The LHC Collimation Project

Implementation of a Phased Approach

R. Assmann

Accelerator & Beams Department, CERN

External Review of the LHC Collimation Project

June 30th - July 2nd 2004

Outline

- **Introduction to collimation in the LHC**
- The LHC Collimation Project
- The phased approach
- Phase 1 collimation: Performance and collimator design
- Conclusion

Introduction

Collimation has become a **major design issue** in building new accelerators and making them work.

Why this? **better performance = higher intensities**

Traditionally: *Control the beam core (low ε, small β^*, good stability) to maximize luminosity!*

Keep beam tails from experiments (background).

New high intensity machines: **High intensity in core and halo!**

Halo/tails become “dangerous” for the machine:

→ **Quenches – Activation – Heating – Damage**

Active and growing community interested in halo and collimation! Very critical for making the LHC a success!

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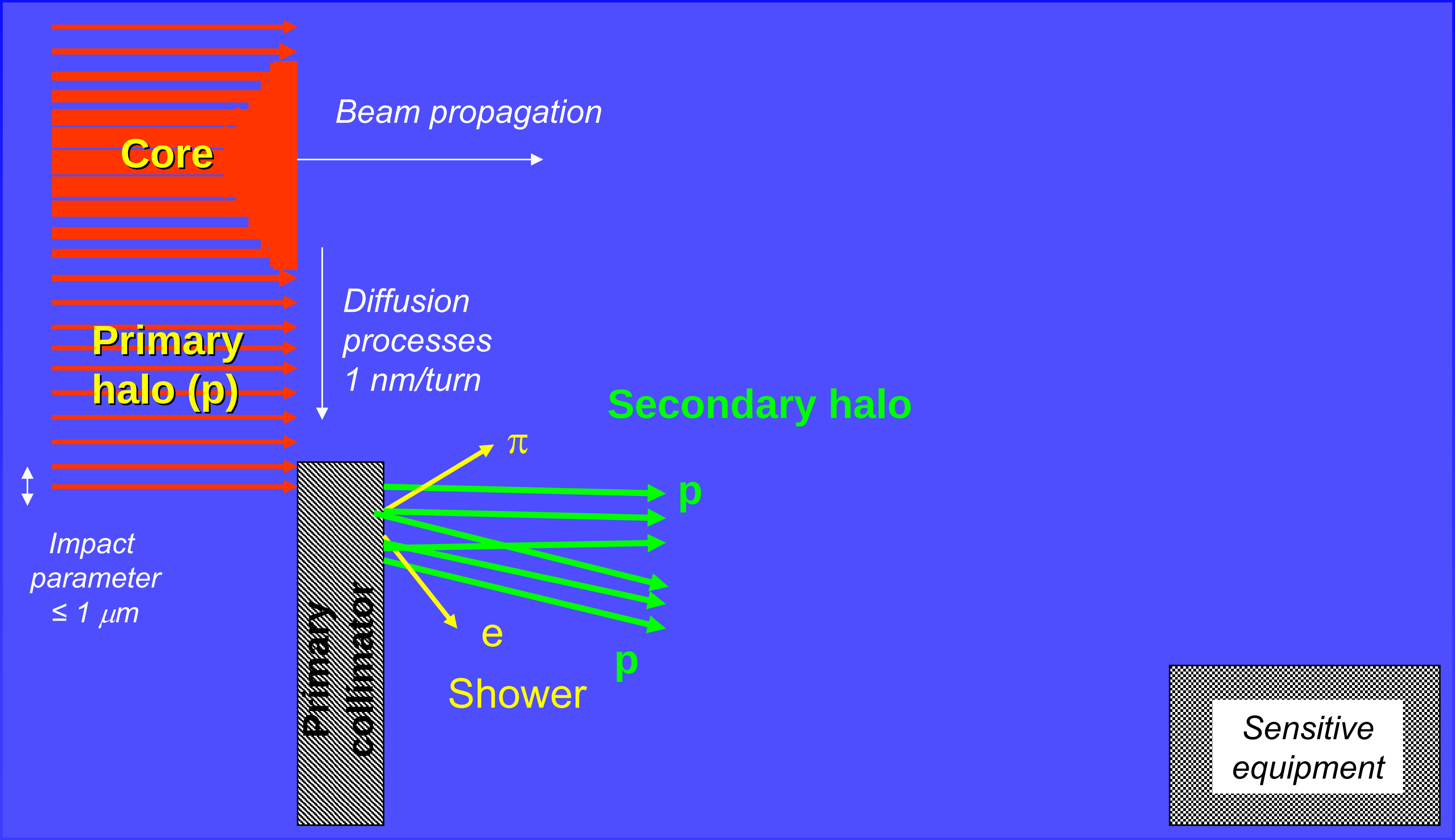
Principle of Beam Collimation



... one stage cleaning ...

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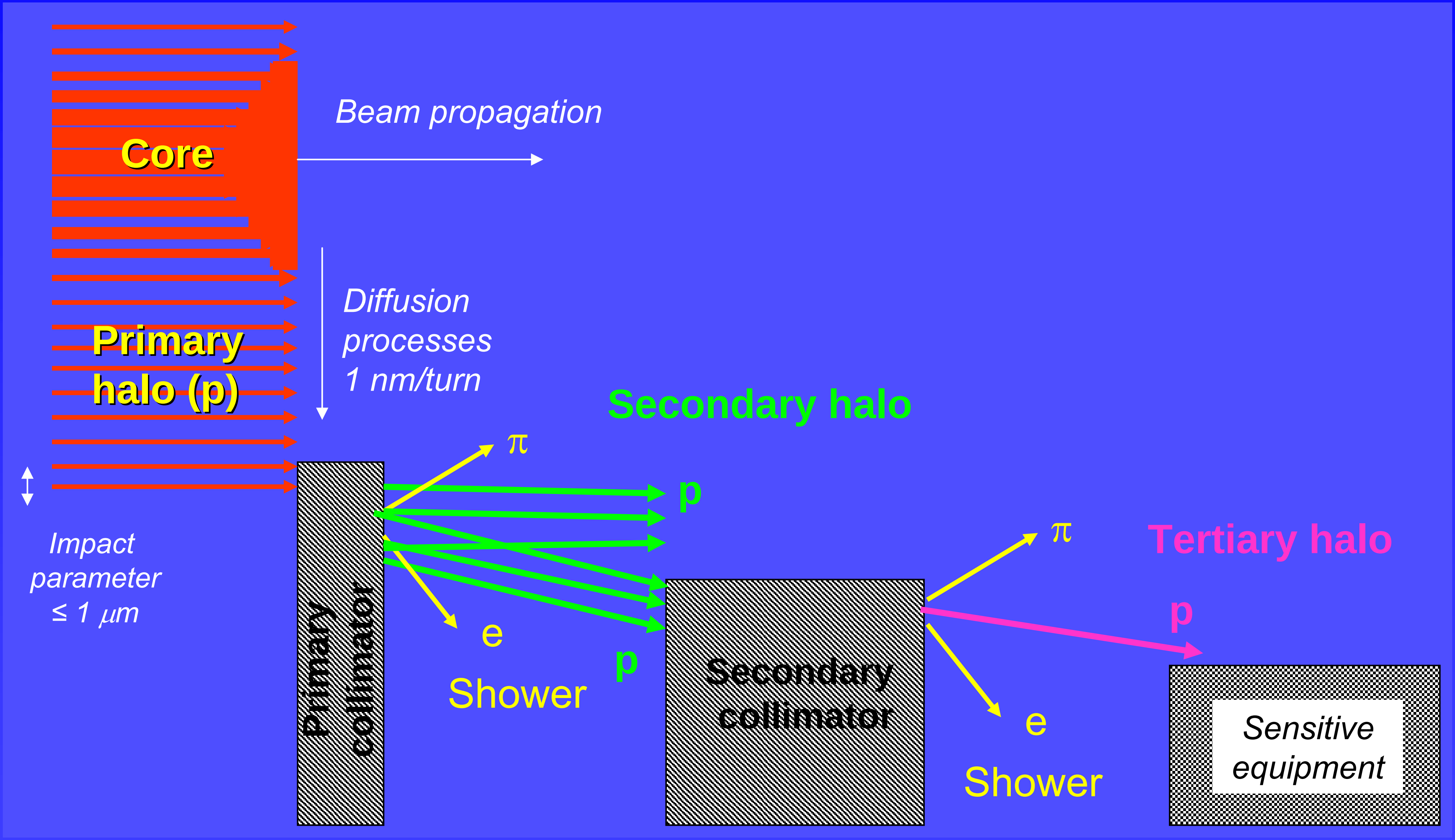
Principle of Beam Collimation



... two stage cleaning ...

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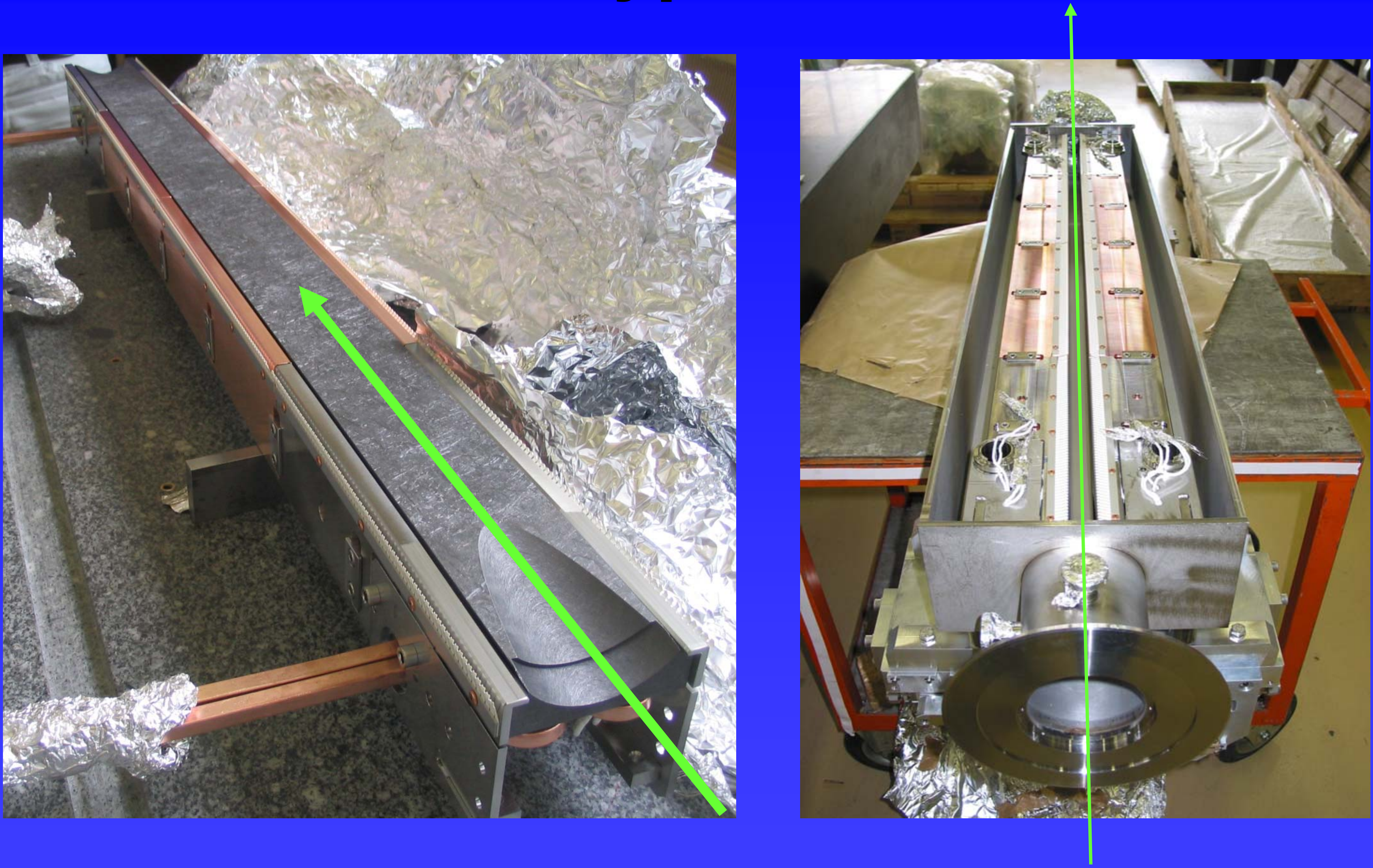
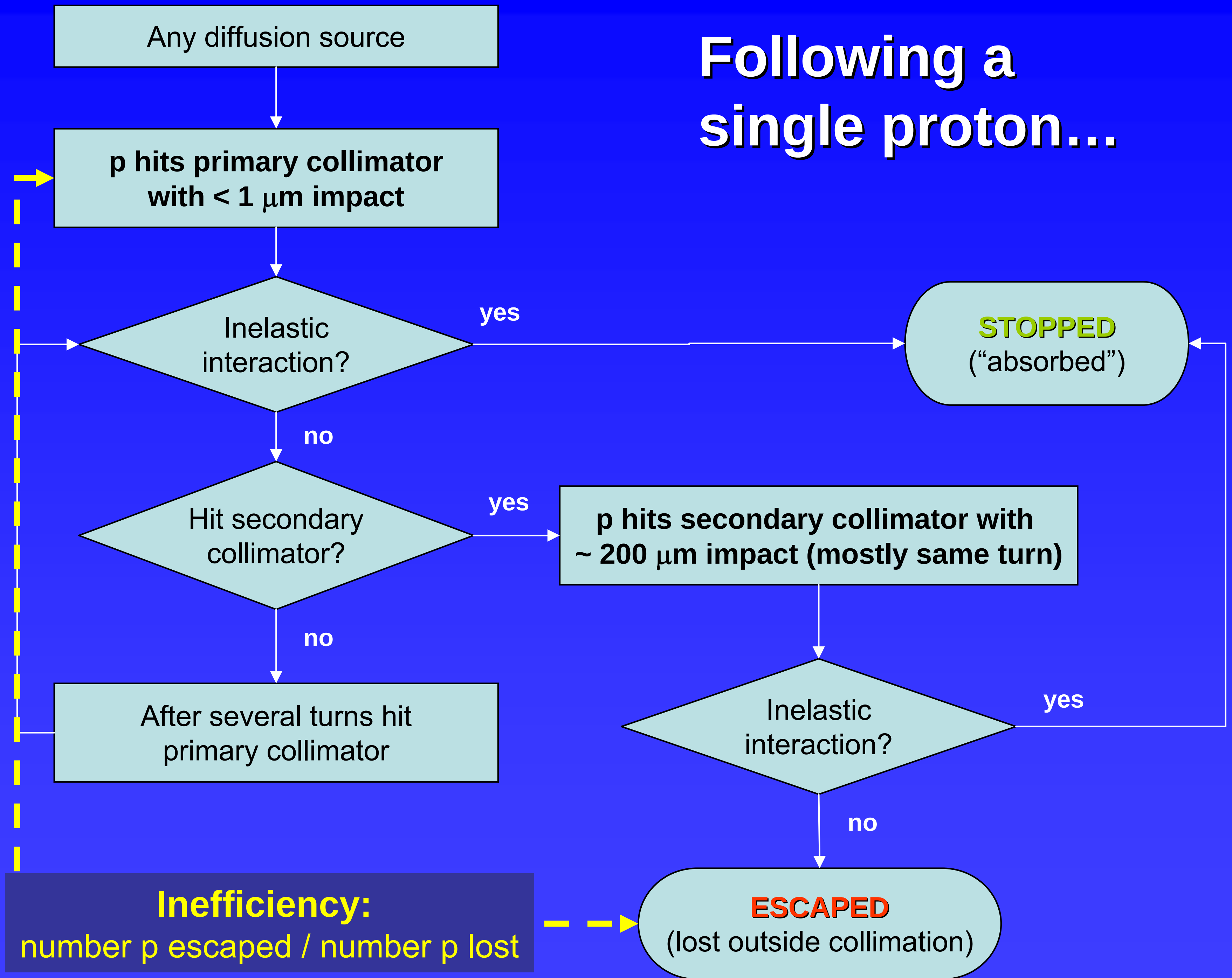
The LHC Type Collimator



If we say collimator:

We mean a collimator with two parallel jaws!
Each jaw controllable in position and angle!

