Beam-Beam Wire Compensation in the LHC for the High-Luminosity Era

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With many thanks to S. Fartoukh, N. Karastathis, Y. Papaphilippou, A. Rossi and K. Skoufaris.

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Topics

- About LHC and beam physics
- The Beam-Beam Long-Range Interaction

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My Contribution

- The BBLR Wire Compensation:
  - A wire as a solution
  - Proof of concept
  - From the prototypes to operational devices

Outline

- **About LHC and beam physics**
- The Beam-Beam Long-Range Interaction
- The BBLR Wire Compensation:
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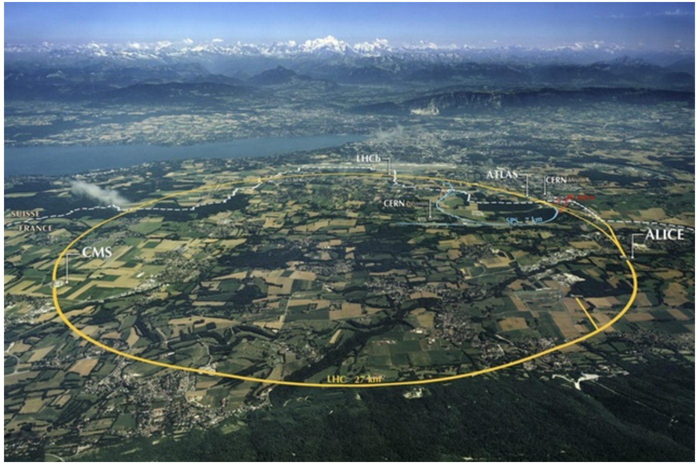
The Two Sides of LHC: Lifetime

- Purpose of LHC: **observe** mathematical **predictions** (ex: Higgs Boson)

- **Two key ingredients: lifetime and luminosity**

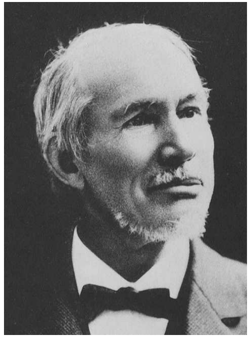
- LHC is made of **2 combined synchrotrons**:
  - **27 km** long machine, ~100 m underground
  - 2 counter-rotating beams at **6.5 TeV (= 9.6E-7 J = energy of a flying mosquito)**
  - Protons are **stored** in the machine for **hours** (typically 10h **lifetime**)
  - **~10 hours light = size of our solar system**

- **How to store protons on such period of time?**



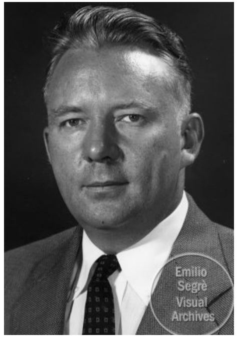
Stability of a system such as an accelerator

- Beams have to circulate for several hours **(billions of turns)** in order to **maximize the integrated luminosity**
- How do you keep particles moving in an accelerator?
- This is answered by the **alternating gradient theory of Courant and Snyder (1957)** [2]
- Simple concept: dipoles **bend the trajectory** of the particles, **quadrupoles define the betatron motion**
- But this is only for **a linear machine…What happened for non-linear effects?**



G. W. Hill

E. D. Courant



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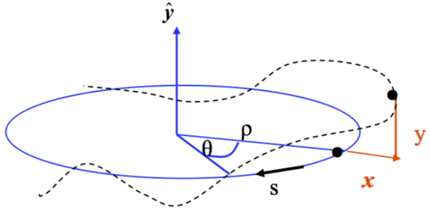

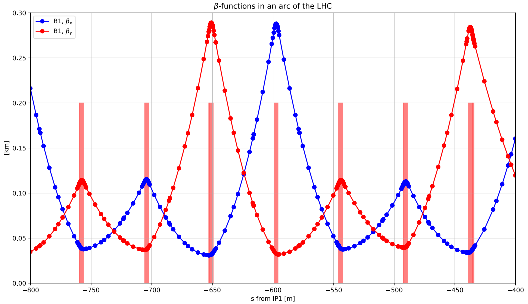

$$u'' + K(s)u = 0$$

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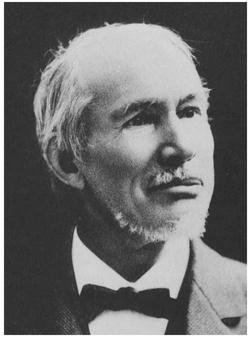

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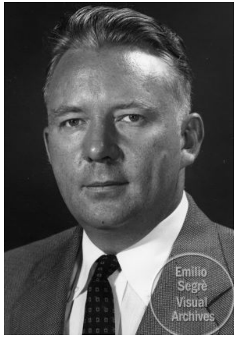

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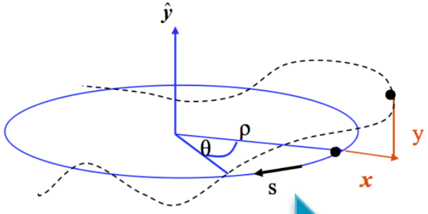
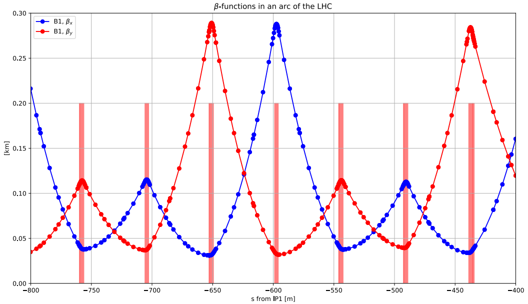
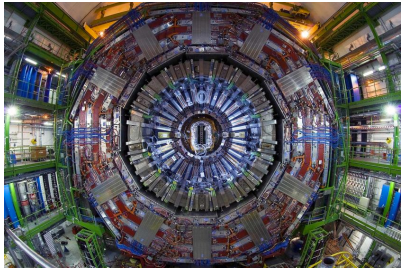


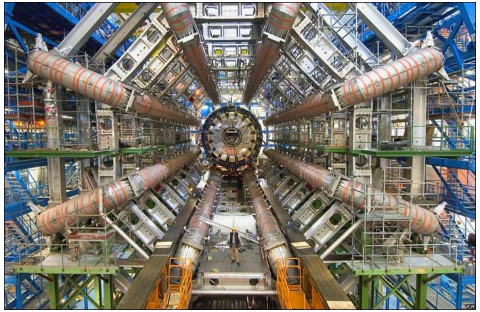


Effects like beam-beam interactions!

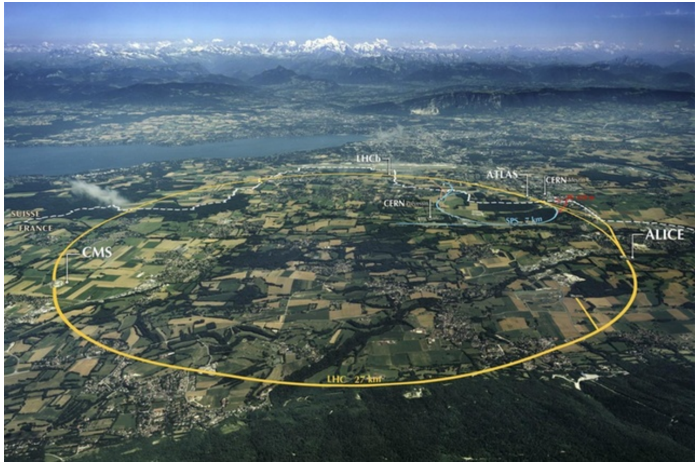
The Two Sides of LHC: Luminosity

- This amount of energy is then brought in an **extremely small volume** (1st time ever that such an energy density is achieved)





- LHC is **a collider**, or *energy concentrator*:
  - Transforms **a high density of energy into mass**
  - Provide **as many collisions** as possible into giant detectors



