BEAM LOSSES DUE TO ABRUPT CRAB CAVITY FAILURES IN THE LHC

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Abstract

A major concern for the implementation of crab crossing in a future High-Luminosity LHC (HL-LHC) is machine protection in an event of a fast crab-cavity failure. Certain types of abrupt crab-cavity amplitude and phase changes are simulated to characterize the effect of failures on the beam and the resulting particle-loss signatures. The time-dependent beam loss distributions around the ring and particle trajectories obtained from the simulations allow for a first assessment of the resulting beam impact on LHC collimators and on sensitive components around the ring. Results for the nominal LHC lattice is presented.

INTRODUCTION

The luminosity upgrade of the LHC aims to reach a leveled luminosity of factor of 5 larger than the nominal design luminosity of $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This increase is foreseen to come from a combination of an increase in the beam current and reduction of beam sizes at the interaction point (IP). To fully exploit the beam size reduction a compensation of the Piwinski angle and luminosity leveling with crab cavities is required [1]. Table 1 shows some relevant parameters for the nominal LHC and foreseen upgrade.

Table 1: Relevant LHC Nominal and Upgrade Parameters

	Unit	Nominal	Upgrade
Energy	[TeV]	3.5-7	7
Protons/Bunch	$[10^{11}]$	1.15	1.7
ϵ_n (x,y)	[μm]	3.75	3.75
σ_z (rms)	[cm]	7.55	7.55
$\mathrm{IP}_{1,5}$ β^*	[m]	0.55-1.5	0.15-0.25
Piwinski Angle	Φ	0.64	1.1-1.4

Due to the immense stored energy in the LHC beams at 7 TeV (350 MJ), protection of the accelerator and related components is critical. For example, at nominal intensity and 7 TeV, 5% of a single bunch is beyond the damage threshold of the superconducting magnets [2]. Approximately, 200 interlocks with varying time constants ensure a safe transport of the beam from the SPS to the LHC and maintain safe circulating beams in the LHC. A worst case scenario for detecting an abnormal beam condition is 40 μs (1/2 a turn), and the corresponding response time to safely extract the beams is is approximately 3 turns [3]. Figure 1 schematically shows the sequence between a failure and safe beam extraction in the LHC.

FAST OR ABRUPT CAVITY FAILURES

Crab cavities deflect the trajectories of the head and tail of the bunch with respect to the synchronous particle. Therefore, RF failures can abruptly change the trajectories and induce unwanted beam losses. These failures can be broadly classified into two categories; 1) Fast failures (single or few turns) caused by sudden cavity quench, power amplifier trips, abrupt RF phase changes and other causes.2) Slow failures caused by vacuum degradation, IR cavity to cavity voltage and phase drifts, etc.. Any crab cavity related failure must fall in the shadow of the minimum 3-turn extraction to ensure machine safety. The high Q_{ext} of the superconducting cavities could favor a slow voltage ramp down, but the voltage slope can be strongly driven by the beam. Therefore, active feedback is essential to guarantee machine protection [4]. Since the only operational crab cavity was realized in KEKB, the time structure of RF failures observed there were used as reference for this study. A detailed analysis of different failures observed in KEKB crab cavities over the period of their operation was made in Ref. [5]. Figure 2 shows the beam current and cavity input and output signals during one such failures. In this failure mode, likely triggered by a quench, the phase oscillates approximately $\pm 50^\circ$ during a time period of 50μs. It continues to oscillate until a beam dump was triggered. Corresponding orbit oscillations were seen by the BPMs as the trajectory offset is directly proportional to a RF phase change. The time scale of 50μs for the 50° phase change corresponds to approximately a little over a

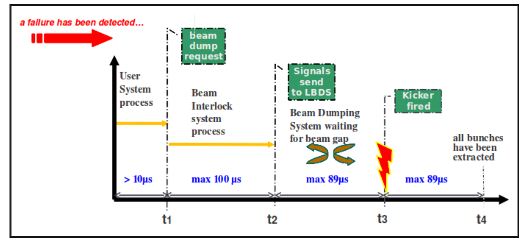

Figure 1: Sequence of a failure detection and full beam extraction in the LHC [3].

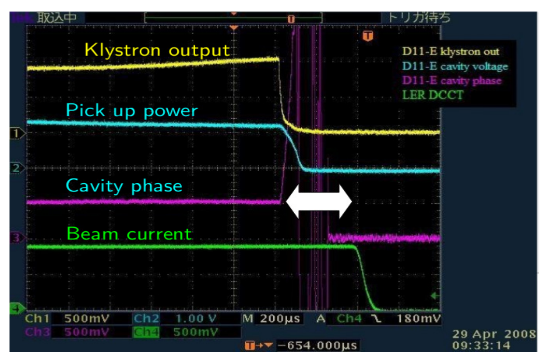

Figure 2: Beam and cavity signals during a cavity failure in the KEKB crab system [5].

* This work partially supported by the US-DOE through LARP

1/2 turn in the LHC and therefore, such a failure is potentially dangerous.

