PHASE ADVANCE INTERLOCKING THROUGHOUT THE WHOLE LHC CYCLE

K. Fuchsberger, A. Calia, M.-A. Galilée, G.H. Hemelsoet, M. Hostettler,
D. Jacquet, J. Makai, M. Schaumann, CERN, Geneva, Switzerland

Abstract

Each beam of CERN's Large Hadron Collider (LHC) stores 360 MJ at design energy and design intensity. In the unlikely event of an asynchronous beam dump, not all particles would be extracted immediately. They would still take one turn around the ring, oscillating with potentially high amplitudes. In case the beam would hit one of the experimental detectors or the collimators close to the interaction points, severe damage could occur. In order to minimize the risk during such a scenario, a new interlock system was put in place in 2016. This system guarantees to keep the phase advance within an acceptable range between the extraction kicker and the interaction point. This contribution describes the motivation for this new system as well as the technical implementation and the strategies used to derive appropriate tolerances to allow sufficient protection without risking false beam dump triggers.

INTRODUCTION

Various options for the operational configuration of the LHC for 2016 were proposed during the 6th Evian Workshop [1] and the LHC Performance Workshop (Chamonix 2016) [2]. In order to reach $\beta^* = 40$ cm, the margins in the collimation hierarchy were reduced. This was possible because the betatron phase advance from the dump kickers (MKD) to the tertiary collimators (TCTs) and triplets was chosen such that the risk of damaging the TCTs or triplets was limited (as close to zero degrees as possible). While this nominal configuration was intrinsically safe in this aspect, adjustments during operation (e.g. tune trims) can change the phase advance and could potentially move out the configuration from the safe regime. To prevent such - potentially risky - situations, a new interlocking layer was put in place to constrain the changes in the phase advance during operation.

From the aspect of software changes, this was a relatively straightforward extension from the existing Power-converter Interlock System (PcInterlock), the primary purpose of which was to prevent against unnoticed closed orbit bumps [3]. However, the strategy of choosing the tolerances and the mechanics to derive current limits had to be revisited for this particular use-case. Some protection aspects as well as general details of the tolerance generation will be explained in more detail in the following sections.

Choosing values for tolerances has to balance sufficient protection against availability aspects. This aspect will become particularly important in the 2017 run, because the optics choice for 2017 - Achromatic Telescoping Squeeze (ATS) [4] - leaves far less room for phase advance adjustments. To not compromise availability, a detailed analysis on the stability of the power converters during the LHC cycle was done and lower limits for current tolerances were derived from this [5].

MACHINE PROTECTION ASPECTS

In the failure case of an asynchronous beam dump in the LHC (the dump kicker, MKD, fires while there is beam passing by), the main part of the miss-kicked particles are absorbed by the collimator between the MKD and the next quadrupole, the so-called TCDQ. However, a certain amount of particles is expected to escape the TCDQ. These particles have still the potential to damage the tertiary collimators (TCTs), in front of the experiments. To avoid such damage, the TCTs are retracted further than the TCDQ, such that the beam can pass and no damage occurs. In order to gain sufficient protected aperture to squeeze β^* to 40 cm, this retraction was reduced from about 6 σ to about 1 σ. This was justified (amongst other arguments) by rematching the phase advance between MKD and TCTs to 0° [6]. This principle is illustrated in Fig. 1.

Even with a rematched phase advance, there was no system in place, which could ensure that this phase advance is stable enough and always fulfills the requirements in the event of an asynchronous beam dump. This gap was filled by the implementation of a new interlocking strategy on the quadrupole currents, as discussed in the following sections.

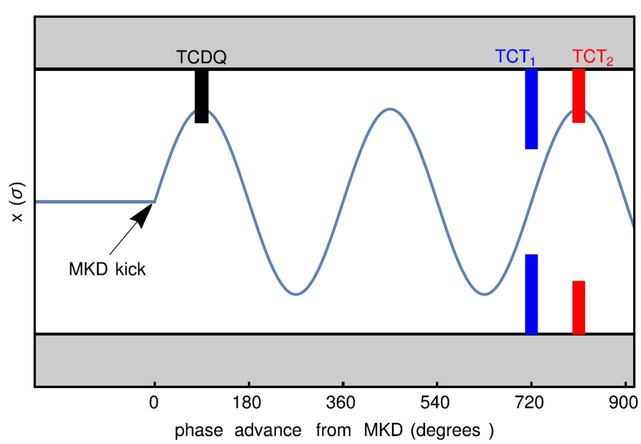

Figure 1: Principle of avoiding damage on the TCTs by constraining the phase advance between MKD and TCT to 0°: If the TCT would be at 90° phase advance, the remaining particles would fully hit the TCTs (case of TCT_2, red). In case of 0° (TCT_1, blue), the beam just passes through the TCTs and no damage occurs. Courtesy of R. Bruce [6].

