OPERATIONAL EXPERIENCE WITH LHC COLLIMATION

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Abstract

A first sub-set of the collimation system has been installed for the 2008 first beam commissioning of the LHC. It included 88 collimators around the ring and the two injection lines. Each collimator has two jaws for which must be controlled and monitored with high precision. The LHC collimation system was put into operation from July to October 2008. The installed system is described and first results from system operation without and with beam are presented. It is shown that the LHC collimation system achieved the specified accuracy and reproducibility of jaw positioning. Next steps in collimation commissioning are described and planned system upgrades for high beam intensities are outlined.

INTRODUCTION

The specification, design and layout of the LHC collimation system was critically reviewed starting in 2001. A major redesign of the system was performed from 2002 to 2004. The system design was frozen in 2004 [1] and phase I series production started.

The LHC collimation system is the by far largest and most advanced installation of this kind that has ever been built. It implements a four-stage cleaning process and should allow reaching unprecedented cleaning efficiency. This is required for handling the high intensity LHC beams: collimation efficiency must be 2-3 orders of magnitude better than in existing and past colliders [2].

STAGED APPROACH

Different functional types and numbers of collimators are summarized in Table 1. LHC collimation is constructed and installed in several stages:

1. A sub-set of the first collimation stage was installed for 2008 beam operation of the LHC, including 88 collimators and absorbers. Experience from these collimators is reported in this report in detail.
2. The installation of the full first stage (phase I) is being completed for 2009 operation of the LHC. It consists of 108 collimators and absorbers, out of which 97 are precision movable devices. This system is adequate for beam commissioning but will not allow nominal beam intensity [3].
3. The second stage (phase II) completes the system with additional advanced collimators and new functionalities. It allows reaching nominal and higher beam intensities in the LHC [4,5]. The design and implementation of phase II is presently being prepared at CERN. Work is done in collaboration with and supported by the LARP effort in the U.S.A. and the EUCARD-ColMat work package in FP7. Completion of the various parts is presently envisaged for the years 2012-14.

Table 1: Total number of collimators to be used for efficient cleaning and passive protection for both LHC beams. The staging for phases I and II is indicated, as well as a possible ultimate upgrade (last column). The new proposal of cryo-collimation [4,5] is included as well.

Functional Type	Phase I	Phase II	
IR3 primary collimator	2	2	2
IR3 scraper	0	2	2
IR3 secondary collimator	8	16	16
IR3 passive absorber	2	2	2
IR3 high-Z collimators	8	8	8
IR3 cryo collimators	0	4	4
IR7 primary collimator	6	6	6
IR7 scraper	0	6	6
IR7 secondary collimator	22	44	44
IR7 passive absorber	6	6	6
IR7 high-Z collimators	10	10	10
IR7 cryo collimators	0	4	4
IR7 collimator reservations	0	0	10
Injection protection collimator	22	22	22
Dump protection collimator	2	2	2
High-Z collimators in experimental regions	20	24	24
Total	**108**	**158**	**168**
Total (movable only)	*97*	*147*	*157*

PHASE I COLLIMATORS

The LHC collimators exist in a number of design variations, mainly changing the jaw material that intercepts beam particles. Jaws are the material blocks put closest to the beam (see below). Robust collimators (primary, secondary, some protection collimators) use a special fiber-reinforced carbon material, which combines extreme robustness with good thermal, electrical and mechanical properties [6]. Collimators for absorbing showers use high-Z materials of copper and/or tungsten. They enhance efficiency while being sensitive to beam damage. Therefore, they are only used at larger distances from the beam. Collimators closest to the beam are all robust for phase I. Here, we focus on the main design and describe the important features of an LHC collimator.

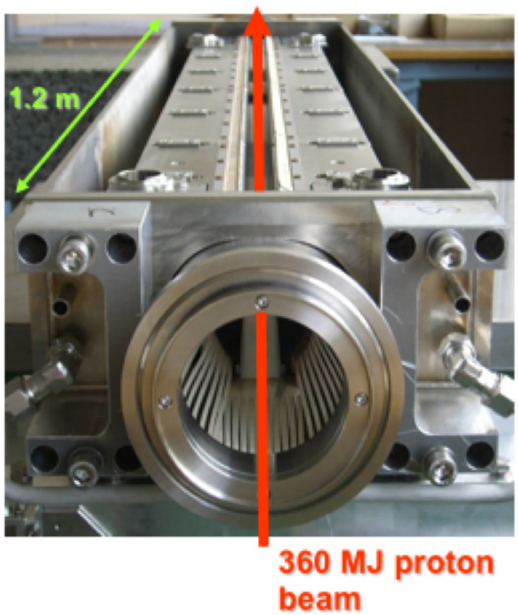

Figure 1: View into an open vacuum tank of an LHC phase I collimator. The two parallel jaws are visible.