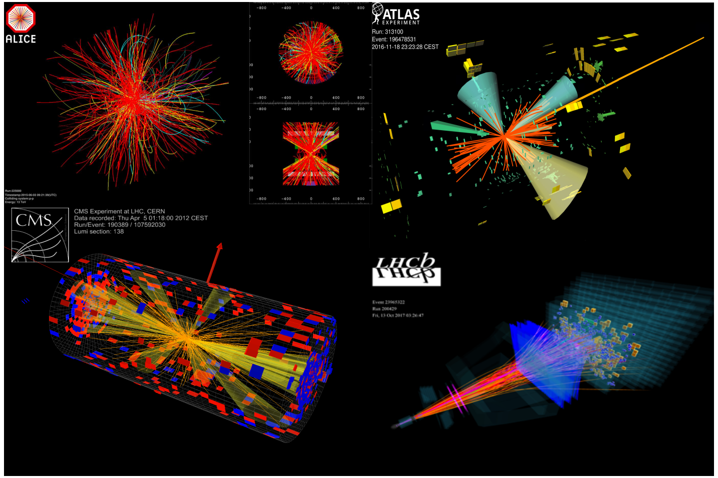
- Key concept: **luminosity**

The Concept of Luminosity

- Luminosity corresponds to the **number of collisions** per second [1] given in $Hz.cm^{-2}$:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

- The typical instantaneous luminosity value of LHC is 10^{34} $Hz.cm^{-2}$
- But an important figure is the **integrated luminosity**
- **The goal of HL-LHC is increase the luminosity by a factor 5 to 10**
- **Synchrotron problem was solved… But now proton-proton interactions (beam-beam) bring non-linear effects**



Symbol	Meaning [Unit]	LHC Values
$N_{1,2}$	Bunch Intensity [p]	1.2E11
N_b	Number of Bunches	~ 2800
f	Revolution Frequency [Hz]	11245
$\sigma_{x,y}$	Transverse Beam Size [m]	1E-5

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The Need of a Crossing Angle

- We have our two beams circulating, ready to collide… What if they collide face to face?

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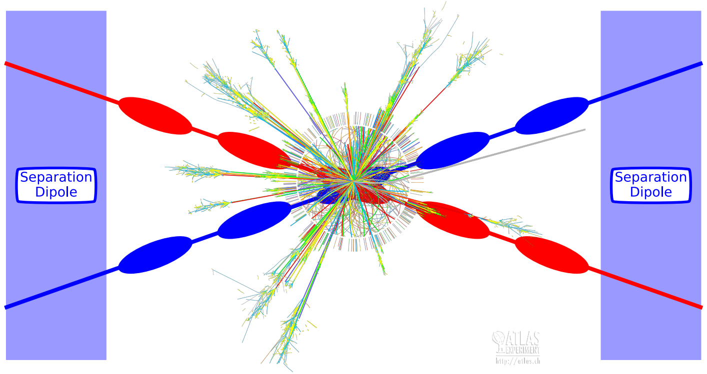
- Solution: **add a crossing angle!**



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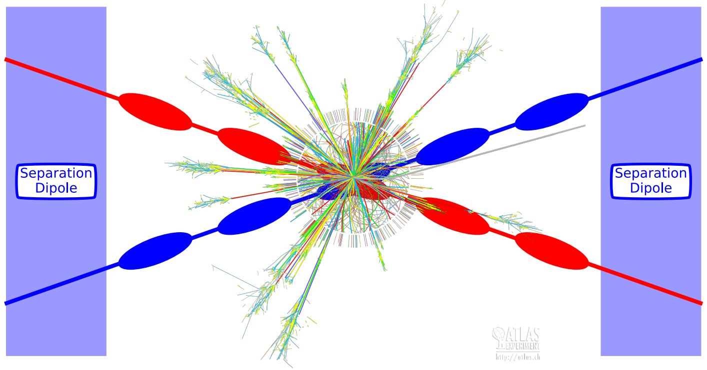
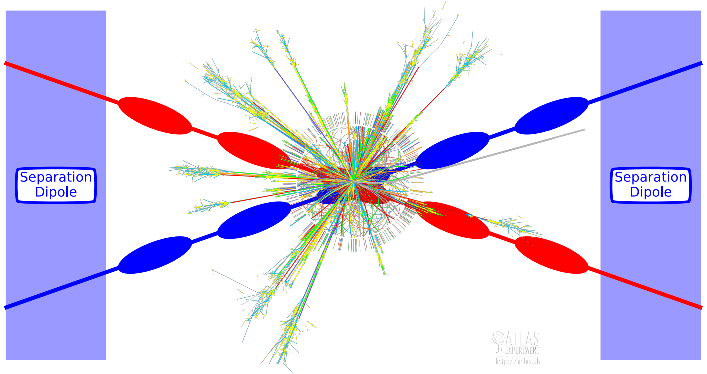


- Solution: **add a crossing angle!**
- But I lied to you…

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \cdot \eta \qquad \eta = \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$

The Need of a Crossing Angle

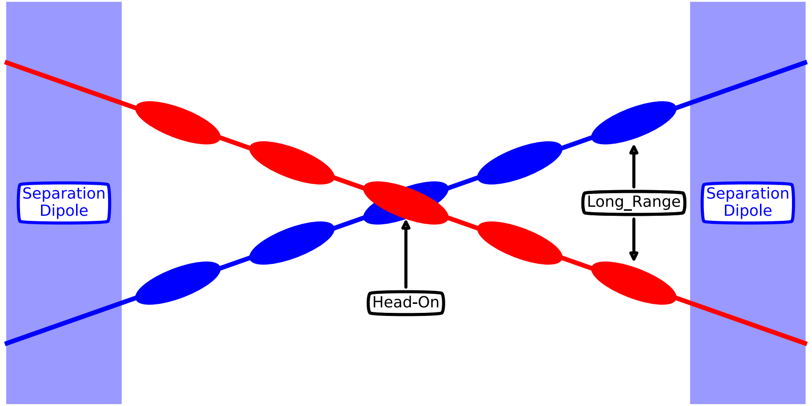
- **We need to reduce the crossing angle to increase luminosity!**



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \cdot S \qquad S = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$

Beam-Beam Long-Range Interaction

- By reducing the crossing angle, the **two beams are becoming very close**
- **Purpose**: maximize the inelastic collisions (= Head-On = Luminosity)
- **Consequence**: increase of the electro-magnetic interaction (= Long-Range = Parasitic collisions)
- BBLR **spoils the beam lifetime** though parasitic collisions and resonances excitation causing extra losses
- The most important problem of a collider like LHC is therefore to **find a trade-off between luminosity and lifetime**



How to relax the trade-off?
Compensate BBLR!

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- **The BBLR Wire Compensation:**
  - **A wire as a solution**
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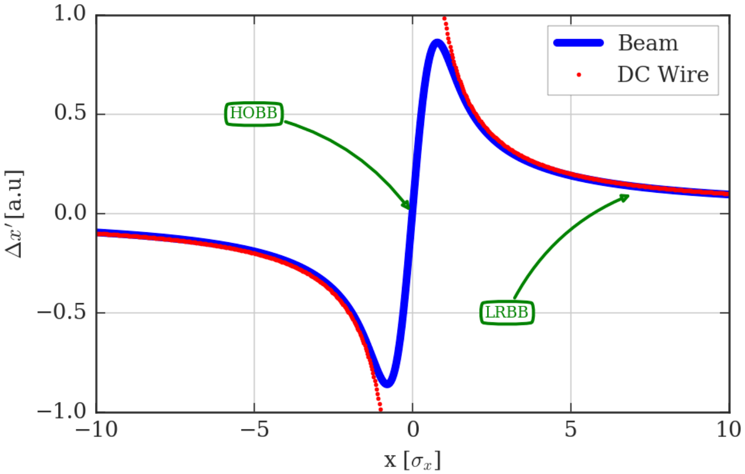
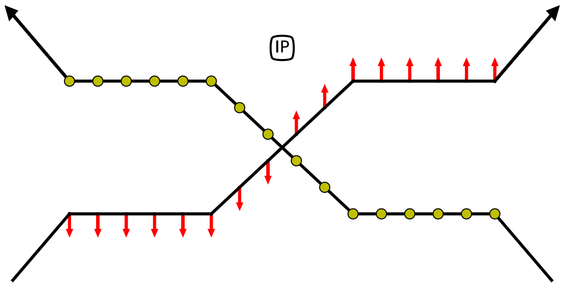
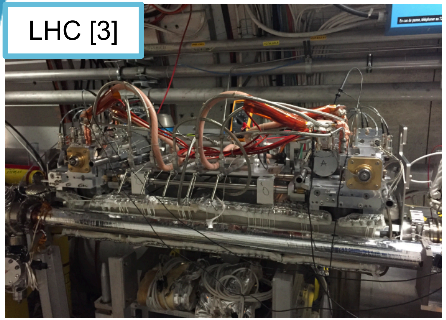
Why a Wire?

