Phase 1 collimation system

IR	Type	Name	Orientation (approx)	Angle [rad]	Material	Alternative material	Length	Setting [inj σ] inj optics	Setting [top σ] squeezed	Half gap [m] inj&ramp	Half gap [m] 7 TeV squeezed	Betax [m]	Betay [m]
3	prim	TCP.6L3.B1	H	0.000	C-C	n/a	0.2 m	8.0	15.0	0.00801	0.00380	128.23	160.36
	sec	TCS.5L3.B1	H	0.000	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00586	0.00287	50.79	336.44
	sec	TCS.A4R3.B1	H	3.063	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00425	0.00208	26.67	362.83
	sec	TCS.B4R3.B1	H	0.078	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00426	0.00209	26.84	359.91
	sec	TCS.A5R3.B1	H	0.155	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00493	0.00241	35.91	304.93
	sec	TCS.B5R3.B1	H	2.972	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00550	0.00269	44.76	275.83
	sec	TCS.C5R3.B1	H	0.156	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00610	0.00299	55.01	251.09
	Total:		**7** components/beam			before: **7**		Study:		Reduce by **2** collimators?			

Note: n1 at 7TeV can in principle be as high as 30 σ. Open at 7 TeV if required. Check abort gap cleaning.
Close betatron and TCDQ somewhat during ramp to protect momentum collimators.

IR	Type	Name	Orientation (approx)	Angle [rad]	Material	Alternative material	Length	Setting [inj σ] inj optics	Setting [top σ] squeezed	Half gap [m] inj&ramp	Half gap [m] 7 TeV squeezed	Betax [m]	Betay [m]
7	prim	TCP.D6L7.B1	V	1.571	C-C	n/a	0.2 m	6.0	6.0	0.00664	0.00168	90.45	156.44
	prim	TCP.C6L7.B1	H	0.000	C-C	n/a	0.2 m	6.0	6.0	0.00501	0.00127	89.13	158.74
	prim	TCP.B6L7.B1	S	2.410	C-C	n/a	0.2 m	6.0	6.0	0.00582	0.00148	87.83	161.07
	sec	TCS.A6L7.B1	H	2.919	C-C	n/a	1.0 m	7.0	10.5	0.00486	0.00185	48.45	320.00
	sec	TCS.B5L7.B1	S	2.593	C-C	Al/Ti/C+Cu	1.0 m	7.0	10.5	0.00782	0.00298	126.54	248.46
	sec	TCS.A5L7.B1	S	0.550	C-C	Al/Ti/C+Cu	1.0 m	7.0	10.5	0.00787	0.00299	131.25	241.96
	sec	TCS.A4L7.B1	V	1.570	C-C	n/a	1.0 m	7.0	10.5	0.00515	0.00196	303.53	69.28
	sec	TCS.A4R7.B1	H	0.371	C-C	n/a	1.0 m	7.0	10.5	0.00568	0.00216	66.92	198.29
	sec	TCS.B4R7.B1	H	3.118	C-C	n/a	1.0 m	7.0	10.5	0.00496	0.00189	64.21	204.36
	sec	TCS.C4R7.B1	V	1.381	C-C	n/a	1.0 m	7.0	10.5	0.00880	0.00335	63.01	207.27
	sec	TCS.F4R7.B1	S	0.592	C-C	Al/Ti/C+Cu	1.0 m	7.0	10.5	0.00746	0.00284	66.17	319.92
	sec	TCS.G4R7.B1	H	2.701	C-C	n/a	1.0 m	7.0	10.5	0.00660	0.00251	68.39	316.97
	sec	TCS.A5R7.B1	V	1.611	C-C	n/a	1.0 m	7.0	10.5	0.00440	0.00168	362.63	50.10
	sec	TCS.B5R7.B1	V	1.530	C-C	n/a	1.0 m	7.0	10.5	0.00442	0.00168	356.63	50.40
	Total:		**14** components/beam			before: **20**							

Total IR3 and IR7 for two beams: **42** before: **54**

450 GeV running with nominal/ultimate intensity?

7 TeV running with 50% intensity max

C+Cu = 10 μm Cu coating on C-C

Tolerances: Relaxed by factor of at least **3** compared to nominal retraction of 1 σ.

Required physical **aperture in triplet** at 7 TeV:

	15.0 σ	no loss in cleaning efficiency
	13.5 σ	accept factor 2 loss in efficiency for 50% of total intensity

Efficiency at 15 σ:	0.05%	
Efficiency at 13.5 σ:	0.11%	
Efficiency at 10 σ:	3.00%	use tertiary collimators to catch this for small beta*
Efficiency at 9 σ:	5.00%	

TCDQ Set to protect physical aperture in triplet (13.5/15 σ, see above)

Tertiary collimators: **16** components for both beams and all IP's
H, V collimators (elliptical?) close to all D1's, used for both beams.
Required for machine protection and local cleaning.