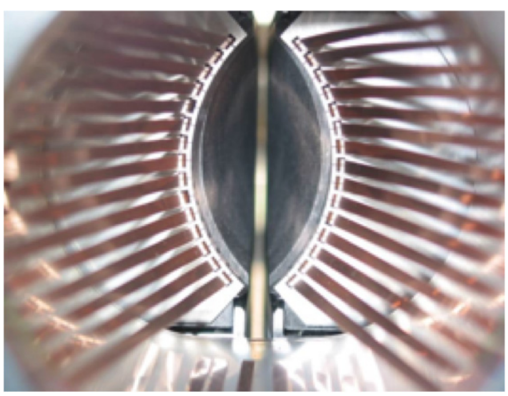

Figure 2: View along the beam line in a horizontal secondary collimator with fiber-reinforced carbon jaws and a typical LHC gap size. The RF fingers are used to guide image currents.

Collimator Design

A phase I collimator houses two parallel jaws inside a vacuum box. The rotation of the tank is used to define a horizontal, vertical or skew collimator. The flat top length of jaws is always 1.0 m, except for primary collimators (0.6 m) and transfer line collimators (1.2 m). The flange-to-flange length of a collimator is 1.48 m. Each jaw is supported at its two extremities and movable both in distance to the beam center and in angle with respect to the beam. Precise stepping motors are used to move the jaws. Movements are monitored independently with precisions sensors (LVDT's, resolvers) [7], implementing triple redundancy. A views of an open collimator tank and along the beam path are shown in Figures 1 and 2. Important specifications include:

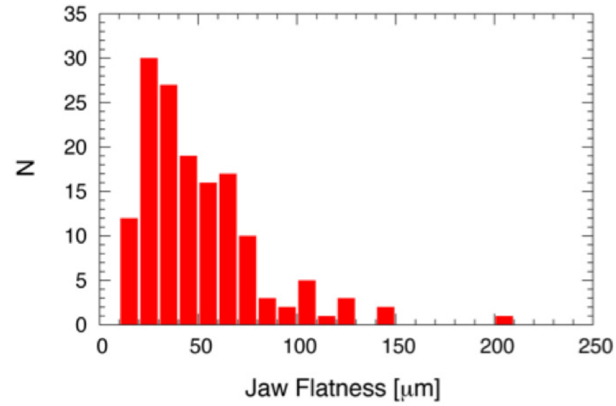

Figure 3: Maximum flatness error for a sample of 148 assembled and installed jaws in series production.

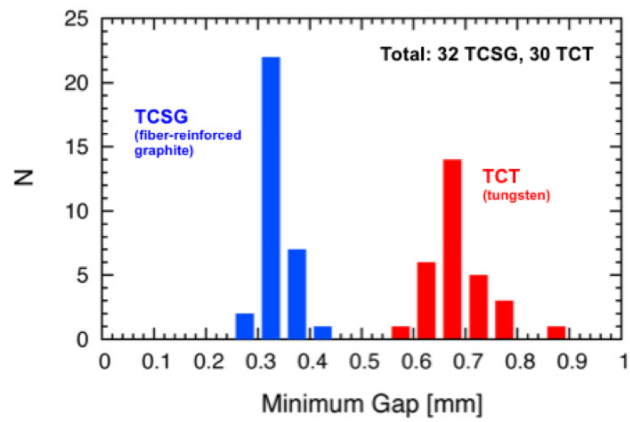

Figure 4: Achieved minimum gap for two families of collimators with different specifications.

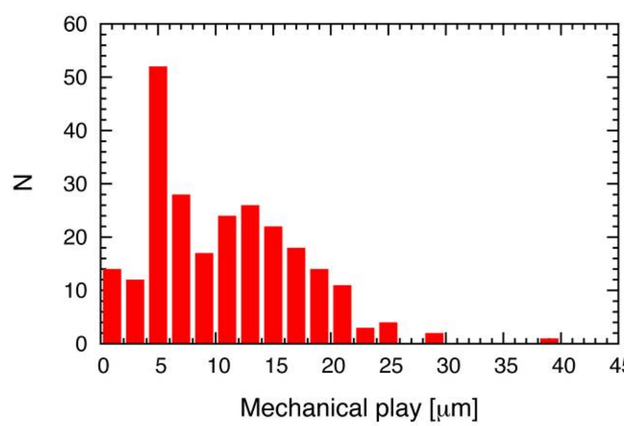

Figure 5: Achieved mechanical play in the LHC collimators for phase I series production.

