Simulations for wire BBLR compensation in HL-LHC

Stephane Fartoukh, Nikos Karastathis,
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CERN, Geneva

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Contents

- Quantification and solution of the problem generated from the BBLR interactions.
- BBLR compensation with wire in HL-LHC v1.3.
- Effect of wires in the external side.
- Conclusions

Relevant talks

- “Experimental tests for BBLR compensation with wires in the LHC”

by Guido Sterbini

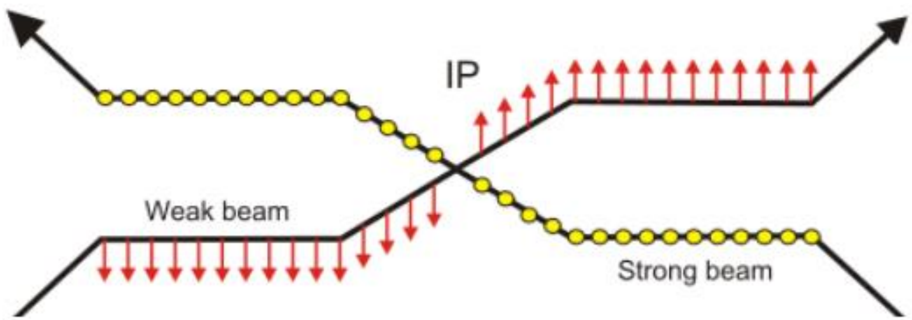
- “Flat optics in the LHC: results of MDs and outlook for HL-LHC”

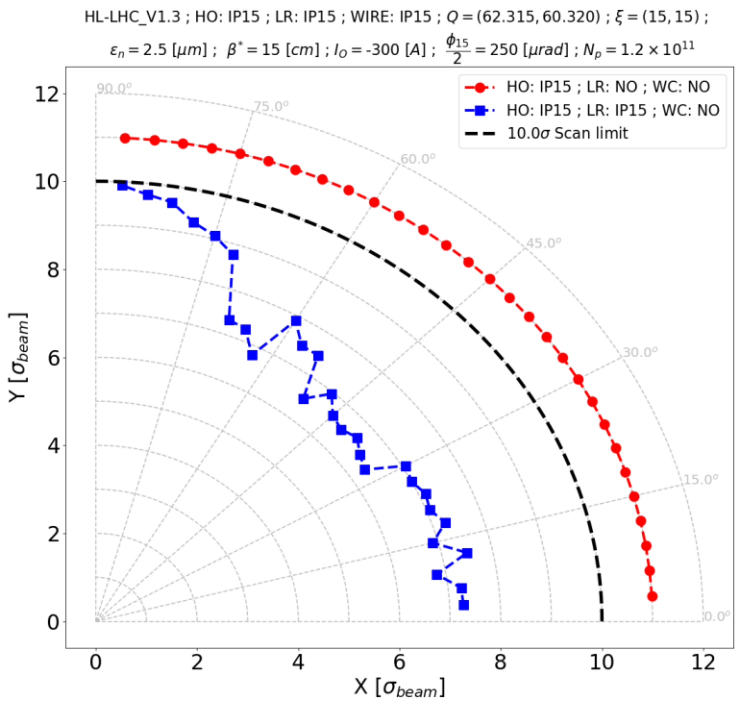
by Stephane Fartoukh

- “Beam-beam simulation in the HL-LHC”

by Nikos Karastathis

Quantification of the BBLR problem





Large DA (lifetime) degradation, at least 3σ, in the presence of the beam-beam long range interaction.

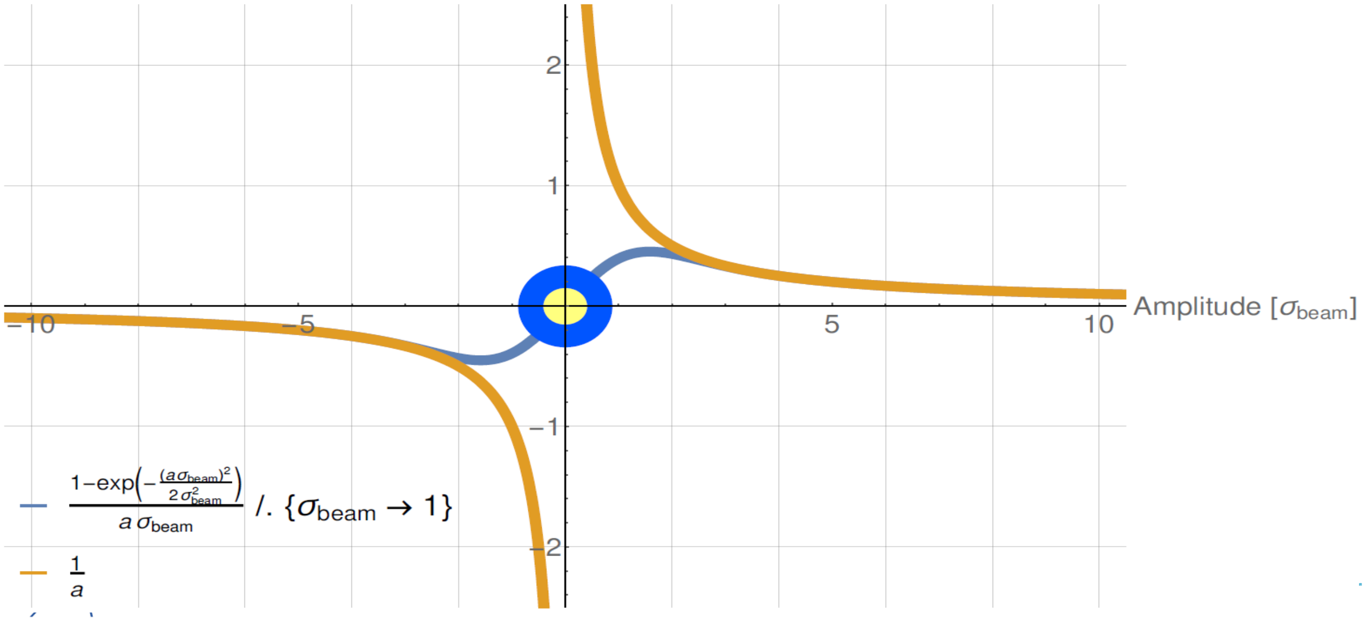
Treatment of the perturbation generated by the BBLR interactions (I)

The integrated electromagnetic field (4D) that is generated by the BBLR encounters (assuming a round beam σx=σy) is given by:

$$\int_{-\infty}^{\infty} B_\theta \; ds = \frac{N_p \; q \; c \; \mu_0 \; \beta_{st}}{2\pi} \; \frac{1 - Exp\left(-\frac{r^2}{2\sigma^2}\right)}{r}$$

This field is similar to the integrated magnetic field from an "infinite" current carrying wire.

$$\int_{-\infty}^{\infty} B_\theta \; ds = \frac{N_p \; q \; c \; \mu_0}{2\pi} \; \frac{1}{r}$$



Treatment of the perturbation generated by the BBLR interactions (II)

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

S. Fartoukh et al.

The wire is calibrated to **compensate the non-linear RDT** that are driven by the long-range beam-beam interactions.

Treatment of the perturbation generated by the BBLR interactions (II)

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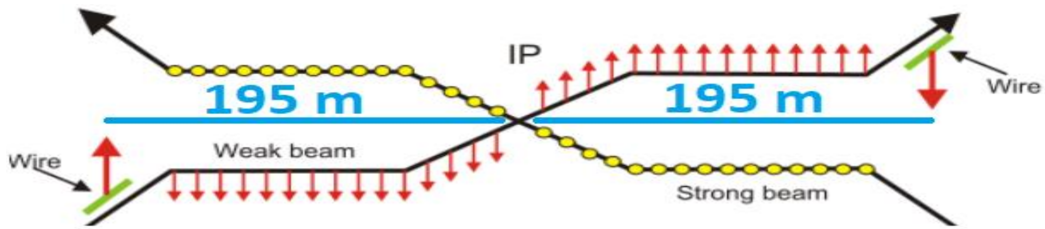

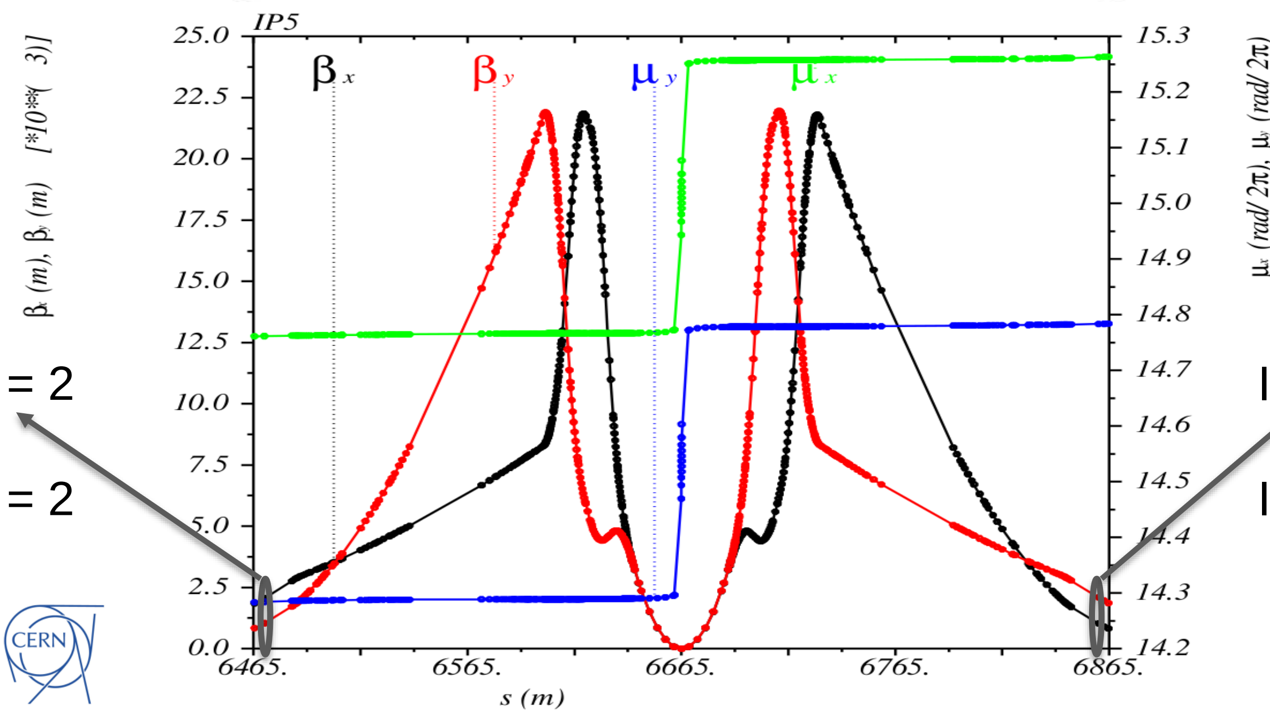

IP5L: $\beta_x/\beta_y = 2$

IP1L: $\beta_x/\beta_y = 2$

IP5R: $\beta_x/\beta_y=0.5$

IP1R: $\beta_x/\beta_y=0.5$

Configuration for the simulated machine

HL-LHC v1.3 configuration table		
Attributes	**Symbol**	**Value [units]**
Energy	E	7000 [GeV]
Bunch population (end of leveling)	N_p	1.2×10^{11} or 1.52×10^{11} [1]
Normalized emittance	ε_n	2.5 [μm rad]
Horizontal tune	Q_x	62.315 or 62.31 [1]
Vertical tune	Q_y	60.32 [1]
Horizontal chromaticity	ξ_x	15 [1]
Vertical chromaticity	ξ_y	15 [1]
Beta function at IP1 & IP5	β^*	15 [cm]
Half crossing angle at IP1 & IP5	$\Phi/2$	230 or 250 [μrad]
Octupole current	I_o	-300 – 0 [A]
Wires longitudinal position from the IP	S_w	+/- 195 [m]
Number of BBLR kicks per IP per side	NBBLR	25 [1]
Number of wires per IP per side	N_w	1 [1]

