Non-Linear dynamics modelling in accelerators, applied to beam-beam long-range compensation for HL-LHC

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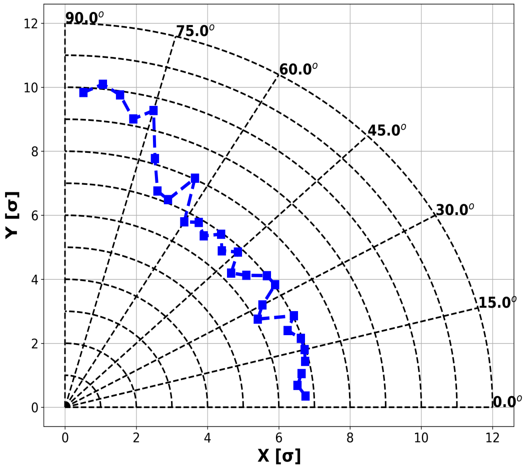
- **High Order Symplectic Integrators With Only Forward Integration Steps**

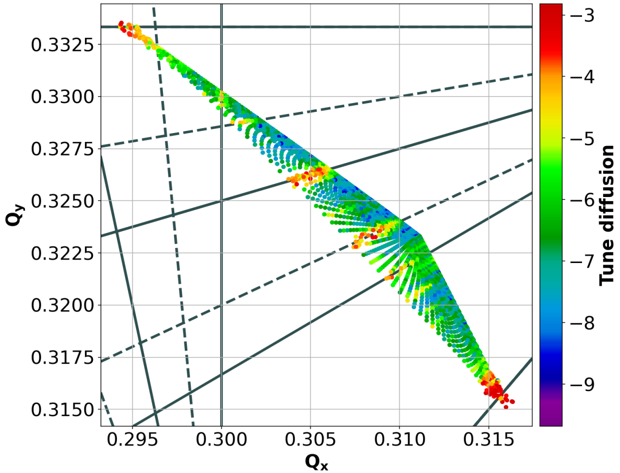
- **Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire**

Symplectic integration

Symplectic integration

- The design towards optimal operation of an accelerator relies heavily on simulations of the particle's motion.
- Based on these simulations, quantities correlated with beam lifetime evaluated for the improvement of machine performance.
  - Dynamics aperture (DA), the region in phase space where stable motion occurs over a certain time span
  - Friquency Maps Analisies, a depiction of resonance phenomena



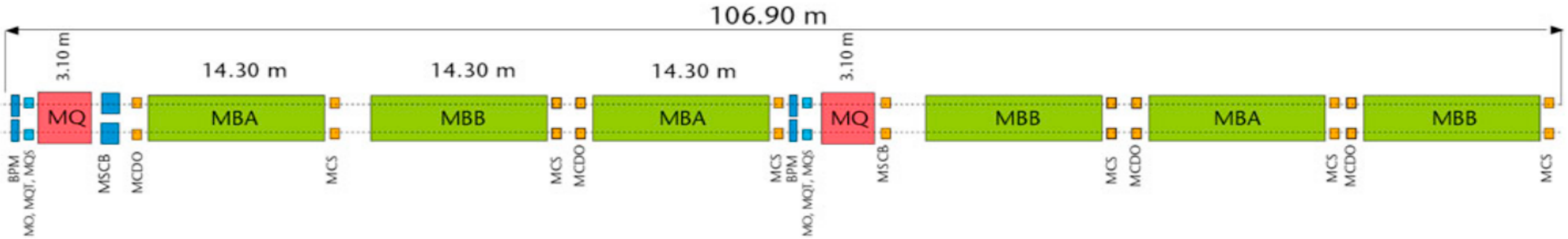


For the case of a collider like the LHC/HL-LHC

Luminosity

Symplectic integration

- For the simulation/study of the particles dynamics (motion), **the equations of motion must be solved for every electromagnetic element** in the lattice.



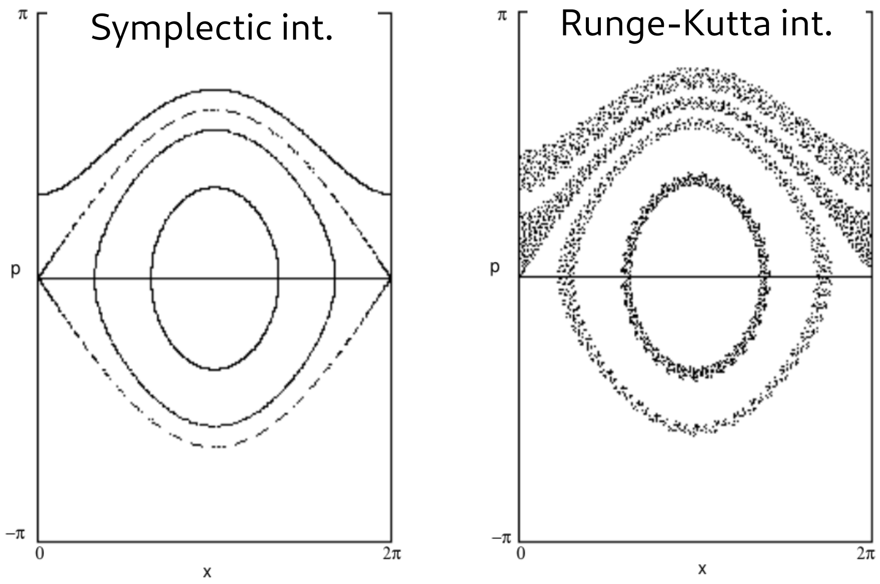
- In order to appreciate the complexity of the integration processes
  - ~10^4 turns per second
  - ~10^4 electromagnetic elements at each turn (RF cavities, multipolar magnets, beam-beam interaction, etc.).

Symplectic integration

- For the majority of the accelerator elements, the **equations of motion can not be solved analytically,** thus **numerical integration scheme must be used**.

- **This integration has to be symplectic.**

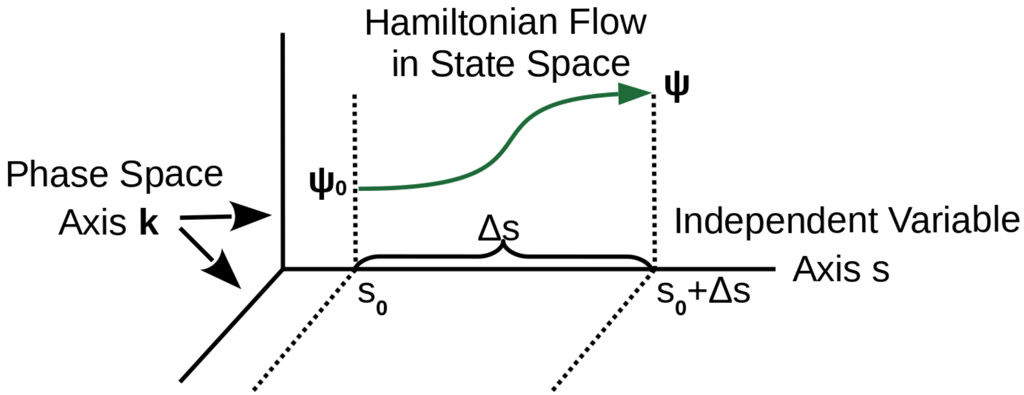
- **Symplecticity** is an inherent feature of any Hamiltonian (conservative) system and **preserve among other mathematical properties, the "energy" of the system.**



