Collimation – Latest Developments

R. Assmann for the Collimation Team

Accelerator & Beams Department, CERN

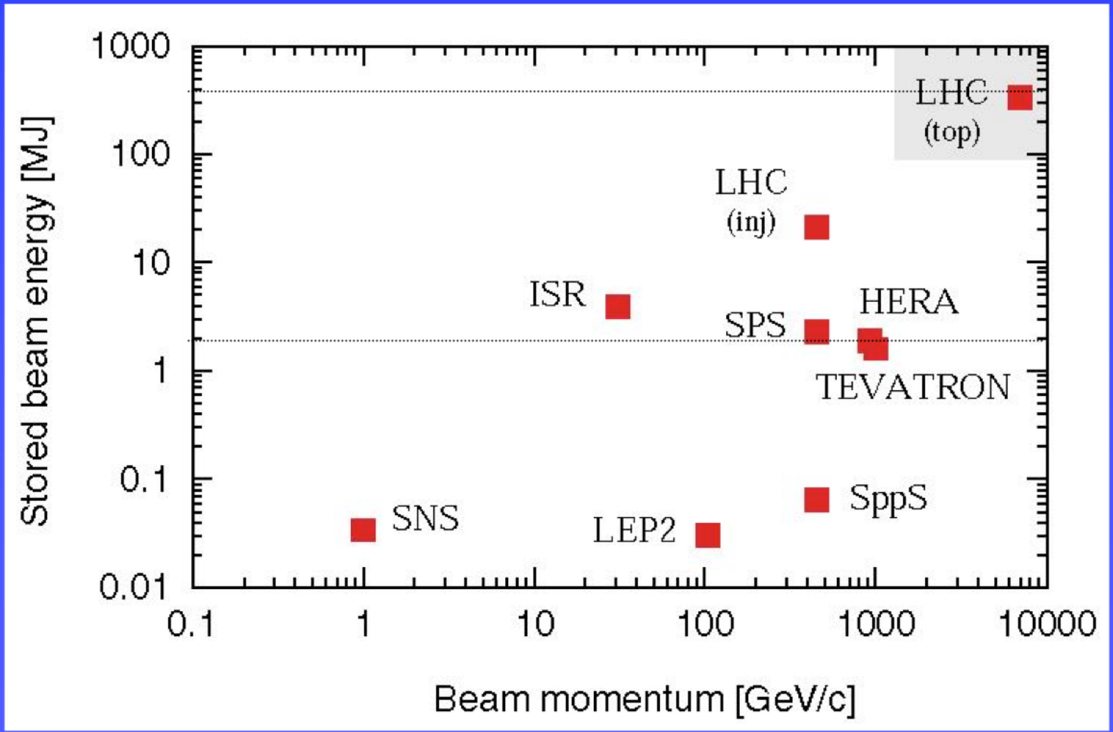
LHC Machine Advisory Committee

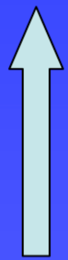
December 8th – 10th 2004

The LHC Collimation 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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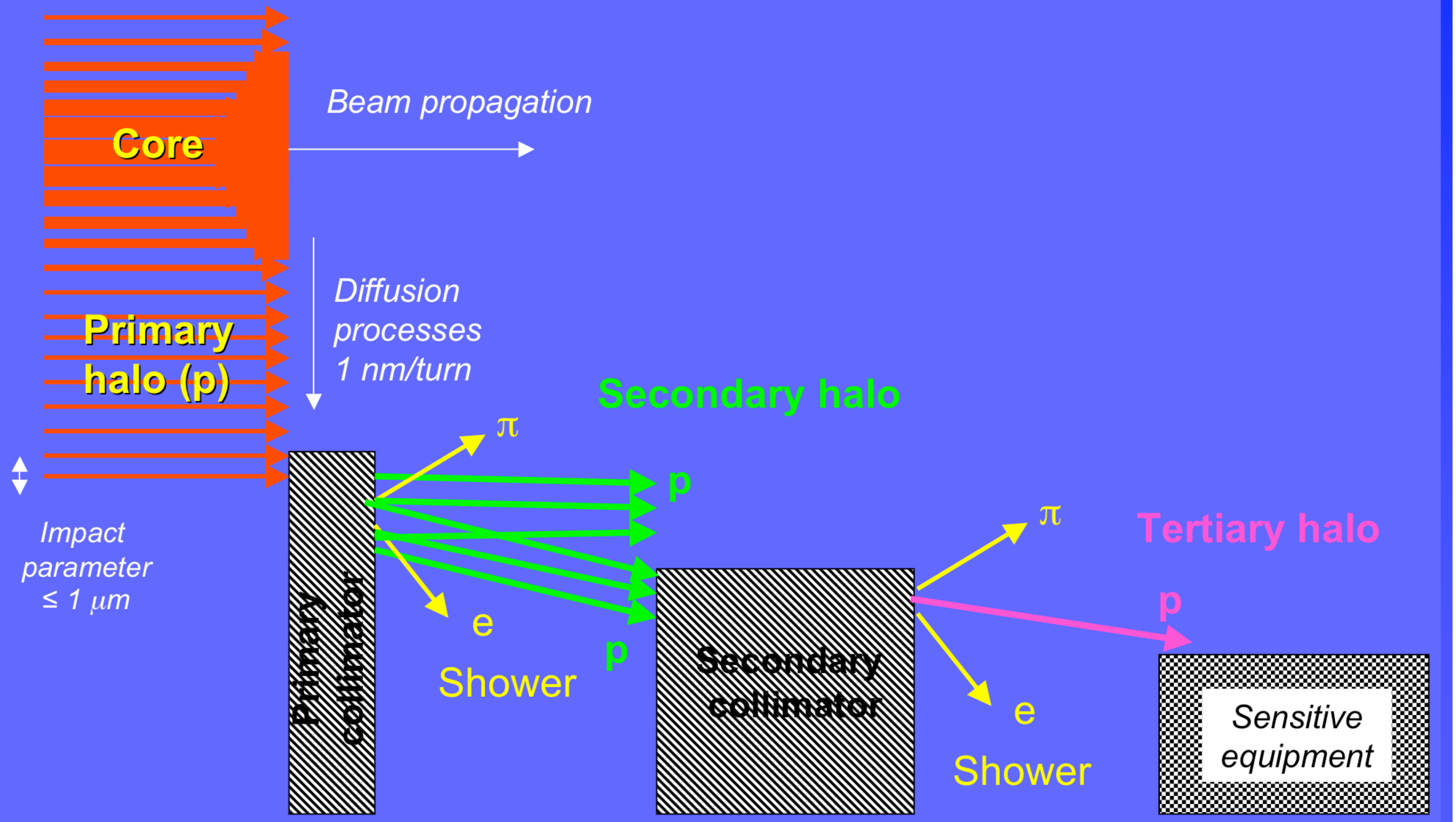
Cleaning of the Beam Halo...



... two stage cleaning ...

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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:**

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.

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Addressing the Worries...

- **Set-up of collimation project in early 2003**
- **Definition of "collimation design philosophy"**
- **Optics and cleaning design for new baseline solution**

➔ *See MAC talk Dec 2003*

- Detailed design work on phase I of new baseline:
  - Collimator design and prototyping
  - Energy flow in cleaning insertions and leakage to downstream
  - Overall layout optimization of cleaning insertions
  - Efficiency studies for beam halo
  - Design verification with beam tests
- Preparation of series production

The Phased Approach (MAC Dec 2003)

LHC Collimation Project CERN

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, IR8** 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

**Phase 3 is the upgrade of absorbers for physics debris in IR1 and IR5.*

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Optics and Cleaning Design (MAC Dec 2003)