TCL collimators:	**8**	(4 more TCL's after 3 years)	
Absorbers:	**16**	or more?	Required for quench and damage protection.
Spoilers/scrapers:	?	Close phase space for machine protection and use for scraping Thin targets	
Crystals:	?	Put short crystals into primary tanks.	

Phase 1b: Push system performance of phase 1

Try to make use of Cu coating to close H, S gaps at 7 TeV, if still existing.

and/or

Use tertiary collimators for halo cleaning.

Recover full luminosity reach?

Phase 2 collimation system

IR	Type	Name	Orientation (appro	Angle [rad]	Material	Alternative material	Length	Setting [inj σ] inj optics	Setting [top σ] squeezed	Half gap [n inj&ramp	Half gap [n 7 TeV squeezed	Betax [m]	Betay [m]
3	prim	TCP.6L3.B1	H	0.000	C-C	n/a	0.2 m	8.0	15.0	0.00801	0.00380	128.23	160.36
	sec	TCS.5L3.B1	H	0.000	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00586	0.00287	50.79	336.44
	sec	TCS.A4R3.B1	H	3.063	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00425	0.00208	26.67	362.83
	sec	TCS.A5R3.B1	H	0.155	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00493	0.00241	35.91	304.93
	sec	TCS.B5R3.B1	H	2.972	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00550	0.00269	44.76	275.83
	sec	TCS.C5R3.B1	H	0.156	C-C	Al/Ti/C+Cu	1.0 m	9.3	18.0	0.00610	0.00299	55.01	251.09
	Total:		7 components/beam			before: 7		Study:		Reduce by two collimators?			
			Note:	n1 at 7TeV can in principle be as high as 30 σ. Open if required. Check abort gap cleaning.									
7	prim	TCP.D6L7.B1	V	1.571	C-C	n/a	0.2 m	6.0	6.0	0.00664	0.00168	90.45	156.44
	prim	TCP.C6L7.B1	H	0.000	C-C	n/a	0.2 m	6.0	6.0	0.00501	0.00127	89.13	158.74
	prim	TCP.B6L7.B1	S	2.410	C-C	n/a	0.2 m	6.0	6.0	0.00582	0.00148	87.83	161.07
	sec	TCS.A6L7.B1	H	2.919	C-C	n/a	1.0 m	7.0	28.0	0.00486	0.00486	48.45	320.00
	sec hyb		**H**		**metallic**		**1.0 m**	**open**	**10.5**	**open**	**0.00185**		
	sec	TCS.B5L7.B1	S	2.593	C-C	Al/Ti/C+Cu	1.0 m	7.0	28.0	0.00782	0.00782	126.54	248.46
	sec hyb		**S**		**metallic**		**1.0 m**	**open**	**7.0**	**open**	**0.00198**		
	sec	TCS.A5L7.B1	S	0.550	C-C	Al/Ti/C+Cu	1.0 m	7.0	28.0	0.00787	0.00787	131.25	241.96
	sec hyb		**S**		**metallic**		**1.0 m**	**open**	**7.0**	**open**	**0.00200**		
	sec	TCS.A4L7.B1	V	1.570	C-C	n/a	1.0 m	7.0	28.0	0.00515	0.00515	303.53	69.28
	sec hyb		**V**		**metallic**		**1.0 m**	**open**	**7.0**	**open**	**0.00131**		
	sec	TCS.A4R7.B1	H	0.371	C-C	n/a	1.0 m	7.0	28.0	0.00568	0.00568	66.92	198.29
	sec hyb		**H**		**metallic**		**1.0 m**	**open**	**10.5**	**open**	**0.00216**		
	sec	TCS.B4R7.B1	H	3.118	C-C	n/a	1.0 m	7.0	28.0	0.00496	0.00496	64.21	204.36
	sec hyb		**H**		**metallic**		**1.0 m**	**open**	**10.5**	**open**	**0.00189**		
	sec	TCS.C4R7.B1	V	1.381	C-C	n/a	1.0 m	7.0	28.0	0.00880	0.00880	63.01	207.27
	sec hyb		**V**		**metallic**		**1.0 m**	**open**	**7.0**	**open**	**0.00223**		
	sec	TCS.F4R7.B1	S	0.592	C-C	Al/Ti/C+Cu	1.0 m	7.0	28.0	0.00746	0.00746	66.17	319.92
	sec hyb		**S**		**metallic**		**1.0 m**	**open**	**7.0**	**open**	**0.00189**		
	sec	TCS.G4R7.B1	H	2.701	C-C	n/a	1.0 m	7.0	28.0	0.00660	0.00660	68.39	316.97

