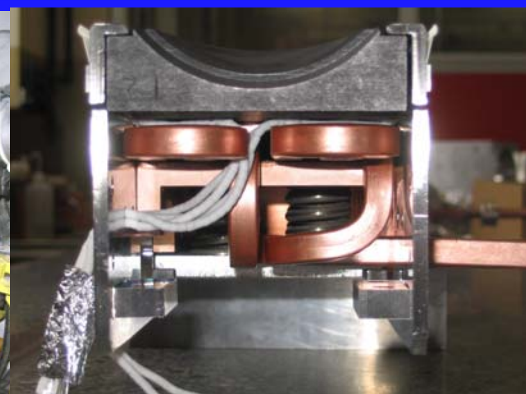
The LHC Collimation System



Ralph W. Aßmann

for the LHC Collimation Project

AB Seminar

10.03.2005

Based on the results of the work by:

O. Aberle, R. Assmann, I. Baishev, A. Bertarelli, H. Braun, M. Brugger, S. Calatroni, E. Chiaveri, F. Decorvet, B. Dehning, A. Ferrari, D. Forkel-Wirth, E.B. Holzer, J.B. Jeanneret, M. Jimenez, M. Jonker, Y. Kadi, V. Kain, M. Lamont, R. Losito, M. Magistris, A. Masi, M. Mayer, E. Metral, R. Perret, L. Ponce, C. Rathjen, S. Redaelli, G. Robert-Demolaize, S. Roesler, F. Ruggiero, M. Santana Leitner, R. Schmidt, D. Schulte, G. Spiezia, P. Sievers, K. Tsoulou, H. Tsutsui, V. Vlachoudis, J. Wenninger, ...

Additional support for beam tests:

G. Arduini, T. Bohl, H. Burkhardt, F. Caspers, M. Gasior, B. Goddard, L. Jensen, R. Jones, T. Kroyer, R. Steinhagen, J. Uythoven, H. Vincke, F. Zimmermann

Formal outside collaborations with...

IHEP (IR3 energy deposition studies)

Kurchatov Institute (radiation effects on C-C jaws)

SLAC, BNL, FNAL (phase 2 R&D and tertiary collimators)

The History of LHC Collimation

- Work on the LHC collimation system started in 1990 with limited resources!
- After LEP: Start of the **Collimation Working Group** end of 2001!
  Main worry: Operational tolerances of cleaning!
- Discussions at Collimation WG and **LTC** showed **serious technical problems**:
  - Assumptions on beam operation were too optimistic!
  - Foreseen collimator materials (Al/Cu) would not resist to beam operation!
- In **October 2002**: Start of the **LHC Collimation Project** with extremely challenging boundary conditions:
  - **Technical**: 2-3 orders of magnitude better collimation required at LHC than at HERA/TEVATRON! Destructive LHC beam!
  - **Design**: No hardware solution for LHC collimation.
  - **Schedule**: 4 years from conceptual design to end of installation.
  - **Complexity**: ~90 ring collimators of various types for multi-stage cleaning.
  - **Radiation**: No coherent concept for handling of beam-induced radiation.
  - **Management**: No CERN team in place.

The LHC Collimation Team

- Key to success: An excellent and motivated team (not afraid of challenges) and support from collimation experts (in particular J.B. Jeanneret).
- Strong management support to **build up a strong team quickly** across different CERN departments and groups, as well as collaborators:
  - **AB department**: accelerator physics, halo modeling, energy deposition, mechanical engineering, operational aspects, controls, beam tests, project management, …
  - **AT department**: vacuum design, integration, quench levels, …
  - **Safety Commission**: modeling of radiation impact, radiation optimization, …
  - **TS department**: lead of mechanical design, mechanical modeling, material qualification, prototyping, drawings for series production, integration, …
  - **IHEP (Russia)** and Fermilab (US): Energy deposition studies.
  - **TRIUMF (Canada):** Collimation optics design.
  - **Kurchatov (Russia):** Radiation damage.
- Excellent collaborative spirit to **solve the problem over the last 2 ½ years**!

Outline

- Requirements (stored energy, quench limit, cleaning, …)
- The "final" solution for the collimation system
- The collimator hardware design
- Other issues
- Conclusion

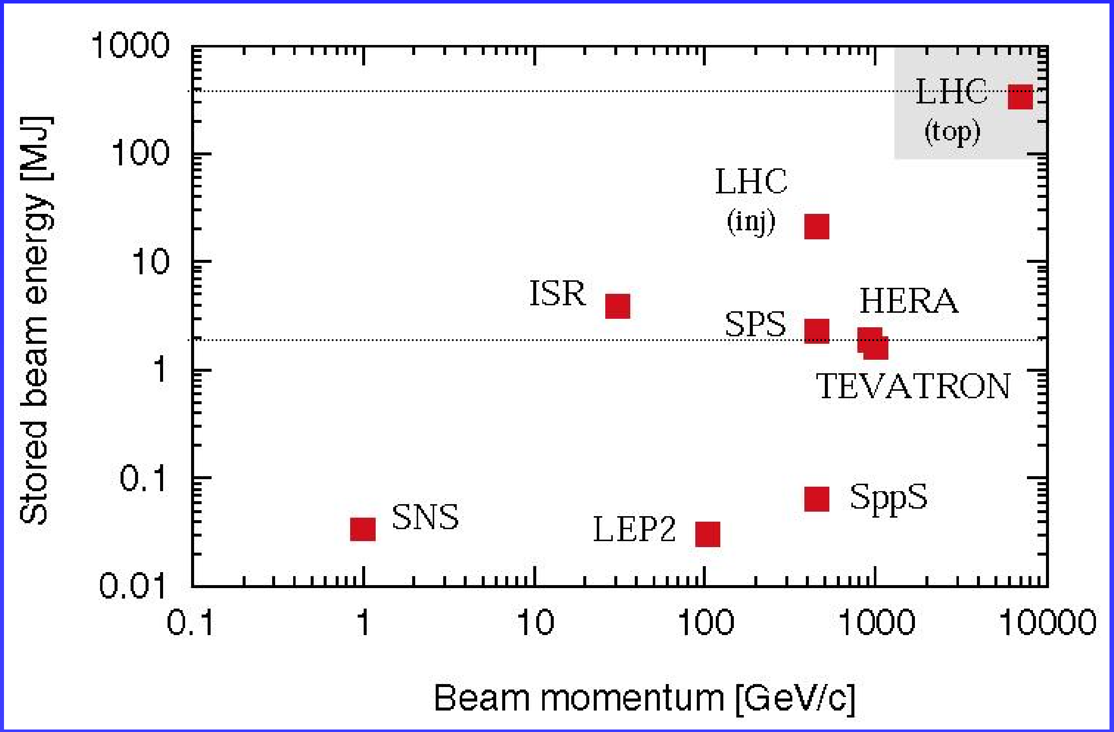
Main topic of this talk!

Requirements

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!



Factor ~ 200

Stored energy: 350 MJ

Quench limit: ~10 mJ/cm^3

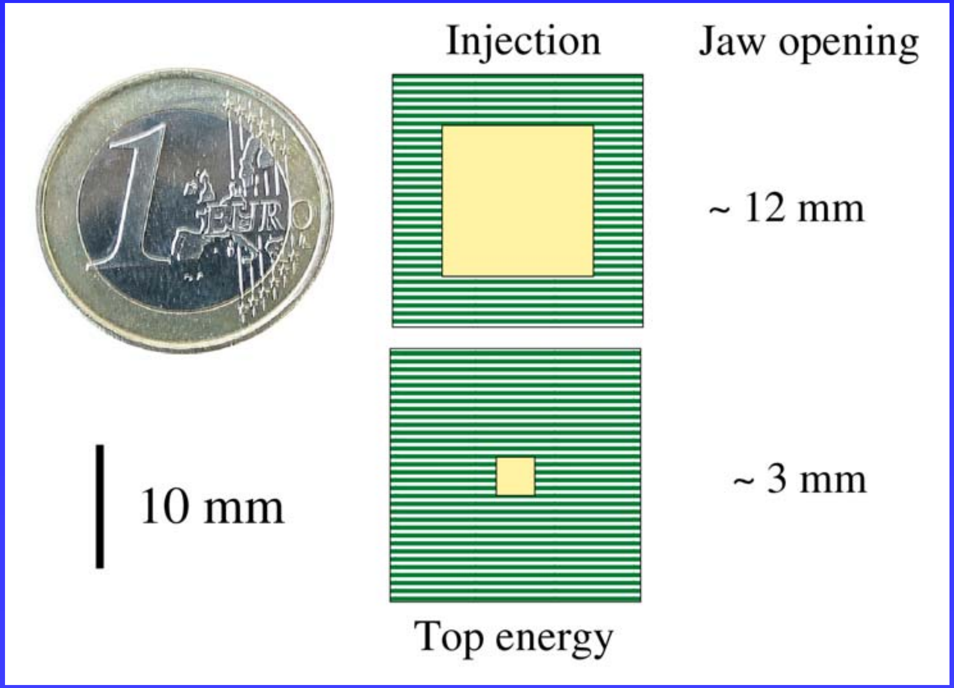
Collimating with small gaps

~ 0.15 ~ 0.6

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

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)!

Worries for the LHC

Can we **predict requirements** and all failures?	10 ×	complexity
Survival of collimators with high density LHC beam?	1000 ×	density
Performance for avoiding quenches?	1000 ×	power/quench limit
Can we handle **mechanical and beam tolerances**?	10 ×	smaller gaps
Peak loss rate (peak heat load: 500 kW)?	100 ×	stored energy
Average loss rate (**radioactivity**)?	100 ×	loss per year

A very difficult problem! **To solve it we must rely on expertise in:**

Accelerator physics – **Nuclear physics** – **Material science**

Mechanical engineering – **Radioprotection**

Without collimation: Store 5 ‰ of nominal intensity (1h lifetime) or always ensure lifetime of 220 h (nominal intensity). **Quench** every magnet 1500 times if beam is lost in 1 turn and distributed over 27 km.

Outline

- Requirements (stored energy, quench limit, cleaning, …)
- **The “final” solution for the collimation system**
- The collimator hardware design
- Other issues
- Conclusion

The "Final" Solution for the Collimation System

You ever got confused on acronyms and phases?

TCP, TCSG, TCSM, TCHS, TCLIA, TCLIB, TCLP, TCLA, TCL, TCS.TCDQ

TCDI, TDI, TCDQ, TCDD, TCDS

Phase 1, Phase 2, Phase 3, Phase 4

Do we really need this "collimation zoo"???

Explain the different kinds of collimators and their purpose!

How to Read Acronyms

- **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**… = Target **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** = ?
  - TCD**S** = **S**eptum
  - TCD**I** = **I**njection transfer lines
- **TD**… = **T**arget **D**ump
  - TD**I** = **I**njection

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*

Complex 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. 32 collimators.
  - 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 CC primary and secondary collimators).
- Catching the cleaning-induced showers (active Cu absorbers).
- Protecting the warm magnets (passive Cu absorbers).

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

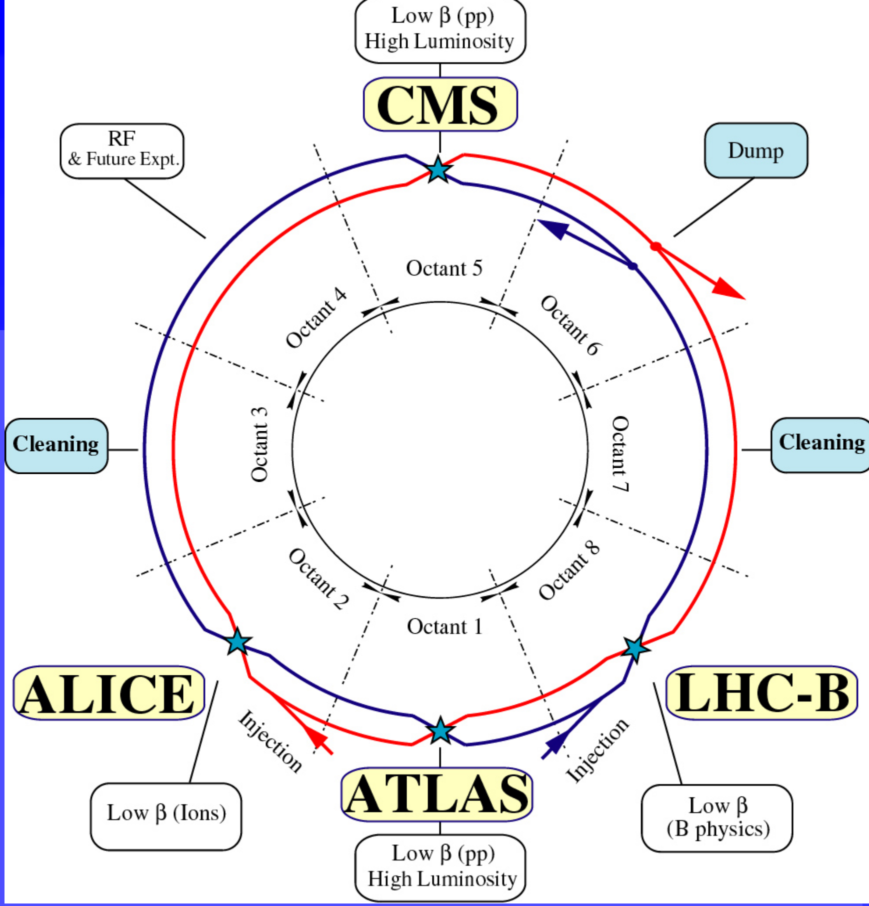
- Intercepting mis-injected beam (TCDI, TDI, TCLI).
- Intercepting dumped beam (TCDQ, TCS.TCDQ).