Symplectic integration

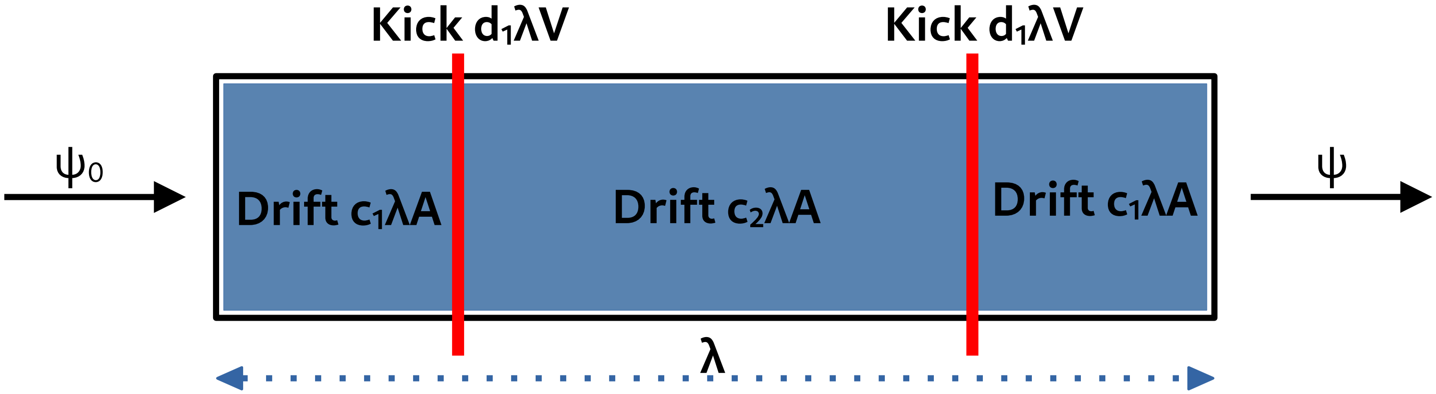
- **Symplectic** are the **integrators** that **transform an initial set of variables** $\psi_0=(q_1,p_1,\ldots,p_N)^T$ **to a new set of variables** $\psi=(Q_1,P_1,\ldots,P_N)^T$ that preserve the "energy".

- Instead of using an arbitrary high order numerical integrator to continuously solve the eq. of motions, a **symplectic map** that transports the particle between distinct positions of an element can be build. This map **approximates as close as possible the continuous trajectory and guarantees the conservation of "energy"**.



Symplectic integration

- **Such a symplectic map/integrator** (that is an approximated solution of the original problem) **can be constructed from a series of drifts and kicks.**

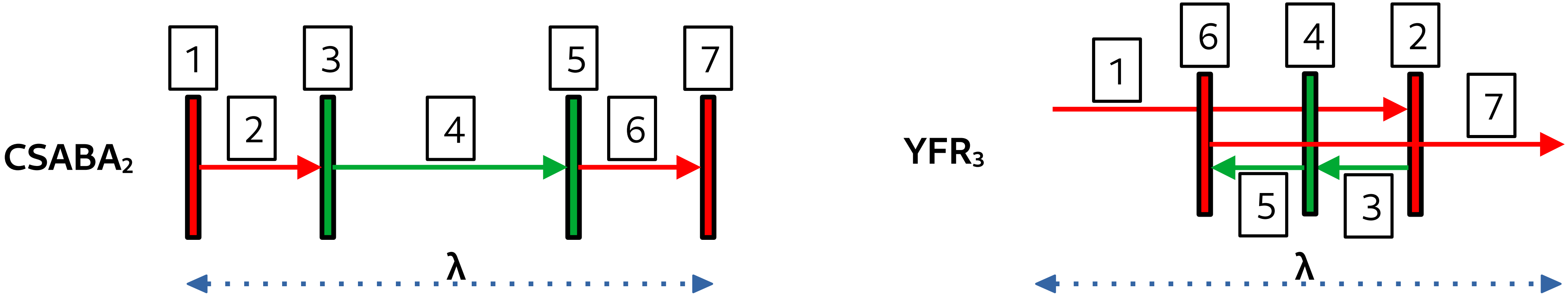


- The accuracy of the integration scheme is controlled by:
  - the number and symmetry of the drifts and kicks
  - the values of the c_n and d_n constants

High Order Symplectic Integrators With Only Forward Integration Steps

High Order Symplectic Integrators With Only Forward Integration Steps

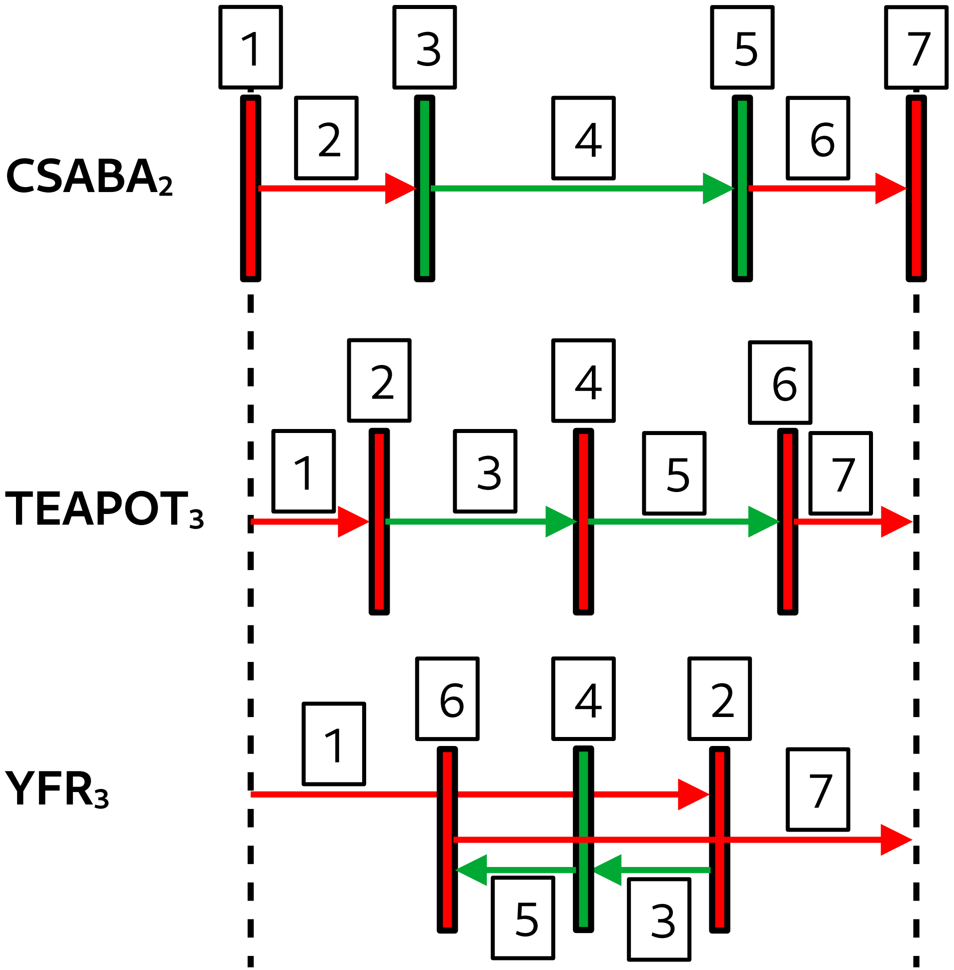
- **For systems with Hamiltonians** presenting certain mathematical properties **like the ones found in particle accelerators, a new set of symplectic integrators called $CSABA_m$ can be used.**
  - Include only positive integration steps (c_n, d_n > 0) that guarantee the stability of the integration scheme even for large integration steps (λ).



High Order Symplectic Integrators With Only Forward Integration Steps

- In order to compare the performances of the $CSABA_m$ symplectic integrators against the integration schemes $TEAPOT_m$ and YFR_3 which are extensively used in accelerators, different benchmark studies are done.

