ABORT GAP KEEPER AND ABORT GAP PROTECTION

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Abstract

In view of the newly implemented variable Abort Gap Keeper (AGK), this paper will review the protection layers that should prevent an injection of beam into the abort gap and identify the critical regions inside the abort gap. In particular, it will examine the accidental injection of several bunches into the abort gap after a filling-pattern change in September 2017 and discuss the lessons learned.

INTRODUCTION: ABORT GAP

MKD rise time and abort gap

To avoid losses during the rise time of the LHC extraction kickers (MKD), a 3 µs long abort gap in the circulating ring has to be kept free of particles. The first RF bucket outside the abort gap is defined as Bucket 1. Particles in Bucket 1 receive a kick corresponding to 100 percent of the reference kick. This is ensured by adjusting the time delay of the MKD waveforms accordingly.

To ensure that no beam is injected into the abort gap, the last legal injection bucket is given by the length of the abort gap and the maximum length of the injected bunch trains, with the latter corresponding to the injection kicker (MKI) flat-top length. This leads to a required length of the so-called Abort Gap Keeper (AGK), which is given by the sum of the abort gap length and the maximum injected bunch train length. A schematic overview of the MKD waveform and the required Abort Gap Keeper length is shown in Fig. 1.

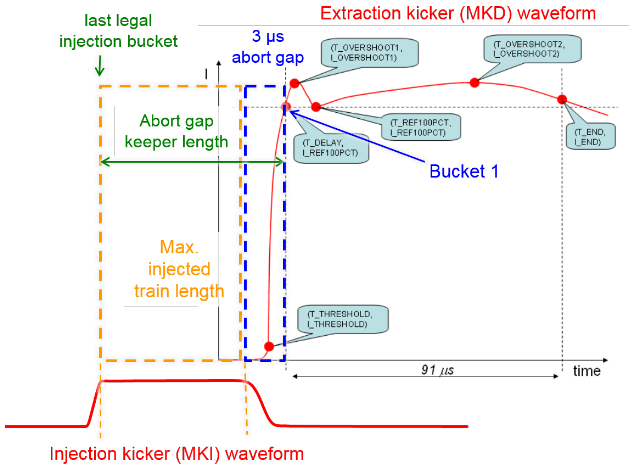

Figure 1: Extraction kicker (MKD) waveform. The 3 µs long abort gap for the MKD rise time and the required Abort Gap Keeper (AGK) length are indicated. Drawing modified from [1].

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Accidental injection into the abort gap leads to the same consequences as a so-called asynchronous beam dump. Asynchronous beam dumps can be caused by loss of synchronisation of the MKD rise time with the abort gap, e.g. in case of failure of the Trigger Synchronisation Unit (TSU), or by erratic pre-firing of an extraction kicker.

In all of these cases, the beam is swept over the machine aperture by the rising edge of the MKDs. Therefore, dedicated diluter blocks are installed in Point 6 to protect the downstream elements. This includes the TCDQ, which is located upstream of the Q4 quadrupole, and the TCDS, which is located upstream of the extraction septa (MSD). An overview is shown in Fig. 2.

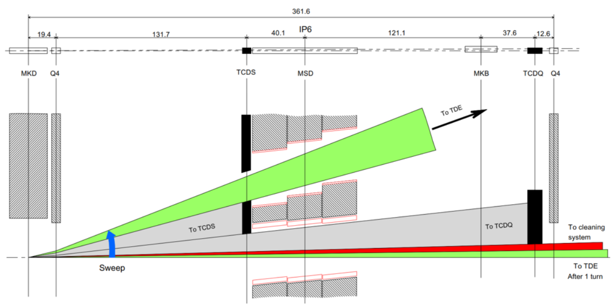

Figure 2: Overview of the TCDQ and TCDS diluter blocks in Point 6 [2].

Beam losses and abort-gap population

The loss profile during such an event strongly depends on the longitudinal beam distribution during the approximately 3 µs long MKD rise time.

