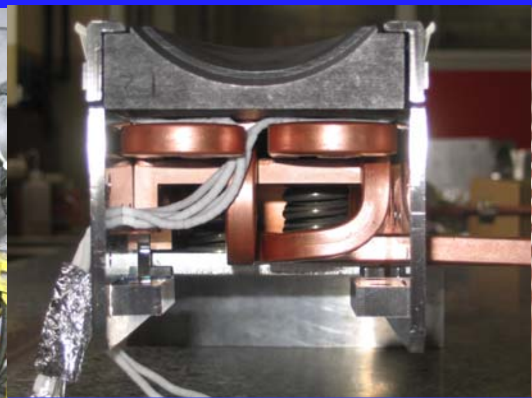
The Role of the Collimation System in Protecting the Aperture

Ralph W. Aßmann

MP Review

11.04.2005

Outline

- The LHC Aperture
- Collimators and Collimation System
- Machine Protection Topics Concerning Collimation
  - MP Features of Collimators
  - First Interception of Beam Losses
  - Local Protection with Collimators
  - Survival of Collimators During Accidents
- Conclusion

LHC Ring Aperture

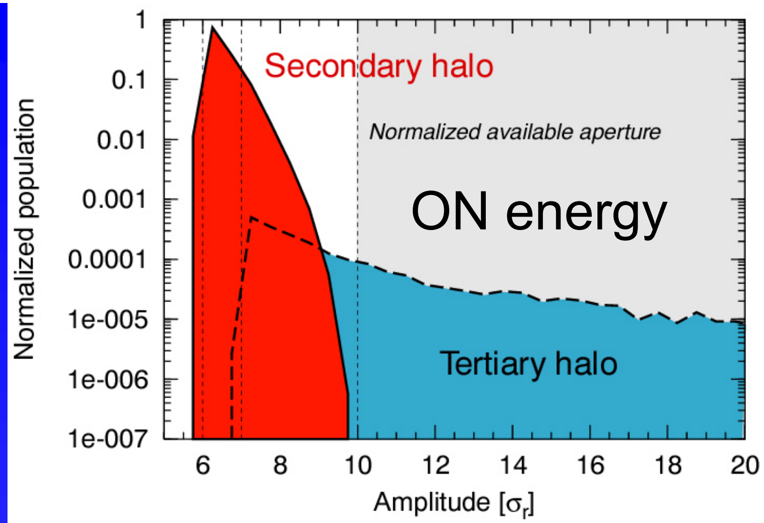
- Definition for LHC design:

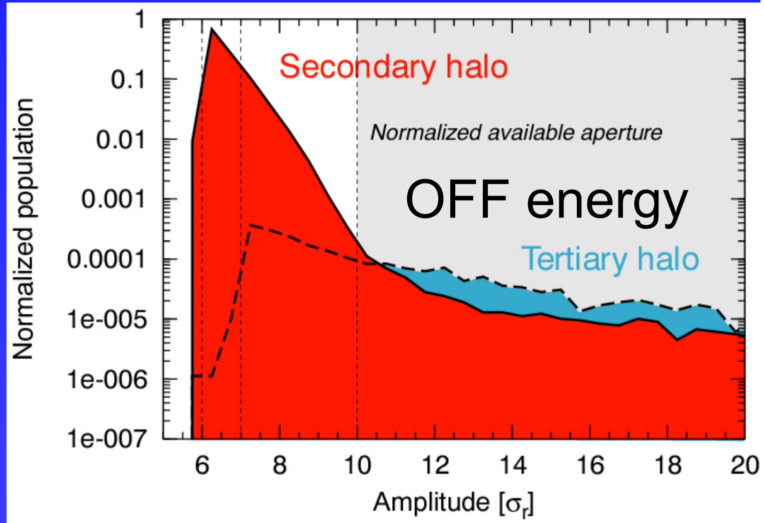
  n1 from APL program (J.B. Jeanneret)

  n1 contains machine tolerances (orbit, beta beat, off-momentum, alignment, mechanical tolerances) and is normalized to shape of secondary halo.

- Guaranteed available aperture in x/y directions:

  Take out shape of on-momentum secondary halo but keep machine tolerances (flat halo). Now defined in “real” beam sigmas.





- n1 = 7: Available **transverse aperture** = 1.2 * 7 σ = **8.4 σ**

  Available **radial aperture** = 1.4 * 7 σ = **9.8 σ**

LHC design value for aperture

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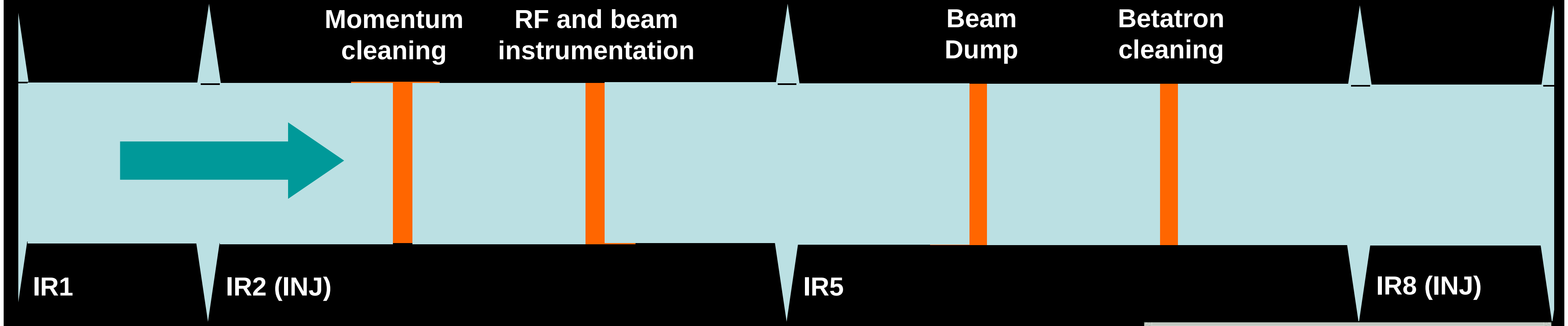
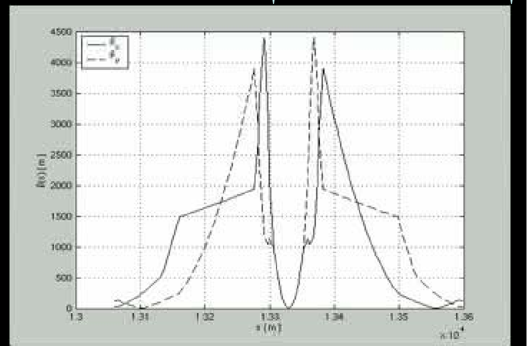
Normalized Aperture

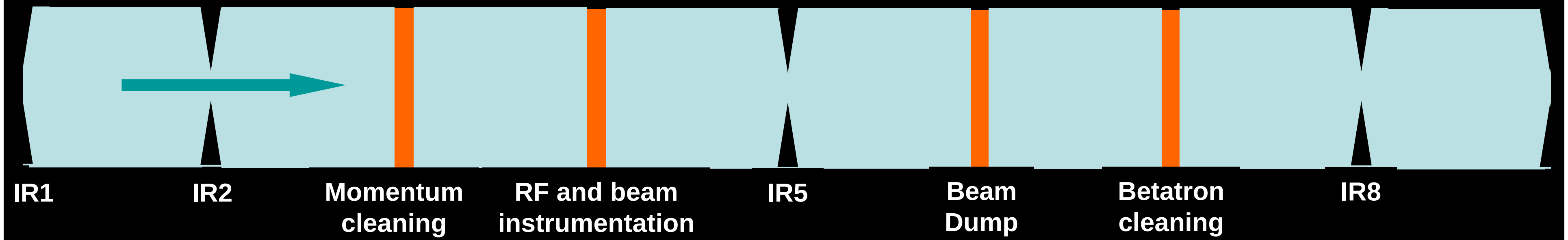
450 GeV (injection):



