

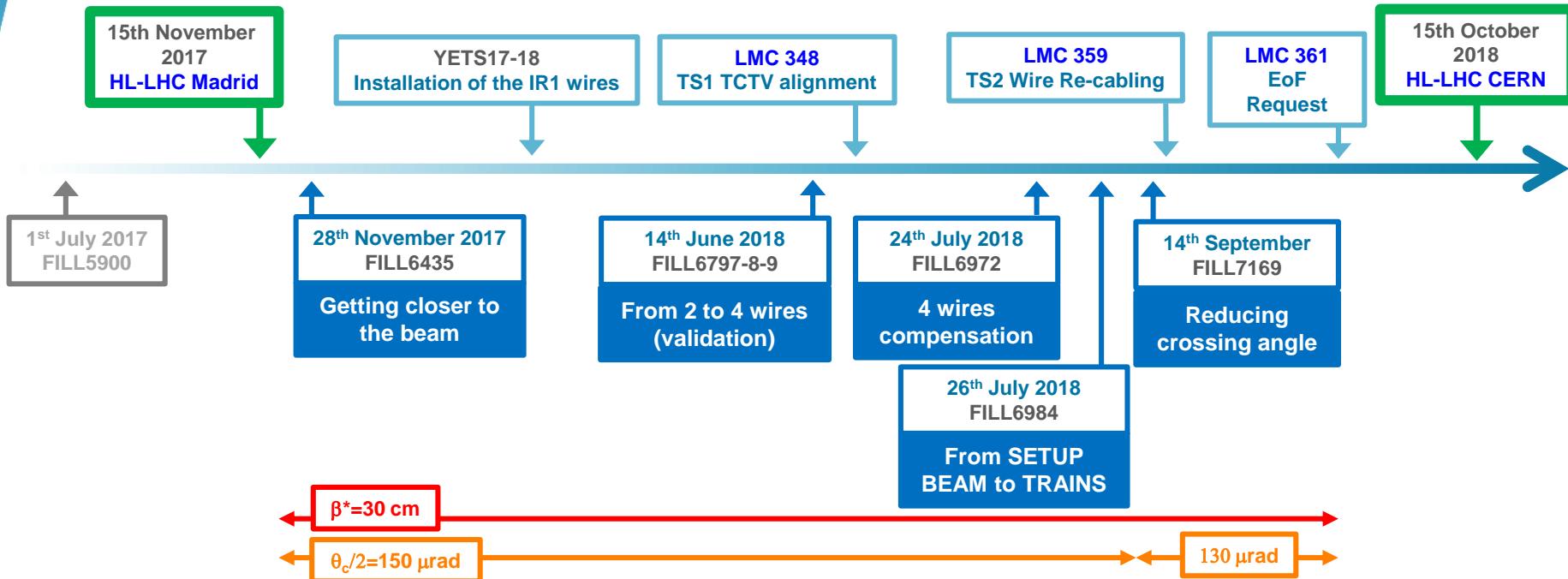


Experimental tests for BBLR compensation with wires in the LHC

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

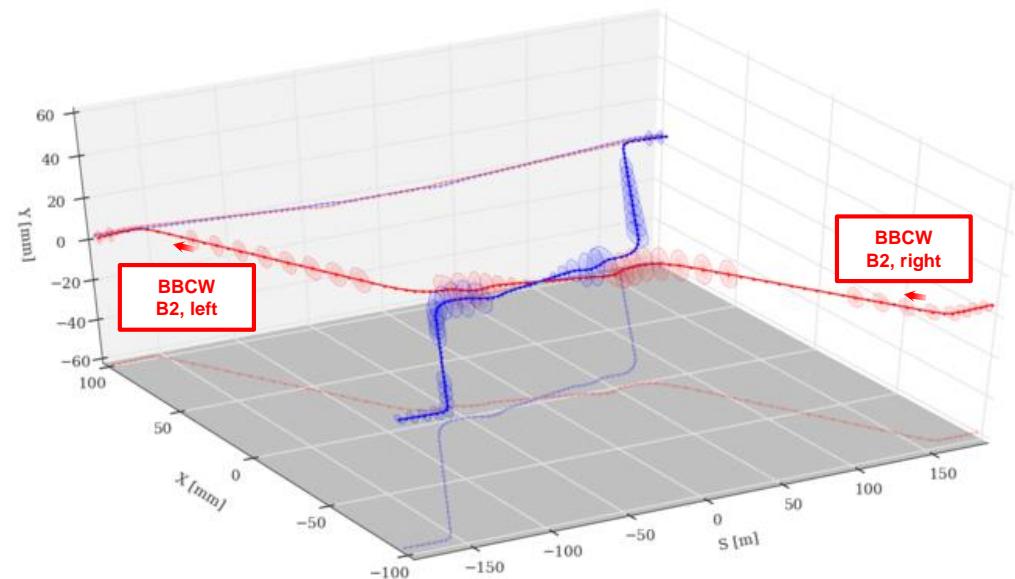
Special thanks to HL-LHC WP2, WP5, WP13 and LHC MD coordinators.

Outlook

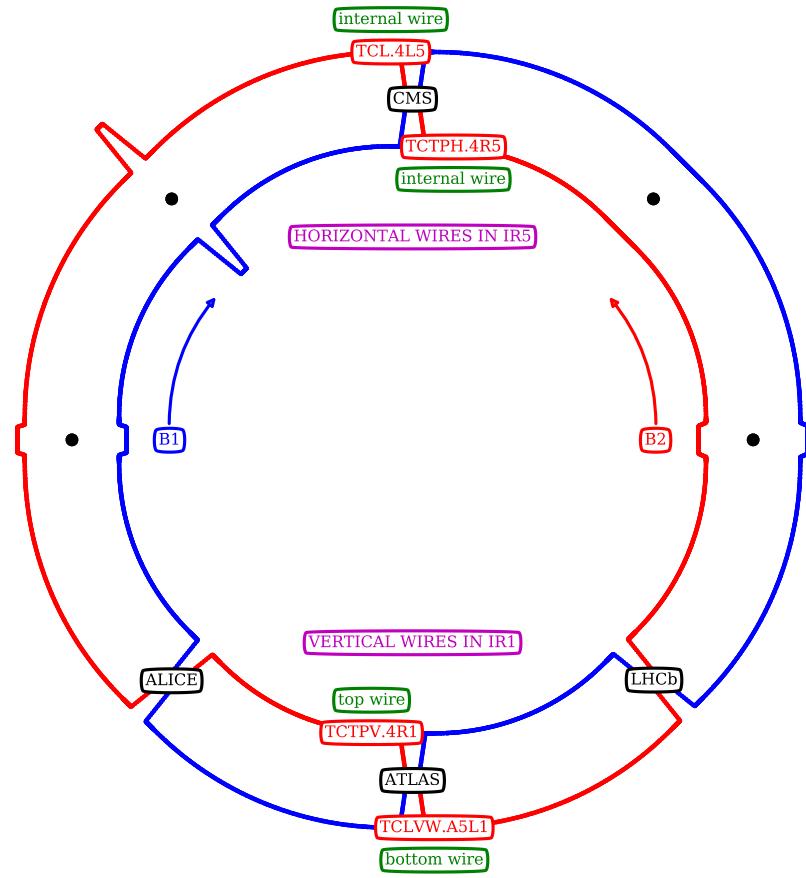


- Introduction on the wire compensation.
- Optimization of the wires settings and experimental constraints.
- Experimental results.
- Plans and summary.

The wire compensation principle



The DC wire compensation



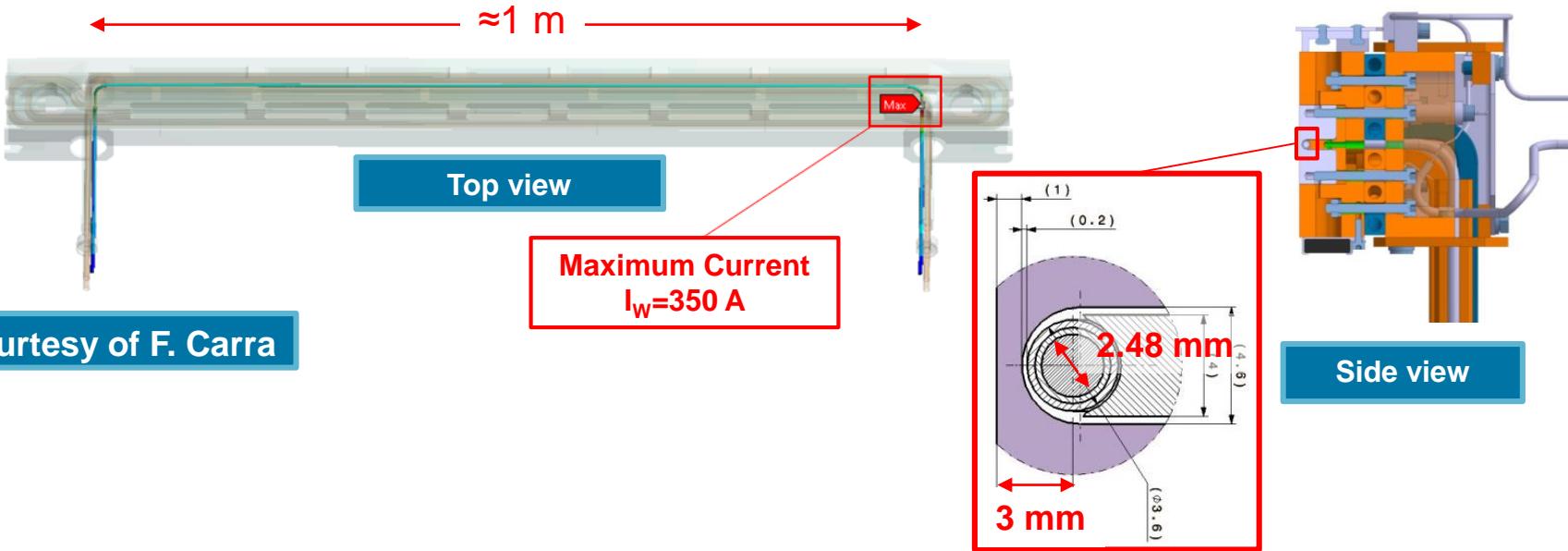
- Since 2018 four wires prototypes (**BBCW**) are installed in LHC (B2, IR1+IR5) with the aim to explore a scenario beyond the Baseline: local compensation of the beam-beam long-range (BBLR) with DC wires.

Integration of the prototype in the collimator

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

Max: 161.15
Min: 27
05/11/2013 15:25

161.15
146.25
131.34
116.44
101.53
86.624
71.718
56.812
41.906
27



Courtesy of F. Carra

- During the 2018, it was performed a complete test campaign to ensure the correct functioning of the wire interlocks, the collimator motors and PUs when the wire is powered therefore to preserve the full functionality of this device as collimator.

Wire settings for RDT compensation

We used the RDT criterion presented and described in details in

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 Shatilov³

The diagram illustrates the equivalence between two methods for compensating Beam-Beam Deflection Terms (RDTs). On the left, under 'Long-range driven RDTs', the formula is given as:

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

On the right, under 'Wire driven RDTs', the formula is given as:

$$c_{pq}^w = N_w \frac{\beta_x^{w \frac{p}{2}} \beta_y^{w \frac{q}{2}}}{d_w^{p+q}}$$

The right-hand side includes labels for 'Wire current' (green box) and 'beam-wire distance' (red box). A double-headed arrow indicates the equivalence between the two expressions.

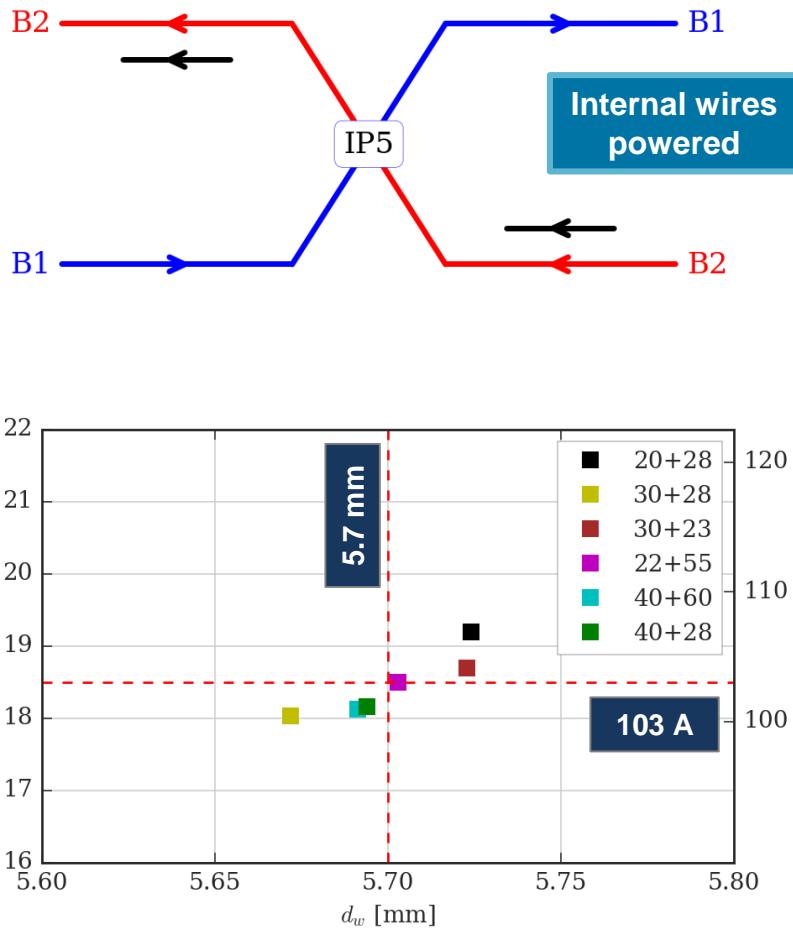
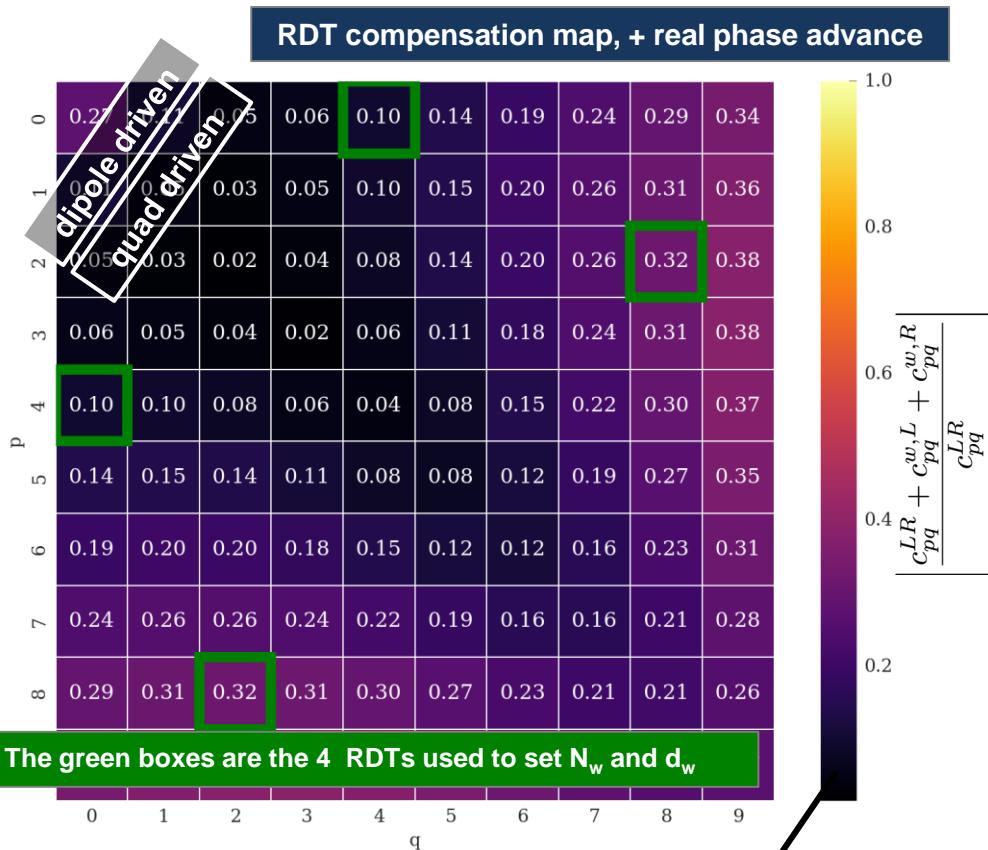
- It is shown as a numerical evidence that by compensating 4 RDTs with 2 wires one can minimize ALL RDTs provided that the wires s-position of BBCW is conveniently chosen.
- In case of sub-optimal s-position and/or beam-wire distance, only a subset of RDT can be compensated/minimized.

IDEAL settings ($\beta^*= 30$ cm, $\theta_c/2=150$ μ rad)

Optimal $I_w=103$ A for $1.15e11$ pbb

Optimal s-position = ± 158.3 m

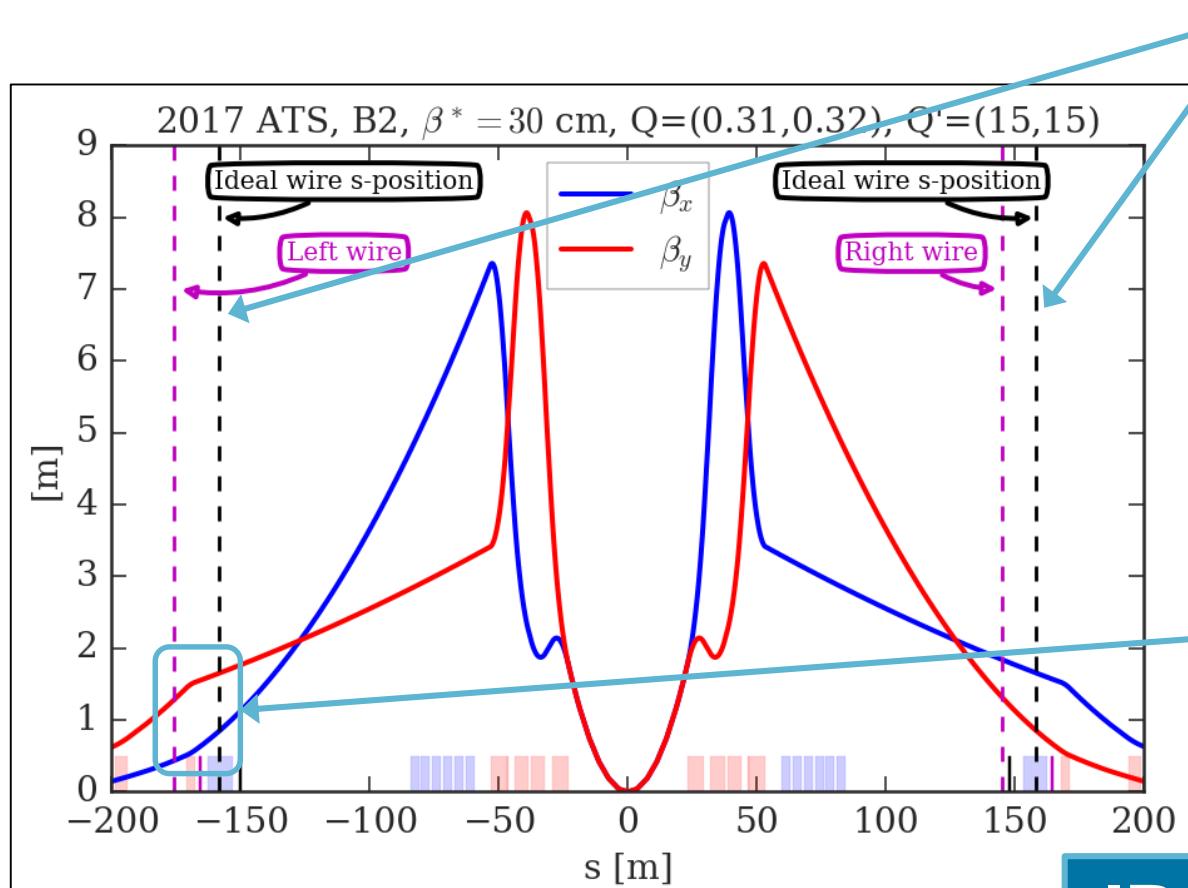
Optimal beam-wire distance = 5.7 mm



REAL s-position (II)

Optimal s-position = ± 158.3 m

⇒ It was not possible to install the wires at the optimal s-positions.

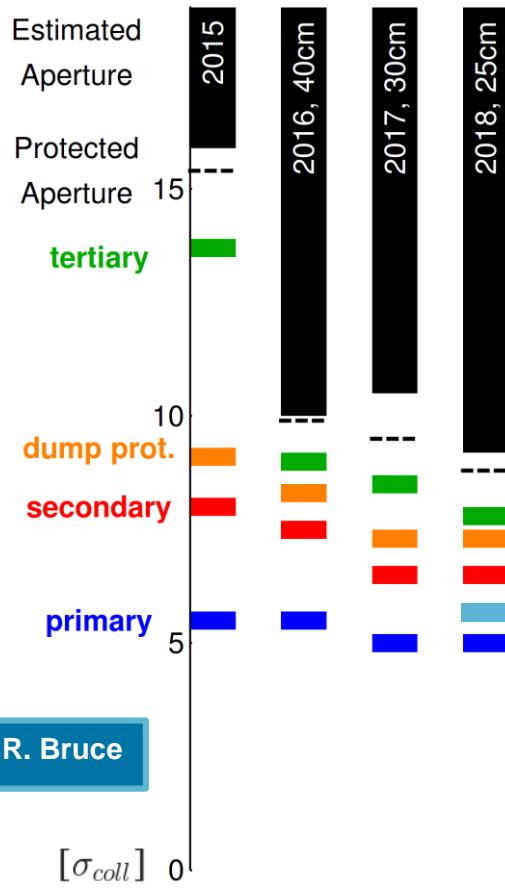


The ideal s-position of the BBCW is ± 158.3 m from the IP5. The actual s-position are -150.03 and 147.94 m.