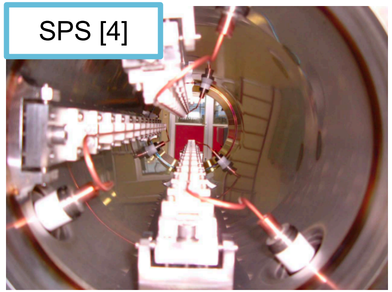
- Early 2000's, it has been proposed for the first time to **compensate the BBLR using a wire** [7,8]
- By placing a wire at the same s-position as the BBLR interaction, **this wire would produce the same kick**
- **Impossible to install one wire per interaction** → ~20 interactions per side per IP + impossible to install a wire **between the beams**
- **Reduce the distributed non-linear effects to a local one that can then be compensated**
- **Two-folded challenge: technical and mathematical**

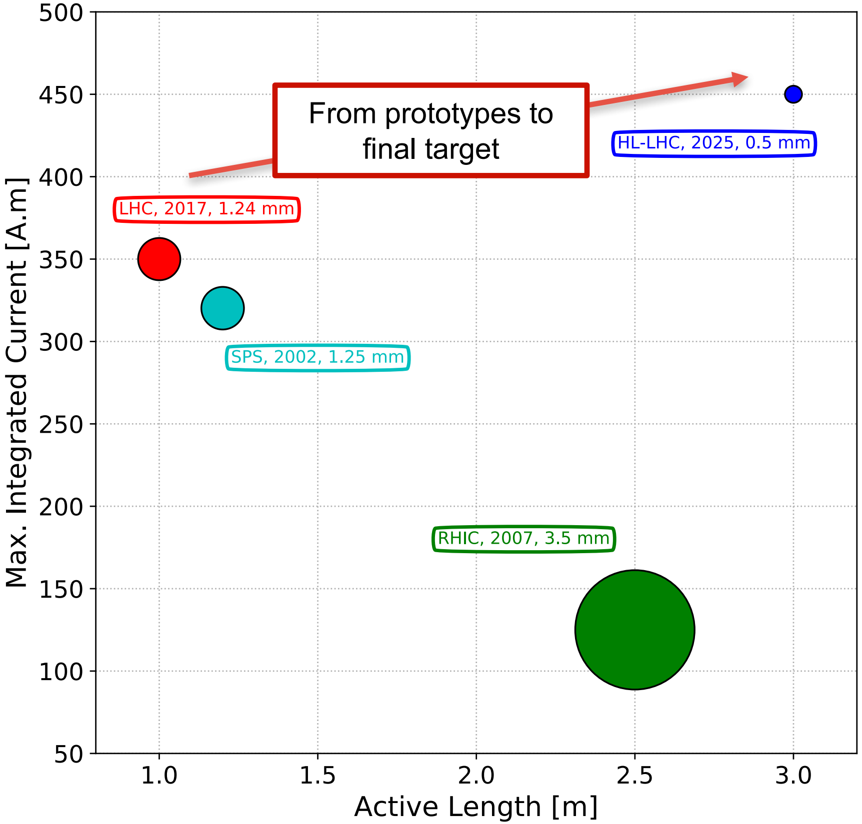


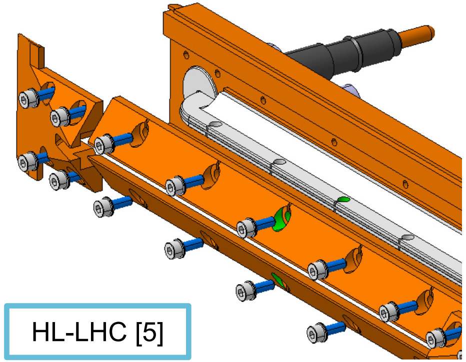


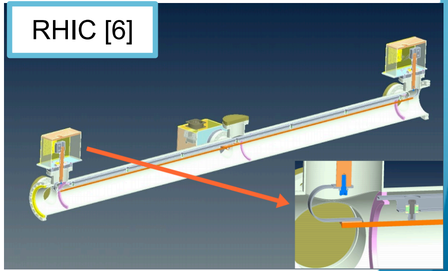
Wire Compensation: a technical challenge


LHC [3]


SPS [4]



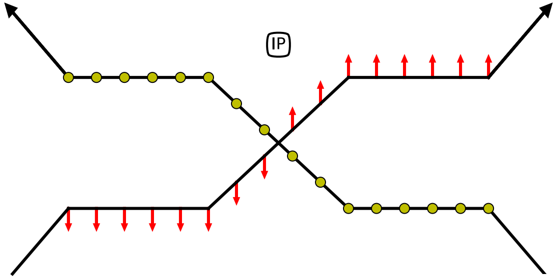

HL-LHC [5]


RHIC [6]

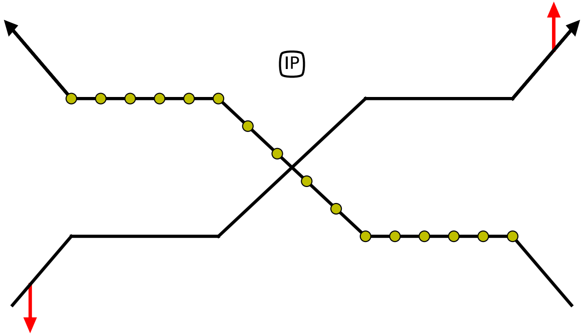
Wire Compensation: a mathematical challenge

- **Reduce the distributed non-linear effects to a local one that can then be compensated**

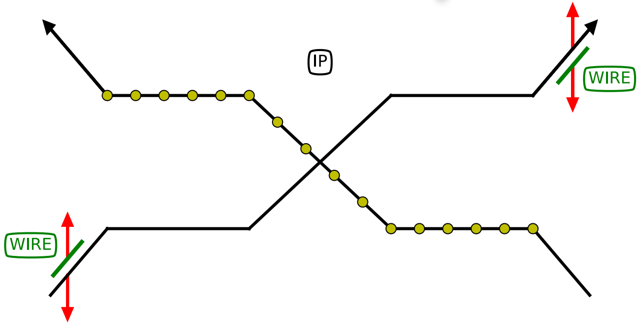
STEP 0



STEP 1



STEP 2



→ Different methods to find the equivalence

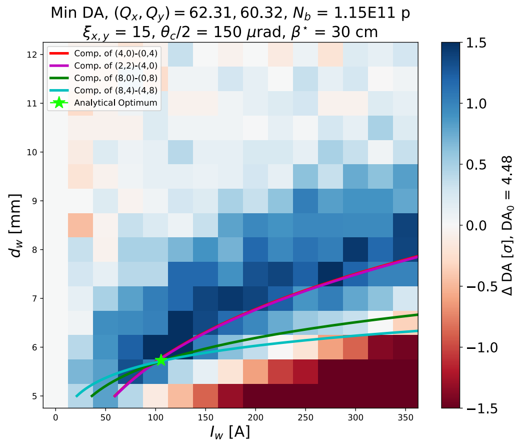
Design of the wires for (HL)-LHC

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

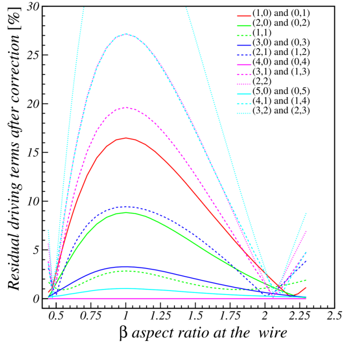
- Idea: compute the **Resonance Driving Terms** induced by the BBLR and by the wires:

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

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



- In ideal case, **compensating 2 RDTs leads to the minimization of all!** [9]



- With a lot of constraints, perfect compensation… But need to relax those constraints

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

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

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

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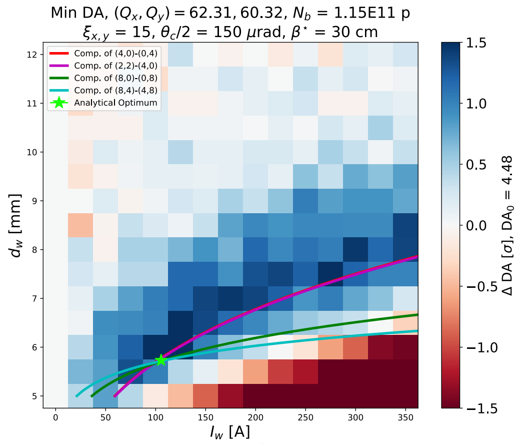

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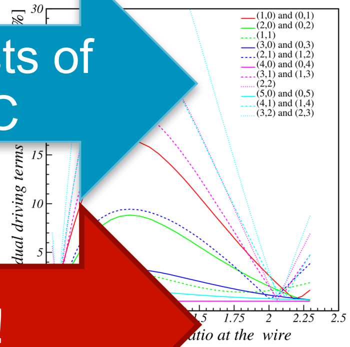


Construction and tests of prototypes in LHC

My contribution !