- Jaws and tank are water-cooled for extracting heat loads of up to 3 kW. Water circuits in- and outside of vacuum must resist a pressure of up to 20 bar.
- The vacuum pressure after bake-out must be smaller than 4×10^{-8} mbar.

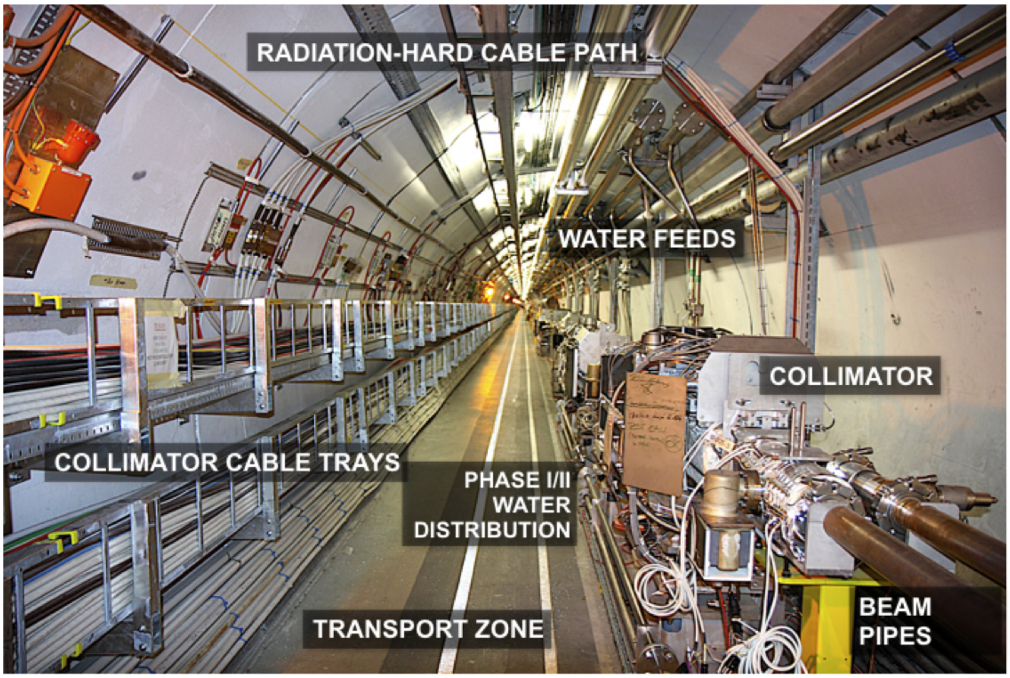

Figure 6: Integration of phase I collimators into the LHC tunnel (IR7 betatron cleaning insertion). The installation and infrastructure was optimized to minimize radiation impact and to prepare remote handling.

- The surface flatness of the collimator jaws must be lower than 40 μm or 80 μm, depending on type of collimator.
- The minimal achievable gap between the two jaws must be smaller than 0.5 mm or 0.8 mm, depending on type of collimator.
- The maximum achievable gap between the two jaws must be larger than 58 mm.
- Each jaw must be movable to 5 mm across the center of the tank, such that LHC orbit movements can be followed.
- Each jaw must allow an angle of up to 2 mrad with respect to the centerline of the tank.
- The maximum dynamic torque for moving the collimators through their full stroke must be smaller than 0.5 Nm.
- The mechanical play on each moving axis must be below 20 μm.

The production was monitored under strict quality assurance procedures to ensure that the design goals are fulfilled and that collimators are adequate for LHC beam operation [8].

The achieved flatness errors and minimum gaps are shown in Figures 3, 4 and 5. It is seen that the target minimum gaps and mechanical plays were achieved for almost all collimators. The flatness turned out to be more challenging due to limitations in series production. The specification was not always fulfilled but flatness errors are still much smaller than the LHC beam size at top energy (200 μm). The flatness could therefore be accepted. Some limited gain was achieved by placing collimators with larger flatness errors at locations of high β-function ("sorting"). All data is available in online databases for supporting operation with the LHC collimators.

Tunnel Layout in Collimation Regions

The tunnel layout in the two cleaning insertions IR3 and IR7 cannot be described in detail in this report. This tunnel layout has been the subject of intense optimization in order to reduce radiation impact and to prepare remote handling for collimators. LHC collimators are designed to intercept a maximum of particles lost from the beam. They will therefore become highly radioactive. A view of the cleaning insertion IR7 is shown in Figure 6.

