COLLIMATION FOR THE LHC HIGH INTENSITY BEAMS

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Abstract

The unprecedented design intensities of the LHC require several important advances in beam collimation. With its more than 100 collimators, acting on various planes and beams, the LHC collimation system is the biggest and most performing such system ever designed and constructed. The solution for LHC collimation is explained, the technical components are introduced and the initial performance is presented. Residual beam leakage from the system is analysed. Measurements and simulations are presented which show that collimation efficiencies of better than 99.97 % have been measured with the 3.5 TeV proton beams of the LHC, in excellent agreement with expectations.

INTRODUCTION

The Large Hadron Collider LHC [1,2] at CERN is the new frontier collider for Particle Physics. Its discovery reach depends critically on the beam energy and the luminosity (event rate) reached. The beam energy is presently limited to 3.5 TeV [3] from non-conformities in the magnet and powering system. Maximizing the stored beam intensity increases the achievable luminosity. A powerful collimation system is required to handle the ultra-intense LHC beams in a super-conducting environment [4,5,6,7]. Only with highly efficient collimation can the LHC targets be reached.

The important beam parameters of the proton beam operation in LHC are compared in Table 1 with the nominal design values, with E being the beam energy, D_z the bunch spacing, $\gamma\varepsilon_{h/v}$ the normalized transverse emittances, N_p the number of protons per bunch, N_b the number of bunches, E_{stored} the stored beam energy, L_{peak} the peak instantaneous luminosity and N_{tot} the total beam intensity. It is seen that the energy stored in the LHC beams passed already much beyond the 2 MJ values achieved in HERA and Tevatron. Milestones of the LHC collimation project are listed in Table 2. It is seen that the work on the LHC collimation system was performed under strong time pressure, as this was the last major LHC system to be designed and produced.

Table 1: Important parameters of LHC operation with proton beams as achieved in 2010 and compared to the nominal design values.

Parameter	Unit	2010	Design
E	TeV	3.5	7.0
Δ_z	ns	150	25
$\gamma\varepsilon_{h/v}$	μm	1.8	3.75
N_p	p	1.2×10^{11}	1.15×10^{11}
Luminosity production			
N_b		368	2808
N_{tot}	p	4.4×10^{13}	3×10^{14}
E_{stored}	MJ	24.8	362
L_{peak}	$cm^{-2}\ s^{-1}$	2×10^{32}	1×10^{34}
Peak intensity at 3.5 TeV			
N_b		424	2808
N_{tot}	p	5.1×10^{13}	3×10^{14}
E_{stored}	MJ	28.5	362

Table 2: Major milestones of the LHC collimation project.

Time	Milestone
01/2003	Start of the LHC collimation project. System and hardware design.
06/2004	System solution approved
10/2004	Verification of collimator prototypes with 450 GeV beam
06/2005	Signature of production contract with industry
09/2008	Minimal system installed in LHC and used for first beam
06/2009	Full initial system installed
10/2010	LHC reaches 28 MJ stored energy in first year of full operation without quench from stored beam

REQUIREMENTS FOR COLLIMATION

Storage rings like the LHC would ideally store charged particles with infinite beam lifetime. In this case there would be no particles and no power lost. However, there are a number of processes that will always lead to beam losses [5]. It would go beyond the scope of this paper to list and discuss them in detail. It is just noted that the collision process for luminosity production itself creates beam diffusion and losses at the aperture restrictions of the ring. Beam losses are therefore unavoidable and become usually stronger as intensity and luminosity is increased.

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*The reported work on the LHC collimation system was performed from 2003 to 2010 and relied on the work of the following persons at CERN and at outside collaborating institutes: O. Aberle, R. Assmann, J.P. Bacher, V. Baglin, G. Bellodi, A. Bertarelli, P. Bestmann, R. Billen, V. Boccone, A.P. Bouzoud, C. Bracco, H. Braun, R. Bruce, M. Brugger, S. Calatroni, F. Caspers, M. Cauchi, F. Cerruti, R. Chamizo, A. Cherif, E. Chiaveri, A. Dallochio, D. Deboy, B. Dehning, M. Donze, N. Hilleret, E.B. Holzer, D. Jacquet, J.B. Jeanneret, J.M. Jimenez, M. Jonker, Y. Kadi, K. Kershaw, G. Kruk, M. Lamont, L. Lari, J. Lendaro, J. Lettry, R. Losito, M. Magistris, A. Masi, M. Mayer, E. Métral, C. Mitifiot, N. Mounet, R. Perret, S. Perrolaz, V. Previtali, C. Rathjen, S. Redaelli, G. Robert-Demolaize, C. Roderick, S. Roesler, A. Rossi, F. Ruggiero, M. Santana, R. Schmidt, P. Sievers, M. Sobczak, K. Tsoulou, G. Valentino, E. Veyrunes, H. Vincke, V. Vlachoudis, T. Weiler, J. Wenninger, D. Wollmann, CERN, Geneva, Switzerland. D. Kaltchev et al, TRIUMF, Canada. I. Bayshev, IHEP, Russia. T. Markiewicz et al, SLAC, USA. N. Mokhov et al, FNAL, USA. A. Ryazanov et al, Kurchatov, Russia. N. Sammut et al, University Malta, Malta. N. Simos et al, BNL, USA.

Movable collimators define aperture restrictions and are the LHC defense against unavoidable losses. They fulfill various tasks:

- Provide passive protection against irregular fast losses and failures [8,9,10,11].
- Provide cleaning [5,7,12,13] for slow losses in the super-conducting environment (see Figure 1).
- Manage radiation impact of beam loss [14,15,16,17].
- Minimize background in the experiments.

The specified peak beam losses at collimators (maximum allowed loss) are as follows [5,7]:

- Slow continuous losses:
  0.01% of beam per s = 50 kW
- Slow peak losses:
  0.1% of beam per s for 10 s = 0.5 MW
- Transient losses:
  5×10^{-5} of beam in 10 turns (~ms) = 20 MW
- Accidental losses:
  up to 1 MJ in 200 ns into 0.2 mm^2 = 5 TW

Numbers refer to the nominal design intensity at 7 TeV. Power loads are more relaxed at lower energies, like 3.5 TeV in 2010. The loss values must be compared to the quench limits of the LHC super-conducting magnets that are for steady state losses in the range of 5 mW/cm^3 to 100 mW/cm^3, depending on magnet type and beam energy [18]. This is illustrated in Figure 2.