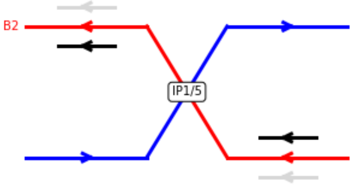
PHYSICAL REVIEW SPECIAL TOPICS—ACC

Compensation of the long-range bea
new configurations for

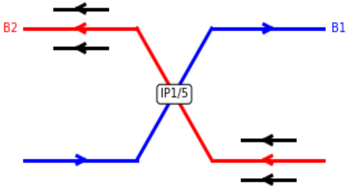
Stéphane Fartoukh,[1,*] Alexander Valishev,[2,†] Yannis Papaphilippou,[1] and Dmitry Shatilov[3]

Experimental Setup in the LHC

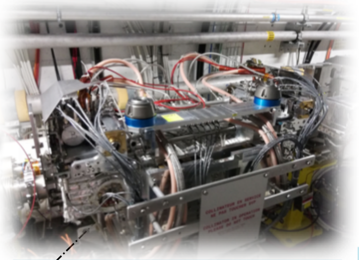
- In 2017 and 2018, wire compensators prototypes have been installed and tested in the LHC
- Wires embedded in **4 collimators around IP1/5** (8 wires)
- 2 possible configurations:
  - **1-jaw powering** configuration (a)
  - **2-jaws powering** configuration (b)
- Challenge: very far from the ideal design !



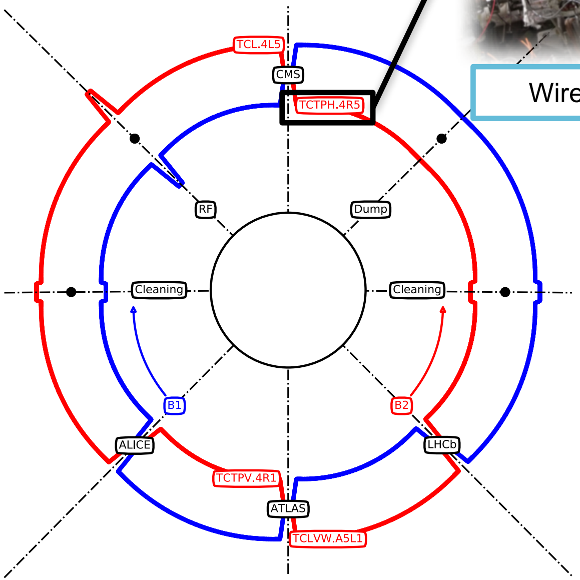
(a)



(b)



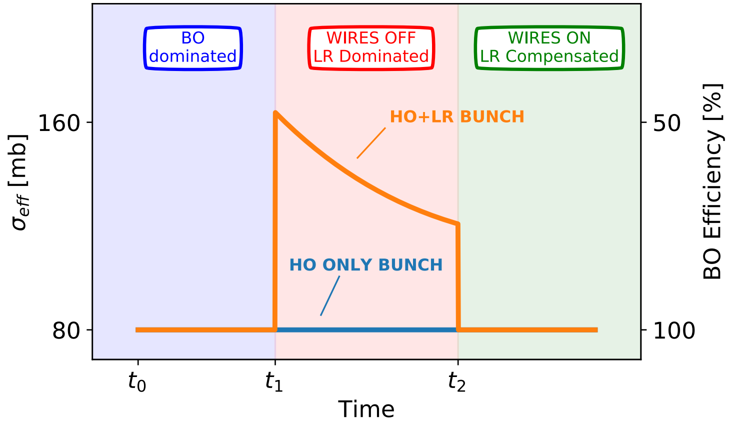
Wires in collimator



LHC Ring and the BBCW

Experimental Protocol

- **Observable**: the effective cross-section
  - **Loss rate normalized by luminosity**
  - Monitors the losses excluding the proton lost by wanted collision



- **Objective** of the experiment:
  - Put the machine in a regime **dominated by the BBLR** (extra losses)
  - Turn on the wires
  - See a reduction of losses

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

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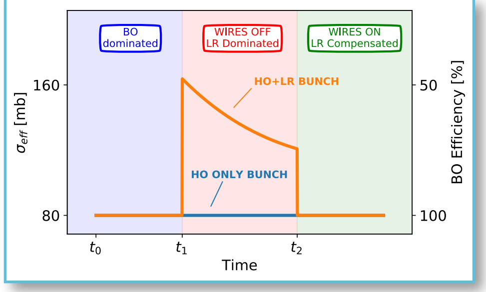
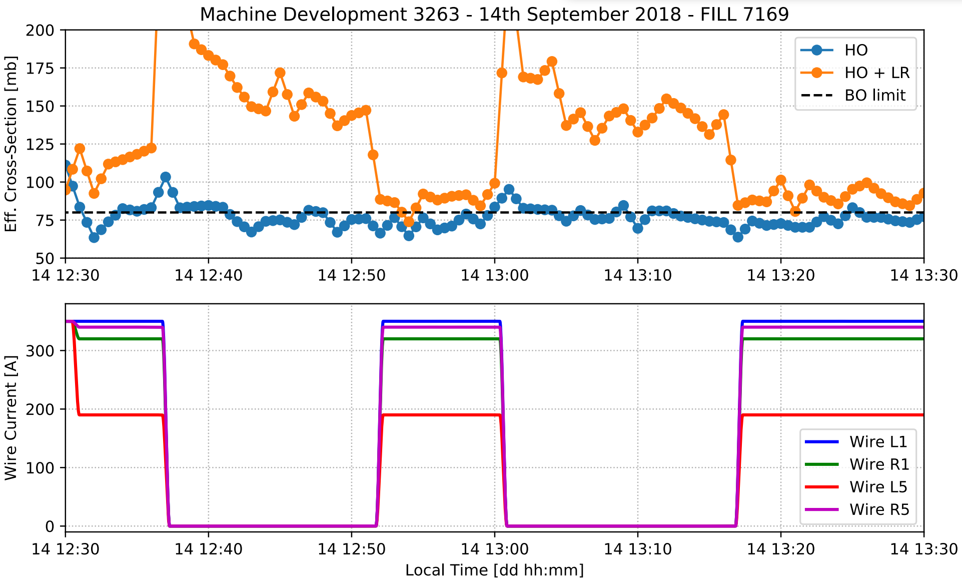
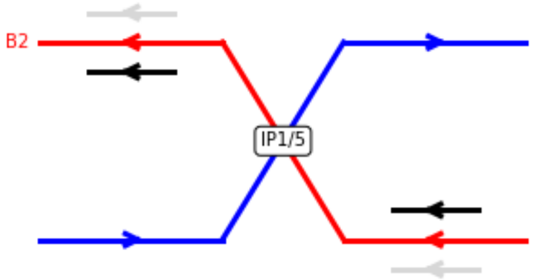
First Experimental Results



- **1-jaw powering** configuration
- Low intensity beam: wires are closer
- **Clear effect** on the effective cross-section, even by **reducing the crossing angle**