Symplectic Integrator	Number of steps involved
$CSABA_m$	2*m+3
$TEAPOT_m$	2*m+1
YFR_3	7

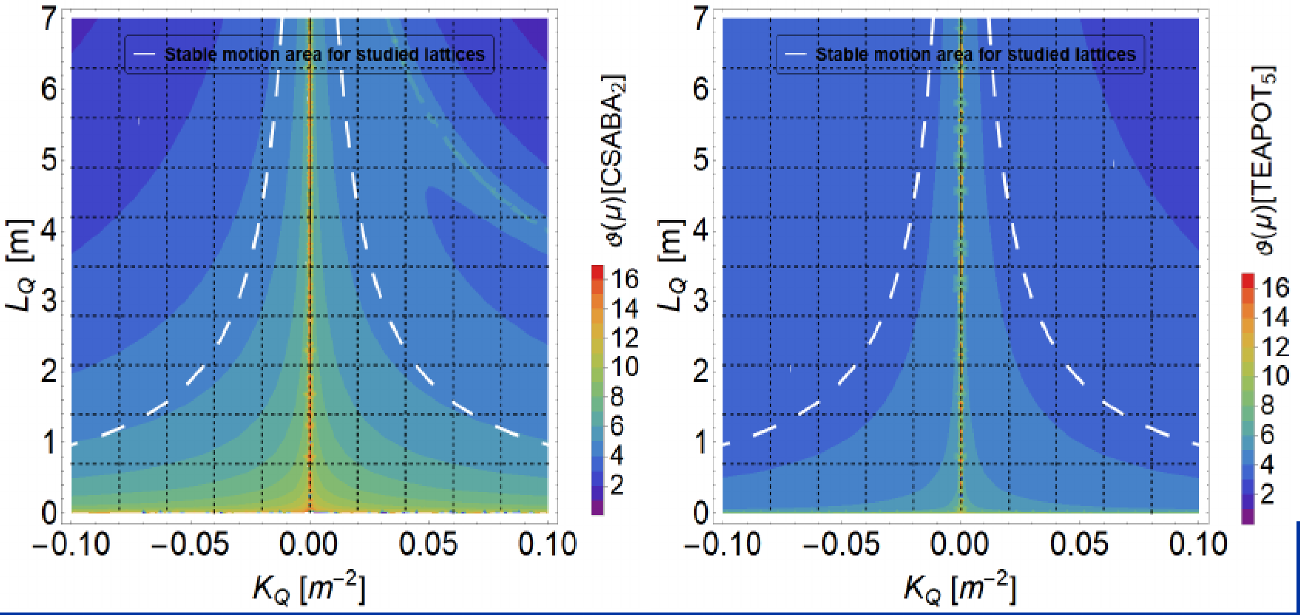


High Order Symplectic Integrators With Only Forward Integration Steps

- Using FODO cells (periodic alternation of drift, dipole and quadrupole magnets), **the accuracy with which the $CSABA_m$ and $TEAPOT_m$ describe the phase advance μ is studied for different values of the quadrupole characteristics (strength K_Q vs length L_Q).**

- **The $CSABA_2$ is at least two orders of magnitude more accurate than the $TEAPOT_5$,** even if the $TEAPOT_5$ consists of more maps, eleven in contrast to seven of the $CSABA_2$.

- For the phase advance calculations **the $CSABA_m$ are not only more accurate than $TEAPOT_m$ but they are also more economical with respect to the integration time.**

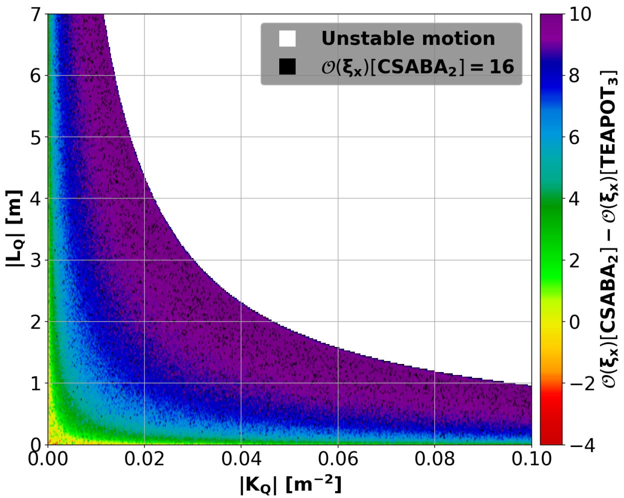


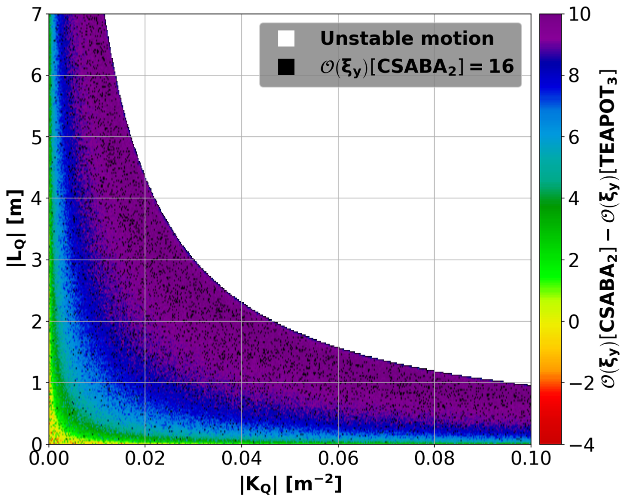
High Order Symplectic Integrators With Only Forward Integration Steps

- Using the same lattice as before but with the addition of sextupoles, **the linear chromaticity from sextupoles** $\xi = \frac{\Delta Q_n}{\delta}$ **and the tune spread with amplitude** $\frac{\partial Q_n}{\partial J_n}$ at both planes (n=x,y) **are also estimated and compared.**

- The **symplectic integrators are used only for the non-linear elements** (same optical functions for all the integrators).

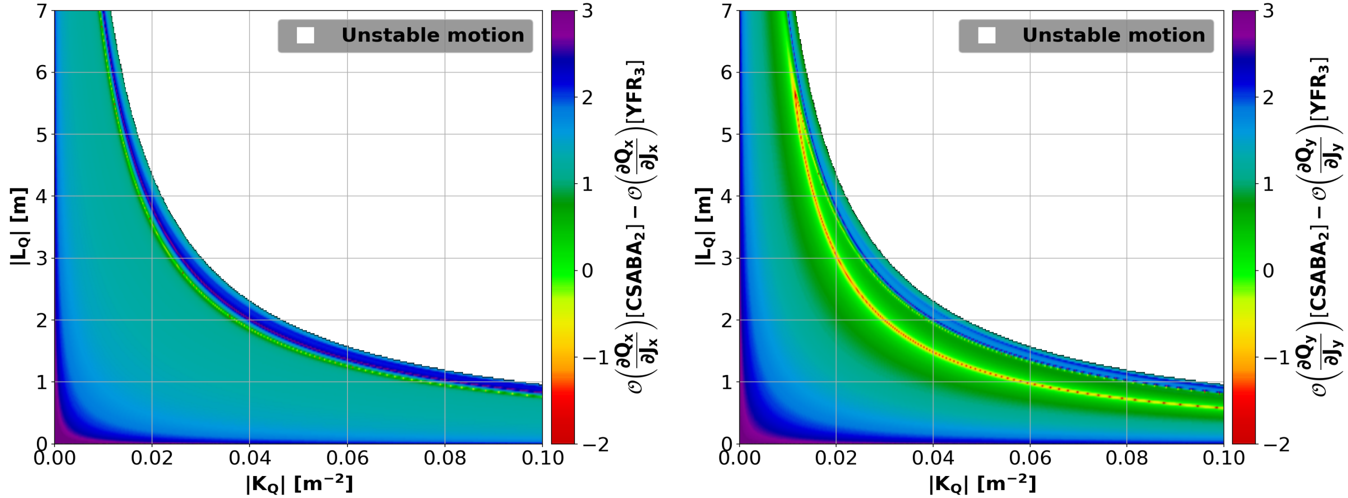
- Between the $CSABA_2$ and the other seven step integrator $TEAPOT_3$**, the $CSABA_2$ is at least one order more accurate for small (K_Q , L_Q) and improves significantly as the values of K_Q and L_Q increased.**





High Order Symplectic Integrators With Only Forward Integration Steps

- At both planes and **for the majority of the (K_Q , L_Q), the CSABA$_2$ can describe the tune spread with amplitude more accurate than the YFR$_3$** by at least one order.



- **The order of accuracy is smoothly degrade as the (K_Q , L_Q) values approach the unstable motion area** (white color). This smooth degradation of the accuracy **is interrupted by narrow bands of lattice configurations** for which the integrator performances are significantly improved **mostly due to particular phase advance between the integrator kicks.**

High Order Symplectic Integrators With Only Forward Integration Steps

- **The integrators effectiveness** to capture the Hamiltonian properties of the system **is better described from the study of an invariant of motion**.