sec hyb		**H**		**metallic**		**1.0 m**	**open**	**10.5**	**open**		**0.00251**		
sec	TCS.A5R7.B1	V	1.611	C-C	n/a	1.0 m	7.0	28.0		0.00440	0.00440	362.63	50.10
sec hyb		**V**		**metallic**		**1.0 m**	**open**	**7.0**	**open**		**0.00112**		
sec	TCS.B5R7.B1	V	1.530	C-C	n/a	1.0 m	7.0	28.0		0.00442	0.00442	356.63	50.40
sec hyb		**V**		**metallic**		**1.0 m**	**open**	**7.0**	**open**		**0.00112**		
Total:		25 components/beam				Phase 1: 14			before: 20				

Total IR3 and IR7 for two beams: **64** Phase 1: **42** before: **54**

Phase 2: **22 additional** low-impedance, low robustness secondary collimators for both beams.

TCDQ: 10 σ H with 0.5 σ tolerance

Note: For known phase advance close some H collimators more, if irregular dumped beam cannot hit.
This keeps the freedom of LHC tune and phase advance.
If irregular dumps are very seldom: Choose more risky closure, e.g. full 6/7 σ coverage.
Hybrid phase only used for stable physics with much reduced number of irregularities. Afford delicate technology.
Tertiary collimators at D1's for cleaning of additional halo.
Mechanical and operational tolerances for hybrid secondaries very demanding.

Technology candidates for hybrid secondary collimators:

(a) Conventional technology: (with some spare surface)

Beryllium   C-C with 10 μm Cu coating   Aluminium   Titanium   Cu doped C

(b) Advanced technology:

Rotary metallic, consumable collimator for risky operation with regular failures and damage
Metallic stripes/tapes on conventional jaw

Summary on different phases:

Phase 1 for 2007

IR3/IR7 collimation	**42** components (instead of 54)	High robustness system (fiber-reinforced graphite) for
		* Injection & ramping up to nominal or even ultimate intensities
		* Survival of all specified beam impact cases.
(baseline solution based on V6.4 collimation)		* 7 TeV commissioning under easiest possible conditions.
(alternative solution is under study, same or fewer coll)		* 7 TeV physics (early years)
		* Support minimum beta* of 1m? Ensure 13.5 σ triplet aperture for 50% int.
		* Mechanical/operational tolerances relaxed by factor ≥ 3
		* Do not rely on TCDQ shadow
		* Conventional mechanical design as used for LEP (minimum cost?)
		* Metallic coating 10 μm on a trial basis (use if it holds, no loss if destroyed)
		* Implement a few spare locations on a jaw (1 additional motor)
		* Metallic jaws at a few "safe" locations?
Tertiary triplet collimators	**16** components (new)	* Used for protection in phase 1
		* Not relied on for cleaning of secondary halo (true tertiary collimators)
		* Further relax tolerances with squeezed optics
TCL collimators	**8** components (unchanged)	* Used for injection & luminosity debris
Total	**66 collimators**	(same as in V6.4 baseline)
Absorbers	≥ 16 components (unchanged)	* Used for damage/quench protection in IR3/7
		* Number to be verified for new system
Spoilers/scrapers	? components (new)	* Used for machine protection and scraping
Space allocations	38 for phase 2 (22), phase 3 (4), and possible upgrade for better cleaning efficiency (12 suppressed coll)	
Crystals	? components (new)	* Possibly put into a primary collimator for tests

Phase 1b for 2008

Push system performance to limit, relying on optional Cu coating and/or tertiary triplet collimators.

Phase 2 for 2008 or 2009

IR7 collimation **22 collimators**

Low impedance hybrid secondary system in IR7:

* Only used in stable physics and towards end of squeeze
* 7 TeV physics: nominal and ultimate luminosities
* Tight tolerances
* Nominal beta*
* Rely on TCDQ shadow at 10 σ for ~2-4 H collimators
* Rely on cleaning from tertiary triplet collimators
* Conventional coll in safe position or innovative "consumable" collimator?

Phase 3 for 2010

TCL collimators **4 collimators**

High luminosity operation

* Intercept IP debris

All phases

Total number of collimators: **92** (26 more than in present baseline, however, spread over 4 years)

Possible upgrade for cleaning efficiency

Proposal optimized to provide a similar cleaning efficiency as the V6.4 system (assume sufficient efficiency/shown for ideal system).