Losses must be intercepted and absorbed at collimators with a high efficiency for avoiding quenches of LHC magnets. The allowed leakage from collimation into SC magnets is about 2×10^{-5} per m of magnet [5]. This is also called collimation inefficiency [7]. The efficiency must then ultimately be better than 99.998 %

THE SYSTEM SOLUTION

The LHC collimation system is designed to provide a four-stage collimation process, thus extending and modifying the two-stage concept developed and used before. The basic philosophy developed for LHC is explained in Figure 3. Robust and non-robust materials are placed around the beam at optimal longitudinal positions, different orientations in the H-V transverse plane and various transverse distances from the beam. The smallest collimation gaps go down to 2 mm at high energy.

The detailed system design was the outcome of a multi-parameter optimization, taking into account nuclear physics processes in the jaws, robustness to beam accidents, collimation efficiency, energy deposition, radiation impact and machine impedance. The optimization relied heavily on various state-of-the-art numerical simulation programs [19,20,21,22,23], some developed for the purpose of LHC collimation. A parallelized simulation program and CPU cluster were set up to numerically optimize the system. We summarize some key characteristics:

- High statistics: 2×10^7 protons tracked over 200 LHC turns of each 27 km. This corresponds to 108 billion proton-km and is equivalent to simulating a proton that travels 700 times the distance sun-earth in an accelerator.
- A detailed model of all magnetic elements and the LHC aperture (vacuum pipes, …) with a resolution of 0.1 m.
- Routines for halo proton generation with sub-micron impact parameters (distance from hit to collimator edge), halo transport and aperture checks.
- Routines for proton-matter interaction, including several elastic and inelastic processes, in particular single-diffractive scattering.
- Chromatically fully correct tracking up to energy offsets of several 10%.

Important decisions were based on simulations: choice of material and length of jaws, 20% reduced number of primary collimators, 25% reduced number of secondary collimators (compared to theory), additional tertiary collimators. The accelerator physics simulations were complemented by full sets of FLUKA energy deposition [18].

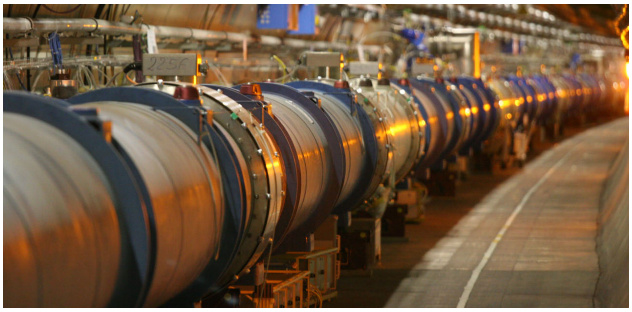

Figure 1: Photograph of the super-conducting LHC magnets in the tunnel.

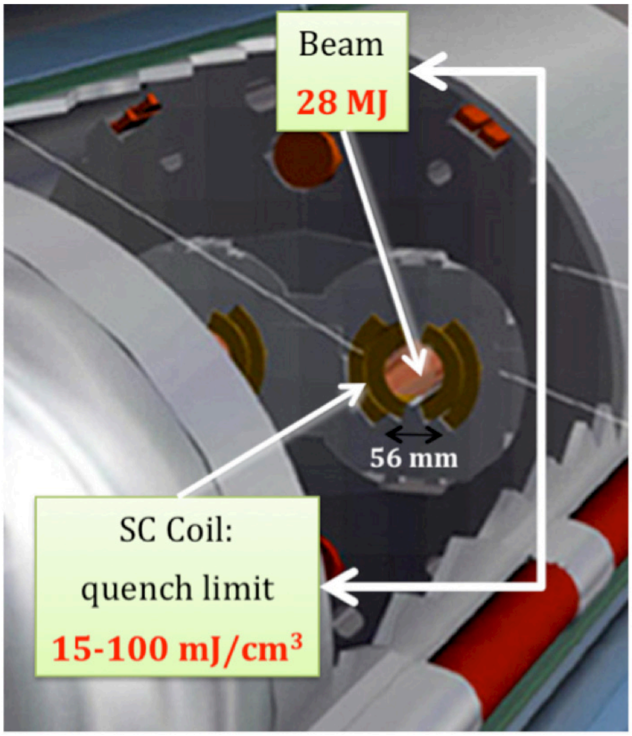

Figure 2: Illustration of the maximum stored energy in LHC during the 2010 run and the 3.5 TeV quench limit of the super-conducting magnets.

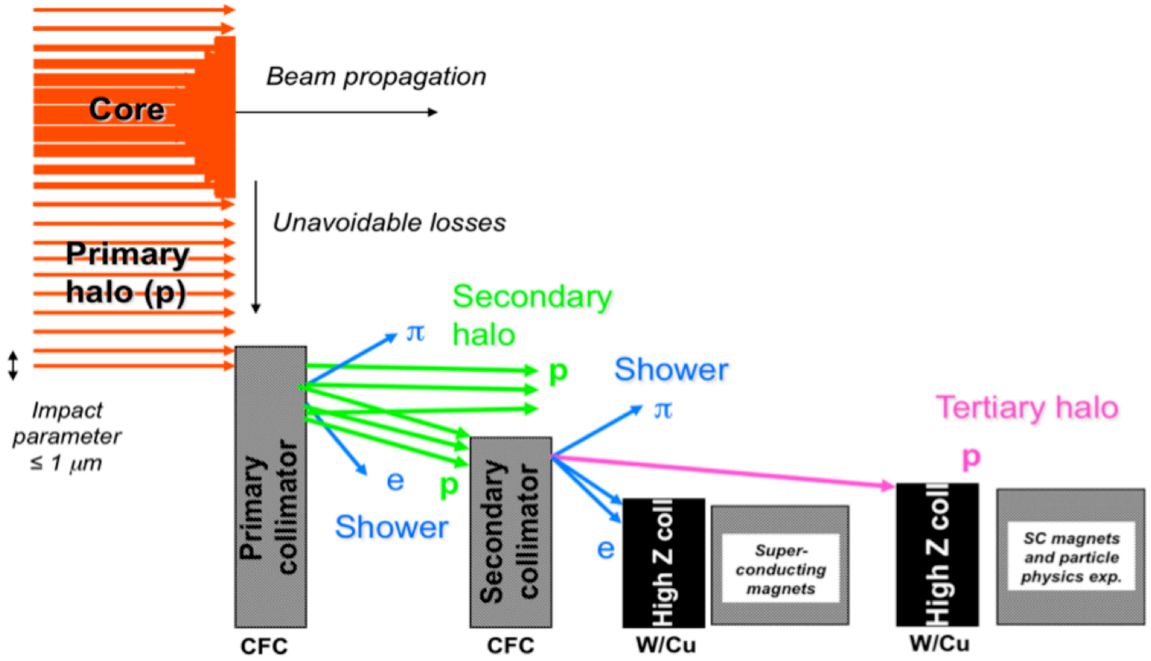

Figure 3: Illustration of the multi-stage collimation philosophy that was developed for the LHC. Robust primary collimators intercept stray particles for horizontal, vertical, skew or momentum offsets and spray losses downstream. Robust secondary collimators intercept much of the losses and dilute them further. At the end of the warm cleaning insertions, non-robust high Z collimators absorb the diluted proton halo and showers. This three stage cleaning takes place over two times 250 m without super-conducting magnets (the cleaning insertions in IR3 and IR7). A fourth stage of non-robust high-Z collimators intercepts tertiary halo close to the particle physics experiments and the sensitive triplet magnets. Additional collimators around the ring (not shown) intercept luminosity-induced debris, absorb radiation and provide passive protection.

