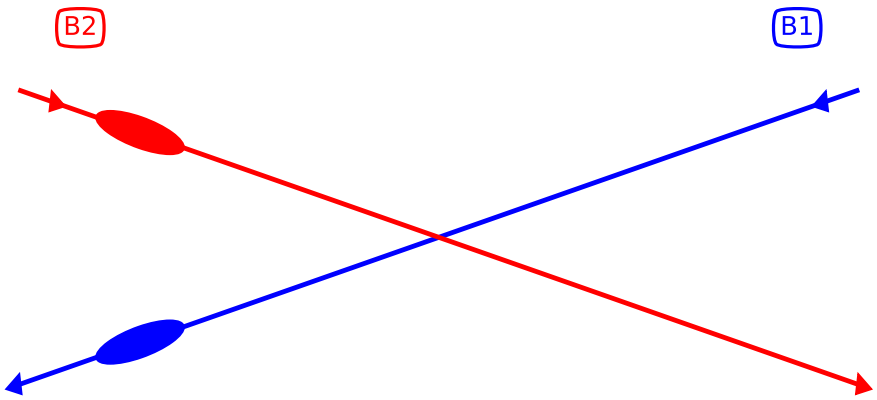

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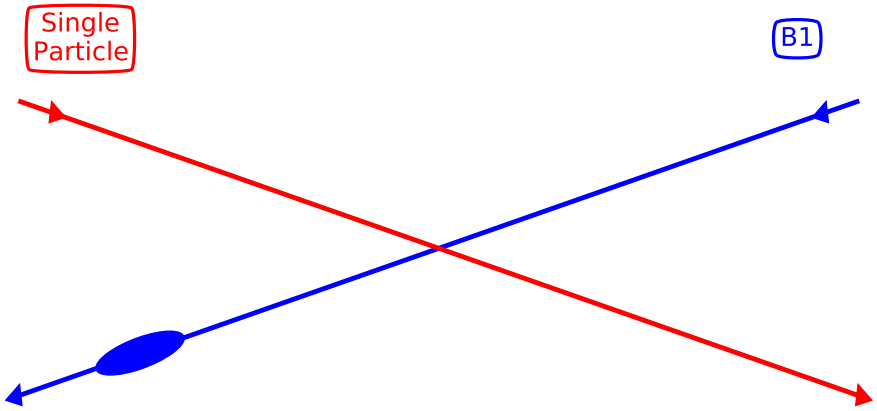

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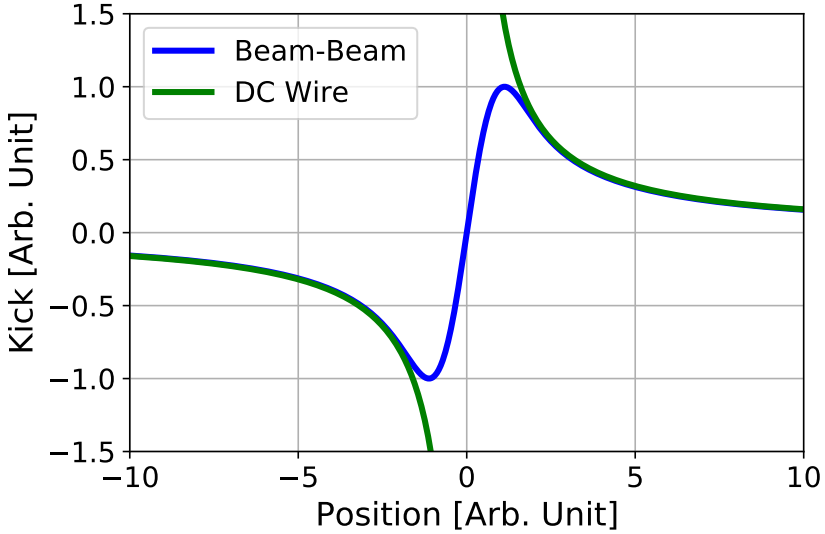
The problem is now reduced to a **magnetostatic problem**. Let's observe the kick received by the weak beam from this BBLR interaction.

"By nature, the head-on beam-beam force derives from a Poissonian potential while the magnetic force of optical lenses is Laplacian, defeating attempts at correcting one by the other, at least exactly. The long-range beam-beam effect is however close to Laplacian for realistic beam-beam separations, opening new compensation possibilities."

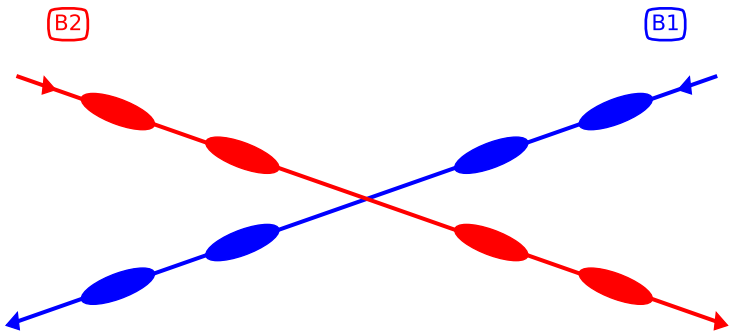
– J.-P. Koutchouk and V. Shiltsev [1]

DC Wire equivalence



- For large beam-beam separations, **a beam and a wire are equivalent in terms of Laplacian** [2, 3].
- A wire located at the bunch location would compensate the considered BBLR interaction.
- **Challenges:**
  - Position of the wire compensators (transverse and longitudinal)
  - Number of wires to installed

Several Encounters



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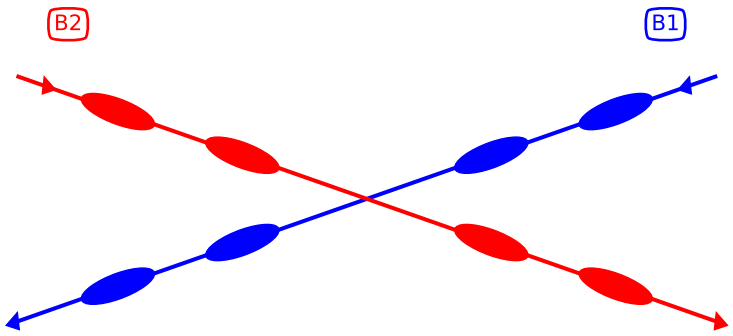

$\Rightarrow$ Single Particle + Thin Lenses

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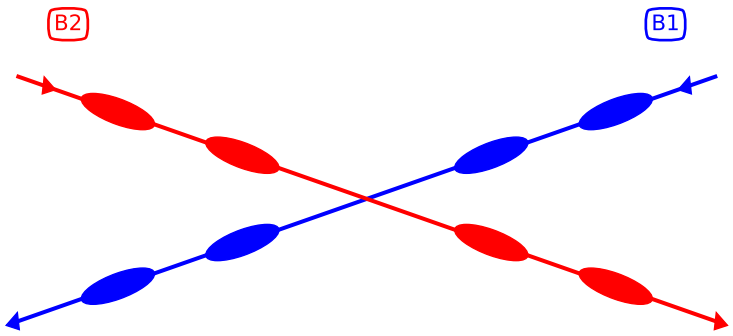

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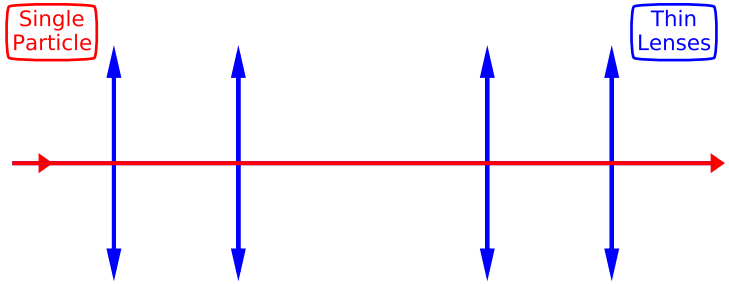

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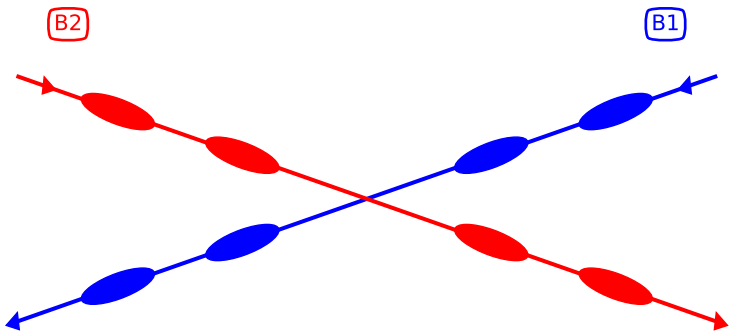

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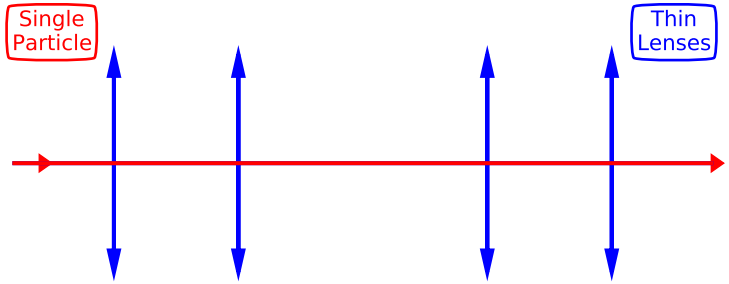
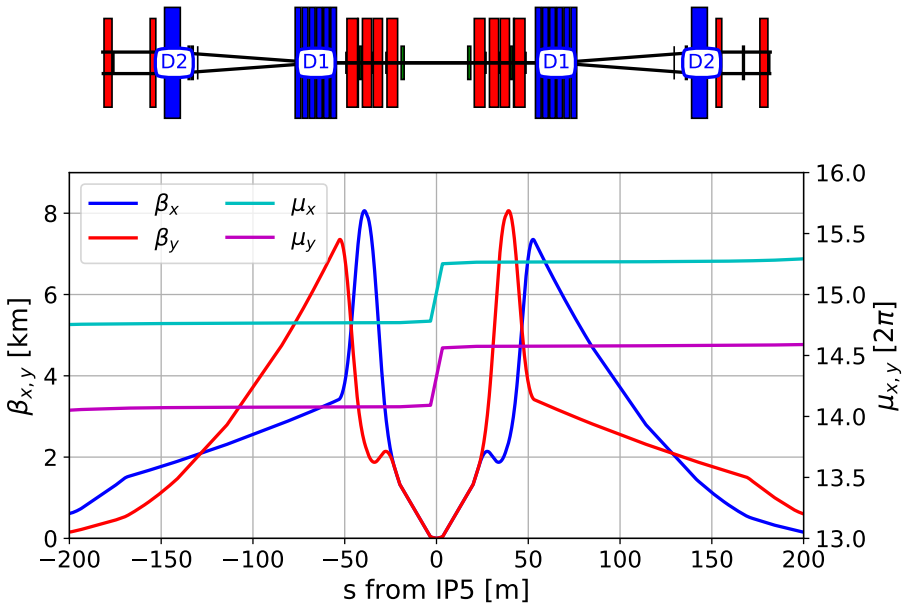


$\Rightarrow$ **How do we sum-up all the contributions? How do we keep the wire equivalence?**

The LHC Optics

Let us take a look at the LHC Interaction Region optics.



- β-function are very high in the IR.
- Consequently, the phase is constant (modulo π) within the IR.

$\Rightarrow$**Possible to sum-up all the contributions!**

Multipolar Expansion of a Thin Lens

In free space, one can expand the magnetic field of a thin lens into multipoles:

$$B_y + iB_x = \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$$

In the perturbative approach, each of the n-multipoles drives **an Hamiltonian** (2D) such as:

$$\mathcal{H}(x, p_x, y, p_y; s) = \sum_{n=0}^{\infty} \mathcal{H}_n + \frac{p_x^2 + p_y^2}{2(\delta + 1)}$$

$$= \sum_{n=0}^{\infty} \frac{1}{1+n} \Re \left[\left(\frac{b_n}{B\rho} + i \frac{a_n}{B\rho} \right) (x + iy)^{n+1} \right] + \frac{p_x^2 + p_y^2}{2(\delta + 1)}$$

Hamilonian Wire Compensation

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$\Rightarrow$ But how do we solve an **infinite system** of n equations?

Resonance Driving Terms Compensation (1)

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 121001 (2015)

Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC

Stéphane Fartoukh,[1,*] Alexander Valishev,[2,†] Yannis Papaphilippou,[1] and Dmitry Shatilov[3]

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- Install one wire on each side of the IP, at a **specific beta aspect ratio**
- Both wires at the same physical transverse distance from the beam (about **6 mm**) and same current (about 100 A)
- Choose two **Resonance Driving Terms** (four by symmetry): all the RDTs are compensated or minimized

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Analytical answer: two equivalent kicks per IP, to be compensated locally by a DC wire, whose settings are chosen correctly.

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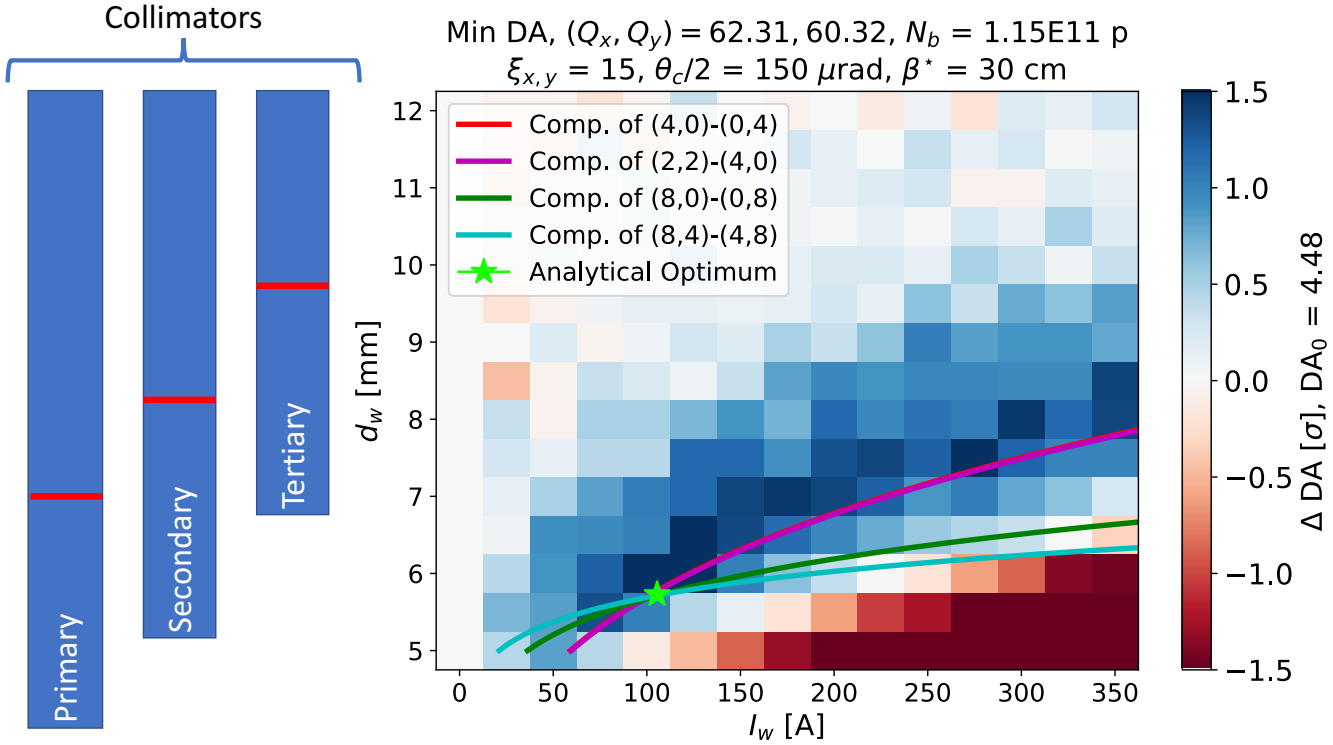
Cons:

- Depends on the number of turns
- Depends on the granularity of the inital amplitude grid

Resonance Driving Terms Compensation (2)



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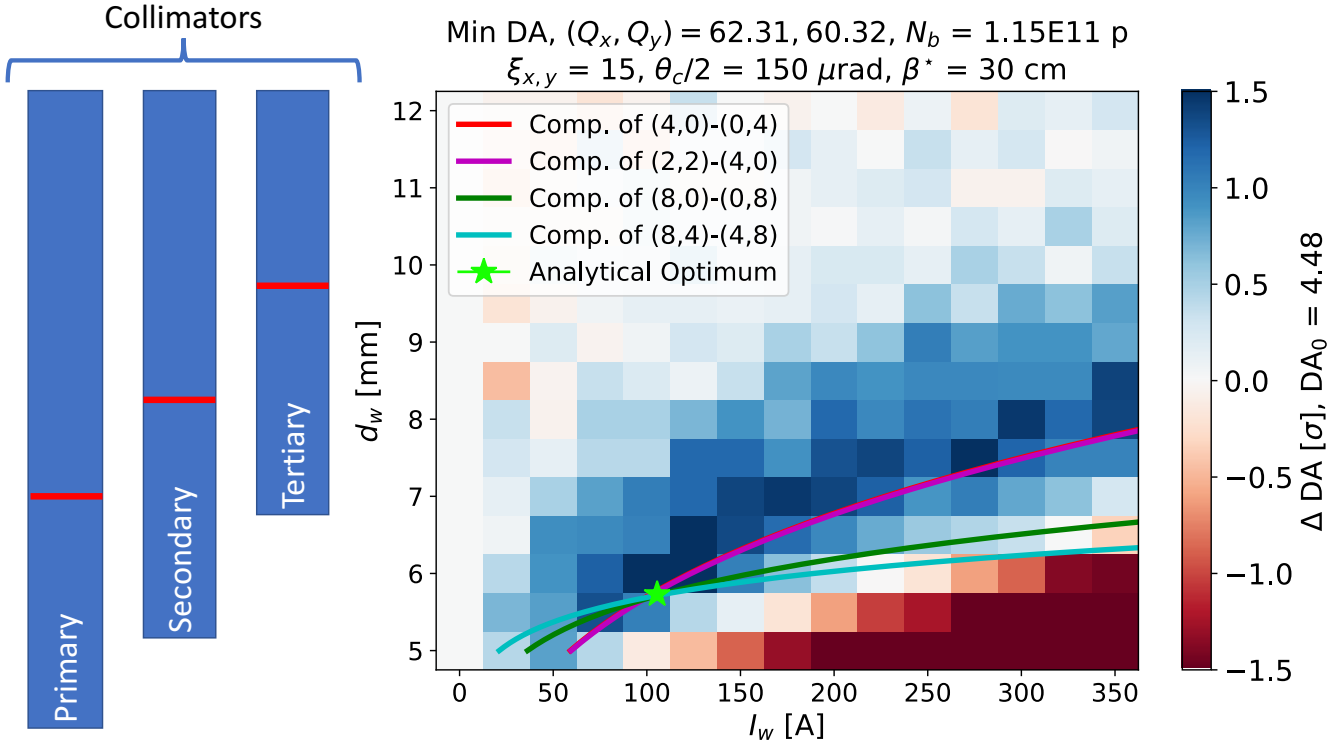