Following a single proton…



Any diffusion source

p hits primary collimator with < 1 μm impact

Inelastic interaction?

yes

STOPPED (“absorbed”)

no

Hit secondary collimator?

yes

p hits secondary collimator with ~ 200 μm impact (mostly same turn)

no

After several turns hit primary collimator

Inelastic interaction?

yes

no

ESCAPED (lost outside collimation)

Inefficiency:
number p escaped / number p lost

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Notes on two-stage collimation

- Protons have very **small impact parameter** on primary collimator:
  → they see only a small length and inelastic interaction cannot be achieved with good probability!
- Primary collimators can be short and **must be complemented by several secondary collimators** each!
- Secondary collimators have bigger impact parameter:
  → They must be **long with good surface flatness** to assure inelastic interaction!
- **Shower products** are assumed to be lost locally in collimator insertion (warm magnets).
- Collimation process is characterized by **inefficiency** (leakage rate).

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Inefficiency and Allowable Intensity

(Luminosity)

Allowed intensity

Quench threshold (7.6 ×10^6 p/m/s @ 7 TeV)

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

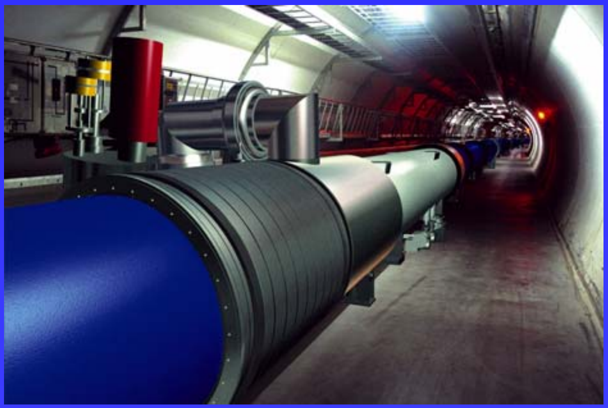
Cleaning inefficiency

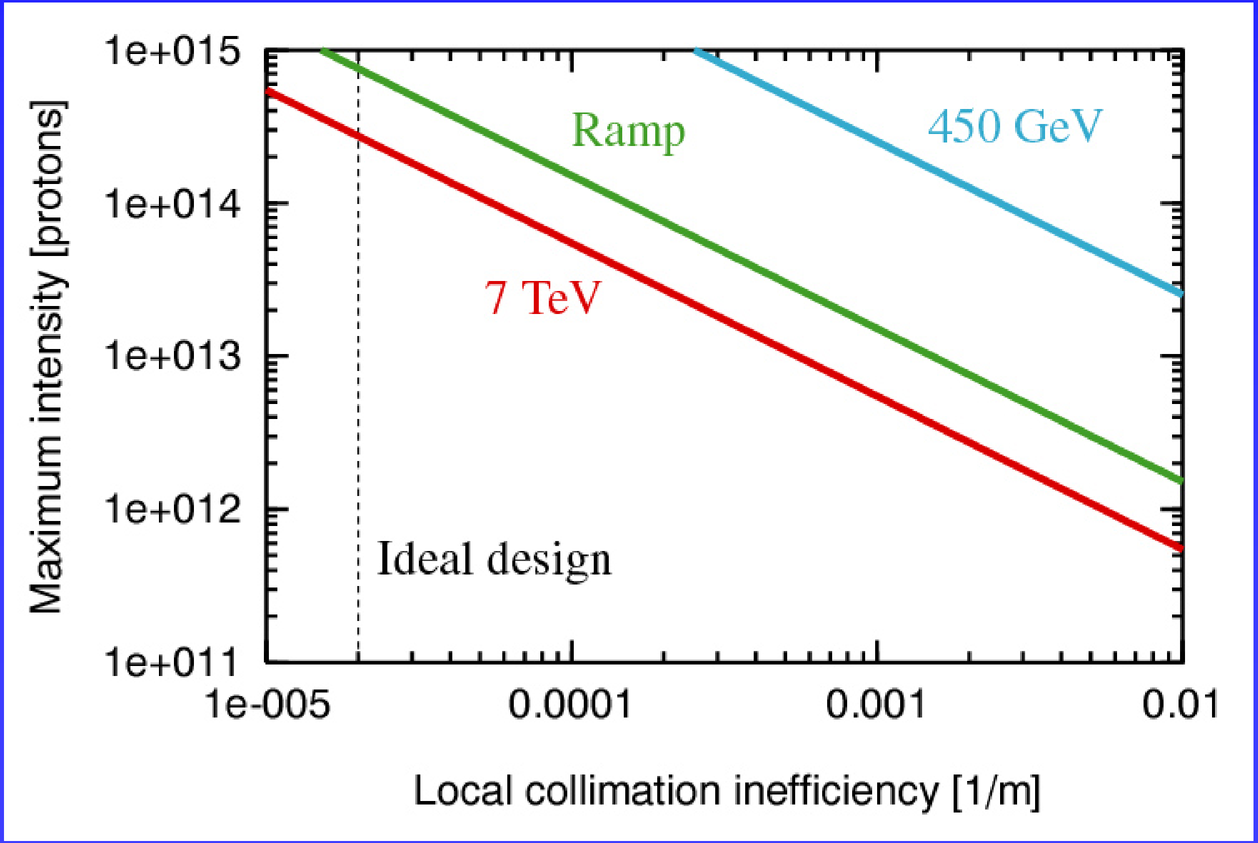
=

$$\frac{\text{Number of escaping p } (>10\sigma)}{\text{Number of impacting p } (6\sigma)}$$

Beam lifetime (e.g. 0.2 h minimum)

Dilution Length (50 m)





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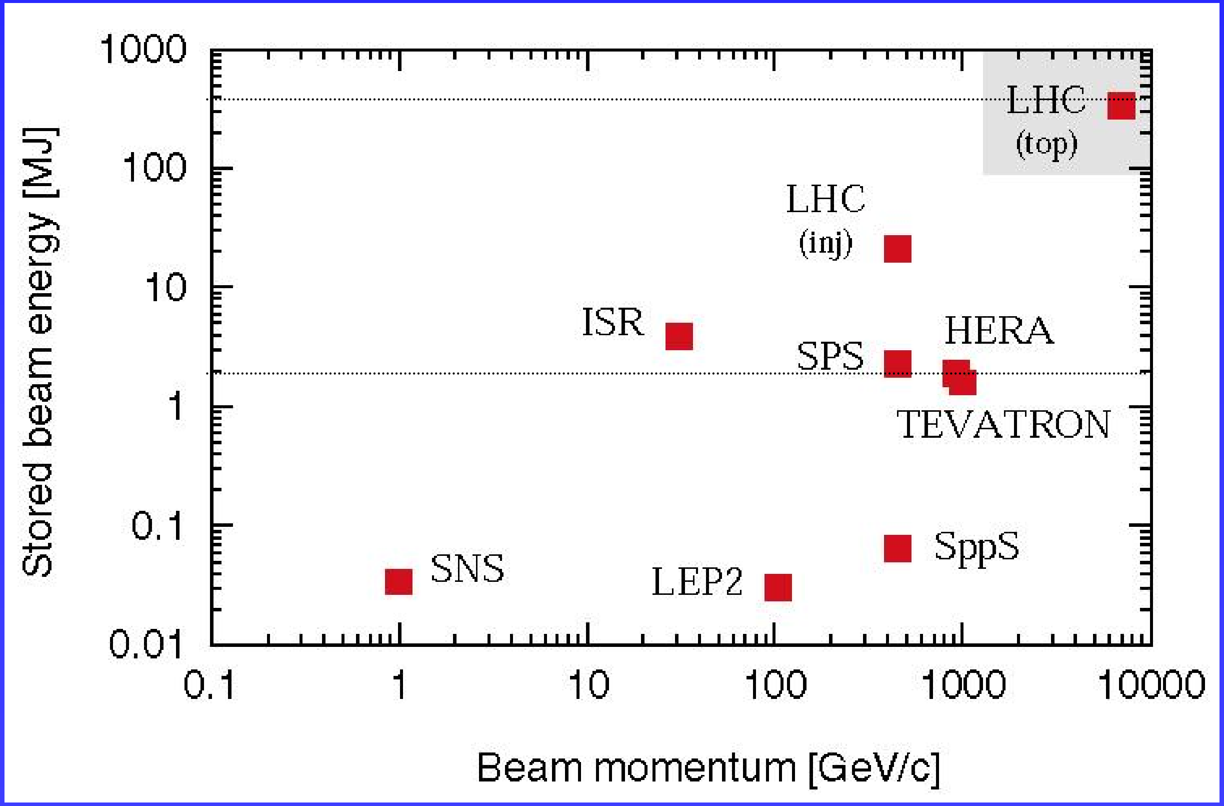
The LHC Challenge

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

Control losses ~ 1000 times better than present state-of-the-art!

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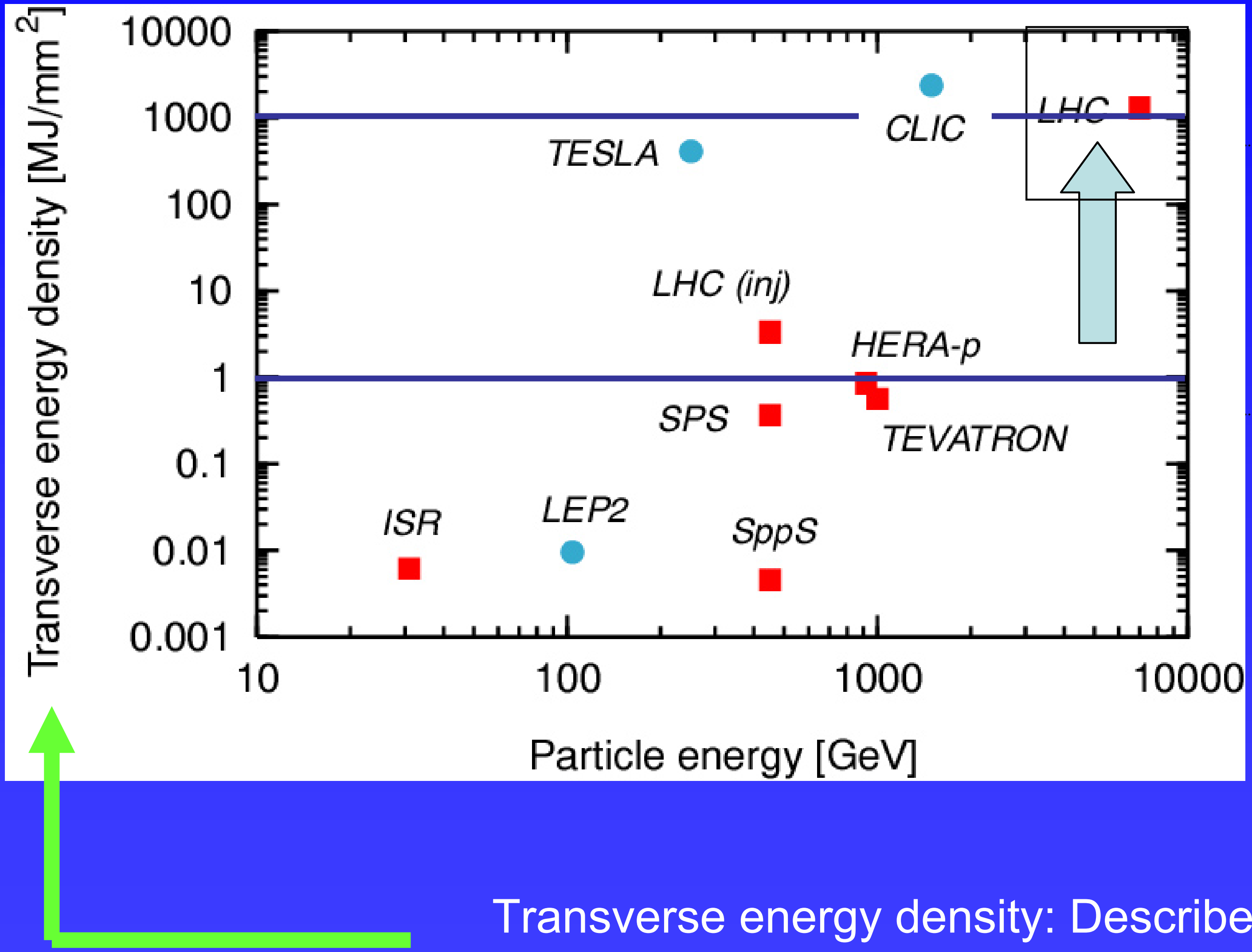
“Destructive” LHC Beams



Transverse energy density: Describes damage potential of the LHC beam (3 orders of magnitude more dangerous than present beams)

