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MACHINE PROTECTION EXPERIENCE FROM BEAM TESTS WITH CRAB CAVITY PROTOTYPES IN THE CERN SPS*

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Abstract

Crab cavities (CCs) constitute a key component of the High Luminosity LHC (HL-LHC) project. In case of a failure, they can induce significant transverse beam offsets within tens of microseconds, necessitating a fast removal of the circulating beam to avoid damage to accelerator components due to losses from the displaced beam halo. In preparation for the final design to be employed in the LHC, a series of tests were conducted on prototype crab cavities installed in the Super Proton Synchrotron (SPS) at CERN. This paper summarizes the machine protection requirements and observations during the first tests of crab cavities with proton beams in the SPS. In addition, the machine protection implications for future SPS tests and for the use of such equipment in the HL-LHC are discussed.

INTRODUCTION

Crab cavities will be used in the HL-LHC to counteract the loss of luminosity due to the increase of the crossing angle [1] by providing a longitudinally dependent transverse kick to the beam. With kicks up to 3.4 MV, they are capable of producing critical beam losses within tens of microseconds in the case of a failure [2, 3]. A reliable interlocking strategy must therefore be employed, to ensure that the beams are extracted by the beam dumping system when a failure or incorrect operational parameters are detected.

In preparation for the series production, tests on prototype CCs were conducted in the SPS, the last accelerator in the injector chain before the LHC [4, 5]. Having a lower energy, less beam intensity and being non-superconducting with short cycles, it provides a flexible and relatively safe base for the prototype tests. Nevertheless the SPS beam is still capable of causing damage when uncontrolled beam losses occur [6], and it is necessary for the CC tests to be conducted either at safe beam intensities/energies, or with appropriate fast hardware interlocks in place. The implementation and testing of these interlocks provides important experience for the HL-LHC and for further use of CCs in the SPS.

CRAB CAVITIES IN THE SPS

The two prototype cavities installed in 2018 were of the Double Quarter Wave (DQW) type and acted vertically on the beam [7]. They were installed in *LSS6* in a cryomodule mounted on a translation table, enabling their removal from the beamline when not in use [8]. The prototype RF Dipole cavities, acting horizontally, will be tested in 2022 at the same location. There are two operational modes for the CCs: phased mode, where both CCs apply the same kick to the bunch; and counter-phased mode, where the second CC cancels the kick of the first, giving transparent operation.

The CC failure modes can be classified as follows: voltage drop, phase jump, detuning and quenching [3]. The maximum orbit offset due to a kick of the CCs, normalized to the transverse beam size σ, follows from:

$$\Delta y(s) = \frac{qV}{E} \cdot \sqrt{\frac{\beta_{CC}\gamma}{\epsilon_n}}$$

where q is the elementary charge, V the CC voltage, E the beam energy, β_{CC} the vertical betatron function at the position of the CCs, ϵ_n the normalized emittance and γ the Lorentz factor. With an emittance of $\epsilon_n = 2.5\,\mu$m · rad and $\beta_{CC} = 76$ m, this gives a kick of 1.12 and 0.35 σ/MV at 26 and 270 GeV respectively, the beam energy range used.

In the SPS, the internal dump has a slightly smaller vertical aperture than the overall machine, namely 7.3 σ at injection energy, but in reality beam losses following a failure depend on the actual orbit as well as the phase advance from the CCs. Due to the rather large aperture of the SPS, it is unlikely that a simple kick from the CCs would cause any unacceptable beam losses. Subsequently, neither voltage drops nor phase jumps are a concern for the SPS.

The worst case is a detuning of the cavity, with a continuous phase slip in resonance with the betatron tune. For a CC voltage of 2 MV and a beam energy of 270 GeV, the rise time of the orbit excursion was determined from simulations with MAD-X [9] to be on the order of 100 SPS turns. Since one SPS turn takes $\sim 23\,\mu$s, relying on the SPS beam loss monitors (BLMs) to detect the resulting losses and dump the beam is not sufficient due to its reaction time of 20 ms [10].

Detuning and similar failures can occur in different ways:

- Synchronization problems between CC and main beam RF: if the frequency between the two RF systems is not synchronized, there is a continuous slip in the phase of the kick with respect to the beam.
- Change of the main RF during energy ramp: In the SPS the CCs cannot follow the rapid frequency swing of the main beam RF of $\Delta f = 130$ kHz during the ~ 6 s long energy ramp from 26 to 270 GeV, making synchronization impossible.
- Low Level RF driving a change of frequency or phase, e.g. due to CC tuning or operational errors.

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BEAM INTERLOCKING

The general damage limit for accelerator equipment has been derived empirically based on a damage experiment [11] and can be calculated from

$$I \cdot \left(\frac{E}{450}\right)^{1.7} < 1 \times 10^{12}$$

where I is the number of lost protons and E their energy in GeV. Fast, localized beam losses above this limit would risk damaging the point of impact. However, depending on the type of accelerator equipment and the local beam size, critical damage can occur well below the above limit [12]. Taking this into account, a safety factor of 10 was introduced for the CC tests, implying ≤ 110 and ≤ 2 nominal bunches of 1.15×10^{11} p^+/bunch at 26 and 270 GeV, respectively.