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POWERCONVERTER INTERLOCK SYSTEM

This interlock system was introduced for the LHC in 2012 [3]. Its primary use case, up to now, was the interlock of orbit corrector currents. The operational principle of this system is the following:

- A reference current-function is defined for each magnetic circuit (power-converter) to interlock, representing the nominal current evolution for each beam process of the LHC, established at the time of commissioning of the nominal cycle.
- On top of this, each circuit and beam process is assigned a tolerance-function (always positive), specifying how much the current of the given circuit is allowed to vary around the reference.
- The PcInterlock system takes the measured current of each circuit and checks if the measurement lies within the reference ± tolerance (both corresponding to the actual point in time of the ongoing cycle). In case the measured current is outside the tolerance band, the respective circuit is considered as interlocking.
- Interlock signals are generated and, depending on different strategies, the beam is dumped as soon as the dump strategy conditions are met. For the orbit correctors, the condition is that at least two circuits for one beam and one plane have to be interlocking to trigger a dump, since closed orbit bumps should be avoided. For quadrupoles, the condition is that already one circuit would trigger a dump, because here a constant phase advance has to be ensured.

Figure 2 shows an example of the current evolution of one power-converter during the squeeze as seen by the PcInterlock system. The reference function is shown in red with a shaded red tolerance band. If the measured current (shown in blue) would go out of the tolerance band, the circuit would interlock.

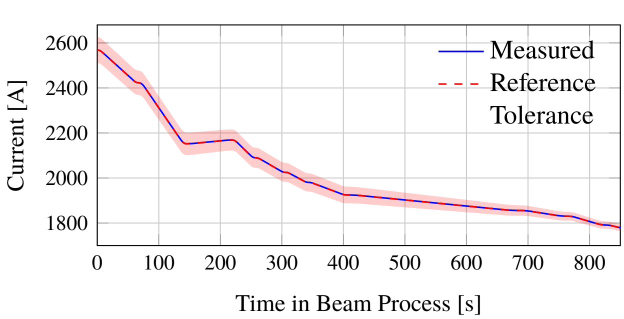

Figure 2: Example power-converter current evolution.

TOLERANCE GENERATION FOR QUADRUPOLES

Deviations from the nominal quadrupole strengths sum up to a total phase error in the machine. The effect of each individual strength error depends on the beta-function at the

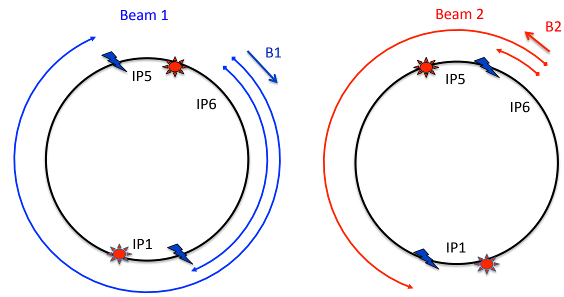

Figure 3: Tolerance generation ranges of the LHC ring.

quadrupole and thus on its position in the machine. For the failure case described here, four distinct ranges of the LHC have to be considered (see Fig. 3): for each beam, the range from the dump kickers (in IP6) to the interaction points IP1 and IP5, respectively.

The total budget for the allowed phase-advance deviation, $\Delta\mu^{\text{budget}}$, is based on machine protection considerations and defined by the Collimation Working Group [6]. In 2016, $\Delta\mu^{\text{budget}} = 30°$ was tolerable, while for 2017, with ATS optics, only $\Delta\mu^{\text{budget}} = 4°$ is acceptable.

Since the tolerances have to be recomputed for every new optics configuration, a simple command line tool, using JMad [7, 8], was developed to perform this repetitive task. The computation is based on the following:

- All phase-advance changes are taken as absolute values, in order to assume the worst cases scenario and avoid sign-convention problems.
- Define magnet families and use the same tolerances for groups of magnets with the same purpose. This keeps the number of different tolerance values small for easier maintainability.

The total phase-advance budget is the sum of phase budgets, $\Delta\mu_f^{\text{budget}}$, per family $f \in F$ (F is the set of all defined families),

$$\Delta\mu^{\text{budget}} = \sum_{f \in F} \Delta\mu_f^{\text{budget}}. \tag{1}$$

These family budgets, $\Delta\mu_f^{\text{budget}}$, are given as inputs to the tolerance generation tool. For simplicity, the computation is done in terms of magnet strength, k, rather then current. The tolerance on the strength, k_m^{tol}, of a magnet $m \in M_f$ (M_f is the set of magnets in family f) is derived as follows:

