LHC Collimation

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for the LHC Collimation Team

5th LHC Radiation Workshop

Session: LHC Cleaning & Long Straight Sections

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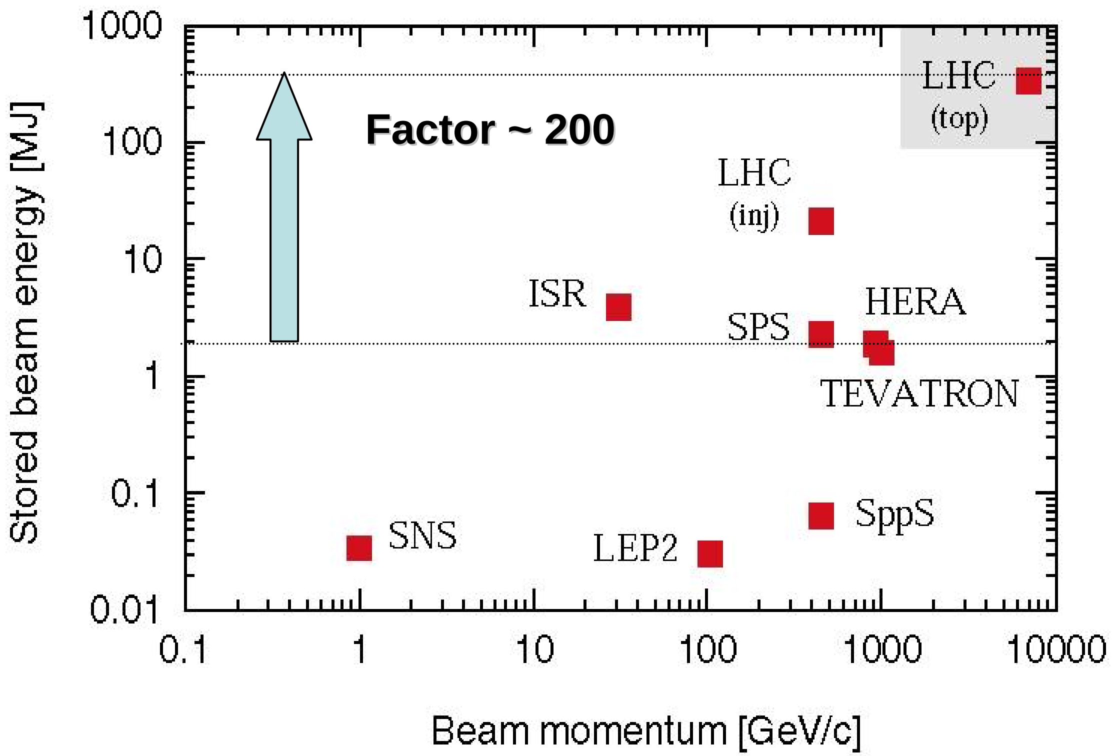
Content:

The Challenge of Stored Energy

The LHC machine: Physics ➔ **High luminosity at high energy**: Great discovery potential!

Accelerator design ➔ **Handling of ultra-intense beams in a super-conducting environment**: Great risk of quenching & damage!



Stored energy: 350 MJ

⇕

Quench limit: ~10 mJ/cm³

Beam Losses

- The LHC storage rings are designed to **store the beams with minimal losses**.
- However, zero losses (infinite beam intensity lifetime) are impossible. **Beam losses are unavoidable!**
- Peak **loss rate** is specified for nominal beam intensity as follows:
  - **1% of beam or 3.5 MJ lost in 10 seconds**
  - **0.2 h beam intensity lifetime or 500 kW power lost for 10 seconds**
- Losses are much beyond the **quench limits** of the SC magnets (10 mJ/cm^3).
- **Cleaning (collimation) systems** are necessary to intercept losses and to absorb them in special warm straight sections (cleaning insertions in IR3 and IR7).
- Beam losses in cleaning insertions have **important side effects**:
  - Heating of equipment.
  - Radiation to equipment, electronics, personnel, environment, …
- Radiation effects depend on **integrated losses over a year**.
  See M. Lamont, LHC Project Note 375.

Efficiency and Allowable Intensity

Allowed intensity

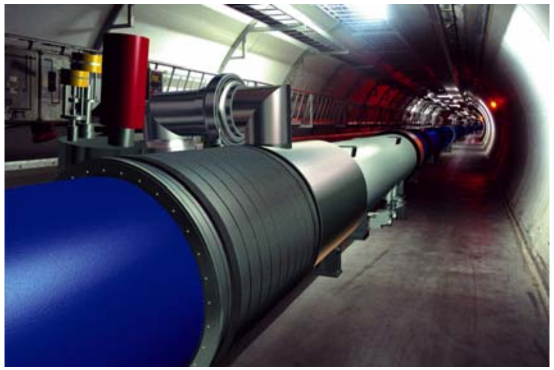
Quench threshold (7.6 ×10⁶ p/m/s @ 7 TeV)

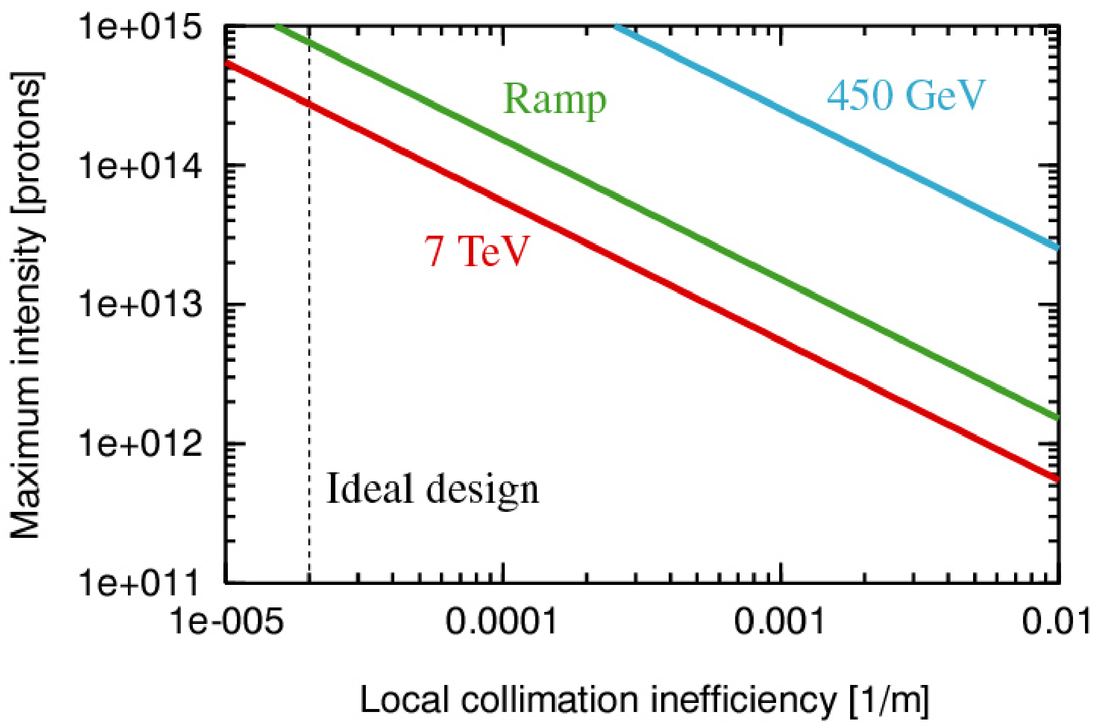
Cleaning inefficiency = Number of escaping p (>10σ) / Number of impacting p (6σ)

$$N_p^{max} \approx \tau \cdot R_q \cdot L_{dil} / \eta_c$$

Beam lifetime (e.g. 0.2 h minimum)

Dilution Length (50 m)





Luminosity and Cleaning Performance

1. Limit bunch current

$$L \propto N_p^2$$

$$\Downarrow$$

$$L \propto \frac{1}{\eta_c^2}$$

2. Limit number of bunches

$$L \propto N_p$$

$$\Downarrow$$

$$L \propto \frac{1}{\eta_c}$$

Minimizing inefficiency is required for **maximizing LHC luminosity**!

