

# HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

## Milestone Report

# Preliminary Estimates of Beam-Beam Effects

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## MILESTONE REPORT

# PRELIMINARY ESTIMATES OF BEAM-BEAM EFFECTS

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### Abstract:

This report presents a summary of the preliminary estimates of possible performance limitations caused by the effects of beam-beam interactions for the baseline HL-LHC operation scenario. The development of modelling methods and tools is discussed, and where possible the simulation results are compared to the 2012 LHC machine operation.

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**Delivery Slip**

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## Executive summary

*A summary is presented of the preliminary estimates of possible performance limitations caused by the effects of beam-beam interactions for the baseline HL-LHC operation scenario. The study relies on the use of numerical simulations of single- and multiparticle dynamics in the collider under the influence of electromagnetic forces exerted by counter-rotating beams. The stability of particle motion is assessed using a variety of methods and tools, and conclusion is made on the robustness of the baseline HL-LHC operation scenario.*

*Since the work heavily relies on simulation tools, a significant effort was put forward towards the development of appropriate software codes. Their benchmarking against each other and available experimental data is discussed.*

*It should be noted that the conclusions of this report need further refinement. In particular, the following aspects shall be the emphasis of future work:*

- a) Simulations taking into account the machine imperfections (magnetic multipole errors, crab cavity field imperfections).*
- b) The effect of bunch-by-bunch variations (the so-called pacman effects).*
- c) Comprehensive examination of alternative operation scenarios (e.g. beam-beam compensation wires).*

## 1. INTRODUCTION

The beam-beam interaction is known to be an important factor limiting the performance reach of present particle colliders. The most important effects of beam-beam interactions are: a) the induced particle losses that decrease the beam lifetime, create high background load for physics experiments, and highheat and radiation load on the collimation system; b) the degradation of beam quality through the beam size blow-up that decreases the luminosity delivered to particle physics experiments.

Owing to the extensive theoretical and simulation campaign during the design of the LHC collider, the beam-beam effects in the present machine are well controlled. However, the HL-LHC machine represents a quantitative as well as a qualitative leap into the unknown territory with respect to beam-beam effects. The baseline HL-LHC configuration makes use of a few novel concepts that have not been used in hadron colliders to full extent, and thus require a careful evaluation. They include: a) luminosity levelling during physics runs by variation of the beta-function at IPs; b) tilting the bunches in the main IPs with the use of RF Crab Cavities; c) significantly high value of the head-on beam-beam tune shift  $\xi$ .

Hence, the scope of Task 2.5 effort was to evaluate the expected impact of beam-beam interactions on HL-LHC machine, and to provide insight on possible limitations. These goals are achieved with the use of numerical simulations that are compared with experimental data where possible. The Task members also took an active part in the Machine Development studies aimed at the experimental investigation of beam-beam effects at the present LHC.

## 2. BEAM-BEAM EXPERIMENTS AT THE LHC

Two main results of Machine Development studies will contribute strongly to the task work: the leveling techniques, in particular via  $\beta^*$ , and the elaboration of possible DA scaling laws.

The feasibility of luminosity leveling by the use of  $\beta^*$  [1][2][3] has been proven technically in three dedicated experiments in 2012, although reproducibility has not been proved yet. In Fig. 1 the luminosity increase as a function of  $\beta^*$  at CMS and ATLAS is compared to the theoretical value. One can notice that collisions from 3 m  $\beta^*$  can be maintained with no major problems. Leveling with transverse offset was regularly used in operation in 2012 in order to deliver an appropriate constant luminosity to the LHCb experiment, however at luminosity value much lower than the one for the high luminosity experiments. No detrimental effect on beam emittance growth is observed when offsets are controlled and kept such that a minimum Landau damping is provided.