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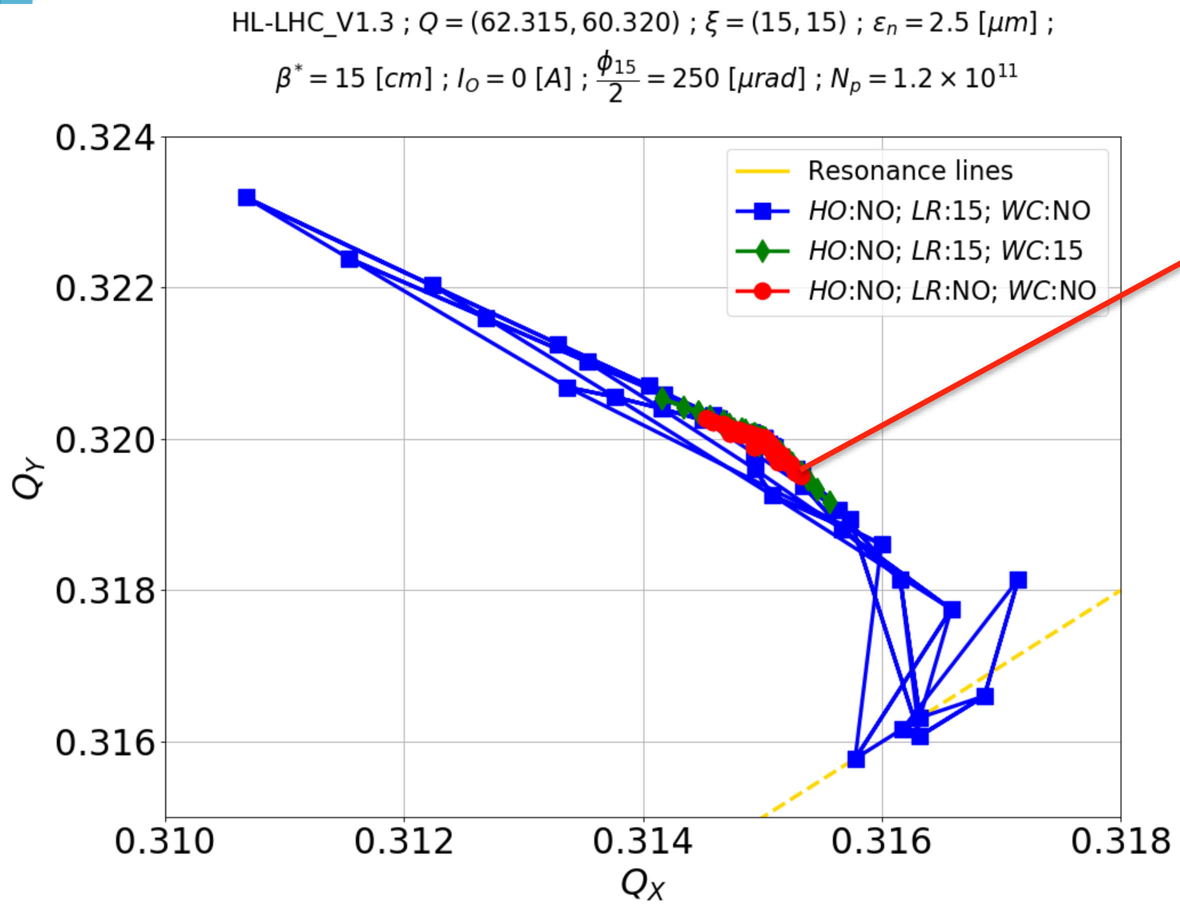
To find the best BBLR compensation for different lattice configurations, a set of DA scans for **different wire currents (I_w)** and **wire transverse positions (D)** are performed.

Tune spread compensation

Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.315 ; 60.32	**1.20E11**	**250 [μrad]**	**10.5 [σ]**	**~5x10^{34} [$cm^{-2}s^{-1}$]**



Small tune spread is generated from the lattice sextupoles.

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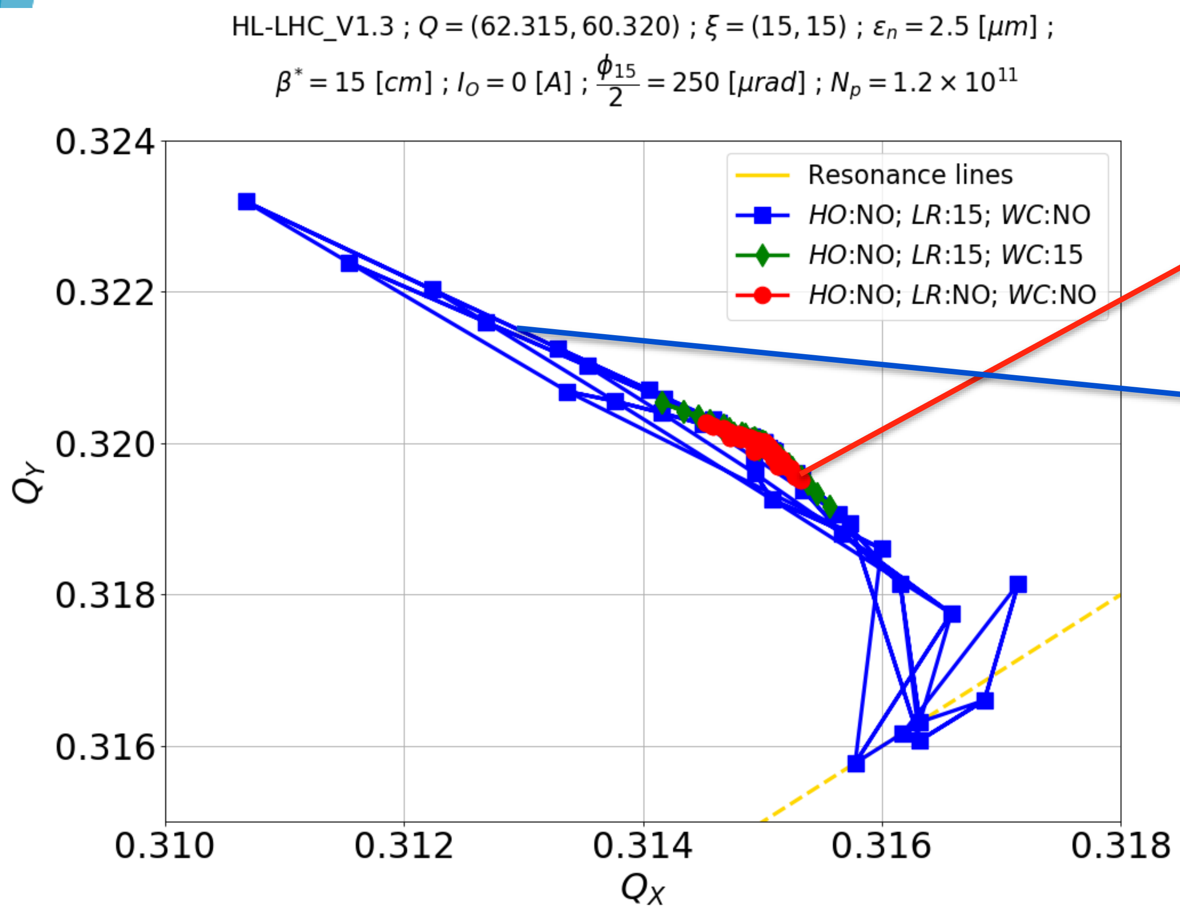

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Destructive tune spread (wings formation) is generated from the long range beam beam interactions.

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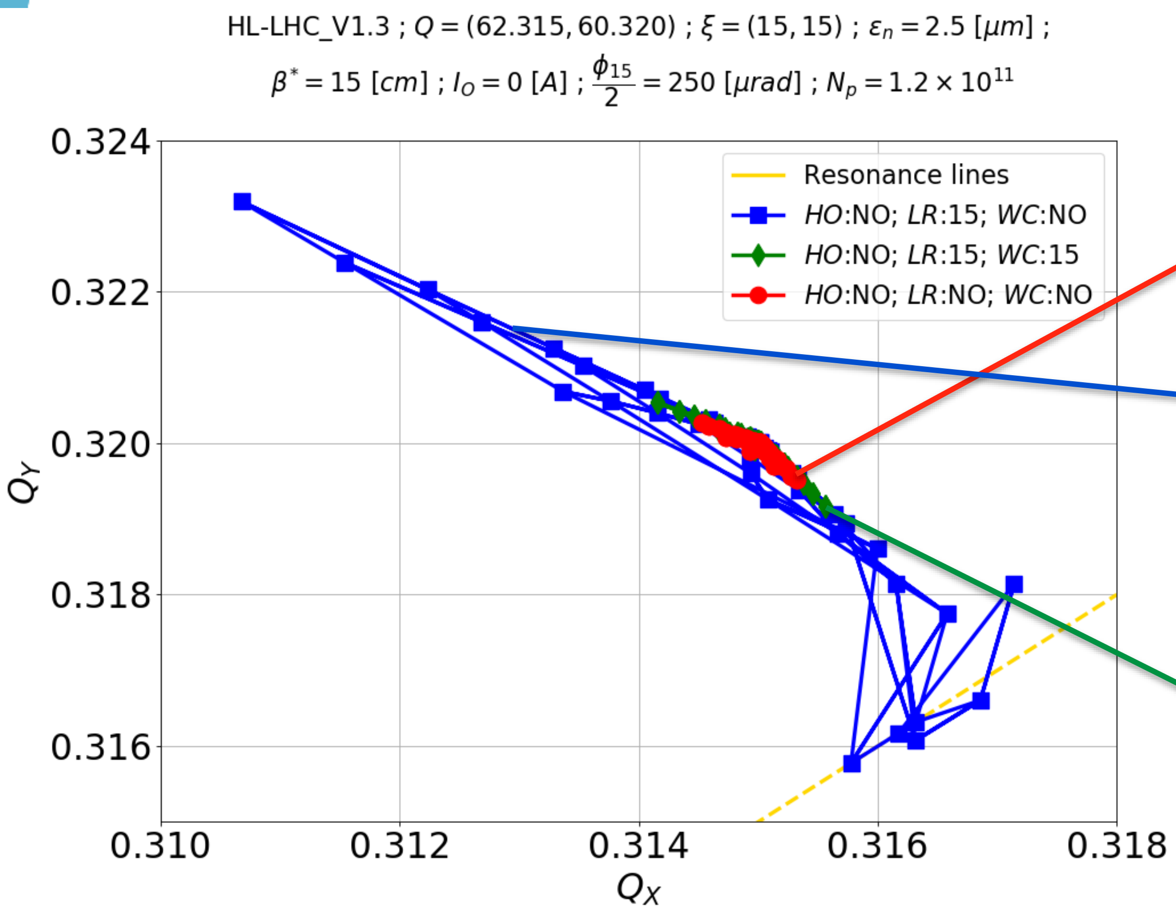


Small tune spread is generated from the lattice sextupoles.

Destructive tune spread (wings formation) is generated from the long range beam beam interactions.

Using the wires the tune spread from the BBLR can be compensated (wings compression).

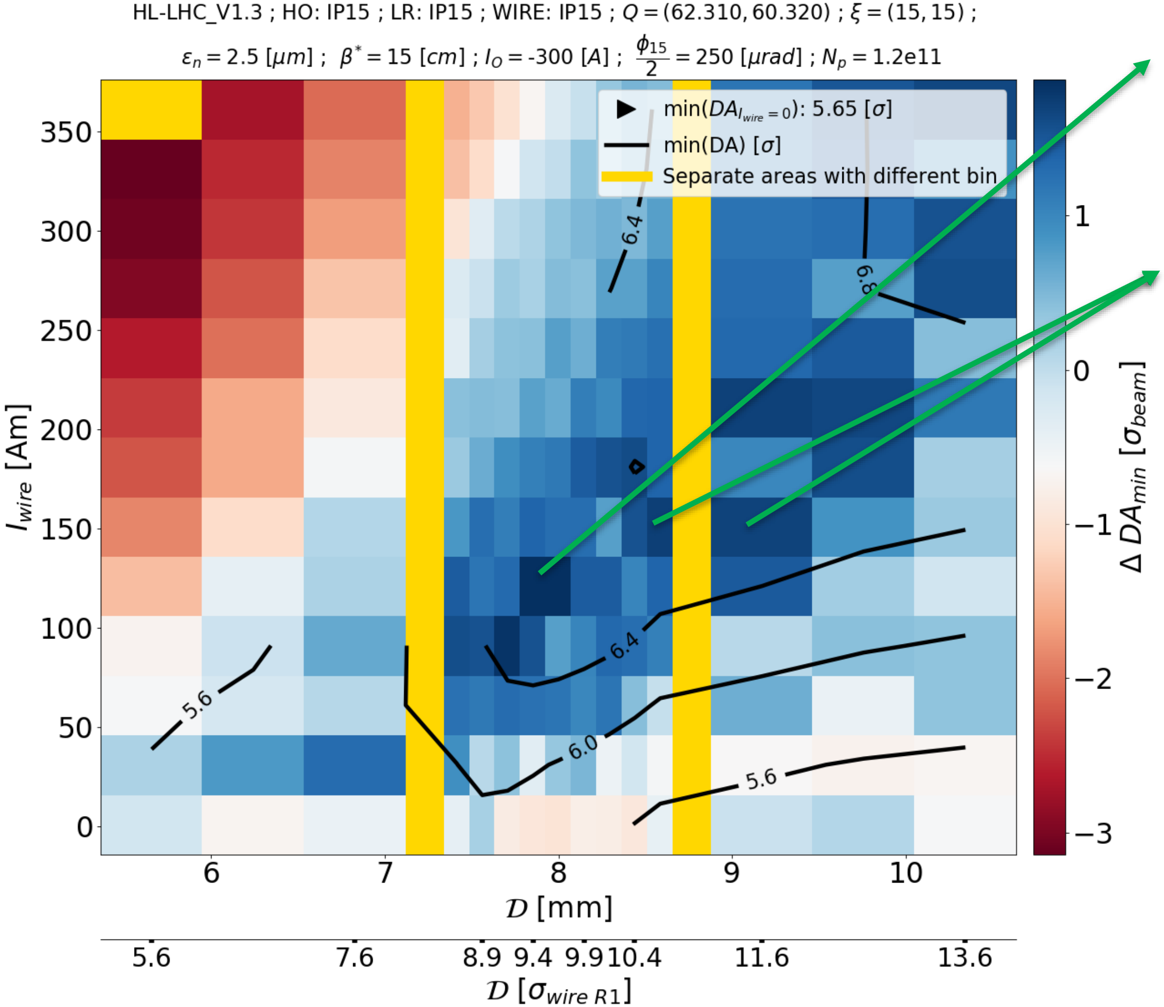
Nominal scenario

For the nominal scenario (round optics) with the optimized tune (62.315,60.32) the min DA is slightly above 6σ.

In order to demonstrate the advantages of using the wire, a non-optimized tune is used (62.31,60.32).

