MACHINE PROTECTION FROM FAST CRAB CAVITY FAILURES IN THE HIGH LUMINOSITY LHC *

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Abstract

The time constant of a crab cavity (CC) failure can be faster than the reaction time of the active protection system. In such a scenario, the beams cannot be immediately extracted, making the the protection of the machine rely on the passive protection devices.

At the same time, the energy stored in the High Luminosity (HL) LHC beams will be doubled with respect to the LHC to more than 700 MJ, which increases the risk of damaging the machine and the experiments in a failure scenario.

In this study we estimate the impact that different CC failures have on the collimation system. We also give a first quantitative estimate of the effect of these failures on the elements near the experiments based on FLUKA simulations, using an updated HL-LHC baseline.

INTRODUCTION

The HL-LHC [1] will be the first hadron machine to use CCs, for which several prototypes have been developed. The prototype selection has been narrowed down to two designs: the RF dipole and the Double Quarter Wave (DQW) [2, 3]. Prior to their installation in the HL-LHC, these CCs will be tested with proton beams in the SPS to study their behavior in real conditions. In particular, it is planned to study the beam response to three different cases of CC trips: RF trips, beam induced failures and system/operator faults [4]. In this context, a tracking simulation including CC failures helps to identify the most relevant failure cases, to assess their impact on the machine, to give feedback for the future installation and to improve the current mitigation strategies.

CRAB CAVITY FAILURES

CCs act as damped oscillators, in which the loaded quality factor Q_L represents how under-damped the oscillator is and characterizes the oscillator's bandwidth relative to its center frequency. The DQW has a high loaded quality factor of $Q_L = 5.3 \times 10^5$, which indicates a low rate of energy loss relative to the stored energy of the cavity. In the case of a controller failure or arc in the CC coupler, the CC voltage will exponentially decay following

$$V = V_0 \exp\left(-\frac{\omega t}{2Q_L}\right) = V_0 \exp\left(-\frac{t}{\tau}\right), \qquad (1)$$

where ω is the angular frequency of the CC field and V_0 its operating voltage. Considering the baseline CC frequency of $f = 400.79$ MHz, we obtain a time constant for these processes:

$$\tau = 421 \ \mu\text{s} = 4.73 \text{ LHC turns}. \qquad (2)$$

While an abrupt change in voltage of the CC will change the angle between bunches at the collision point, a phase slip will kick the densely populated core of the proton bunch. Nevertheless, a phase slip alone can only happen if the wrong signal is fed to the cavity either by a failure in the control system or by the operator. In the rest of the cases, the three paremeters: voltage, frequency and phase are interdependent and closely related to the structure of the cavity. To study these correlations, detailed CC behavior models are being developed [5]. The study presented here focuses only on phase slips happening at constant or decaying voltage.

For a fast phase variation we can expect high power requirements from the CC, which sets a limit on how much the phase can change per time unit [6, 7]:

$$\left.\frac{d\phi(t)}{dt}\right|_{max} = \frac{\omega}{2Q_L}\sqrt{\frac{8(R/Q_\perp)\, Q_L\, P_{max}}{V_0^2} - 1}\,, \qquad (3)$$

where $R/Q_\perp$ is the geometric shunt impedance and P_{max} is the maximum power per cavity. Considering the baseline values for the DQW of $R/Q_\perp = 429\ \Omega$, $P_{max} = 100$ kW and the CC voltage used in this study $V_0 = 2.84$ MV, one obtains

$$\left.\frac{d\phi(t)}{dt}\right|_{max} = 56°/\text{ turn}\,, \qquad (4)$$

corresponding to a detuning of $\Delta f = 1.7$ kHz. Any such failure risks to cause significant beam losses, which should occur on the LHC collimation system [8] if the received kicks are not large enough to directly reach the machine aperture.

TRACKING SIMULATION SETTINGS

The SixTrack [9] tracking code version 4.5.33 was used in order to study the effect of a linear CC phase slip on the beam. The model of the HL-LHC used in the simulation follows the current baseline layout and optics HLLHCv1.2 [1]. The relevant HL-LHC parameters considered are summarized in Table 1. The phase slip was reproduced with the dynamic kick module [10], and the collimators installed through the collimation routine [11]. The simulations presented here have been performed for Beam 1.

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Table 1: Relevant Parameters Used in This Study

Parameter	Symbol	Value
Beam energy at collision	E [TeV]	7
Tot. crossing angle (IP1 & IP5)	θ [μrad]	590
Minimum β*	β* [m]	0.15
Norm. transverse emittance	ϵ_n [μm]	2.50
RMS energy spread	σ_s [0.0001]	1.13
RMS bunch length	σ_l [cm]	7.55
CC RF frequency	f_{cc} [MHz]	400.79
N° of CCs [1]	n_{cc}	4

[1] per beam, per IP side.

