# Setting Up Simulations of Failure Scenarios for a Crab Cavity in the Nominal LHC

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## Abstract

The Crab Cavity (CC) represent a possible solution for the problem of the reduction of the luminosity due to a crossing angle. The CC apply a transversal kick on the beam particles that varies with the longitudinal position along the bunch in order to produce a head-head collision and increase the geometry luminosity. For that reason the people of BE-ABP has been developed studies for the implementacion of the CC in the LHC.

Because the CC is a superconducting RF cavity so is esencial to study the failures scenarios at the damage impact that it could be generate to the lattice. So for that reason we set up the simulations of these failures of the CC in the nominal LHC.

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# I : Introduction.

The CC is a superconducting RF cavity operated in a transverse dipole mode, which provides a transverse kick on the beam particles that varies with the longitudinal position along the bunch. The kick produces a rotation on the bunch in order to achieve a head-on collision and therefore increases the luminosity [1].

So in the case for a horizontal crabed beam, the transverse kick which produce the CC can be described for:

$$\Delta p_x = -\frac{qV\sin(\phi_s + \frac{\omega z}{c})}{E_s} \tag{1}$$

where $q$ the particle charge, $V$ the voltage of the CC, $\phi_s$ the synchronous phase of the CC, $\omega$ the angular frequency of the CC, $z$ the longitudinal coordinate of the particle with respect to the bunch center, $c$ the velocity of ligth and $E_s$ the particle energy [1].

For the LHC-CC failures scenarios we should consider two different schemes:

CASE A :Local Crab Cavity.
CASE B :Global Crab Cavity.

## I.A : Local Crab Cavity (LCC)

Local Crab Cavity (LCC), in this case we put a crab cavity close to the interaction point (IP) in such way that the phase advance difference between the CC and the IP is close to $\frac{\pi}{2}$ and a symetric position with respect to the IP we introduce other CC whichs compensates the tranverse kick of the first one (Figure 1). So the effect of CC is just in a very specific region of the lattice (Figure 2).

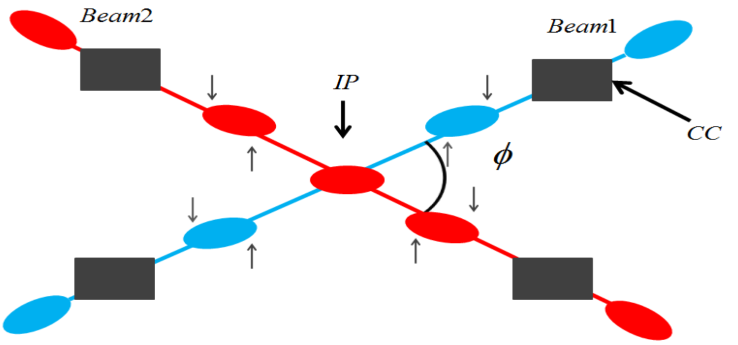

Figure 1: Scheme of the effect of the LCC in the bunch.

And for the previous work, we have that the voltage for the the two LCC. For the left is

$$V_L = \frac{cE_s\tan(\frac{\phi}{2})}{q\omega\sqrt{\beta_{IP}\beta_{CCL}}\sin\Delta\Psi_1} \tag{2}$$

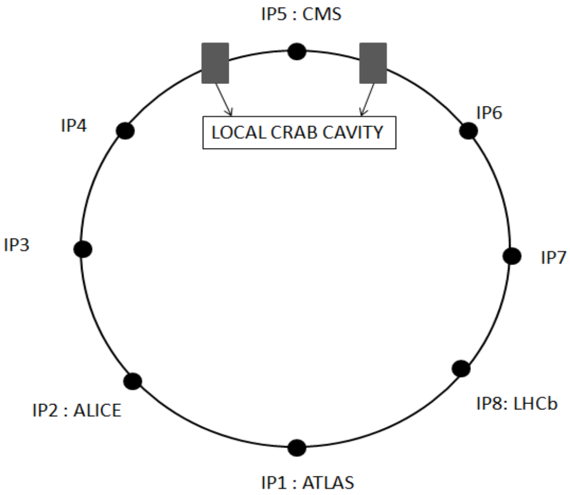

Figure 2: The LCC scheme in the lattice of the LHC for a horizontal crossing angle.

