HiLumi
HL-LHC PROJECT

Beam-Beam Long-Range Compensation using DC wires for (HL-)LHC

A. Poyet on behalf of our awesome wire team

CERN

CAS 2018 Thessaloniki– 20th November 2018

Outline

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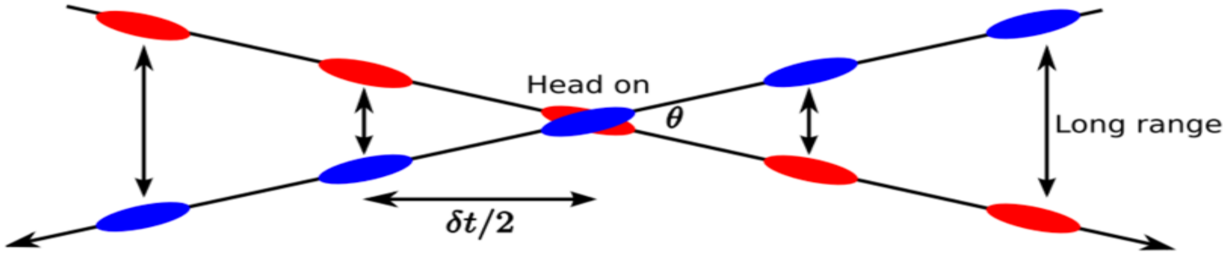
1. **Introduction: context and objectives**
   1. Context: BBLR interaction
   2. Considered solution: the wire compensator
   3. Objectives
2. BBLR compensation in the LHC
   1. Semi-analytical model
   2. Optimized current/distance for compensation
3. Experimental campaign
   1. Experimental setup
   2. Main results of the compensation using wires
   3. Alternative: ATS optics and octupoles
4. Conclusion

Context: BBLR interaction

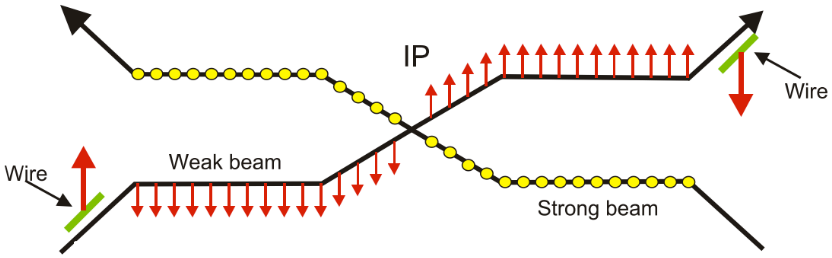
- In a collider, particles collide in the so-called IPs (4 in the LHC case):
  - At the IP: **Head-On (HO) interaction**
  - With a longitudinal offset with respect to the IP (same vacuum chamber): **Beam-Beam Long-Range (BBLR) interaction**

- Machine performance is degraded by the presence of those parasitic collisions around IP1 and IP5 (mainly)

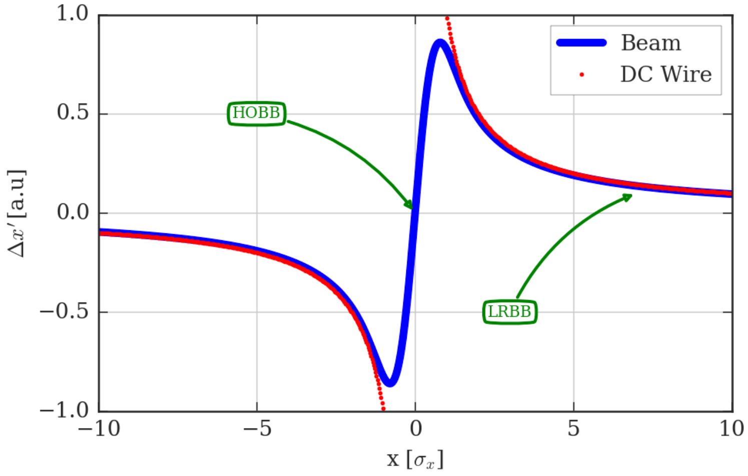


Considered Solution: Wire compensators

- In 2002, **J-P. Koutchouk** proposed for the first time the idea of compensating the LRBB interaction with a **DC wire**.



- Far enough, **the wire and the strong beam are equivalent**.

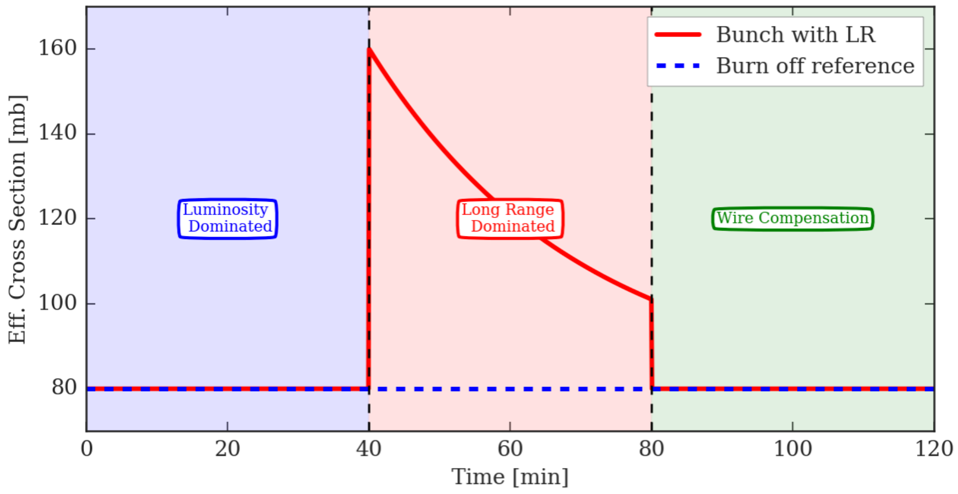


- Even though the **wire is not in the HL-LHC baseline**, its potential with flat optics has been highlighted by S. Fartoukh et al., PRST-AB 18, 121001, 2015 and confirmed by the 2017/2018 experimental campaign.

Objectives

- Using the actual LHC to prove the concept of BBLR compensation with **the wire compensators,** seeing a beneficial effect on the **beam lifetime**.
- Best observable: bunch by bunch **effective cross-section.** Allows us to compare the losses from a bunch, with respect to the luminosity losses. An ideal MD:

$$\sigma_{eff} = -\frac{1}{\sum_i \mathcal{L}_i}\frac{\mathrm{d}N}{\mathrm{d}t}$$



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p, q	Pole order
$\beta^{w}_{x,y}$	Beta functions at the wires locations
$\beta_{x,y}(s_k)$	Beta function at the LR locations
$N_{w,L,R}$	Integrated current in the wires
d_{bb}	Physical beam-beam separation
$d_{w,L,R}$	Distance beam-wire

Semi analytical model

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

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(Received 3 September 2015; published 1 December 2015)

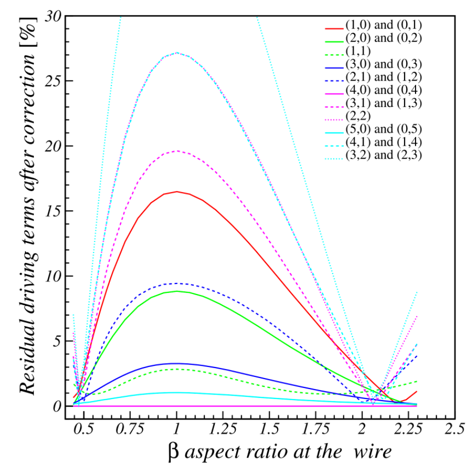
- RDT excited by the LRBBI:

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

- RDT excited by the wires:

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

- The goal is to compensate all of them, by compensating only two (four by symmetry), hence the two wires.
- **In the ideal case, compensation 2 (4) RDT leads to a minimization of all**