Smaller emittance and beam size
Higher beta at experimental triplets

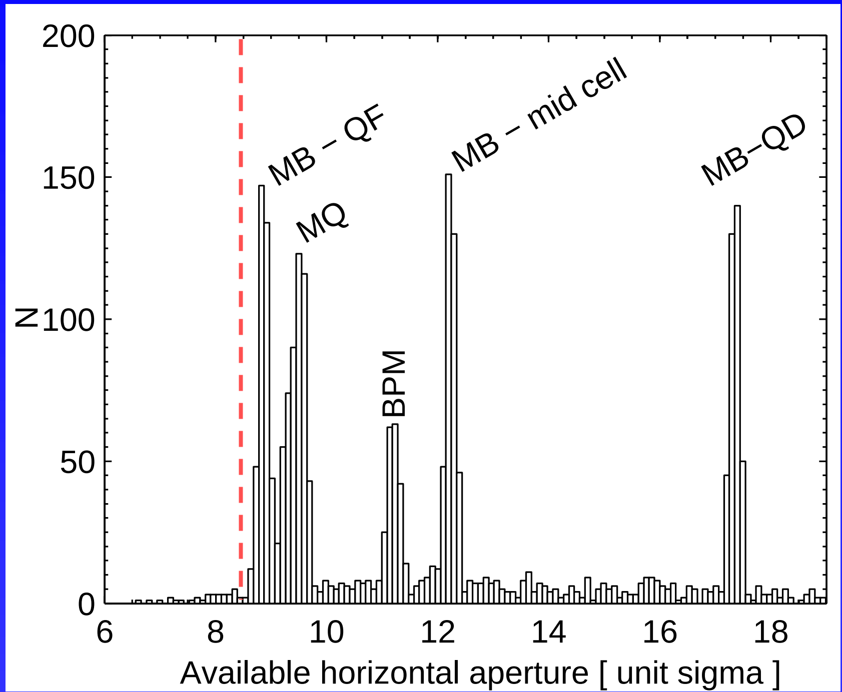


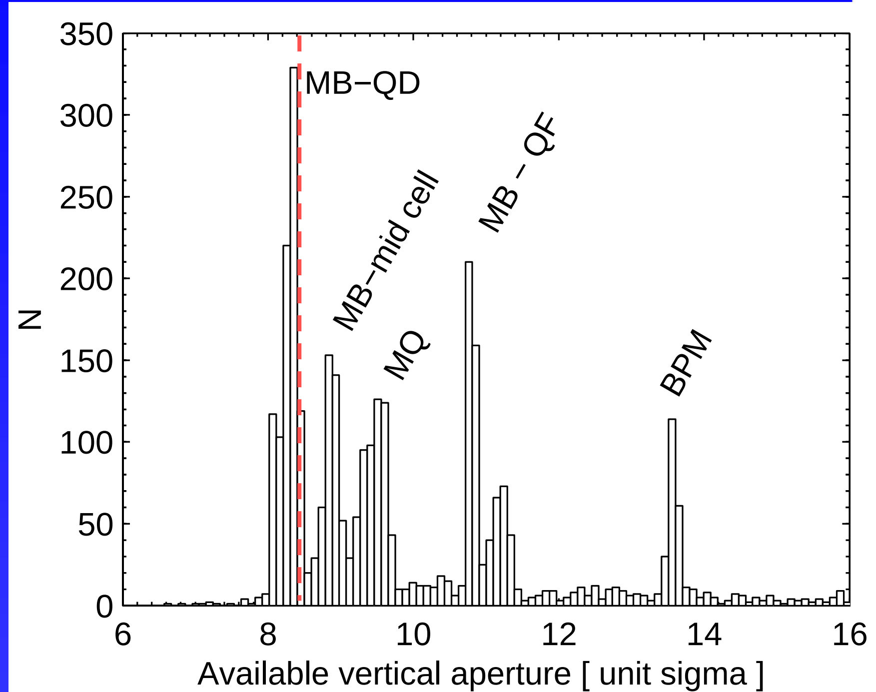
7 TeV (collision):



β*: 0.55 m ➔ 17 m (IR1)

Distribution of Available Aperture (Injection)





S. Redaelli et al

Beam 2	**Warm**	**Cold**	
Horizontal	**6.68**	**7.70**	σ_x
Vertical	**7.65**	**7.60**	σ_y

Warm H limits in IR3!

Gain ~ 1 σ with smaller energy offset!

No chromaticity measurement during injection!

➔ Reasonable: $a_{ring} = 7.5\ \sigma$

All loss studies rely on full and detailed LHC aperture model ➔ S. Redaelli.

Design Aperture Imperfections

The design aperture has **allowances** for imperfections:

- Maximum beta beat: **20%**
- Maximum orbit: **4 mm** (3 mm at triplets)
- Spurious dispersion: **30%**
- Mechanical tolerances: **0.2-2.5 mm** depending on element
- Allowance for $\delta p/p$: **0.05 %**

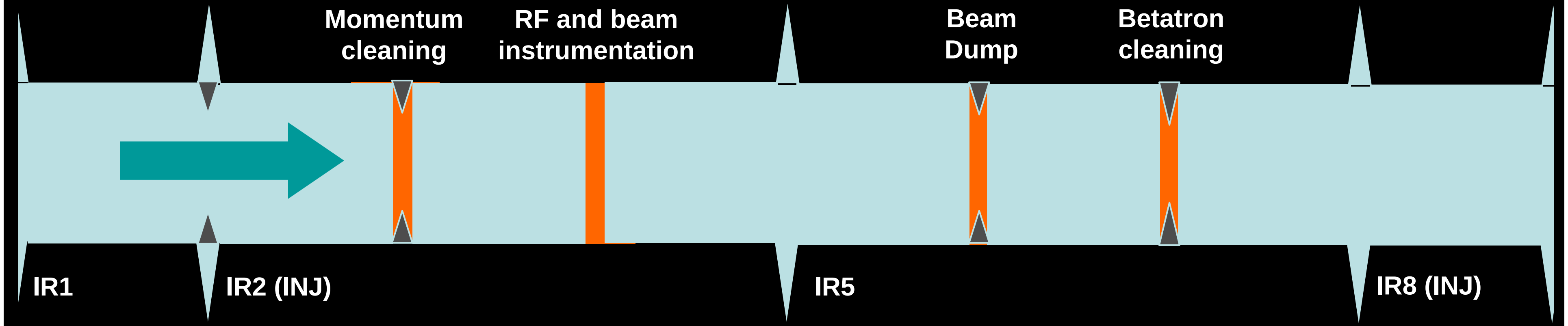
These are design assumptions established many years ago for the LHC project.

Difficult requirements: **What can be achieved realistically?**

In case that tolerances are not met: **Reduction in available aperture!**

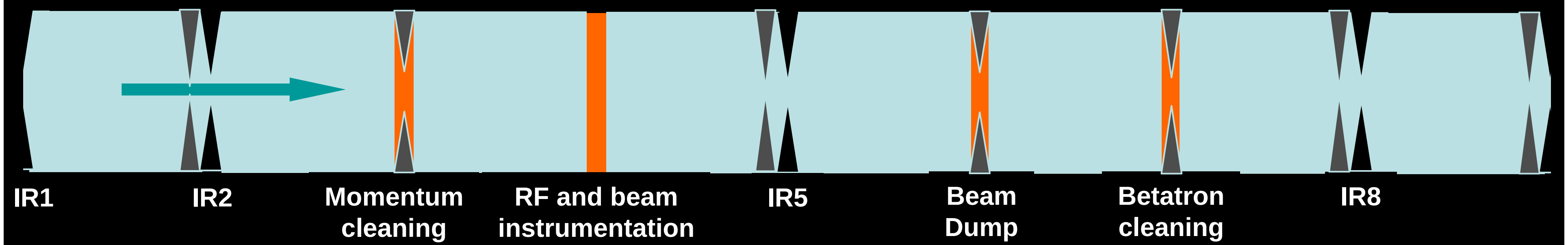
Aperture and Collimators

450 GeV (injection):



Smaller emittance and beam size
Higher beta at experimental triplets

7 TeV (collision):



➔ Various collimators for cleaning and protection around the ring…

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Overview: Collimators and Protection Devices

- **Collimators**: ➔ 20 + 15 per beam (TCP, TCSG + TCSM)
  - Interact with primary, secondary or tertiary beam halo.
  - Scattering devices for spoiling and inducing inelastic interactions for protons lost from the beam!
  - Precise devices with two jaws, used for efficient beam cleaning. Small gaps and stringent tolerances.
  - Absorb little energy. Very robust.
- **Movable absorbers**: ➔ 20 per beam (TCT, TCLA, TCLP)
  - Interact with shower products from p-p and p-collimator interactions.
  - Devices for absorbing the lost energy.
  - High-Z jaws. Larger gaps and more relaxed tolerances.