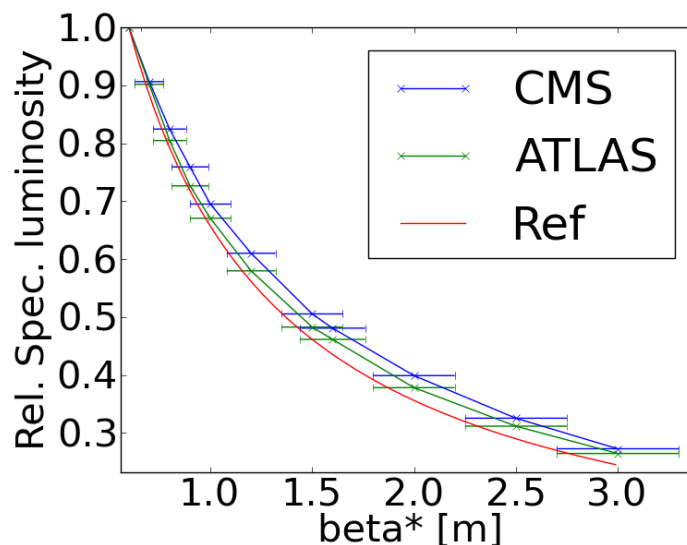


Fig. 1 Measured CMS (blue line), ATLAS (green line) and theoretically expected (red line) specific luminosities as a function of  $\beta^*$ . Error bars assume a 20% beta-beating error

The long-range beam-beam experiments demonstrated [4] the possibility of deriving scaling laws for the dynamic aperture with such parameters as energy, intensities, crossing angles,  $\beta^*$  and number of collisions without the use of massive tracking campaigns. Although the method does not allow evaluating the absolute value of DA, it makes the study of possible scenarios for the HL-LHC faster and more flexible. All experiments of long range interactions have been reproduced with Dynamic Aperture simulations. In all cases the threshold triggering a serious reduction of the beam lifetime occurs when a dynamic aperture of 4 to 5 sigmas is reached in the corresponding simulations as shown in Fig. 2 where for two different experiments the onset of losses has been related to corresponding DA simulations. In the experiments the lifetime reduced from approximately 20 hours down to 3 hours. This is significantly lower than the beam lifetime due to burn-off, expected to be 17 hours for a levelled luminosity of  $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , and therefore this is considered to be unacceptable, if future experiments confirm this reduction in steady state, as it would significantly reduce the performance in terms of integrated luminosity. Similar results have been determined with an independent study in [5].

