Chapter 13

Cleaning Insertions and Collimation Challenges

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High-performance collimation systems are essential for operating efficiently modern hadron machine with large beam intensities. In particular, at the LHC the collimation system ensures a clean disposal of beam halos in the superconducting environment. The challenges of the HL-LHC study pose various demanding requests for beam collimation. In this paper we review the present collimation system and its performance during the LHC Run 1 in 2010–2013. Various collimation solutions under study to address the HL-LHC requirements are then reviewed, identifying the main upgrade baseline and pointing out advanced collimation concept for further enhancement of the performance.

1. Present LHC Collimation

In this introductory section the present LHC collimation system is reviewed. Its main features are presented and the highlight performance achievements during the LHC Run 1 are recalled. The possible limitations and challenges for the collimation in the HL-LHC era are then discussed.

1.1. Introduction to LHC multi-stage collimation

The LHC collimation system is designed to safely dispose of beam losses in order to reduce the risk of quenches of superconducting magnets and damage of accelerator components. The cleaning functionality is required in case of unavoidable transverse betatron — as well as off-momentum losses. For this purpose, two dedicated warm LHC insertions address betatron (IR7) and momentum (IR3) cleaning separately [1]. A very efficient halo cleaning, as required to operate with unprecedented stored beam energies in a superconducting collider, is achieved through a multi-stage cleaning. This is illustrated

Fig. 1. Illustrative scheme of the multi-stage collimation cleaning at the LHC. Primary and secondary collimators (darkest grey) are the devices closest to the circulating beam and are made of robust carbon-fiber composites. Shower absorbers and tertiary collimators (lighter grey) sit at larger apertures and are made of a Tungsten alloy to improve absorption. Collimators of different families are ordered in a pre-defined collimation hierarchy that must be respected in order to ensure the required system functionalities. The collimator hierarchy is ensured by defining collimator settings in units of local beam size at the collimator location.

schematically in Fig. 1. The present system deployed for the LHC operation between 2010 and 2013 is designed to provide a cleaning efficiency above 99.99% [2], i.e. to ensure that less than 10^{-4} of the beam losses is lost in superconducting magnets. The collimation system includes 43 movable ring collimators per beam. The complete list including injection protection collimators in the transfer lines (built within the LHC collimation project) is given in Table 1. For completeness, the injection protection TDI blocks and the one-side beam dump collimator TCDQ are also listed (see Chapter 19). The full system comprises 108 collimators, 100 of which are movable.

Beam halo collimation is achieved by placing very precisely blocks of materials close to the circulating beams, while respecting a pre-defined collimator hierarchy that ensures optimum cleaning in a multi-stage collimation process. The list of collimator families with the main parameters such as material, orientation and total number of devices is given in Table 1. Since the collimator “jaws” sit close to the beam (e.g., the minimum collimator gap in 2012 was 2.1 mm, i.e. jaws were 1.05 mm apart from the circulating beam), the collimation system also has a critical role in the passive machine protection in case of beam failures that cannot be counteracted by active systems (see

Chapter 12). Primary and secondary collimators in IR7 are the closest to the beam and are made of robust carbon-fiber composites (CFC) that withstand the most critical failures. However they contribute significantly to the machine impedance because of the low conductivity of the CFC and this determines the smallest gaps that can be used. Other absorbers and tertiary collimators sit at larger gaps in beam size unit. They can be less robust than primary and secondary collimators because they are less exposed to beam losses. Thus, metal-based jaws with a higher stopping power can be used. The operation of LHC Run 1 proved that the collimation hierarchy constrains the LHC performance in terms of minimum achievable β^* , determined by the maximum aperture that can be protected [3]. For example, in 2012 the minimum machine aperture in the triplet magnets was about 11σ for a β^* of 60 cm. The betatron cuts from the collimators (see Fig. 1) ranged from 4.3σ (primary cut) to 9σ (tertiary cut). This 2σ is required to ensure adequate magnet protection in presence of transient orbit and optics drifts in the IRs. The momentum cut from the IR3 collimators was 0.2% for the reference particle with zero betatron amplitude.

In addition to the beam halo cleaning, the collimation system has also other important roles that can be summarized as follows:

- **Passive machine protection:** the collimators are the closest elements to the circulating beam and represent the first line of defence in case of various normal and abnormal loss cases, see also Chapter 12. Due to the damage potential of the LHC beams, this functionality has become one of the most critical aspects for the LHC operation and commissioning. In particular, it must be ensured that the triplet magnets in the experiments are protected during the betatron squeeze [3].
- **Active cleaning of collision debris products:** this is achieved with dedicated (TCL) collimators located on the outgoing beams of each high-luminosity experiment that catch the debris produced by the collisions keeping losses below the quench limit of the superconducting magnets in the matching sections and dispersion suppressors around the interaction points.
- **Experiment background optimization:** this is one of the classical roles of collimation systems in previous colliders like ISR, SppS and Tevatron. For the LHC, the contribution to background from beam halo has always been expected to be small, thanks to the good IR7 collimation cleaning that induces only limited losses close to the experiments. The initial run confirmed this expectation [4].
- **Concentration of radiation losses:** for high power machines, it is becoming increasingly important to be able to localize beam losses in confined and optimized “hot” areas rather than having a distributed activation of equipment

along the machine. This is an essential functionality to allow easy access for maintenance in the largest fraction of machine.