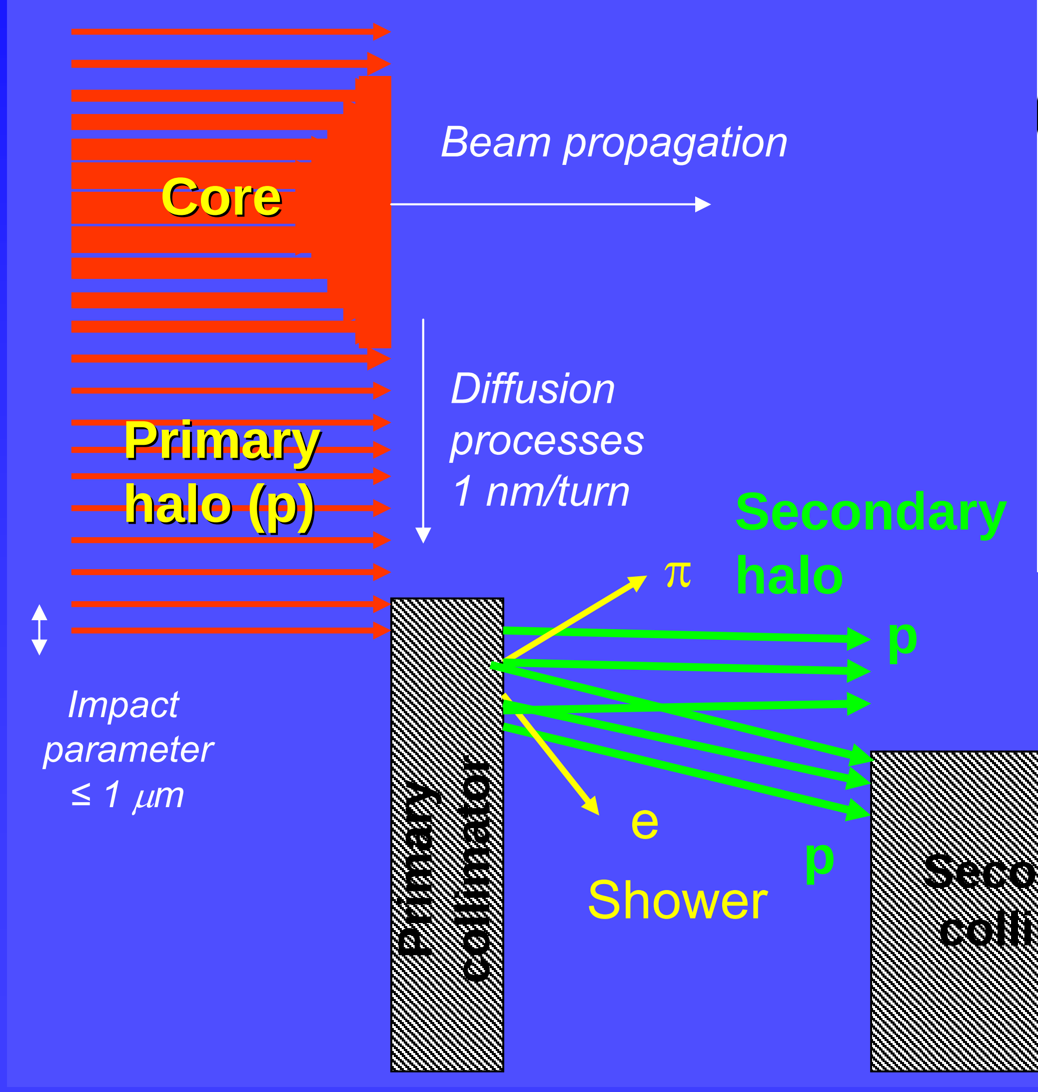
- Scraping and halo diagnostics (thin scrapers).

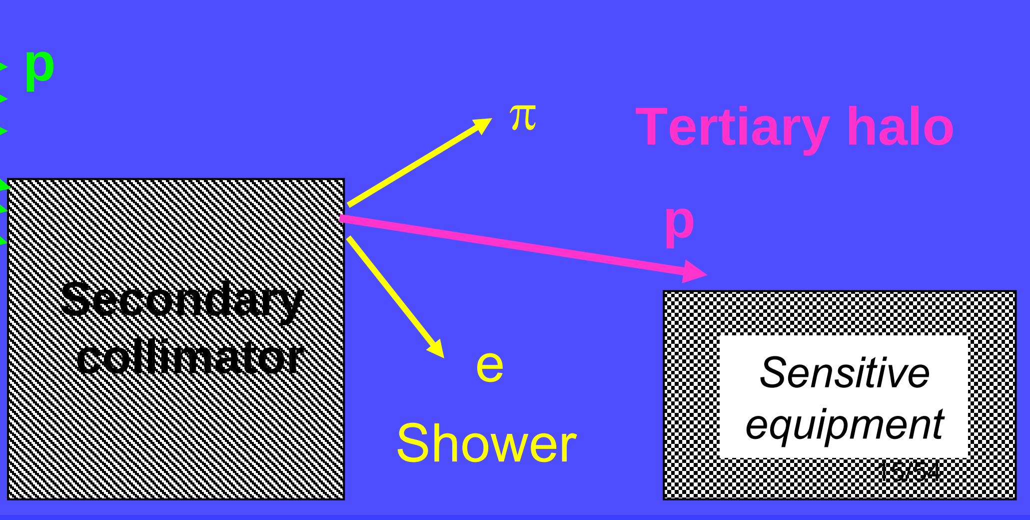
Go through the different functions now…

(I) Two-Stage Cleaning

Betatron: IR7
Momentum: IR3



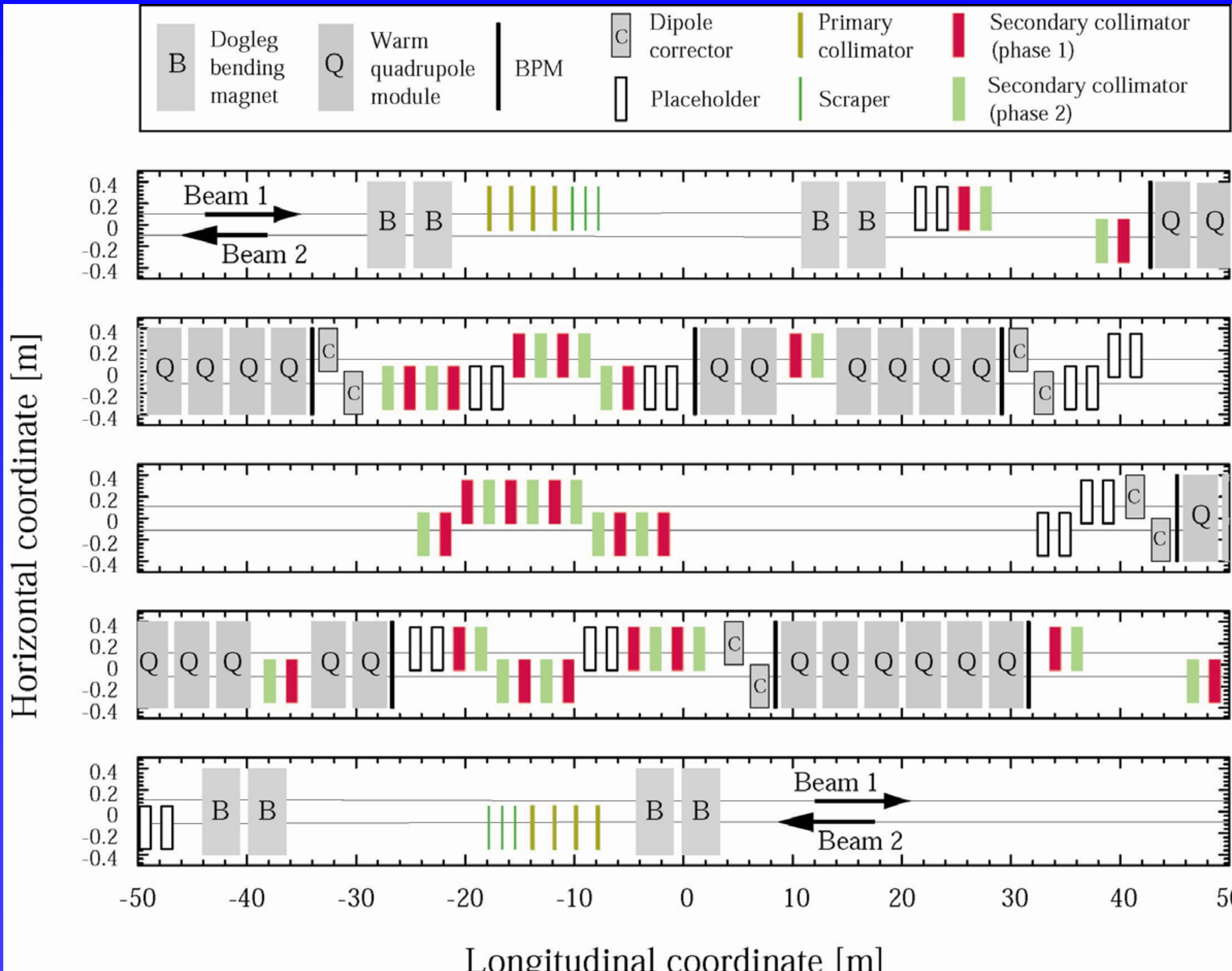




Collimators for Beam Cleaning

- Primary and secondary collimators must be closest elements to the beam → **robust design**.
- Maximum robustness → Low Z jaw material: **Carbon-carbon**.
- Optimizing p-CC interactions → **1 m active jaw length**.
- Maximum robustness → **Impedance limitation**.

New Machine Layout IR7 (V6.5)



Placeholder:

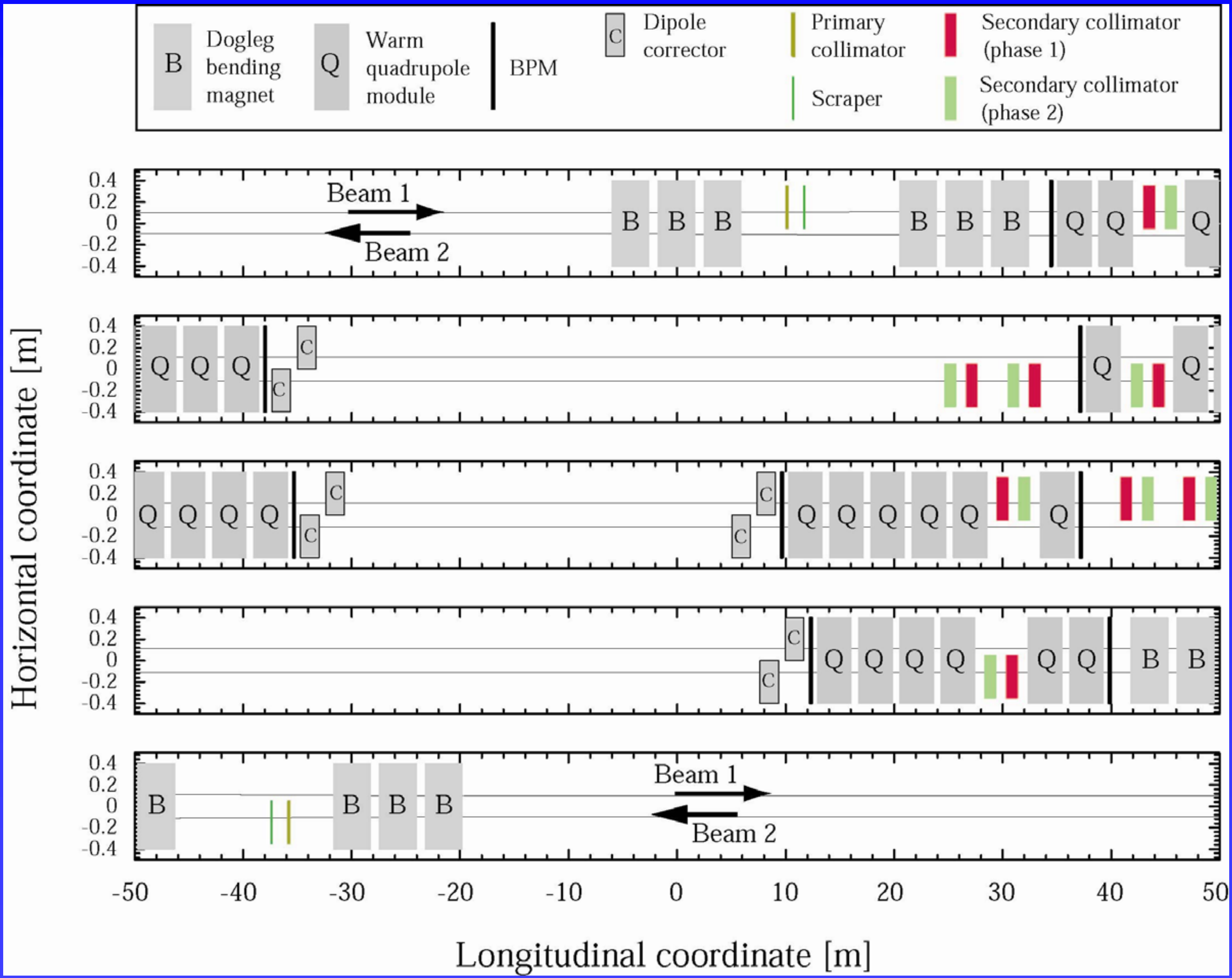
Eliminated collimators. Also called phase 4!

Layout opti-mized for:

- Cleaning.
- Impedance.
- Radiation.
- Integration.
- Aperture.

Phase 2 integrated!

New Machine Layout IR3 (V6.5)

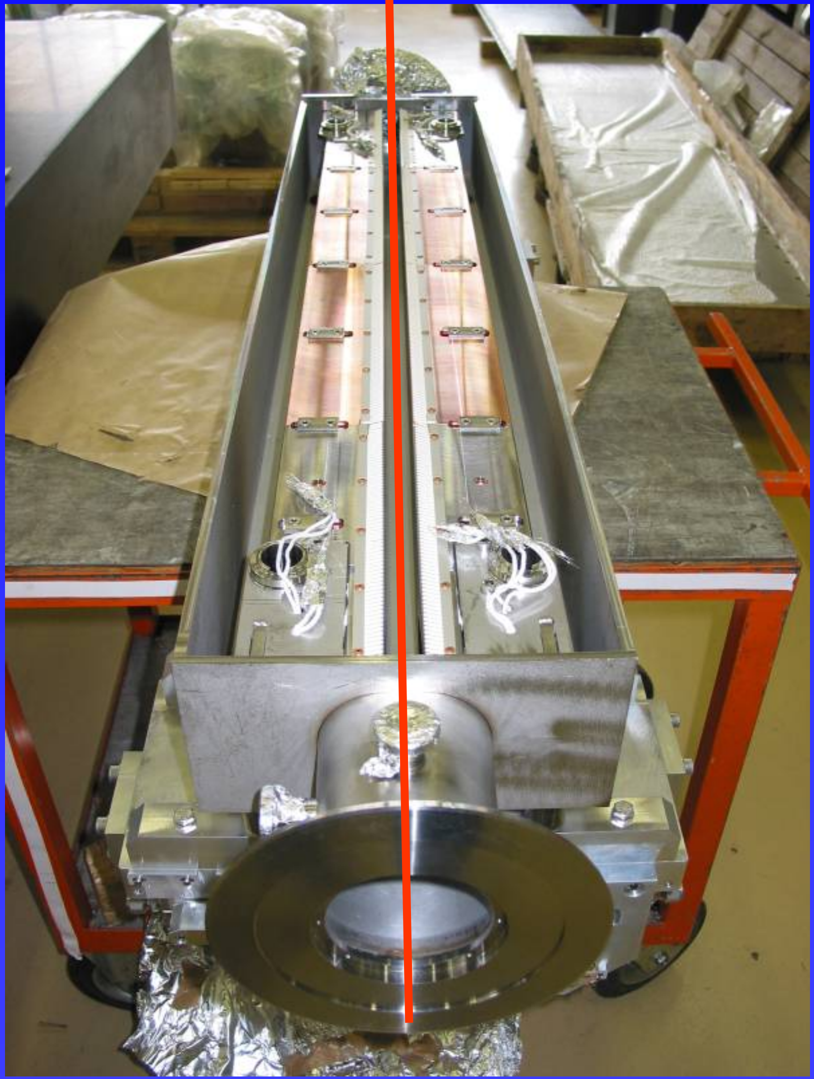


Layout optimized for:

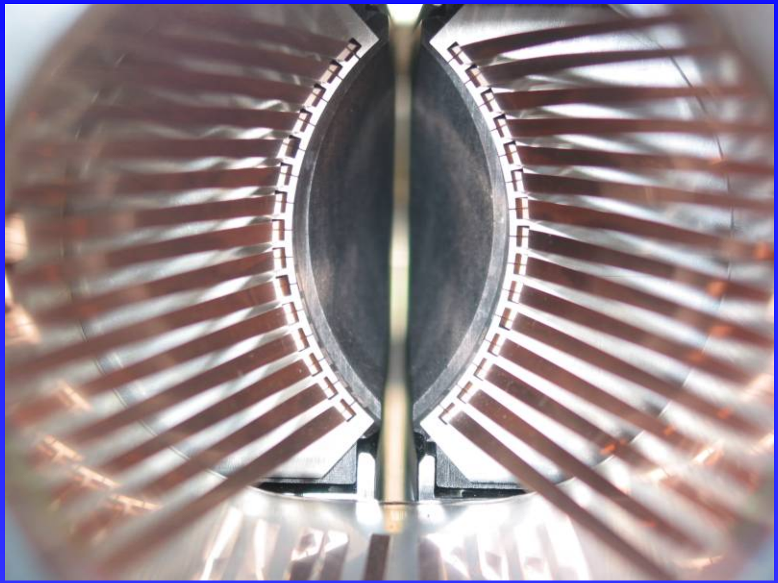
- Cleaning.
- Impedance.
- Radiation.
- Integration.
- Aperture.

