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CRAB CAVITY FAILURES COMBINED WITH A LOSS OF THE BEAM-BEAM KICK IN THE HIGH LUMINOSITY LHC*

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Abstract

Crab cavities are an essential component of the High Luminosity LHC (HL-LHC) project. In case of a failure they can create large transverse kicks on the beam within tens of microseconds and, therefore, require a fast extraction of the circulating beam. In this paper, the effects of different crab cavity failures in combination with the missing beam-beam kick following the dump of only one HL-LHC beam are presented and consequences for the interlocking strategy of crab cavities are discussed.

CRAB CAVITIES IN THE HL-LHC

Crab cavities (CCs) are to be employed in the High Luminosity LHC (HL-LHC) to compensate for the loss of luminosity caused by the increased crossing angle [1, 2]. This compensation is achieved by tilting the proton bunches in the crossing plane to restore head-on collisions. However, a tilted bunch also means a wider transverse beam size, which, if not compensated downstream of the interaction point (IP), can lead to increased losses were the beam to move due to another failure.

The current baseline is to have two CCs per beam and side for the IPs associated with the ATLAS (IP1) and CMS (IP5) experiments, totaling 16 cavities. Since each of them is to be powered and controlled individually by separate systems, it is assumed that only one CC would fail at a given time. The CC failures considered in this paper are any kind of failure leading to a voltage drop in one cavity or a change of the RF phase of the CC. Typical examples include powering failures and quenches. The high coupling of the cavity implies a short time constant on the order of 400 µs (~ 4.5 LHC turns) for such a voltage drop, having an exponential decay [3]. As for the phase change, the rate of change is limited by the available power of the RF system with an upper limit at about 28.6 deg per LHC turn (89 µs) [4]. For the sake of simplicity, phase and voltage failures are treated separately, however most failures would have an effect on both. To simulate the worst-case scenarios, the Low Level RF (LLRF) is assumed to be actively driving the phase failure, e.g. due to incorrect user input.

Another failure occurring in conjunction with a CC failure could aggravate its severity and such combined failures that are causally linked need to be studied. It is assumed that the instrumentation that the cavities are to be equipped with allows detection of any failure within one µs [1, 5], whereafter the beam permits are removed and the beams are dumped within three LHC turns (270µs) [6]. However, the beams are not dumped at the same moment and this paper focuses on a combination with a loss of the so-called beam-beam kick (BBK).

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COHERENT BEAM-BEAM KICK

The coherent BBK is an electromagnetic interaction between counter-circulating bunches, which results in a transverse kick. In the LHC, the loss of the BBK due to the dump of one beam can move the other beam by up to 1.35 σ [7]. During high intensity beam operation the beam permits of the two beams in the LHC are linked, i.e. if a fault requiring a protection dump of one beam occurs, the second beam will be dumped as well. Nevertheless, the dumping of the second beam can be delayed by up to two turns.

As illustrated in Fig. 1, the abort gaps of the two beams overlap only in IPs 1 and 5. Therefore, parts of the remaining beam will experience a loss of the BBK in different IPs for the first two turns and the beams can in practice not be dumped at exactly the same moment. The resulting RMS orbit offsets are summarized in Table 1 in units of beam σ during the first two turns, indicating in which IPs the BBK is lost.

The horizontal and vertical orbit excursions of beam 1 and beam 2 for the most critical cases are shown in Fig. 2. The tracking simulations were performed with MAD-X [8] by sequentially removing the long range BBK in the IPs.

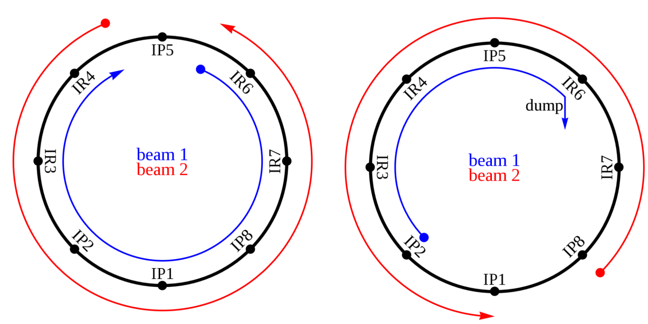

Figure 1: Schematic of the beams during normal operations (left) and during the dump of beam 1 (right). The abort gaps are only synchronized in IPs 1 and 5. The beam dumping system is located in IR6 and the betatron collimation system in IR7. Different parts of the beams experience a loss of the BBK due to dumping the other beam in different IPs on the first two turns.

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Table 1: Loss of BBK – definition of the different cases. The ratio of beam affected in each case, as well as the IPs in which the BBK is lost and the resulting RMS orbit excursions are presented. The sequence of the loss of the BBK in the IPs is indicated. Bold figures refer to the second LHC turn.