and the rigth CC is

$$V_R = \quad -\left(\sqrt{\frac{\beta_{CCL}}{\beta_{CCR}}}\cos\Delta\Psi_{CC} - \alpha_{CCR}\sin\Delta\Psi_{CC}\right)\frac{cE_s\tan(\frac{\phi}{2})}{q\omega\sqrt{\beta_{IP}\beta_{CCR}}\sin\Delta\Psi_2} \tag{3}$$

where, $c$ is the speed of the light, $E_s$ the particle energy, $\alpha_{CCR}$ is the $\alpha$ function in the right CC, $\phi$ the crossing angle, $\omega$ the CC frequency, $\beta_{IP}$ is the $\beta$ funtion in the interacion point (IP),$\beta_{CCL}$ is the $\beta$ funtion in the left CC, $\beta_{CCR}$ is the $\beta$ funtion in the right CC, $\Delta\Psi_1$ is the difference of the phase advance between the left CC and the IP, $\Delta\Psi_2$ is the difference of the phase advance between the IP and the right CC and $\Delta\Psi_{CC}$ is the difference of the phase advance between the left CC and the right CC.

## I.B : Global Crab Cavity (GCC)

In the case of Global Crab Cavity, we put the CC in such way that $\cos(\Delta\Psi - \pi Q) \approx 1$, we dont introduce another CC which compensates the effect of first CC (Figure.3). So the effect of the transverse kick is in the entire lattice (Figure.4).

And the voltage for a GCC is

$$V = \tfrac{cE_s\tan(\frac{\phi}{2})}{q\omega\sqrt{\beta_{IP}\beta_{CC}}}\tfrac{2\sin(\pi Q)}{\cos(\Delta\Psi-\pi Q)} \tag{4}$$

where, $c$ is the speed of the light, $E_s$ the particle energy, $\phi$ the crossing angle, $\omega$ the CC frequency, $\beta_{IP}$ is the $\beta$ funtion in the interacion point (IP), $\beta_{CC}$ is the $\beta$ funtion in the CC and $\Delta\Psi$ is the difference of the phase advance between the CC and the IP.

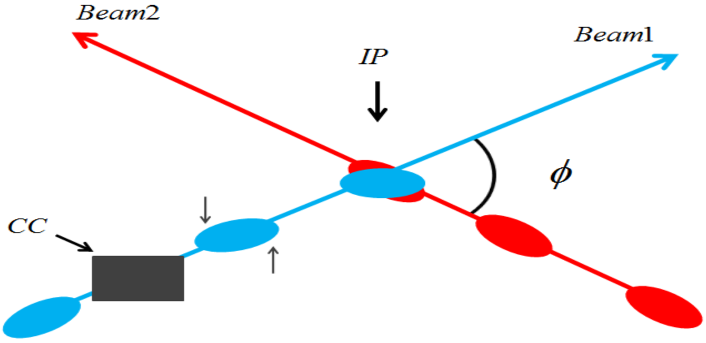

Figure 3: Scheme of the effect of the GCC in the bunch.

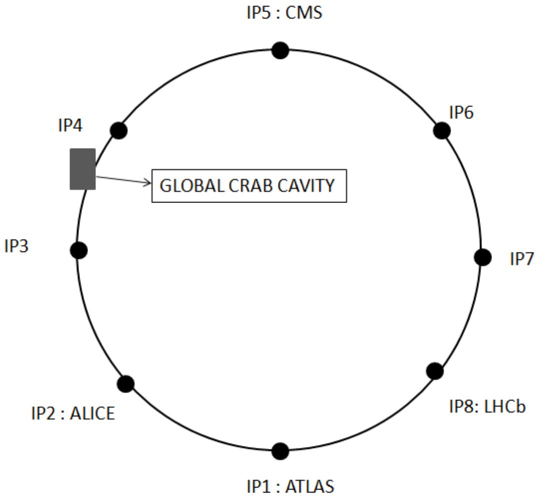

Figure 4: The GCC scheme in the lattice of the LHC for a horizontal crossing angle.