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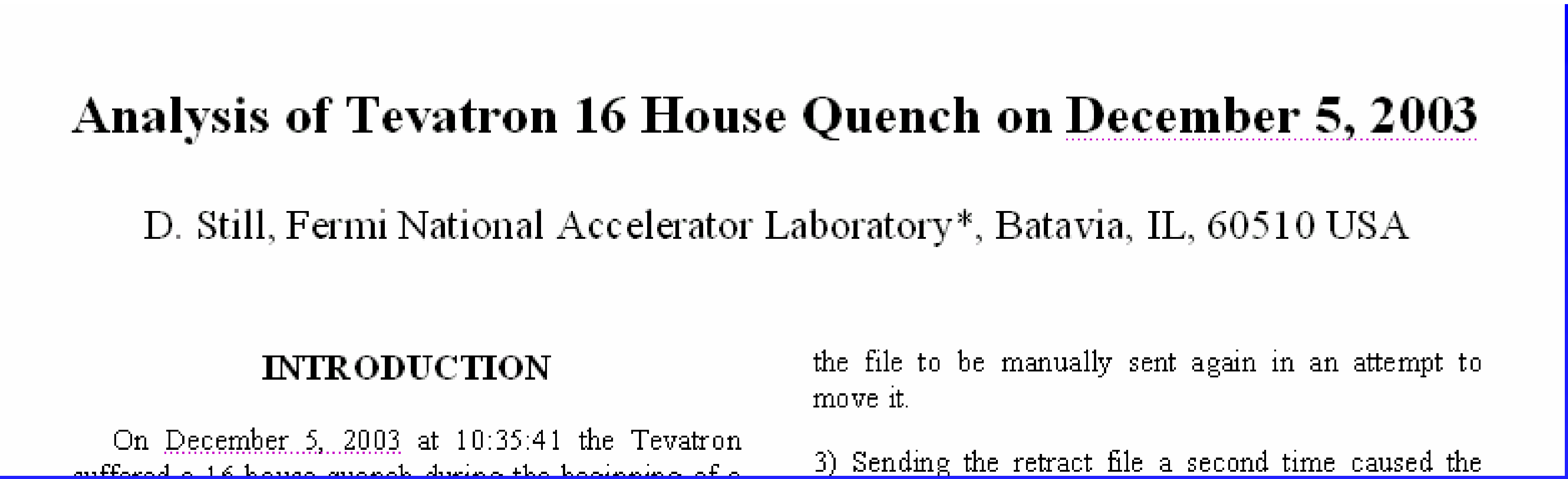


Analysis of Tevatron 16 House Quench on December 5, 2003

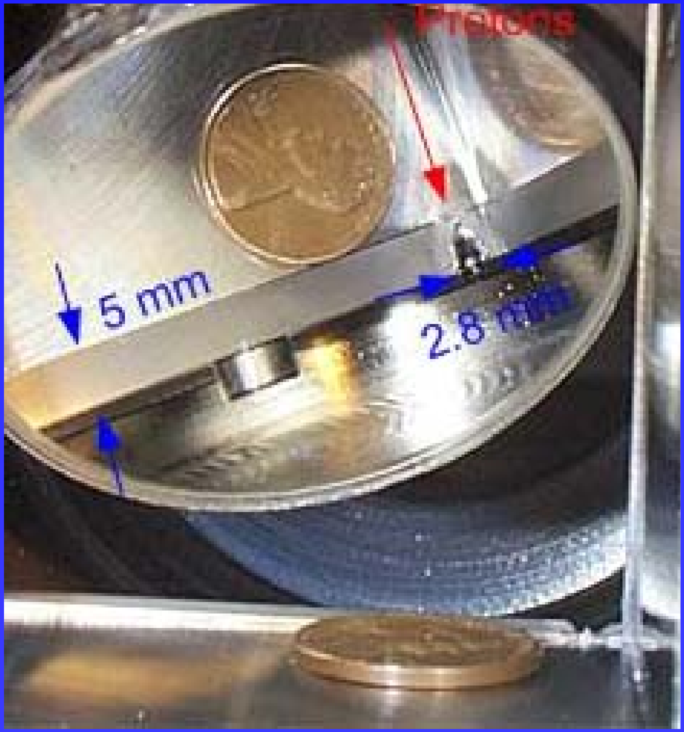
D. Still, Fermi National Accelerator Laboratory*, Batavia, IL, 60510 USA

INTRODUCTION

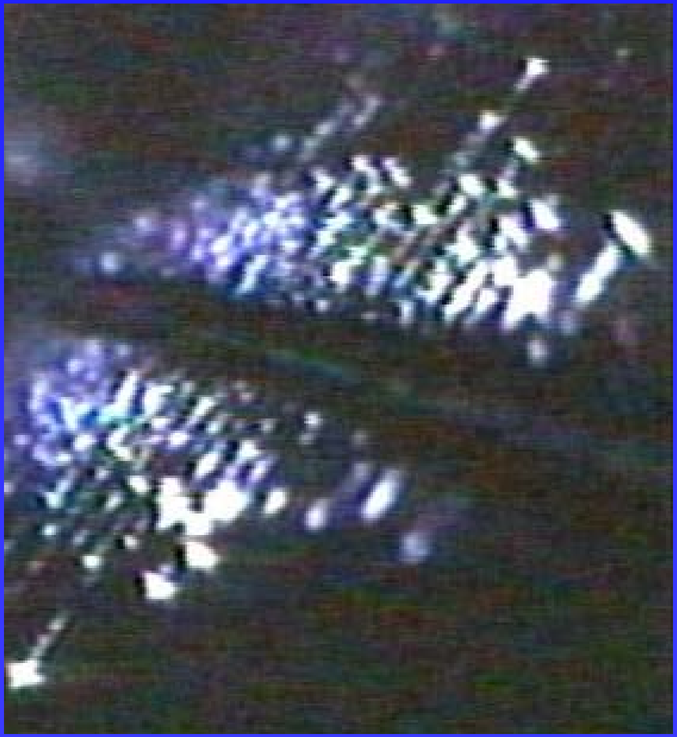
On December 5, 2003 at 10:35:41 the Tevatron

the file to be manually sent again in an attempt to move it.

3) Sending the retract file a second time caused the



Primary collimator (W)



Secondary collimator (W)

Magnetic spool piece

➔ Many more examples exist: E.g. damage to HERA collimators!

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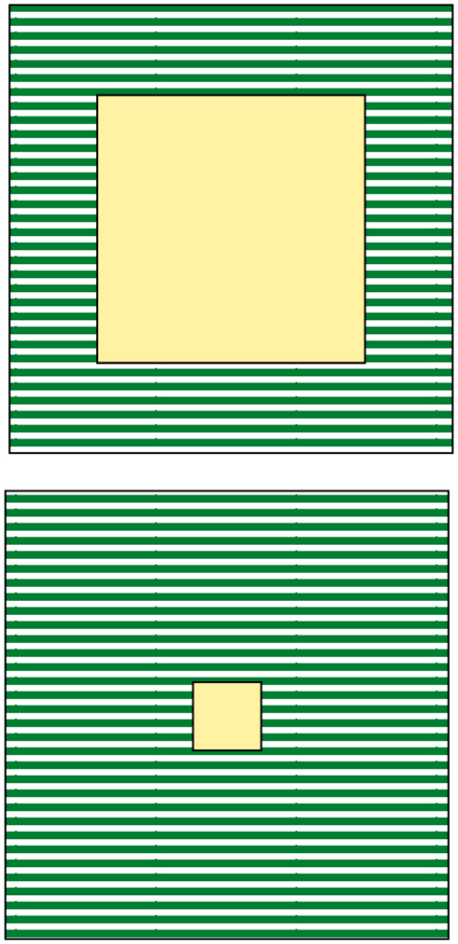

Injection

Jaw opening

~ 12 mm

~ 3 mm

Top energy

10 mm

Some Numbers

High stored beam energy (melt 500 kg Cu, required for 10^{34} cm^{-2} s^{-1} luminosity)	**~ 350 MJ/beam**
Small spot sizes at high energy (small 7 TeV emittance, no large beta in restricted space)	**200 μm (at coll.)**
Large transverse energy density (beam is destructive, 3 orders beyond Tevatron/HERA)	**1 GJ/mm^2**
High required cleaning efficiency (clean lost protons to avoid SC magnet quenches)	**99.998 % (~ 10^{-5} 1/m)**
Collimation close to beam (available mechanical aperture is at ~10 σ)	**6-7 σ**
Small collimator gap (impedance problem, tight tolerances: ~ 10 μm)	**~ 3 mm (at 7 TeV)**
Activation of collimation insertions (good reliability required, very restricted access)	**~ 1-15 mSv/h**
Big system	**IR3, IR7, other locations**

(nominal design parameters)

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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 first-class expertise in various areas**:

Accelerator physics:	Understanding and simulation of loss mechanisms and beam halo, design of efficient multi-stage collimation.
Nuclear physics:	Proton- and ion-induced showers in collimators and other equipment (7 TeV protons on fixed targets).
Material science:	Effects of proton beam on various materials. Beam-induced damage. Elastic and inelastic deformations. Thin coatings.
Mechanical engineering:	Robust collimators with precise mechanical movement and highly efficient cooling.
Radioprotection:	Handling of radioactivity in collimator regions (material, personnel).

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The LHC Collimation Project

September 2001	*Start of Beam Cleaning Study Group / Collimation WG*
January 2002	*CERN meeting on LHC collimators*
January 2003	**AB Project on LHC Collimation** + ATB group
July 2003	Phased approach approved
September 2003	Mechanical engineering started with TS department
January 2004	Start of prototype production
June 2004	New collimation layout in IR3 and IR7
August 2004	Installation of prototype collimators into SPS/TT40
	Call for tender for series production
December 2004	**Contract for series production (FC)**
Summer 2007	Collimation ready for beam commissioning

- ➔ Extremely tight schedule: Many CERN staff working very hard (fast)...
- ➔ **Before series production**: **External review** of design decisions.

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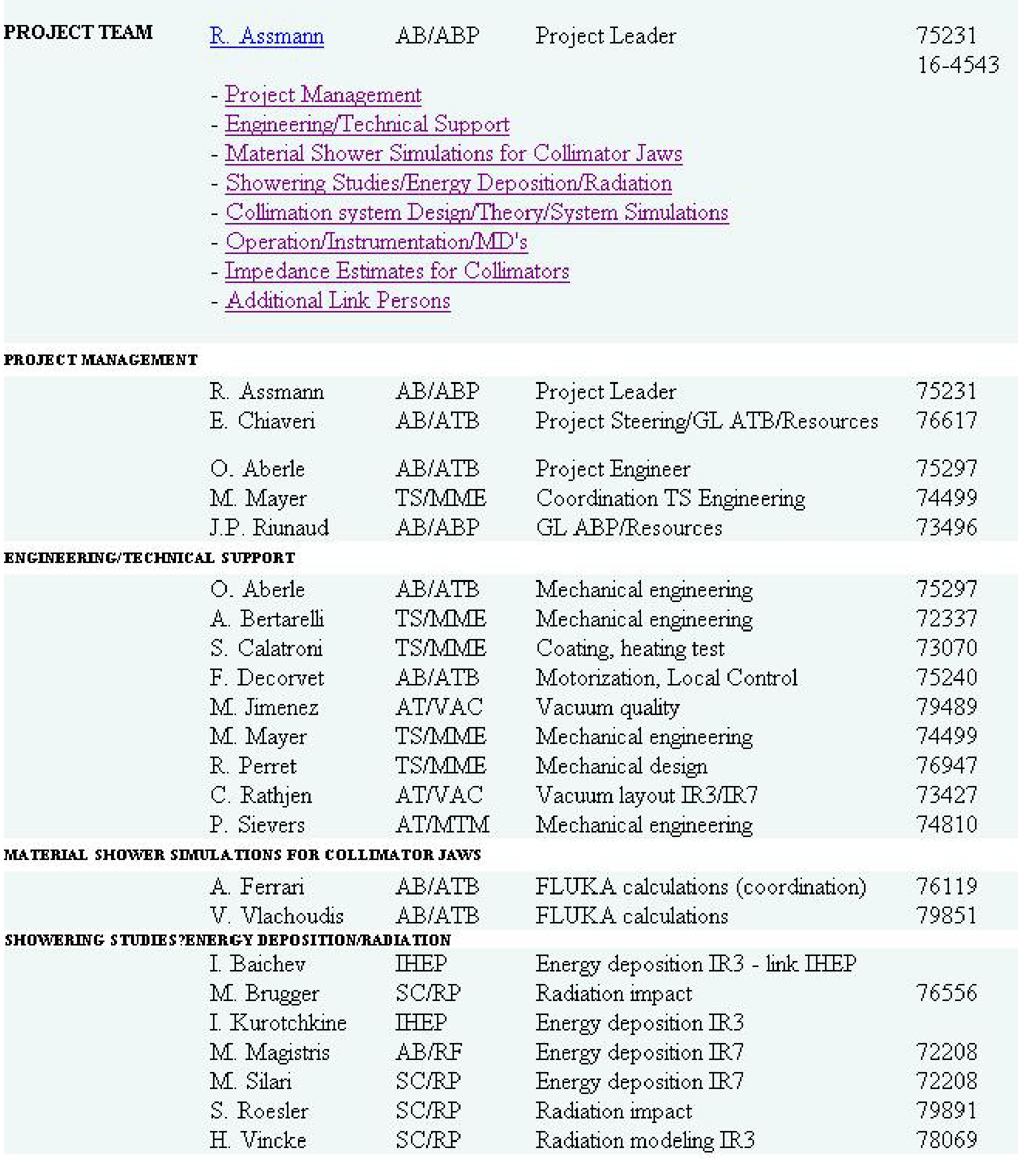
Mandate

- Finalize the design of the LHC collimation system in IR3 and IR7, taking into account all relevant requirements concerning robustness, performance, fabrication, installation, maintenance, machine protection and beam operation.
- Produce prototype collimator tanks for TCP, TCS, and TCL type collimators and verify their performance.
- Supervise production and installation of the full system.
- Commission the system without and with beam. Support routine operation.

Fulfilling this mandate requires close collaboration among different groups and departments: AB/ABP, AB/ATB, AB/BDI, AB/BT, AB/CO, AB/OP, AT/VAC, AT/MTM, TS/ME, TS/CV, TS/EL, TIS/RP, … + external collaborators at TRIUMF, IHEP.

