

# FAST CRAB CAVITY FAILURES IN HL-LHC\*

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## Abstract

Crab cavities (CCs) are a key ingredient of the High-Luminosity Large Hadron Collider (HL-LHC) to ensure head on collisions at the main experiments (ATLAS and CMS) and fully profit from the smaller  $\beta^*$  provided by the ATS optics [1]. At KEKB, CCs have exhibited abrupt changes of phase and voltage during a time period of few LHC turns and considering the large energy stored in the HL-LHC beam, CC failures represent a serious risk to the LHC machine protection. In this paper, we discuss the effect of CC voltage or phase changes on a time interval similar to, or longer than, the one needed to dump the beam. The simulations assume a realistic steady-state distribution to assess the beam losses for the HL-LHC. Additionally, some strategies are studied in order to reduce the damage caused by the CC failures.

## INTRODUCTION

The HL-LHC upgrade program aims to use CCs together with the reduction of the beam sizes at ATLAS and CMS interaction points (IP) and an increase of the beam intensity to enhance the integrated luminosity per year by up to a factor of 10 with respect to the nominal LHC [2, 3]. The relevant optics parameters for the HL-LHC scenario are summarized in Table 1. For the simulations of failure scenarios we have conservatively assumed a normalized emittance of  $3.75 \mu\text{m}$  (equal to the LHC design). LHC or HL-LHC will be the first hadron collider to operate with CCs.

Table 1: Relevant Optics Parameters of the HL-LHC

Parameter	Symbol	Value
Energy	E [TeV]	7
Protons/bunch	$N_b$ [ $10^{11}$ ]	2.2
Bunches	n	2808
rms bunch length	$\sigma_z$ [cm]	7.55
Beta function at IP1,5	$\beta^*$ [m]	0.15
Normalized Emittance	$\epsilon$ [ $\mu\text{m}$ ]	2.5
Full crossing angle	$\phi$ [ $\mu\text{rad}$ ]	590
Main/Crab RF	$\omega$ [MHz]	400
Revolution period	$\tau$ [ $\mu\text{s}$ ]	89
Synchrotron period	$\tau_s$ [LHC turns]	562

During KEKB CC operation some fast failures were observed in which the phase changed  $\pm 50^\circ$  within  $50 \mu\text{s}$  or the voltage dropped to zero within  $100 \mu\text{s}$  [4]. Similar failures at the HL-LHC could compromise the machine pro-

tection. Indeed, if an abnormal beam behavior is detected at the LHC, the Beam Interlock System and the LHC Beam Dumping System take up to 3 turns (about  $300 \mu\text{s}$ ) to extract the full beam [5].

## SETUP

A group of three CCs with voltage around 3 MV per beam side around ATLAS and CMS were installed. As in previous studies [6, 7], the last CC which closes the “Crab bump” at CMS experimented the CC failures. These consist in the change of the voltage to zero or the phase by  $90^\circ$  as a linear function with the numbers of turns. The Phase Failures (PF) and Voltage Failure (VF) were produced at intervals of 1, 3 and 5 LHC turns. The CC failures began once the distribution reached the quasi-stationary-state (QSS).

## QSS

To obtain the QSS the particles were tracked with and without CCs for several synchrotron periods until the beam impact rate changes slowly and becomes negligible with respect to the initial period (in average 1 particle per billion per turn). This ratio gives similar beam lifetime than the one observed in the beam filling at the LHC in 2012 [8].

## Beam Distribution

To estimate the impacts for the realistic distribution, we use halos at different transverse amplitudes in the horizontal phase space with a smear of  $0.1 \sigma$  (“thin-halo”) and a 2D Gaussian with matching beam conditions for the vertical and longitudinal phase space.

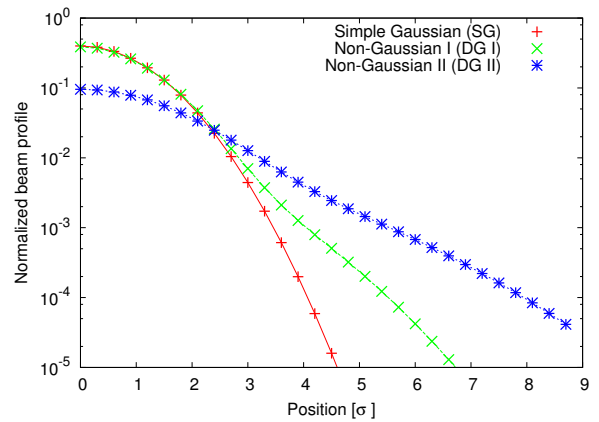


Figure 1: The normalized horizontal beam profiles used for this work. The description of the distributions was explained in detail in the previous work [6].