Risks in cleaning efficiency:

Linear tracking underestimates inefficiency by factor 2-3.
Dilution of losses around the ring could be below 50 m.
Problems with off-momentum beta beat might prevent small collimator gaps?
Cleaning efficiency for ions has never been estimated for any machine!?
The LHC lifetime might drop below allowed 0.2/1.0 hours.
Quench limits in magnets are less favourable than assumed.
Operational tolerances on transient changes might be tough to be met.
Extrapolation by 3 orders of magnitude is too far to exclude surprises.

Better cleaning efficiency:

Two possibilities: More collimators and/or longer jaws.

* Gain factor 2 by re-adding the 12 suppressed collimators (use space allocations).
* Upgrade during LHC running: Propose solutions targeted to observed problems.

Overall installation schedule 2007-2010

Year	Number of collimators	Number of additional devices (absorbers, scrapers, ...)
2007	66	≥ 16
2008	0	0
2008/9	22	0
2010	4	0

Irregular and regular scenarios

* Multi turn failures are not included, as they should result in beam dump before the beam impacts on collimators.
* Full failure of beam dump is not included ($0.01y^{-1}$). Collimators will be destroyed.

Location	Energy	Plane	Type	Imapct	Frequency
IR7 collimation	.45 TeV	H V	Large injection oscillation from transfer line, SPS, injection elements.	1 full batch	unknown
	.45 TeV	V	Kicker flash over.	0.8 batch	$0.1\ y^{-1}$
	.45 TeV - 7 TeV	H	Asynchronous dump (number for 7 TeV)	5 bunches	$\geq 1\ y^{-1}$
	.45 TeV - 7 TeV	H	Dump single-module prefire (number for 7 TeV)	8 bunches	$\geq 1\ y^{-1}$
	.45 TeV - 7 TeV	**S**	**Fraction of H/V impact for similar cases. Skews are often not fully skew. 7 sigma S can catch above 8.5 sigma for secondaries?**	**fraction of above**	**see above**
	.45 TeV - 7 TeV	H V primary	Drop in beam lifetime to 0.2 h for 10s.	4e11 p/s	$0.5\ d^{-1}$
	.45 TeV - 7 TeV	H V primary	Drop in beam lifetime to 1 h for longer times.	0.8e11 p/s	$1\ d^{-1}$
	.45 TeV - 7 TeV	H V secondary	Drop in beam lifetime to 0.2 h for 10s.	0.4e11 p/s	$0.2\ d^{-1}$
	.45 TeV - 7 TeV	H V secondary	Drop in beam lifetime to 1 h for longer times.	0.08e11 p/s	$0.5\ d^{-1}$
IR3 collimation	**.45 TeV - x TeV**	**H**	**Irregular dump can affect momentum collimators when they sit at 8/9.3 sigma (TCDQ at 10 sigma)**	**1-2 bunches?**	**≥ 1 y-1**
	.45 TeV	**H**	**Large injection oscillation from transfer line, SPS, injection elements.**	**1 full batch**	**unknown**
	.45 TeV	H	Loss of 5% uncaptured beam at start of the ramp (within 1 s). This is 1 MW for this 1 s.	1.5e13 p/s	$2\text{-}3\ d^{-1}$

Testing possibilities

Location	Hardware	Purpose	Date
CERN lab	Jaw materials.	**Vacuum** and outgassing tests.	ongoing
RHIC	RHIC copper jaw.	Understanding of **showering and cleaning efficiency for ions**.	to be started
CERN lab	Prototype jaw.	Tests on **material properties** (mechanical, electrical, tolerances, ...)	Sep-03
Sandia?	Collimator jaw without (and with) eventual coating.	Test of **robustness** with beam impact (LHC MAC).	Oct-03
SLAC	Collimator jaw without (and with) eventual coating.	Test of **robustness** with beam impact of high density electron beam (LHC MAC). Measurement of **impedance**.	Jan-04
CERN lab	Prototype collimator with jaws, tanks, motors, electronics.	Test of **vacuum tightness, outbaking procedure, mechanical tolerances** on jaws in tank, **functionality, reliability**.	Apr-04
RHIC	Prototype secondary collimator including all motors and control.	Test of functionality, reliability, cleaning efficiency with beam in **regular RHIC operation**. Cleaning efficiency with **ions**.	Oct-04
HERA	Crystal set-up. Design, hardware, manpower provided by INFN (collaboration W. Scandale et al).	Test of crystals for LHC collimation as an upgrade option.	Oct-04
SPS	Prototype secondary collimator including all motors and control.	Test of functionality, reliability, and **robustness** with the injection LHC beam. Test for **local electron cloud**?	2006