Small inefficiency is also required for **minimizing beam-induced background**!

NOTE: Beam loss is a local phenomenon! Local restrictions can occur!

➔ Same beam current all around the ring
➔ Increase local aperture to minimize beam loss
➔ **Increase β*** to increase aperture in the triplet

Complex LHC Collimation System

- In total **150 collimator locations** in LHC and transfer lines! Reserved space above 300 m!
  - Injection: up to 39 collimators per beam (phase 1)
  - Top energy: up to 41 collimators per beam (phase 1)
- In total **132 of these locations** are in the ring and part of the collimation project. **Phased approach**:
  - **Phase 1**: For commissioning in 2007. Up to ~half of nominal beam intensity…
    86 collimators.
  - **Phase 2**: For achieving nominal performance with advanced collimators.
    30 phase 2 collimators available for commissioning in 2011?
  - Phase 3: For beyond 50% of nominal luminosity.
    4 collimators of phase 1 design ➔ Merged with phase 1.
  - Phase 4: Suppressed 14 collimators in IR3/IR7 (loss of 30% in cleaning efficiency).
    10 collimators. Will not be prepared!
- There are **5 different collimator designs** for phase 1! Design differences have been minimized!
- There are **different azimuthal orientations**: 0º (H), 45º (skew), 90º (V) each with ± δ!

Functional Description

- Two-stage cleaning (**robust CFC primary and secondary collimators**).
- Catching the cleaning-induced showers (**active Cu/W absorbers**).
- Protecting the warm magnets (**passive absorbers**).

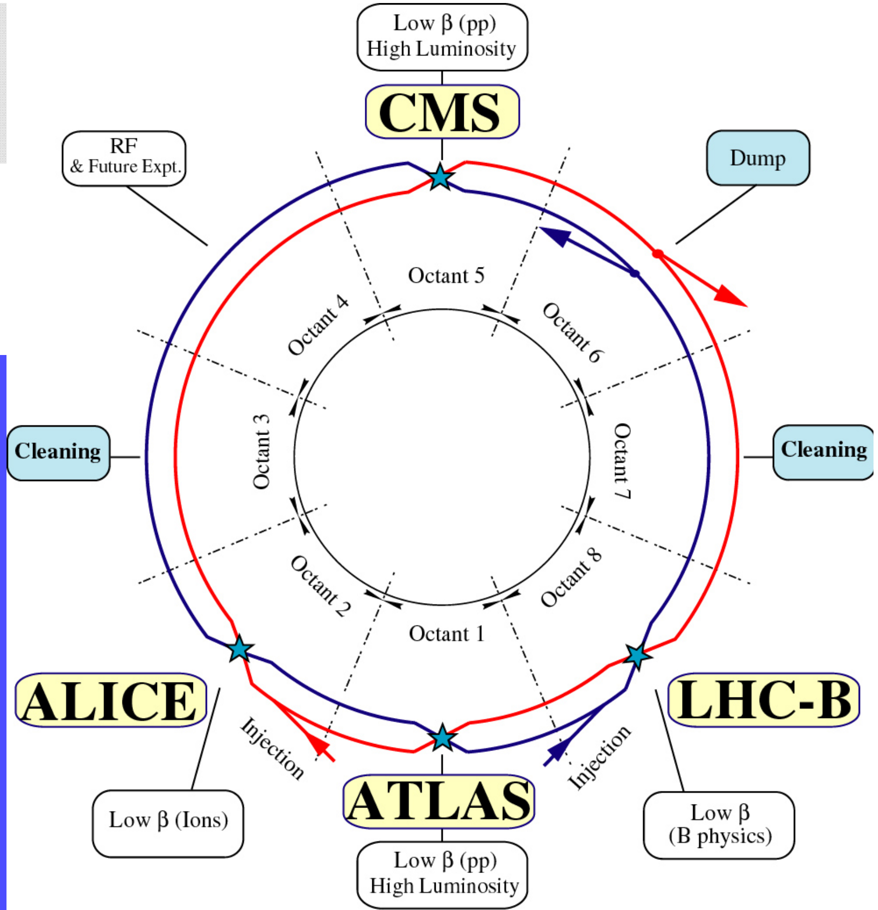
- Local cleaning and protection at triplets (**tertiary Cu/W collimators**).
- Catching the p-p induced showers (**active Cu absorbers**).