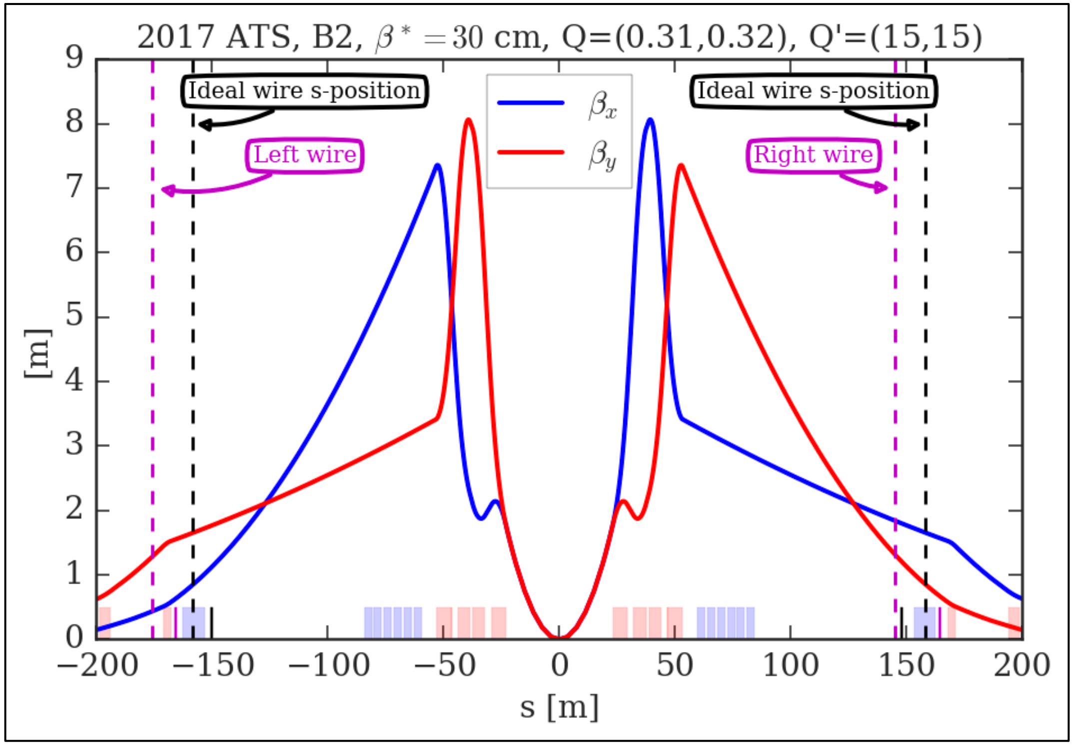


S.Fartoukh and al., *Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC*, Phys. Rev. ST Accel. Beams **18**, 121001 (2015)

Current optimisation

- LHC, the wires are in a **suboptimal position** (longitudinal and transverse)
- The transverse position is imposed by the collimator settings

- We optimize therefore the current in order to compensate the **(4,0)-(0,4) RDT (octupole-like resonance)**



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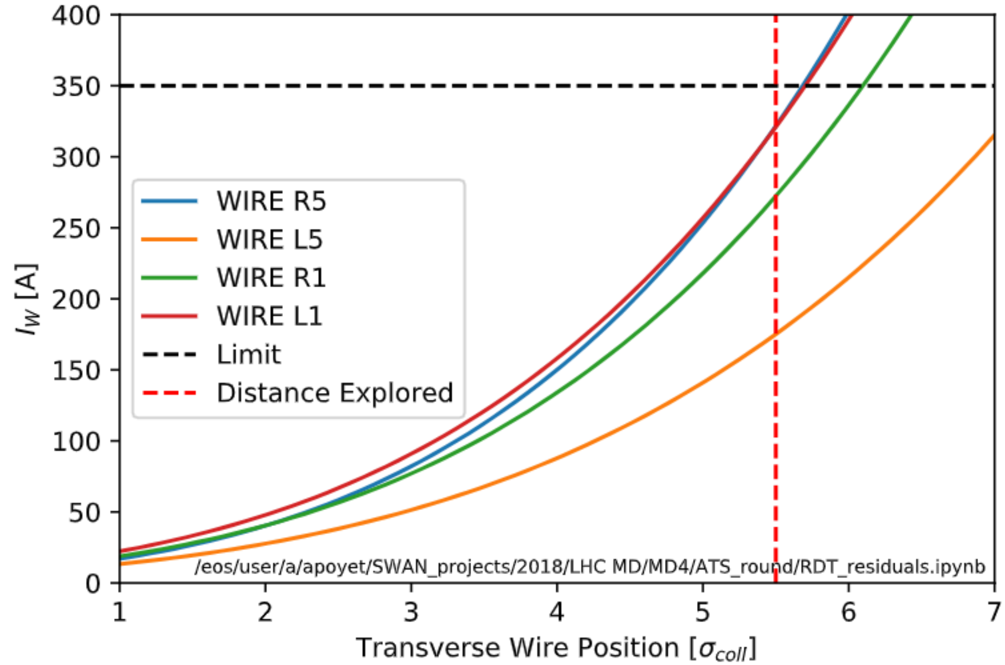

$$N_R = \frac{d_R^{p_1+q_1+p_2+q_2}\left(c^{LR}_{p_1,q_1} d_L^{p_1+q_1} \beta_{x,L}^{p_2/2}\beta_{y,L}^{q_2/2} - c^{LR}_{p_2,q_2} d_L^{p_2+q_2}\beta_{x,L}^{p_1/2}\beta_{y,L}^{q_1/2}\right)}{d_L^{p_1+q_1} d_R^{p_2+q_2}\beta_{x,L}^{p_2/2}\beta_{x,R}^{p_1/2}\beta_{y,L}^{q_2/2}\beta_{y,R}^{q_1/2} - d_L^{p_2+q_2} d_R^{p_1+q_1}\beta_{x,L}^{p_1/2}\beta_{x,R}^{p_2/2}\beta_{y,L}^{q_1/2}\beta_{y,R}^{q_2/2}}$$

$$N_L = \frac{d_L^{p_1+q_1+p_2+q_2}\left(c^{LR}_{p_1,q_1} d_R^{p_1+q_1}\beta_{x,R}^{p_2/2}\beta_{y,R}^{q_2/2} - c^{LR}_{p_2,q_2} d_R^{p_2+q_2}\beta_{x,R}^{p_1/2}\beta_{y,R}^{q_1/2}\right)}{d_L^{p_2+q_2} d_R^{p_1+q_1}\beta_{x,L}^{p_1/2}\beta_{x,R}^{p_2/2}\beta_{y,L}^{q_1/2}\beta_{y,R}^{q_2/2} - d_L^{p_1+q_1} d_R^{p_2+q_2}\beta_{x,L}^{p_2/2}\beta_{x,R}^{p_1/2}\beta_{y,L}^{q_2/2}\beta_{y,R}^{q_1/2}}.$$

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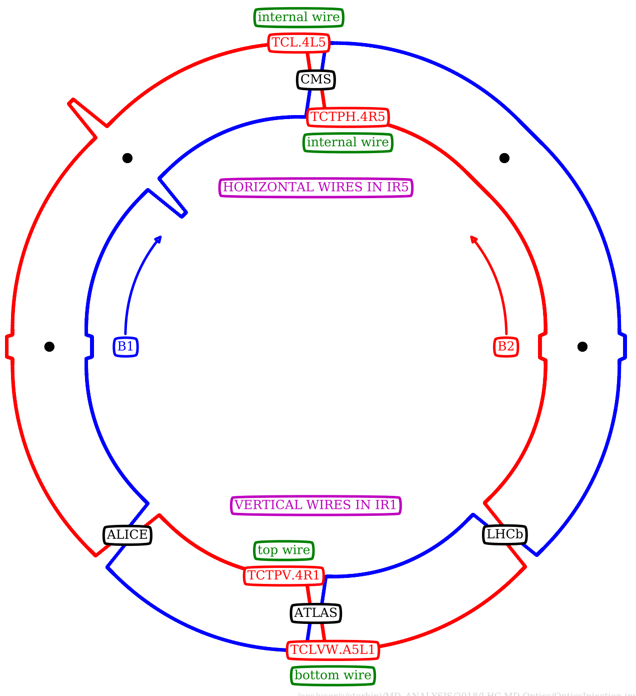
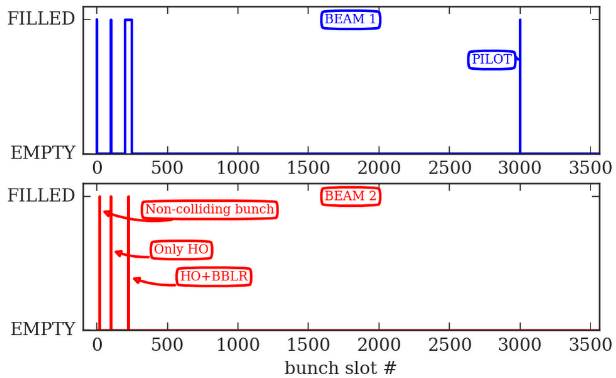
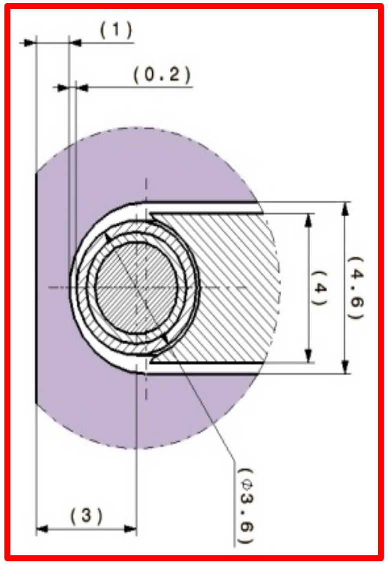
Experimental setup