## II : Collimation Studies

In order to understand and learn the tools which is necesary for the study of the CC's effect in the beam, we reproduced the previous results [2]. Due to a CC modifies the particle's z-dependent closed orbit, its important to consider how the CC will affect the particles orbits, so in order to protect the important and expensive devices, exits a special team which study and try to avoid it, the Collimation team.

The Collimations system in the LHC is designed to protect the cold magnets and to absorb the beam halo outside of a specified transverse beam size. The collimators are blocks in which the beam halo outside is deposited to avoid hit the superconducting magnets.

They are differents types of collimators: The primary collimator (TCP) the closets ones to the beam (6 beam sigmas of the jaw opening with respect to the ideal trayectory); The secondary collimator (TCSG); The tertiary collimator (TCTH); the absorbs for showers in cleaning insertions (TCLA) and the collimator to protect the machine during the beam dump (TCDQ). The difference of the jaw opening of the TCP and TCSG is about one beam sigma. Given that the TCSG should never be hit by the primary beam halo.

In the LHC they are two main regions where the collimators are concetrade: IR3 (momentum cleaning) and IR7 (betatron cleaning.

To study the worst scenario, we take the impact parameter (the distance at which the particle hit the collimator with respect of collimator's edge). If the particles impact a longer distance than the impact parameter it will absorb for the collimator (Figure.5a), if dont hit the collimator will reabsorb for the beam (Figure.5b). So the worst case is in which the particle hit the collimator a same or smaller distance than the impact parameter. In this case the impact of the beam with the collimator will produce secondary particles which could be absorbed for th other collimators or could be deposited in the superconducting magnets(Figure.5c).

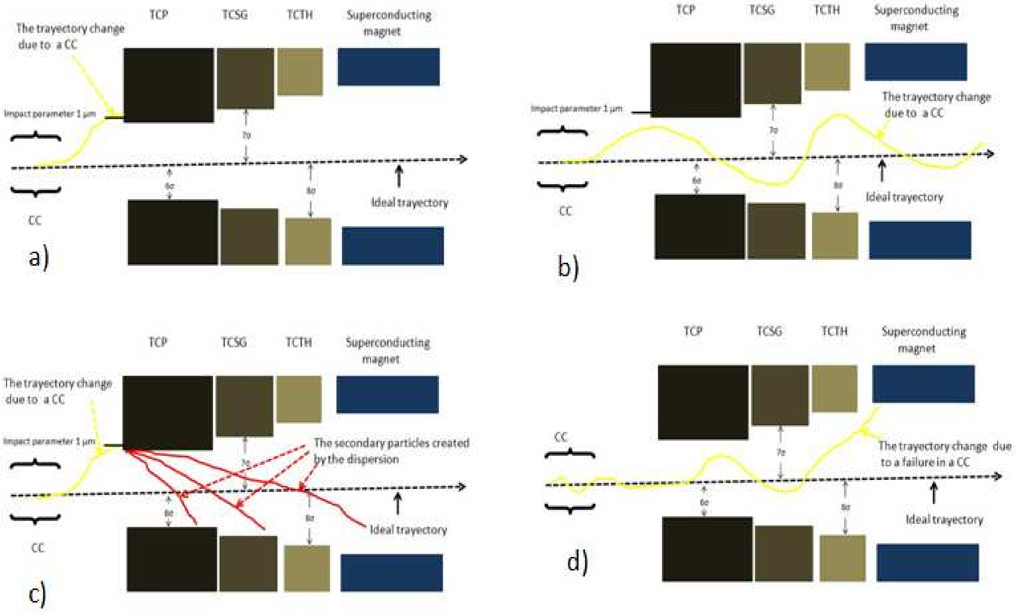

Figure 5: Scheme of the effect of the CC in the beam trayectory. a) The particle is absorb for the collimator. b) The particle is reabsorb for the beam. c) The particle hit the collimator and produce a secondary particles which can be deposited in other collimators or in the superconducting magnets. d) The Particle trayectory when the CC has a failure (Its voltage drop to zero or a change of the phase in a few turns.

