VERY FAST LHC CRAB CAVITY FAILURES AND THEIR MITIGATION

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Abstract

For the high-luminosity LHC upgrade program (HL-LHC), the installation of crab cavities (CCs) is needed to compensate the geometric luminosity loss due to the crossing angle and for luminosity leveling [1]. The baseline is a local scheme with CCs around the ATLAS and CMS experiments. In a failure case (e.g. a control failure or arcing in the coupler), the voltage and/or phase of a CC can change significantly with a very fast time constant of the order of 1 to 10 LHC turns. This can lead to large, global betatron oscillations of the beam.

The impact of CC failures on the beam dynamics is discussed and the results of dedicated simulations are presented. Mitigation strategies to limit the impact of CC failures to an acceptable level are proposed.

INTRODUCTION

The HL-LHC program aims at (virtual) peak luminosities that are 20-25 times above the nominal LHC luminosity [1]. In order to achieve this, the beam size at the interaction points (IPs) has to be reduced, which implies an increase of the crossing angle to keep the beam-beam separation constant [1]. CCs are needed to compensate the associated geometric luminosity loss and for luminosity leveling. Optimized optics solutions based on the Achromatic Telescopic Squeezing (ATS) scheme are proposed [2, 3]. The baseline is a local crab cavity scheme with three CCs ($n_{CC} = 3$) per beam on either side of IP1 (ATLAS) and IP5 (CMS)[1].

Normal Operation

CCs lead to dipolar transverse deflections with a sinusoidal modulation that is determined by the CC frequency f, a so-called tilt-kick [4]. For a CC phase of $\Phi = 0$, the optimal voltage amplitude to compensate the crossing angle Θ is for a CC upstream of the IP given by:

$$V_0 = -\frac{c \cdot E \cdot \tan(\frac{\Theta}{2})}{q \cdot 2\pi f \cdot \sqrt{\beta^* \beta_u} \cdot \sin(\Delta\varphi) \cdot n_{CC}} \qquad (1)$$

where c is the velocity of light, E the particle energy, q the particle charge and β^* and β_u the beta functions at the IP and at the CC upstream of the IP, respectively [4]. $\Delta\varphi$ is the betatron phase advance from the CC to the IP and n_{CC} the number of CCs per beam on either side of the IP.

For an optimal closure of the tilt-kick, the betatron phase advance between the CCs upstream and downstream of the IP should be $\Delta\varphi_{CC} = 180°$. The optimal voltage amplitude of the downstream CCs is given by:

$$\tilde{V_0} = -\sqrt{\frac{\beta_u}{\beta_d}} \cos(\Delta\varphi_{CC}) \cdot V_0 \qquad (2)$$

with β_d being the beta function at the downstream CC.

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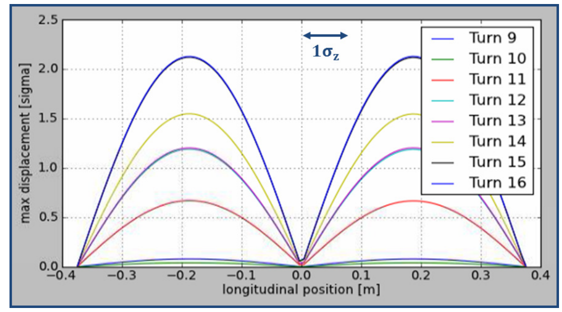
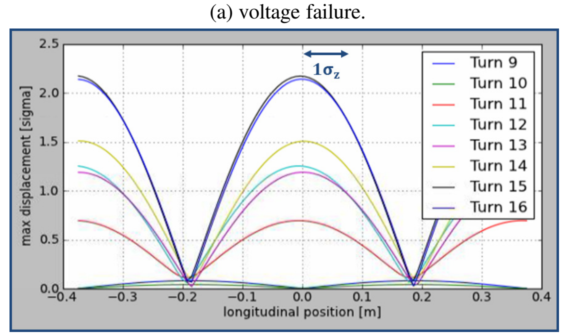
[1] In the following, often (where noted) $n_{CC} = 1$ is assumed for simplicity. The results can be easily scaled according to Eq. 4.



(a) voltage failure.



(b) phase failure.

Figure 1: The maximal displacement as function of the longitudinal position in the bunch for a dynamic failure of the compensating CC with $n_{CC} = 1$. The failure starts at turn 10. In (a) the voltage of the compensating CC is reduced. In (b) the phases of the crab cavities upstream and downstream of the IP are changed in opposite directions.

Failure Scenarios

The CC failures can be classified in three categories [5]:

- **Slow (external) failures:** E.g. a power cut, thermal problems or mechanical changes (tuner) are failures with slow time constants ($\tau \gg 1\,\mathrm{ms}$).
- **Fast external failures:** E.g. a control-logics failure, operational failure or equipment failure can lead to voltage and/or phase changes of the CCs with a time constant τ that is determined by the external Q-value: $\tau = Q_{ext}/\pi f$ [4]. For a 400 MHz CC with $Q_{ext} = 1,250,000$, the time constant is $\tau \approx 1\,\mathrm{ms} \approx 10$ turns.
- **Internal Failures:** E.g. an arc in the coupler, CC quenches or strong multipacting are potentially very

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fast failure scenarios (Q_{ext} is not directly involved). Time constants of $\tau < 1$ turn are possible.