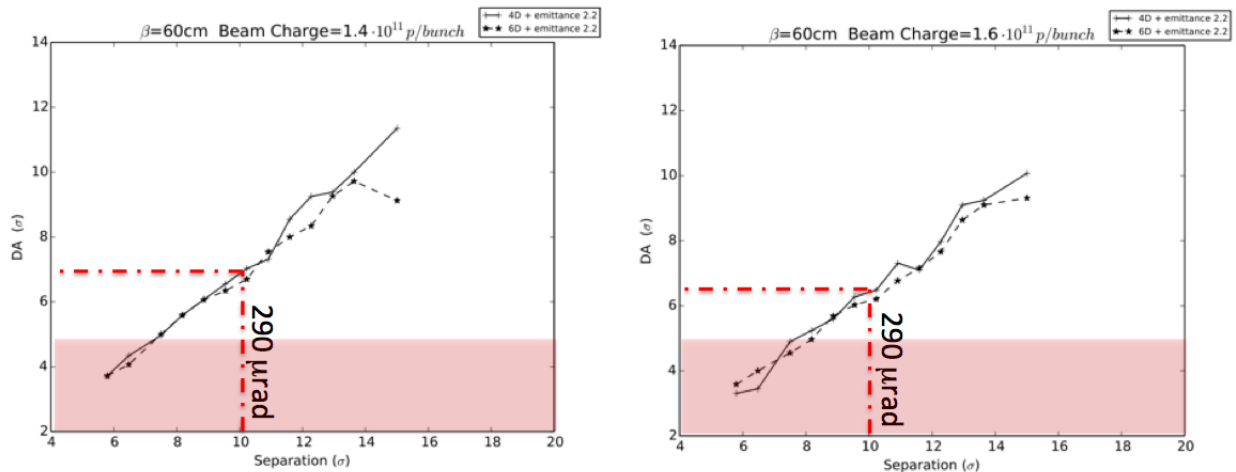


Fig. 2 Dynamic aperture simulations as a function of the first beam-beam encounter normalized separation for a beam emittance of  $2.2 \mu\text{m}$  (typical 2012 operational value). The two plots refer to two different experiments in the LHC for different bunch populations. The pink shaded area corresponds to values of the simulated dynamic aperture below which significantly reduced lifetimes have been observed during the experiments. During 2012 a full crossing angle of  $290 \mu\text{rad}$  was used in operation, for this angle dynamic apertures larger than 6 sigmas were expected from simulations for the considered bunch populations.

### 3. SIMULATION CODE DEVELOPMENT AND BENCHMARKING

The investigation of beam-beam effects for present LHC machine was mostly performed with the use of weak-strong approximation. This well-tested approach allows evaluating long-term particle stability in a very detailed accelerator model, and exploring wide ranges of the machine and beaming parameters. A number of computer simulation codes exist that have been under active development and in use for decades. The Task 2.5 team chose to perform the beam-beam simulations for HL-LHC with two codes: SixTrack [6] and Lifetrac [7]. Both programs have been successfully used for the design and optimization of past and existing colliders: SixTrack for LHC and RHIC, and Lifetrac for VEPP-4, DAFNE, and Tevatron. The two codes are capable of calculating the area of stable motion in phase space – the Dynamical Aperture, and hence a direct comparison of the results is possible. In addition to DA, Lifetrac also makes use of the Frequency Map Analysis plots and, more importantly, can calculate the long-term evolution of macroscopic beam parameters, such as the intensity, emittance and luminosity lifetimes. The performance reach for weak-strong codes at modern computing clusters is a few million turns, which is equivalent to few minutes of the machine time.

Before simulations of beam-beam interactions could proceed in earnest, a significant effort was applied to ensuring the accuracy of implementation of the machine lattice model in both codes. Fig. 3 presents a comparison of the DA calculation with SixTrack and Lifetrac for a sample machine configuration. The agreement is remarkable considering the fact that in this case each particle was tracked for one million turns through approximately 12,000 magnetic elements of the HL-LHC accelerator optics.

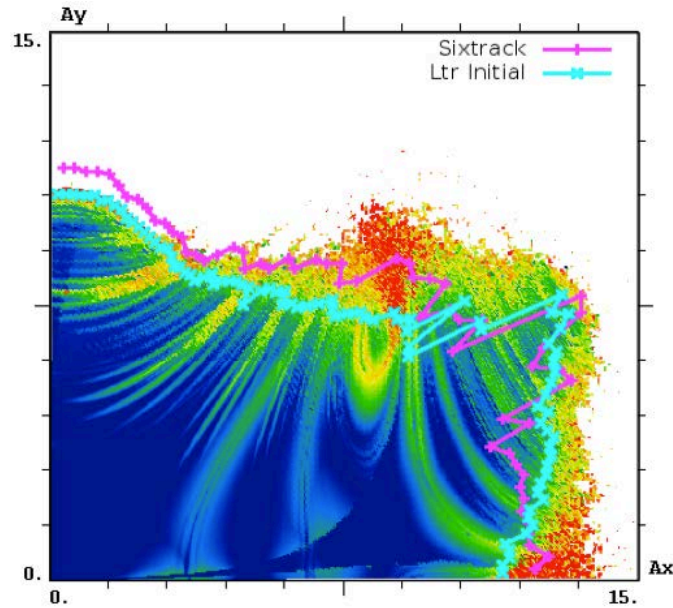


Fig. 3. One-million turns DA for HL-LHC lattice with multipole errors, without beam-beam interactions, simulated with SixTrack (purple) and Lifetrac (cyan). Colour contour lines show the magnitude of tune diffusion (FMA, colour code for tune diffusion is from blue  $10^{-7}$  to red  $10^{-3}$ ). The axes are labelled in units of rms beam size for an emittance of  $2.5 \mu\text{m}$  (sigma).

