# Loss Control and Collimation for the LHC

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**Abstract.** The total energy stored in the LHC is expected to reach 360 Mega Joule, which is about two orders of magnitude higher than in HERA or the Tevatron. Damage and quench protection in the LHC require a highly efficient and at the same time very robust collimation system. The currently planned system, the status of the project and the expected performance of the collimation system from injection up to operation with colliding beams will be presented.

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## INTRODUCTION

The energy stored in the LHC beams is unprecedented. At nominally $3.23 \times 10^{14}$ protons per beam of 7 GeV/c momentum, the total energy stored reaches 362 MJ which by far exceeds other machines, see Fig. 1.

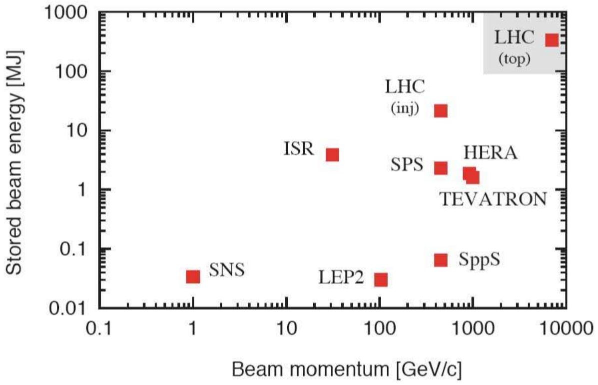

**FIGURE 1.** Comparison of the total energy stored in the beams of high energy accelerators [1].

A very small fraction of the particles touching the aperture in the superconducting part of the accelerator would quench the magnets.

The collimation system is designed to remove halo particles in regular operation, to reduce the risk for damage and quenches of the superconducting equipment, to minimize backgrounds to the experiments and to minimize and localize the impact of radiation and radioactive activation.

For recent literature on the LHC collimation system, see also [1]. The mechanical design of the LHC collimators is described in [2].

In the summary presented here, we also include a discussion of the special requirements for collimation at injection, with beam cleaning by scrapers in the SPS and the issue of single pass collimation relevant for the transfer of the beams from the SPS into the LHC.

Active protection against accidental beam losses with interlocks and beam dump are discussed in the contribution of R. Schmidt to these proceedings [3].

## Multi-turn (ring) and single pass (transfer line) collimation

Fig. 2 illustrates collimation in phase space in one transverse plane (here illustrated for the horizontal position $x$ and angle $x'$).

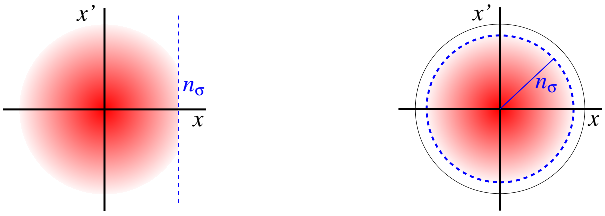

**FIGURE 2.** Left: Single sided cut as relevant for a single passage at a scraper or collimator. Right: round cut after many passages.

We refer to collimator settings in number of $\sigma$, $n_\sigma$, where $\sigma$ is the nominal r.m.s beam size.

"Shaving" with single sided scrapers as planned in the SPS is sufficient to obtain approximately round beams in phase space within a few turns. Several groups of two sided collimators at different phase advances (like 0, 45, 90 and 135°) will instead be necessary to limit maximum amplitudes to $n_\sigma$ in the transfer lines.

The expected reduction in intensity and luminosity by scraping is shown in Fig. 3 and Table 1. A detailed description can be found in [4].

