Preliminary results of the BBLR compensation experiment in LHC during MD4

Y. Papaphilippou, A. Rossi and **G. Sterbini** on behalf of the BBLR compensation team

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WP2, 5th December 2017

Objectives of the experiment

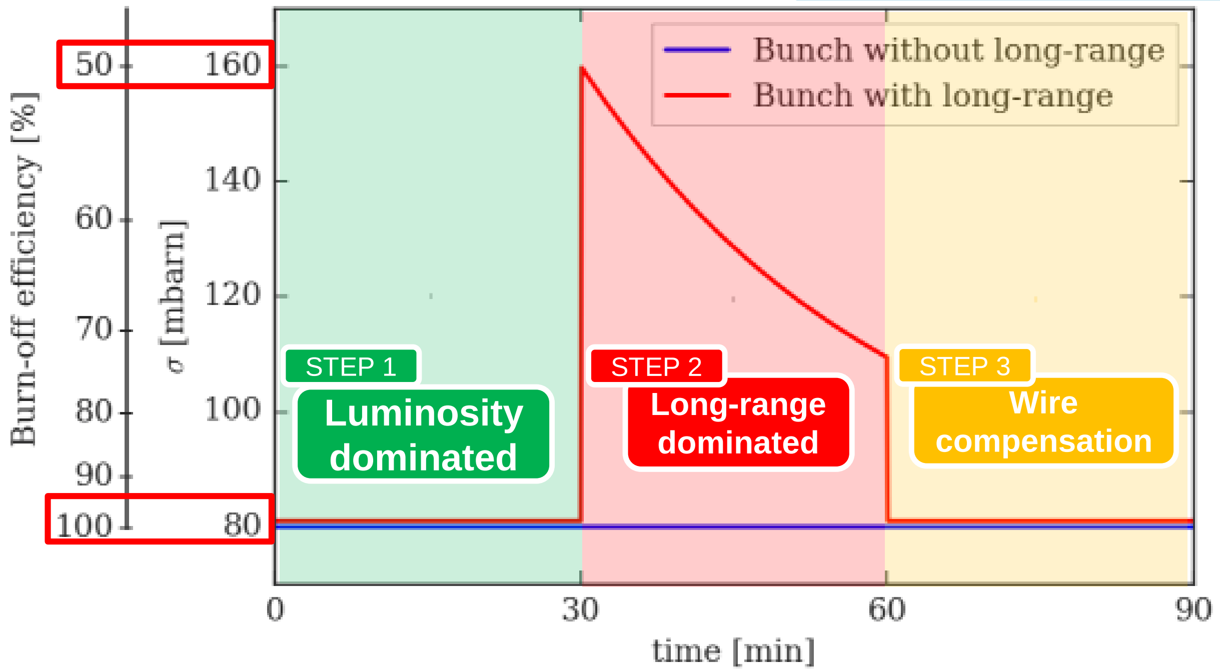
- **Prove the beneficial effect of the BBCW** in a regime dominated by long-range beam-beam effect, ensuring in the mean time that the linear effects of the wire (orbit and tunes) are compensated.
- Our privileged observable is the bunch "**effective cross-section**":

$$\sigma_{EFF} = -\frac{1}{\sum_{IP} L_{IP}} \frac{dN}{dt}$$

Instantaneous luminosity

Intensity loss-rate

The IDEAL compensation, 2 bunches in B2



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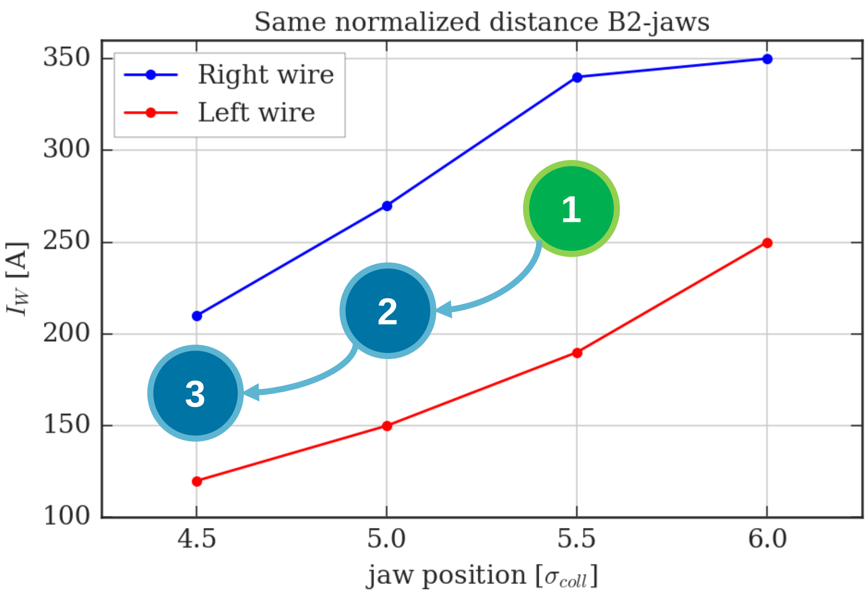
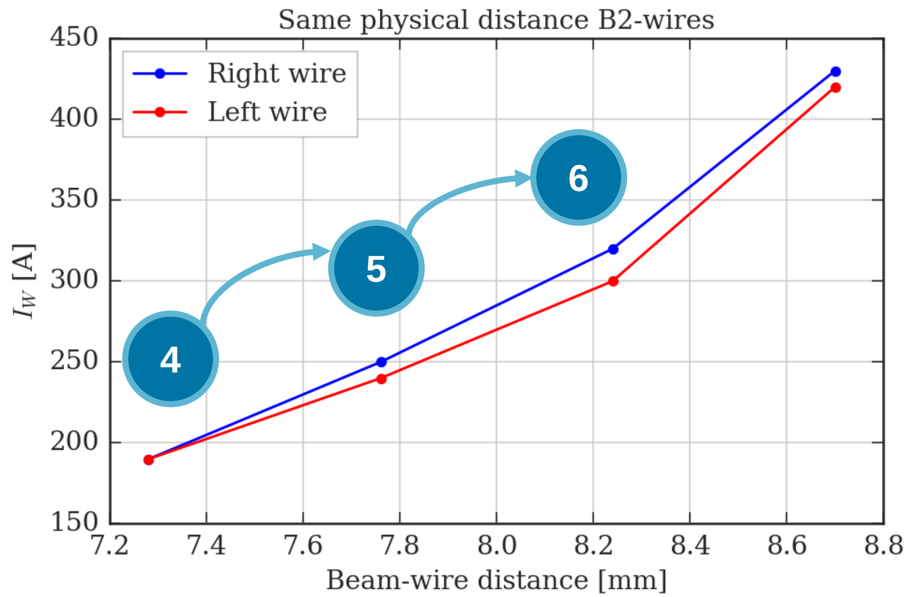
Aim of MD2202 in MD4

- Explore the following set of distances/current that compensate the octupolar term due to B1 in IR5.

Approach from PRST-AB, 18, 121001 (2015)





- Due to problems during the MD (2 dumps) we could explore only the position/currents set 1.

Differences between the MD1* and MD4

1 July ’17 (MD1)

- β^* = 40 cm
- half-Xing angle = 120 urad
- 3 bunches in B2
- 1 train in B1(not stable)
- Non local tune correction
- Jaw of wire collimator at 6 σ
- Max current in the wires (350 A) to look for an effect
- Nominal octupoles.

29 November ’17 (MD4)

- β^* = 30 cm
- half-Xing angle = 150 urad
- 2 bunches in B2
- 3 trains in B1
- Orchestrated Q4/5 tune correction
- Jaw of wire collimator at 5.5 σ
- Optimized current in the wires (340/190 A in R/L)
- Octupoles at the maximum in B1 and 0 A in B2.

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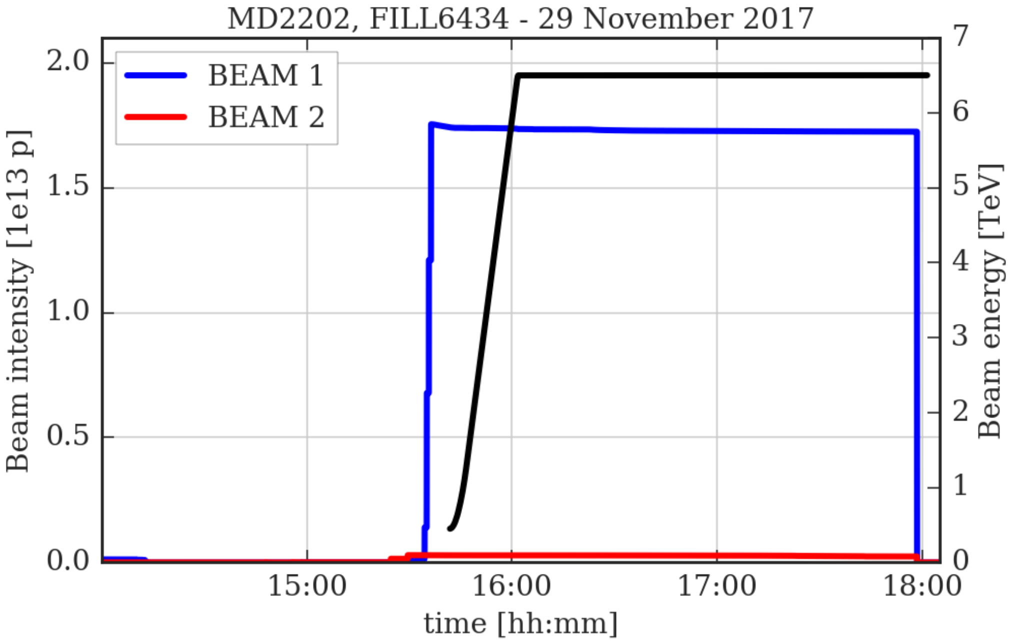
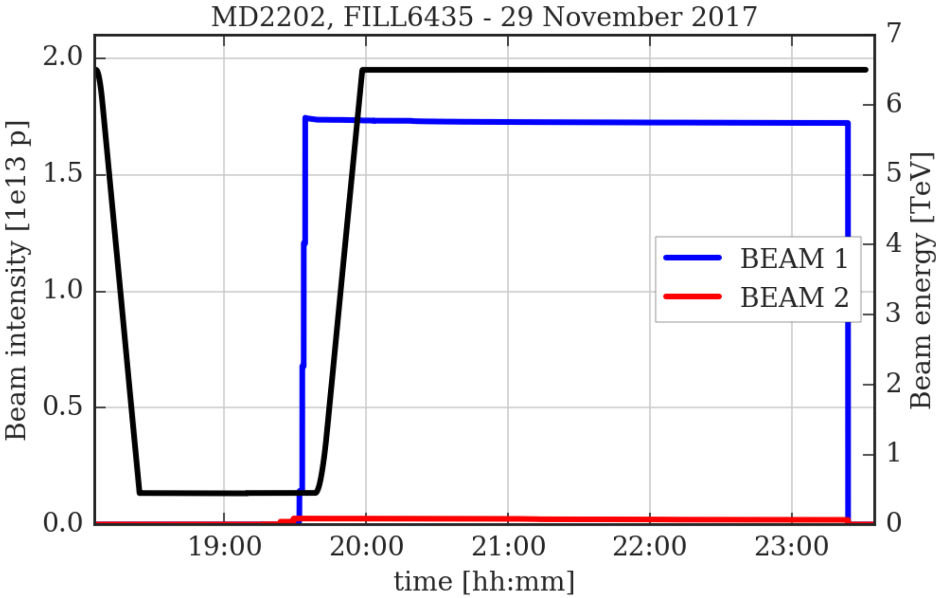
* The results of the MD2202 in MD1 was discussed in WP2 Meeting 102.

FILL6434 and FILL6435

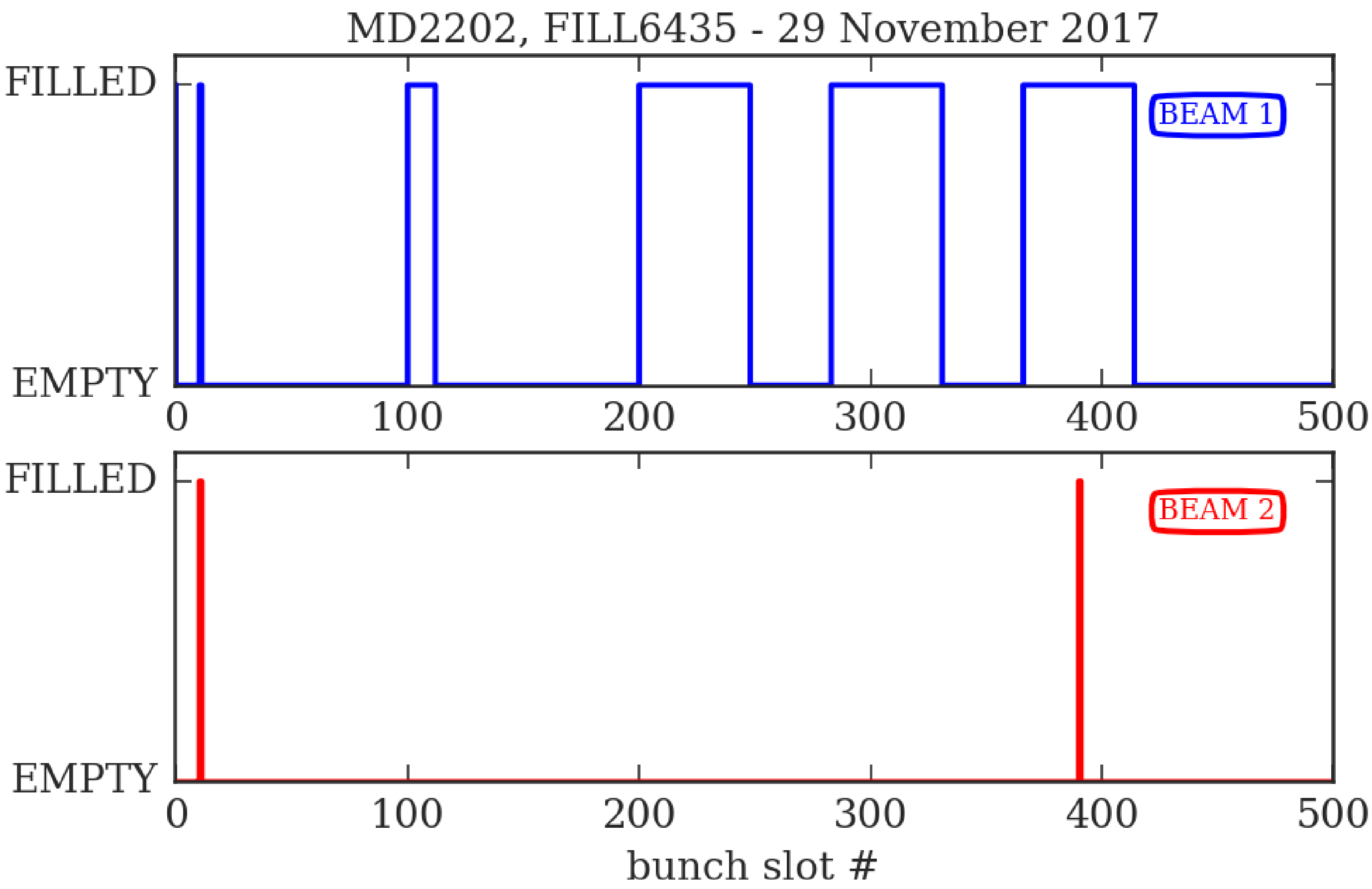


FILL6434 dumped on an interlock of the Q4/5 in IR5 used for the tune feedforward.

FILL6435 dumped on a PS trip (Q8, not related to the MD).
We will consider this only this fill.

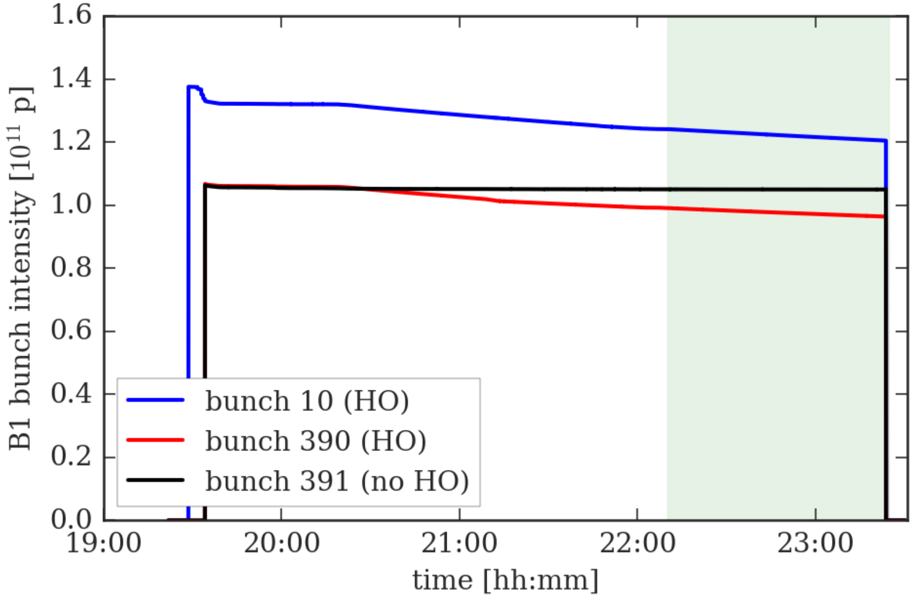


Filling scheme



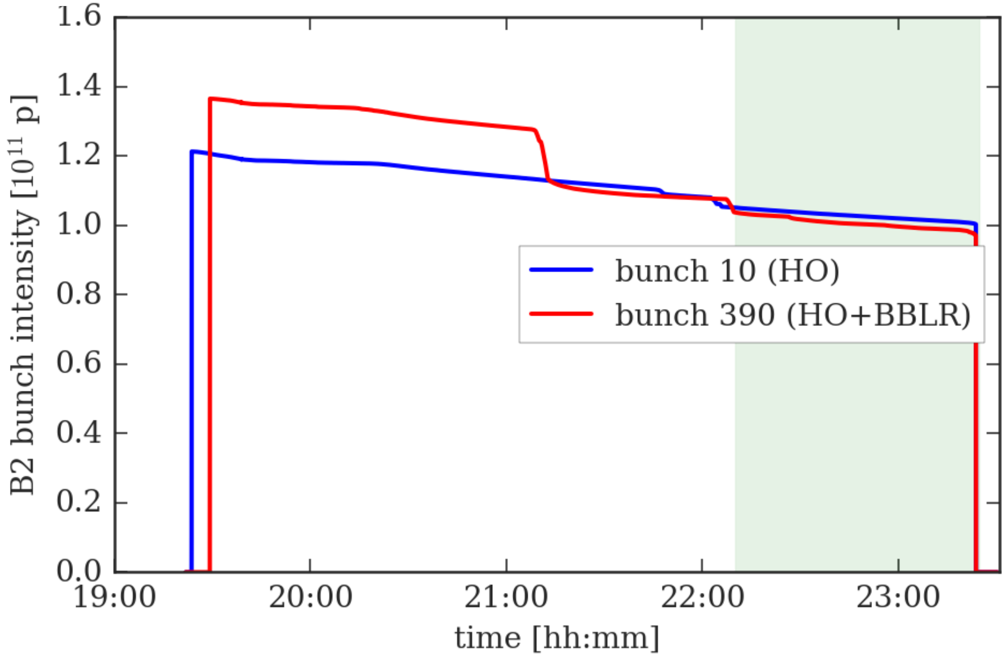
- **B1 was stable during the two fills.**