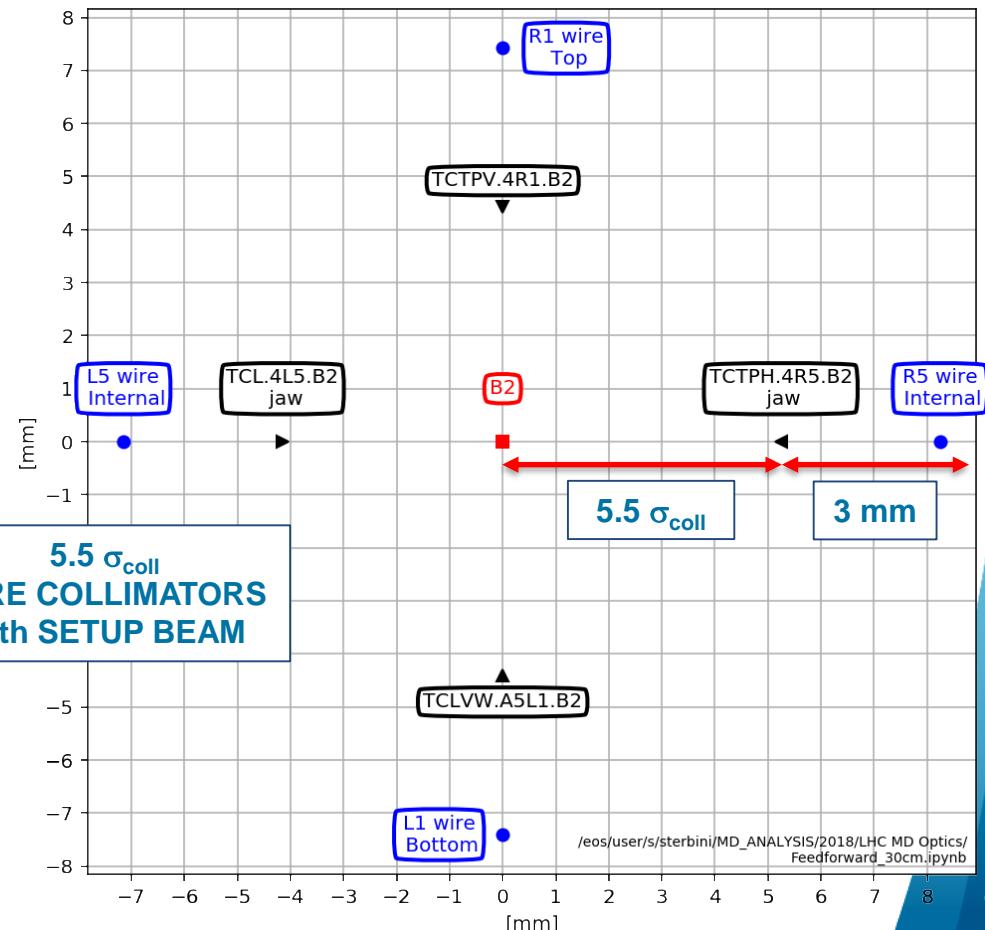
Even a small modification of the s-coordinate has an impact on the symmetry and the optimal beta ratio.

REAL beam-wire distance

Optimal beam-wire distance = **5.7 mm**
 ⇒ It is not possible to operate the wires at the optimal distance wrt the beam.



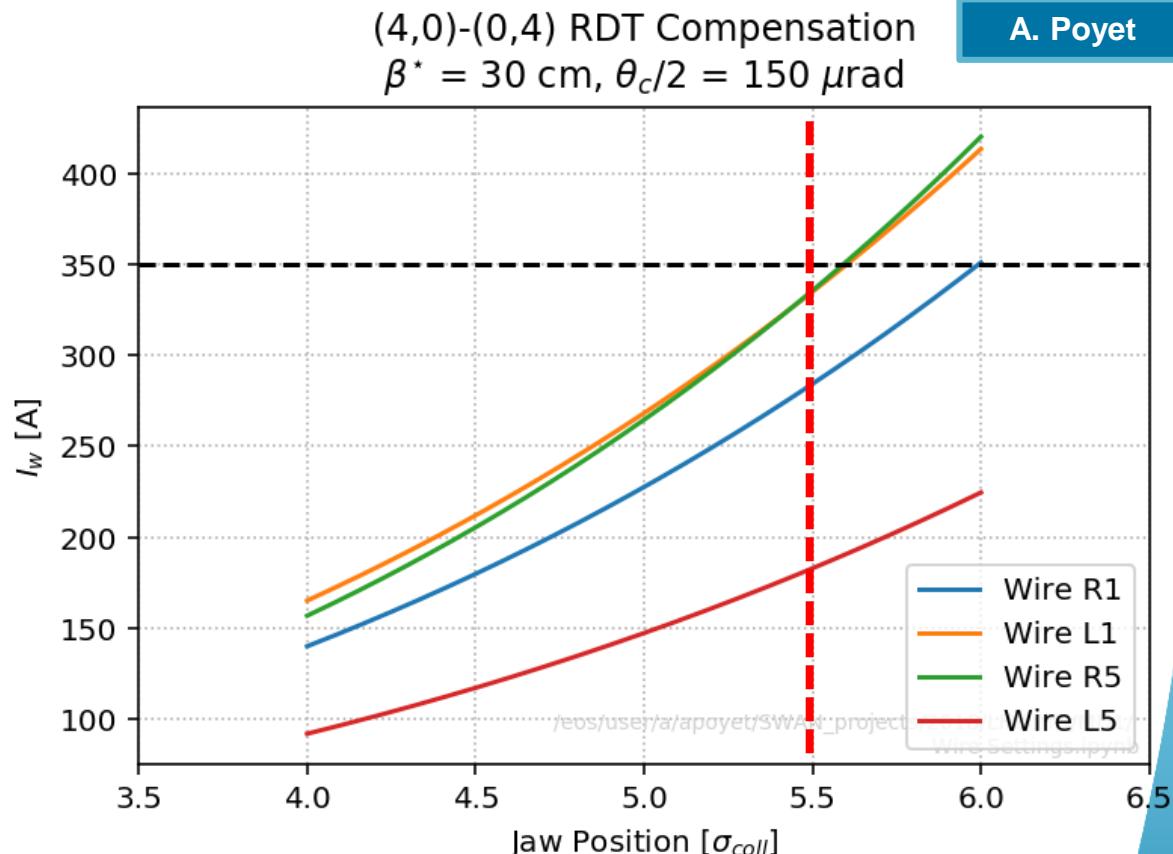
Wire	Plane	Wire-beam distance [mm]	σ_{coll} [mm]
R1	V	+7.42	0.80
L1	V	-7.41	0.80
R5	H	+8.24	0.95
L5	H	-7.15	0.75



IDEAL \Rightarrow REAL: back to 2 RDTs compensation

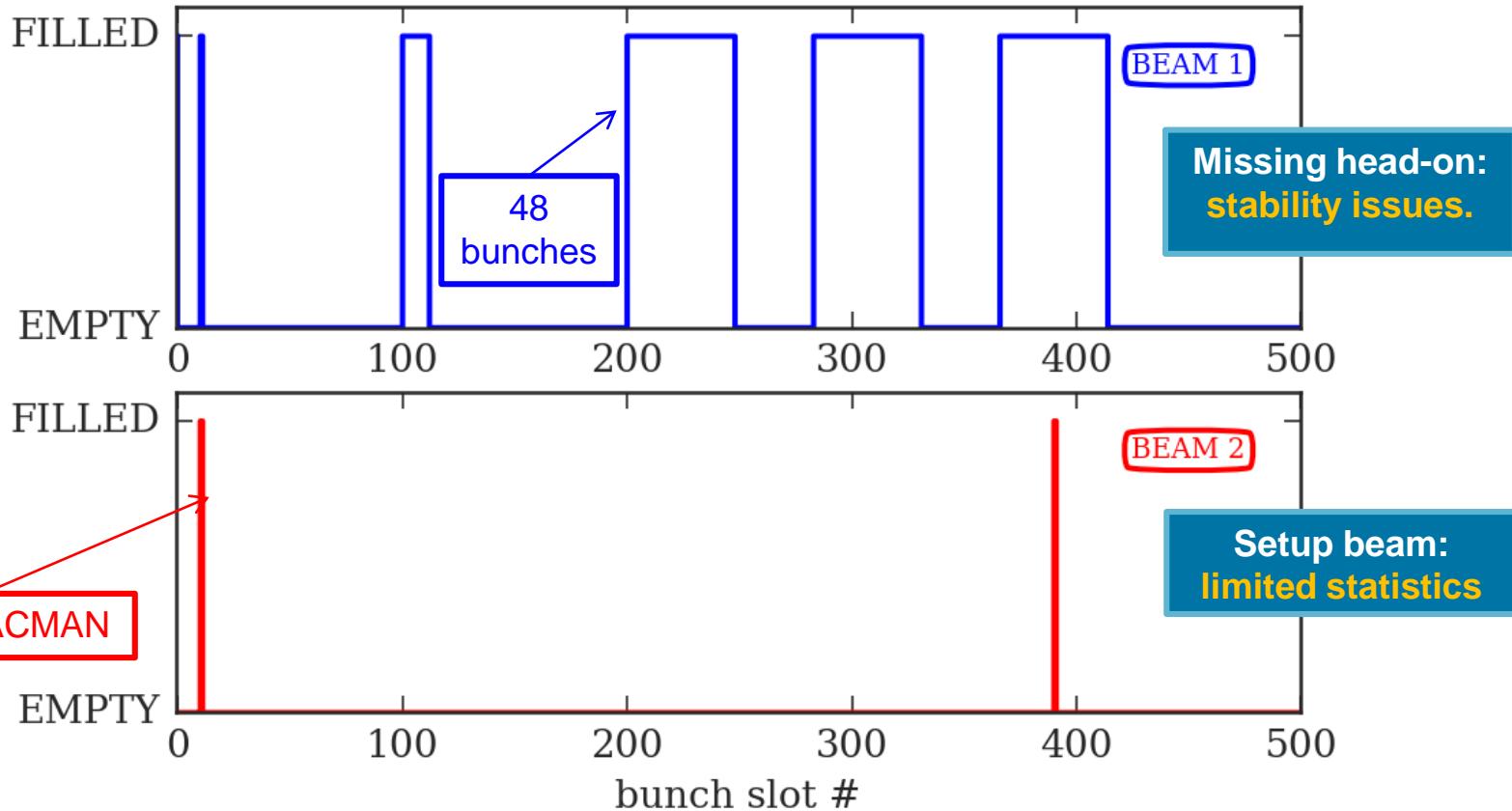
Technical constraints: **only two RDTs** with the 2 wires **at the same jaw position in σ_{coll}** .

- We choose to compensate **(4,0) and (0,4)**: first order amplitude detuning.
- Tracking studies needed for tuning the optimal position and current [see K. Skoufaris's presentation].



IDEAL \Rightarrow REAL: asymmetric filling scheme

- To approach the wire to the beam the B2 has to be $< 3 \times 10^{11}$ p (SETUP BEAM).
- We will mainly concentrate on the two bunches of B2 (Only HO and HO+BBLR).



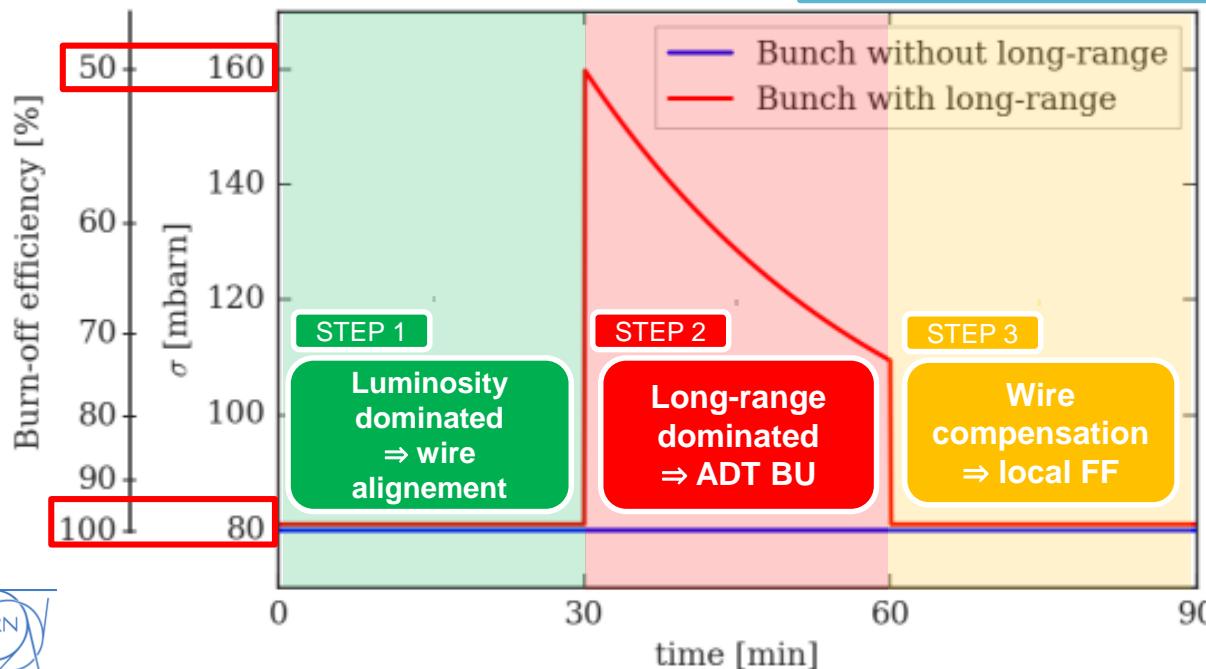
Objectives of the experiments

- Prove the beneficial effect of the WIRES in a regime dominated by long-range beam-beam effect, ensuring in the meantime that the linear effects of the wire (orbit and tunes) are compensated with feedforwards. Our privileged observable is the bunch “**effective cross-section**”:

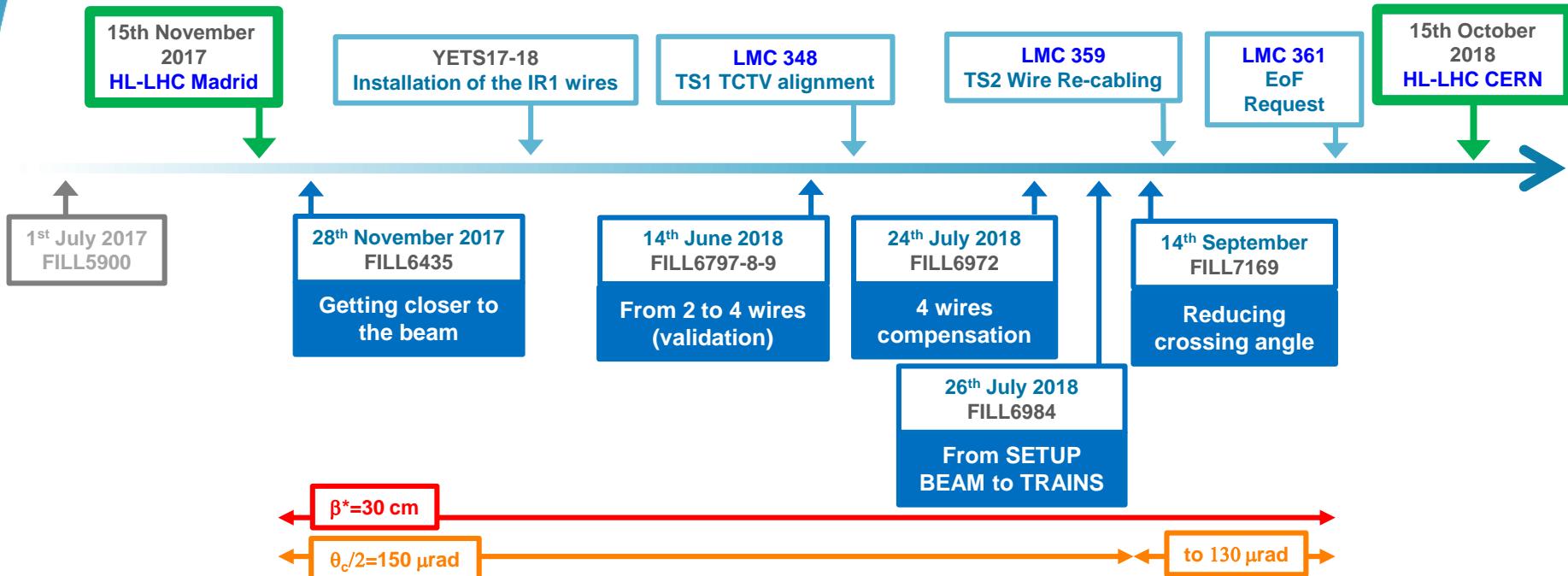
$$\sigma_{EFF} = -\frac{1}{\sum_{IP} L_{IP}} \frac{dN}{dt}$$

Instantaneous luminosity Intensity loss-rate

The IDEAL compensation,
2 bunches in B2

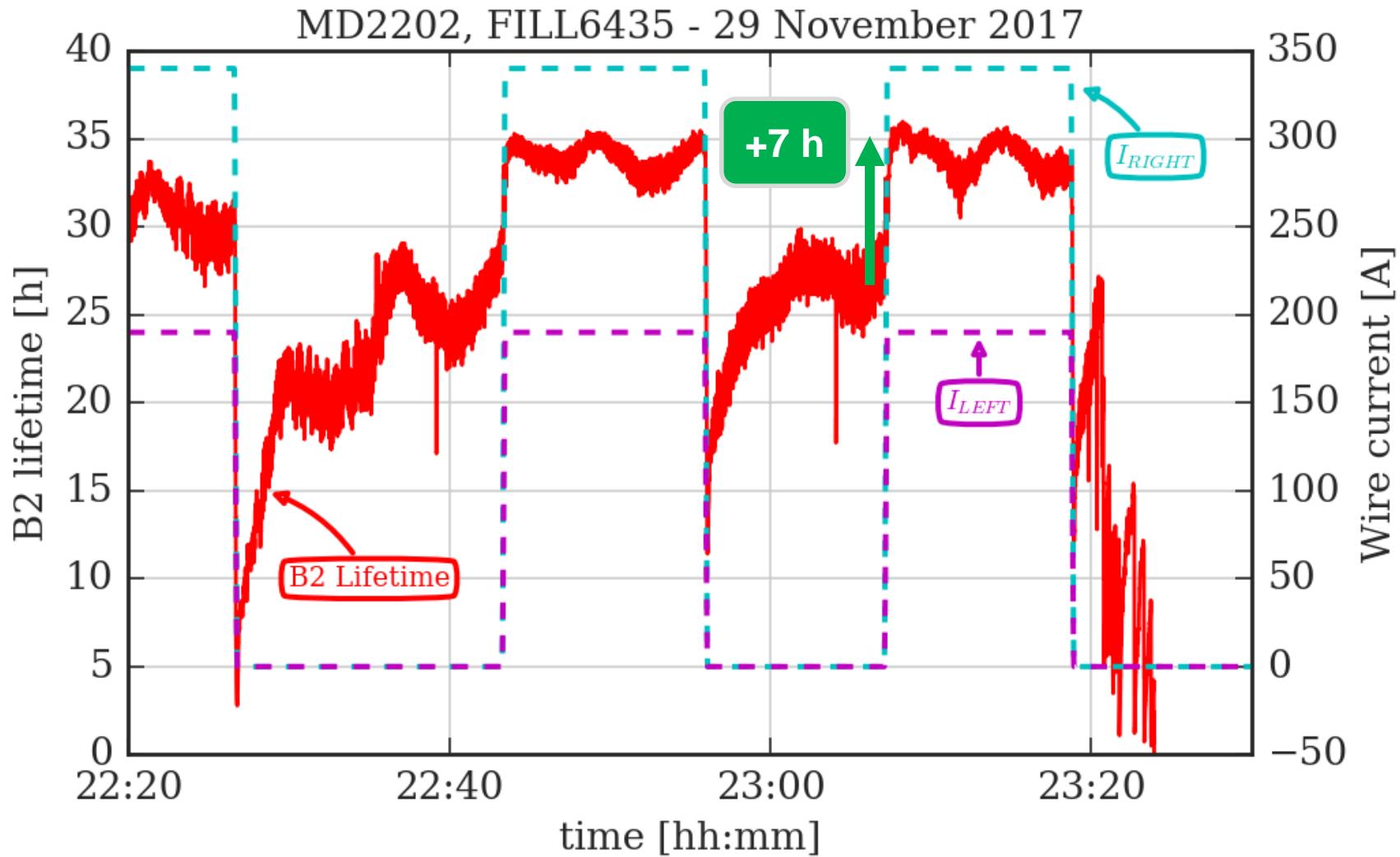


Outlook



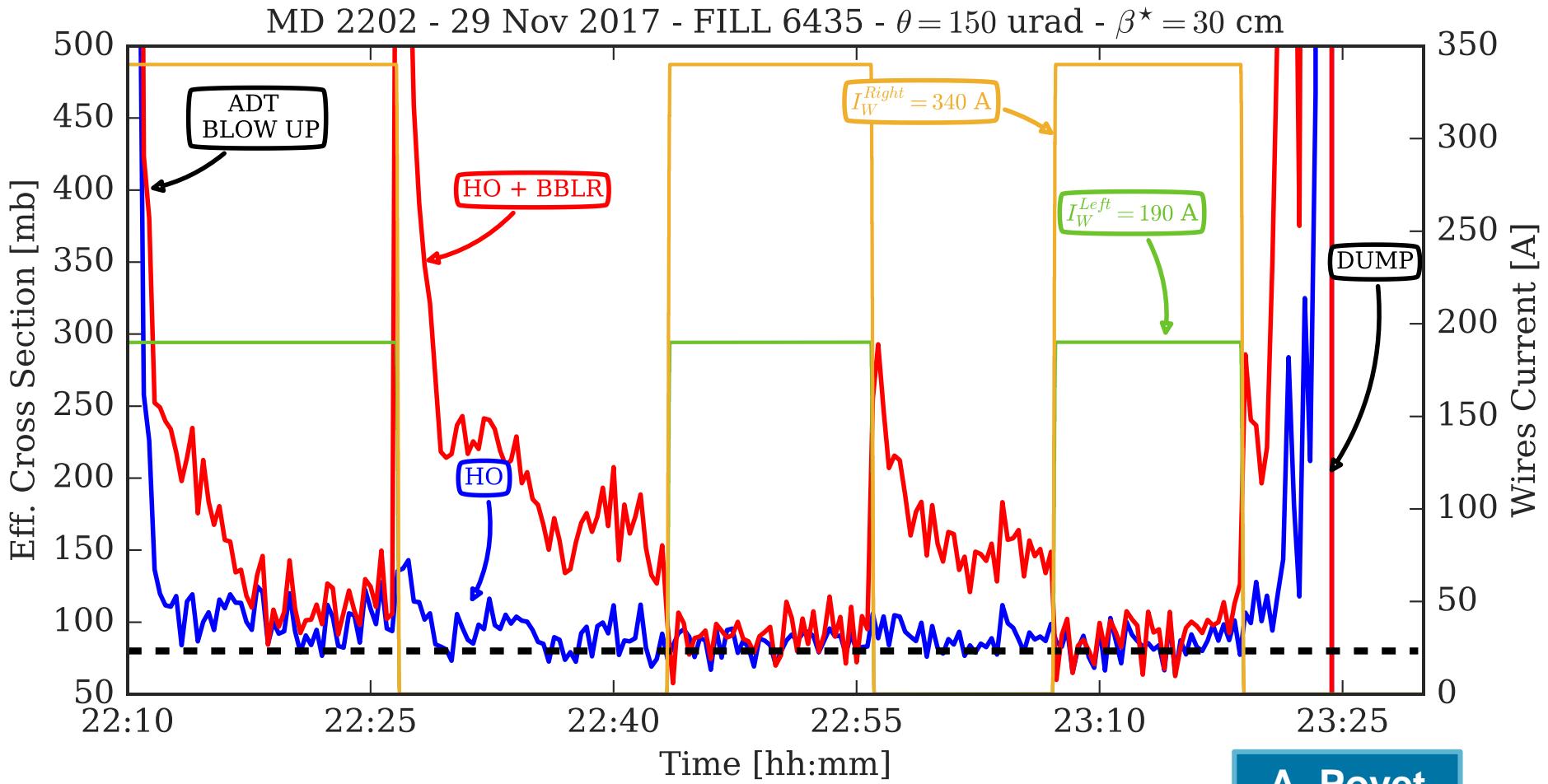
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Getting from 6 to 5.5 σ_{coll} (only 2 wires)