- **Local protection of equipment and improvement of lifetime:** Dedicated movable or fixed collimators are used to shield equipment. For example, eight passive absorbers are used in the collimation insertions in order to reduce total doses to warm dipoles and quadrupoles that otherwise would have a short lifetime in the high-radiation environment foreseen during the nominal LHC operation.
- **Beam halo scraping and halo diagnostics:** Collimator scans in association to the very sensitive LHC beam loss monitoring system proved to be a powerful way to probe the population of beam tails [5, 6], otherwise too small compared to the beam core to be measured by conventional emittance measurements. Thanks to their robustness, the present primary collimators can also be efficiently used to scrape and shape the beams, like in [7].

In order to fulfil all these functionalities, the LHC collimation system features an unprecedented complexity compared to previous state-of-the-art in particle accelerators. Table 1 (right) lists, for example, the degrees of freedom for collimator movements and the number of interlock functions of the 2012 system [8]. As a comparison, the Tevatron collimation system had less than 30 degrees of freedom. For this reason, the possibility to operate reliably the collimation system has always been considered as a major concern for the LHC performance.

Table 1. Left: Collimators for the LHC Run 1 in 2010–2013. For each type, acronyms, rotation plane (horizontal, vertical or skew), material and number of devices are given. Right: Various degree of freedom for collimation movements as deployed for the LHC operational cycle in 2012–2013. About 400 motors are moved in discrete steps or according to functions of time in order to ensure optimum collimator settings in all phases of the operational cycle.

Functional type	Name	Plane	Num.	Material	Parameters	Number
Primary IR3	TCP	H	2	CFC	Movable collimators in the ring	85
Secondary IR3	TCSG	H	8	CFC	Transfer line collimators	13
Absorbers IR3	TCLA	H,V	8	W	Stepping motors	392
Primary IR7	TCP	H,V,S	6	CFC	Resolvers	392
Secondary IR7	TCSG	H,V,S	22	CFC	Position/gap measurements	584
Absorbers IR7	TCLA	H,V	10	W	Interlocked position sensors	584
Tertiary IR1/2/5/8	TCT	H,V	16	W/Cu	Interlocked temperature sensors	584
Physics absor. IR1/5	TCL	H	4	Cu		
Dump protection IR6	TCSG	H	2	CFC	Motor settings: functions / discrete	448/1180
	TCDQ	H	2	C	Threshold settings versus time	9768
Inj. prot. (lines)	TCDI	H,V	13	CFC	Threshold settings versus energy	196
Inj. prot. IR2/8	TDI	V	2	C	Threshold settings versus β^*	384
	TCLI	V	4	CFC	Temperature thresholds	490
	TCDD	V	1	CFC		

1.2. Brief recapitulation of collimation performance in LHC Run 1

The cleaning performance of the LHC collimation system is measured by the so-called *local cleaning inefficiency*, η_c , defined as the number of proton lost $N_{\text{lost}}(s \rightarrow s + \Delta s)$ per unit length at a longitudinal s position in the ring, normalized by the total losses in the collimators, N_{abs} :

$$\eta_c = \frac{N_{\text{lost}}(s \rightarrow s + \Delta s)}{N_{\text{abs}}} \frac{1}{\Delta s}.$$

In simulations, losses are sampled using Δs bins of 10 cm. In practice, losses in the machine are measured at the discrete locations of beam loss monitors (BLMs). An example of cleaning measured at the LHC during the 2012 run at 4 TeV is given in Fig. 2 [9]. In this case, losses measured at the ~ 3600 BLMs around the ring are normalized by the peak loss at the horizontal primary collimator in IR7 (horizontal loss map). The local IR7 losses, showing the limiting cleaning locations in the dispersion suppressor, DS, (right side of IR7 for B1), are given in Fig. 3. In this example, a cleaning efficiency above 99.993% is achieved. Note that, with the exception of a few isolated peaks in the DS, the rest of the cold machine experiences losses that are more than one order of magnitude smaller.

In Fig. 4, the achieved cleaning inefficiency as a function of time is given for the different loss map campaigns carried out in 2012 [9]. These are validation tests performed regularly during the run to monitor the system performance by generating on purpose high losses on the primary collimators in controlled conditions. The highest (worst) inefficiency measured at cold locations is given

Fig. 2. Collimation cleaning measured at 4 TeV with $\beta^* = 60$ cm in IR1/5 in case of horizontal beam losses. Courtesy of B. Salvachua for the collimation team [9].

Fig. 3. Local IR7 losses from the graph in Fig. 2. Courtesy of B. Salvachua for the collimation team [9].

