MACHINE PROTECTION STUDIES FOR A CRAB CAVITY IN THE LHC

B. Yee-Rendon*#, R. Lopez-Fernandez, CINVESTAV-IPN, México City, México
T. Baer, J. Barranco, R. Calaga, A. Marsili, R. Tomas, F. Zimmermann,
CERN, Geneva, Switzerland

Abstract

Crab cavities (CCs) apply a transverse kick that rotates the bunches so as to have a head-on collision at the interaction point (IP). Such cavities were successfully used to improve the luminosity of KEKB. They are also a key ingredient of the HL-LHC project to increase the luminosity of the LHC. As CCs can rapidly change the particle trajectories, machine protection studies are required to assess the beam losses due to fast CC failures. In this paper, we discuss the effect of rapid voltage or phase changes in a CC for the HL-LHC layout using measured beam distributions from the present LHC.

INTRODUCTION

The high-luminosity LHC upgrade program (HL-LHC) uses CCs together with improvements of other LHC parameters (see Table 1) in order to increase the integrated luminosity per year by up to a factor of 10 with respect to the nominal LHC [1]. Prototype CCs will first be tested at the SPS. After the installation in 2007, CCs have played an important role for luminosity record at the KEKB e^+e^- collider. LHC or HL-LHC will be the first hadron collider to operate with CCs.

Table 1: Relevant Parameters of the HL-LHC Under Study

Parameter	Unit	Value
Energy	[TeV]	7
Protons/bunch	[10^{11}]	1.7
bunches		2808
rms bunch length	[ ]	7.55
Beta function at $IP_{1,5}$	[m]	0.15
Normalized Emittance	[ ]	3.75
Full crossing angle	[µrad]	590

During KEKB CC operation some fast failures were observed in which the phase changed by ±50° within 50 µs or the voltage dropped to zero within 100 µs [2]. Similar failures at the HL-LHC could compromise the machine protection. 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 µs) to extract the full beam [3].

To quantify the risk and explore possible mitigation techniques, an extensive comparison of beam loss simulations for LHC and HL-LHC had been performed with an emphasis on fast CC failures [4, 5].

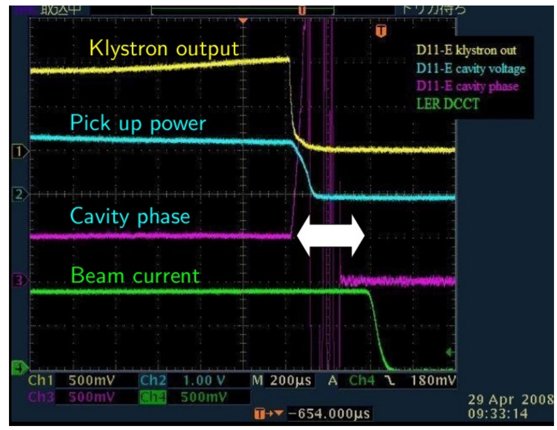

Figure 1: Very fast CC failure observed at KEKB. In this example the CC-RF phase changed by ±50° in 50 µs [2].

SIMULATION SET UP

The CC simulations for LHC and HL-LHC are executed with the help of the computer programs MAD-X and SixTrack [4].

The CCs are first modeled by MAD-X. The CC scheme considered in the present study consists of three CCs per beam on either side of IP5 (CMS experiment). The RF voltage per CC is 3.8 MV and 4.2 MV for the left and right side, respectively. All LHC CCs are operated at a frequency of 400 MHz.

The beam losses (i.e. both the particles absorbed by the collimators as well as particles lost elsewhere in the ring) are computed using the tools developed by the collimation team. A modified version of the SixTrack for failure CC was implemented for this study [6].

Simulated Cases

Using SixTrack several million particles (typically 6 x 10^6) are tracked over a few hundred turns to evaluate the effect of CC failures in 3 cases:

- ***Normal Operation (NO):*** This case defines a reference for the cases with failure. This simulation consists of (1) one free turn (with CC voltage and phase equal to zero), (2) 10 turns for ramping up of the voltage from zero to the nominal voltage (in general 10 turns are chosen simulate an adiabatic ramping), and about 190 turns with the nominal CC voltage and phase ("plateau").

*Work supported by US-LARP, and Conacyt
#contact: bruce.yee.rendon@cern.ch

- ***Voltage failure (VF):*** This case is similar to the ***NO*** case, with the only difference is that, in the second half of the simulation, the CC voltage decreases to zero over a certain number of turns (which depends on the speed of the failure), while the CC phase remains constant as in the ***NO*** case.
- ***Phase failure (PF):*** Analogously to the ***VF*** case, during the last turns of the simulation in the ***PF*** case the phase changes by 90° with respect to the initial phase, at constant CC voltage.

For the simulations presented next, the failures were made to occur 18 turns before the end, i.e. on the turn number 182, at which time a steady state distribution was firmly established. The voltage and phase were then changed over a few turns (1, 3, and 5) in order to simulate a fast CC failure [4,5]. Only one of the three CCs on the right side of IP5 was assumed to fail in this study.