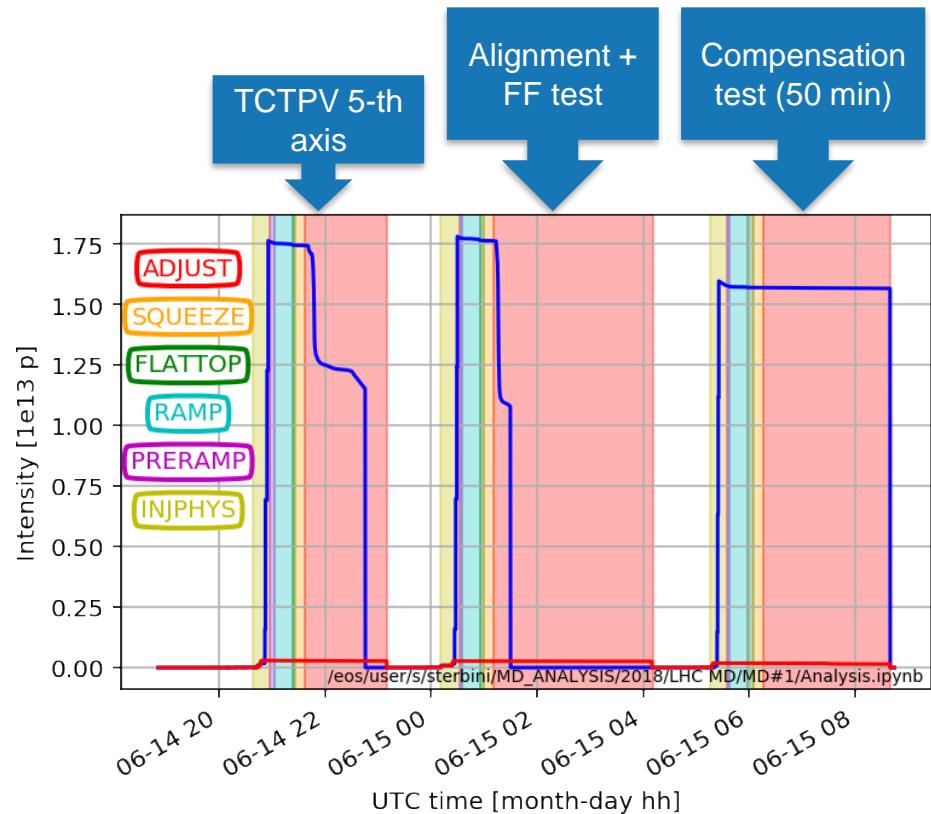
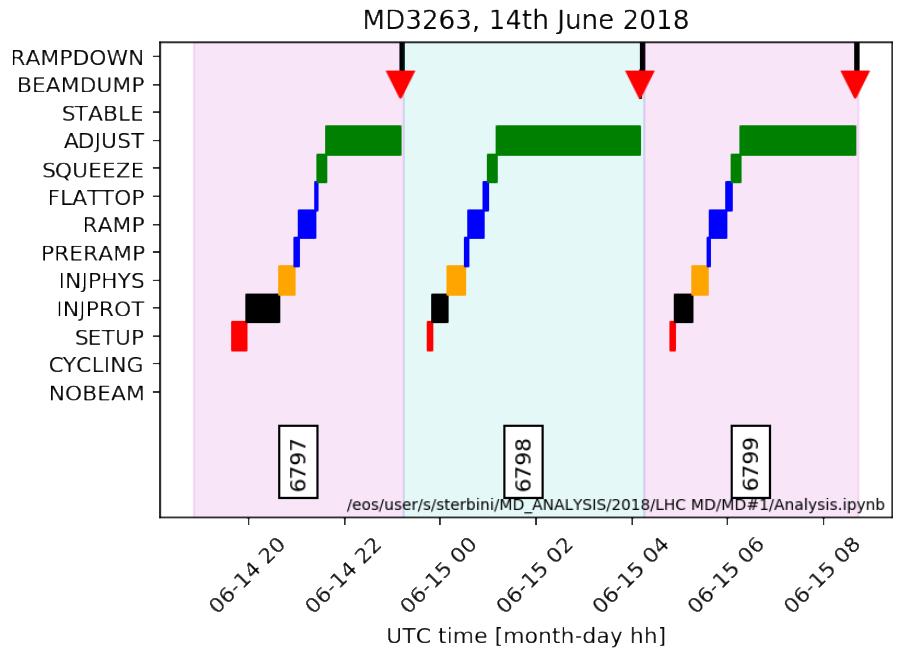
Positive effect of the wires visible on beam lifetime.

Getting from 6 to $5.5 \sigma_{\text{coll}}$ (only 2 wires)



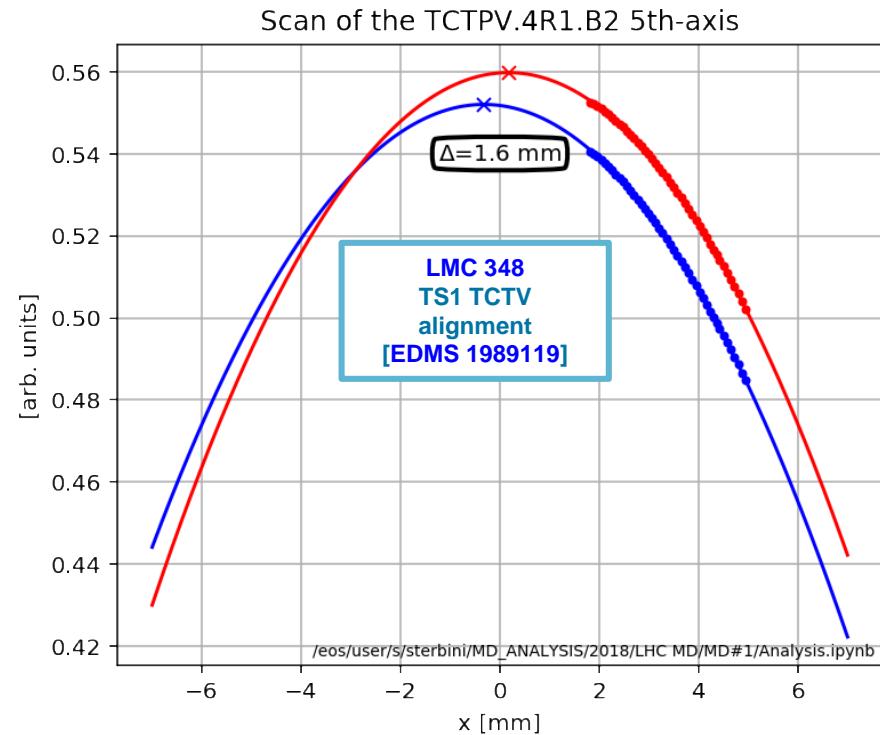
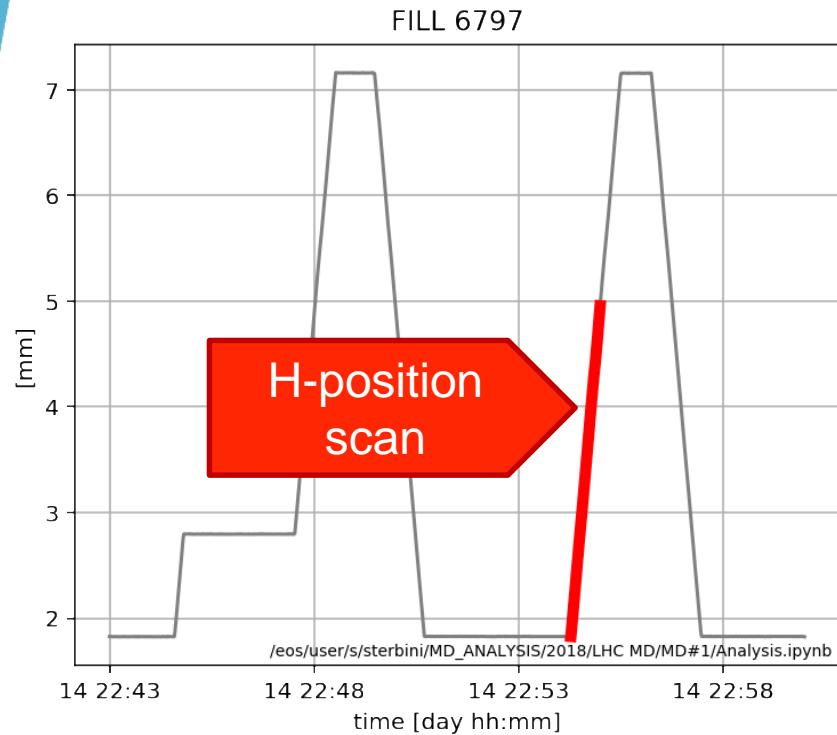
- Positive effect of the wires visible on the bunch affected by the beam-beam long-range. Super-PACMAN unaffected.

First tests with the 4 wires



- Results of the MD jeopardized by the strong beam instability after SQUEEZE. Mainly used for checking the alignment and the feedforwards.

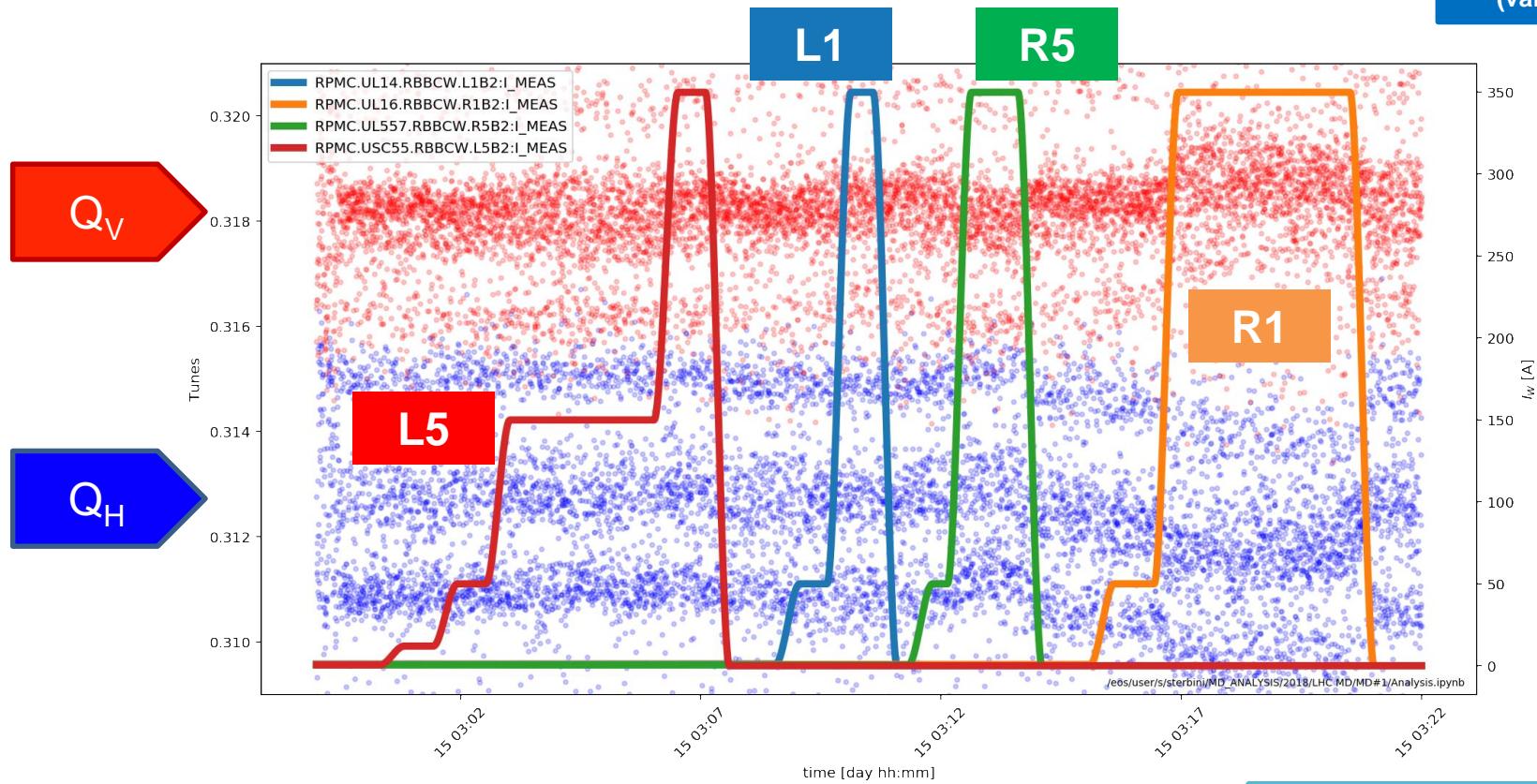
Alignment of the TCTPV



Credit to N. Fuster, S. Redaelli, A. Poyet, A. Rossi, I. Lamas Garcia

- The 5th axis “manual” alignment performed during TS1.

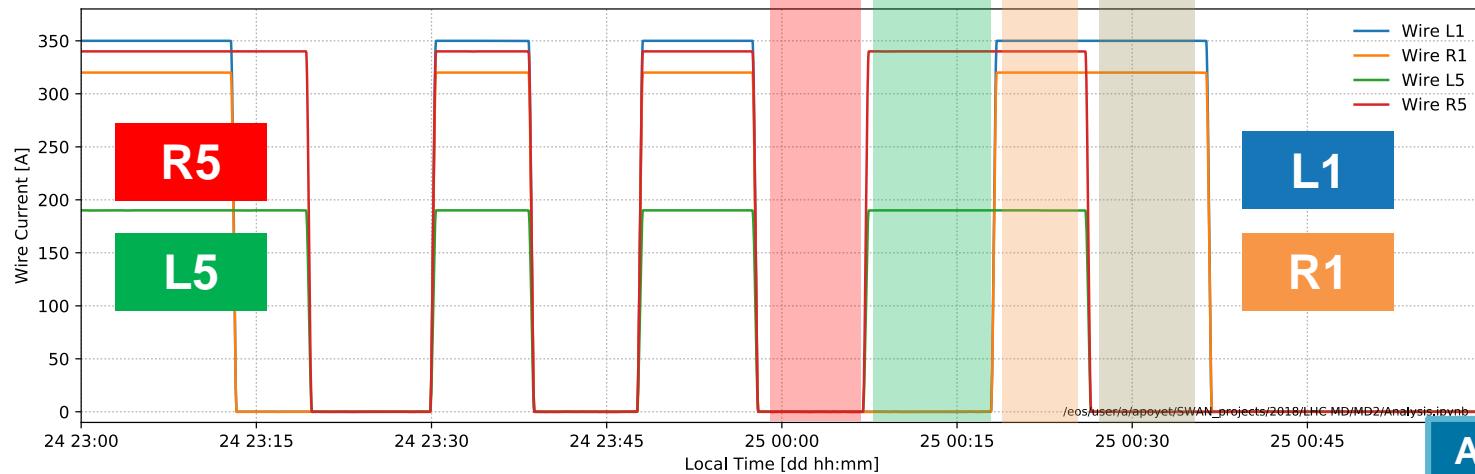
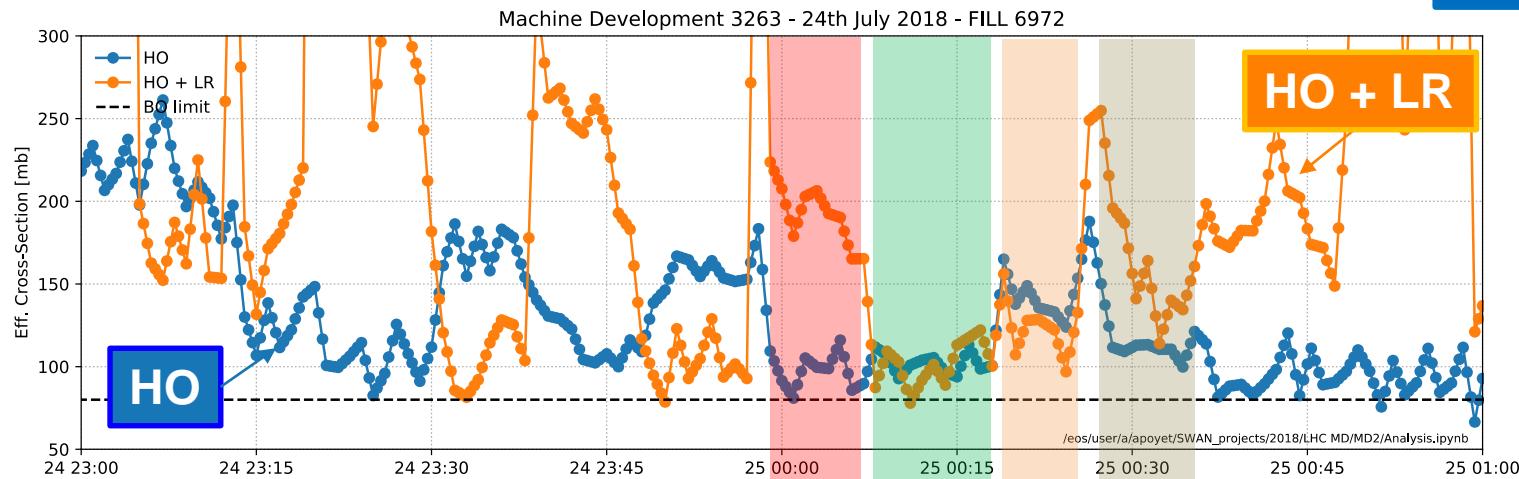
First tests with the 4 wires



Credit to M. Solfaroli
and G.-H. Hemelsoet

- The 4 wires where powered to check the Q-feedforwards. As expected the R1 feedforward was less efficient (solved with the 5th axis manual alignment in TS1).

4 wires compensation

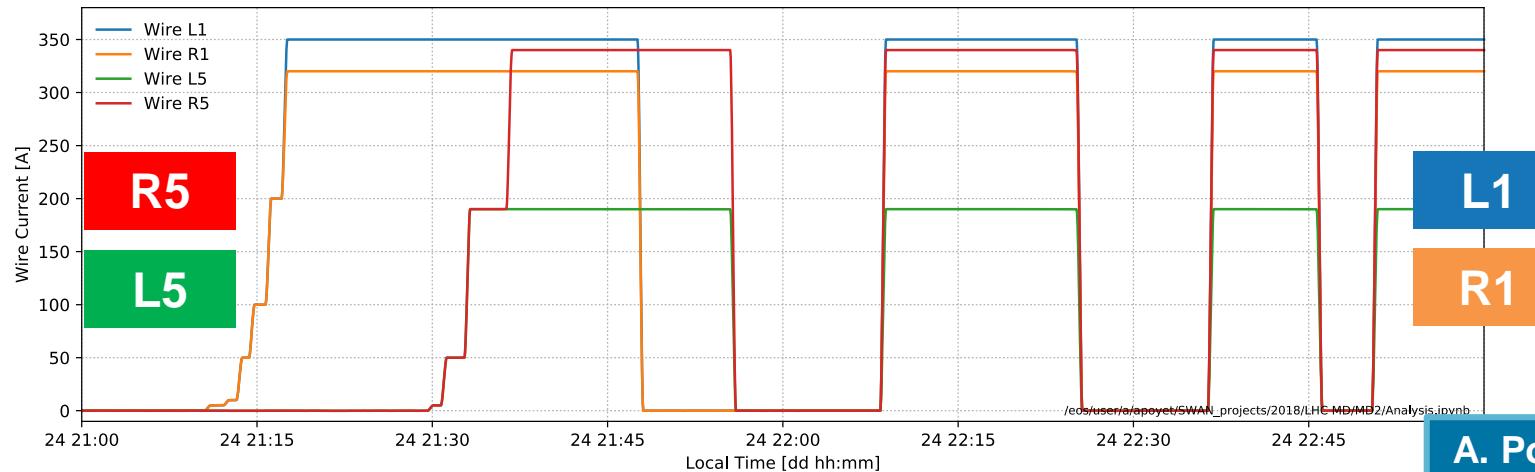
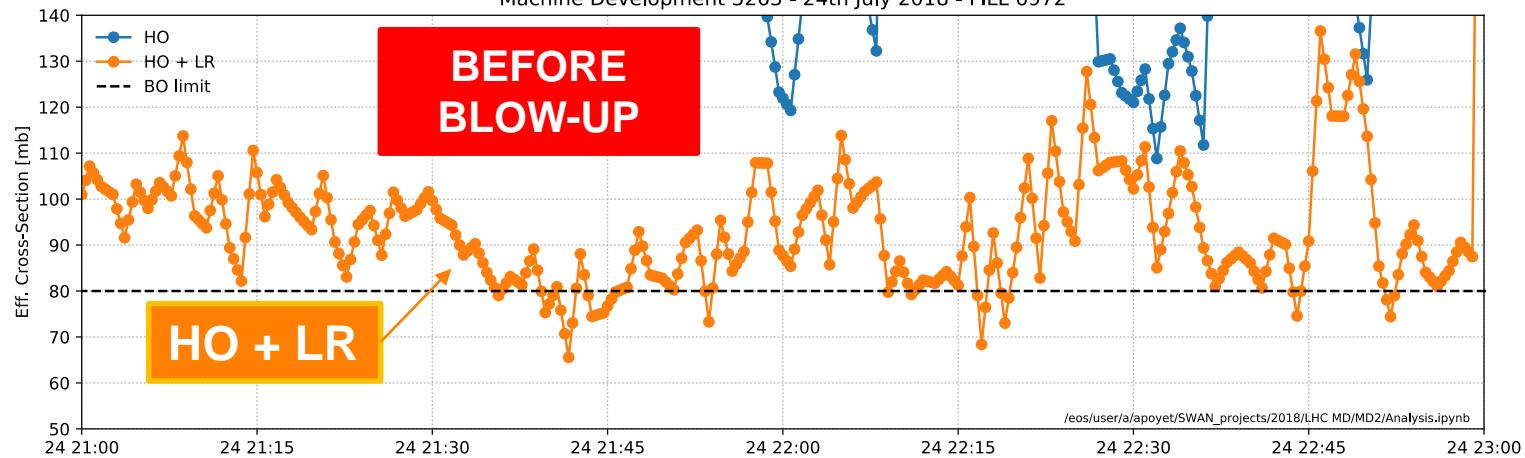


A. Poyet

- Compensation with 4 wires. The effect of the IR1 wires (sub-optimal position) is less evident if compared with the effect of the IR5 wires.