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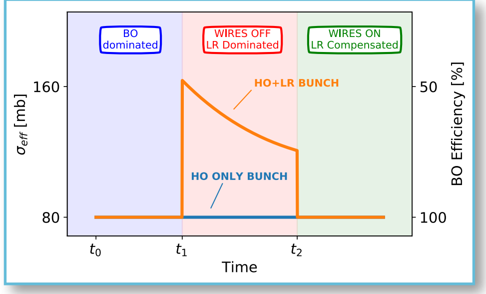
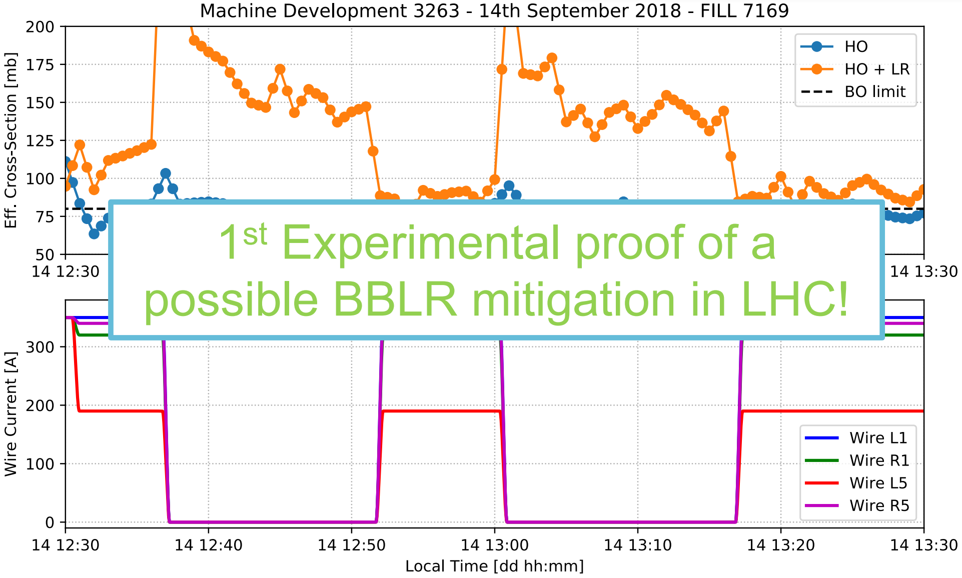
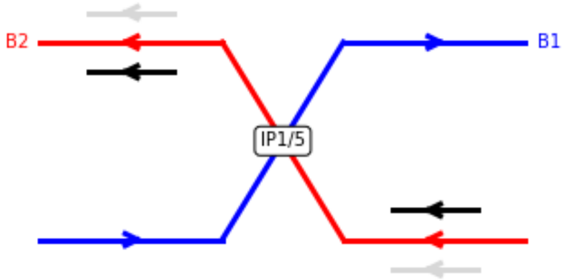


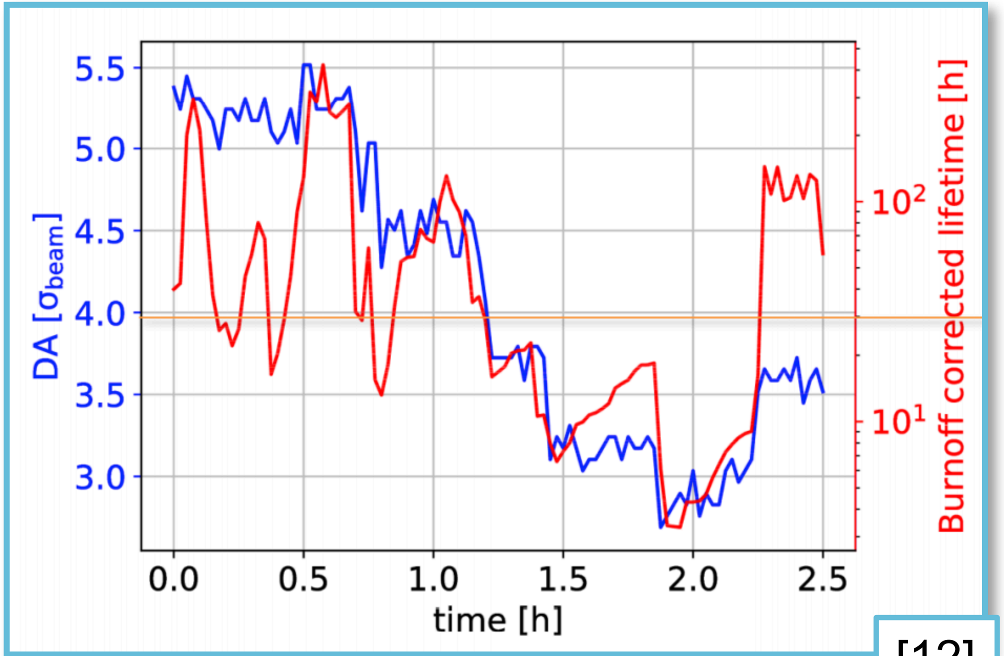


1^{st} Experimental proof of a possible BBLR mitigation in LHC!



Dynamic Aperture in a Nutshell

- Even with nowadays computers: impossible to track millions particle for hours.
- From [11]: ***“The DA is the amplitude of the phase space region where stable motion occurs”***
- Even though DA depends on the considered number of turns, there is a **good correlation between DA and lifetime**

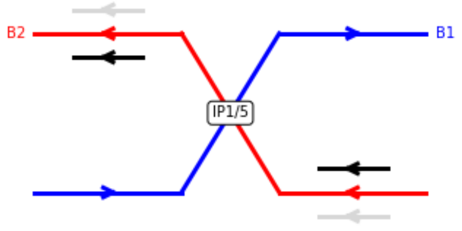


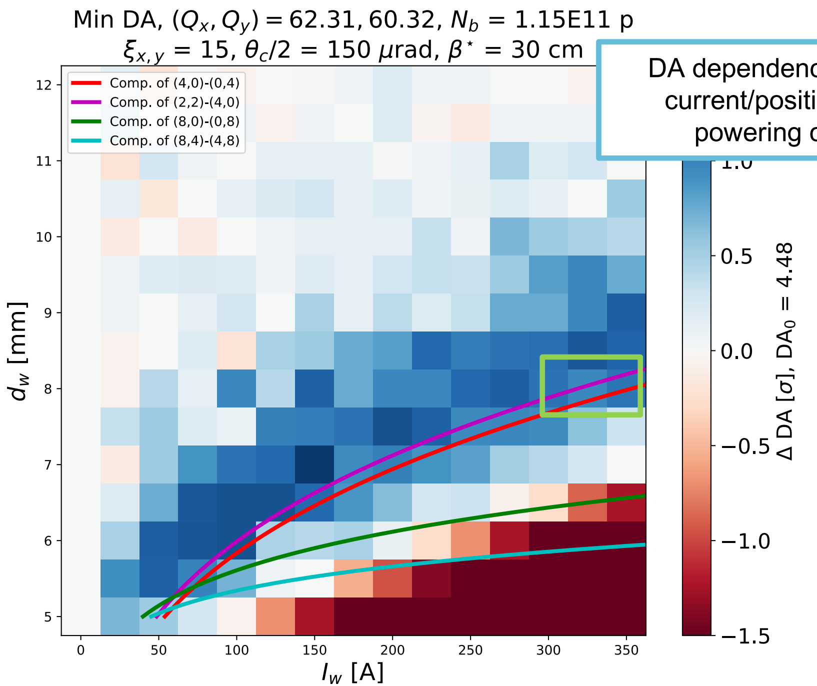
[12]

Benchmarking with the experiment

- First experimental setup: **1-jaw powering** configuration
  - Only one wire powered
  - Safe beam: **wires are closer**
  - Wires powered to compensate one given **RDT**

- DA analysis: no more crossing of the RDT lines but still **~1.3 σ DA gain**





DA dependency on wires current/position (1-jaw powering config.)