To protect against detuning failures with high intensity beams, a fast hardware RF interlock based on a phase difference between the CCs and the SPS main RF system was implemented and successfully tested (see Fig. 1). During the interlock validation test, the CC frequency was slowly changed, while the main RF frequency remained constant. As the threshold is reached, the RF interlock signal (blue) switches to high. This is recognized by the beam interlock system (BIS) which in turn triggers the beam dump. The beam is dumped within five turns, giving a total reaction time of $< 120\,\mu$s after the phase threshold was reached.

This interlock protects against any detuning failures, as it is faster than the rise-time of losses in even the worst conceivable cases. However, it can only be activated after the CCs have been synchronized with the main beam RF system. Otherwise it would abort the beam due to the phase slip between the CCs and the main RF during the first part of every cycle [5]. To determine the maximum allowed phase shift and to derive the required thresholds of the phase interlock, dedicated beam experiments were performed.

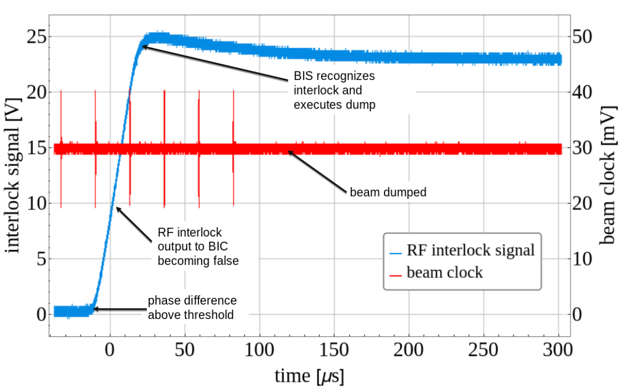

Figure 1: Test of the hardware interlock on phase difference between CCs and main beam RF. As the phase difference reaches its threshold, the RF interlock signal (blue) to the beam interlock system (BIS) changes to high making the BIS trigger a beam dump. The beam clock (one "spike" per turn) is shown in red.

OBSERVED FAILURES

During the CC beam tests two different types of events leading to significant beam losses were observed: a slow partial beam loss over seconds and a very fast full beam loss within several milliseconds. Both types were caused by detuning-like issues.

Slow Losses

occurred due to an issue with the tuner loop of one of the CCs on several occasions, such that a low voltage (< 10 kV) was induced with a varying frequency. This led to the vertical betatron tune being crossed several times, inducing beam losses. Due to the low voltage, the beam was lost over a relatively long time, from 0.5 s up to the full cycle of 19 s, and this type of failure could be adequately protected against by the BLM system.

Fast Losses

were caused by having the CCs fixed at a certain frequency and then letting the beam ramp from 26 GeV to 270 GeV. During the energy ramp, the CC kick crossed the betatron tune several times. Figure 2 shows the orbit offset in units of beam σ, as measured by beam position monitors (BPM), as well as the beam response as simulated by a four-dimensional (longitudinal and vertical) transfer matrix method during one of the observed fast loss events. There is a good agreement between measurement and simulation until the beam intensity drops below the sensitivity of the BPMs.

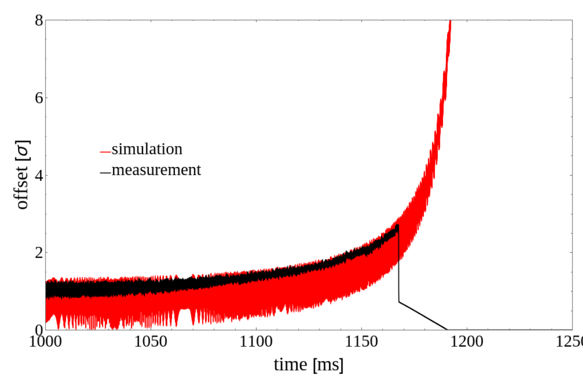

Figure 2: Measured (black) and simulated (red) orbit offset during ramp with CCs at 1 MV. The beam is excited by the effective phase slip of the CC excitation due to the beam revolution frequency changing as an effect of the beam energy increase.

The decay time, defined as a drop of the beam intensity from 90% to 10% of the initial value was measured at different beam energies by setting one of the CCs to activate, with a voltage of 0.8 MV, at different times during the ramp. Capture losses due to the ramp are excluded from the decay time estimate. The results are shown in Fig. 3. The measurements (green, red, blue and cyan) show the beam intensity, while the black curve corresponds to the phase slip of the CC excitation on the beam as it changes throughout the ramp, starting at 1000 ms. The dashed red lines indicate the tune

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(0.18) and its complement. The temporal resolution of the intensity measurement is 5 ms.