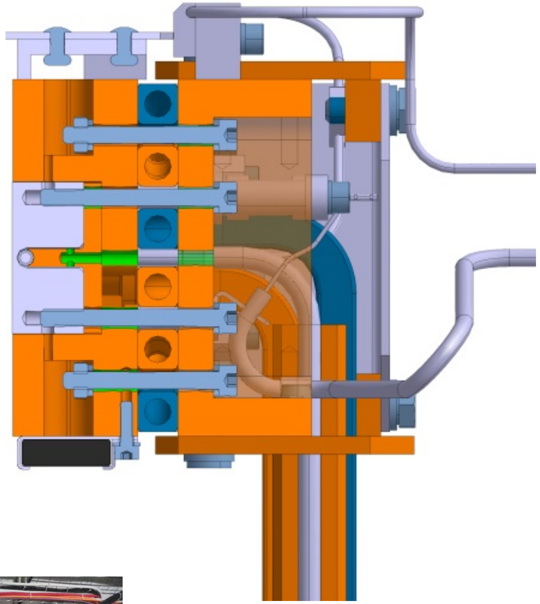
- During the two last YETS, 4 wire collimators have been installed around IP1 and IP5.
- B1 is composed of **trains of bunches**, B2 is composed of **2 or 3 bunches** (Nb < 3e11): one suffering HO+LRBB, one suffering HO (and for **tune measurements**).
- The wires are embedded in the collimators jaws, at 3 mm from its border