LHC Collimation Project CERN

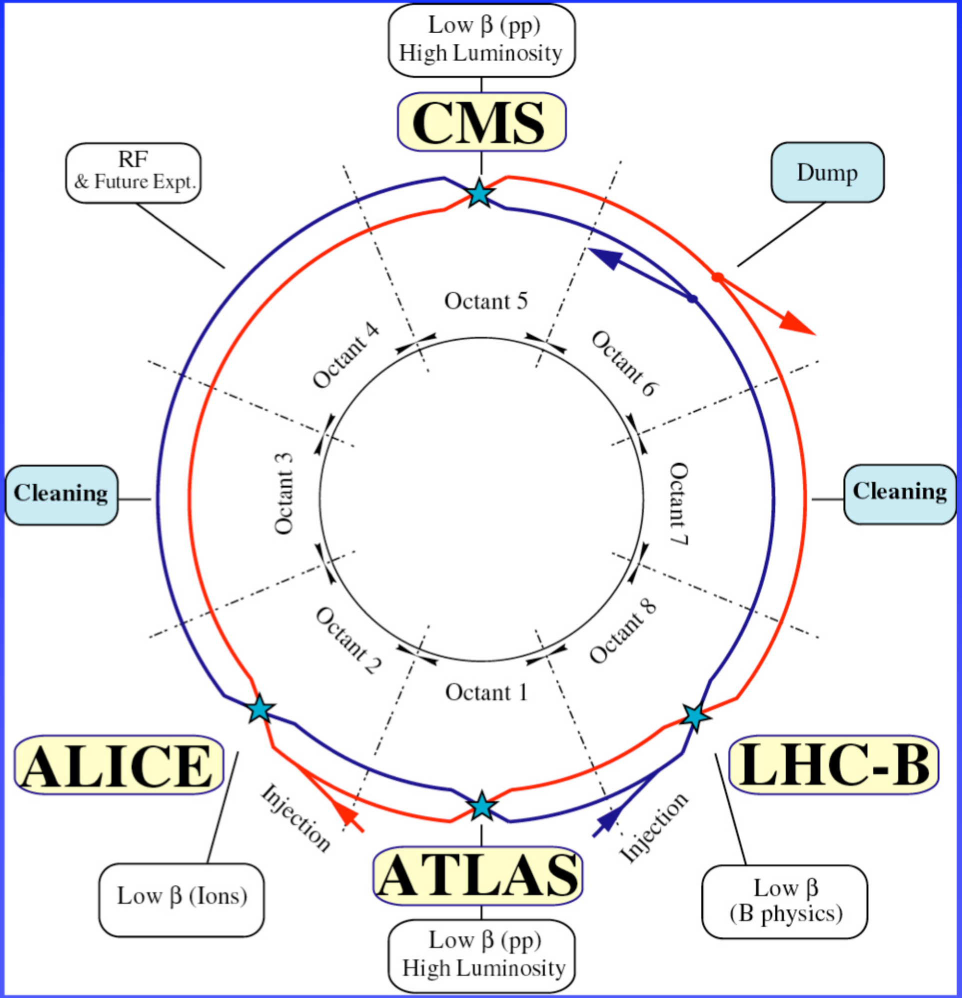
Two warm LHC insertions dedicated to cleaning:

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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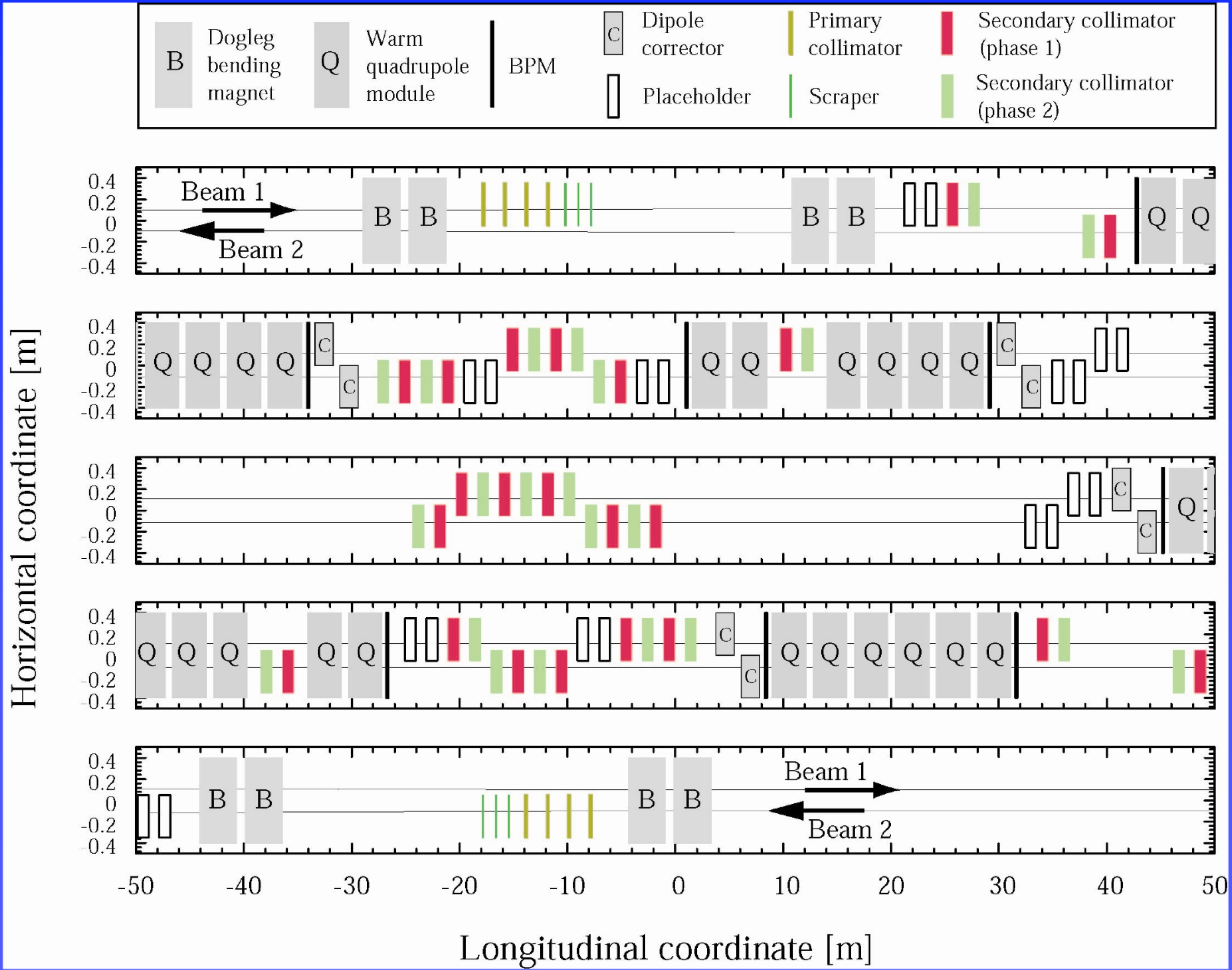
New Machine Layout IR7 (V6.5)



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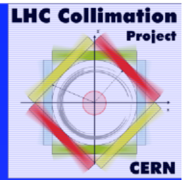
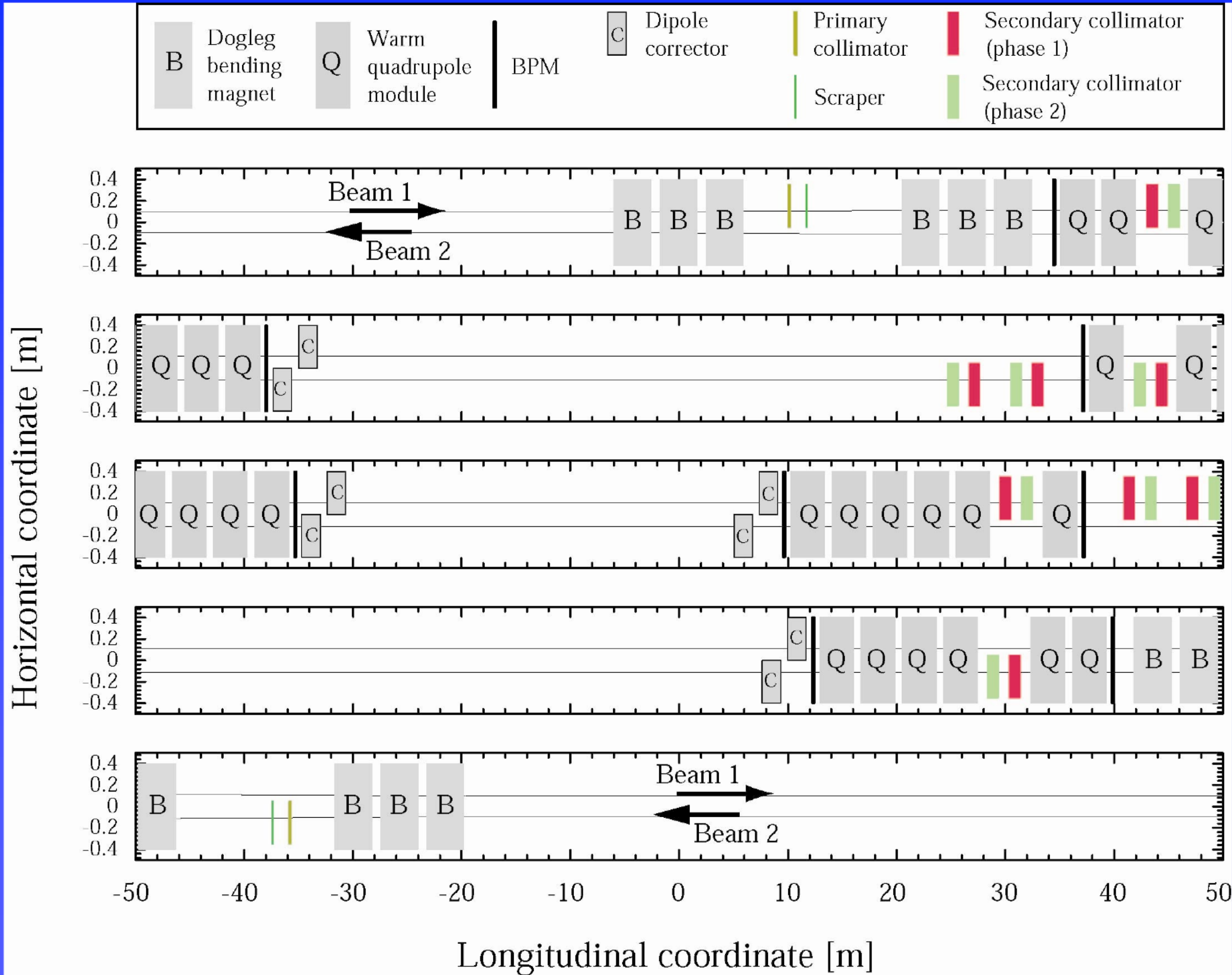
New Machine Layout IR3 (V6.5)