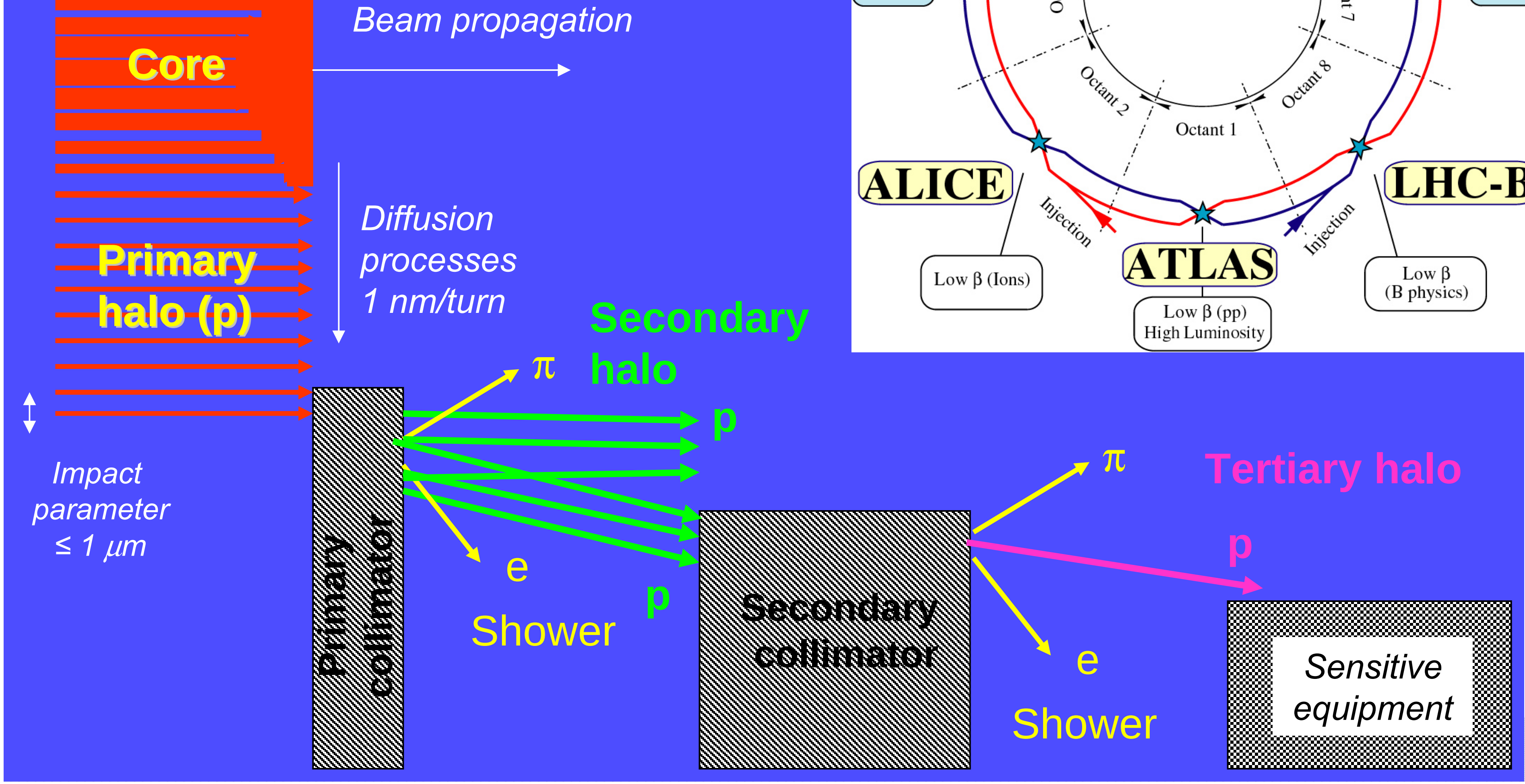
- Intercepting mis-injected beam (**TCDI, TDI, TCLI**).
- Intercepting dumped beam (**TCDQ, TCS.TCDQ**).

- Scraping and halo diagnostics (**thin scrapers**).

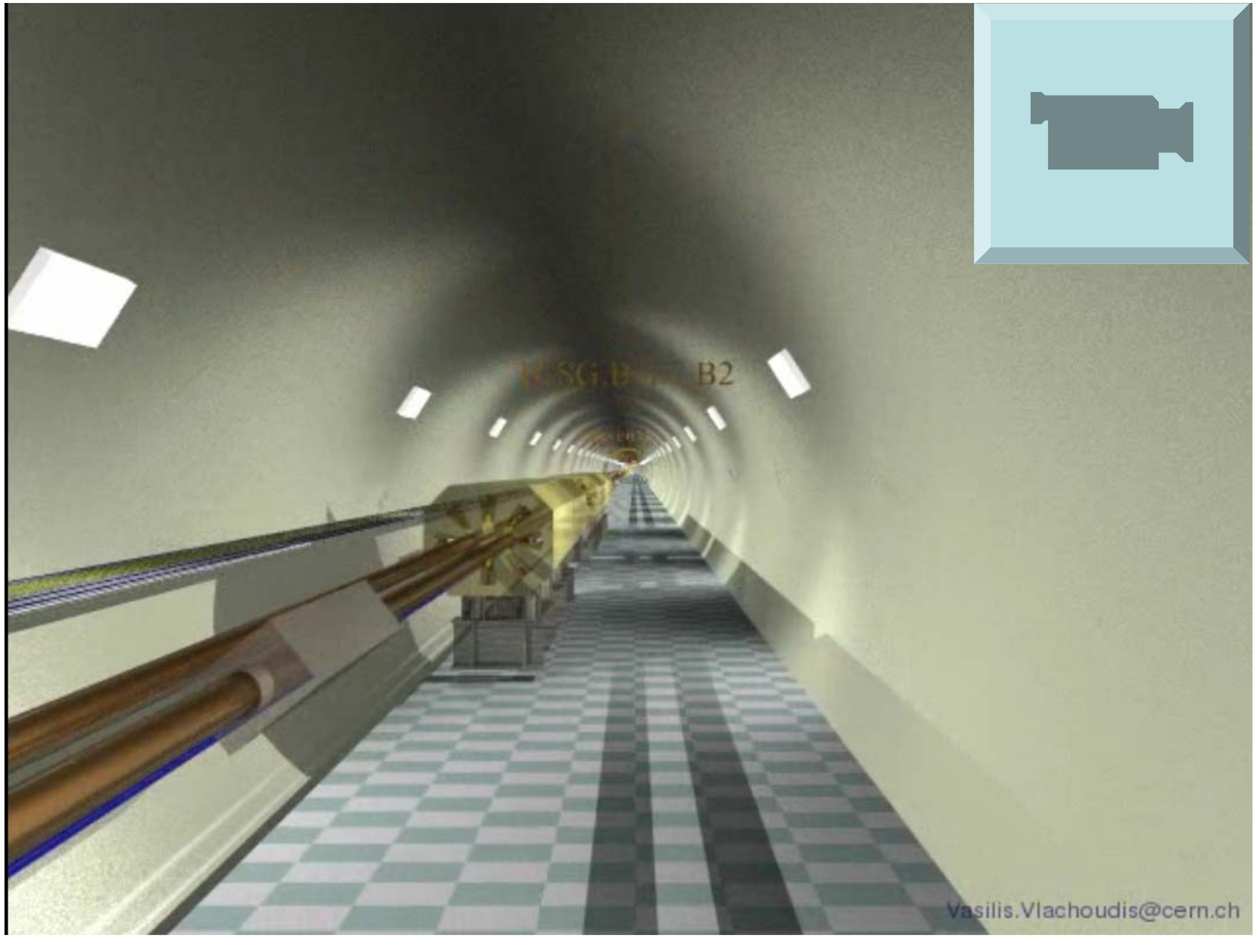
Two-Stage Cleaning

Betatron: IR7
Momentum: IR3





Calculating Energy Deposition



For IR7 (CERN):