FILL6435



Beam 1, mild losses due to burn-off

Beam 2, losses dominated by blow-up



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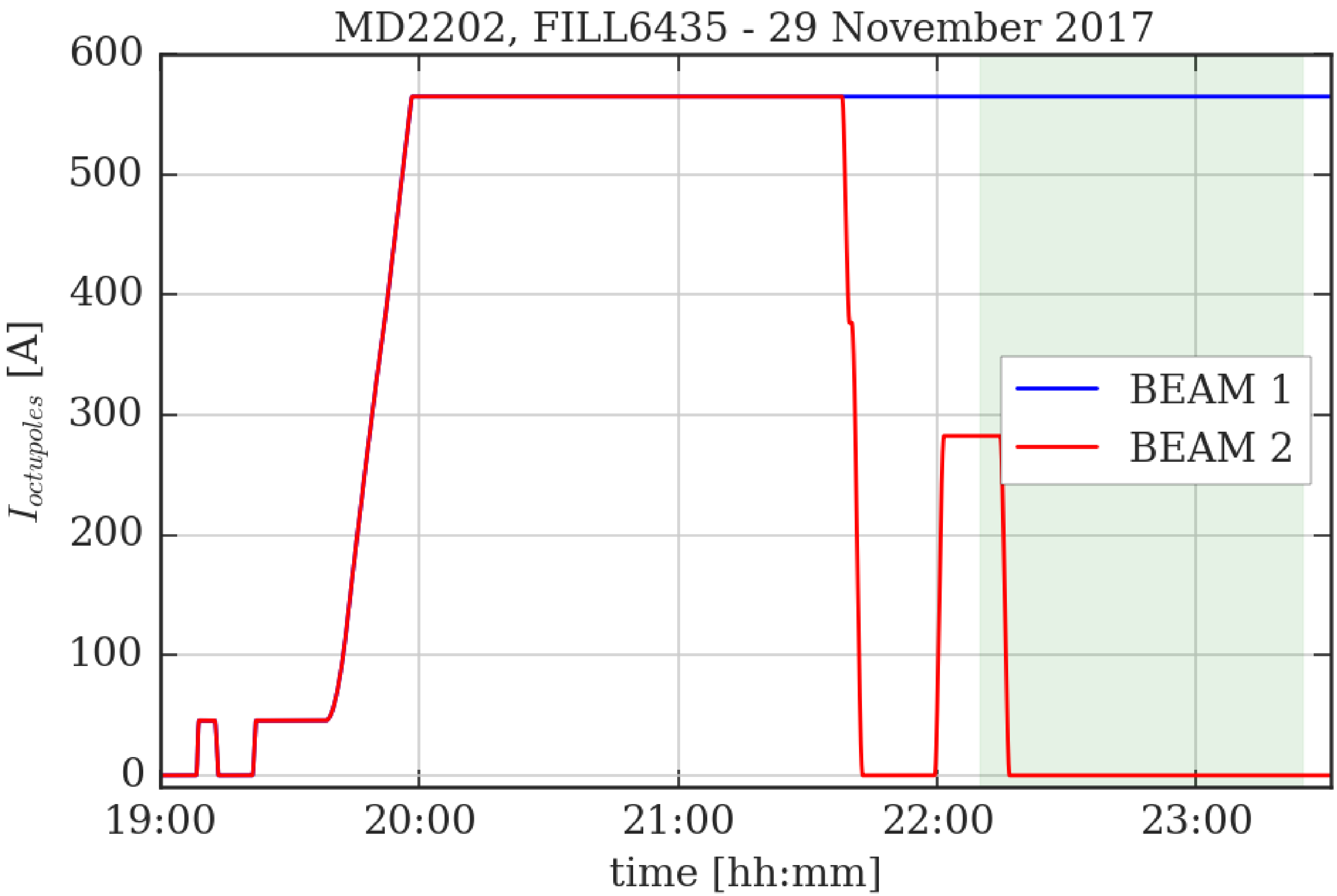
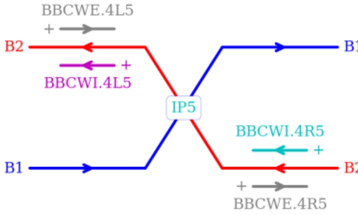
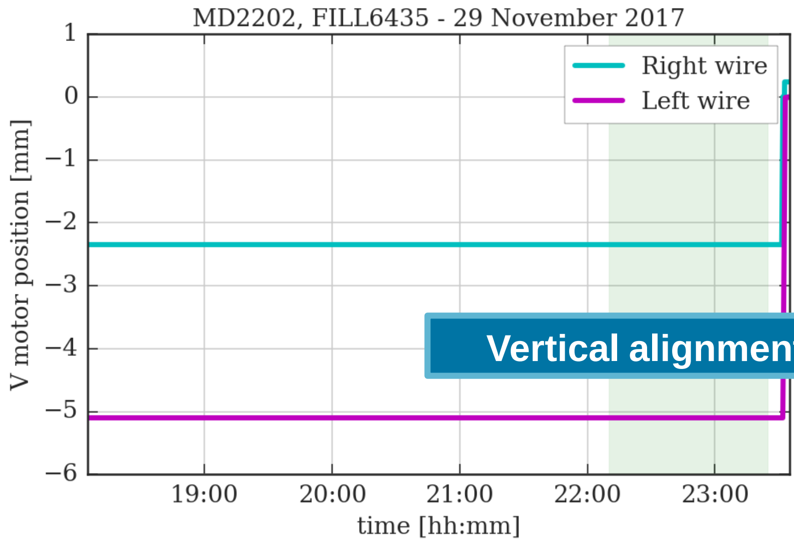
Octupoles strategy

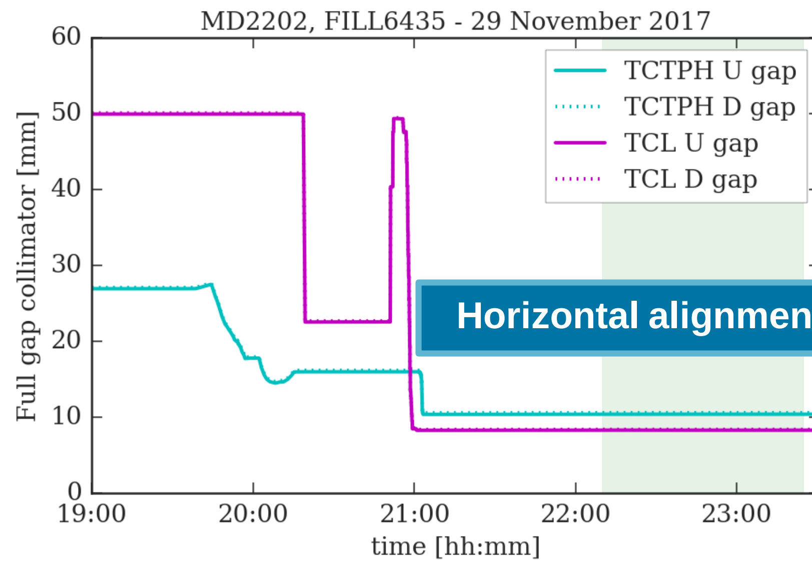


Wires powering and positioning

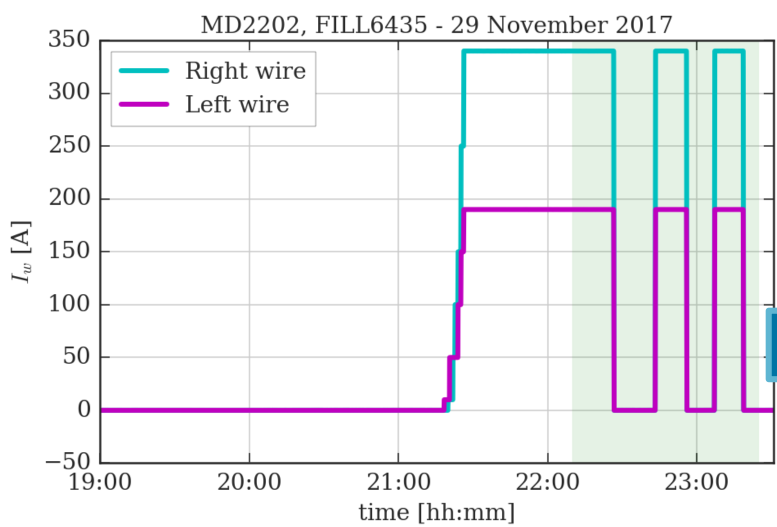




Vertical alignment



Horizontal alignment

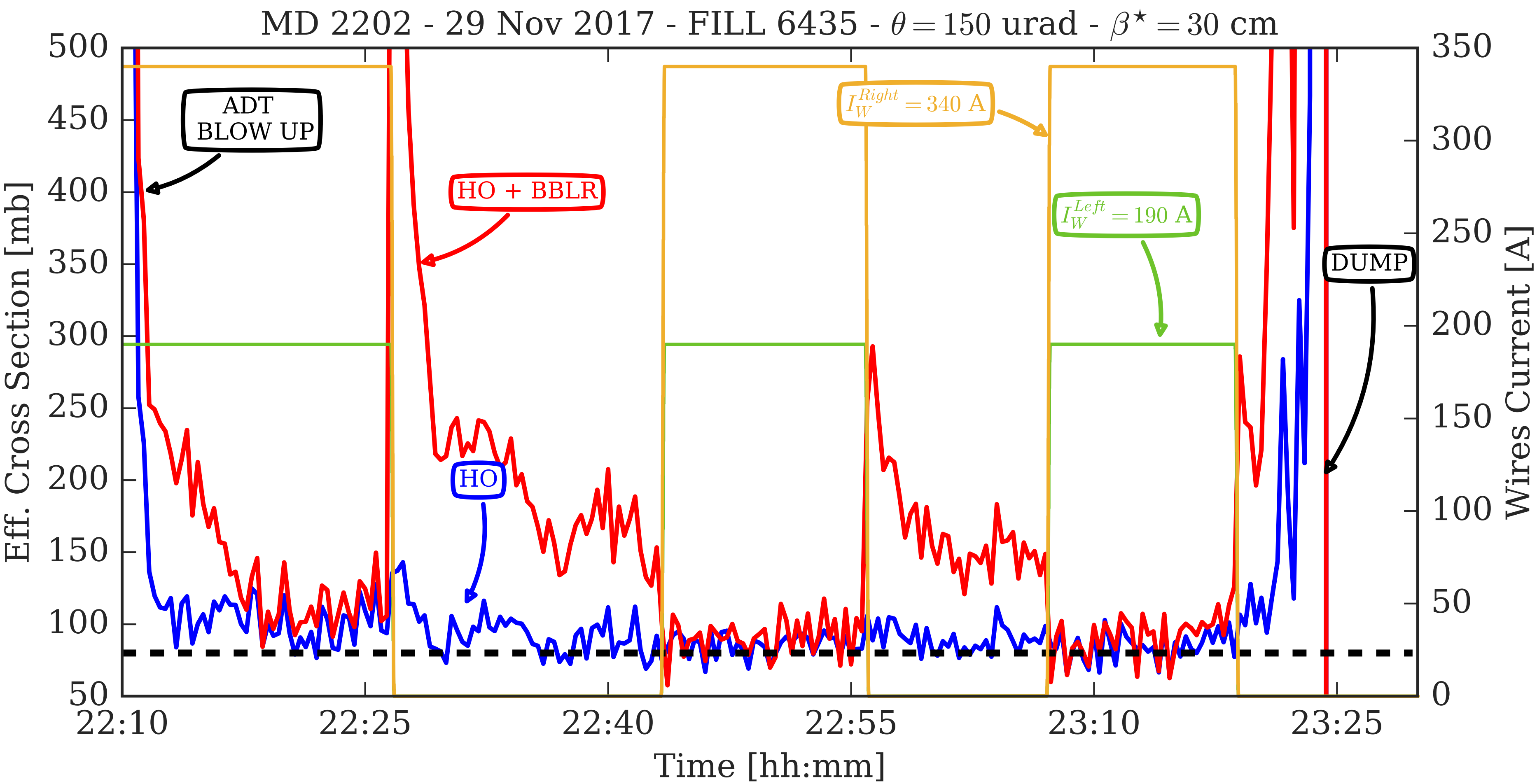


Power cycle (3 x ON/OFF)

Result at 340/190 A and jaw at 5.5 σ_{coll}

- **Positive effect of the wires visible on beam lifetime.**

Result at 340/190 A and jaw at 5.5 σ_{coll}

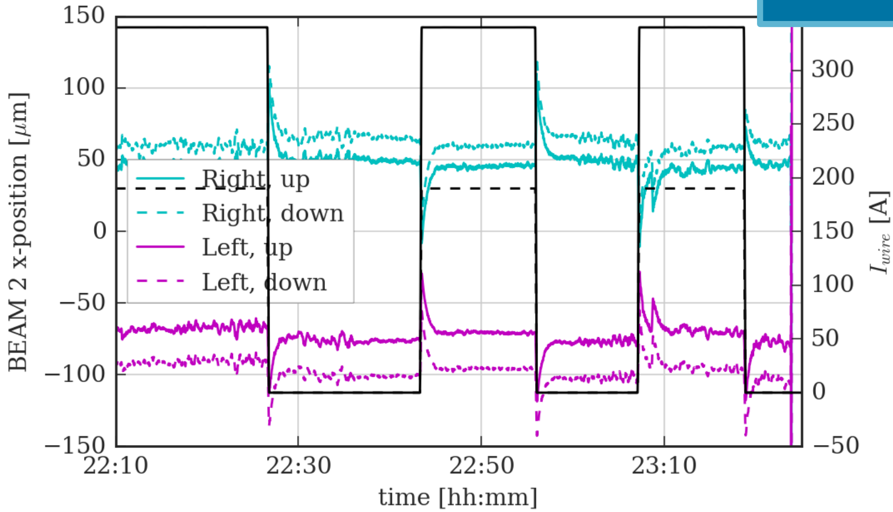


A. Poyet

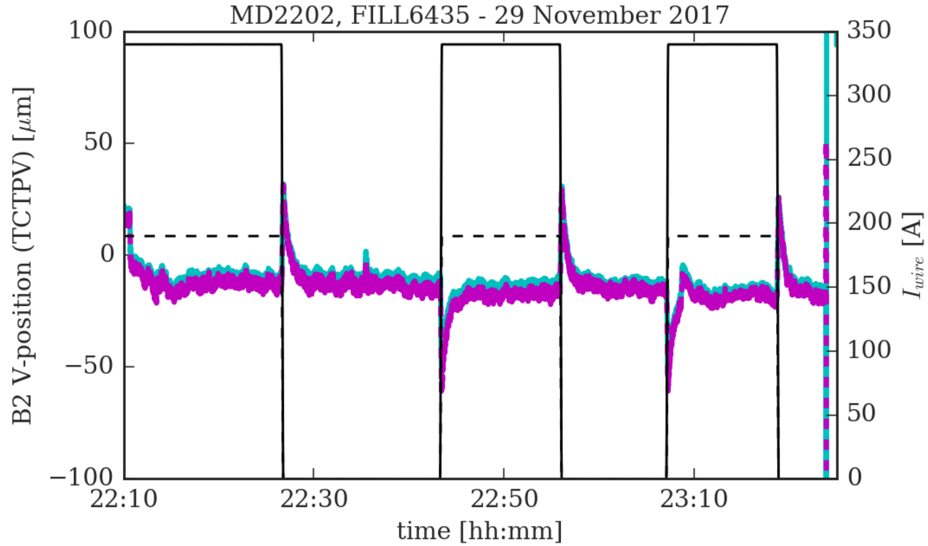
- **Positive effect of the wires visible on the bunch affected by the beam-beam long-range.**

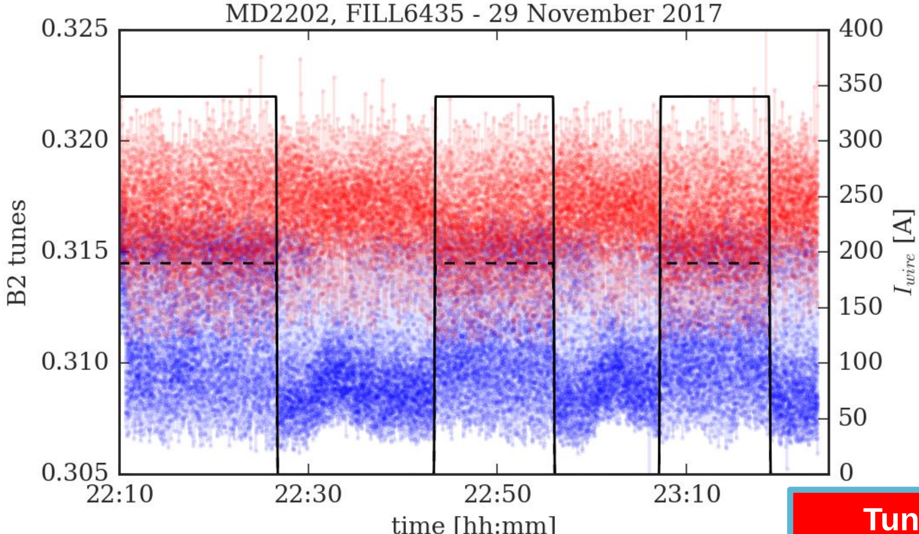
Result at 340/190 A and jaw at 5.5 σ_{coll}

Horizontal stability



Vertical stability





Tune stability

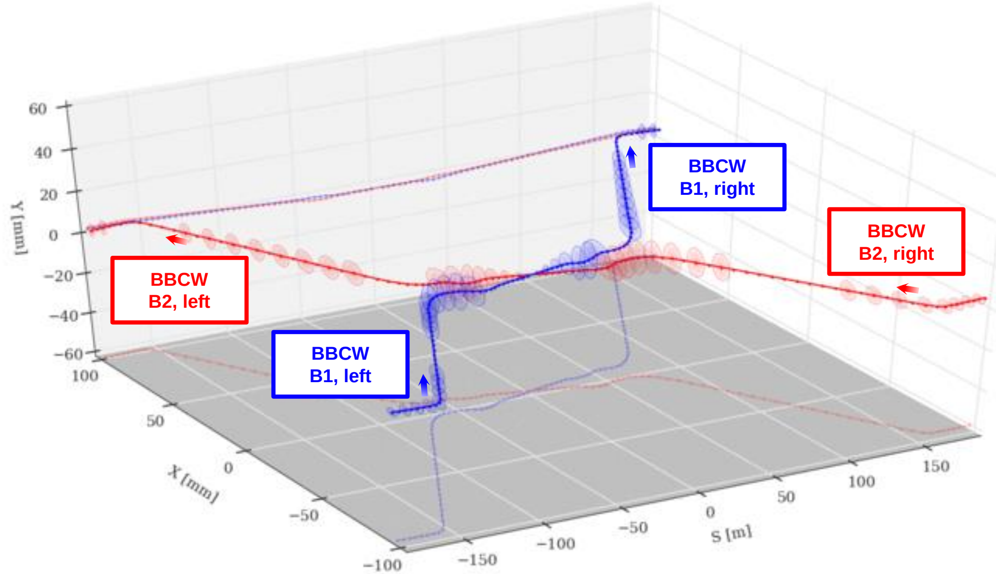
Summary

- Despite we could perform only ~1/3 of the MD program, the results of the MD4 seem to **confirm and improve** the observations done MD1.
- For the next MD (2018), a bunch with not collision (like in MD1) for the tune measurement is going to be considered (check minimum intensity required and stability).

BACK-UP SLIDES

The wire compensation principle

- The long-range kick (BBLR effect) can be **compensated by using a DC wire**.
- The wire compensation is **not** in the HL-LHC baseline (see R. Tomàs talk).
- Its **potential for HL-LHC with flat optics or in combination with crab-crossing** was shown by S. Fartoukh et al., PRST-AB 18, 121001, 2015.

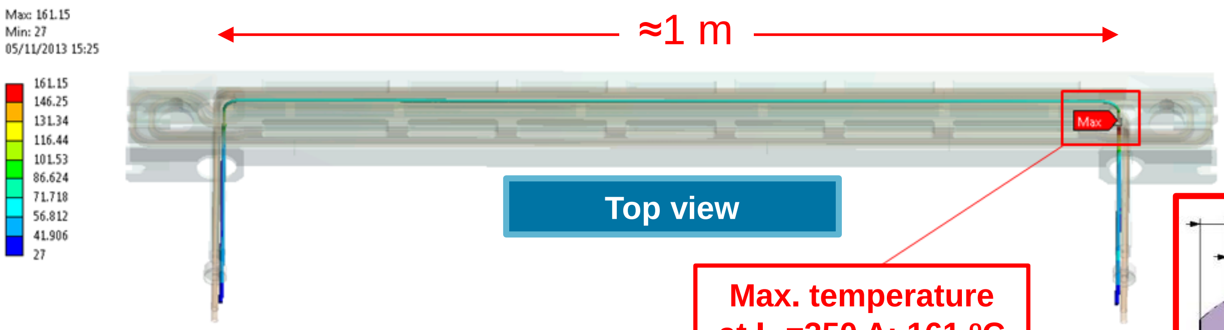


The BBCW principle

- **Since 2017 two wire prototypes (BBCW) are installed in LHC**. In this presentation, the HW setup and the latest LHC experimental results of the LHC wire compensation will be reported.