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[1] www.cern.ch/lhc-collimation-project/team.htm

**TABLE 1.** Reduction in luminosity and intensity by (multiturn) collimation of both beams in one plane at $n_\sigma$. For originally Gaussian profiles.

| $n_\sigma$ | rel. loss in Luminosity | rel. loss in Intensity |
|---|---|---|
| 2.0 | 13.4% | 13.5% |
| 2.5 | 3.7% | 4.4% |
| 3.0 | 0.8% | 1.1% |
| 3.5 | 0.14% | 0.22% |
| 4.0 | 0.02% | 0.03% |

A cleaning before injection at about $3.5\,\sigma$ is a good compromise: the loss in luminosity is negligible and the radiation and activation by the scraped particles small. A much wider cut would not give more luminosity and only reduce the level of protection. A much tighter collimation would imply regular losses.

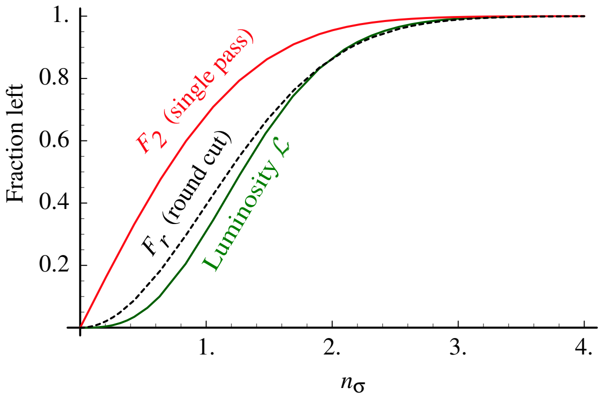

**FIGURE 3.** Fraction $F_r$ of particles left after many passages at a scraper (corresponding to a round cut in phase space) and the relative luminosity $\mathscr{L}$. The fraction of particles left after a single passage through a two-sided scraper $F_2$ is also shown.

## INJECTION FROM THE SPS

Beams will be injected at 450 GeV from the SPS ring through about 3 km long transfer lines into the LHC. Nominal injection intensities require extraction of up to 288 bunches of $1.15 \times 10^{11}$ or together about $3.3 \times 10^{13}$ protons in 4/11 of an SPS turn or $7.86\,\mu$s. This intensity is already about 20 times above damage, and four orders of magnitude above the quench level. The physical LHC ring aperture relevant for injection is only about $7.5\,\sigma$ [5]. Injecting these high intensities cleanly into the tight LHC aperture is a major challenge.

The LHC collimation at injection will effectively start in the SPS with halo scraping at about $3.5\,\sigma$ just before extraction. A set of three scrapers, one horizontal, one vertical and one diagonal, is foreseen. This allows to limit the maximum particle amplitudes in real space to an approximately circular shape, see Fig. 4.

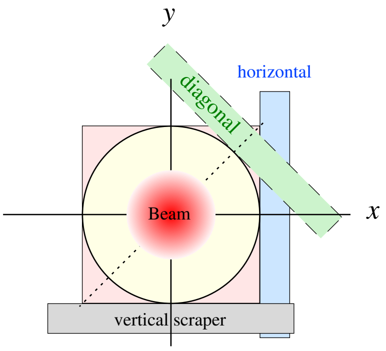

**FIGURE 4.** Illustration of the scraping in the SPS.

## BEAM TRANSFER INTO THE LHC

The beams extracted from the SPS will have to pass through several kilometres of transfer lines before they reach the LHC. The design goal is to minimize emittance blow-up and losses in the beam transfer. The SPS and LHC are not exactly in the same plane, and rotation and coupling effects are an issue. They have recently been studied and minimised by applying small tilt angles to the quadrupoles in the transfer lines [6].

The transfer lines are pulsed and will be turned off when no injection is required. Failures leading to local loss of the injected beams cannot completely be excluded. A set of horizontal and vertical transfer line collimators will be installed towards the end of the transfer line. Their main function is to reduce and dilute the beam intensities sufficiently in a single pass in case of (rare) failures, to avoid damage at injection into the LHC. This requires two-sided collimators at several betatron phases, see Fig. 5.

The apertures relevant for injection are summarized in Table 2.