Beam Distribution

The standard LHC collimation studies track halo distributions to evaluate beam losses [7]. Beam measurements in the LHC have revealed that the real distribution is similar to a Gaussian, but with highly overpopulated tails [8, 9]. In this study a double Gaussian distribution is used to approximate a more realistic transversal beam profile (see Figure 2) and a Gaussian for the longitudinal one.

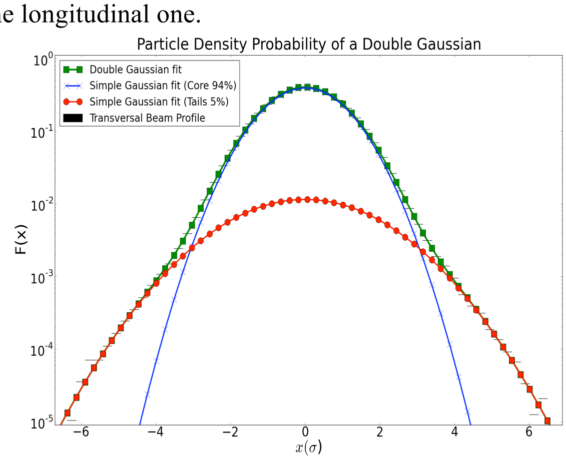

Figure 2: Single and double Gaussian fits to a beam profile measured by CMS [8, 9].

Different steady-state (SS) distributions were simulated in order to evaluate the beam losses due to a CC failure.

SS I

In order to increase the statistics in the tails, where the particles are more likely to hit an aperture and avoid CPU limitations a distribution beyond 2σ is generated, without the inner core which will be not lose in the aperture. In this case the failure happens on the turn number 182 as indicated above.

SS II

Another approach to study failures in the steady state is using the surviving beam distribution obtained in the ***NO*** case. This distribution is used as input and the failure initiated after a couple of turns at constant crab voltage.

SIMULATION RESULTS

For SS I type of studies, the particles lost in this first stage of the simulation, setting up the steady state, often outweigh the particles lost due to the CC failures, which are produced over the last turns. In our analysis we ignore these initial losses and take into account only the losses occurring after the failure.

Absorbed Particles

The "absorbed" particles refer to the particles which are lost on the collimators. Figure 3 shows, for both SS scenarios, the fraction of absorbed particles with respect to the total number of particles present at the moment of the CC failure, plotted versus the duration of the failure (time for voltage/phase).The green and red boxes represent the failures in voltage and phase respectively, compared with the baseline, i.e. no failure (the blue dotted line).

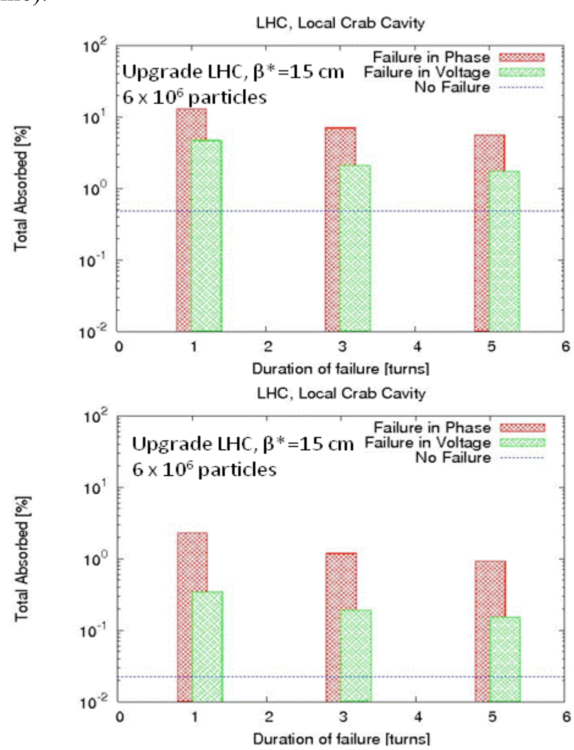

Figure 3: Fraction of particles absorbed on the collimators for SS I (top) and SS II (bottom).

Lost Particles

The "lost" particles refer to those lost over the rest of the machine, excluding collimators. Figures 4 and 5 present, for both SS scenarios, the percentage of lost particles with respect to the total number of particles present at the moment of the CC failure, plotted versus the turn number, counted from the start of the failure. The red bars refer to failures in 1 turn; the green ones boxes to 3-turn failures; and the blue to 5-turn failures,

ISBN 978-3-95450-122-9

and the blue dotted line to the no-failure case (***NO***).