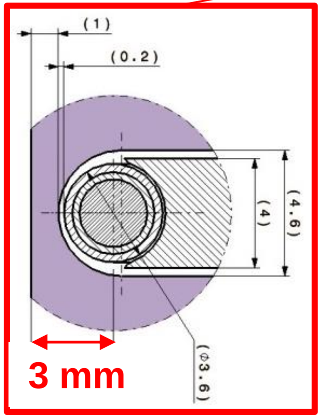
Integration of the wire in the collimator jaws

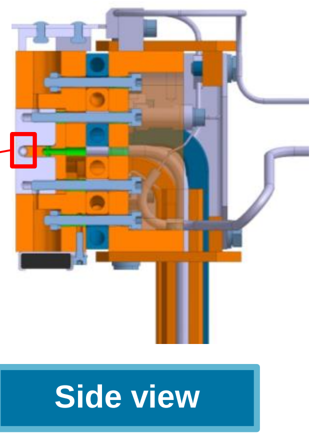
- The **wire-beam distance has to be of the order of few mm** (function of θ_c and s-position): LHC wires prototypes are embedded in the jaw of two operational tertiary collimators.



Max. temperature at I_W=350 A: 161 ºC

Courtesy of F. Carra



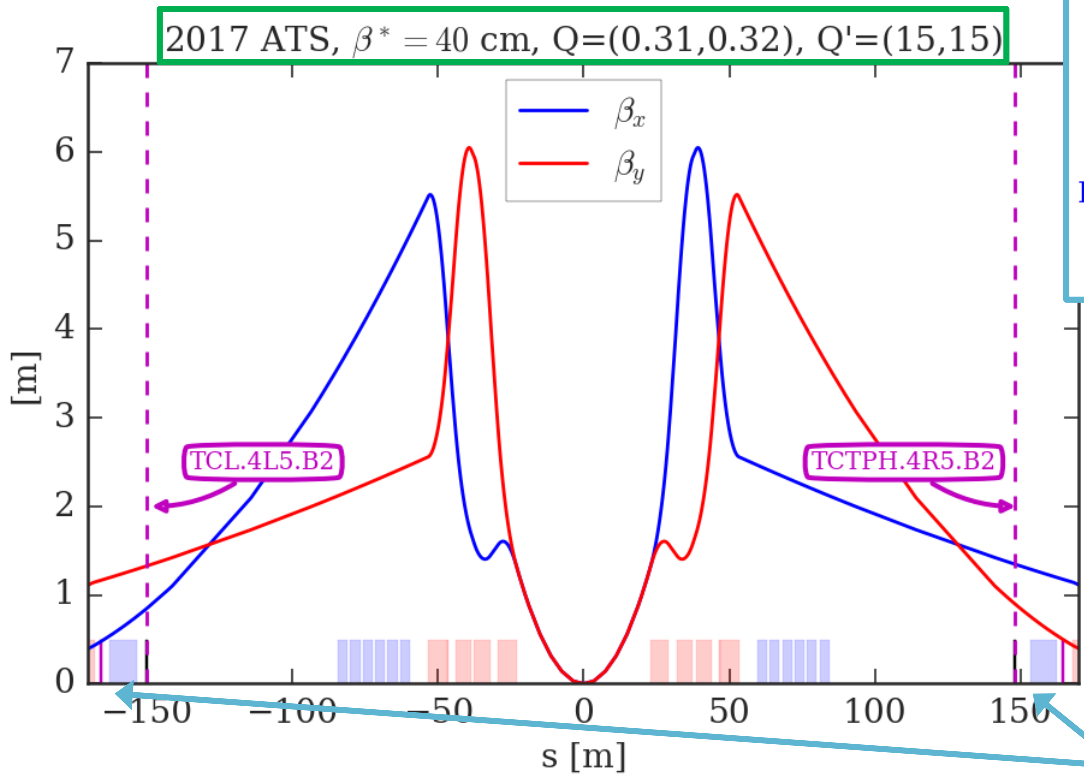


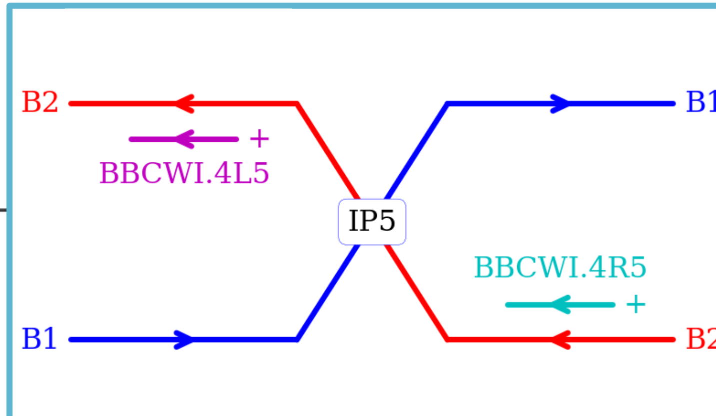
- During the 2017, BE-BI, EN-STI and the Collimation teams performed a complete test campaign to ensure the correct functioning of the wire interlocks, the collimator motors and PUs when the wire is powered.

The BBCW position in LHC

The 2 BBCWs were installed in two **H-collimators of B2 in IR5** (TCTPH.4R5.B2 and TCL.4L5.B2), close to the D2 separation dipoles.

Longitudinal position of the BBCW and optics used in the experiment



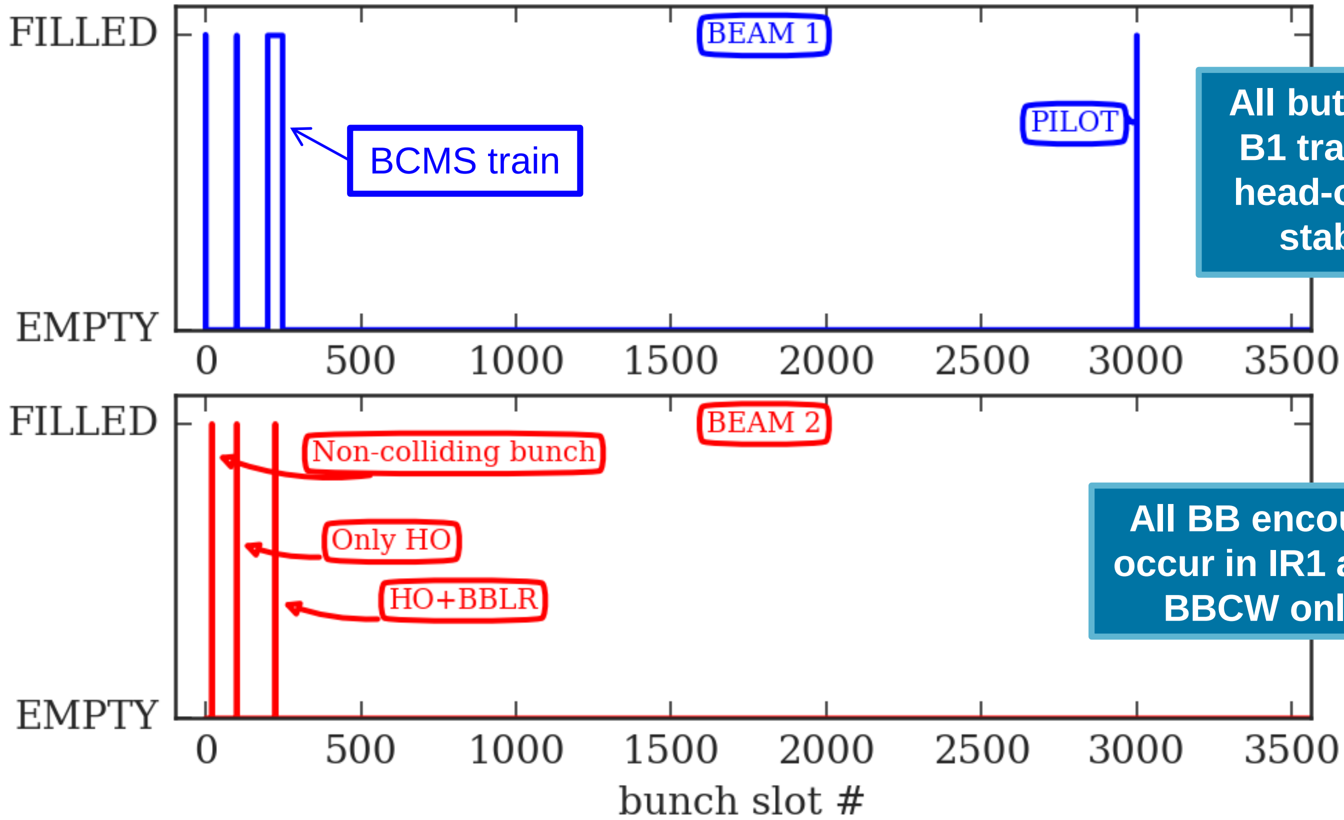


H-plane position of the BBCW

The ideal s-position of the BBCW is ±159 m from the IP5. The actual s-position are -150.03 and +147.94 m.

Asymmetric filling scheme

- To approach the wire to the beam the B2 has to be <3e11 p ("safe" limit).
- We will mainly concentrate on the two bunches of B2 (Only HO and HO+BBLR).



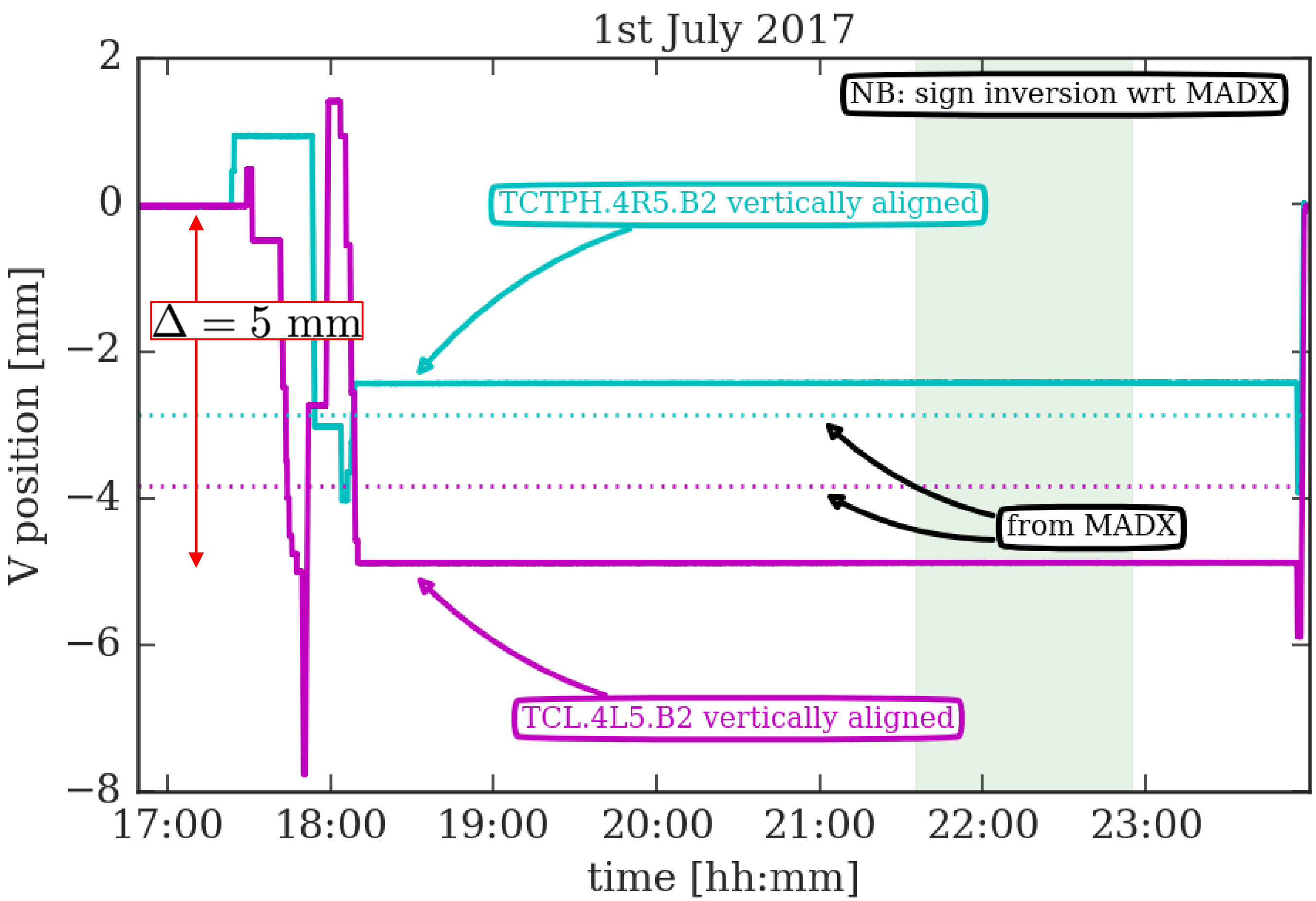
All but 1 bunch in the B1 train do not have head-on encounters: stability issues.

All BB encounters will occur in IR1 and IR5 but BBCW only in IR5.

Vertical alignment of beam-wires

STEP 1

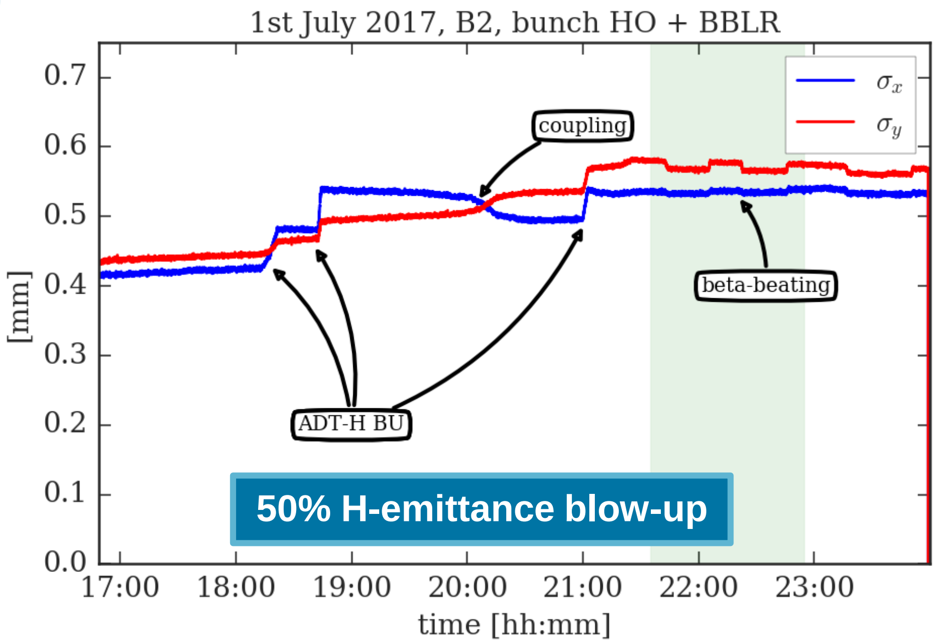
Luminosity dominated



- Important vertical offset (up to 5 mm) to be corrected with the vertical alignment procedure. Not trivial due to lack of V PUs [credit to N. Fuster and S. Redaelli].

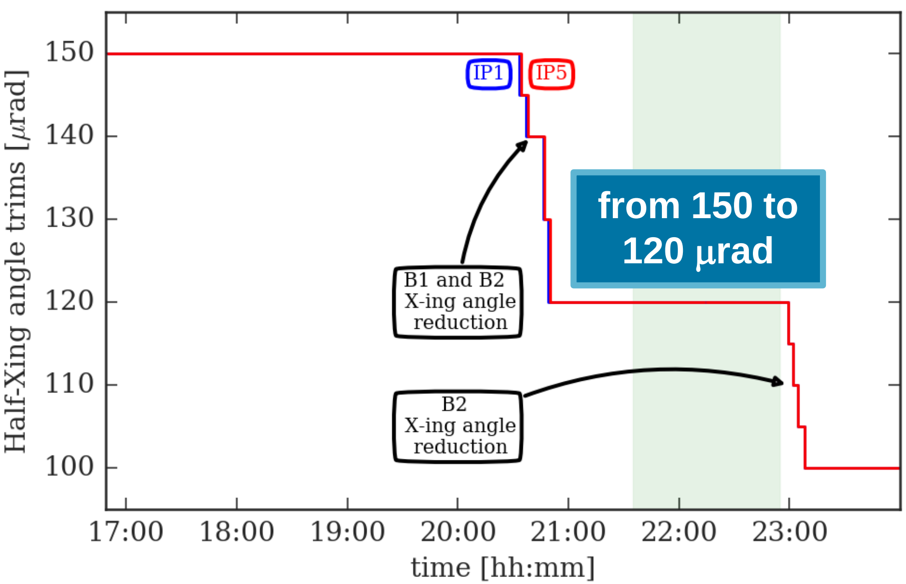
Pushing B2 to the BBLR regime

STEP 2
Long-range dominated

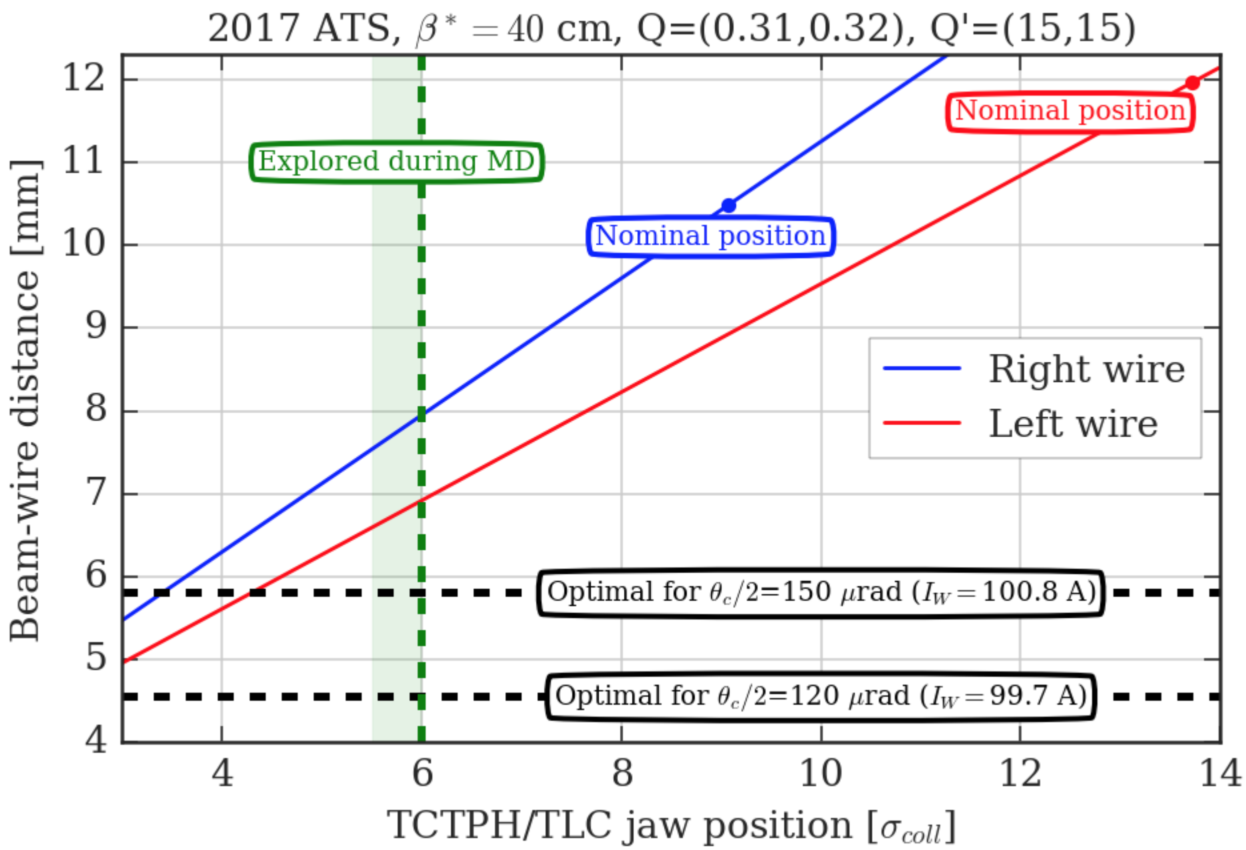


To increase the BBLR effect:

1. B2 **H-emittance blown-up** to 5-6 mm mrad [credit to D. Valuch, S. Papadopoulou and M. Fitterer].
2. The tunes were set to a **sub-optimal working point** (0.31, 0.32).
3. And the **half-Xing angle was reduced to 120 μrad**. Important synergy with the OP experience of the crossing angle anti-leveling [credit to M. Hostettler].