Therefore is important to define and study the local cleaning inefficiency of the collimation systems. For study the Local Cleaning Inefficiency, we generate Local Loss Map (which are plots in which show us the local concentration of the particles losses in the LHC).

We make the analysis for the symplest case. One GCC which crabbed the beam 1 in the horizontal plane. First with the help on the program MAD-X (Methodical Accelerator Desig) is a general purpose accelerator and lattice desing program [3]. We install the GCC in the lattice at 30 meters upstream of the IP4 in order to improve the luminosity at IP5 (CMS Detector) and we obtain the optics parameters for obtain the value of the voltage equation 5 [4].

$$V = \frac{cE_s \tan(\frac{\phi}{2})}{q\omega\sqrt{\beta_{CC}\beta_{IP}}} \frac{2\sin(\pi Q)}{\cos(\Delta\Psi - \pi Q)} \quad (5)$$

and the optics parameters are in the Table 1,

Table 1: Optics Parameters for a GCC

| Parameters | [Units] | Value |
|---|---|---|
| $q$ | e | 1 |
| $c$ | $10^8 \frac{m}{s}$ | 3 |
| $E_s$ | $TeV$ | 7 |
| $\phi$ | $\mu radians$ | 285 |
| $\omega$ | $MHz$ | 800 |
| $\beta_{IP}$ | $m$ | 0.55 |
| $\beta_{CC}$ | $m$ | 255.965 |
| $Q$ | | 64.31 |
| $\Delta\Psi$ | $radians$ | 7.673 |

where, $c$ is the speed of the light, $E_s$ the particle energy, $\phi$ the crossing angle, $\omega$ the CC frequency, $\beta_{IP}$ is the $\beta$ funtion in the interacion point (IP), $\beta_{CC}$ is the $\beta$ funtion in the CC and $\Delta\Psi$ is the difference of the phase advance between the CC and the IP.

The results is $V = 9.07$ MV [4].

Now we use the program SixTrack which its results that are essential for verifying the long term stability of the high energy particles in the LHC [5]. SixTrack has several input files, but for this analysis we just use fort.2 (Geometry Input) and fort.3 (Parameters Input).

In fort.2 we define the GCC and give the values of the voltage that we previous got for MAD-X with the next value in the Table 1.

Table 2: Optics Parameters for a GCC

| Parameters | [Units] | Value |
|---|---|---|
| $Voltage$ | MV | 9.07 |
| $\omega$ | $MHz$ | 800 |
| $PhaselagooftheCC$ | $radian$ | 0.55 |

In fort.3, in the block "CRAB", its very important because in there we can change the voltage and the phase of the CC. For this analysis we just change the voltage. We specify the number of turns in which the CC will be turn on (t1 =free turn), then the number of turns to ramping up the voltage of the CC from zero to the CC's voltage the voltage (t2= number of ramping up), after that has a number of voltage with a constant voltage (t3= number of plato) and finally the number of turns that the CC's voltage falls zero (t4= number of ramping down) (Figure 6).