The codes were also extensively benchmarked on a number of cases with beam-beam interactions. Fig. 4 shows an example comparison of DA for the HL-LHC configuration with  $\beta^*=10$  cm, crossing angle of  $740 \mu\text{rad}$ , and baseline beam parameters – number of particles per bunch  $N_p=2.2 \times 10^{11}$ ,  $\varepsilon=2.5 \mu\text{m}$ . After a number of improvements in both codes and refinements in the treatment of the machine model, the agreement in all cases is at the level of 20% or better. This is sufficiently accurate for the purpose of evaluating the performance variants.

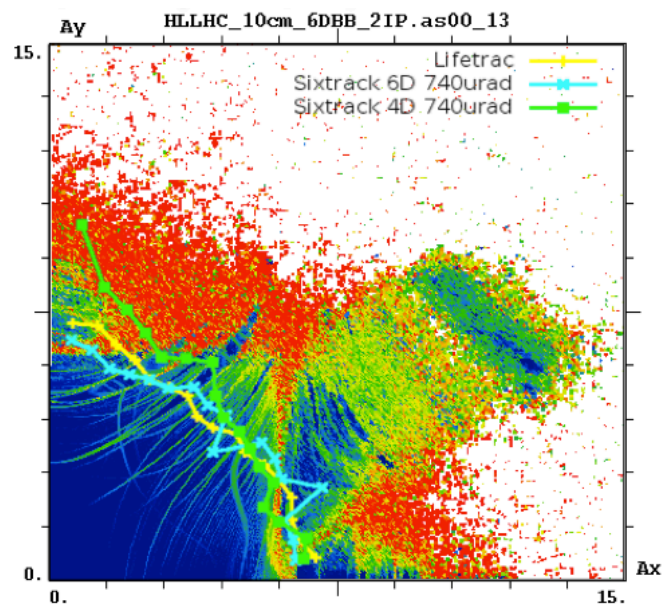


Fig. 4. One-million turns DA for HL-LHC lattice without multipole errors, with beam-beam interactions, simulated with SixTrack (cyan) and Lifetrac (yellow). Colour contour lines show the magnitude of tune diffusion (FMA, colour code for tune diffusion is from blue  $10^{-7}$  to red  $10^{-3}$ ). The axes are labelled in units of rms beam size for an emittance of  $2.5 \mu\text{m}$  (sigma).



Lifetrac multiparticle tracking was cross-checked with the LHC 2012 performance data [8], and demonstrated good agreement: the simulated non-luminous intensity loss rate was approx. 2% per hour, which agrees with the observed 1-3%. The luminosity lifetime degradation did not exceed 1% per hour, and is also compatible with the 2012 operation data. More systematic analysis of the 2012 data is in progress and will be the subject of further comparison with simulations to validate our models.

#### 4. EVALUATION OF BASELINE SCENARIO

In this work, the criteria used for the evaluation of beam dynamics were the same as in the LHC design study. In particular, we aimed at the one-million turn DA value of 6 beam sigma or more. The motivation for the choice of such margin is explained at some length in Ref. [6]. In short, the beam-beam driven diffusion at small amplitudes is quite slow, and the  $10^6$  turns of tracking typically does not represent the really long-term stability boundary. In the majority of studies, the 6-beam sigma DA corresponds to the true stability boundary of about 4 beam sigmas with the appearance of chaotic spikes [6]. Although the benchmarking of the machine studies with simulations seem to indicate that losses start to appear only at values of the crossing angle for which the simulated dynamic aperture is as low as 4 beam sigma it must be noted that other studies indicate that the simulations of the dynamic aperture of the installed LHC overestimate the dynamic aperture by 20 to 30 %. [9]. Studies are ongoing to provide additional criteria associated with beam observables and confirm the validity of the above criterion, in particular:

- losses at the primary collimators
- core emittance blow-up,

that can be compared with expected limits associated with collimation (power deposition on the primaries and losses in the cold elements resulting from collimation inefficiencies) and can be used to assess the impact on luminosity lifetime.