Fig. 4. Collimation cleaning inefficiency at the worst location in the DSs at either side of IR7 for both beams and planes as measured throughout the 2012 operation with protons (4 TeV, $\beta^* = 60$ cm). Courtesy of B. Salvachua [9].

for each plane and beam. This defines the system performance reach in terms of its capability to protect cold magnets from quenches. Highest losses are always recorded at the DSs around IR7, consistently with the simulation predictions. The cleaning inefficiency is very stable throughout the year and remains typically below a few 10^{-4} .

It is important to note that this performance was achieved with one single beam-based alignment per year for the collimators in IR3 and IR7. This is a major achievement for a large and distributed system like the one deployed at the LHC. This result was achieved thanks to the excellent stability of the machine (orbit, optics, etc.) and of the collimator settings. On the other hand, work to

improve the alignment speed remains important: note that some 15 alignment campaigns were required in 2012 in order to setup the collimators in the experimental regions to match the requirements of new machine configurations requested by the experiments. This aspect represented an important constraint to the LHC operation in the Run 1 that is being addressed by a system upgrade during LS1 by adding collimators with integrated beam position monitors for orbit control and fast alignment, see below.

In 2012, the collimators were operated with full gaps as small as 2.1 mm (case of the vertical primary collimators in IR7), as required to push the β^* performance reach down to 60 cm [3]. Primary collimators were set in millimetres to their 7 TeV reference settings of 5.7σ . This is another important commissioning milestone illustrating that the collimator mechanics and control design choices (see next section) are adequate for the LHC small beam challenge.

On the other hand, the operation with small gaps increases the impedance of the machine (see Chapter 15), dominated by primary and secondary collimators in IR3/7. The 2012 operation was significantly affected by beam losses throughout the operational cycle [10]. The interplay between impedance and beam-beam effects is one of the possible sources of instabilities, which were instead not observed in 2011 with same normalized beam-beam separation and larger collimator settings. The operation at smaller gaps also causes naturally larger losses because the primary betatron collimators cut closer into the beam core. Studies are on-going to understand the performance limitations after LS1 from the collimation losses but it is already clear that an important ingredient for the performance in the HL-LHC era will be the reduction of the collimator impedance [11], in particular in view of the operation with larger single-bunch intensities. The backup solution to open further the collimators is always available but this has a non-negligible cost in terms of achievable β^* .

1.3. Preliminary LHC intensity reach from collimation

For a given collimation cleaning, the performance estimate in terms of total intensity reach, $I_{\max}$, before quenching the magnets can be calculated for a given quench limit of superconducting magnets, R_q , and for a minimum allowed beam lifetime throughout the operational cycle, $\tau_b^{\min}$:

$$I_{\max} \leq \frac{R_q \tau_b^{\min}}{\eta_c}.$$

Here, the quench limit R_q is expressed in protons lost per metre per second. In reality, the performance reach estimates rely on, apart from dedicated measure-

ments with beam, complex integrated simulations that combine multi-turn tracking of halo particles and energy deposition studies to compute the loss distribution in the magnet coils. This is then used as input for dedicated quench analysis tools. The most recent simulations were presented and discussed in detail at the collimation project review in May 2013 [12]. It is important to note that the performance reach estimates are based on experimentally achieved losses during LHC quench tests (see for example [13]).

Putting together the best knowledge of the various inputs, and assuming conservatively a minimum allowed lifetime of 0.2 h as suggested by an external review panel [14], one can estimate a total intensity reach for proton operation between a factor of 1.5 and 3 more than the present HL-LHC baseline (i.e., 3 to 6 times more than the nominal LHC intensity). It is important to realize that these estimates are based on the operational experience at lower LHC energy and at reduced total beam intensity (50 ns bunch spacing instead than the nominal 25 ns). Estimates are therefore intrinsically affected by uncertainties, in particular:

- extrapolation of quench limits to higher energies (margins in superconducting magnets may not follow the expected scaling laws);
- simulated cleaning inefficiency versus energy;
- assumption that the minimum lifetime does not degrade at higher energies, with reduced bunch spacing and increased collimator impedance;
- scaling of simulation results to higher energies.

It is therefore important to prepare alternative solutions in case of unexpected limitations and in order to ensure appropriate safety margins for the HL-LHC operation. The uncertainties listed above will be addressed by monitoring the performance in the post-LS1 operation.

1.4. *Challenges of HL-LHC parameters*

For higher luminosity operation of the LHC, the challenges for the collimation system are pushed forward in various respects. For the same collimation cleaning and primary beam loss conditions, the factor ~ 2 increase in total stored beam energy foreseen by the HL-LHC parameters requires a corresponding improvement of cleaning performance to achieve the same losses in cold magnets. Total losses might also exceed the robustness limit of collimators. The system is designed to withstand without damage lifetime drops down to 0.2 h during 10 s, corresponding to peak losses up to 500 kW. The larger stored energy also imposes more severe challenges for the collimator robustness against standard loss scenarios. Brighter beams impose potentially higher demands on the

collimator material and design. The higher peak luminosity challenges entails the definition of new concepts for physics debris cleaning and an overall redesign of the IR collimation layouts. For example, in the present layout the inner triplet represents the IR aperture bottleneck and is protected by two dedicated tertiary collimators per plane per beam. Future optics scenarios might add critical aperture restrictions at magnets further away from the IP, requiring additional cleaning and protection.