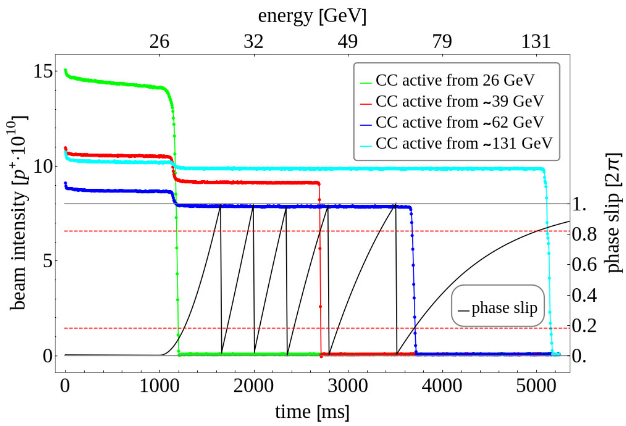

Figure 3: Change of beam intensity during the energy ramp, when activating the crab cavities at different energy levels. The starting time corresponds to the moment of injection. The energy ramps start at 1000 ms. The green, red, blue and cyan curves show the beam intensity during the different measurements. The black curve shows the phase slip as it changes throughout the ramp, and the dashed red lines indicate when it crosses the tune and its complement.

The beam was quickly lost in all cases. The observed decay times are summarized in Table 1. There is not a simple dependence of the decay time on the beam energy. To better understand this, the measurements in Fig. 3 is shown in more detail in Fig. 4, with the normalized intensity, from the moment that the CCs are switched on, versus the effective phase slip of the CCs. The vertical beam tunes are indicated by the black lines.

Table 1: Summary of decay times defined as going from 90% to 10% of the initial beam intensity, excluding capture losses due to the ramp.

energy [GeV]	26	39	62	131
decay time [ms]	40	15	40	60

The 26 GeV case of Fig. 3 corresponds to the BPM measurement in Fig. 2. The beam is fully lost before reaching the betatron resonance which is due to the low beam rigidity and the small normalized aperture. Furthermore, significant losses start already at time 1140 ms. This cannot solely be explained by the mean orbit offset of the bunch, and is believed to be due to space charge induced tune depression, which is up to $\Delta Q \approx 0.1$ in the nominal SPS [13].

With increasing beam energy, the beam rigidity increases, implying a slower loss rise time. Meanwhile the reduced tune depression causes a faster loss rise time. However, the latter is mainly relevant if the tune is approached from below. The fastest observed loss rise time was for an effective approach of the tune from above (39 GeV case) with a full beam loss in < 20 ms, which is significantly faster than the 62 GeV case where the tune was approached from below.

For the 131 GeV case the CCs were switched on just at the moment when the resonance should have occurred, which could explain the small initial response and the increased decay time of the beam intensity.

The experimental results confirm that a dedicated phase interlock is required to avoid the loss of a major part of the beam due to detuning-like errors. Based on the results discussed above and taking into account the values of the horizontal and vertical tunes ($Q_h = 0.13$, $Q_v = 0.18$), the phase interlock for CC tests in the SPS should not allow a phase change of more than ±15 degrees.

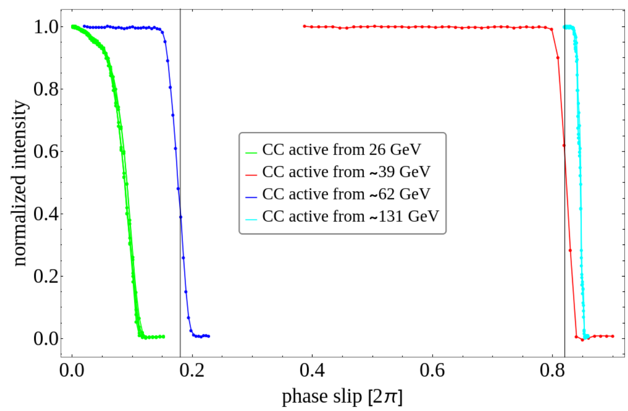

Figure 4: Energy scan of the fast losses during ramp, with the normalized beam intensity versus the phase slip. The black vertical lines indicate the vertical tune, as well as its complement. The beam intensity resolution is 5 ms.

CONCLUSIONS

For the first time machine protection tests have been performed with CCs in a proton accelerator. These tests confirmed the results of previously studied failure scenarios. The fastest losses observed were due to resonant beam excitation during the energy ramp of the beam, when the phase of the crab cavity crosses the betatron tune. To allow the operation of CCs in the SPS with unsafe beam intensities, a fast hardware interlock of the phase difference between the main beam RF and CC RF is required. In addition, it needs to be ensured that the CC voltage stays below 50 kV during the energy ramp, as its frequency cannot follow the change of the main RF. Should the crab cavities be used during high intensity SPS operations, this requirement needs to be ensured by a hardware interlock on the voltage.

Due to the significantly higher stored energy in the beams in the future HL-LHC, the CCs will require dedicated hardware interlocks of voltage, frequency and phase to avoid very fast kicks and resonant excitation of the beam leading to critical losses in the collimation region.

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