CLEANING (continuous)

- **Diluters**: ➔ 4 + 7 per beam (TDI, TCLI, TCDQ + TCDI)
  - Interact with mis-kicked beam or irregular beam tails (injection and dump protection).
  - Strong dilution (emittance blow-up) and partial absorption of energy

PROTECTION (accidents)

- **Scrapers**: ➔ 3 per beam (TCHS)
  - Thin one-sided objects. Used for beam shaping and diagnostics.

SPECIAL (exceptional)

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Detailed Table

Phase	Acronym	Material	Length [m]	Number	Locations	INJ	TOP	Purpose
	Scrapers							
1	**TCHS**	tbd	tbd	6	**IR3, IR7**			Beam scraping
2	***TCHS***	tbd	tbd	2	**IR3, IR7**			*Skew beam scraping*
	Collimators							
1	**TCP**	C-C	0.2	8	**IR3, IR7**	**Y**	**Y**	Primary collimators
1	**TCSG**	C-C	1.0	30	**IR3, IR7**	**Y**	**Y**	Secondary collimators
1	**TCSG**	C-C	1.0	2	**IR6**	**Y**	**Y**	Help for TCDQ set-up
2	***TCSM***	tbd	tbd	30	**IR3, IR7**			*Hybrid secondary collimators*
4	***TCS4***	tbd	tbd	10	**IR7**			*Phase 4 collimators*
	Diluters							
1	**TDI**	Sandwich	4.2	2	**IR2, IR8**	**Y**		Injection protection
1	**TCLI**	C	1.0	4	**IR2, IR8**	**Y**		Injection protection
1	**TCDI**	C	1.2	14	**TI2, TI8**	**Y**		Injection collimation
1	**TCDQ**	C-C	6.0	2	**IR6**	**Y**	**Y**	Dump protection
	Movable Absorbers							
1	**TCT**	Cu/W	1.0	16	**IR1, IR2, IR5, IR8**		**Y**	Tertiary collimators
1	**TCLA**	Cu	1.0	16	**IR3, IR7**	**Y**	**Y**	Showers from collimators
1	**TCL/TCLP**	Cu	1.0	4	**IR1, IR5**		**Y**	Secondaries from IP
3	***TCL/TCLP***	Cu	1.0	4	**IR1, IR5**		**Y**	*Secondaries from IP*

150 locations in ring and transfer lines. 86 collimators in 2007 for the two rings ➔ powerful and complex system!

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Acronyms for Collimator-Like Objects

- **TC**… = **T**arget **C**ollimator
  - TC**P** = **P**rimary collimator
  - TC**SG** = **S**econdary collimator **G**raphite
  - TC**SM** = **S**econdary collimator **M**etal
  - TC**HS** = **H**alo **S**craper
- **TCL**… = **T**arget **C**ollimator **L**ong
  - TCL**I** = **I**njection protection (types A and B)
  - TCL**P** = **P**hysics debris
  - TCL**A** = **A**bsorber
- **TCD**… = **T**arget **C**ollimator **D**ump
  - TCD**Q** = **Q**uadrupole (protect quadrupole for mis-dumped beam)
  - TCD**S** = **S**eptum
  - TCD**I** = **I**njection transfer lines
- **TD**… = **T**arget **D**ump
  - TD**I** = **I**njection

Example: Injection Settings (in σ_β, δ=0)

a_{abs}	=	~ 10.0 σ	Active **cleaning** absorbers in IR3 and IR7
a_{sec3}	=	9.3 σ	Secondary **cleaning** collimators IR3 (H)
a_{prim3}	=	8.0 σ	Primary **cleaning** collimators IR3 (H)
a_{ring}	=	**7.5 σ**	**Ring cold aperture**
a_{prot}	≥	**7.0 σ**	TCDQ (H) **protection** element at dump
a_{prot}	=	**6.8 σ**	TDI, TCLI (V) **protection** elements (injection)
a_{sec}	=	**6.7 σ**	Secondary **cleaning** collimators IR7
a_{prim}	=	**5.7 σ**	Primary **cleaning** collimators IR7
a_{TL}	=	**4.5 σ**	Transfer line collimators (ring **protection** at **6.9 σ**)

Example: Exposure to Irregular Beam Dump

Beam dump:
Designed to extract beam within 2 turns.
Pulse rise time of 3 µs (dump gap).

Failure modes:

See presentation by B. Goddard, Jan Uythoven et al!

Most relevant for collimation:

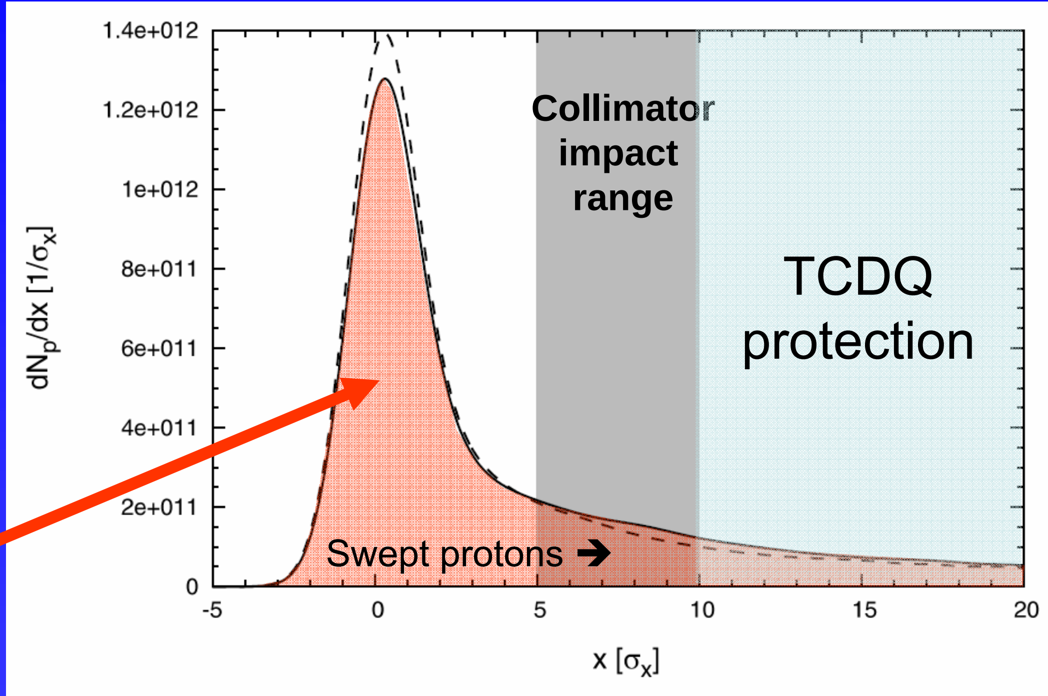
Dump action from 1 of 15 modules, others retriggering after 0.7 µs at 7 TeV, not synchronized with dump gap.