- **The invariant is affected by the numerical precision** of the tracking algorithms which disturb the symplecticity **and from the integration scheme used**. Thus, **the more accurate integrators will be affected less.**

- **Such an invariant of motion are the transverse tunes**.

High Order Symplectic Integrators With Only Forward Integration Steps

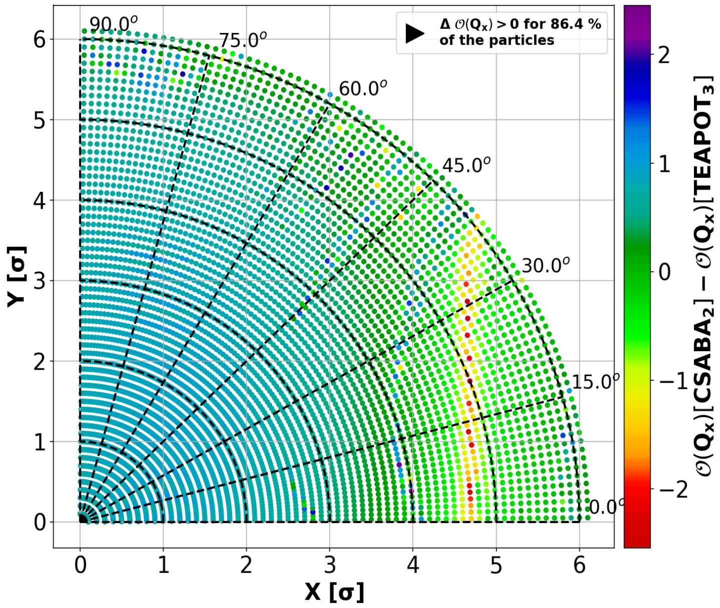
- For this study a lattice similar to the LHC with linear chromaticity set to 15 units, maximum octupole current and without RF cavities and beam-beam interactions is used.

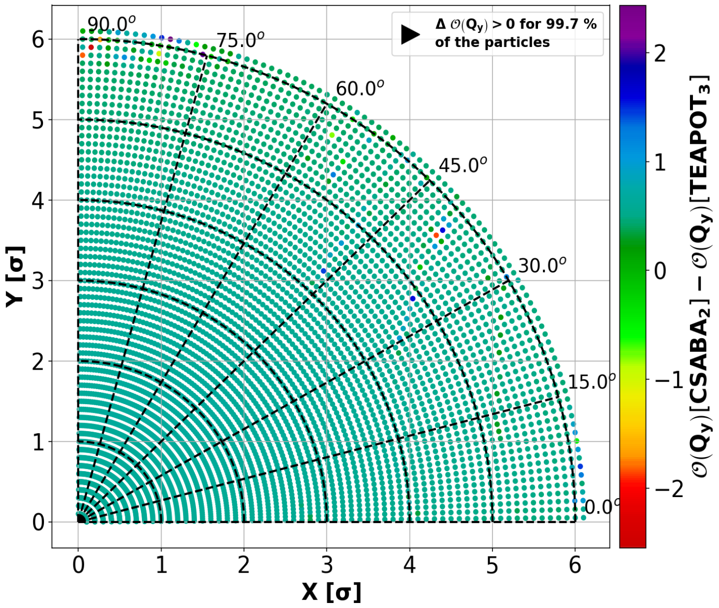
- For the calculation of the tune target values, **the exact solutions for the linear elements is used and for the nonlinear ones a ray tracing leapfrog is applied** (as the one employed by usual accelerator particle tracking tools such as SIXTRACK).

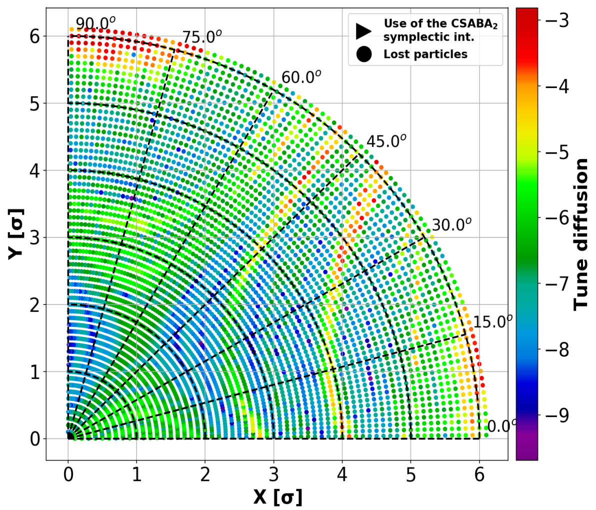
- The density of kicks used at each non-linear element, is identical to the one needed for the reproduction - up to double precision (16^{th} decimal), of the deflection caused by a quadrupole ($m \geq 1000$).

High Order Symplectic Integrators With Only Forward Integration Steps

- In the **horizontal (vertical) plane**, the **CSABA$_2$** is more accurate than the TEAPOT$_3$ ($\Delta(Q_x)$>0) for the 86.4% (99.7%) of the initial conditions. The **average improvement is close to one order** of magnitude (mean$\Delta(Q_x)$=0.8).







High Order Symplectic Integrators With Only Forward Integration Steps

- This new set of symplectic integrators $CSABA_m$ are ideal for Hamiltonian systems like the ones found in accelerators and consist of only forward integration steps - that guaranty the stability of the integrator even with large integration steps.

- From the analytical and numerical studies, the $CSABA_m$ symplectic integrators are more accurate than the other integration schemes. Most of the times the accuracy difference is larger than one order of magnitude.

- These findings indicate that the implementation of these new symplectic integrators in particle/beam tracking codes will be very beneficial.

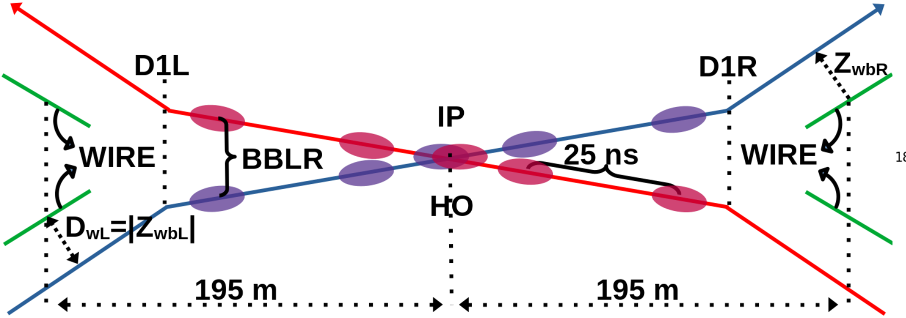
- Currently we are working on the implemention the $CSABA_m$ to the standard integration library recently developed by ABP (X-suite).

Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

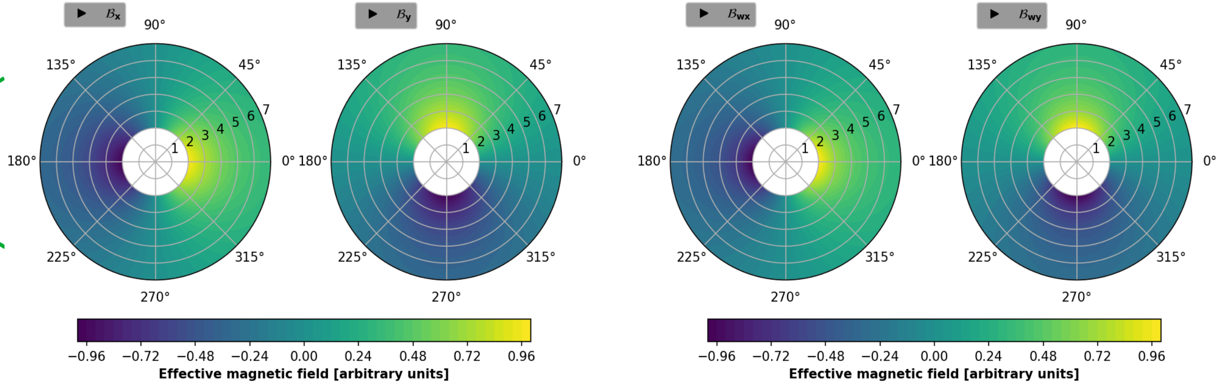
- Before and after the interaction points (IPs) and up to the separation dipoles (D1) **the particles interact with the electromagnetic field generated from the counter rotating bunches** (every 12.5 ns). These interactions are **called beam-beam long range (BBLR) interactions.**