Here it is important to note that collimators must be operated fully remotely. The low level control is far away from the collimators in radiation-safe areas.

Collimator Position Control

The design of LHC collimator control and first experience is described in [9]. Collimators are driven completely remotely from the CERN Control Center CCC.

Collimator settings are crucial for the safety of the LHC accelerator, the experiments and the collimation system itself. Therefore separate control paths and controls hardware are used to drive the stepping motors and to independently survey the actual movements. The position survey relies on six LVDT position sensors mounted on each collimator. These sensors measure the position of the four jaw extremities in each tank and the up- and downstream gaps defined by the jaws. The measurements provide important redundancy (6 measured values for 4 degrees of freedom). The collimator observables during operation are illustrated in Figure 7.

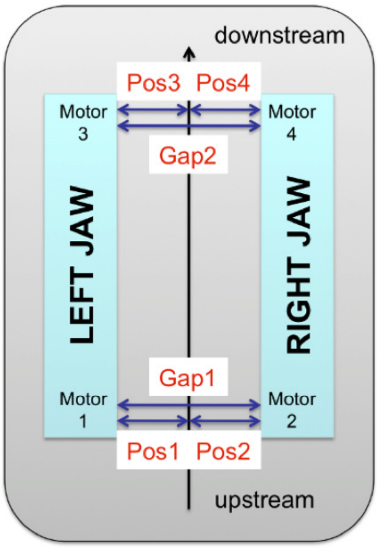

Figure 7: Remote measurements (4 positions and 2 gaps) on each collimator, as provided by six LVDT's.

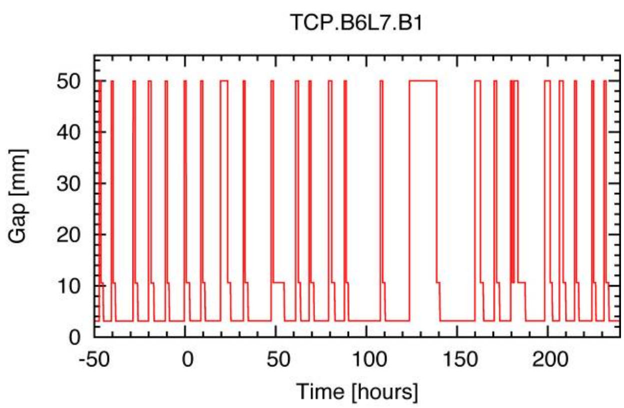

Figure 8: Cycling of a primary collimator in IR7 over more than 10 days in October 2008.

2008 OPERATION WITHOUT BEAM

In 2008 LHC collimators were mainly operated without beam. Operational tests included in particular a 10 day reliability and reproducibility run of 28 collimators with 168 position sensors. The collimators were driven over 10 days through a realistic operational cycle, as shown in Figures 8 and 9. No adjustments on positions or sensor calibrations were performed during these 10 days. The independent position survey from LVDT's was used to calculate for every collimator the maximum difference between requested setting and measured position. This we define as the maximum reproducibility error.

The tightest tolerances apply for small gaps, namely for collision settings. The histogram of maximum reproducibility errors for collision settings is shown in Figure 10. It is seen that out of 168 sensors only one sensor showed more than 30 μm error. Due to redundancy of sensors it can be concluded that this is a faulty sensor reading.

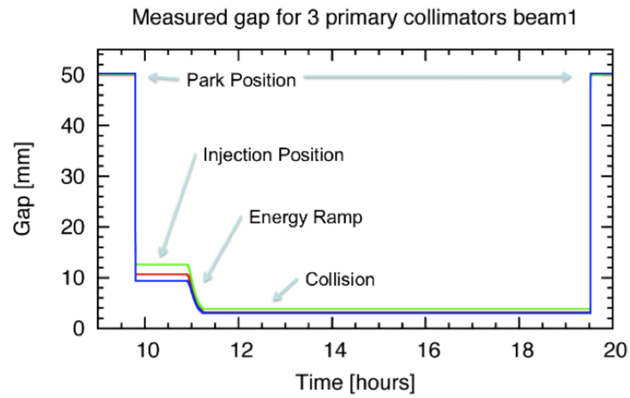

Figure 9: Operational cycle executed by 3 collimators in IR7 over 10 days, mimicking the real collimator position functions (the difference in absolute gap is due to difference in beta functions for the three collimators shown).