2. Present and Future Collimator Design Concepts

In this section, the present design of the LHC collimator is recapitulated and the on-going studies for possible improvements are reviewed. This covers design features for improved operation of the system, a reduced impedance design and new material studies for future HL-LHC challenges.

2.1. Collimator design for precision and robustness

Two photographs of the present LHC collimator are given in Fig. 5, where a horizontal and a 45° tilted collimator are shown. An example of the tunnel installation layout for a IR7 collimator is given in Fig. 6. The LHC collimators are built as high precision devices in order to ensure the correct hierarchy of devices along the 27 km ring with beam sizes as small as 200 microns. Details of the collimator design can be found in [20]. Key features of the design are (1) a jaw flatness of about 40 microns along the 1 m-long active jaw surface, (2) a surface roughness below 2 microns, (3) a 5 micron positioning resolution (mechanical, controls), (4) an overall setting reproducibility below 20 microns

Fig. 5. Photograph of a horizontal (left) and a skew (right) LHC collimator. The latter has the vacuum tank open to show the two movable CFC jaws.

Fig. 6. Photograph of the active absorber TCLA.B6R7.B1 as installed in the betatron cleaning insertion.

[21], (5) a minimal gap of 0.5 mm, (6) evacuated heat loads of up to 7 kW in steady-state regime and of up to 30 kW in transient conditions. Primary and secondary collimator are made of robust carbon-fiber reinforced carbon composite (CFC) that is designed to withstand without significant permanent damage beam impacts for the worst failure cases such as impacts of a full injection batch of $288 \times 1.15 \times 10^{11}$ protons at 450 GeV and of up to $8 \times 1.15 \times 10^{11}$ protons at 7 TeV [22]. Other collimators made of tungsten heavy alloy or copper, obviously, do not have the same robustness and are only operated at larger distances from the circulating beams.

2.2. Collimator with embedded beam position monitors

The collimator design has been recently improved by adding two beam position monitors (BPMs) on either extremity of each jaw [23]. An example of a CFC jaw prototype with this new design is shown in Fig. 7. This concept will allow a fast collimator alignment as well as a constant monitoring of the beam orbit at the collimator as opposed to the BLM-based alignment that presently can only be performed during dedicated low-intensity commissioning fills. The BPM buttons will improve significantly the collimation performance in terms of operational

Fig. 7. New carbon/carbon collimator jaw with integrated BPMs at each extremity to be installed as secondary collimator in the dump insertion IR6. A detail of the BPM is given on the left side. A variant of this design, made with a Glidcop support and Tungsten inserts on the active jaw part, will be used for the tertiary collimators in all IRs.

flexibility and β^* reach [3]. The BPM-embedded design is considered as the baseline for future collimation upgrades. The concept has been tested extensively at the CERN SPS with a collimator prototype with BPMs [24, 25, 26]. Based on these results, 18 new collimators with integrated BPMs will already be installed during LS1, replacing the present tertiary collimators in all experiments (critical for β^* reach) and the secondary collimators in the dump region. Note that the BPM design is equally applicable to all collimators regardless of the jaw material.

2.3. Rotatory collimator design

The rotatory collimator design developed at SLAC proposes a “consumable collimator” concept based on two round jaws with 20 flat facets that can be rotated to offer to the beam a fresh collimator material in case a facet is damaged [27]. This concept provides a low-impedance design that is based on standard non-exotic materials. It is conceived for a high-power operation, with a performing 12 kW active cooling system to withstand the extreme power loads experienced by the secondary collimators in IR7. A photograph of this device before closing the vacuum tank is given in Fig. 8, where the rotatory glidcop (a copper alloy) jaws are visible. The first full-scale prototype of this advanced collimator concept has recently been delivered to CERN [28] and is being tested in preparation of beam tests. The ultimate goal is to validate the rotation mechanism after high-intensity shock impacts at the HiRadMat facility, aimed at demonstrating that the concept of consumable collimator surface can indeed work for the works LHC beam load scenarios. The precision accuracy of this prototype and the impedance are also being tested together with its vacuum performance.

Fig. 8. Photograph of the SLAC rotatory collimator prototype jaws before assembly in the vacuum tank. Courtesy of T. Markiewicz (SLAC).

2.4. Status of R&D on novel advanced collimator materials

One key element to ensure that next-generation collimators meet their challenging requirements lies in the development and use of novel advanced materials for the collimator jaws as no existing metal-based or carbon-based material possesses the combination of physical, thermal, electrical and mechanical properties which are required by the extreme working conditions. A rich R&D program has been launched to find optimum materials to improve robustness and impedance of the collimators. Several families of novel materials have been studied and developed, also in the frame of the FP7 EU programs EuCARD and EuCARD2 and in partnership with an Italian SME (Brevetti Bizz, San Bonifacio, Verona, Italy).