As an example we also complemented the single-particle dynamic aperture evaluation with multi-particle tracking studies, which allows for the estimation of emittance growth rates and luminosity lifetime degradation.

In the baseline HL-LHC scenario, the 2808 bunches (25 ns spacing) in each beam will begin colliding with the intensity of  $N_p=2.2\times 10^{11}$  particles per bunch and transverse normalized emittance of  $2.5 \mu\text{m}$ . The bunches will be tilted by Crab Cavities at each of the two main IPs to ensure head-on collisions despite the trajectories crossing at an angle of  $590 \mu\text{rad}$ . The luminosity will be leveled at the constant value of  $5\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  by varying the beta-function from  $\sim 69 \text{ cm}$  at the beginning of the fill to  $15 \text{ cm}$  at the end. Assuming negligible transverse emittance growth, the separation of beams at parasitic crossings will thus vary from 26 sigma at the beginning of the fill to 12.5 at the end. Hence, we can distinguish three stages of a fill from the point of view of beam-beam effects:

- Beginning of fill: weak long-range interactions (26 sigma separation) and strong head-on, characterized by the value of beam-beam tune shift  $\xi=0.031$ , determined by the beam brightness  $\xi\sim N_p/\varepsilon$ .
- Middle of fill: appreciably high long-range and head-on interaction.
- End of fill: weak head-on ( $\xi=0.015$  due to the particle burn-off in collisions) and relatively strong long-range (12.5 sigma separation).

For simulations, we picked a number of cases representing worst-case scenarios for these stages (Table 1). In all simulations the beams in addition to IR1 and IR5 also collided without separation at IR8 (LHCb), which further enhanced the negative impact of beam-beam effects on dynamics.

$\beta^*$ (cm)	$N_p$ ( $10^{11}$ )	X-Angle ( $\mu\text{rad}$ )	BB Separation ( $\sigma$ )	CC (MV)	$\xi$
40	1.65	360	12	7.7	0.024
40	2.2	360	12	7.7	0.031
15	1.06	590	12.5	12.5	0.016
15	1.06	440	9	9	0.016

Table 1. Simulation parameters for selected cases

In Fig. 5 the results of DA simulations for the representative cases are presented. One observes that even for the case of significantly enhanced beam-beam interactions with  $\xi=0.031$  and crossing angle of  $360 \mu\text{rad}$  (12 sigma), the dynamical aperture is above or near the target value of 6. The complimentary simulation of evolution of a multiparticle bunch (Fig. 6) yields the luminosity lifetime in excess of 400 hours for the end-of-fill case, and 80 hours for the worst case configuration.

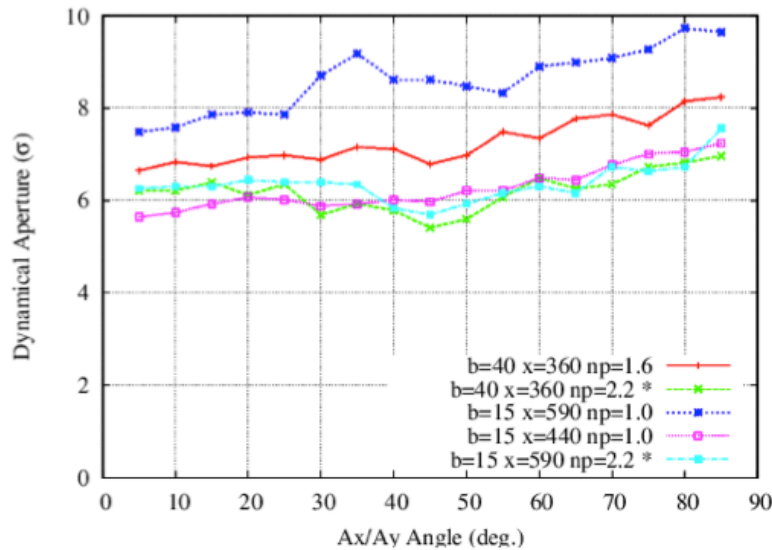


Fig. 5. One-million turns DA for HL-LHC lattice without multipole errors, with beam-beam interactions for selected machine configurations. Lifetrac simulation.