The LHC collimator-induced impedance was reviewed (not thought to be problem). A surprise was found in 2003: collimators drive LHC impedance, even if metallic collimators are used. The LHC impedance depends strongly on the collimator settings. Detailed simulations provided predictions that were tested in prototype tests with SPS beam [24,25]. The LHC beams are stabilized with the transverse damper feedback system and octupoles.

The detailed description of the design process would go beyond the scope of this paper but we point to the relevant publications.

The distribution of various types of collimators around the LHC 27 km circumference is illustrated in Figure 4. It is noted that the sketch only includes the collimators that have been installed for the first years of LHC operation (“collimation phase 1”).

The number of various collimators is summarized in Table 3. LHC collimation initially relies on 107 devices of which 98 are movable elements. It is foreseen that the system will be increased to 127 devices in a first upgrade and to 169-179 devices in a second upgrade.

The system provides tight collimation all through injection, ramp, squeeze and collision. It catches safely all losses that occur while intensity is increased. This includes “normal” losses (scattering, emittance growth, diffusion, …) and losses with equipment failures.

THE LHC COLLIMATOR DESIGN

The LHC collimator concept [26,27] relies on two parallel jaws that define a slit for the beam (see Figure 5). The beam and its halo are well constrained with a two-sided concept. The collimator box can be turned in the H-V plane to collimate horizontal, vertical or skew halo.

Simplifications with one-sided designs and L-shaped jaws were discussed during the design phase but were not pursued due to concerns about operational stability.

The mechanical concept of the LHC collimator is illustrated in Figure 6. We describe the main features:

- The two parallel jaws are supported on a sliding table where they glide on rails.
- The support posts on each end of the vacuum tank are passed through flexible vacuum bellows that deform with jaw movements.
- Stepping motors [28] on the sliding table (outside vacuum) precisely move the jaws in distance and angle to the beam.
- Switches limit the stroke of the jaw movement to the valid range, including limits on the jaw gap (anti-collision switches).
- Position sensors (LVDT’s and resolvers) monitor jaw position and the gap [28] between the two jaws (relying on precise 3D calibration outside – inside

gap during production). Positions/gaps are surveyed with triple redundancy.

- Temperature sensors monitor the temperature in the collimator jaws. Cables are passed with vacuum feed-throughs.
- Microphones are used to detect any shock waves induced by beam hits.

The photograph of an open collimator tank with installed jaws is shown in Figure 7.

The main specifications for the various types of LHC collimators are summarized in Tables 4 and 5. The detailed analysis of the LHC requirements made it clear that collimators for the LHC must act as high precision devices. Extensive 3D measurements were performed during prototyping and production to ensure conformity of the hardware and to record all calibration data for LHC operation.

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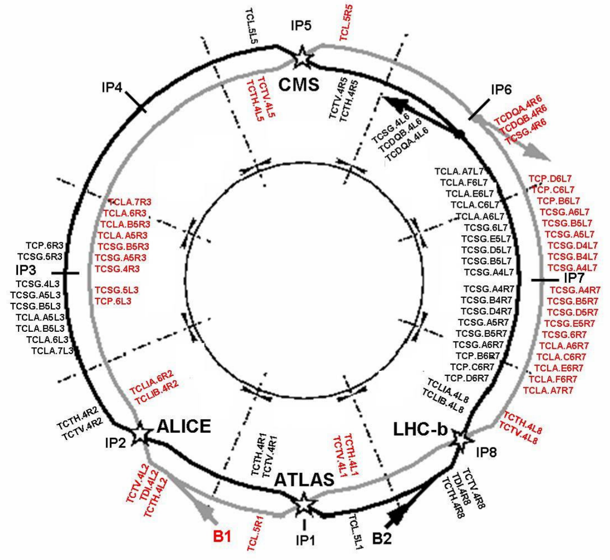

Figure 4: Longitudinal distribution of collimators around the 27 km long LHC ring. Collimators for beam 1 (red) and beam 2 (black) are distinguished.

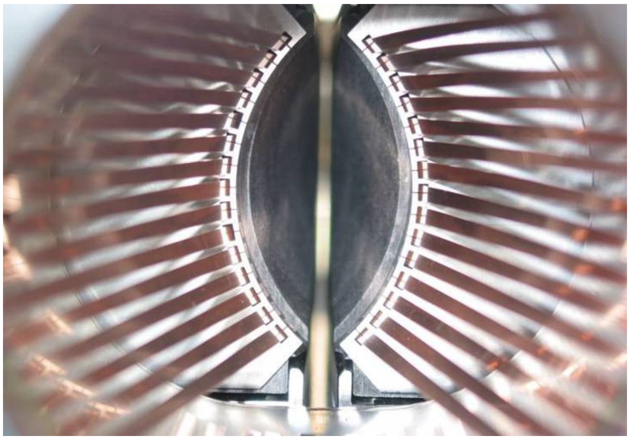

Figure 5: Photograph of a TCP/TCS type collimator along the beam path. The two jaws define a collimating slit.

The LHC collimator design (see Figure 6) has the unique feature that it is possible to measure a gap outside of the beam vacuum that can be directly referred to the collimation gap seen by the beam. Ensuring proper calibration of inside versus outside gap in production (see Figure 8) allows LHC operation to directly measure and know the collimation gaps around the ring. Similar is true for jaw positions.

The achieved results [29, 30, 31] on minimal collimator gaps, jaw flatness errors and mechanical plays are summarized in Figures 9, 10 and 11. Some non-conformities in jaw flatness could not be avoided and were addressed by installing the affected jaws at locations of larger beta functions (therefore larger gaps). Figure 12 shows a photograph of 3D alignment in industry.

Table 3: Number of LHC collimators as used in 2010 ("phase 1" system for first years) and foreseen evolution in two future upgrades.