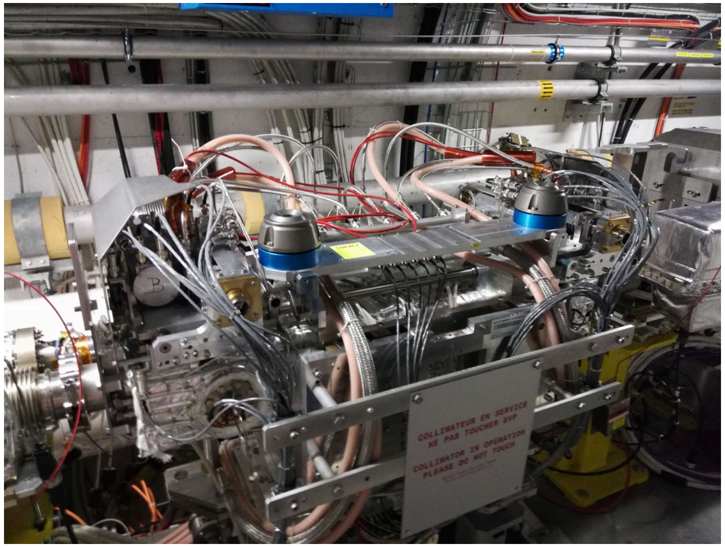




Experimental setup

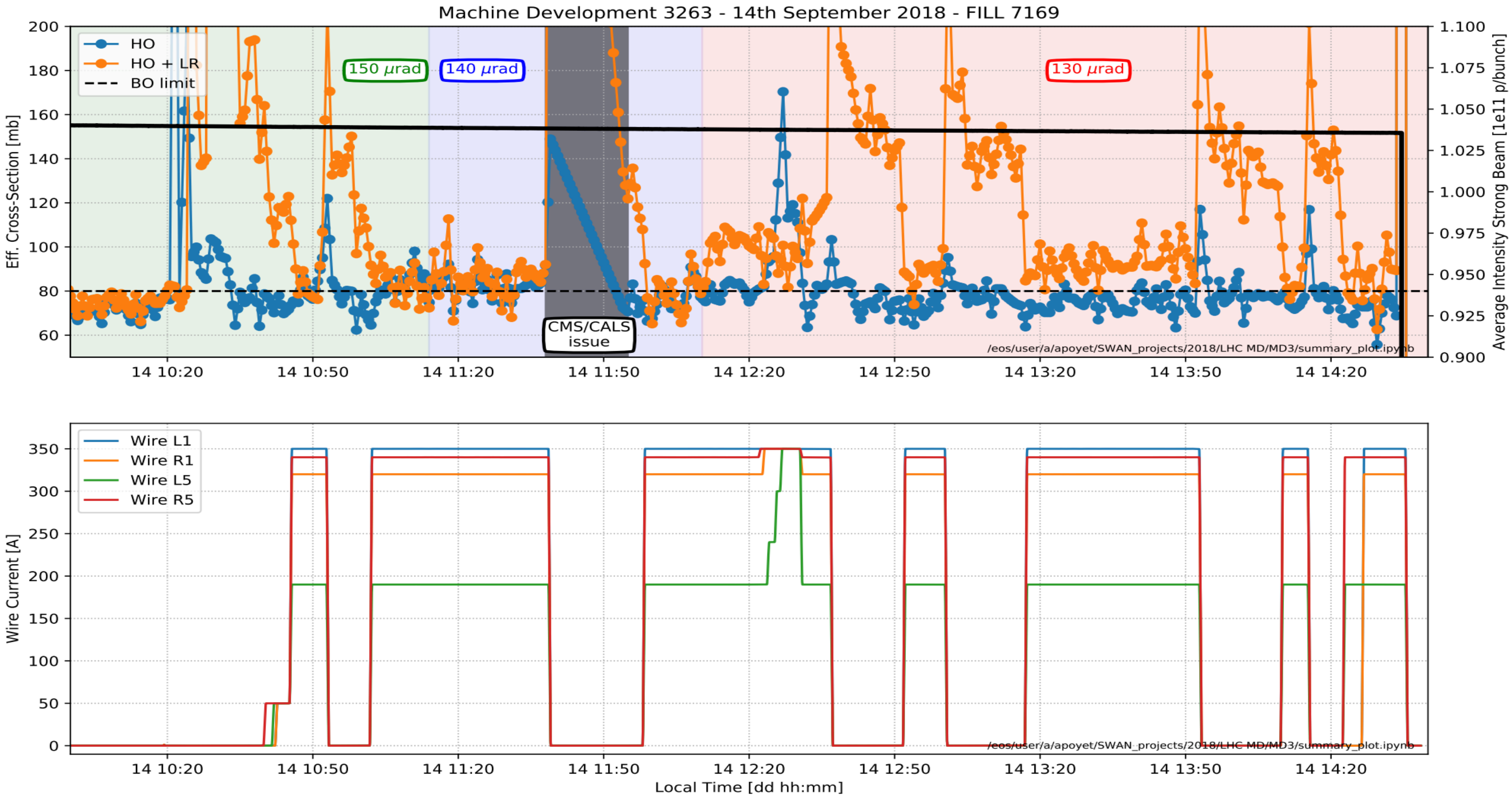






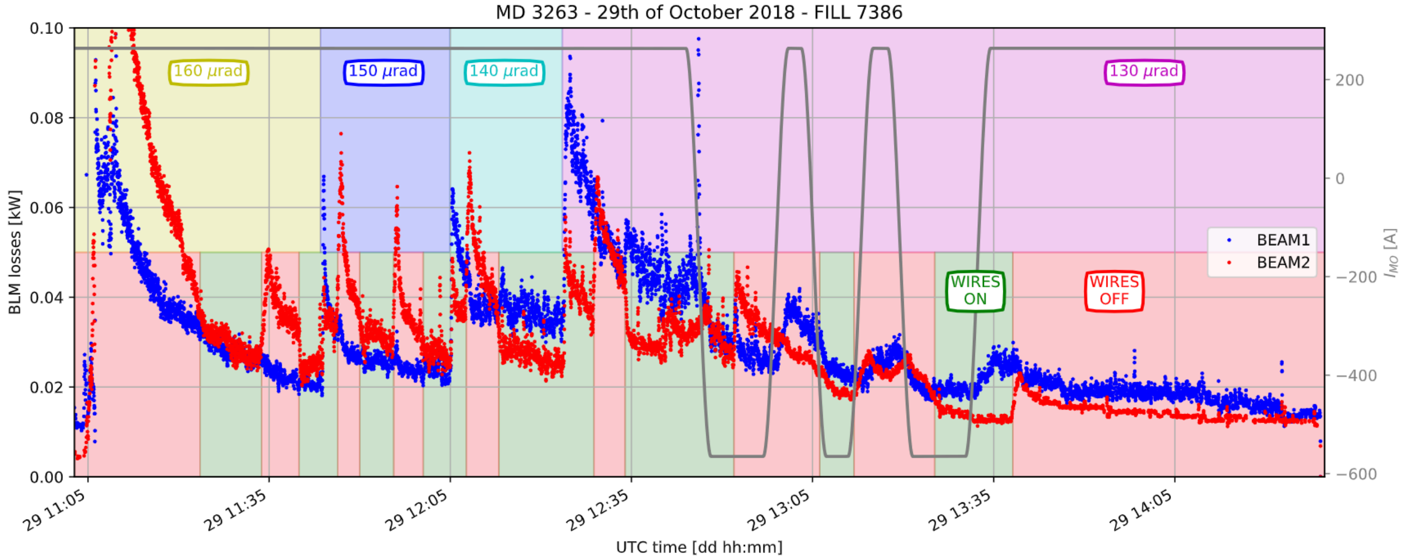
Experimental results: MD#3

- During MD#3, we powered the wires in both IPs, and reduced the crossing angle with **compensation ON: the beneficial effect of the wires is clear!**



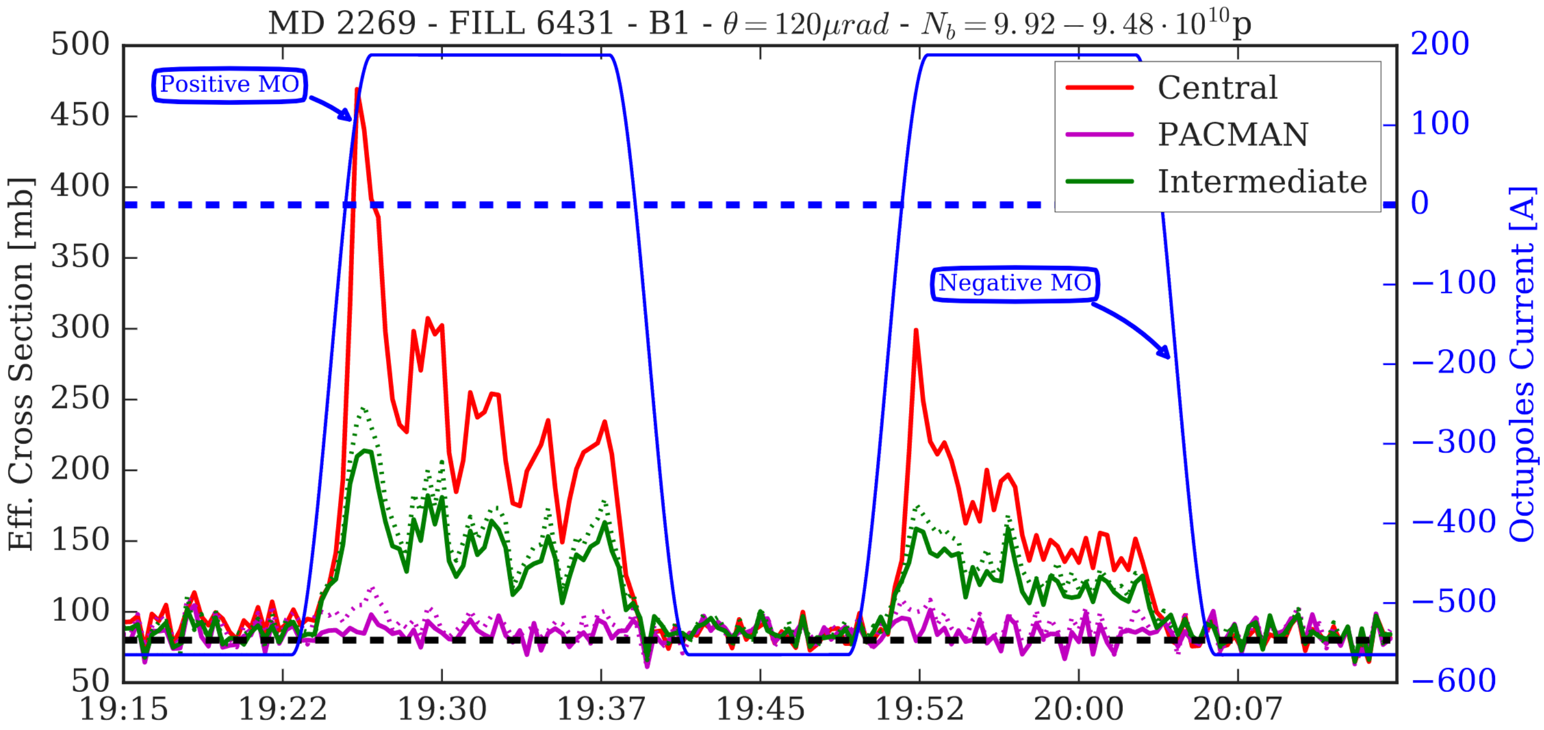
Experimental results: MD#4

- In between the two MDs, a change of hardware allowed us to lead the experiment with trains (collimators opened, two wires in series → even multipoles doubled)
- **Trains = more statistics: effect visible on the beam losses**
- This test completed the range of possibilities with the present setup: we are ready for LS2 ☺



An alternative: ATS and the octupoles

- MD 2269: ATS round optics MD and compensation of the BBLR interaction with the octupoles
- **Promising results for a possible compensation of the BBLR interaction by reverting the polarity of the octupoles**



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Conclusion

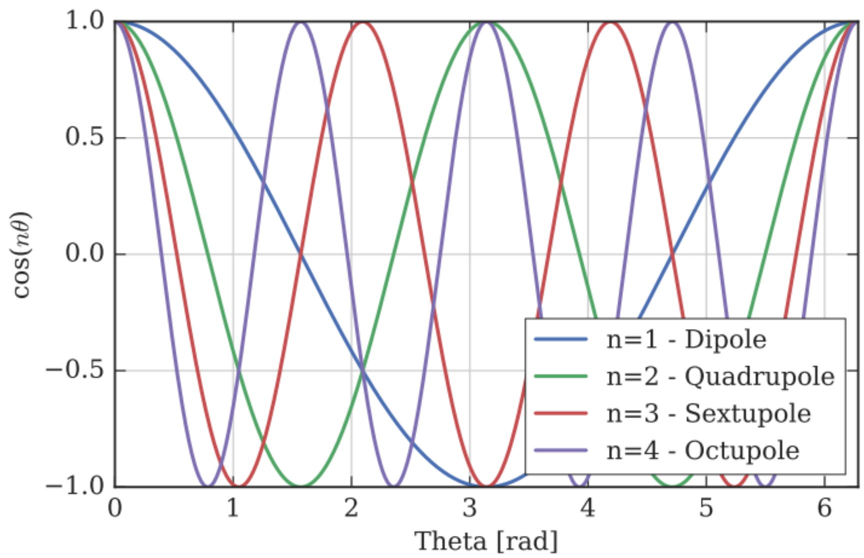
- For 15 years, the idea of BBLR compensation using DC wires has been developed, and improved
- **2015: semi-analytical model for wire compensation, in an ideal case (HL-LHC)**
- **2017/2018: during the experimental campaign, we observed the beneficial effect and the potential of the wire**
- BBCWs remain out of the HL-LHC baseline for the moment: they are mainly made for flat optics (LHC Run III?), or in case of crab cavities failure.
- We are working hard to make this ‘Plan B’ ready, in case it becomes a ‘Plan A’

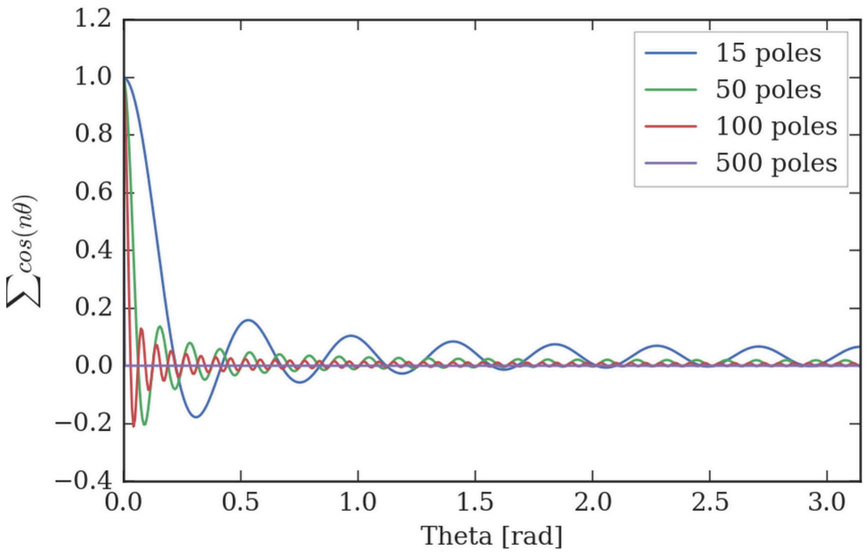
Thank you for your attention!