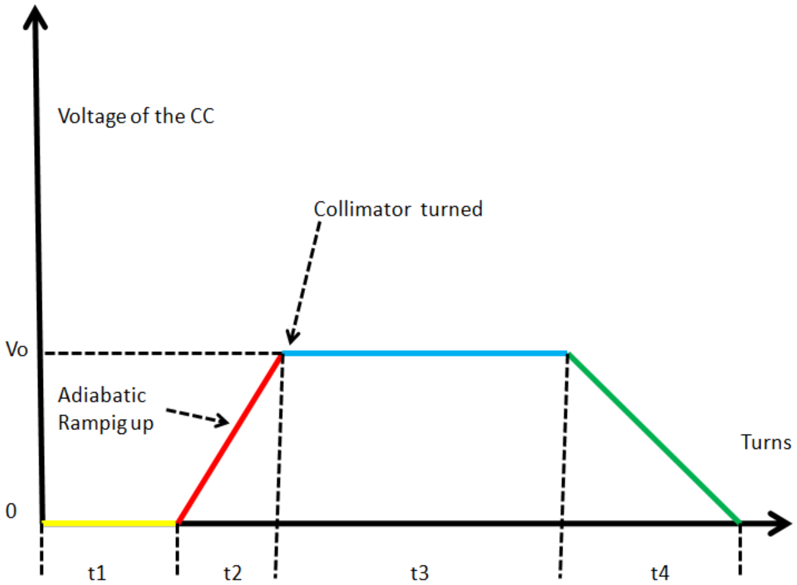

Figure 6: The Squeme of the change of the voltage for a CC. The t1 is the number of free turn, t2 the number of turn for the ramping up, t3 the numbers of turn for the plato and t4 the number of turns for ramping down.

To reproduce the worst scenario, the impact parameter must be $1\mu m$ we use a horizontal halo distribution at $5.958\sigma$ with a $0.0015\sigma$ as smear (Figure 7) similar that the previous work [2, 6].

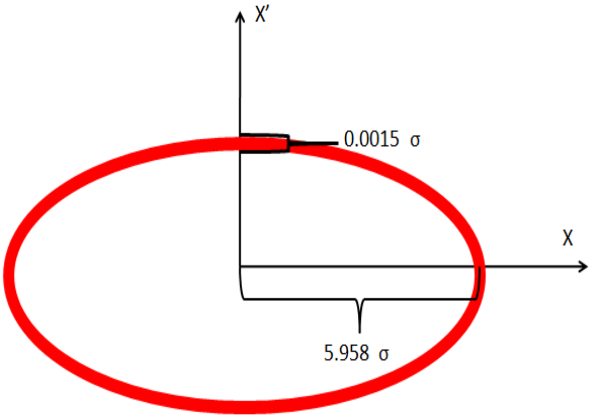

Figure 7: The horizontal halo distribution at $5.958\sigma$ with a $0.0015\sigma$ as smear.

So first we check that the CC apply the correct transverse kick to the bunch for the IP5 by a BPM (Figure 8) for a GCC of 800 MHz and 400 MHz (without a transverse and longitudinal position offset and with a offset energy of $2.5\sigma_p$) a linear kick and without CC.The results are very close with the previous work [2].

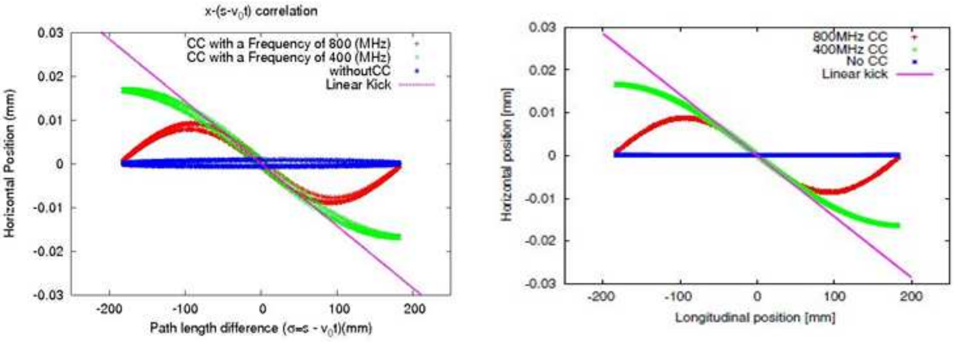

Figure 8: This is the correlation of the relative horizontal and longitudinal position with respect to the synchronous particle, without a transverse and longitudinal position offset and with a offset energy of $2.5\sigma_p$. Using a CC of 800MHz, 400MHz and without CC. The number of the tracking turns is 1000.In the left our results in the rigth a previous result.

