LHC ABORT GAP FILLING BY PROTON BEAM

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Abstract

Safe operation of the LHC beam dump relies on the possibility of firing the abort kicker at any moment during beam operation. One of the necessary conditions for this is that the number of particles in the abort gap should be below some critical level defined by quench limits. Various scenarios can lead to particles filling the abort gap. Time scales associated with these scenarios are estimated for injection energy and also coast where synchrotron radiation losses are not negligible for uncaptured particle motion. Two cases are considered, with RF on and RF off. The equilibrium distribution of lost particles in the abort gap defines the requirements for maximum tolerable relative loss rate and as a consequence the minimum acceptable longitudinal lifetime of the proton beam in collision.

INTRODUCTION

The existence of particles in the LHC [1] abort gap can be a serious problem when dumping the beam if no precautions are taken. Different solutions for monitoring and cleaning the abort gap have been found and implemented in RHIC [2] and TEVATRON [3]. They are also under study for LHC [4] - [10].

Sources of longitudinal particle loss in the LHC at 7 TeV can be [1] intra-beam scattering (with emittance lifetime 61 h at 7 TeV), Touschek scattering, RF noise with a relatively full bucket, controlled emittance blow-up on the ramp (from 0.7 eVs to 2.5 eVs) with possible differences in emittance from bunch to bunch and from batch to batch, and finally beam instabilities. Among the different factors which can reduce the debunched beam component during the coast in LHC, synchrotron radiation damping (emittance damping time 13 h at 7 TeV) plays a significant role.

Particles that have escaped from the bucket move around the ring and fill the abort gap. Energy loss of these particles due to synchrotron radiation provides natural cleaning at 7 TeV which is discussed in more detail below. We start with an estimation of the relevant time scales with RF off and RF on. In the following section a comparison of the calculated density of lost particles in the abort gap with the tolerable value gives the limitation on the allowed particle loss rate. If this limit is exceeded, active cleaning, which can be done using the LHC transverse damper [9], becomes necessary.

TIME SCALES

The LHC beam and machine parameters used in our estimations are presented in Table 1 for bottom and top energies [1]. The LHC abort gap is 3 μs long. The values

Energy E_s	TeV	0.45	7
T_0	μs	88.9	88.9
$f_{rf} = 1/T_{rf}$	MHz	400.79	400.79
RF voltage V_0	MV	8	16
T_{s0}	ms	15.1	41.9
Rad. loss/turn U_0	keV	10^{-4}	7.0
$\phi_s = U_0/(eV_0)$		$\sim 10^{-8}$	4.4×10^{-4}
$\delta E_{bunch}/E$		8.6×10^{-4}	2.2×10^{-4}
$\delta E_{bucket}/E$		9.7×10^{-4}	3.5×10^{-4}
$\delta E_{col}/E$		3×10^{-3}	1×10^{-3}

Table 1: The LHC beam and machine parameters at injection and on the flat top.

$\delta E_{col}/E$ are the relative momentum cuts due to the momentum collimation system, in order to protect the superconducting magnets from quenches. They are fixed to be between the bucket height and the ring momentum aperture $\delta E/E \simeq 6 \times 10^{-3}$, with some room left for the secondary halo leaving the collimation system [1, 11].

With RF off particle motion relative to the synchronous particle is the same with or without radiation losses. The time needed to fill the 3μs abort gap from both sides is 5.1 s at 450 GeV and 20 s at 7 TeV. However in the case of RF failure (even of one cavity or klystron) the beam-induced voltage quickly grows to its maximum permitted value and the beam must be dumped immediately.

Particle lifetime at 7 TeV due to energy loss, defined here as the time needed to reach the momentum collimators, varies from 69.3 s to 108.5 s according to the initial energy of the particle in the nominal bunch. For a full bucket the minimum value is 57 s.

With RF on (but without radiation loss) the time $T_{2\pi}$ it takes for an uncaptured particle to travel one RF period is a function of the maximum energy deviation relative to the bucket height $q = \delta E_{max}/\delta E_{bucket}$ ($q > 1$)

$$T_{2\pi}(q) = T_{s0}\frac{K(1/q^2)}{\pi q}, \quad (1)$$

where T_{s0} is the period of small synchrotron oscillations and $K(x)$ is a complete elliptic integral of the first kind.