Crab Cavities

The simulated failure scenario affects the downstream CCs of the ATLAS experiment (IP1), where the crossing and CC kick plane is vertical. The CCs are situated between the double aperture dipole D2 and quadrupole Q4.

Failure Scenarios

For this study, the maximum possible phase change per turn found in Eq. (4) was considered. A linear phase change of 56° per turn was applied during 4 turns, then kept constant for 15 additional turns. This phase slip was paired with two different voltage behaviors: constant and decaying voltage as described in Eq. (1), with τ = 4 LHC turns. The different failure cases shown in Fig. 1 were simulated.

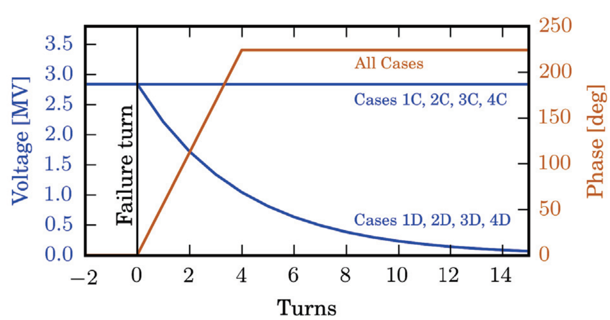

Figure 1: Evolution of the phase and voltage for the different failure cases, where the first digit indicates the number of CCs failing, **C** indicates constant voltage and **D** decaying voltage.

Beam Distribution

Due to the time dependence of the phase slip, each bunch of the beam will see different phases. Separate simulations for each bunch would be needed in order to study this effect, since SixTrack tracks one bunch per run. In this paper, only one bunch is simulated and scaled to the full beam. Further studies are foreseen, in which the time variation of the phase is taken into account for the different bunches.

For the simulations of this study, a double Gaussian beam profile was used as a representation of the bunch in the transverse plane (Fig. 2), which has been found to fit well observed beam distributions [12] and has been used in previous CC failure studies [13]. In the longitudinal plane, a Gaussian distribution was matched to the RF bucket size.

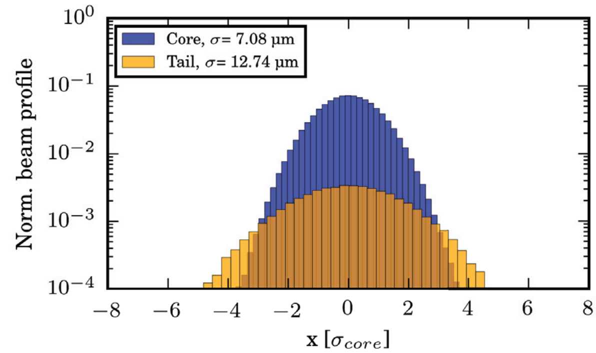

Figure 2: Normalized horizontal beam profile for the simulation, where σ_{tail} = 1.8 σ_{core}. The core represents 95 % of the total bunch and the tail 5%.

Collimation System

The opening of the collimators used in the tracking simulation are summarized in Table 2 [15].

Table 2: Openings in Terms of σ (ϵ_n = 3.5 μm)

Collimator	Opening [σ]
Primary IR7	5.7
Secondary IR7	7.7
Absorber IR7	10
Primary IR3	15
Secondary IR3	18
Absorber IR3	20
Secondary IR6	8.5
Dump protection IR6	9
Tertiary IR2/8	30
Tertiary IR1/5	10.9

RESULTS & DISCUSSION

Losses in the Collimation System

The results from the tracking simulations are summarized in Fig. 3, in terms of losses from the simulated bunch on the collimators. We can observe that in the cases at constant voltage, the losses are almost an order of magnitude higher compared to the cases at decaying voltage after 10 turns. This is expected, since the strength of the kick is proportional to the amplitude of the voltage. For the case of only 1 CC failing, no losses were observed with decaying voltage. The results also show that the losses in general increase an order of magnitude with the number of CCs failing, suggesting that simultaneous failures of CCs should be strictly avoided [16]. Nevertheless, there are no obvious mechanisms that would affect several CCs in the same way in a synchronous manner.

Fig. 4 shows the distribution of losses around the ring. All lost protons have first hit a primary collimator in the betatron cleaning insertion (IR7), which is the main loss location. Here, 0.11 % of the beam was lost in 4 turns. The losses not intercepted by the collimators are very low ($\sim \times 10^{-5}$ %), which indicates a good cleaning efficiency.