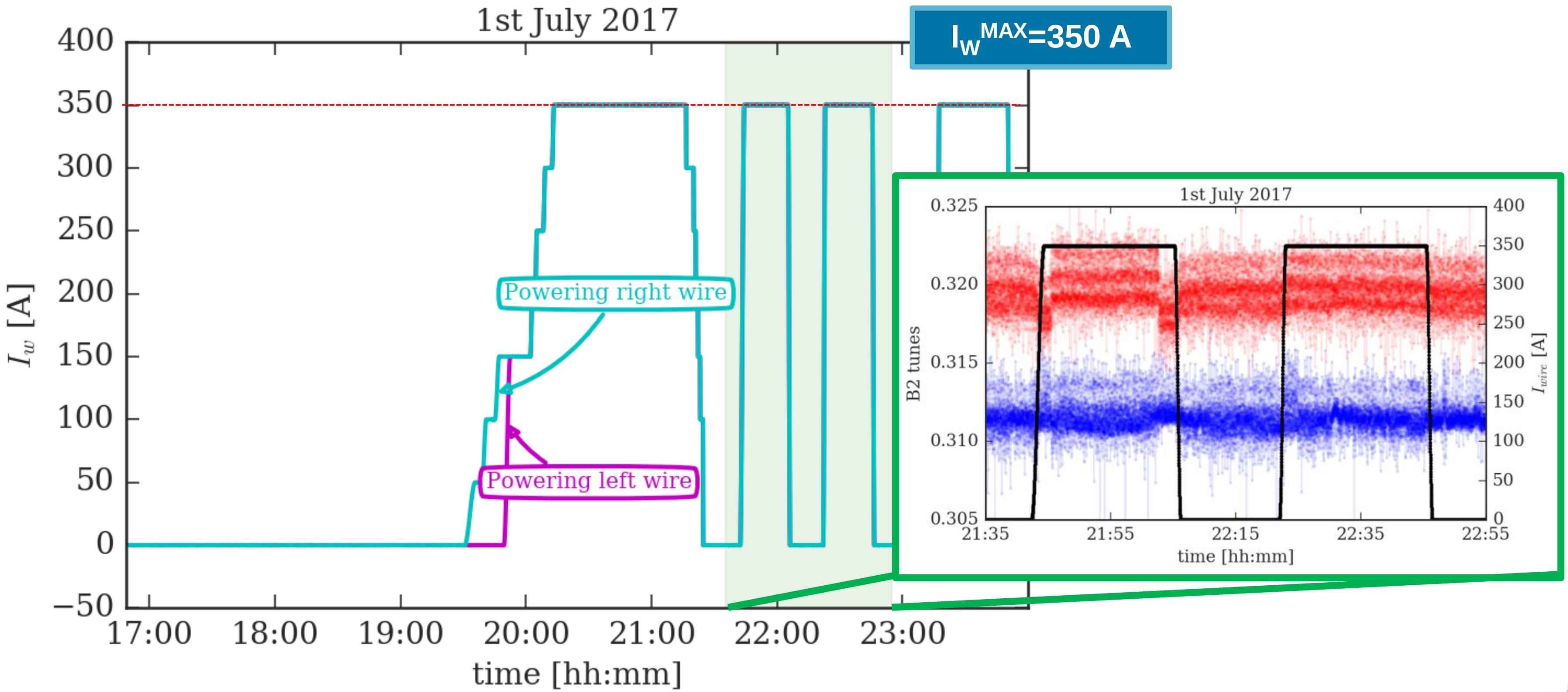
Approaching the wires to the beam



- There are practical limits in the positioning of the wire with respect to the beams even for low intensity MD beams.
- Given this constraint, the current can be used as a knob to cancel the effect of one specific magnetic multipole.

Switching ON/OFF the compensation

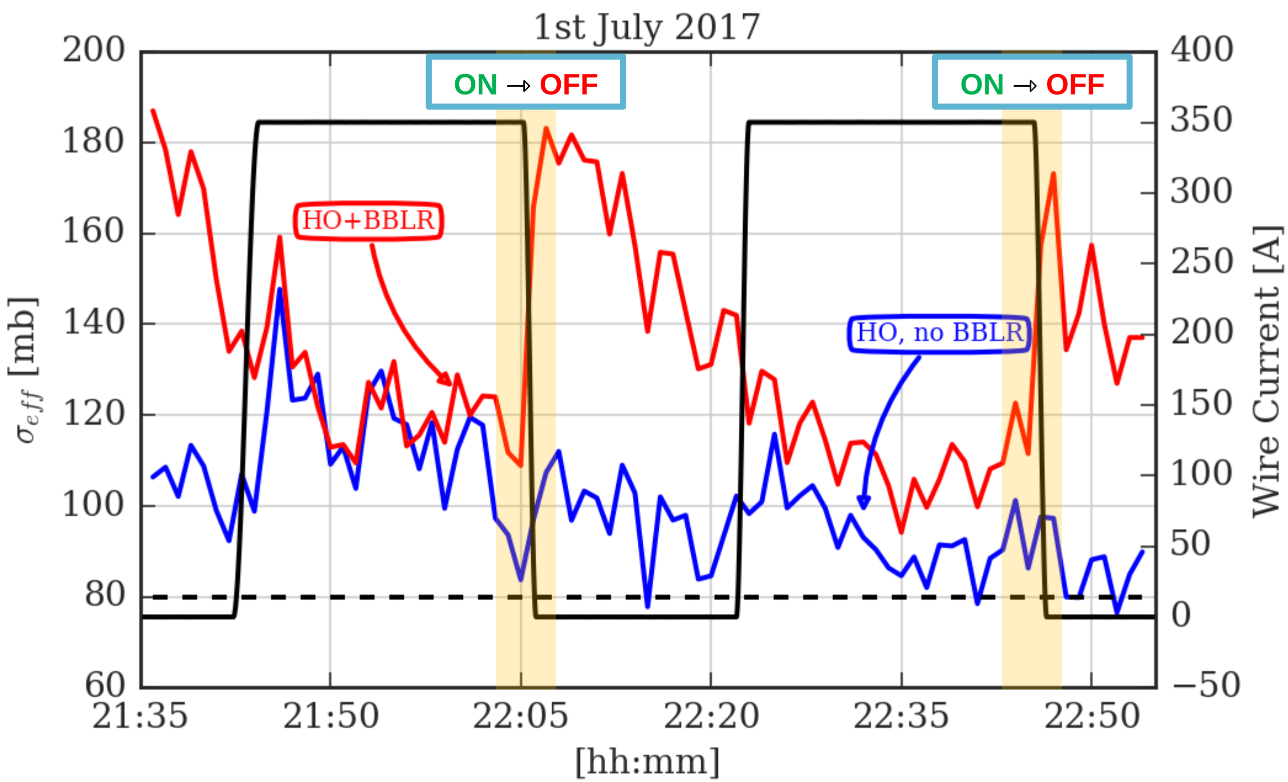
STEP 3
Wire compensation



- The wires were switched ON-OFF for several powering cycles.
- During the powering of the wires, the tunes of the beam (and its position) has to be controlled with high precision: dipolar and quadrupolar contributions of the wires were compensated with feed-forward trims [credit to M. Solfaroli and G.-H. Hemelsoet].

Results on the compensation (I)

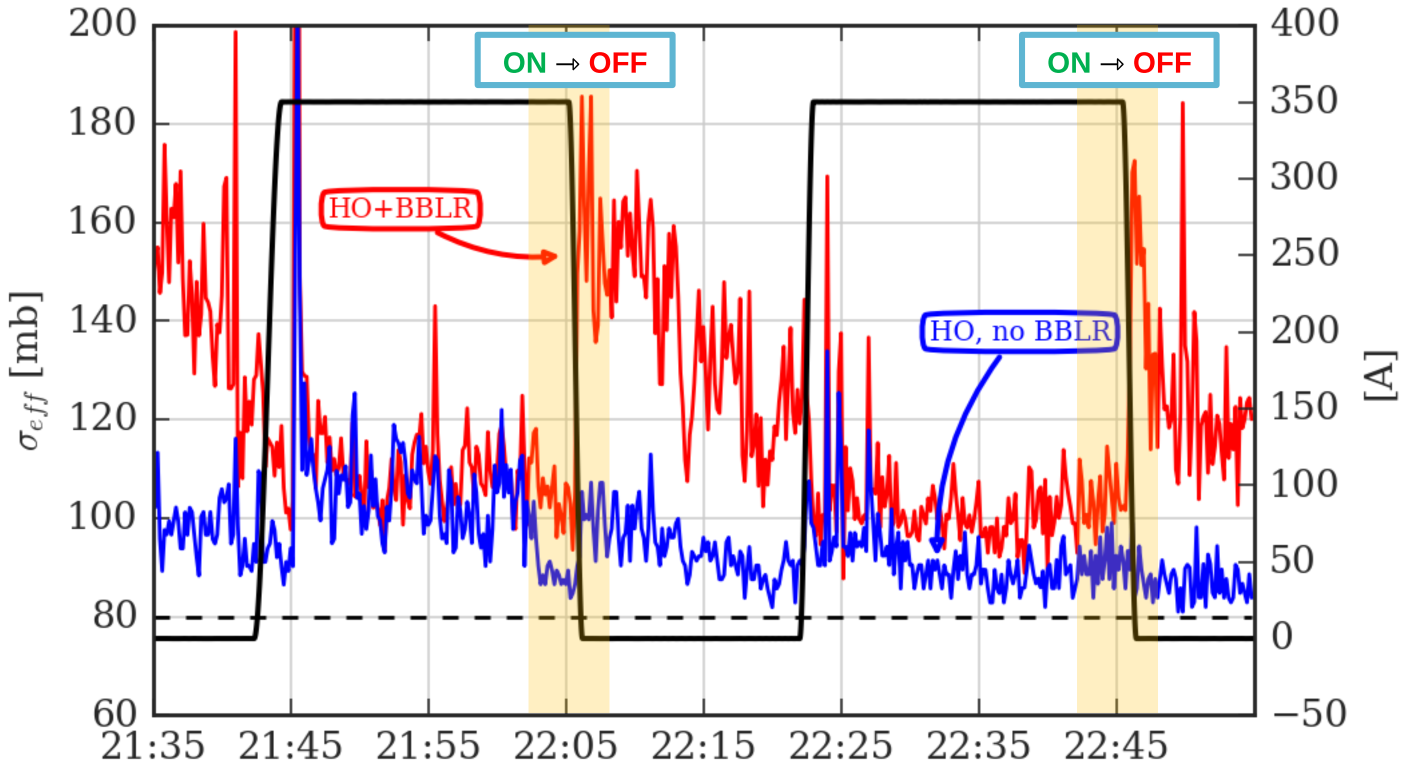
STEP 3
Wire compensation



- Compensation seen from the σ_{eff} [credit to N. Karastathis].
- **Clear effect on the BBCW when switching-off: signal compatible with a contraction of the dynamic aperture of the machine.**

Result on the compensation (II)

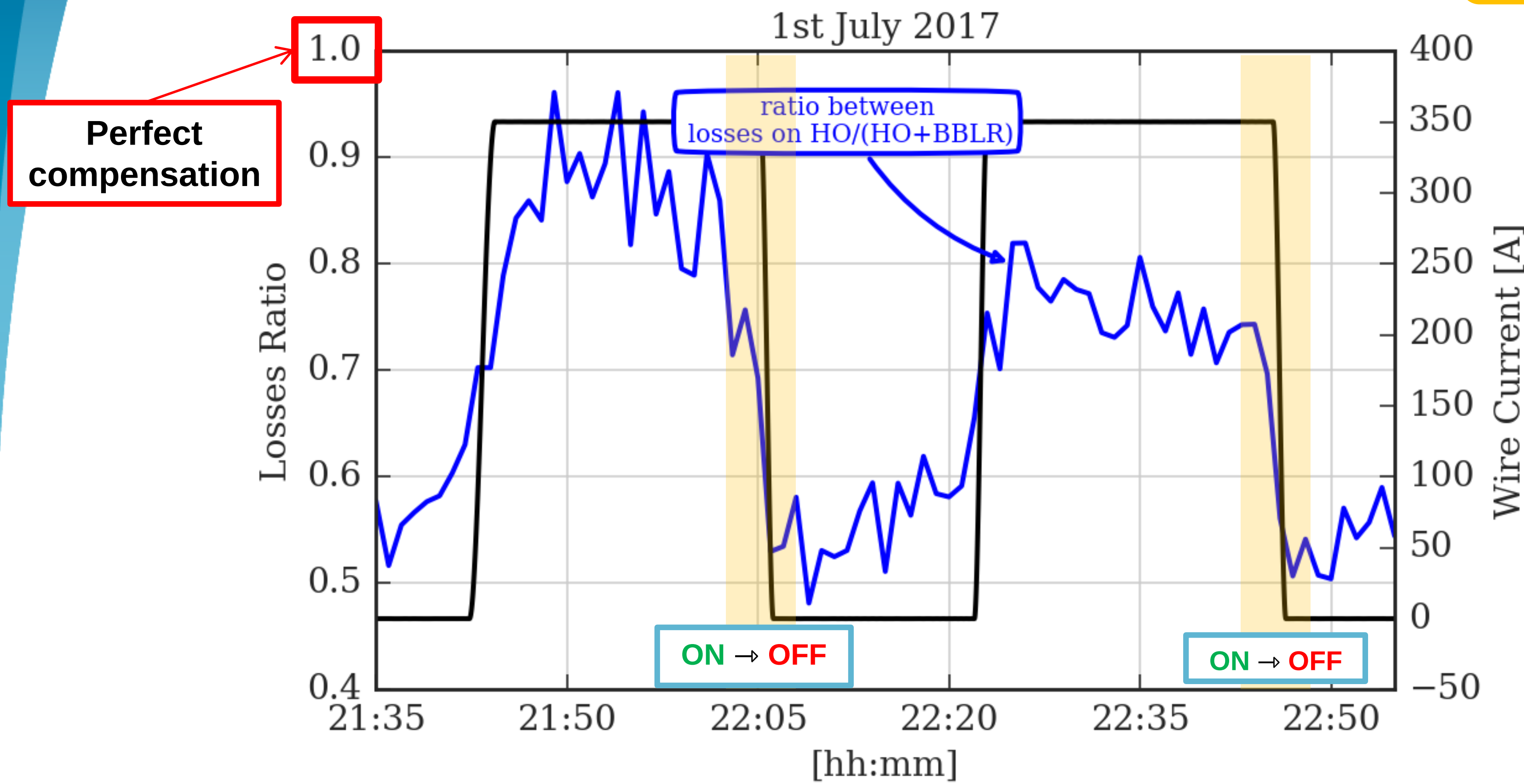
STEP 3
Wire compensation



- Using dBLM signals to compute the cross-section [credit to A. Poyet, A. Gorzawski]: **improved time resolution.**
- A constant calibration factor was adopted to rescale the BLM reading to the FBCT losses.

Result on the compensation (III)

STEP 3
Wire compensation



- From the bunch-by-bunch intensity signals we can measure the effectiveness of the compensation on the losses [credit to M. Hostettler].
- **Clear effect of the BBCW.**

Analysis of the BBCW compensation

S. Fartoukh et al.
PRST-AB 18, 121001

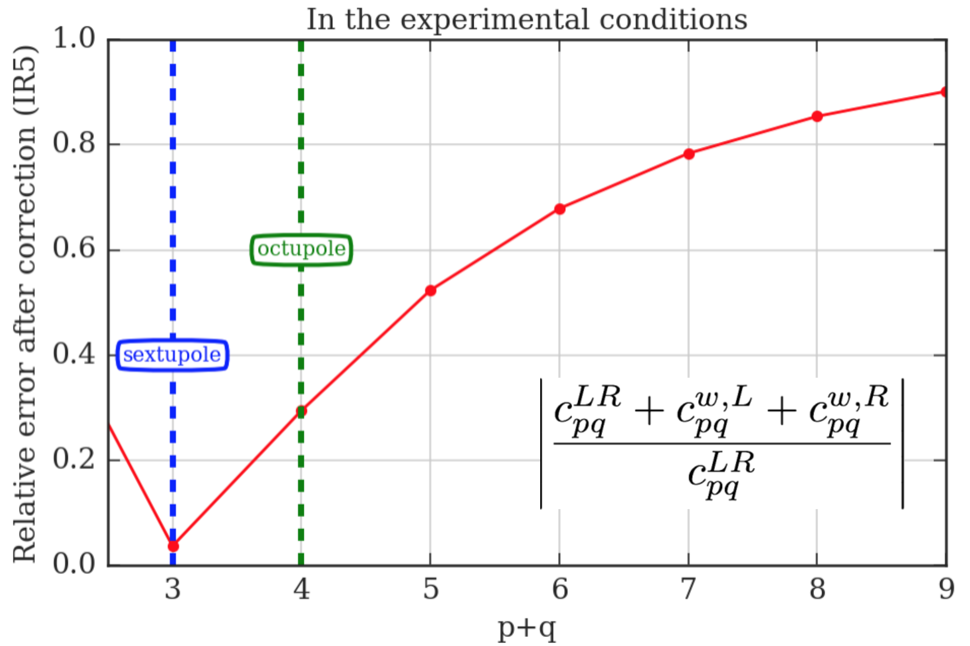
- Given the constraint on the minimal beam-wire distance, it was not possible to compensate all the resonances excited by the B1.
- We used the maximum current of the wires (350 A) to attack as much as possible the BBLR octupolar term.
- The octupolar terms induced by the BBLR in IR5 was reduced by **75%**.

Strong-beam driven resonance

$$c_{pq}^{\rm LR} \equiv \sum_{k\in {\rm LR}} \frac{\beta_x^{p/2}(s_k)\,\beta_y^{q/2}(s_k)}{d_{bb}^{p+q}(s_k)}$$

BBCW driven resonance

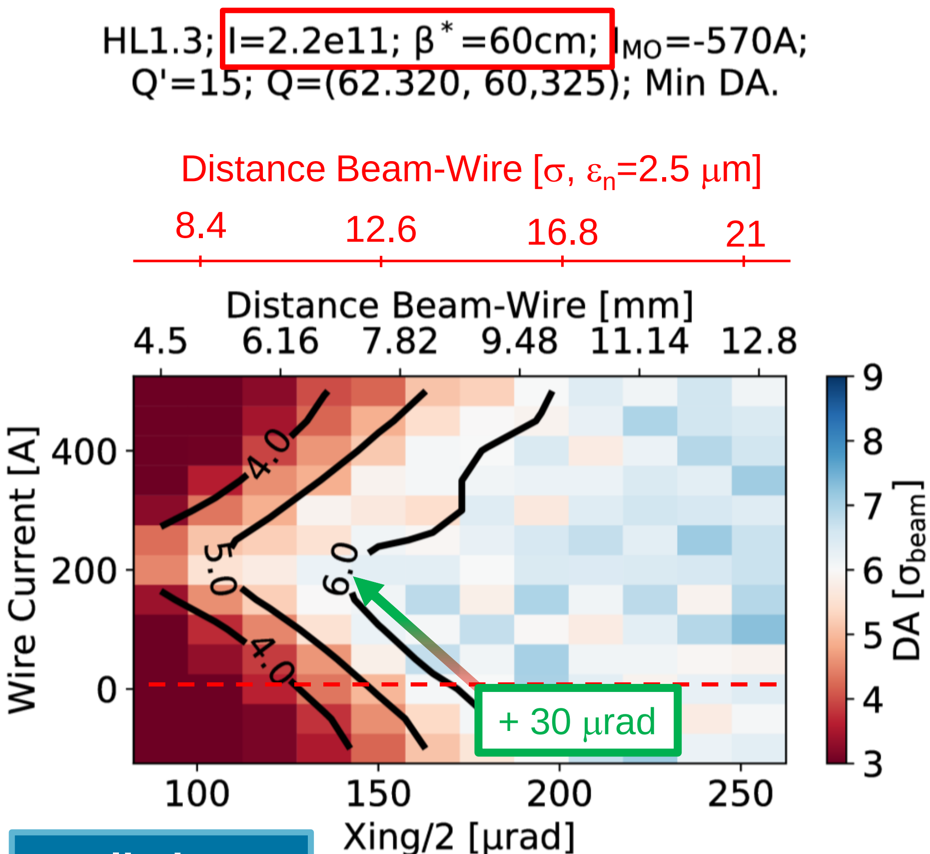
$$\begin{cases} c_{pq}^{w.{\rm L}} \equiv N_{w.{\rm L}} \times \dfrac{(\beta_x^{w.{\rm L}})^{p/2}(\beta_y^{w.{\rm L}})^{q/2}}{(d_{w.{\rm L}})^{p+q}} \\ c_{pq}^{w.{\rm R}} \equiv N_{w.{\rm R}} \times \dfrac{(\beta_x^{w.{\rm R}})^{p/2}(\beta_y^{w.{\rm R}})^{q/2}}{(d_{w.{\rm R}})^{p+q}} \end{cases}$$



Compensation studies: from LHC to HL-LHC

- In the beam-beam team significant **efforts are put on the wire compensation tracking studies** with the two-fold aim to benchmark the LHC results and optimize the HL-LHC scenario with the wires.