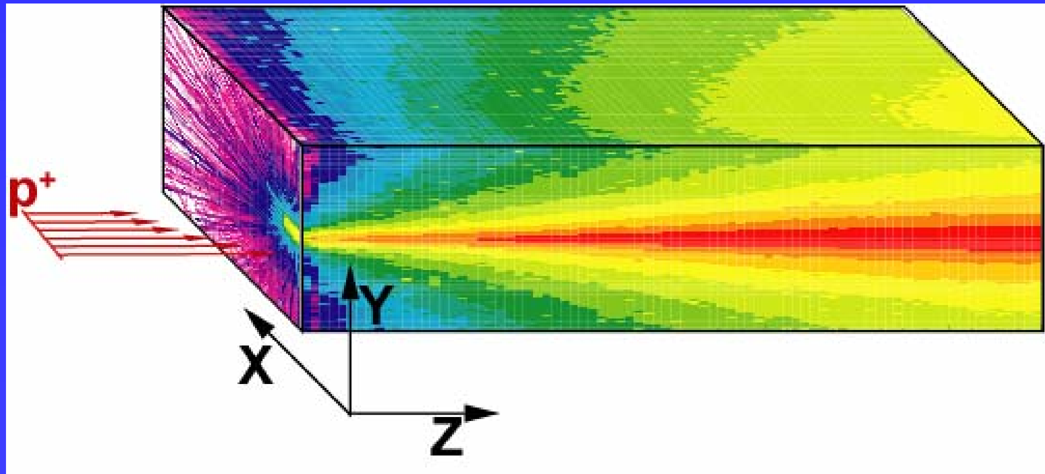
Frequency difficult to predict

Assume at least once per year!

Up to 8 bunches can hit a collimator at 7 TeV.

Up to 280 bunches can hit at 450 GeV (injection error).





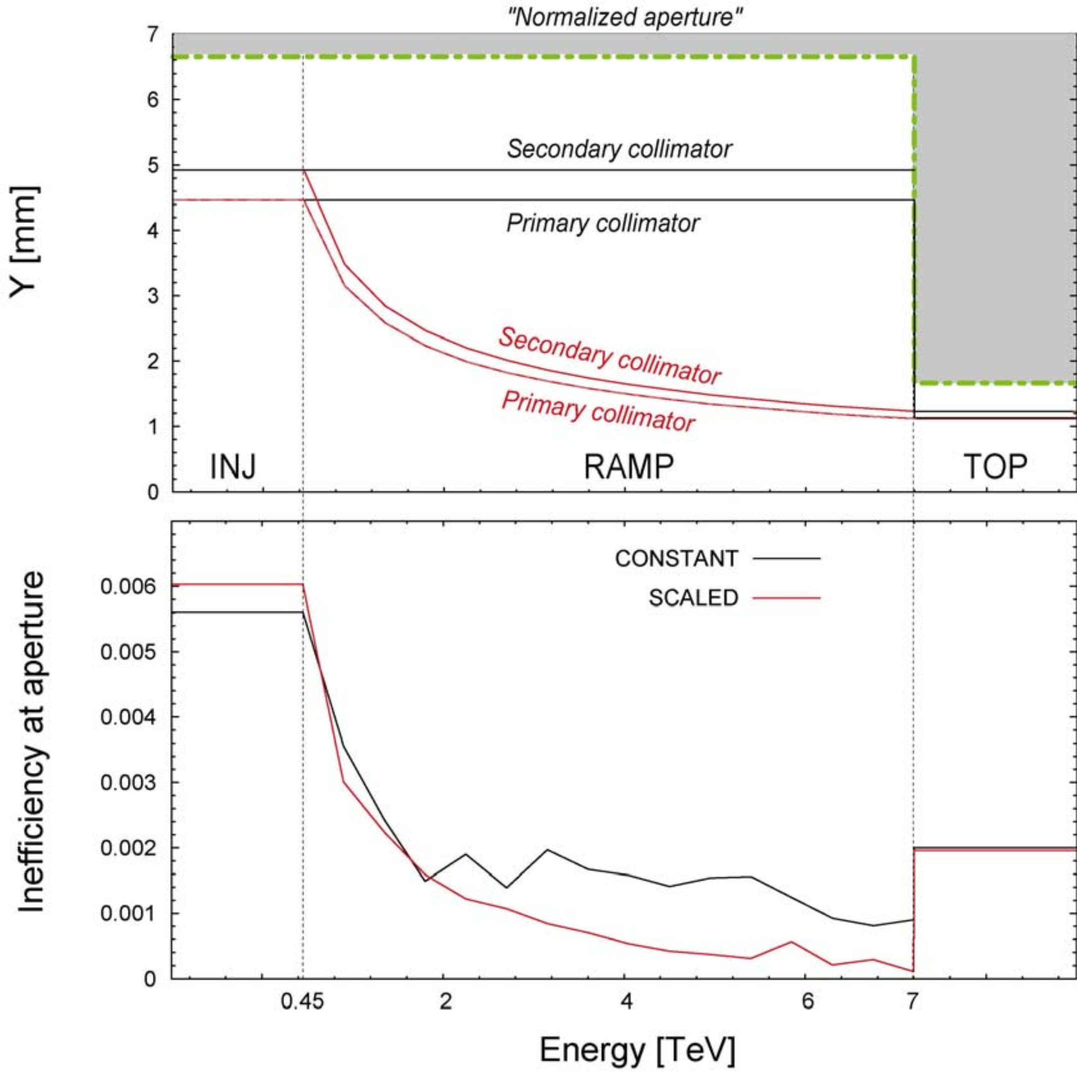
A. Ferrari, V. Vlachoudis

Settings at 7 TeV

(in σ_β, δ=0, nominal β^*)

a_{abs}	=	~ 20.0 σ	Active absorbers in IR3
a_{sec3}	=	18.0 σ	Secondary collimators IR3 (H)
a_{prim3}	=	15.0 σ	Primary collimators IR3 (H)
a_{abs}	=	~ 10.0 σ	Active absorbers in and IR7
a_{ring}	**=**	**8.4 σ**	**Triplet cold aperture**
a_{prot}	=	**8.3 σ**	TCT **protection** & cleaning at triplet
a_{prot}	≥	**7.5 σ**	TCDQ (H) **protection** element
a_{sec}	=	**7.0 σ**	Secondary collimators IR7
a_{prim}	=	**6.0 σ**	Primary collimators IR7

Energy Ramp



Efficiency improves if collimators are closed:

However, tolerances become tighter!