4 wires compensation

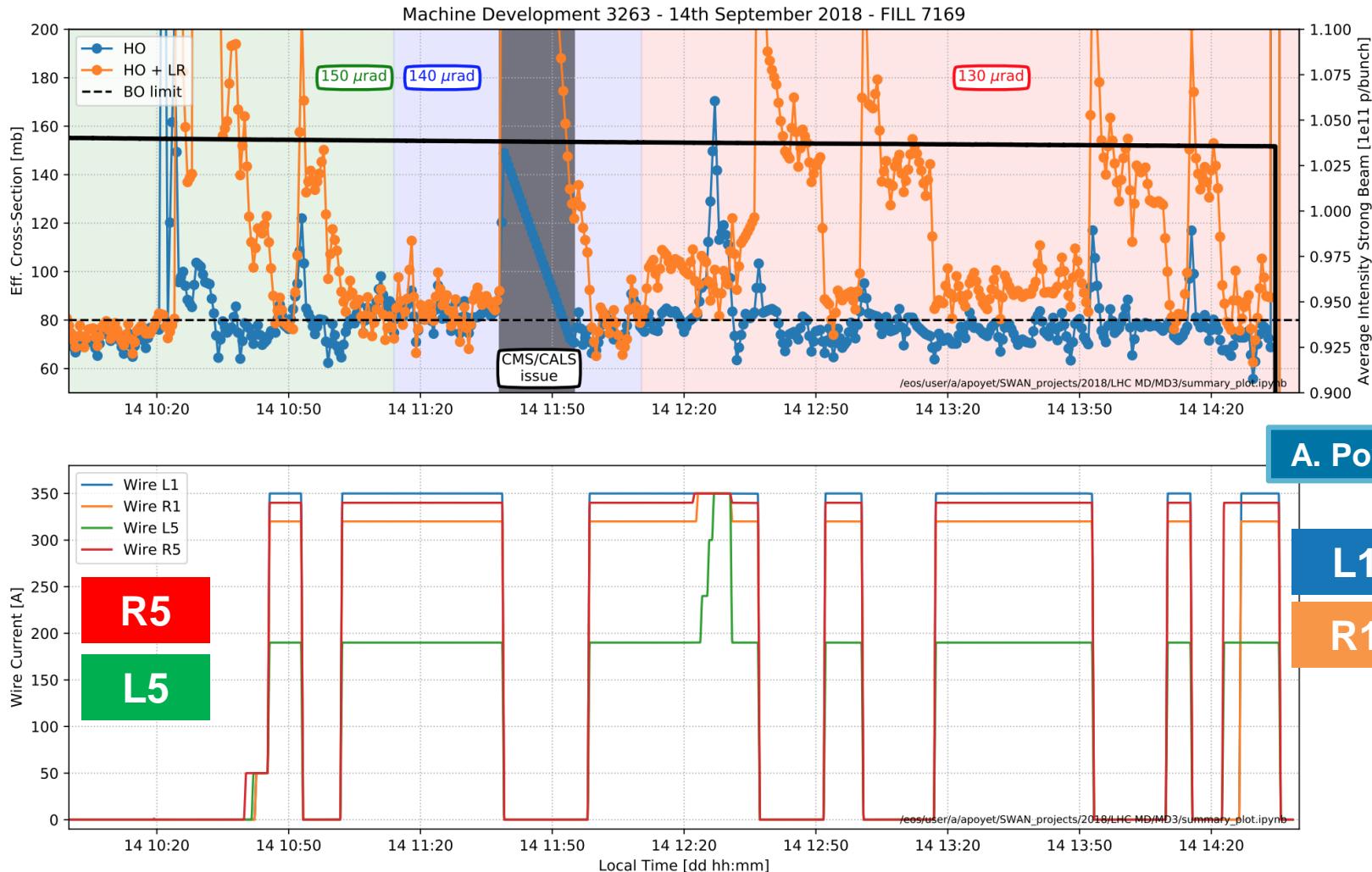
Machine Development 3263 - 24th July 2018 - FILL 6972



A. Poyet

- Test with standard B2 emittance (no BU). A marginal effect of the wires is still visible.

Crossing angle and compensation

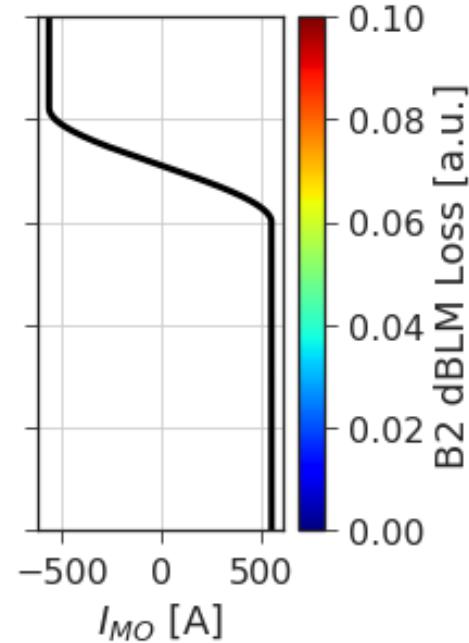
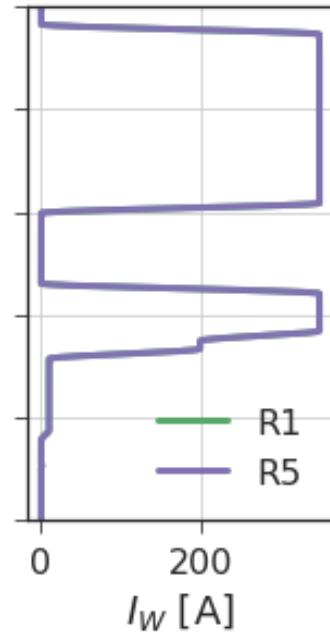
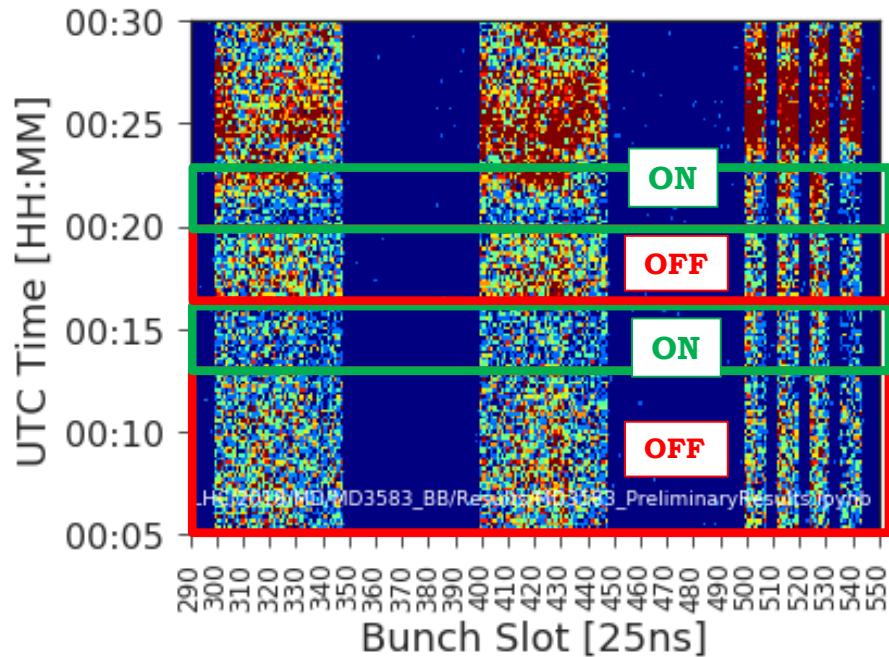


- Very clear effect of the compensation even at reduced crossing (130 μ rad)!

Compensation with trains

N. Karastassis

WIRES AT NOMINAL POSITION

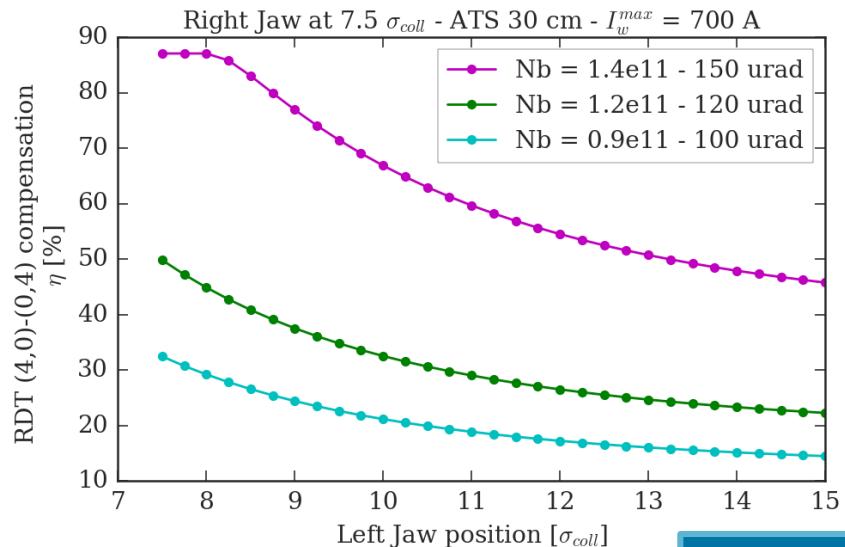
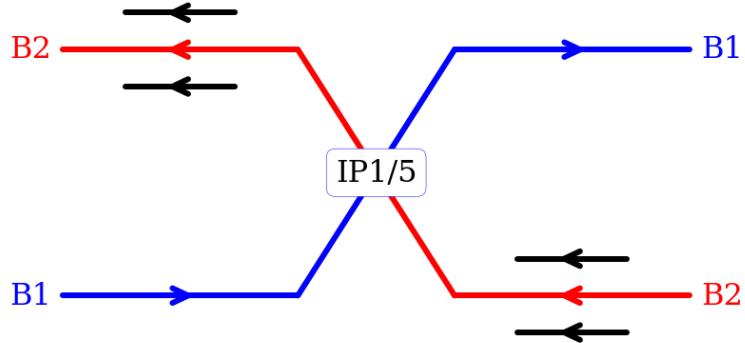


- As an end-of-MD test the right wires were switched ON ($\beta^*=30$ cm and $\theta_c/2=150$ mrad). Signals from dBBLM are compatible with reduction of losses on the bunches suffering beam-beam long-range.

Can we use trains of bunches?

LMC 359
TS2 Wire Re-cabling
LMC 361
EoF Request

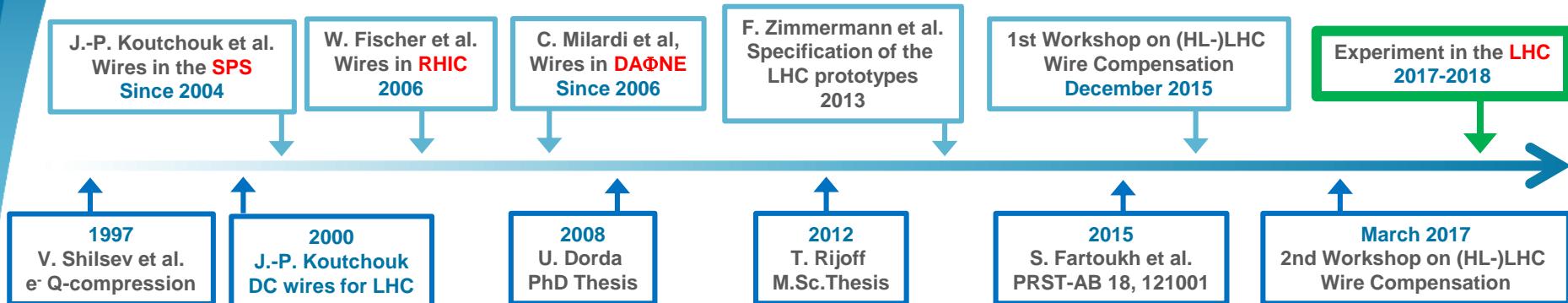
- The goals is to explore the potential of this setup in operational conditions.
- During TS2 the wires were re-cabled in series [EDMS 2027144].
- In this way (only for the “even” multipoles) one double the available I_w and could see an effect also at nominal position [see MD].
- ⇒ Dedicated MD allocated for that purpose.



A. Poyet

Summary and next steps

- During the last year a rich measurements program to explore the potential of the wire compensation in HL-LHC was performed. A positive effect of the compensation was systematically observed even within the constraints of a sub-optimal setup.
- All the measurement were conducted with round optics and almost the totality with SETUP beam.
- The wires were recabled during the TS2: this opens the way to test them in nominal condition (EoF requested and MD4 slot probably available).
- Next step is the study optimal technical implementation of wires in the HL-LHC layout (\Rightarrow next 2 talks).



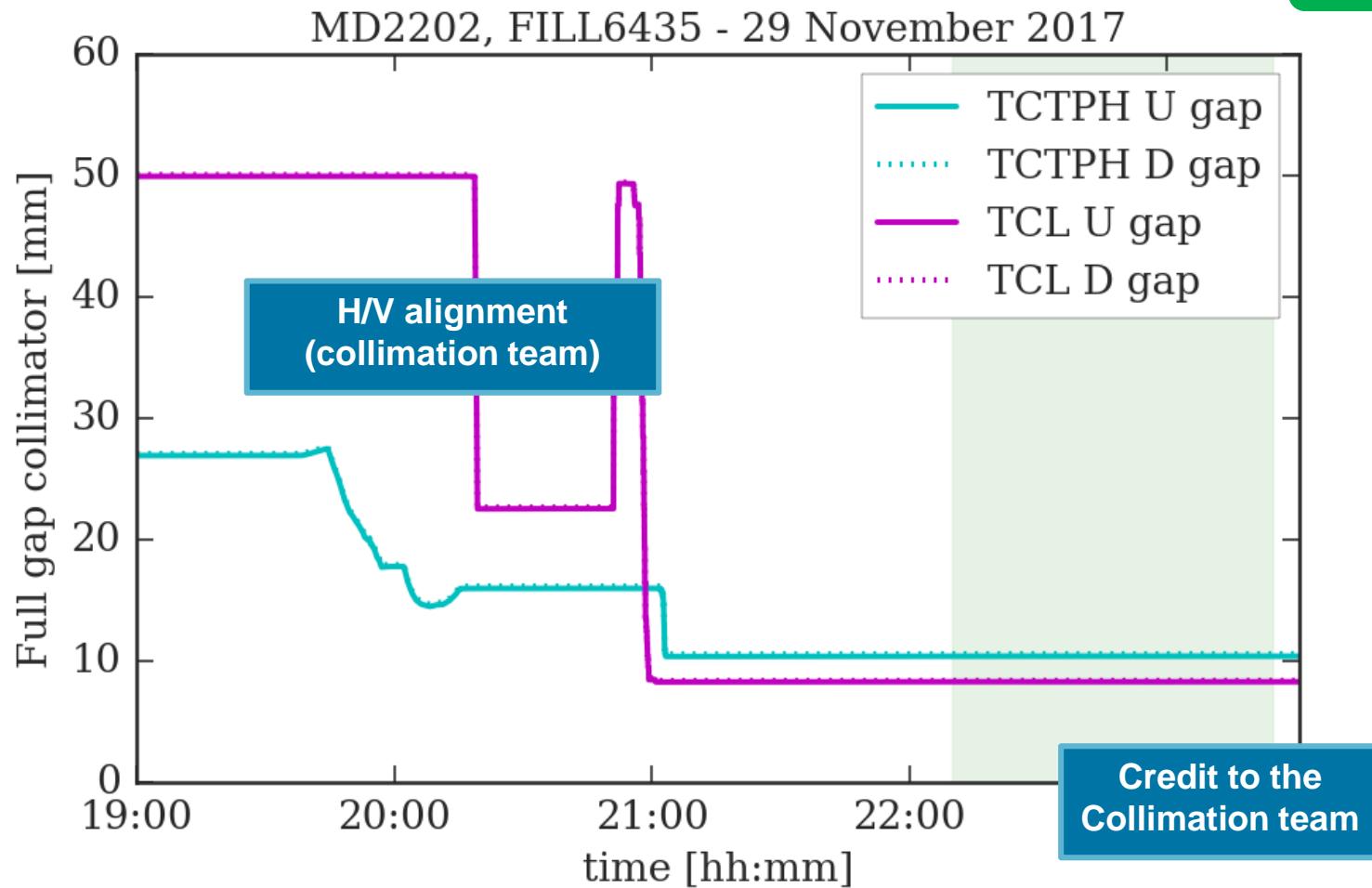
Thank you for the attention!

On behalf of the BBLR wire compensation team

*D. Amorim, G. Arduini, H. Bartosik, A. Bertarelli, R. Bruce, X. Buffat, L. Carver, C. Castro, 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, J. Wenninger, C. Xu, C. Zamantzas, P. Zisopoulos and all participants to the design, production and commissioning of the wire compensator prototypes an **HL-LHC WP2, WP5, WP13 and LHC MD coordinators**.*

BACK-UP SLIDES

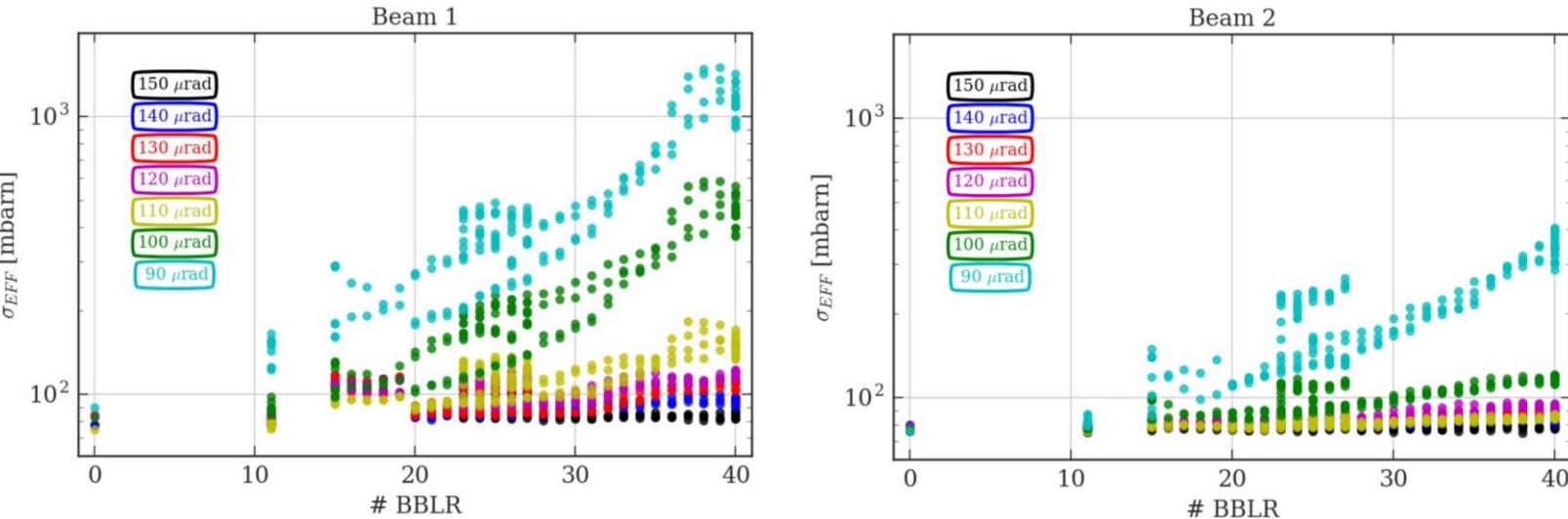
Vertical alignment of beam-wires



- Important vertical offset (up to 5 mm) to be corrected with the vertical alignment procedure. Not trivial due to lack of V PUs.

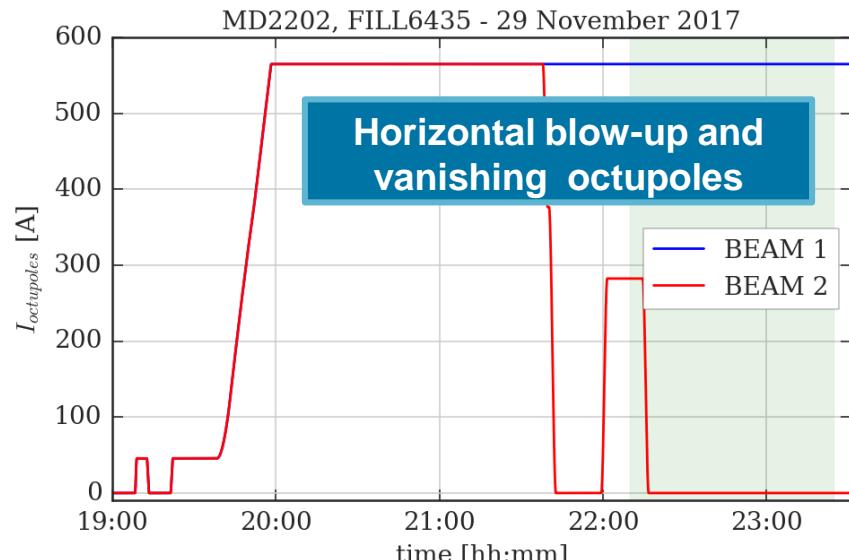
Pushing B2 to the BBLR regime

Interlude of B1 and B2 difference



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).