As one expects, for particles very close to the separatrix ($q \sim 1$) this time is infinitely long, but for $q = 1.01$ (1.1) the time $T_{2\pi}/T_{s0} = 1.06$ (0.67).

To increase the reliability of the beam dump system, when filling the rings on the flat bottom, the abort gap will always be in front of the first injected batch. The abort gap will then be mainly filled by particles with negative energy deviation, a significant part of the lost particles with positive energy deviation being kicked out during injection of the next SPS batch. At injection energy $T_{2\pi}$ is 16 ms (10.1 ms) for $q = 1.01$ (1.1). It will take 19.2 s (11.3 s) for these particles to cross the length of the abort gap (900 m).

With energy collimation at $\delta E_{col}/E = 3 \times 10^{-3}$ during the ramp a flash of capture losses starts ~ 18 s after the beginning of acceleration and lasts ~ 1 s. For these particles the duration of the flash defined by their amplitude of oscillation is ~ 1 s.

Due to radiation loss **on the flat top** there is an accelerating bucket with $dE_s/dt = 0$ and $\sin\phi_s \simeq \phi_s = U_0/(eV_0)$. Lost particles with positive energy deviation in the range $1 - \pi\phi_s/4 < q < 1 + \pi\phi_s/4$ pass through the hole between the buckets, of size $\delta\phi \simeq 2\sqrt{\pi\phi_s}$ ($\delta\phi = 0.074$ rad or 4.25 deg at 7 TeV), and start to move in the opposite direction with negative energy deviation. This time is shown in Fig.1. For most of the particles the time needed to pass through the hole between the buckets when they start to drift one RF period away is $\geq 1.6\,T_{s0} = 67$ ms. Below we consider how the abort gap is filled by particles with negative energy deviation.

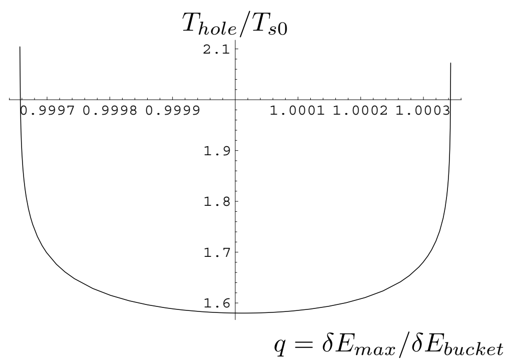

Figure 1: The time needed, normalised to T_{s0}, for an uncaptured particle to pass through the hole between buckets (travelling $\sim$ one RF period) at 7 TeV as a function of q.

The time taken by an uncaptured particle with initial energy deviation q to cross the length of the abort gap can be found [10] from the approximate expression

$$t_{gap}(q) \simeq \frac{T_{s0}}{\pi}\sum_{n=1}^{n_{gap}}\frac{K(1/q_n^2)}{q_n} \simeq \frac{2T_{s0}}{\pi^2\phi_s}[G(q_{max}) - G(q)], \quad (2)$$

where $q_{max}(q) = \sqrt{q^2 + \pi\phi_s(n_{gap} - 1)}$, $n_{gap} = 1200$ and

$$G(q) = qE(\frac{1}{q^2}) \simeq \frac{\pi}{2}\,q\,(1 - \frac{1}{4q^2}), \;\; G(1) = 1.$$

Here $E(x)$ is a complete elliptical integral of the second kind. Fig. 2 shows $t_{gap}(q)$. Particles move faster and faster as they lose energy. The maximum time to cross the abort gap, ~ 25 s, is for particles starting close to the separatrix.

