Beam Loss and Collimation at LHC

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Abstract. Beam loss and collimation issues at LHC can only be briefly outlined in three pages, but some emphasis is given to the bibliographic material.

TABLE 1. Some LHC nominal parameters related to beam losses

Luminosity	10^{34}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Normalised emittence	3.75	μm
β^* at crossing	0.5	m
σ^* at crossing	16	μm
Bunch population	$1.05\ 10^{11}$	protons
Stored bunches	2800	
Injection energy	450	Gev
Collision energy	7000	Gev
Injected intensity	$12 \times 2.5\ 10^{13}$	protons
Stored intensity	$3\ 10^{14}$	protons
Stored energy	(per beam)	
Injection	12×2	MJ
	$\equiv 12 \times 4$	kg melted Cu
Collision	304	MJ
	$\equiv 800$	kg melted Cu

1. INTRODUCTION

In high energy proton colliders, the beam squeezing at the collision point is limited by the aperture and the strength of the final focus quadrupoles. High luminosity is therefore reached with high stored intensity. This is the case of LHC, see Table 1. The combination of high momentum and high intensity results in high injected and stored energies, while the main magnets are superconducting. Equipment integrity and quench prevention are therefore major issues. Several systems will be installed to protect the ring and ensure reliable operation. Many single pass low-Z absorbers will be installed (e.g. injection and dump insertions), while safe and strict injection procedures will be implemented [1, 2]. A multi-turn collimation system will capture multi-turn transient and steady losses. Finally, fast beam loss monitors installed both near the collimators and around the ring will trigger the machine protection system for beam dump action. We restrict the scope of this paper to the collimation system.

2. BEAM LOSS ISSUES

2.1. Quench limits

High energy protons impacting the vacuum chamber of a s.c. magnet develop a hadronic shower and deposit energy over an effective length of about one meter in particular in the coils of the s.c. magnets [3]. The maps of energy density obtained with simulation codes [6, 7, 8] are compared to both the heat reserve in the cables between the working and the critical temperature (transient losses) and to the heat flow allowed by the same temperature difference (steady losses). In the first case, the heat reserve is time dependent. In LHC magnets, if the energy deposition occurs in $\Delta T < 2.5$ ms, only the heat reserve of the metal can be used, because of a limitation of energy transfer at the interface metal/helium. Full use of the heat reserve of the helium occurs if $\Delta T \approx 50$ ms [3]. Quantitative values expressed in proton losses per meter of vacuum chamber are given in Table 2.

2.2. Regular losses

Regular losses can be split into three basic cases, quantified in Table 2.

Injection errors Even with collimation in the transfer lines and in the kicker sections, losses might occur during the first few turns, for example because of a failure of the damping of the injection oscillation. We consider losses up to 5% of an injected batch.

Ramping Because of phase errors, noise or uncontrolled instabilities during the long injection process, protons lying out of RF buckets will be lost at the beginning of the ramp. The flash of losses will last about one second [9]. We consider an upper limit of 10% of longitudinal losses.

Steady losses at collision A few hours will be spent between the dump of the stored beams and the restora-

TABLE 2. Expected regular transient (top) and steady (bottom) losses compared to quench limits. Transient quench limits are time-dependent, see text.

Case	ΔN [p]	ΔN_q [p/m]	$\eta = \Delta N_q / \Delta N$ [1/m]
Injection	$1.25\ 10^{12}$	10^{9}	$8\ 10^{-4}$
Ramping	$3\ 10^{13}$	$2.5\ 10^{10}$	$8\ 10^{-4}$
	$\dot{N}$ [p/s]	$\dot{N}$ [p/m/s]	$\eta = \dot{N}_q / \dot{N}$
7 TeV	$8\ 10^{10}$	$8\ 10^{6}$	10^{-4}

tion of colliding conditions. Efficient production therefore requires large beam lifetimes, i.e. $\tau > 10$ hr, but poorer performance, e.g. $\tau \approx 1$ hr must be allowed during trial periods.