Nominal scenario

Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.31 ; 60.32	1.20×10^{11}	250 [μrad]	10.5 [σ]	$\sim 5 \times 10^{34}$ [$cm^{-2}s^{-1}$]

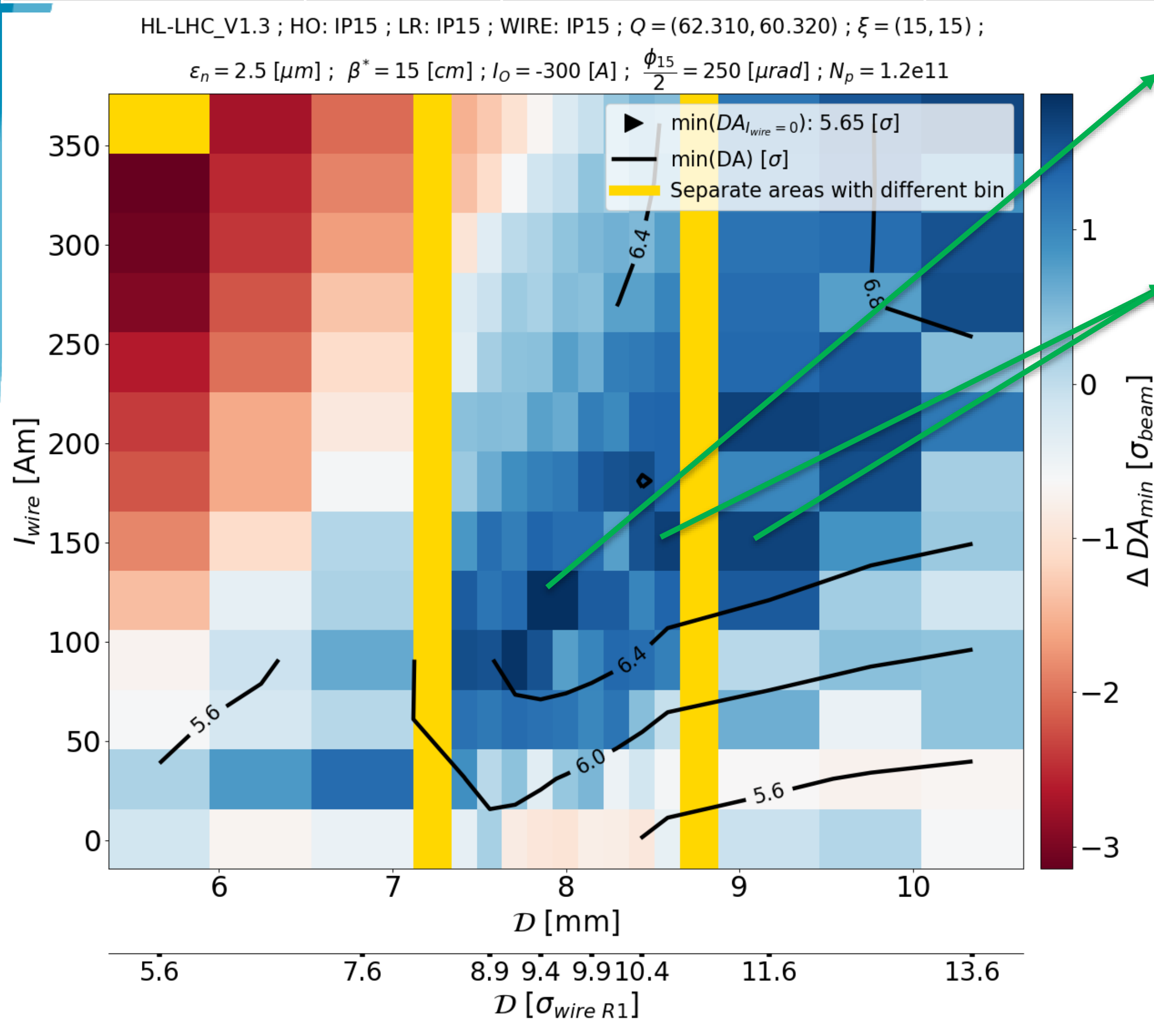


2 wire configurations (I_w & D) can guarantee **1.9σ higher min DA** (from below **6σ** to > **7.5σ**)

2 cases with fully acceptable wire current (I_w<200Am) at **large wire transverse distance** (D>10σ) that **improve the min DA by 1.8σ**.

Nominal scenario

Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.31 ; 60.32	1.2×10^{11}	250 [μrad]	10.5 [σ]	4.8×10^{34} [$cm^{-2}s^{-1}$]



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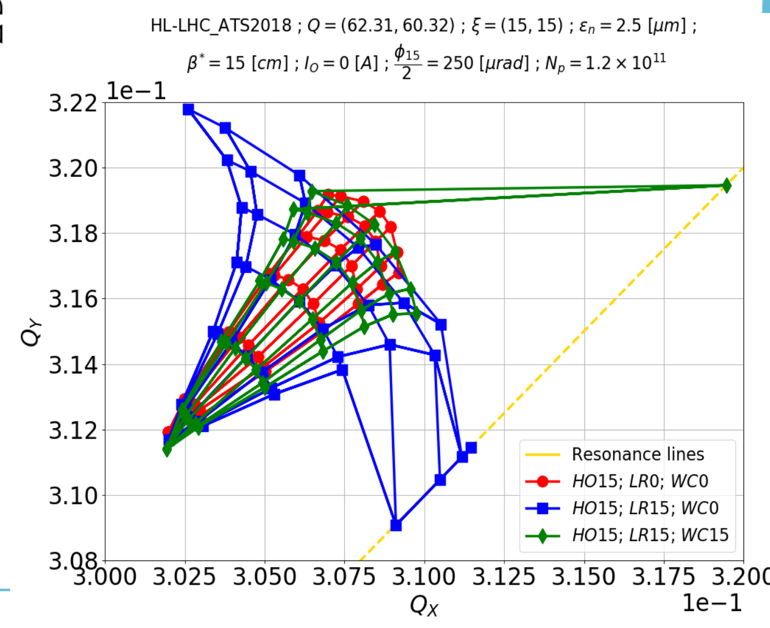
2 cases with fully acceptable wire current (Iw<200Am) at **large wire transverse distance** (D>10σ) that **improve the min DA by 1.8σ**.



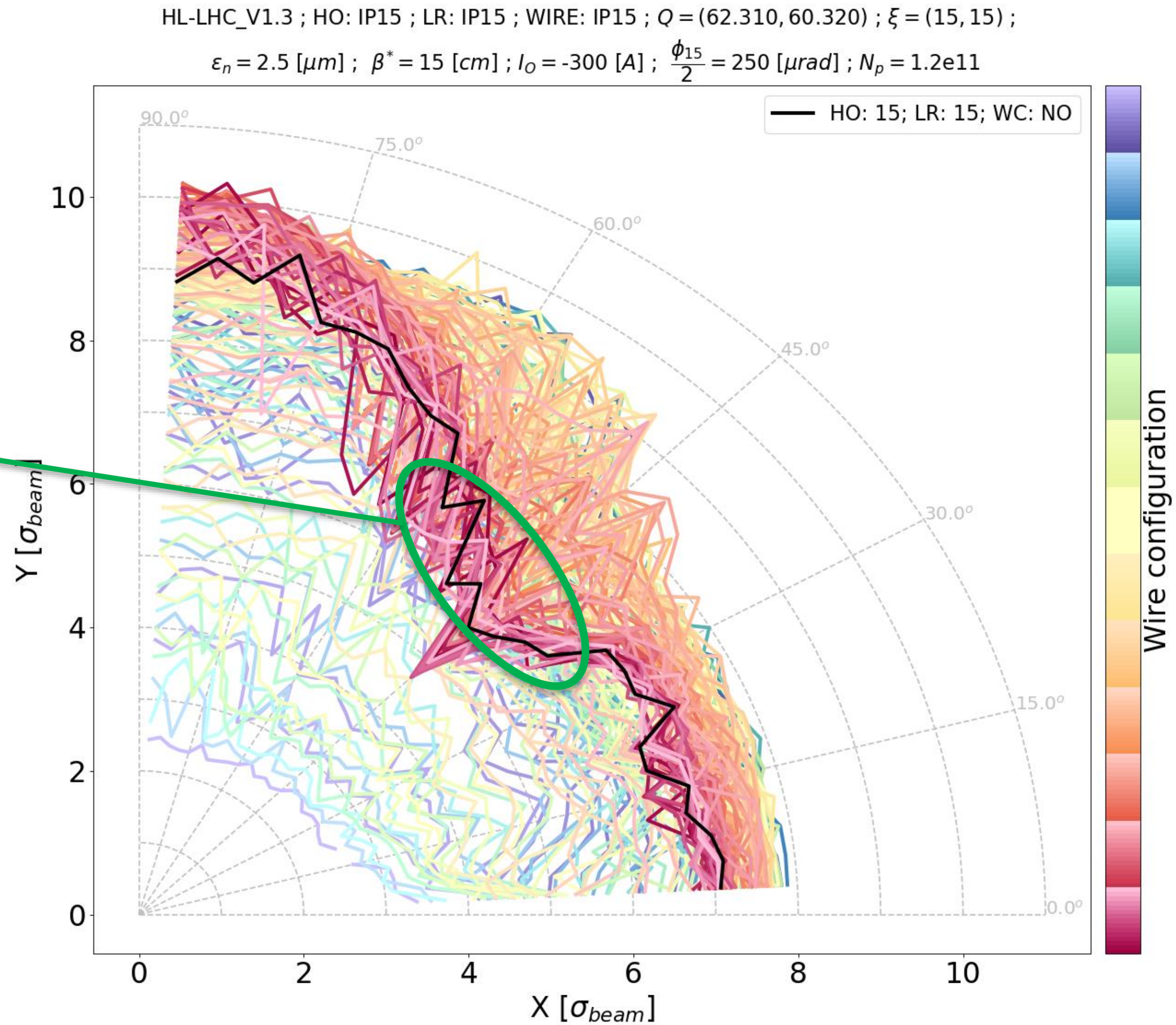
Nominal scenario

A single value that describe the min DA and corresponds to a single trajectory in the phase space is not enough to describe the effect of the wire on the different particles (different phase space trajectories). Thus, a more detailed DA analysis is performed.

The number of the scanned angles is increased to 29.

The area with the worst DAs (effective area) is further analysed.

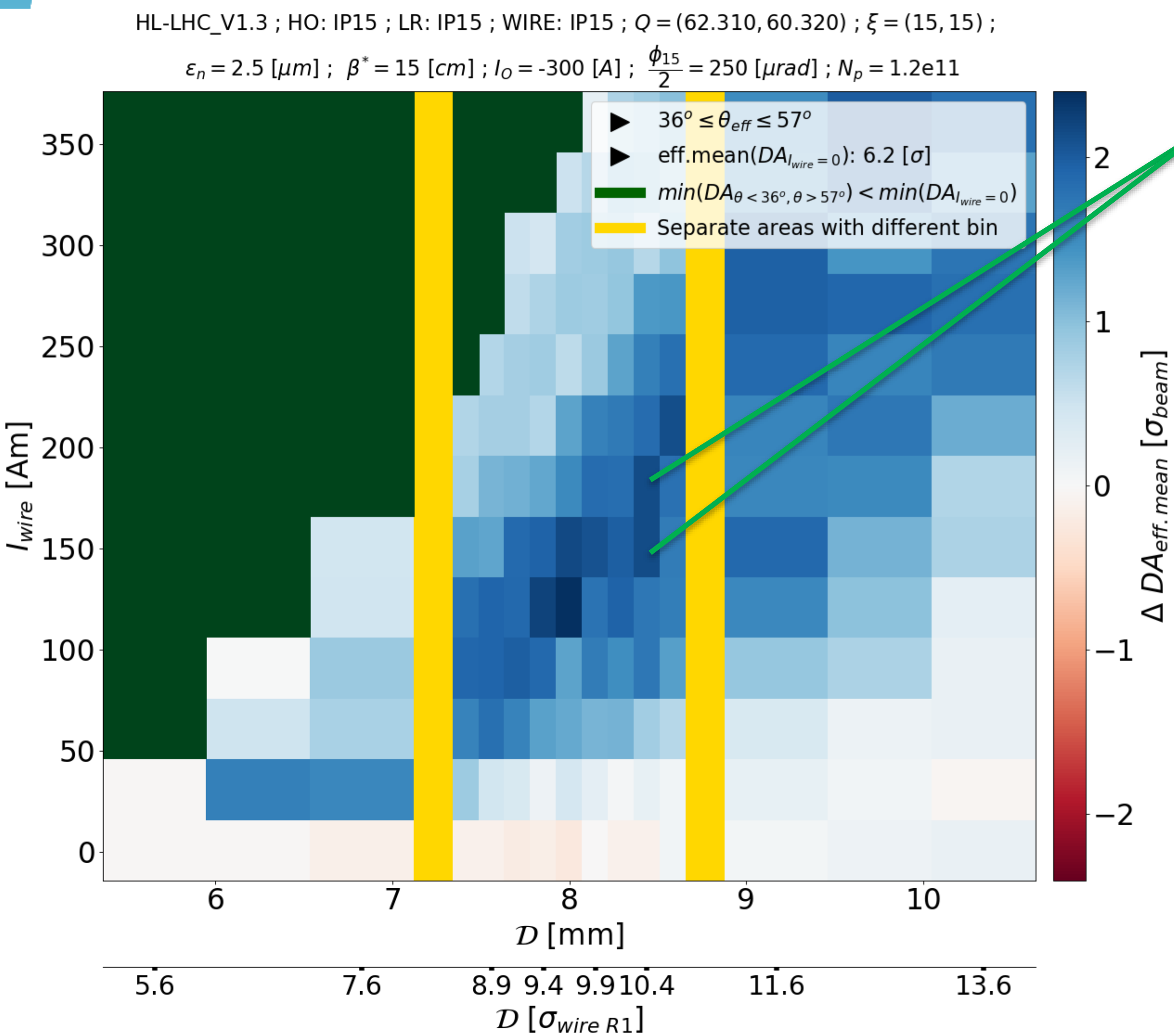
Using a step of 3º, the worst DA without wire (black line) is located between the angles 36º - 57º.