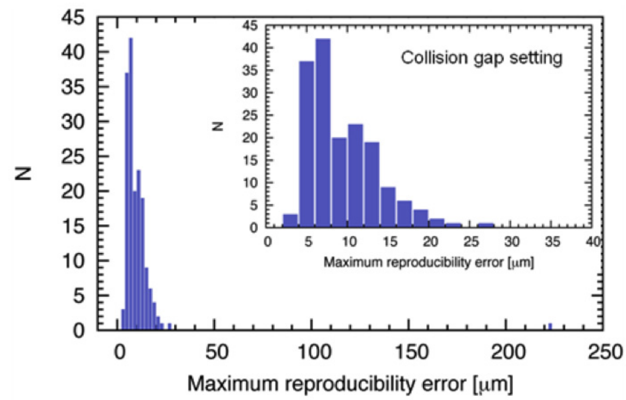

Figure 10: Maximum error in reproducibility over the 10 days reproducibility and reliability run. The inlet shows a zoom into the peak.

The results from the operational test without beam show that collimators can be remotely controlled around the ring to better than 30 μm (the width of a human hair), most even better than 15 μm. The measured error includes contributions from setting errors and drifts, mechanical reproducibility and sensor errors and drifts over 10 days. It was shown that the system could be controlled as specified and even better.

2008 OPERATION WITH BEAM

Operational experience with the LHC collimation system during beam operation was very limited in 2008, due to the premature end of the beam commissioning. Collimators played an important role in the commissioning of the first turn. They were used as intermediate stoppers for dumping the beam at strategic points (mainly the experiments) around the ring. The shower particles escaping from the collimators were recorded by the particle physics experiments and useful to check the detector response (so-called splash events).

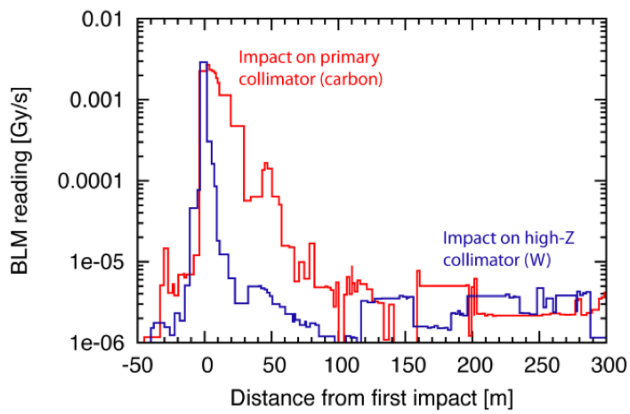

Figure 11: Readings of beam loss monitors downstream of LHC beam impacts on a carbon primary collimator (red data) and a tungsten high-Z collimator (blue line). Impact on the collimator is at zero position.

The LHC beam was used to record the response from beam loss monitors downstream of collimators. The beam consisted of a single bunch of intensity 5×10^9 protons and was at injection energy (450 GeV). Two different cases are shown in Figure 11:

1. Impact of beam on the first secondary collimator in IR7 with carbon jaws. All downstream collimators are closed (also carbon collimators for first 150 m). The exponential reduction of beam loss signals was fitted and an exponential decay length of 17.4 m was found.
2. Impact of beam at the first high-Z collimator at the end of the IR7 (tungsten jaw). All downstream collimators are closed which in this case were additional tungsten collimators. An exponential decay length of 1.7 m was found.

The data illustrates the much lower absorption with the carbon-based robust collimators, which was fully expected. The data shows in addition that the BLM response downstream of collimators was working reliably. The systems were ready for collimation setup with LHC beam. Once beam commissioning is resumed for the LHC, the collimation system will be set up for protection and efficiency. The 2008 beam data does not allow any conclusions on collimation efficiency and protection quality.

CONCLUSION

The LHC collimation system is being implemented in a staged approach. The phase I system has been produced under strict quality assurance procedures. The achieved production quality has been presented and ensures that LHC collimators can be used as precision devices.

The 2008 system included 88 collimators with 172 jaws and more than 300 degrees of freedom for position and angle control. It constituted the largest and most complex collimation system ever put into operation. The system worked as specified without beam, demonstrating mechanical jaw position control and stability of better than 30 μm over 10 days.

Beam loss response with first LHC beam impacting on collimators was recorded, confirming qualitatively the expected the difference between low-Z and high-Z collimators. The limited beam time did not allow any attempt to set up cleaning and/or passive protection in the LHC ring. However, all systems were ready for this task, which will now be performed in 2009 with the full phase I system of 108 collimators.

The completion of the collimation system (phase II) is presently under preparation. With its 158 collimators it will upgrade cleaning efficiency by more than one order of magnitude and will allow for nominal and higher LHC beam intensities.

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