The lifetime or time it takes for an uncaptured particle with initial q to be lost on the collimation system is

$$t_{life}(q) \simeq \frac{2T_{s0}}{\pi^2\phi_s}[G(q_{lim}) - G(q)], \quad (3)$$

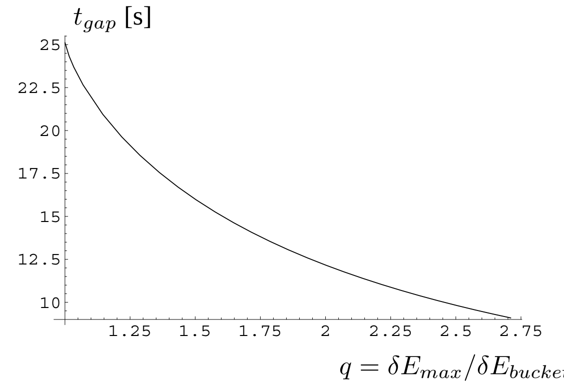

Figure 2: The time needed for an uncaptured particle to cross the abort gap (3.0 μs) at 7 TeV as a function of the normalised initial maximum energy deviation.

where $q_{lim} \simeq 3$ is defined by the collimation system (see Table 1) and $G(3) = 4.58$. Then the maximum lifetime for particles starting from the separatrix is:

$$t_{life}(q_{min}) \simeq t_{life}(1.0) = 2T_{s0}/(\pi^2\phi_s)\cdot 3.58 = 69.4\,\mathrm{s}.$$

PARTICLE DISTRIBUTION

Let us assume that the particles which have escaped from their bucket form a thin layer close to the separatrix. The flux j_0 of the lost particles from the bucket is

$$j_0 = \rho(\phi)\dot{\phi} = dN_{loss}/dt, \quad (4)$$

where ϕ is the azimuthal coordinate (RF phase) and dN_{loss}/dt is the loss rate per bunch.

Particles starting at a distance (expressed in the number of RF periods or buckets) more than

$$n_{cr} = \Delta\phi/(2\pi) = (q_{lim}^2 - 1)/(\pi\phi_s) = 8/(\pi\phi_s) \simeq 5820 \quad (5)$$

will be lost on the collimation system ($q_{lim} = 3$) before arriving at the abort gap so that only $\sim 1/6$ of the ring contributes to filling the abort gap (see Fig. 3).

The equilibrium distribution in the abort gap builds up with time scales $t \geq t_{life} \simeq 70$ s. In this case the line density at point ϕ in the gap can be found by summing up the contributions from n_{cr} upstream buckets:

$$\rho(\phi) = \sum_1^{n_{max}}\rho_n(\phi) = \sum_1^{n_{max}}\frac{j_0}{|\dot{\phi}_n(\phi)|}\,. \quad (6)$$

For $\phi \leq \phi_{sn}$

$$\dot{\phi}_n(\phi) \simeq -\sqrt{2}\omega_{s0}\sqrt{1 - \cos\phi - \phi_s(\phi - \phi_{sn})}, \quad (7)$$

where $\phi_{sn} = 2\pi(n-1)n_{bb} + \pi$, n_{bb} is the number of RF periods between bunches (in LHC $n_{bb} = 10$), $\phi = 0$ is at the beginning of the abort gap and $n_{max} = n_{cr} - \mathrm{Integer}[\phi/(2\pi)]/n_{bb}$. Finally, in the gap,

$$\rho(\phi) \simeq \frac{dN_{loss}/dt}{2\pi\phi_s\omega_{s0}^2 n_{bb}}[\dot{\phi}_{max} - \dot{\phi}_1(\phi)], \quad (8)$$

where $\dot{\phi}_{max} \simeq -2q_{lim}\omega_{s0}$ is defined by collimation.