We also check the behavior of the bunch at IP5 when we change the voltage of the CC, we put a BPM and plot turn by turn for a GCC of 800 MHz (without a transverse and longitudinal position offset and with a offset energy of $2.5\sigma_p$) and a linear kick(Figure 9). We obtain similar results that the previous work.

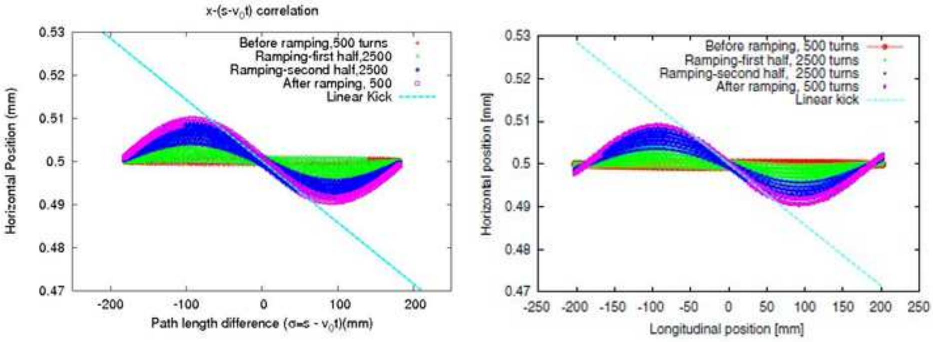

Figure 9: This is the correlation of the relative horizontal and longitudinal position with respect to the synchronous particle, without a transverse and longitudinal position offset and with a offset energy of $2.5\sigma_p$ . Using a CC of 800MHz, when we ramping for a different turns. In the left our results in the right a previous result.

This last plot we use without collimation block on fort.3, because it was not necesary and with the collimation block we just can made around 200 turns [4].

Finally we get the LLM for a GCC of 800 MHz, with a voltage of 9.07 MV, without transverse and longitudinal position offset adn with a offset energy of $\sigma_p = 1 \times 10^{-4}$ which crab the beam 1 in the horizontal plane for the nominal LHC (top energy, $\beta_{IP5} = 0.55$ )(Figure 10).

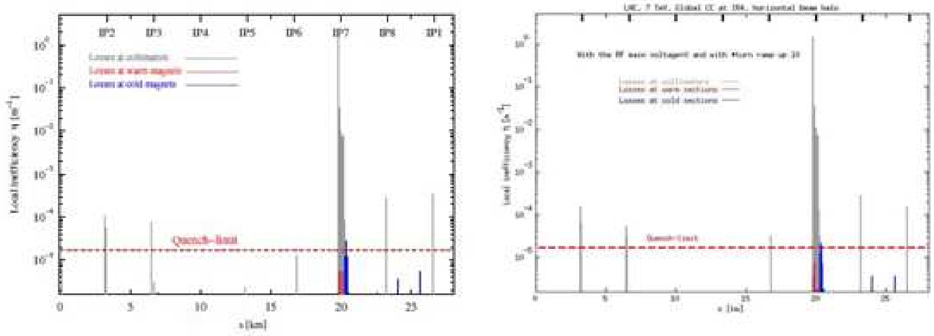

Figure 10: Local loss map for nominal LHC (top energy, $\beta_{IP5} = 0.55$ ) with one GCC and horizontal beam halo.In the left our results in the rigth a previous result.

## III : CC Failures Scenarios.

Now we can know the tools for the study. To start with the CC failures scenarios, we create own distribution using the program Python [4]. Python is a programming language that lets you work more quickly and integrate your systems more effectively [7]. We use a symple random gaussian distribution (Figure 11).