A measured abort-gap population during a regular asynchronous beam dump test is depicted in Fig. 3 in blue. For these tests, a single bunch is placed in Bucket 1 and the radio frequency is switched off, such that the beam debunches and drifts into the abort gap [3].

Four regions can be distinguished. The particles that receive a small kick escape the TCDQ. They recirculate in the ring and are either lost at downstream collimators or extracted at the second turn. The particles that receive a stronger kick are lost on the TCDQ or on the TCDS, respectively. Finally, the particles that are close to Bucket 1 escape the TCDS and are extracted at the first turn. They enter the dump channel, but follow a non-nominal trajectory.

Therefore, in order to understand the loss behaviour in case of asynchronous beam dumps, it is not sufficient to consider only the total abort-gap population. This is illustrated in Fig. 4. The top graph shows measured beam losses at the TCDQ as a function of the total abort-gap population for all asynchronous beam dump tests performed in 2016/17. No obvious correlation is visible. However, by plotting the

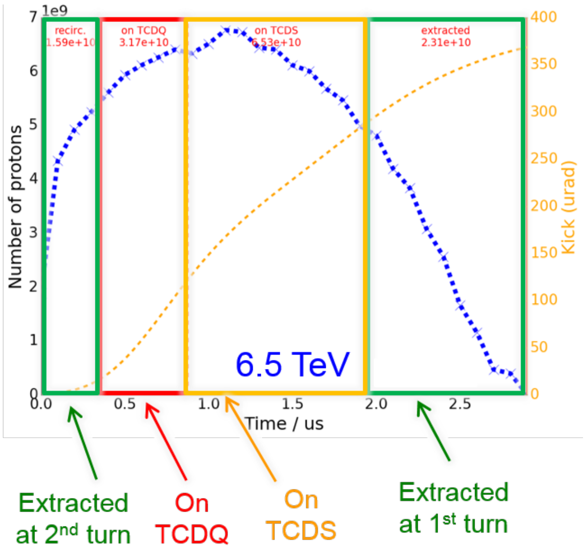

Figure 3: Measured abort-gap population during an asynchronous beam dump test on May 15, 2016. The regions of particles that would hit the TCDQ, hit the TCDS, and the ones extracted on the first or second turn, respectively, are highlighted. The expected kick from the MKDs is depicted in orange.

beam losses as a function of protons calculated to hit the TCDQ, the expected correlation of losses over impacting protons becomes visible (bottom graph).

The region close to the TCDQ edge is considered the most critical region inside the abort gap. The reason is that, on the one hand, the particles just escaping the TCDQ have the highest risk of hitting and potentially damaging collimators in the ring, while, on the other hand, the particles that hit the TCDQ close to its edge have the highest probability of causing quenches to the superconducting magnets in Point 6.

Beam losses and energy dependence

In addition, the consequences of an asynchronous beam dump depend strongly on the beam energy. A dedicated Machine Development time (MD) to investigate the consequences of asynchronous beam dumps was performed during the MD4 block in December 2017 (MD2930: "Asynchronous Beam Dump Test with Bunched Beam"). It demonstrated that, at least for current beam optics, even a full 450-GeV train hitting the TCDQ does not lead to a quench of superconducting magnets. This was validated with trains of 48 bunches and intensities of up to 1.25×10^{11} protons per bunch. However, at a beam energy of 6.5 TeV, a single pilot bunch with 1.8×10^{10} protons was sufficient to cause the beam-induced quench of one main dipole (MB.A8R6) and one quadrupole (MQY.4R6) for Beam 1 and one quadrupole (MQY.4L6) for Beam 2.

For a full asynchronous dump with filled abort gap, the situation at top-energy would get worse. Since the TCDQ half-gap position (in millimetres) is reduced with increasing beam energy, the number of bunches that would fully hit the TCDQ increases from approximately 14 at injection energy to approximately 21 at 6.5 TeV. Table 1 lists the TCDQ parameters for injection and flat-top energy.