HiLumi HL-LHC PROJECT
CERN

Nominal scenario

Between 36º and 57º where the largest DA degradation occurred there are wire configurations that **improve the average DA** (effective mean DA) **by 2.4σ**.



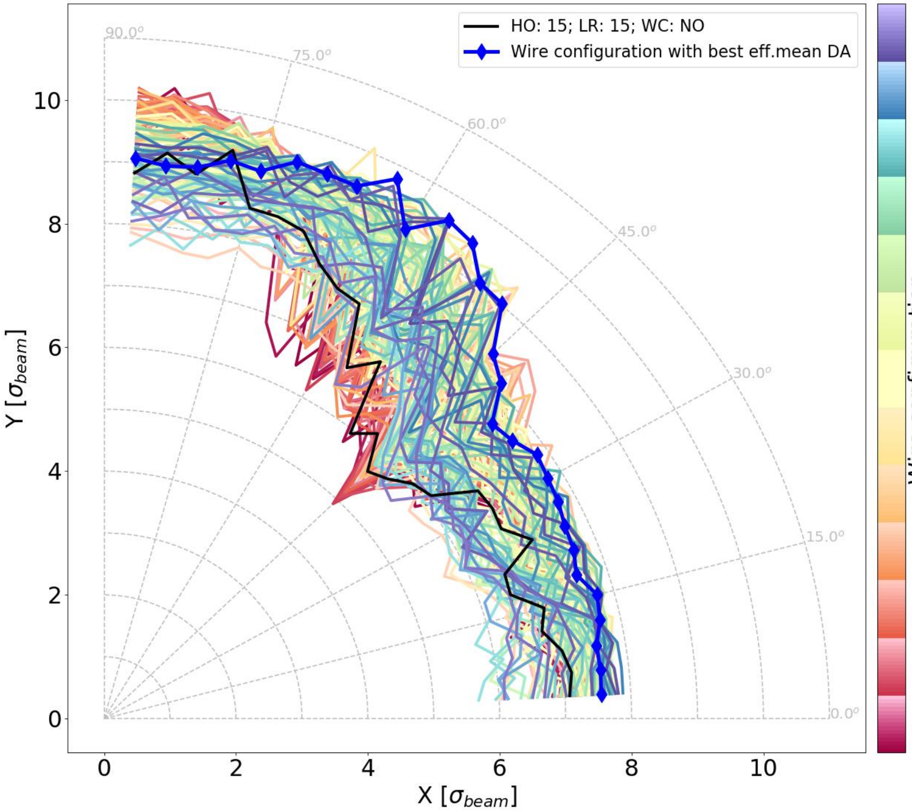
Fully acceptable wire current (Iw<200Am) at **large wire transverse distance** (D>10σ) that **increase the effective mean DA by 2.2σ.**

Nominal scenario

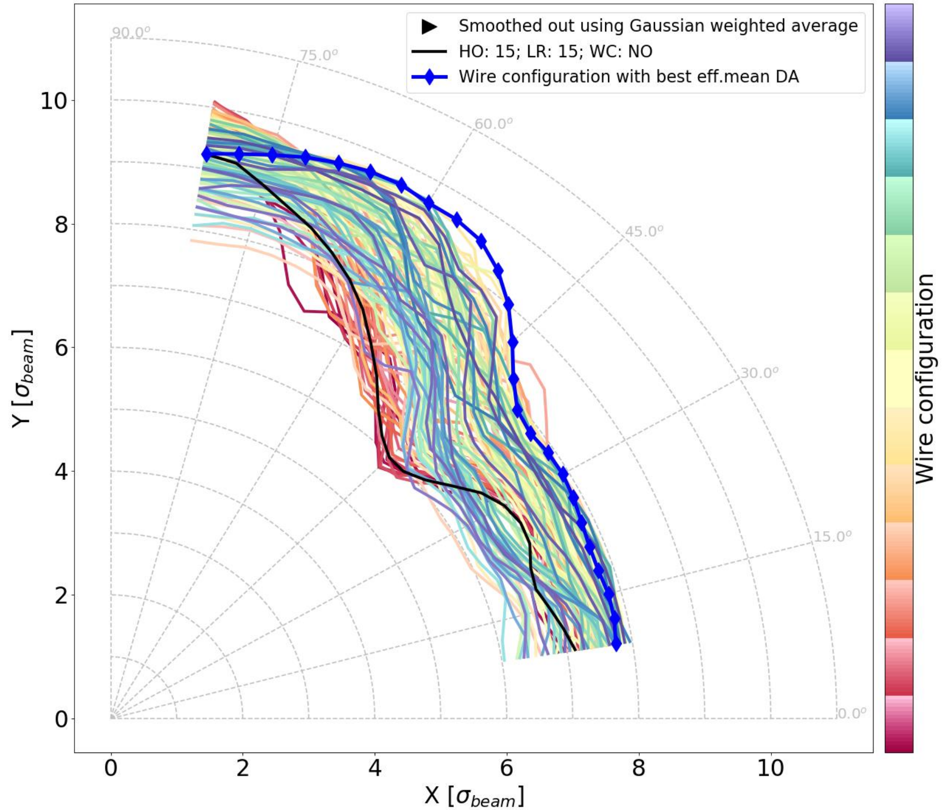
By plotting only the wire configurations with positive effective mean DA the beneficial effect of the wire (blue curve with rhombus) is clear.

A more detailed analysis of the strongest resonances vs angle is needed.

Without smoothing

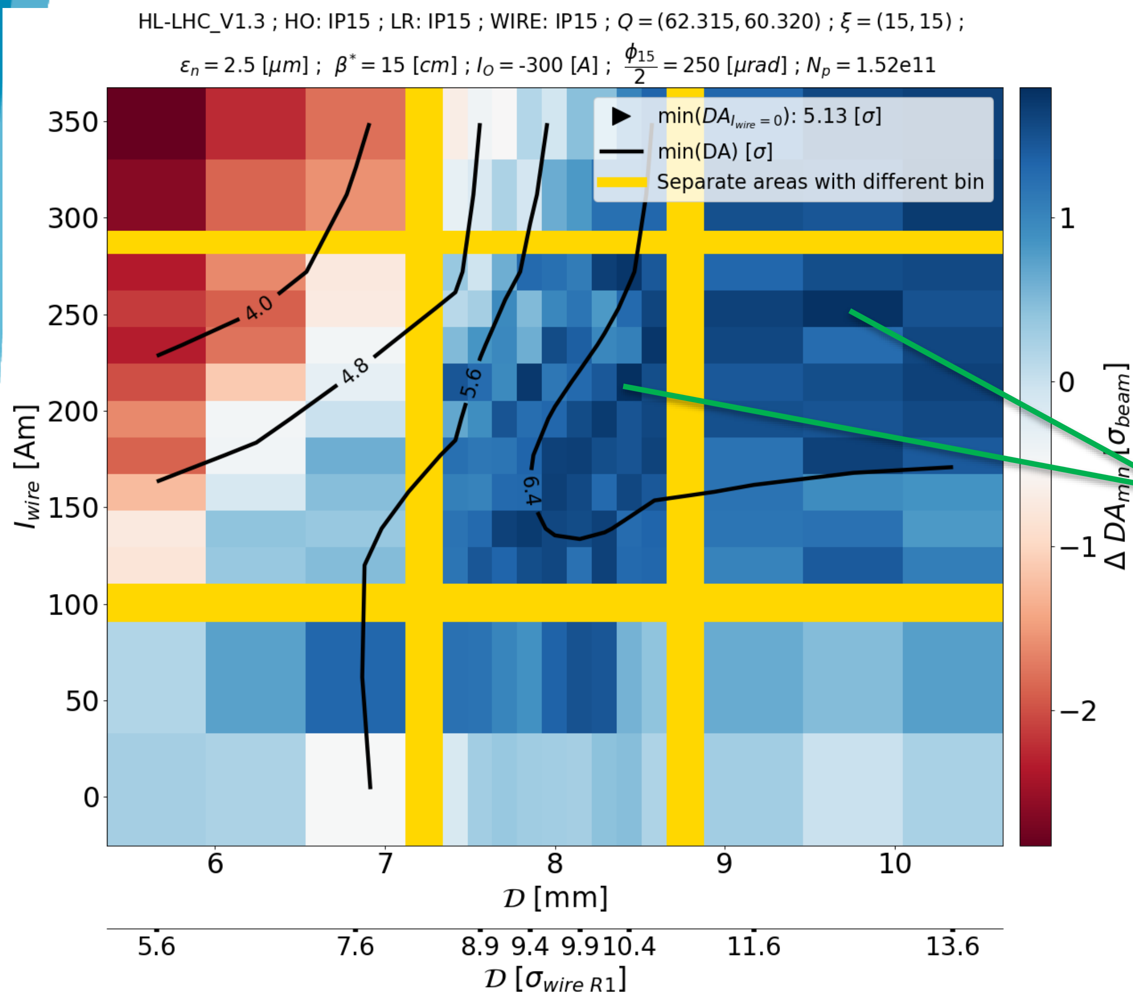


Smoothed using
Gaussian weighted average



Ultimate scenario

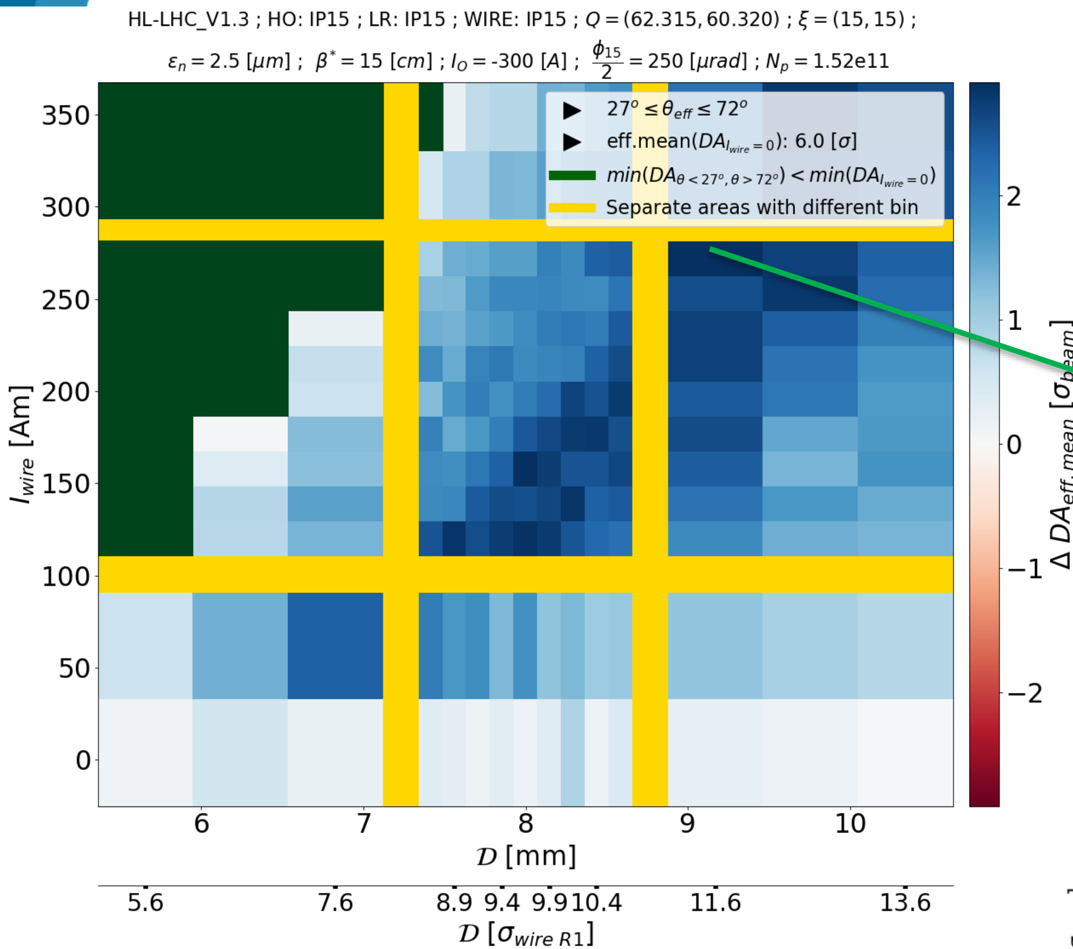
Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.315 ; 60.32	1.52×10^{11}	250 [μrad]	10.5 [σ]	7.7×10^{34} [$cm^{-2}s^{-1}$]



A large set of wire configurations with **D≥10σ guarantees more than 1.5σ improvement of the min DA**

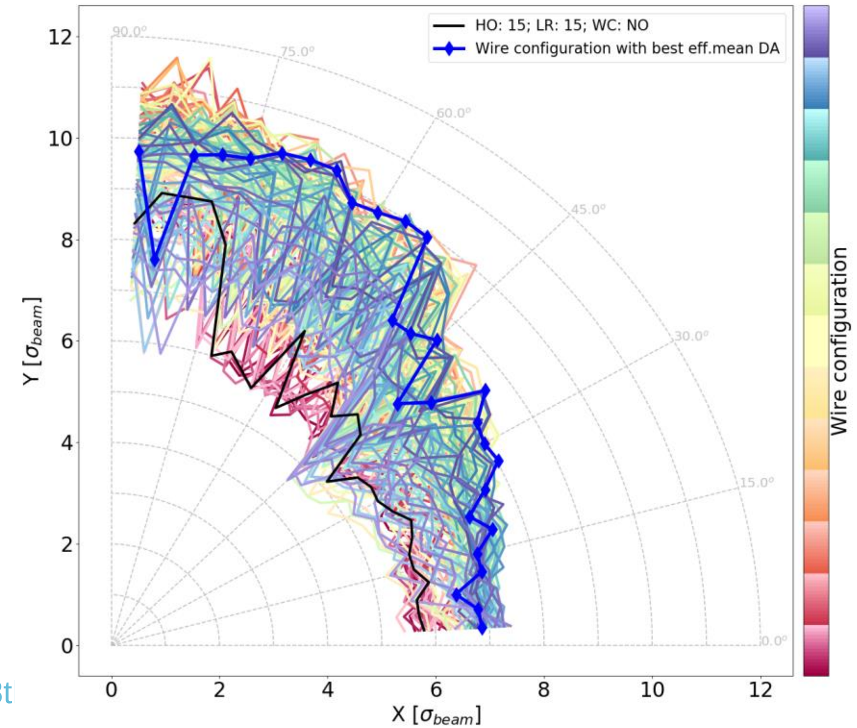
The **best improvement** from these configurations is **1.8σ** (from **5σ** to almost **7σ**)

Ultimate scenario



There is a large number of wire configurations with **D≥10σ that guarantees more than 2σ improvement of the effective mean DA**.