Simulation Setup

To study the impact of fast failure of a crab cavity in the LHC, a thin crab cavity element is added to tracking programs (MADX and SIXTRACK) together with a complete description of the LHC lattice and its collimation system. Single particle tracking using tools developed for collimation efficiency studies are used to determine the local loss maps and to estimate the fraction of the particles impacting the aperture [6]. Detailed tracking studies were already carried out to study the collimation cleaning efficiency of the beam halo in the presence of a steady-state global crab cavity where the head and the tail of the bunches follow different orbits than the synchronous particle. These orbit offsets are proportional to the crab dispersion and found to have very little or no impact on the cleaning efficiency and the hierarchy of the collimation system [7].

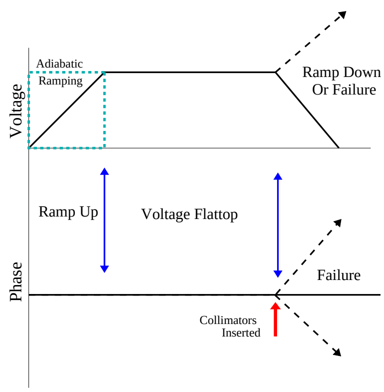

Figure 3: Crab cavity voltage and phase cycle for failures.

During a crab cavity failure, trajectory offsets occur only in the bunch head and the tail for a voltage change or as a shift of the bunch core for a phase shift. Therefore, a full bunch distribution is required to assess the various failures and the related particle losses along the ring. A distribution (typically 5×10^6 particles) is tracked through a cycle of adiabatic ramping, steady state and a model failure as depicted in Figure 2. The adiabatic ramping of at least 10 turns is required to prevent emittance dilution. Two scenarios of crab crossing, namely the global and the local schemes are treated in this paper. As a qualitative schematic, the particle trajectory at $2\sigma_z + \sigma_{\delta p/p}$ (Figure 4 top) is plotted in the case of the non closure of the "crab bump" due to a failure or absence of the second cavity in the local scheme.

Tracking Results

For simplicity, the artificial failures in the simulation were induced as a linear function in time for both voltage and phase. Studies were performed for abrupt changes occurring within one to five turns to evaluate the most pessimistic cases. Figure 5 shows the longitudinal pattern of the particles either lost or absorbed for a 3-turn 90° phase failure. An artificially large beam ($\sigma_{x,y}$ increase by factor

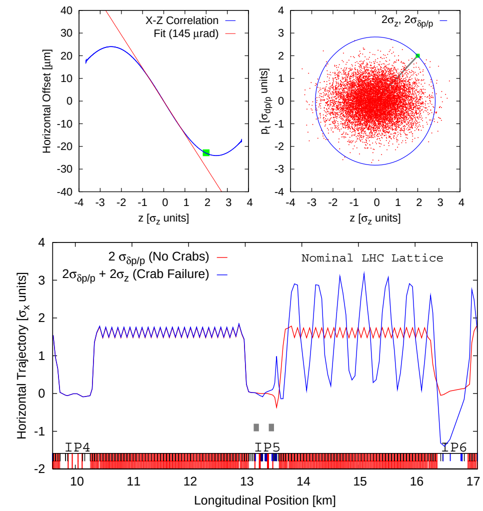

Figure 4: Horizontal trajectory of a particle at $2\sigma_z + 2\sigma_{\delta p/p}$ induced by the non-closure of the bump from a local crab cavity. The nominal trajectory for a $2\sigma_{\delta p/p}$ is plotted as a reference.

3) was used to enhance the effect due to low statistics of lost particles. Since, the initial distribution is large, losses are expected even in the case of non-failure as the collimation system is nominally placed at 6σ. The losses are mainly concentrated in the collimation regions with some others in the warm sections. No losses beyond the quench limit were found thereby demonstrating that the machine is protected from an sudden failure before the beam is ejected.

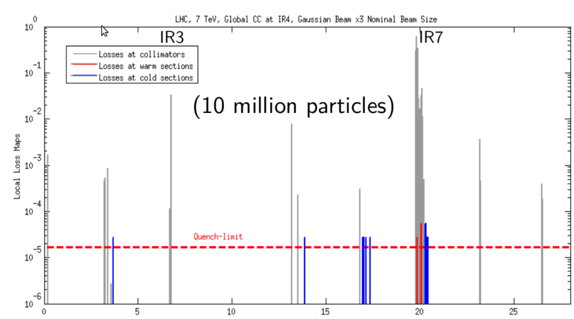

Figure 5: Longitudinal loss map for a particle distribution of $\times3$ larger beam size and a 3-turn 90° phase failure with a global crab cavity in the nominal LHC.

The total number of particles absorbed in the collimation system were recorded for voltage and phase failures as a function of time. These simulations were carried out for failure in a single global crab cavity and also for a local crossing scheme with a failure induced on one side of the IP. For simplicity, only crab crossing at one IP is assumed. Figure 6 shows a histogram of the total number of absorbed particles as a function of failure time for both voltage and phase failures. The voltage is abruptly increased by a factor of 2 or the phase is changes by 90° to simulate the respective worst case failure scenarios. The beam size was enlarged to a factor of 1.5 to account for a larger tail population sometimes observed in the LHC [8].