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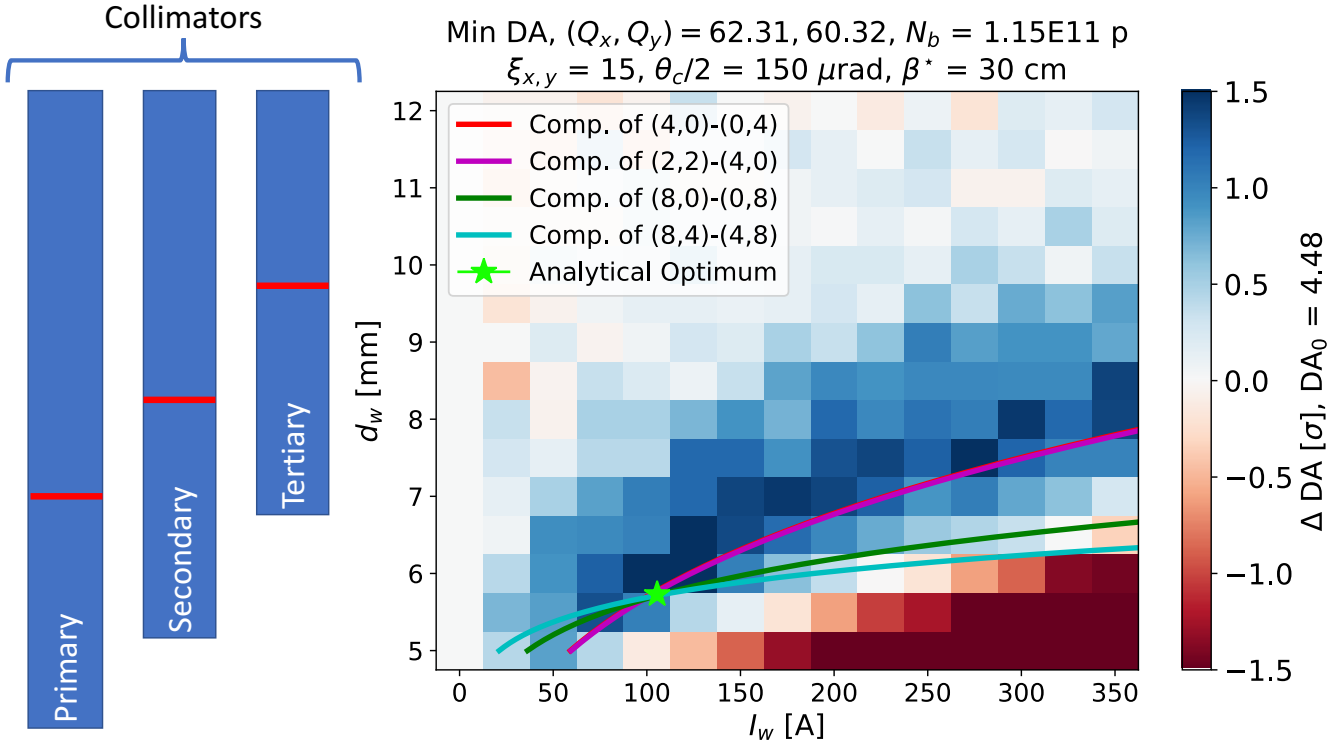
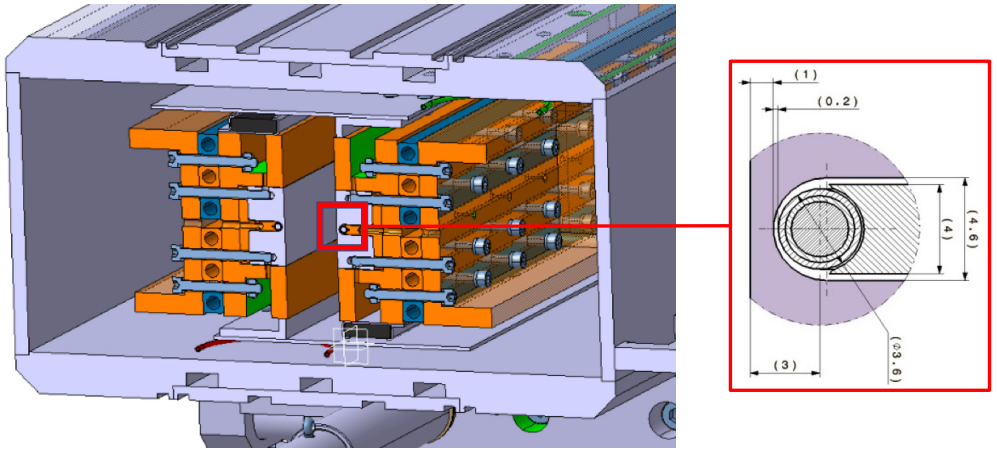


- The **DA** can be improved by several wire configurations
- Correlation between DA and **octupolar resonances**

My Contribution: relax the analytical recipe, targeting the **octupolar resonances**, placing the wires further away from the beam, and powering them with higher currents

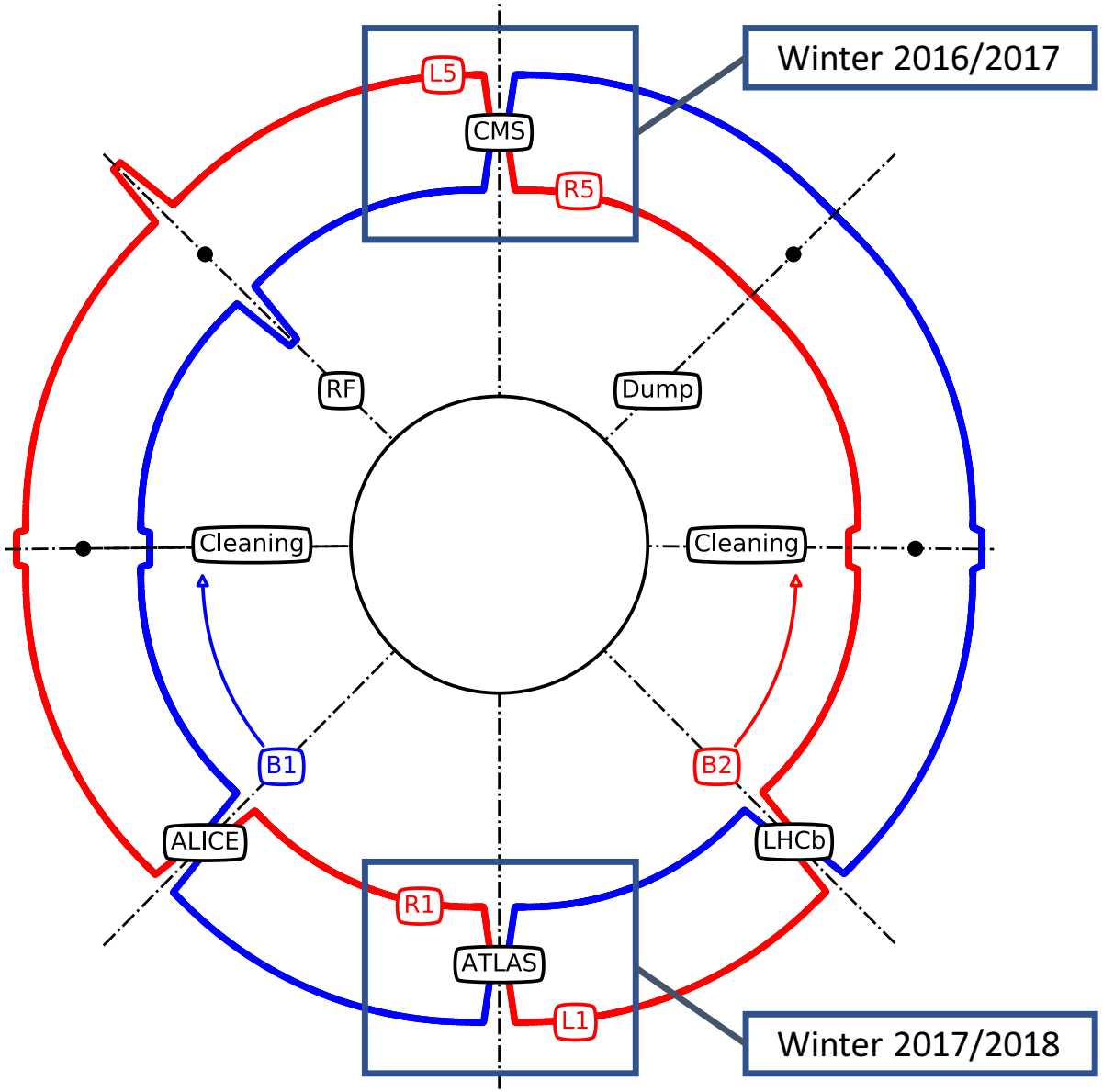
LHC Hardware and Layout

What actual hardware do we have?



- Wires in tertiary collimators (3 mm behind the jaws)
  - **Half the analytical solution distance**
- About 1 m long, 2.5 mm diameter, up to 350 A
- Each jaw houses a wire, possible to power them in series

The LHC Ring and the Wires



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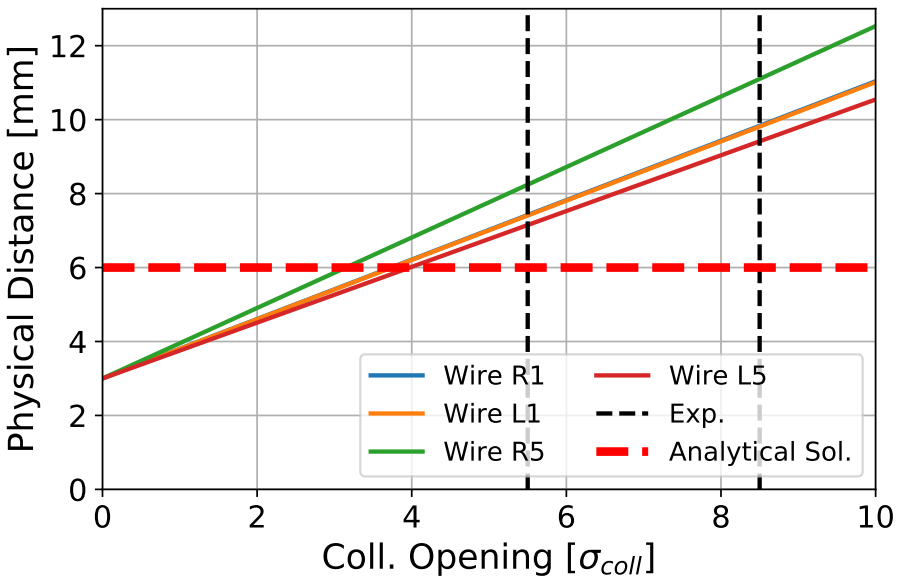
Wire Settings: A Constrained Distance



- Analytical proposal **not reachable**
- Two distances were explored in the experiments:
  - **Close to the theory**: proof-of-concept, wire collimators opened at 5.5 σ_{coll}, low intensity for B2 (LI experiment)
  - **Close to the operational conditions**: nominal operation settings, wire collimators opened at 8.5 σ_{coll}, high intensity for B2 (HI experiment)

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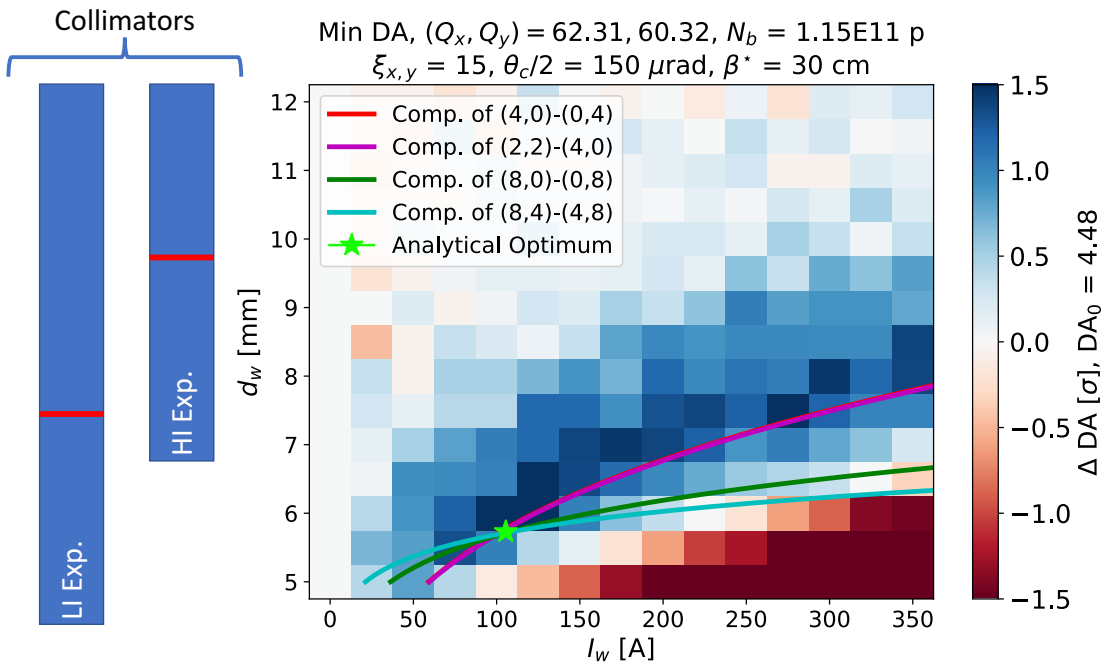
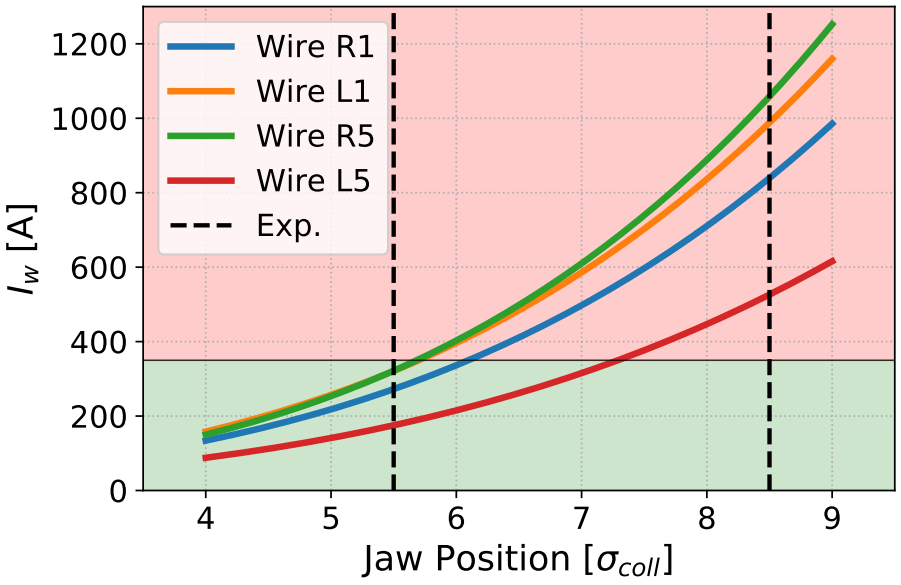
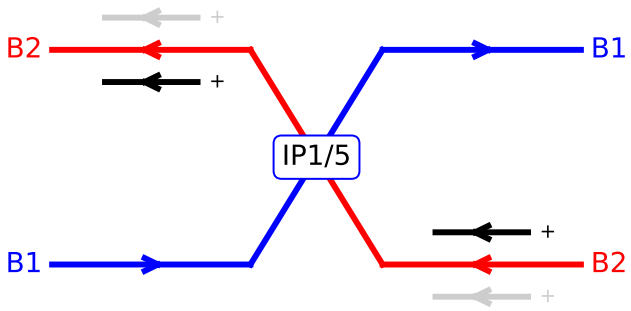


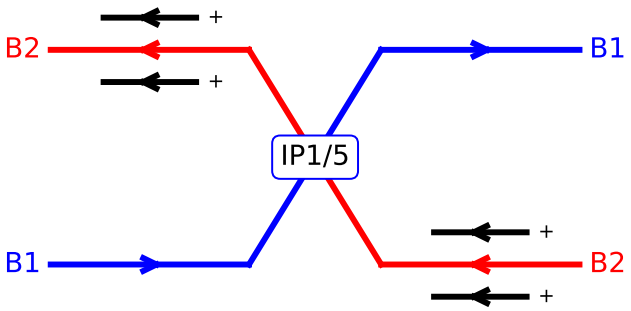
Expected to see a clearer effect of the wires in the case of the Low Intensity experiment.

Wire Settings: Recovering with Current



- **Optimized to compensate the octupolar resonances**
- If needed, **use of the 2-jaws powering configuration**





Observables and Objectives

The observable of the experiment is the **effective cross-section**, which is the loss rate normalized by the luminosity:

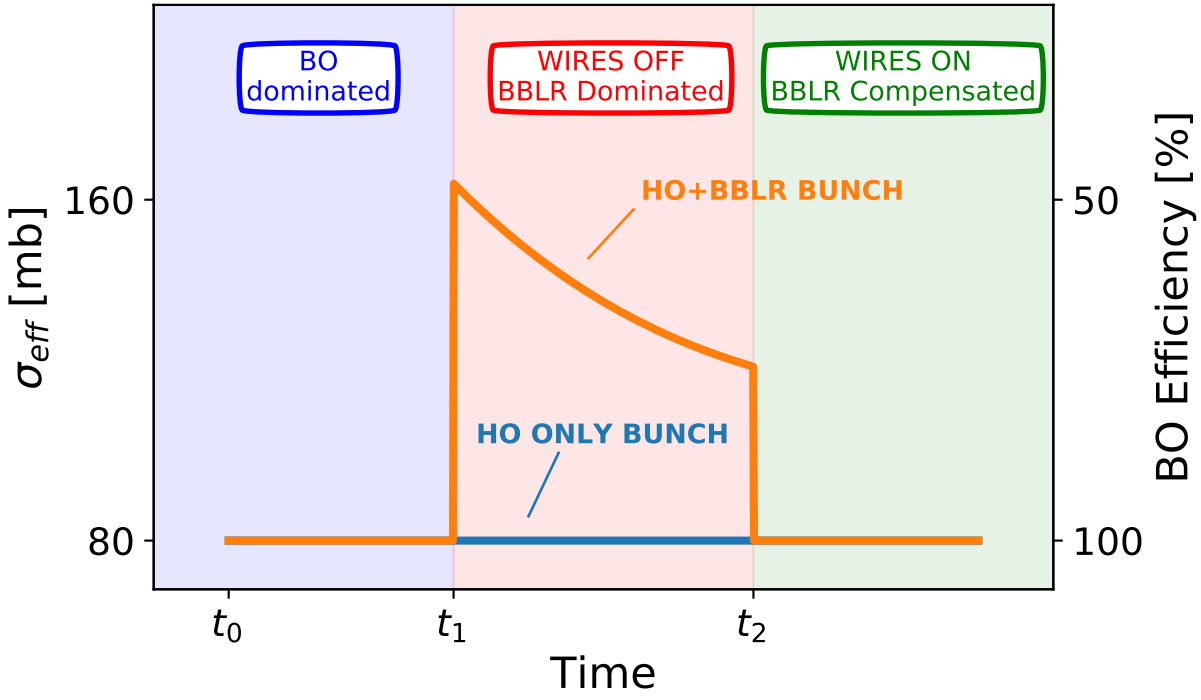
$$\sigma_{eff} = \frac{1}{\sum_{n \in IP} \mathcal{L}_n} \frac{dN}{dt},$$

- **Correlated to DA**
- dN/dt obtained by differenciating the bunch intensity
- Ideal collider, $\sigma_{eff} \sim$ **80 mb** (at 6.5 TeV)
- Burn-off efficiency:
  - $\sigma_{eff} \sim 80$ mb: losses only due to luminosity (100 %)
  - $\sigma_{eff} > 80$ mb: additional losses (< 100 %)

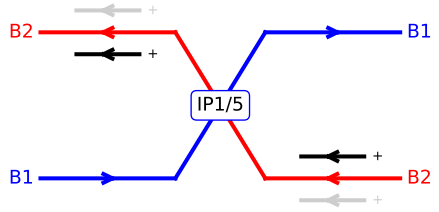
Observables and Objectives

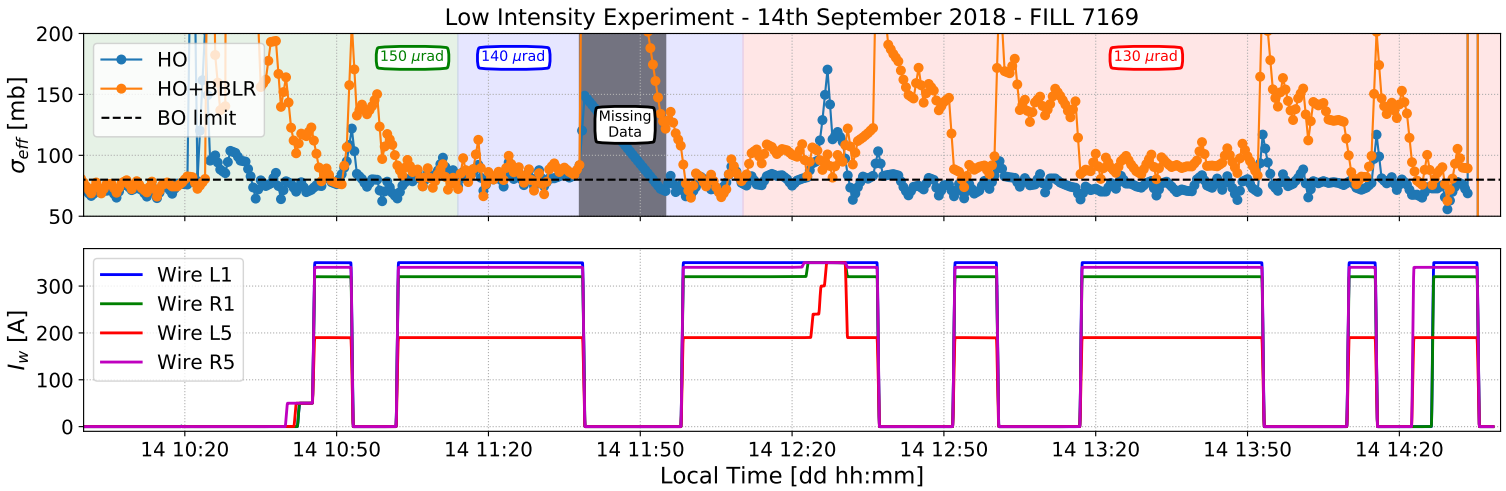
Comparison of two bunches:

- One **colliding HO only**
- One **colliding HO** + additional **BBLR interactions**



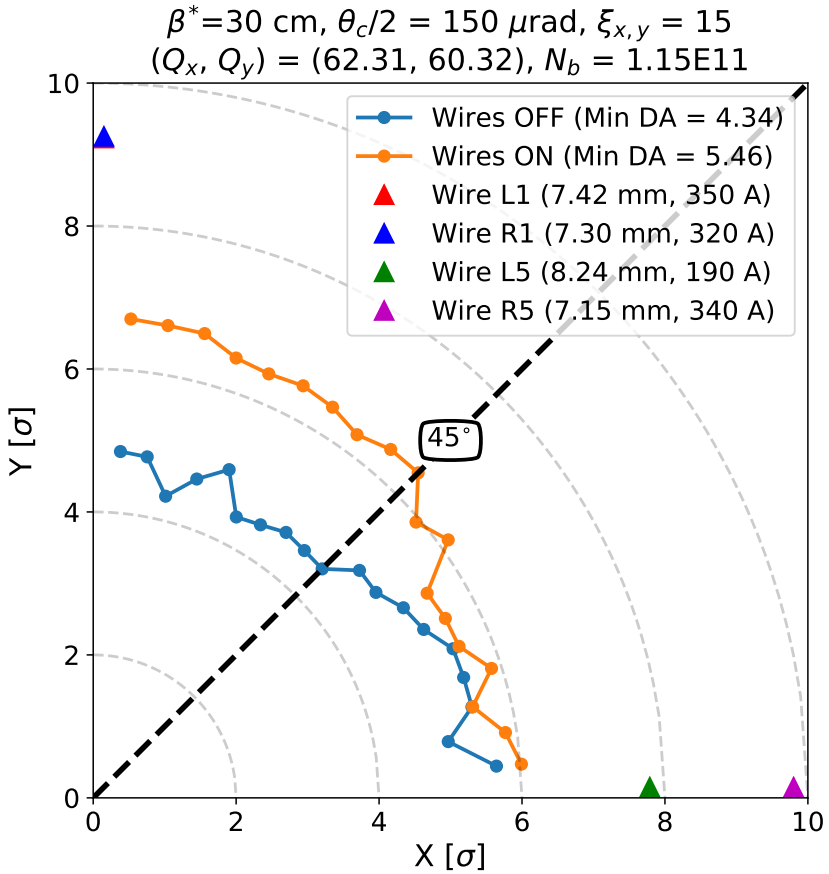
LI Experiment Results





- **Clear effect** of the wires on the effective cross-section
- Possibility to **reduce the crossing angle** down to 130 μrad without additional losses
- **First experimental evidence** of a possible BBLR compensation using DC wires

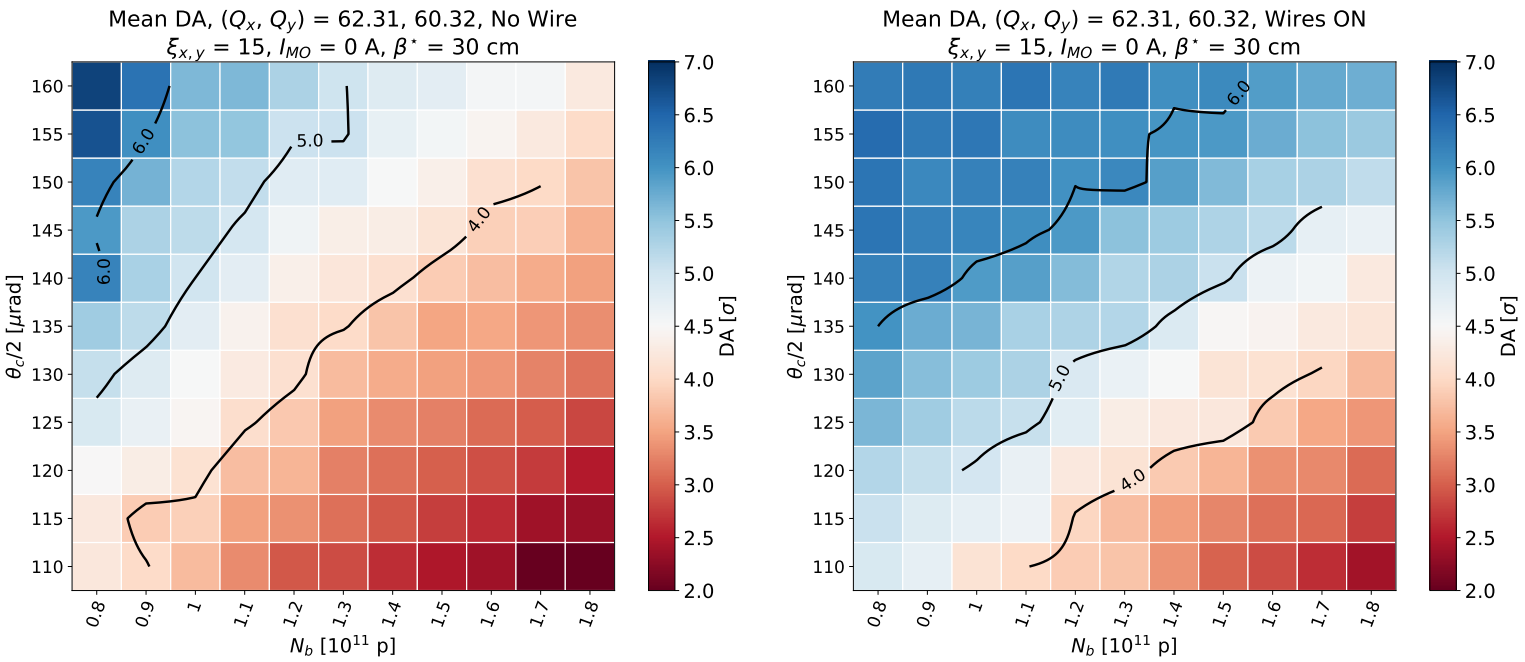
LI Experiment: Numerical Benchmark (1)



Improvement mostly in the vertical plane:

- Asymmetry of the DA without the wires
- Compression of the footprint corner closer to the diagonal

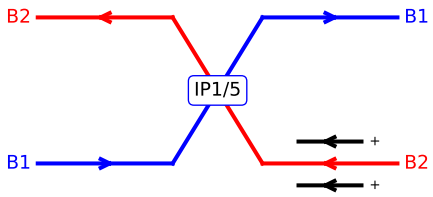
LI Experiment: Numerical Benchmark (2)

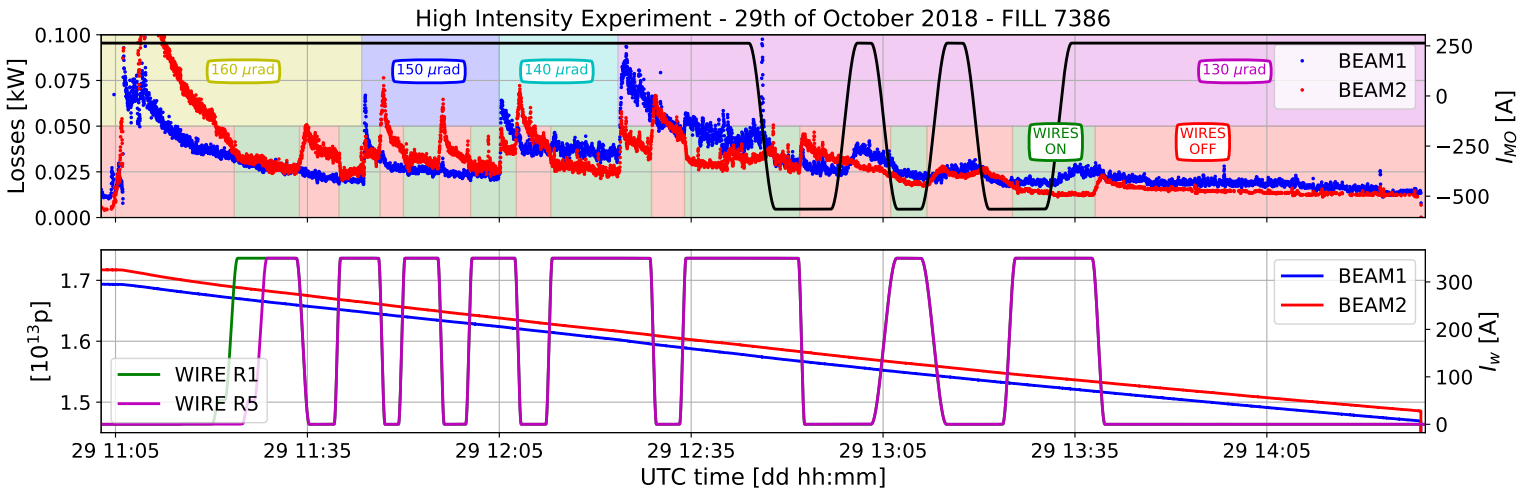


(a) Wires OFF. (b) Wires ON.

- Wires OFF: for $N_b = 1.1 \cdot 10^{11}$ p, **impossible to reduce** the crossing angle lower than 150 μrad.
- Wires ON: **possibility to reduce the crossing angle** down to 130 μrad without reducing the DA below 5 σ, **clear correlation** DA/σ_{eff}

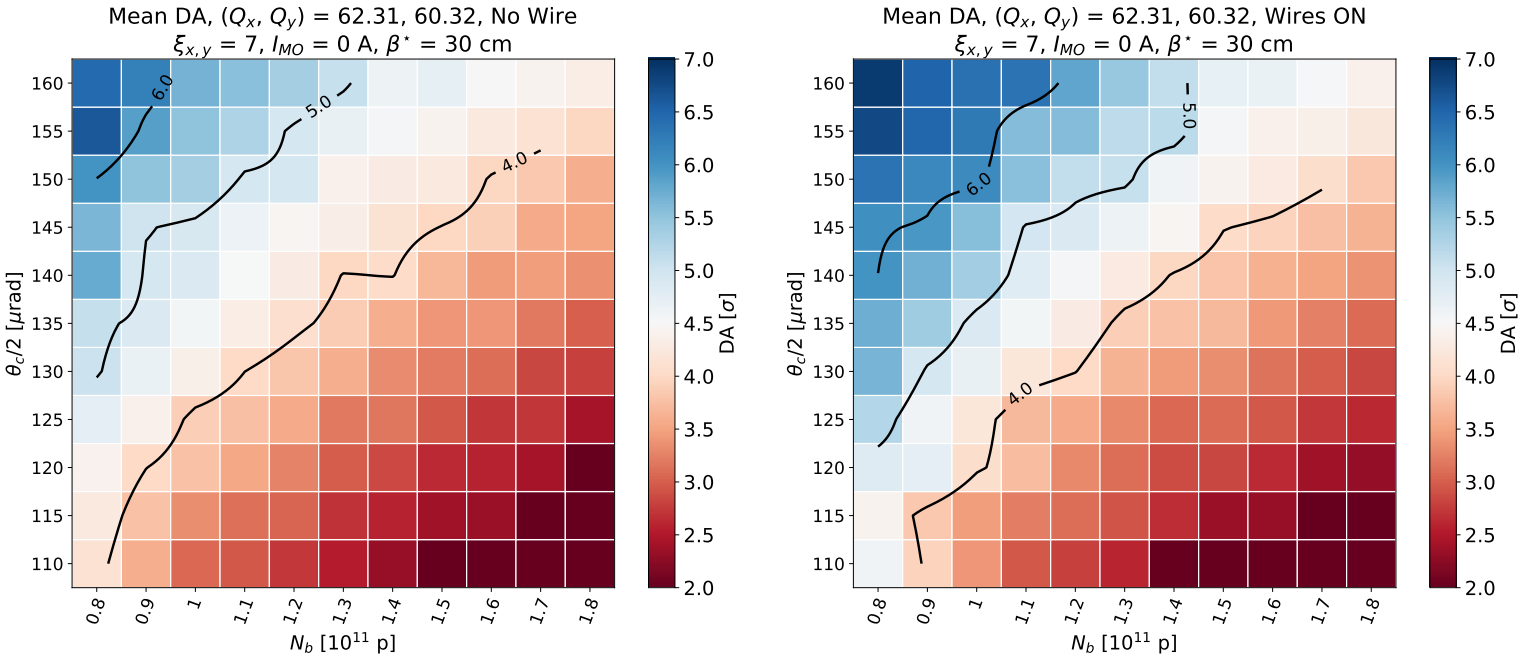
HI Experiment Results





- **Challenge:** one wire collimator per IP, 2-jaws powering
- As expected, the **wires effect is reduced**:
  - Observing the beam losses instead of the effective cross-section
  - **Reduction of B2 losses**, B1 remains unaffected
  - **Possible reduction the crossing angle**

HI Experiment: Numerical Benchmark



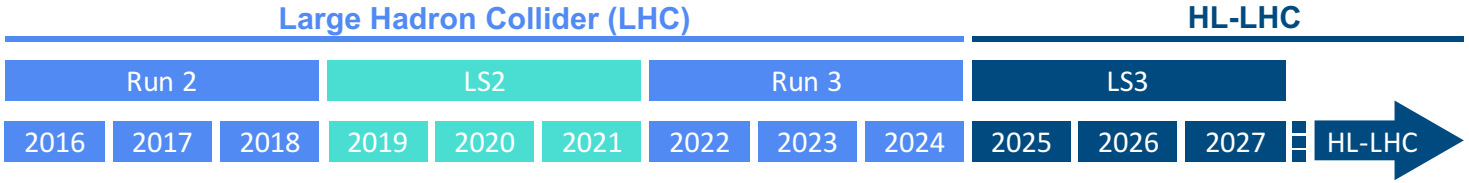
(a) Wires OFF. (b) Wires ON.

- Possible **slight crossing angle reduction**
- Less efficient than LI experiment
- As for LI experiment, **good agreement** DA/losses

Outline

- Introduction and Motivations
- BBLR Compensation Using DC Wires
- Experimental Campaign in the LHC
- Towards the LHC Run 3
- Conclusions

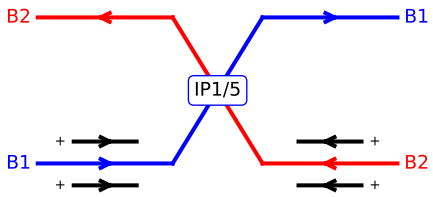
LHC Run 3: Objectives and Challenges

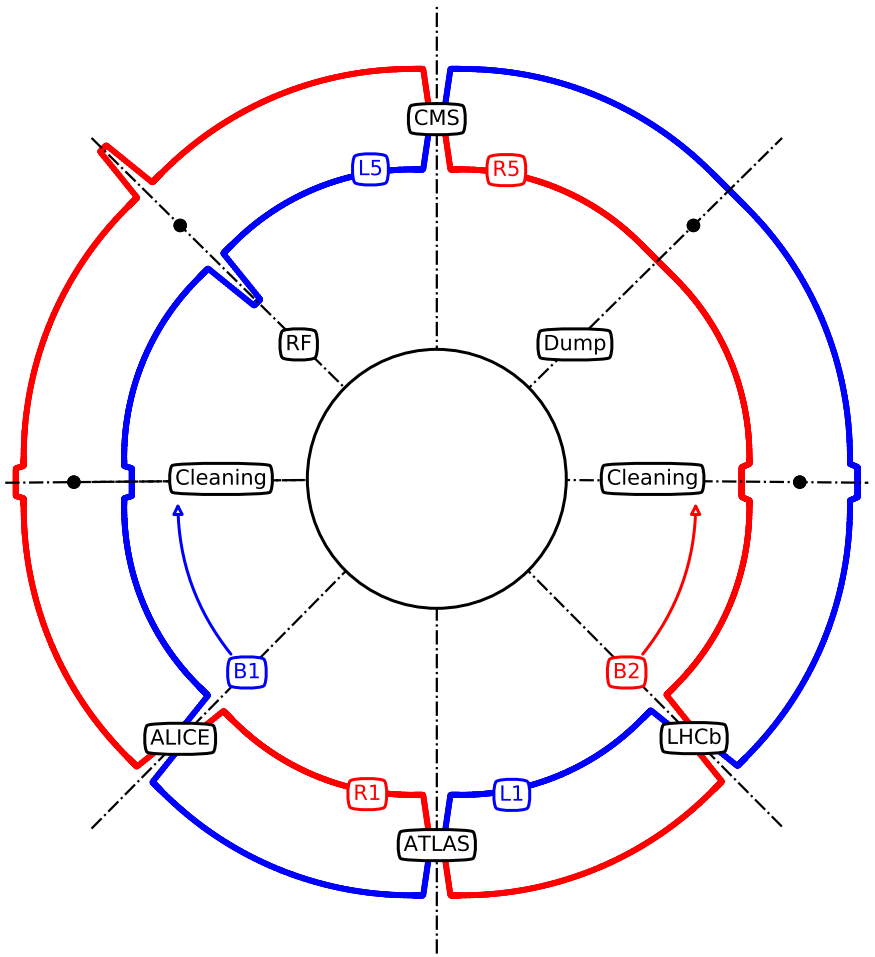


We are now in the middle of the **Long Shutdown 2** (LS2), preparatory step for the last LHC Run before the HL-LHC era. A delay of about one year is currently observed due to the sanitary situation.

- **LS2:** completion of the injectors upgrade (LIU)
- **LS3:** LHC upgrade
- **Goals** of Run 3:
  - Beam intensity ramp up to $1.8{\cdot}10^{11}$ protons per bunch
  - Find solutions to cope with the increased brightnesses
- **Challenge:** include the wire compensators!

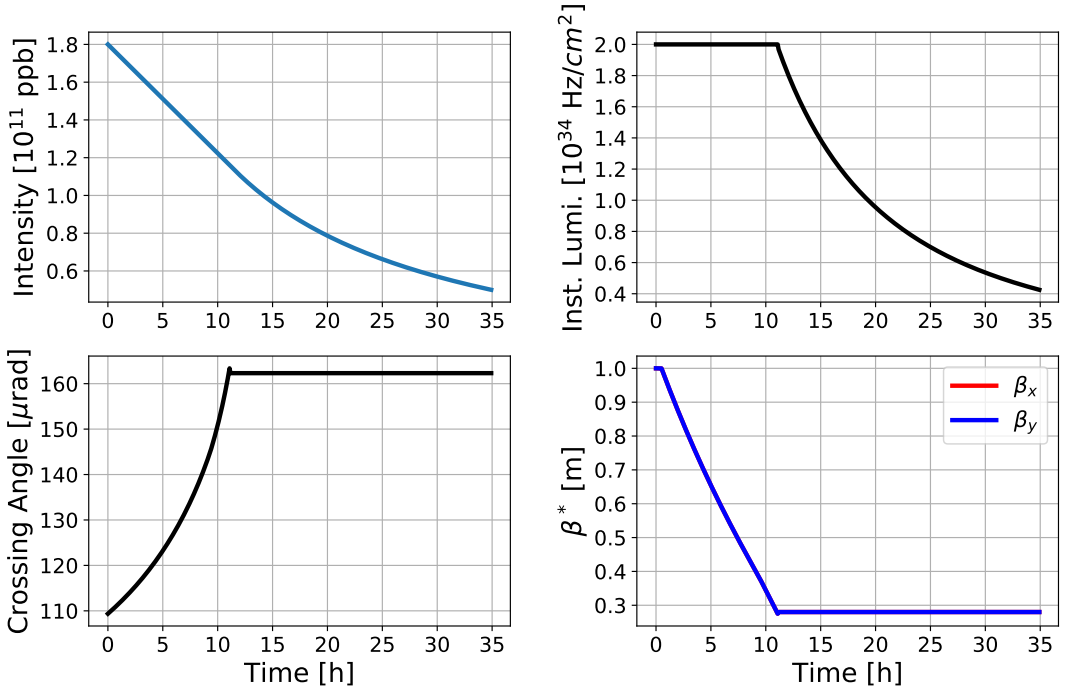
Run 3: A New Wires Layout





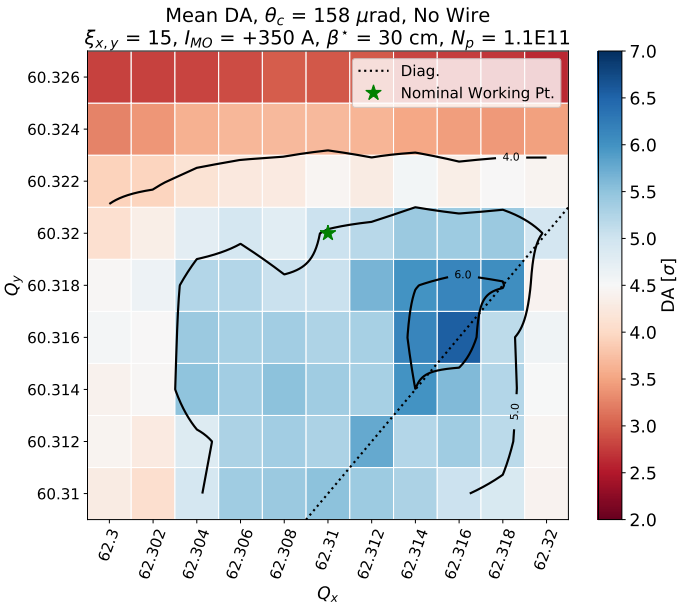
⇒ **Change of layout done!**

A Dynamical and Complex Cycle

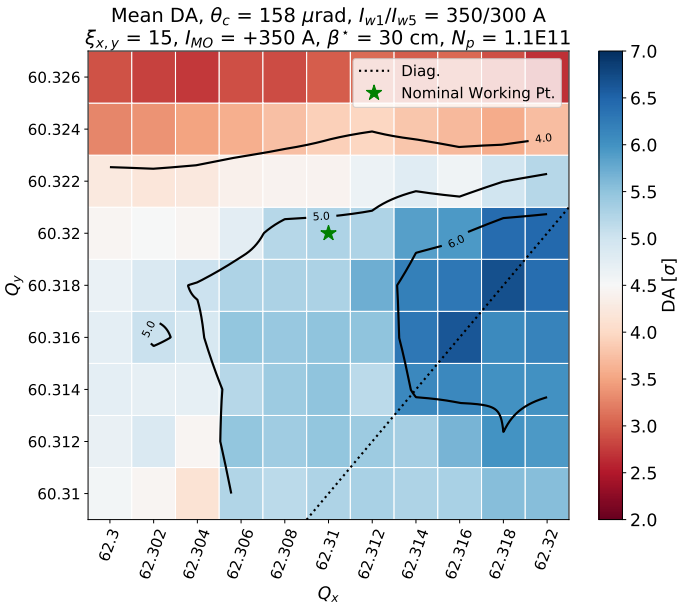


- Run 3 is based on a luminosity β^*-leveling
- Integrate the wire compensators:
  - Full **commisionning** of a new device
  - **Availibility** of the hardware
  - **Orchestration** with the cycle
- **Proposal:** power the wires systematically **at the end of each fill**

Scenario Proposal: Tune Scans



(a) Wires OFF.