The people involved…



PROJECT TEAM	R. Assmann	AB/ABP	Project Leader	75231 16-4543

- Project Management
- Engineering/Technical Support
- Material Shower Simulations for Collimator Jaws
- Showering Studies/Energy Deposition/Radiation
- Collimation system Design/Theory/System Simulations
- Operation/Instrumentation/MD's
- Impedance Estimates for Collimators
- Additional Link Persons

PROJECT MANAGEMENT

R. Assmann	AB/ABP	Project Leader	75231
E. Chiaveri	AB/ATB	Project Steering/GL ATB/Resources	76617
O. Aberle	AB/ATB	Project Engineer	75297
M. Mayer	TS/MME	Coordination TS Engineering	74499
J.P. Riunaud	AB/ABP	GL ABP/Resources	73496

ENGINEERING/TECHNICAL SUPPORT

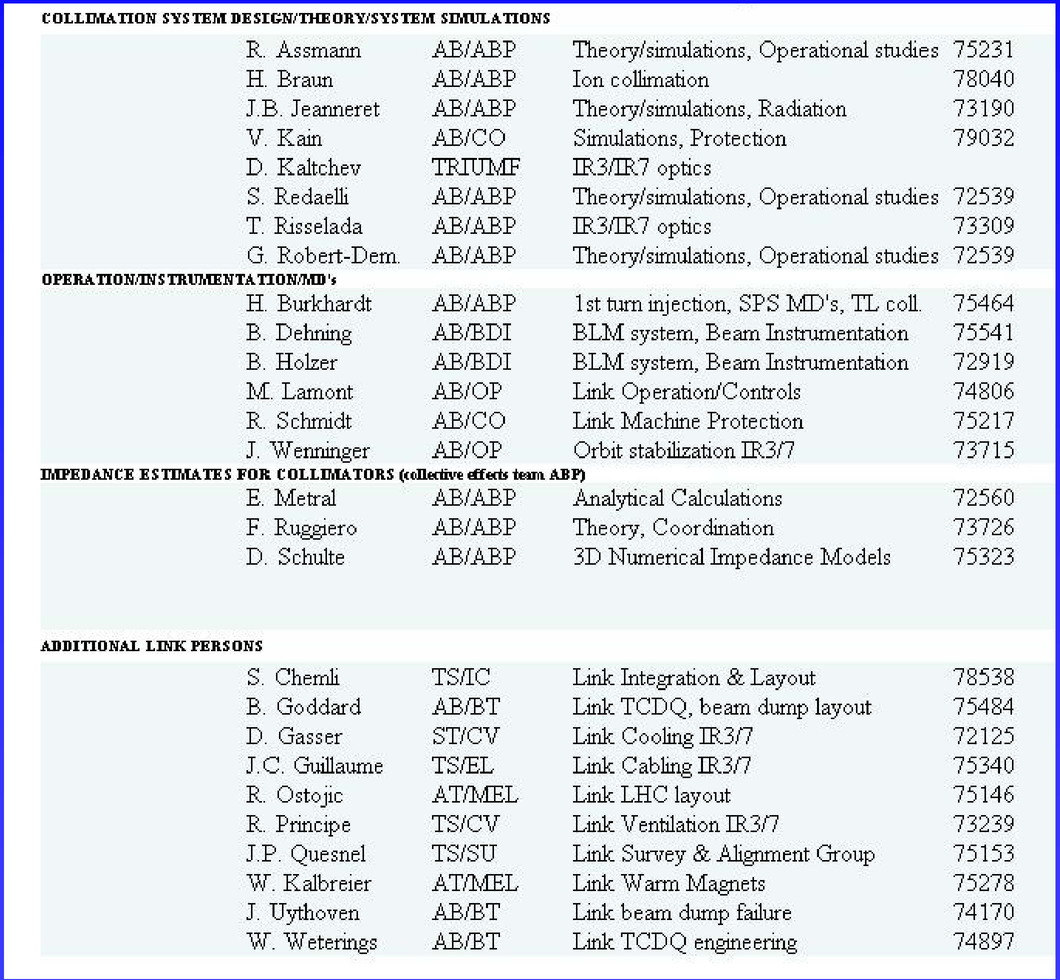
O. Aberle	AB/ATB	Mechanical engineering	75297
A. Bertarelli	TS/MME	Mechanical engineering	72337
S. Calatroni	TS/MME	Coating, heating test	73070
F. Decorvet	AB/ATB	Motorization, Local Control	75240
M. Jimenez	AT/VAC	Vacuum quality	79489
M. Mayer	TS/MME	Mechanical engineering	74499
R. Perret	TS/MME	Mechanical design	76947
C. Rathjen	AT/VAC	Vacuum layout IR3/IR7	73427
P. Sievers	AT/MTM	Mechanical engineering	74810

MATERIAL SHOWER SIMULATIONS FOR COLLIMATOR JAWS

A. Ferrari	AB/ATB	FLUKA calculations (coordination)	76119
V. Vlachoudis	AB/ATB	FLUKA calculations	79851

SHOWERING STUDIES?ENERGY DEPOSITION/RADIATION

I. Baichev	IHEP	Energy deposition IR3 - link IHEP	
M. Brugger	SC/RP	Radiation impact	76556
I. Kurotchkine	IHEP	Energy deposition IR3	
M. Magistris	AB/RF	Energy deposition IR7	72208
M. Silari	SC/RP	Energy deposition IR7	72208
S. Roesler	SC/RP	Radiation impact	79891
H. Vincke	SC/RP	Radiation modeling IR3	78069



COLLIMATION SYSTEM DESIGN/THEORY/SYSTEM SIMULATIONS

R. Assmann	AB/ABP	Theory/simulations, Operational studies	75231
H. Braun	AB/ABP	Ion collimation	78040
J.B. Jeanneret	AB/ABP	Theory/simulations, Radiation	73190
V. Kain	AB/CO	Simulations, Protection	79032
D. Kaltchev	TRIUMF	IR3/IR7 optics	
S. Redaelli	AB/ABP	Theory/simulations, Operational studies	72539
T. Risselada	AB/ABP	IR3/IR7 optics	73309
G. Robert-Dem.	AB/ABP	Theory/simulations, Operational studies	72539

OPERATION/INSTRUMENTATION/MD's

H. Burkhardt	AB/ABP	1st turn injection, SPS MD's, TL coll.	75464
B. Dehning	AB/BDI	BLM system, Beam Instrumentation	75541
B. Holzer	AB/BDI	BLM system, Beam Instrumentation	72919
M. Lamont	AB/OP	Link Operation/Controls	74806
R. Schmidt	AB/CO	Link Machine Protection	75217
J. Wenninger	AB/OP	Orbit stabilization IR3/7	73715

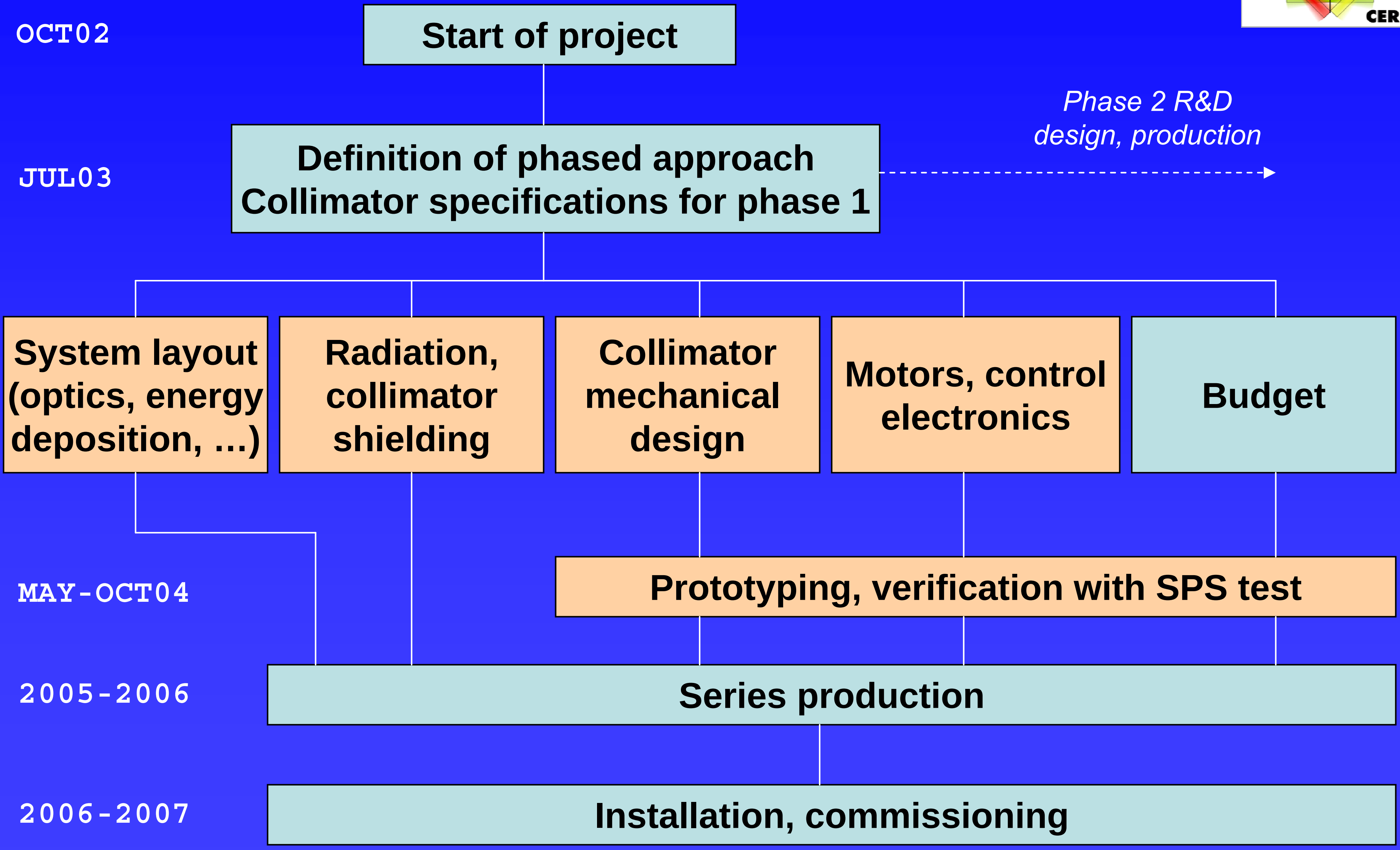
IMPEDANCE ESTIMATES FOR COLLIMATORS (collective effects team ABP)

E. Metral	AB/ABP	Analytical Calculations	72560
F. Ruggiero	AB/ABP	Theory, Coordination	73726
D. Schulte	AB/ABP	3D Numerical Impedance Models	75323

ADDITIONAL LINK PERSONS

S. Chemli	TS/IC	Link Integration & Layout	78538
B. Goddard	AB/BT	Link TCDQ, beam dump layout	75484
D. Gasser	ST/CV	Link Cooling IR3/7	72125
J.C. Guillaume	TS/EL	Link Cabling IR3/7	75340
R. Ostojic	AT/MEL	Link LHC layout	75146
R. Principe	TS/CV	Link Ventilation IR3/7	73239
J.P. Quesnel	TS/SU	Link Survey & Alignment Group	75153
W. Kalbreier	AT/MEL	Link Warm Magnets	75278
J. Uythoven	AB/BT	Link beam dump failure	74170
W. Weterings	AB/BT	Link TCDQ engineering	74897

Main work flow



OCT02

Start of project

JUL03

Definition of phased approach
Collimator specifications for phase 1

Phase 2 R&D design, production

System layout (optics, energy deposition, ...)

Radiation, collimator shielding

Collimator mechanical design

Motors, control electronics

Budget

MAY-OCT04

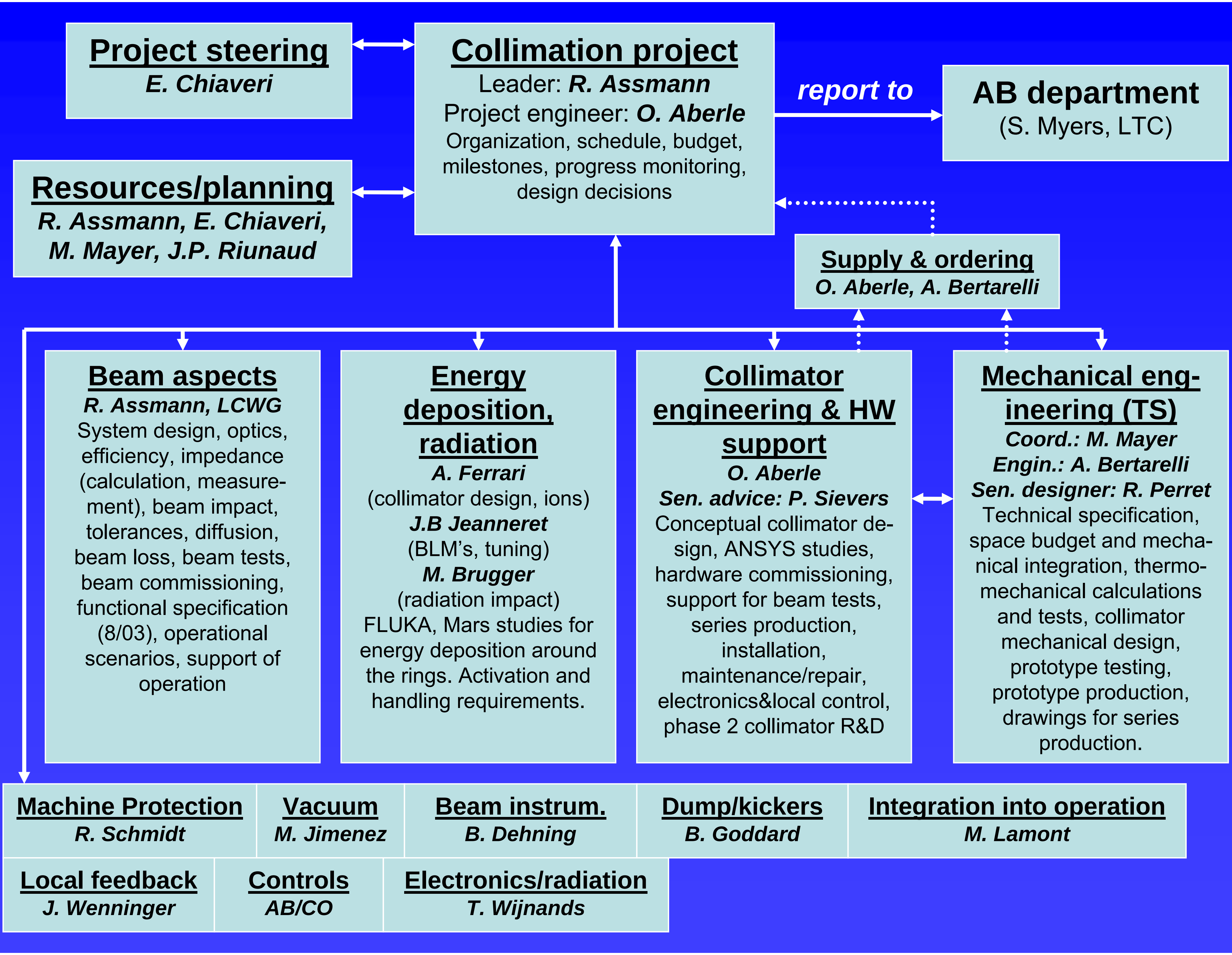
Prototyping, verification with SPS test

2005-2006

Series production

2006-2007

Installation, commissioning



Project steering
E. Chiaveri

Collimation project
Leader: ***R. Assmann***
Project engineer: ***O. Aberle***
Organization, schedule, budget, milestones, progress monitoring, design decisions

report to

AB department
(S. Myers, LTC)

Resources/planning
R. Assmann, E. Chiaveri, M. Mayer, J.P. Riunaud

Supply & ordering
O. Aberle, A. Bertarelli

Beam aspects
R. Assmann, LCWG
System design, optics, efficiency, impedance (calculation, measurement), beam impact, tolerances, diffusion, beam loss, beam tests, beam commissioning, functional specification (8/03), operational scenarios, support of operation

Energy deposition, radiation
A. Ferrari
(collimator design, ions)
J.B Jeanneret
(BLM's, tuning)
M. Brugger
(radiation impact)
FLUKA, Mars studies for energy deposition around the rings. Activation and handling requirements.