Spare slides

Multipolar expansion

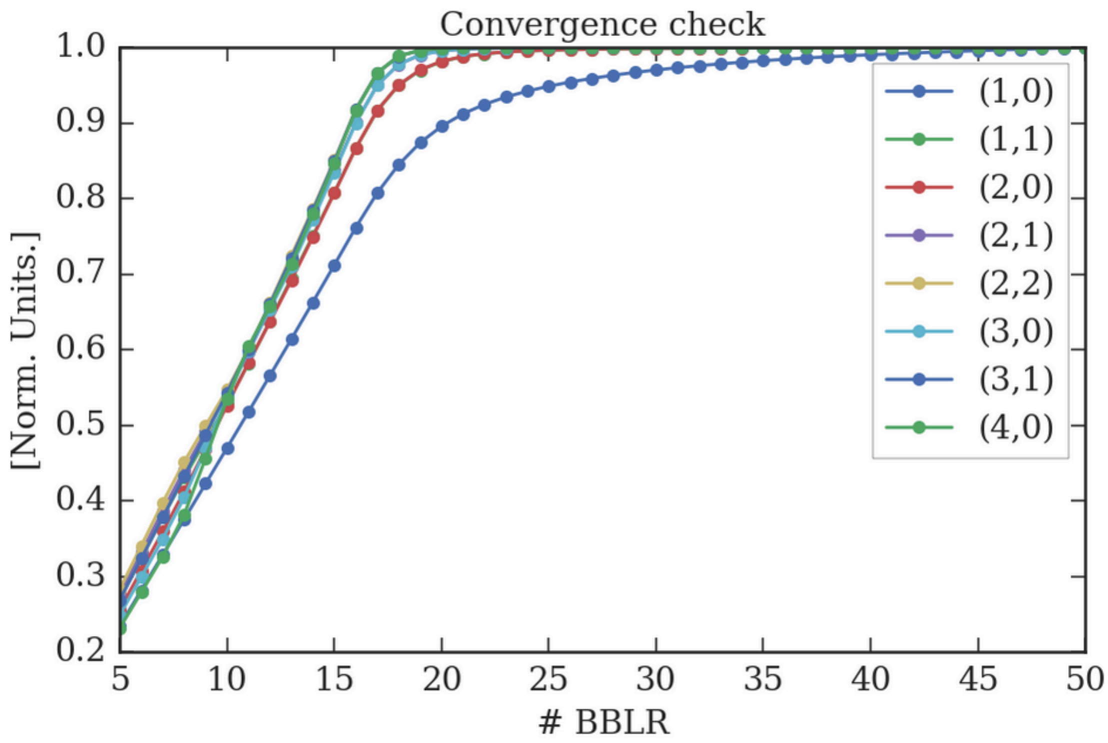
- The magnetic field created by a bi-Gaussian (truncated) beam in free space can be expanded in multipoles (Maxwell), as a sum of cosine for instance
- Increasing the number of multipoles taken into consideration, we tend to a Dirac distribution in angle, ie, a DC wire





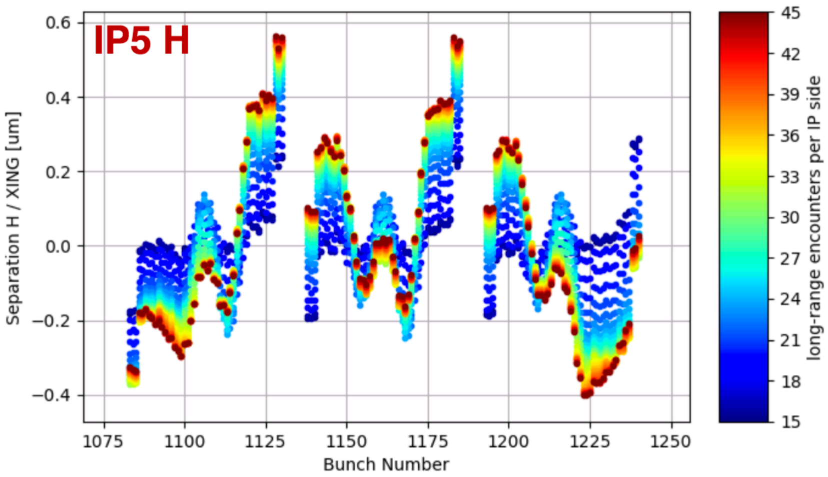
Counting the encounters

- One important question: how many encounters should take into consideration?
- Depends on the considered multipole → **convergence study**

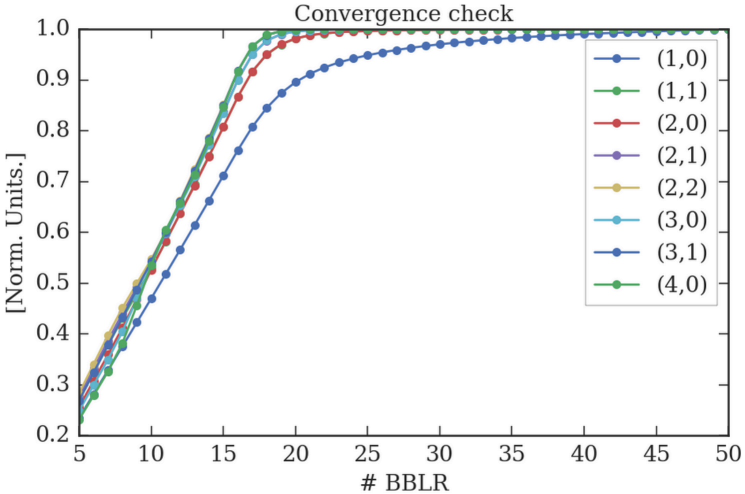


Counting the encounters

- As we are interested only in the non linear resonances, one can consider **25 encounters/side/IP.**
- We retrieve the result predicted by TRAIN: to get the dipolar convergence, one has to consider around 40 encounters/side/IP
- In the following, we focus on the (4,0)-(0,4) resonance compensation.



Courtesy of M. Hostettler



Semi analytical model

- In **Phys. Rev. ST Accel. Beams 18, 121001 (2015)**, S. Fartoukh et al proposed a semi-analytical model to describe the LRBB interaction and its compensation with 2 DC wires. We are using this approach with the following working hypotheses:
  - **Round optics**, two IRs with **H and V alternated crossing-angle**
  - **Weak-strong regime**: one of the beam is assumed to be constant, with a much larger intensity than the other one
  - The wires act on the weak beam (they mimic the strong beam, seen as a **DC wire**)
  - The paper assumes **the same currents and the same beam-wire distances for the 2 wires**
  - **The phase advance between the two wires is 0 or 180 degrees**

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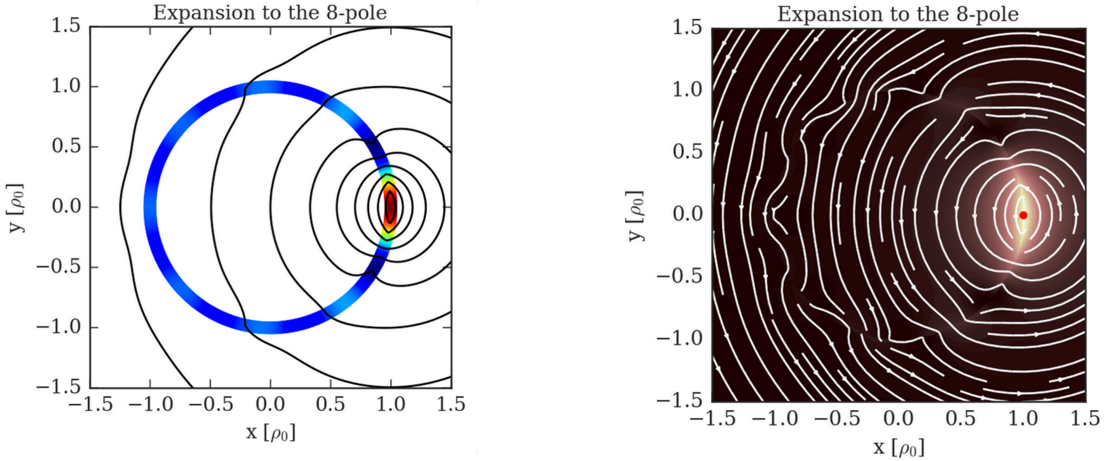
H/V orientation and octupolar term (I)