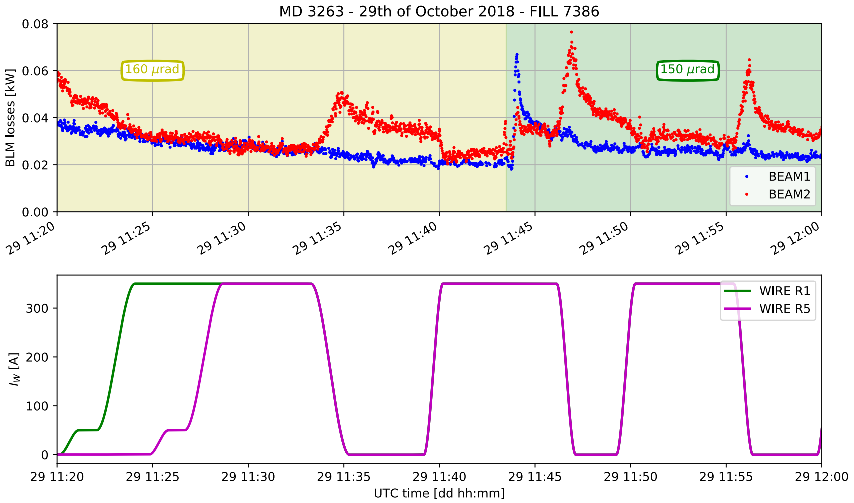
Wire Compensator	s from IP [m]	$I_{w,4004,MD}$ [A]	$d_{w,MD}$ [mm]
Wire R1	176.17	350	-7.39
Wire L1	-145.94	320	7.42
Wire R5	150.03	190	-7.15
Wire L5	-147.94	340	8.24

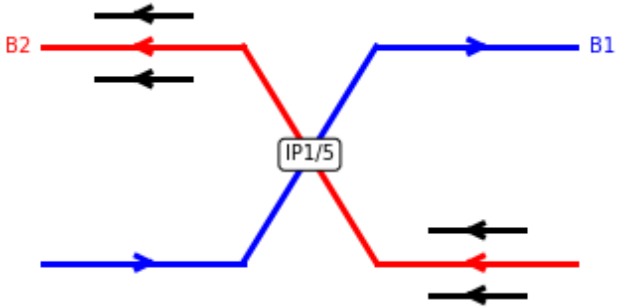
Outline

- About LHC and beam physics
- The Beam-Beam Long-Range Interaction
- **The BBLR Wire Compensation:**
  - A wire as a solution
  - Proof of concept
  - **From the prototypes to operational devices**

Towards operation: high intensity experiment

- **2-jaws powering** configuration
- High intensity beam: wires are further
- **Visible effect** on the beam losses, possibility to **reduce the crossing angle** without increasing the losses



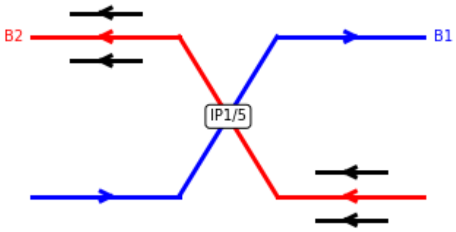


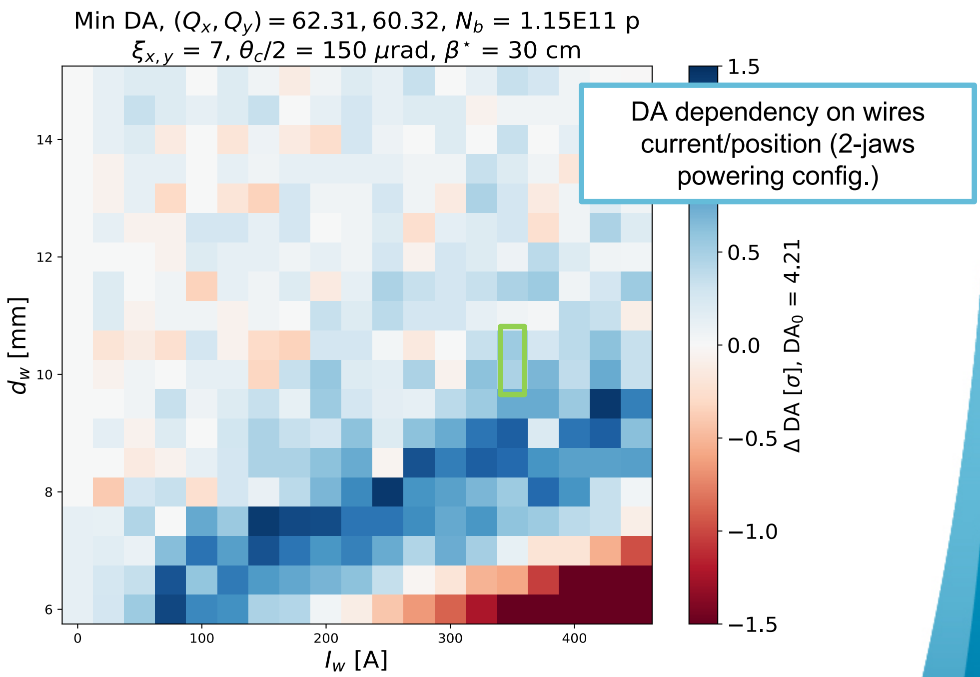
Results in more details in [10]

Benchmarking with the experiment

- Second experimental setup: **2-jaws powering** configuration
  - Both wires powered
  - Only 1 collimator per IP
  - Non-safe beam: **wires are further**
  - Wires powered up to their maximal possible currents

- From the scan, similar possible improvements (not reachable experimentally)





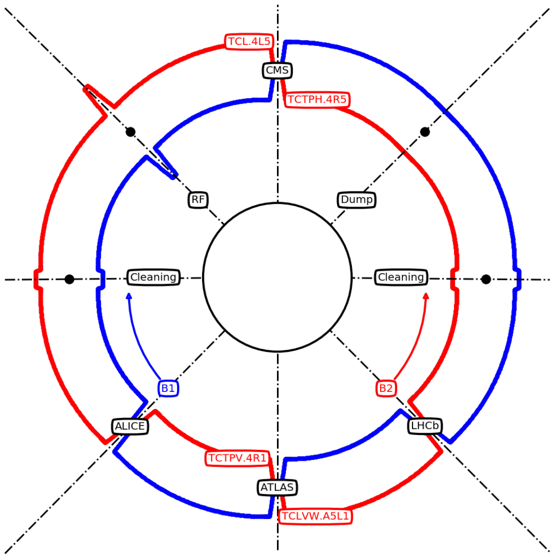
Wire Compensator	s from IP [m]	$d_{w,OP}$ [mm]
Wire R1	176.17	N.A.
Wire L1	-145.94	9.83
Wire R5	150.03	N.A.
Wire L5	-147.94	11.1

Even though it is not common, those results (experiments and simulations), let to a change of hardware in view of the next LHC Run 3!

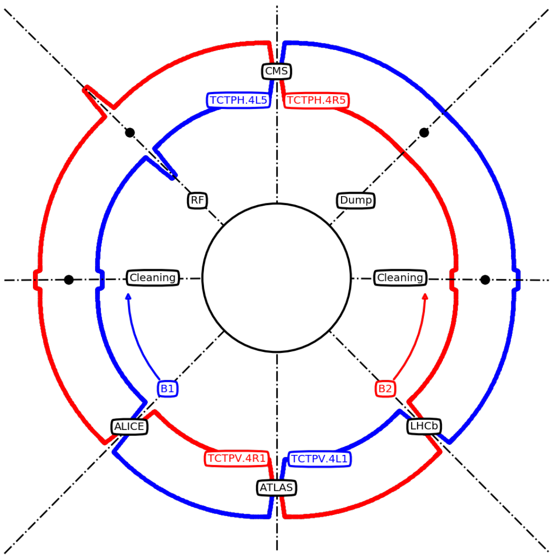
Prototypes – supposed to be used for a proof of concept – became operational devices.

Hardware change

RUN 2 CONFIGURATION



RUN 3 CONFIGURATION

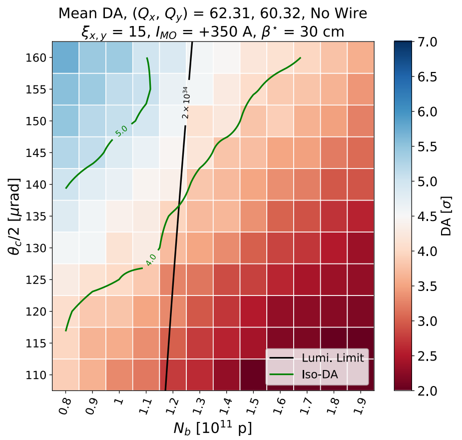


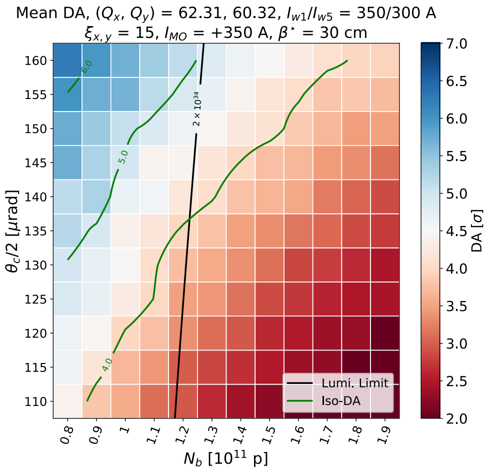
Wires are foreseen to be powered systematically at the end of each physics production fill

Towards Run III: Possible performance improvement?