The driving requirements for new material's development are: (1) low resistive-wall impedance in order to avoid beam instabilities, (2) high cleaning efficiency, (3) high geometrical stability to maintain the extreme precision of the collimator jaw during operation despite temperature changes and (4) high structural robustness in case of accidental events like single-turn losses (see Chapter 12). It is interesting to note that several of these requirements are shared with other advanced thermal management applications, so that the object of this R&D program may have interesting spin-offs on industries for Aerospace, Medical, Nuclear, Electronics, etc.

Fig. 9. Left: SEM view of CuCD: 175 μm diamonds surrounded by the Cu phase. The white spots on diamond surfaces are boron carbides (right). Right: Molybdenum-Graphite composite reinforced with carbon fibers.

A new family of materials, with promising features, has been identified: metal-carbon composites. These materials combine the outstanding thermal and physical properties of two carbon allotropes, diamond and graphite, with the electrical and mechanical properties of metals. The best candidates are Copper-Diamond (Cu-CD) and Molybdenum-Graphite (Mo-Gr), shown in Fig. 9. In particular, Mo-Gr may provide interesting properties regarding operating temperature, thermal shock resistance and, thanks to its availability in a wide range of mass density, also energy absorption capability. Additionally, this material may be effectively coated with pure molybdenum, dramatically decreasing the RF impedance contribution of future collimators. The addition of carbon fibers increases the mechanical strength of Mo-Gr.

A complex and comprehensive experiment was carried out at CERN HiRadMat facility [29, 30] to assess the consequences of highly energetic particle pulses impacting on sample collimator materials. Tests were also performed on a fully functional LHC collimator with Inermet180 jaws [31]. This is the heavy tungsten alloy that the present tertiary collimators are made of. The experiment aimed at the characterization, mostly in real time, of six different materials impacted by 440 GeV intense proton pulses. Chosen materials were a combination of relatively conventional metals for collimation applications, such as Inermet, dispersion-strengthened copper (Glidcop) and molybdenum, and of novel composites under development including Cu-CD and carbon-fiber reinforced Mo-Gr. The design of the test set-up required innovative solutions in terms of lighting, support stabilization, radiation resistance and noise control.

Preliminary post-irradiation observations indicate that both Cu-CD and fiber reinforced Mo-Gr survived the high intensity impacts. Copper-Diamond (Cu-CD) has been developed by RHP-Technology, Seibersdorf, Austria, and studied for particle accelerator applications in the frame of the EuCARD collaboration.

Cu-CD is made of 60% synthetic diamonds, 39% copper powder and 1% boron powder, mixed and sintered by rapid hot pressing: diamonds enhance the material thermal conductivity while decreasing density. Boron is added to create a bridging between Cu matrix and diamond re-enforcement by forming boron carbides (B_4C) at interfaces. However, the strength of the resulting composite is limited because the boron carbide links are brittle and they are present only on a limited fraction of the diamond surface. An additional drawback is posed by the difficulty to machine these materials.

In the case of Mo-Gr, the preferential recrystallization of graphite planes during rapid hot pressing at temperatures in excess of 2500 °C leads to a compact structure, assuring outstanding thermal properties in the principal direction (even more than 700 W/m-K of thermal conductivity) and fair mechanical properties. In addition, coating Mo-GR jaws with a layer of pure Mo is being developed as a way to reduce the collimator impedance. The coating would reduce the surface resistivity by about a factor of 20 compared to Mo-GR (while maintaining sufficient robustness) and by more than a factor 100 compared to CFC. The benefit on the impedance budget of the collimation system would be significant: in the relevant frequency range, impedance would be reduced to 10% of the one of the CFC jaws (Fig. 10).

Fig. 10. Collimation impedance versus frequency: impedance ratio between Mo coating on Mo-Gr (50 μ m layer) and present CFC jaw. A secondary collimator is considered. Courtesy of N. Mounet.

3. Improved Cleaning of Dispersion Suppressor Losses

In this section, the present baseline solution for improving the collimation cleaning, based on adding local collimation at the high-loss locations in the

dispersion suppressors, is described for the different relevant LHC insertions. This is a technically challenging solution due to the tricky integration into cold areas but otherwise very robust from the beam physics view point. It relies on intercepting losses before they hit the magnets. This solution applies both for experimental and collimation insertions.

3.1. *Introduction to local DS collimation*

The limiting locations for collimation losses, both in the cleaning insertions and in the experimental regions, are the cold dispersion suppressors immediately downstream of the straight sections. This is the first high dispersion location seen by the outgoing particles that change their rigidity in the insertion, from interactions with the collimator materials (cleaning insertions) or from the collision with the other beam (experimental insertions). The dedicated momentum cleaning insertion in IR3 cannot catch local single-turn effects: if the change of a particle's rigidity is larger than the acceptance of the arc, these particles are lost before reaching IR3. The DSs around IR7 might limit the performance both for proton and for heavy ion operation. The proton limitations were discussed in the introductory section of this chapter. In addition, ion losses in the DSs around the experiments might limit the achievable peak luminosity if the DSs are not adequately protected.