Above the loss rates quoted in Table 2, it may be necessary to dump the beams to avoid magnets quenches. More elaborated specifications can be found in [4, 5]. The ratio $\eta = \Delta N_q / \Delta N$ or $\eta = \dot{N}_q / \dot{N}$ (Table 2) clearly indicates that protons must be captured before reaching the vacuum chamber. This is the task devoted to the collimation system. Its efficiency must be larger than $1/\eta$. This is described in Sect. 3.

2.3. Accidental losses

While regular losses can induce magnet quenches, accidental losses can damage machine components in the absence of adequate protection schemes. Apart from the specific protections evoked in Sect. 1, the collimators which must be the aperture limit of the ring are inherently exposed to capture fast accidental losses and must therefore be adequately resistant to high energy deposition. The worst identified case is related to a particular dump failure, whenever one of the 15 kicker modules is self triggered. The other modules are triggered soon after ($\sim 1\mu$s), but the effective slower rise of the kick results in the impact of many bunches at the edge of at least one collimator. The density of protons may be as high as 6 nominal bunches over $200 \times 200 \mu\text{m}^2$ [5]. Only low-Z materials can survive this [10]. We performed a preliminary stress analysis of a beryllium jaw exposed to the impact of 10 bunches at 7 TeV in the condition discussed in Sect. 2.3. The energy density map was obtained with the MARS code [11] and a time-dependent stress analysis was performed with the ANSYS FE code. The maximum dynamic stress calculated for this case within linear elastic analysis is quite local but quite high, $\sigma_{max} = 1.6$ GPa, and is well above the ultimate tensile strength of beryllium $\sigma_{uts} \simeq 1.1$ GPa. Further analysis is going on to establish the extent of plastic deformation or local rupture. We also consider improvements to the retriggering scheme of the kicker and the use of sophisticated low-Z materials (graphite family) for the few collimators which will be exposed to this kind of events.

3. TWO-STAGE COLLIMATION

In order to meet a collimation inefficiency $\eta < 10^{-4}$ m^{-1}, a two-stage collimation system is needed [13, 14]. The impact parameter at the edge of a primary collimator is small ($\sim \mu$m) with multi-turn losses, leaving the protons with a high probability to be scattered out of the jaw. Secondary collimators are therefore necessary to absorb this secondary halo. Provided adequate phase advances between collimators (Sect.3.1), the size of the secondary halo $A_{sec-halo}$ can be kept smaller than the normalised geometrical aperture of the ring A_n. The inefficiency is then calculated with using the phase-space dilution of the tertiary halo (emitted by the secondary collimators) above $A_{sec-halo}$.

3.1. Optics

The optics of a two-stage two dimensional collimation system is designed by considering that protons are scattered out of a collimator in all directions. This 'stochastic coupling' imposes the use of several secondary jaws per primary collimator (in LHC four of them). Their location is optimum for well defined and correlated transverse betatron phase advances [15]. In the case of ramping, momentum collimation must be used. Conflicting optics requirements imply to use separate insertions for betatron and momentum collimation, even if the optics principles are similar in both cases [15]. In an insertion of finite length, the best correlation of the phase advances can only be approached. The location and the transverse tilt of the jaws are calculated numerically [16, 17]. The optics of the two insertions of LHC are discussed in [18].

3.2. Geometrical aperture

For cost optimisation, the aperture of the magnets is kept small and must be carefully optimised and checked. The normalised aperture must satisfy everywhere the condition

$$A_n(s) > A_{sec-halo} \ . \qquad (1)$$

The normalised primary aperture n_1 delimited by the collimators was chosen to $n_1 = 7$. With the secondary jaws set at $n_2 = 8.2$, the size of the secondary halo is $A_{sec-halo} = 10$. A code coupled to MAD [19] takes into account mechanical, closed orbit and optics errors to match the optics with aperture constraints by respecting the condition 1, see Fig. 1.