Collimator engineering & HW support
O. Aberle
Sen. advice: P. Sievers
Conceptual collimator design, ANSYS studies, hardware commissioning, support for beam tests, series production, installation, maintenance/repair, electronics&local control, phase 2 collimator R&D

Mechanical engineering (TS)
Coord.: M. Mayer
Engin.: A. Bertarelli
Sen. designer: R. Perret
Technical specification, space budget and mechanical integration, thermo-mechanical calculations and tests, collimator mechanical design, prototype testing, prototype production, drawings for series production.

Machine Protection
R. Schmidt

Vacuum
M. Jimenez

Beam instrum.
B. Dehning

Dump/kickers
B. Goddard

Integration into operation
M. Lamont

Local feedback
J. Wenninger

Controls
AB/CO

Electronics/radiation
T. Wijnands

External collaborations

Lot’s of excellent knowledge at CERN but not covering all relevant work (manpower) and expertise (new challenges):

TRIUMF:	Collimation optics design (completed).
IHEP:	Energy deposition studies. Radiation impact.
Kurchatov:	Damage to Carbon from the LHC beam (how long will the collimators survive?) → radiation damage to material properties... (just started)
SLAC:	*Design/construction of a phase 2 advanced collimator for LHC beam test in 2008.*
BNL:	*Cleaning efficiency in an operating machine.*
Fermilab:	*Energy deposition studies. Quench protection.*

US-LARP program

Strong contacts with DESY and other laboratories...

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Scope of the Project

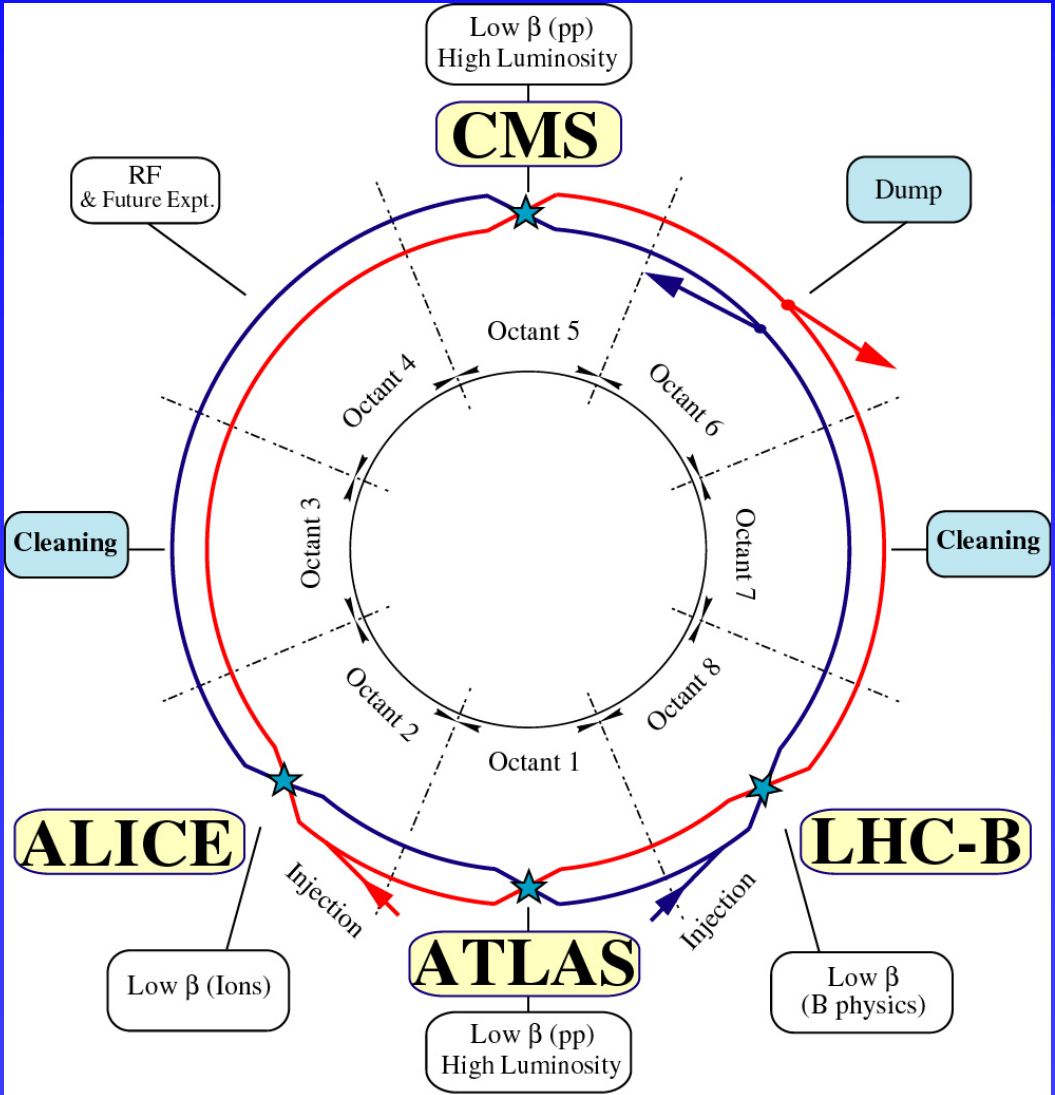
Two warm LHC insertions dedicated to cleaning:

IR3 ➔ Momentum cleaning

IR7 ➔ Betatron cleaning

Building on collimation system design that started in 1992!

Various collimators in experimental insertions IR1, IR2, IR5, IR8.



➔ Four collimation systems: Momentum and betatron for two beams!

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Challenges for LHC Collimation

Good robustness

High efficiency

Low impedance

SOLUTION?

Low activation

Reasonable cost
Fast schedule

Reasonable tolerances

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No ONE General Purpose System

Tradeoffs:

Good robustness (carbon) ←→ Low impedance (metal)
High efficiency (good absorption) ←→ Good robustness (bad absorption)
Low impedance (short jaws) ←→ High efficiency (long jaws)

1. **Advancing state-of-the-art by 2-3 orders of magnitude.**
2. **Conflicting requirements.**

→ **No unique solution for everything (injection, ramp, collision, …):**

Various sub-systems with dedicated usages, targeted at specific requirements (e.g. maximum robustness at injection/ramp, minimum impedance at collision).

Phased approach for minimum initial investment, minimum number of components, assuring to be ready in time. Possibility of upgrades.

The Phased Approach

1) **Maximum robustness, minimum cost IR3/IR7 collimation system** (C based) for injection&ramping, commissioning, early physics (running at impedance limit). Thin metallic coating for going further (survival of coating unclear).

2) **“Tertiary” collimators in IR1, IR2, IR5, IR7** for local protection and cleaning at the triplets.

3) Thin targets for **beam scraping**.

Phase 1

4) **Metallic “hybrid” secondary collimators in IR7** for nominal performance, used only at end of squeeze and stable physics.

Phase 2

5) **Additional placeholders** for upgrading to maximum cleaning efficiency.

Phase 4

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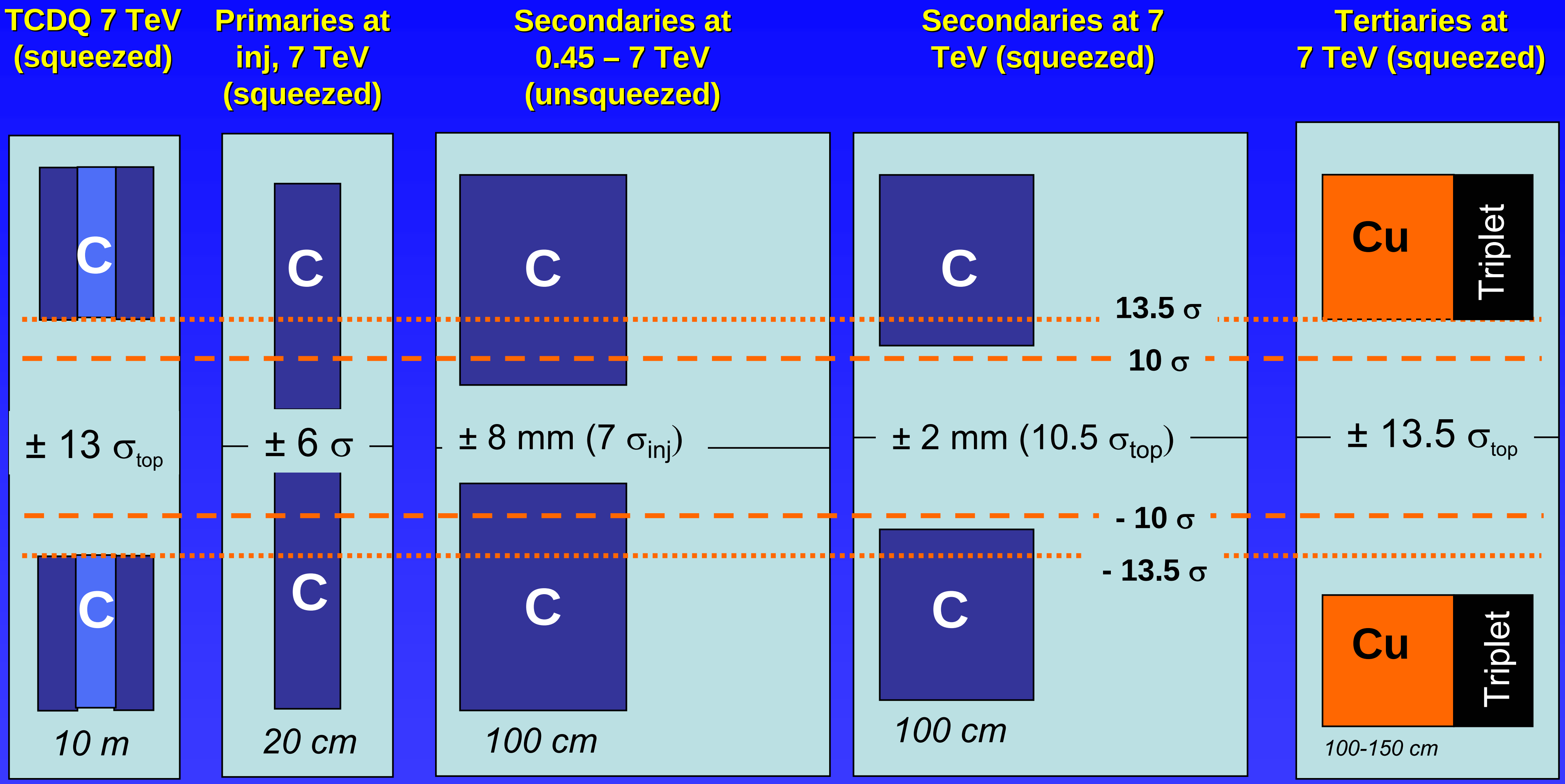
Phase 1: The robust 3-stage system for injection/ramp and early physics



Primaries very robust, robust low-Z secondaries, relaxed tolerances: mechanical and for orbit/beta beat, good efficiency.

Space allocations for phase 2 upgrade.

Triplet protection (possible later local cleaning at triplets).