The **best improvement** from these configurations is **2.9σ.**



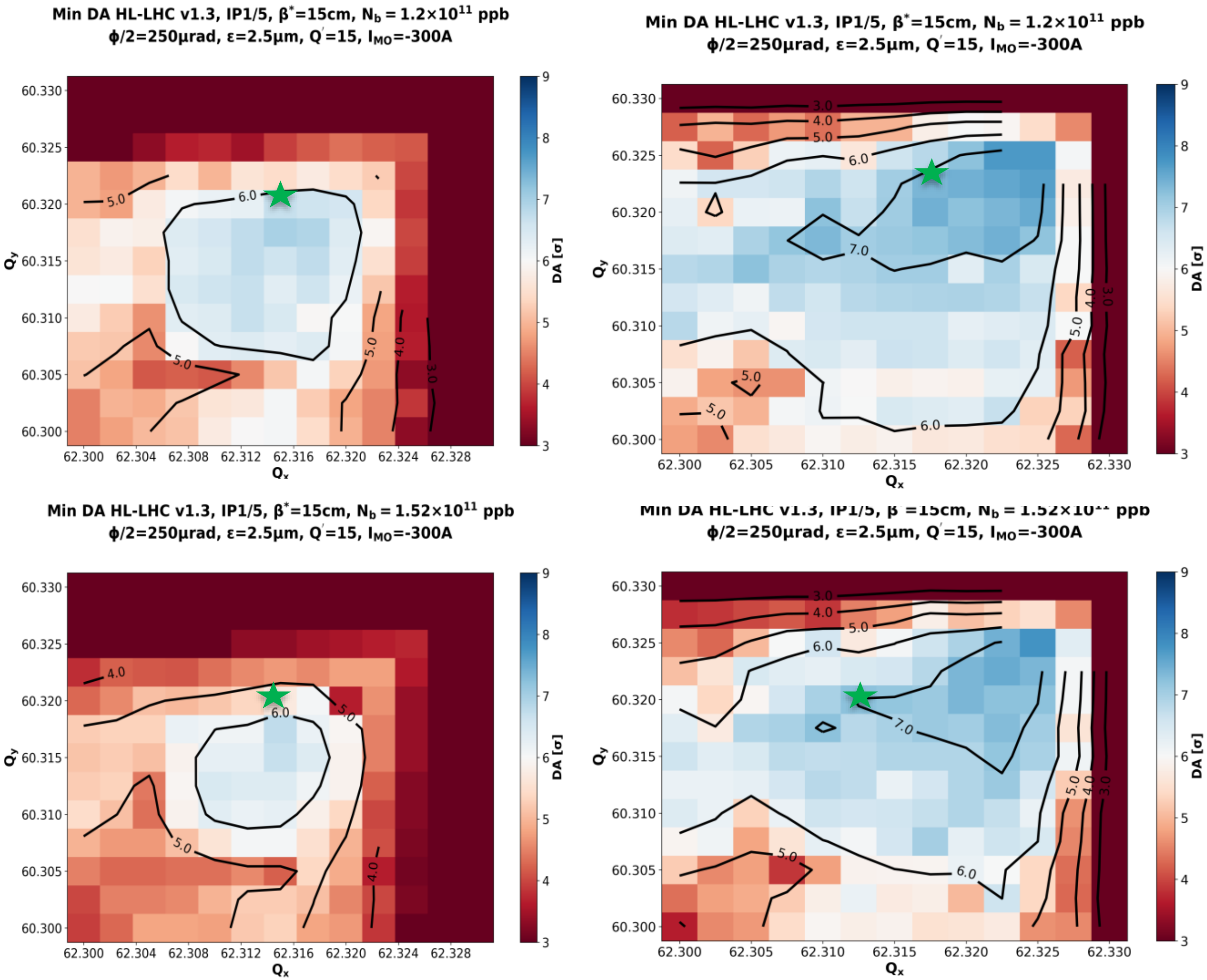
Tune scans for Nominal and Ultimate scenario

By N. Karastathis

No wire | **With wire**

Nominal

Ultimate



With the use of the wire compensators, **the area of the good working tunes is increased**.

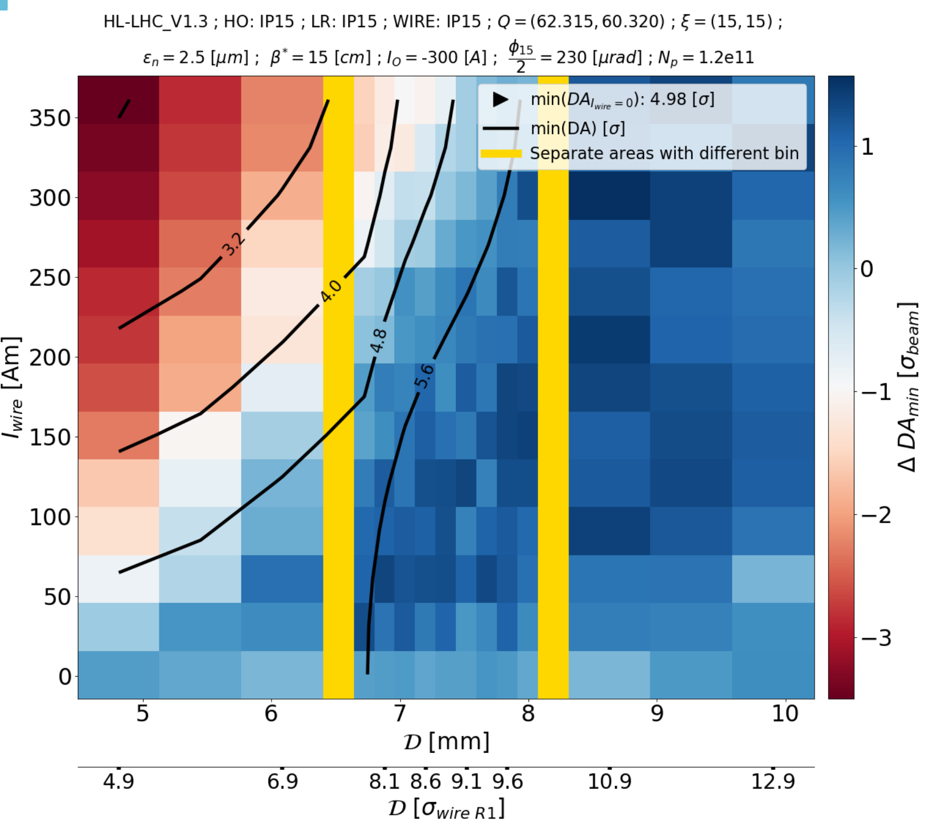
A new working tune (green stars) **can further improve the already positive performances of the wire** (even further away of the **diagonal**)

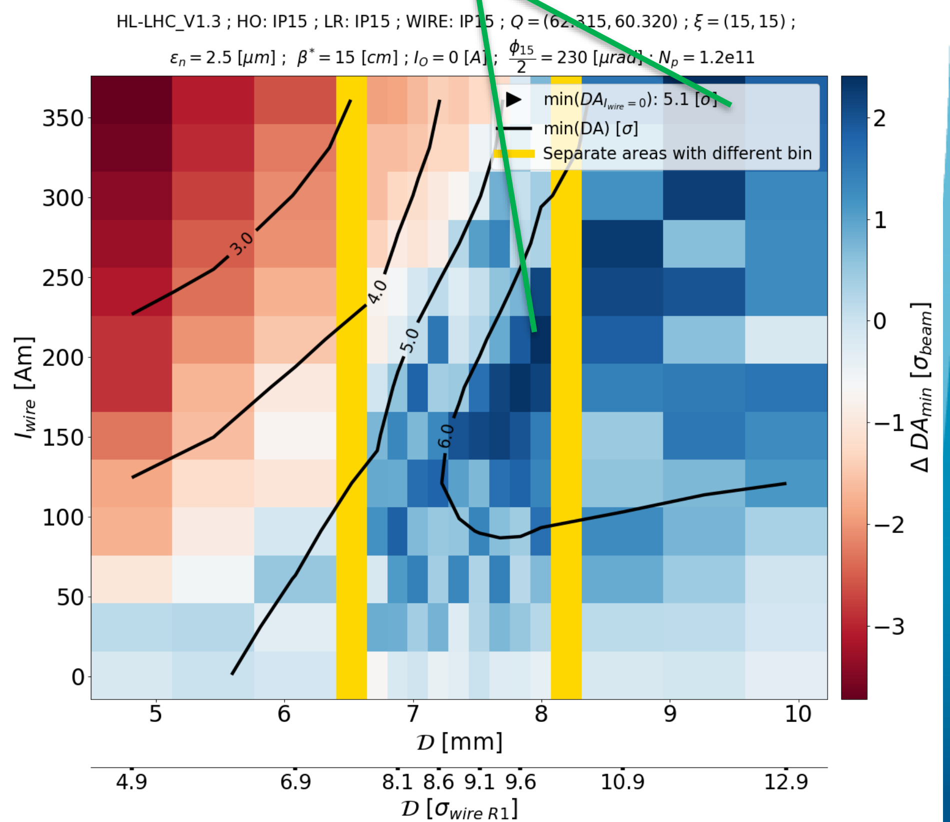
Pushed nominal scenario

Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.315 ; 60.32	1.2×10^{11}	230 [μrad]	9.7 [σ]	5.2×10^{34} [$cm^{-2}s^{-1}$]

Even with the octupoles at -300 [A] (over-compensation) there are **many wire configurations with D≥10σ that guarantee min DA greater than 6σ** (good lifetime).

There are many wire configurations with **D≥10σ that guarantee more than 2σ improvement of the min DA**.
The **best improvement** from these configurations is **2.4σ** (from **5** to **7.5σ**)

