# BEAM-BEAM STUDIES FOR FCC-hh

J. Barranco García*, T. Pieloni*, EPF, Lausanne, Switzerland
X. Buffat, S. V. Furuseth, CERN, Geneva, Switzerland

*Abstract*

The Future Circular Collider hadron-hadron (FCC-hh) design study is currently exploring different IR design possibilities including round and flat optics or different crossing schemes. The present study intends to evaluate each scenario from the beam-beam effects point of view. In particular the single particle long term stability to maximize beam lifetimes and luminosity reach is used to quantify the differences. The impact of strong head on interactions on the beam quality and lifetime is addressed by means of GPU accelerated simulations code featuring a weak-strong 6-dimensional beam-beam interaction.

## INTRODUCTION

The FCC-hh study aims at colliding protons at 100 TeV center of mass energy [1, 2]. The beam-beam effects studies are a fundamental part of the design of the interaction regions [3]. The FCC-hh will be equiped with two high-luminosity experiments at the Interaction Points (IPs) called A and G [3] plus two recently added low luminosity ones at IPs called B and L which are not discussed in these studies. Assuming head on collisions at IP A and G using crab cavities the beam-beam parameter is $\xi_{\mathrm{bb,2\ IPs}}$=0.03. In this paper we present preliminary studies of the long term stability of the colliding beams by means of dynamic aperture studies using the SixTrack code together with the first results on head-on driven loss mechanism compared to LHC data.

## CROSSING SCHEME DESIGN

As for the case of the LHC [4] the long range (LR) interactions will produce a tune shift with opposite sign between the horizontal and vertical planes depending on the plane of separation of the LR interactions. For this reason the LHC high luminosity experiments feature an alternating crossing, vertical for the ATLAS experiment and horizontal for the CMS to compensate for the associated tune shift due to LR interactions of the bunches experiencing different number of LR interactions (PACMAN bunches) [5]. However the other cases horizontal-horizontal (HH) and vertical-vertical (VV) or even alternating the operation between both planes might be of interest for example for minimizing radiation damage [6]. Figure 1 shows the minimum dynamic aperture (DA) as a function of crossing angle in both IP A and G for the three crossing plane schemes. In order to ensure the design figure of merit of 6$\sigma$ DA simulations show a crossing angle of ~170 µrad for HV and HH cases. This corresponds to a normalized separation of the first LR encounter of $d_{\mathrm{sep}}$=14.5$\sigma$. These results were obtained using the latest stable version of the lattice [7] that shows nevertheless very good agreement with previous results with previous versions [8]. The HV case is the current baseline and the HH results look promising, but not the VV for the nominal working point. The difference between the HH and VV can be explained from the FCC-hh nominal working point $Q_{x,y}$=(0.31,0.32) and the detuning suffered in each case. For the HH the beam will be focused in the horizontal plane while the VV is in the vertical plane as shown in [8], since the vertical tune is initially closer to the vertical third order resonance $Q_y$=0.33 explains why the DA drops to zero in the VV case. A rematch of the working point in the VV case should be envisaged to recover the DA levels of the other scenarios.

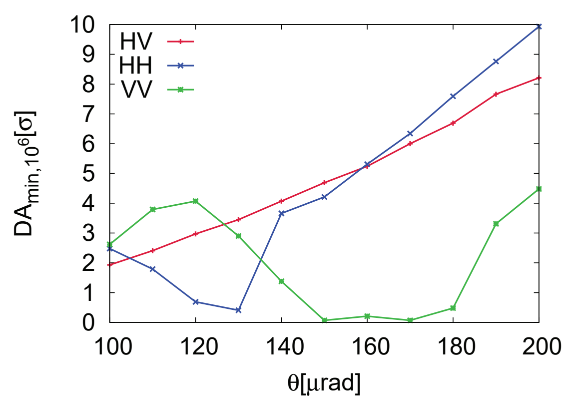


Figure 1: Dynamic aperture as a function of the crossing angle in IPs A and G for three different crossing schemes: HV, HH and VV. Nominal bunches with maximum number of long ranges are used in these simulations.