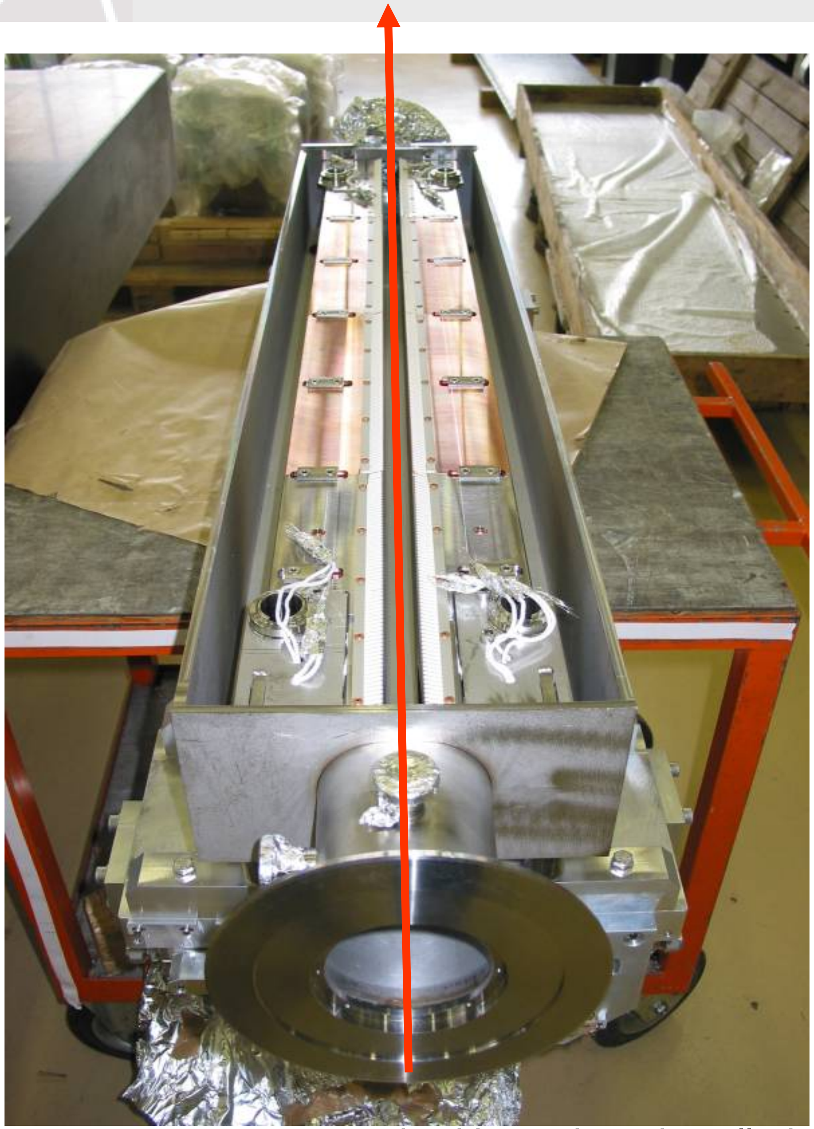
Detailed FLUKA model with all magnets, magnetic fields, collimators (correct openings and angles), tunnel dimensions, RR's and UJ. Automatic tracking/FLUKA interface.

For IR3 (IHEP):

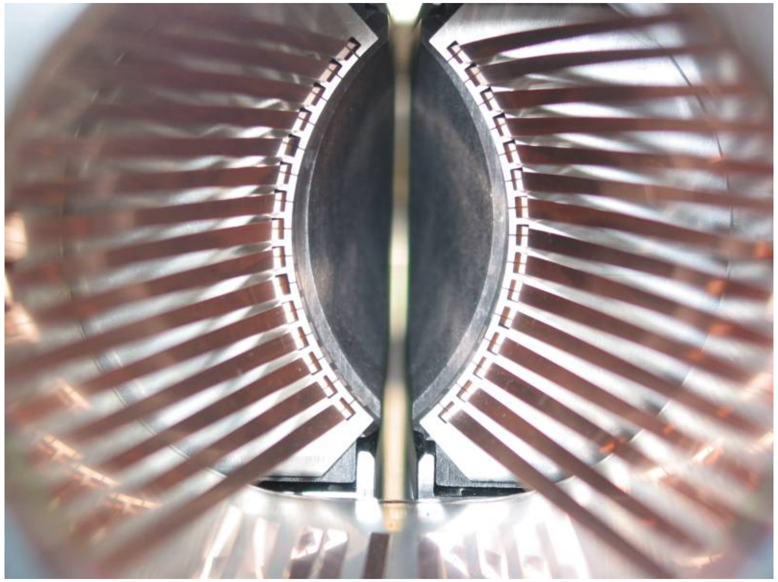
Established STRUCT model.

Detailed simulations started once the collimation layout was essentially fixed.

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!

Robustness of IR3/IR7 Collimators

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

Transparency of Collimators at 7 TeV

Material	Density g/cm^3	Escaping %
Aluminum	2.7	88.8
Beryllium	1.848	97
Copper	8.96	34.4
Graphite	1.77	96.4
Titanium	4.54	79.5

Example for 1 m long jaws!

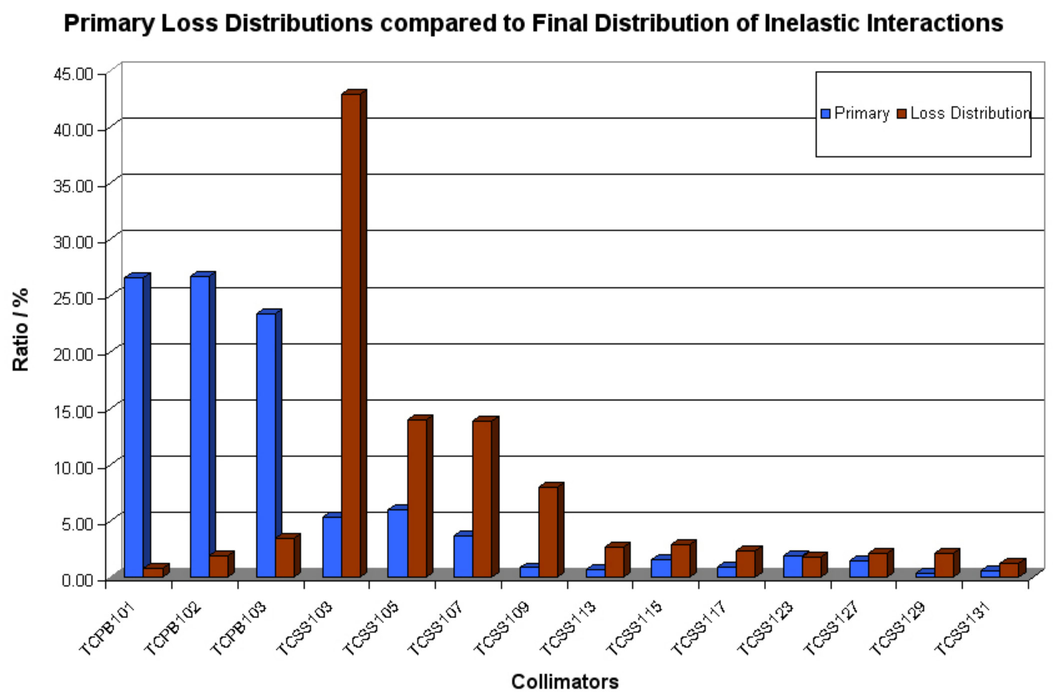
Secondary collimators intercept halo ➔ Shower energy escapes to downstream!

Obsolete Cu design: **34 %** escapes

New CC design: **96 %** escapes

What happens downstream?