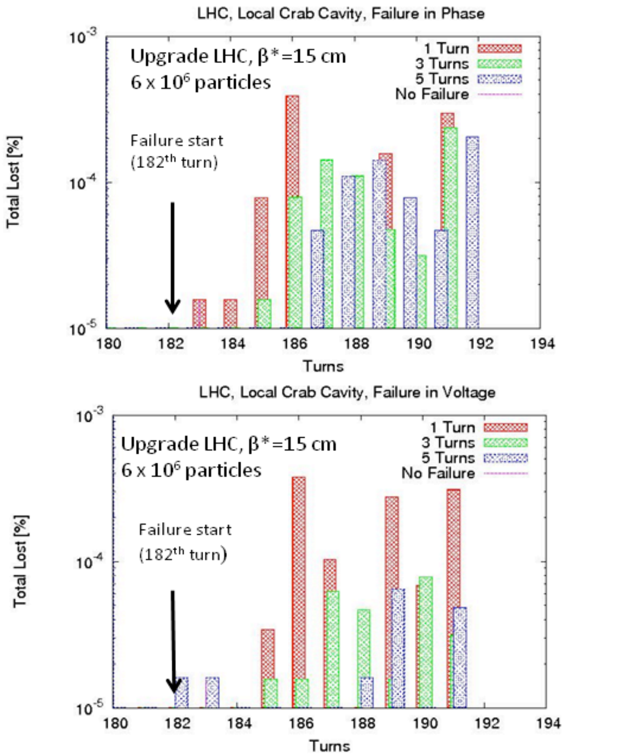

Figure 4: Fraction of particles lost for SS-I phase failure (top) and voltage failure (bottom).

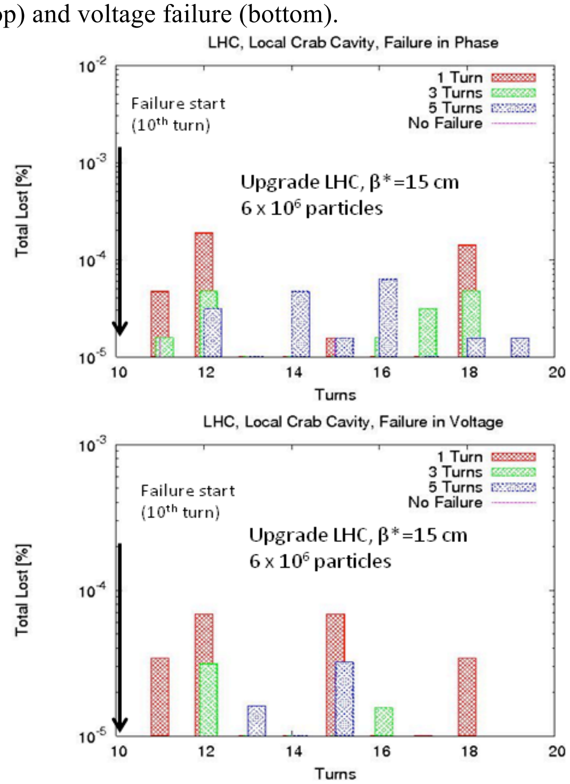

Figure 5: Fraction of particles lost for SS-II phase failure (top) and voltage failure (bottom).

Table 2: Energy Deposited on the Collimators and in Other Regions for the Worst Case Scenario: Phase Failure in One Turn

Energy	Unit	CASE I	CASE II
Collimators	MJ	5.64	12.21
Other regions	J	960	2090

CONCLUSIONS

It is found that CC phase failures are more harmful in terms of beam losses than the voltage failures, this is in agreement with previous results [4, 6]. The failures in 3 and 5 turns generate smaller losses. Therefore, the 1- turn failure represents the most dangerous scenario for LHC machine protection.

The energies deposited for the SS I and SS II are not very different, with SS II yielding a larger value than SS I (Table 2). This difference can be attributed to the fact that some core particles (not included in SS-I) may impact on the collimator or be lost elsewhere in the aperture and the approach applied in order to calculate the equivalent energy deposited.

Future, studies will consider multiple simultaneous CC failures, in order to assess the complete scenario.

ACKNOWLEDGMENTS

The authors would like to thank M. Zerlauth for helpful discussions and comments. This project was supported by US-LARP, Conacyt and Research supported by EU FP7 EuCARD and HiLumi LHC (grant agreements no. 227579 and 284404).

REFERENCES

[1] O. Brüning et al, "The Large Hadron Collider", Progress in Particle and Nuclear Physics, 2012
[2] K. Nakanishi, et al, "Beam Behavior due to Crab Cavity Breakdown", IPAC10, 2010.
[3] J. Wenninger, "Machine Protection Specifications", EuCARD/LARP LHC-CC10 workshop, 2010.
[4] T. Baer et al, "Beam Losses due to Crab Cavity Failure in the LHC," IPAC11, 2011.
[5] T. Baer, et al, "LHC Machine Protection against very fast Crab Cavity Failures", IPAC´11, TUPZ009, 2011.
[6] R. Calaga et al, "Beam Losses Due to Abrupt Crab Cavity Failures in the LHC", PAC´11, 2011.
[7] LHC Collimation Project, http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/code-tracking-2009.htm.
[8] The CMS Collaboration, "Absolute Calibration of the CMS Luminosity", CMS PAS EWK-11-001, 2011.
[9] F. Burkart et al, "Absolute Calibration of the CMS Luminosity", IPAC´11, THPZ030, 2011.