B1	Missing BBK for:		RMS orbit offset σ	
Case	Beam %	IPs	Turn 1	Turn 2
1	25	5, **1**, **2**	0.52	0.83
2	50	5, **8**, **1**, **2**	0.52	0.74
3	25	2, 5, **8**, **1**	0.54	0.68
B2				
1	12.5	1, 8, **2**	0.39	0.56
2	12.5	1, 8, **5**, **2**	0.39	0.55
3	50	2, 1, 8, **5**	0.39	0.57
4	25	8, **2**, **1**	0.19	0.36

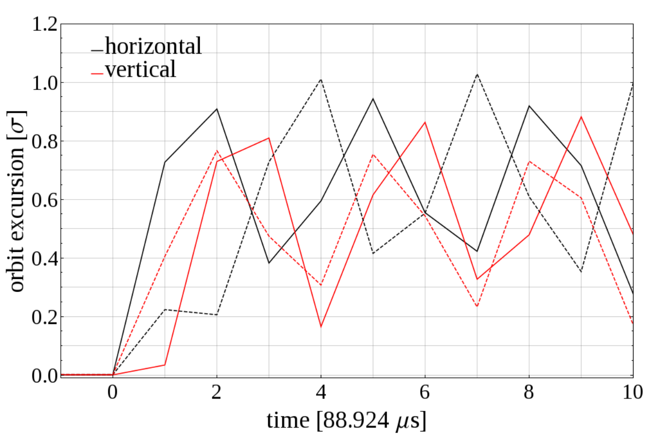

Figure 2: Normalized horizontal and vertical orbit excursions for beam 1 (solid lines), case 1, and beam 2 (dashed lines), case 3, following the dump of the other beam, with the time in units of LHC turns. The cases are explained in Table 1.

ESTIMATION OF THE LOSSES

Detailed loss studies using e.g. SixTrack [9] are time consuming. Here, a fast method for estimating the losses is presented. A few particles distributed on the closed orbit along the longitudinal axis are tracked throughout the failure using MAD-X [8], giving the residual crabbing at the primary collimators (TCP) during the first few turns after a CC failure. The orbit offset caused by the loss of the BBK at the TCPs, as described above, is added linearly. This is justified, as offsets during the first three LHC turns (270 µs) are on the order of one beam σ. The contribution from each case in Table 1 is then weighted according to the fraction of the beam it applies to. The TCPs are considered as black absorbers and the transverse bunch distribution is integrated from the collimator jaw position taking the transverse beam offset at each longitudinal position into account. The integration is weighted longitudinally by a Gaussian with an RMS size of 9 cm [10].

The measured overpopulated tails of the LHC beam have been modeled as a double Gaussian distribution [11–13]. The beam core consists of a Gaussian distribution containing 62 % of the particles, while the beam halo consists of a Gaussian distribution with a factor two larger standard deviation and 38 % of the particles. The combined distribution is cut at 5.7 σ (assuming an emittance of 3.5 µm) in accordance with the TCP settings [14]. The following formula summarizes the integration procedure, giving the fraction of lost particles:

$$1-\frac{1}{\alpha}\int_{-4\sigma_t}^{4\sigma_t} N(t|0,\sigma_t^2)\int_{LL(t)}^{UL(t)} C\cdot N(x,y|0,\sigma_{x,y}^2)+ (1-C)\cdot N(x,y|0,(D\cdot\sigma_{x,y})^2)d(x,y)dt\,,$$

where $N(t|0,\sigma^2)$ is a Gaussian distribution, σ_t the longitudinal RMS bunch size, $\sigma_{x,y}$ the transverse RMS bunch sizes, $C = 0.62$ the intensity ratio between core and the halo bunch profiles, $D = 2$ the bunch size factor, and α is a normalization factor. $UL(t)$ and $LL(t)$ are the upper and lower limits of transverse integration, taking the collimator jaw position and the beam offsets due to the BBK and the CC failure into account. Due to the crabbing these integration limits depend on the longitudinal position in the bunch.

Limits for Beam Losses and SixTrack Benchmark

The maximum allowed beam losses are defined by the LHC collimation system located in the betatron collimation region (IR7), which can withstand up to 1 MJ of energy deposited instantaneously from beam losses. This corresponds to eight nominal LHC bunches of 1.15×10^{11} protons per bunch at 7 TeV. In HL-LHC [1], the bunch intensity will increase to 2.2×10^{11} protons per bunch, which, given the maximum of 2748 bunches foreseen per beam, would put the limit at 0.14 % of the full beam.

For benchmarking purposes, a comparison between this method and SixTrack simulations [4] was presented previously [15, 16], where only the CC failure is considered without any loss of the BBK. It was shown that this method tends to underestimate the losses by up to a factor two for the first few turns.

Voltage Failure

In case of a powering failure, the voltage drop follows an exponential decay with a time constant of approximately 400 µs (4.5 LHC turns). This leads to a large uncompensated crabbing outside of the IPs, with the tails reaching an offset from the orbit of up to 0.44 σ. For both IPs 1 and 5, the CC leading to the largest orbit offsets at the TCPs was used, however the differences are small since the kicks are symmetric around the bunch center and the optics functions are similar. The estimated beam losses as a percentage of the total beam intensity are shown in Table 2.