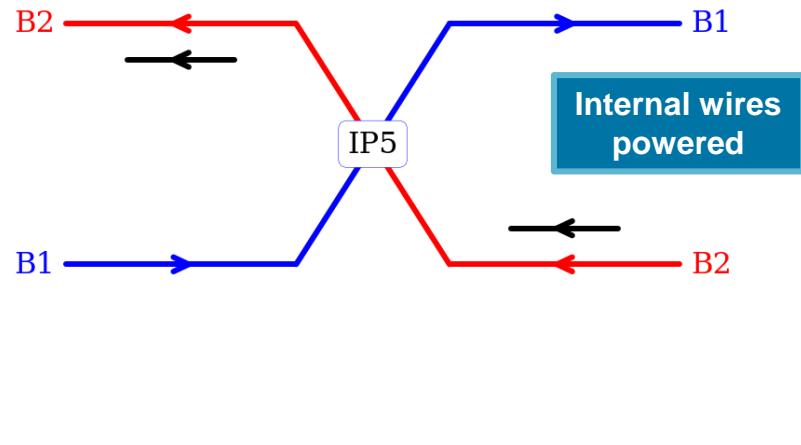
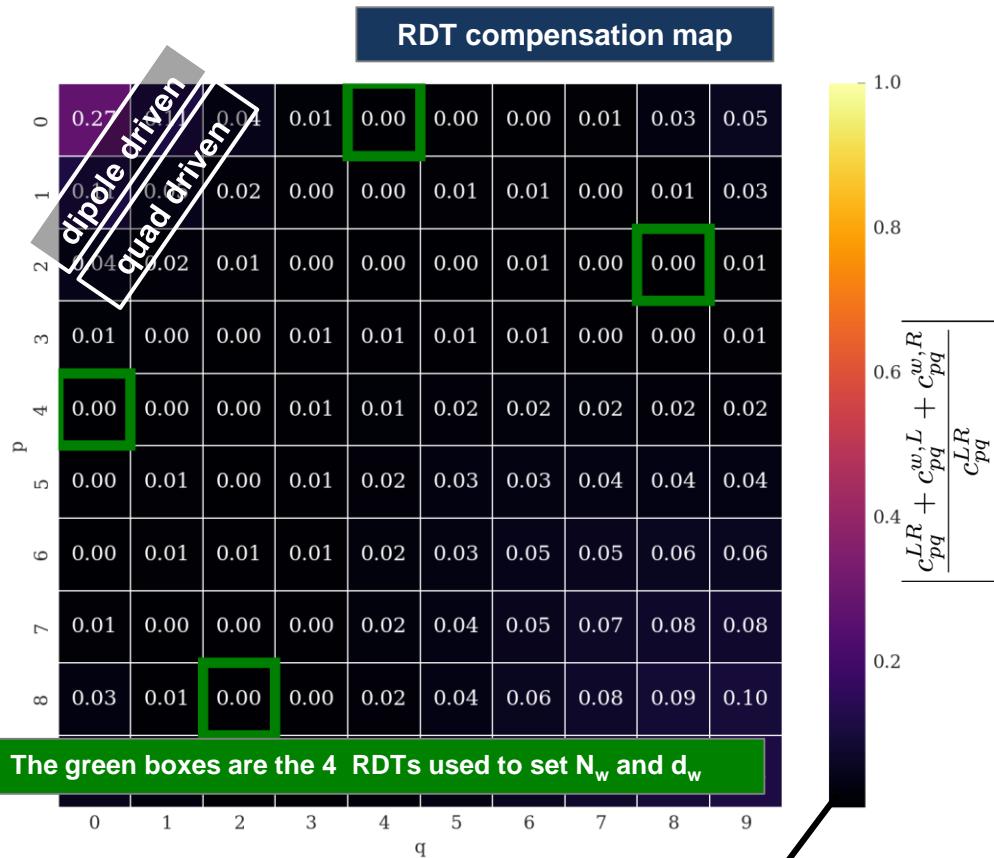


IDEAL BBCW settings ($\beta^* = 30$ cm, $\theta_c/2 = 150 \mu\text{rad}$)

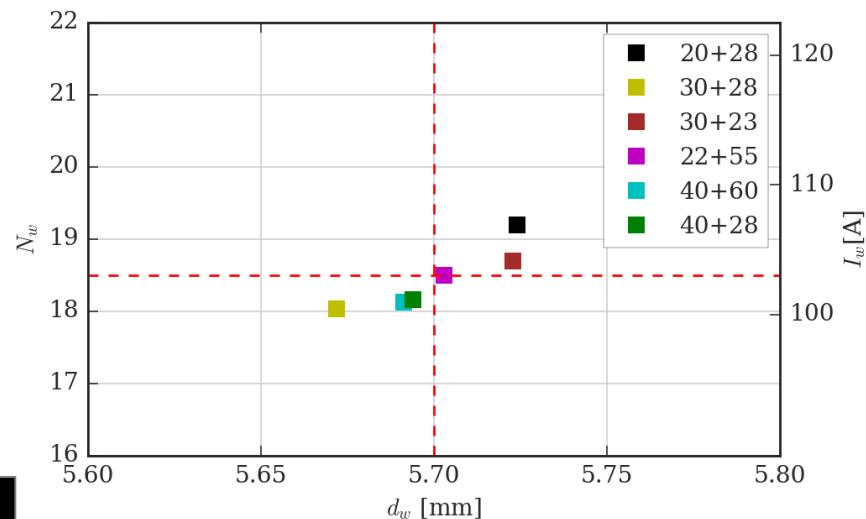
Optimal $I_w = 103$ A for $1.15\text{e}11$ pbb

Optimal s position = ± 158.3 m

Optimal beam-wire distance = 5.7 mm

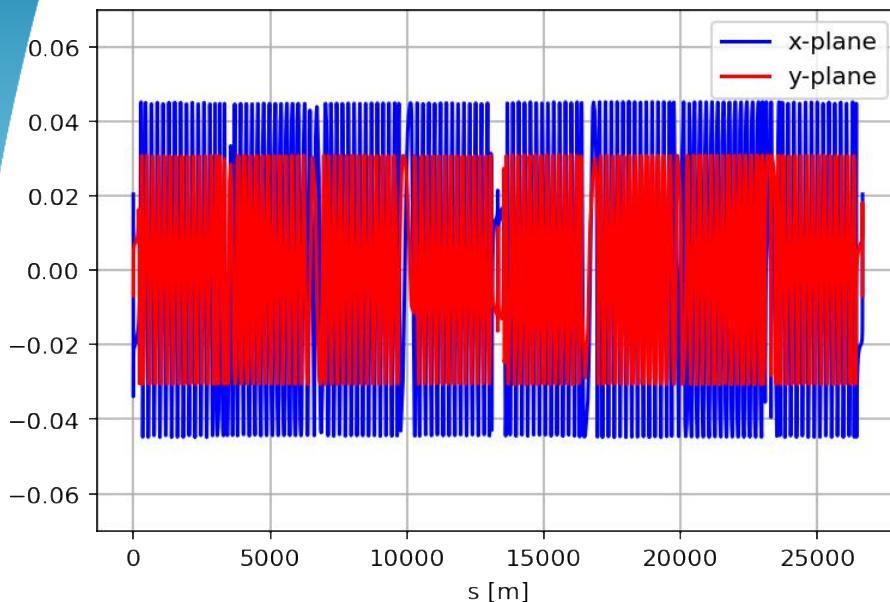


2017 ATS, $\beta^* = 30$ cm, $Q = (0.31, 0.32)$, $Q' = (15, 15)$



Local correction in Q4/5. Motivation and implication.

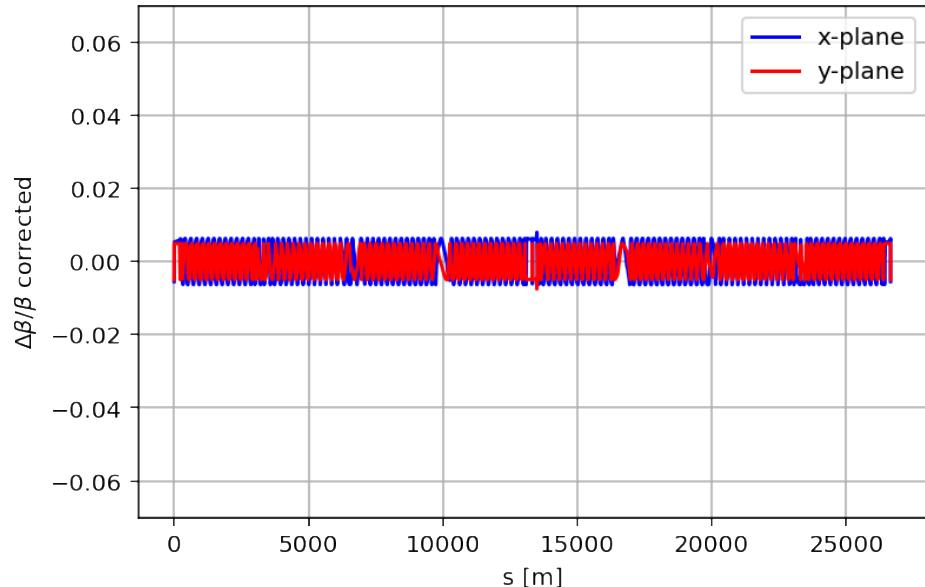
RIGHT WIRE IR5



An example of β -beating induced by a wire (R5, 350 A at $5.5 \sigma_{\text{coll}}$)

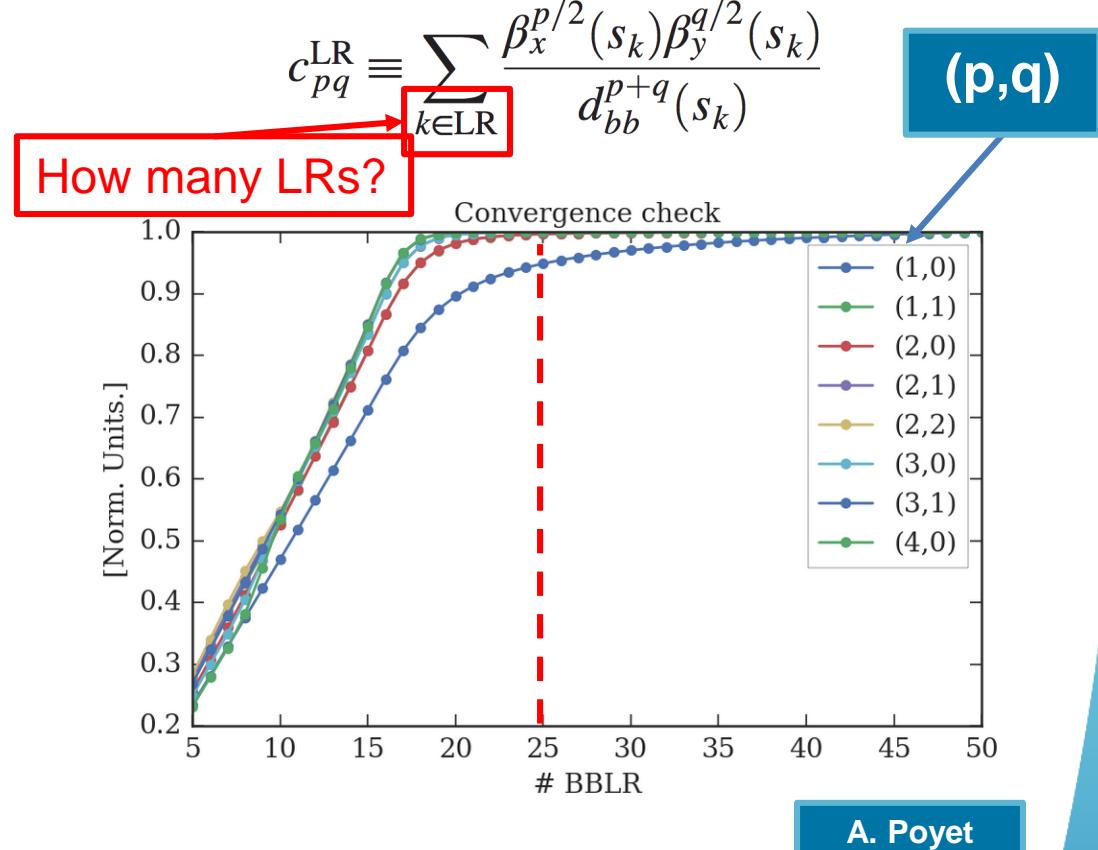
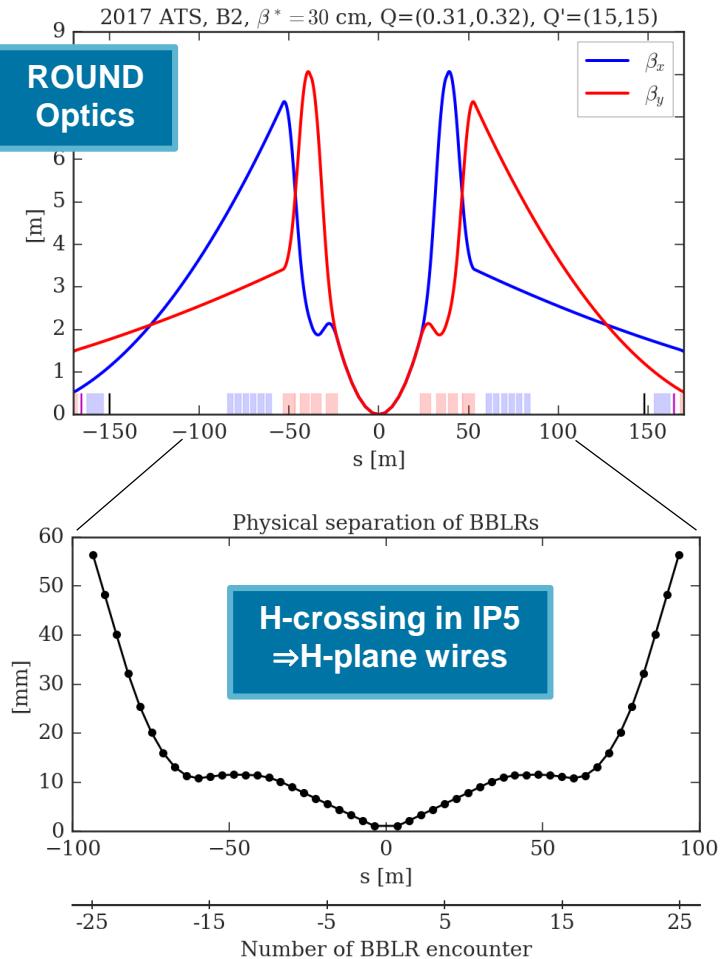
β -beating corrected using the Q4 and Q5 (350 A at $5.5 \sigma_{\text{coll}}$). Provided that **PC interlock settings** on these 8 quads is relaxed during the MD.

RIGHT WIRE IR5



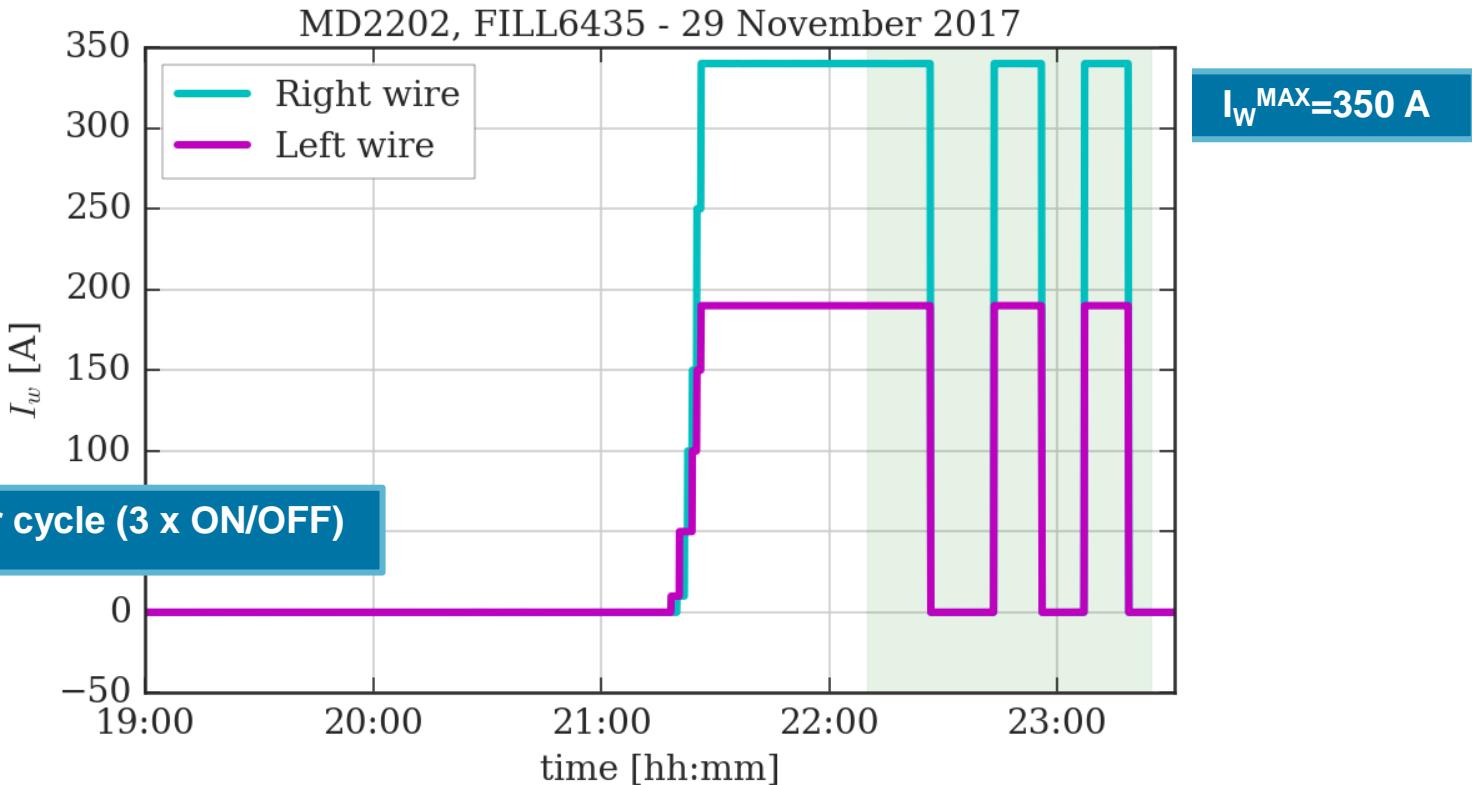
From the formalism to the experiment

We will consider the LHC optics used in the second part of 2017 (ATS with $\beta^* = 30$ cm, $\theta_c/2 = 150 \mu\text{rad}$). It corresponds to the condition of the second experiment (we will consider only IP5).

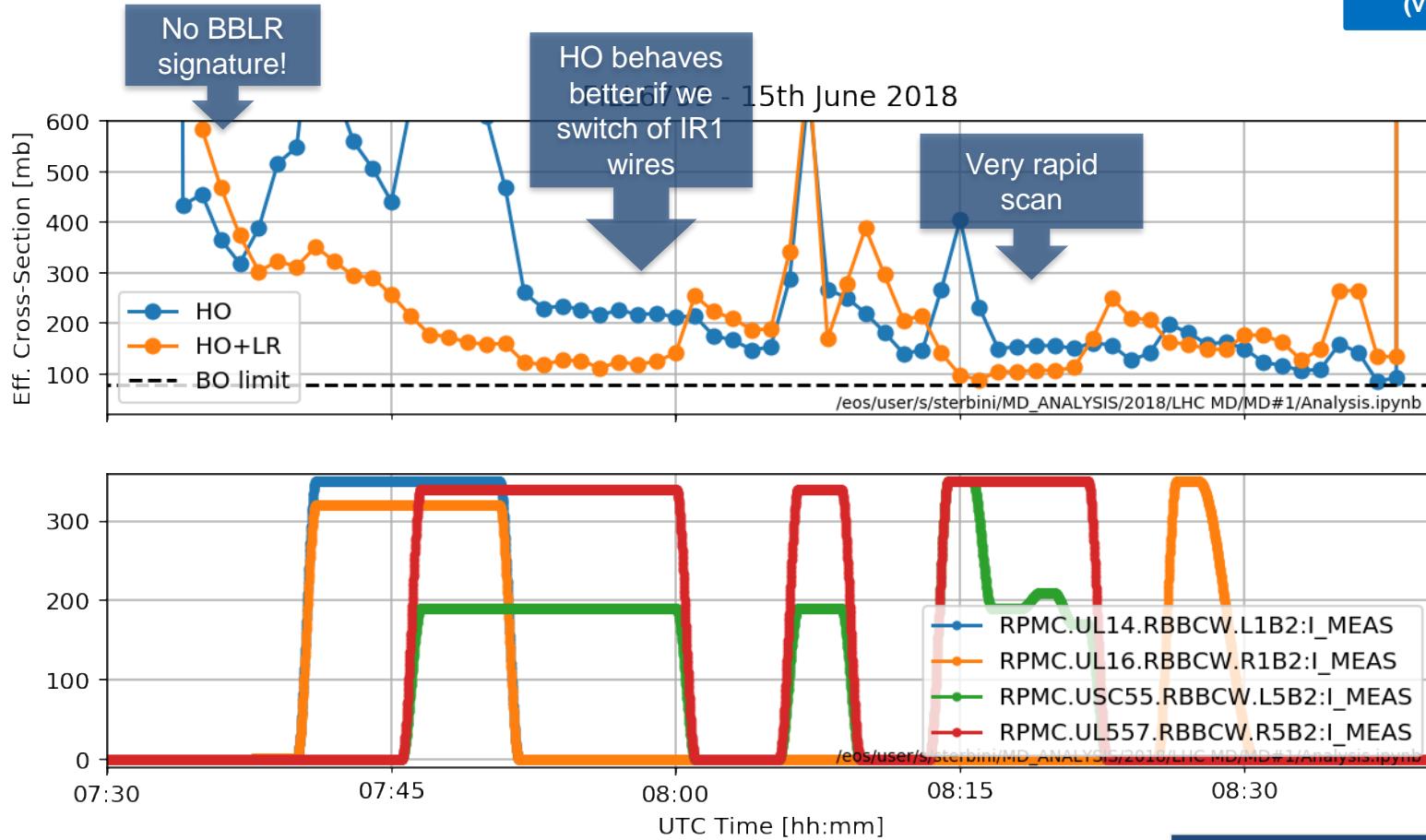


We consider 25 encounter per side of the IP.

