LHC MACHINE PROTECTION AGAINST VERY FAST CRAB CAVITY FAILURES

T. Baer*, CERN, Switzerland and University of Hamburg, Germany; R. Calaga, BNL, USA
R. Tomas, J. Tuckmantel, J. Wenninger and F. Zimmermann, CERN, Switzerland

Abstract

For the high-luminosity LHC upgrade program (HL-LHC), the installation of crab cavities (CCs) is essential to compensate the geometric luminosity loss due to the crossing angle [1]. The baseline is a local scheme with CCs around the ATLAS and CMS experiments. In a failure case (e.g. a CC quench), the voltage and/or phase of a CC can change significantly with a fast time constant of the order of a LHC turn [2]. This can lead to large, global betatron oscillations of the beam. Against the background of machine protection, the influence of a CC failure on the beam dynamics is discussed. The results from dedicated tracking studies, including the LHC upgrade optics, are presented. Necessary countermeasures to limit the impact of CC failures to an acceptable level are proposed.

INTRODUCTION

The HL-LHC program aims at peak luminosities that exceed the nominal LHC luminosity by a factor 5 [1]. In order to achieve this, the beam size at the interaction points (IPs) has to be reduced and the crossing angle increased. CCs are needed to compensate the associated geometric luminosity loss and for luminosity leveling. An optics solution based on the Achromatic Telescopic Squeezing scheme with a beta function at the IP of $\beta^* = 15\,\mathrm{cm}$ is proposed [3].

At KEK-B, CCs are successfully in operation since February 2007 [4]. During the operation, very fast CC failures with a complete voltage decay in $100\,\mu\mathrm{s}$ (about one LHC turn) and phase changes by up to $50\,°$ in $50\,\mu\mathrm{s}$ were observed. Figure 1 shows the behavior of CC voltage and phase in case of such a fast failure.

For the LHC, the protection against very fast CC failures is a major challenge. The LHC Beam Interlock System (BIS) and Beam Dump System are designed to extract the beam safely from the machine if a critical failure is detected. Nevertheless, it may take up to about $3\,\mathrm{turns} \approx 300\,\mu\mathrm{s}$ until the whole beam is dumped after a system connected to the BIS detects the failure [5].

ANALYTICAL DESCRIPTION OF STATIC CRAB CAVITY FAILURES

Normal Crab Cavity Operation

The transverse kick of a CC with angular frequency ω, phase Φ, and voltage $V = V_0 \cdot \sin(\Phi + \omega t)$ is given by

$$\Delta p_x = -\frac{q}{E} \cdot V_0 \cdot \sin\left(\Phi + \frac{\omega z}{c}\right) \qquad (1)$$

* contact: Tobias.Baer@cern.ch

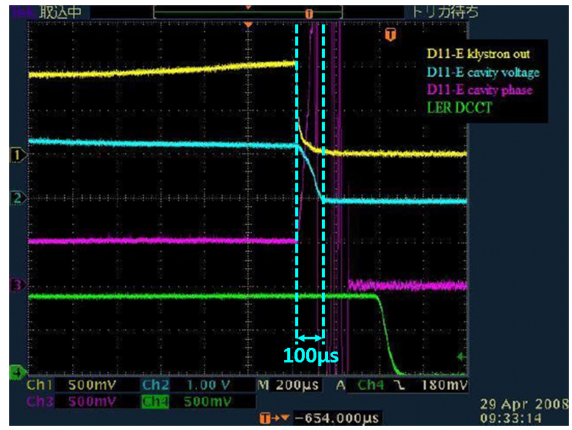


Figure 1: KEK-B CC voltage and phase after a fast failure. The voltage decays completely in $100\,\mu\mathrm{s}$. Large oscillations of the cavity phase are observed. (courtesy of K. Nakanishi et al. [4])

where q is the particle charge, E the particle energy, z the longitudinal particle position w.r.t. the bunch center, c the velocity of light and x the plane of the crossing angle and the kick of the CCs [6].

During normal operation, the CC voltages are tuned to compensate the crossing angle Θ for the core of the bunch. Assuming a nominal CC phase of $\Phi = 0$, the optimal voltage for a single CC upstream of the IP is given by:

$$V_0 = -\frac{c \cdot E \cdot \tan(\frac{\Theta}{2})}{q \cdot \omega \cdot \sqrt{\beta^* \beta_{CC}} \cdot \sin(\Delta\varphi)} \qquad (2)$$

with β^* and β_{CC} being the beta functions at the IP and at the CC, respectively [6]. $\Delta\varphi = \varphi_{IP} - \varphi_{CC}$ denotes the betatron phase advance from the CC to the IP.

In order to allow an optimal closure of the tilt-kick, the betatron phase advance between the CCs upstream and downstream of the IP should be $180\,°$. The amplitude of the voltage of a single CC downstream of the IP is $\tilde{V}_0 = -R_{22} \cdot V_0$ with R_{22} being the (2, 2) element of the optical transfer matrix from the CC upstream of the IP to the CC downstream of the IP [6].