- **The beam-beam long range (BBLR) interactions can be compensated with DC wires.**



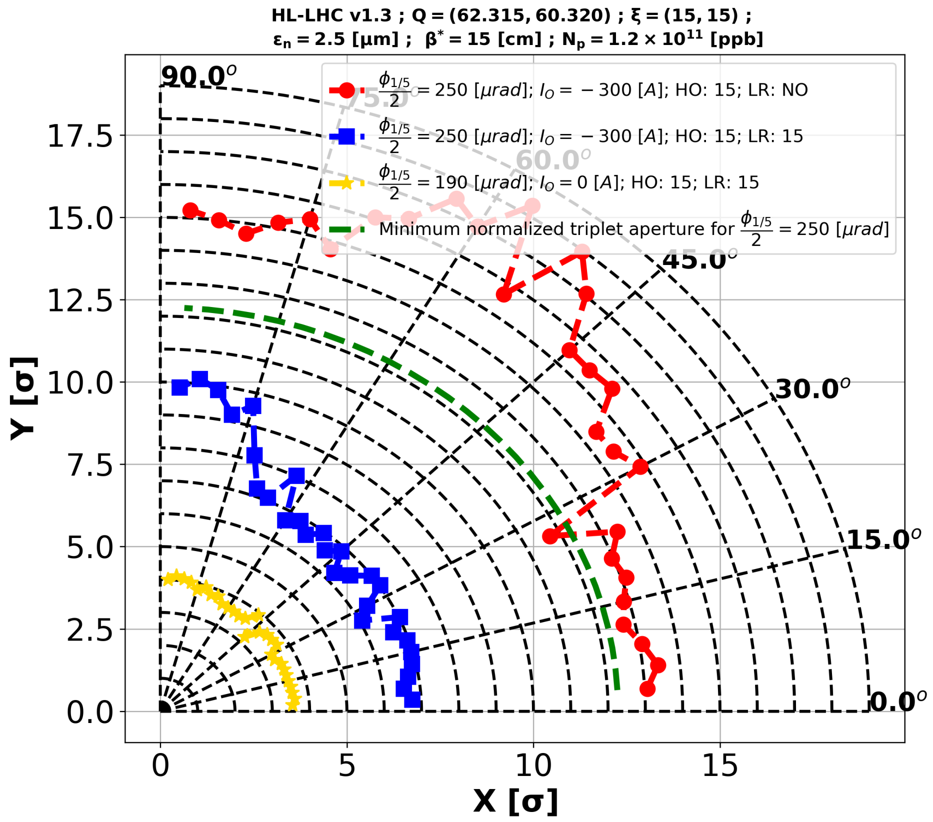
BBLR E/M field

DC wire E/M field



Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

- **The effect of the BBLR interactions is detrimental for the beam dynamics and will be even more significant after the high luminosity upgrade of the LHC** due to higher bunch population over smaller emittance and the stronger focusing at the IPs.



Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

- Ring sections located at 195 m left and right of the IP1 and IP5 are reserved for a possible future installation of DC wires.

- The transverse distance of the wire from the weak beam (D_w) should respect the machine protection restrictions (tertiary collimators).

  - **Start of collisions, D_w** must be **larger than 18/17.4 σ for the baseline/ultimate** scenario.

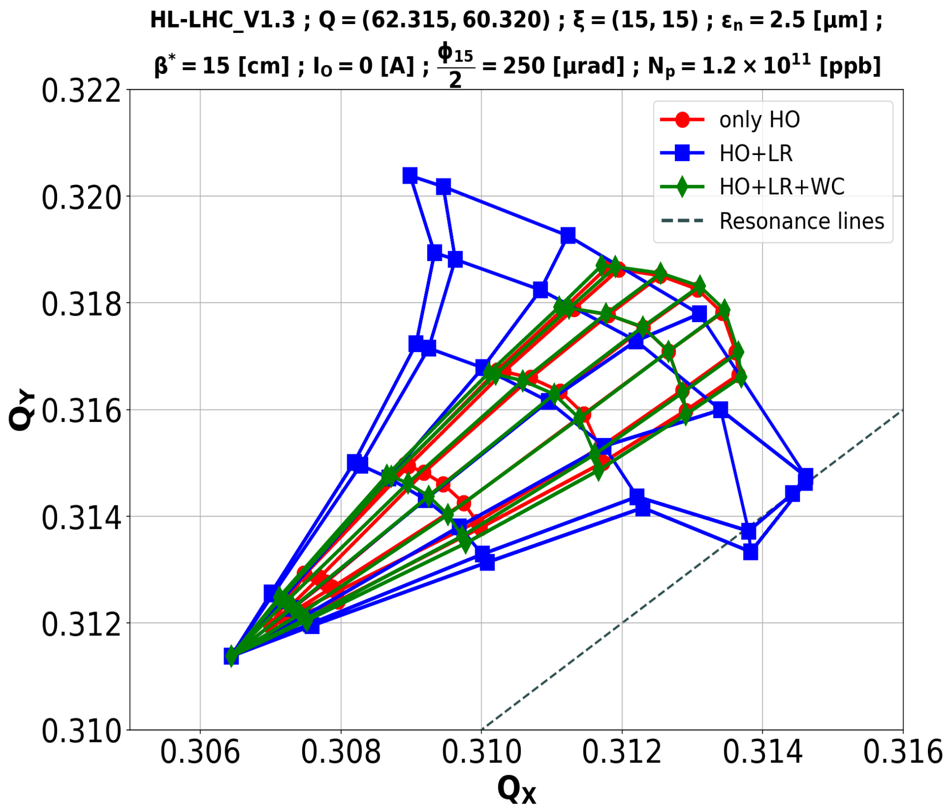
  - **End of luminosity leveling, D_w** must be **larger than 10.4 σ** plus wire thickness (~1mm).

- **The goal is to find the wire current (I_w) and its transverse distance from the beam (D_w) that guarantee $DA_{min} \geq 6\ \sigma$ (which guarantees good beam lifetime) and respect the D_w restrictions.**

Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

Footprint:

- with only head on collision (HO)
- with the addition of BBLR interaction (HO+LR), wings formation.
- with the addition of wire compensator (HO+LR+WC), **very good compensation of the footprint wings**.