Switching ON/OFF the compensation

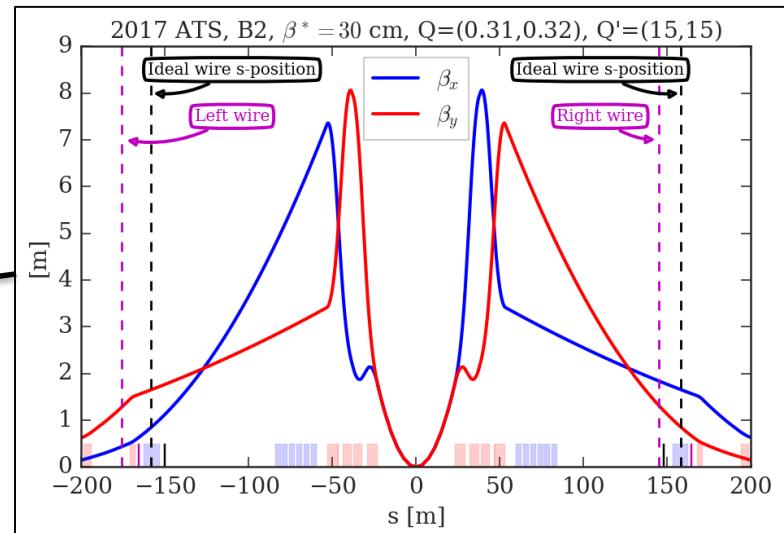
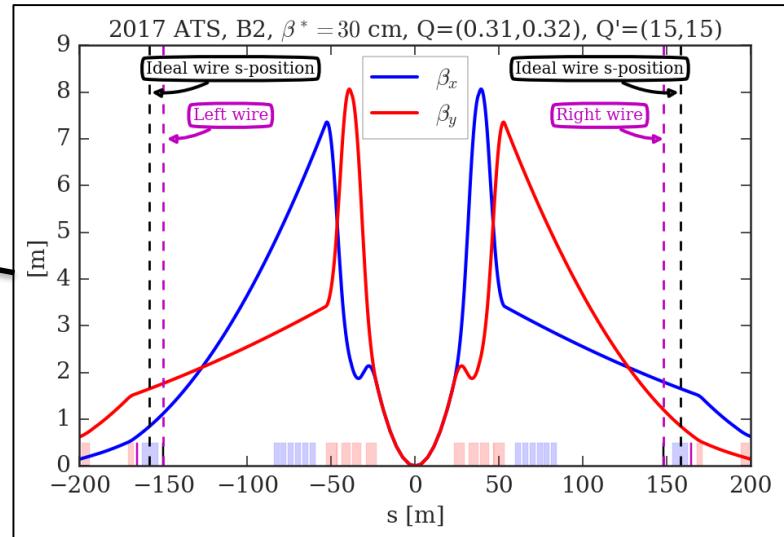
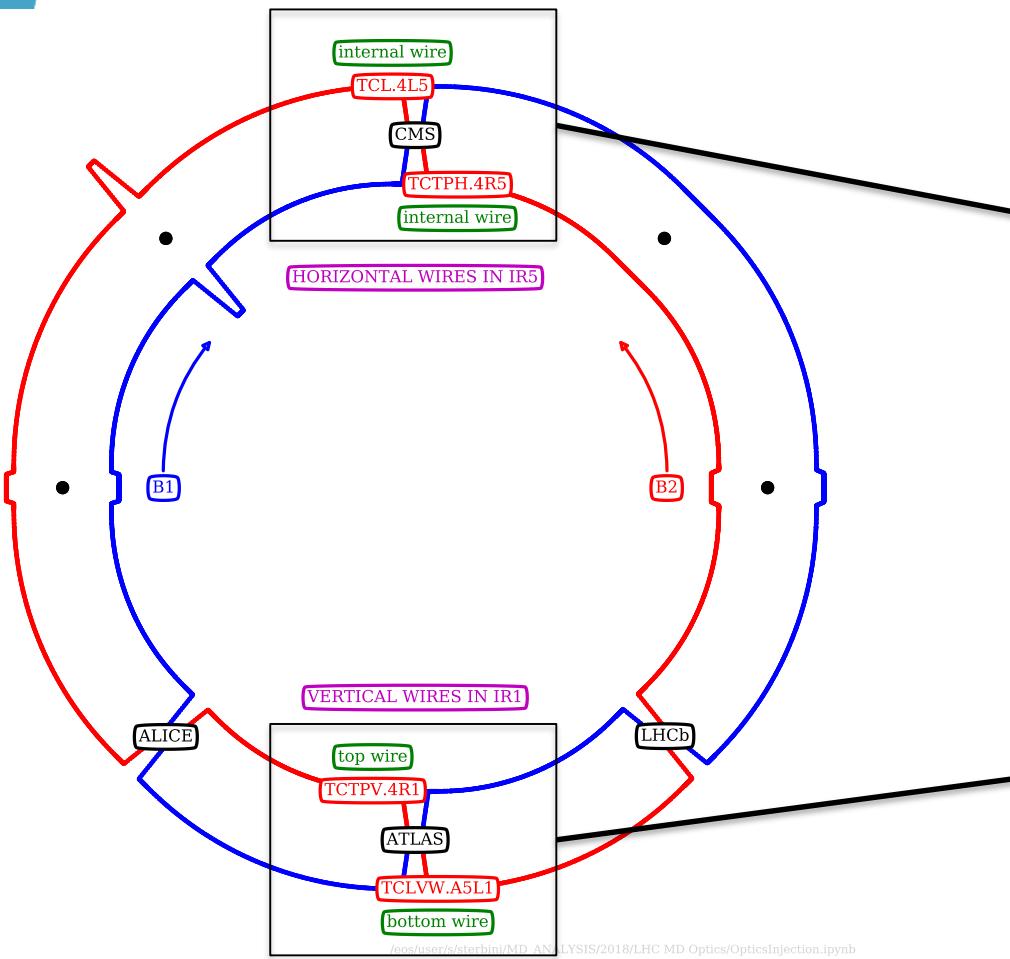


- The wires were switched ON-OFF for several powering cycles.
- During the powering of the wires, the tunes of the beam (and its position) has to be controlled with high precision: dipolar and quadrupolar contributions of the wires were compensated with feed-forward trims [credit to M. Solfaroli and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



Credit to A. Poyet

REAL s-position (I)

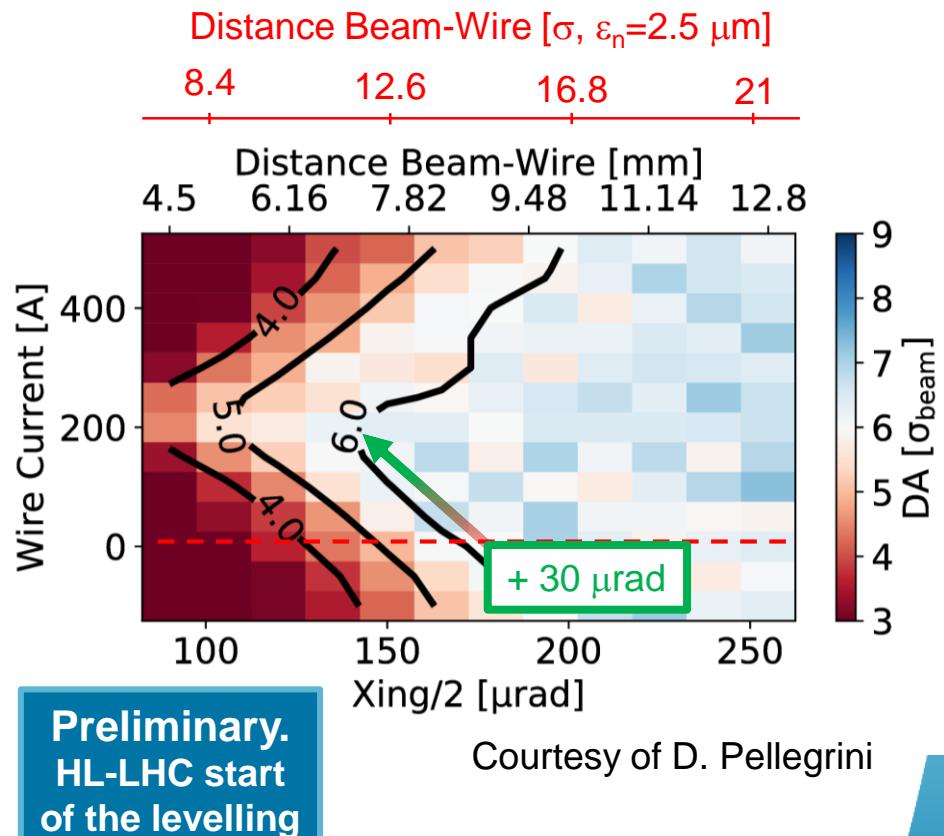


The **TCLVW.A5L1.B2** is NOT an operational collimator.

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 $30 \mu\text{rad}$ for the half-crossing angle.

HL1.3; $I=2.2\text{e}11$; $\beta^*=60\text{cm}$; $I_{\text{MO}}=-570\text{A}$;
 $Q'=15$; $Q=(62.320, 60,325)$; Min DA.



Analysis of the BBCW compensation

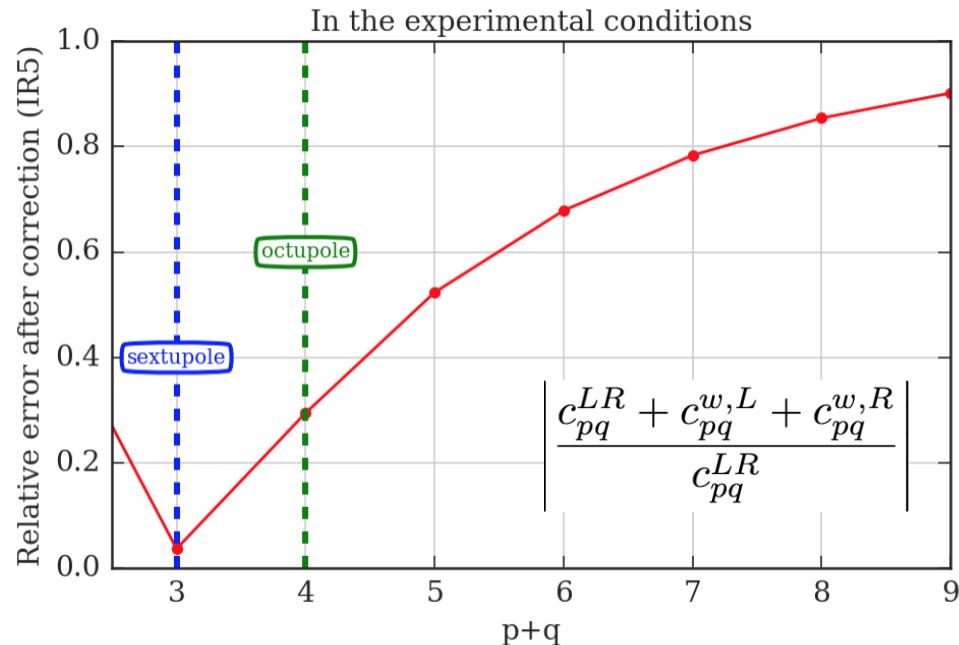
- Given the constraint on the minimal beam-wire distance, it was not possible to compensate all the resonances excited by the B1.
- We used the maximum current of the wires (350 A) to attack as much as possible the BBLR octupolar term.
- The octupolar terms induced by the BBLR in IR5 was reduced by **75%**.

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

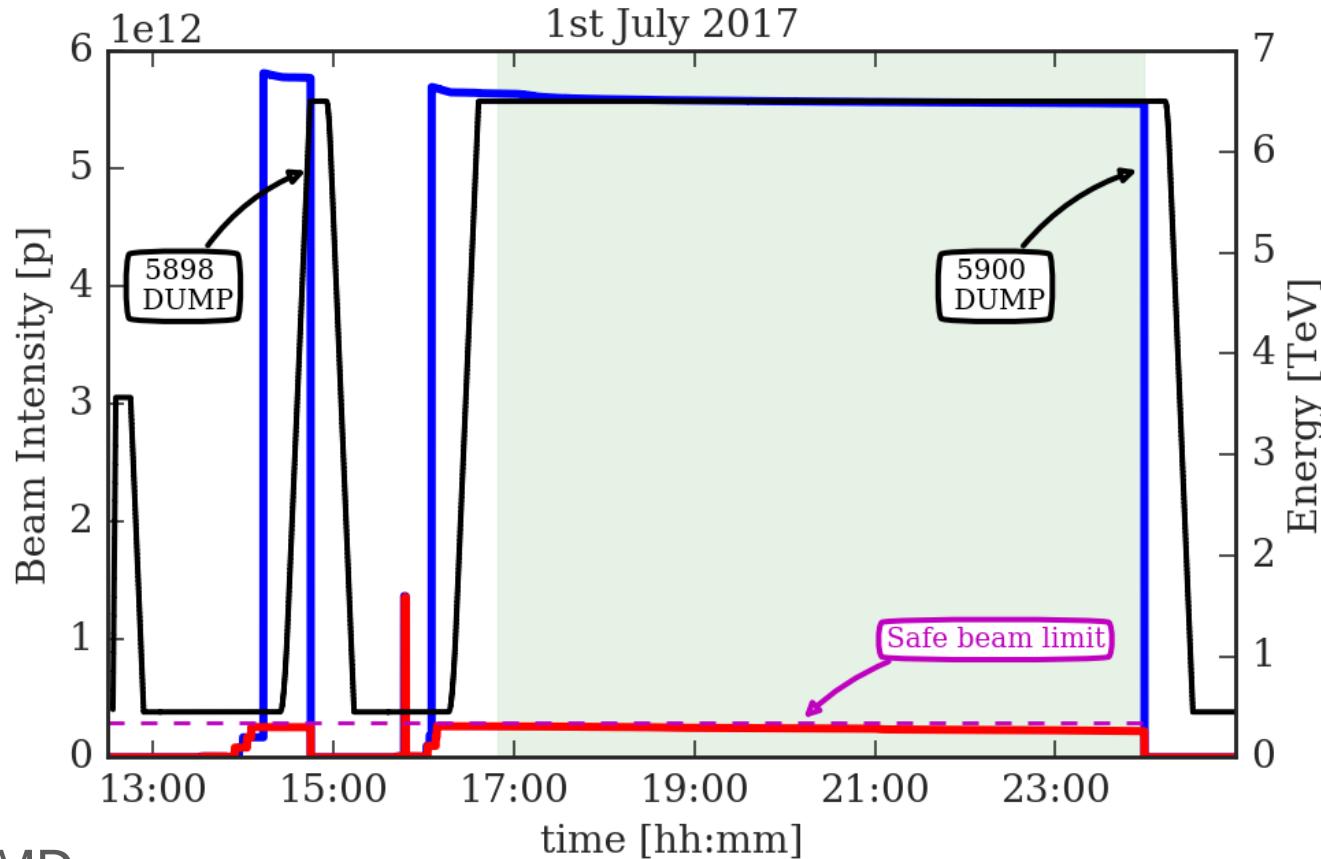
Strong-beam
driven resonance

BBCW driven
resonance

$$c_{pq}^{\text{LR}} \equiv \sum_{k \in \text{LR}} \frac{\beta_x^{p/2}(s_k) \beta_y^{q/2}(s_k)}{d_{bb}^{p+q}(s_k)}$$
$$\begin{cases} c_{pq}^{w,\text{L}} \equiv N_{w,\text{L}} \times \frac{(\beta_x^{w,\text{L}})^{p/2} (\beta_y^{w,\text{L}})^{q/2}}{(d_{w,\text{L}})^{p+q}} \\ c_{pq}^{w,\text{R}} \equiv N_{w,\text{R}} \times \frac{(\beta_x^{w,\text{R}})^{p/2} (\beta_y^{w,\text{R}})^{q/2}}{(d_{w,\text{R}})^{p+q}} \end{cases}$$



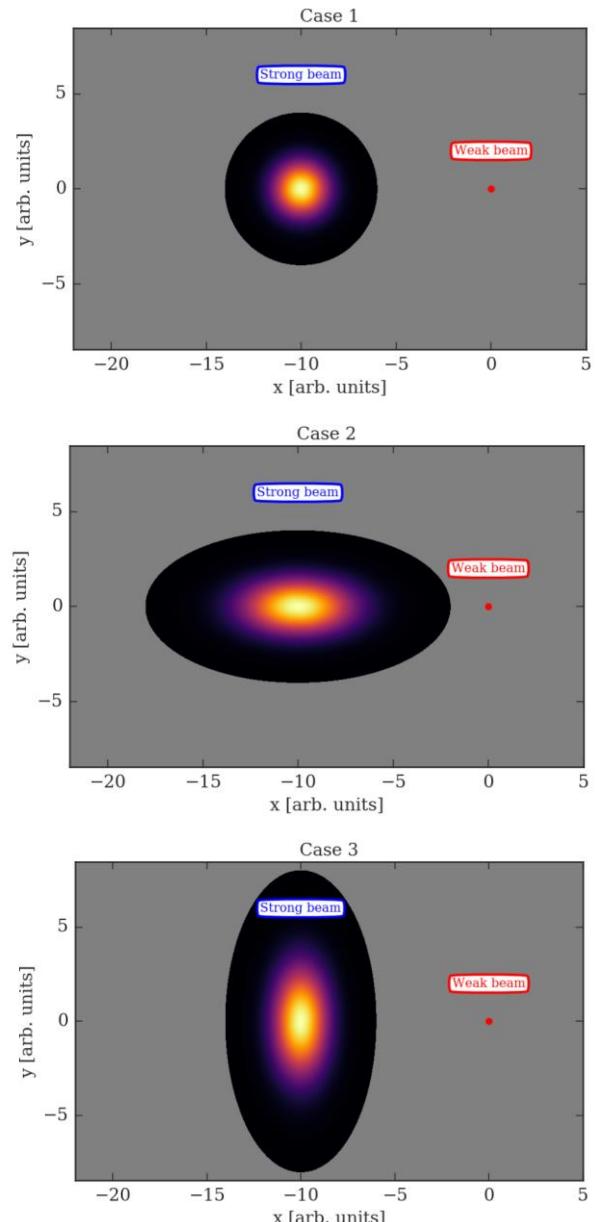
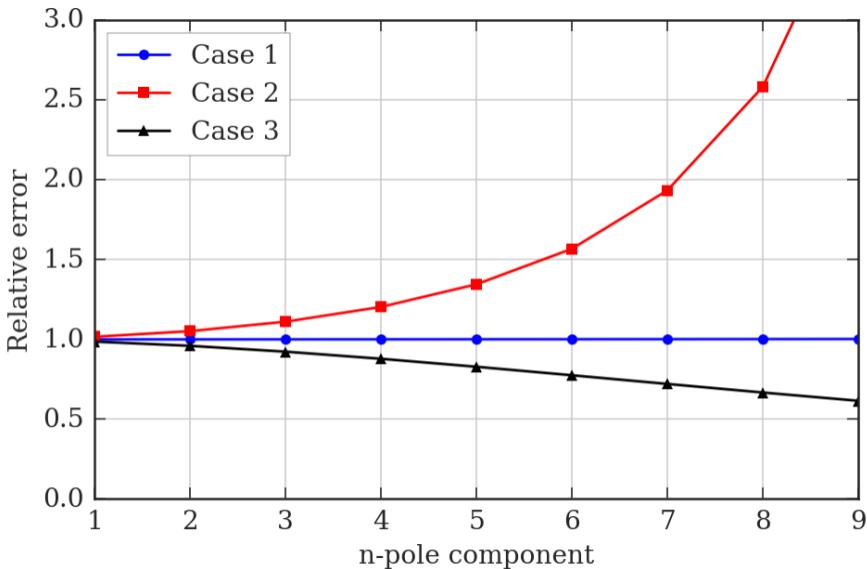
MD2202



- 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.

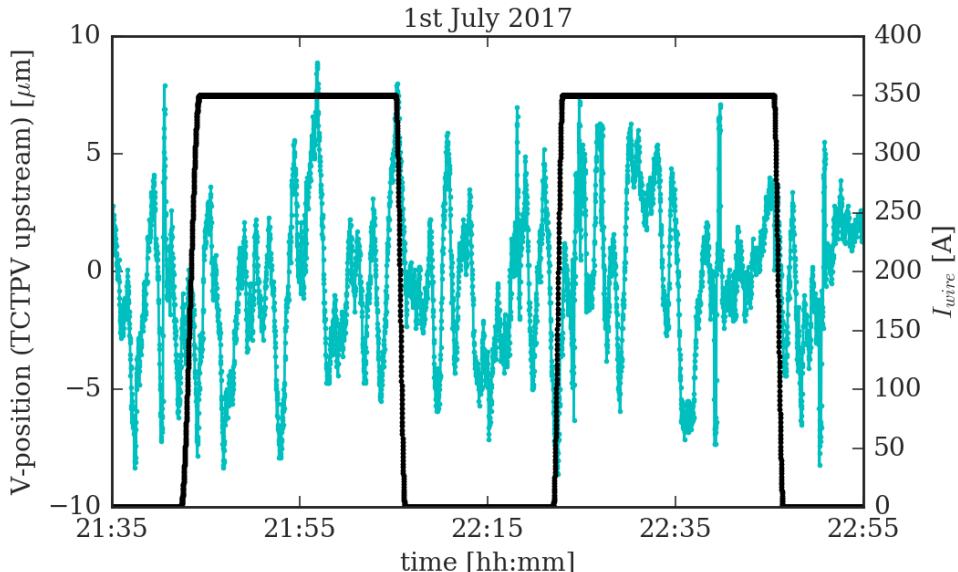
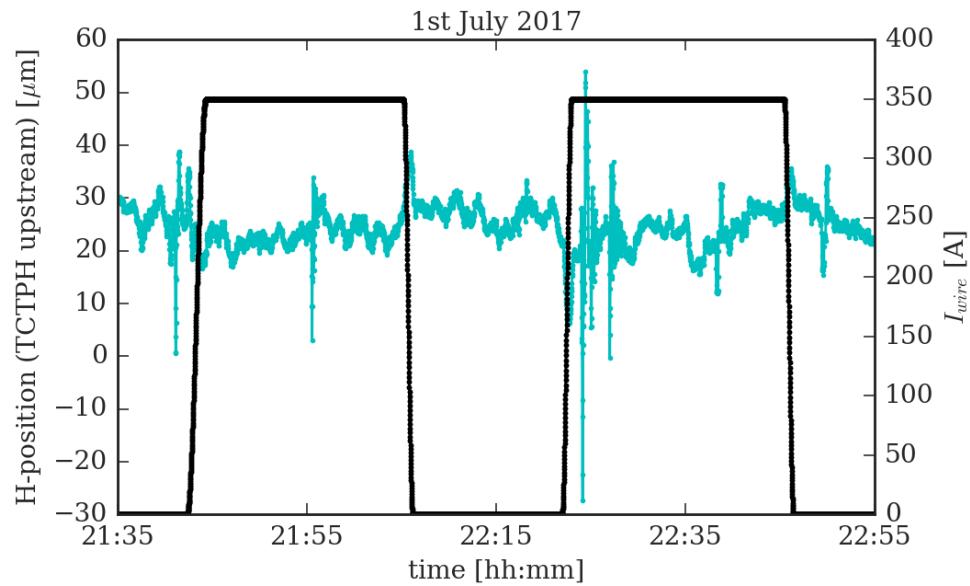
“Strong beam”-wire equivalence

- 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)

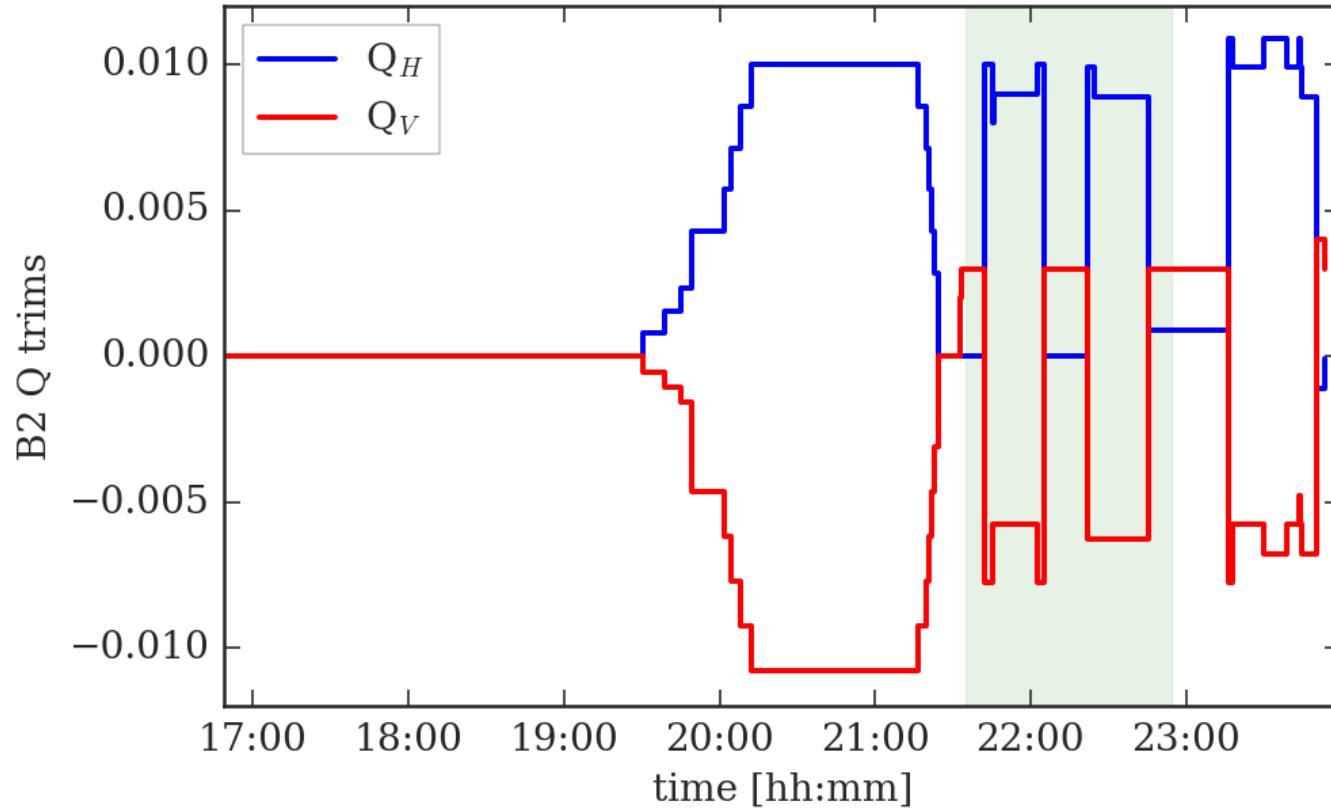


BBCW MD: sanity checks on H/V-position

- 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.