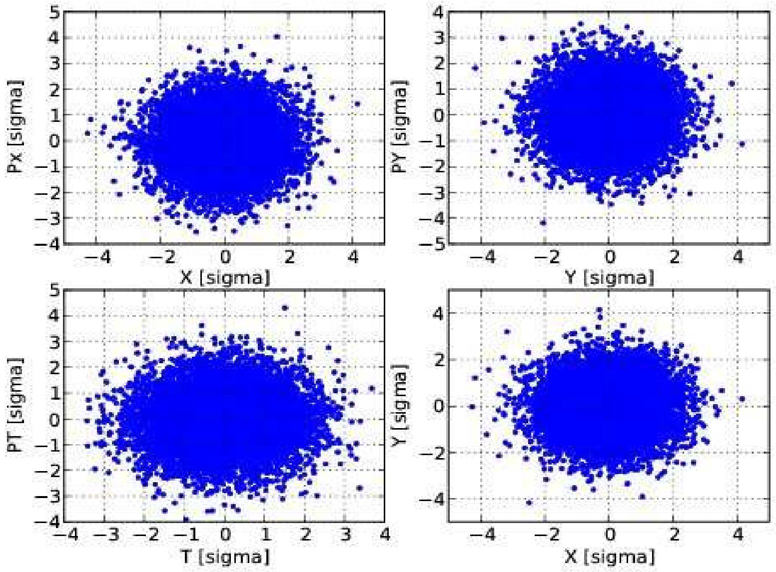

Figure 11: Symple random gaussian distribution created by Python.

Now for this analysis we change the phase and the voltage of the CC using the block "CRAB" in fort.3. Here also we can change the phase of the CC in the same way like the voltage (Figure 12), we can specify the number of turns free (T1), the number of ramping up (T2), the number of plato (T3), the number of the rampin down (T4) and we can also choice the final phase of the CC [4]. an indepedent way.

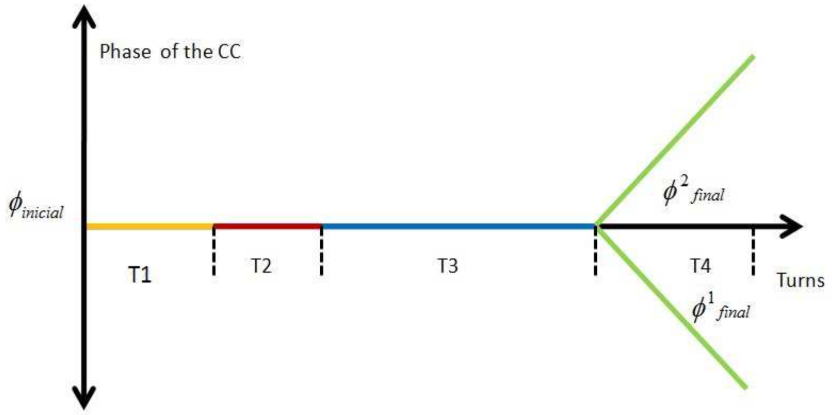

Figure 12: The Squeme of the change of the voltage for a CC. The T1 is the number of free turn, T2 the number of turn for the ramping up, t3 the numbers of turn for the plato, T4 the number of turns for ramping down and two choice for the final phase $\phi_f^2inal$ or$\phi_f^1inal$.

So we put a BPM in order to se the effect of the CC in the IP5 (like the analysis before )when we change the voltage and the phase. We turn 8001 for a GCC of 800 MHz (without a transverse and longitudinal position offset and with a offset energy of $2.5\sigma_p$), we change the voltage with 1 free turn, 2500 turn for the ramping up, 5000 turns for the plato and 1 turns for the ramping down. The change in the phase will be 1 free turn, 2500 for the ramping up, 2500 for the plato and 2501 for the ramping down, with a final phase of $-50^o$ and $50^o$ (Figure 13. We change the phase of the CC when it is in the plato turns in order to establish “steady-state” conditions with crab cavity and collimator before simulating a crab-cavity failure.