Phase 2 integrated!

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

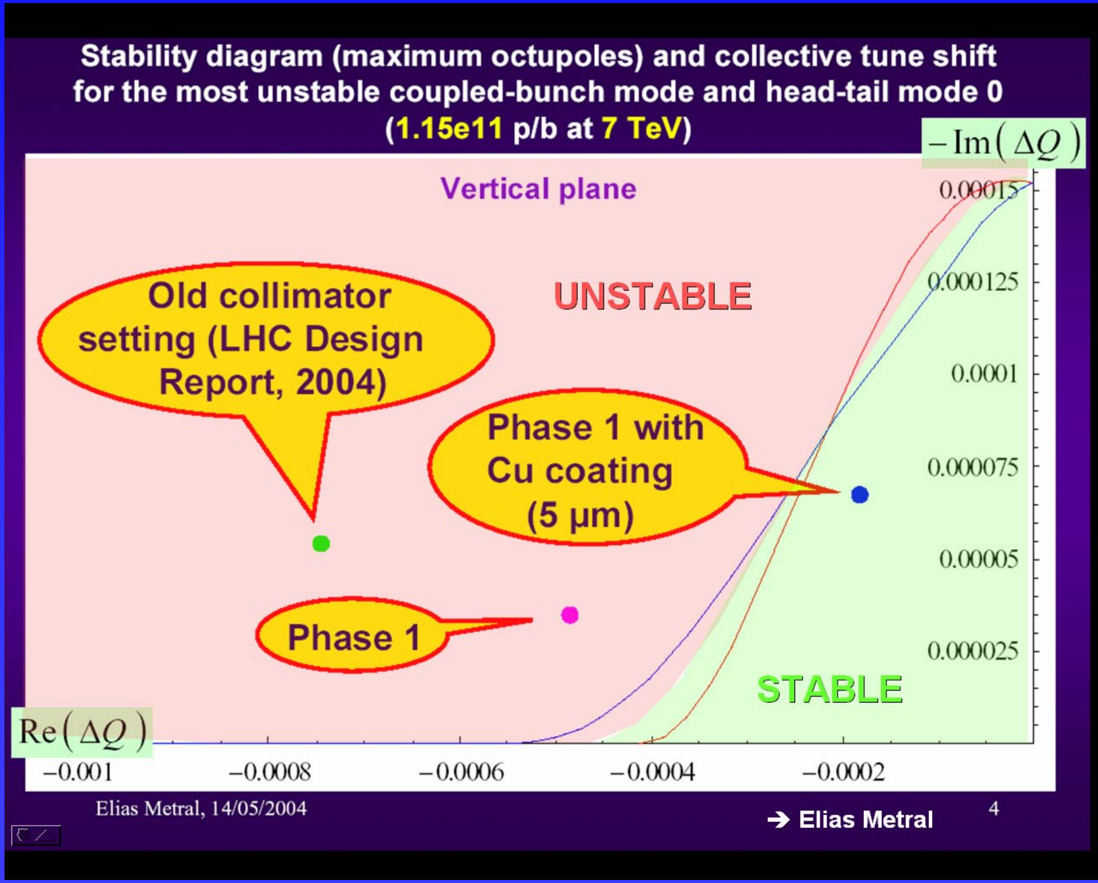
- Acceptable beam loss to **regular machine equipment** and **metallic absorbers**:
  - 1e12 p at injection: 4e-3 of beam
  - 5e9 p at 7 TeV: **2e-5 of beam**
- Acceptable beam loss to **C-C collimators/absorbers**:
  - 3e13 p at injection: 10% of beam
  - 8e11 p at 7 TeV: **3e-3 of beam**

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.

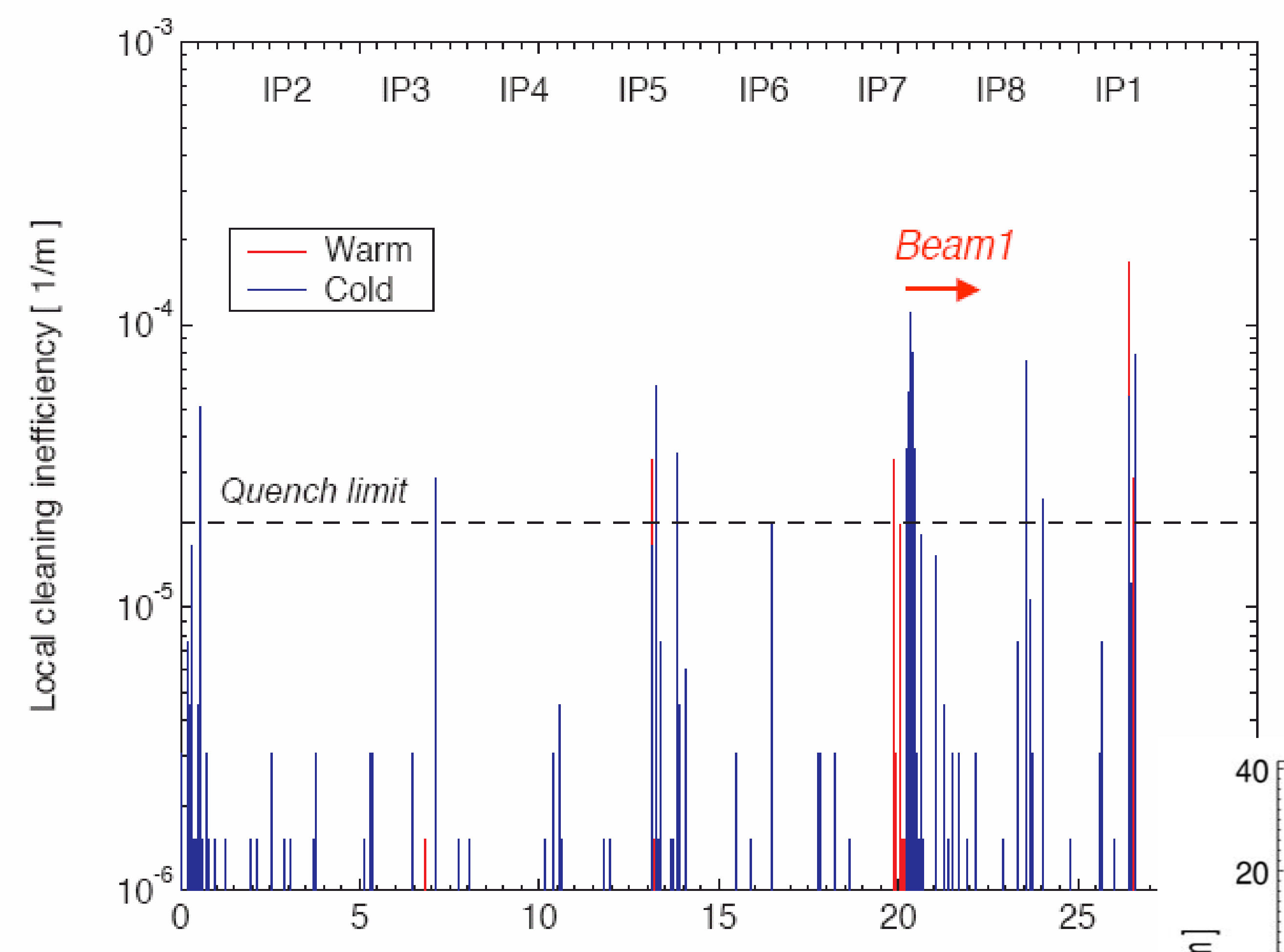
Impedance Limit from IR3/IR7 Collimators

- Increase from collimators (nominal settings) for the imaginary part of the **effective vertical impedance**:
  - 8 kHz:
    factor 3 for injection
    factor 69 for 7 TeV
  - 20 kHz:
    factor 3 for injection
    factor 145 for 7 TeV



- Large increase in impedance must be actively counteracted by transverse feedback and octupoles!
- Phase 2 collimators to overcome impedance and improve efficiency!

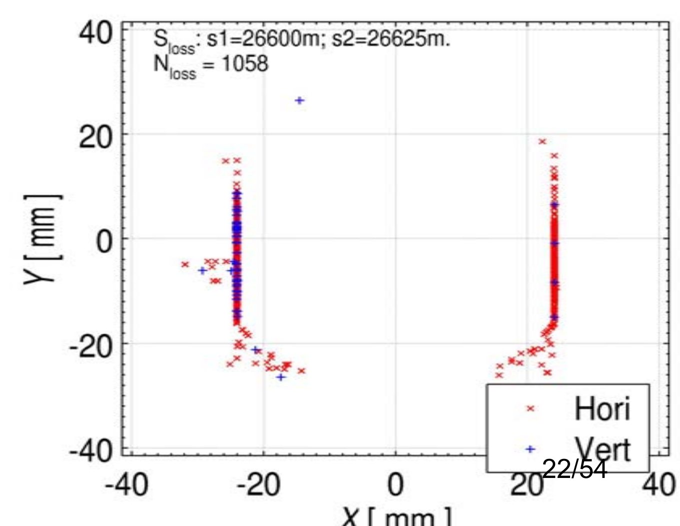
Cleaning Efficiency in IR7



Ideal IR7 cleaning.
Ideal aperture.
0.2h beam lifetime.

Peaks in triplets at 7 TeV:

Cure with tertiary collimators!