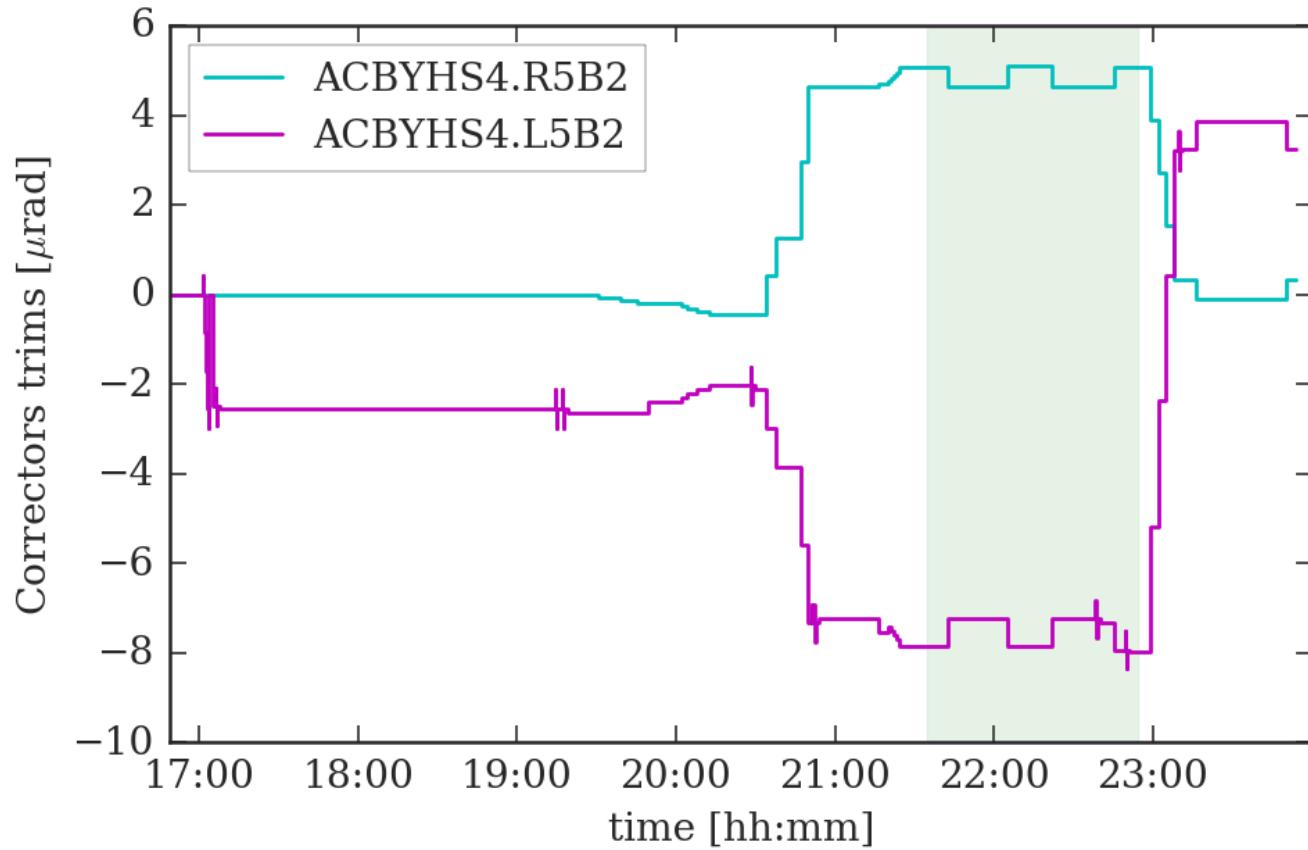


BBCW MD: Q trims



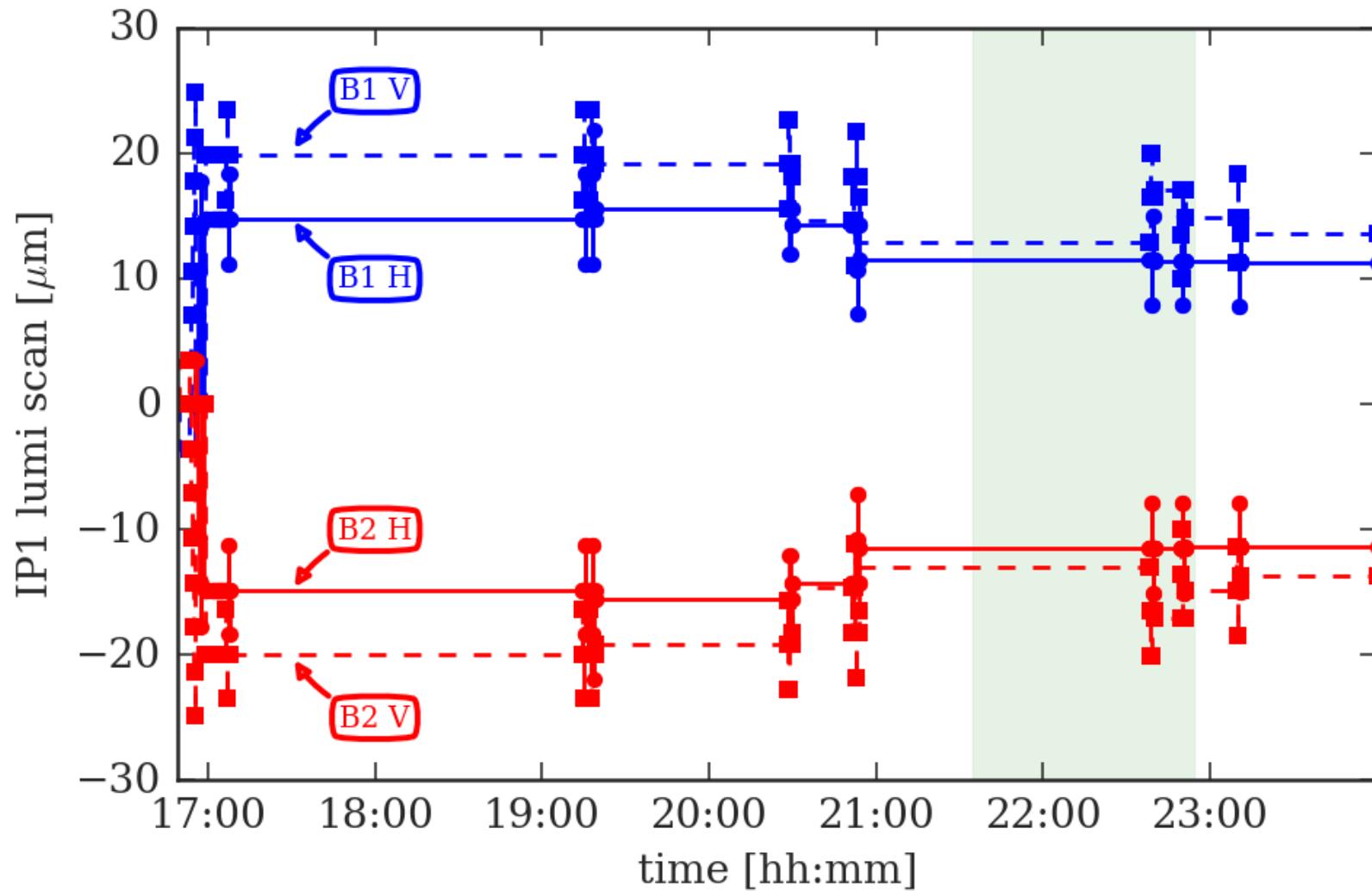
The Q-trims are mostly due to the feedforward.

BBCW MD: dipolar trims

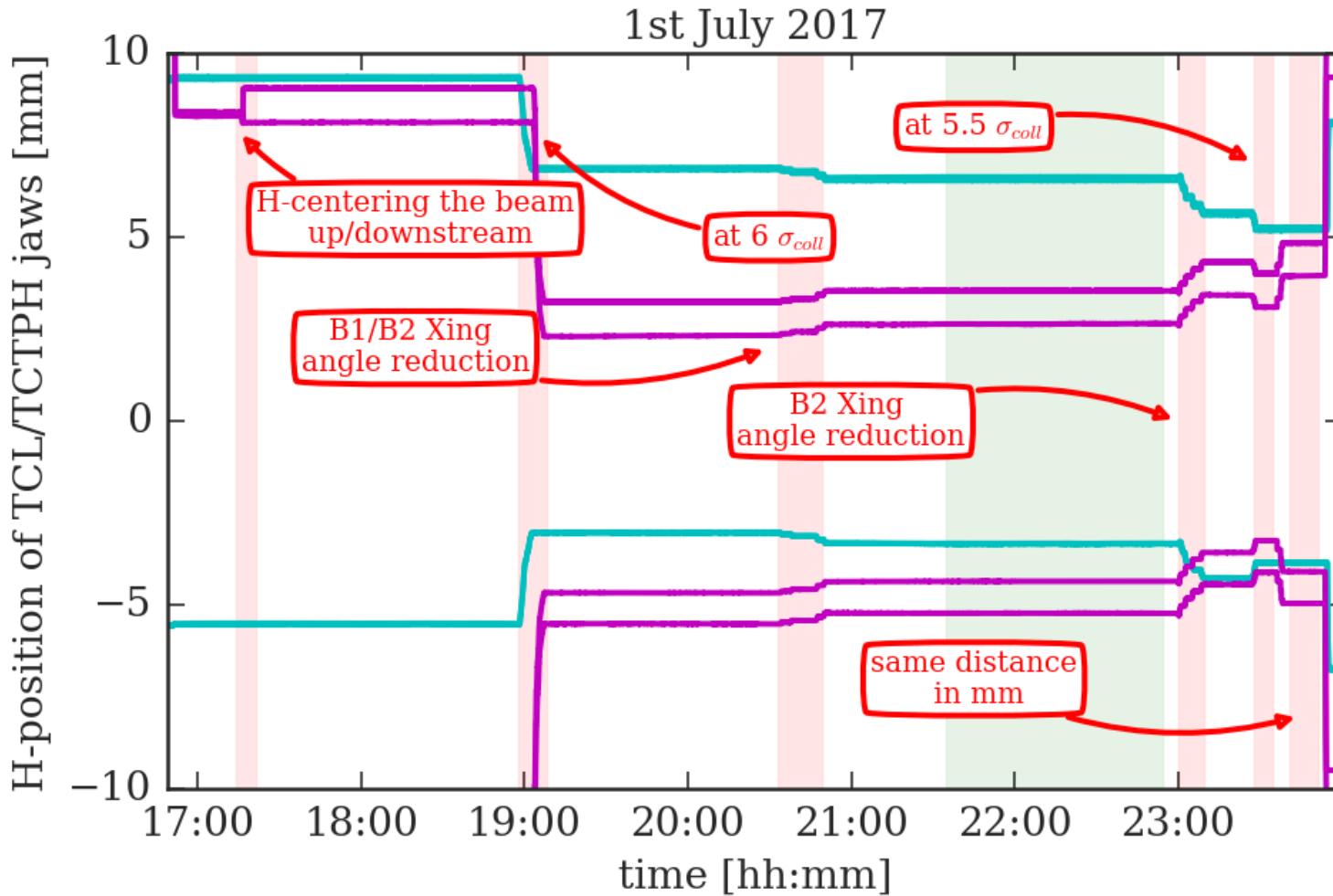


The correctors trims are mostly due to the crossing angle settings.

BBCW MD: optimizing HO collision



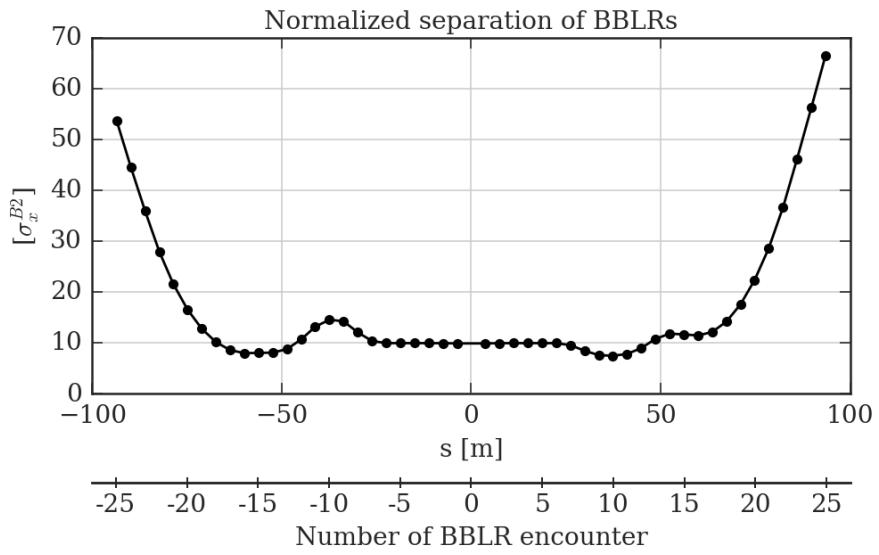
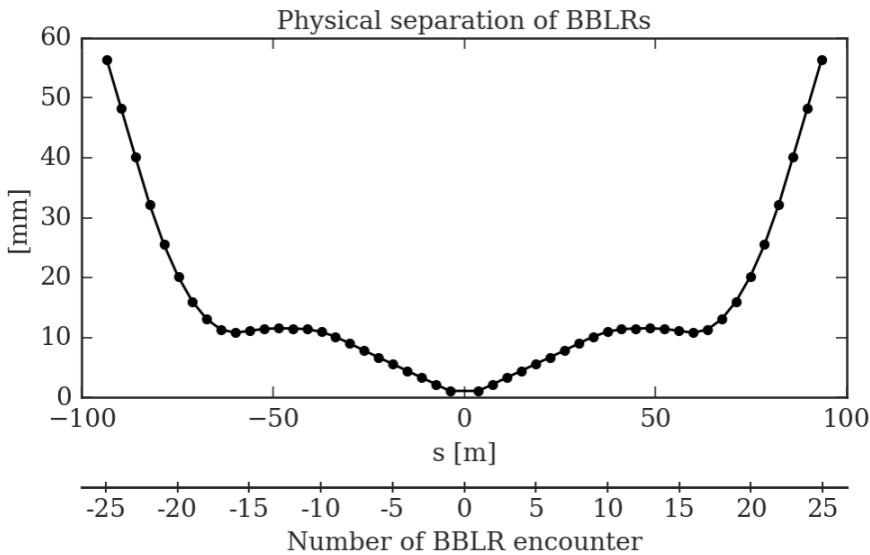
BBCW MD: wires H-positioning



The hectic activity on the BBCW positioning.

ATS 2017 optics

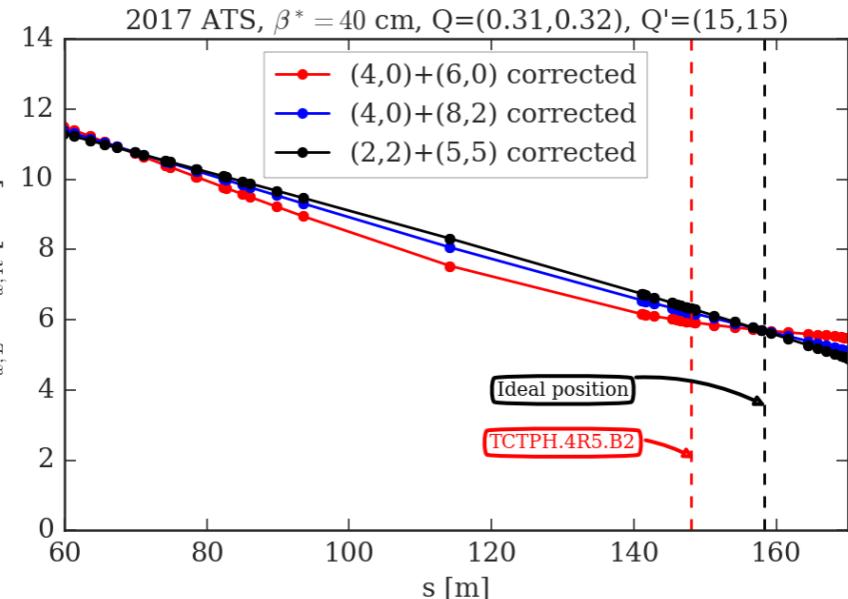
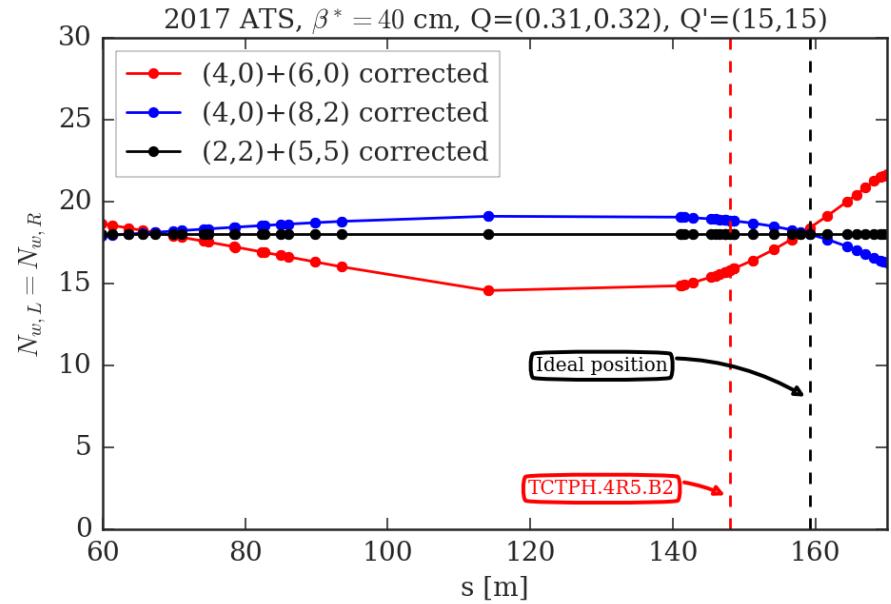
	NAME	X	PX	Y	PY	BETX	BETY	sigma_x at 3.5 um at 6.5 TeV [mm]
7062.030793	TCL.4L5.B2	1.527841e-03	0.000054	0.003836	-4.970527e-05	845.954861	1327.127536	0.653755
7212.060793	IP5	1.936385e-15	-0.000150	-0.001500	-9.267840e-15	0.400000	0.400000	0.014216
7360.005793	TCTPH.4R5.B2	-1.422381e-03	0.000034	0.002863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



RDT criterion for ATS 2017 and $\theta_c=150 \mu\text{m}$

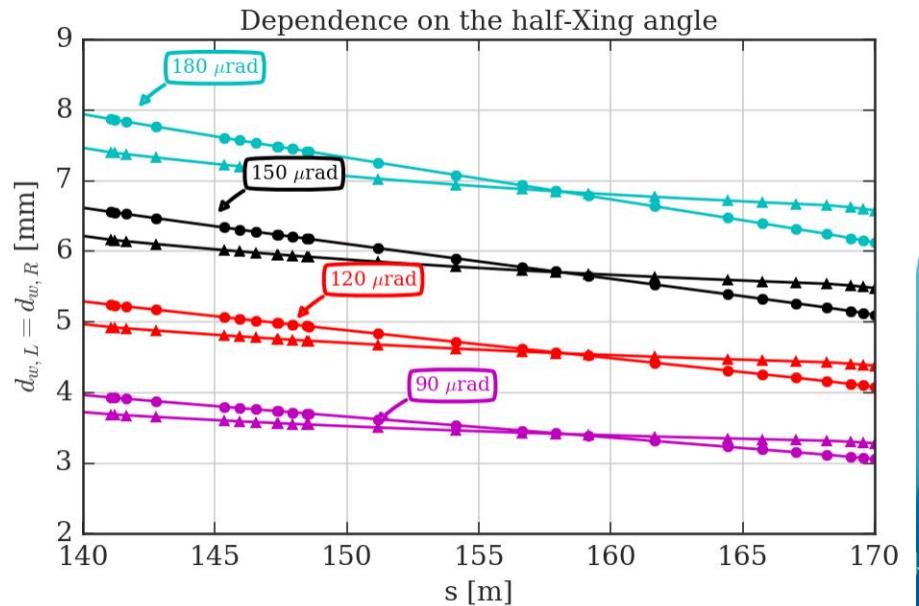
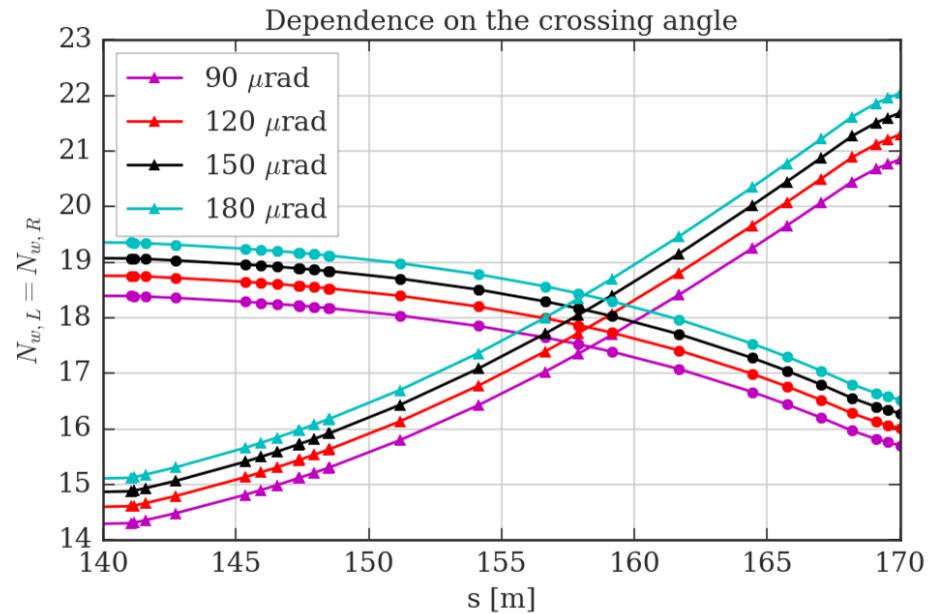
By plotting the $N_w(s)$ and $d_w(s)$ for different RDT minimization strategy, one sees there are specific s -positions, s_{opt} , that minimizes more than the usual 4 RDTs.