**TABLE 2.** Apertures relevant for injection.

| $n_\sigma$ | comment |
|---|---|
| $3.5 \pm 0.5$ | Halo scraping in the SPS |
| 5.0 | Setting of transfer line collimators |
| 7.5 | LHC ring transverse aperture at injection |

The transfer line collimator setting at $5\,\sigma$ allows for the expected beam position jitter, tolerances on the collimator jaw alignment and some mismatch [7, 8].

Special protection against mis-firing of kickers at injection is also provided. On the SPS side, the tight septum aperture is protected against mis-firing of the extraction kicker by the "TPSG" diluter [9]. On the LHC side, the beam passes first through the injection septa which

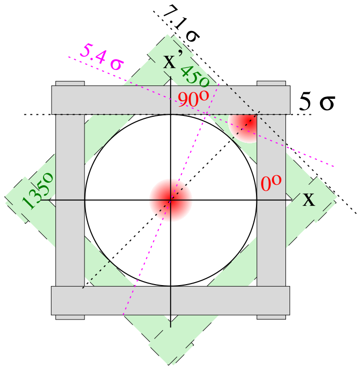

**FIGURE 5.** Illustration of the phase space limits achieved with collimation in the transfer lines with four two-sided collimators per plane, positioned at $0, 45, 90, 135^\circ$ in phase advance. The maximum amplitude for collimation at $5\sigma$ is $5.4\sigma$.

are protected by the transfer line collimators and is then finally deflected on the LHC design orbit with a vertical kicker. In the LHC, there will be dedicated, passive protection devices (TDI, TCLI), to protect the LHC against damage in case of mis-firing of the injection kickers [10].

## FILLING AND RAMPING

After setup and tuning, the actual filling of the LHC can be expected to take about 10 minutes ($2 \times 12$ injections every 21.6 s from the SPS). It is planned, to set primary collimators in the LHC to $5.7\sigma$ at injection and secondary collimators to $6.7\sigma$ [5]. This reduces the tertiary halo of the circulating beams to below the quench level at the physical apertures (on average about $10\sigma$) [1].

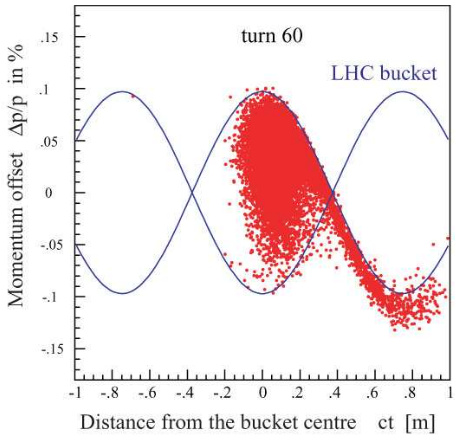

**FIGURE 6.** Illustration of particles 60 turns after injection with 0.33 ns time and $-3 \times 10^{-4}$ momentum offset between the SPS and the LHC, in which about 5% of the particles are lost from the rf-bucket.

The rf-momentum acceptance (bucket half height) is about $10^{-3}$, both in the SPS and LHC. A phase or energy mismatch at injection results in off-momentum particles outside the LHC bucket, see Fig. 6. These particles remain within the momentum acceptance of the momentum collimators in the LHC of about $3 \times 10^{-3}$ and slowly (of order 10 s) fill the abort gap. It is planned to use the transverse damper to kick these particles to larger amplitudes, such that they are removed with the LHC collimation system [11].

Any remaining off-momentum particles will be removed by the momentum collimation at the beginning of the ramp [12]. It is estimated, that up to 30% of the total nominal beam intensity could be removed at the beginning of the ramp without quenching the LHC (to be verified by detailed tracking).