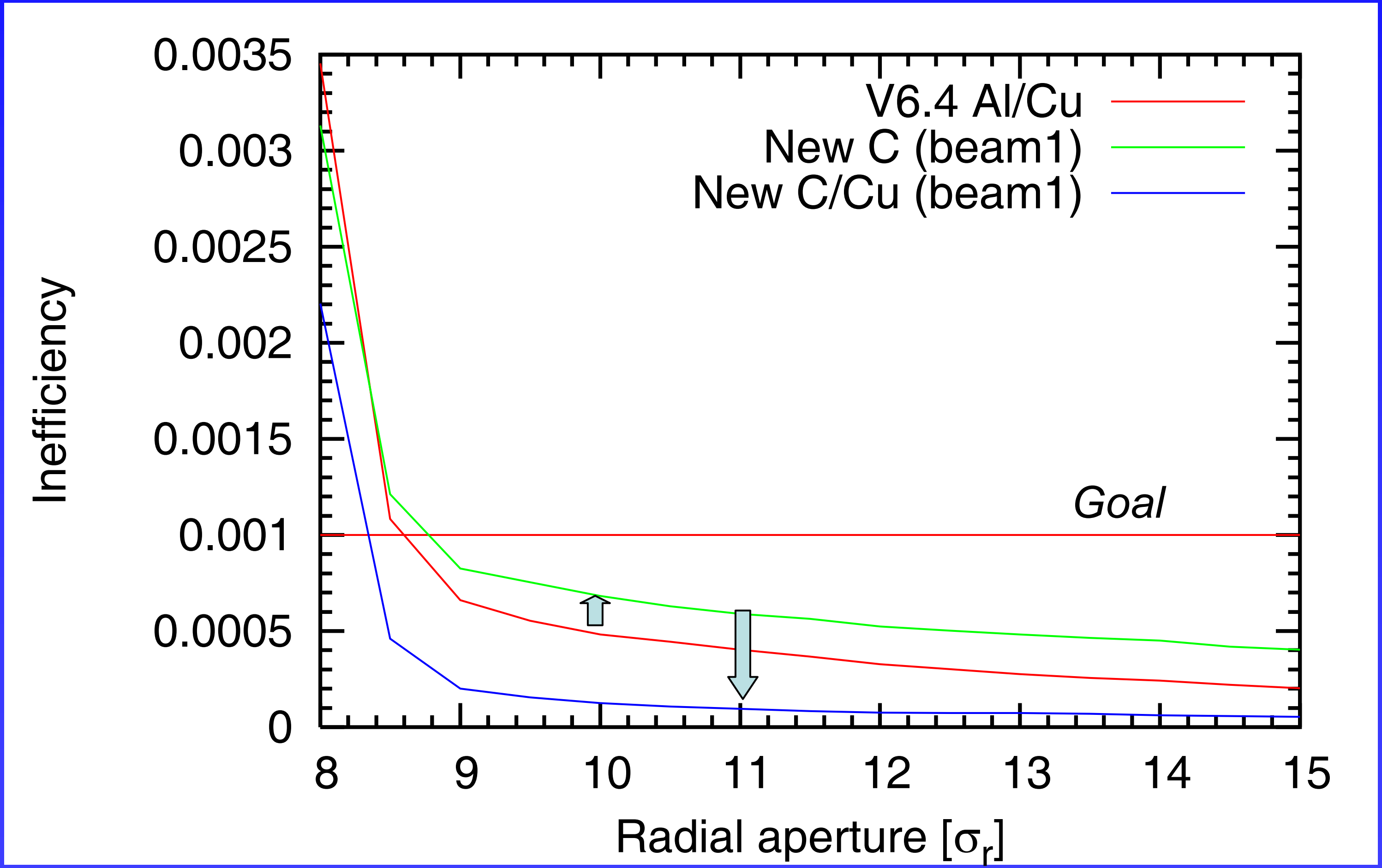
IR8: Nominal optics with β^* = 10 m

7 TeV leakage less than 10^{-4}/m!

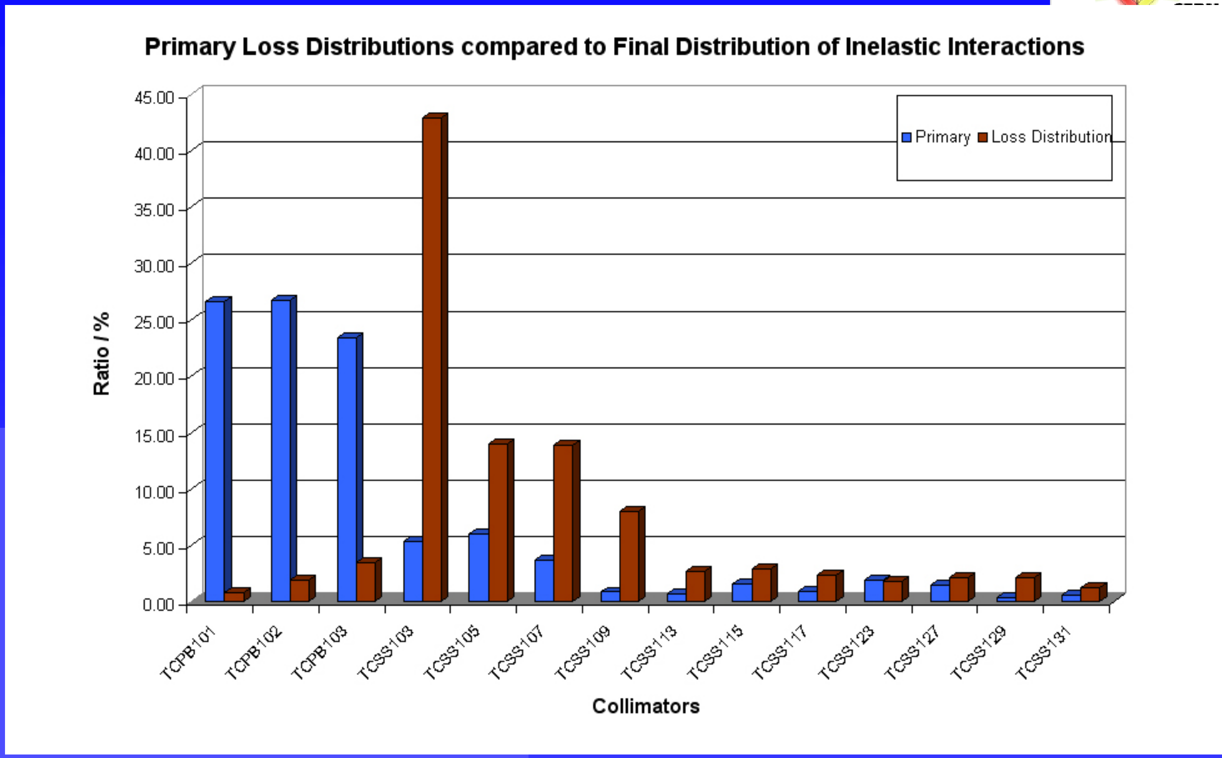
R. Assmann

7 TeV ultimate reach for 6/7σ

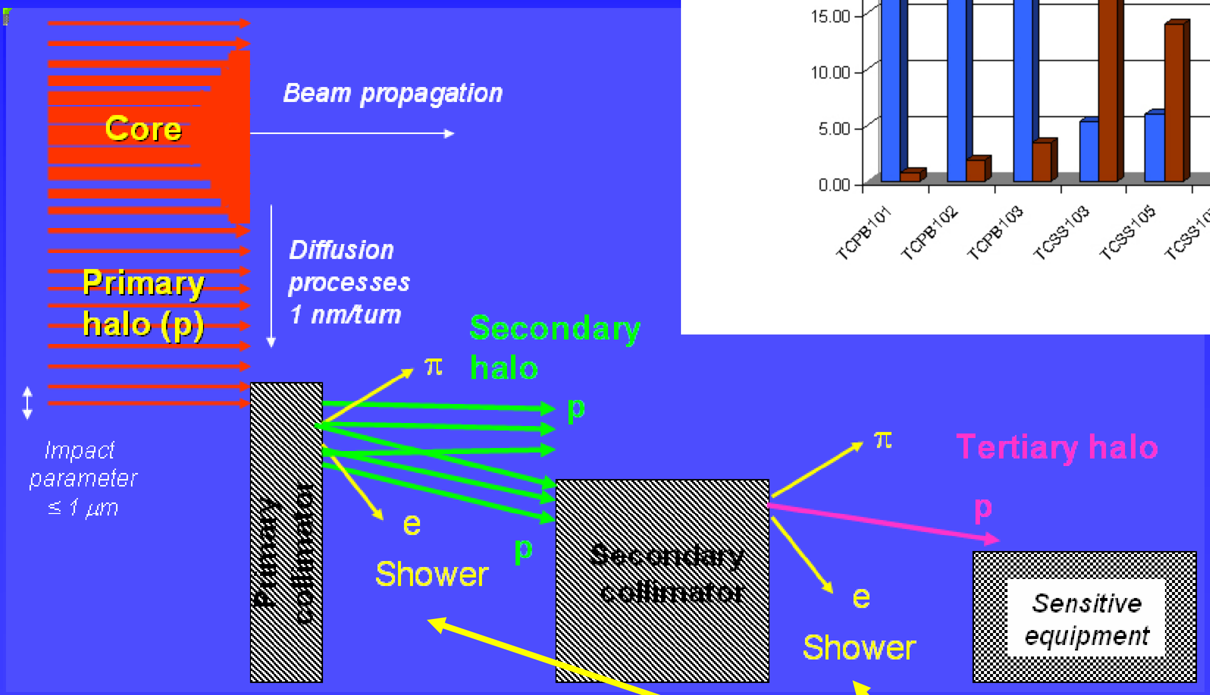
Assuming advanced **1m Cu secondary collimators installed in space for hybrids**: Fixes impedance and gains efficiency (only for stable physics)!



(II) Catching the Cleaning-Induced Showers



M. Brugger et al



Where do the showers go?

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

A. Ferrari, V. Vlachoudis

Example for 1 m long jaws!

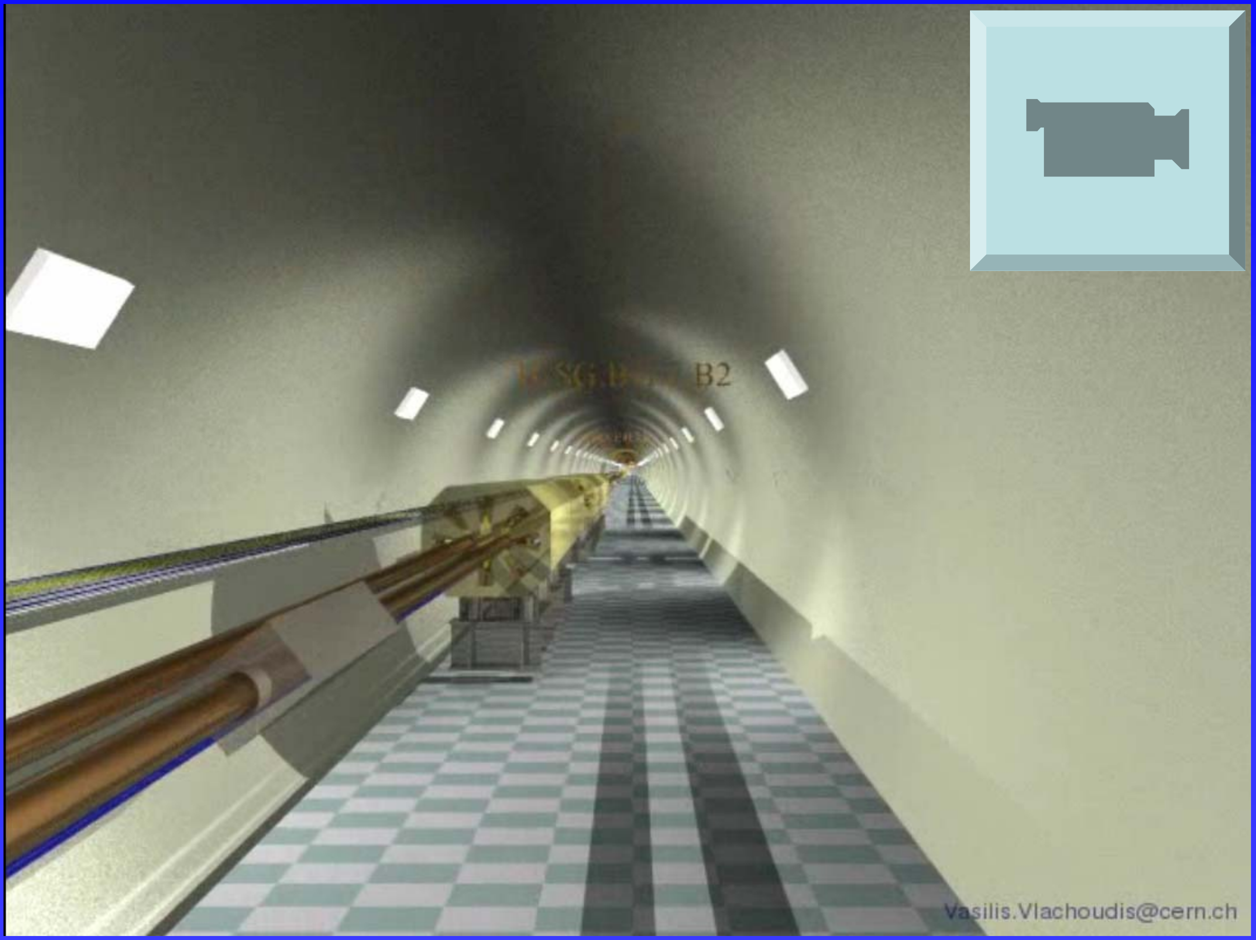
Secondary collimators intercept halo ➔ Shower energy escapes to downstream!

Old Cu design: **34 %** escapes

New CC design: **96 %** escapes

What happens downstream?

The FLUKA Model



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.

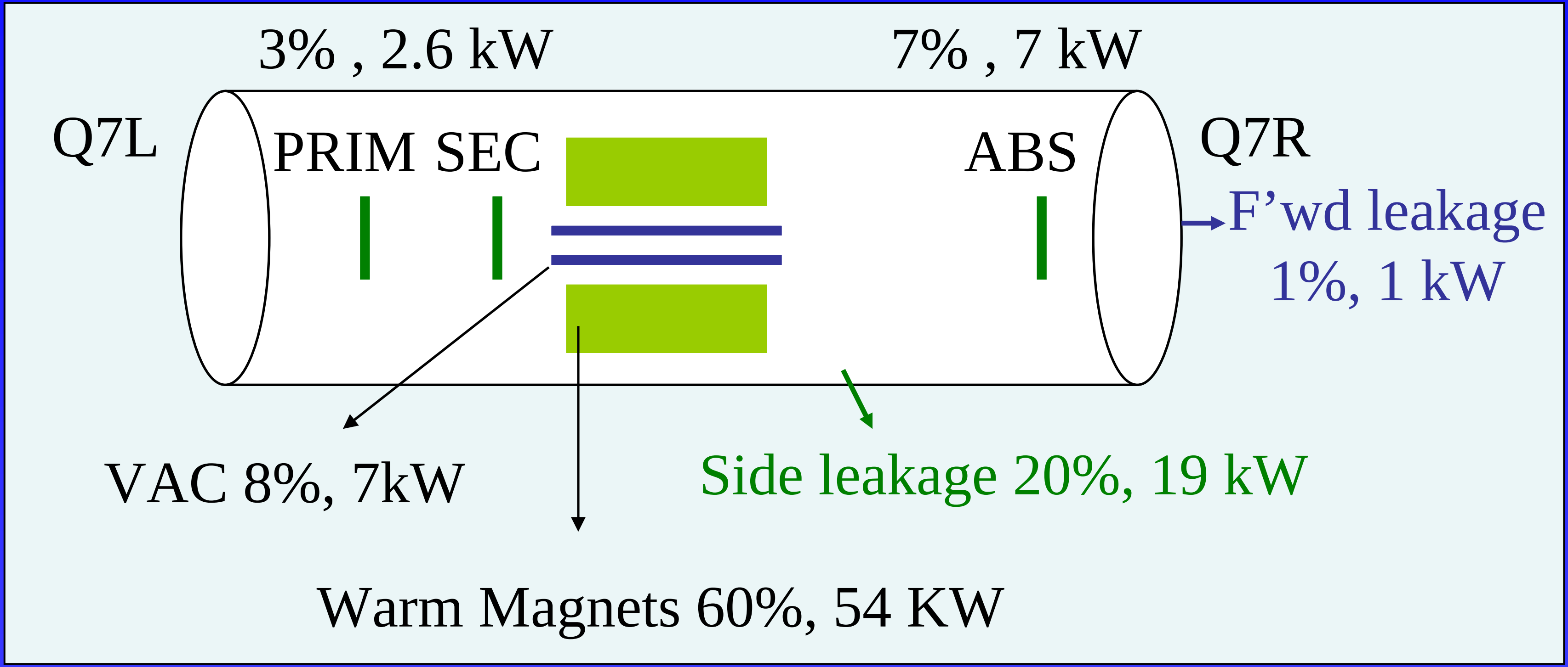
For IR3 (IHEP):

Established STRUCT model.

Detailed simulations started once the collimation layout was essentially fixed.

Momentum Cleaning IR3:

Power flow (τ = 1h , P_{tot} = 90kW)



J.B. Jeanneret, I. Baishev

- Need **active and passive absorbers** to limit load on auxiliary systems
- Consequences for vacuum ...

Lifetime limits at 7TeV
due to quenching of SC magnets

	Local Allowed Lifetime [hours]	
SC magnet	No TCL	4 TCL
MCBCV	150	1.2
Q6	18	0.3
Q7	18	0.2
MB8a	15	1.8
MB8b	36	1.3
Q8	9	2.5