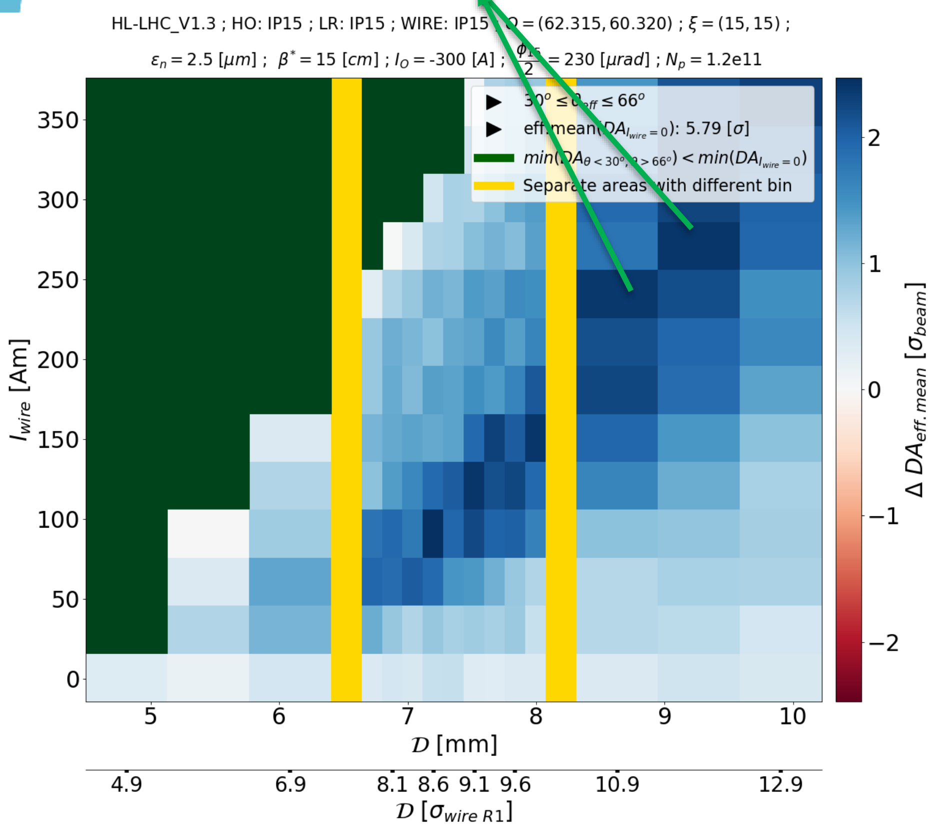




Pushed nominal scenario

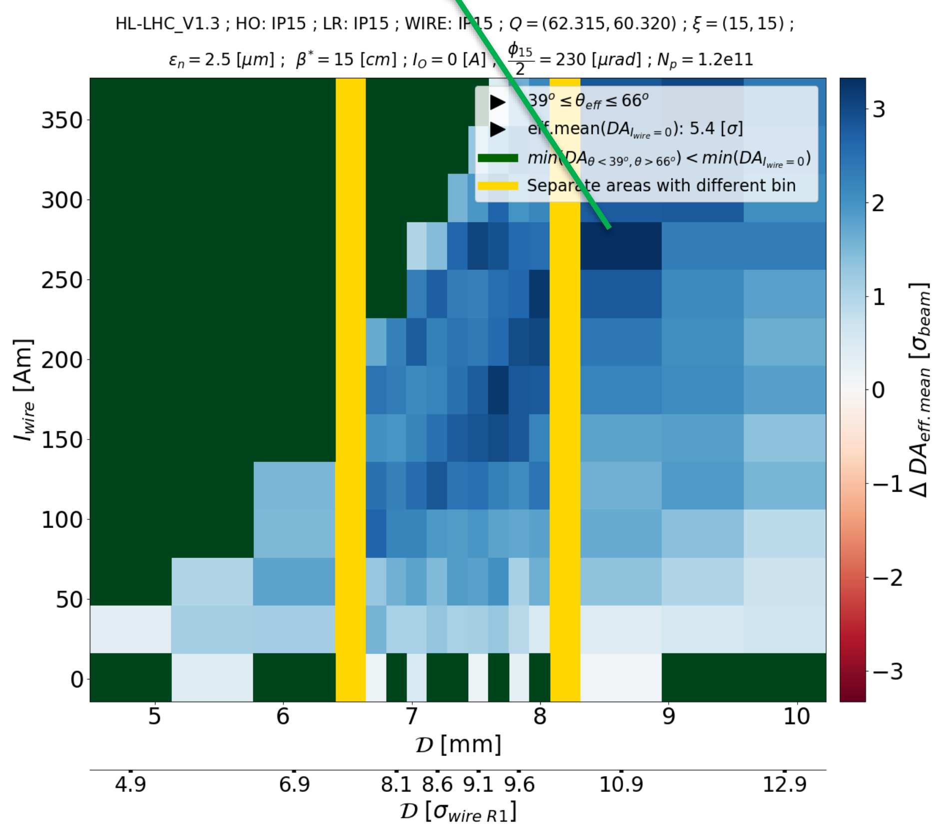
Many wire configurations with **D≥10σ guarantee more than 2σ improvement of the effective mean DA**.

The **best improvement** from these configurations is **2.4σ.**



Many wire configurations with **D≥10σ guarantee more than 2σ improvement of the effective mean DA**.

The **best improvement** from these configurations is **3.3σ.**

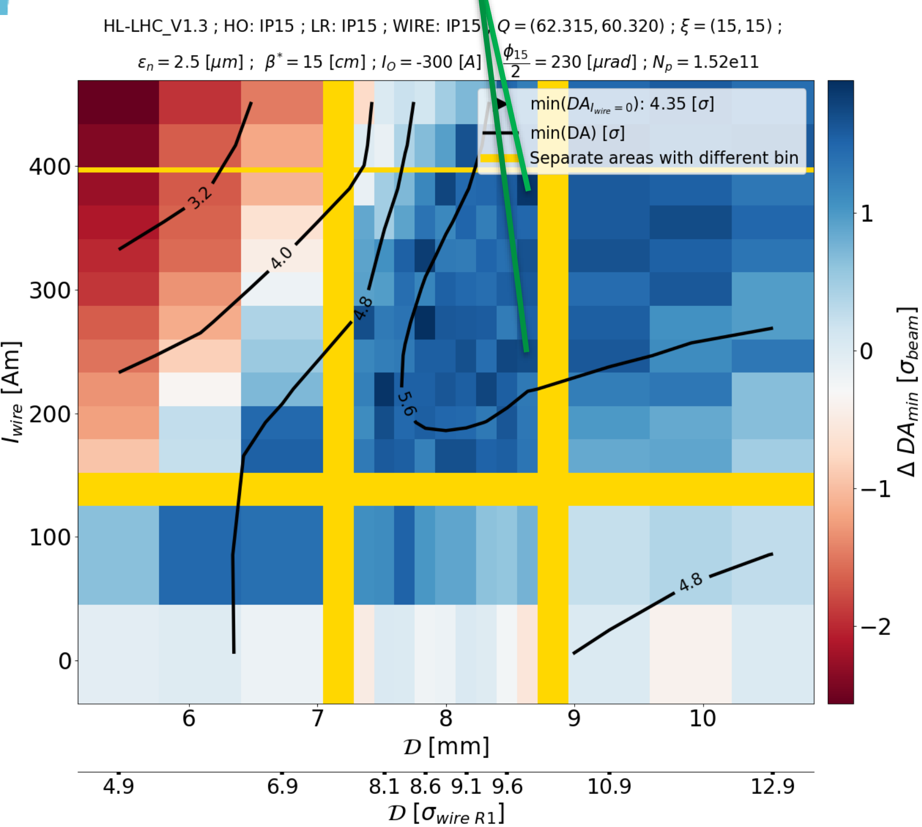


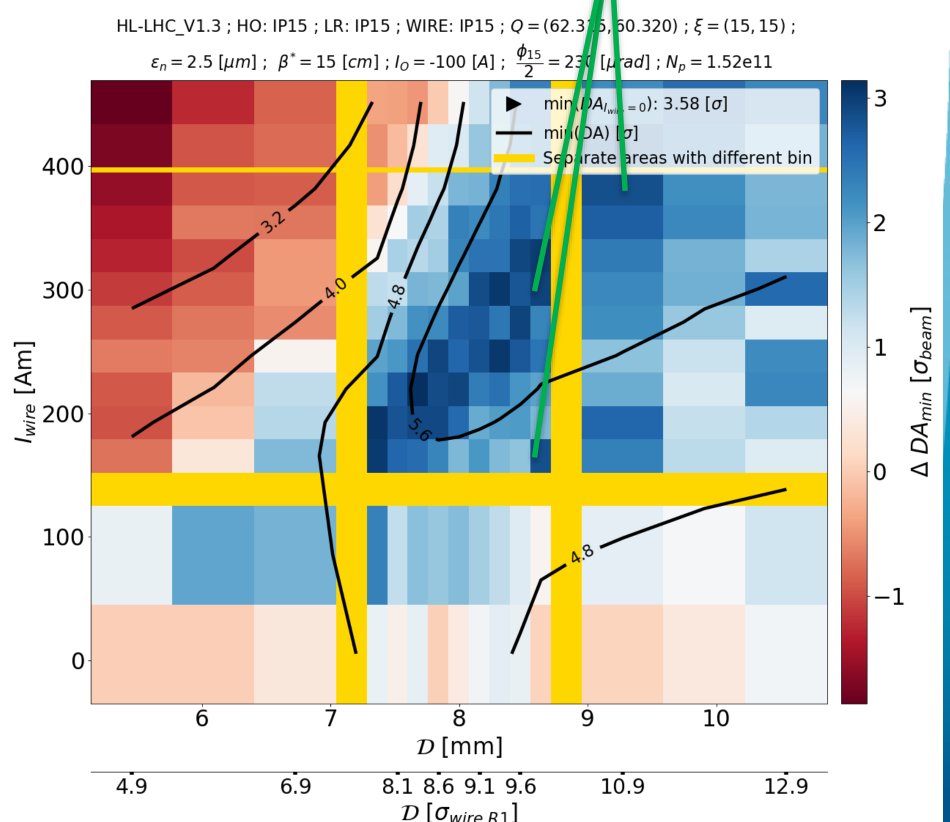
Pushed ultimate scenario

Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.315 ; 60.32	1.52×10^{11}	230 [μrad]	9.7 [σ]	8.4×10^{34} [$cm^{-2}s^{-1}$]

Even with the octupoles at -300 [A] (over-compensation) there are **2 wire configurations with D=10σ that guarantee min DA at 6σ** (good lifetime).

With octupoles at -100 [A] (the over-compensation is reduced) there are **wire configurations with D≥10σ that guarantee min DA at 6.6σ.**

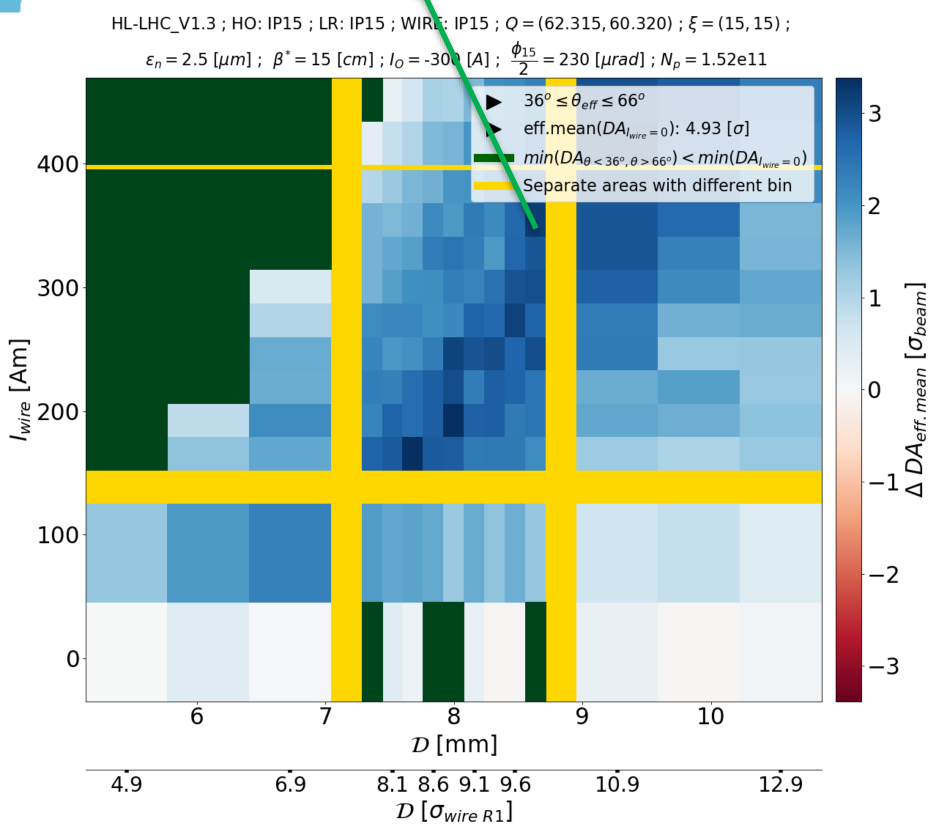




Pushed ultimate scenario

Many wire configurations with **D≥10σ guarantee more than 2.5σ improvement of the effective mean DA**.

The **best improvement** from these configurations is **3.2σ.**



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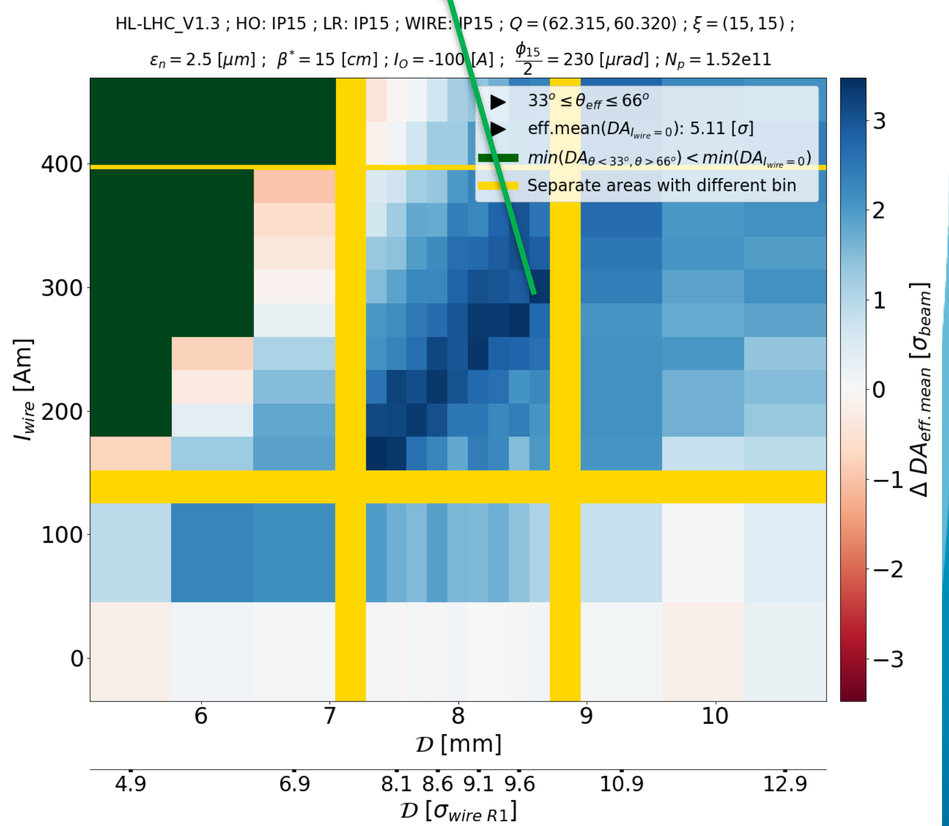
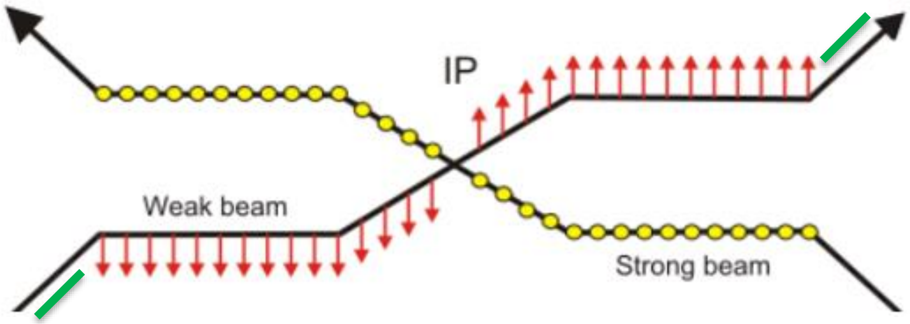
The **best improvement** from these configurations is **3.3σ.**