The envelope of the line density (maximum and minimum values) inside the abort gap is shown in Fig. 4. This line density is normalised to its amplitude ρ_{max} found in the rest of the ring in the steady-state situation

$$\rho_{max} = \frac{dN_{loss}/dt}{\pi\phi_s\omega_{s0}n_{bb}}(q_{lim} - 1). \quad (9)$$

At 7 TeV this line density, expressed in protons/m, (and not in protons/rad as above) is

$$\rho_{z,max} \simeq 8.4\, dN_{loss}/dt\,. \quad (10)$$

During the dump kicker rise, the particles in the abort gap are sprayed transversely and impact on a protection device (TCDQ), which shadows the magnets located downstream, but does not absorb all the energy deposited [12]. The effective peak energy deposition in the nearby quadrupole per unit longitudinal proton density is $\epsilon_p = 5.7 \times 10^{-10}$ J/(cm^3 p/m). With a quench limit $\epsilon_q = 6.4 \times 10^{-3}$ J/cm^3, the critical line density in the gap is

$$\rho_c = \epsilon_q/\epsilon_p = 1.1 \times 10^7 \,\mathrm{p/m}. \quad (11)$$

From the condition $\rho_{z,max} < \rho_c$ the limitation for the loss rate per bunch is

$$dN_{loss}/dt < 1.3 \times 10^6 \quad \mathrm{s}^{-1}. \quad (12)$$

For an exponential decay of the number of captured particles

$$dN_{loss}/dt = N_0 \exp^{-t/t_0}/t_0. \quad (13)$$

and the nominal intensity per bunch $N_0 = 1.1 \times 10^{11}$ we obtain a beam lifetime of $t_0 \sim 23.3$ h.

The fact that the dump kicker rise occurs at the head of the gap (left edge of Fig. 4), where $\rho \simeq \rho_{z,max}/2$, gives finally a minimum required beam lifetime of $t_0 \sim 12$ h.

This value will be evaluated more precisely once the TCDQ is closer to its final design. We also note that fortunately the particles must move across the entire gap before

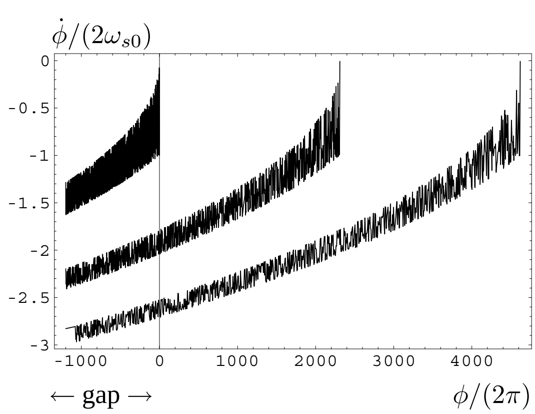

Figure 3: Trajectories of lost particles in phase space. Particles with $\dot{\phi}/(2\omega_{s0}) > 3$ are lost at the collimation system.

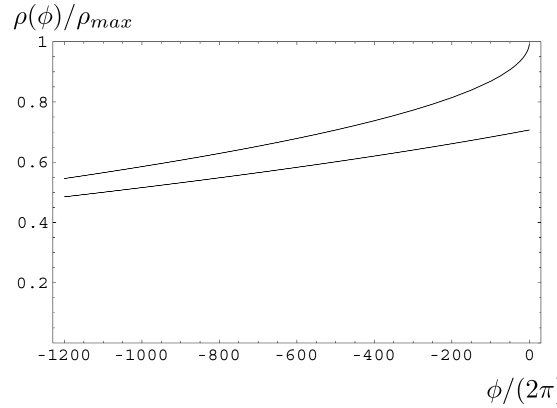

Figure 4: The envelope of the maximum and minimum values of the normalised line density inside the abort gap at 7 TeV.

reaching its head, which is the critical location. It is therefore very convenient to use the central segment of the gap for active cleaning.

On the flat bottom, due to the fact that the LHC filling time (9.5 min per ring or 19 min if both are filled in parallel) is comparable to the time it takes for uncaptured particles to make one full turn (from 9.5 to 6 min with q in range 1.01 - 1.1), no equilibrium particle distribution can be formed in the abort gap. For a 5% capture loss up to 3×10^8 p/m of coasting beam can be found in front of the first batch after $\sim$ 20 s. For capture losses this value is maximum after injection of the first and the last batches. Also taking into account other possible sources of particle loss the total line density in the abort gap at 450 GeV can be close to the tolerable density 10^9 p/m, and active cleaning of the abort gap [9] could be necessary.

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