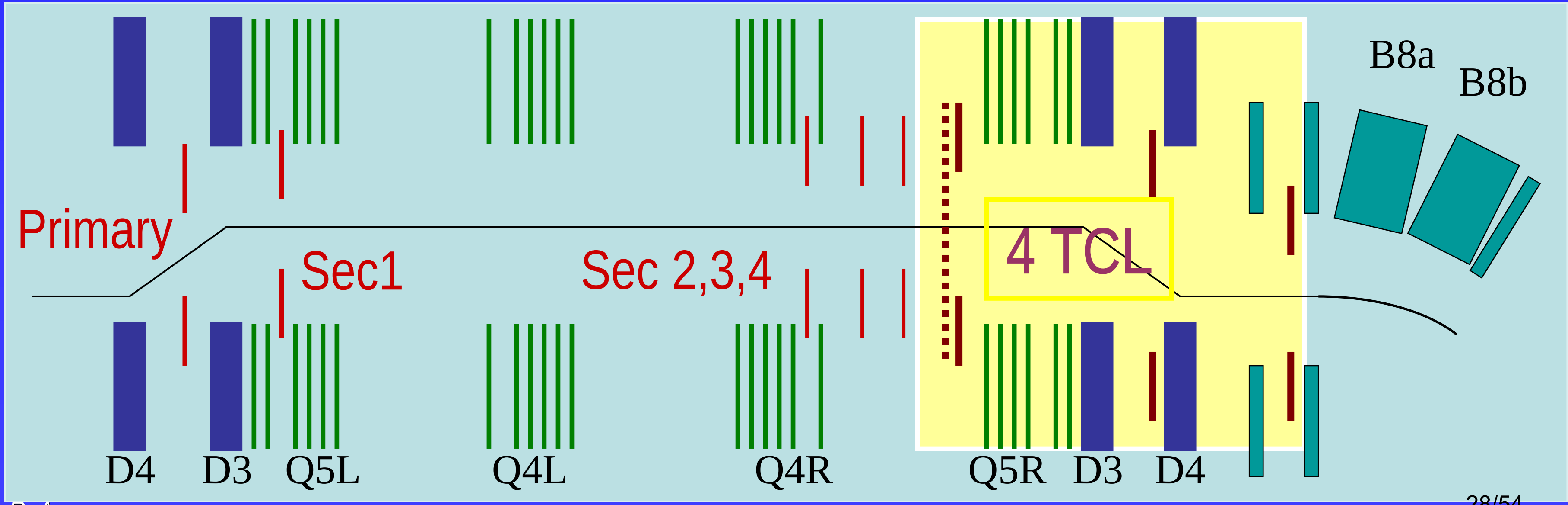
TCL = Active absorbers TCLA

Design goal for nominal intensity: **0.2 h**

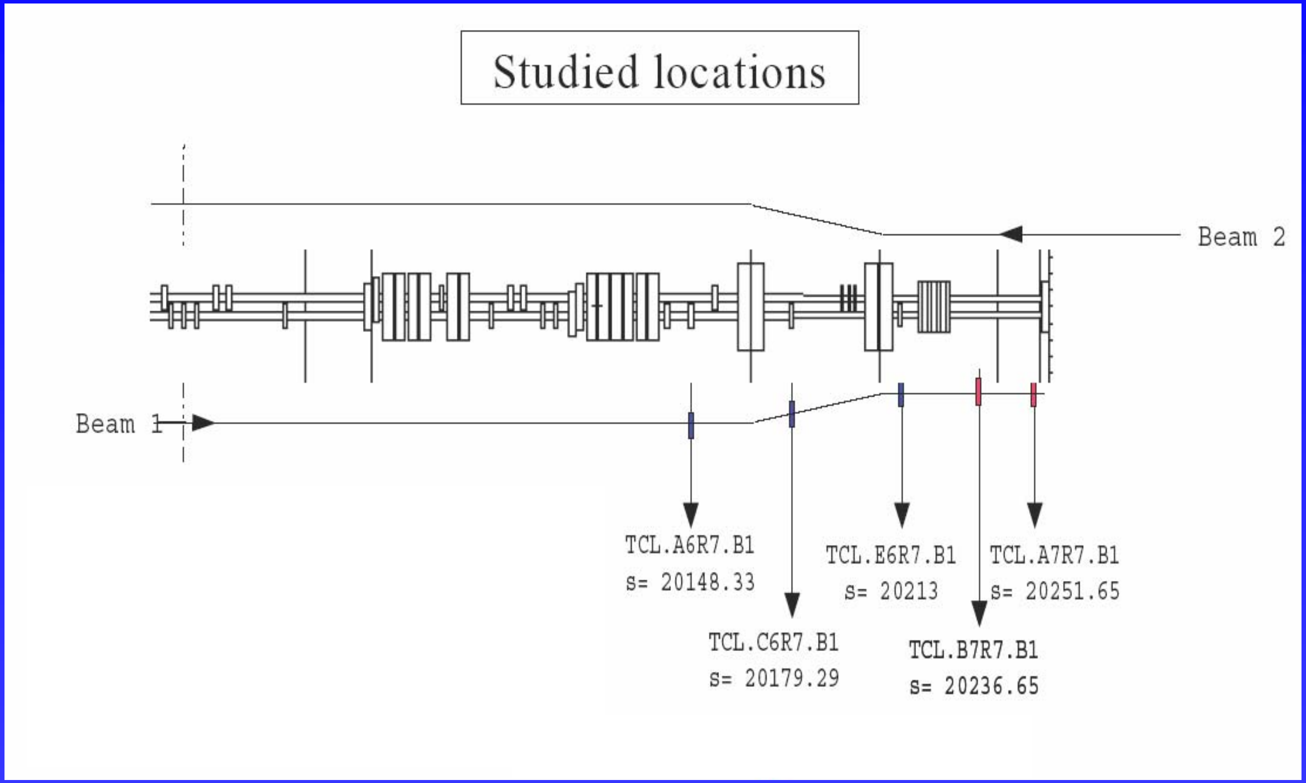
Gain from absorbers: **Factor 60**

Live with **2.5h minimum momentum lifetime** in momentum cleaning.

I. Baishev, J.B. Jeanneret



Betatron Cleaning IR7



Quench limit:

1-5 mW/cm^3

M. Santana et al

Maximum power deposition in super-conducting coils:

330 mW/cm^3 No absorbers	→	9.0 mW/cm^3 3 absorber	→	2.5 mW/cm^3 4 absorber	→	**2.1 mW/cm^3** 5 absorber

Studies are being finalized! Final decision in next weeks!

Active Absorbers

Add 16-18 active absorbers gains:

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

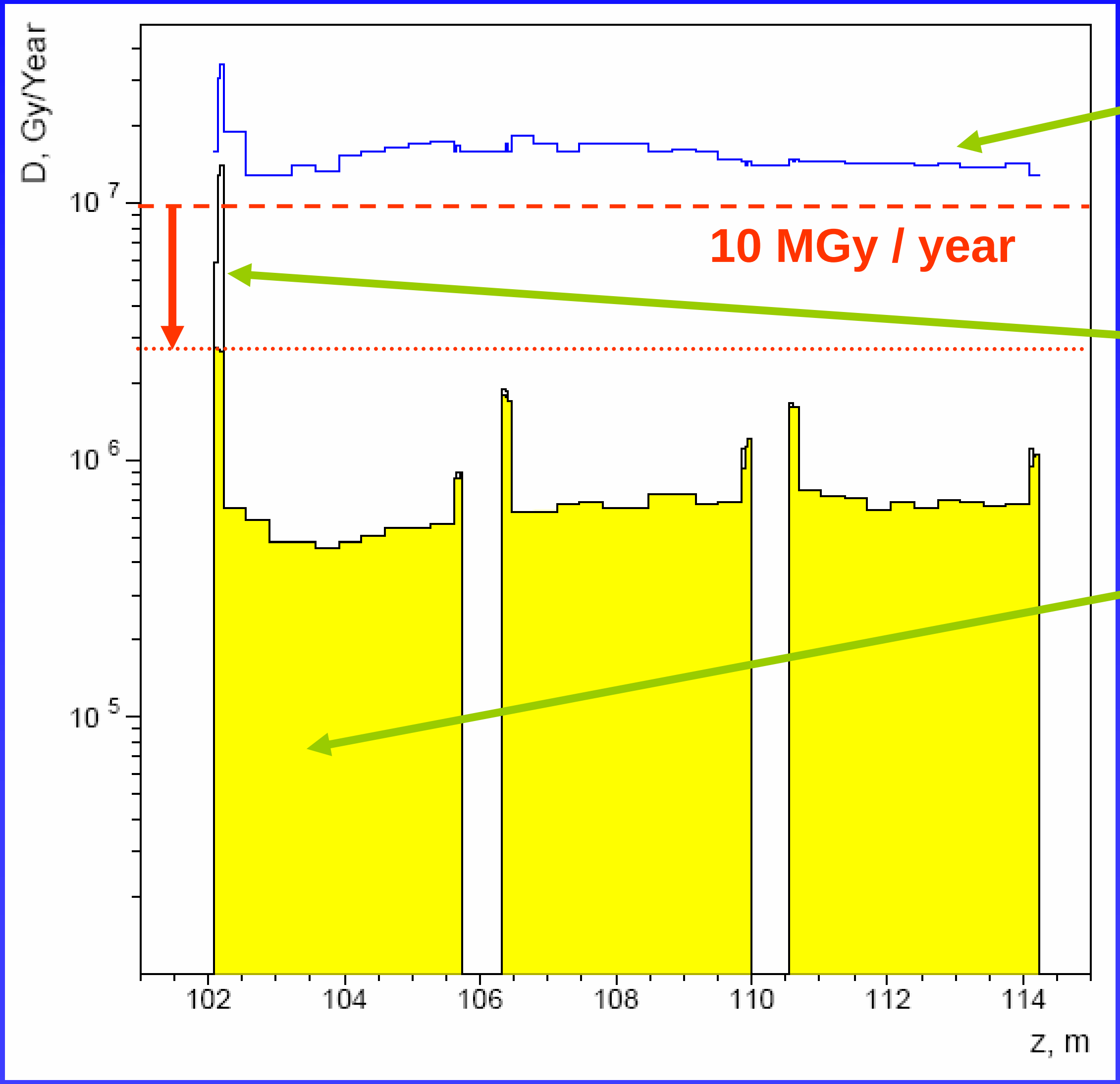
Important addition to the collimation system!

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

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

(III) Protecting the Warm Magnets

IR3: Dose to the D3 magnet



Dose to vacuum pipe

In coils without passive absorber

In coils with passive absorber

Recent worry:

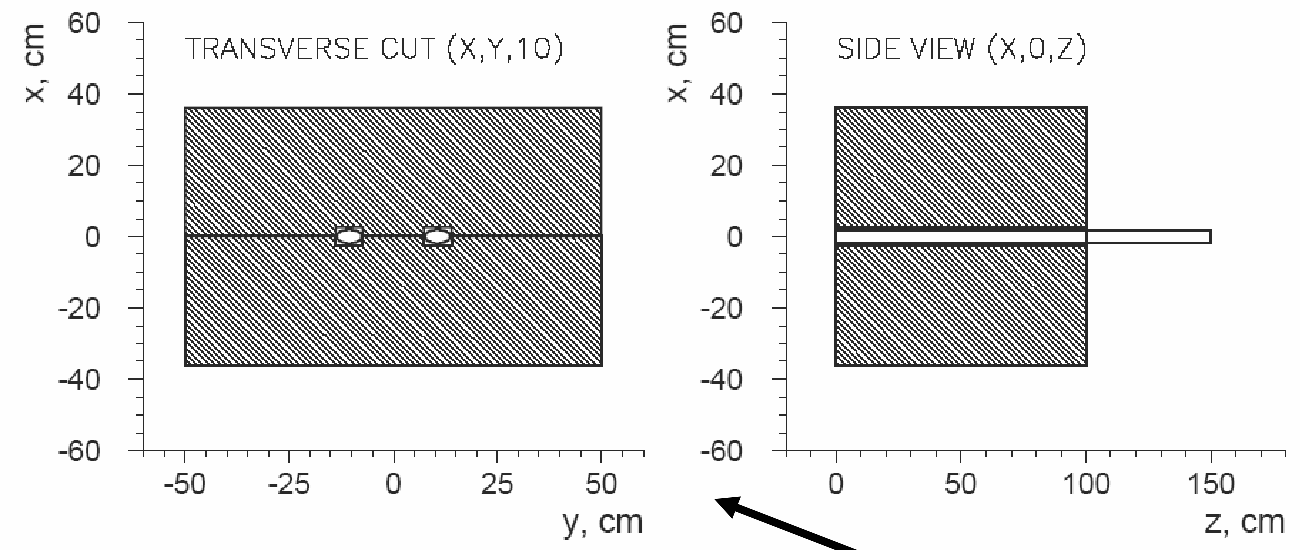
Quench of SC link cable running along IR3 collimators!

➔ Ongoing studies...

R. Assmann

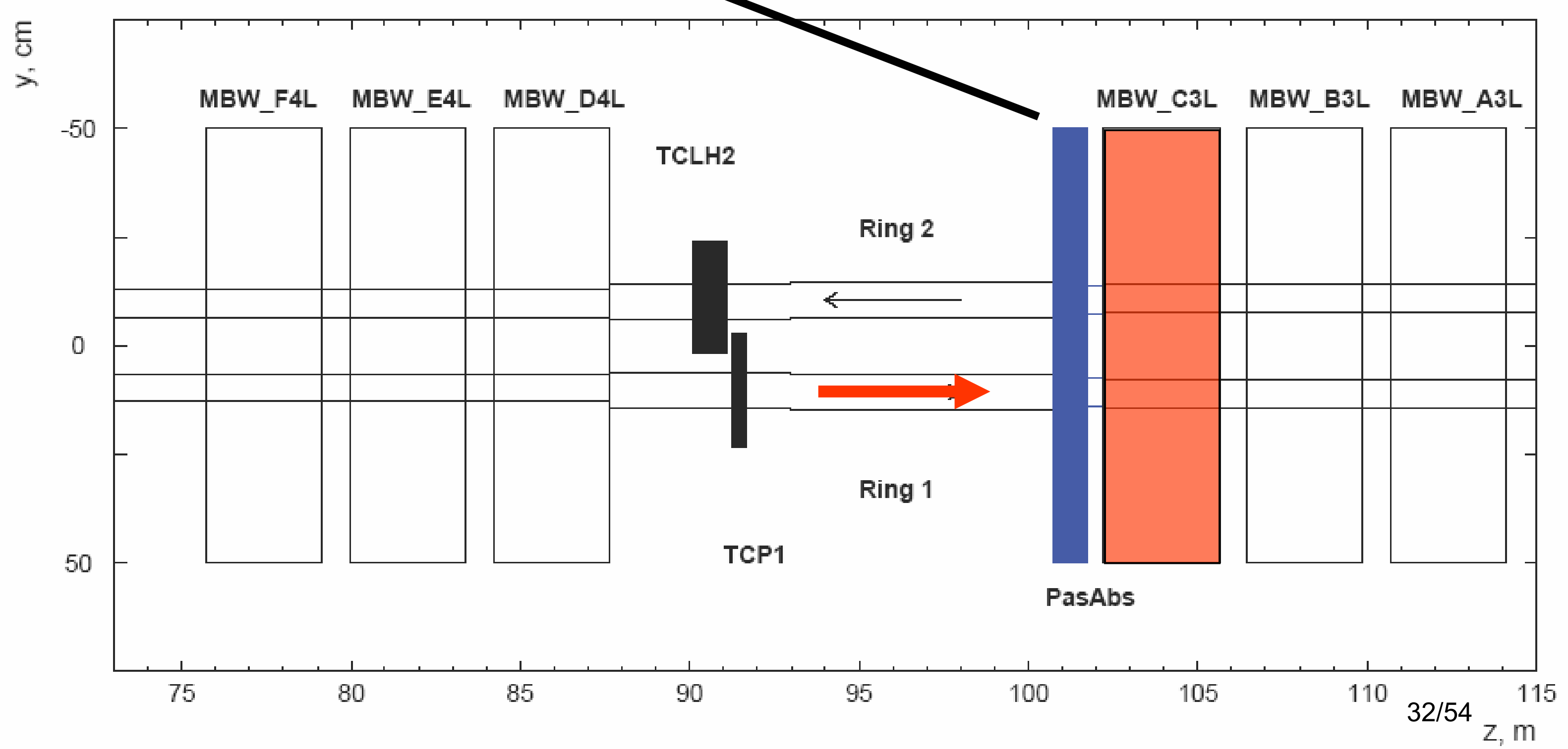
J.B. Jeanneret, I. Baishev

Passive Absorbers



Survival:
3 y → > 10 y

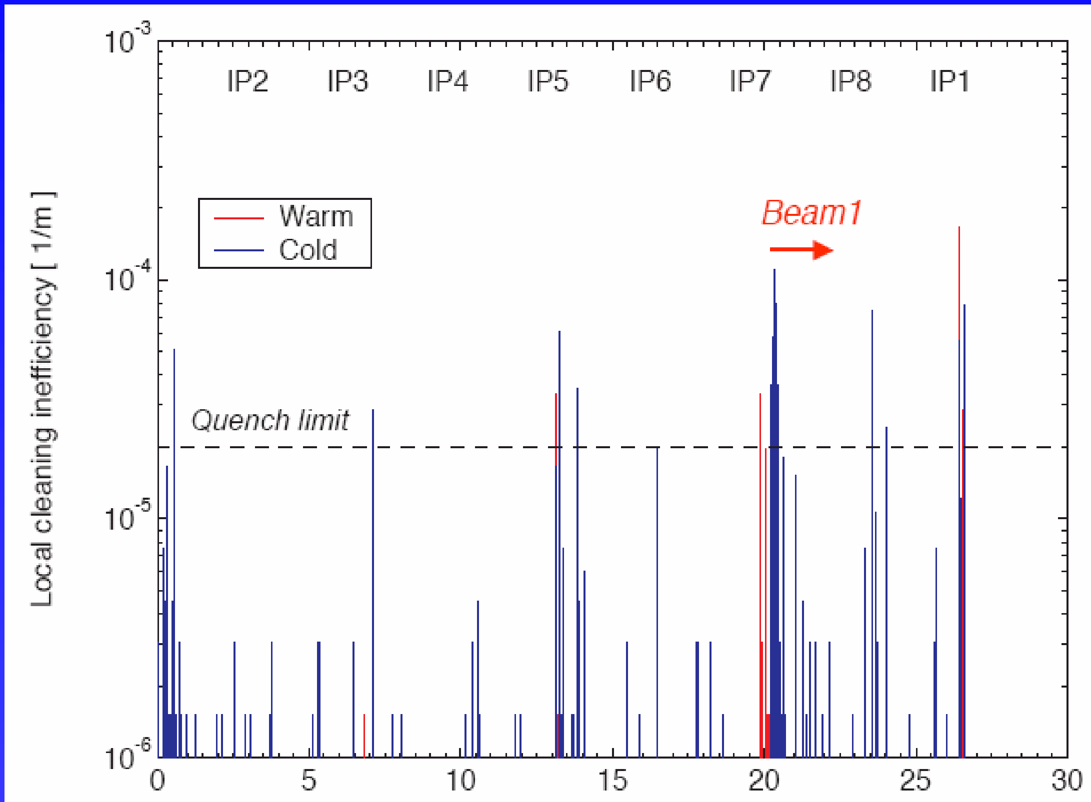
Not yet designed!