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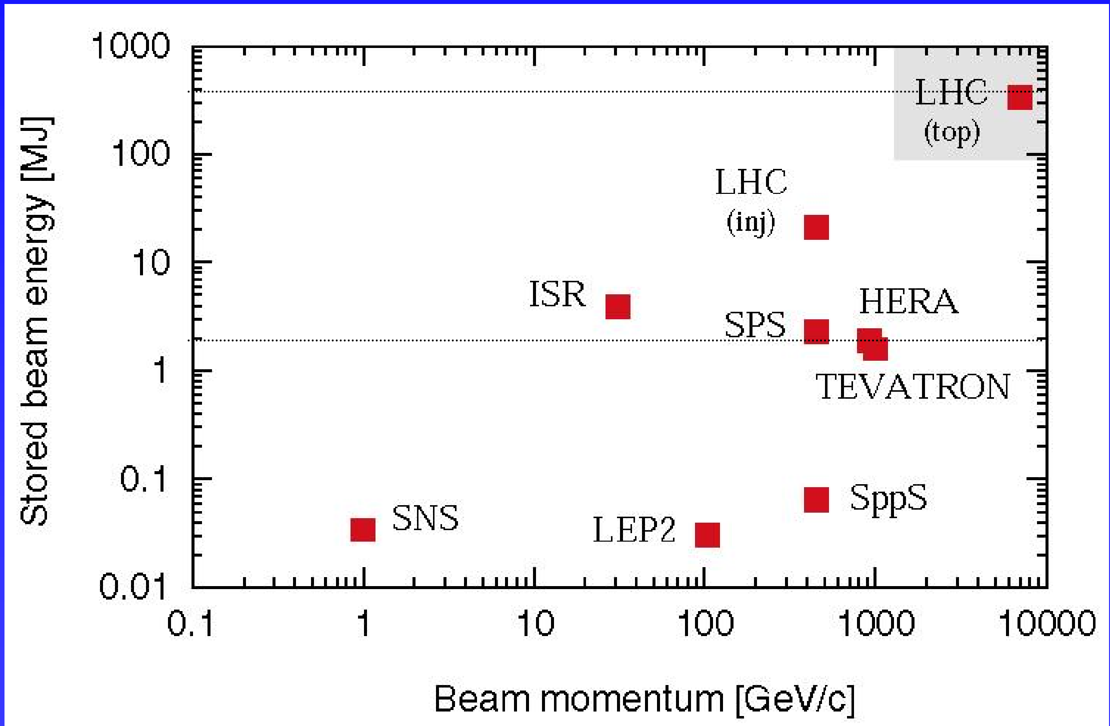
Beam Cleaning in the LHC

The LHC machine: First collider ever where continuous and efficient cleaning is required during all phases of beam operation (above a few % design intensity).



Factor ~ 200

Stored energy: ***360 MJ***

Quench limit: ***~10 mJ/cm³***

Beam losses cannot be avoided. E.g.: 500 kW for 1% of beam lost in 10 seconds!

Cleaning → Protect cold aperture against energy deposition from protons (quenches)!

Requirement: Cleaning collimators are closest elements to the beam!

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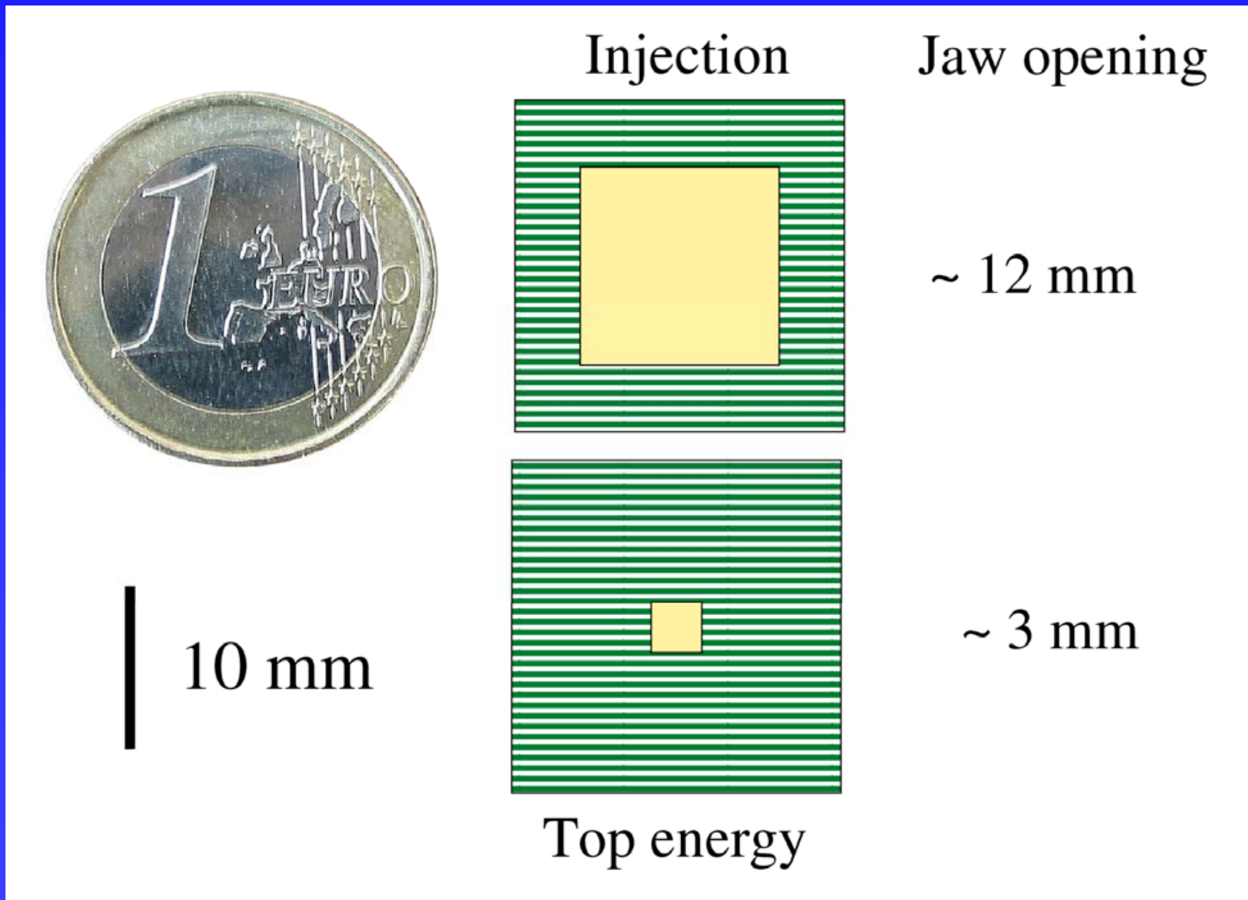
Collimating with Small Gaps

~ 0.15 ~ 0.6

$$a_{coll} \leq a_{triplet} \cdot \sqrt{\frac{\beta_{coll}}{\beta_{triplet}}} \cdot \left(\frac{A^{max}_{primary}}{A^{max}_{secondary}} \right)$$

Collimator gap must be **10 times smaller** than available triplet aperture for nominal luminosity!

Collimator settings usually defined in sigma with nominal emittance!



LHC beam will be physically quite close to collimator material and collimators are long (up to 1.2 m)!