Catching the Cleaning-Induced Showers



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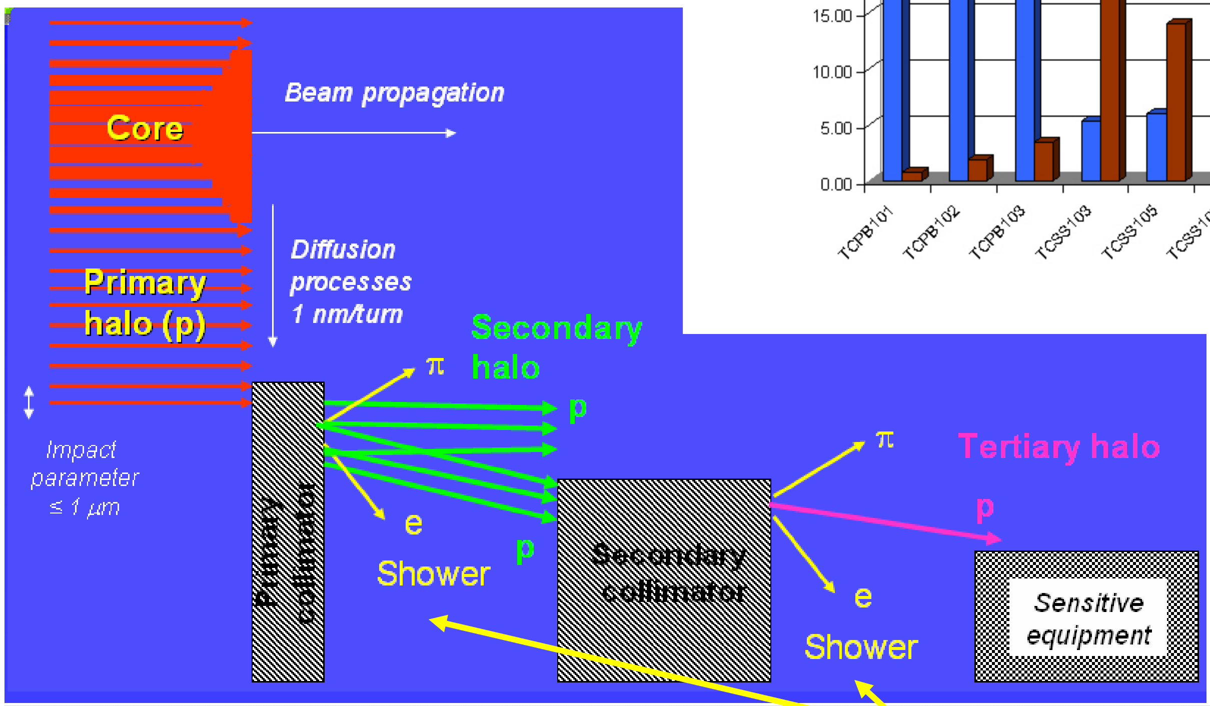
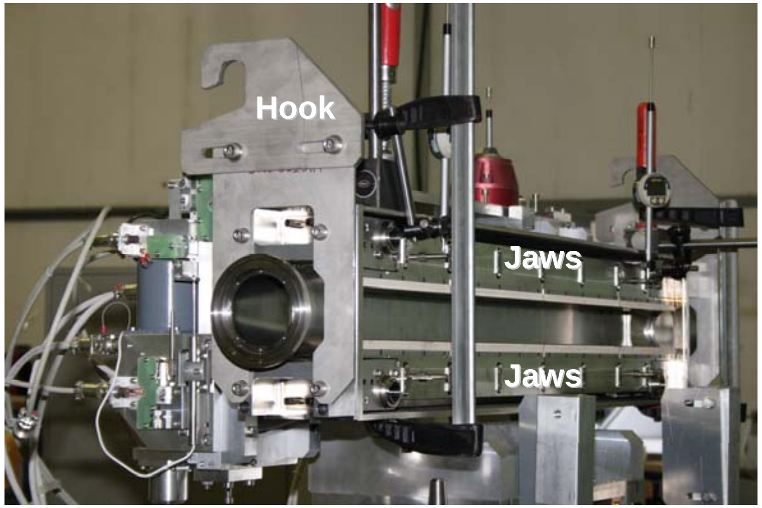
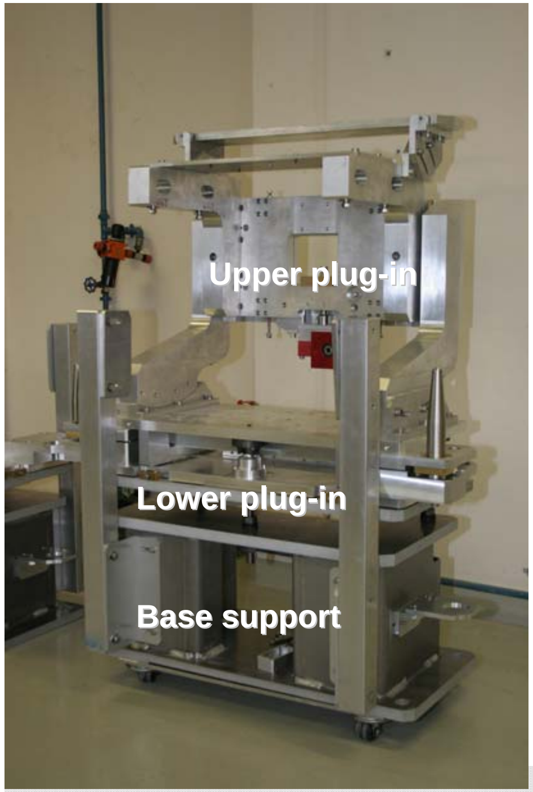


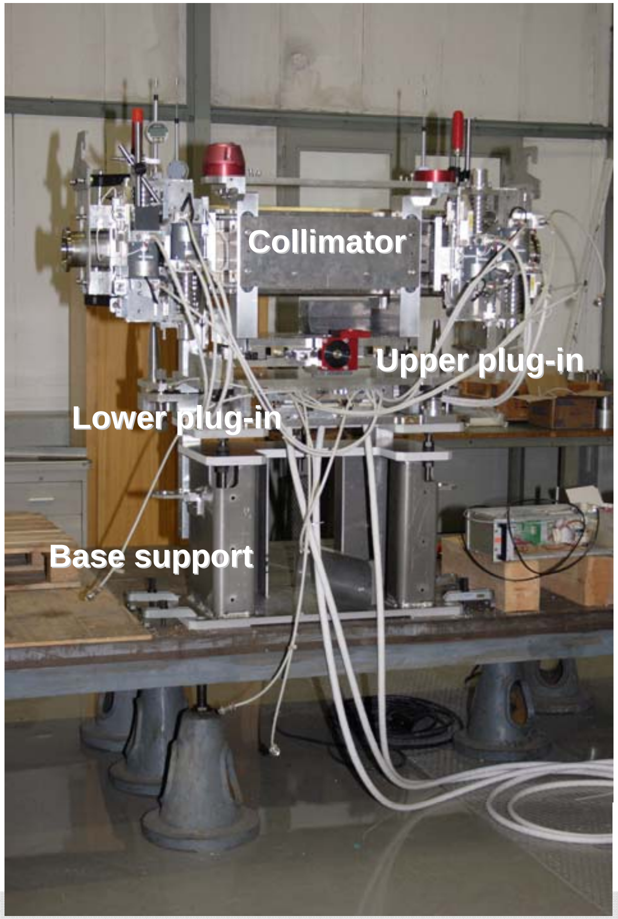
Where do the showers go?