Since the absolute losses are strongly dependent on the bunch distributions, $\sigma_{x,y}$, a steady state case without a cavity failure is used as a reference to properly account for the losses induced only from the failure (see Fig. 6). The primary losses occur in the IR7 and IR3 which are the dedicated collimation sections in the LHC. Some losses are also evident at the tertiary collimators in the interaction regions. The total number of absorbed particles is approximately a

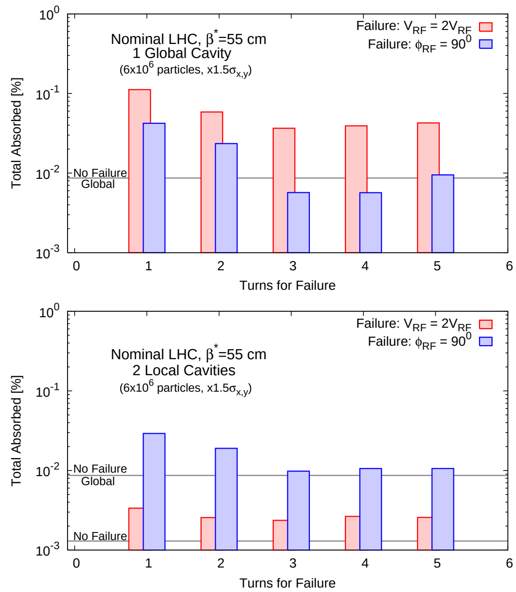

Figure 6: Percent of the total particles absorbed in the collimation system after a crab cavity failure for global (top) and local (bottom) schemes.

factor 2 or more larger in the case of the global scheme for both failure scenarios with the same crossing angle. It is also evident that a voltage doubling deposits more particles into the collimation system than a phase failure, while the situation is reversed in a local scheme. It should be noted that nominal collimation system is set up without any optimization for global or local schemes.

The percent of lost particles uncaptured by the collimation system may give a qualitative estimate of the damage to the machine before the beam dump system can react. Figure 7 shows a histogram of the total number of lost particles in each turn due to 90° cavity phase shift for different failure times. Due to extremely low statistics of lost particles a factor of 3 larger transverse beam size was used to artificially enhance the particle losses. A reference of steady state without any failure but with the same $\times 3$ beam size is also plotted to distinguish the actual losses from the failure. The particle losses appear above the reference on or after the second turn for both global and local cases. Even with an extremely large beam size, the particles losses are in the 1×10^{-6} level of the total population.

For the upgrade optics of the LHC far smaller β^* are foreseen (see table 1). It was shown in Ref [9] that the maximal displacement of the particles inversely scale with β^* and the frequency of the crab cavity. Therefore particle losses may become important with decreasing β^* and detailed simulations are required to quantitatively characterize the loss maps. The losses scale strongly with the cavity voltage, thereby focusing towards a multi-cavity system to minimize losses due to failures. However, the complexity of the system may drive the number of the cavities to a minimum. Therefore, a two-cavity module is seen as a good compromise and also compatible with the voltage requirements for β^* of 15cm [10]. Additionally, the foreseen upgraded collimation system should be included in the simulations together with a possible optimization for the respective crab scheme.

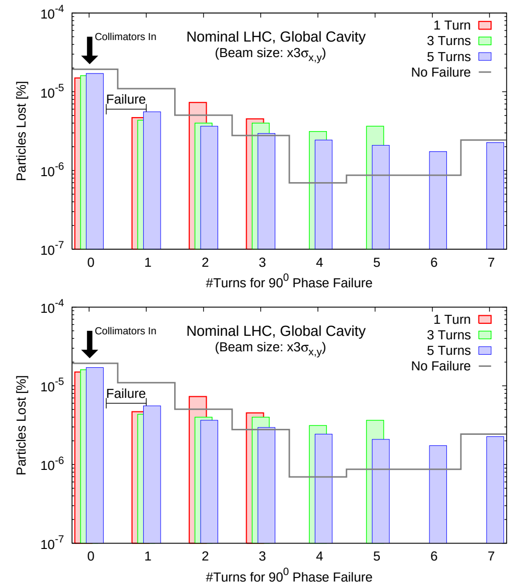

Figure 7: Percent of the total particles lost elsewhere in the LHC ring due to crab cavity failure.

CONCLUSIONS

Abrupt voltage and phase changes in a crab-cavity phase are simulated to characterize the effect on the nominal LHC beam and the resulting particle-loss signatures using the nominal lattice parameters. The time-dependent beam loss distributions around the ring show that the majority of the lost particles are absorbed in the collimation system and the losses elsewhere in the ring are at the 1×10^{-6} level of the original population. Detailed simulations for the upgrade optics and upgrade collimation system are required to assess the impact and to determine tolerances for the time constants for the failure modes at a High-luminosity LHC upgrade.

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