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Then, we obtained the approximate particle impacts on collimators and aperture for a specific distribution by folding these distributions with the thin-halo results. The quality of this approximation depends on the step size of the transverse amplitude in the thin-halo simulations. The distributions used for folding are shown in Fig. 1 and the corresponding population beyond  $4\sigma$  is presented in Table 2.

Table 2: Beam Fraction for Each of the Distributions with Respect to the HL-LHC full beam

Distribution	% of population beyond $4\sigma$
Simple Gaussian (SG)	0.03
Non-Gaussian I (DG I)	0.53
Non-Gaussian II (DG II)	6.85

## RESULTS

The results obtained by folding the results of thin-halos are presented in the Fig. 2 including the threshold for the superconducting magnets and the elastic limit on the primary collimators.

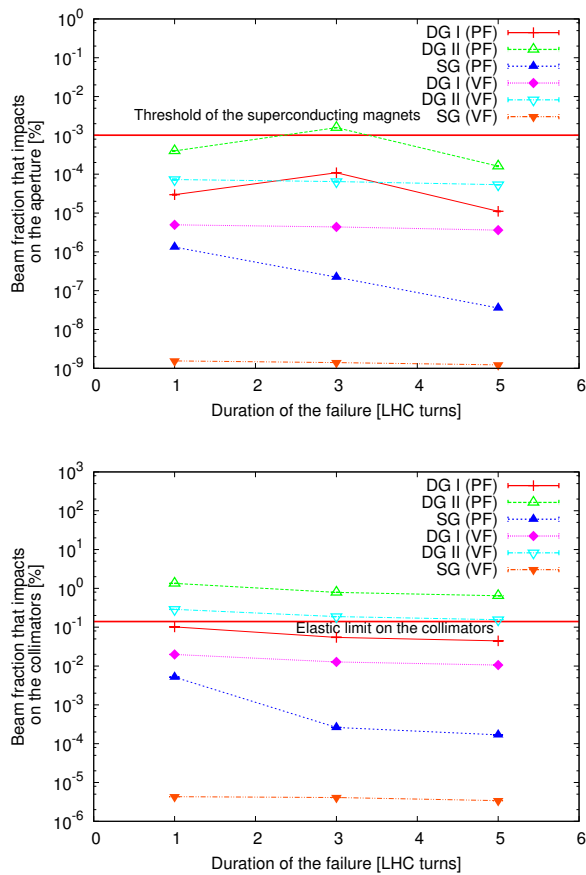


Figure 2: Beam fraction that impacts on the aperture (top) and collimators (bottom) considering the different failure cases in voltage and phase for all distributions. Errors are included.

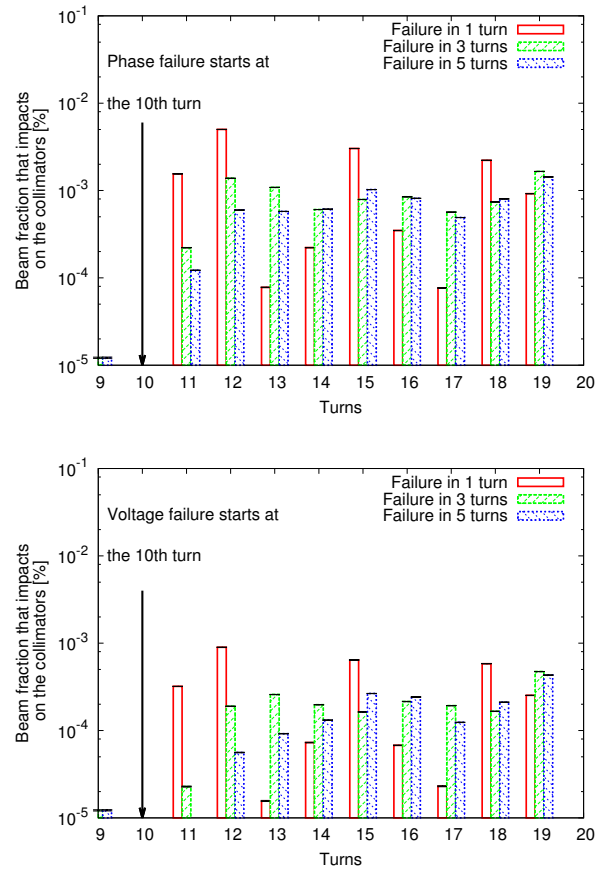


Figure 3: Beam fraction that impacts on the collimators turn by turn, after the failure started, for the **PF** (top) and **VF** (bottom) cases considering the **DG II** distribution. Errors are included.

