

## AN IMPROVED COLLIMATION SYSTEM FOR THE LHC

R. Abmann, O. Aberle, A. Bertarelli, H. Braun, M. Brugger, O. Brüning, L. Bruno, S. Calatroni, E. Chiaveri, B. Dehning, A. Ferrari, B. Goddard, E.B. Holzer, J.B. Jeanneret, M. Jimenez, V. Kain, M. Lamont, M. Mayer, E. Métral, R. Perret, S. Redaelli, T. Risselada, G. Robert-Demolaize, S. Roesler, F. Ruggiero, R. Schmidt, D. Schulte, P. Sievers, V. Vlachoudis, L. Vos, E. Vossenbergh, J. Wenninger, CERN, Geneva, Switzerland, I.L. Aigueiri, I. Baishev, I. Kurochkin, IHEP, Russia, H. Tsutsui, Sumitomo Heavy Industries, Ltd., Japan, D. Kaltchev, TRIUMF, Vancouver, Canada

### Abstract

The handling of the high-intensity LHC beams in a super-conducting environment requires a high-robustness collimation system with unprecedented cleaning efficiency. For gap closures down to 2.2 mm no beam instabilities must be induced from the collimator impedance. A difficult trade-off between collimator robustness, cleaning efficiency and collimator impedance is encountered. The conflicting LHC requirements are resolved with a phased approach, relying on low  $Z$  collimators for maximum robustness and hybrid metallic collimators for maximum performance. Efficiency is further enhanced with an additional cleaning close to the insertion triplets. The machine layouts have been adapted to the new requirements. The LHC collimation hardware is presently under design and has entered into the prototyping and early testing phase. Plans for collimator tests with beam are presented.

### INTRODUCTION

Each of the two LHC rings will handle a stored beam energy of up to 350 MJ ( $3 \times 10^{14}$  p at 7 TeV), two orders of magnitude beyond the achievements in the Tevatron or HERA [1] (see Fig. 1). Comparing transverse energy densities, LHC advances the state of the art by even three orders of magnitude, from 1 MJ/mm<sup>2</sup> to 1 GJ/mm<sup>2</sup>. This makes the LHC beams highly destructive. At the same time the superconducting (SC) magnets in the LHC would quench at 7 TeV if small amounts of energy (about 30 mJ/cm<sup>3</sup>, induced by a local transient loss of around  $2 \times 10^6$  protons) are deposited into the SC coils [2]. A so-called “primary beam halo” will continuously be filled by various beam dynamics processes and the beam current lifetime will be finite [3]. The handling of the high intensity LHC beams and the associated proton loss rates requires a powerful collimation system with the following functionality:

*Halo cleaning:* Efficient and reliable cleaning of the beam halo during the LHC beam cycle, such that beam-induced quenches of the super-conducting magnets are avoided. Out of  $2 \times 10^5$  protons lost at the collimators at 7 TeV, not more than 1 proton may escape and impact on any given meter of the LHC cold aperture [4].

*Background tuning:* Minimization of halo-induced backgrounds in the particle physics experiments.

*Protection:* Passive protection of the machine aperture against abnormal beam loss. Beam loss monitors at the collimators detect unusually high loss rates and generate a

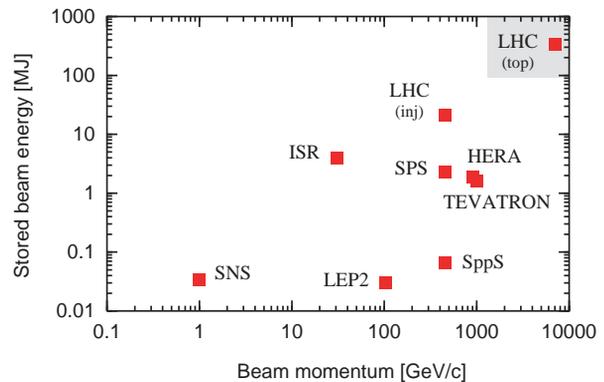


Figure 1: Stored beam energy in different proton colliders versus the beam momentum.

beam abort trigger [5, 6].

*Abort gap cleaning:* Abort gap cleaning is required for avoiding spurious quenches after normal beam dumps [7].

*Scraping:* Shaping of beam tails and halo diagnostics.

Design work on an appropriate LHC collimation system started in 1990 [8]. The design evolved significantly over the years [9, 10], reflecting both the difficulties to meet the LHC requirements and the challenge of advancing the state of the art in beam cleaning and collimation into a new regime. The latest critical revision of the LHC collimation system started in 2002 [11] and is coordinated by the LHC collimation project [12] since 2003. An improved collimation system has been worked out.