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While the uncompensated crabbing due to the failing CC does indeed aggravate the beam losses, the majority of the losses are caused by the missing BBK. The CCs account for less than 20 % of the losses. None of the considered cases pose a risk during the first turn, however during the second turn all beam 1 cases lead to losses above the 1 MJ limit. For beam 2, the offsets due to the BBK are smaller and only a CC failure in IP5 approaches this limit.

Table 2: Summary of losses due to failures (designated by IP number) compared to losses only due to the loss of the BBK (referred to as *none*). Values in bold are above the 1 MJ limit; 0.14 % assuming the full HL-LHC beam.

	Loss [% of beam]			
B1	Voltage drop		Phase slip	
CC fail in IP	Turn 1	Turn 2	Turn 1	Turn 2
1	0.056	**0.196**	0.061	**0.389**
5	0.058	**0.208**	**0.166**	**0.824**
none	0.055	**0.187**	0.055	**0.187**
B2				
1	0.005	0.093	0.015	0.111
5	0.009	0.108	0.056	**0.496**
none	0.003	0.088	0.003	0.088

Phase Slip

It is conceivable that the reference phase is set to a different value in one CC, e.g. by an incorrect user input. The maximum phase change per turn, with a constant voltage, is limited by the available RF power and can be calculated from Eq. 4.57 in [4] to 28.6 deg/turn, assuming the current baseline values of frequency $f = 400.789$ MHz, quality factor $Q_L = 5 \times 10^5$, $(R/Q_\perp) = 430\,\Omega$, maximum power $P_{max} = 80$ kW and cavity voltage $V_0 = 3.4$ MV [17].

There is a multitude of different characteristics possible for a phase failure, however to be conservative it is assumed that the reference phase is set to a new value larger than 60 degrees off, and that the LLRF tries to reach this new reference point as quickly as possible while maintaining the operational voltage. There will, thus, be a continuous change of the phase for the first two turns.

The sudden change in the phase of the CC effectively kicks the beam such that it oscillates around a new closed orbit. As the CC voltage becomes non-zero for the longitudinal center of the bunch, the beam core will also be kicked significantly, resulting in beam losses. The results are summarized in Table 2. A failure in IP5 for beam 1 is the worst case, surpassing the 1 MJ limit already on the first turn. It is then reached for the other beam 1 case, as well as one of the beam 2 cases, on the second turn. The significantly lower losses in the beam 2 IP1 case are due to the more favorable phase advance of 16 degrees from the IP1 CCs to the TCPs (chapter 5.4, [4]).

DISCUSSION

The characteristics of the voltage failure are relatively well-defined, however for the phase slip failure there is a wide parameter space available. In this paper, the phase was assumed to be changing at a maximum for two consecutive turns, leading to beam losses exceeding the 1 MJ limit in several of the discussed cases, with the worst case reaching an estimated 5.9 MJ. For the voltage failures, the worst case reaches 1.5 MJ, whereas the BBK alone would give approximately 1.3 MJ after two turns.

In order to mitigate these risks, it is important to interlock the phase and voltage of the CCs. Furthermore, the beam permits of both beams must be removed simultaneously, which would lead to a maximum delay of one turn between their respective dumps. Since beam 1 passes IR6, the location of the LHC beam dumping system, before IR7, the betatron collimation region, beam losses due to a loss of the BBK would only appear for beam 2. If a phase slip were to occur, there could be losses above the limit already on the first turn for beam 1 after beam 2 is dumped.

A method to delay the arrival of critical beam losses after a CC failure is to ensure phase advances below ~ 20 degrees between CCs and TCPs. This would effectively circumvent the TCPs that are meant to intercept the beam during failures. Furthermore, it would require interlocking on these phase advances, which is already done in the LHC from the beam dump kickers to the tertiary collimators [18].

Both for the voltage failures and the phase slips, there would be a constant change of the kick on the beam within the turn, such that each bunch would see slightly different kicks. However, in the above calculations, the CC kick was added at the end of each turn such that the whole beam sees the maximum kick, giving a conservative estimate.

CONCLUSIONS

The beam losses due to various Crab Cavity (CC) failures together with a loss of the Beam Beam Kick (BBK) have been estimated using the simple method proposed in this paper. While a voltage failure of one CC increases the beam losses due to a loss of the BBK, if the other beam is dumped first, these losses are mainly due to the BBK and not the CC failure. All the failures considered in beam 1 would risk exceeding the 1 MJ limit of quasi-instantaneous beam losses in the collimation system due to a loss of the BBK in the second turn. For beam 2, the losses are lower and a voltage failure in combination with the loss of the BBK is not sufficient to reach this limit.

Phase slip failures are significantly more critical as the 1 MJ limit is reached in three out of the four studied cases. To mitigate these failures, the phase and voltage of the CCs needs to be interlocked.

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