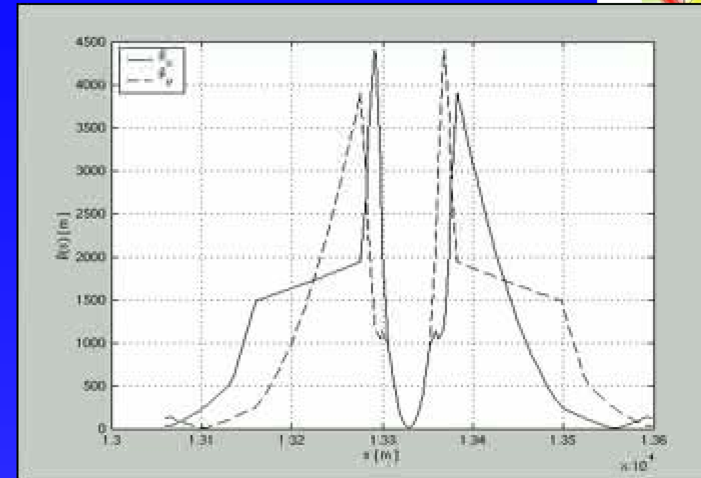


I. Kurochkine

R. Assmann

(IV) Local Cleaning and Protection at Triplets





S. Redaelli, S. Fartoukh

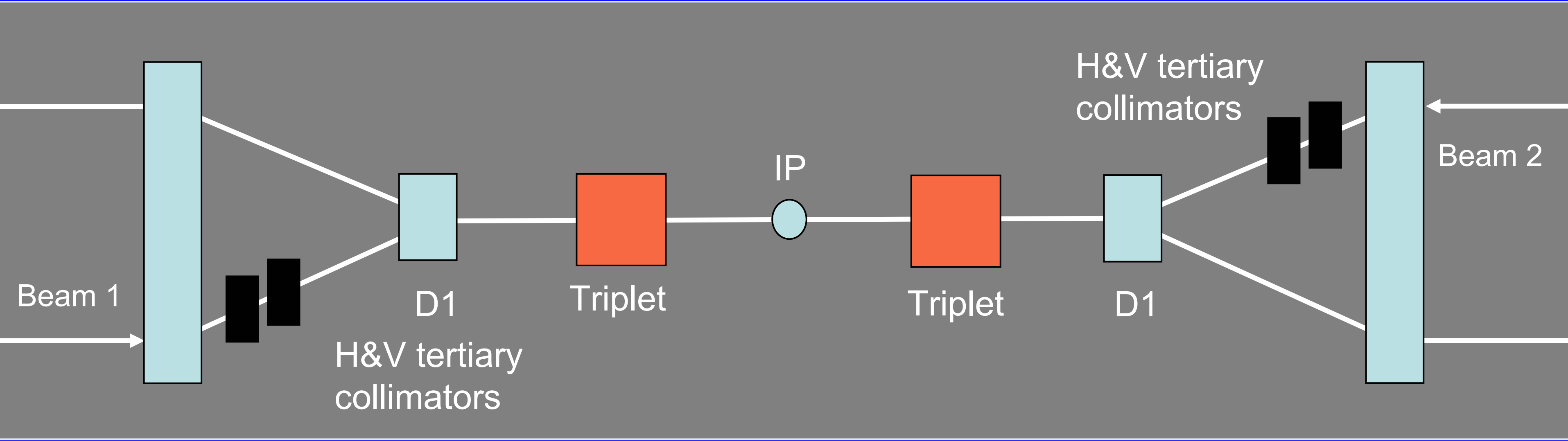
β*: 0.55 m ➔ 17 m (IR1)

Triplets at the LHC experiments become **aperture bottlenecks** at 7 TeV with squeezed optics (increase of β* at the triplets)!

Triplets not protected against incoming beam (**cleaning and machine protection**)!

Add **local protection** (tertiary collimators) to complement cleaning and TCDQ protection!!

Tertiary Collimators



At small β^* we also have small phase advance to triplet!

Shadow against incoming beam halo on triplet aperture!

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

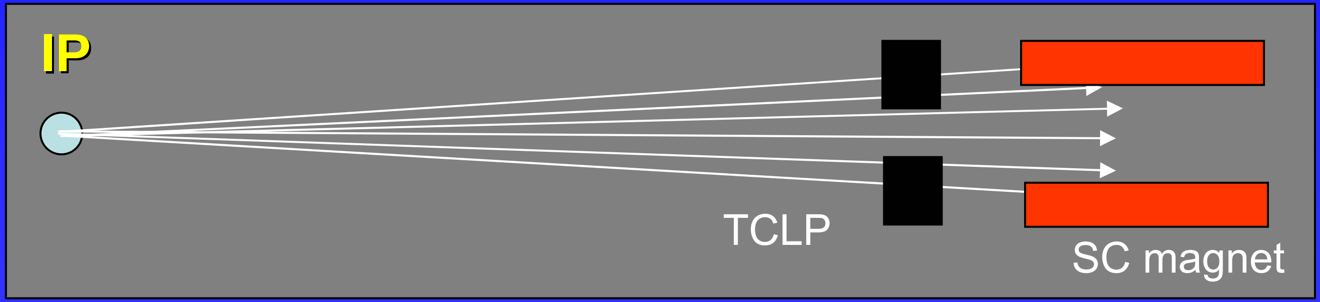
➔ 16 additional collimators (Cu/W jaws)!

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

(V) Catching the p-p Induced Showers

Work for TCLP first done by I. Baishev/J.B. Jeanneret and checked by N. Mokhov:

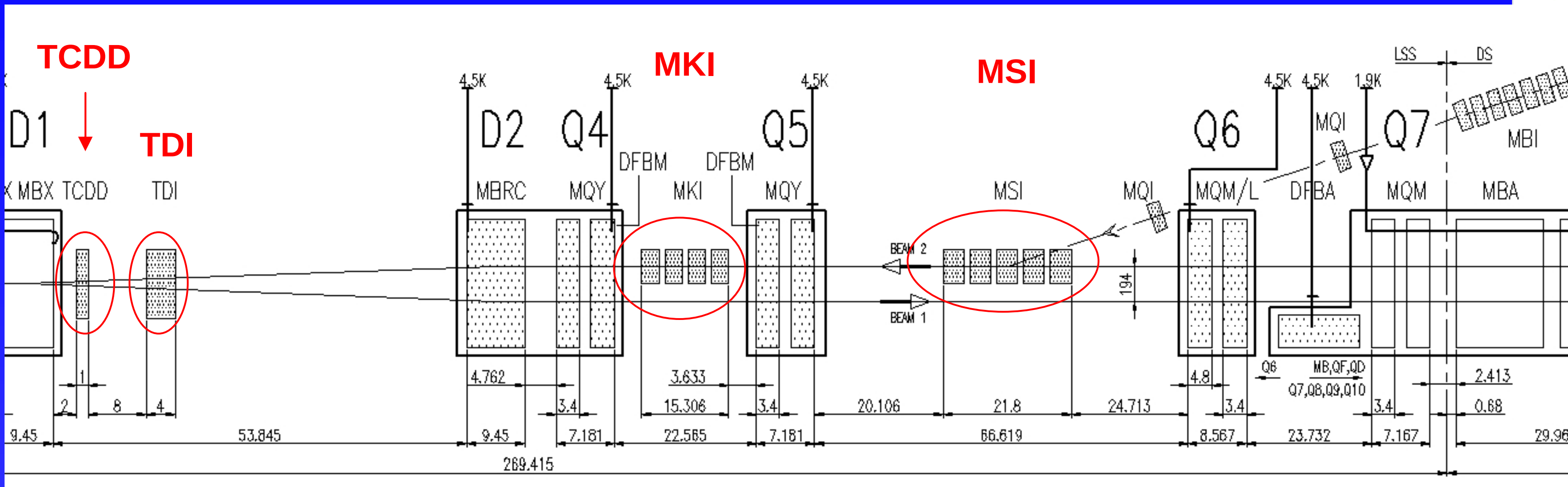
- Showers from p-p interaction in high luminosity points (IR1/IR5) propagate towards outside machine.

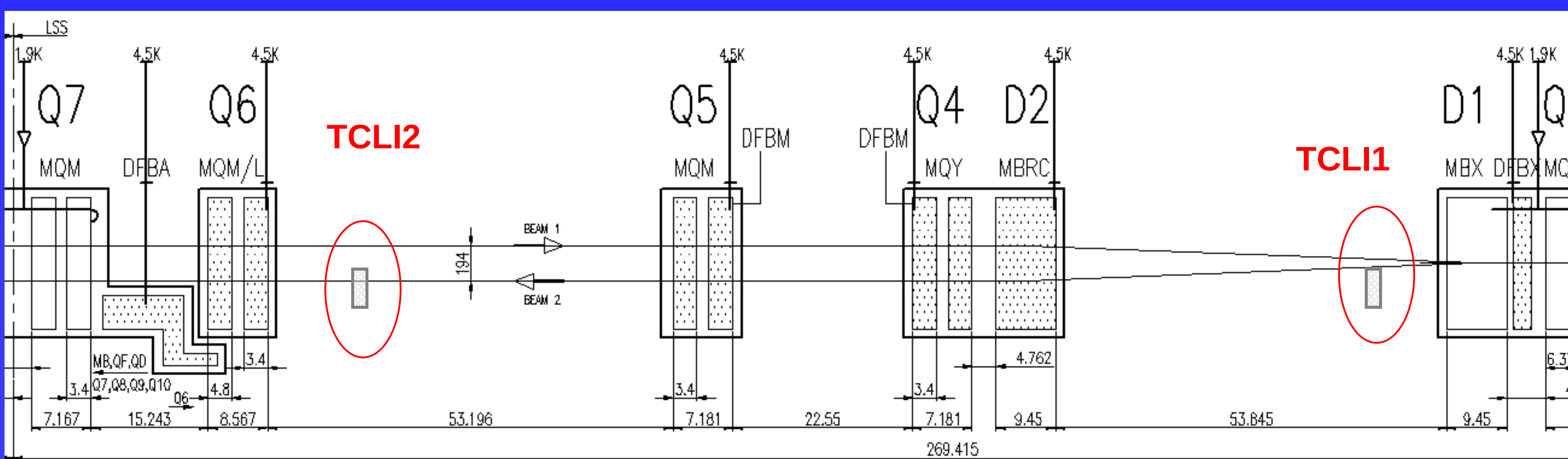


- Showers can quench magnets.
- Absorbers at Q5 and D2 to intercept debris (complement the TAN).
- Quality of absorption can directly limit the luminosity!

No change: In total 8 TCLP's for nominal luminosity!

(VI) Intercepting Mis-Injected Beam





V. Kain, B. Goddard

No change: 4 TCLI's to complement injection protection from TDI!

(VII) Scraping and Halo Diagnostics

- Scrapers are thin, one-sided objects to scrape the beam (beam shaping) and to diagnose the beam halo.
- Scrapers are standard tools in accelerators.
- **Scraping is “dangerous” with the LHC beams!**
- Could use primary collimators for scraping. However, if there is damage then a repair is mandatory (➔ downtime of the LHC).
- Have dedicated scrapers:
  - Horizontal
  - Vertical
  - Momentum
- Scrapers could also include crystals for tests of crystal collimation…

New objects: 3 scrapers per beam

Interim Summary

In course of re-design:

- Some 14 collimators were removed (not efficient).
- Some 34 collimators had to be added for achieving performance goals (factor ~100 improvement was achieved).
- Some 6 scrapers were added as operational tools for beam shaping and halo diagnostics.

Several independent studies support the design decisions, as explained!

Consistency with solutions at other super-conducting colliders (e.g. tertiary collimators at Tevatron).

Example: Injection Settings (in $\sigma_\beta, \delta=0$)

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

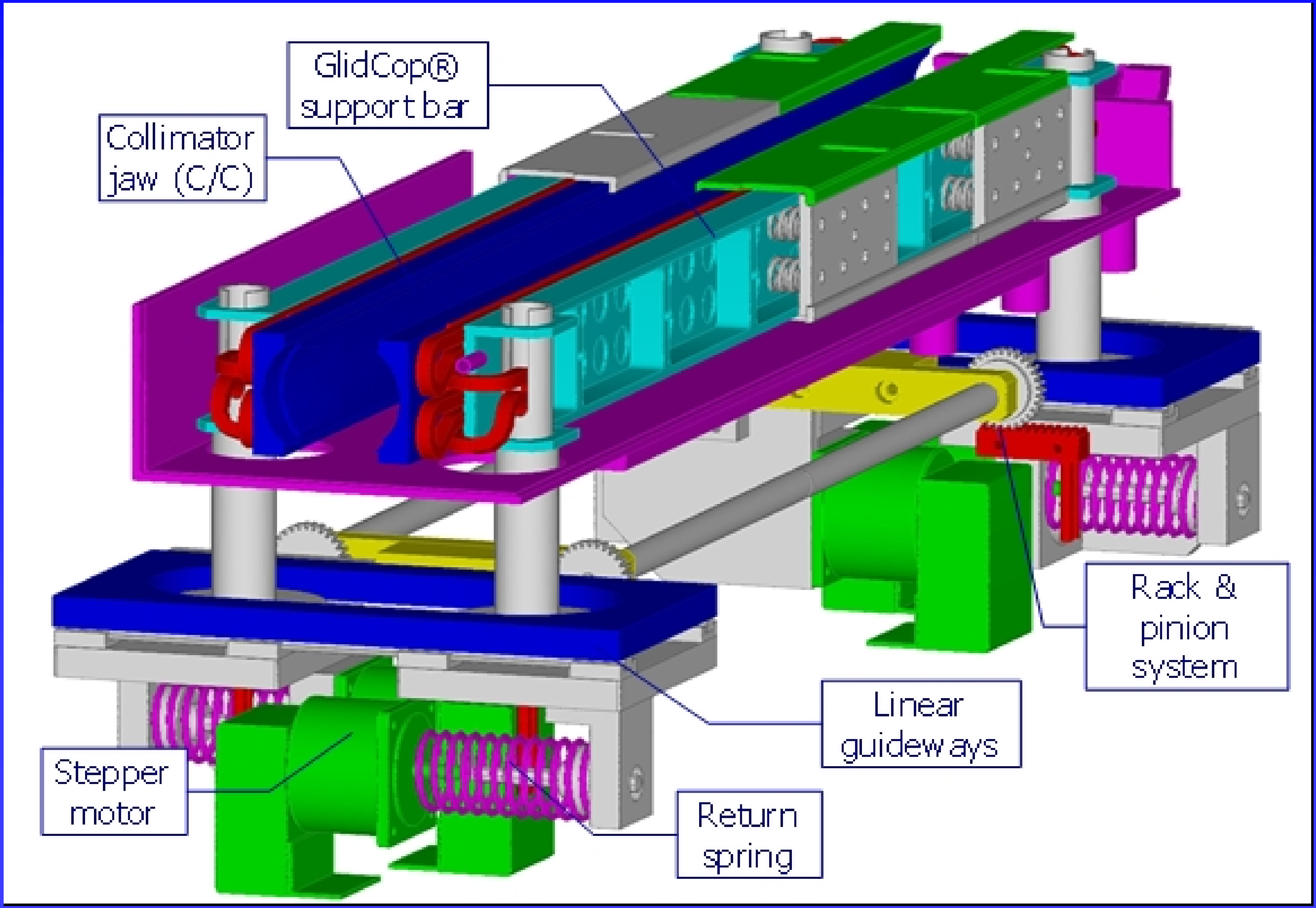
➔ Tight settings below “canonical” 6/7 σ collimation settings!

