STUDY WITH ONE GLOBAL CRAB CAVITY AT IR4 FOR LHC*

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Abstract

Modern colliders bring into collision a large number of bunches per pulse or per turn to achieve a high luminosity. The long-range beam-beam effects arising from parasitic encounters at such colliders are mitigated by introducing a crossing angle. Under these conditions, crab cavities (CC) can be used to restore effective head-on collisions and thereby to increase the geometric luminosity. In this paper, we discuss the beam dynamics issues of a single global crab cavity (GCC) for both nominal LHC optics and one upgrade LHC optics.

INTRODUCTION AND OPTICS

The Large Hadron Collider (LHC), which now has started beam commissioning at CERN, has the design luminosity as $10^{34} cm^{-2} s^{-1}$ at the two high-luminosity proton-proton experiments ATLAS (located at IP1) and CMS (located at IP5) [1]. Studies aimed to further raising the LHC luminosity are being carried out since 2001, from 2004 onwards jointly by the European CARE-HHH network and by US-LARP. Among them, for the early-separation (ES) scheme and the full crab crossing (FCC) scheme, crab cavities are an essential ingredient of the upgrade.

It was predicted that crab-cavities could restore an effective head-on collision at the IP for both linear colliders [2] and circular colliders [3]. The crab cavity gives rise to a z-dependent horizontal or vertical kick on the beam particles (depending in the crossing plane), as well as to a change in the longitudinal momentum (or energy). In circular colliders, crab cavities may be configured according to either one of two schemes, namely as local or global crab cavities. Both local and global crab schemes have been studied for an LHC upgrade [4]. Due to the constraints on space in the LHC tunnel for the two beam separation, and other factors, it is much more realistic that only one global crab cavity (800-MHz) will be installed in IR4 for the first phase, to test the crab cavity in hadron colliders for the first time.

The required voltage for the global crab cavity is expressed in Formulae 1 [4].

$$V = \frac{c \cdot E \cdot \tan(\frac{\theta}{2})}{\omega \cdot \sqrt{\beta^* \cdot \beta_{crab}}} \cdot \left|\frac{2\sin(\pi Q)}{\cos(\Delta\varphi - \pi Q)}\right| \qquad (1)$$

where V denotes the voltage of the global crab cavity, c the velocity of light, E the particle energy, θ the full crossing angle, ω the angular frequency of the crab cavity, β^* the beta function at the Interaction Point, β_{crab} the beta function at the crab cavity location, Q the betatron tune of the storage ring, and $\Delta\varphi$ the phase advance between the crab cavity location and the IP.

* Work supported by the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).

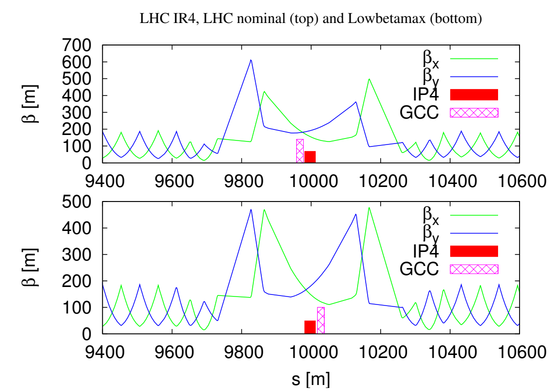

Figure 1: β function in IR4: nominal LHC (top) and Lowbetamax (bottom)

The crab optics parameters are shown in Figure 1, where the crab cavity location is around 30 m upstream (nominal LHC) and downstream (Lowbetamax) IP4 respectively. The crab cavity voltage is 9.3 MV and 25 MV for the nominal LHC and one upgrade optics (Lowbetamax [5]) respectively, which can be further decreased by adjusting the LHC optics in IR4.

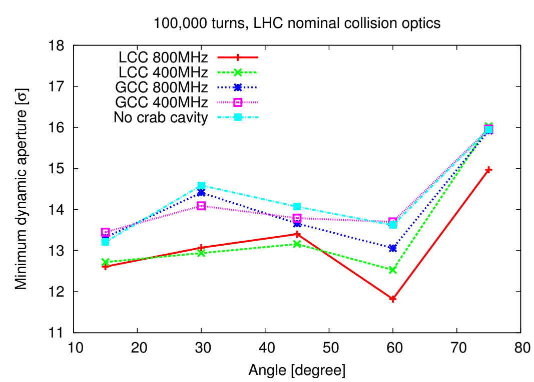

Figure 2: Dynamic aperture for nominal LHC optics

DYNAMIC APERTURE

For LHC at 7 TeV top energy, to have a sufficiently linear montion of particles at the amplitude of 6 σ, which is the half jaw opening of the primary collimators (TCPs), the simulated dynamic aperture is required to be at least a factor of two larger. The dynamic aperture is gotten by tracking particles with different initial coordinates in SixTrack over 100,000 turns. For the imperfections of the optics, the measured non-linear magnetic errors are included (both normal and skew multipole coefficients) up to a_{15} and b_{15} orders, as well as the tune and chromaticity correction, and the corrections of the main dipole field errors by the b_3, b_4, and b_5 spool-piece families. The beam energy is 7 TeV and the initial momentum offset is set to be 0.00027. From the minimum dynamic aperture (nominal LHC) averaged by using 60 seeds of the non-linear magnetic errors, which is shown in Figure 2, we observe a maximum 2 σ degradation of dynamic aperture compared to the nominal case without crab cavity. The conclusion is similar for the lowbetamax optics [4].