- For HL-LHC, **preliminary results without a full optimization** of the longitudinal and transverse wire position, are showing an additional gain of the order of 30 μrad for the half-crossing angle.



Preliminary. HL-LHC start of the levelling

Courtesy of D. Pellegrini

Summary and plans

- During 2017 it was observed for the first time in LHC the effect of a direct compensation of the BBCW. Present understanding indicates that it can be related to the partial compensation of the octupolar effect.
- **In two weeks:** new MD (compensation at β^*=30 cm). AIM: explore the parameter space and correlate it with the analytical model and the tracking results. Margins of improvements on the beta-beating and the orchestration of the feedforward trims, the systematic measurement of the B2 profiles, the B2 tail re-population during the compensation…
- **In YETS17/18:** two vertical wires will be installed in IR1 (s-position of the wires less favorable than in IR5 for the compensation).
- **In 2018:** compensation experiment in IR1 and IR5.
- In parallel to the experimental studies, significant efforts put in simulation studies to benchmarking the LHC results and to study in more details the wire potential for the HL-LHC.

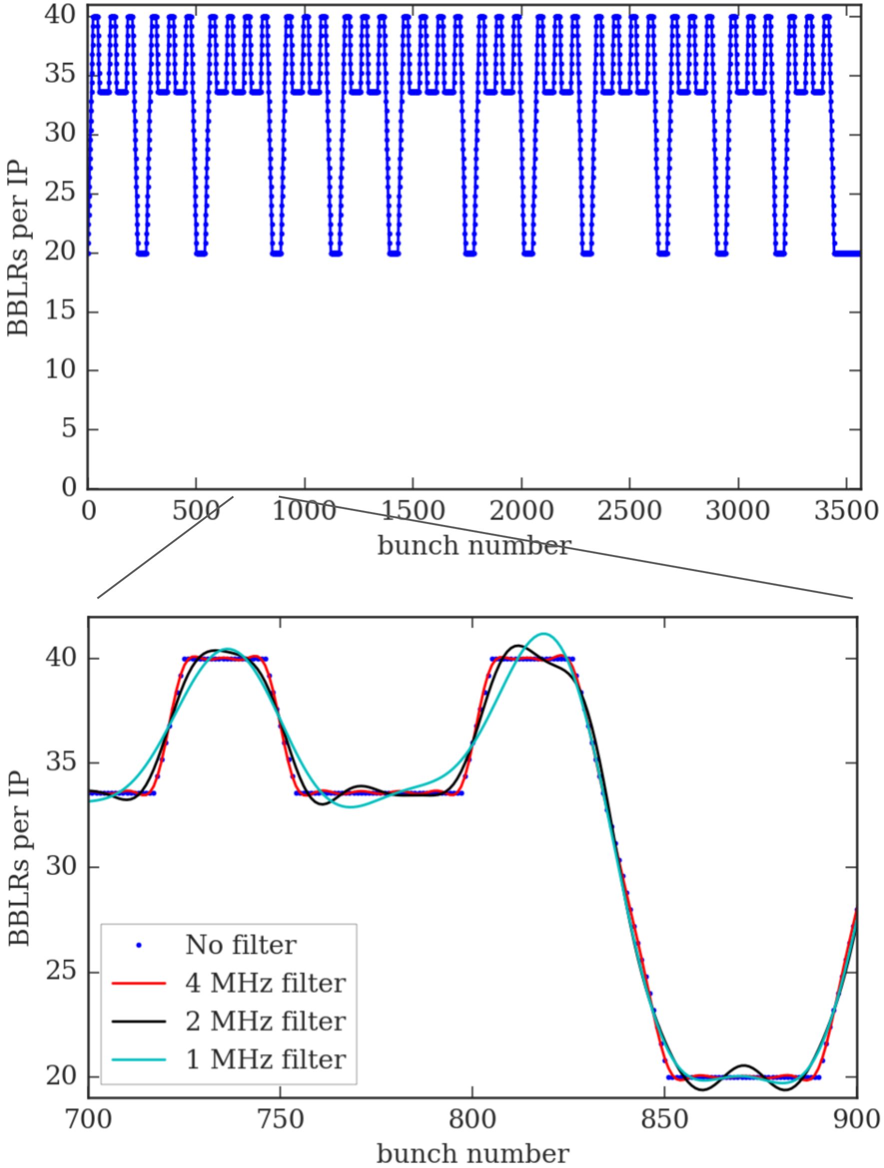
Thank you for the attention!

BBLR compensation MD team: *D. Amorim, H. Bartosik, R. Bruce, X. Buffat, L. Carver, G. Cattenoz, E. Effinger, S. Fartoukh, M. Fitterer, N. Fuster, M. Gasior, M. Gonzales, A. Gorzawski, G.-H. Hemelsoet, M. Hostettler, G. Iadarola, R. Jones, D. Kaltchev, K. Karastatis, S. Kostoglou, I. Lamas Garcia, T. Levens, A. Levichev, L. E. Medina, D. Mirarchi, J. Olexa, S. Papadopoulou, Y. Papaphilippou, D. Pellegrini, M. Pojer, L. Poncet, A. Poyet, S. Redaelli, A. Rossi, B. Salvachua, H. Schmickler, F. Schmidt, K. Skoufaris, M. Solfaroli, G. Sterbini, R. Tomas, G. Trad, A. Valishev, D. Valuch, C. Xu, C. Zamantzas, P. Zisopoulos and all participants to the design, production and commissioning of the wire compensator prototypes (WP2, WP5, WP13 and LHC MD coordinators)*.

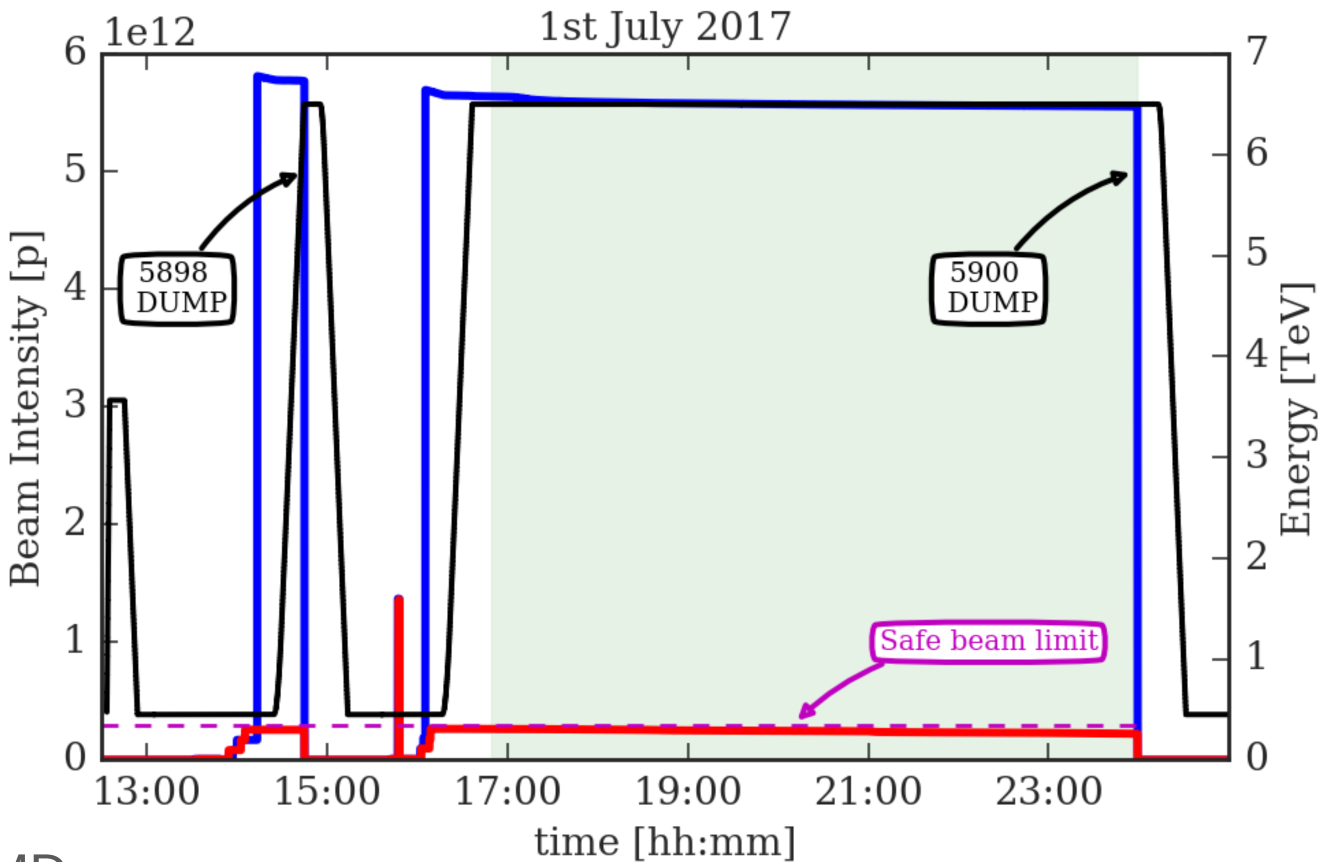
PACMAN bunches and I_w modulation

The needed I_w modulation BW is of the order of 4 MHz (x10 lower than the bunch frequency).

The wavelength in vacuum of a 4 MHz EM wave is ~75 m.



MD2202



- 10 h MD.
- The FILL5898 was dumped (RF on B1, not clear the reason, RF experts suggest a glitch on the interlock). Half-RF detuning.
- The observations we report concern the FILL5900. Full-RF detuning.

Numerical results from the RDT

We will use the RDT criterion presented and described in details in

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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]

Goal: compensate the BBLR RDTs by using 2 BBCs per IP.

Strong-beam driven RDTs

$$c_{pq}^{\mathrm{LR}} \equiv \sum_{k\in \mathrm{LR}} \frac{\beta_x^{p/2}(s_k)\beta_y^{q/2}(s_k)}{d_{bb}^{p+q}(s_k)}$$

BBCW driven RDTs

$$\begin{cases} c_{pq}^{w.\mathrm{L}} \equiv N_{w.\mathrm{L}} \times \dfrac{(\beta_x^{w.\mathrm{L}})^{p/2}(\beta_y^{w.\mathrm{L}})^{q/2}}{(d_{w.\mathrm{L}})^{p+q}} \\ c_{pq}^{w.\mathrm{R}} \equiv N_{w.\mathrm{R}} \times \dfrac{(\beta_x^{w.\mathrm{R}})^{p/2}(\beta_y^{w.\mathrm{R}})^{q/2}}{(d_{w.\mathrm{R}})^{p+q}}, \end{cases}$$

Assuming

1. the same N_w and d_w for both BBCWs,
2. that the strong beam acts as a DC wire,
3. that the phase advance between BBLRs and BBLRs/BBCW is 0 or 180 deg.

the paper gives **N_w and d_w to compensate 4 RDTs (p1q1, q1p1, p2q2, q2p2) in closed form.**

It is shown as a numerical evidence that by compensating 4 RDTs one can minimize ALL RDTs *if the position of BBCW is conveniently chosen*.

Using the paper's formalism, we will show numerical results on the present LHC (2017 ATS).

IDEAL CASE: 2 BBCW for IP at s_{opt}=+-159 m

RDT compensation map

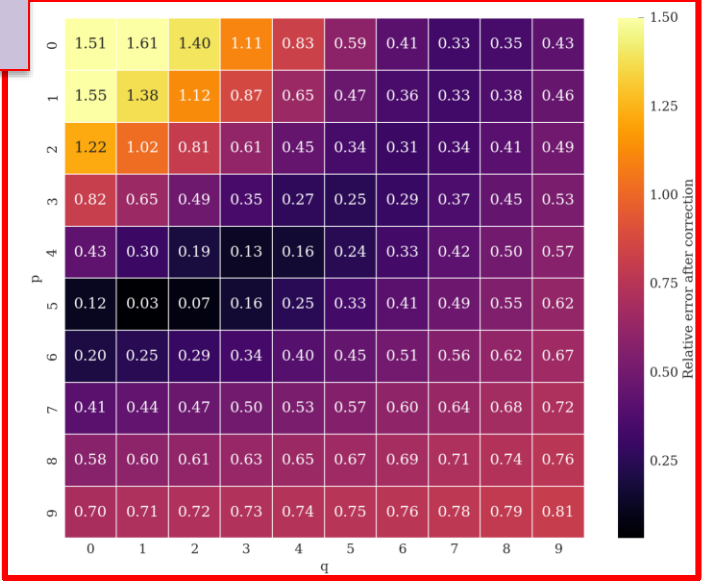
in color code

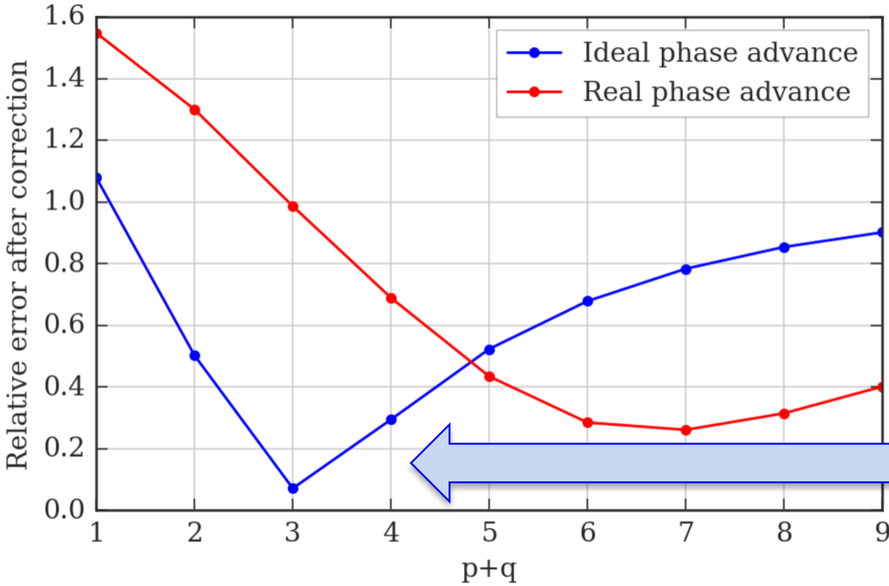
$$\left| \frac{c_{pq}^{LR} + c_{pq}^{w,L} + c_{pq}^{w,R}}{c_{pq}^{LR}} \right|$$

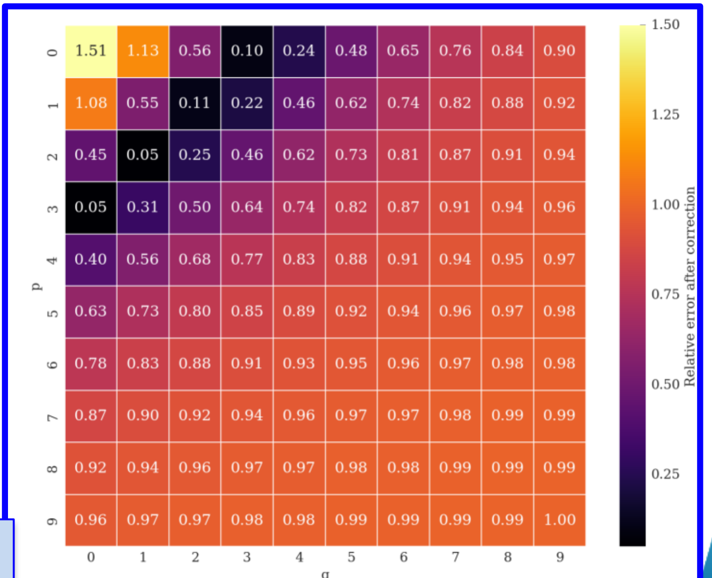
As expected (under the mentioned assumptions) the compensation is covering many more RDTs than the 4 used to set the BBCWs (green boxes). The p+q=1 and p+q=2 could be addressed by using “local” linear magnets (Q4s and the Q4 correctors).

The MD results and the RDT

Real phase advance considered



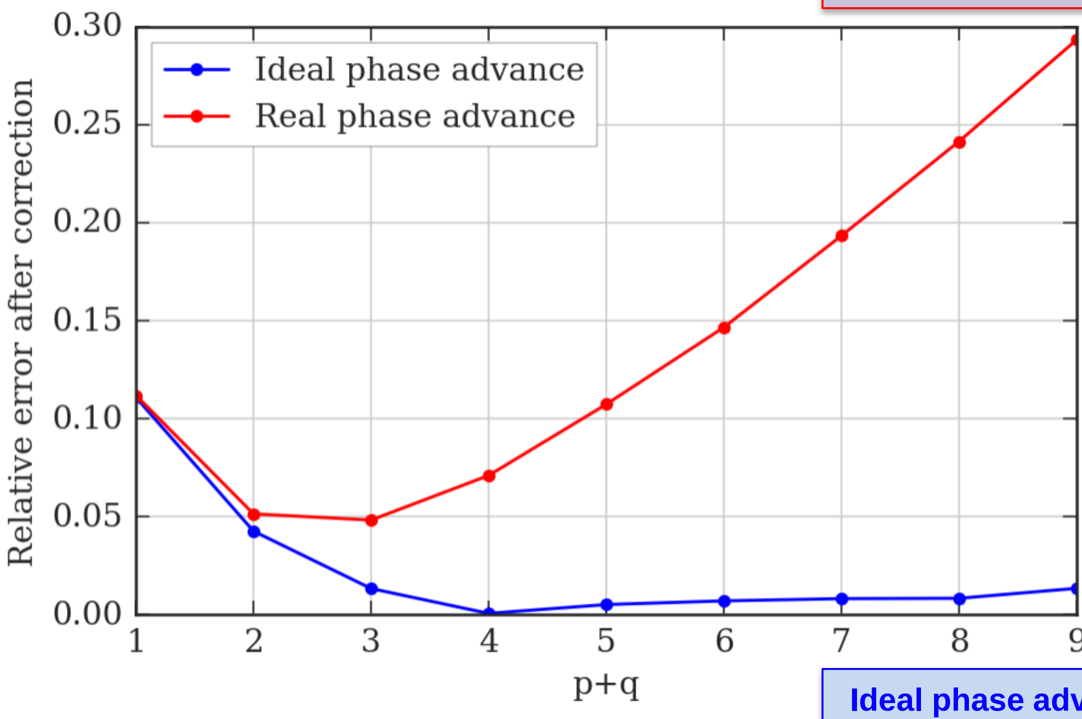




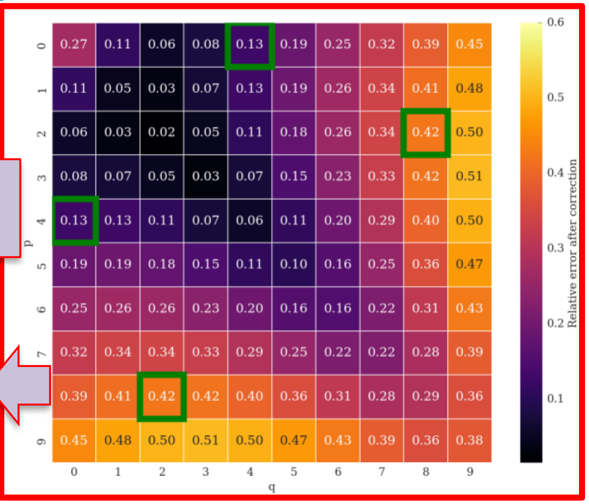
The observed effect of the BBCW can be related to a partial compensation of the detuning terms.