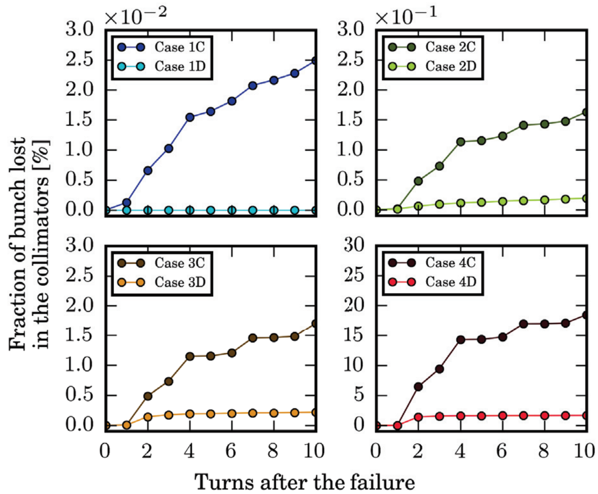

Figure 3: Cumulative fraction of the bunch lost in the collimation system for the cases described in Fig. 1.

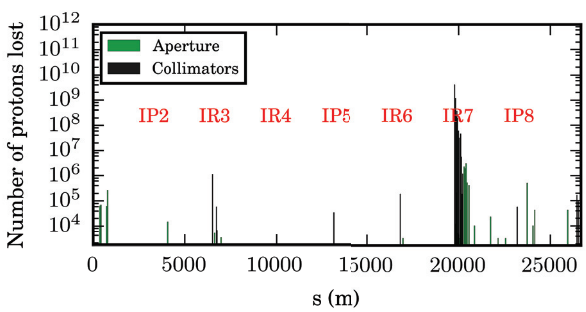

Figure 4: Losses around the ring for Case 2C before dump, in 10 cm bins, scaled to the total beam intensity.

For the current LHC, a beam abort is initiated in case of an abnormal increase of beam loss signal in the collimator BLMs, and will be completed within 2 or 3 turns. This will happen if 3×10^{10} protons or more are lost in half a turn or less [17]. A summary of the number of protons lost in the collimation system before the beam is dumped is presented in Table 3, where the fraction of bunch lost was scaled to the total beam intensity. In all the cases where the beam is dumped, the failure is detected during the first or second turn after the failure.

Table 3: Turn after the failure in which the beam abort is initiated, and the number of protons lost p_{loss} in the collimation system before the beam is dumped, for each failure case.

Case	Turn	p_{loss}	p_{loss} [%]
1C	2	9.7×10^{10}	0.016
1D	-	No Losses	0
2C	2	6.7×10^{11}	0.11
2D[1]	-	1.2×10^{11}	0.02
3C	2	7.3×10^{12}	1.2
3D	2	1.1×10^{12}	0.19
4C	1	8.6×10^{13}	14.3
4D	2	9.7×10^{12}	1.6

[1] values cumulated for 10 turns. No beam abort is triggered.

It has been estimated that a collimator should survive if 8 bunches, of 1.15×10^{11} protons each, spaced by 25 ns impact on a secondary collimator during an asynchronous beam dump at collision energy [18]. From Table 3 we can conclude that the damage limit of the collimators is reached for any failure of 3 or more CCs, before the beam is dumped. Nevertheless, an accurate assessment of the impact of the obtained losses in the collimation system requires detailed energy deposition studies.

FLUKA Simulations

In case of CC failures, the experiments and superconducting magnets near them are exposed to showers from the tertiary collimators (TCTs), which can be hit by protons outscattered from the collimation insertion. In order to assess the effects of these showers in the experimental insertions, FLUKA [19,20] shower simulations were carried out based on the loss distribution predicted by SixTrack. The most impacted TCT is the horizontal TCT4. Only the case of a phase slip affecting 2 CCs at constant voltage (Case 2C) was considered, being the most unfavorable among the realistic cases. The most impacted magnet is the D1 separation dipole located 50 m downstream of the TCTs. The maximum energy density in the D1 coils is found to be about 7×10^{-10} mJ/cm^3 per inelastic proton collision in the TCT4. while it is about an order of magnitude lower in the neighbouring triplet quadrupoles. Assuming a transient quench level of a few 10 mJ/cm^3, one can therefore expect a quench of the D1 if losses on the TCT would exceed a few 10^{10} protons. On the other hand, thermo-mechanical studies have shown that already a few 10^9 protons can damage the TCTs depending on the transverse impact distributions on the TCT front face [21]. For the considered case, 2.7×10^7 protons impacted the TCT, which is well below the damage limit of the TCT and poses no risk for quenching or damaging downstream magnets, nor the experiments.

CONCLUSION

A realistic estimation of a CC phase slip and of the time constant of a CC voltage decay was presented, following the current baseline parameters for the DQW and HL-LHC. The results show that for the failure of 1 or 2 CCs, the losses in the collimation system and the downstream magnets before the beam is dumped are below the damage limits. Further studies should assess if several CCs could be simultaneously quenched if they are exposed to particle showers from beam losses, and consider the RF Dipole parameters.

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