Major milestones in LHC collimation

Sep-01	Start of Beam Cleaning Study Group/Collimation WG (AP/OP issues)
Jan-02	**CERN meeting on collimators: Foreseen materials do not withstand LHC operation.**
Jun-02	Consensus on detailed requirements.
Oct-02	LHC collimation project started. ATB group founded. (new hardware responsibility, project set-up)
Dec-02	**Installation in IR3 and IR7 delayed to provide time for finalizing the insertion design (LHC project)**
Jan-03	**Review of impedance: Collimator impedance of C jaws is way too large for nominal settings (AB/ABP)**
Feb-03	Simulation chain set-up: Beam tracking - FLUKA - ANSYS. (AB/ABP + AB/ATB + AT)
Mar-03	LTC review on impedance limitation from collimators. First short discussion of "three-stage hybrid" system.
Mar-03	**Graphite jaws can be accepted in LHC ultra-high vacuum if precautions are met (AT/VAC)**
Apr-03	**Sufficient optics flexibility for meter movements in IR7 (TRIUMF).**
Apr-03	**Beam impact from irregular dumps reduced from ~20 bunches to ~8 bunches (AB/BT)**
May-03	**Efficiency results cross-checked: factor 2-3 uncertainty in inefficiency. (AB/ABP, TRIUMF, IHEP)**
May-03	**Fiber-reinforced graphite withstands all specified beam impact cases. (AB/ATB + AT)**
May-03	**Dose rate for 1.5 h intervention is high but not prohibitive: 1-2 mSv. (EST/RP)**
May-03	**Installed collimator length in IR7 can be reduced by 40%, IR3 collimators opened at 7 TeV. (AB/ABP)**
May-03	**Some first estimates of slow loss impact indicate that C can resist low lifetimes. (AB/ATB + AT)**
Jun-03	**A thin few micron coating can reduce impedance on average by factor 5. (AB/ABP)**
25-Jun-03	**Proposal of a staged system with tertiary collimators and hybrid phase to the LTC:** * Accept basic strategy and connected constraints? * Freeze types of collimators and lengths? * Freeze basic functionality, tolerances for different stages, conventional design choice?

Required milestones in LHC collimation *(2nd half 2003& first half 2004)*

Jul-03	Start of **detailed design work** for the LHC collimators, required to ensure schedule. (AB/ATB, EST)
Jul-03	Complete **space budget** for cleaning insertions (collimators, vacuum components, magnets, instrumentation, …) (AB/ABP, AB/ATB, AB/BDI, AT/VAC, TIS/RP, AT/MS, …)
Sep-03	Finalize **new optics** design and achievable cleaning efficiency. (AB/ABP, TRIUMF)
Sep-03	Test results for collimator jaws with chosen material. (AB/ATB)
Sep-03	**3D impedance simulations** for LHC collimators and tanks. (AB/ABP)
Sep-03	Confirm **impedance tolerance** from octupole excitation and damper. Strategy of usage. (AB/ABP, AB/RF)
Sep-03	More detailed estimate of **personnel exposure** due to collimator maintenance. (TIS/RP, AB/ATB, AT/VAC)
Sep-03	Complete **specification of BLM's, other BI** at collimators, used for set-up/optimization of collimation. (AB/ABP, AB/OP, AB/BDI)
Sep-03	More detailed budget estimate.
Nov-03	Results of a robustness test with beam of collimator material. (AB/ABP, AB/ATB)
Dec-03	Complete review of energy deposition in cleaning insertions and **decision on required absorbers**. (AB/ATB, IHEP)
Dec-03	Complete review of radiation in cleaning insertions. Final **decision on local handling/shielding**. (TIS/RP, IHEP)
Dec-03	Complete review of **loss distribution around the ring** (local cleaning efficiency and loss rates). (AB/ABP, AB/CO)
Dec-03	Complete review of impact of tertiary collimators on **experimental background**. (AB/ATB, FNAL)
Dec-03	Complete review of **cleaning efficiency for ions**. (AB/ABP)
Dec-03	Decision on any measures against local electron cloud. (AT/VAC, AB/ABP, AB/ATB)
Dec-03	**Freeze cleaning insertions.**
Jan-04	Experimental results on collimator impedance and effect of coating. (AB/ABP)
Jan-04	Start of detailed studies on set-up and optimization of LHC collimation system. (AB/ABP)
Apr-04	**First prototype collimator produced.** (AB/ATB)
Apr-04	Final budget estimate.
Jul-04	Laboratory tests of collimator prototype completed. (AB/ATB)
Jul-04	Prediction of cleaning performance with measured prototype characteristics. (AB/ABP)