Functional Type	**2010**	**Upgrade**	
		I	II
IR3			
primary coll. TCP	2	4	2
scraper TCHS	0	0	2
sec. coll. TCS	8	16	16
absorber TCAP	2	2	6
high-Z coll. TCLA	8	8	8
cryo collimators	0	4	4
IR7			
primary coll. TCP	6	6	6
scraper TCHS	0	0	6
sec. coll. TCS	22	22	44
absorber TCAP	6	6	6
high-Z coll. TCLA	10	10	10
cryo collimators	0	0	4
coll. reservations	0	0	10
IR2, IR8, transfer lines (incl 2 TDI)			
injection coll.	19	19	19
IR6 (incl 2 TCDQ)			
dump collimator	4	4	6
IR1, IR2, IR5, IR8			
cryo collimators	0	0	4
high-Z coll. TCT	20	26	26
Total	**107**	**127**	**169-179**
Total (movable)	*98*	*118*	*160-170*

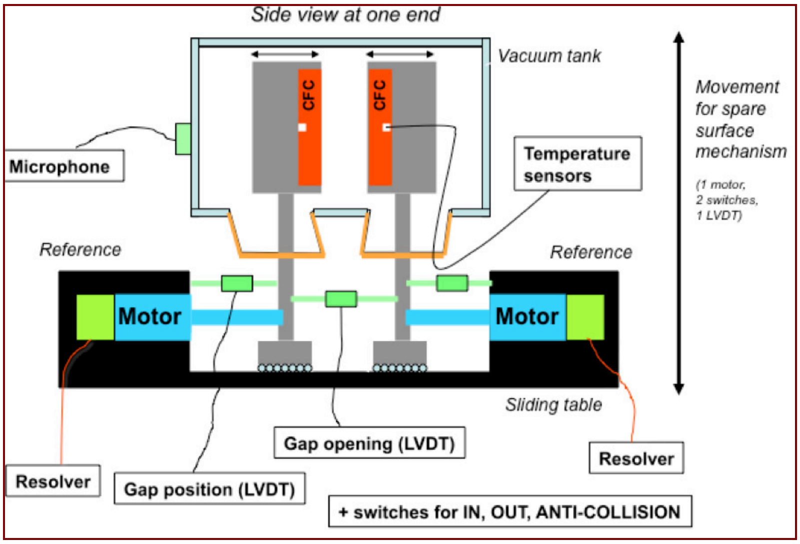

Figure 6: Illustration of the mechanical concept for the LHC collimator (here TCP/TCS type). See detailed explanation in text.

Table 4: Specifications for primary (TCP) and secondary (TCS) collimators of the LHC. All collimators have two parallel jaws. TCP and TCS collimators are single beam collimators.

Parameter	Unit	Specification
Jaw material		CFC (carbon fiber-reinforced carbon)
Jaw length TCS	cm	100
TCP	cm	60
Jaw tapering	cm	10 + 10
Jaw cross section	mm^2	65 × 25
Jaw resistivity	μΩm	≤ 10
Surface roughness	μm	≤ 1.6
Jaw flatness error	μm	≤ 40
Heat load	kW	≤ 7
Jaw temperature	°C	≤ 50
Pressure cooling water	bar	≤ 20
Bake-out temp.	°C	250
Residual vacuum pressure	mbar	$\leq 4\times10^{-8}$
Minimal gap	mm	≤ 0.5
Maximal gap	mm	≥ 58
Stroke beyond beam axis	mm	5
Max. jaw angle	mrad	2
Mechanical play	μm	≤ 20
Jaw pos. control	μm	≤ 10
Angle control	μrad	≤ 15
Reproducibility	μm	≤ 20
Max dynamique torque for stroke	Nm	≤ 0.5

Table 5: Main specifications for other LHC ring collimators. All collimators have two parallel jaws and accommodate either a single or two beams. Parameters not listed are the same or similar as in Table 4.

Parameter	Unit	Specification
Jaw material		
TCT, TCLA		W
TCL, TCLP		Cu
TCLI		CFC
Jaw length (flat top)	cm	100
Jaw tapering	cm	10 + 10
Jaw flatness error	μm	≤ 80
Minimal gap		
TCT, TCLA	mm	≤ 0.8
TCL, TCLP	mm	≤ 0.8
TCLI	mm	≤ 0.5
Beams in tank		
TCTH, TCTVA		1
TCLIB		1
TCL, TCLP		1
TCTVB, TCLIA		2

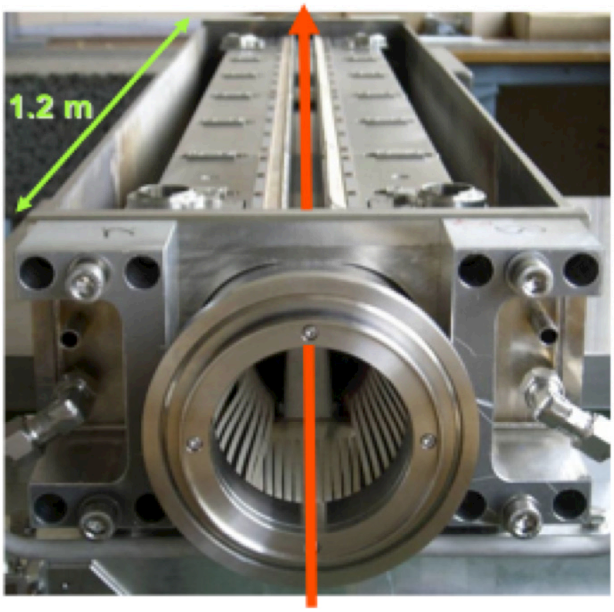

Figure 7: Photograph of a TCP/TCS type collimator during production. Image currents of the beam are guided by silver-coated RF fingers, visible at the tank entry and on top of the jaws. The jaws and the vacuum tank are water cooled.

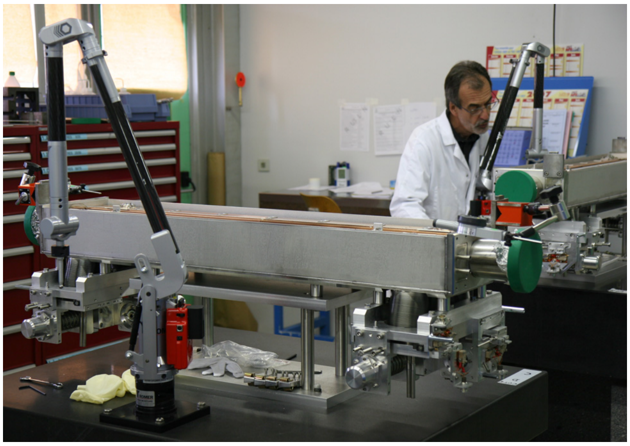

Figure 8: Precision alignment and survey of collimators with installed jaws during production.