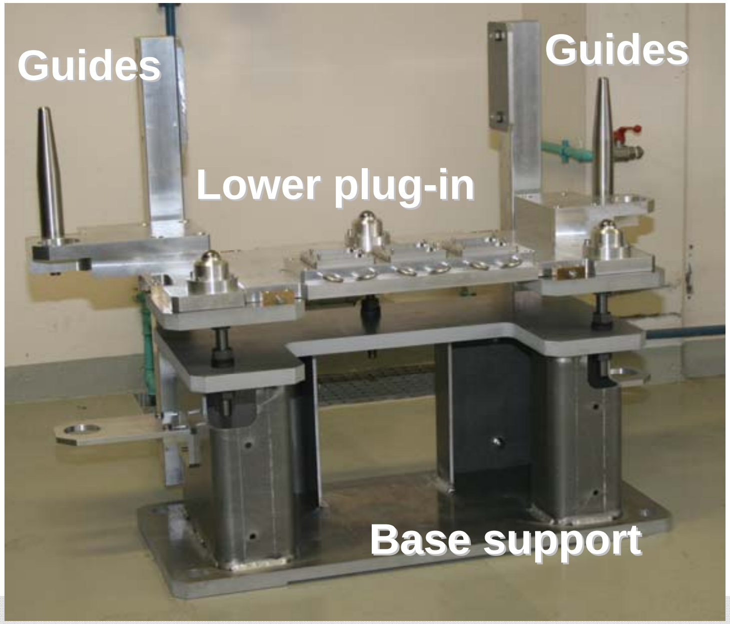
Radiation Optimization at Collimators

- Quick plug-ins for fast exchange of collimators…
- Minimizes dose to personnel…

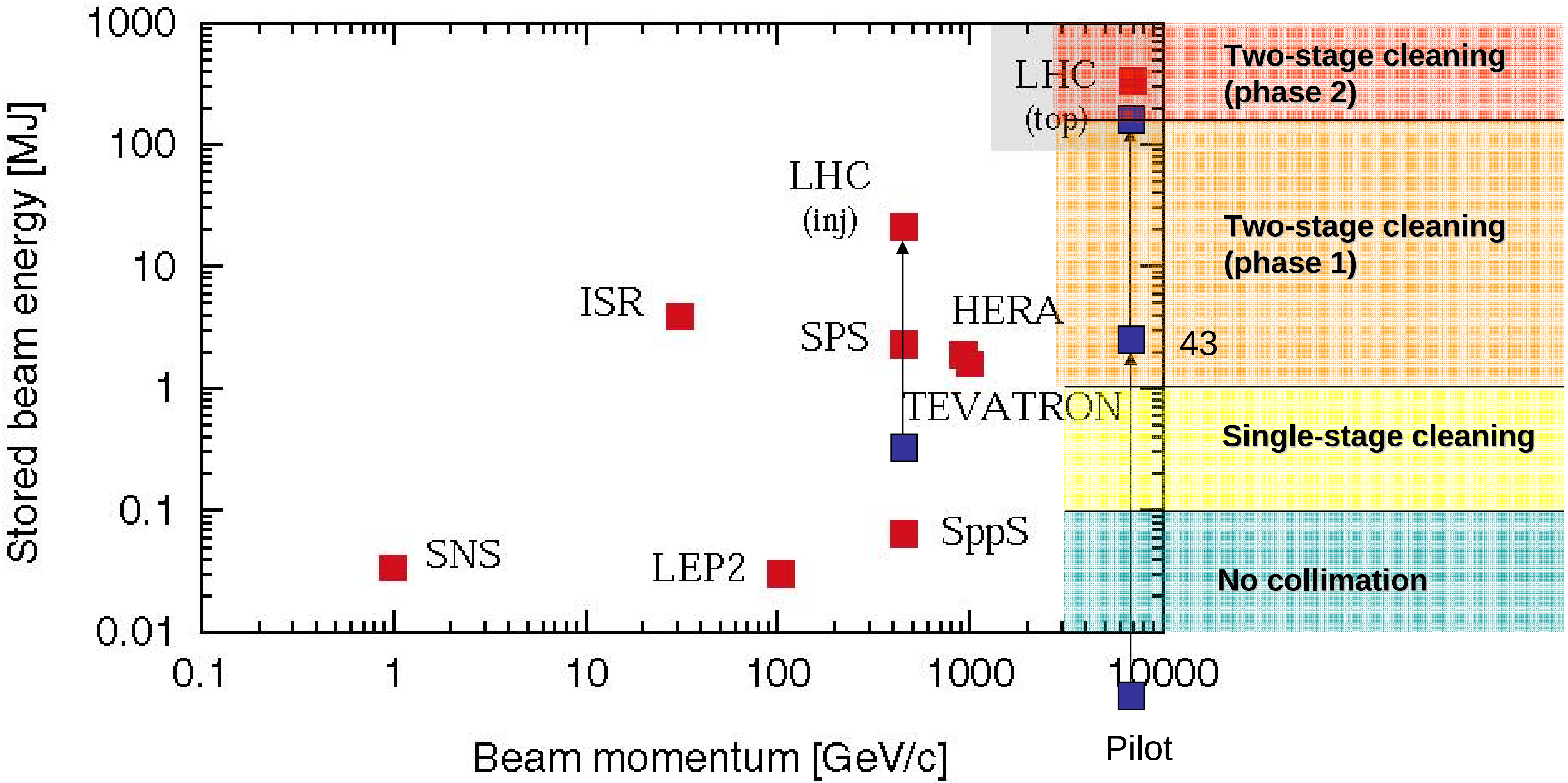








Commissioning of Cleaning System



Commissioning Plans

- **Collimation and machine protection will be important for any interesting physics run, including 43 on 43 bunches!** There is no “easy” start for cleaning and background!
- However, **radiation issues will be much relaxed initially**: we do not expect strong activation, trips of electronics, … during initial runs (except some things are really wrong)!
- Some thoughts on **“optimized” commissioning** of collimation:
  - Use available collimators/absorbers even early on (e.g. tertiary collimators to protect triplets for some pilot bunch tests at 7 TeV).
  - Relax on setting accuracy (this is what is difficult and lengthy) not on number of elements.
  - Coarse settings might even be achieved with BPM readings, for sure with a fast beam-based set-up (10 min in SPS test).
  - Define a minimal and relaxed collimation/protection set-up for usage and then follow evolutionary approach for tuning up a full two-stage cleaning!
- “Safety first” will **maximize efficiency of operation and commissioning**:
  - For several collimator types only 1 spare!
  - Learn a maximum at lower intensity where damage is more limited!
  - Only go to high intensity (43 bunches at 7 TeV) once collimation/protection is basically working?
- Proposal for a **simple and relaxed early system**… (more at Chamonix 2006)

Minimal Single-Stage Cleaning/Protection System with Circulating Beam

1. Put 3 betatron primary collimators to coarse 6 σ setting (single-stage cleaning always in cleaning insertions). Put 1 momentum primary collimators to 8.5 σ.
2. Put 8 TCLA absorbers in cleaning insertions to coarse 10 σ position (shadow SC arc aperture and capture shower debris).
3. Set up 1 TDI and 1 TCLI for injection protection (collimators can be out during set-up).
4. Set up 1 TCDQ for dump protection.
5. Accumulate and ramp.
6. Set up ~8 TCT's at 7 TeV to protect triplets and reduce background, even if not squeezed.