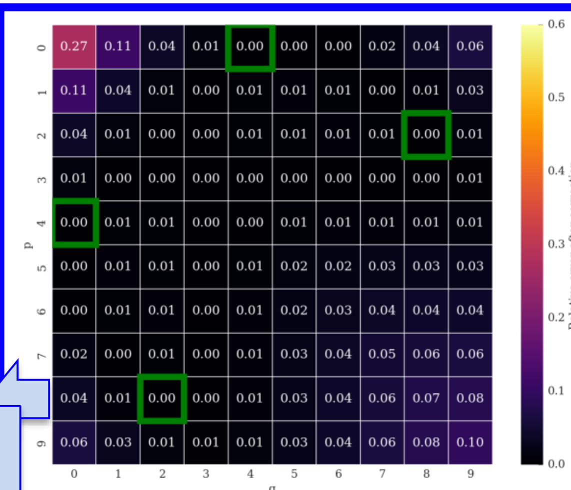
Ideal phase advance considered (β*→0)

IDEAL CASE: considering the phase advance.



Real phase advance considered



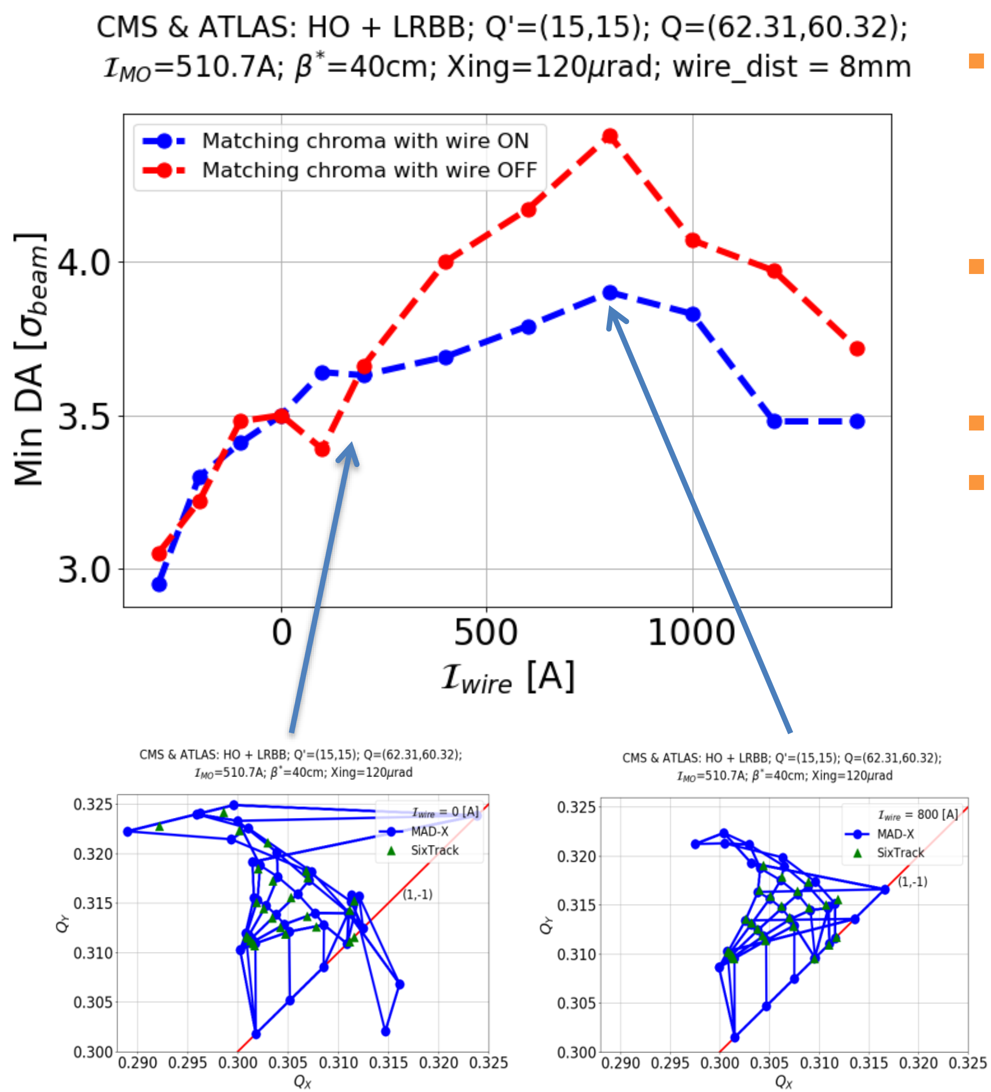


Ideal phase advance considered (β*→0)

One can quantify a posteriori the effect of the phase advance.

The compensation of the RDT does degrade. The compensation of detuning terms (Q-footprint compression) is not affected.

DA simulations with Wire in MD-like conditions I



- MD-like conditions: d_w=8 mm. LR in IR1/5 but wire only in IR1, real aspect ratio at wire position, phase advances.
- A modest gain of DA is observed for 8 mm wire-beam distance.
- Optimal DA for 800 A.
- With no rematch of the chromaticity (as in the MD), the gain of DA is improved.

- Good agreement between footprints from MADX and Sixtrack.
- Improvement observed but no clear identification of the optimum.

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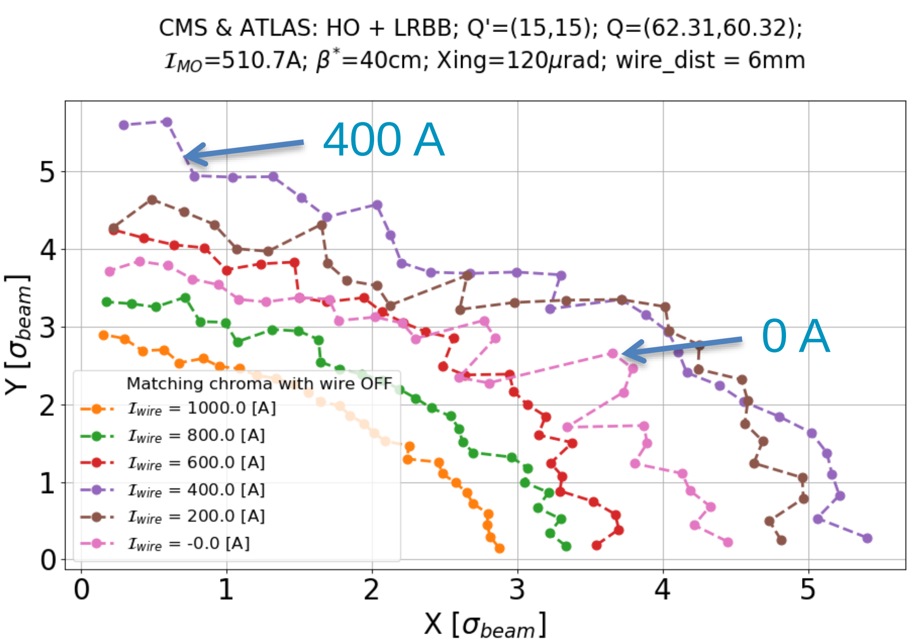
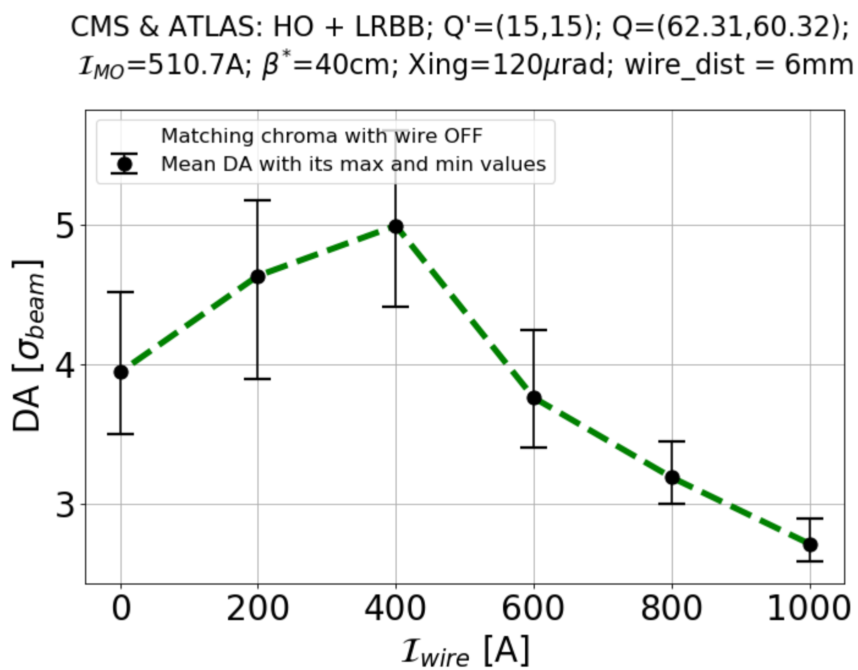
DA simulations with Wire in MD-like conditions II

- Push d_w to 6 mm
- Still not ideal conditions: LR in IR1/5 but wire only in IR1, aspect ratio at wire position, phase advances.
- **1σ** (@2.5 μm) DA gained for an optimal wire current of ~400 A.
- Clear improvement over all the angles.





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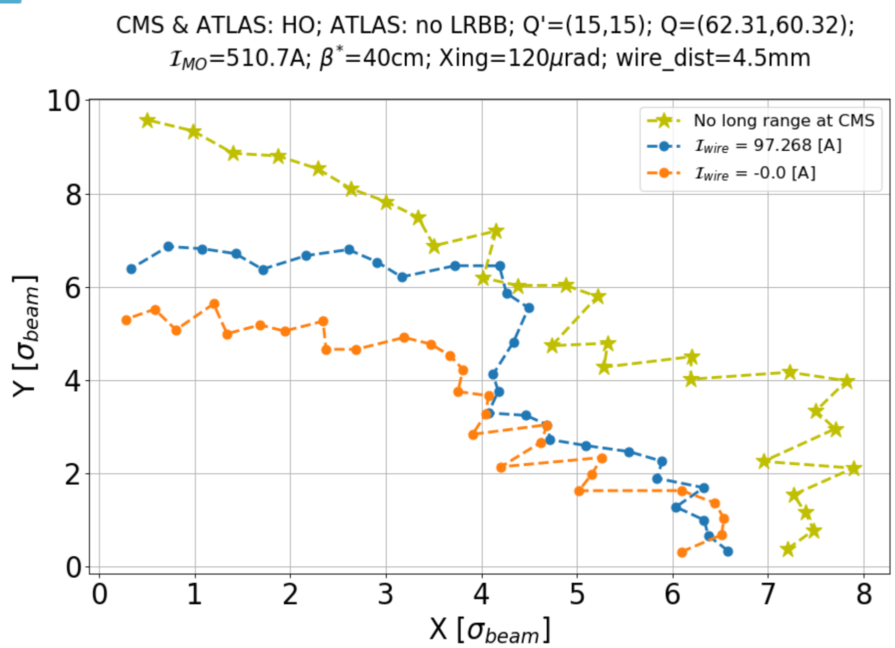
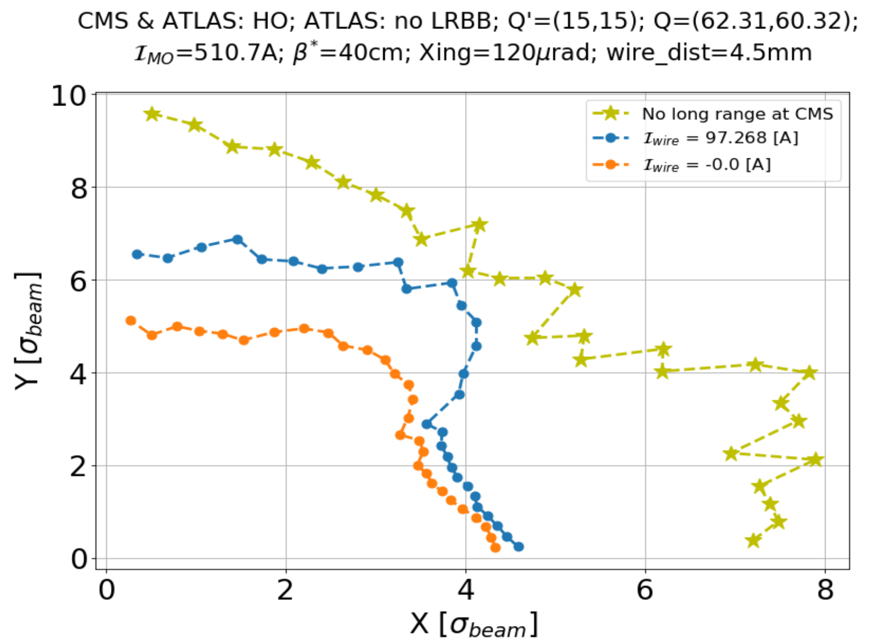
“Strong beam”-wire equivalence: tracking

Standard Strong Beam



Zero-emittance-long-range Strong Beam



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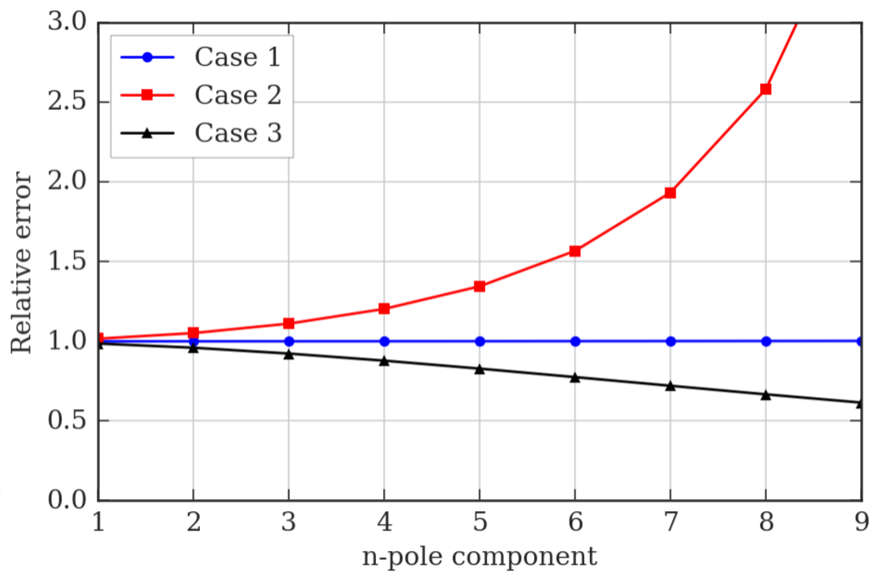
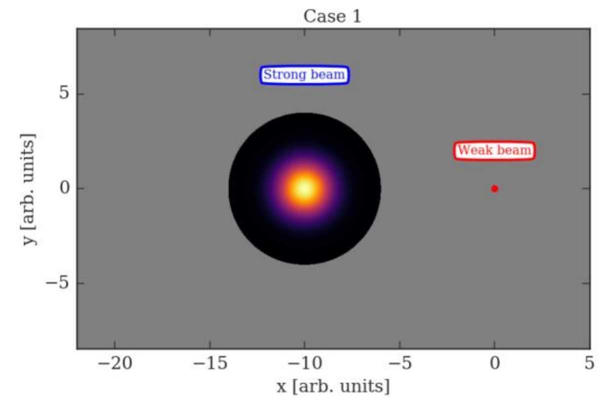
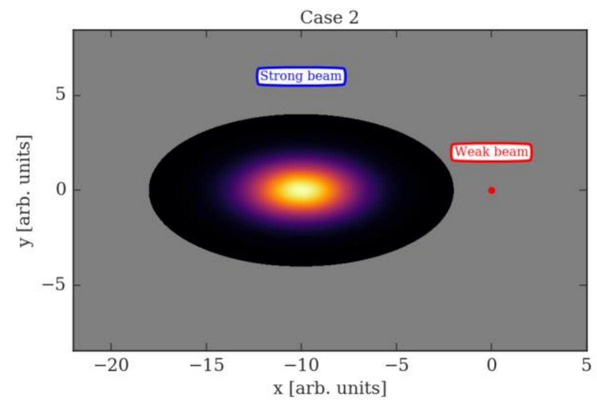
- The zero-emittance-LR strong beam does not show a better DA.
- Effect of phase advance? Plans to test with the wire at ~70 m for better phases.

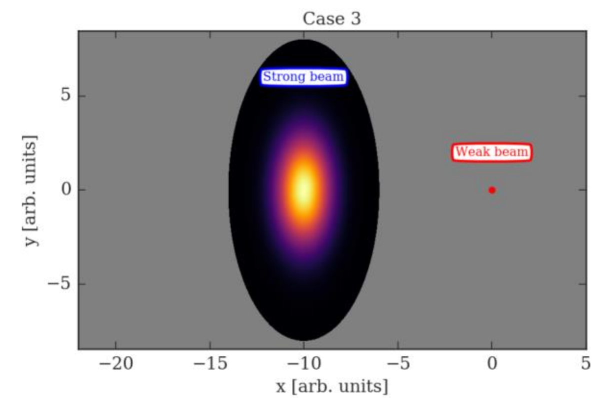
“Strong beam”-wire equivalence

- For $\beta_x \neq \beta_y$ the “strong beam”-wire equivalence is not valid anymore
- We compare the strong beam field and the wire field in terms of multipoles
- Case 1: $\beta_x = \beta_y$, perfect equivalence
- Case 2: $\beta_x = 4 * \beta_y$, see plot below
- Case 2: $\beta_y = 4 * \beta_x$, plot below
- We assume bi-Gaussian density (4 σ cut)









HiLumi HL-LHC PROJECT

First attempts of BBCW in HLLHC1.3

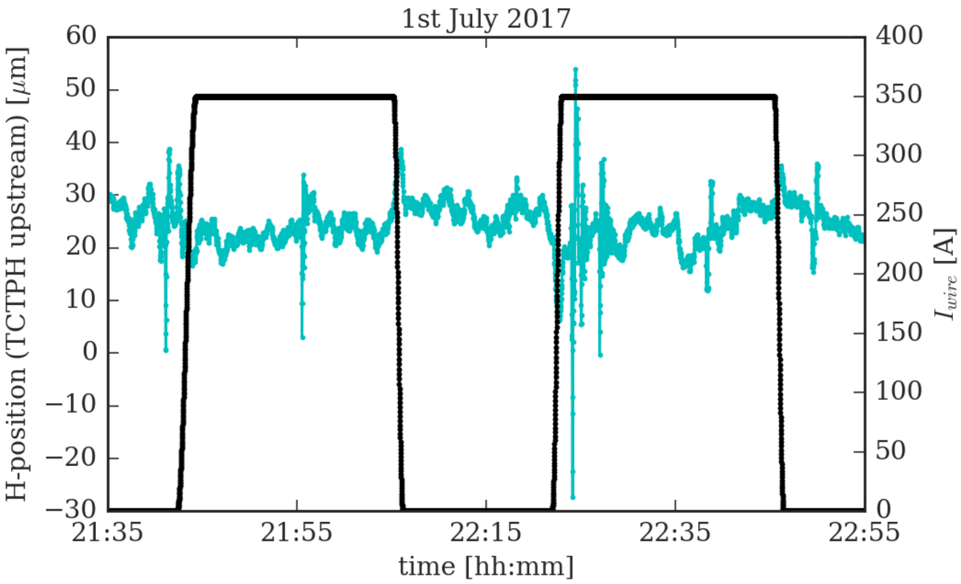
- B1 tracking with **operational settings** for emittance, tunes, chroma, octupoles.
- **4 wires** (L/R IP1/5) installed in the crossing plane.
- The wires are arbitrarily placed at **+/-150m** from the IPs.
- The **distance** is tuned so that the beam-wire normalised separation is the same as the normalised crossing.
- Likely a **suboptimal** configuration to be further refined.