The addition of magnetic multipole errors and of the multipolar correctors in the triplet to the machine lattice does not deteriorate significantly the dynamic aperture. Figs. 7, 8 show the DA as a function of crossing angle for two values of  $\beta^*$  (40 and 15 cm, respectively) with multipole errors. The dynamic aperture remains larger than 6 sigmas for all bunch populations considered for the nominal crossing angle of  $590 \mu\text{rad}$  and at  $\beta^*=40$  cm. At  $N_p=1.6 \times 10^{11}$ , the crossing angle could be reduced to values lower than  $400 \mu\text{rad}$  showing that margin is available either to reduce the crossing angle or to level at higher luminosity.. At  $\beta^*=15$  cm and  $N_p=1.1 \times 10^{11}$ , the minimum acceptable crossing angle is  $\sim 470 \mu\text{rad}$  while for the nominal

crossing angle the maximum bunch population compatible with minimum acceptable dynamic aperture is  $N_p=1.5 \times 10^{11}$ .

These results provide confidence in the robustness of the baseline HL-LHC scheme with respect to beam-beam effects.

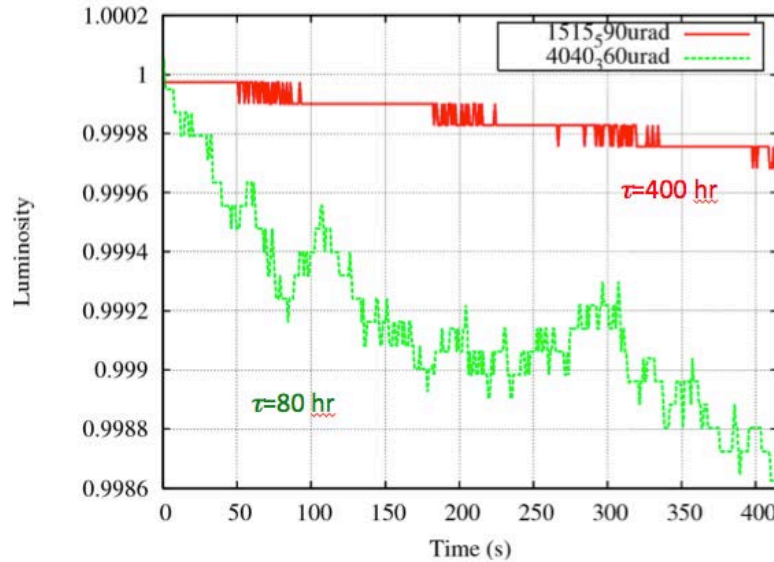


Fig. 6. Luminosity lifetime induced by beam-beam effects for HL-LHC lattice without multipole errors simulated with Lifetrac. Red - end-of-fill configuration, green – worst case configuration.