This system involves **22 movable elements per beam** with **increased margin for set-up errors and transient beam changes** (orbit, beta-beat):

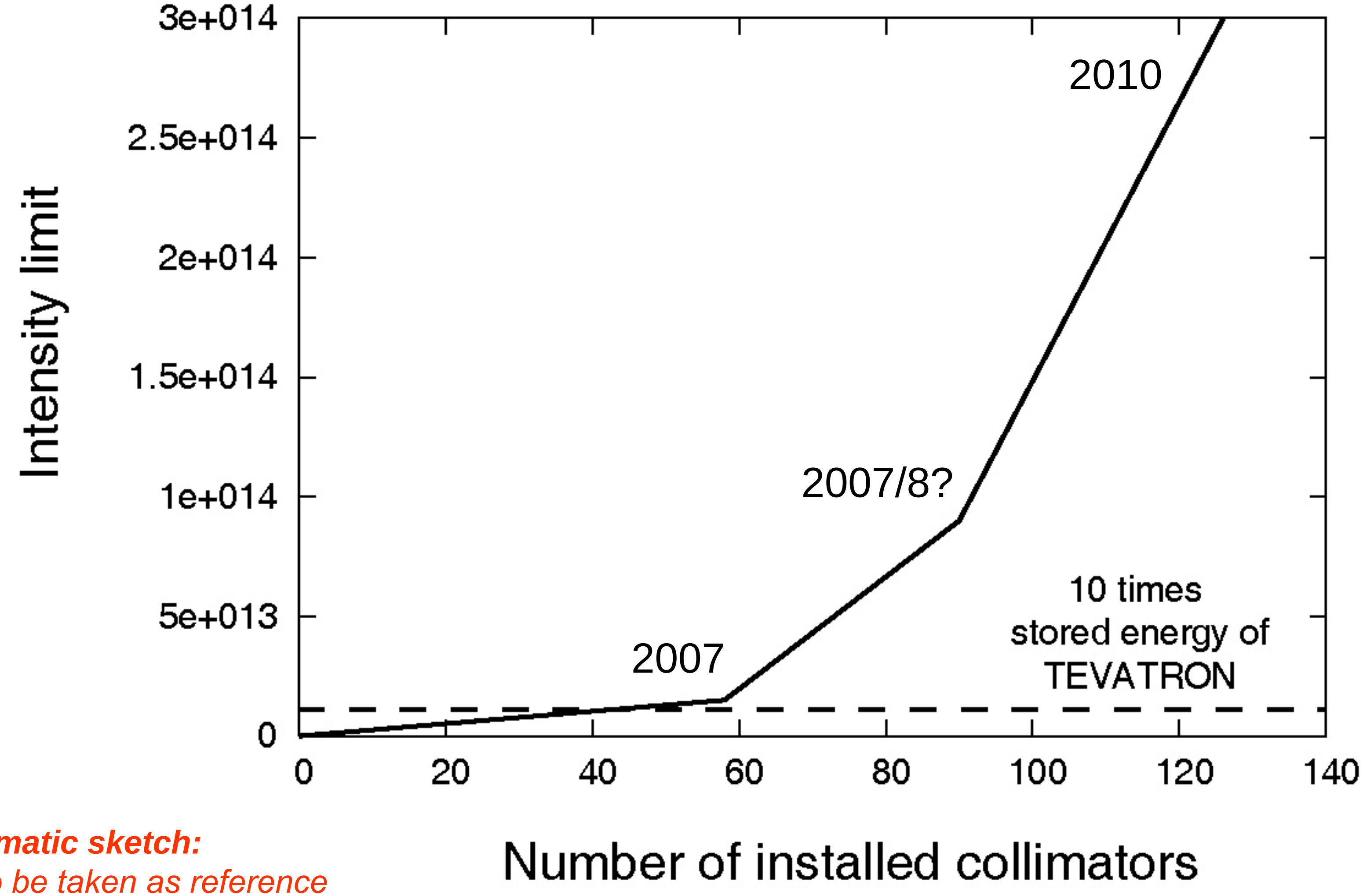
Injection:	3.0 mm margin instead of 1.0 mm margin
7 TeV:	0.6 mm margin instead of 0.2 mm margin

Fully functional 1 stage cleaning with injection and dump protection, as well as full protection of triplets!

Required time for set-up: ~1 day per beam based on SPS experience!

Extend towards two-stage system by moving in secondary collimators! Reduce margin!

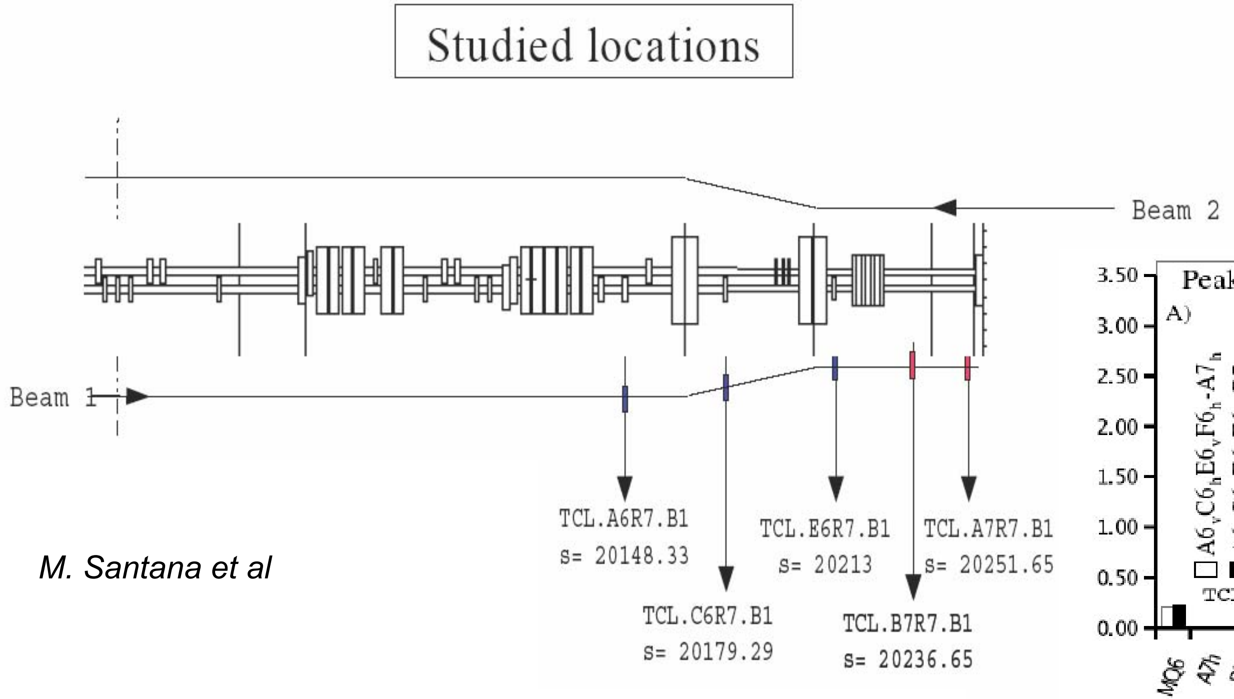
Expected Intensity Limit versus Number of Installed/Used Collimators



(in both LHC rings and transfer lines)

Schematic sketch:
Not to be taken as reference for collimation performance!