BETA BEATING

Crab cavities introduce another kind of beta beating, which depends on the longitudinal position inside the bunch. The effect of the crab cavity is modelled by a horizontal corrector (with z-dependent strength) at the location of the crab cavity. The additional beta beating caused by the crab cavity for a particle with 1 σ longitudinal offset is comparatively small with respect to the existing off-momentum beta beating, as is shown in Figure 3 (nominal LHC). For the lowbetamax optics, the maximum beta beating caused by the crab cavity is within $\pm 0.6\%$ [4].

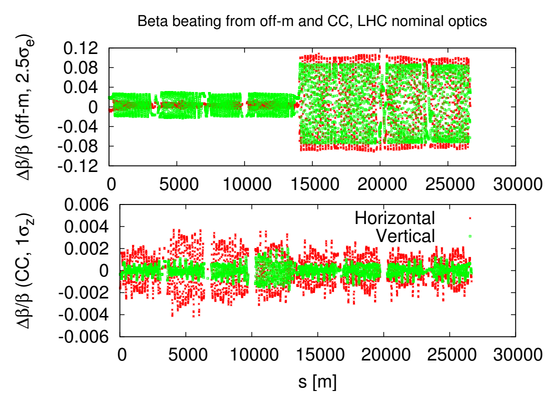

Figure 3: Off-momentum beta beating for the nominal LHC optics with a relative momentum offset of 0.00027 (top); z-dependent 'beta beating' due to the global crab cavity (bottom)

LUMINOSITY

We apply the GUINEA-PIG code [6] to a storage ring, in order to simulate the single-bunch geometric luminosity at the LHC. For the nominal LHC optics without crab cavity, the simulated luminosity is in good agreement with the design value. At the same time, we study the luminosity formulae with crab cavity analytically, to compare with the simulation results of GUINEA-PIG. We start from the original formulae shown in [7], and finally get the luminosity reduction factor L/L_0 in comparison with the head-on collision case as expressed in formula 2 [4].

$$R = \frac{cos(\theta_c/2)\cdot c}{\pi\cdot\sigma_z^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} exp(-\frac{c^2t^2}{\sigma_z^2} - \frac{s^2cos^2(\theta_c/2)}{\sigma_z^2} - \frac{sin^2(\theta_c/2)(-2k_{cr}s + sin(k_{cr}(s-c\cdot t)))^2}{4k_{cr}^2\sigma_x^2})dtds \qquad (2)$$

In Figure 4, the normalised luminosity from the analytical formulae 2 are plotted together with the simulation results from GUINEA-PIG, where good agreement is found between these two. The smaller inside figure shows a close-up view of the result with $\beta^* = 0.55m$.

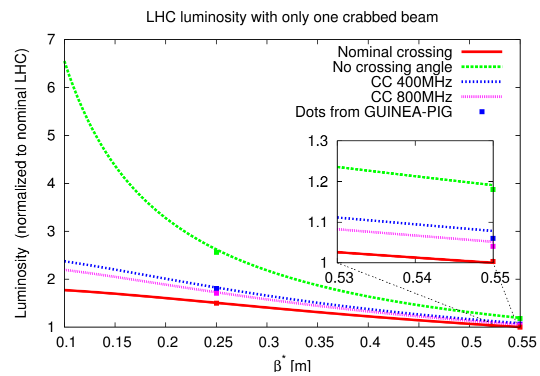

Figure 4: Comparison of normalised luminosity between analytical formulae (curves) and GUINEA-PIG simulations (dots), with only one horizontally crabbed beam (by a crabbing angle of $\frac{\theta_c}{2}$) at IP5