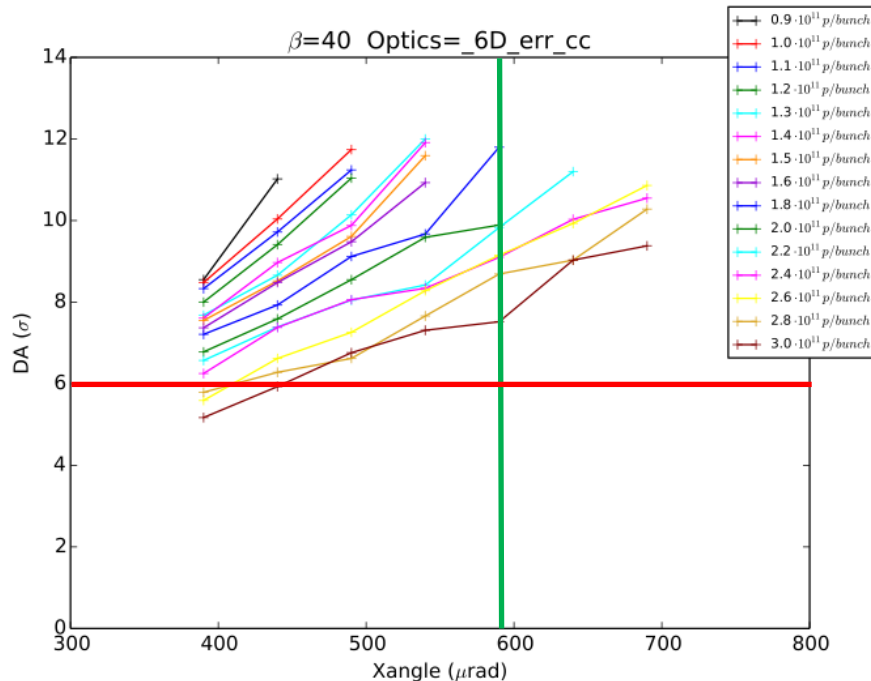


Fig. 7. One-million turns DA for HL-LHC lattice  $\beta^*=40$  cm with multipole errors and multipolar triplet correctors, with beam-beam interactions as a function of full crossing angle at IR1,5 for different values of beam intensity. SixTrack simulations. The nominal crossing angle and the minimum acceptable dynamic aperture are indicated by the green and red lines.

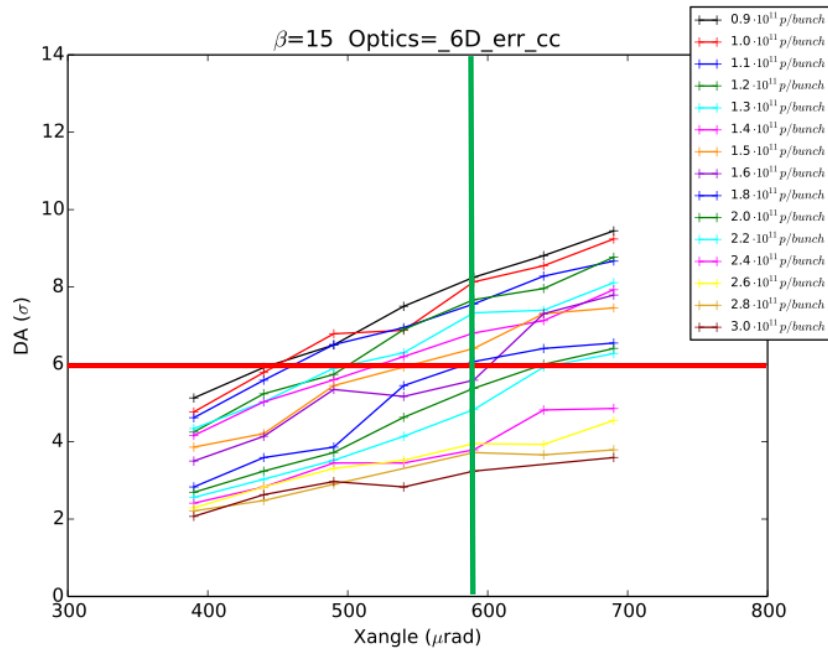


Fig. 8. One-million turns DA for HL-LHC lattice  $\beta^*=15$  cm with multipole errors and multipolar triplet correctors, with beam-beam interactions as a function of full crossing angle at IR1,5 for different values of beam intensity. SixTrack simulations. The nominal crossing angle and the minimum acceptable dynamic aperture are indicated by the green and red lines

Pacman effects have also been evaluated and have shown not to have relevant impact on DA as shown in Fig 9. The long range variations at IP1 and IP5 are resulting in a very small asymmetry in the footprint and no impact on long term tracking has been noticed. Simulations have been evaluated with  $1.1 \times 10^{11}$  protons per bunch for the end of store scenario at 15 cm  $\beta^*$ .