- Experimentally, **we observed that it is possible to reduce the crossing angle**, without increasing the losses [10]
- DA dependency on crossing angle and bunch intensity confirms this result
- Run III scenario: **crossing angle anti-levelling up to 162 μrad [13]**
- Possible use of the wires: power at the **end of the fill to reduce the crossing angle**, keeping the DA ~ 5σ
- **Clear possible gain:**
  - **1.2e11 p → 150 μrad**
  - **0.8e11 p → 135 μrad**

DA without wires

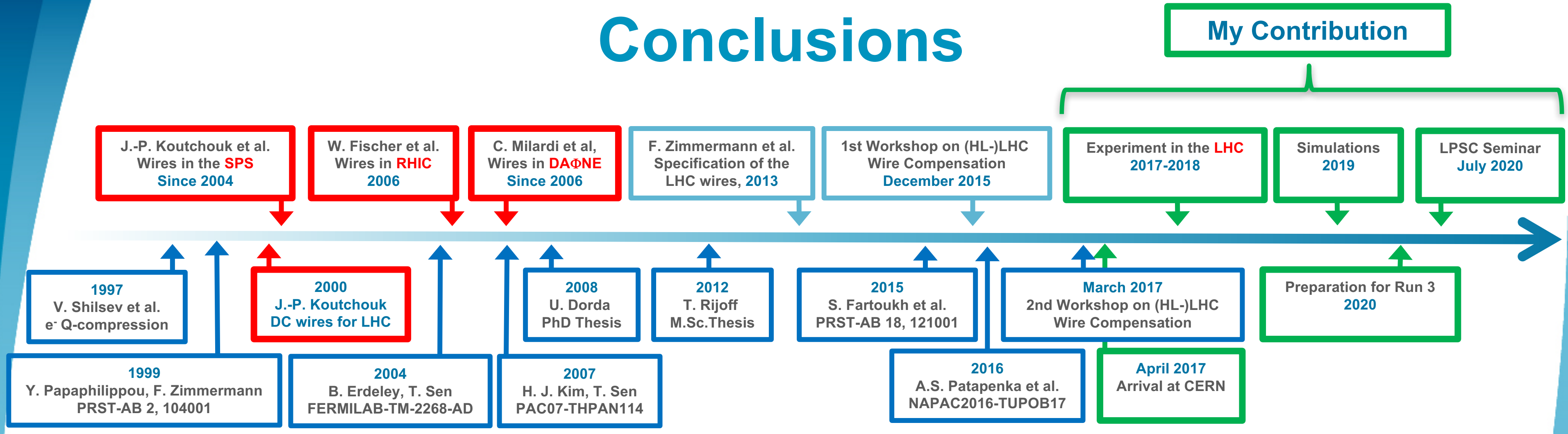




DA with 2 wires (coll. at 8.5 σ)

Conclusion: my PhD timeline

Conclusions



- **Next steps** of the PhD:
  - 1st priority: **write, document** the work that is done.
  - Summer task: **define a jury** and **prepare the defence** (foreseen in May 2021)
  - Additional possible work:
    - Using TPSA: propose a possible **alternative dimensioning of the wire compensators**, with a single passage approach
    - Study of the BBLR effect on the **diffusion of the beam core**

Thank you for your attention!

Credits : thanks to the wire compensators team !

Some References

[1] W. Herr, *Concept of Luminosity*, CAS in Zeuthen, Germany, 2003

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[4] J.-P. Koutchouk and al., *Experiments on LHC Long-Range Beam-Beam Compensation in the SPS*, EPAC04, 2004

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[6] R. Calaga and al., *LR Beam-Beam Compensation in RHIC*, ICFA Beam-Beam Workshop, CERN, 2013

[7] Y. Papaphilippou and F. Zimmermann, *Estimates of Diffusion Due to Beam-Beam Long-Range Collisions*, PRAB, 2002

[8] J.-P. Koutchouk, *Correction of the Long-Range Beam-Beam Effect in LHC using Electromagnetic Lenses, CERN Note*, 2001

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[9] S. Fartoukh and al., *Compensation of the bean-beam long-range interaction as a path towards new configurations for the high-luminosity LHC*, PRAB, **18**, 121001, 2015

[10] A. Poyet and al., *MD3263: BBLR Compensation Using DC Wires in the LHC*, CERN-ACC-NOTE-2019-0053

[11] M. Giovannozzi, *Review of Dynamic Aperture Concept,* Non-Linear Beam Dynamics WG, 5th December 2019

[12] D. Pellegrini, *Dynamic Aperture Requirements From Lifetime Considerations*, 7th HL-LHC Collaboration Meeting, Madrid, 2017

[13] N. Karastathis and al., *Run 3 Operational Scenario Validation*, LHC Run 3 Working Group, 30th November 2018

[14] A. Poyet and al., *BBLR Wire Compensation Feed-Forward in Run 3*, 193rd Machine Protection Panel Meeting, 19th June 2020

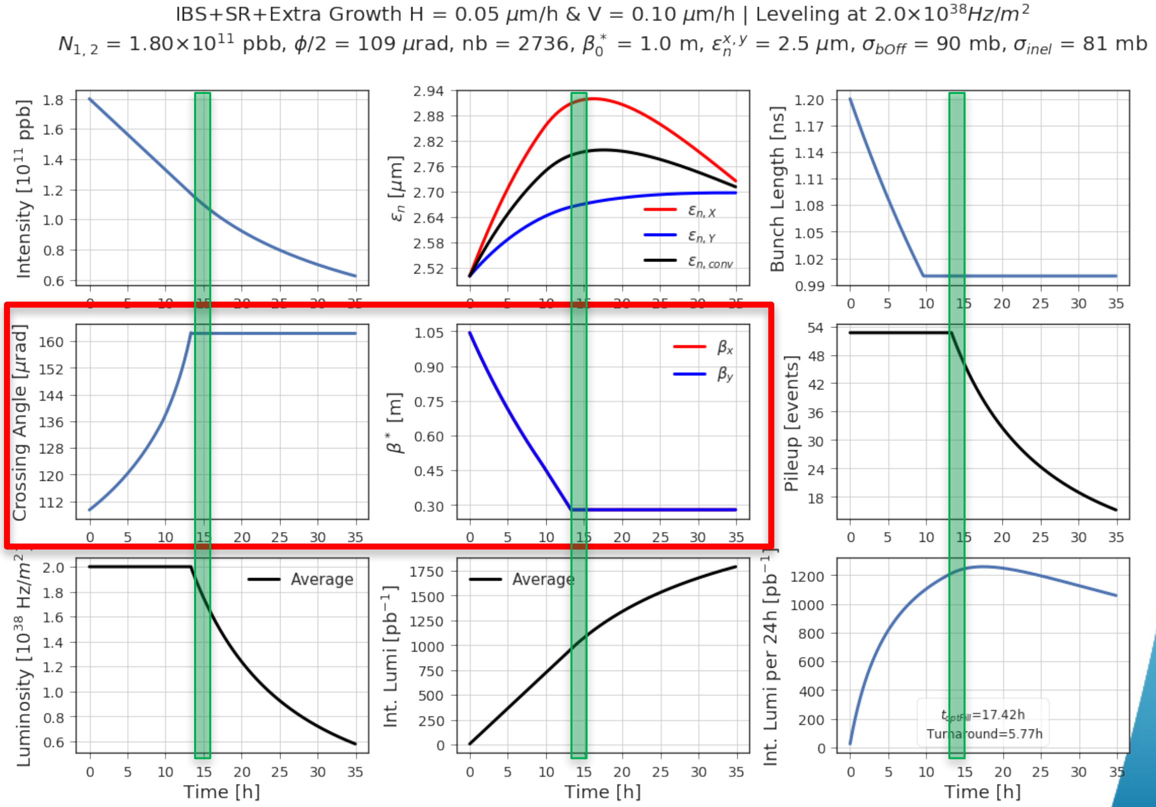
[15] A. Rossi and al., *Machine protection aspect of BBLR Operation in Run 3*, 193rd Machine Protection Panel Meeting, 19th June 2020

Back-up

Foreseen Run 3 LHC Fill

S. Fartoukh and N. Karastathis

- In 2022: **round optics** with IP1 crossing in V-plane and IP5 crossing in H-plane.
- The wires could be switched on at the **end of the leveling**.
- We assume Run3 collimation settings similar to Run2 ones.