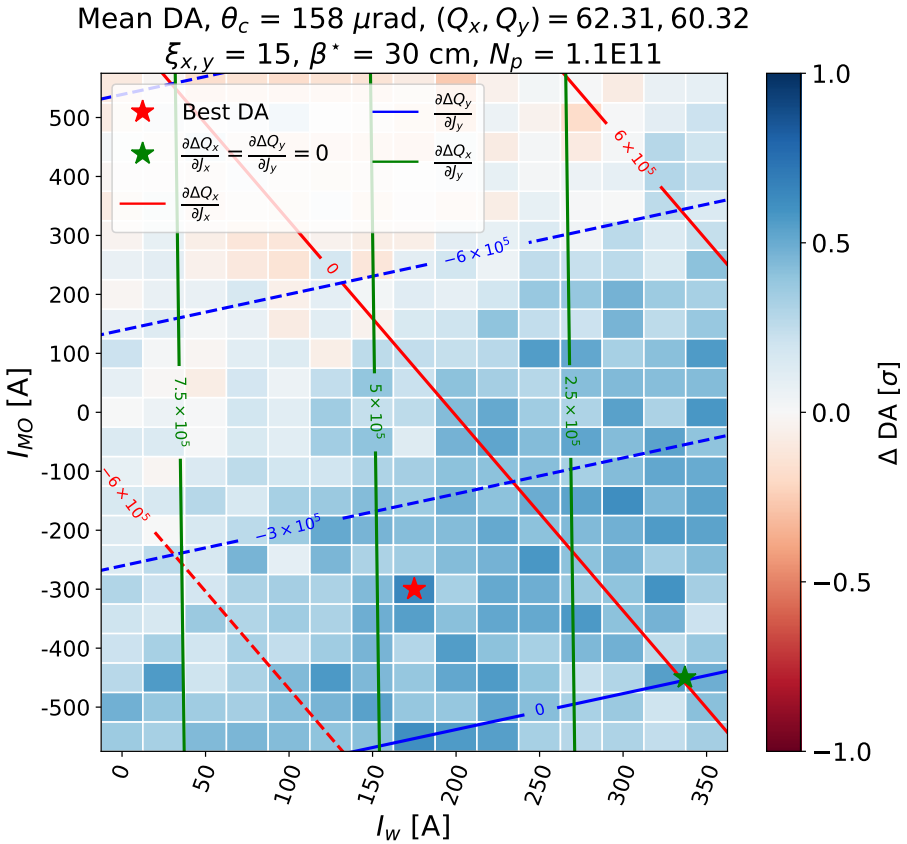


(b) Wires ON.

- **The wires enlarge** the area where DA $> 5\ \sigma$.
- Mostly around the working point and the diagonal.
- **Marginal effect:** can we do more?

Scenario Proposal: Wires Vs. Octupoles

First hint: what about the lattice octupoles? Experiments were led during Run 2, showing good results.



- **Negative octupoles** to mitigate BBLR interactions.
- Correlation between DA and **vertical detuning**.
- **DA improvement** up to 0.7 σ.

Towards Performance Gain

Our proposal for the next LHC Run 3:

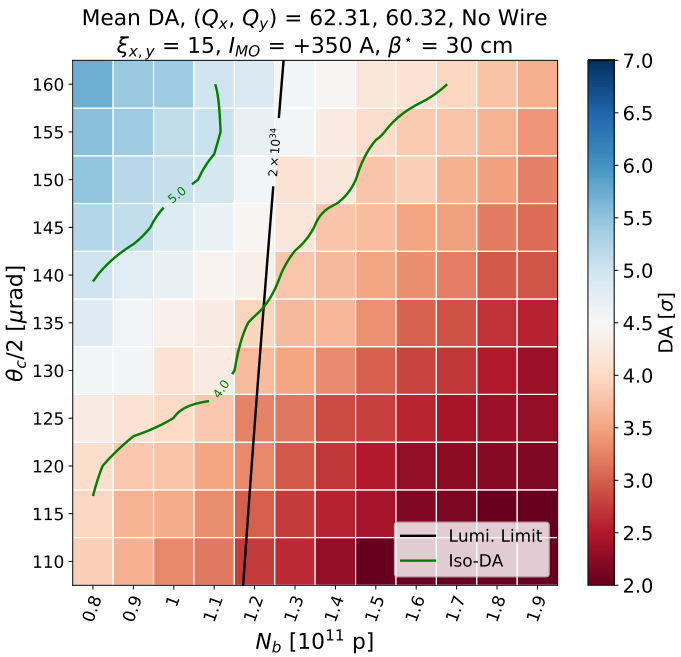
- Operate with **negative octupoles** (-350 A).
- **Tighter** wire collimators (7.5 σ_{coll}).

Collimator Opening	Wire IR1	Wire IR5
7.5 σ_{coll}	8.39 mm	11.15 mm
8.5 σ_{coll}	9.1 mm	12.23 mm

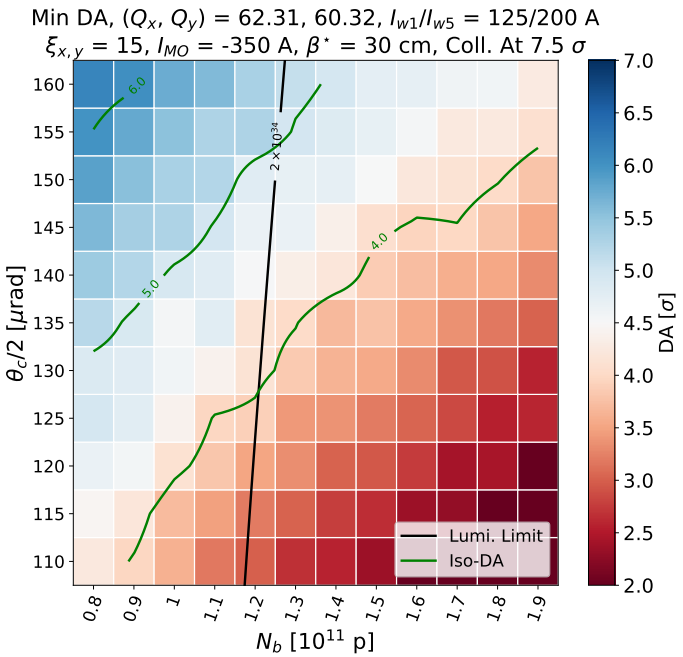
Reduction of the physical transverse beam-wire distance by about 1 mm, which is important, considering the octupolar terms ($1/d_w^4$).

$\rightarrow$ **Can we gain performance?**

Performance Gain: N_b Vs. θ_c



(a) Nominal - Wires OFF.



(b) Proposal - Wires ON.

With **our proposal**:

- Possible **reduction of crossing angle** (145 µrad).
- Improve **the integrated luminosity** by about 2 %.

Outline

Conclusions

⇒ **How can we compensate the BBLR interactions in the LHC using DC wires?**

- Wires settings: **RDT compensation mechanism**.
- **First experimental evidence** of a BBLR compensation.
- Good simulations/experiments **agreement**

⇒ **What are the limitations of the current hardware?**

- Beam-wire distance **constrained** by collimation.
- **Local beam diagnosis** for wire alignment.

⇒ **What are the perpespectives to be drawn from the LHC experience, in view of the HL-LHC era?**

- LHC Run 3: **gain experience**.
- HL-LHC: **complementary solution** to crab cavities.

Thank you for your attention !

References I

[1] J.-P. Koutchouk and V. Shiltsev, "Beam-beam compensation schemes," in *Handbook of Accelerators Physics and Engineering*, ch. 4.14, pp. 391 – 394, World Scientific, forst ed., 1999.

[2] Y. Papaphilippou and F. Zimmermann, "Estimates of Diffusion due to Long-range Beam-beam Collisions," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 5, p. 074001. 22 p, Jul 2002.

[3] J.-P. Koutchouk, "Principle of a correction of the long-range beam-beam effect in LHC using electromagnetic lenses," Tech. Rep. LHC-PROJECT-NOTE-223, CERN, Geneva, Mar 2000.

[4] S. Fartoukh *et al.*, "Compensation of the long-range beam-beam interactions as a path towards new configurations for the High Luminosity LHC," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 18, p. 121001. 23 p, Sep 2015.

[5] E. Todesco and M. Giovannozzi, "Dynamic aperture estimates and phase space distortions in nonlinear betatronic motion," *Phys. Rev. E*, vol. 53, pp. 4067–4076. 26 p, Oct 1995.

Back-up Slides

Strengths of a Multipolar Lens

With the following definitions of the normal and skew strengths:

$$k_n = \frac{1}{B\rho}\frac{\partial^n B_y}{\partial x^n} = \frac{b_n}{B\rho}$$
$$k_n^{(s)} = \frac{1}{B\rho}\frac{\partial^n B_x}{\partial y^n} = \frac{a_n}{B\rho}$$

$\Rightarrow$ **We have a quantification of the effect of a single lense, but can we reduce the distributed non-linear kick? How many equivalent kicks do we need?**

Example with the Octupolar Term

Let us assume the $(J_{x,y}, \mu_{x,y})$ space. The linear detuning with amplitude can be defined as:

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The goal is to find the **correponding wire Hamiltonian** that compensate the BBLR one.

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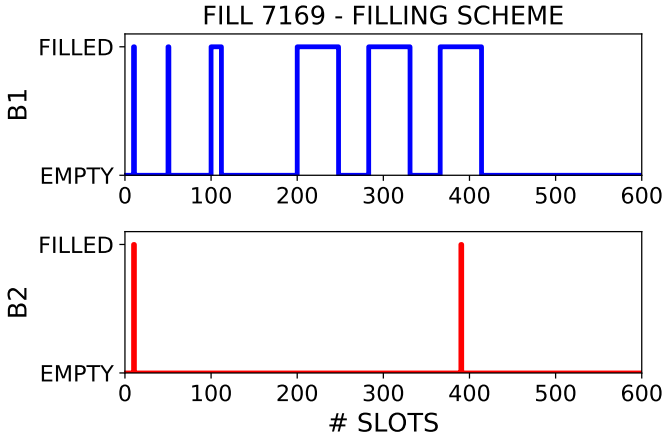
The goal is to find the **correponding wire Hamiltonian** that compensate the BBLR one.

- This is possible and *easy*: system of 2 equations, with a_3^w and b_3^w unknown
- But how do we solve an **infinite system** of n equations?

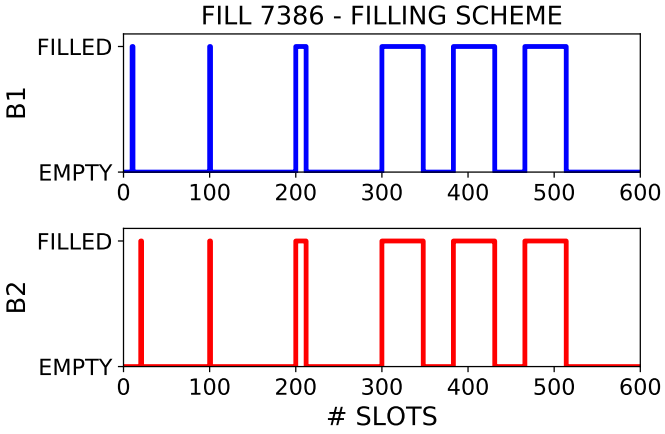
Experimental Campaign: Filling Schemes

The BBLR compensation experimental campaign was divided in two part:

- **Close to the theory**: proof-of-concept, wire collimators opened at 5.5 σ_{coll}, low intensity for B2 (LI experiment)
- **Close to the operational conditions**: nominal operation settings, wire collimators opened at 8.5 σ_{coll}, high intensity for B2 (HI experiment)



(a) Low Intensity Experiment



(b) High Intensity Experiment

Tunes Feed-Forward (1)

The wires cannot compensate the low order effects of the BBLR interactions, and those effects are anyway optimized during operation (orbit feedback, and self-compensation of the tune shifts):

- Orbit distortion induced by the wires: recovered from orbit feedback
- Tune shifts: up to 10^{-2} and requires a tunes feed-forward system

Done locally to avoid β-beating, using the Q4 and Q5 quadrupoles.

Tunes Feed-Forward (2)

We want:

$$(\Delta KL)_{Q4} = \alpha_{Q4} \cdot \frac{(IL)_w}{d_w^2} \tag{1}$$

With:

$$\alpha_{Q4} = \frac{\mu_0}{2\pi B\rho} \frac{\beta_x^w \beta_y^{Q5} - \beta_y^w \beta_x^{Q5}}{\beta_x^{Q4} \beta_y^{Q5} - \beta_x^{Q5} \beta_y^{Q4}} \tag{2}$$

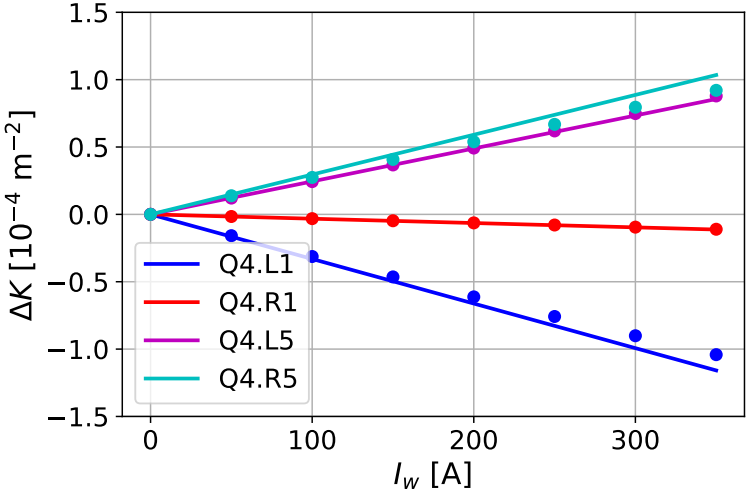


Figure: Q4 for the LI experiment.

Alignement of the wires

- The housing jaw is assumed to be aligned within the nominal operation sequence
- Need to align the 5th-axis of the collimator
  - Needs a scan of the 5th-axis position
  - Recording the BPM signal
  - Aligned position: maximum of the obtained parabola

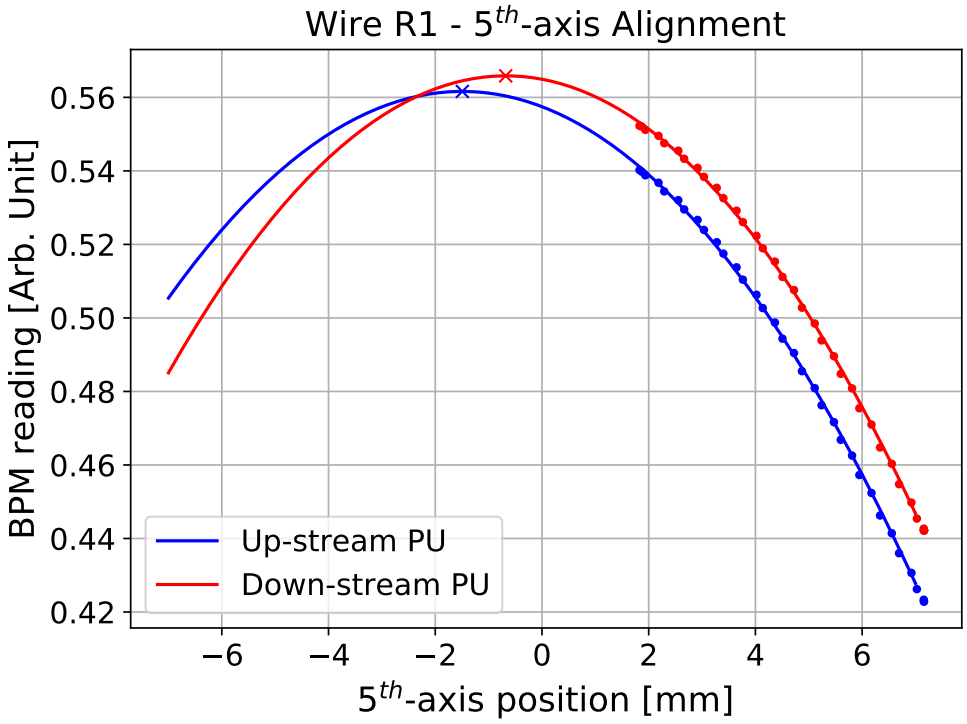


Figure: Alignement of the R1 wire collimator.

β-beating induced by the wires

With MAD-X, one can get the β-beating induced by the wires and their tunes feed-forward system.

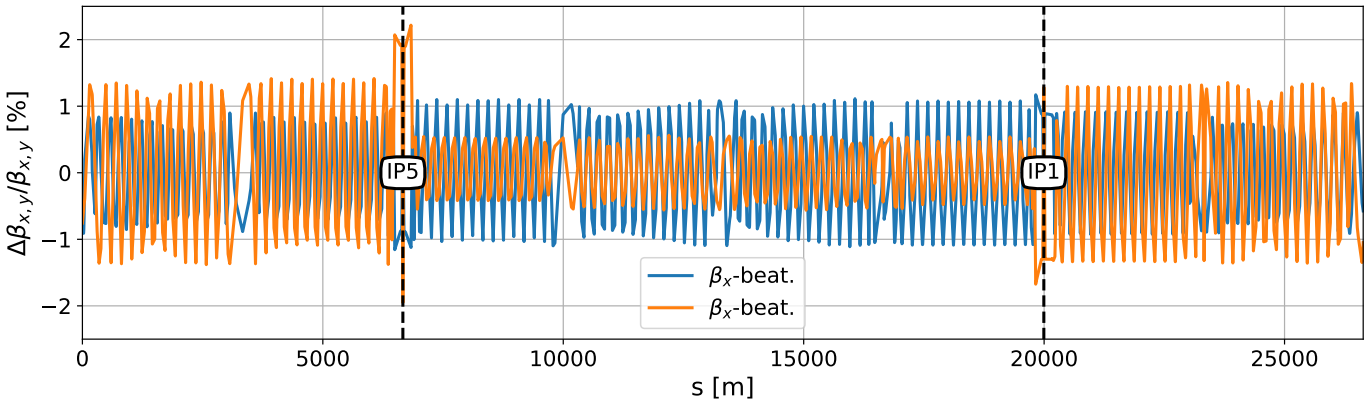


Figure: LI experiment.