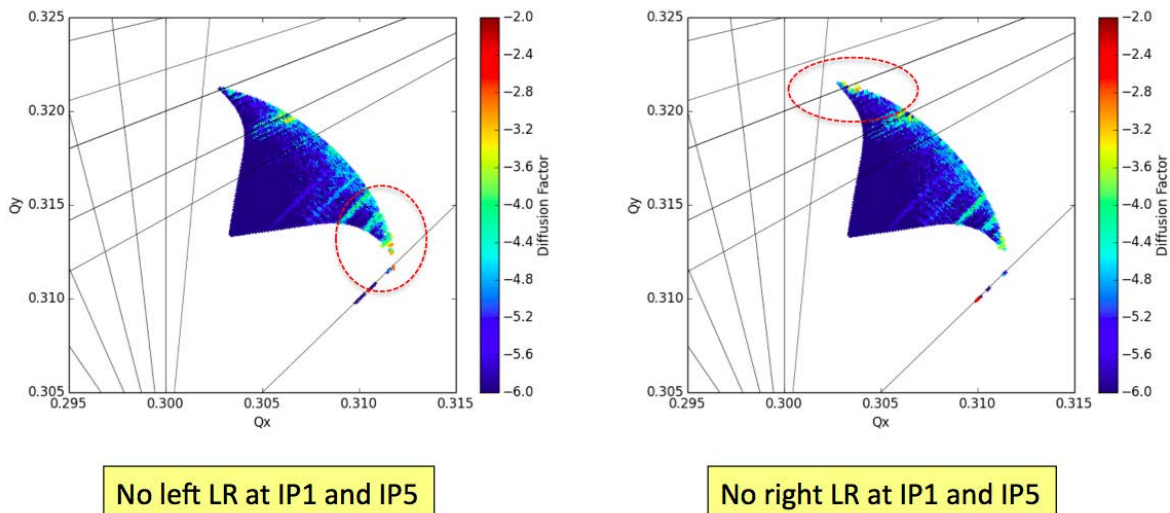


Fig. 9. Frequency Map Analysis results from SixTrack code for two extreme PACMAN bunches missing half the long range interactions on the left and right side of IP1 and IP5. Simulations are at the end of the store at intensities  $1 \times 10^{11}$  ppb and beam-beam separations of  $12.5 \sigma$ .

The end of store configuration will be very similar to the LHC nominal case. With intensities of  $1 \times 10^{11}$  protons per bunch and long range beam-beam separations of  $12.5 \sigma$  one should expect a maximum offset at IP1 and IP5 of about  $0.1 \sigma$ . The spread over the bunch train is of the same order  $0.1-0.2 \sigma$ . Long range orbit effects will not have major impact on luminosity. The detailed simulation of the pacman effects during the levelling phase is ongoing and it will include orbit, tune and chromaticity shifts.

## 5. FUTURE PLANS / CONCLUSION / RELATION TO HL-LHC WORK

The evaluation of beam-beam effects in HL-LHC baseline scenario demonstrated the viability of chosen concept. The simulations with weak-strong codes predict stable operation with sufficient safety margin. However, it remains to be seen how the imperfections of implementation affect the robustness of the system. Preliminary results of simulations with multipole errors (lattice SLHC v3.1b) are encouraging, further simulations need to be extended to the case of the latest lattice configuration and the sensitivity to the individual multipolar errors studied to provide additional feedback for the field quality of the new insertion magnets and for the strength of the triplet correctors.

Further machine development studies with 25 ns beams to benchmark the simulations will be performed during Run II to confirm the criteria used for the definition of the minimum dynamic aperture considered.

Another essential subject not covered by this report is the collective stability of particle bunches and the impact of various noise sources, such as the crab cavity and damper noise on beam-beam effects. The work on this aspect is in progress. Lastly, the evaluation of bunch-to-bunch variations of beam-beam effects is under investigation. With much progress on the most important elements of the study, the Task is on track for meeting the Deliverable 2.5 in 6 months.

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## ANNEX: GLOSSARY

Acronym	Definition
ATLAS, CMS, LHCb	LHC physics detectors
BBLR	Long-Range Beam-Beam Compensator
CC	Crab Cavity
DA	Dynamical Aperture
FMA	Frequency Map Analysis
HL-LHC	High Luminosity Large Hadron Collider
IP	Interaction Point
IR	Interaction Region
RF	Radio Frequency