COLLIMATION SETUP WITH BEAM

As a first step the collimators must be adjusted to the stored beam. As the beam position is a priori not known to the required accuracy, a beam-based setup procedure [30,31,32,33] is performed. First, the primary collimators are used to create reference cuts in phase space. Then all other jaws are moved symmetrically around the beam until they touch the phase space cut and create about equal beam loss. This process is called halo-based adjustment and was optimized for LHC purposes (in fact applying an iterative process from the reference collimator to all other jaws). As a result one obtains information about the beam center inside collimators and beam size variation from collimator to collimator.

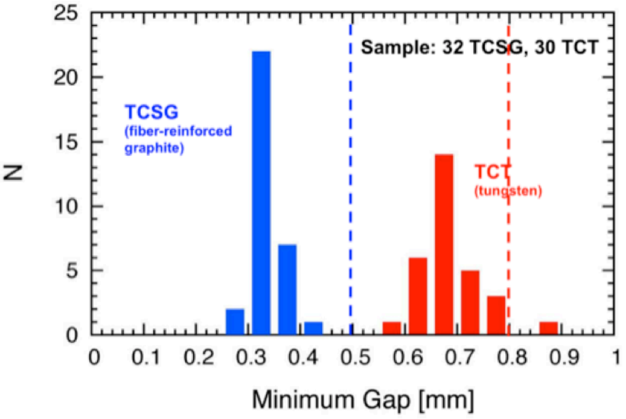

Figure 9: Measured minimum gaps during production for TCP/TCS and TCT type collimators.

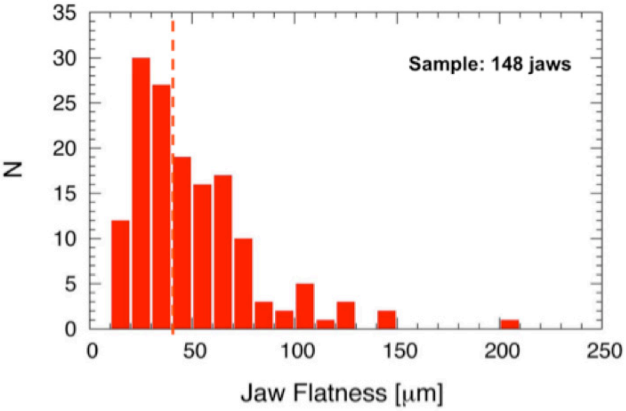

Figure 10: Achieved jaw flatness measured in the assembled and installed collimator jaws.

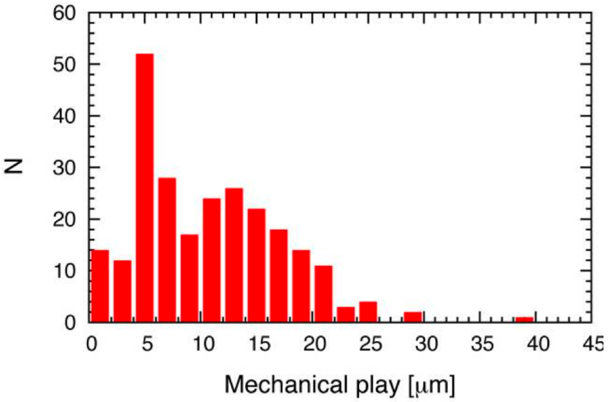

Figure 11: Achieved mechanical plays as measured on installed collimators.

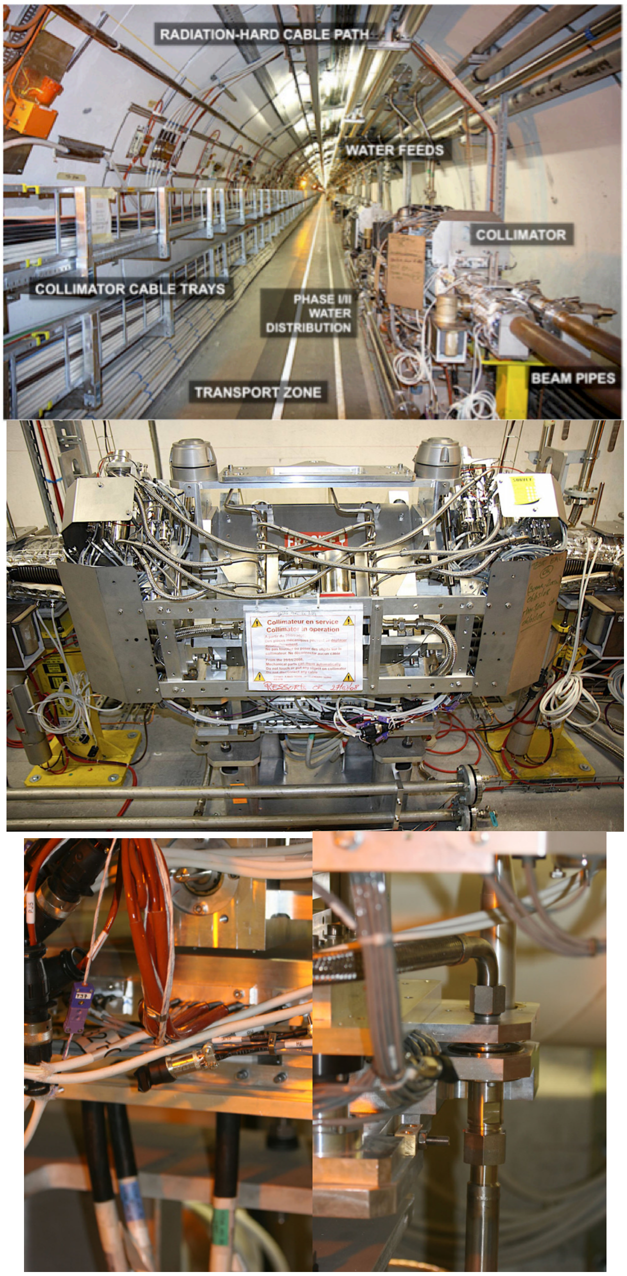

Figure 12: Collimation system as installed in the LHC tunnel. View along IR7 (top), side view of equipped collimator (middle) and view of electrical quick plugs (bottom left) and water quick connections (bottom right).

The results of beam-based measurements [31,33] were used for the LHC as follows:

- Injection: beam center and calibrated beam size are used to move collimators to ± N sigma around the beam.
- Top energy: beam center and nominal beam size (beta beat < 20%) are used to move collimators to ± N sigma around the beam.

The theoretical target settings for the various types of collimators around the ring are determined from simulations, usually in terms of nominal beam size (1σ) to establish a required collimator hierarchy. The settings used for LHC collimation up to end of August 2010 are listed in Table 6.