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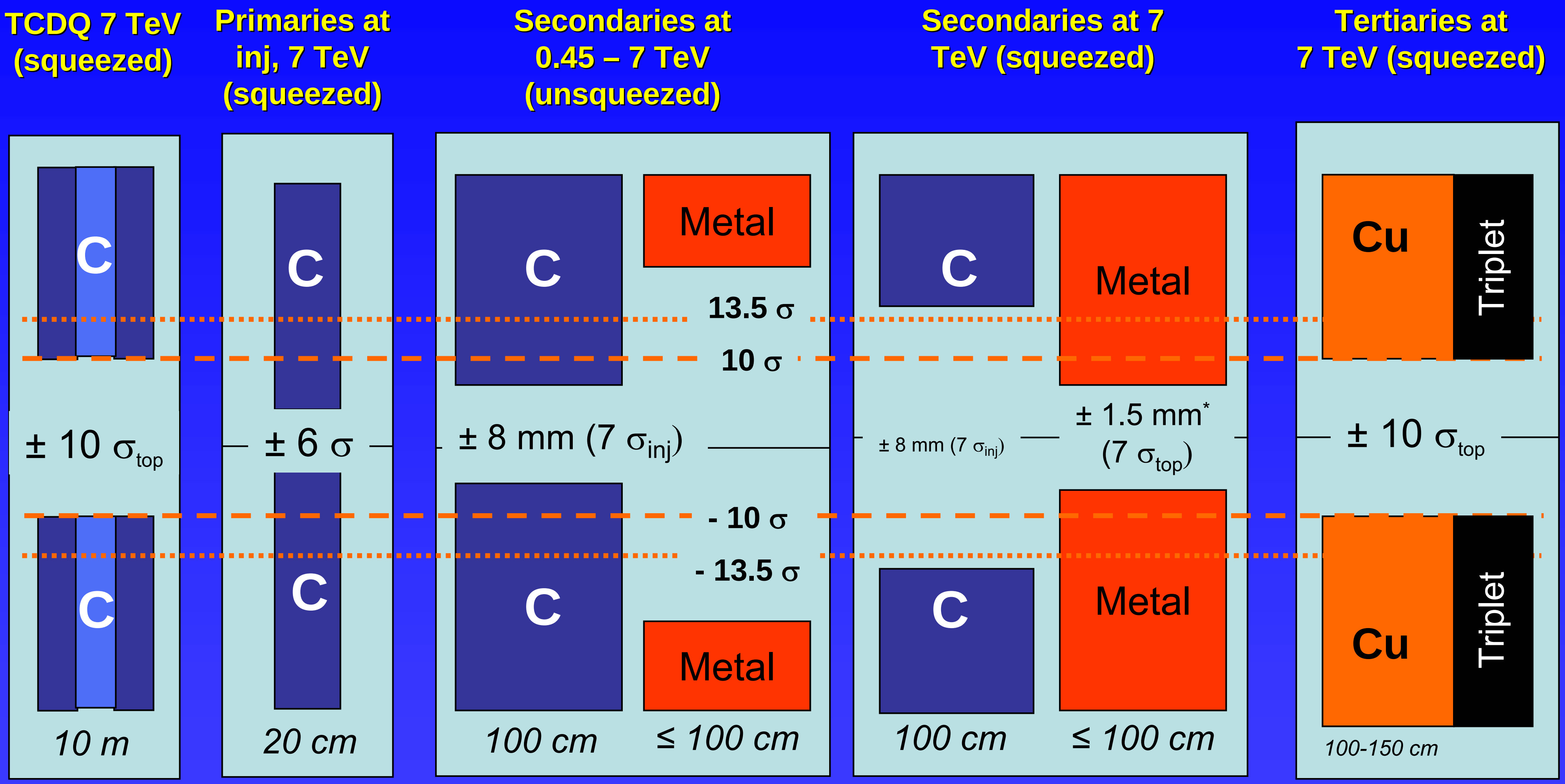
Phase 2: The robust 3-stage system plus low impedance hybrids



*A few hybrid collimators (1-2) might be retracted to 10.5 σ (into shadow of TCDQ). Take into account known phase advances for any given configuration.

Hybrid secondaries with metallic surface, only used towards end of squeeze and in stable physics (only dump failure relevant for H collimators in phase).

Rely on local triplet cleaning for these few collimators.

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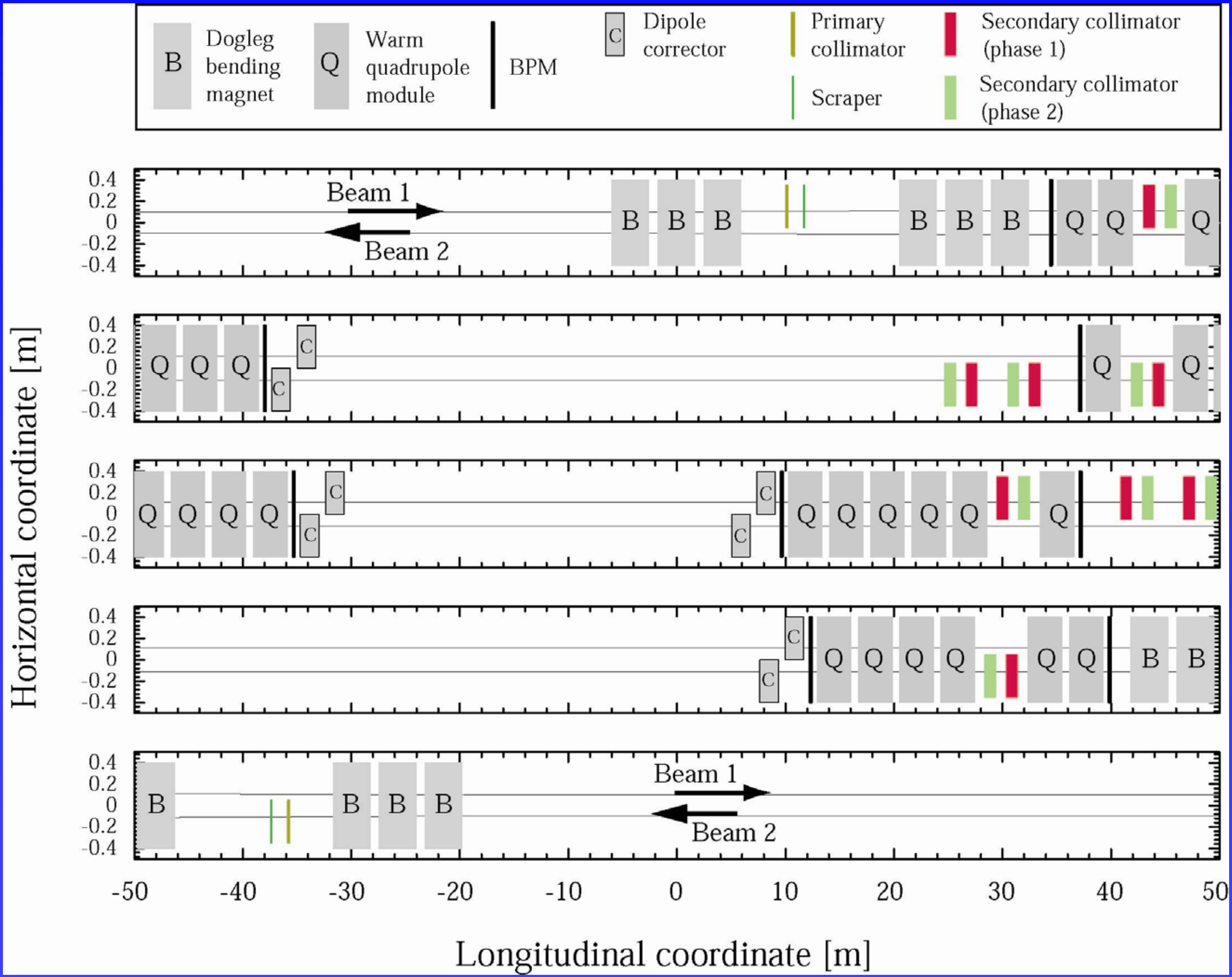
New Machine Layout IR3



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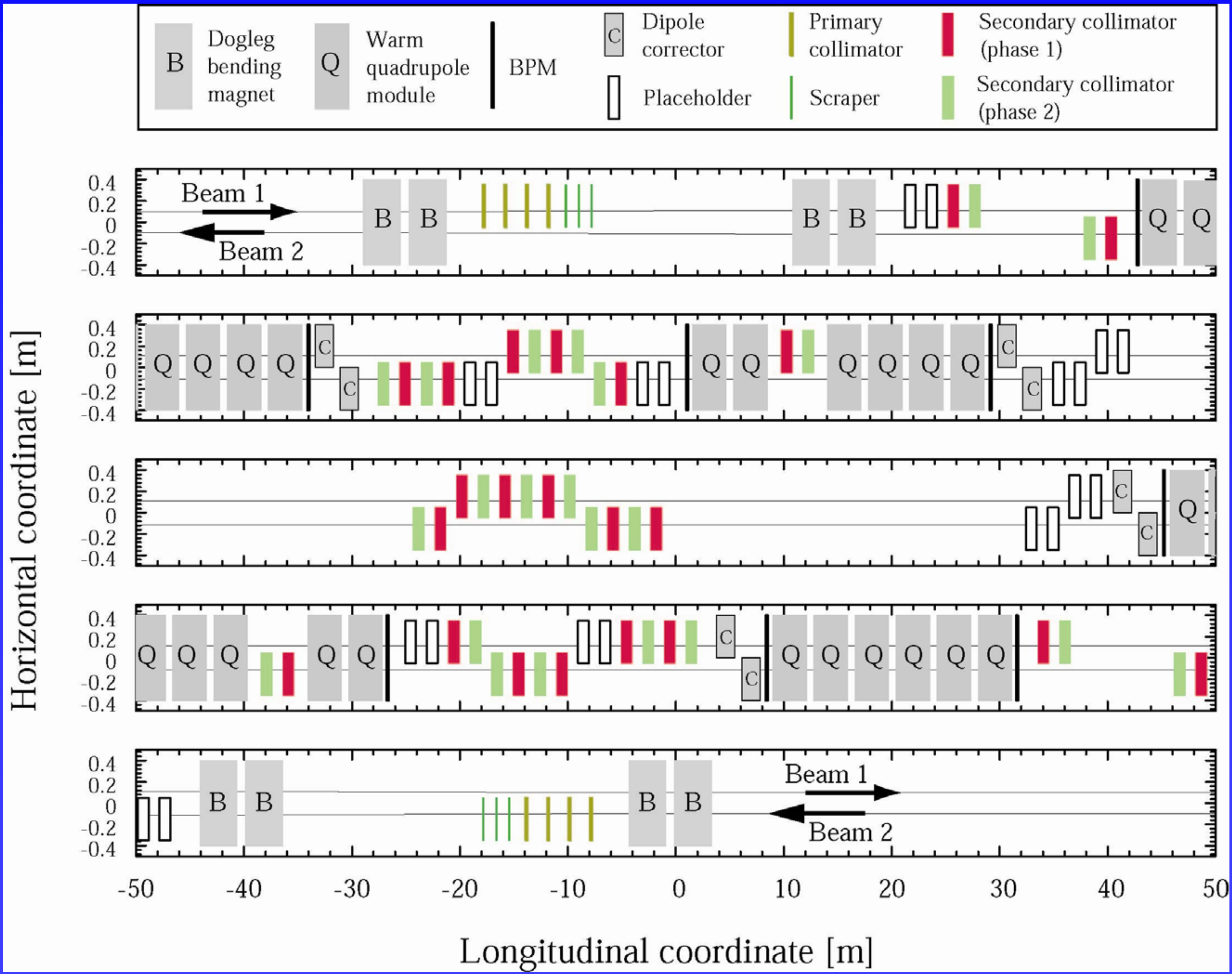
New Machine Layout IR7



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Collimators / Scrapers / Absorbers

Components of the collimation system are distinguished by their function:

Collimators:	Elastic and inelastic interactions of **beam protons**. Precise devices with two jaws, used for efficient beam cleaning. Small gaps and stringent tolerances.
Scrapers:	Used for **beam shaping and diagnostics**. Thin one-sided objects.
Absorbers:	Absorb **mis-kicked beam** or products of proton-induced **showers**. Movable absorbers can be quite similar in design to collimators, but mostly with high-Z jaws. Larger gaps and relaxed tolerances.

Precise set-up and optimization in first line affects collimators!

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Components for the Collimation System (Phase 1)

	Label	Number per beam	Material	Jaw length [m]
Collimators				
Primary betatron	TCP	3	CC	0.2
Secondary betatron	TCSG	11	CC	1.0
Primary momentum	TCP	1	CC	0.2
Secondary momentum	TCSG	4	CC	1.0
Tertiary triplets	TCT	6	Cu/W	1.0
Scrapers				
Betatron	TCHS	2	tbd	tbd
Momentum	TCHS	1	tbd	tbd
Absorbers				
Injection errors	TCLI	2	CC	1.0
Luminosity debris	TCLP	2	Cu/W	1.0
Cleaning showers	TCLA	(8)	Cu/W	1.0

Focus of review
Most difficult!

Number of objects:
80 + 13 spares

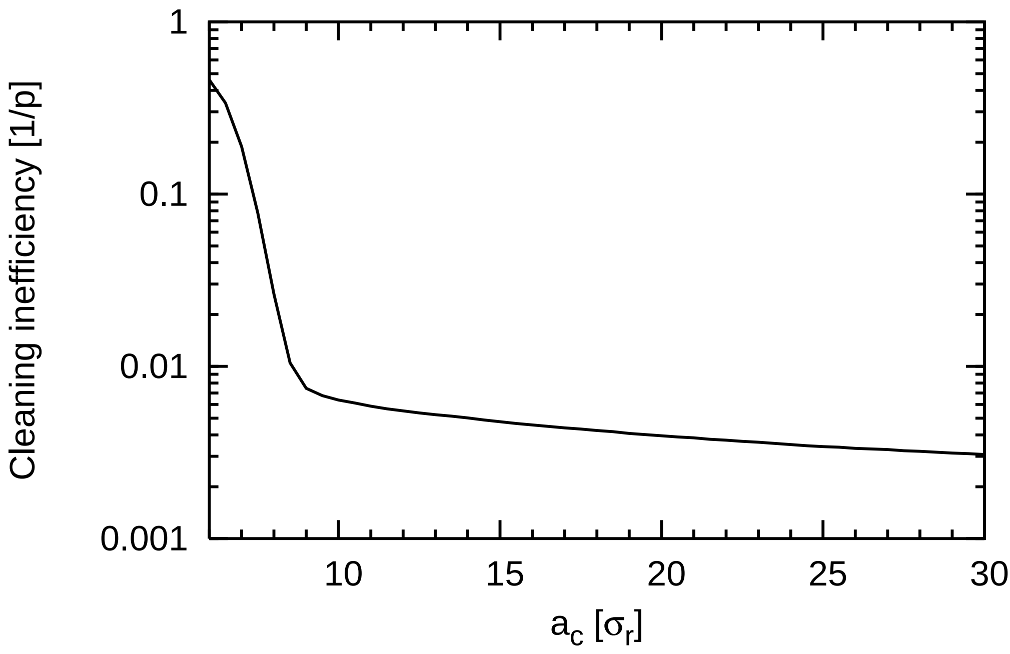
Per beam:

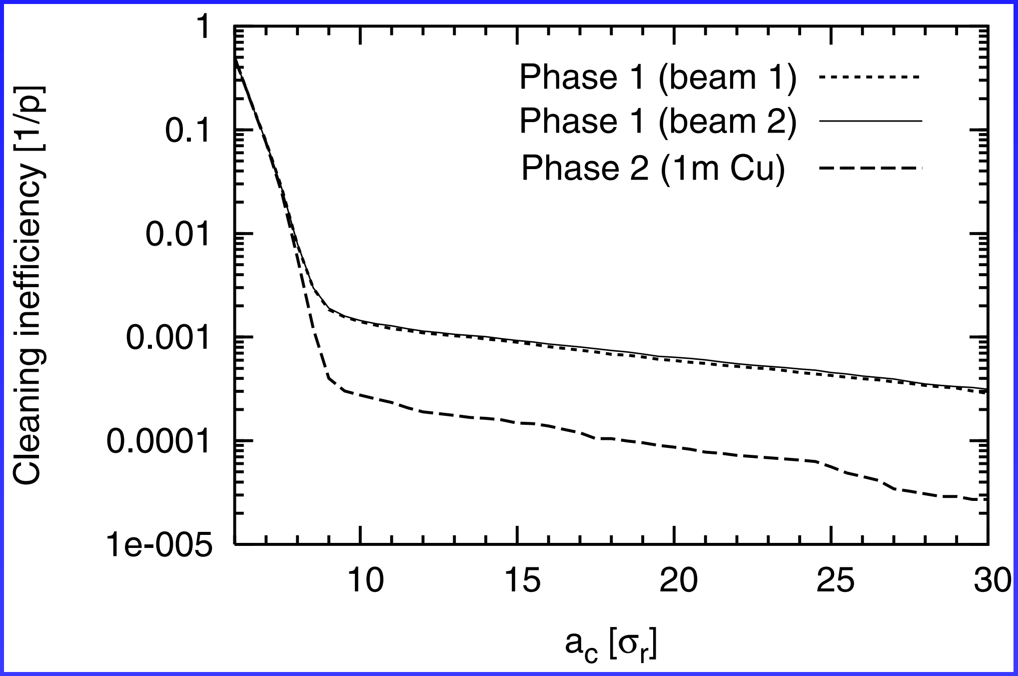
25 collimators
3 scrapers
12 absorbers

Performance

Efficiency:

Phase 1: Efficiency reduced with respect to old solution!
Phase 2: Potential of efficiency extended 2-3 times beyond old solution!