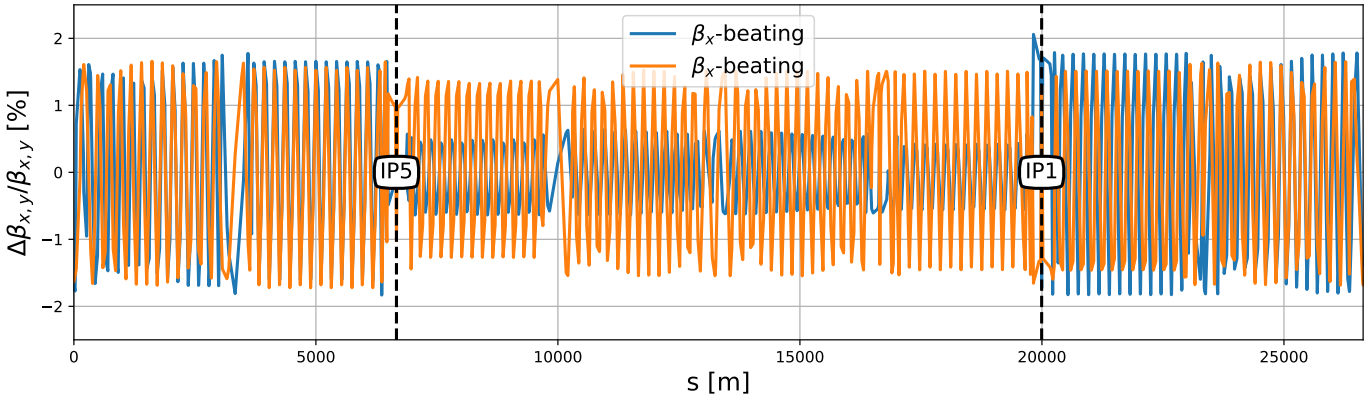
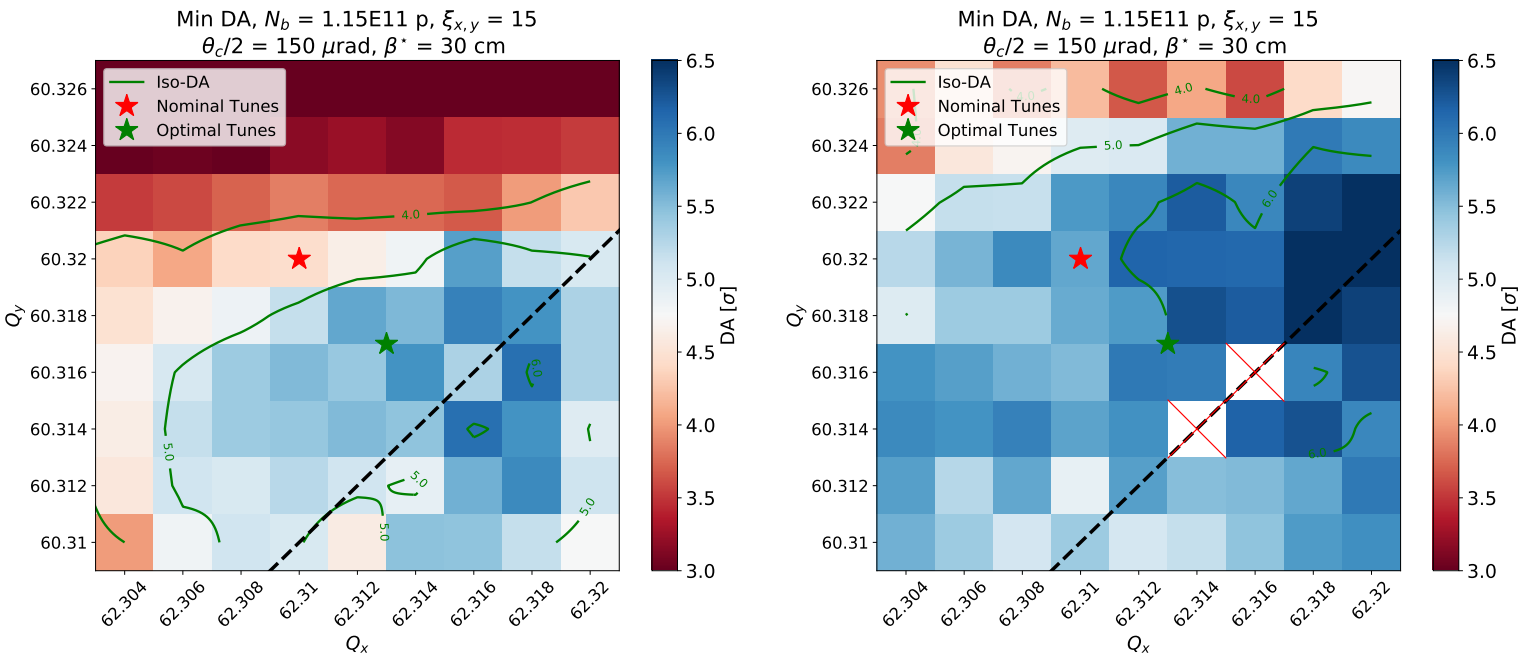


Figure: HI experiment.

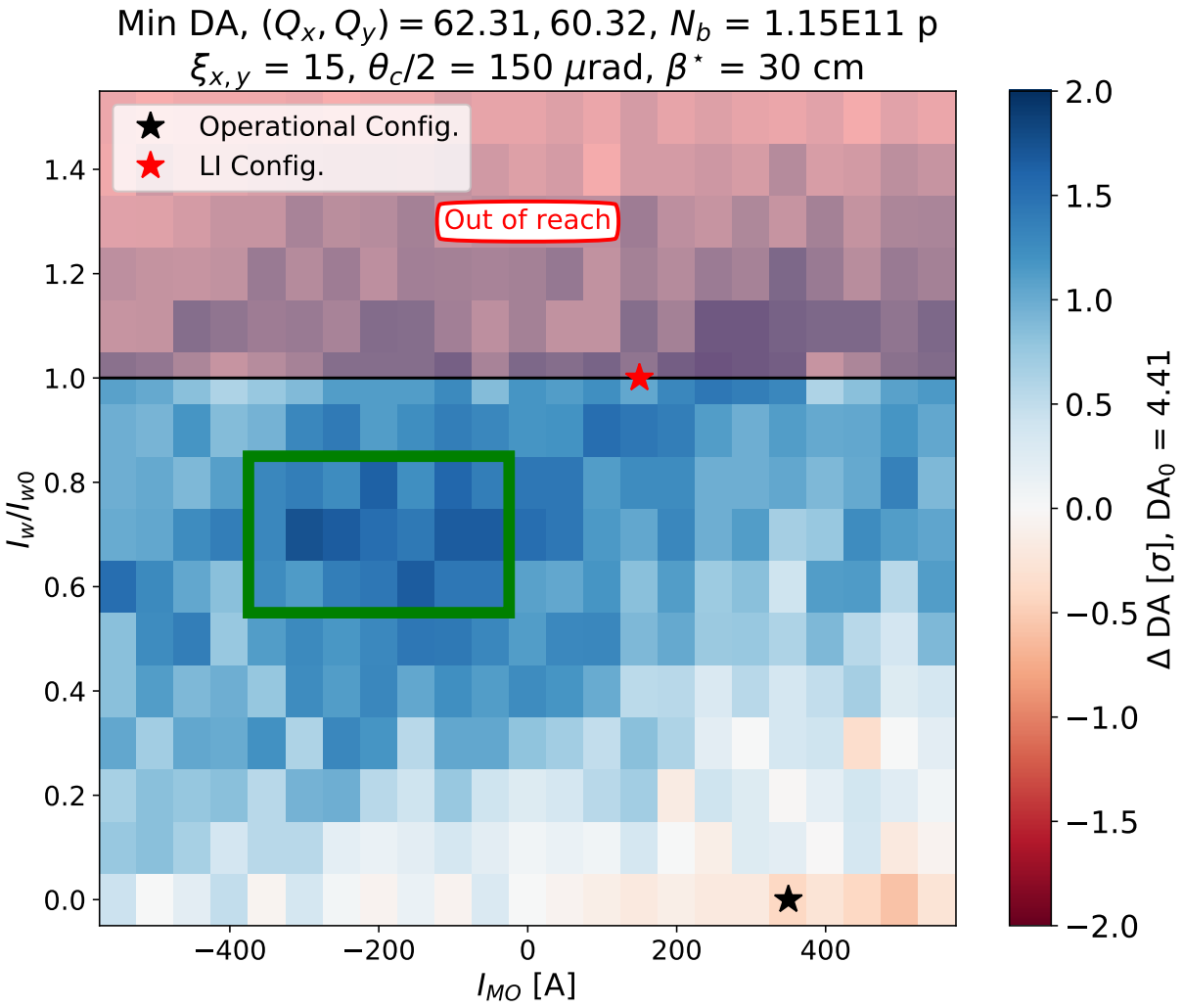
LI Experiment: Numerical Benchmark (3)



(a) Wires OFF. (b) Wires ON.

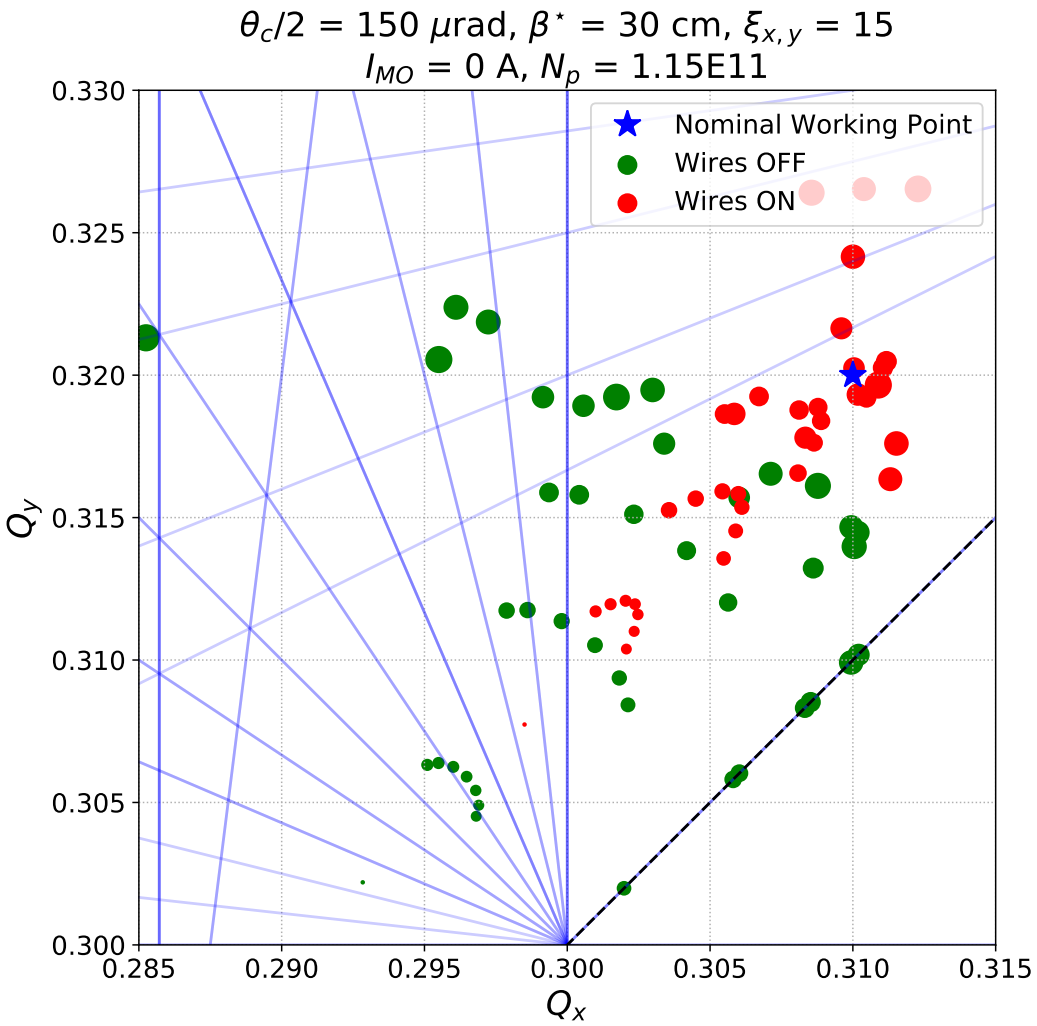
The wires allow for an opening of the tune space, create a more confortable region to accomodate additionnal non-linear effects (beam-beam, e-clouds...).

LI Experiment: Numerical Benchmark (4)



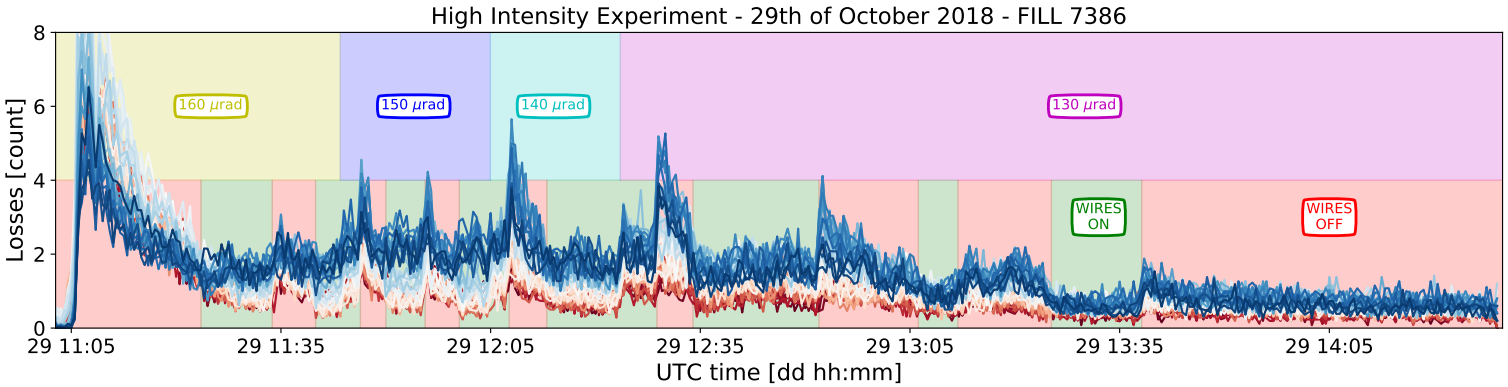
Strong negative octupoles can help mitigating the BBLR interactions.

LI Experiment: Numerical Benchmark (5)



The wires allow for a compression of the tune footprint by compensating the BBLR induced tune spread.

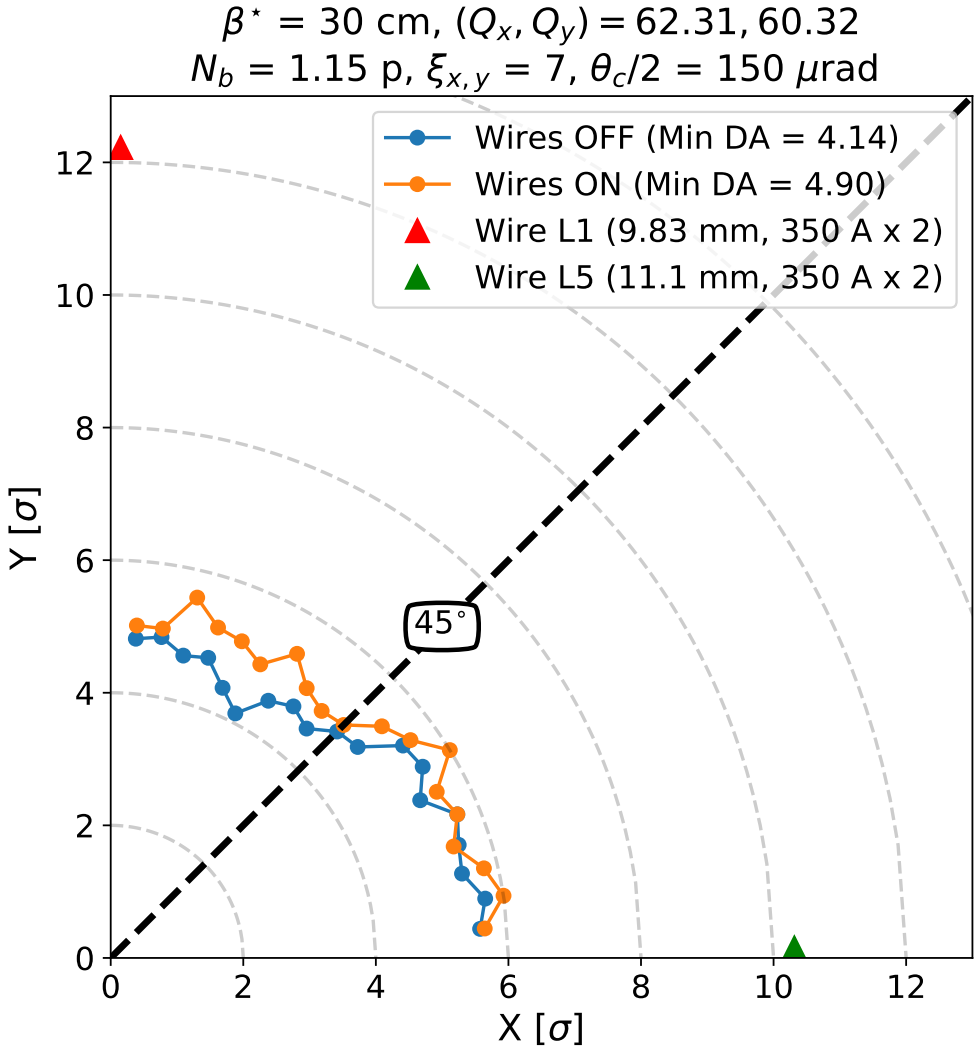
HI Experiment Results (dBLM)



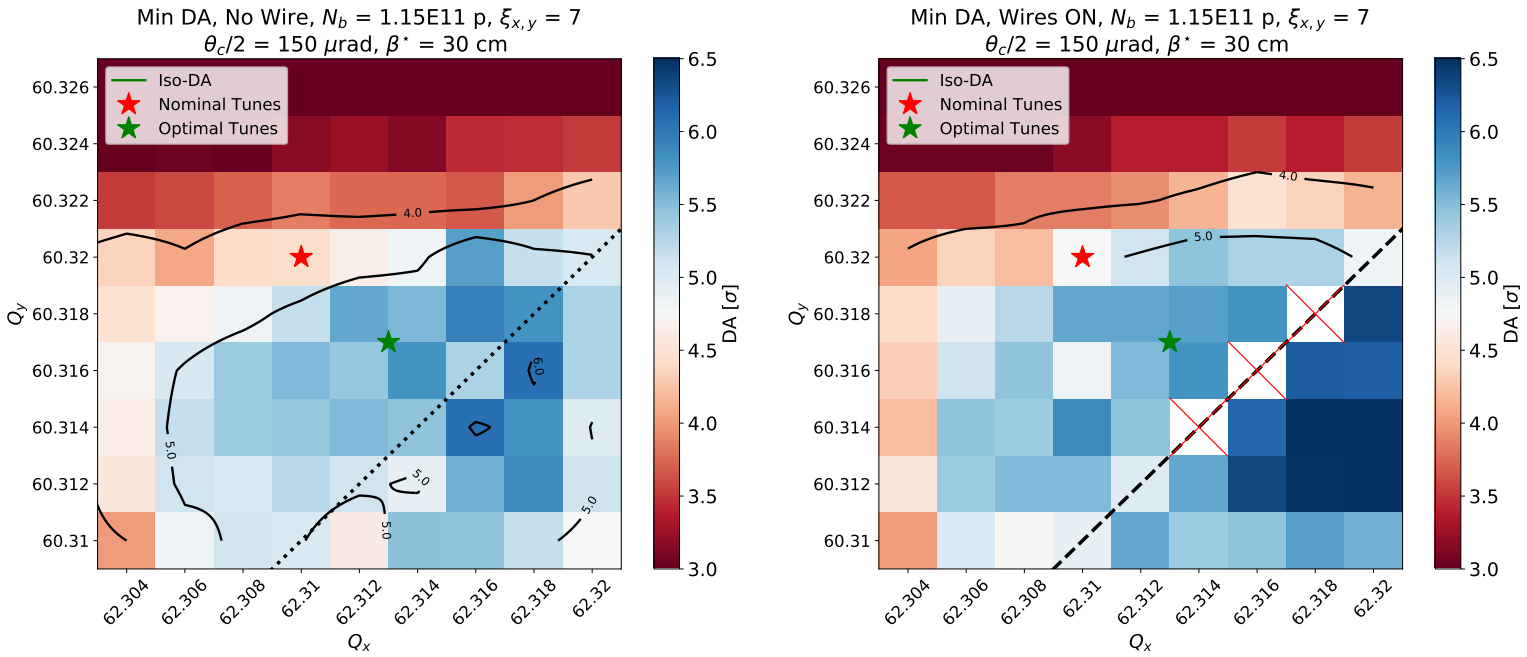
- Bunch-by-bunch losses: identification of a losses pattern
- The bunches located at the end of the train lose more than the ones at the beginning
- Not BBLR pattern but **electron clouds effect**

HI Experiment: Numerical Benchmark (2)

Similar studies were carried out for the HI experiment.