β* = 60 cm	H Beta [m]	V Beta [m]
wire_l1.b1	1052	1181
wire_r1.b1	1178	1054
wire_l5.b1	1054	1182
wire_r5.b1	1181	1055

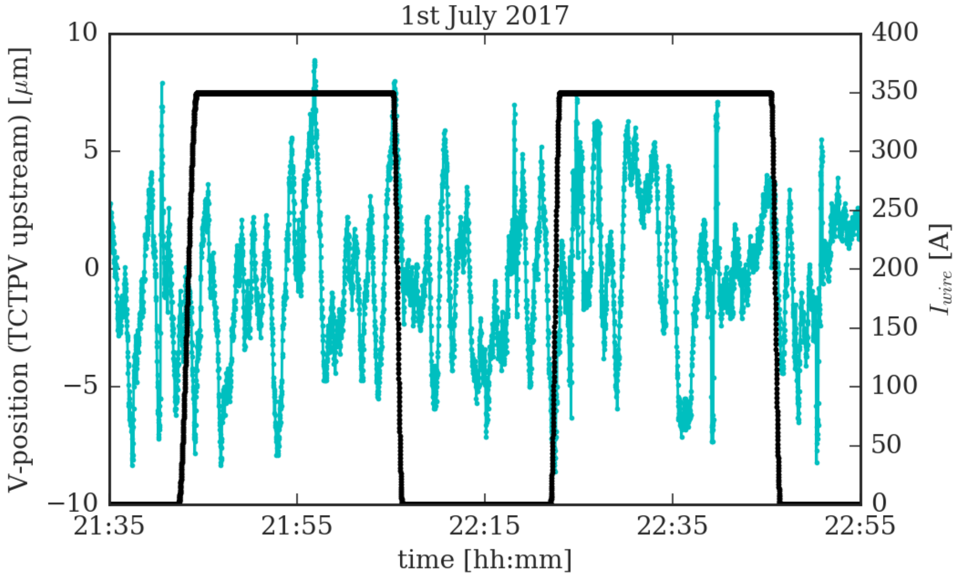
β* = 20 cm	H Beta [m]	V Beta [m]
wire_l1.b1	3006	3641
wire_r1.b1	3649	2999
wire_l5.b1	2995	3645
wire_r5.b1	3636	3003

BBCW MD: sanity checks on H/V-position

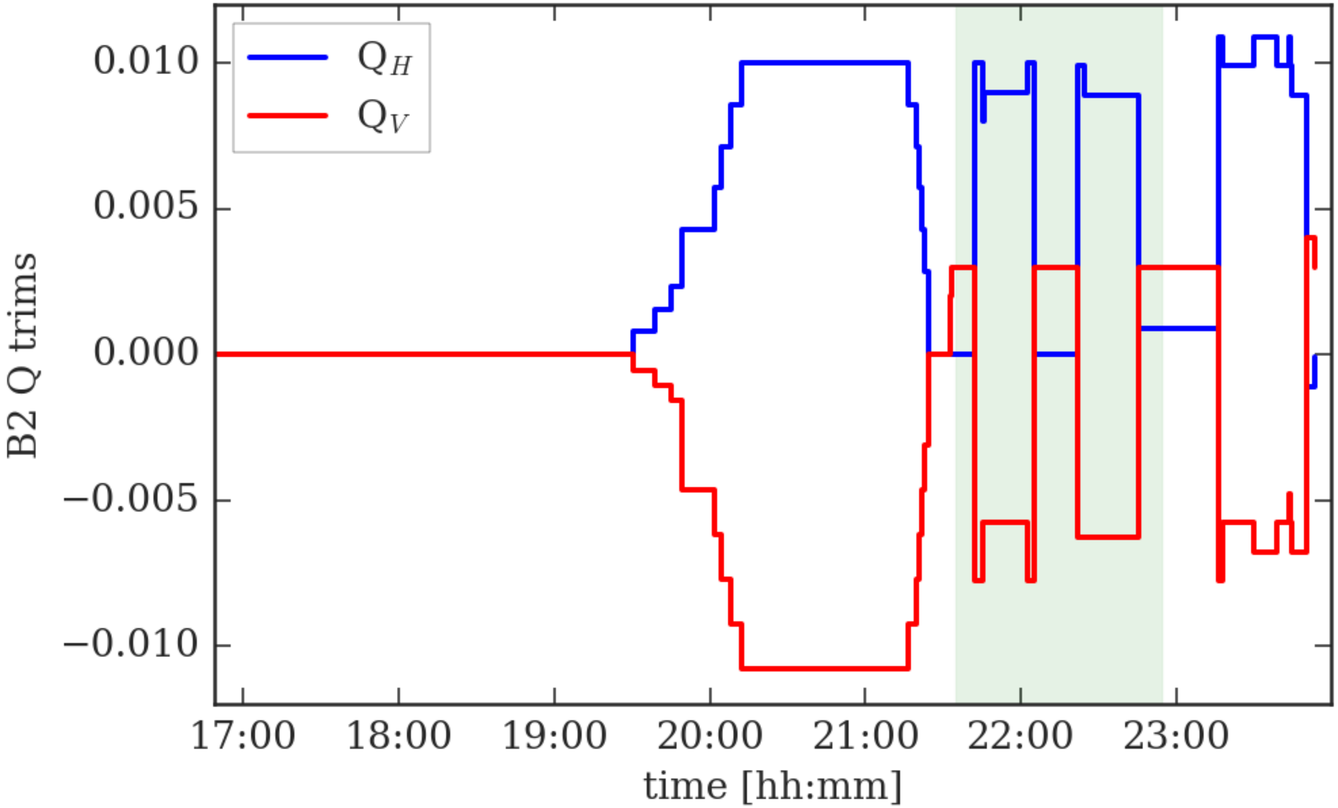
- The H-position of the beam is well under control.



- The V-position and correctors behaviour confirm a very good V-alignment of the BBCW.

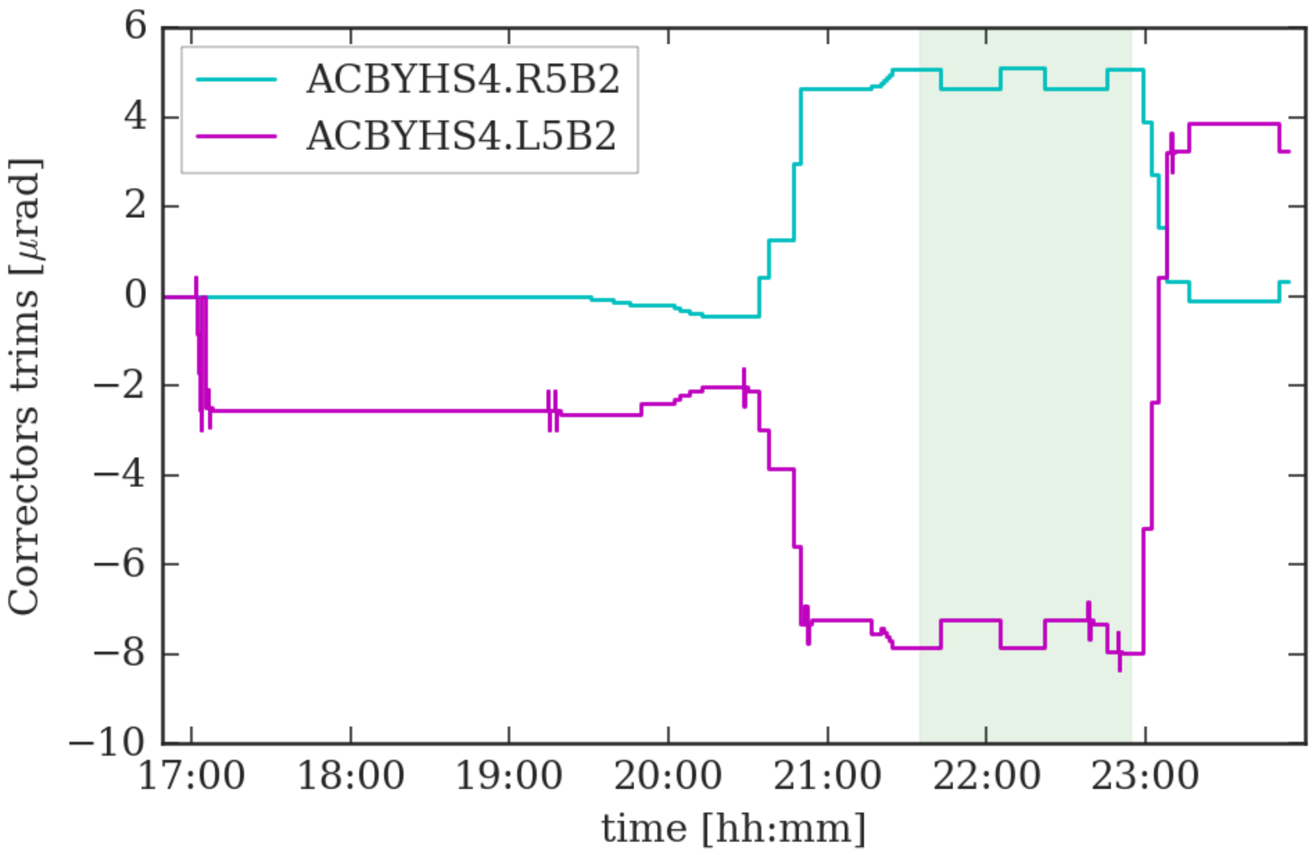


BBCW MD: Q trims



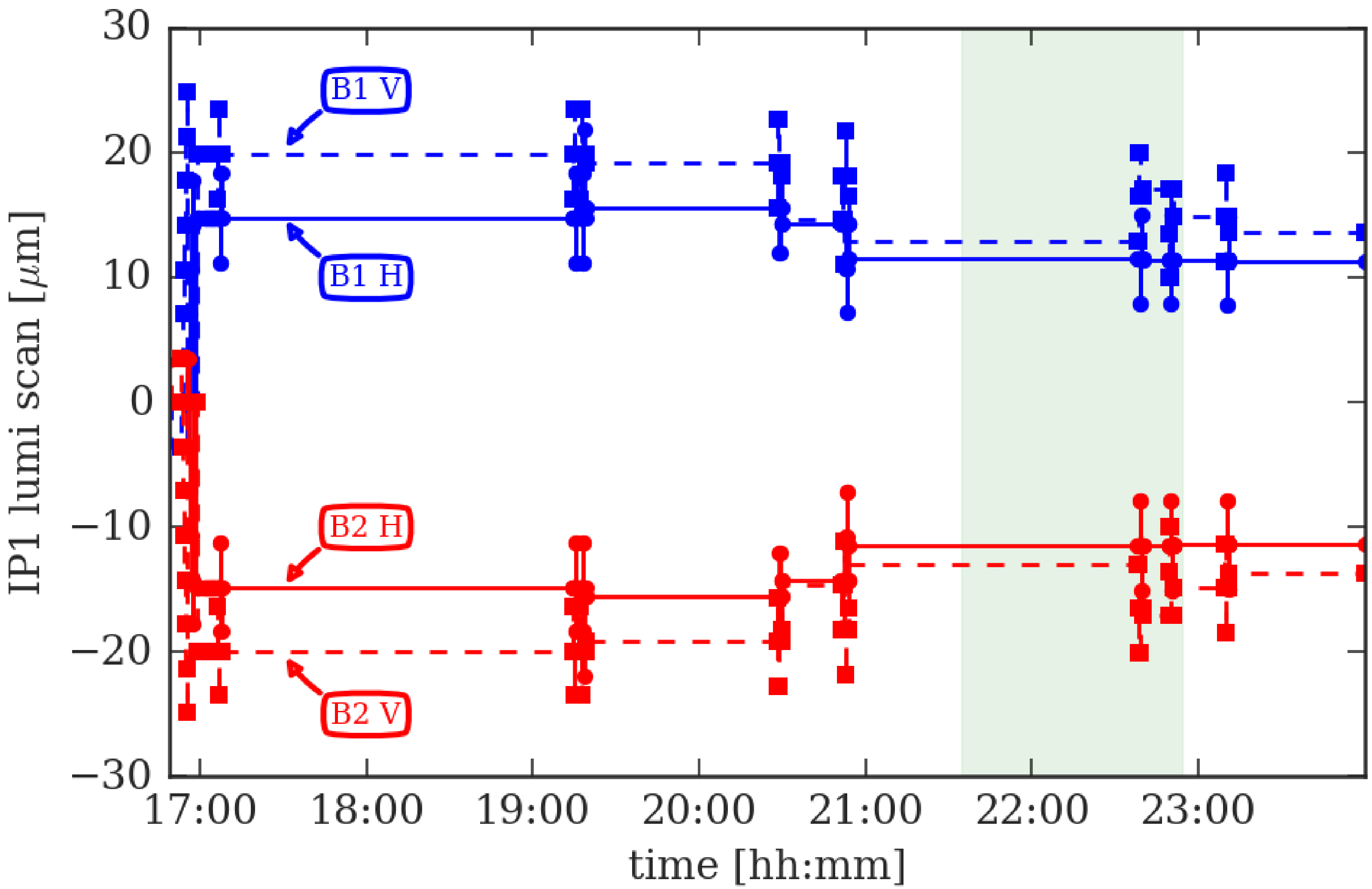
The Q-trims are mostly due to the feedforward.

BBCW MD: dipolar trims

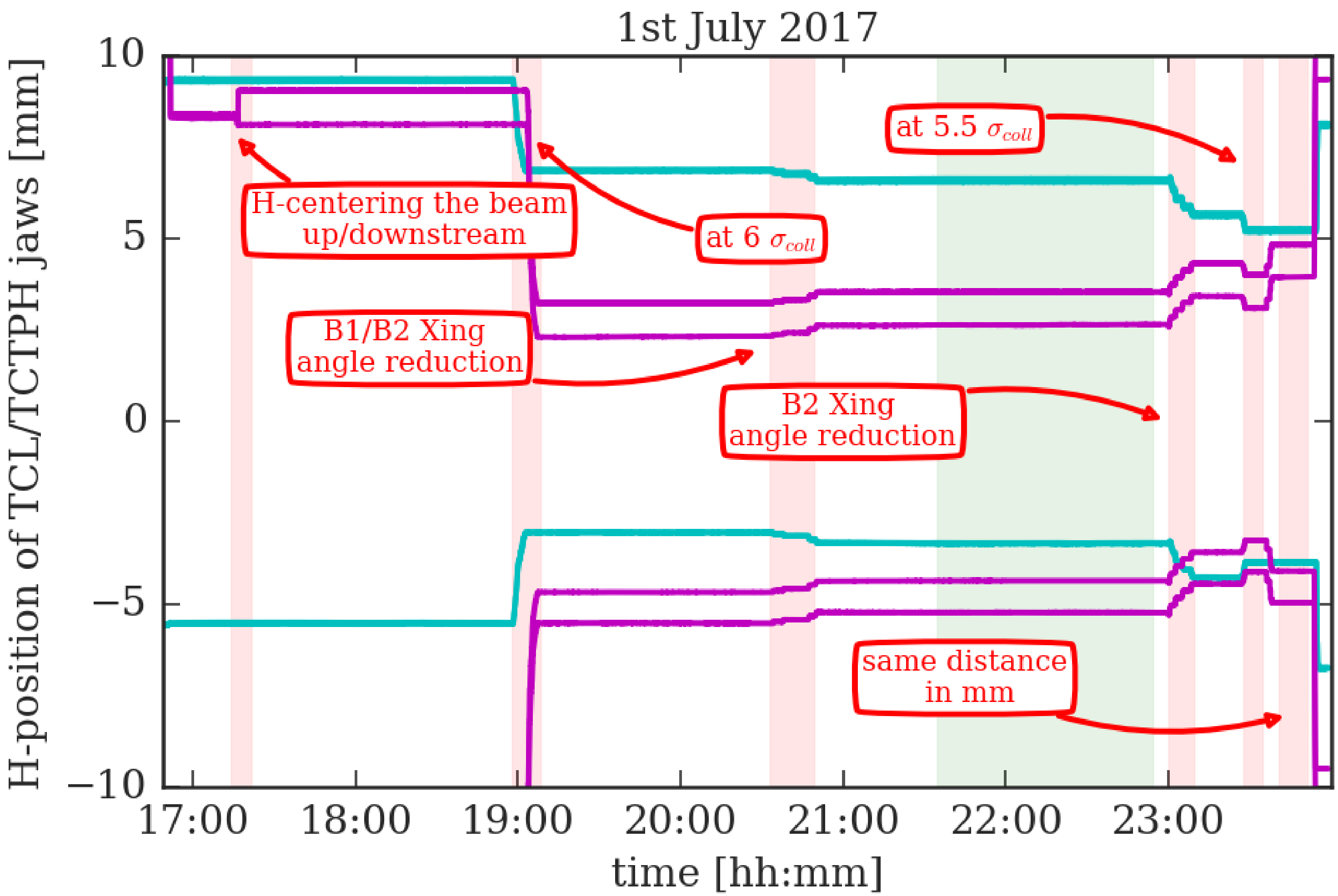


The correctors trims are mostly due to the crossing angle settings.

BBCW MD: optimizing HO collision

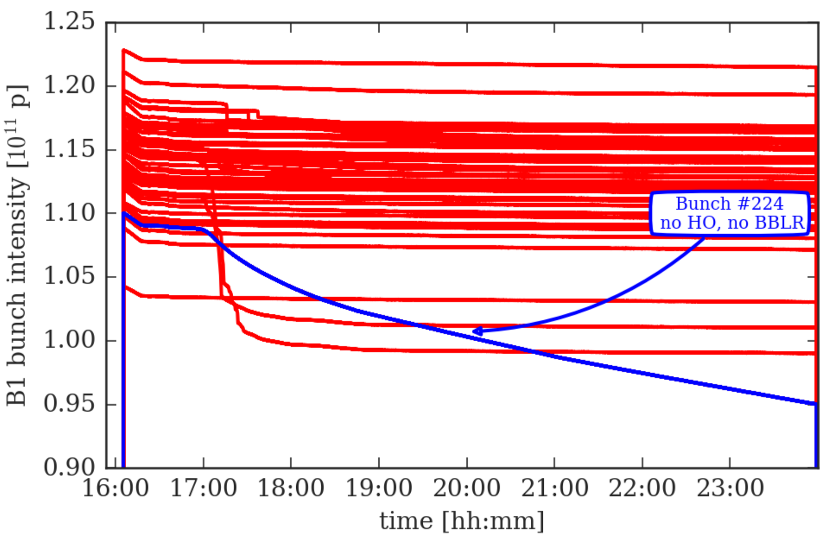


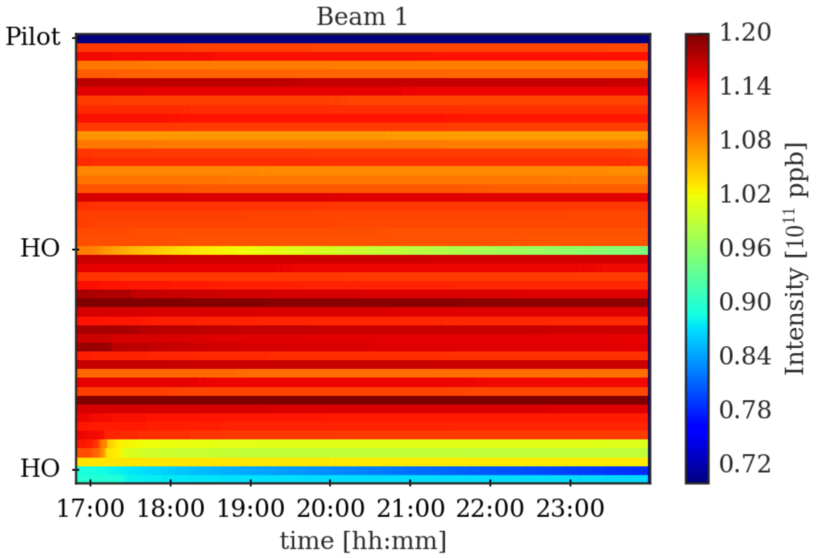
BBCW MD: wires H-positioning

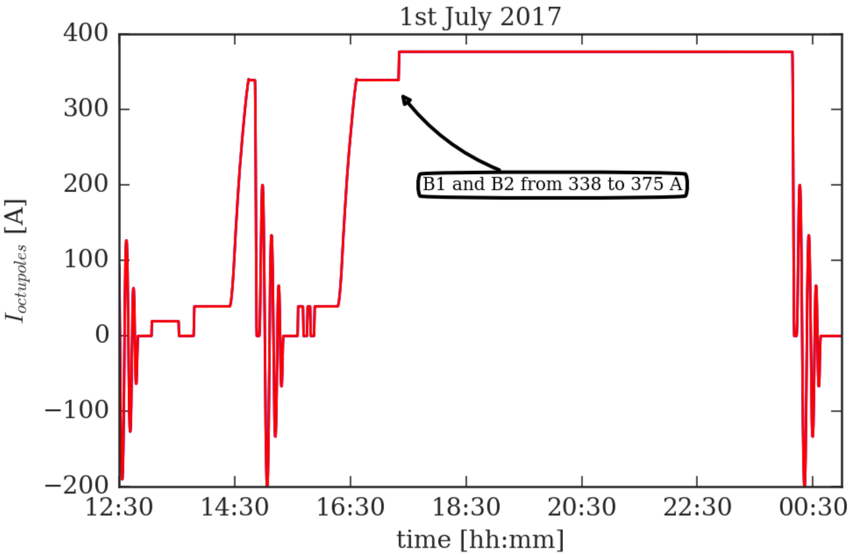


The hectic activity on the BBCW positioning.