These results used for design goals. Difficult to use for predicting quenches in the LHC cold aperture!

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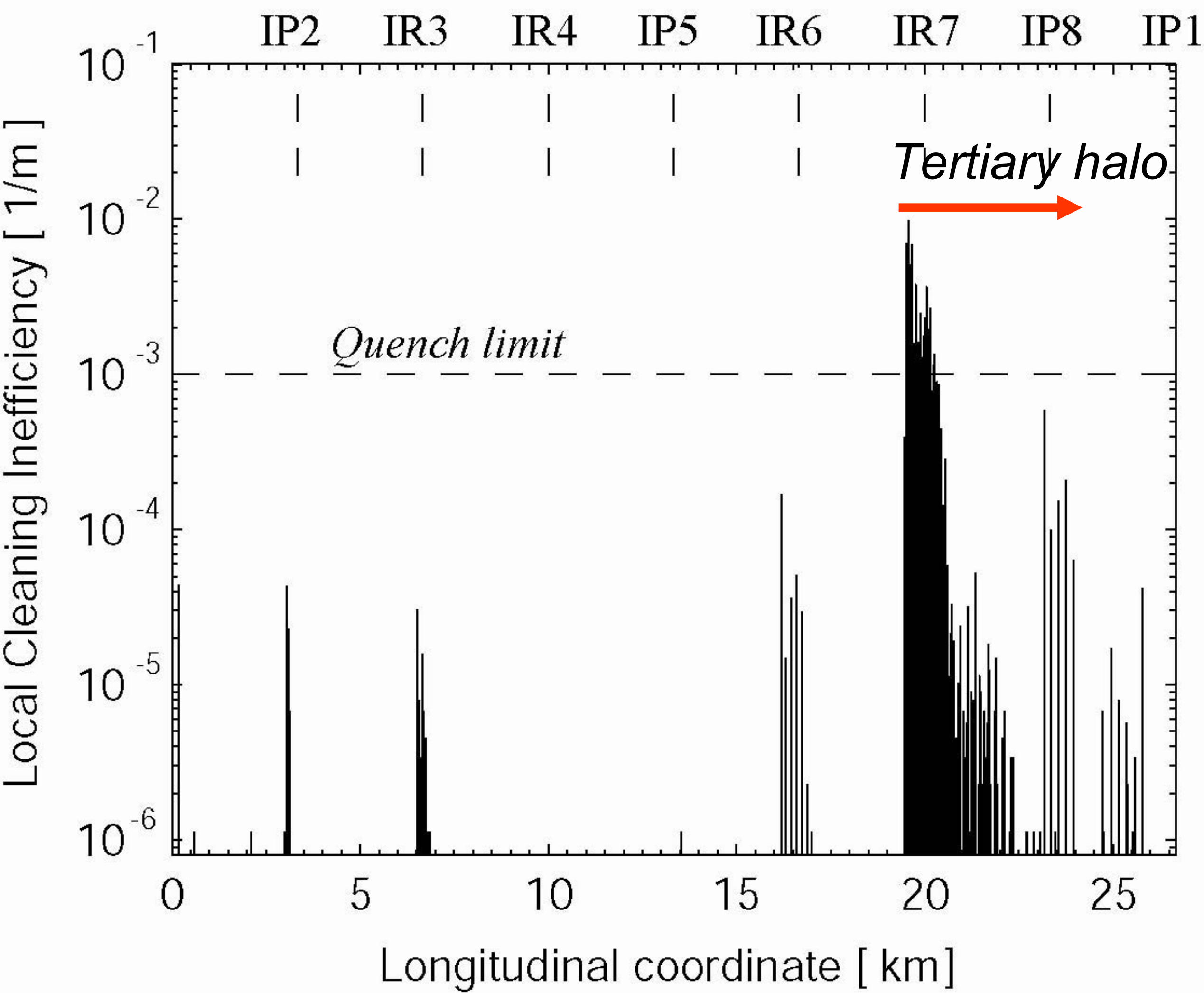
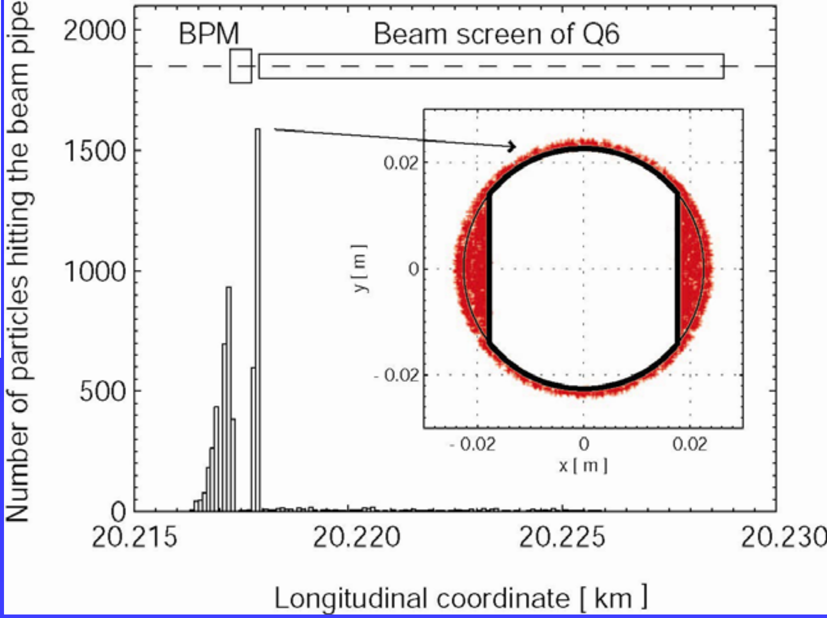
Loss Maps Around the Ring: Injection



Aperture model for 27,000 m LHC with 0.1 m longitudinal resolution: ~ 270,000 loss points!

➔ S. Redaelli
G. Robert-Demolaize

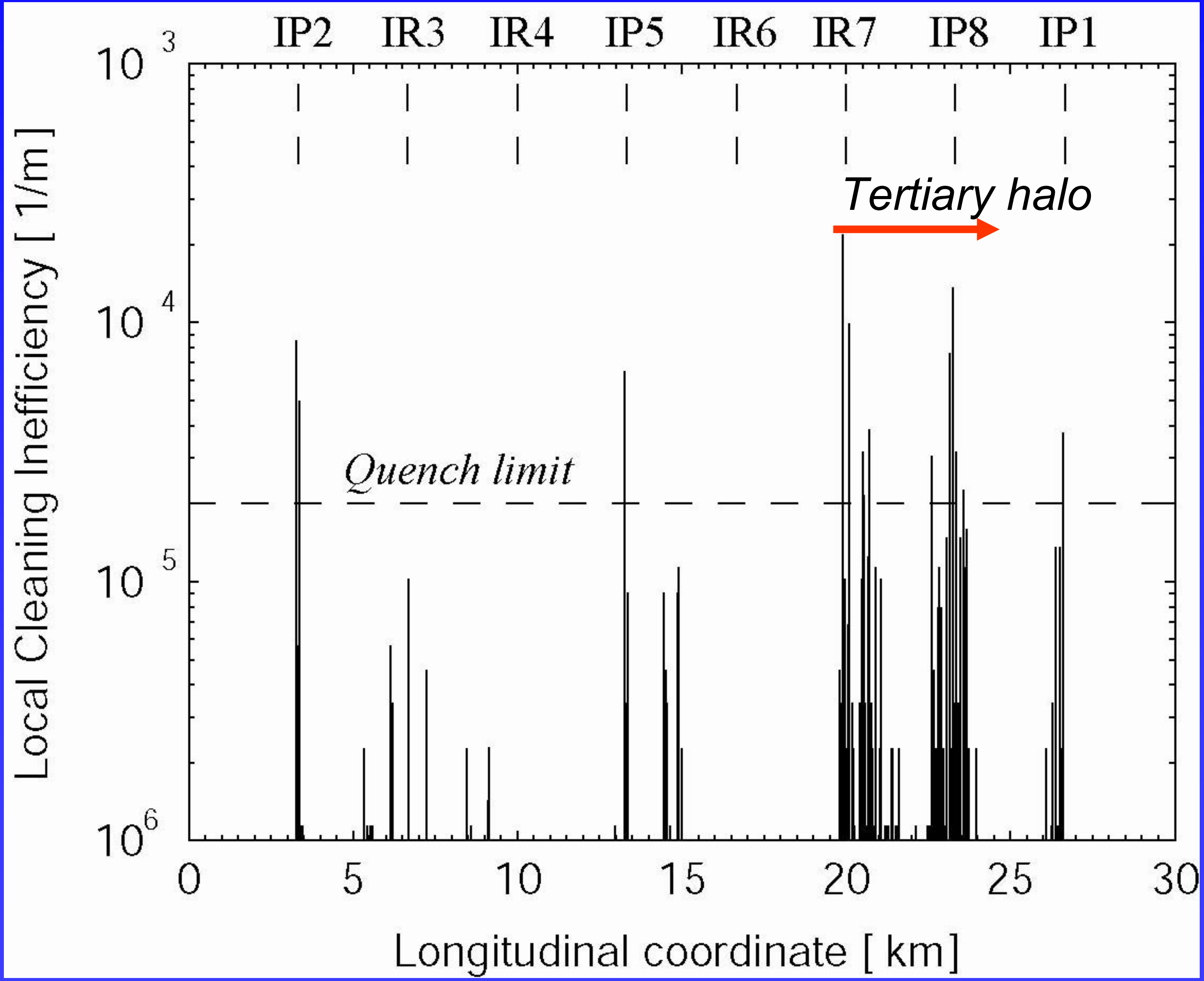
Q6 downstream of betatron cleaning: first SC magnet



Acceptable!? **Understand effect of azimuth on quench. Help further with absorbers in IR7!**

R. Assmann

Loss Maps Around the Ring: Collision



IR8: Initial optics with β^* = 1 m

Peaks in all triplets:

Cure with tertiary collimators!

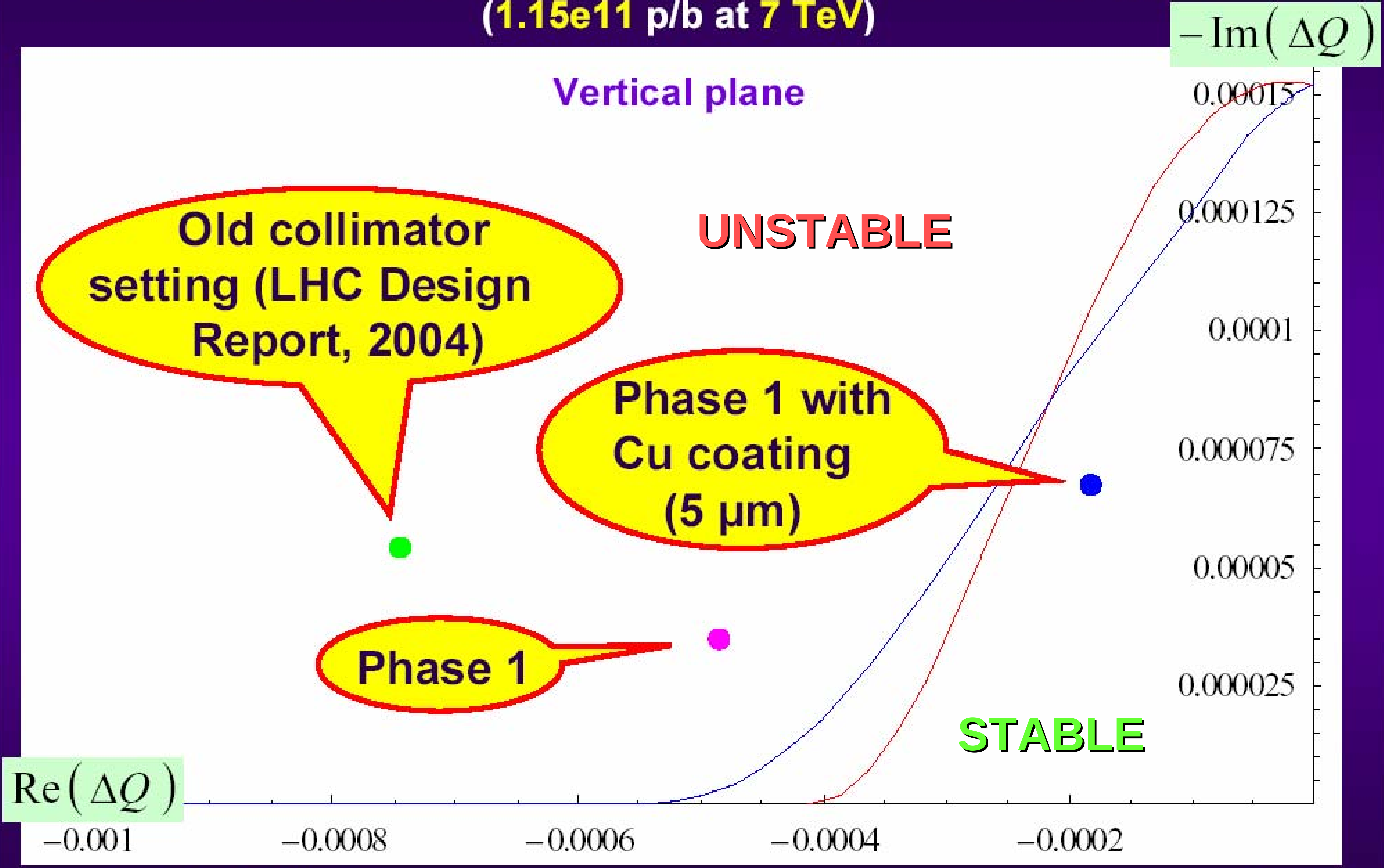
Work is ongoing...
Massive computing effort:
9×10^6 p tracked over 100 turns through each LHC element!
27,000 loss points checked in aperture!