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Collimator Design and Prototyping

Example for strong collaborative effort **across different departments** at CERN:

AB	(specification, energy deposition, motorization and sensors, project home)
TS	(mechanical design, ANSYS, prototyping)
AT	(vacuum issues for jaws)
SC	(radiation issues)

Mechanical design effort led by TS department!

Start of design:	**September 2003**
Start of prototyping:	February 2004
Laboratory tests:	July 2004
Installation for beam tests:	August 2004
Beam tests:	**October/November 2004**

Collimator Specification

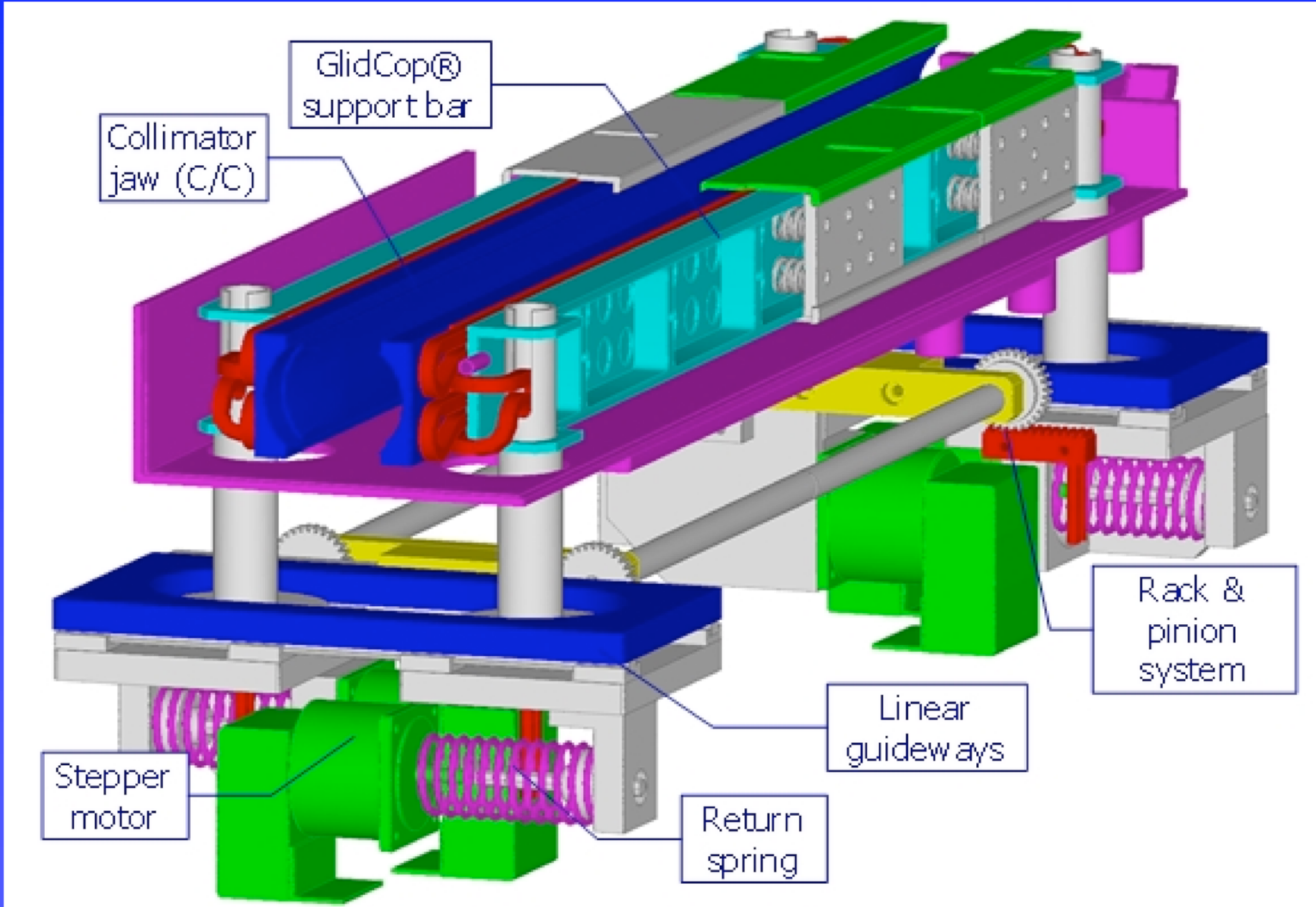
Parameter	Unit	TCP	TCS
Azimuthal orientation		X, Y, S	various
Jaw material		C or C-C	C or C-C
Jaw length	cm	20	100
Jaw tapering	cm	2×10	2×10
Jaw dimensions	mm^2	65×25	65×25
Jaw coating			
Jaw resistivity	$\mu\Omega$m	minimal	minimal
Surface roughness	μm	≤ 1	≤ 1.6
Surface flatness	μm	25	25
Heat load	kW	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	≤ 10	≤ 10
Control jaw-beam angle	μrad	≤ 15	≤ 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 was robustness:

➔ **Carbon-carbon**

Resistivity (7-25 μ_m)
Short lead times

Collimator Scheme

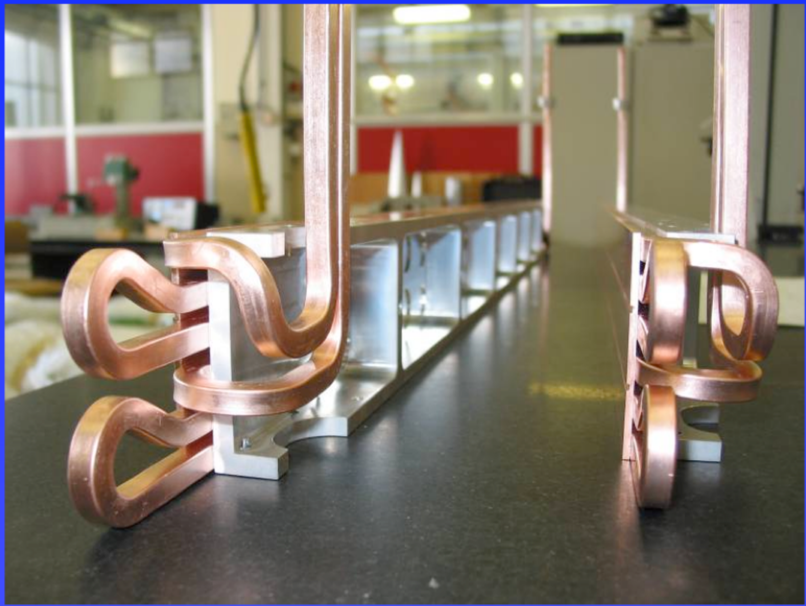


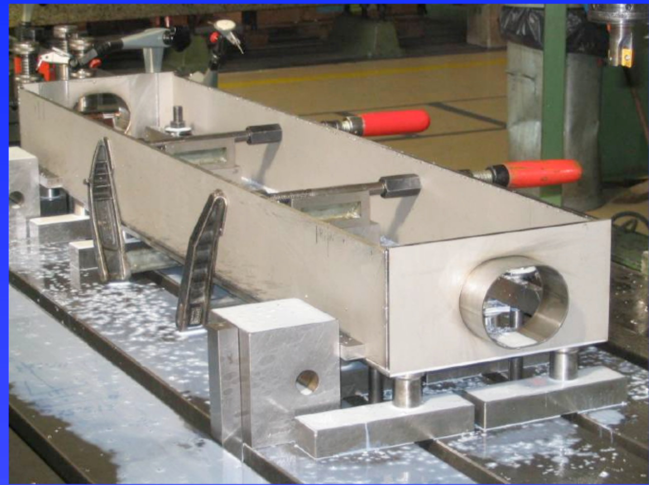
A. Bertarelli, R. Perret et al

LHC Collimation Project CERN

Building the LHC collimator

Jaw clamping support with cooling





Vacuum tank

Completed jaw

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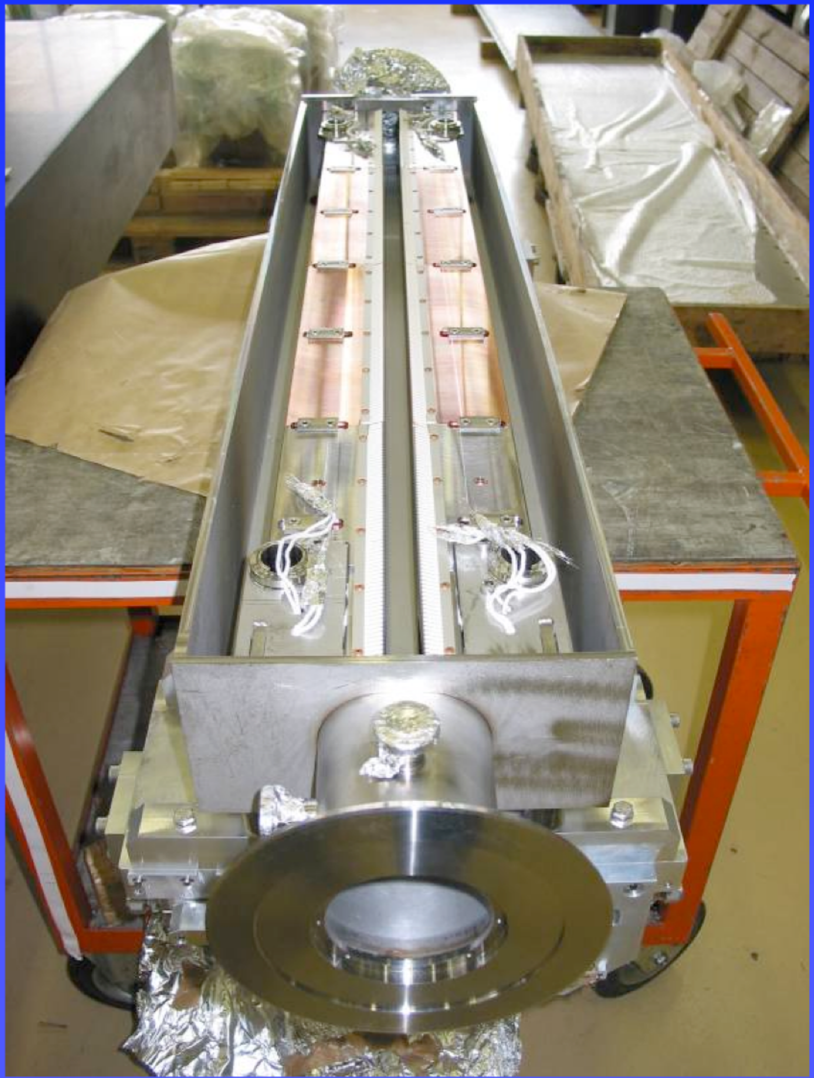
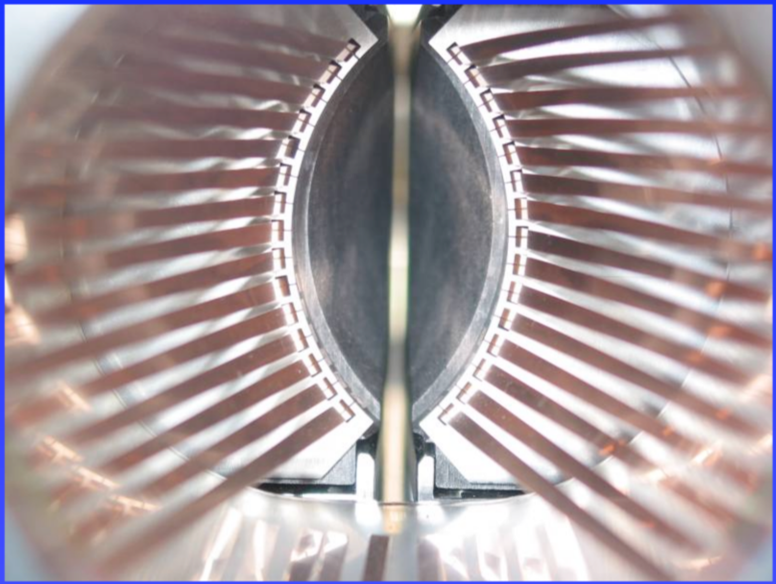
Building the LHC collimator