A possible solution to this problem is to add local collimators in the dispersion suppressors, which is only feasible with a major change of the cold layout at the locations where the dispersion start rising. Indeed, the present system's multi-stage cleaning is not efficient at catching these dispersive losses. Clearly, the need for local collimation depends on the absolute level of losses achieved in operation and the quench limit of superconducting magnets. In this design phase when the quench limits and the operational performance are not yet known accurately enough at energies close to 7 TeV, it is important to take appropriate margins to minimize the risk of being limited in the future (post-LS1 operation and even more in the HL-LHC era).

Our present best guess on the needs for DS collimation in the different IRs, for proton and heavy-ion beam operation, is summarized in Table 2 [32]. For the betatron cleaning, the present performance reach estimates indicate that the intensity goal should be within reach albeit with reduced safety margins. The situation changes for HL-LHC due to some specific features of the loss maps with the Achromatic Telescopic Squeeze (ATS) optics [33]. These interim conclusions are subject to a re-evaluation of the beam performance and of the quench limits during the post-LS1 operation in 2015.

Table 2. Summary of need for DS collimation in the different insertion points, for the operation until LS3 and beyond (HL-LHC era).

		Until HL-LHC (before LS3) [$L=2.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, $I_{\text{ion}}=3.2 \times 10^{14} \text{p}$]		HL-LHC era (after LS3) [$L=5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, $I_{\text{ion}}=6.2 \times 10^{14} \text{p}$]	
		Protons	Ions	Protons	Ions
IR7	Betatron cleaning	Needed? (unlikely)	Needed? (unlikely)	Needed TBC for ATS	Needed?
IR3	Momentum cleaning	Not needed	Not needed	Not needed	Not needed
IR1/5	ATLAS/CMS	Not needed	Needed	Needed? (unlikely)	Needed
IR2	ALICE	Not needed	Needed	Not needed	Needed
IR8	LHCb	Not needed	Not operating	Not needed	Not needed LHCb operating?

The driving factor that calls for an implementation of DS collimation already in LS2 is the ion case. This applies to IR1, 2 and 5 even though the priority shall be given to ALICE during ion physics time. This is described in detail below in this section. On the other hand, thanks to an upgraded layout of the physics debris collimation in IR1 and IR5 that takes place in LS1 [16, 17], no limitations from luminosity losses are expected in the high-luminosity points for proton operation with the present layout that will remain until LS3. This must be re-evaluated for the final HL-LHC layout [19].

3.2. DS collimation solutions for proton and ion cases

In the past, a solution was conceived that relied on moving the position of a number (24 per IR) superconducting dipoles and quadrupoles, together with associated cold powering elements like DFBs and shuffling modules, in order to free enough space for installing collimators in cells 8 and 10 [34]. This major layout change was made possible by using the space of the connection cryostat in cell 11, just upstream of the Q11. In its first concept, this solution was considered for IR3 for the so-called combined momentum and betatron cleaning. The solution based on displacing magnets was the only viable — though clearly very challenging — option for improving the cleaning during LS1, also taking into account constraints from radiation to electronics that favored an installation in IR3 rather than in IR7. The evaluation of the collimation operational performance in 2011 and 2012 indicates, as discussed above, that no immediate limitations from betatron cleaning should be expected in the post-LS1 era. Earliest actions for DS collimation are therefore postponed until LS2 [35, 36]. This has the advantage of allowing a much more elegant solution based on two shorter, higher field dipoles that could be used to replace one present 15 m long dipole by

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Fig. 13. Simulated loss maps around the 27 km long LHC ring without (top) and with (bottom) local DS collimators around IR7. The baseline HL-LHC ATS optics with $\beta^* = 15$ cm in IP1/5 is used. From [39].

Fig. 14. Simulated power density map in the horizontal plane of DS dipoles for nominal 7 TeV operation and a beam lifetime of 0.2 h (4.5e11 protons lost per second). Comparison of the present layout and a layout with two TCLDs. Results correspond to relaxed collimator settings. Beam direction is from the right to the left. From [40].

optics. The improved performance must be compared against the expected quench limits at 7 TeV for a certain assumed beam lifetime. This is done by detailed energy deposition studies that are used to quantify the energy deposited in the coil of the superconducting magnets [40]. For example, the case of 0.2 h lifetime for the nominal LHC beam is illustrated in Fig. 14. It is seen that the

presence of local DS collimators as in Fig. 12 reduces the peak energy deposition by about a factor of 10 compared to the present layout with standard dipoles. If the LHC total intensity reach were limited by collimation losses with the present layout without DS collimation, this solution would allow increasing the intensity reach by the same factor.

Although the loss maps generated by collimation of heavy-ion beams in IR3 and IR7 are different because of the wider range of nuclear interactions that can occur in the primary collimator material [51], it has been shown [52] that these collimators will also achieve a substantial reduction of the losses in the IR7 dispersion suppressors.