## COLLIMATION IN THE LHC RING

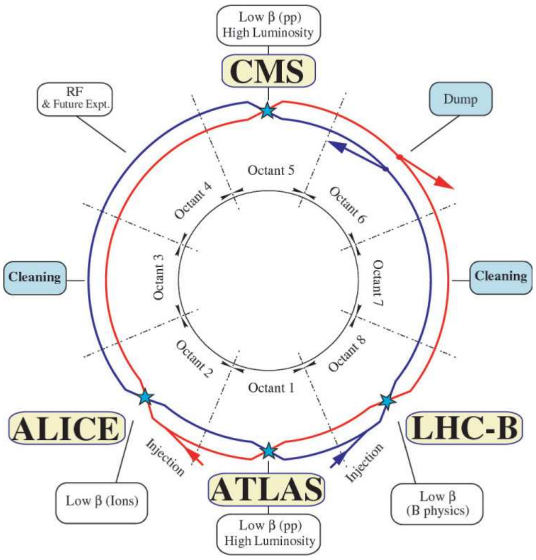

**FIGURE 7.** Schematic layout of the LHC ring.

A schematic view of the LHC ring with its eight octants and straight sections is shown in Fig. 7. The eight, each over 400 m long straight sections will also be referred to as "IR" for interaction region or insertion, even if the beams will only be brought into collisions in the four insertions equipped with physics experiments. Two other insertions are dedicated to collimation and equipped with warm magnets only: IR 3 for momentum, and IR 7 for betatron cleaning.

A cleaning inefficiency of $\eta < 10^{-4}$ will be required at top energy, see Fig. 8. $\eta$ is the rate of losses per meter of ring, divided by the primary loss rate. The high efficiency requires the use of a two-stage collimation

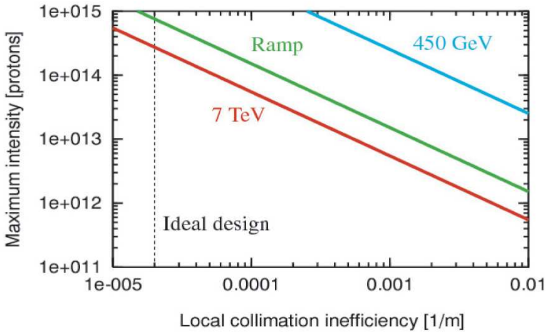

**FIGURE 8.** Maximum total intensity, as function of the local collimation inefficiency, for injection, top energy and the start of the ramp. A beam lifetime of 0.2 h at top energy and 0.1 h at injection is assumed. The ideal design value for local inefficiency is also indicated [13].

system [13]. The main components of the collimation system are listed in Table 3.

**TABLE 3.** Main components for the collimation system

| | Label | Number per beam | Material | Jaw length [m] |
|---|---|---|---|---|
| Betatron Collimation | | | | |
| Primary | TCP | 3 | CC | 0.2 |
| Secondary | TCSG | 11 | CC | 1.0 |
| Tert. Trip. | TCT | 6 – 8 | Cu/W | 1.0 |
| Momentum Collimation | | | | |
| Primary | TCP | 1 | CC | 0.2 |
| Secondary | TCSG | 4 | CC | 1.0 |

The primary collimators are relatively short. Their main function is to scatter the protons to larger amplitudes into the longer secondary collimators and initiate there cascades with inelastic interactions. Carbon-Carbon (CC) will be used as material for the jaws of the primary and secondary collimators. The low beta insertion triplets are protected with higher density tertiary collimators (TCT).

In addition, there will be scrapers for beam shaping and diagnostics and some special purpose absorbers like the TDI, TCLI to protect against kicker mis-firing.

The main reason for the choice of carbon based jaws rather than metals (like Be/Cu) for the primary and secondary collimators is robustness. The carbon jaws chosen are designed to survive full beam impact at injection. This has meanwhile been successfully tested in the SPS. The maximum tolerated power loss from the beams on the collimators is 100 kW and up to 500 kW over 10 s corresponding to 1% beam loss in 10 s. The cooling is achieved using copper in connection with the jaws.

Good surface flatness and alignment of the collimators with respect to the beam is required. At the collision energy of 7 TeV, average r.m.s beam sizes are about 200 $\mu$m. The collimator jaws are designed for a surface flatness of 25 $\mu$m over 1 m.