### *PACMAN Bunches*

As mentioned earlier PACMAN bunches will encounter different number of beam-beam interactions and thus will not profit from the full passive compensation so being shifted into a different area of the tune diagram sampling different resonances. For this reason the DA for this type of bunches should be evaluated separately. In Fig. 2 the minimum dynamic aperture is shown for nominal bunches and PACMAN ones for the HV case. Two different type of PACMAN are studied: with only LR on the left of IP A and G and with only LR encounters on the right. In both cases significant larger DA is expected for the PACMAN bunches for the nominal crossing angle of 170 µrad.

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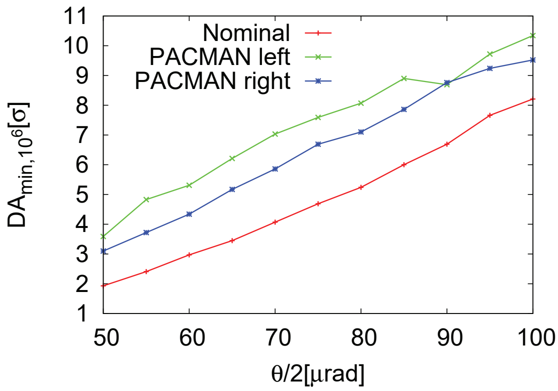



Figure 2: PACMAN bunches dynamic aperture as a function of the crossing angle for the nominal HV case. The case PACMAN left means only LR encounters on the left of IP A and G are included and similar to the right case.

### *Intensity Fluctuations and Chromaticity Effect*

Figure 1 shows an idealistic scenario where only beam-beam effects are present. In order to define a more realistic crossing scheme other known effects like chromaticity, multipolar errors and octupoles should be taken into account. In Fig. 3 the effect of high chromaticity on the DA is shown as well as the impact of possible intensity fluctuactions. A 20% intensity decrease that corresponds to the maximum beam-beam parameter of $\xi_{\mathrm{bb,2\ IPs}}$=0.03 during the fill as shown in [9] relaxes the crossing angle to ~160 μrad. A large chromaticity value of 15 units typically used to stabilize the beams [10] implies the need for an additional 10 μrad. This effect is already significant, so further studies should include all the issues mentioned above to set up correctly the margins needed in the crossing angle for operation.

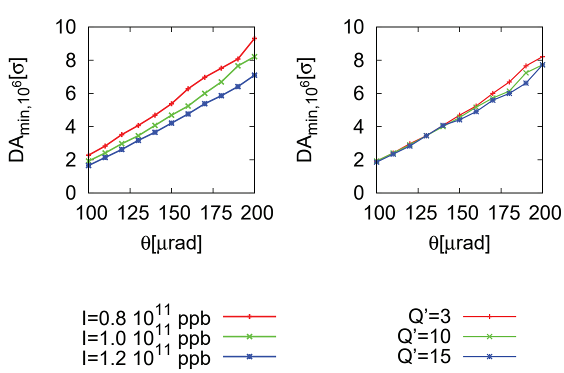



Figure 3: Left, dynamic aperture as a function of the crossing angle scan in IPs A and G for the HV case for 20% intensity variations. Right, dynamic aperture as a function of the crossing angle scan in IPs A and G for the HV case and different chromaticities.