The case of ion losses from collision products in IR2 [52, 53, 54, 12] is treated differently. The magnets in the DS might quench in this case due to the production of “beams” with different rigidities from ultraperipheral electromagnetic interactions of the counter-rotating beams at the collision point. The dominating processes are bound-free pair production (BFPP) where electron-positron pairs are created and an electron is caught in a bound state by one (BFPP1) or both (BFPP2) nuclei, thus changing their charge, and 1- or 2-neutron electromagnetic dissociation (EMD1 and EMD2) where one of the colliding ions

Fig. 15. 1σ envelope of the main Pb^{82+} beam (violet) together with the dispersive trajectories of ions undergone BFPP1 (red), BFPP2 (orange), EMD1 (light green) and EMD2 (dark green) coming out of the ALICE experiment in nominal optics. The DS collimator appears as a black line. Varying its opening allows different secondary beams to be intercepted.

emits one or two neutrons, respectively, thus changing mass. Further photo-induced processes also take place, but the four ones mentioned here have the higher cross sections. An example of ion beams produced in collisions of $^{208}\text{Pb}^{82+}$ nuclei in IR2 is given in Fig. 15. The BFPP1, producing $^{208}\text{Pb}^{81+}$, is the dominant process for this ion and the corresponding beam can carry about 150 W for the foreseen upgrade ALICE luminosity peak of $6 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$. Detailed energy deposition simulation for the cases without and with DS collimators replacing the dipole MB.A10R2.B1 indicate that 0.5 m of copper are sufficient to reduce the peak losses in the cold magnet by a factor of 25. This would ensure a safe operation with the upgraded ALICE luminosity. Without local collimation, losses would be up to a factor of 2 above the quench limits, depending on the models used for the quench analysis [12].

During heavy-ion operation, a similar situation prevails around the ATLAS and CMS experiments in IR1 and IR5 and further installations of DS collimators may eventually have to be considered. Thanks to optical differences in these insertions, there is some flexibility in positioning of the collimator assemblies [12].

3.3. Status of prototyping and design

The design of the new DS collimators, designated as TCLDs, and of the bypass cryostat necessary to install a warm collimator are well advanced thanks to the preparatory work done for the possible implementation in LS1, based on moving magnets [36]. A bypass cryostat prototype was built (see Fig. 16) to perform the necessary tests at cold to validate this concept. These tests are ongoing at the time of writing. The TCLD collimator design was also very advanced. On the other hand, the new baseline that relies on shorter 11 T dipoles has been reviewed from the integration point of view [12]. The space is tight and the length of all components and transitions must be carefully optimized. The present baseline is that the TCLD will have an active jaw length of 80 cm that proved to be sufficient to improve the cleaning in all relevant cases. Tungsten heavy alloy is assumed for the material because the TCLD will hardly be exposed to large beam load, so we do not see the need at this stage to consider advanced materials. In order to ensure more flexibility for the case of ion beams, where positive changes of the beam rigidity also occur, a 2-jaw design is considered for the moment.

From the RF view point, designs with transverse RF finger (as in the present system) as well as a with ferrite blocks to absorb high order modes (as in the collimators with BPMs) are being comparatively assessed. The latter design is shown in Fig. 17, where a detail of the collimator jaw corner is given.

Fig. 16. Photograph of the prototype bypass cryostat (QTC) designed to install a warm collimator in the cold DSs.

Fig. 17. Detail of one corner of the TCLD collimator to be installed in the DS between two new 11 T dipoles. The present design foresees an 80 cm long jaw made of tungsten (the first of 4, 20 cm tungsten tiles is shown) and will have two jaws. Designs with transverse RF fingers or ferrite tiles are being comparatively assessed to reduce the detrimental effects of trapped RF modes.

4. Advanced Collimation Concepts for HL-LHC

Other advanced collimation concepts that still require R&D and therefore cannot be considered yet as a baseline are discussed in this section.

4.1. Halo diffusion control techniques

The 2012 operational experience indicates that the LHC collimation would profit from halo control mechanisms. These were used in other machines like HERA and Tevatron. The idea is that, by controlling the diffusion speed of halo

particles, one can act on the time profile of the losses, for example by reducing rates of losses that otherwise would take place in short time, or simply by controlling the static population of halo particles in a certain aperture range. These aspects were recently discussed at a collimation review on the possible usage of the hollow e-lens collimation concept at the LHC [41], where it was concluded that hollow e-lenses could be used at the LHC for this purpose. In this case, a hollow electron beam, running parallel to the proton or ion beam, is used to generate an annular beam in the transverse (x, y) plane. This hollow beam induces a field affecting halo particles above a certain transverse amplitude and can change their transverse speed. The conceptual working principle is illustrated in the left part of Fig. 18. A solid experimental basis achieved at the Tevatron indicates that this solution is promising for the LHC ([42] and reference therein).

Fig. 18. Illustrative view of the collimation system with integrated hollow e-lens or equivalent halo diffusion mechanism (left) and of an ideal crystal-based collimation (right). A reduced collimator layout than the one in Fig. 1 is adopted to show the betatron cleaning functionality only (one side only). Halo control techniques are used to globally change the diffusion speed of halo particles and rely on the full collimation system remaining in place. Crystals entail a change of concept where the whole beam losses are concentrated, ideally, in one single beam absorber per plane.