Beam Dynamics of Static Crab Cavity Failures

With the voltage given by Eq. 2, the transverse displacement of a particle at the longitudinal position s due to the kick of a single CC (we consider only the CC upstream of the IP here) is

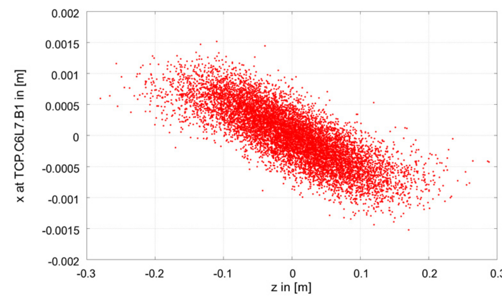
$$\frac{\Delta x(s,\Phi,z)}{\sigma_x(s)} = \frac{\sqrt{\beta_{CC}}}{\sqrt{\epsilon_x}} \cdot \Delta p_x \cdot \sin\left(\varphi(s) - \varphi_{CC}\right)$$
$$= \frac{c \cdot \tan(\frac{\Theta}{2})}{\omega \cdot \sigma_{x,IP} \cdot \sin(\Delta\varphi)} \sin\left(\Phi + \frac{\omega z}{c}\right) \sin\left(\varphi(s) - \varphi_{CC}\right) \tag{3}$$

with ϵ_x being the transverse emittance and $\sigma_x(s) = \sqrt{\beta(s)\epsilon_x}$ the transverse beam size. Values for nominal LHC optics and the LHC upgrade optics [3] are given in Table 1.

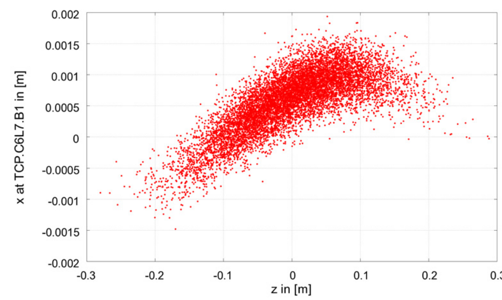
Since the working point of the LHC is close to a third order resonance, static failures which result in disturbed trajectories outside of the interaction region, will not add up, but mainly cancel out after three consecutive revolutions.

In case of a voltage failure of a single CC (e.g. due to a cavity quench) the tilt-kick of the CCs is no longer locally compensated. The displacement outside of the interaction region is given by Eq. 3. Figure 2a shows the bunch shape after a drop of the voltage of one cavity to $V_0 = 0$.

In case of a phase error (i.e. $\Phi \neq 0$) the CC no longer tilt-kicks the bunch, but also kicks the bunch center. According to Table 1, for a 90 ° phase shift, the bunch center can be displaced by up to about $4\,\sigma$ for the upgrade optics and about $1\,\sigma$ for nominal optics. Assuming that the phase error is limited to one CC only, the uncompensated tilt-kick from the second CC comes on top, resulting in even larger displacements. The resulting bunch shape is shown in Fig. 2b.



(a) Voltage failure.



(b) 90 ° phase error.

Figure 2: The bunch shape at the primary collimator TCP.C6L7.B1 after an instantaneous voltage change to $V_0 = 0$ of the CC downstream of IP5 (a) and after an instantaneous 90 ° phase shift of the CC upstream of IP5 (b) for beam 1. x denotes the transverse coordinate, z the longitudinal coordinate. The trajectories of 10.000 particles are tracked using the LHC upgrade optics and single 400 MHz CCs in the local scheme around IP5.

DYNAMIC CRAB CAVITY FAILURES

Crucial for the impact of a real CC failure is its timescale. The natural (i.e. without additional RF input) time constant τ of a superconducting CC is determined by the external Q-value: $\tau = 2 \cdot Q_{ext}/\omega$ [7]. For a 400 MHz CC with $Q_{ext} = 1,250,000$ the resulting time constant is $\tau = 1\,\mathrm{ms}$. The resulting natural voltage decay is not more than $\frac{\Delta V}{V_0} = 1 - \exp\left(-\frac{89\,\mu s}{1\,\mathrm{ms}}\right) = 9\,\%$ per turn. A phase change is limited to $\arctan(\frac{1-\frac{\Delta V}{V_0}}{\frac{\Delta V}{V_0}}) = 5.3\,°$ in the first turn.

Dynamic MAD-X tracking studies based on the upgrade optics with $\beta^* = 15\,\mathrm{cm}$ were carried out. A local scheme around IP5 with single CCs on either side of the IP is considered. The collimators are set according to [8]. 10.000 particles in a Gaussian particle distribution with a normalized emittance of $\epsilon_{x,y}^{n,1\sigma} = 3.75 \cdot 10^{-6}\,\mu\mathrm{m} \cdot \mathrm{rad}$ are tracked for 30 turns with the failure starting after 10 turns. In case of a voltage decay of a single CC only $0.2\,‰$ of the particles are lost within 20 turns after the failure. In case of a phase error, $0.5\,‰$ of the particles are lost. The significance of the timescale of the failure is seen when reducing Q_{ext} to $750,000$: Then a fraction of $2.4\,‰$ (5 times more) of the particles is lost in case of a phase error. All particles are lost at primary collimators.