So far only tertiary halo: Include also secondary halo.

Future data generated from SIXTRACK!

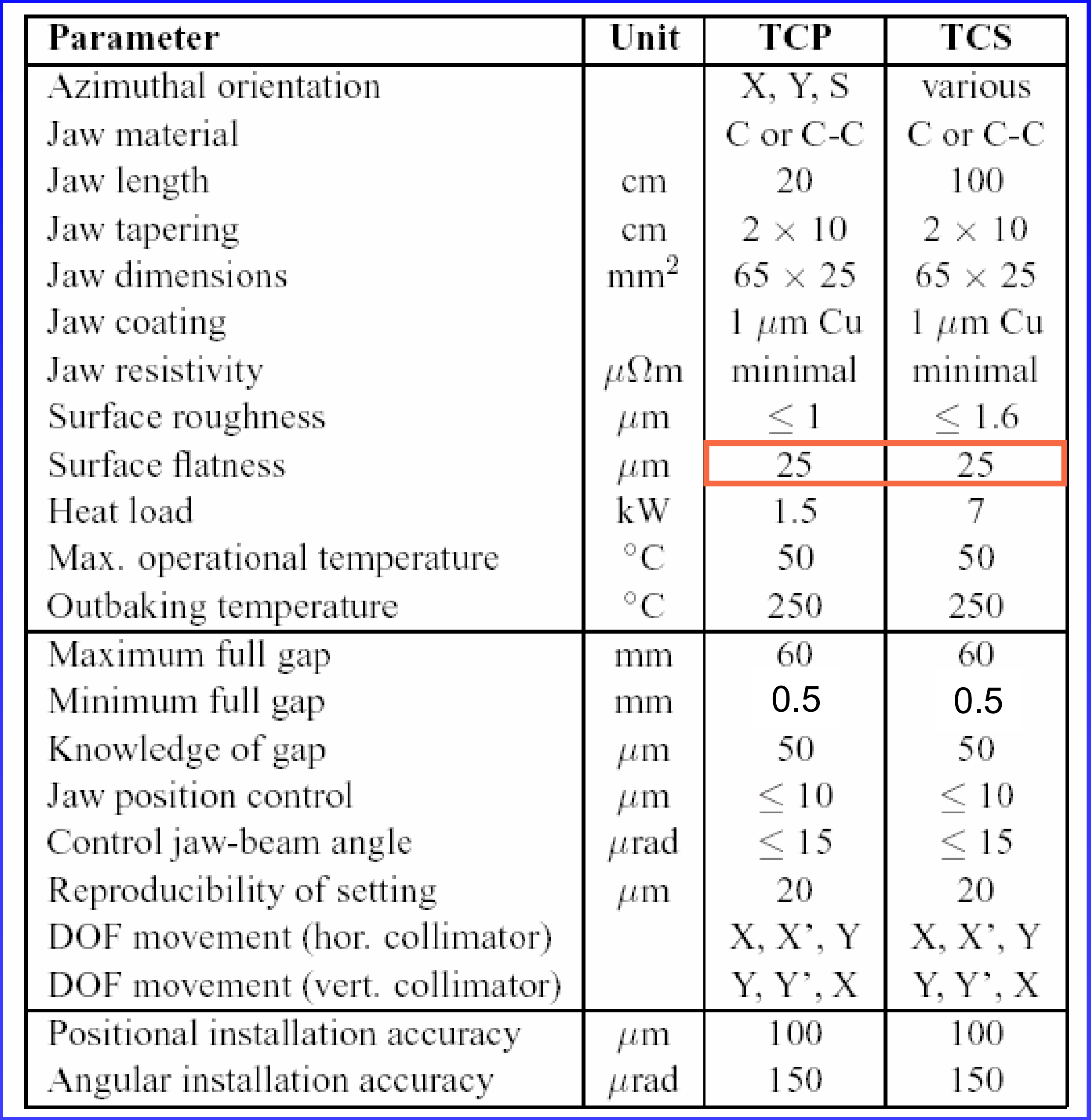
R. Assmann

Stability diagram (maximum octupoles) and collective tune shift for the most unstable coupled-bunch mode and head-tail mode 0 (1.15e11 p/b at 7 TeV)



➔ Elias Metral

Maximum Robustness Jaws for Phase 1



Parameter	Unit	TCP	TCS
Azimuthal orientation		X, Y, S	various
Jaw material		C or C-C	C or C-C
Jaw length	cm	20	100
Jaw tapering	cm	2 × 10	2 × 10
Jaw dimensions	mm^2	65 × 25	65 × 25
Jaw coating		1 μm Cu	1 μm Cu
Jaw resistivity	μΩm	minimal	minimal
Surface roughness	μm	$\lesssim 1$	$\lesssim 1.6$
Surface flatness	μm	25	25
Heat load	kW	1.5	7
Max. operational temperature	°C	50	50
Outbaking temperature	°C	250	250
Maximum full gap	mm	60	60
Minimum full gap	mm	0.5	0.5
Knowledge of gap	μm	50	50
Jaw position control	μm	$\lesssim 10$	$\lesssim 10$
Control jaw-beam angle	μrad	$\lesssim 15$	$\lesssim 15$
Reproducibility of setting	μm	20	20
DOF movement (hor. collimator)		X, X', Y	X, X', Y
DOF movement (vert. collimator)		Y, Y', X	Y, Y', X
Positional installation accuracy	μm	100	100
Angular installation accuracy	μrad	150	150

Driving criteria for material:

Resistivity (7-25 μΩm)
Short lead times

Design work and prototyping under way
TS leads effort:

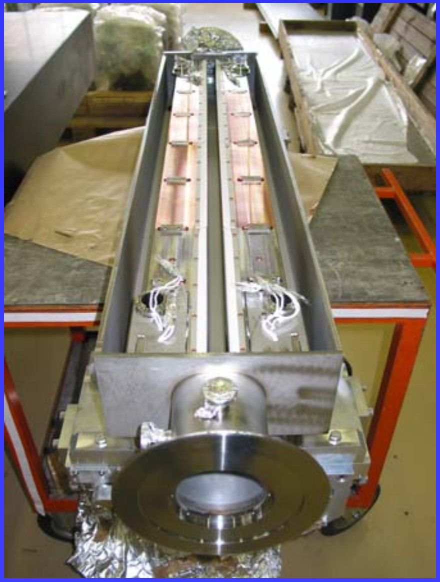
A. Bertarelli
M. Mayer
S. Calatroni

Visit of collimator Friday morning!

Design “phase 1” secondary collimators

- More **conventional design** (next iteration on LEP concept) with advanced features.
- Two graphite jaws, movable in angle and position, **maximum robustness**, concept of spare surface.
- **Full redundant read-out** of gap at both ends, gap center, jaw positions. In addition temperature sensors and sensors for damage detection.
- **Thin coating** for impedance reduction (coating destroyed in case of direct beam hit, graphite unaffected).
- Mechanical “automatic” opening with motor failure (motor pressing against spring).
- **Quick plug-ins** for electrical and water connections. Fast exchange flanges. Short installation and replacement time! Crucial for radiological reasons!
- **Three prototypes** being constructed now. **Surface flatness is a critical parameter.**
- Tests of prototypes with **SPS beam** after Aug 2004.

Secondary Collimators Take Shape



SPS

R. Assmann

The SPS Tests

1. SPS ring:

   Show that the LHC prototype collimator has the required functionality and properties (mechanical movements, tolerances, impedance, vacuum, loss maps, …).

2. TT40 extraction:
   Show that an LHC collimator jaw survives its expected maximum beam load without damage to jaw material nor metallic support nor cooling circuit (leak). ➔ 2 MJ on 1 mm × 1 mm area!

Crucial project milestone

(installation 18Aug04)

Mechanical engineering
Tolerances
Prototype production
Control and motorization
Set-up of a single LHC collimator with beam

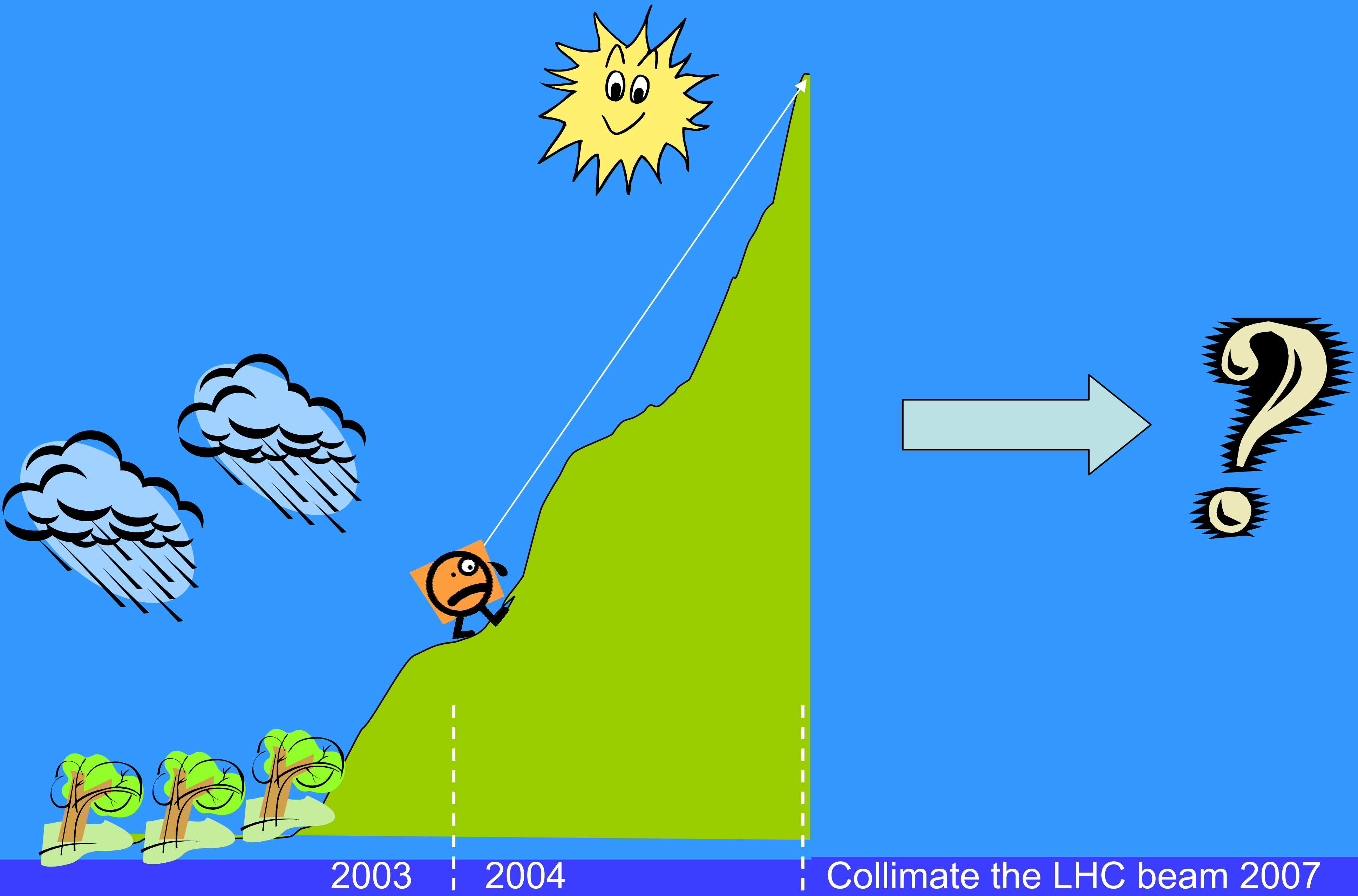
Conclusion

- This introductory talk should set the scene and get you into a collimation mood!
- Picked some important topics! Other important issues were not covered in this talk!
- 20 more talks to come → much more technical detail for a complete picture of the work done and being done!
- Don't expect a complete and frozen picture! Things are still moving fast, but important issues have been frozen:
  - **Collimation requirements**
  - **Phased approach**
  - **Layout of cleaning insertions**
  - **Choice of low Z carbon-based material**
  - **Design of phase 1 collimators (TCP and TCS)**
- If no bad surprises: Ready for LHC beam in 2007!

Ongoing work

- **Prototyping and design** of all phase 1 components (so far focused on secondary and primary collimators). Testing in laboratory and with beam.
- **Motorization and control** (motor control, collimator control, collimation system control). High precision control with high reliability.
- Preparation of **series production** of components.
- System layout: Placement of **absorbers** and **radiation handling** (energy deposition studies).
- **Collimation efficiency**: Beam loss around ring. Compare to quench limits. Influence of errors/physics models. Massive computing effort.
- Procedures: Performance during set-up. **Setting up** a single collimator and the whole system. Massive computing effort.
- **Radiation damage** in the Carbon collimators from LHC beam (structural, electrical, thermal, ...): How long do the collimators survive? (Kurchatov)
- A possible design for an advanced **phase 2 collimator**! (SLAC-US LARP)

The LHC “collimation mountain”



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Five sessions upcoming

1. Baseline assumptions and requirements for collimators.
2. Mechanical design and prototyping of phase 1 collimators.
3. Energy deposition and its consequences/cures.
4. LHC performance with phase 1 collimation and collimation set-up/optimization.
5. Operation and control. Radioprotection.

Use time for questions and discussion...
Additional time for discussion on Friday morning...