### PHASED APPROACH

Two long straight sections in the LHC are dedicated to collimation (“cleaning insertions”). The collimators and other equipment must be compatible with a number of important design constraints [13]:

*Efficiency:* For achieving high efficiency a proton hitting a secondary collimator must undergo an inelastic interaction with high probability. It is then stopped for circulation. This is traditionally achieved with high  $Z$  materials. If a low  $Z$  material is used the jaws must be made long.

*Robustness:* The collimators must be sufficiently robust to withstand normal and abnormal operational conditions without damage [14]. Shock beam impact due to mis-kicked beam is expected to occur with 2.7 MJ/mm<sup>2</sup> over 200 ns at least once per year. It has been shown that carbon-based jaws with a length of up to 1 m provide the required

robustness and efficiency [15]. Metallic materials including Copper and Beryllium are excluded.

*Power load and cooling:* The total power loss from the beams is specified to be up to 500 kW for 10 s and 100 kW continuously (per beam). The peak loss rate corresponds to a 1% loss of stored beam in 10 s. Though this loss is distributed, several 10 kW can impact on some collimators. Collimators must have efficient cooling and maintain their geometrical tolerances for changing heat loads.

*Precision:* The LHC aperture [4] requires the LHC collimators to be set at around  $6\sigma$  for primary and  $7\sigma$  for secondary collimators. At 7 TeV nominal optics the beam size is about  $200\mu\text{m}$  at the collimators, imposing a relative accuracy in setting of primary and secondary collimators of less than  $100\mu\text{m}$ . Several errors can affect the effective relative accuracy: surface flatness of jaws, collinearity of jaws and beam, accuracy and reproducibility of jaw positioning, orbit drifts and transient beta beat. As errors can be additive, stringent tolerances must be met, e.g. a  $25\mu\text{m}$  surface flatness is specified over the 1 m long jaw.

*Impedance:* With collimator full gaps as low as 2.2 mm significant resistive wall impedance can be induced. In fact it is seen that the 7 TeV machine impedance is mostly induced by the C-based collimator jaws [13]. In order to limit this effect the collimators were moved towards higher beta values and a material with low electrical resistivity should be used.

*Radiation:* Much of the stored LHC beam will end up on the collimators. The LHC collimators and adjacent equipment will become highly radioactive [17] and must be designed for quick handling.

The analysis of the different constraints showed that they cannot be reconciled by one general solution. A phased approach was therefore developed.

**Phase 1** During phase 1 collimation the emphasis is put on maximum robustness and flexibility. For beam currents above 30% of nominal design, the LHC performance might be limited by the collimator-induced impedance (limitation on  $\beta^*$  or total intensity). Table 1 lists the components foreseen for phase 1 collimation. Three types of devices are distinguished based on their functions:

*Collimators* are used to control the loss of primary beam protons, as they go from the primary halo (intercepted by primary collimators) to the secondary halo (intercepted by secondary collimators) to the tertiary halo (lost in the aperture or intercepted by tertiary collimators) and finally to the quaternary halo (lost in the aperture). Collimators are precise devices with two jaws, used for efficient beam cleaning. *Scrapers* are used for beam shaping and diagnostics. Scrapers are special one-sided thin objects. *Absorbers* are used to absorb mis-kicked beams or the products of proton-induced showers, as they are produced in the cleaning insertions or during the p-p interaction in the experimental IP's. Movable absorbers are quite similar to collimators, but often use high Z jaw materials and have less stringent tolerances as they are operated with larger aperture settings.

Table 1: The LHC collimation system during phase 1. Listed is the function, label, number  $N_b$  of components per beam, material and jaw length  $L_{jaw}$  without tapering.

	Label	$N_b$	Mat	$L_{jaw}$
<i>Collimators</i>				
Primary betatron	TCP	3	CC	0.2 m
Secondary betatron	TCSG	11	CC	1.0 m
Primary momentum	TCP	1	CC	0.2 m
Secondary momentum	TCSG	4	CC	1.0 m
Tertiary triplets	TCT	6	Cu/W	1.0 m
<i>Scrapers</i>				
Betatron	TCHS	2	tbd	tbd
Momentum	TCHS	1	tbd	tbd
<i>Absorbers</i>				
Injection errors	TCLI	2	CC	1.0 m
Luminosity debris	TCLP	2	Cu/W	1.0 m
Cleaning showers	TCLA	(8)	Cu/W	1.0 m

In total 25 collimators, 3 scrapers and about 12 absorbers will be installed during phase 1 for each beam. The largest sub-system is the betatron cleaning system with 14 collimators per beam for cleaning in horizontal, vertical and skew directions. The overall system size reaches about 80 components plus 13 spares during phase 1 for both beams.