Vacuum tank with two jaws installed



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

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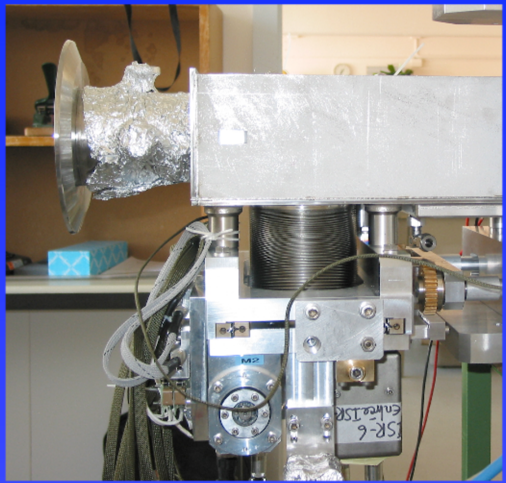
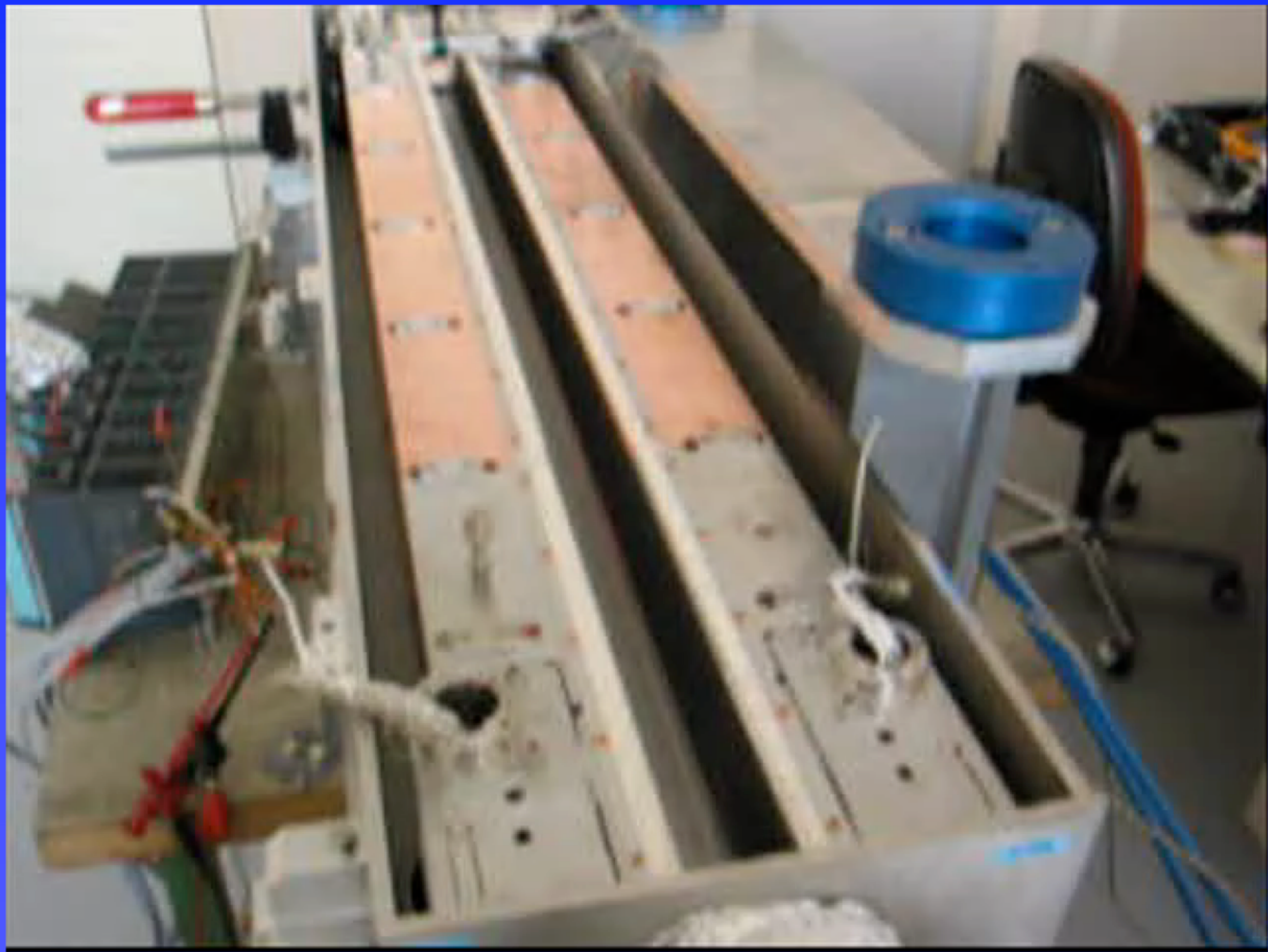
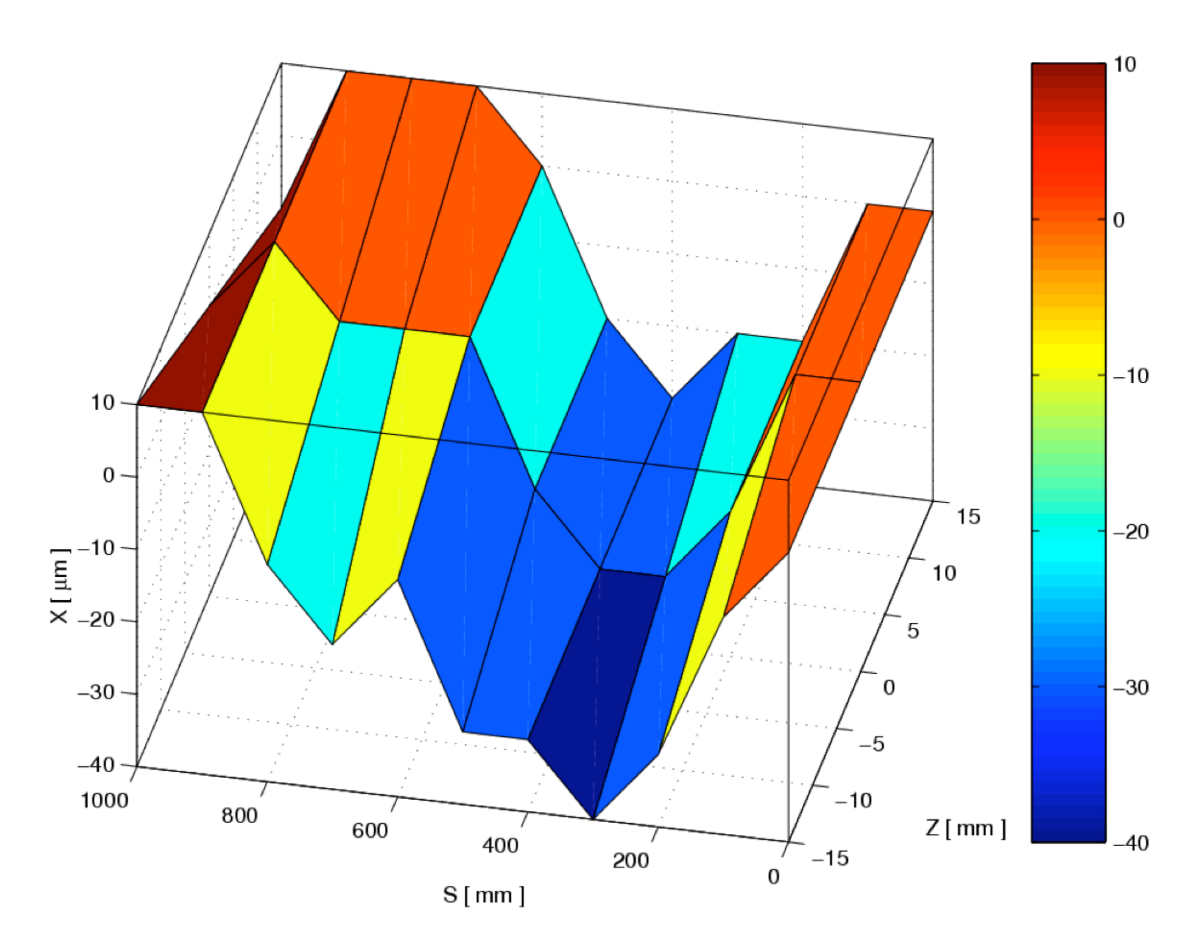
Moving the jaws...





Surface flatness

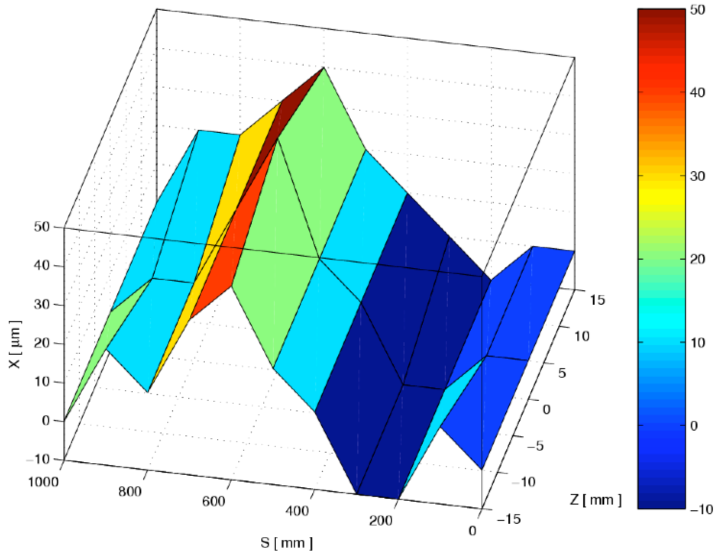


After 250 °C bakeout:

40 – 60 µm

flatness on clamped jaw!

Flatness specification changed to 40 µm *(stricter tolerances on other parameters)!*