Effect of wires in the external side

What are the wires performances if they are placed at the wrong (external) position



and

I) the wire transverse position (D) is fixed at 10σ and a non-optimized tune is used

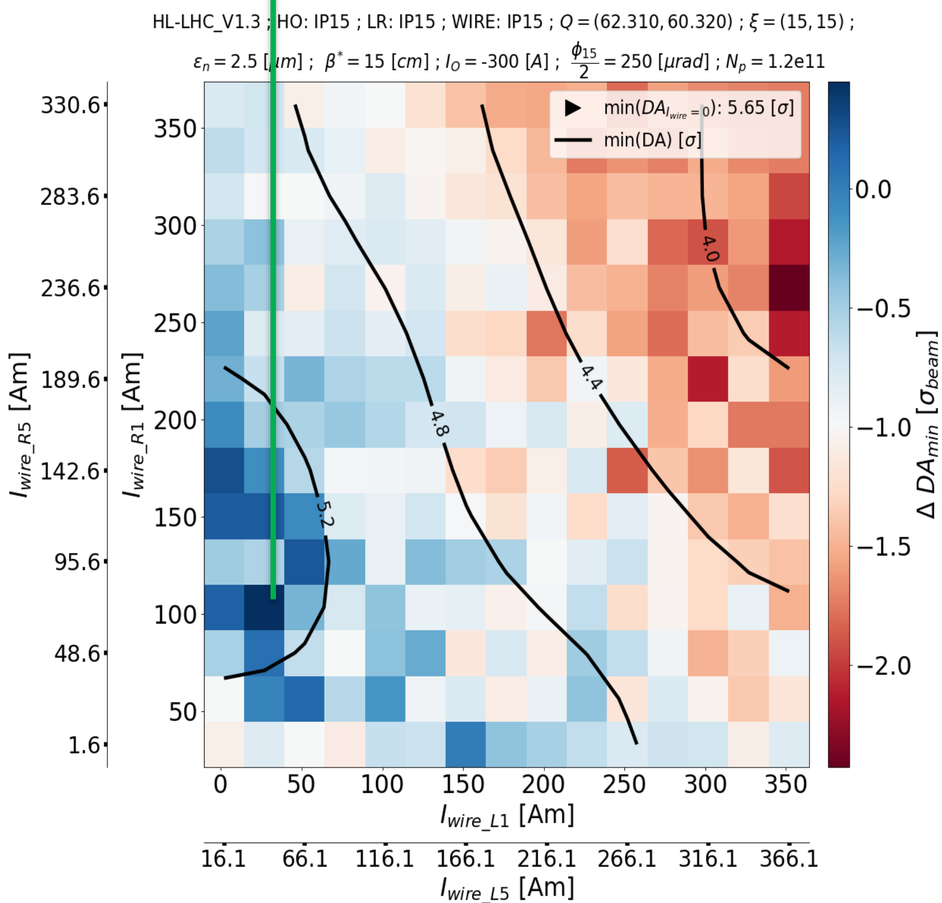
II) the half-crossing angle is at 230 μrad and a non-optimized tune is used

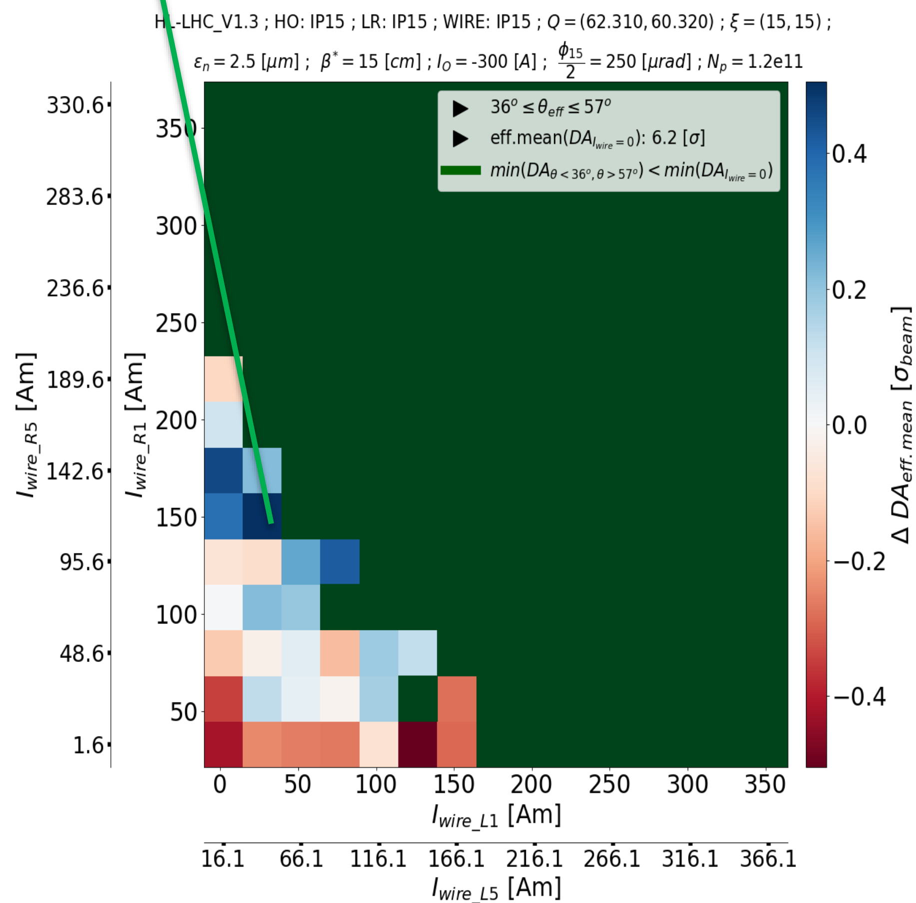
Effect of wires in the external side (I)

Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.31 ; 60.32	1.2×10^{11}	250 [μrad]	10.5 [σ]	5×10^{34} [cm^{-2}s^{-1}]

0.5σ min DA improvement that guarantees 6σ min DA.

0.5σ improvement of the effective mean DA with **low wire current** and **large wire transverse distance**.



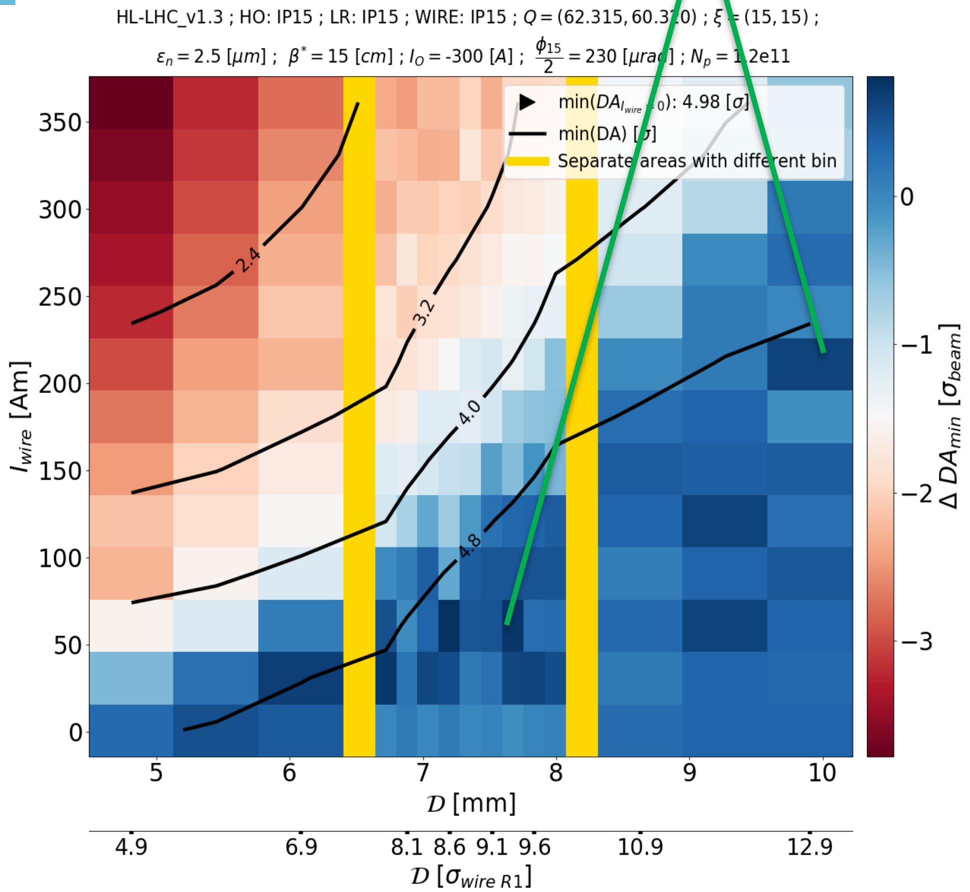


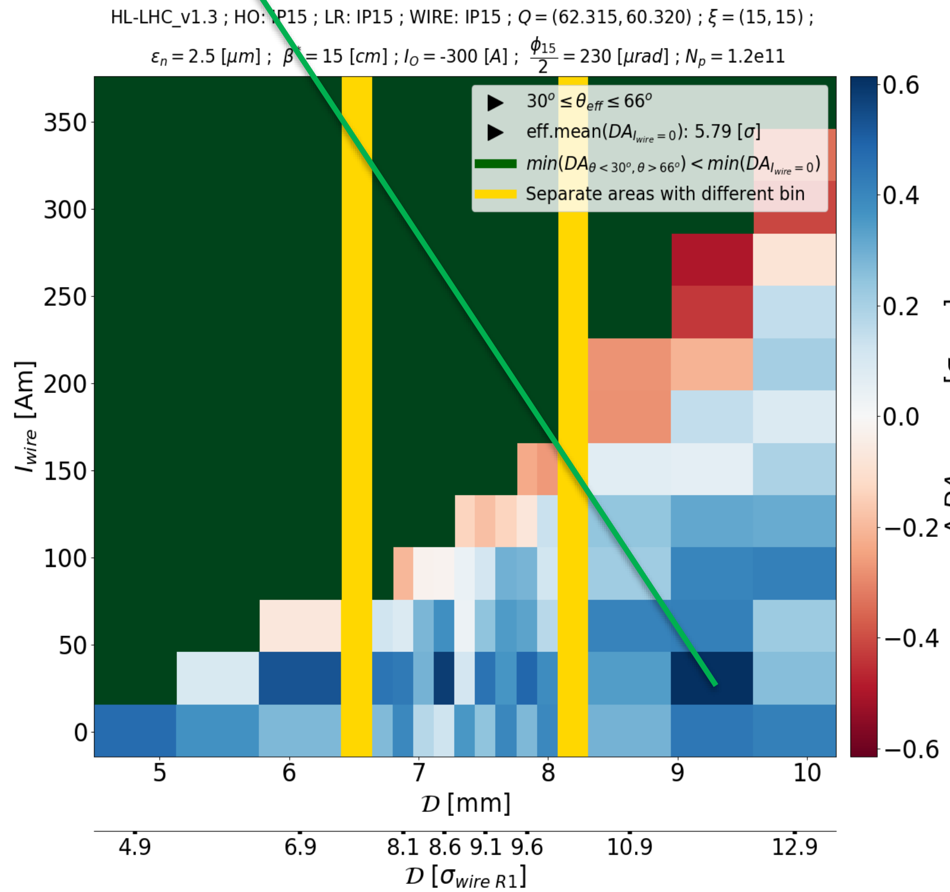
Effect of wires in the external side (II)

Lattice tunes	Np	Half crossing angle	Normalized crossing angle	Luminosity
62.315 ; 60.32	1.2×10^{11}	230 [μrad]	9.7 [σ]	5.4×10^{34} [$cm^{-2}s^{-1}$]

0.9σ min DA improvement that guarantees a min DA close to 6σ.

0.6σ improvement of the effective mean DA with **low wire current** and **large wire transverse distance.**





Conclusions

- In all the studies presented, the wire compensator guarantees a **significant improvement** of the min and effective mean **DA** (**high chromaticity**, any **octupole**, **nominal** and **ultimate**)

  - A very good min DA (>7σ) or effective mean DA is always found at transverse wire distance larger or equal to 10σ from the weak beam.

  - Possibility to increase the produced luminosity by reducing the crossing angle and/or increasing the bunch population without sacrificing the lifetime (min DA>6σ).

  - Reduce significantly the triplet irradiation by reducing the crossing angle.

- With all the good wire configurations (positive Δ[eff.meanDA]) the area of the good working tunes is enlarged
  - WP can be kept constant during leveling

- The wires can give **positive results** even if they are placed at **bad position** (external transverse placement).

- A deeper understanding of the impact of the different resonances is needed through **non-linear dynamics analysis** (FMAs,…)

- The impact of the wire on lifetime is being assessed.

- An operational scenario for round beams with wires is being evaluated.

Thank you for your time!