## FLAT VERSUS ROUND OPTICS

As a possible operational scenario for the FCC-hh a flat optics case is also under investigation. Flat optics implies different $\beta$-functions at the IPs in the horizontal and vertical planes as for example in [11]. However, experience from beam-beam studies has shown that to ensure the same DA the normalized separation for flat optics needs to be substantially larger with respect to round. For the case of HL-LHC it was found to be 50% [12]. In Fig. 4, round optics DA (red) is shown versus beam-beam separation compared to a flat optics case with $\beta^*$ ratio of 4 (green). It is known as well that due to the different beam sizes in both planes the passive compensation is broken so for a flat optics the LR tune shift not compensated for the nominal bunches. Of course it is possible to compensate for this tune shift. This is shown in Fig. 4 (blue) Despite the tune shift is compensated still a ~ 30% larger separation is needed to guarantee similar performance as the round case.

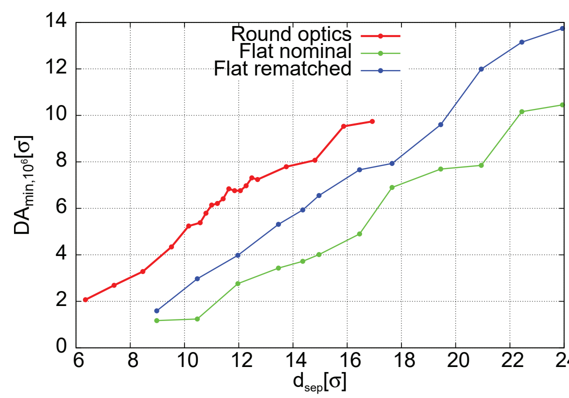
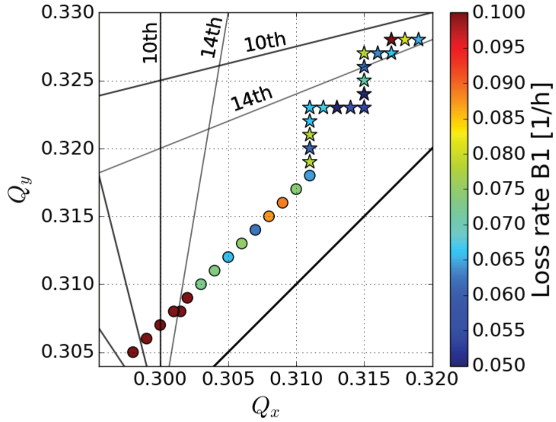



Figure 4: Minimum dynamic aperture for different beam-beam normalized separations for flat (green) and round (red) optics. In order to compensate the tune shift in the flat case a rematched flat optics case is added for comparison (blue).

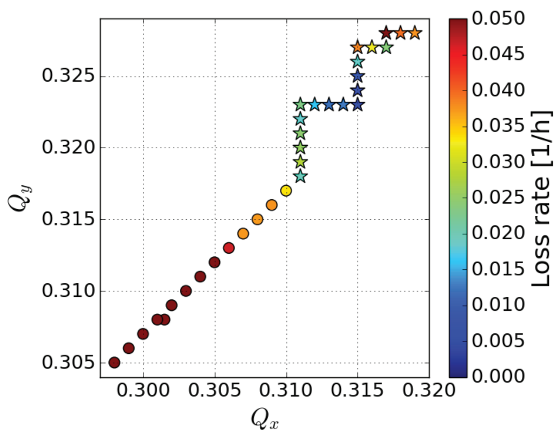
## LIMITATION DUE TO HEAD-ON BEAM-BEAM INTERACTIONS

The effect of head-on interactions on the beam quality, in particular on the emittance is not well described by DA simulations. Yet quantifying the mechanisms degrading the beam quality in realistic conditions is crucial in order to both evaluate and optimize the performance reach of the FCC-hh. In order to understand and quantify the beam lifetime degradation and emittance growth efficiently in various pushed scenarios, a GPU accelerated simulation code implementing a weak-strong model of the beam-beam interactions with a crossing angle as in [13] was developed [14]. The transfer between the IPs are modelled as a linear transfer matrices, taking into account the effect of chromaticity.