At the review [41], it also became clear that, if loss spikes were limiting the LHC performance after LS1, the hollow e-lens solution would not be viable because it could only be implemented in a next long shutdown at the earliest (driven by time for the integration into the cryogenics system). It is therefore crucial to work on viable alternatives that, in case of need, might be implemented on an appropriate time scale. Two alternatives are presently being considered:

- Tune modulation through noise in the current of lattice quadrupoles;
- Narrow-band excitation of halo particles with the transverse damper system.

Though very different from the hardware point of view, both these techniques rely on exciting tail particles through resonances induced in the tune space by

appropriate excitations. This works in the assumption of a presence of correlation between halo particles with large amplitudes and corresponding tune shift in tune space (de-tuning with amplitude). Clearly, both methods require a solid experimental verification in a very low noise machine like the LHC, in particular to demonstrate that this type of excitations do not perturb the beam core emittance. Unlike for hollow e-lenses that act directly in the transverse plane by affecting particles at a amplitudes above the inner radius of the hollow beam, resonance excitations methods required a good knowledge of the beam core tune even in dynamic phases of the operational cycle, so the possibility to use these techniques at the LHC remains to be demonstrated. For this purpose, simulation efforts are on going with the aim of defining the required hardware interventions during LS1 that might enable beam tests of these two halo control methods early on in 2015. Ideally, these measurements would profit from appropriate halo diagnostic tools, see Chapter 14. But we are confident that conclusive measurements could be achieved with the techniques describe for example in [5].

4.2. *Crystal collimation*

Highly pure bent crystal can be used to steer high-energy particles that get trapped between the potential of parallel lattice planes. Equivalent bending fields up to hundreds of Tesla can be achieved in crystals with a length of only 3–4 mm, which allows in principle to steer halo particles to a well-defined point. As opposed to a standard collimation system based on amorphous materials, requiring several secondary collimators and absorbers to catch the products developed through the interaction with matter (see Fig. 2, right), one single absorber per collimation plane is in theory sufficient in a crystal-based collimation system [43]. This is shown in the scheme in Fig. 18 (right). Indeed, nuclear interactions with well-aligned crystals are much reduced compared to a primary collimator, provided that high channeling efficiencies of halo particles can be achieved (particles impinging on the crystal to be channelled within a few turns). This is expected to reduce significantly the dispersive beam losses in the DS of the betatron cleaning insertion compared to the present system that is limited by the leakage of particles from the primary collimators. Simulations indicate a possible gain between 5 and 10 [44] even for a layout without an optimized absorber design. The crystal collimation option is particularly interesting for collimating heavy-ion beams thanks to the reduced probability of ion dissociation and fragmentation compared to the present primary collimators. SPS test results are promising [45].

Another potential of crystal collimation is a strong reduction of the machine impedance due to the facts that (1) only a small number of collimator absorbers is required and that (2) the absorbers can be set at much larger gaps thanks to the large bending angle from the crystal (40–50 μrad instead than a few μrad from the multiple-Coulomb scattering in the primary collimator). On the other hand, an appropriate absorber design must be conceived in order to handle the peak loss rates in case of beam instabilities: the absorber must withstand continuous losses up to 1 MW during 10 s while ensuring the correct collimation functionality. This is a change of paradigm compared to the present system where such losses are distributed among several collimators. Other potential issues concern the machine protection aspects of this system (what happens if the crystal is not properly aligned and channels an important fraction of the total stored energy to the wrong place?) and the operability of the system that requires mechanical angular stability in the sub- μrad range to be ensured through the operational cycle of the LHC (injection, ramp, squeeze and collision).

Promising results have been achieved in dedicated crystal collimation tests at SPS performed from 2009 within the UA9 experiment [45, 46, 47]. On the other hand, some outstanding issues about the feasibility of the crystal collimation concept for the LHC can only be addressed by dedicated beam tests at high energy in the LHC. For this purpose, a study at the LHC has been proposed that might already take place in the LHC Run 2 after LS1 [48]. The main purpose of this test with LHC beams is to demonstrate the feasibility of the crystal-collimation concept in the LHC environment, in particular to demonstrate that such a system can provide a better cleaning of the present high-performance system throughout the operational cycle. Until a solid demonstration is achieved, this scheme cannot be considered for future HL-LHC baseline scenarios.

4.3. Improved optics scenarios for the collimation insertions

Alternative optics concepts in IR7 can be conceived in order to improve some present collimation limitations without major hardware changes. For example, non-linear optics schemes derived from the linear collider experience [49] were considered for IR7. The idea is that one can create a “non-linear bump” that deforms the trajectories of halo particles and effectively increases their transverse amplitudes in a way that allows opening the gaps of primary and secondary collimators. These studies are well advanced from the optics point of view but for the moment it was not easily possible to find a layout solution providing the same cleaning as the present system [50]. These studies, and other aimed at increasing the beta functions at the collimators, are on-going.

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