- To compensate all the RDTs, the wire has to be **in the crossing plane** (which is not the case in IP1 for flat optics).
- But if we consider **the octupolar term only (RDT (4,0)-(0,4)), the H or V orientations are equivalent**
- To obtain a perfect octupole, one shall create an azimuthal current distribution like:

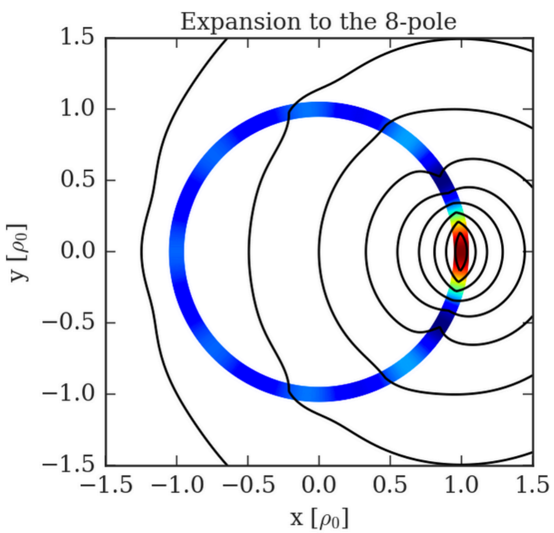
$$I_\phi = I_0 \cos 4\phi$$

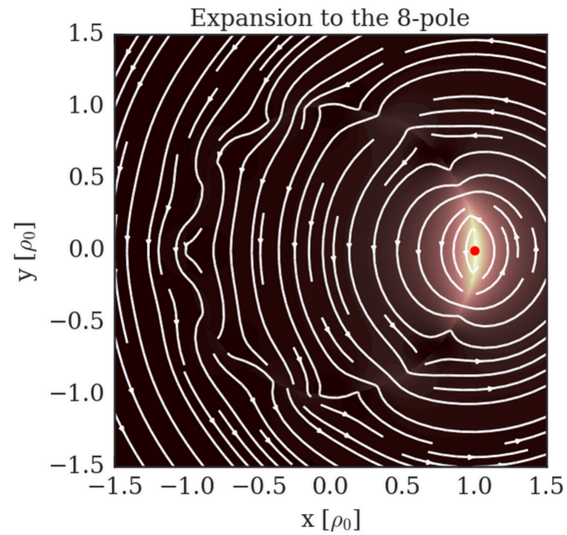
- Technically impossible: one would need an infinite number of wires! But we can excite only some components of the field, coming closer to an octupole, removing the others



H/V orientation and octupolar term (I)

- Considering only up to the octupolar term → not so far from the field created by a wire

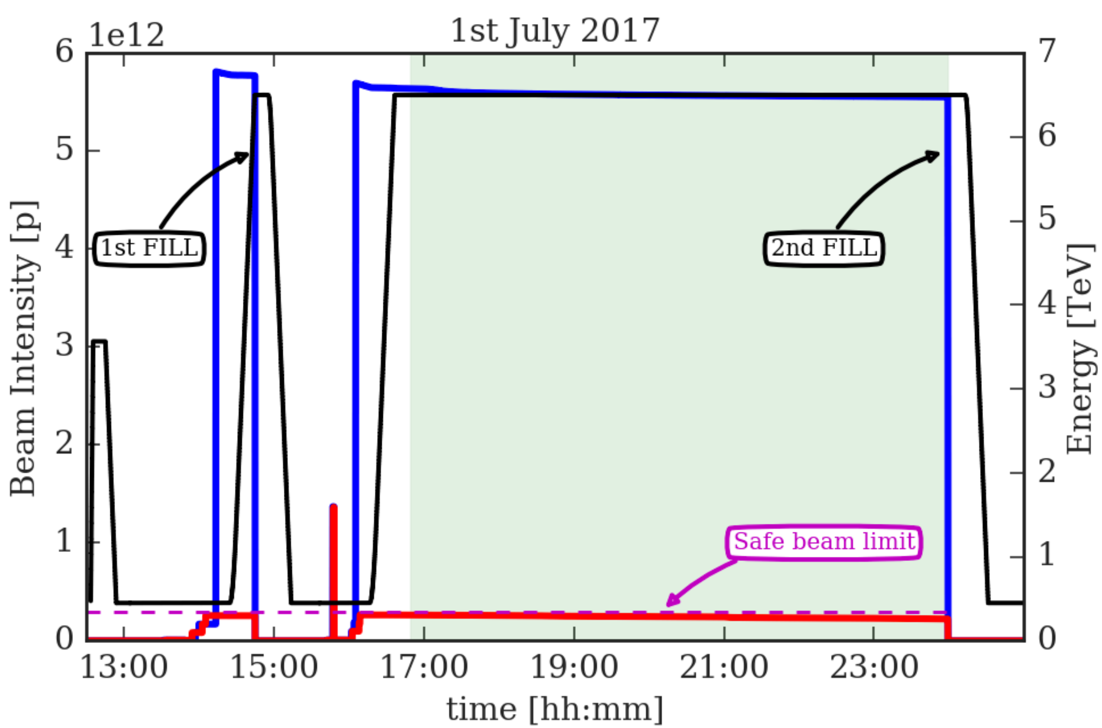




- Rotating the poles of an octupoles does not change the field → H or V orientations of the wires are equivalent
- Raise another question: **can we power both the inner and external wires?** This would double the octupolar compensation while the two sextupolar components would vanish

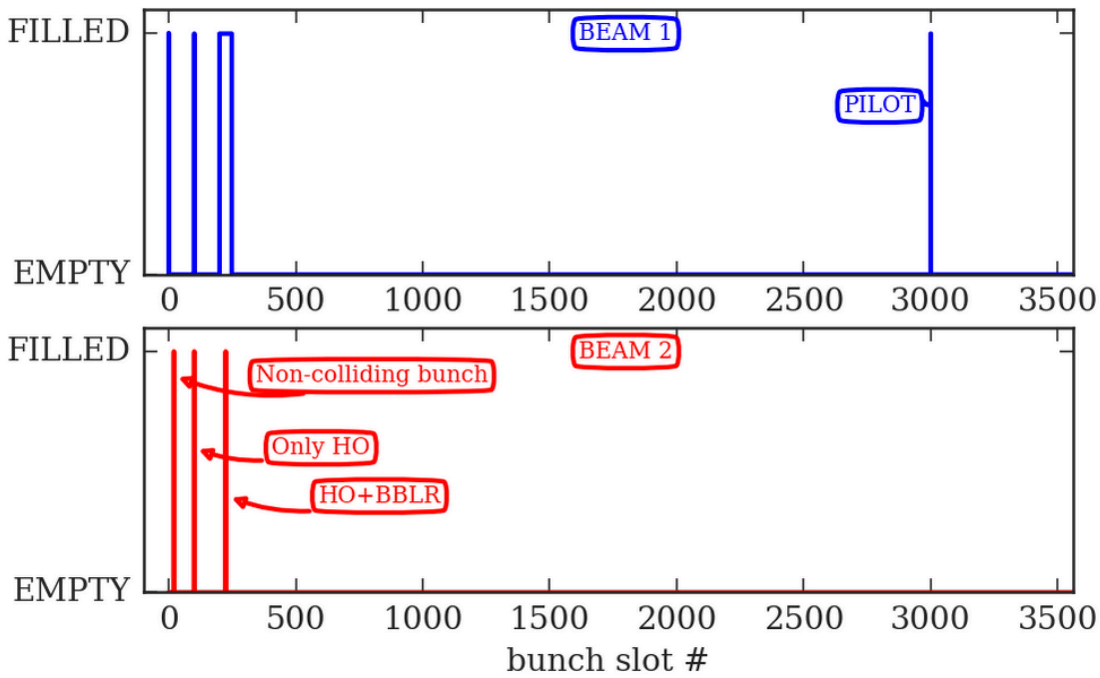
MD1: the very first try

- 1st July: **10h** MD dedicated for BBCW demonstration
- We got around 6 hours of ADJUST dump (dump of the first fill due to RF problems on B1)
- ATS with beta star at 40cm