These values have to be compared to the design peak beam losses of the LHC collimation system, which are $5 \cdot 10^{-5}$ of the beam for transient losses with a duration of 10 turns and in an accidental case up to 8 consecutive bunches, i.e. $2.8\,‰$ of the beam [8].

It has to be noted that the tracking studies only respect natural cavity changes. A strong external RF feedback could lead to faster voltage and/or phase changes. Also no misalignments, optics errors or magnetic field errors are taken into account.

MITIGATION STRATEGIES

Fast CC failures that imply a global betatron oscillation are a severe machine protection issue. The displacement for static and dynamic failures is proportional to the constant prefactor in Eq. 3:

$$Z = \frac{c \cdot \tan(\frac{\Theta}{2})}{\omega \cdot \sigma_{x,IP} \cdot \sin(\Delta\varphi)}. \tag{4}$$

Taking into account that the crossing angle Θ is proportional to $1/\sqrt{\beta^*}$, and assuming $\Delta\varphi = 90\,°$ yields

$$Z \propto \frac{1}{\omega \cdot \beta^* \cdot n_{cc}}. \tag{5}$$

Where n_{cc} is introduced as the number of independent CCs on either side of the IP. This important scaling law points

Table 1: Transverse displacement due to the uncompensated kick of a single $400\,\mathrm{MHz}$ CC for nominal LHC optics ($\beta^* = 55\,\mathrm{cm}$, $\Theta = 285\,\mu\mathrm{rad}$) and LHC upgrade optics ($\beta^* = 15\,\mathrm{cm}$, $\Theta = 580\,\mu\mathrm{rad}$) with $\Delta\varphi = 90\,°$, $\sin(\varphi(s) - \varphi_{CC}) = 1$ and a transverse normalized emittance of $\epsilon_x^{n,1\sigma} = 3.75\,\mu\mathrm{m} \cdot \mathrm{rad}$.

	nominal optics	upgrade optics
Displacement of particle with $z = 7.55\,\mathrm{cm}$ ($= 1 \cdot \sigma_z$)	$0.60\,\sigma_\mathrm{x}$	$2.36\,\sigma_\mathrm{x}$
Maximal displacement with $\sin\left(\Phi + \frac{\omega z}{c}\right) = 1$	$1.02\,\sigma_\mathrm{x}$	$3.98\,\sigma_\mathrm{x}$

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. The LHC upgrade optics foresees up to two CCs per beam on either side of the IP. It needs to be taken into account that each additional CC increases the total impedance. Figure 3 shows the maximal displacement as a function of β^*.

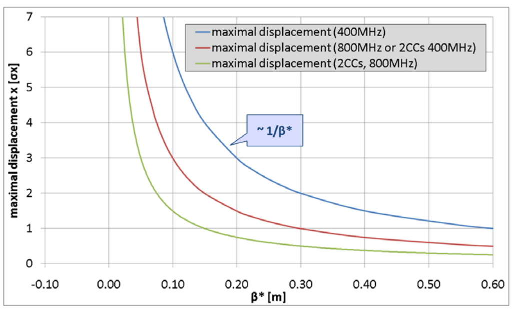


Figure 3: The maximal displacement for $\sin\left(\Phi + \frac{\omega z}{c}\right) = 1$ as a function of the beta function at the IP by a single or two independent $400\,\mathrm{MHz}$ or $800\,\mathrm{MHz}$ CCs.

Beam Halo

Beam based tests in 2010 and 2011 showed that the transverse particle distribution in the LHC is far from an ideal Gaussian distribution. Highly overpopulated tails containing up to $4.5\,\%$ of the beam beyond $4\,\sigma$ (measured beam size) from the beam centre were observed [9]. This corresponds to a stored energy of about $16\,\mathrm{MJ}$ for nominal operation. In a fast failure scenario, significant amounts of the beam halo (several MJ) can be lost within a few turns. It must be ensured that either the collimation system can provide passive protection against these losses or that the tail population can be controlled, for example by using a hollow electron lens.

Mitigation on the Cavity Level

The timescale of the losses is of crucial importance, as the tracking studies show. Corresponding mitigation strategies are on the level of the cavity and try to minimize and delay the effect of a failure on the beam [2]. In order to achieve a fast reaction time, the failure detection has to be done on the cavity level as well. It has to be taken into account that a reliable failure detection is complicated when a feedback system counteracts the failure symptoms at the same time.

SUMMARY AND OUTLOOK

CC failures can have time constants of the order of a few LHC turns and can lead to global betatron oscillations with amplitudes of several beam sizes. The displacement is given by Eq. 3, the time constant is determined by the external Q-value of the CC. Especially critical are phase errors since then the densely populated bunch center is displaced. For nominal operation, a simple scaling law (cf. Eq. 5) 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. A passive protection against a loss of the beam halo has to be ensured (e.g. a depletion of the beam halo by a hollow electron lens could mitigate the problem).

The beam halo will be included in future tracking studies. Furthermore, the implications of a strong external feedback will be studied.

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