S. Redaelli et al

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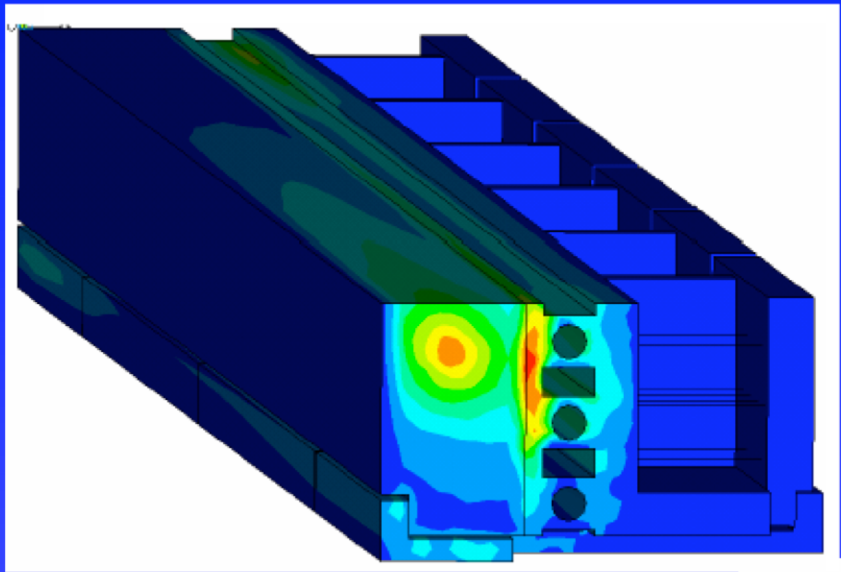
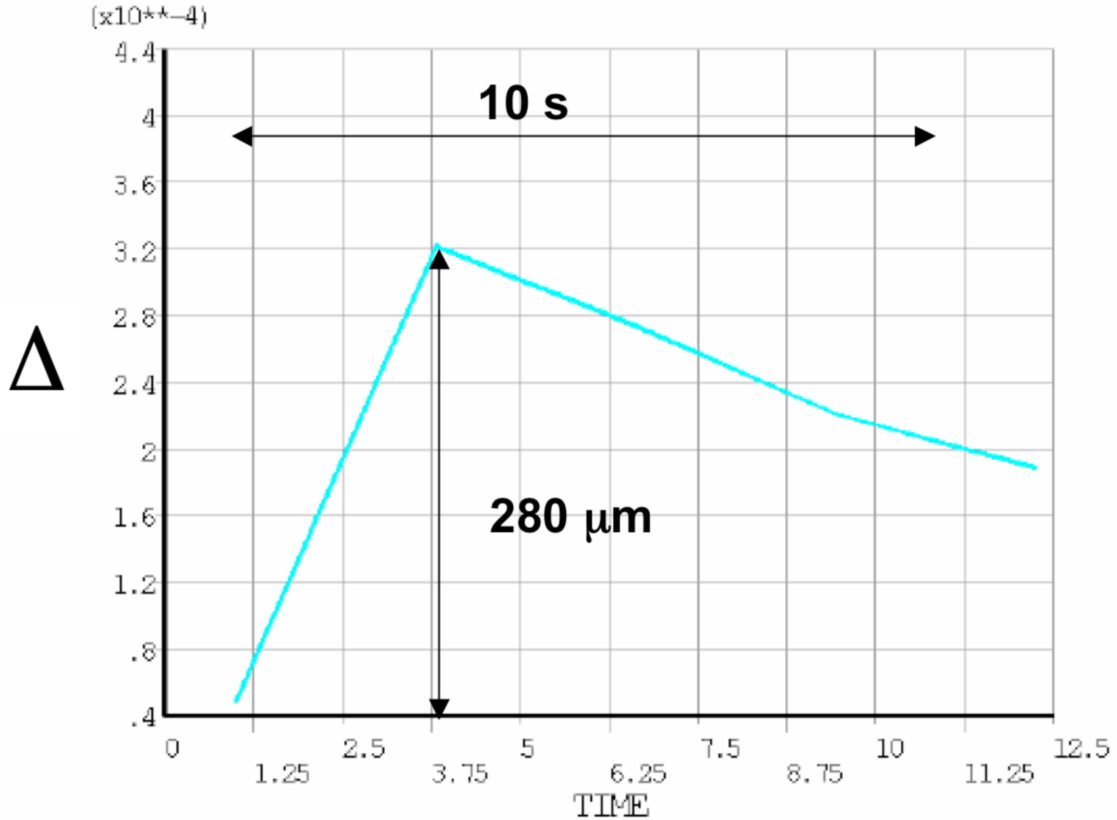
Deformation with Transient Beam Heating



A. Bertarelli
A. Dallachio

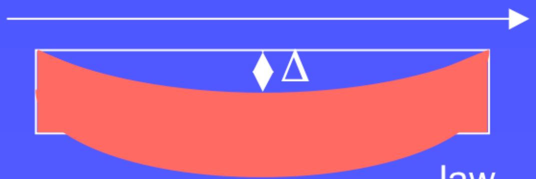
Time dependent "banana" effect (ANSYS)



Halo data - *AB/ABP*

Energy deposition for 10 s drop of lifetime to 0.2 h (1% of beam lost in 10 s) - *FLUKA team*

Collimator deforms away from beam ➔ only reduction in efficiency for a few collimators!



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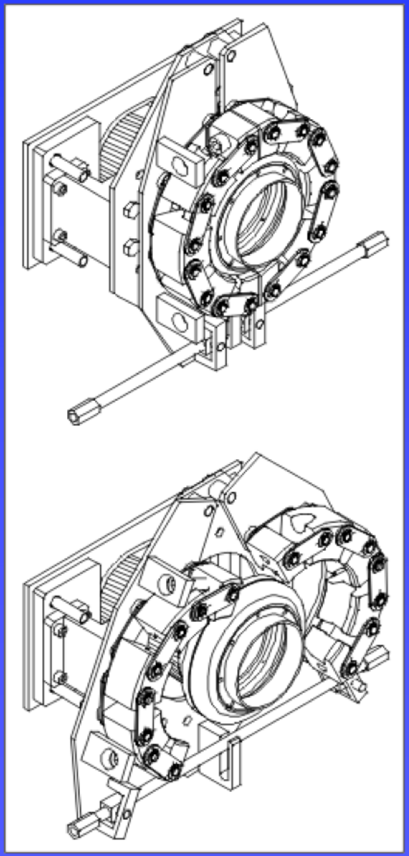
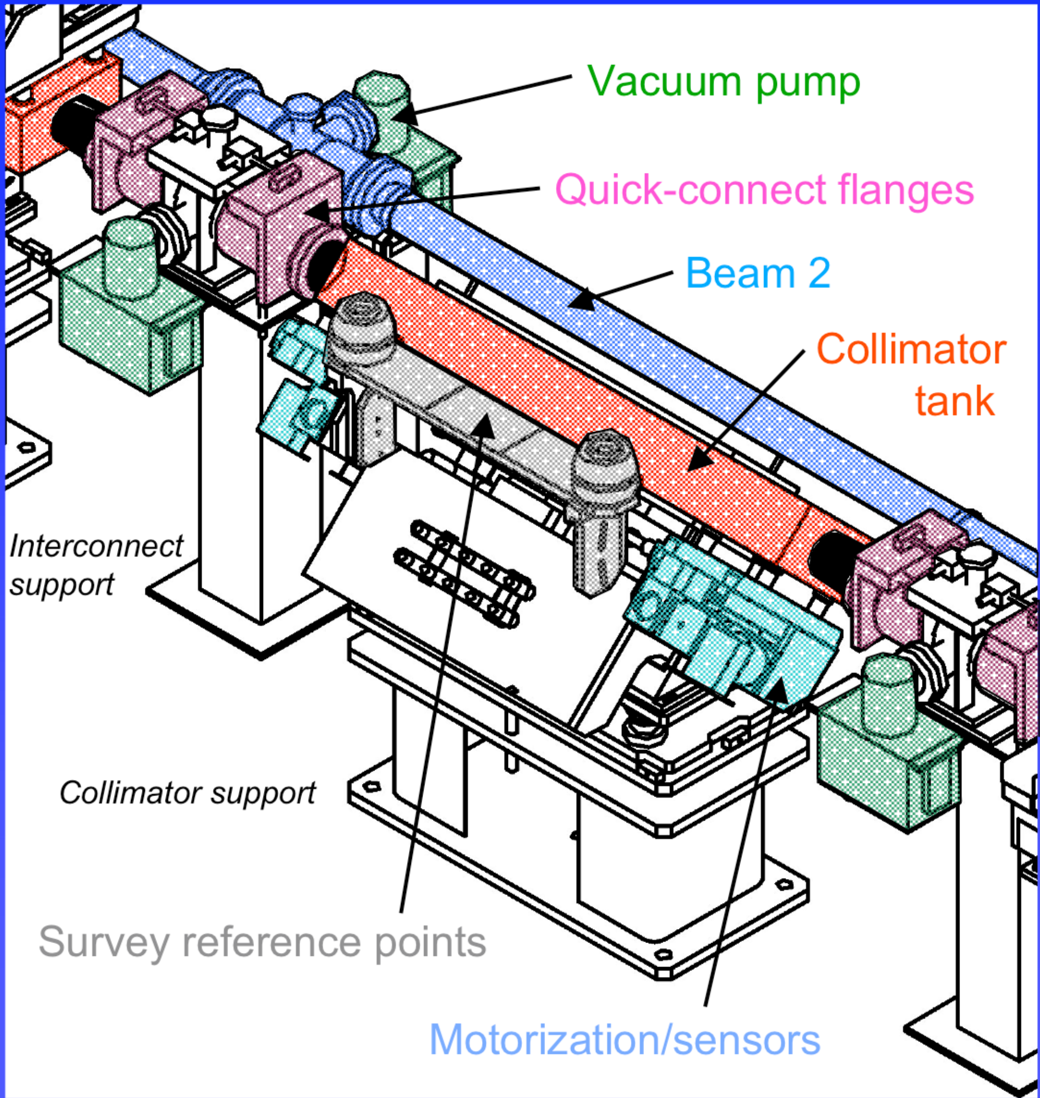
Other collimator features