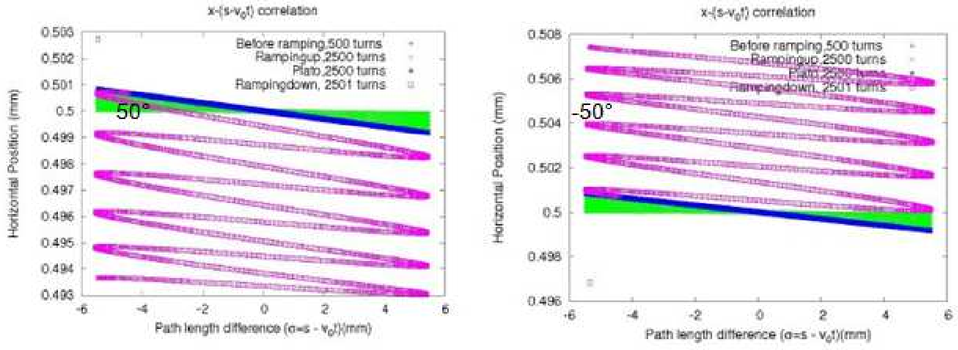

Figure 13: The BPM of IP5 for a GCC of 800 MHz (without a transverse and longitudinal position offset and with a offset energy of $2.5\sigma_p$).The change in the phase will be 1 free turn, 2500 for the ramping up, 2500 for the plato and 2501 for the ramping down, with a final phase of $-50^o$ and $50^o$ .

Finally we obtain the LLM for a GCC of 800 MHz, with a voltage of 9.07 MV, without transverse and longitudinal position offset adn with a offset energy of $\sigma_p = 1 \times 10^{-4}$ which crab the beam 1 in the horizontal plane for the nominal LHC (top energy, $\beta_{IP5} = 0.55$ ) (when we have a tracking of 202 turns, we change the voltage in 1 free turn, 10 turn for the ramping up (to have a adiabatic process and avoid the grow emittance), 191 turns for the plato and 0 turns for the ramping down. The change in the phase will be 1 free turn, 10 for the ramping up, 190 for the plato and 1 for the ramping down, with a final phase of $50^o$ (Figure 14).

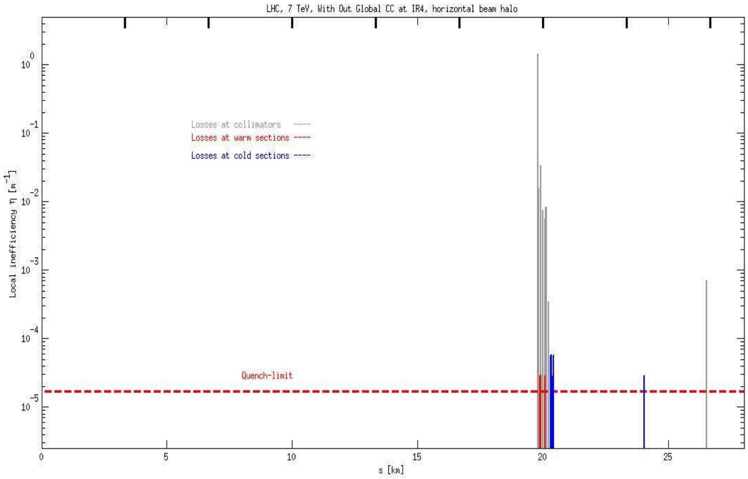

Figure 14: Local loss map for nominal LHC (top energy, $\beta_{IP5} = 0.55$ ) with one GCC and horizontal beam halo, when we change the final phase of the CC to $50^o$ in 1 turn.

# IV : Conclusion and Future work.

We have all the tools that we requered for the analysis,we can use MAD-X for the optics and the SixTrack for generate the LLM, we can reproduce the results of previous work which it help to us to understand the behavior of the CC.

Now we all these tools we Set Up Simulations of Failure Scenarios for a Crab Cavity in the Nominal LHC. So we can start with this analysis.

Here the are some ideas about the future work.

- Scan the change of the phase.

- Scan the change in the number of turns of the phase change.

-The study in an upgrade scenario.

- Implement to the LCC.

- Use the RF signals from KEKB cavities like input on SixTrack.

# References

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