1. For each $m \in M_f$, the phase-advance change $\Delta\mu_s$, resulting from a fixed change in magnet strength ($\Delta k_m = 10^{-5}\ \text{m}^{-2}$) is estimated linearly for each segment $s \in S$ (S is the set of segments to consider, see Fig. 3). The *phase response*, $r_{m,s}$, of the magnet m on segment s is then defined as:

$$r_{m,s} = \frac{\Delta\mu_s}{\Delta k_m}. \tag{2}$$

2. The (worst case) response of a whole family f is then given by

$$R_{f,s} = \sum_{m \in M_f} \left| r_{m,s} \right|. \tag{3}$$

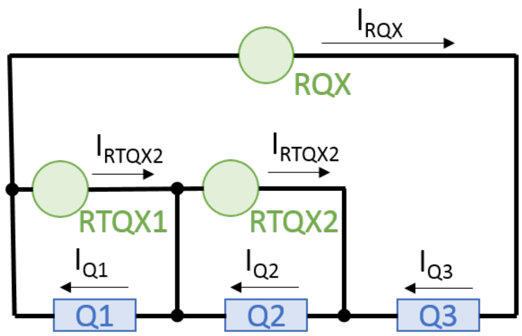

Figure 4: Powering logic of the triplets. The blue rectangles indicate the three triplet quadrupoles (Q1, Q2, Q3) and the three power-converters (RQX, RTQX1, RTQX2) are displayed as the green circles.

3. From this a resulting tolerance per family and segment can be derived:

$$k^{\mathrm{tol}}_{f,s} = \frac{\Delta\mu^{\mathrm{budget}}_{f}}{R_{f,s}}. \tag{4}$$

4. The final family tolerance, k^{tol}_{f}, which will be applied to each magnet in f, is given by:

$$k^{\mathrm{tol}}_{f} = \min\left(k^{\mathrm{tol}}_{f,s}\right) \qquad \text{with} \qquad s \in S. \tag{5}$$

Configuration Management

To keep the interlock system simple and reliable, the interlocking is always done on current-level. However, to configure the system, it is much more convenient to work on k-level, as described in the previous section. Therefore, the tolerances are configured on k-level and stored in the LHC Software Architecture (LSA), from which the PcInterlock takes its settings. LSA internal mechanisms (so-called *makerules*) are used to convert the strength values to currents. LSA is the natural place to perform this transformation, because all required information is already available: e.g. the magnet transfer-functions that describe the relation between the magnet current and the magnetic field, as well as the beam momentum at a given time.

Special attention has to be given to the triplet circuits. These circuits consist of three magnets and three power converters, using a nested powering scheme as sketched in Fig. 4. All other quadrupoles have a one-to-one relation to their power-converter. The currents through the three triplet quadrupoles ($Q1, Q2, Q3$) are given by:

$$I_{Q1} = I_{RQX} + I_{RTQX1}, \tag{6a}$$
$$I_{Q2} = I_{RQX} + I_{RTQX2}, \tag{6b}$$
$$I_{Q3} = I_{RQX}. \tag{6c}$$

The standard makerule for the driving current would simply invert these equations and distribute the current to the power-converters as follows:

$$I_{RQX} = I_{Q3}, \tag{7a}$$
$$I_{RTQX1} = I_{Q1} - I_{Q3}, \tag{7b}$$
$$I_{RTQX2} = I_{Q2} - I_{Q3}. \tag{7c}$$

This strategy would not work for the tolerance generation, because e.g. the tolerance for I_{RTQX1} would become zero in case the calculated tolerances for I_{Q1} and I_{Q3} would be equal. Therefore, the following strategy was chosen to calculate the triplet current tolerances:

$$I^{\mathrm{tol}}_{RQX} = \min\left(\frac{I^{\mathrm{tol}}_{Q1}}{2}, \frac{I^{\mathrm{tol}}_{Q2}}{2}, I^{\mathrm{tol}}_{Q3}\right), \tag{8a}$$
$$I^{\mathrm{tol}}_{RTQX1} = \frac{I^{\mathrm{tol}}_{Q1}}{2}, \tag{8b}$$
$$I^{\mathrm{tol}}_{RTQX2} = \frac{I^{\mathrm{tol}}_{Q2}}{2}. \tag{8c}$$

LOWER TOLERANCE LIMITS

The main part of this paper focused on the machine protection point of view. However, it also has to be taken into account that if tolerances would be set too tight, the machine availability could be compromised. In this case, the risk of false dumps, due to, e.g., fluctuations of the magnet currents, would be increased. To avoid such situation, detailed analysis was performed on the data of quadrupole currents for the years 2015 and 2016. It could be shown that reasonable tolerances are achievable, even for the tightened constraints of ATS optics in 2017. Details of this analysis, as well as concrete values for tolerances, can be found in [5].

CONCLUSIONS

The new interlocking strategy on quadrupole currents for the LHC is motivated by the tighter requirements on phase-advance changes between MKD and TCTs to protect against damage of the TCTs in case of an asynchronous beam dump. The new interlock is based on the well-established PcInterlock system, which takes the measured currents of the magnetic circuits and compares them to reference functions. To set the tolerances for the interlocks correctly, a special tool was created, distributing the allowed tolerance according to the different purpose of the magnets. The interlock became active in mid-run of 2016 and will be active in 2017 right from the beginning.

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