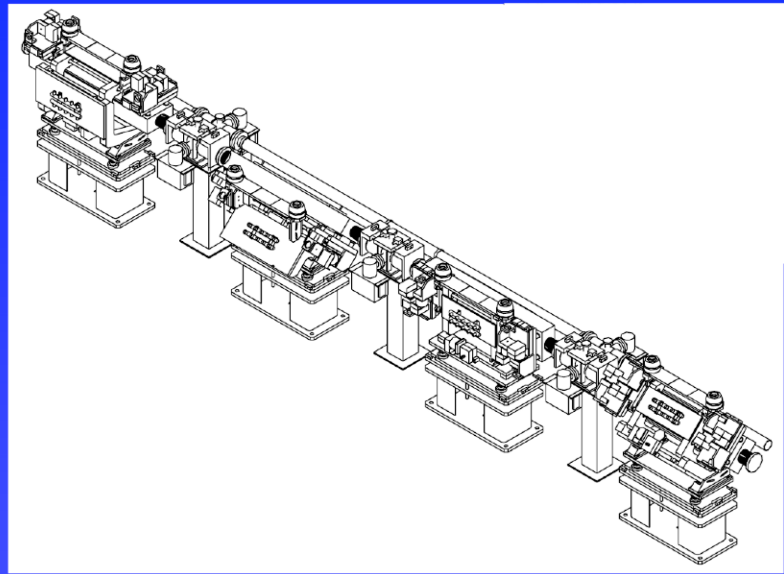
- Automatic **jaw retraction** in case of motor failure (no collimators stuck in the beam)
- In-situ **spare concept** by moving the whole tank (move to fresh surface if we scratch the surface with beam)
- Direct **measurements of jaw positions and absolute gap** (we always know where the jaws are)
- Precision **referencing system** during production
- Measurements of jaw **temperature**
- **Radiation impact optimization**: Electrical and water quick plug-ins, quick release flanges, ceramic insulation of cables, ...
- **RF contacts** to avoid trapped modes or additional impedance



C. Rathjen, AT/VAC

Collimator Supports and Inter-Connects



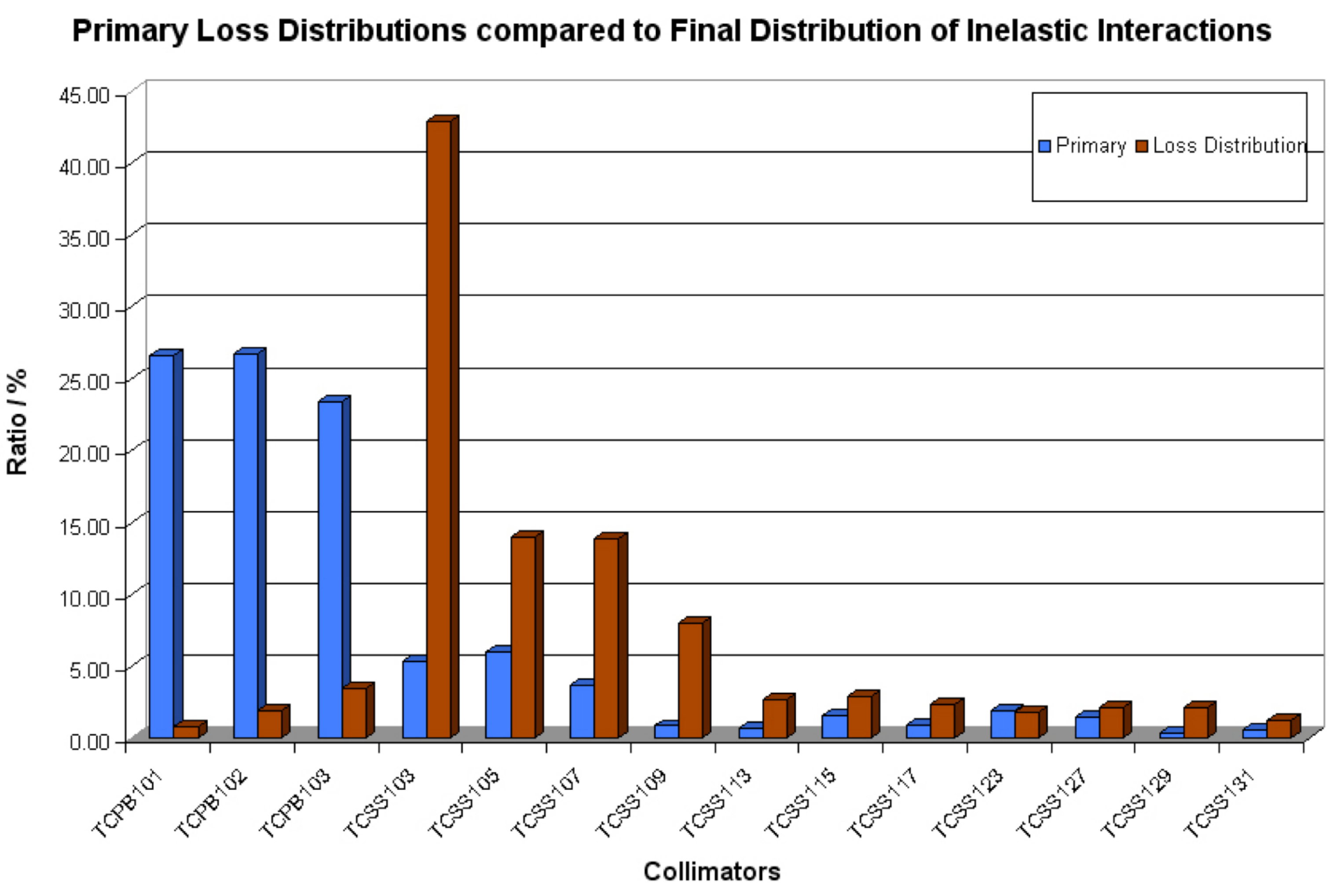


R. Perret et al

Energy flow in cleaning insertions and leakage to downstream

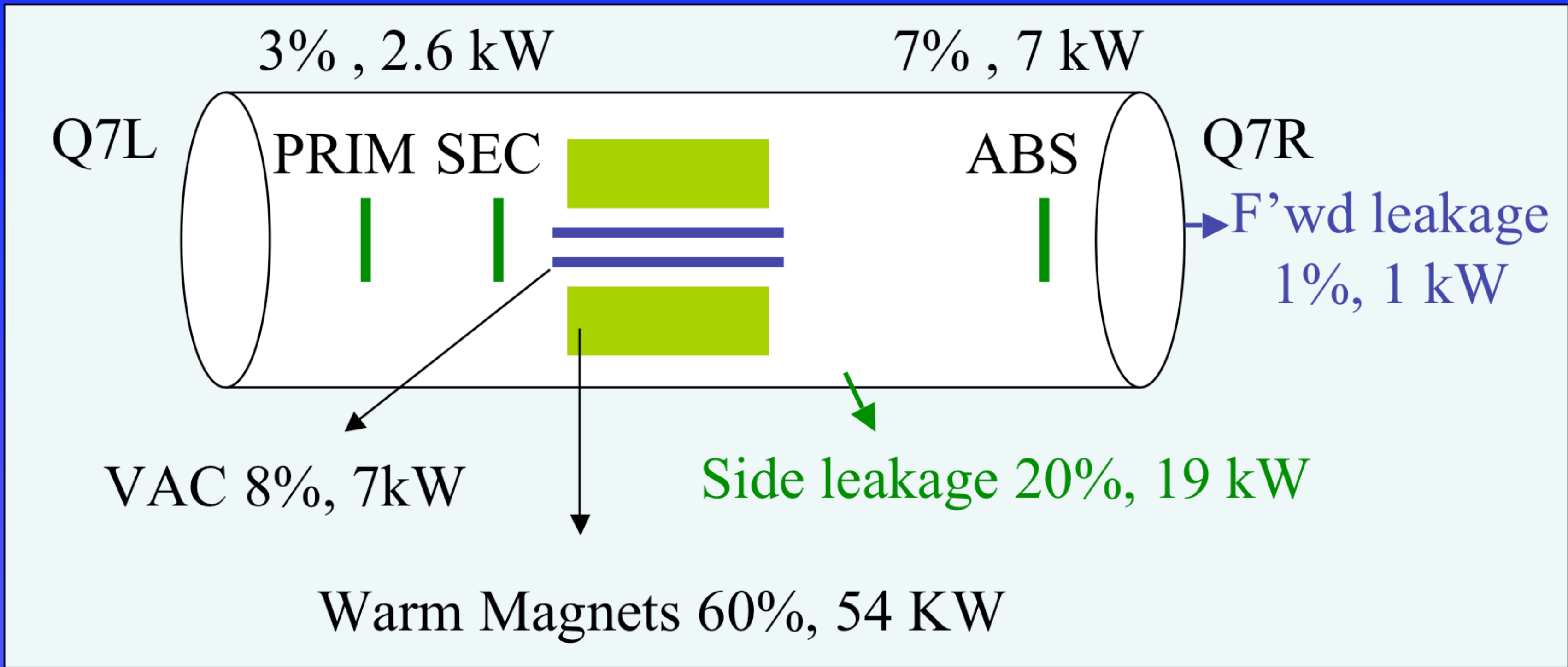
- Multi-turn tracking of **proton halo (primary – secondary – tertiary)** provides locations of inelastic interactions in jaws around the LHC ring (AB/ABP):
  - Efficiency of halo cleaning (later).
  - Only proton halo is transported over long distances.
- Energy is carried by **proton-induced showers**:
  - Showering studies in IR3 (IHEP) and IR7 (CERN_FLUKA team).
  - Showers lost locally
- Information on:
  - Energy load on downstream cold regions.
  - Heating and radiation to components.