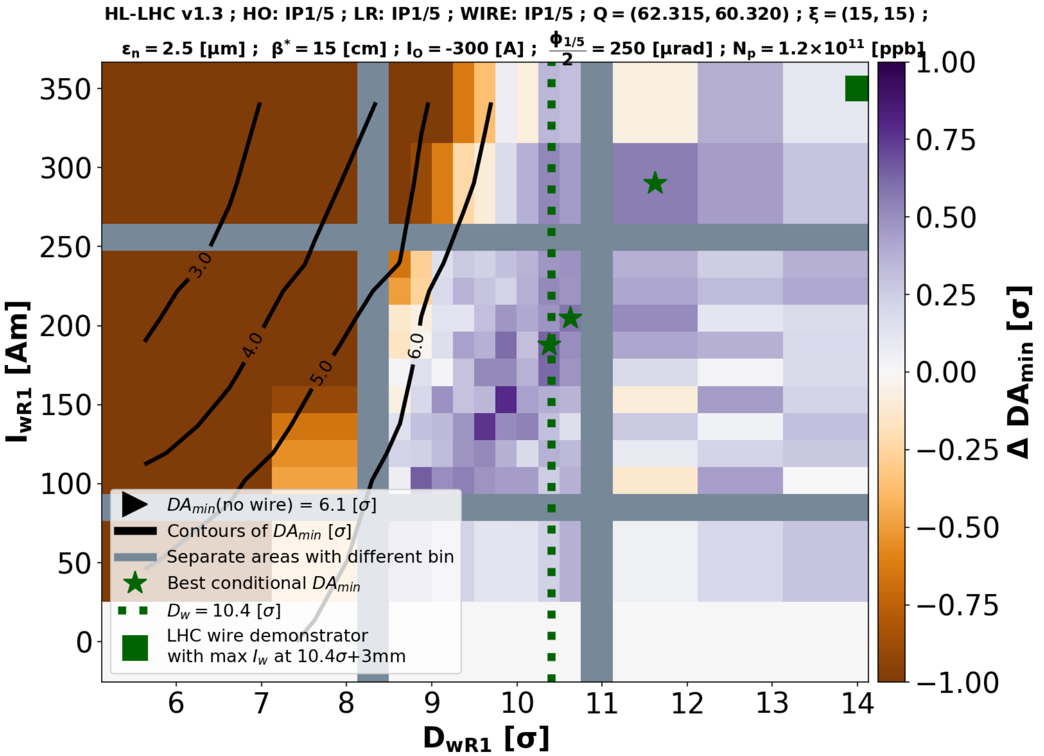


Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire – Nominal scenario

- After optimization studies, the **DA_{min} for the nominal scenario of the HL-LHC** at the end of the luminosity leveling **without the use of DC wires is DA_{min}(no wire)=6.1 σ**.

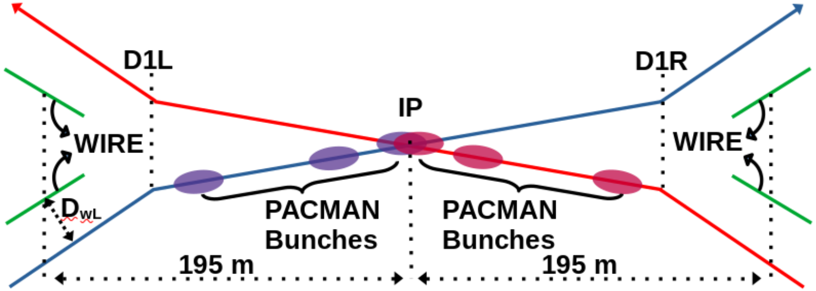
- **Making use of the DC wires, the DA_{min} can be improved up to Δ DA_{min}=0.7 σ** with configurations guarantee D_w>10.4 σ (green asterisks).

- The **most powerful configuration** (smaller D_w and larger I_w) **of the DC wire demonstrators in LHC**, is shown with a green square and **guarantee only a marginal DA improvement.**

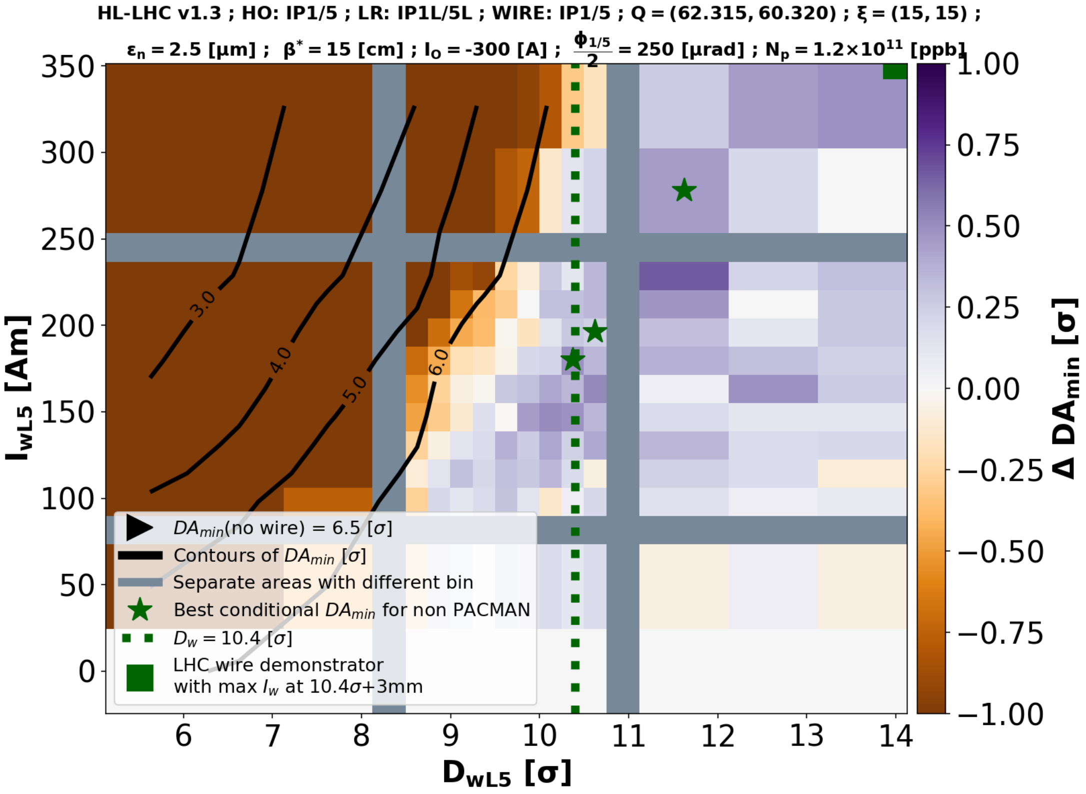


Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire – Nominal scenario

- The bunches at the tails of the train (sequence of bunches) experience less BBLR interactions and are called PACMAN bunches, $N_{BBLR}-1 \geq N_{PACMAN} \geq N_{BBLR}/2$.



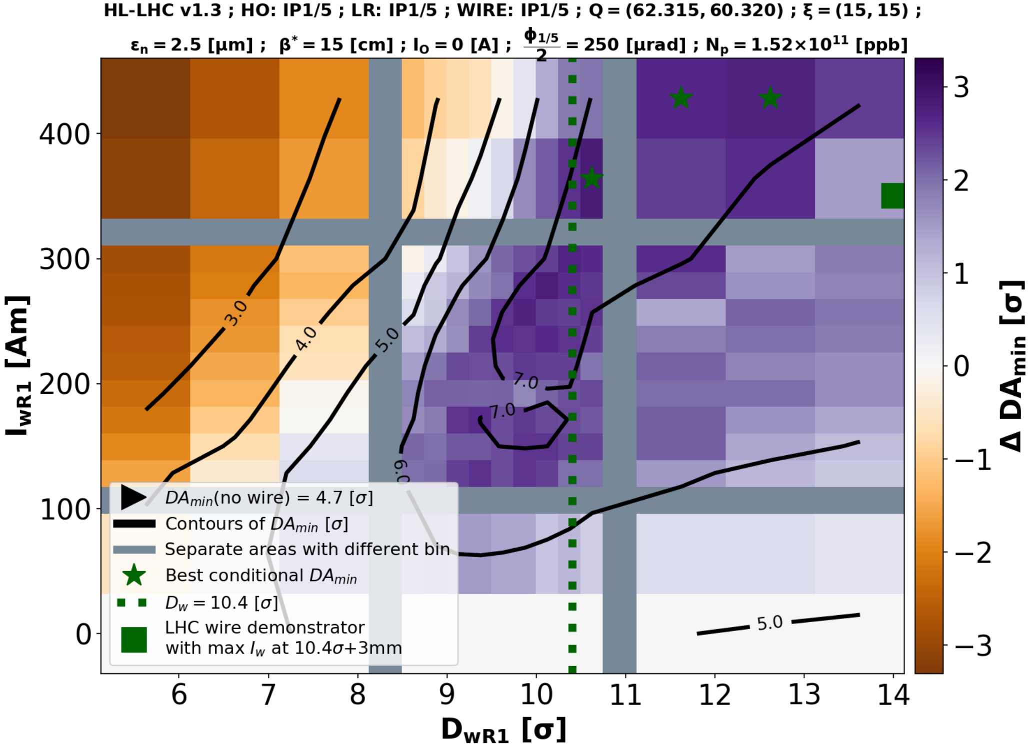
- Using the nominal scenario and simulating a PACMAN bunch that experience only the left BBLR interactions of the IR1 and IR5 ($N_{PACMAN}=N_{BBLR}/2$), **the Δ DA_{min} is up to 0.5 σ with the same good wire configurations** found before (green asterisks).



Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire – Ultimate scenario

- For the **ultimate scenario of the HL-LHC** at the end of the luminosity leveling there is **not a lattice configuration that guarantee DA_{min}>6 σ.**

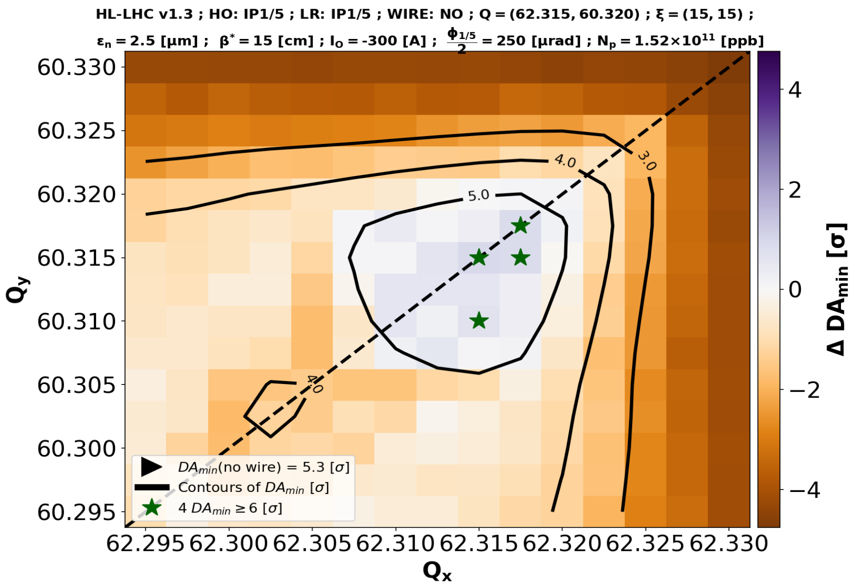
- **Many good DC wire configurations** (DA_{min}≥6 σ) compatible with the machine protection limitations exist. The best of them are indicated with green asterisks and gives **DA_{min} up to 7.6 σ** (~3 σ improvement over the case without wire).

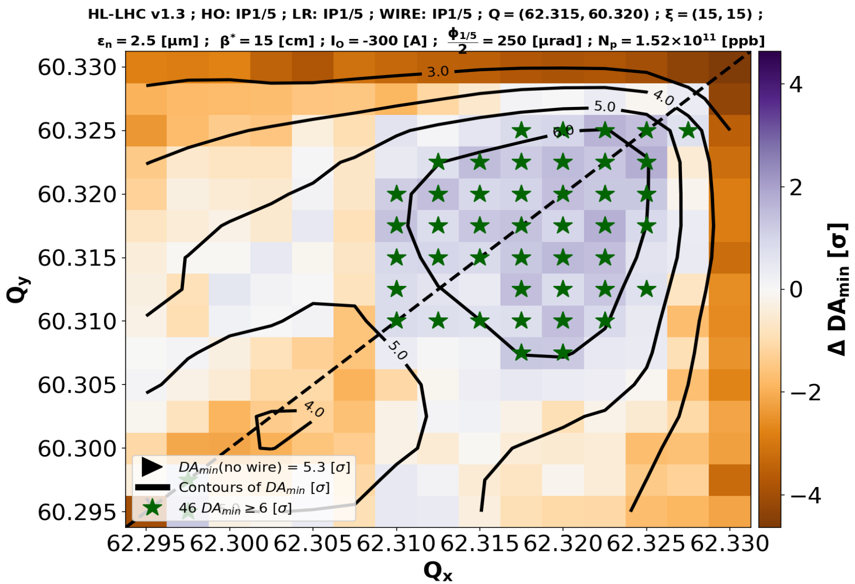


Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire – Ultimate scenario

- There is **not a working point above the diagonal that guarantee DA_{min}>6 σ**.

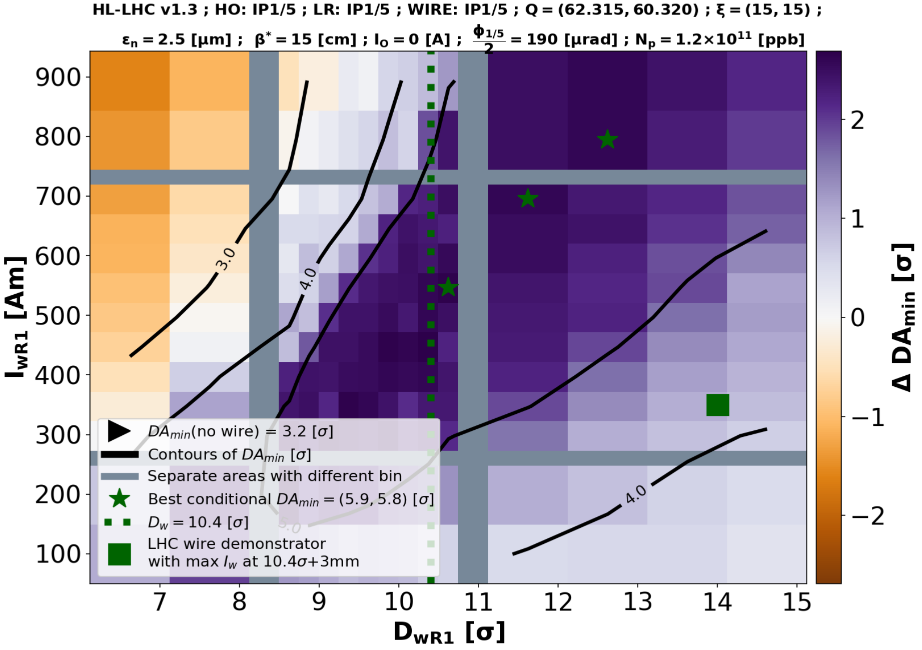
- Using one of the good DC wire configurations (with D_w>10.4 σ), **a large "island" with good working points (DA_{min}≥6 σ) appears.**

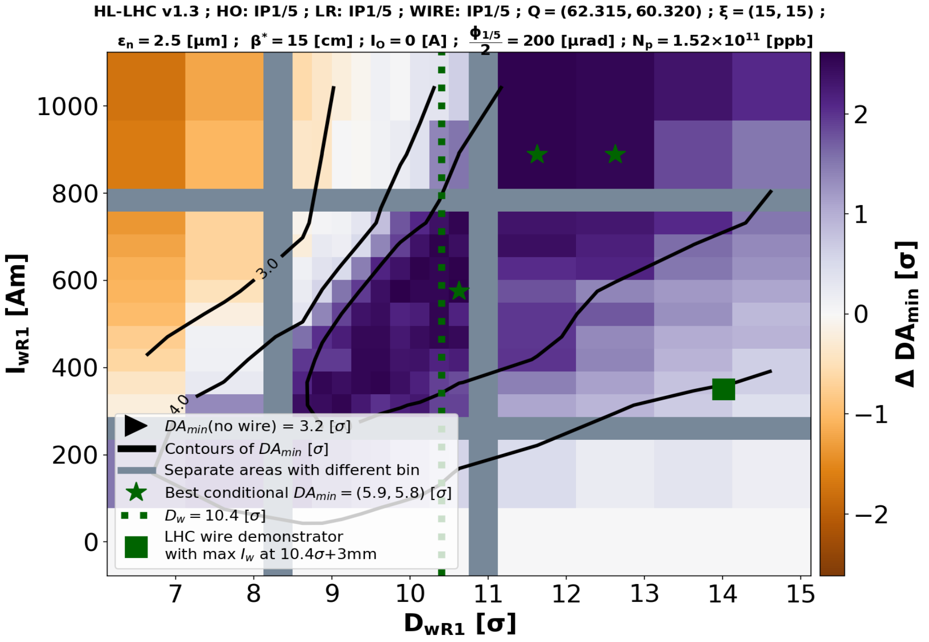




Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

- Due to the good DA_{min} results at the nominal and ultimate scenarios **with the use of DC wires, the crossing angle can be reduced up to $\Phi_{1/5}$=380 μrad (~25% redaction) for the nominal and up to $\Phi_{1/5}$=400 μrad (~20% redaction) for the ultimate (improved nominal/ultimate scenarios) maintaining DA_{min}≈6 σ and D_w>10.4 σ.**