The actual collimator settings for the hardware (in mm and number of steps for stepping motors) are then calculated based on beam-based data and the required normalized settings. The following constraints are taken into account:

- Provide good efficiency.
- Provide the correct collimator hierarchy (slow primary losses at primary collimators).
- Protect the accelerator against the specified design errors.
- Provide continuous cleaning and protection during all stages of beam operation: injection, prepare ramp, ramp, squeeze, collision, physics.
- Provide maximum tolerances to beam and various collimator families.
- Provide warning thresholds on all collimator axis positions versus time.
- Provide interlock thresholds on all collimator axis positions versus time.
- Provide interlock thresholds on all collimator gaps versus beam energy.

The settings for LHC collimation are a complex problem with some 100,000 numbers required for controlling the system during the full beam cycle [31,33]. In order to avoid errors a redundant calculation is performed in two CERN groups: the time-dependent settings are calculated and provided by the accelerator physics group, while the energy-dependent collimation gaps are generated by the operations group.

Table 6: Settings for various collimator families, here expressed as phase space cuts in betatron space (IR7) and off-momentum (IR3). The affected collimation planes are indicated. All settings are listed in terms of nominal betatron beam size (σ). The settings refer to LHC run conditions as used up to end of August 2010. They were later adjusted for bunch train operation with 150 ns bunch spacing.

	Unit	**Plane**	**Set 1**	**Set 2**	**Set 3**	**Set 4**
Condition			Injection optics	Injection optics	Collision optics, separated	Collision optics, colliding, crossing angle
Energy	[GeV]		450	3500	3500	3500
Primary cut IR7	[σ]	H. V, S	5.7	5.7	5.7	5.7
Secondary cut IR7	[σ]	H, V, S	6.7	8.5	8.5	8.5
Quartiary cut IR7	[σ]	H, V	10.0	17.7	17.7	17.7
Primary cut IR3	[σ]	H	8.0	12	12	12
Secondary cut IR3	[σ]	H	9.3	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H, V	10.0	17.6	17.6	17.6
Tertiary cut experiments	[σ]	H, V	15-25	40-70	15	15
TCSG/TCDQ IR6	[σ]	H	7-8	9.3-10.6	9.3-10.6	9.3-10.6

COLLIMATION RESULTS WITH BEAM - PRELIMINARY

The LHC collimation process is constantly visible in the control room for high beam intensity. Unavoidable beam losses occur constantly (typical lifetimes in 2010 around 75 hours) at the primary collimators and can be observed online by operations.

The LHC collimation system performance was checked after setup with provoked beam losses. For this purpose a betatronic beam loss is generated by crossing the 1/3 integer tune resonance in H or V plane. Off-momentum efficiency is checked by generating energy errors with RF frequency trims. The losses around the ring are recorded [34,35] and then analyzed. As these losses occur under well controlled conditions, they can be compared in detail with simulations. Measurements are shown in Figures 13, 14 and 15 in direct comparison with simulations. The 450 GeV simulation results shown were published years before measurements.

The following preliminary conclusions can be taken:

- We can characterize losses. E.g. off-momentum losses after RF cavity trips occur in the momentum cleaning in IR3. Betatronic losses occur in the betatron cleaning system in IR7.
- Essentially all losses are intercepted at primary collimators in betatron and momentum cleaning insertions.
- There is a very small leakage to super-conducting magnets. The leakage is around 3×10^{-4}, for both 450 GeV and 3.5 TeV. This is in very good agreement with the predictions and the system design.
- The achieved cleaning efficiency is then 99.97% and better.
- Performance is limited by some very characteristic locations, as predicted. At higher energies the limiting location is in the dispersion-suppressor, due to single diffractive scattering. The vast majority of the magnets are protected at 3.5 TeV with an efficiency of 99.999% and better.
- The 3.5 TeV loss pattern with a β^* of 2 m shows the expected losses at tertiary collimators close to the experiments. The triplets and experiments are well protected against halo losses, as designed for.
- The largest discrepancy between measurement and predictions occurs for losses at IR6 collimators. They show up to 100 times higher leakage from IR7 than predicted. This can be due to the small normalized distance to the secondary collimation cut and therefore a high sensitivity to secondary beam halo.

The stability of the collimation system was very satisfactory, illustrating the gains due to the precision design and production of collimators. This is shown in Figure 16, which shows that leakage into super-conducting magnets was kept at the 3×10^{-4} level for 4 months without a re-setup of the collimation system.