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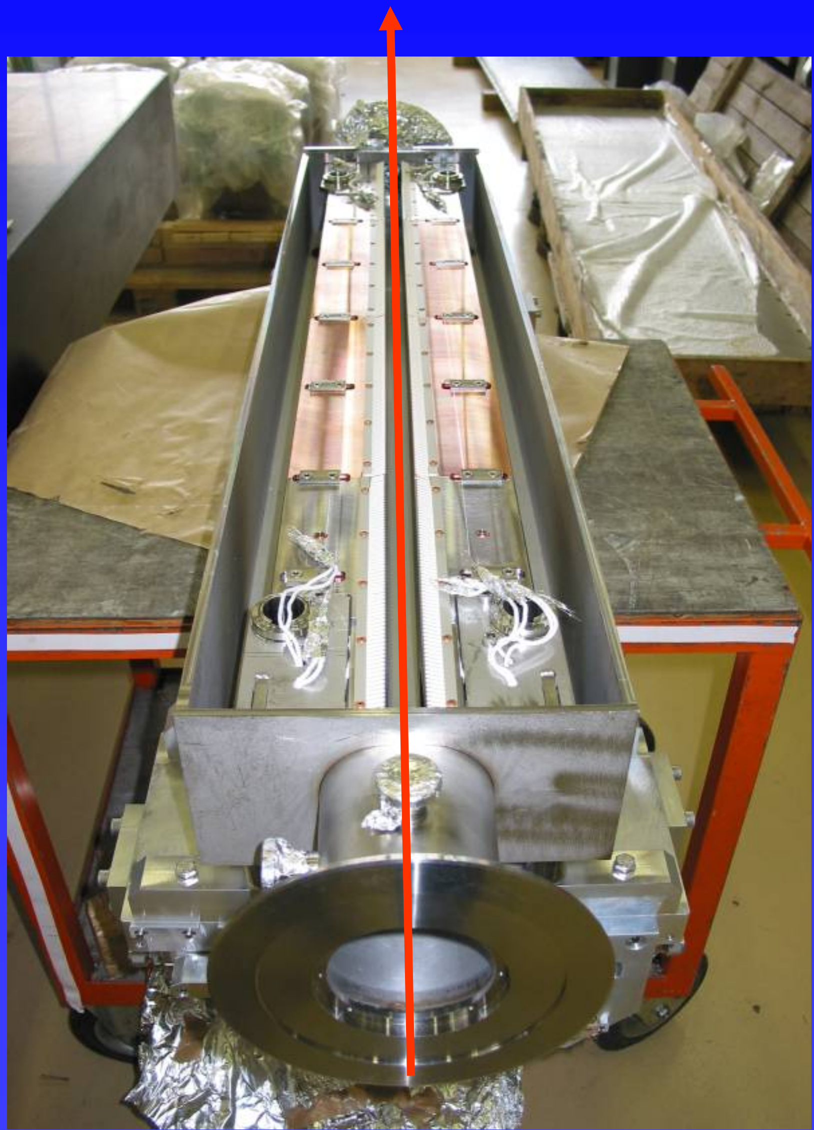
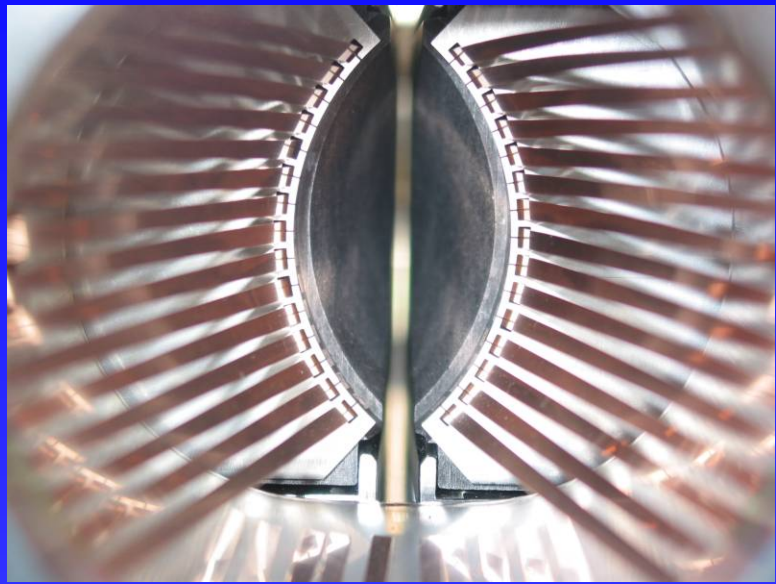
The LHC Phase 1 Collimator



Vacuum tank with two jaws installed



Beam passage for small collimator gap with RF contacts for guiding image currents

Designed for maximum robustness:

Advanced CC jaws with water cooling!

Also have collimators with Cu and W jaws!

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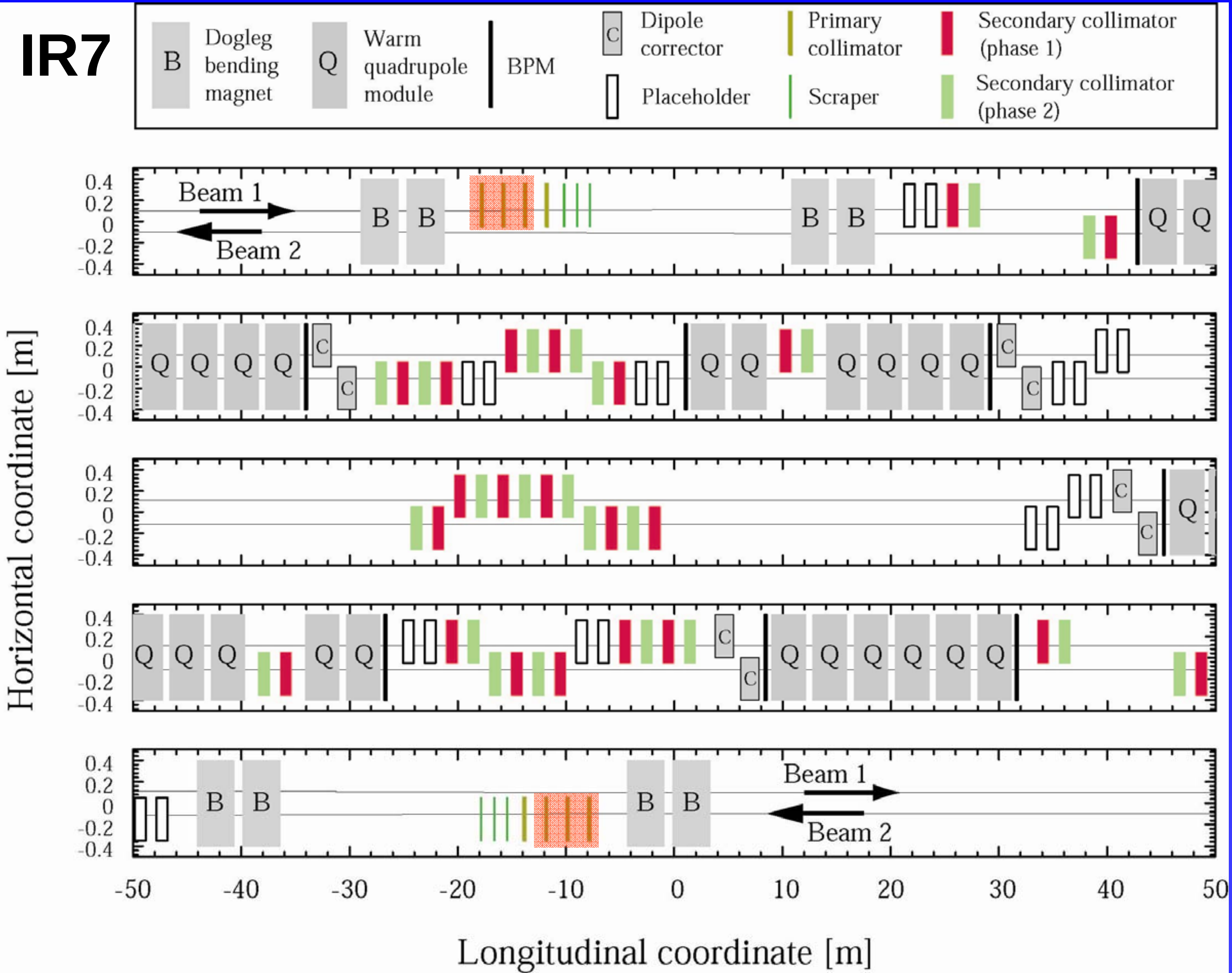
Specific MP Features of Collimators

Collimation was not designed for machine protection as first purpose but for beam cleaning!

Nevertheless, collimators play important role in machine protection:

- Two jaws per collimator (beyond Tevatron and RHIC standard):
  - Cleaning works with only one jaw per collimator ➔ Important additional investment!
  - Two jaw design provides an aperture limitation in both directions: Much safer against operational errors (beam always gets closer to one of the two jaws)!
  - Collimators provide good (not perfect) passive protection: All primary multi-turn beam losses occur at a collimator. Cleaning provides reasonable phase space coverage.
  - Redundancy in the system for cleaning (live without single jaws).
- Monitoring of jaw positions, collimator gaps and hardware (➔ talk by OA):
  - Independent motor control and monitoring system.
  - Jaw positions and gaps monitored continuously with 40 μm accuracy.
  - Monitoring of hardware parameters (jaw temperature, shock impact, …).
- Maximum reliability:
  - Maximum robustness. Concept of spare surface (movement orthogonal to collimation plane ➔ fresh surface for local damage)!
  - Automatic jaw retraction for motor or power failures.
  - Fast handling and service-free or fast service (radiation constraints).