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

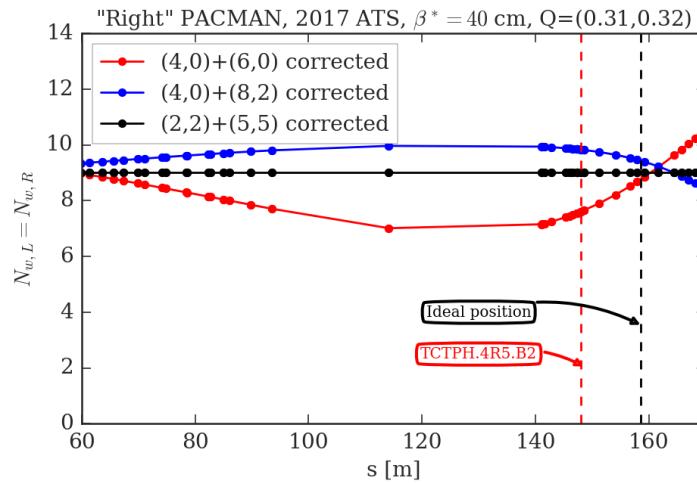
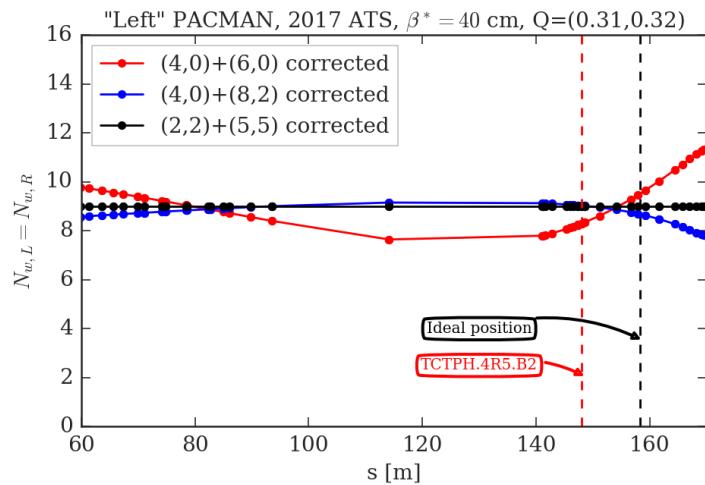
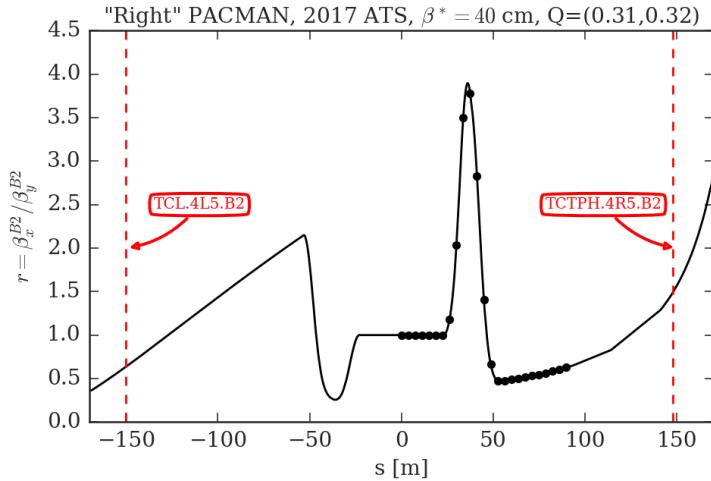
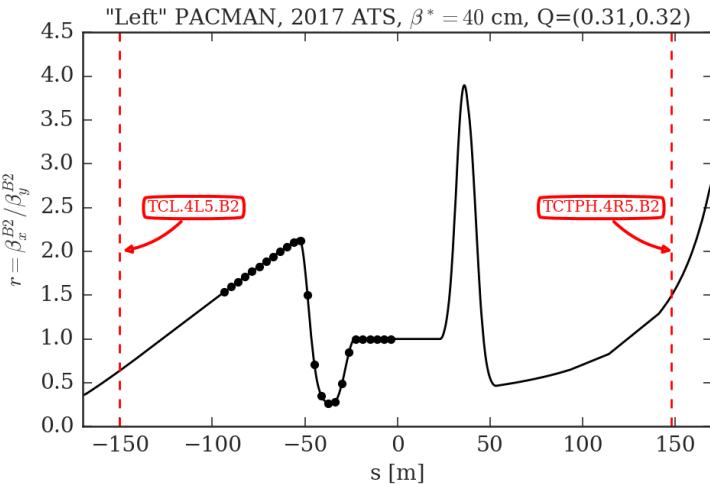


s_{opt} , N_w and d_w on crossing angle

- 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.



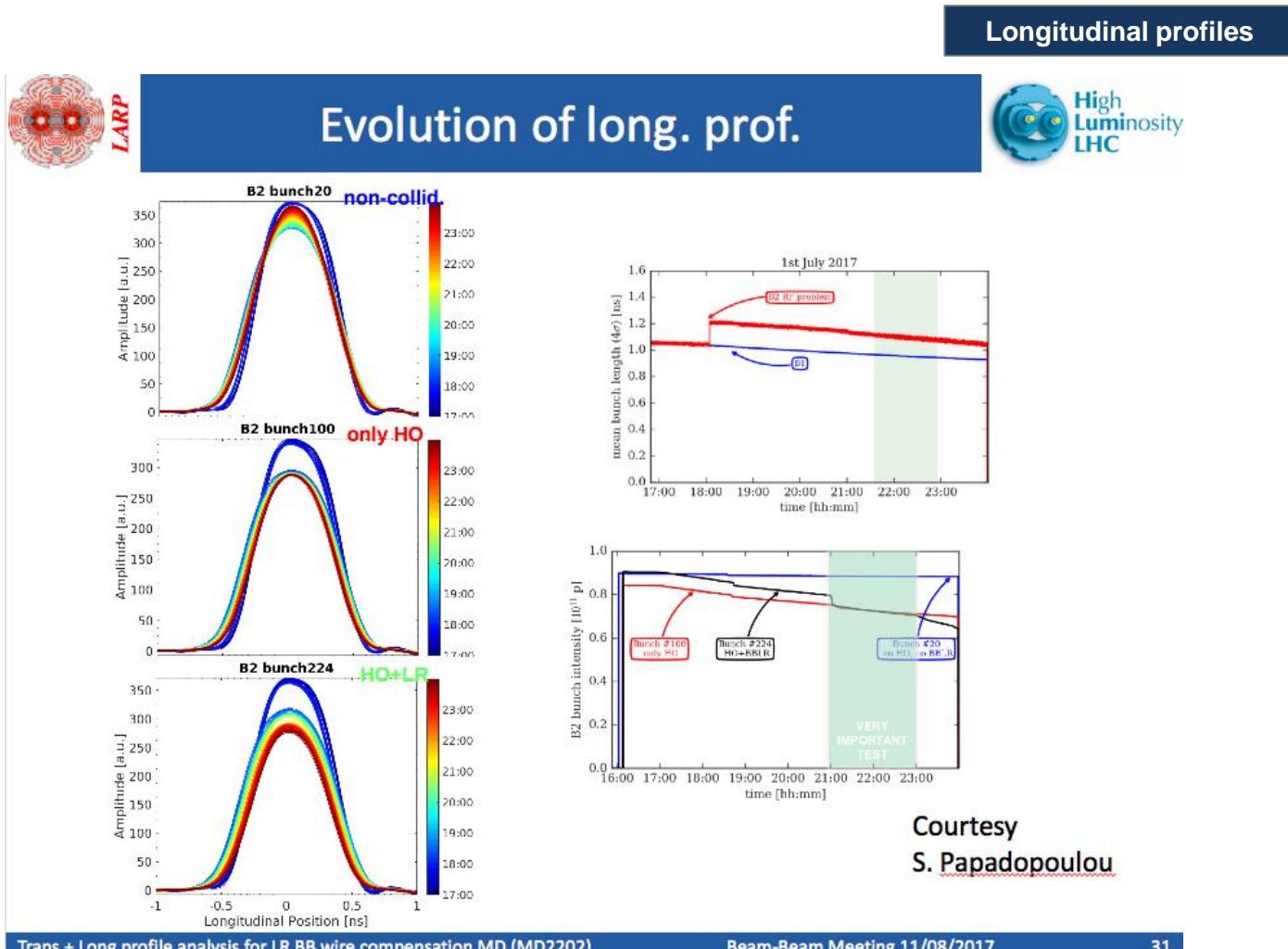
PACMAN bunches and s_{opt}



The s_{opt} depends on the PACMAN pattern.

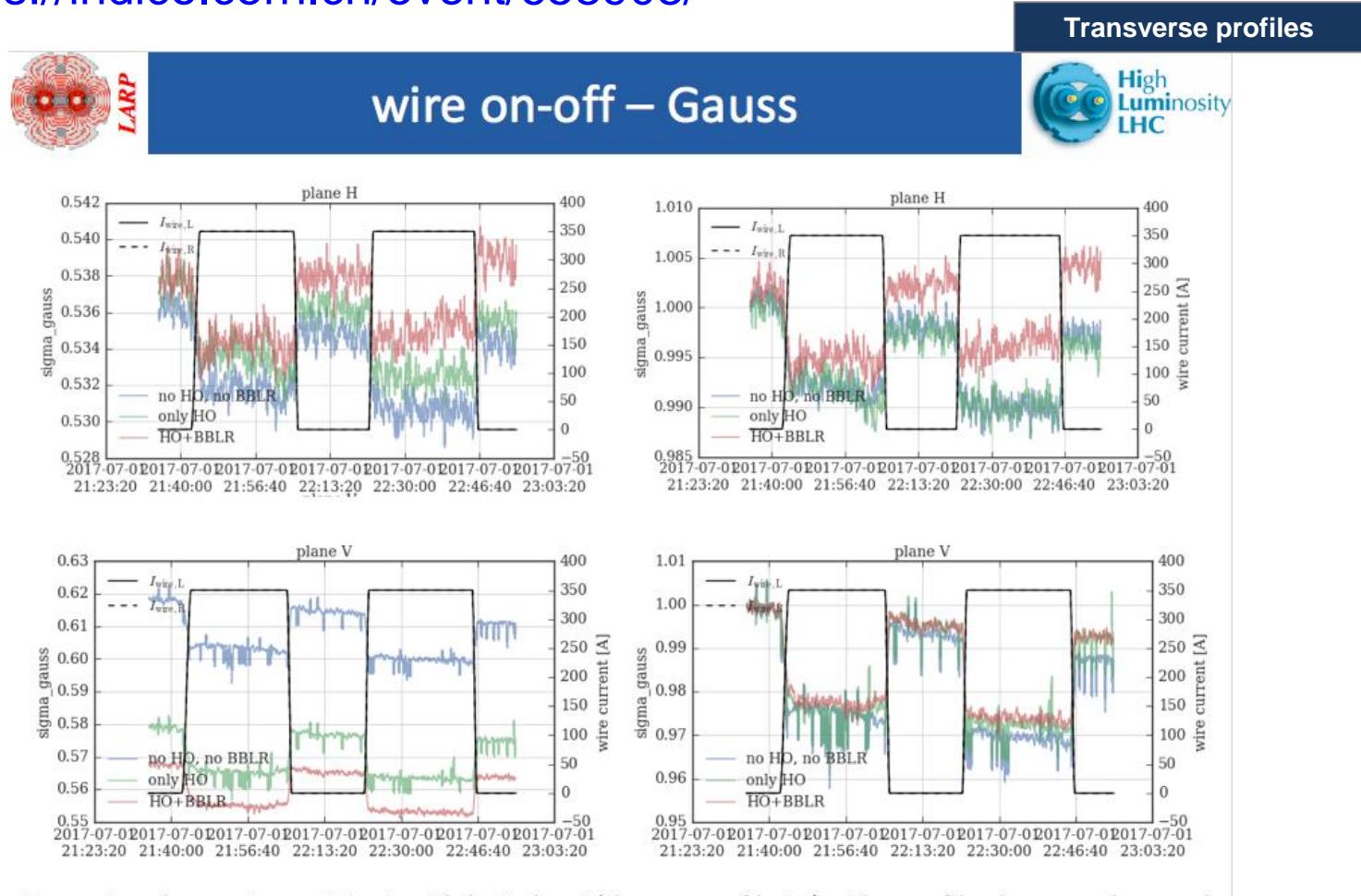
BBCW impact of the beam profiles (I)

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



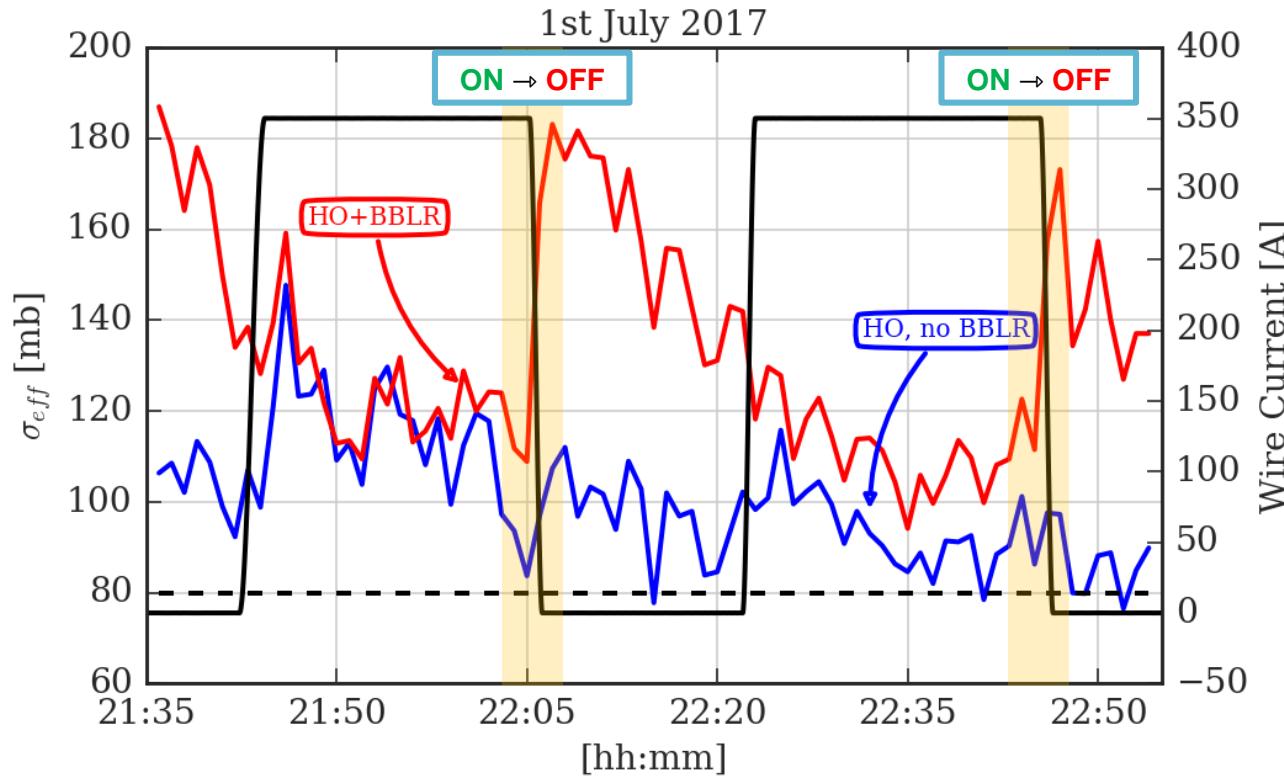
BBCW impact of the beam profiles (II)

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



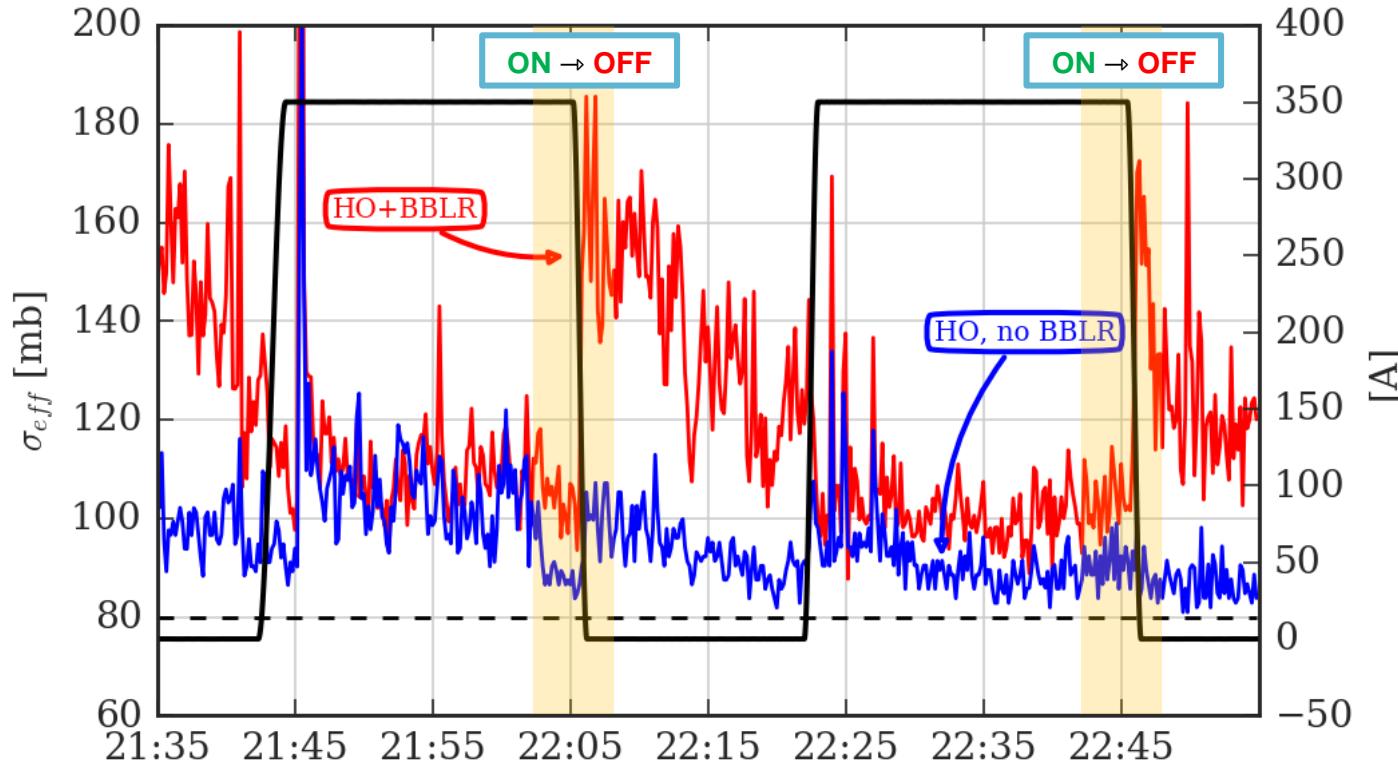
Beam size change is consistent with beta-beat (decrease of beta) + the profile changes observed

Results on the compensation (I)



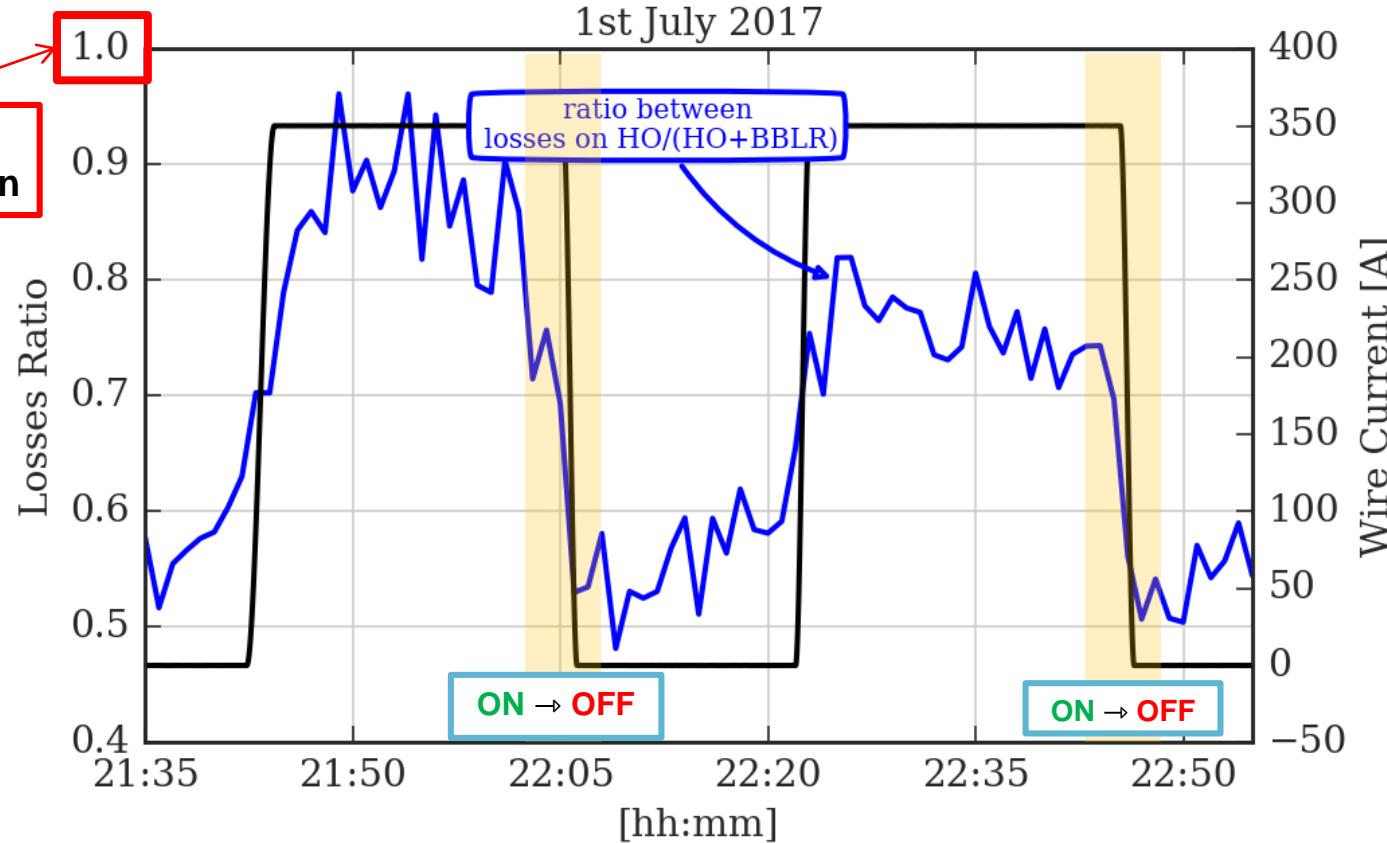
- Compensation seen from the σ_{eff} [credit to N. Karastathis].
- Clear effect on the BBCW when switching-off: signal compatible with a contraction of the dynamic aperture of the machine.**

Result on the compensation (II)



- Using dBBLM 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)



- 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.**