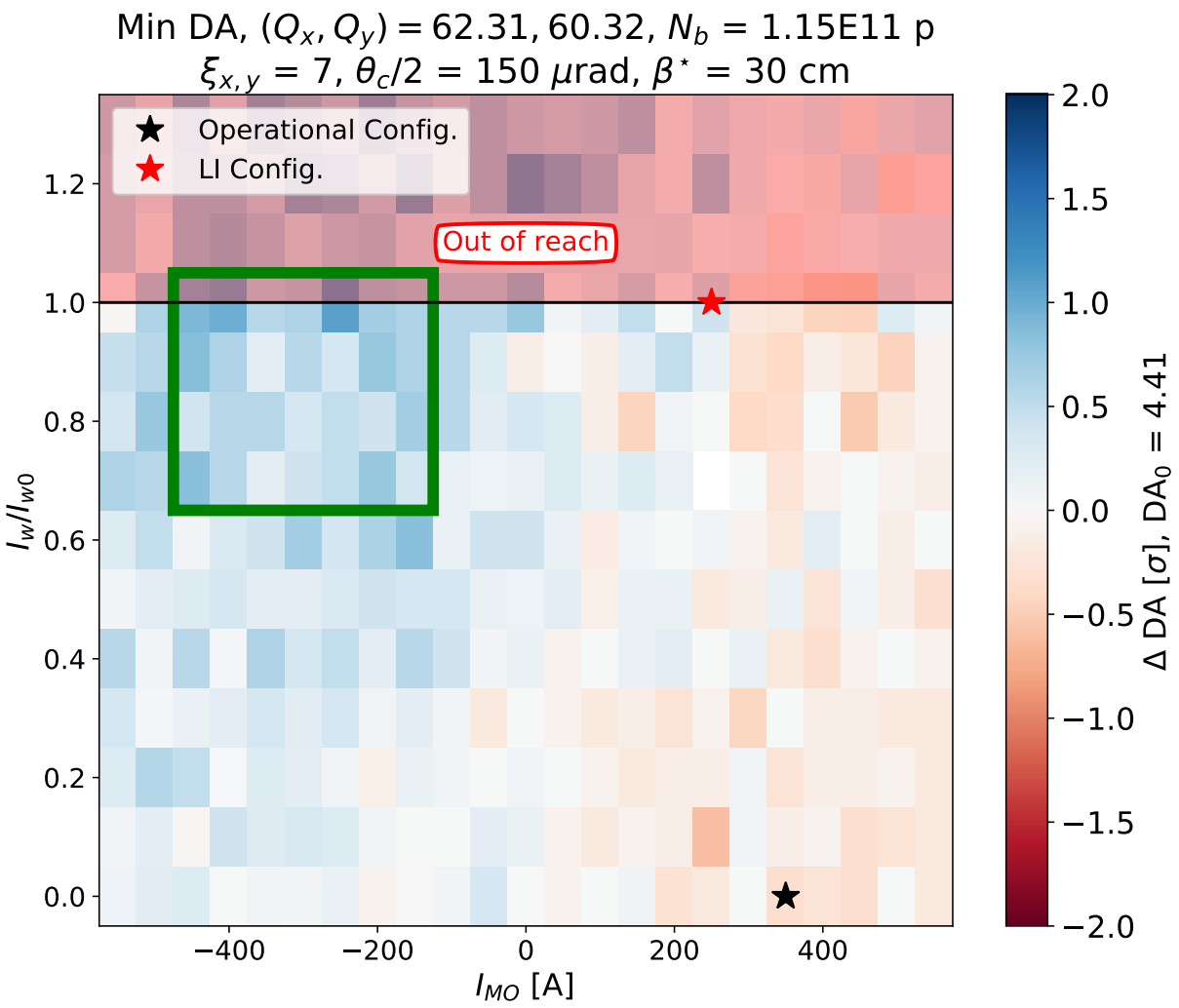
HI Experiment: Numerical Benchmark (3)



(a) Wires OFF. (b) Wires ON.

The effect of the tune space is less evident than in the LI experiment case.

HI Experiment: Numerical Benchmark (4)



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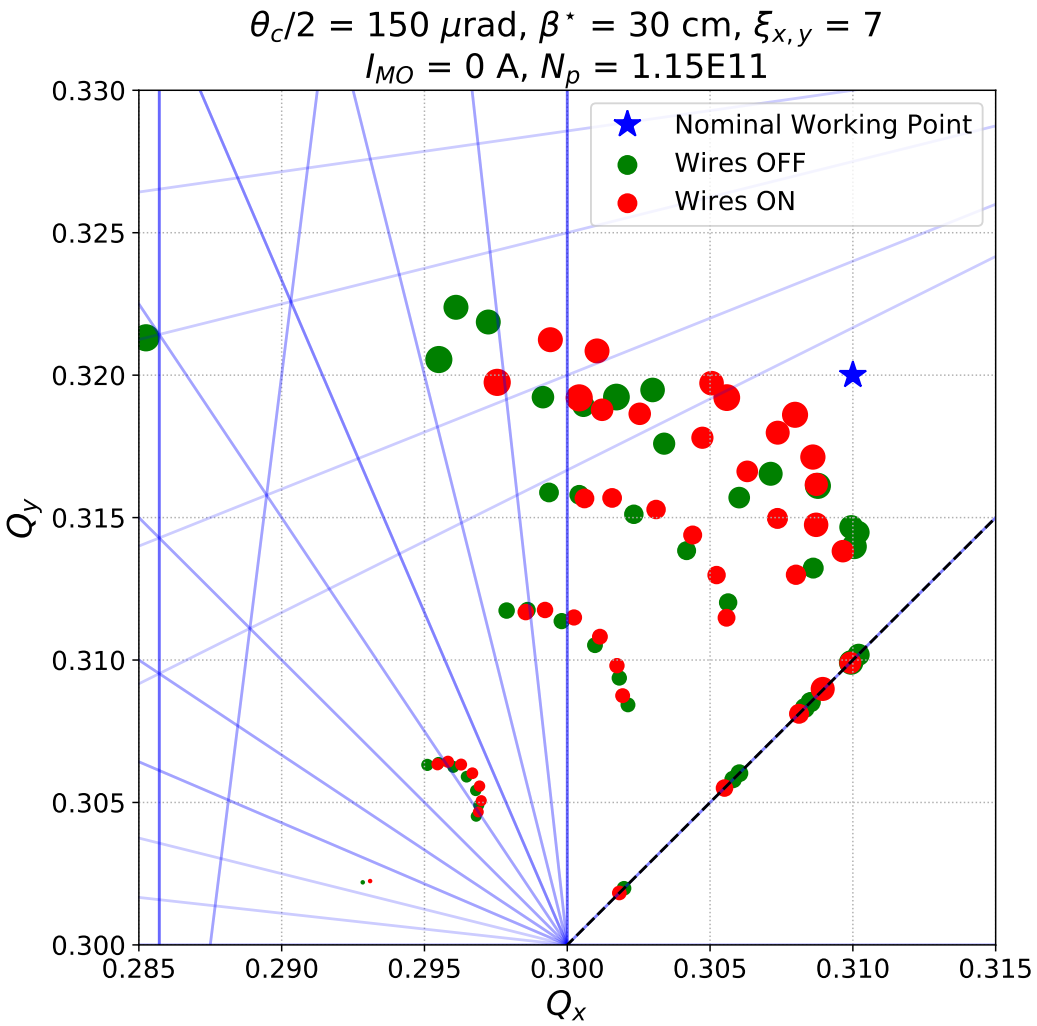
HI Experiment: Numerical Benchmark (5)

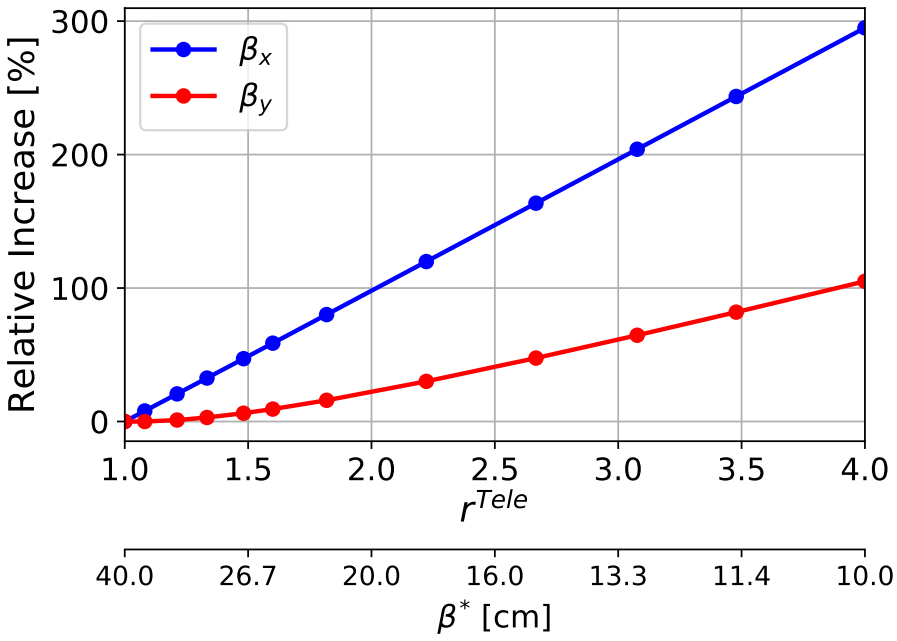


The effect of the wires on the tune footprint is less evident than in the LI experiment case.

Objectives and Motivations

The objective is to take advantage of the main ATS by-products:

- Tele-squeeze done using the matching quadrupoles of the nearby IRs
- The β-beating wave propagating in the arcs reaches its peaks at the sextupoles and octupoles location
- The efficiency of the octupoles is increased for high telescopic indexes



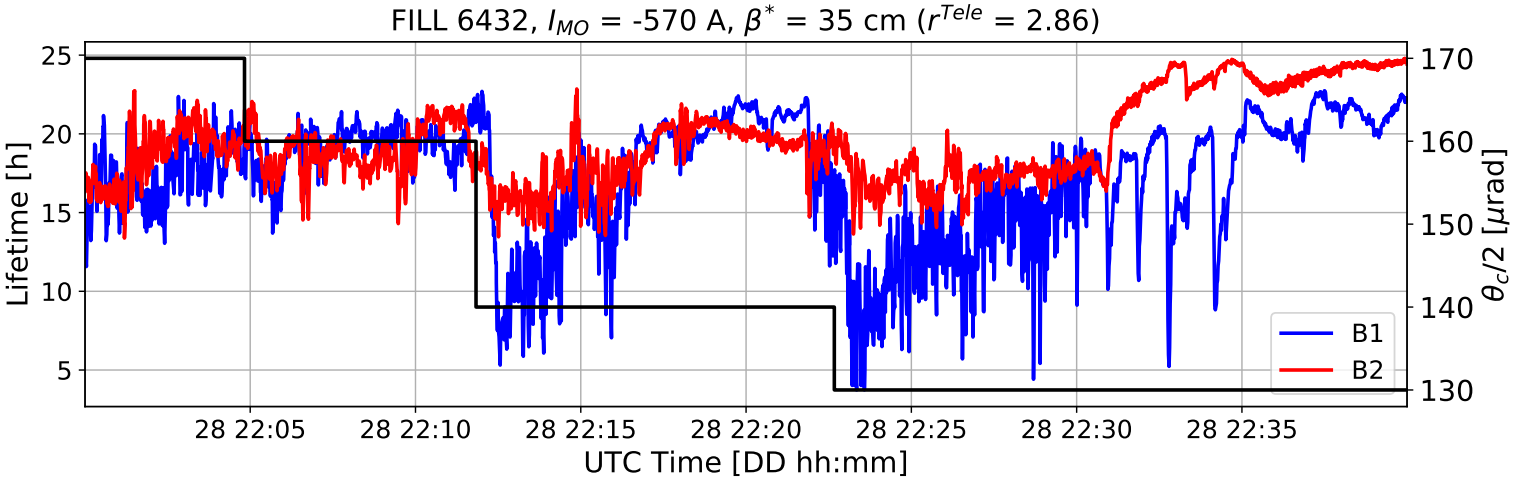
Objectives and Motivations

In parallel to the wire experiments, several experiments were carried out with high tele-indexes:

- With round optics:
  - Crossing angle reduction with strong negative octupoles
  - Octupoles current scans at low crossing angle
- Effect of the octupoles and the crossing angle with flat optics

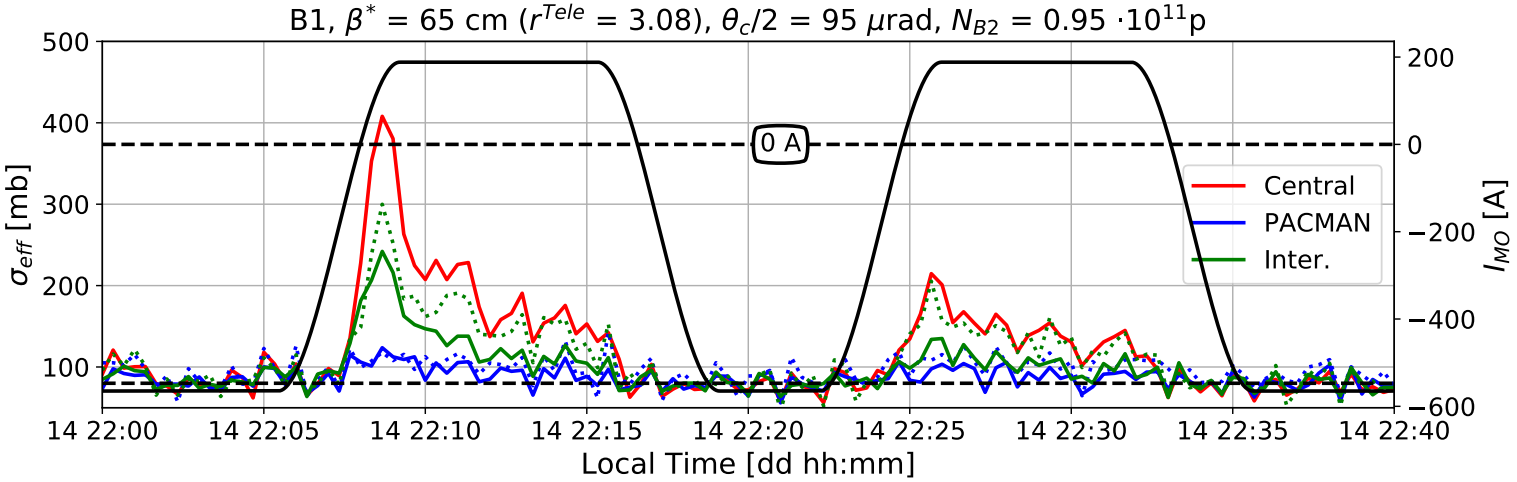
The observables are the beam lifetime and the bunch-by-bunch cross-section. For all the experiments, both are composed of several trains of bunches.

Round Optics: Crossing Angle Reduction



- Tele-index of 2.86
- Strong negative octupoles (I_{MO} = -570 A)
- Reduction of the crossing angle from 170 µrad (10.6 σ) down to 130 µrad (8 σ)
- Beam lifetime maintained around 20 h

Round Optics: Octupoles Scan at Low Crossing Angle



- Tele-index of 3.08
- Low crossing angle of 95 µrad (8.1 σ)
- **Clear effect** of the octupoles polarity on the effective cross-section
- BBLR pattern: the central bunch always loses more
- Similar results are observed for B2

A Word About Flat Optics

Unlike round optics, the β-functions at the IP are not the same in both planes ($\beta_x^* \neq \beta_y^*$):

- We define an aspect ratio $r^* = \beta_X^*/\beta_{||}^*$
- The crossing angle is set in the plane or larger β^*
- In order to restore the luminosity geometrical factor, one has to ensure that:

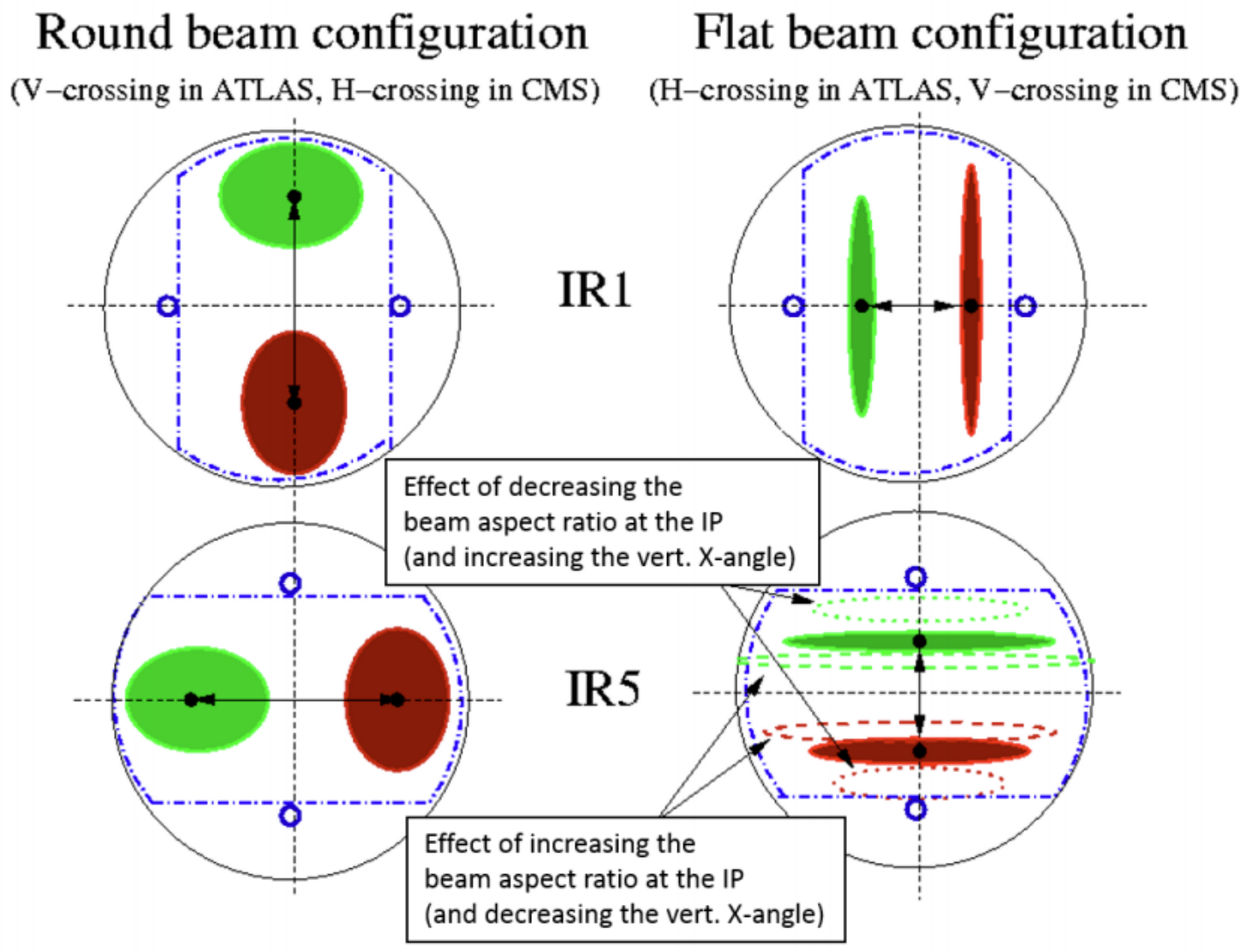
$$\beta_{eq}^* = \sqrt{\beta_X^* \beta_{||}^*} \sim \text{Cst.} \tag{3}$$

- The luminosity can be written:

$$\begin{aligned}\mathcal{L}_{\text{Flat}}(\beta_{eq}^*, r^*) &= \mathcal{L}_{\text{Round}}(\beta_{eq}^*) \times F(\beta_{eq}^*, r^*) \\ &= \mathcal{L}_{\text{Round}}(\beta_{eq}^*) \times \left[\sqrt{1 + \frac{1}{r^*}\left(\frac{\Theta_c \sigma_z}{2\beta_{eq}^2}\right)^2}\right]^{-1}\end{aligned} \tag{4}$$

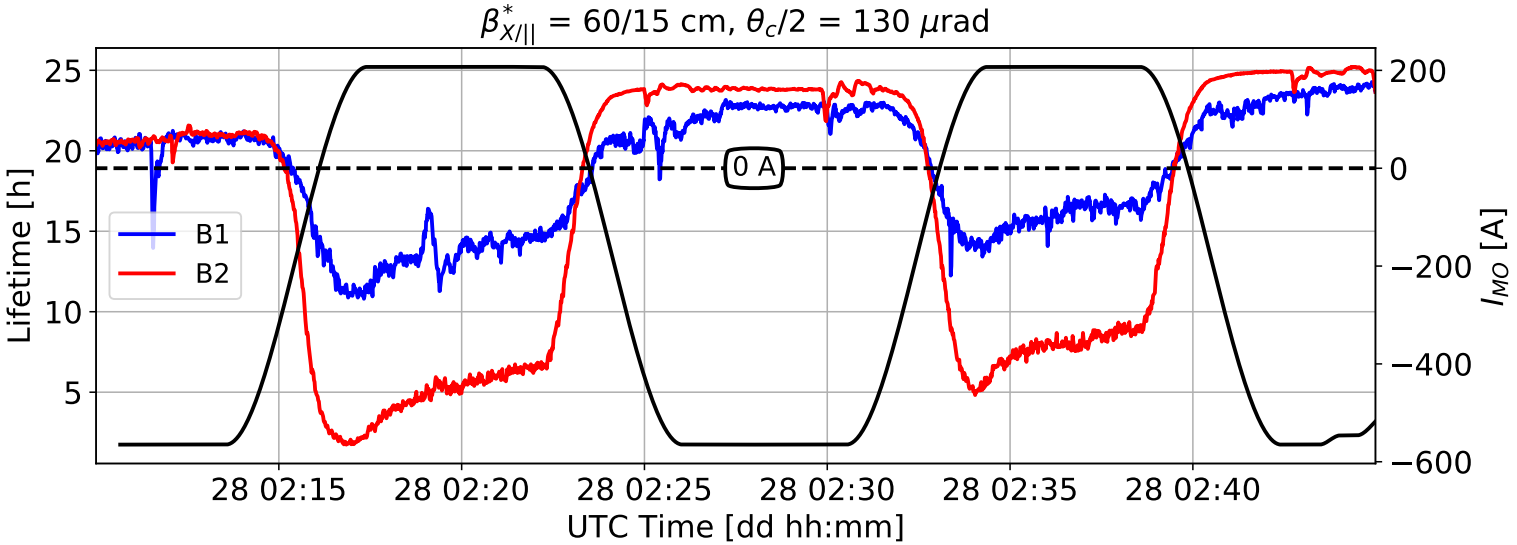
Θ_c: normalized crossing angle
σ_z: RMS bunch length

Flat Optics in Practice



Courtesy of S. Fartoukh

BBLR Mitigation with Flat Optics



- Octupoles scan done with $\beta^*_{X/||} = 60/15$ cm and a crossing angle of 130 µrad (10.6 σ)
- **Clear effect** of the octupoles polarity on the beam lifetime (drop of 5-10 h when reverting to positive current)
- Scans at lower crossing angle were also performed

Wire Compensators for Run 3

During LS2, two out of the four wire collimators are being moved from Beam 2 to Beam 1.