Tighter for larger beta beat (smaller cold aperture)!

Outline

- Requirements (stored energy, quench limit, cleaning, …)
- The “final” solution for the collimation system
- **The collimator hardware design**
- Other issues
- Conclusion

The Collimator Hardware Design



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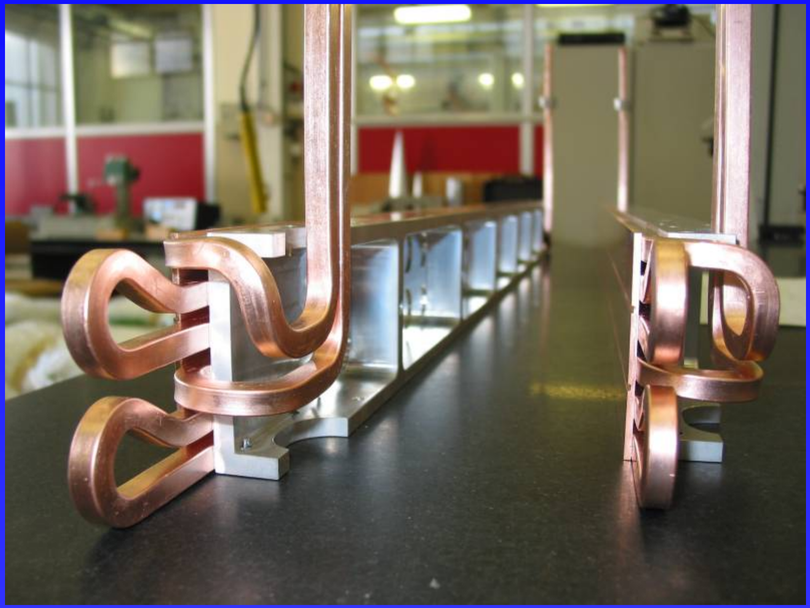
Led by TS department…

Prototyping

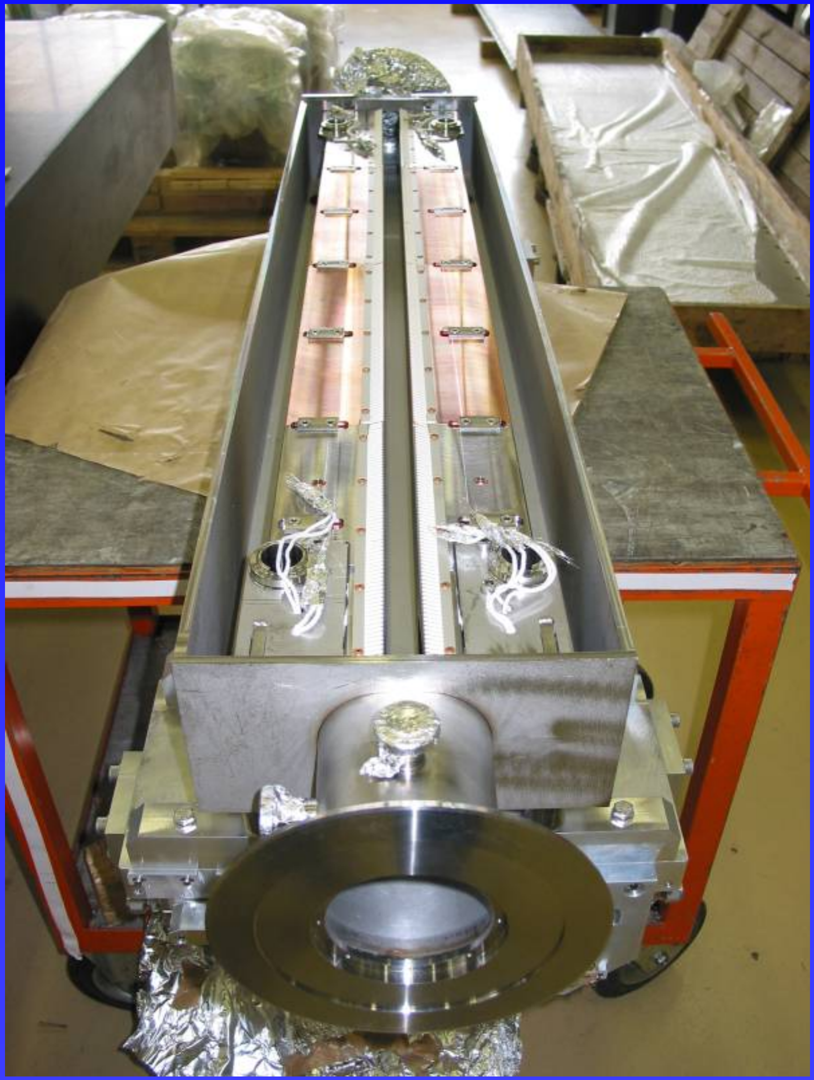
Jaw clamping support with cooling



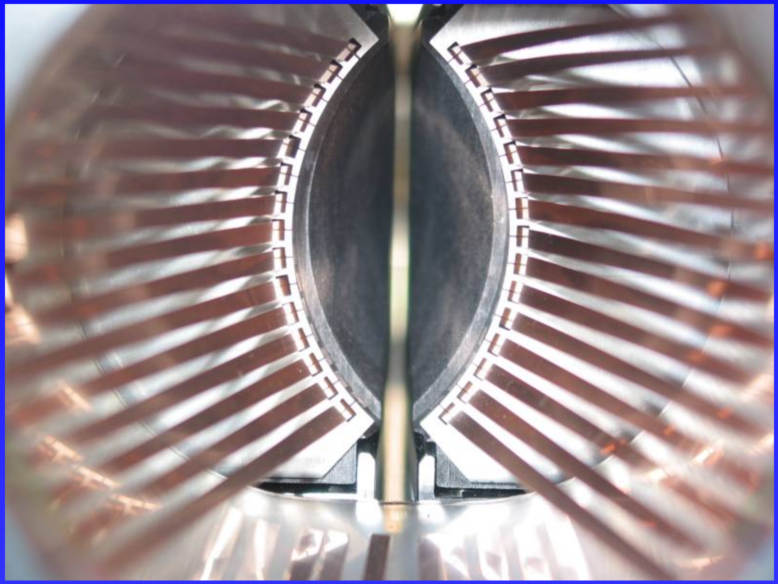
Vacuum tank

Completed jaw

Prototyping



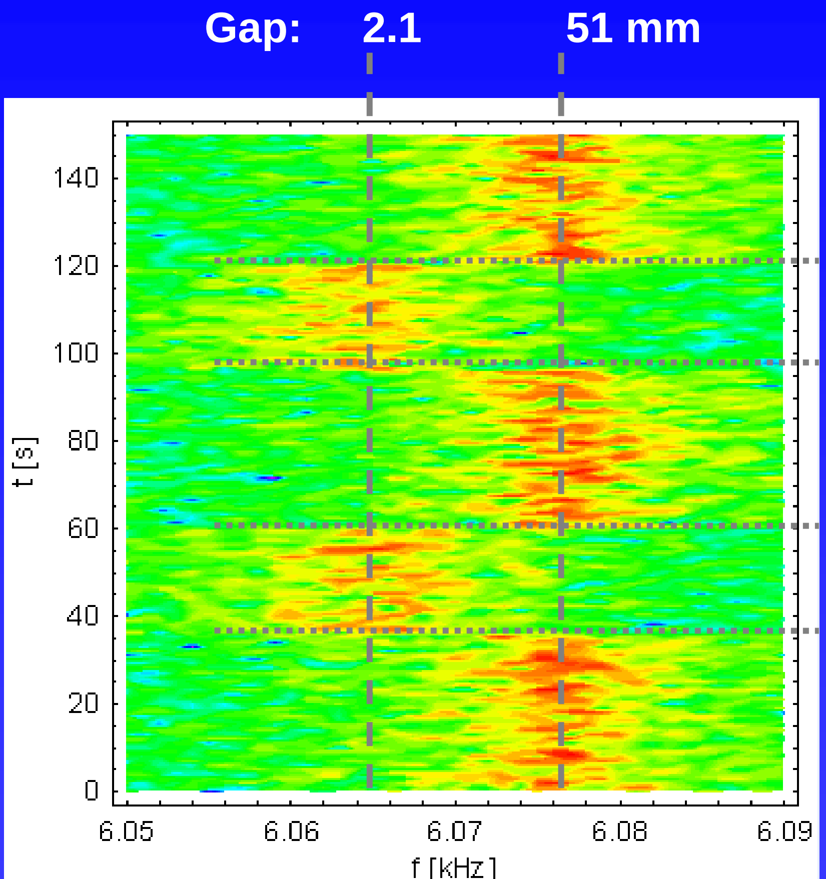
Vacuum tank with two jaws installed



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

Design validated!

Collimator Beam Tests: Impedance & Gap



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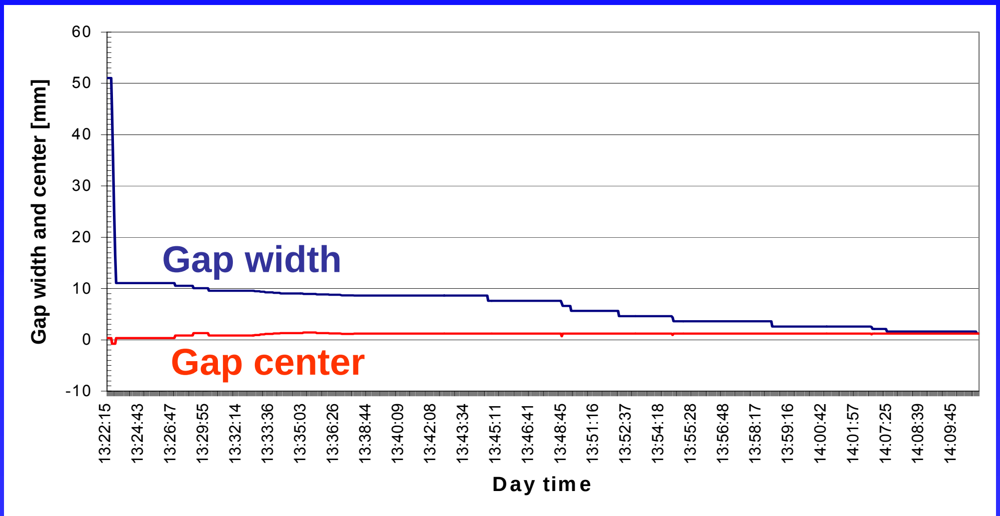


Down to 1 mm gaps with stored beam

➔ **Gaps smaller than required in LHC achieved!**

Beam-based alignment with 50-100 μm accuracy!

Reproducibility: ~ 20 μm

SPS tune depends on collimator gap!

Expected tune change observed within factor 2!

Impedance estimates are strongly confirmed by experiment!

Design validated!

Collimator Beam Tests: Robustness

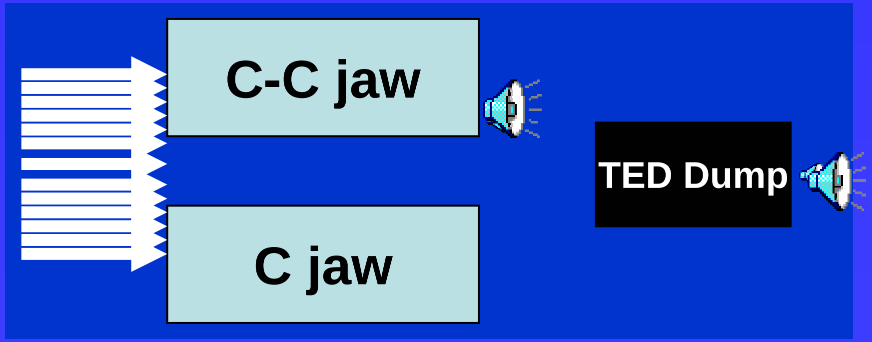
Take:

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!