Figure 3 shows the percentages of the beam impacts turn by turn for the CC failures using the **DG II** distribution. The histogram of the beam impacts on the collimators and the aperture around the lattice for the **PF** case in 1 turn using the **DG II** distribution is presented in Fig. 4.

## Mitigation Strategy

In addition, a mitigation strategy is implemented to quantify the possible reduction of the beam impacts for the **PF** cases. The strategy consists in gradually drop to zero the voltages of both of the CC pairs associated with the failure in the consecutive turns after the failure is detected. The voltage drop is exponential with a natural time constant of  $800\mu s$  (8–10 LHC turns) for a CC with  $Q_L = 10^6$  and frequency of 400 MHz. The results of the mitigation calculated for the **DG II** distribution are shown in Table 3.

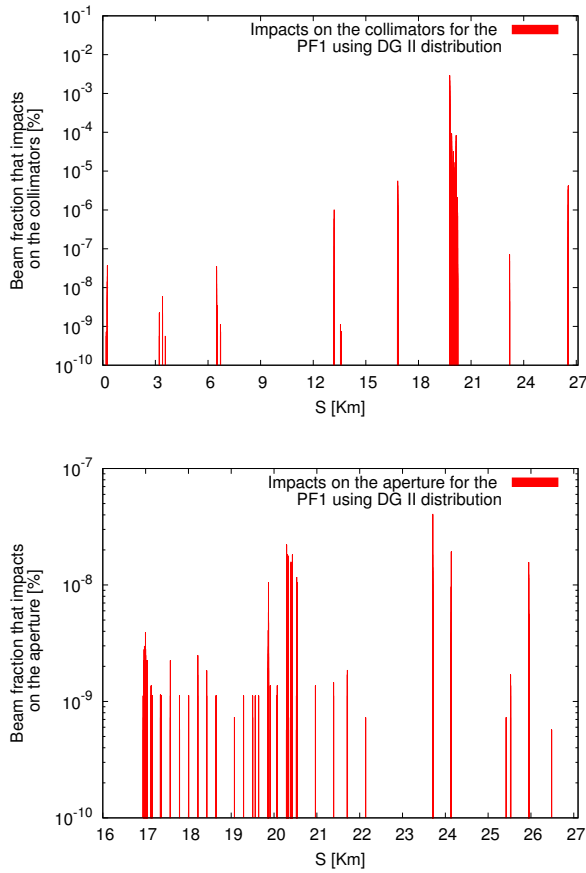


Figure 4: Distribution of the impacts on the collimators (top) and the aperture (bottom) considering a phase failure in 1 turn for the **DG II** distribution.

Table 3: Percentage of Reduction of the Beam Impacts Using the Mitigation Strategy for the **PF** Cases

Distribution	Duration of the phase failure [turns]	% of the beam impacts reduction	
		Collimators	Aperture
<b>DG II</b>	1	~41	~50
	3	~56	~93
	5	~64	~21

## CONCLUSION

These results are consistent with previous studies [6, 7, 9], in particular, these results improve those obtained in Ref. [6]. The percentages of beam impacts produced by the CC failures of the Simple Gaussian distribution are below the elastic limit of the collimators and the threshold of the superconducting magnets. Nevertheless, for the Non-Gaussian distributions the percentages are beyond the limits of the safety operation.

The beam impacts exhibited a periodicity of three turns on the higher peaks. Moreover, these results shown the distribution of the impacts around the lattice. The primary col-

limator TCP.C6L7.B1 is the one which interacts more with the beam.

Additionally, the mitigation strategy for the phase failure reduces in average 53 % of the impacts. In the future, halo monitoring and control during LHC operation become an essential operational tool for guaranteeing the machine safety with crab cavities operation. This work is part of an ongoing R&D effort for the HL-LHC [10].

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