BBCW MD: instability of B1



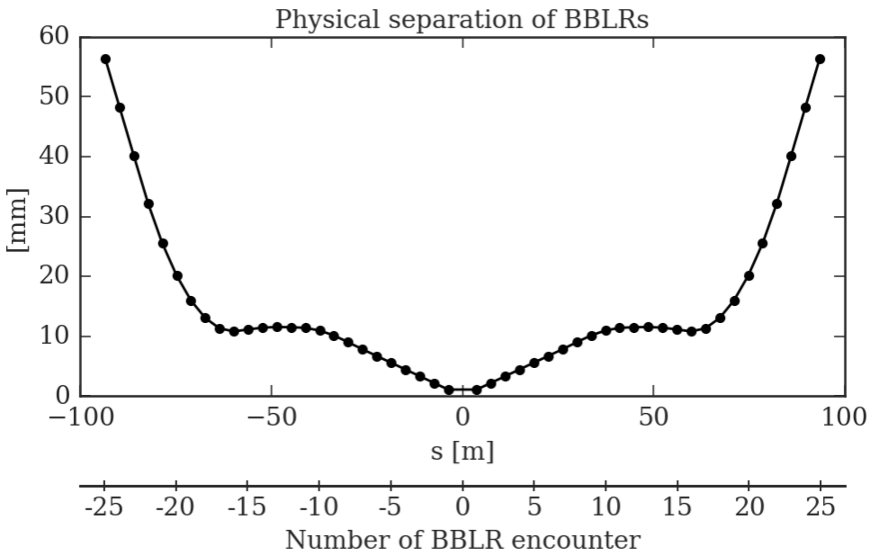


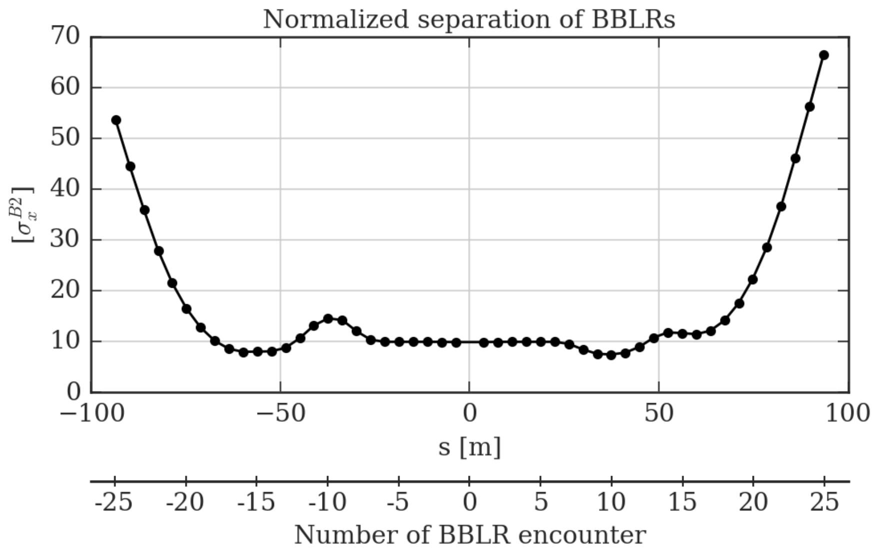


- During next MD we will use stronger octupole settings to avoid the instability of the non-colliding bunches in B1.

ATS 2017 optics

	NAME	X	PX	Y	PY	BETX	BETY	sigma_x at 3.5 um at 6.5 TeV [mm]
7062.030793	TCL.4L5.B2	1.527841e-03	0.000054	0.003836	-4.970527e-05	845.954861	1327.127536	0.653755
7212.060793	IP5	1.936385e-15	-0.000150	-0.001500	-9.267840e-15	0.400000	0.400000	0.014216
7360.005793	TCTPH.4R5.B2	-1.422381e-03	0.000034	0.002863	3.456410e-05	1349.329513	903.299673	0.825659

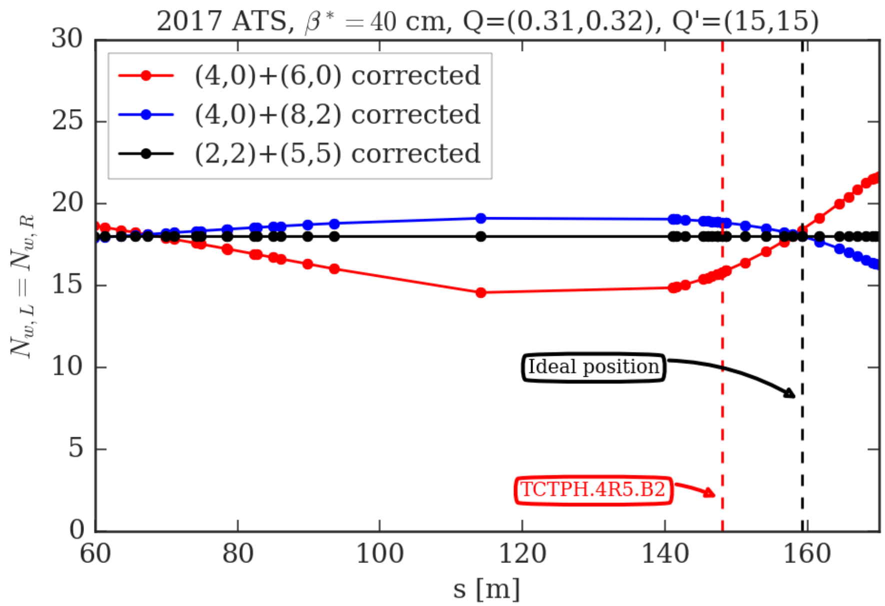


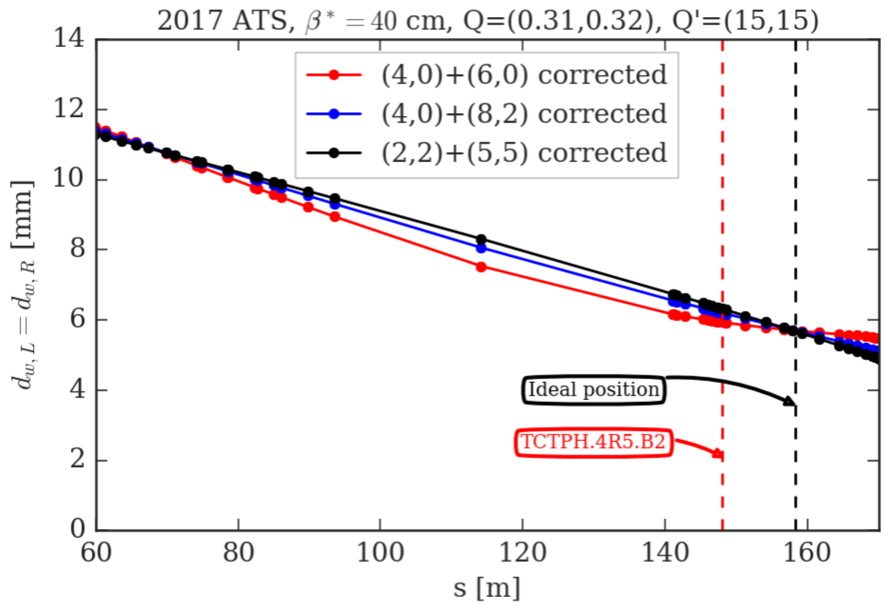


RDT criterion for ATS 2017 and θ_c=150 μm

By plotting the $N_w(s)$ and $d_w(s)$ for different RDT minimization strategy, one sees there are specific s-positions, s_{opt}, that minimizes more than the usual 4 RDTs.

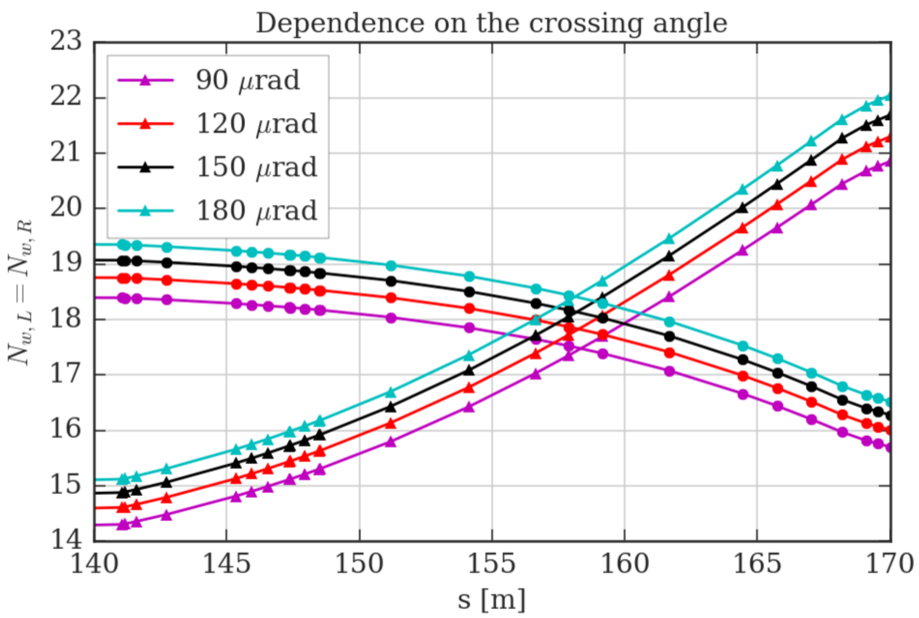
The BBCW is positioned ~10 m apart with respect to the optimal position.

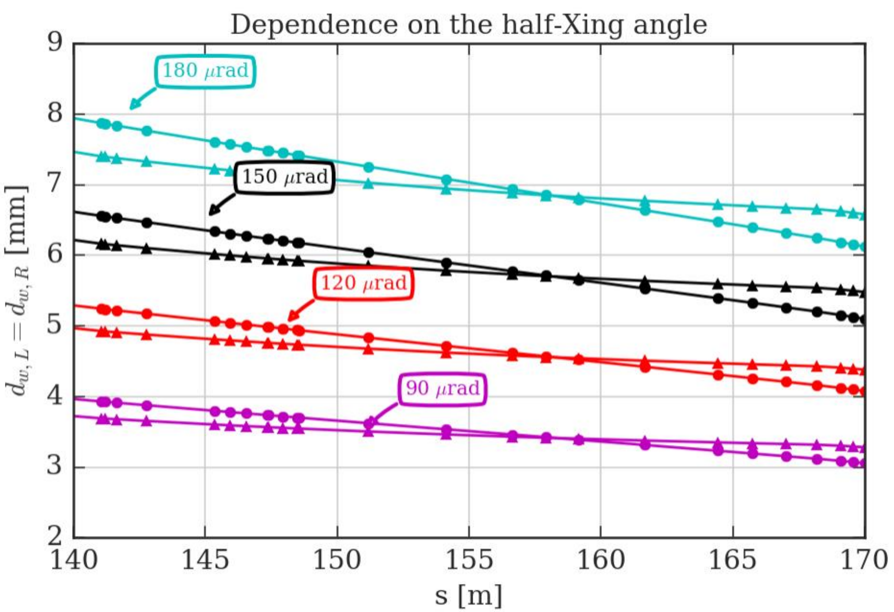




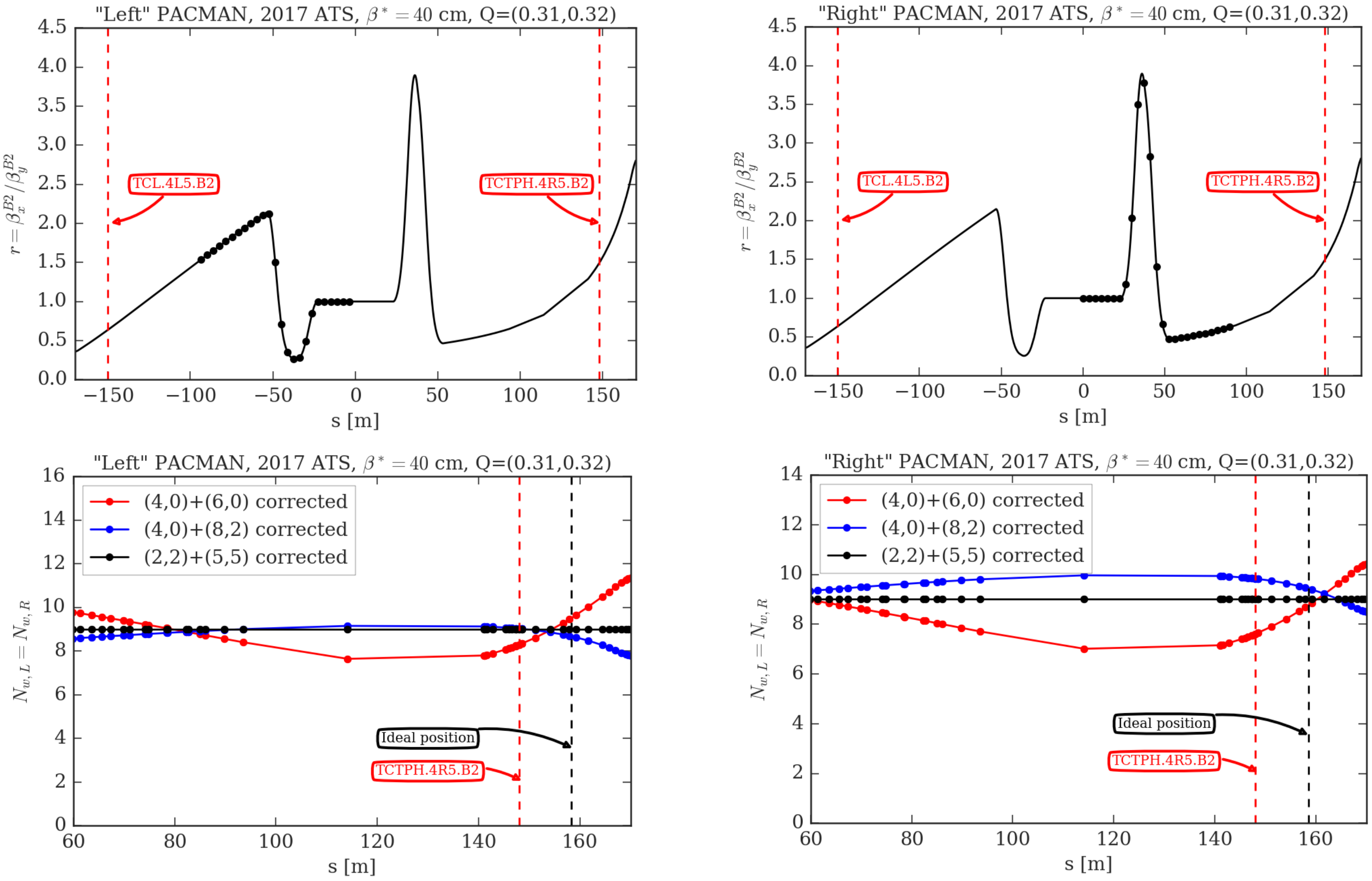
s_{opt}, N_w and d_w on crossing angle

- There is no dependence of s_{opt} on the crossing angle.
- N_w dependence on the crossing angle is marginal (smaller crossing angle, smaller N_w).
- d_w is linearly dependent on the crossing angle.





PACMAN bunches and s_{opt}

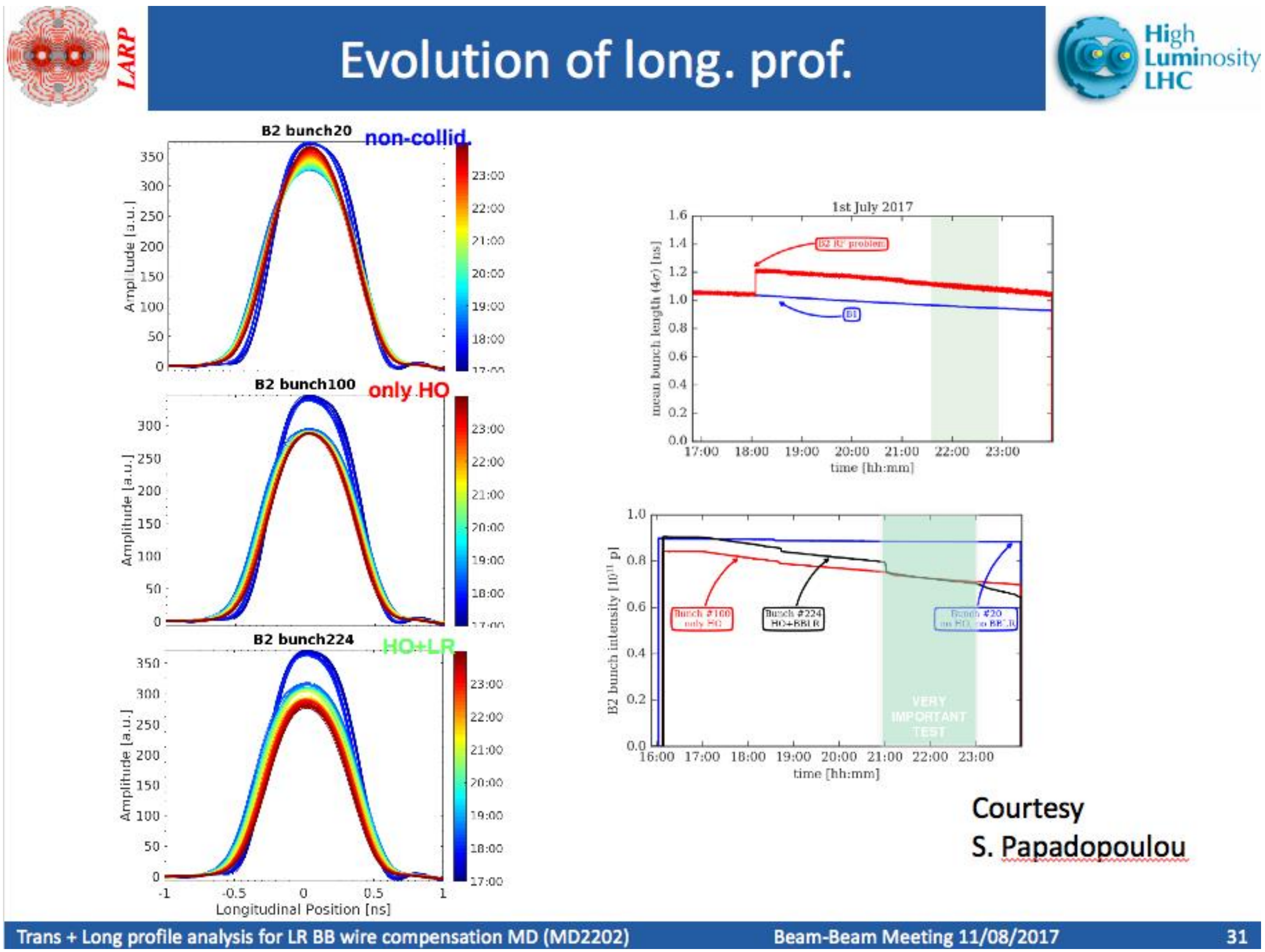


The s_{opt} depends on the PACMAN pattern.

BBCW impact of the beam profiles (I)

- A very detailed presentation by Miriam and Stefania at https://indico.cern.ch/event/658908/

Longitudinal profiles



BBCW impact of the beam profiles (II)

- A very detailed presentation by Miriam and Stefania at https://indico.cern.ch/event/658908/

Transverse profiles