It is planned to set primary collimators to about 6 and secondary collimators to about 7 $\sigma$ in the LHC at 7 TeV. This implies relatively tight gap openings between collimator jaws. Depending on the the local optics, the full gap opening may be as small as 2.2 mm. The transverse impedance of the collimators is an issue and may result in collective instabilities which ultimately limit the LHC beam intensities [14].

The collimation efficiency is currently being studied and optimised with the help of detailed tracking studies. Fig. 9 shows an example of a loss map in the LHC ring from a recent simulation involving $9 \times 10^6$ particles tracked over 100 turns. The losses mainly peak at high $\beta$ in the insertions which can largely be absorbed with the tertiary triplet collimators (TCT).

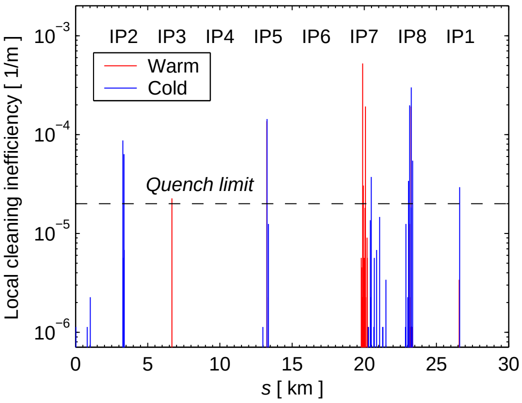

**FIGURE 9.** Distribution of losses around the LHC ring obtained by detailed tracking with primary and secondary collimators [1].

## STATUS AND COLLIMATOR TEST IN THE SPS

Two prototype secondary LHC collimators have recently been constructed and were successfully tested in the SPS. A mounted jaw with the attached Cu cooling can be seen in Fig. 10.

Four 24 hour tests with beam were scheduled in the SPS, and two of these tests took place before this workshop. First, preliminary results are reported here.

The collimators moved and scraped beams reproducibly. Most of the measurements were done with coasting beams in the SPS at the highest possible energy of 270 GeV. Beam lifetimes were good. A slow, but significant halo re-population was observed.

Several series of impedance measurements were performed. The collimators were opened and closed period-

**FIGURE 10.** Secondary LHC collimator jaw. The 1 m long flat carbon surface and tapering at both ends, the support and Cu cooling is visible.

ically. Fig. 11 shows the results of tune measurements[2] and collimator jaw positions as function of time. The collimator jaws were closed to a gap of about 2 mm which corresponds roughly to $2\sigma$. Small, but significant tune shifts of about $2 \times 10^{-4}$, in broad agreement with expectations, were observed.

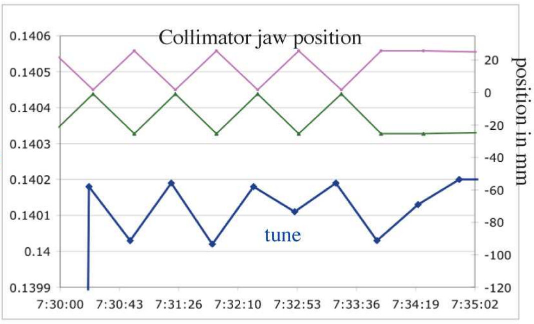

**FIGURE 11.** Collimator jaw movements and tune changes observed in SPS tests.

## CONCLUSION

Collimation and loss control is one of the main challenges for the LHC. Clean injection from the SPS through the pulsed transfer lines into the tight LHC aperture, with scraping before extraction, and the minimisation of any optics mismatch resulting in emittance blow-up will be very important.

First LHC collimator prototype tests in the SPS gave very encouraging results.

Much higher stored beam energies than for any previous particle accelerator will have to be handled in the LHC and require a very efficient and robust collimation system from the start-up.

## ACKNOWLEDGEMENT

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[2] recorded with the standard SPS tune meter, re-fitted off-line by the author