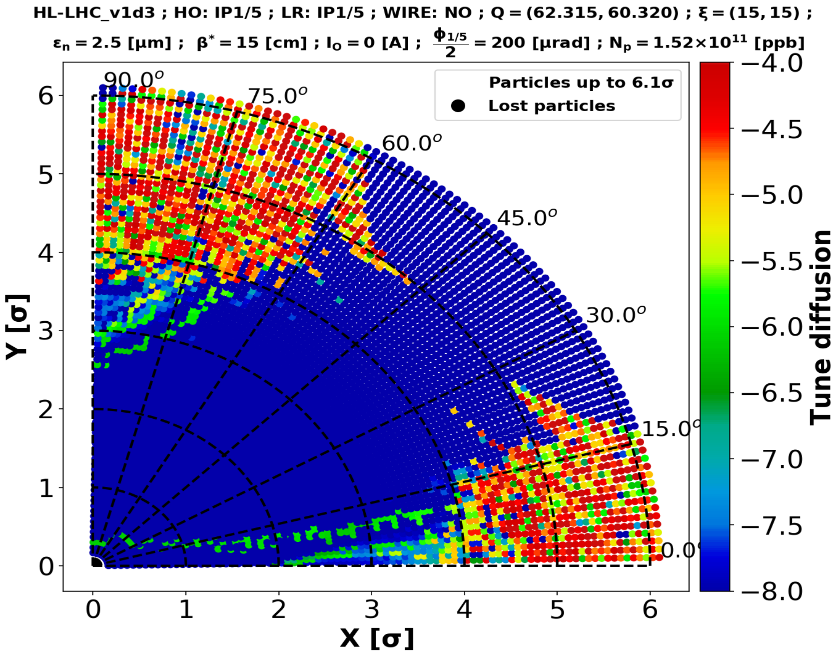




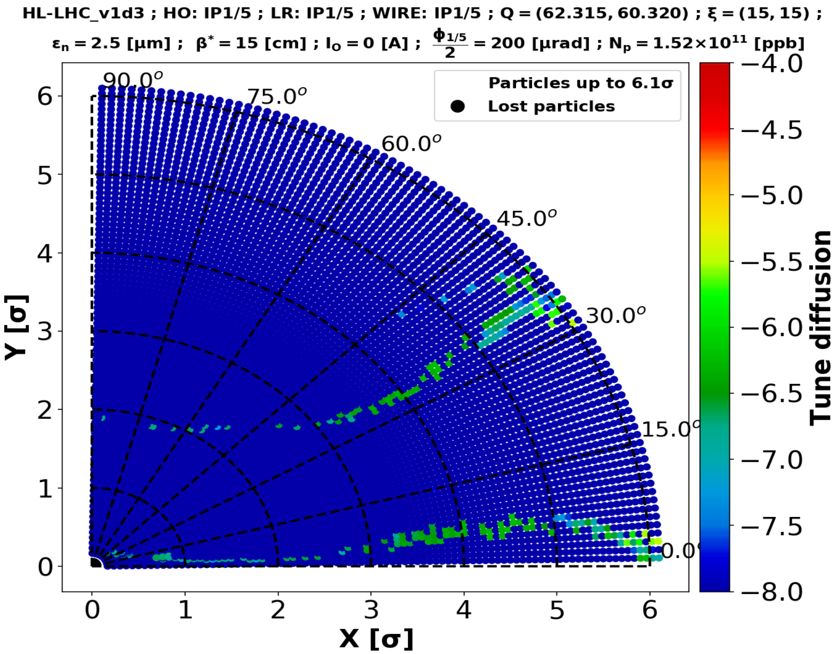
Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

- The **beneficial impact of the wire compensators at the improved ultimate scenarios can be also seen from a Frequency Map Analysis.**

Without DC wire



With DC wire

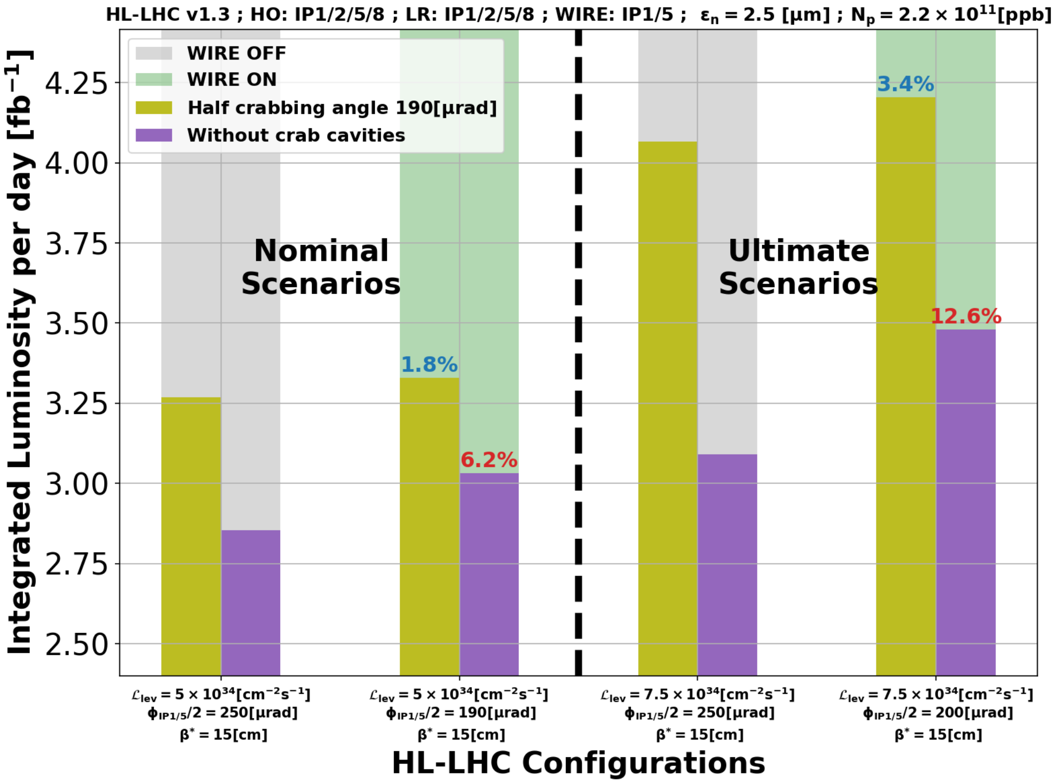


Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire - Luminosity

- The crossing angles during the luminosity leveling at the improved scenarios can be kept constant and due to the smaller crossing angle the integrated luminosity is increased.

- **With the improved nominal scenario, the gain in integrated luminosity with the crab cavities on is ~2% over the existing nominal and ~6% if the crab cavities are off.**

- **The increment is more significant with the improved ultimate scenario. The gain over the current ultimate (with DA_{min}(no wire)=4.7 σ) is ~3.5% with crab cavities and ~12.5% without crab cavities.**



Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

- It is demonstrated that for a variety of DC wire configurations, the detrimental effect from the long range beam beam interaction in different scenarios of the HL-LHC can be mitigated.

- Many of these good configurations respect the machine protection restrictions without sacrificing the beam lifetime.

- The gain in DA provide the margin for a flawless operation of the machine.

- With the use of wire compensators, the crossing angle of the nominal and the ultimate scenarios can be reduced by 25% and 20% respectively.

Mitigation of the Long Range Beam-Beam Interactions in HL-LHC with DC Wire

- With the improved nominal and ultimate scenarios, the integrated luminosity per day is slightly increased with crab cavities and recovers half of the lost luminosity without the crab cavities.

- Because of the crossing angle reduction the crab cavities voltage can be also reduced without sacrificing the machine performance. Furthermore, the strength of the magnets (corrector) that generate the crossing bumps, the heat load and the integrated radiation that is mainly deposited in the final focus quadrupoles can be reduced.

- Simple short HW models are being tested

Thank you for your attention.

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