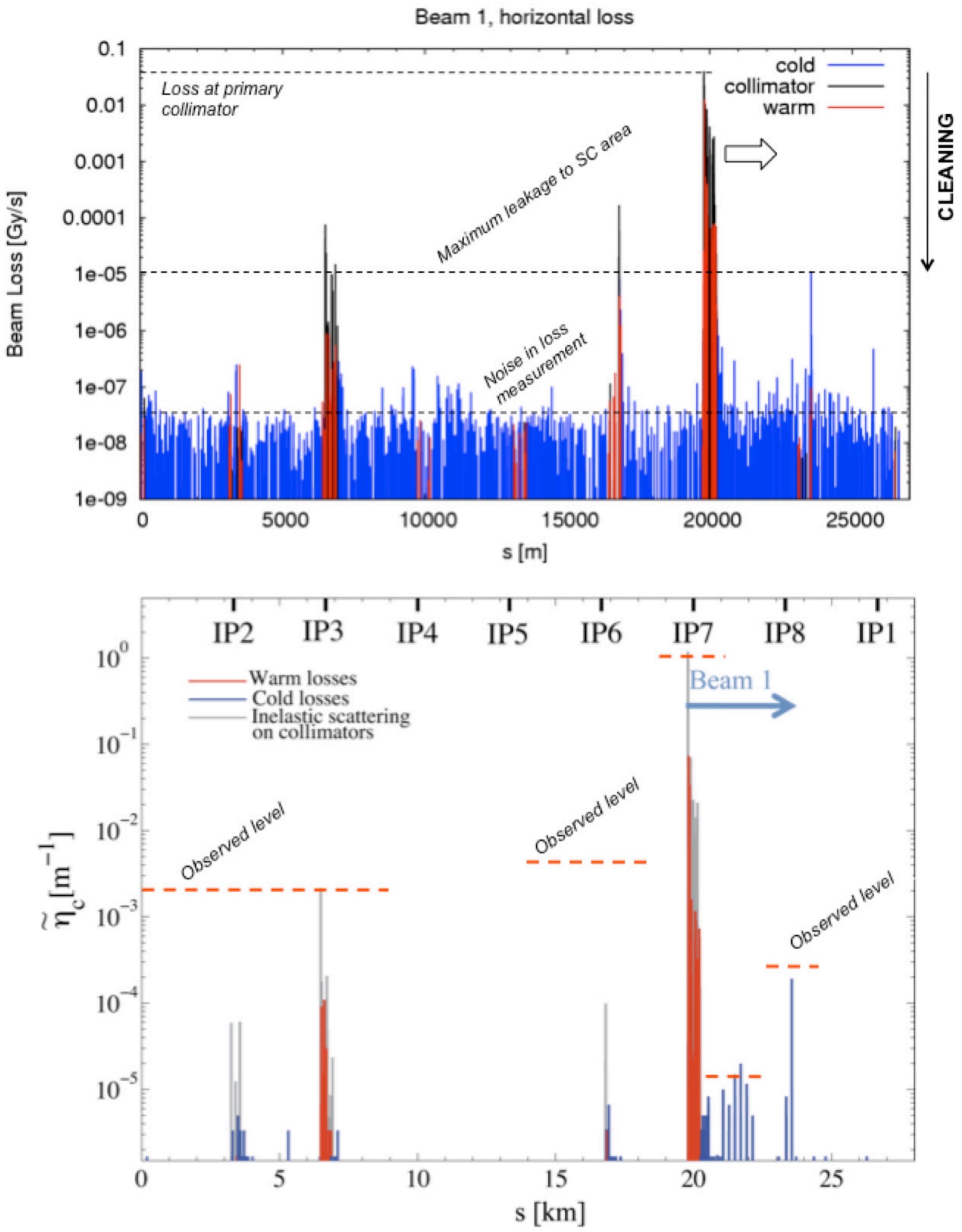

Figure 13: Measured (top) and simulated (bottom) beam loss around the LHC ring for a horizontal beam loss in beam 1 at the primary collimators in IR7 and at 450 GeV. Measurements are in Gy/s and must be normalized to the losses at the primary collimator (highest peak) to obtain cleaning inefficiency as shown in the simulation. The bottom plot (no imperfections) was published in 2008 (before the measurements) as part of the PhD thesis of C. Bracco (p. 74 in [23]). The bottom figure indicates the measured loss levels in typical parts of the ring.

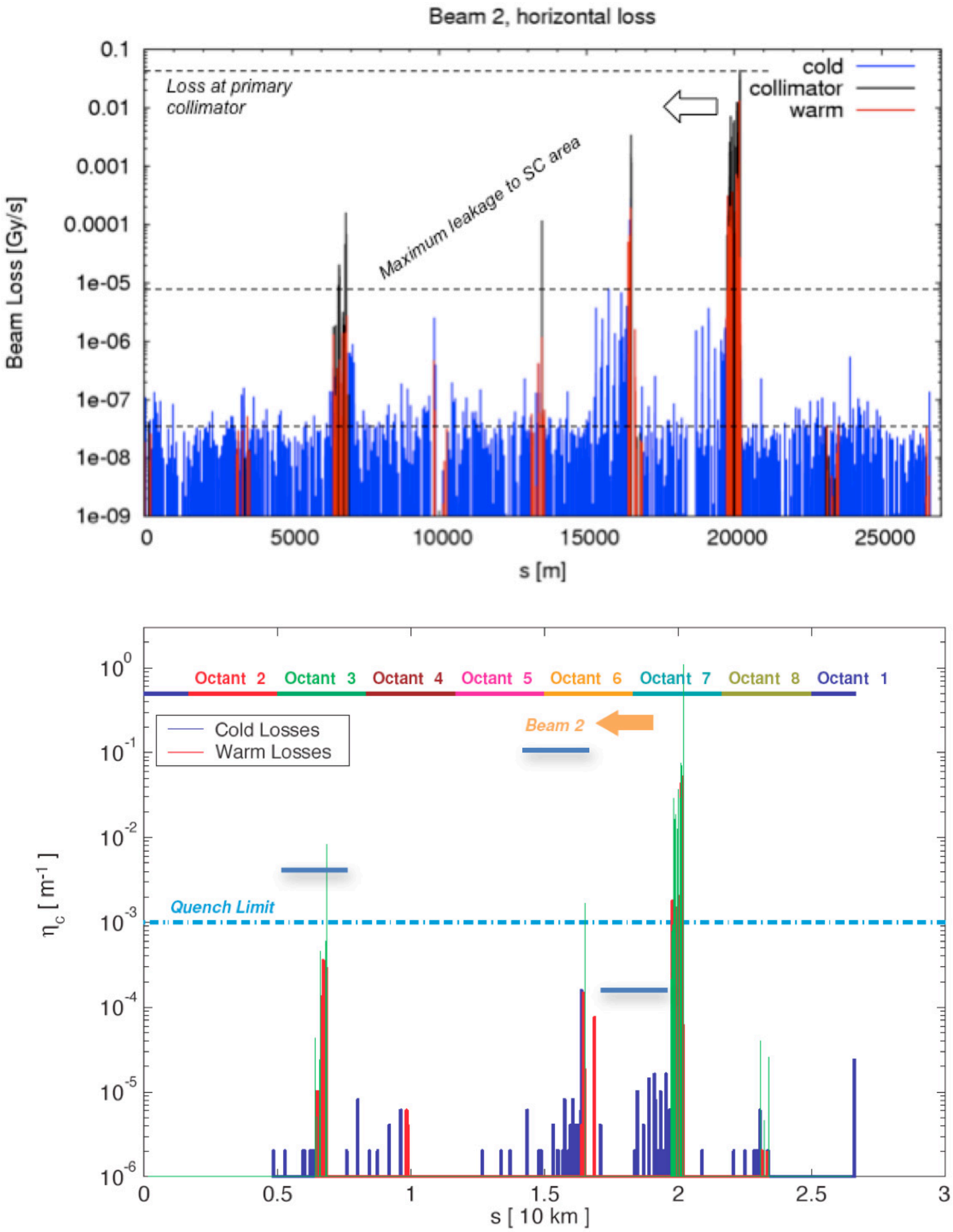

Figure 14: Measured (top) and simulated (bottom) beam loss around the LHC ring for a horizontal beam loss in beam 2 at the primary collimators in IR7 and at 450 GeV. Measurements are in Gy/s and must be normalized to the losses at the primary collimator (highest peak) to obtain cleaning inefficiency as shown in the simulation. The bottom plot (with nominal orbit imperfections) was published in 2006 (before the measurements) as part of the PhD thesis of G. Robert-Demolaize (p. 114 in [21]). The bottom figure indicates the expected quench limit for nominal loss rates and the observed loss rates in some characteristic locations.