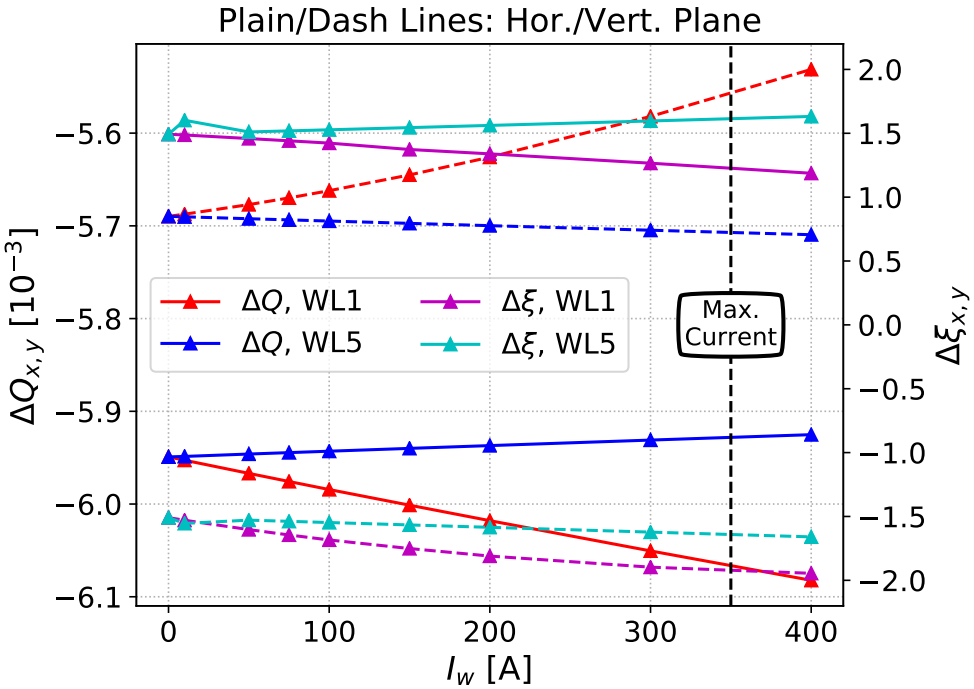
Beam	Wire	Dist. from IP [m]	Plane	d_w [mm]
B1	L1	-145.94	V	9.1
	L5	-147.94	H	12.23
B2	R1	145.94	V	9.1
	R5	147.94	H	12.23

- Wires powered at 350 A
- 2-jaws powering configuration
- Important tune shifts (10^{-2} level) that have to be compensated

Run 3: Tune Feed-Forward

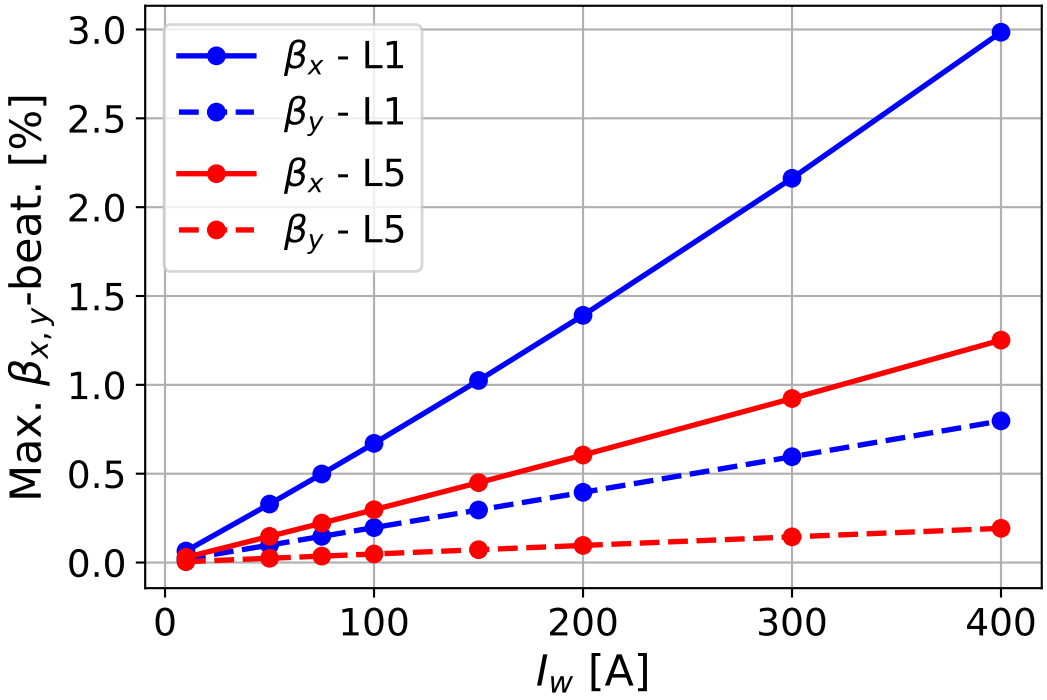
Unlike the LHC Run 2, the tune feed-forward is done using the Q4 quadrupoles located on each side of the IP:

- High tele-indexes: increased arc sextupoles efficiency leading to chromaticity aberrations
- Reduction of the β-functions at the Q5 locations: does not scale with β^* reduction



Run 3: β-beating

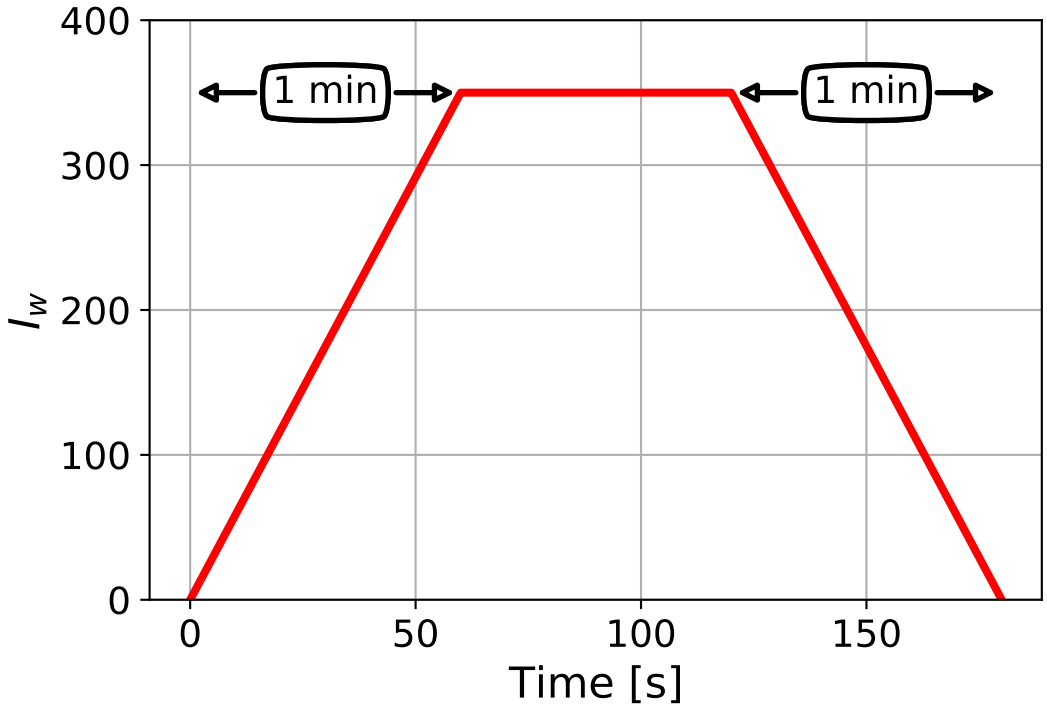
The β-beating induced by the wires and their feed-forward is limited.



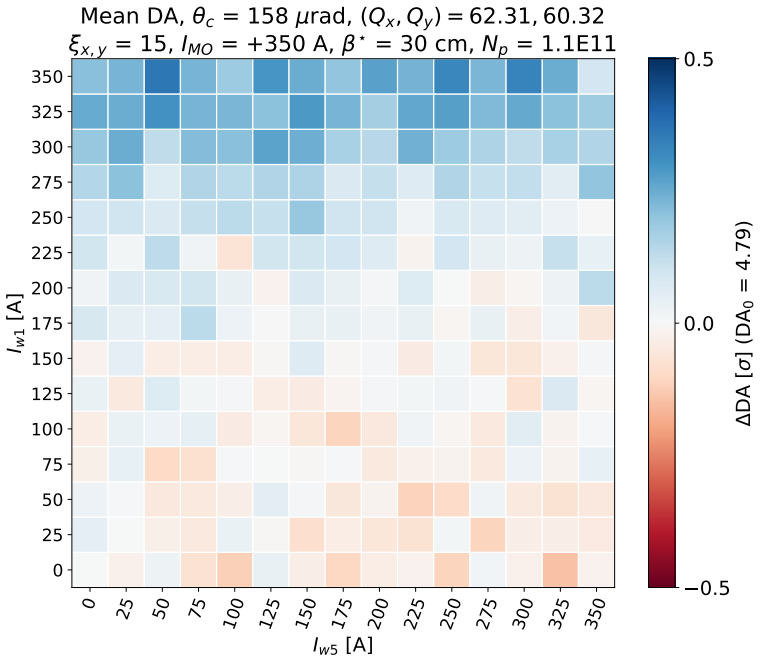
Run 3: Wire Ramp Proposal

It is important to have a slow ramp up of the wires ramp up:

- Avoid asynchronous ramp between the wires and the feed-forward
- Avoid eventual orbit distortions that would not be corrected by the LHC orbit feedback

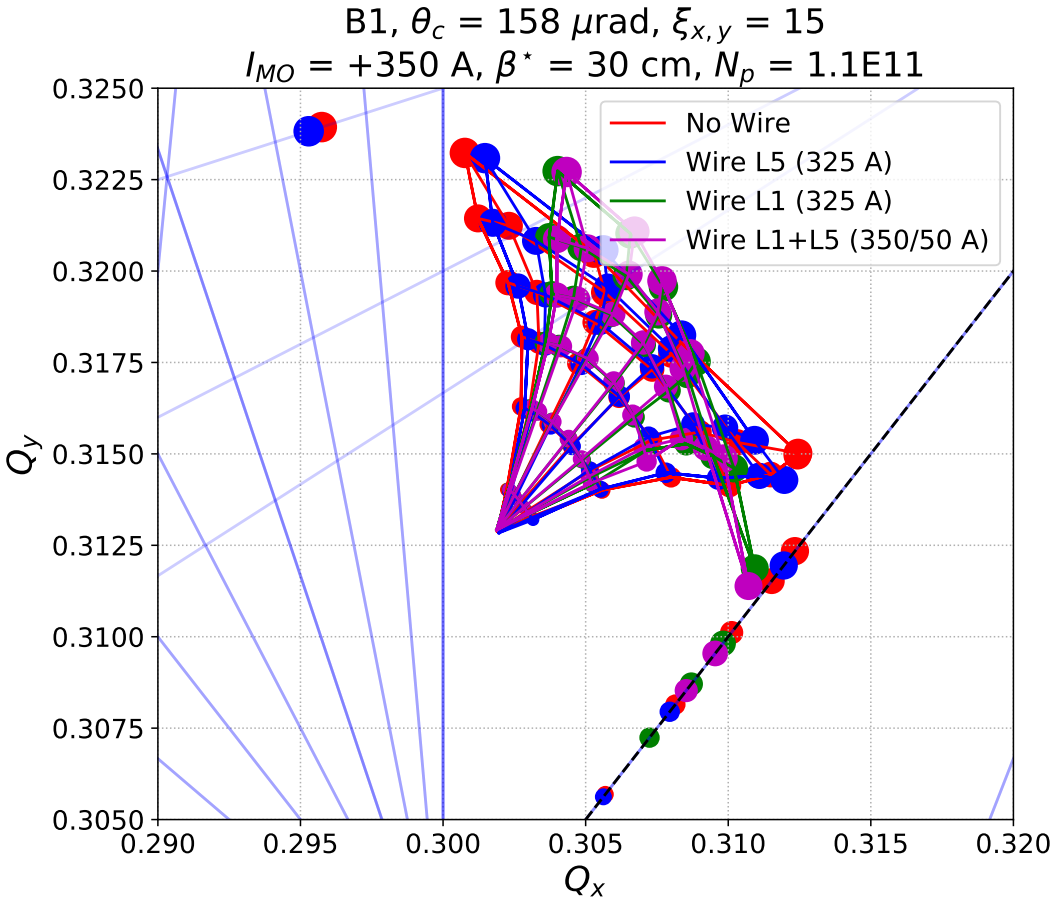


Nominal Scenario: Wire Currents (1)



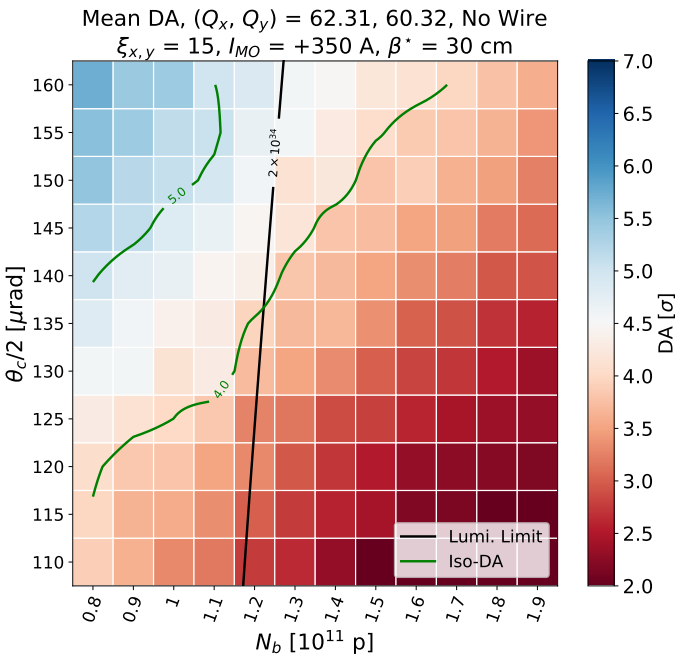
- **Positive effect** of the wires located in IR1 (wires in IR5 located further): improvement of about 0.35 σ.
- Correlation with the chromaticity shift: the wires in IR1 induce a shift of 2 units. However, similar results are obtained by correcting the chromaticity.
- Improvement mostly in the vertical plane (see Backup)

Nominal Scenario: Wire Currents (2)

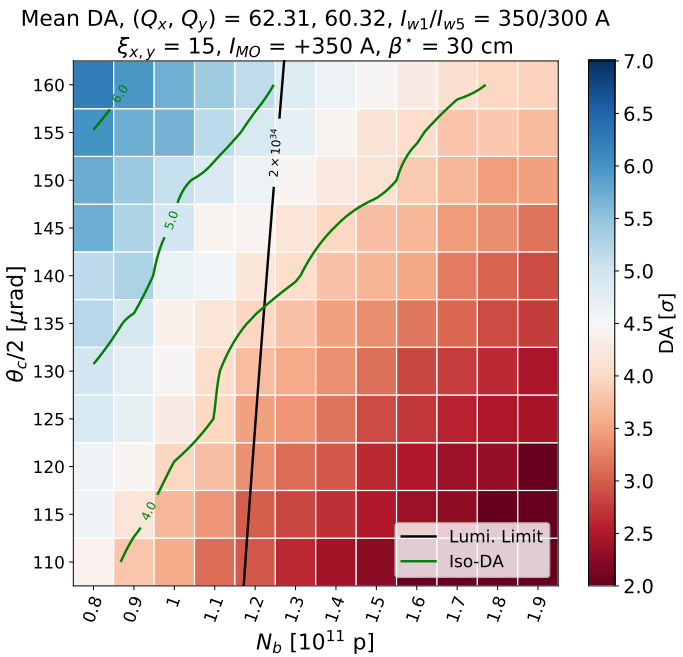


Good correlation between the DA improvement and the footprint compression.

Nominal Scenario: N_b Vs. θ_c



(a) Wires OFF.

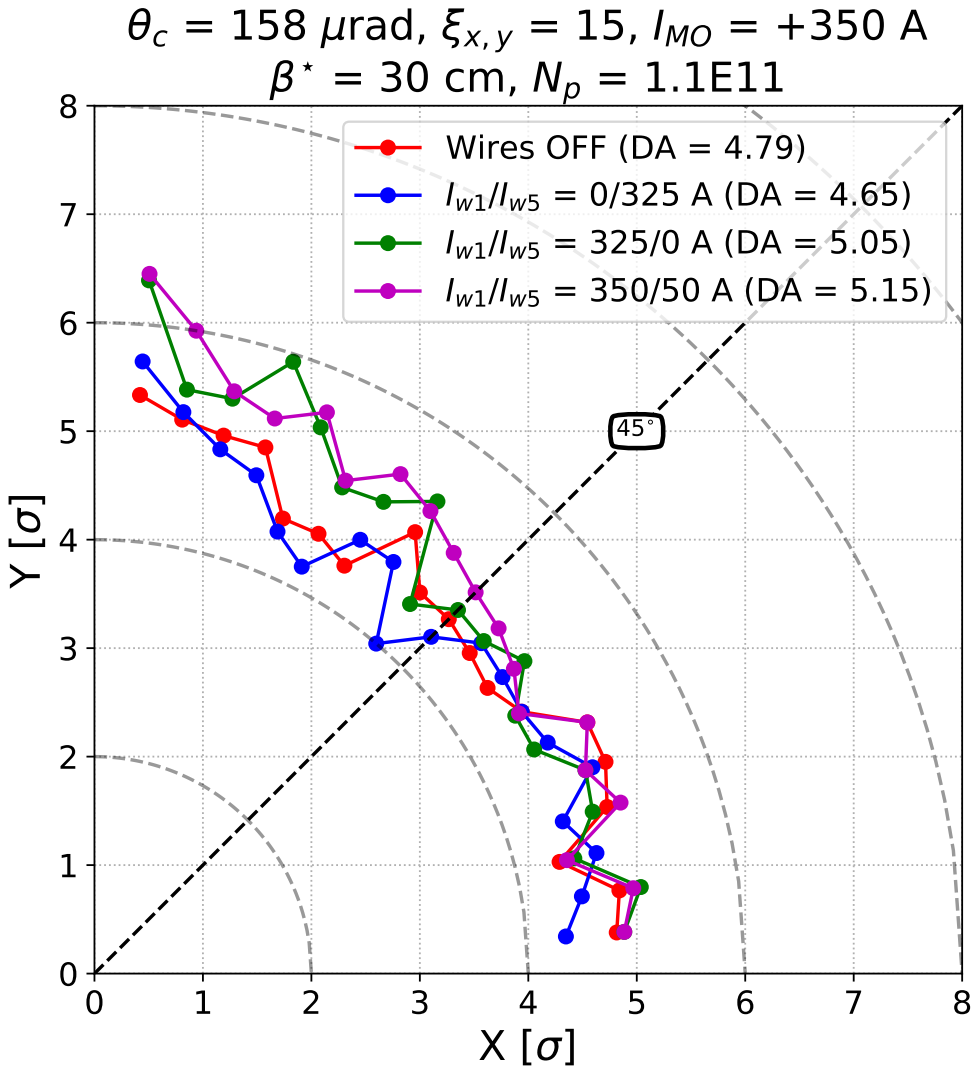


(b) Wires ON.