After detecting a critical failure, the LHC Beam Interlock System and Beam Dump System extract the beams safely from the machine within 3 turns $\approx 300\,\mu$s [4].

Due to the fast time constant, failures of the second and third category are a major machine protection challenge.

CRAB CAVITY FAILURE SIMULATIONS

In the following, the results of MAD-X simulations of dynamic and static CC failures are presented[2]. The simulations are based on the *SLHCV3.1b* upgrade optics with symmetric $\beta^*_{x,y} = 15\,\mathrm{cm}$ and a full crossing angle of $\Theta = 590\,\mu\mathrm{rad}$ [3]. Complementary failure studies with nominal LHC optics can be found in [6].

In order to isolate the effect of the CC failure on the beam dynamics, the maximal transverse displacement

$$\bar{x} = \sqrt{x_\beta^2 + \left(\alpha \cdot x_\beta + \beta \cdot x'_\beta\right)^2} \qquad (3)$$

with $x_\beta = x - D_x \frac{\Delta p}{p}$ and $x'_\beta = x' - D_{x'} \frac{\Delta p}{p}$ is considered in the following (x is the transverse particle position, x' the transverse momentum divided by the longitudinal momentum and D_x and $D_{x'}$ the corresponding dispersions). With this definition, $\bar{x}$ is apart from the interaction regions constant around the accelerator.

External Failures

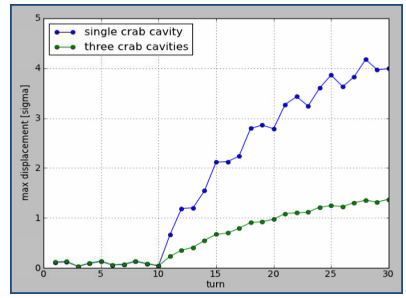
Dynamic simulations of voltage and phase failures with a time constant that is determined by Q_{ext} were done.

When a single CC has a voltage failure, the tilt-kick of the CCs is no longer locally compensated. The fastest externally driven voltage change is given if an oscillation which is inverse to the nominal oscillation is excited in the CC, while no longer driving the nominal oscillation. The maximal voltage change is then $\frac{\Delta V}{V_0} = 2 \cdot \left(1 - \exp\left(-\frac{89\,\mu s}{1\,\mathrm{ms}}\right)\right) = 17\,\%$ per turn. Figure 1a illustrates the maximal displacement as function of the longitudinal position. Particles at $\pm 2.4\,\sigma_z$ have the largest displacement of up to $2.1\,\sigma_x$ within 5 turns after the failure.

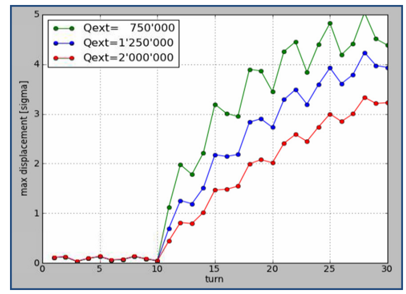
In case of a phase error, the CC no longer tilt-kicks the bunch, but also kicks the densely populated bunch center. The maximal externally driven phase change of a CC is 5.3° in the first turn [4]. The failure is worst, if the CCs upstream and downstream of the IP change phases in opposite directions, then the bunch center is maximally displaced by up to $2.1\,\sigma_x$ within 5 turns (Fig. 1b).

Figure 2a shows the temporal evolution of the maximal displacement for both cases. With $n_{CC} = 3$ but with only one erroneous CC, the resulting maximal displacement is reduced by about a factor 3. In Fig. 2b, the influence of Q_{ext} is illustrated.

[2]The simulations assume a failure of the beam 1 CCs around IP5.



(a) Failure evolution for different n_{CC}.



(b) Failure evolution for different Q_{ext}.

Figure 2: The maximum of the data from Fig. 1 is shown for each turn with one and three CCs per beam on either side of the IP (a) and for different Q_{ext} with $n_{CC} = 1$ (b).

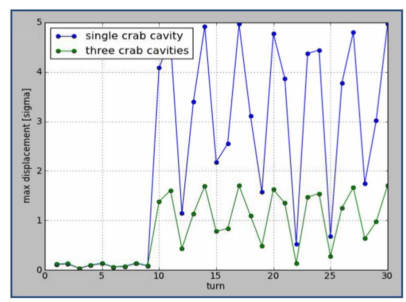


Figure 3: The maximum displacement for each turn after an instantaneous CC failure (from turn 10 onwards) of one compensating CC for $n_{CC} = 1$ and $n_{CC} = 3$.