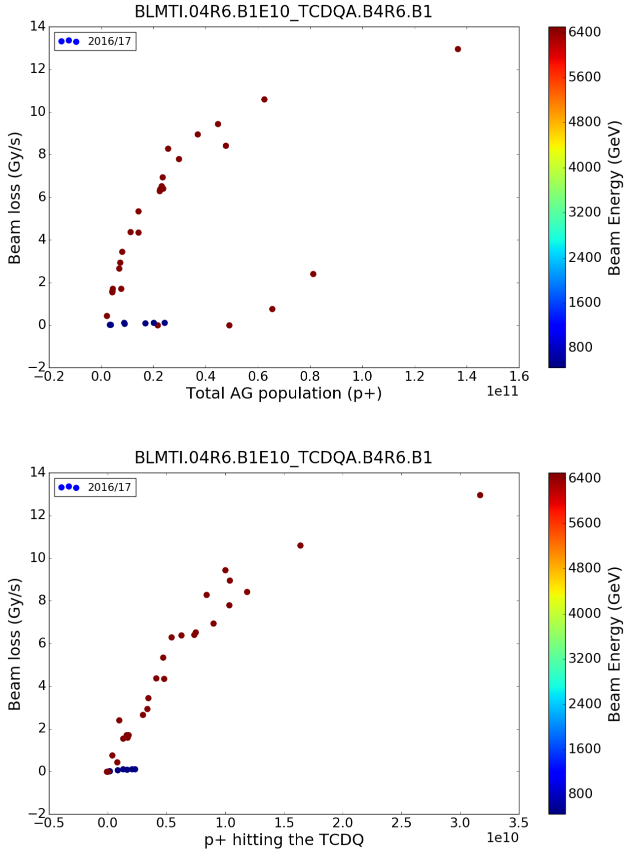

Figure 4: Beam losses at the TCDQ for all 34 asynchronous beam dump tests 2016/2017 as a function of the total abort-gap population (top) and as a function of protons calculated to hit the TCDQ (bottom).

Table 1: TCDQ settings for injection and flat-top energy.

Beam Energy	**TCDQ position**	**Number of bunches hitting the TCDQ**
450 GeV	16 mm	≈ 14
6.5 TeV	4.0 mm	≈ 21

Therefore, ramping the machine with significant beam in the abort gap can be considered as main risk. A proposed solution would be the operational use of a sequencer task that dumps the beam before the ramp if the abort-gap population is above a certain threshold.

ABORT GAP KEEPER (AGK) AND ABORT GAP PROTECTION

Hard-coded AGK

Until 2016, a hard-coded AGK was used that was fixed for a certain number of injected bunches. Every change of the AGK length required the release of a new TSU firmware and an intervention in the tunnel, followed by the required revalidation.

Until 2016 the AGK was set up for 288 bunches. Thus, the use of shorter trains, e.g. of 144 bunches, translated into a loss of luminosity due to the unused injection slot. This led to the decision to implement a new variable AGK. A schematic drawing of the AGK setup for 288 bunches and 144 bunches, respectively, is given in Fig. 5.

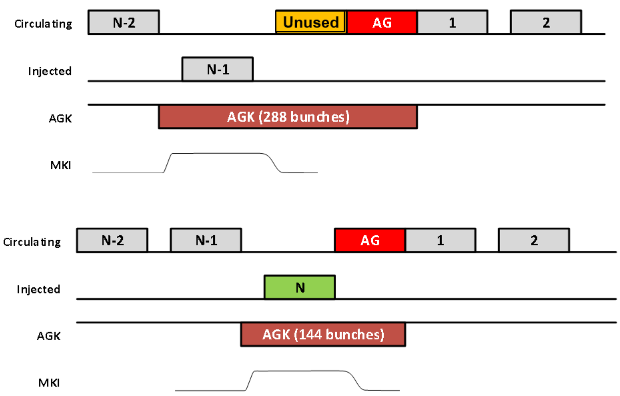

Figure 5: Abort Gap Keeper (AGK) setup for 288 bunches, used until 2016, (top) and the setup for 144 bunches (bottom). The unused injection slot for the 288-bunch setup is displayed in orange.