The primary and secondary collimators in the cleaning insertions have a high robustness design (low Z jaws) and will provide the highest tolerance for beam loss during first beam commissioning and first physics. They have each two carbon-based jaws with a  $5\mu\text{m}$  coating, efficient cooling of jaws and tank, independent position and angle control for each jaw, transverse jaw movement parallel to jaw surface (used as spare surface), automatic jaw retraction in case of failures, external measurement of internal gap size/center/angle, temperature monitoring, etc. A more detailed design description is given in [16].

**Phase 2** In order to overcome the impedance limitation during operation with phase 1 collimation, it is envisaged to complement the phase 1 secondary collimators (TCSG) with metallic phase 2 collimators (TCSM). These collimators can use an advanced design and would only be used during stable physics running, when the probability of impact of mis-kicked beam is much reduced for most collimators. A rotating design might allow to cope with infrequent damage. From Table 1 it is seen that the phase 2 installation would require 15 collimators per beam. The use of higher Z materials opens the possibility to enhance cleaning efficiency by a factor 5 [13].

**Layout** The two cleaning insertions of the LHC were re-designed in order to provide the required space for the phased approach. The layout was adapted in order to (1) provide 2 m space per collimator (jaw + tapering + tank + inter-connection), (2) include space for upgrade phases,

(3) move collimators to higher beta values for minimum impedance and (4) optimize the collimator locations and magnet orientations with respect to radiation protection issues. The new layouts are described in [18].

## PROTOTYPING AND BEAM TESTS

The design and prototyping of a secondary graphite collimator was started in Sep. 2003. The mechanical design and prototyping is described in detail in [16]. Pictures of the first prototype collimator are shown in Figure 2.



Figure 2: Pictures of the prototype for a secondary CC collimator TCSG. Left: Tank installed with two jaws. Right: View of 1.2 m long CC jaw with RF tapering.

Three TCSG prototype collimators are presently being constructed at CERN. One will be used for in-depth laboratory tests. The other collimators will be tested with beam:

*Test on beam-based set-up and impedance:* A horizontal collimator will be installed into the SPS ring. A 270 GeV proton beam of variable emittance will be stored. It is expected that the collimator can be closed to a full gap between 3-4 mm, close to LHC requirements. Beam-based set-up of small gaps will be tested with the help of Beam Loss Monitors (BLM's). It will then be tried to measure the collimator-induced impedance with variable gap sizes. A measurement of the collimator impedance in this set-up is difficult, due to its small value compared with SPS impedance.

*Robustness test:* A second horizontal collimator will be installed in the SPS extraction line. A full high-intensity LHC batch will be extracted from the SPS and sent for testing of shock impact on a collimator jaw. It is envisaged that five extractions are sent onto the jaw with different transverse offsets (1-5 mm). The collimator and its infrastructure (e.g. cooling) is expected to survive this robustness test without damage.

## CONCLUSION AND OUTLOOK

An improved collimation system has been designed for the LHC. The system provides two stage cleaning of momentum and betatron offsets (horizontal, vertical, skew di-

rections), a local third stage cleaning at the exposed triplets, scraping for beam shaping and diagnostics and absorption of proton-induced showers. The number of components for individual subsystems has been minimized.

Various conflicting requirements are reconciled with a phased approach which has been implemented into the LHC layout. The first phase of collimation will provide maximum robustness collimators with high impedance. The phase 1 TCP and TCSG collimators have been specified and designed in detail. Prototyping of phase 1 carbon-based collimators is far advanced. Two LHC collimators will be installed into the SPS during August 2004 and will be tested with beam. In parallel work is continuing for phase 1. Important studies concern a highly reliable and radiation-resistant motorization and control, the detailed energy balance and location of absorbers, the radiation damage to carbon in the LHC and preparations for series production. Beyond this a massive computing campaign has been started with novel numerical tools [4], aiming at reliable prediction of beam loss and cleaning efficiency in the LHC, analysis of optics tolerances during operation and development of procedures for set-up and commissioning.

The present layout of the LHC includes space reservations for upgrades in the collimation system. In order to overcome impedance limitations and to maximize cleaning efficiency, it is envisaged that advanced but also delicate collimators will be installed for phase 2 collimation.

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