Very Fast (Internal) Failures

For failures with time constants $\tau < 1$ turn, the maximal displacement for one erroneous CC and $n_{CC} = 1$ is about $4\,\sigma_x$ in the first turn after the failure [4]. Because the fractional tunes ($Q_x = .31$, $Q_y = .32$) are close to the third order resonance, the effect partially cancels out after three consecutive revolutions[3]. Figure 3 shows the evolution of the maximal displacement.

MITIGATION STRATEGIES

Fast CC failures that imply large global betatron oscillation are a severe machine protection concern. As shown in [4], for static and dynamic failures, the maximal displacement is proportional to:

$$\bar{x} \propto \frac{c \cdot \tan(\frac{\Theta}{2})}{f \cdot \sigma_{x,IP} \cdot \sin(\Delta\varphi) \cdot n_{CC}} \propto \frac{1}{f \cdot \beta^* \cdot n_{cc}} \qquad (4)$$

[3]Under the assumption that the failure remains constant (e.g. at $V_0 = 0\,\mathrm{V}$) after an instantaneous change of the CC properties.

with $\sigma_{x,IP}$ being the transverse beam size at the IP. This important scaling law points out that the impact of a CC failure is defined by the CC frequency, β^* and the number of independent CCs on either side of the IP (without common failure scenarios). Figure 4 illustrates the maximal displacement as a function of β^*. Especially a flat optics at the IP could mitigate the impact of a CC failure without decreasing the peak luminosity. According to Eq. 4, the impact of a CC failure could be further reduced by the use of beam-beam wire compensators, which would allow for a reduced beam-beam separation and a corresponding reduction of the crossing angle Θ [1].

Beam Halo and Passive Protection

Beam based tests in 2010/11 showed that the transverse particle distribution in the LHC has highly overpopulated tails, which contain up to $4\,\%$ of the beam beyond $4\,\sigma$ [7]. This corresponds to a stored energy of $20-25\,\mathrm{MJ}$ with HL-LHC parameters. The collimation system is designed for fast accidental beam losses of up to $1\,\mathrm{MJ}$ [4]. It has to be ensured that in a fast CC failure scenario the beam losses stay below that limit, for example by depleting the transverse beam halo by a hollow electron lens [8]. Table 1 summarizes examplary operational scenarios, which would respect these limitations.

Table 1: Operational scenarios with losses below $1\,\mathrm{MJ}$ within 5 turns, also after an instantaneous CC failure. $\sigma_{<1\,\mathrm{MJ}}$ denotes the distance (in multiples of the transverse beam size) from the primary collimator jaws which has to be depleted below a stored energy of $1\,\mathrm{MJ}$. Three independent CCs per beam on either side of the IP ($n_{CC}=3$) with $Q_{ext}=1,250,000$ are assumed. Magnet quenching in case of a CC failure is not excluded.

	Scenario 1	Scenario 2	Scenario 3
f	400 MHz	800 MHz	400 MHz
β^*	15 cm	15 cm	25 cm
$\sigma_{<1\,\mathrm{MJ}}$	$1.7\,\sigma_x$	$0.9\,\sigma_x$	$1.0\,\sigma_x$

Active Protection

A complementary mitigation strategy is a strongly coupled CC feedback between the CCs upstream and downstream of the IP [9]. With this approach, erroneous voltage and phase changes of a CC could be compensated on μs timescales by the other CCs. The reliability of the system will be demonstrated by a coupled feedback loop which is planned to be installed for the 200 MHz traveling wave cavities in the CERN Super Proton Synchrotron [9].

SUMMARY AND OUTLOOK

CC failures with very fast time constants of the order of one turn can lead to global betatron oscillations with amplitudes of several rms beam sizes. Particularly critical are phase errors since then the densely populated bunch center is displaced. A simple scaling law (cf. Eq. 4) shows that the maximal displacement is inversely proportional to the CC frequency, β^* and the number of independent CCs on either side of the IP. In order to ensure a passive protection against very fast CC failures, a depletion of the beam halo by a hollow electron lens is proposed. A strongly coupled CC feedback is a complementary mitigation approach.

A better understanding, especially of the very fast internal failures and their influence on the CC properties is still needed. Corresponding studies are foreseen for 2012.

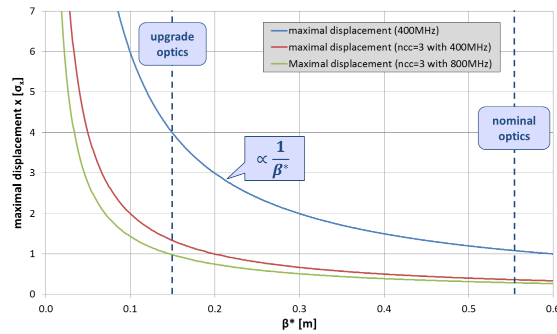


Figure 4: The maximal transverse displacement directly after an instantaneous CC failure as a function of β^* for different numbers of independent 400 MHz or 800 MHz CCs.

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