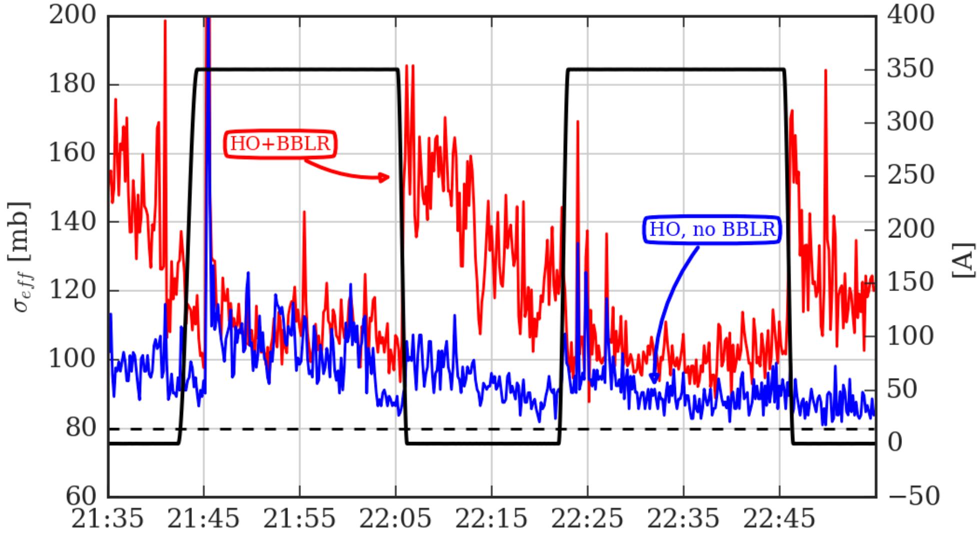
MD1: the very first try

- Asymmetric filling scheme (weak-strong regime). B2 is composed of one non-colliding bunch, one suffering HO+LRBB (IP1 + IP5), and one suffering HO only.



MD1: the very first try

- After vertical alignment of the wires, and pushing the machine in a LR dominated regime (crossing angle pushed at 120 urad), we turned on and off the wires (**jaws at 6 sigma, 350 A**).

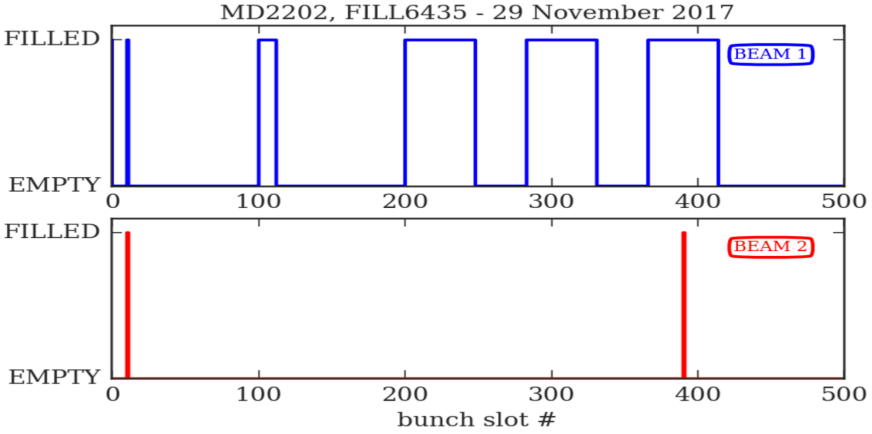


- Effect of the wires visible **when we turned them off only** → not necessary convincing for people out of the team
- MD4 had to confirm and improve these results

MD4: confirmation and improvement

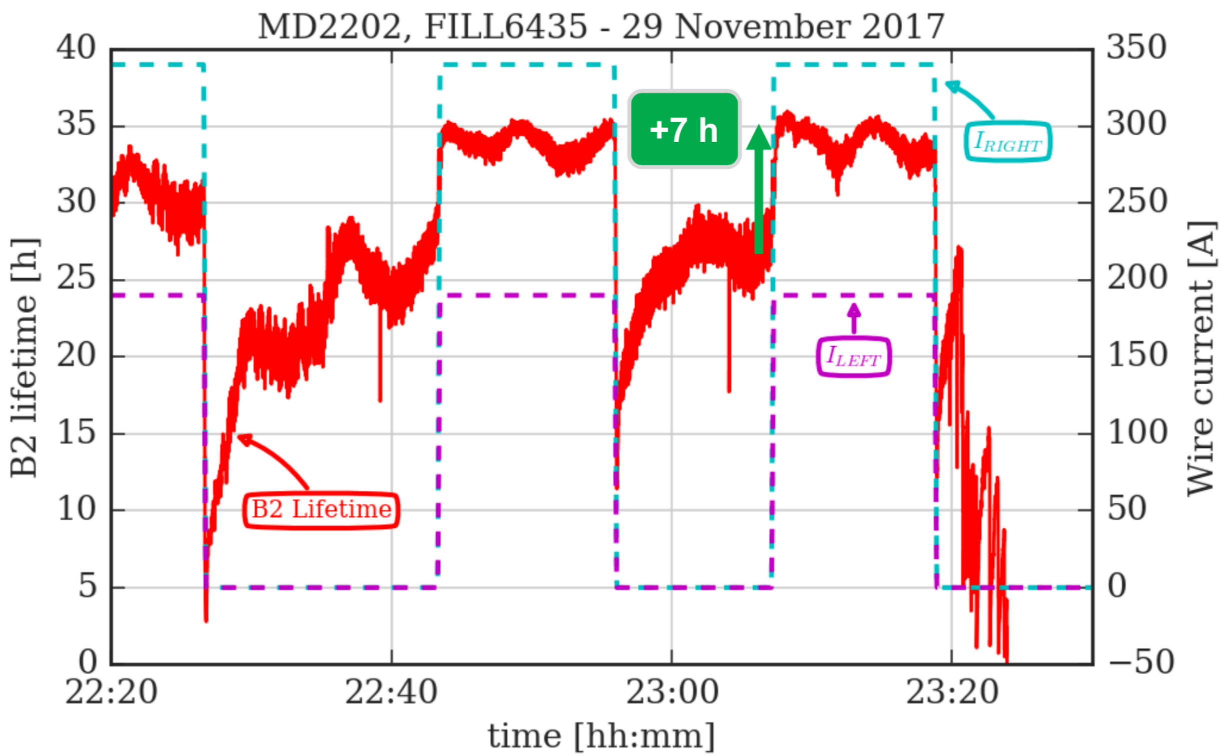
- Some differences with MD1:
  - Beta star 30 cm
  - Crossing angle at 150 urad
  - Only 2 bunches in B2 (no tune measurement possible)
  - 3 trains in B1 instead of 1 (stability issues in MD1)
  - Maximum octupoles for B1
  - Orchestration for tune correction with Q4/5
  - Optimized current, jaws at 5.5 sigma