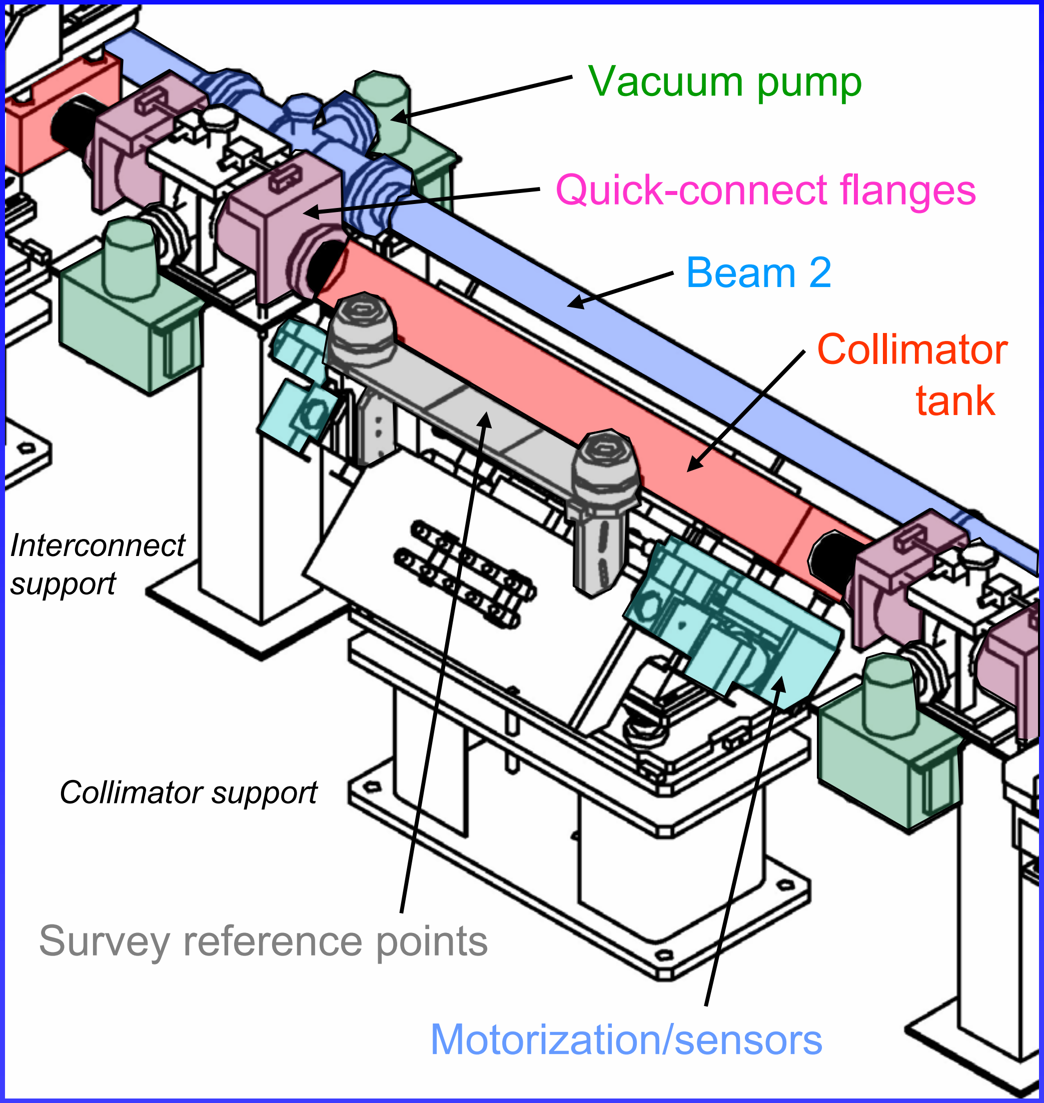


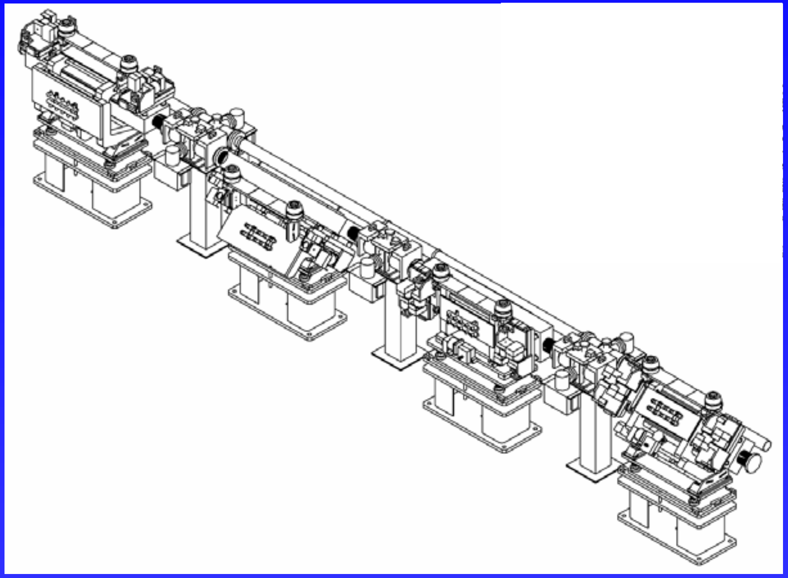

C-C (left) and C (right) jaws after impact

No sign of any damage!

Design validated!

Ongoing: Collimator Supports and Inter-Connects





R. Perret et al

Outline

- Requirements (stored energy, quench limit, cleaning, …)
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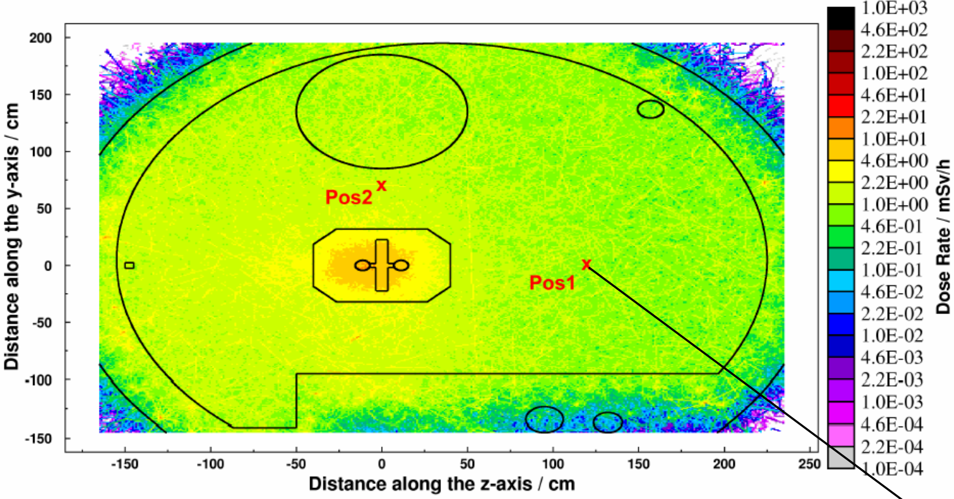
Radiation Optimization

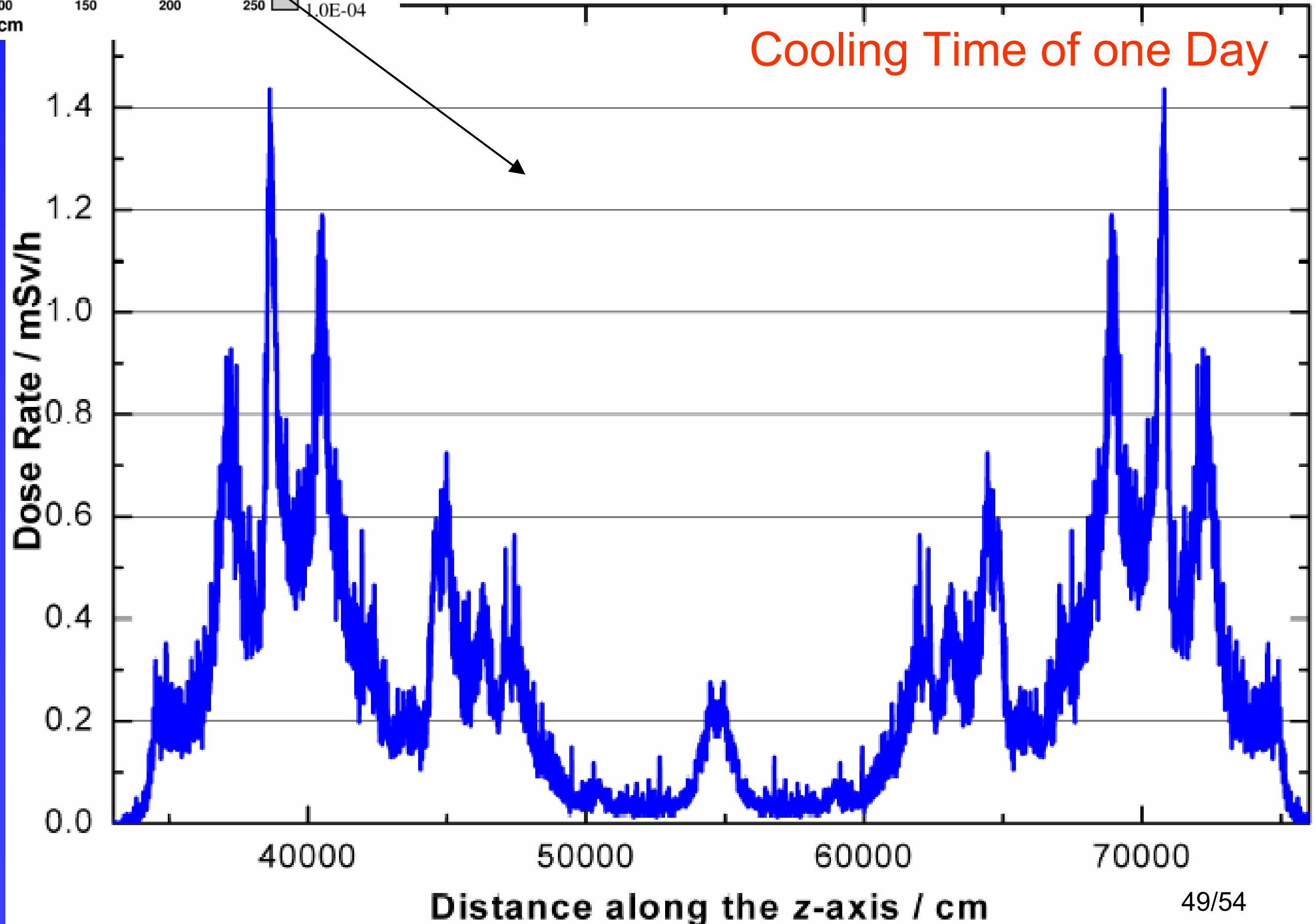
Radiation optimization was a priority in the re-design of the collimation system:

- **Fewer interventions** with better and more robust hardware, e.g. robust collimators, spare surface in collimators, automatic jaw retraction, vacuum interconnects, absorbers for protecting magnets.
- **Intervention points away from hot spots**, e.g. magnets turned such that connectors are on the opposite side from shower impact. Access to SC link cable in IR3 relocated.
- **Faster interventions**, e.g. quick connects for vacuum, electricity, water.

An **infrastructure layout** that is optimized for radiation impact was proposed. Further optimization and final integration is pursued by P. Proudlock and P. Collier through the TCC.

Personnel Dose IR7





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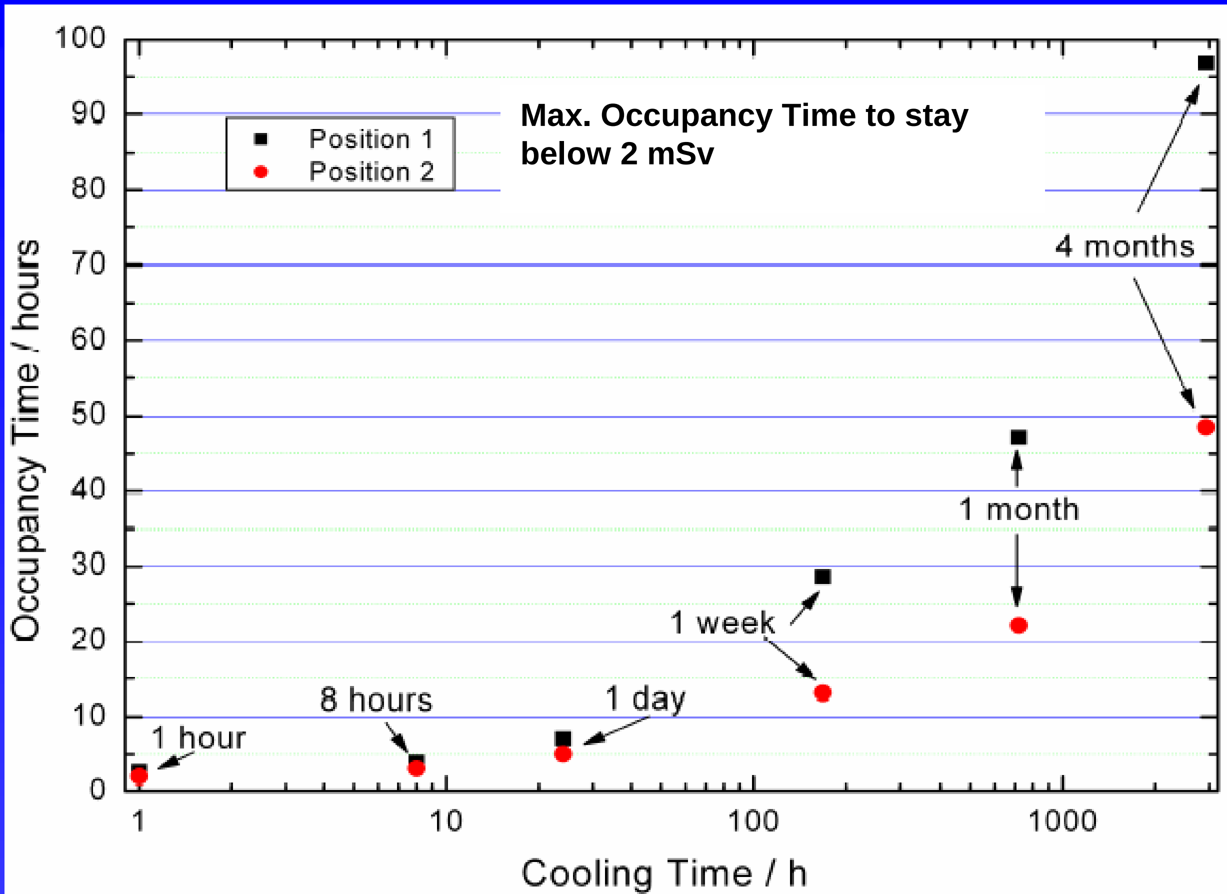

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Collimator exchange in IR7 (simple scenario)							
Actions	**Time required (min)**	**1h**	**8h**	**1d**	**1w**	**1m**	**4m**
Access	4 min	0.03	0.02	0.01	0.003	0.002	0.001
Exchange	1 h	4.7	3.4	2.7	1.6	0.9	0.4
Return	10 min	0.03	0.02	0.01	0.003	0.002	0.001
	Sum	**4.8**	**3.4**	**2.7**	**1.6**	**0.9**	**0.4**

Not Covered in this Talk

Background control for the experiments:

- No request received to have collimators for background control.
- Background will be controlled as a side-product of minimizing particle losses in the SC magnets (quench prevention).
- Tertiary collimators in experimental insertions might be used for background also?
- Background control is outside of the collimation project, but strong concerns have been received in external reviews. Follow-up by TS!

Collimation of ions:

- Will use the same collimators as protons, therefore no separate mentioning.
- Two-stage cleaning does not work for ions.
- Expect intensity limitations.
- No solution so far (the laws of physics are against us).

Transfer line collimation

Conclusion

A very **busy 2 ½ years** are behind us:

- Inside the collimation project we have established **132 collimator locations** in the two rings.
- **~95% are frozen**, ~5% are still being reviewed. Decision in next weeks.
- Cleaning **insertion layout was optimized** for aperture, impedance and cleaning!
- The **robustness** of the LHC main collimators was **improved by a factor 100**, validated with prototyping and beam test.
- Other key features of the collimators were validated with beam (small gaps, impedance, cooling, …).
- Some 14 collimators were removed.
- Some 40 additional collimators must be used to **gain a factor 100 in cleaning**.
- Radiation optimization was performed to **prevent excessive dose to personnel**.

For the first time we have a collimation system that (more or less) works on paper for the LHC beam intensities, taking into account all known issues!

LHC requirements are very tough: The excellent performance predicted is still tight!

What now?

- Three out of the five collimator designs are ready for series production! Others must be ready by the end of 2005! **Series production for 125** phase 1, phase 3 and spare collimators is on its way (FC next week)!

We are on schedule for beam commissioning in 2007!

- Hope to achieve **50% of nominal intensity**. Simulations with all ring collimators has just been set up → predict overall performance soon!
- **Phase 2 collimator locations** are fully integrated into the collimation system for a collimation upgrade: Less impedance and better cleaning efficiency!?
- R&D on various design directions at CERN (to be started) and US-LARP.
- Beam tests for phase 2 in 2008, production in 2008/9, **installation in 2010**.

The path to nominal beam intensities is prepared through a well-defined upgrade path!

Further design work: Supports, other designs, motorization, sensors, electronics, **controls**, preparation of operation, phase 2

Big work load 2005/2006: Production, tests and installation!

Thank you for your attention!