Backup slides

Bassetti-Erskine formulas

- 4D treatment of the beam-beam long range interaction (Bassetti-Erskine)

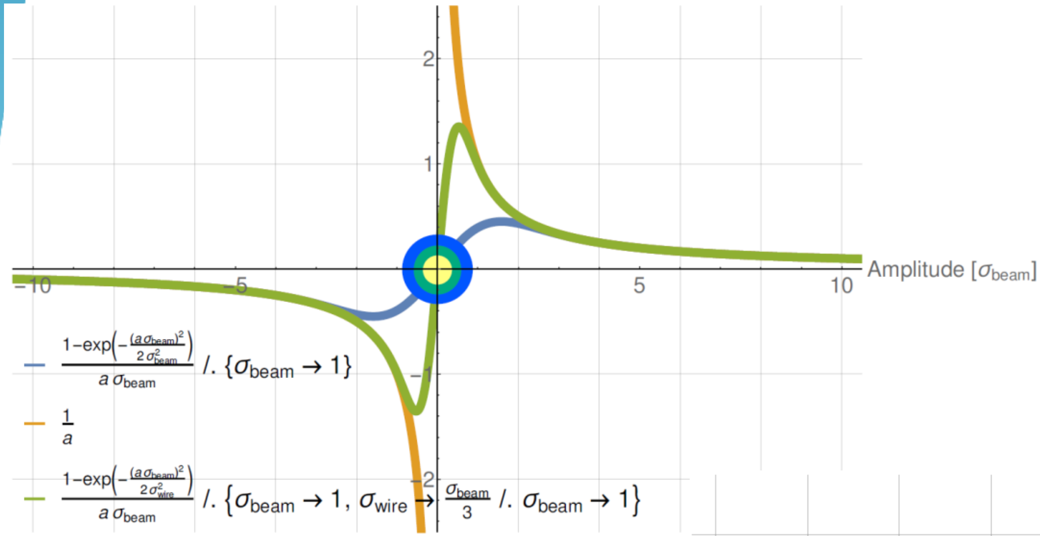
$$B_\theta = -\frac{\beta_{st}}{c}\ E_r \ \rightarrow\ F_\perp = q\ E_r\ (1+\beta_{we}\beta_{st}) = q\ E_{reff} \quad \text{and for } \sigma_x > \sigma_y:$$

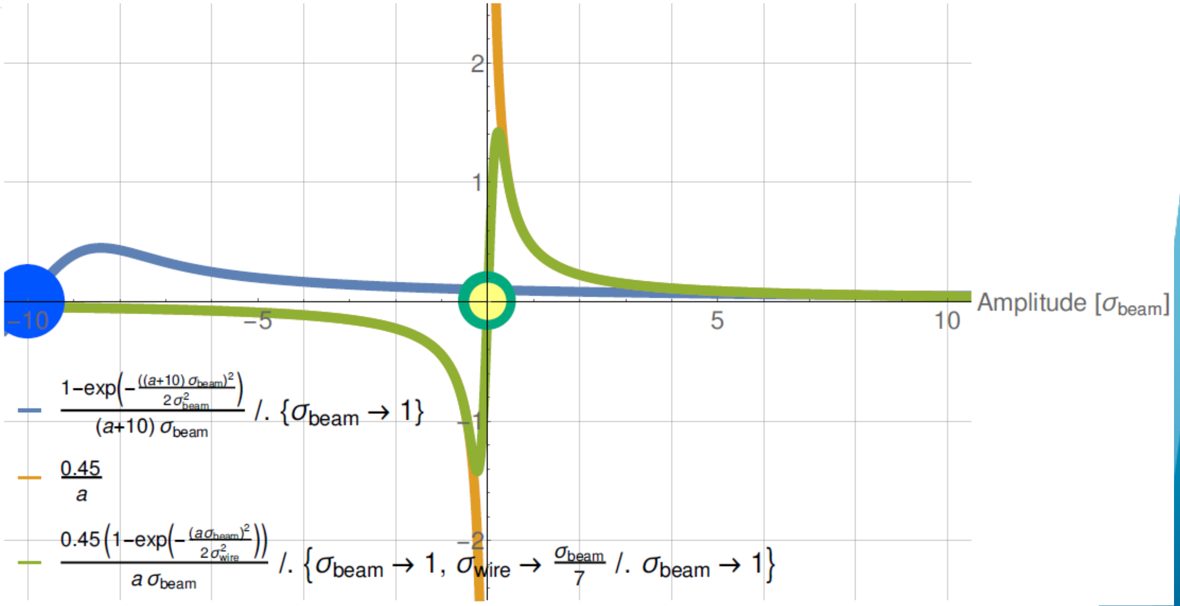
$$\int_{-\infty}^{\infty} E_{xeff}\ ds = \frac{N_p\ q\ (1+\beta_{we}\beta_{st})}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\Im\left[\mathcal{F}\left(\frac{x+\imath y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - Exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)\mathcal{F}\left(\frac{x\sigma_y^2+\imath y\sigma_x^2}{\sigma_x\sigma_y\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

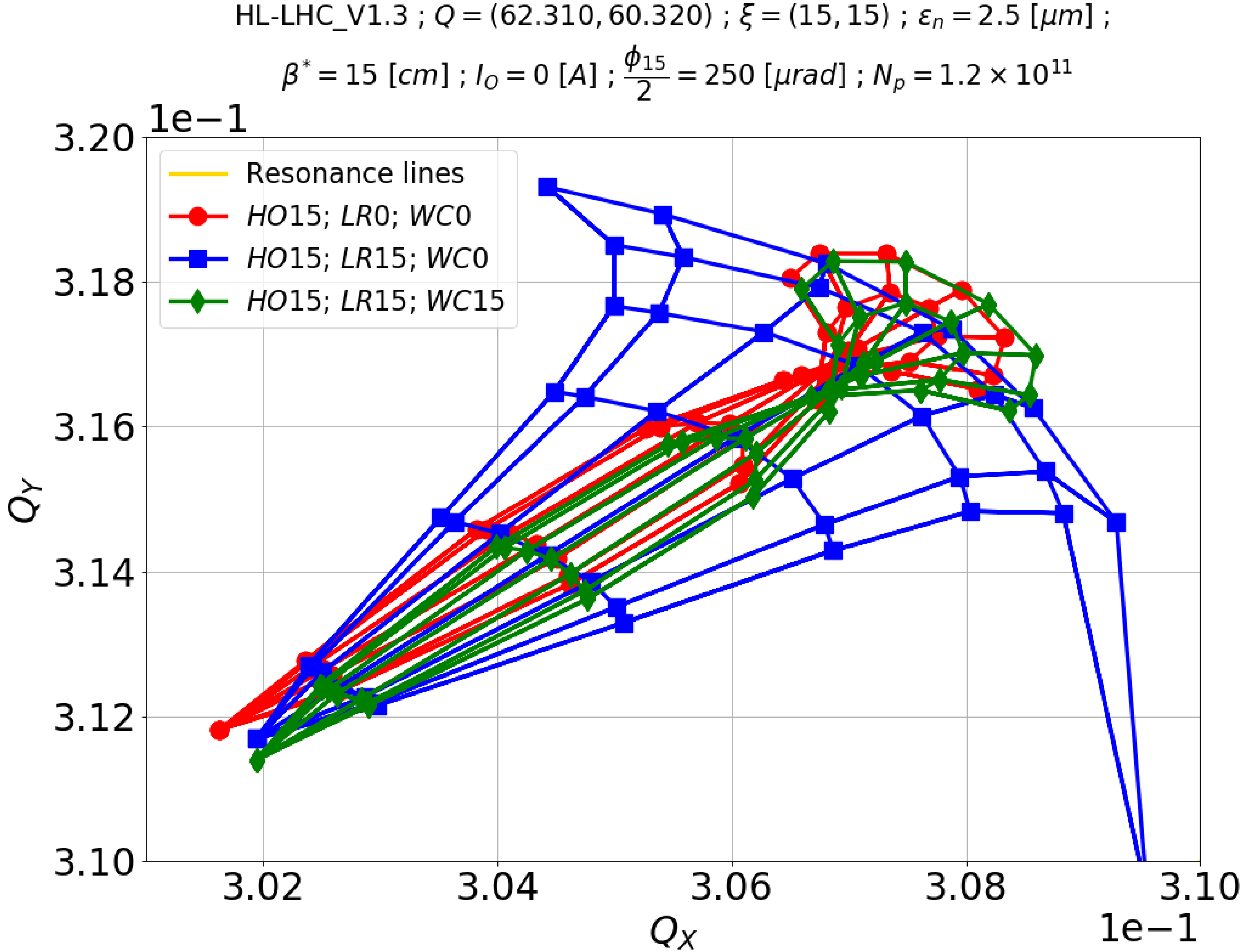
$$\int_{-\infty}^{\infty} E_{yeff}\ ds = \frac{N_p\ q\ (1+\beta_{we}\beta_{st})}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\Re\left[\mathcal{F}\left(\frac{x+\imath y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - Exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right)\mathcal{F}\left(\frac{x\sigma_y^2+\imath y\sigma_x^2}{\sigma_x\sigma_y\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

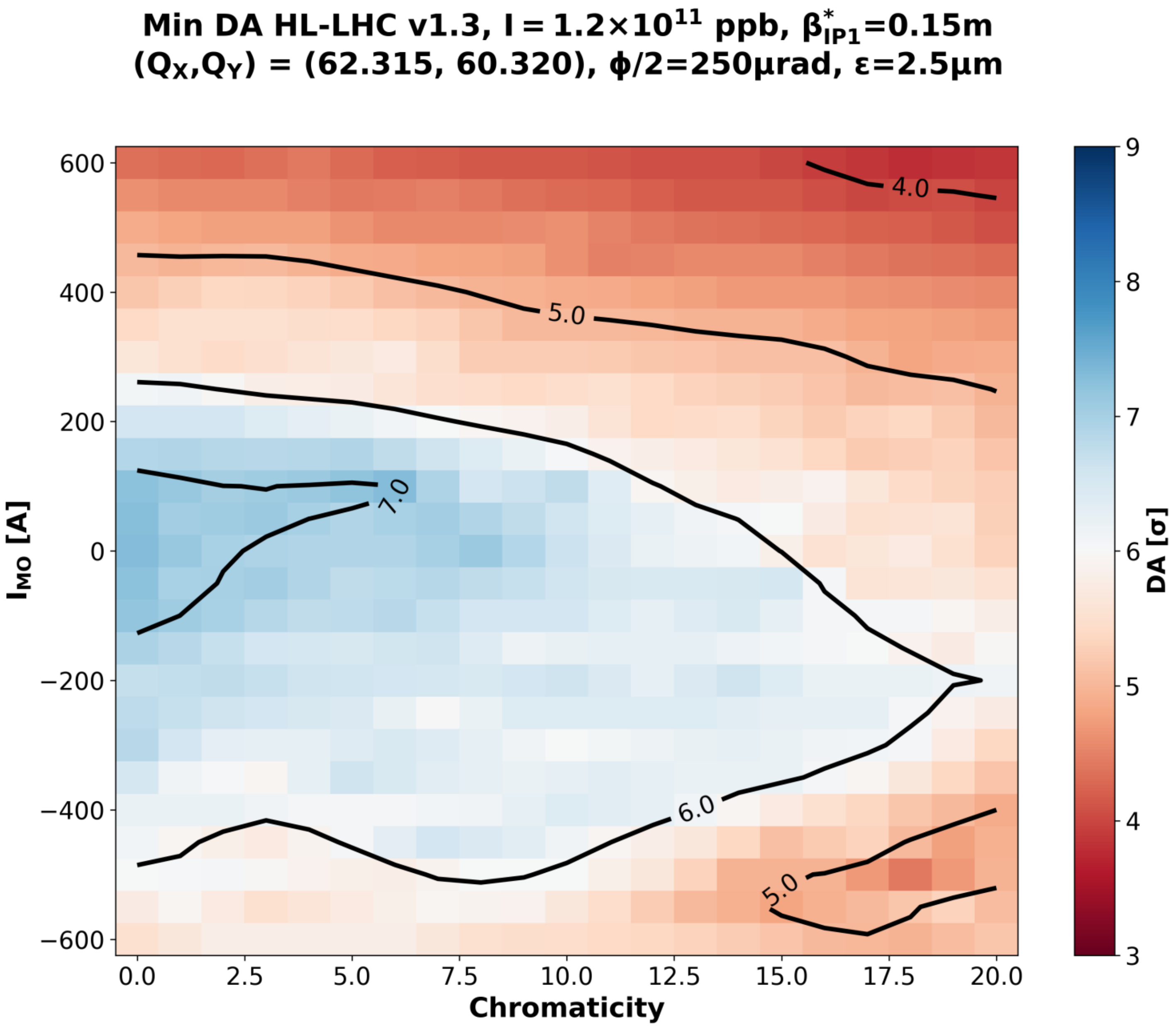
All the quantities are measured from the center of the strong beam in the lab rest frame

Beam-beam field vs wire-like beam-beam field vs wire field






HL-LHC_V1.3 ; $Q = (62.310, 60.320)$; $\xi = (15, 15)$; $\varepsilon_n = 2.5$ [μm] ;
$\beta^* = 15$ [cm] ; $I_O = 0$ [A] ; $\frac{\phi_{15}}{2} = 250$ [μrad] ; $N_p = 1.2 \times 10^{11}$
1e−1
3.20
3.18
3.16
3.14
3.12
3.10
Q_Y
Resonance lines
$HO15$; $LR0$; $WC0$
$HO15$; $LR15$; $WC0$
$HO15$; $LR15$; $WC15$
3.02
3.04
3.06
3.08
3.10
Q_X
1e−1



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