- Only 2 *real* hours due to two dumps, not related to the MD



MD4: confirmation and improvement

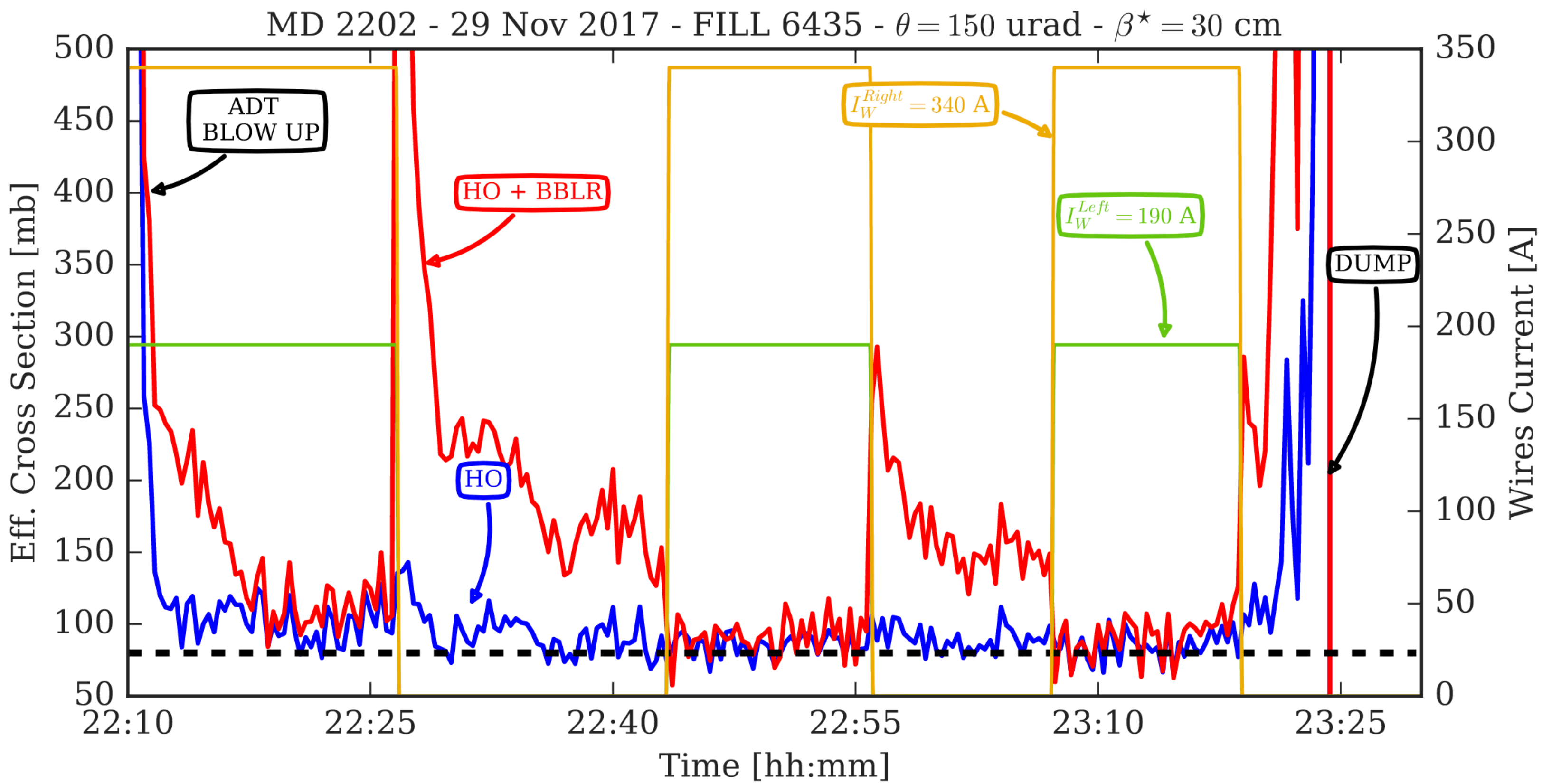
- Results of the compensation:



- **Lifetime gain of 7 hours!**

MD4: confirmation and improvement

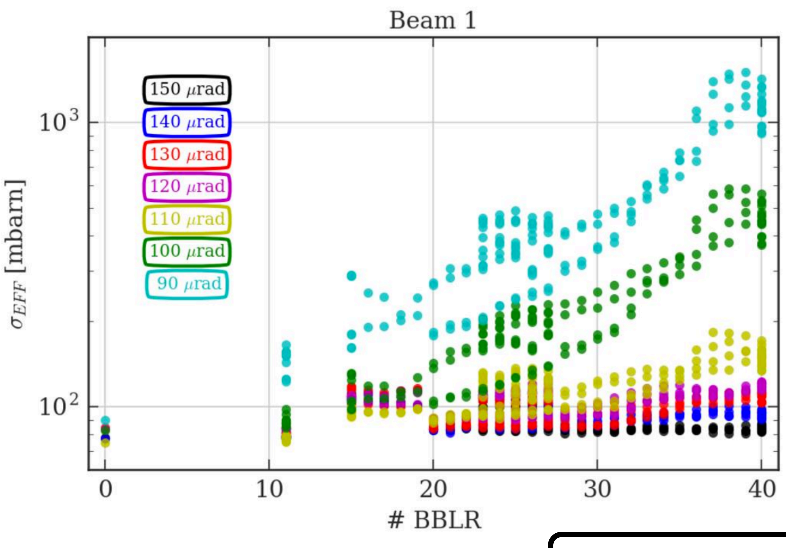
- Results of the compensation:

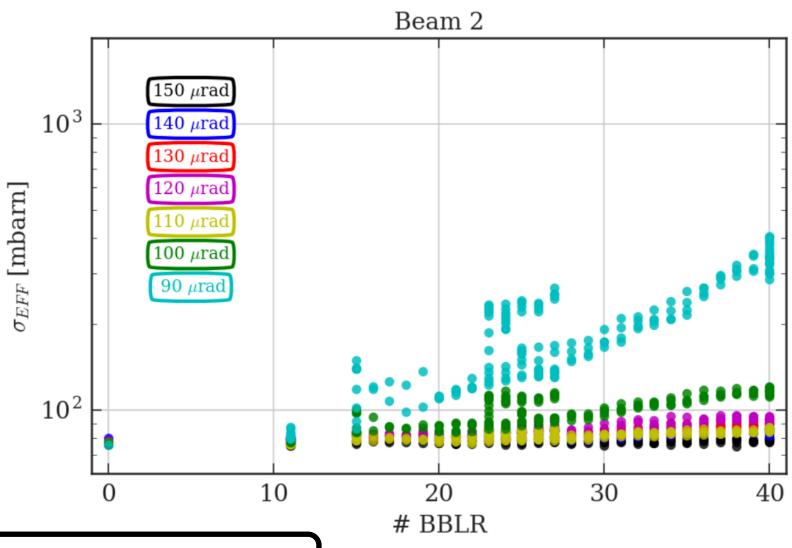


- Effect when we turn **ON and OFF** → much more convincing!

BB effect: finding the good observable

- **MD 2201**: evaluate the LRBB interaction as a function of the crossing angle (BCMS and 8b4e with ATS 40 cm)
- Symmetric filling scheme this time: **2 BCMS trains and 1 8b4e train per beam** (collisions in IP1 and IP5 only).
- Objective: plot the **effective cross-section as a function of the number of encounters**, for different crossing angles.

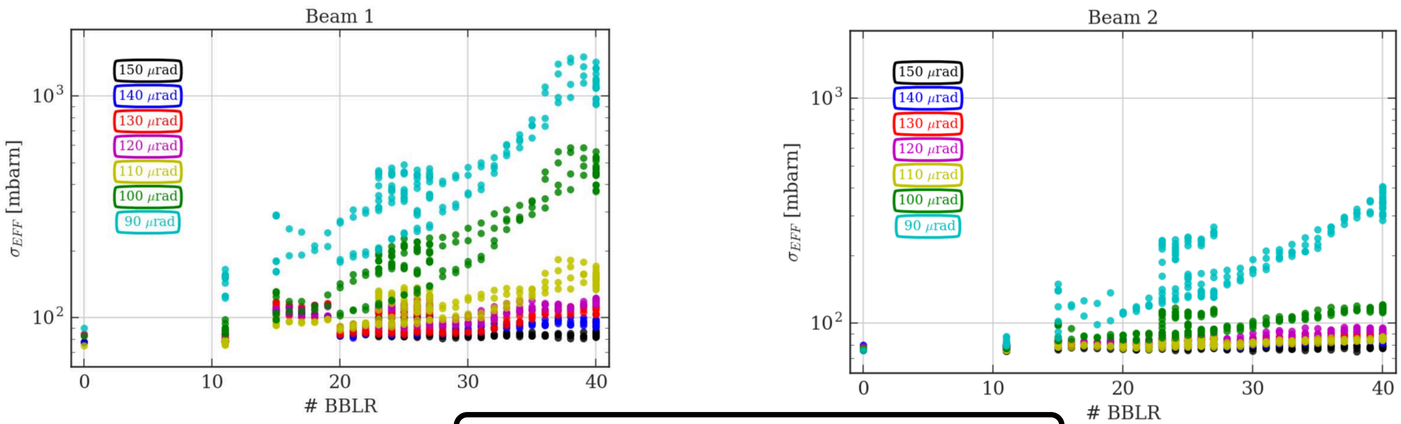




Courtesy of G. Sterbini

BB effect: finding the good observable

- As expected, the losses due to LR increase with the number of encounters
- As observed in the past, B2 is less sensitive to LRBB effects
- Different behaviors are observed for a same number of LR encounters and difference between 8b4e and BCMS
- **One would like to find an observable to avoid this spread, since the effective cross section is not represented by a function of the number of LR → octupolar force instead?**



Courtesy of G. Sterbini