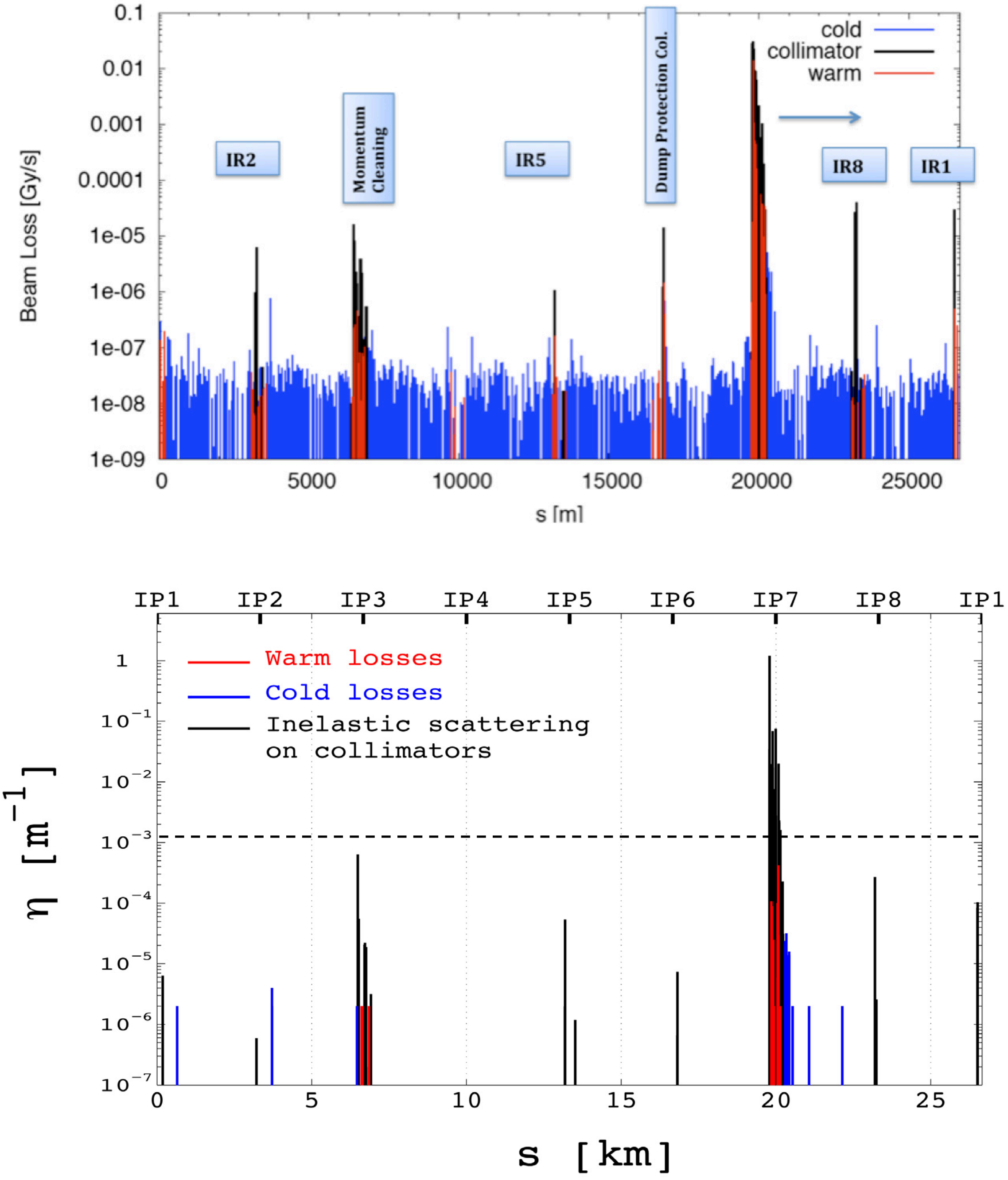

Figure 15: Measured (top) and simulated (bottom) beam loss around the LHC ring for a vertical beam loss in beam 1 at the primary collimators in IR7 and at 3.5 TeV. The β^* was 2 m in measurements and simulations. Measurements are in Gy/s and must be normalized to the losses at the primary collimator (highest peak) to obtain cleaning inefficiency as shown in the simulation. The bottom plot (without imperfections) indicates the observed loss rates in the experimental insertions (dashed line).

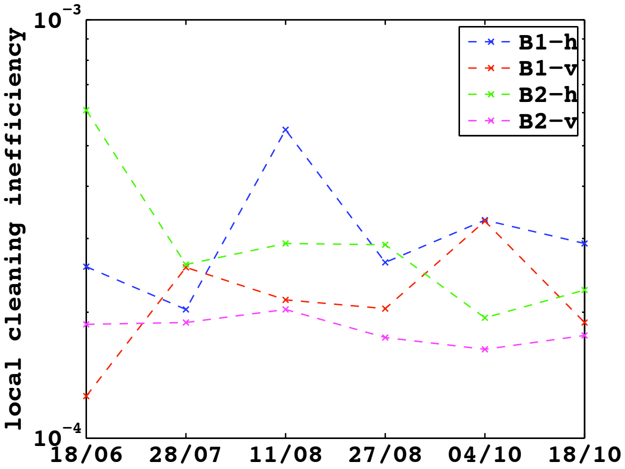

Figure 16: Collimation leakage from betatron cleaning in IR7 into super-conducting magnets (inefficiency) versus time in 2010. The data is for betatron losses at 3.5 TeV and a β^* of 3.5 m.

CONCLUSION

The LHC collimation system has been designed, produced, installed and commissioned over the last 8 years (of course, also based on previous studies). The system is the biggest, most precise and most complex system built so far. It provides a four-stage collimation scheme for the LHC beams, requiring some 100,000 parameters for controlling it during the full LHC beam cycle.

The full system was successfully commissioned with beam and it was shown that it works with the expected, very high performance level. Predicted loss locations (dispersion suppressors) are protected with 99.97% efficiency while the vast majority of super-conducting magnets is protected with 99.999% efficiency.

The system has shown an excellent stability over the 2010 run. The simulations are confirmed both by loss locations and magnitude of leakage. Collimation and beam cleaning were major contributors for allowing the LHC to extend the intensity frontier in just 6 months, passing Tevatron [36], HERA, RHIC, … in stored energy by more than a factor 14 by end of October 2010. This was achieved without a single quench with stored beam.

Upgrades [37-49] are being prepared to improve collimation by a further factor 5-10 over the next years.

ACKNOWLEDGEMENTS

The LHC collimation project team, as listed on the title page, achieved the work reported here. It was and is my pleasure to work with this excellent group of technicians, engineers and physicists. In addition, thanks to all the world experts helping with advice and support over the years. Particular thanks go to Mike Seidel from PSI who chaired the collimation project reviews at CERN and who invited me for this presentation. Our success reflects the rapid progress in the field and would not have been possible without the advice and open collaboration by many friends in various institutes.

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