New variable AGK

In 2016 a temporary solution for a variable AGK was implemented, which was consolidated during the EYETS 2016/17 [4]. This variable AGK regenerates a new AGK window at the MKI level. Then a Fine Delay Card is used to generate the variable-length AGK signal at the injection points P2 and P8. This allows to change the AGK length from the control room without intervention in the tunnel. A revalidation of the AGK settings with beam is required after every change [5]. The schematics of the fixed AGK and the new variable AGK are shown in Fig. 6.

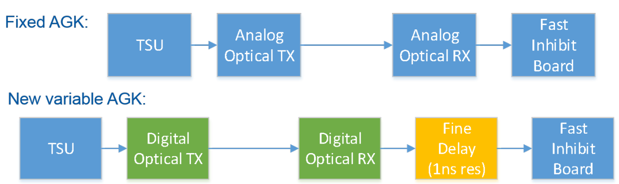

Figure 6: Schematics of the hard-coded or fixed AGK and the new variable AGK.

INJECTING INTO THE ABORT GAP: THE INCIDENT ON SEPTEMBER 4, 2017

On September 4, 2017, the machine was set up for the operational use of 8b4e beams. The 8b4e beam requires 56 bunches in 80 bunch slots per PS batch. Thus, two PS batches injected into the LHC give 112 bunches in 168 bunch slots. However, the MKI and the AGK had been set up for 3 batches of 48 bunches of BCMS, which give 144 bunches in only 160 bunch slots [6]. This caused the MKI to be too short by 8 bunches.

Therefore, these last 8 bunches were injected onto the MKI falling edge. The injection was nevertheless still within tolerances. Even though one could observe injection oscillations for the last 6 bunches of Beam 2, the transverse losses were still relatively low [6]. An overview of the filling schemes that were used before and after the change is given in Fig. 7.

Figure 7: Filling schemes that were used before and after changing the LHC set-up from BCMS beams to 8b4e in September 2017.

The last 7 bunches of the train were injected into the abort gap. Since the first bucket of the last injected train was not in the abort gap, no interlock was triggered. This led to an abort-gap population, as measured by the BSRA, of 6.6×10^{11} protons for Beam 1 and 7.0×10^{11} for Beam 2. As this was realized during the ramp, the beam was dumped by the operators at a beam energy of approximately 2 TeV.

The bunches in the abort gap received small kicks between 0.15 µrad and 1.2 µrad from the MKD rising edge. This translates into a 50 µm to 400 µm horizontal offset at the TCDQ, which corresponds to less than 1 sigma in flat-top values. Therefore, the bunches escaped the TCDQ, recirculated in the ring and were dumped at the second turn with minor losses. Consequently, the External Post-Operational Checks (XPOC) [7] showed a clean dump.

The measured and simulated bunch positions at the BTVDD screen upstream the beam dump are shown in Fig. 8 for the dump on September 4, 2017. For the simulation, the relevant beam parameters as well as the measured current waveforms for all extraction and dilution kickers were downloaded directly from the LHC Logging Data Base or the Post Mortem framework via a python interface. Then, using the measured calibration factors, the current is converted to a kick angle and the waveforms are corrected for the time of flight as well as for the measured time delays that are caused by eddy currents and the signal-propagation delays. As last step, a MAD-X [8] routine is used to transport every bunch center from the first extraction kicker to the dump [9].

Simulation and measurement agree within the error bars. The bunches that were accidentally injected into the beginning of the abort gap are indicated. Note that the absolute beam position on the screen was fitted for the simulation.