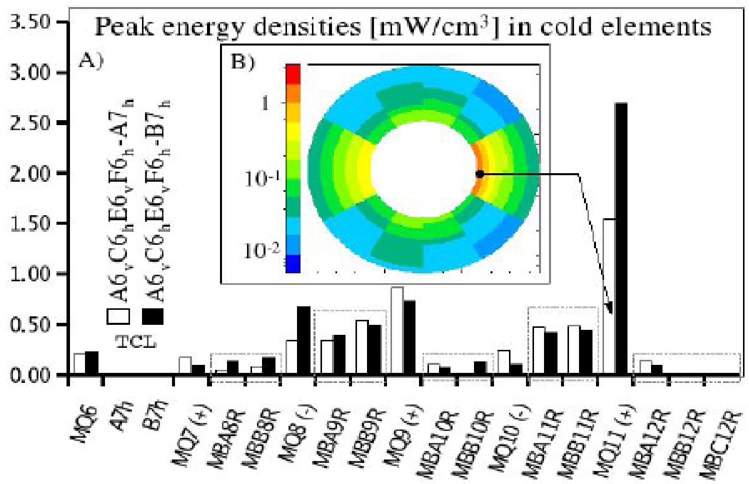
Betatron Cleaning IR7



M. Santana et al

Quench limit:

1-5 mW/cm³



Maximum power deposition in super-conducting coils:

330 mW/cm³ No absorbers ➔ 9.0 mW/cm³ 3 absorber ➔ 2.5 mW/cm³ 4 absorber ➔ **1.5 mW/cm³** 5 absorber

FLUKA team: **A. Presland, A. Ferrari, V. Vlachoudis, M. Magistris, M. Santana-Leitner**

Active Absorbers

Add in total **18 active absorbers** in IR3 and IR7 gains:

- **factor ~100 in cleaning of showers!**
- **factor 10 in radiation to electronics!**
- **factor 2-10 in halo load.**

Important addition to the collimation system!

Design: Like **secondary collimators with Cu/W jaw**. Need to be fully movable for effectiveness!

Need to handle them carefully ➔ Very sensitive for beam damage!

Shielding and Radiation to Electronics

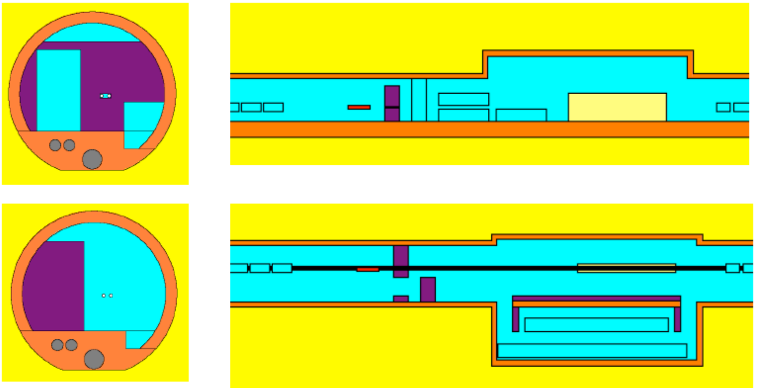
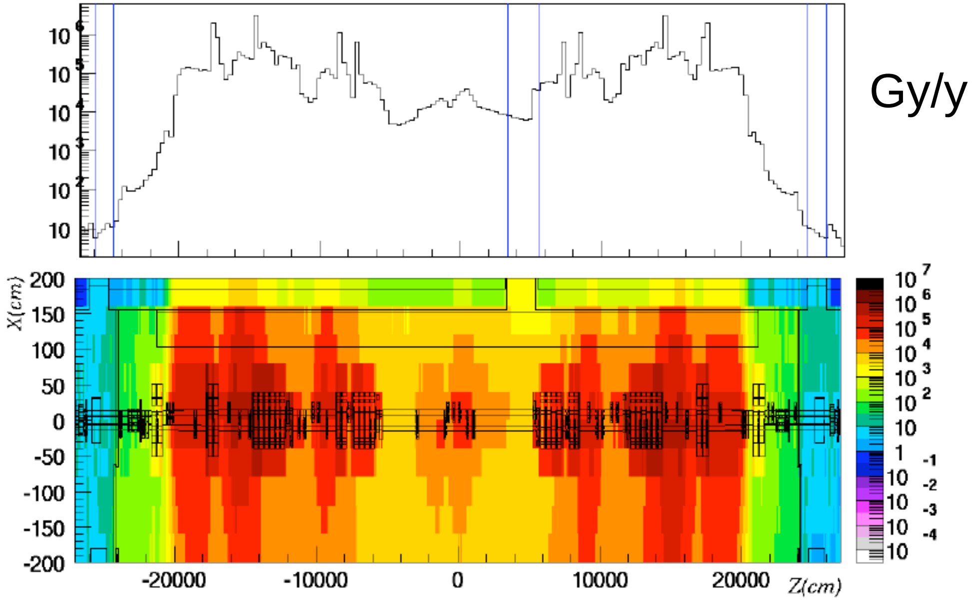


Figure 2 Schematic representation of the shielding proposed for the RR73/77 regions. The purple colour stands for iron (density 7.2 gr/cm^3), the orange colour is for the concrete walls and the blue colour stands for the air. Inside the RR region the two boxes represent the racks for the electronics, where the scoring was made (in air).



Radiation levels at the electronic rack positions at IR7 (average values for the racks situated on the ground floor). The statistical error is ≤20%.

	Dose (Gy/y)	Hadrons > 20 MeV (cm^{-2}/y)	1 MeVeq. flux (cm^{-2}/y)
UJ76	0.5	8 _10^8	2 _10^9
RR73/77	0.3	1 _10^8	6 _10^8

K. Tsoulou et al, LHC Project Note 372

Passive Absorbers

- Passive absorbers must protect MBW's from showers.
- Design goal: **< 5 MGy/y** for 10 year survival!
- Achieved: **10 MGy/y**
- Unresolved issue: Replace MBW after several years?
- **Studies ongoing!**

Max dose, MBW coils, MGy/year

	1 cmc	Larger bin
No absorber	260	206
40 mm radius	260	200
30 mm radius	23	17
25 mm,large	17	13
ellipses	10	8
ellipses ideal	1.3	0.5
20 mm radius	11	8

Important contribution from radiation scattered inside the beam pipe

M. Magistris et al

Conclusion

- **Beam losses** are expected to be a **performance limitation for the LHC**.
- **Low current limitations** due to reduced collimation and efficiency during set-up and optimization (learning curve):
  - Cleaning efficiency (quenches).
  - Background in the experiments.
- **Minimal medium current limitations** (stable beam around 10% of nominal intensity?).
- **High current limitations** (around nominal intensity) could include:
  - Cleaning efficiency (quenches).
  - Background in the experiments in IR2 and IR8.
  - Radiation to the electronics.
  - Damage to equipment in cleaning insertions (due to radiation or operational errors).
  - Access restrictions to highly radioactive collimation areas.
  - Excessive integrated losses.
- A **powerful phase 1 collimation system** with unprecedented performance will reduce these limits to the achievable minimum. Further advances with **phase 2** of LHC collimation.