Interception of Betatron Oscillations



Collimators cover about 200 degree phase advance!

Most beam losses will first be intercepted at a collimator in a warm insertion!

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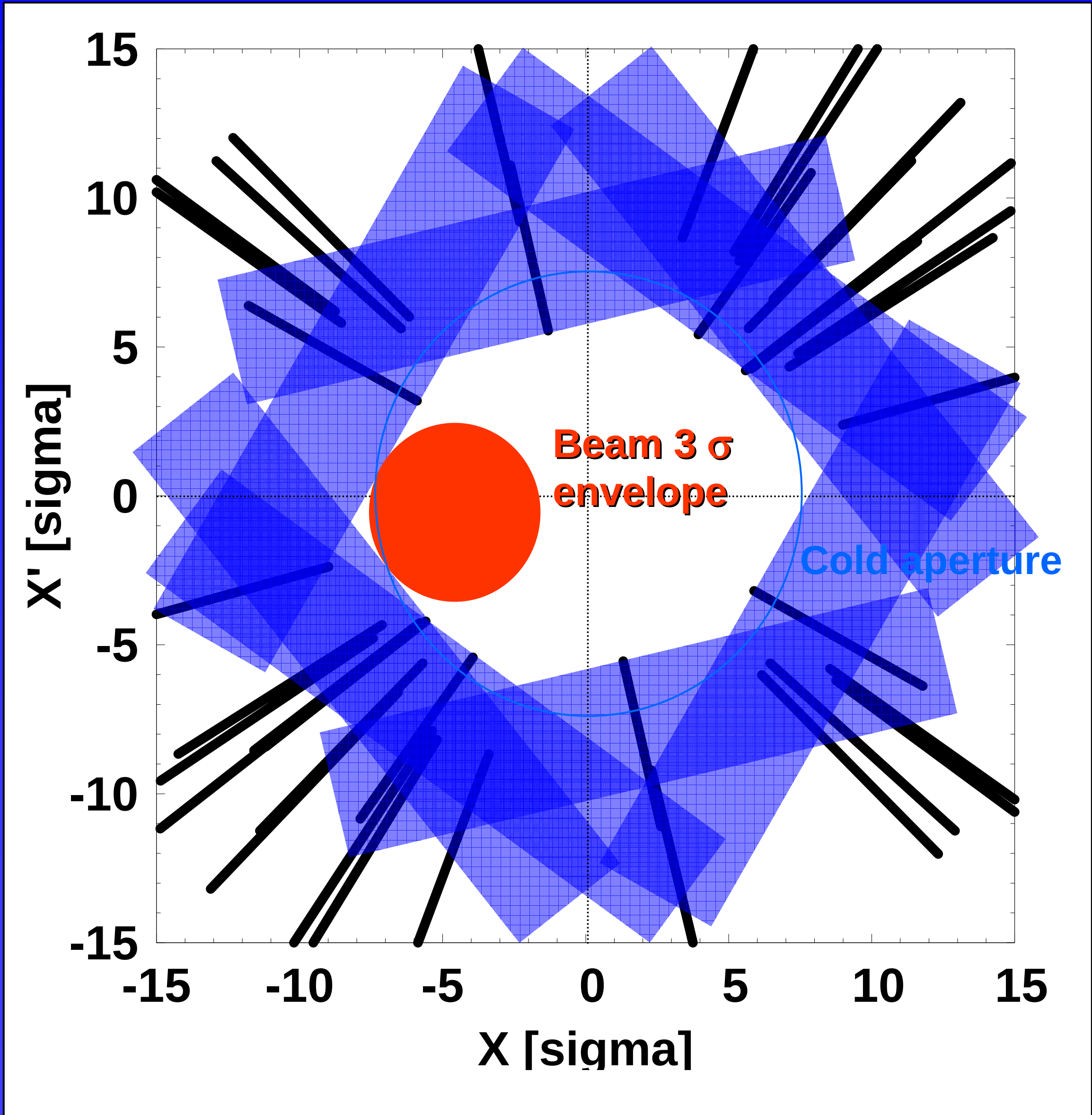
Normalized Phase Space Coverage Injection



Decent **coverage of phase space**:

Beam will likely **first be intercepted at a collimator or absorber or diluter** (also for asymptotic orbit change)!

BLM's at collimator protect against beam loss!

Not very comfortable margin though (profit from tighter settings)!

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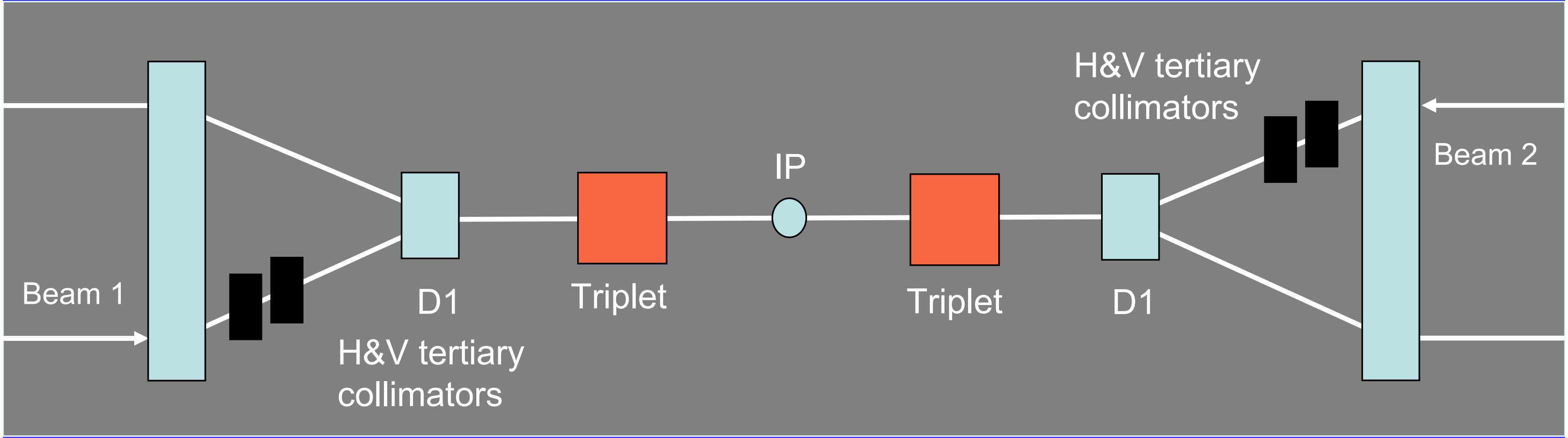
Local Protection: Tertiary Collimators



Shadow against incoming beam halo or mis-kicked beam on triplet aperture!

Two collimators (H+V) for each incoming beam at each IP!

➔ 16 additional collimators (Cu/W jaws)!

Replace in case of beam hit (better than triplets)!