Modern Treatment of Accelerator Physics

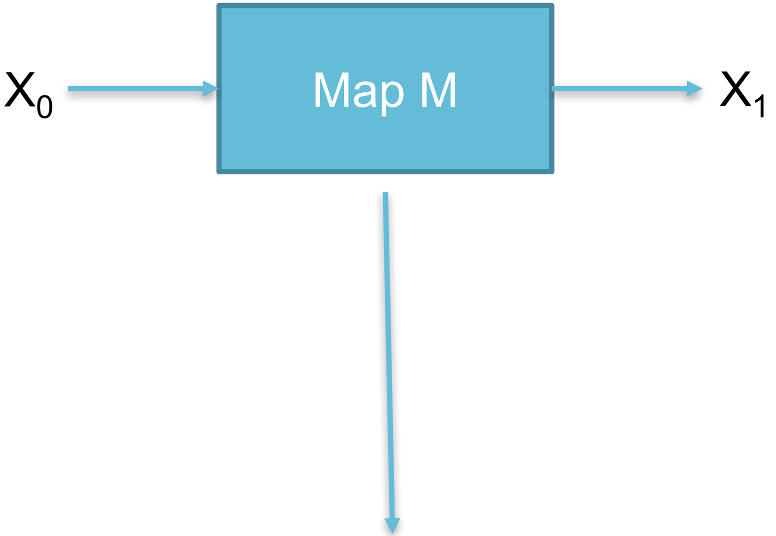
- Truth is: **no machine is linear** simply because **they could not work**.
- How do we deal with non linearities?
- No global analytical solution, but we do we need it?
  - **Answer: No!**
- Given a set of initial conditions, we want to **know the coordinates of our particles at another point**, maybe after one turn (for circular machines)
- Solution: **Maps**!

S. Lie

W. R. Hamilton

Modern Treatment of Accelerator Physics

- How to get such maps?
- Maps can be **matrices** (linear case) or something else like:
  - Taylor Maps
  - **Symplectic** integrators
  - Lie transformations
- One particular technique used to get a map: tracking + TPSA
- The idea is to obtain an analytical one-turn map from tracking using Differential Algebra
- We then express the final vector in phase space as function of the initial coordinates



$$\Delta x_f = 0.06972\Delta x_i + 167.77\Delta p_i$$

$$\Delta p_f = -0.00530\Delta x_i + 1.5885\Delta p_i$$

Towards another dimensioning method

- Using TPSA…

- One can imagine a single passage model, with non-linear kicks due to the BBLR

- Once we get the effect of the BBLR on the one-turn map, one can get design the wire compensators

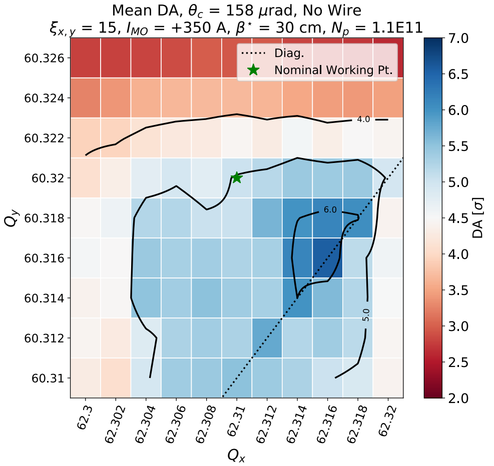
- Possible to consider only one IP, and the rest of the machine is simply a rotation in normalized phase space.

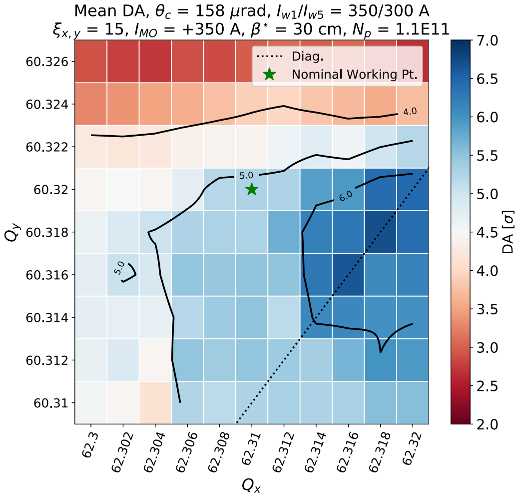
ON-GOING

Towards Run III: Wires and tune optimization

- Wires are now prepared to be used in operation during the LHC Run III
- In those conditions, tertiary collimators are foreseen to be opened at 8.5σ[1]
- It is known that DA can be optimized by adjusting the tunes [5]
- Wires open the tune space
  - Especially around the 3rd integer resonance
  - Interesting to accommodate additional non-linear effects (e-cloud)

DA dependency on tunes (no wires)



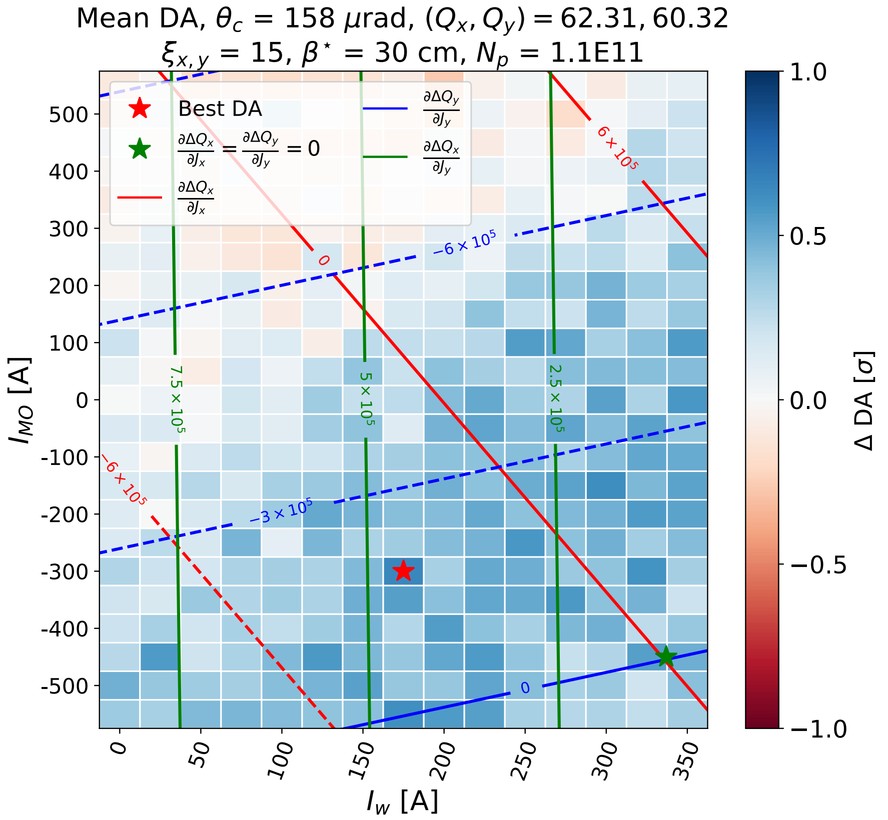


DA dependency on tunes (2 wires, coll. at 8.5σ)

[1] For comparison, the case with the collimators opened at 7.5σ was also studied

Towards Run III: Compromise wires/octupoles

- Experimentally, it has been shown that **octupoles can be used to mitigate BBLR** interactions (with high tele-index) [6]
- Octupoles are needed for **coherent stability**
- A **compromise** between wires and octupoles can be considered
- **Negative octupoles** could help the compensation scheme of the wires
- Instead of RDT compensation, the target is to **compensate the amplitude detuning due to BBLR**



Towards Run III

- Other aspects have been studied for LHC Run 3 in terms of DA (see back-up):
  - Impact of tunes and wires on DA
  - Compromise between wires and octupoles for DA improvement

- Technical implementation:
  - Tune feed-forward of the wires (keep the machine tunes constant during operation) [14]
  - Wires interlock: the beams have to dumped in case of failure [15]