In order to verify the predictions of the beam dynamics models in conditions comparable to the HL-LHC and FCC-hh, an experiments dedicated to the understanding of




(a) Measurement




(b) Simulation

Figure 5: Measurement of the beam lifetime in collision at the LHC with a large beam-beam parameter compared to GPU accelerated simulations including the effect of 6D beam-beam interactions, chromaticity and additional source of incoherent noise.

the limitations due to large beam-beam parameter was performed in the LHC [15]. The standard setup of the 2016 run was used, in particular $\beta^* = 0.4$ m and the full crossing angle between the beams at the IP was 280 µrad. The measured lifetime of a bunch with an intensity just below $2 \cdot 10^{11}$ p within a transverse emittance around 1.5 µm colliding in IPs 1 and 5 are shown in Fig. 5a, while varying the transverse tunes. The estimated total beam-beam tune shift, taking into account the measured intensity and emittances, as well as the crossing angles in the two IPs varied from -0.016 to -0.015 during the first scan represented by the coloured dots starting up and moving down the diagonal. During the second scan represented by coloured stars, starting down and moving up the diagonal, the beam-beam tune shift varied between -0.021 to -0.018. The chromaticity was high during both scans, about 10 and 15 units respectively. The best lifetime was obtained with tunes slightly different than the nominal ones, $Q_x = 0.315$, $Q_y = 0.323$, it is consistent with the estimation of the luminosity burn off of ~5%. The difference w.r.t. the best lifetime can be attributed to the effect of the working point in the presence of strong head-on beam-beam effects, which are compatible with the results obtained with simulations (Fig. 5b). A source of noise in the transverse plane of amplitude of $10^{-4}$ was introduced on top of the numerical model described above. This artificial noise emulates the effect of intrabeam scattering and other sources noise such as the transverse feedback. The amplitude was chose to be compatible with the measured average emittance growth.

Since the diffusion mechanisms driven by head-on beam-beam interactions vanish at large oscillation amplitudes, the particles rarely reach the oscillation amplitude in the simulation corresponding to the actual position of the collimators in the machine. Nevertheless, in the machine other effects such as the lattice non-linearities are driving the diffusion at large amplitudes. Eventually such effects should be included in the numerical model in order to obtain a reliable estimation of the beam lifetime, here we rather consider a simplification by assuming that particles reaching 5 beam $\sigma$ are lost to compute the beam lifetime.

Both the experiment and the simulations show an important effect on the beam lifetime when the single particles' tune, that are shifted to lower frequencies w.r.t. to the machine tune due to the beam-beam interactions, are in the vicinity of the $10^{th}$ and $14^{th}$ order resonances. Interestingly, the lifetime reduction when approaching the resonances below the vertical $3^{rd}$ order resonance is not visible in simulations without a crossing angle. The presence of a crossing angle therefore plays an important role in the beam quality degradation mechanism with large beam-beam parameter.

Despite the limitation of the numerical model, the prediction of the beam lifetime seem in reasonable agreement with experimental data. Thanks to its parallel implementation, the model may be used to performed extended parametric study of the FCC-hh scenarios.

## CONCLUSIONS

Preliminary studies for the FCC-hh collider ultimate scenario have been presented for a beam-beam parameter of $\xi_{\mathrm{bb,2\ IPs}}$=0.03 and a total of 232 LRs interactions. Different crossing angle schemes are explored (HV,HH,VV) which show the potential of the HV and HH almost equivalent in DA terms without a rematch of the working point. PACMAN bunches show for both cases better performance pointing to the nominal bunches dominating the DA studies. The impact of high chromaticity with evaluation of the intensity dependency shows that larger crossing angles will be required to allow for margins including 2 extra low luminosity experiments and for the impact of other stronger non-linearities (i.e. octupole magnets, multipolar errors in the magnets).

A new GPU accelerated simulated code include fully 6D beam-beam with crossing angle is available to quantify efficiently the beam degradation mechanisms in various scenarios. The first comparsion to LHC data gives promising results.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