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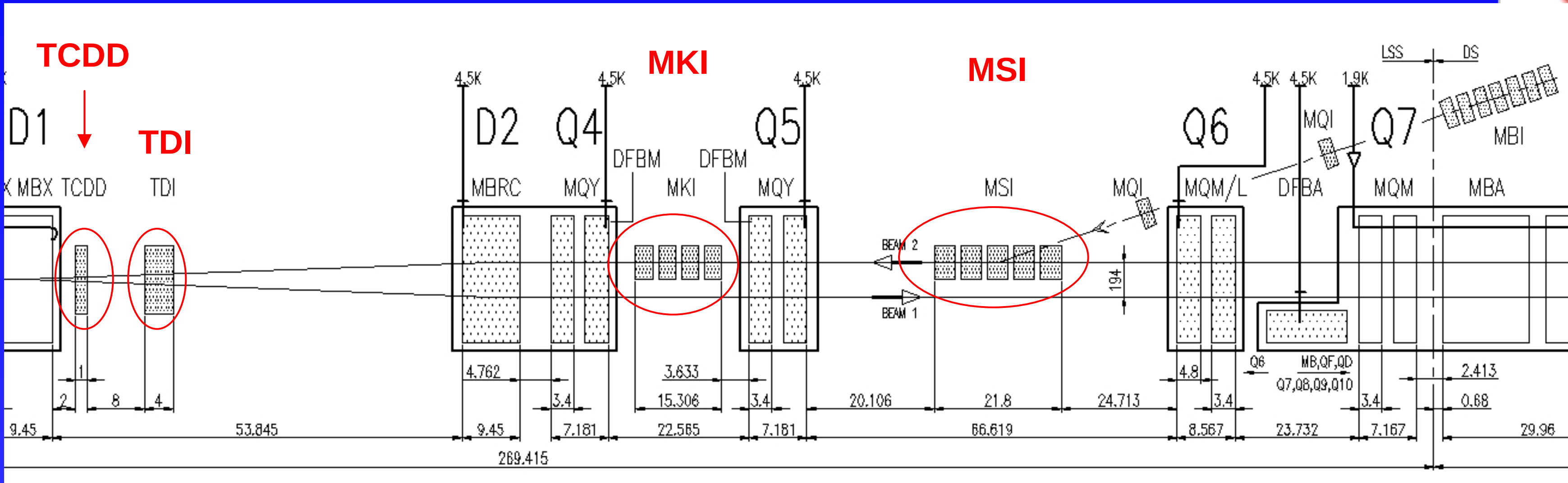
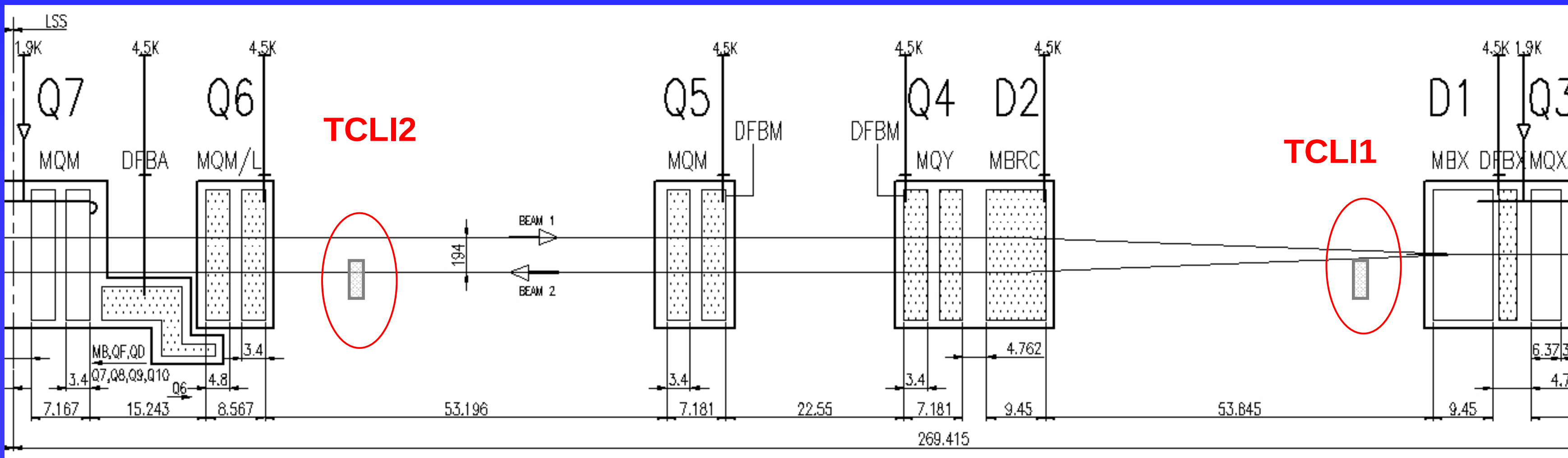
Local Protection: Injection Collimators

LHC Collimation Project CERN





V. Kain, B. Goddard

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Self-Protection of Collimators

- Impact of the full LHC beam will damage and destroy any collimator or other beamline element in the LHC (potentially many at once).
- Collimators are the most at risk elements in the LHC (beam cleaning collimators are closest to the beam and not protected by machine protection elements).
- They are mandatory for the cleaning of beam losses ➔ damage will induce limitations on the beam intensity!
- LHC collimators have been designed with robustness as highest priority (for phase 1).
- However, if severe damage occurs collimators must be replaced: About 2 weeks downtime per collimator exchange. Limited number of spares (~18%).
- Collimators must be protected against damage for efficient running!
- Interlocks from collimation for abnormal beam losses are required (temperatures and BLM measurements)!

Allowable Losses

- Acceptable shock beam impact to **regular machine equipment** and **metallic absorbers**:
  - 1e12 p at injection: 4e-3 of beam
  - 5e9 p at 7 TeV: **2e-5 of beam**
- Acceptable shock beam impact to **C-C collimators/absorbers**:
  - 3e13 p at injection: 10% of beam
  - 8e11 p at 7 TeV: **3e-3 of beam**

100 times better robustness!

- Maximum **allowed continuous loss rates at collimators** (goal):
  - 100 kW continuously.
  - 500 kW for 10 s (1% of beam lost in 10s).
  - **1 MW** for 1 s.

Collimator Beam Tests: Robustness

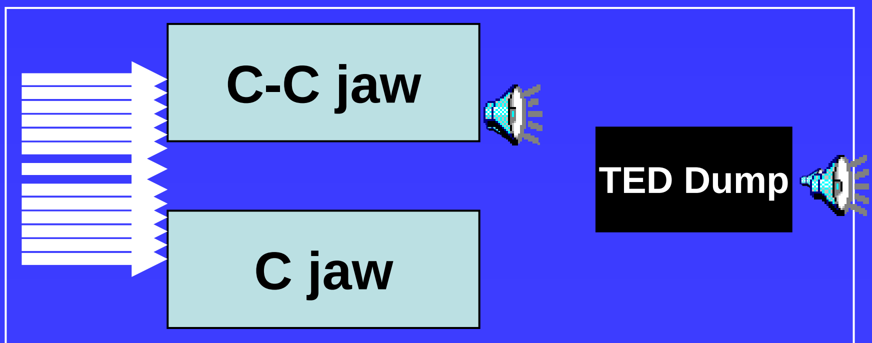
Take:

450 GeV
3 10^{13} p
2 MJ
0.7 x 1.2 mm^2

equivalent

Full Tevatron beam
½ kg TNT

… and hit each jaw 5 times!



C-C (left) and C (right) jaws after impact

No sign of any damage!

Robustness validated!

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Conclusion

- LHC aims at 200-300 times more stored energy than achieved before with lower quench limits of the LHC SC magnets.
- The LHC aperture is tight: Achieved design is ~ 7.5 σ at machine aperture restriction with tight operational tolerances.
- Most collimators in the LHC are used for beam cleaning of multi-turn losses. These collimators are the elements in the LHC closest to the beam and most robust. Cleaning must be done from injection to collision.
- Collimators provide reasonable passive protection against multi-turn losses with emittance blow-up or orbit drifts (via early interception of beam losses).
- Several collimators are used for local protection against mis-kicked beam from irregular dumps and injections: protection of experimental triplets from TCT, protection of ring from TCLI.

Conclusion continued

- There is a close inter-dependence of settings for cleaning and protection → system must be considered as one system.
- The LHC collimation implements several important features for machine protection (machine protection), most importantly two jaws per collimator and an independent monitoring system.
- LHC collimators are up to 100 times more robust than metallic LHC equipment. However, they are highly exposed and adequate self-protection is very important for efficient operation! Crucial link to machine protection!
- Further talks the from collimation team:
  S. Redaelli: Loss Maps after beam cleaning
  O. Aberle: How can we ensure collimator settings?