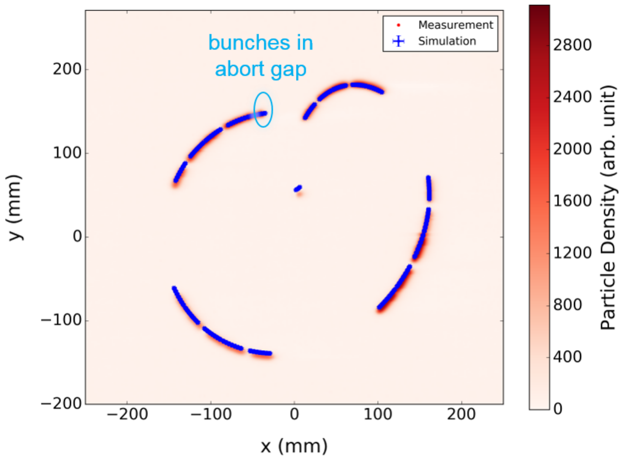

Figure 8: Measured (red) and simulated (blue) bunch positions at the BTVDD screen upstream the beam dump (TDE) for the dump on September 4, 2017 at 15:24 hours. The bunches that had been injected into the beginning of the abort gap are indicated.

LESSONS LEARNED AND CURRENT PROTECTION SCHEME

Several direct consequences were drawn from the incident on September 4, 2017. First, the *Injection Sequencer* [10] now blocks, and not only gives a warning, if the injected train length does not match with the MKI length. As previously, it warns if the first requested bucket is inside the abort gap. Second, the *Filling Scheme Editor* now considers the AGK length when a new filling pattern is defined. Furthermore, any change of a filling pattern now requires an EDMS document.

In addition, new features have been implemented in the *Software Interlock System (SIS)* [11]. The SIS now also checks if the last injected bucket would be injected into the abort gap. Before, only the first requested bucket was checked for injection into the abort gap. This issue was already present for the fixed AGK but never appeared.

The now existing abort-gap relevant interlocks in the SIS are summarized below. All of these interlocks are currently maskable. The details of the protection settings in the Injection Sequencer and in the SIS are provided in [12].

List of abort-gap-relevant SIS checks:

- Check that the SPS train length from the BQM is consistent with the MKI kick length in the SIS setting
- Check that the last injected bunch will not be in the abort gap
- Check that the requested injection bucket is not inside the AGK forbidden region (checked in the INJ_PERMIT tree and in the INJ_B1(2)_PERMIT trees)
- Check that the requested number of bunches does not exceed the allowed limit
- Check the consistency of the AGK, MKI and Fast Inhibit Board (FIB) settings against the SIS settings
- Check that the FIB arming length/period is within tolerances

Independently, the consistency of requested and measured AGK length is checked in the “MKI2/8 BETS/AGK/Erratic” tab of the *Injection BIS*.

In preparation of two MDs that required injection into the Abort Gap during the MD4 block in December 2017, it turned out that the *MKI fine delay settings* can be used to move the abort gap to another position in the ring. Therefore, a full bunch train could be injected onto the MKD rising edge without any change of the AGK settings as such. Obviously, it still required the masking of all relevant SIS interlocks, and ignoring the Injection Sequencer warning.

As a first consequence of the MDs, the MKI fine delay settings are now recorded in LSA. They are currently protected by RBAC roles. An improved protection could be achieved by checking the consistency of the settings in the SIS.

CONCLUSIONS AND OUTLOOK

A new variable AGK was implemented in 2016/17. It allows to efficiently adapt the AGK length without intervention in the tunnel, e.g. in case of a filling pattern change.

The change from BCMS to 8b4e beams on September 4, 2017, revealed a flaw in the abort-gap protection. A too long train could be injected without triggering an interlock and 7 nominal bunches were placed inside the abort gap. This loophole was directly closed and the SIS now checks if the last injected bucket, and not only the first injected bucket, would be injected into the abort gap.

In addition, further protection layers have been implemented. The Injection Sequencer now blocks, and not only warns, if the MKI length does not match with the injected train length, and any change of the filling pattern now requires an EDMS document.

Experimental results confirmed that the consequences of an asynchronous beam dump strongly depend on the beam energy. Therefore, a sequencer task that prevents the ramp in case of a too high abort-gap population could be implemented in operation.

Recent findings showed that the MKI fine delay settings can be used to move the abort-gap position and inject beam onto the MKD rising edge. Currently, these settings are protected by RBAC roles. If required, the consistency of the settings could be checked by the SIS. Additionally, the relative position of the AGK with respect to the MKI waveform might be monitored in the Injection Quality Check (IQC).

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