3.3. Scattering in jaws and inefficiency

A Monte-Carlo simulation of nuclear and electromagnetic scattering near the edge of a jaw is coupled to

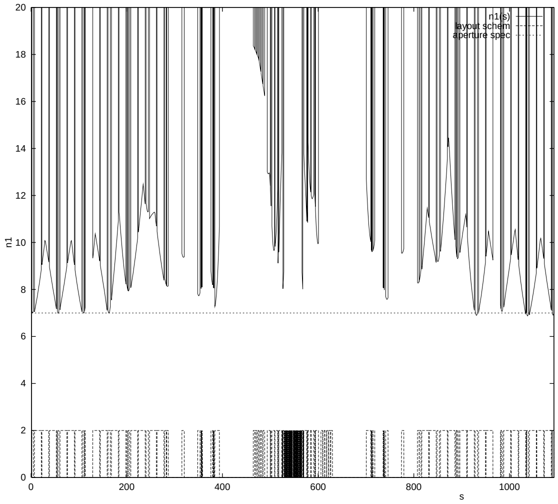

FIGURE 1. The normalised aperture of the insertion 1 of LHC after matching with aperture constraints, expressed in terms of equivalent primary aperture $n_1(s)$.

multi-turn tracking around the ring to compute collimation efficiency. Up to recently two codes were used. The K2 code [20] allows high statistics but the dilution of the tertiary around the ring must be analysed separately. The STRUCT code [21] can produce a map of losses along the ring. Both codes have limited chromatic properties, making their use sometimes delicate. The K2 code was successfully checked in an experiment with coasting beams at 120 GeV in the SPS ring at CERN [22]. Used for LHC (and VLHC), K2 indicates inefficiencies somewhat better than the the specified $\eta = 10^{-4}$ m^{-1}, provided that the aperture is $A_n > 10$, see Fig. 2. Calculations with linear an non-linear optics errors and imperfect collimators are underway, by integrating the K2 and the STRUCT scattering module in MAD/SIXTRACK and DIMAD [23].

4. MORE ABOUT SIMULATION CODES

At this workshop, Weiren Chou advocated for more certification of the K2 and STRUCT codes. We can only agree with him, but it must be understood that a beam loss experiment in a ring is delicate and requires substantial machine time, while specific instrumentation is sometimes needed. On the other hand these codes need consolidation, see Sect. 3.3. This can only be envisaged with adequate resources. Beam loss and collimation are now essential systems in high intensity proton machines but this branch of accelerator science is nevertheless lacking resources and adequate recognition. Upgrades must thus be envisaged in parallel of further certification. A generic code combining low and high energy scattering and true 6D-tracking with linear and non-linear errors would be

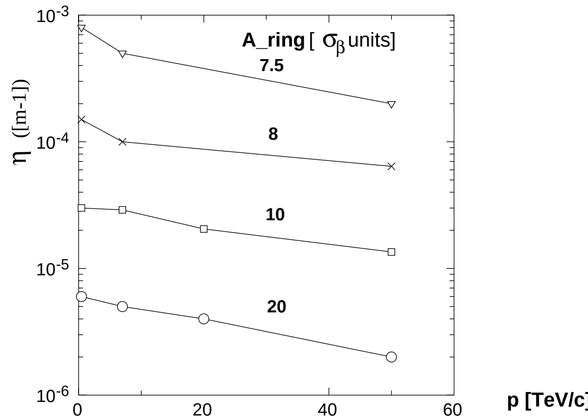

FIGURE 2. The inefficiency η of a two-stage betatron collimation system simulated with K2 for different beam momenta. Here three primary collimators are used (delimiting an octagonal normalised aperture, with primary and secondary retraction of the jaws $n_1 = 6$ and $n_2 = 7$ respectively.

much useful. This might the subject of a session in a future workshop of this series.

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[1] CLPR or CLPN stand for CERN-LHC-Project Report or Note