- Without wires, assuming $N_b = 1.1 \cdot 10^{11}$, 158 μrad is the limit.
- By powering the wires, a slight crossing angle reduction is possible.
- **No performance gain**.

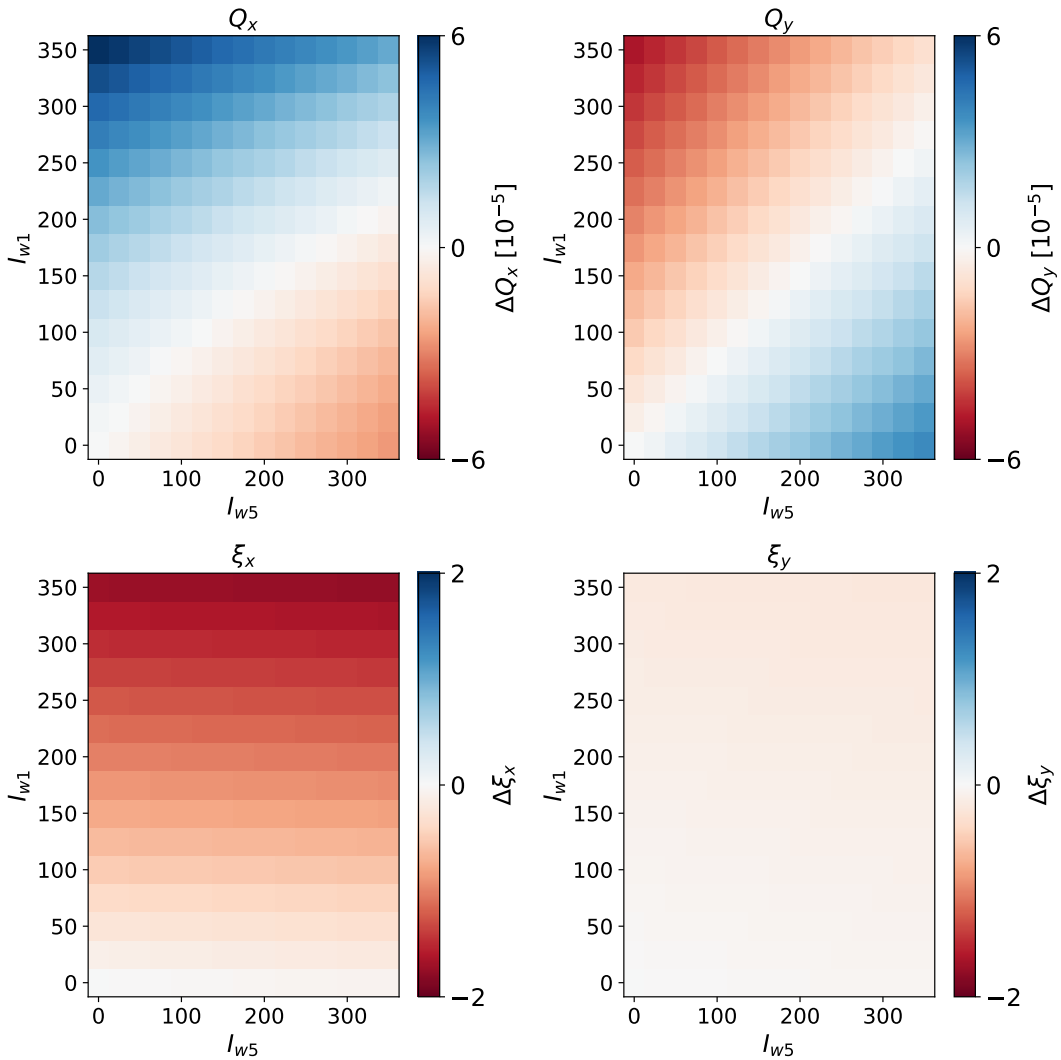
Run 3: DA in the Configuration Space

The DA improvement is mostly observed in the vertical plane.



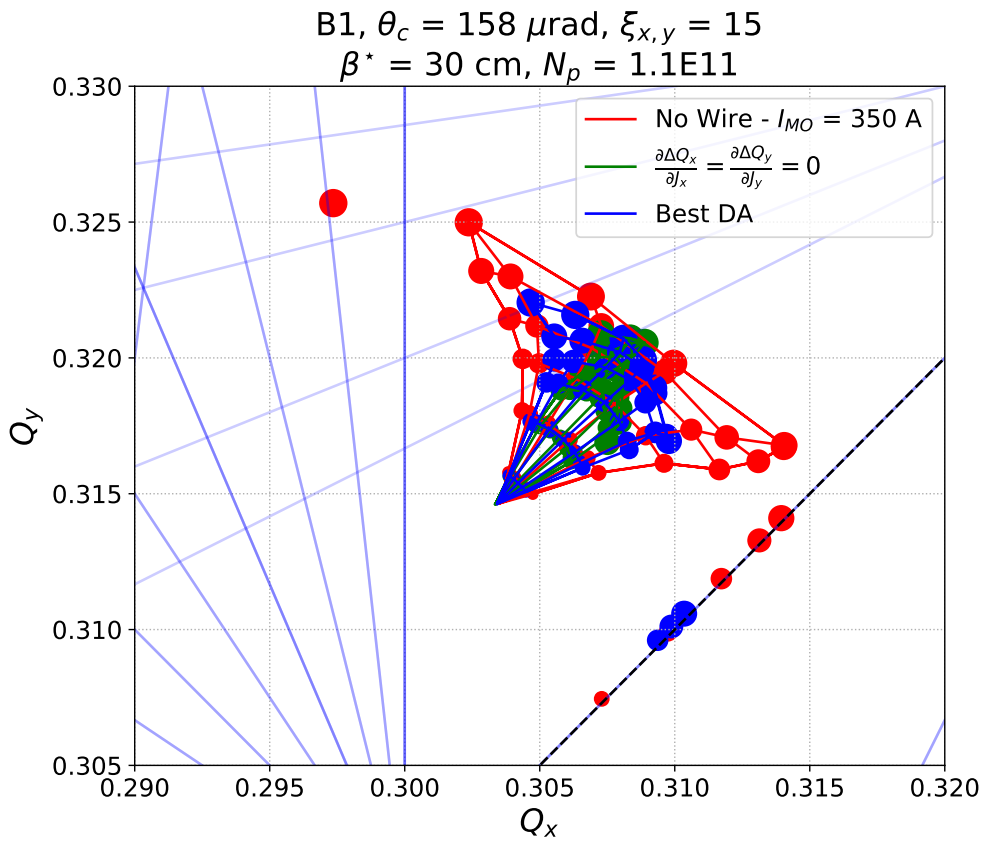
Run 3: Simulations Checks

While scanning the wire currents, it is important to check that the observed DA variations are due to the wires.



Nominal Scenario: Wires Vs. Octupoles

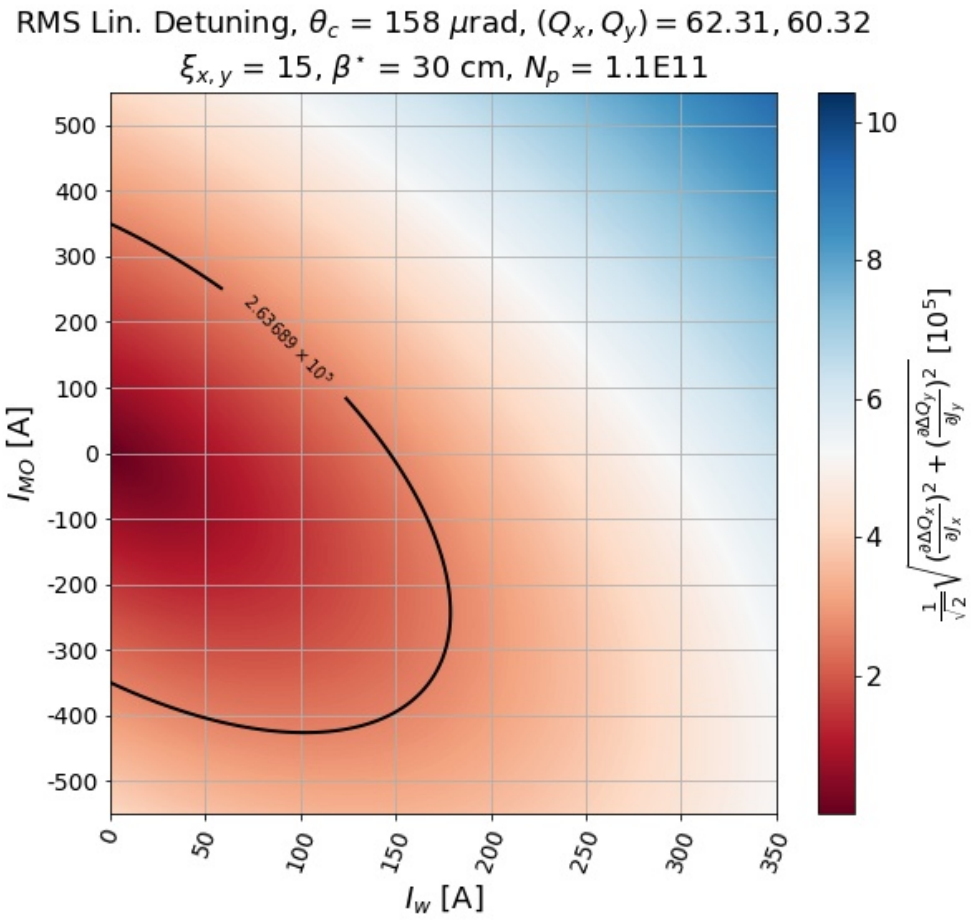
One can translate the DA into footprint compression, and see a **good correlation**.



The wires could be used in order to revert the polarity of the octupoles without loss of linear detuning with amplitude, and therefore, stability (see Backup).

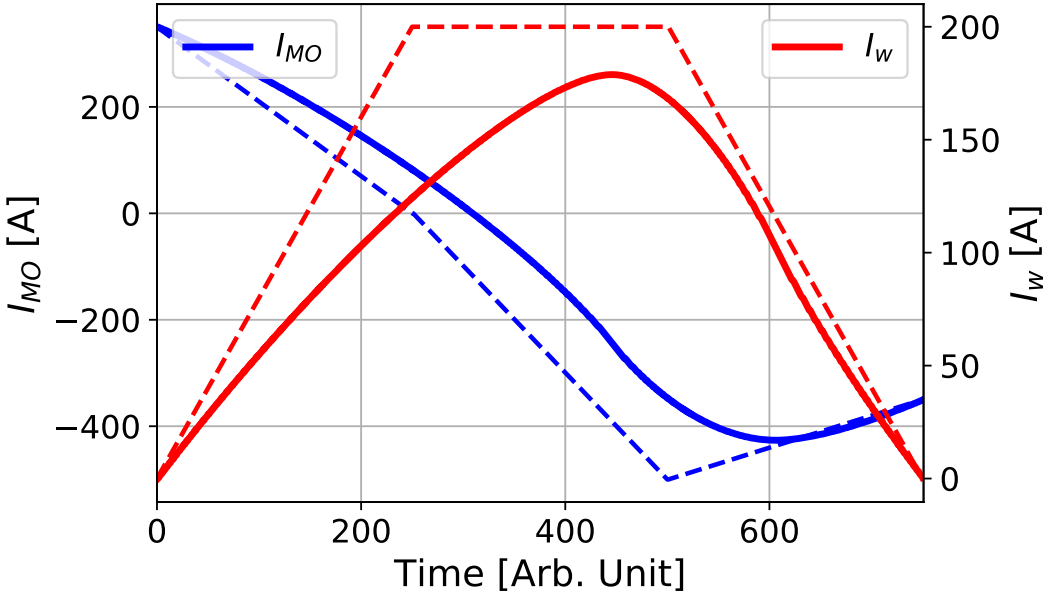
Run 3: Octupole Jump (1)

Reverting the octupoles polarity could lead to instabilities when $I_{MO} = 0$ A. The wires can be powered in order to maintain the detuning.



Run 3: Octupole Jump (2)

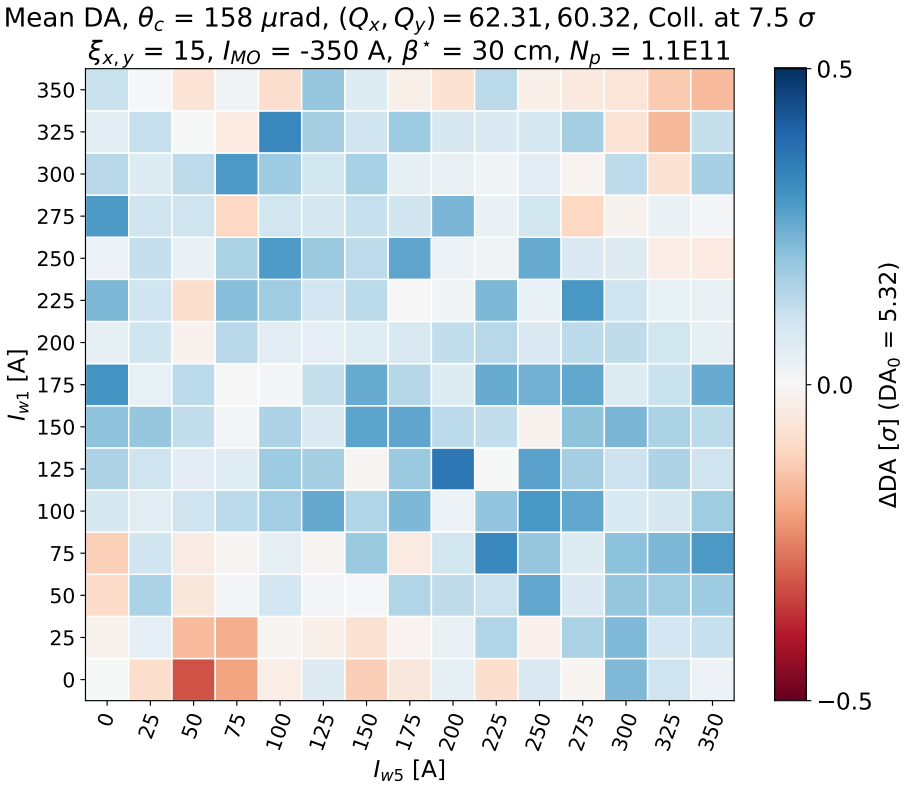
Proposal for a possible knob implementation, powering the wires as a function of the octupoles current.



- 3 steps ramp up and down.
- RMS-like detuning stays above the nominal one (no wires, octupoles powered at +350 A).
- No loss of beam stability.

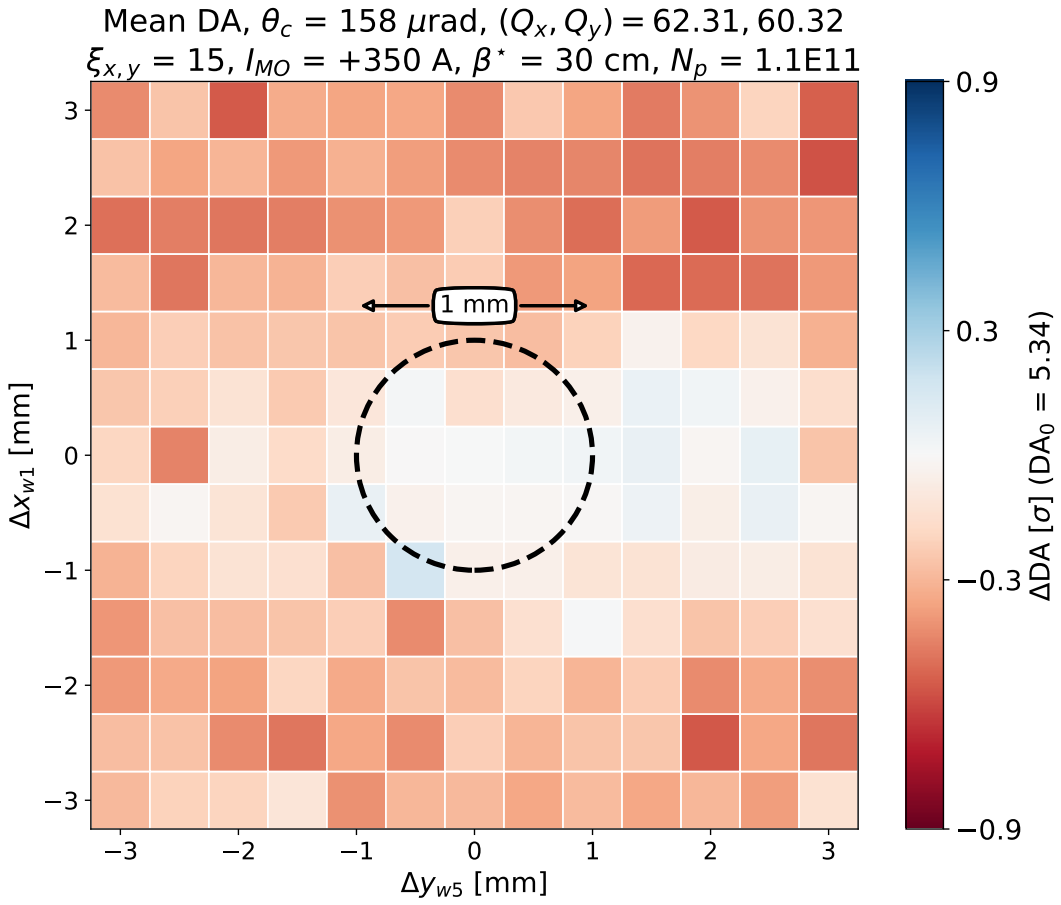
DA Vs. Wire Currents

We can study the effect of the wires on the DA, in this *optimal* configuration.



- **Relative gain** of about 0.4 σ.
- **Absolute gain** of about 1 σ (compared to the nominal scenario without wires)

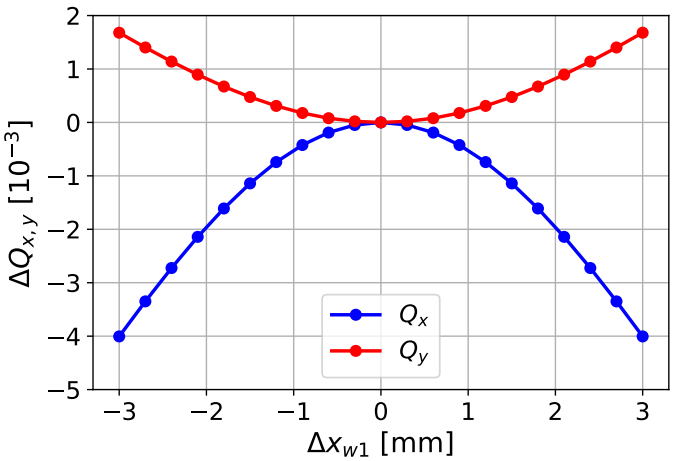
Hardware Limitations: 5th-axis Misalignment



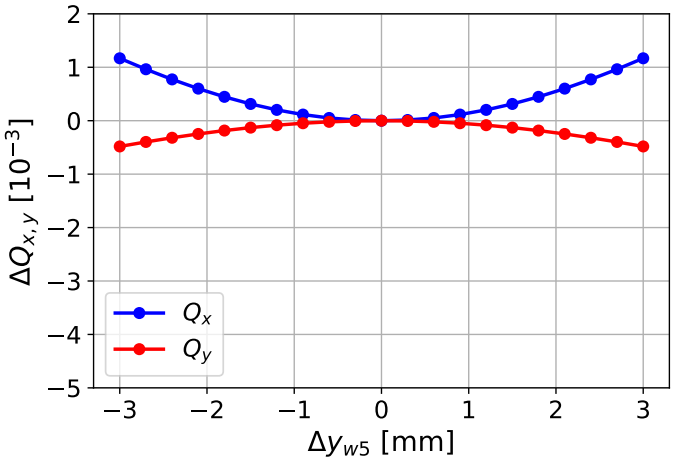
- For a misalignement lower than 1 mm, no critical effect. For larger misalignement, DA can drop by 1 σ.
- Underlines the importance of having the possibility to move the housing device: **avoid bulky collimator jaws**.

Hardware Limitations: Aligning Without BPMs

The alignment of the wires is eased by the use of the BPMs. Can we do it without them?



(a) IR1.



(b) IR5.

- Move the 5th-axis and monitor the induced tune shifts (no FF).
- Tune shifts up to $\sim 5{\cdot}10^{-3}$ for large misalignments.
- Typical limit of tune measurements in the LHC: 10^{-4}.
- For precise alignment: need for **local beam diagnosis**.