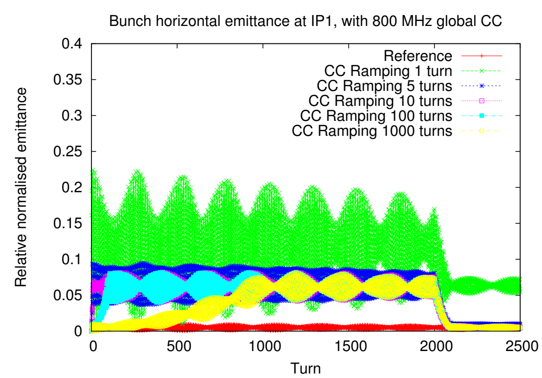

Figure 5: Emittance growth from CC ramping

EMITTANCE GROWTH

The transverse kick from the global crab cavity could excite extra betatron oscillations of the beam, and if the ramping up process of the crab cavity is not adiabatic, the beam transverse emittance can be increased even after the crab cavity is ramped down. Here the MADX thintrack module is modified to calculate the bunch emittance via a statistical treatment [4]. The crab cavity voltage is ramped up from turn 0, for 1, 5, 10, 100, and 1000 turns respectively. Then between 2000 and 2100 turns, the crab cavity voltage is ramped down. The horizontal emittance growth is shown in Figure 5, where it can be seen that for a ramping up speed longer than 10 turns, the emittance can be recovered after the crab cavity voltage is ramped down (which confirms with previous study [8]). When the crab cavity is on, the projected emittance growth is between 6% and 13%. No obvious emittance growth is found by tracking with the nonlinear sources alone (beam-beam kick, the nonlinear magnetic fields error, and all the Landau octupoles), and no obvious difference is found for the crab cavity ramping cases with and without these sources.

COLLIMATION

The LHC collimation system is designed to protect the accelerator and to absorb the beam halo outside of a specified transverse beam size. To compute the cleaning efficiency with crab cavity for the steady-state beam distribution, in the simulation the collimators should be switched on after the crab cavity has been ramped up. 44 phase-one collimators are used without magnet errors. The beam halo is generated at 5.958 σ with 0.0015 σ as smear, and contains 5,760,000 particles. The global cleaning inefficiency which is defined as the leakage rate for a specified aperture A_c [9] is shown in Figure 6, and only small difference is found between the case with and without crab cavity.

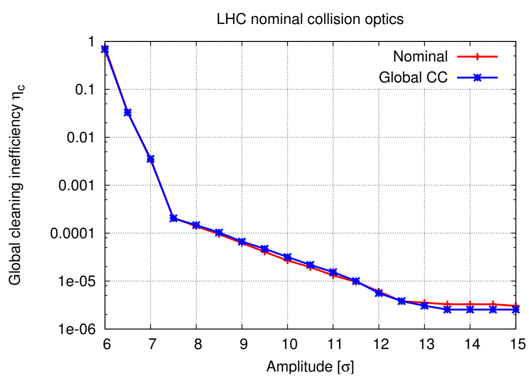

Figure 6: Global cleaning inefficiency with CC

The local cleaning inefficiency which is defined as the local concentration of the particle losses along the ring [9] (with a resolution up to 10 cm), is shown in Figure 7. Overall, most of the halo particles are absorbed by the collimators and the loss on the cold magnets is mainly in the dispersion suppressor downstream of IP7. Furthermore, if we look at the local loss map of the case with global crab cavity, we find that it is similar to the case without crab cavity, and the cold loss is mostly still under the quench limit. For the cases without and with CC, the average off-momentum impact parameter is 50 μm and 70 μm respectively for the first turn. We also consider the crab cavity's impact on the orbit at each collimator (z-dependent crab dispersion). A general longitudinal amplitude is defined to combine the off-momentum dispersion and crab dispersion together. The most pessimistic case (crab dispersion at $1\sigma_z$) is used to get the CC disturbed phase space cut, as shown in Figure 8. In that case the available phase space is decreased by a half σ at the most.

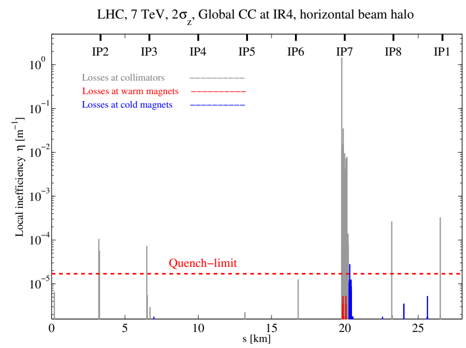

Figure 7: Loss map for Nominal LHC (top energy, $\beta^*_{IP1,5} = 0.55m$), with crab cavity and horizontal halo

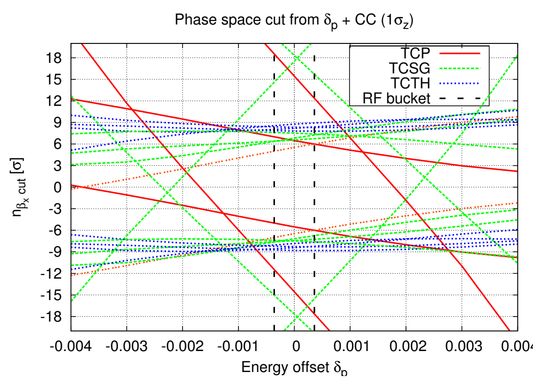

Figure 8: CC disturbed phase space cut, with the hierarchy of primary, secondary and tertiary collimators

We acknowledge C. Bracco (MATLAB code), U. Dorda, M. Giovannozzi, and F. Schmidt.

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