From halo tracking to losses



M. Brugger et al

Power flow IR3, $\tau = 1h$, $P_{tot} = 90kW$



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

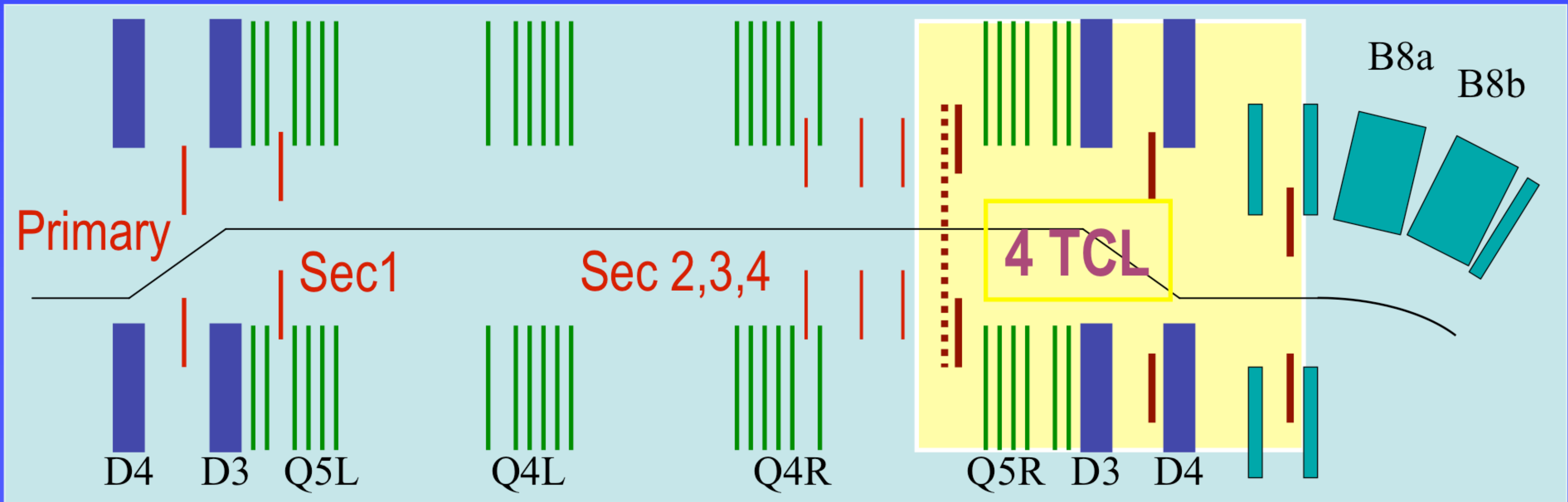
TCL = Active absorbers

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



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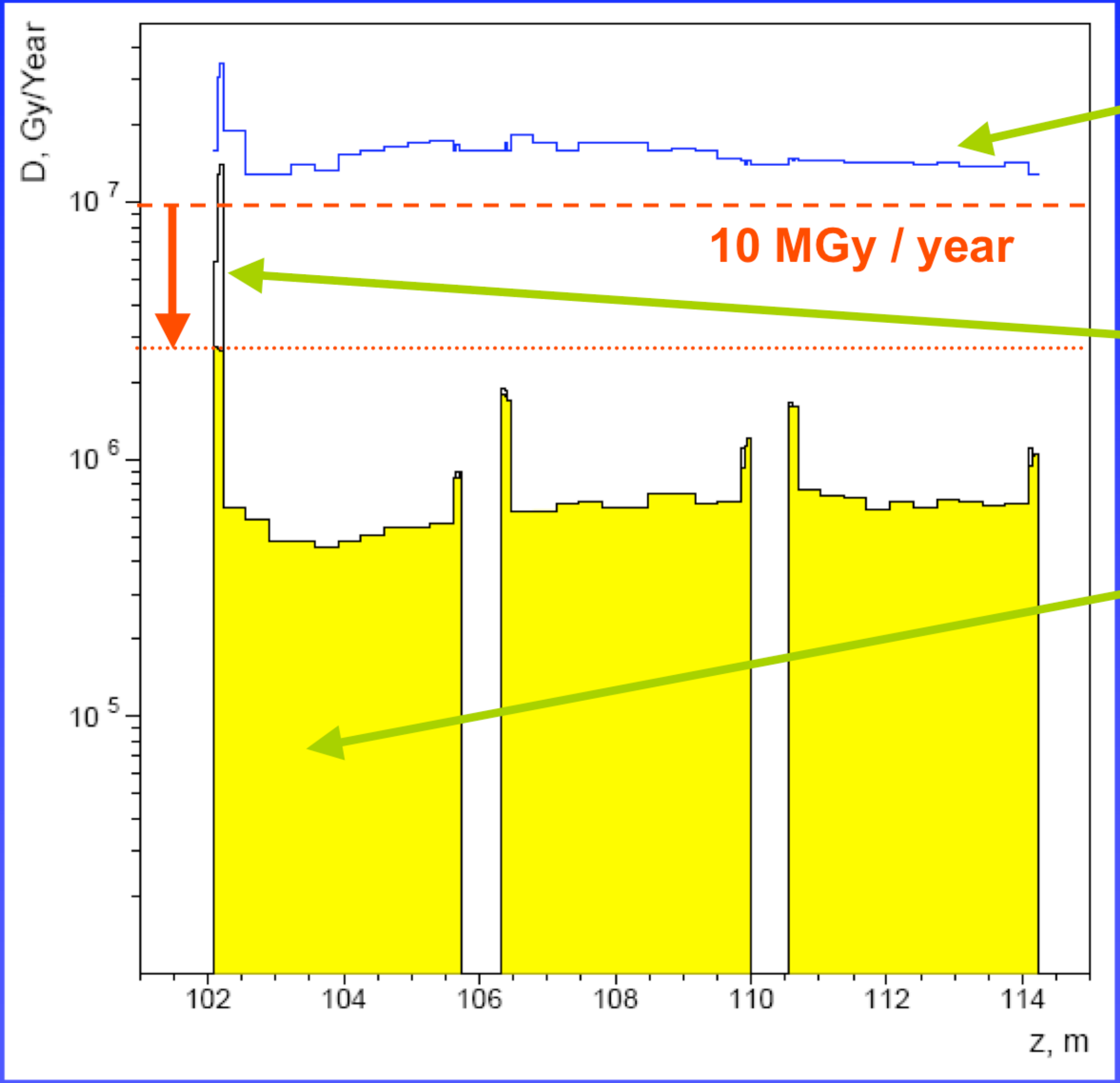
IR3: Dose to the D3 magnet



J.B. Jeanneret, I. Baishev

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…

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Detailed FLUKA Description of IR7

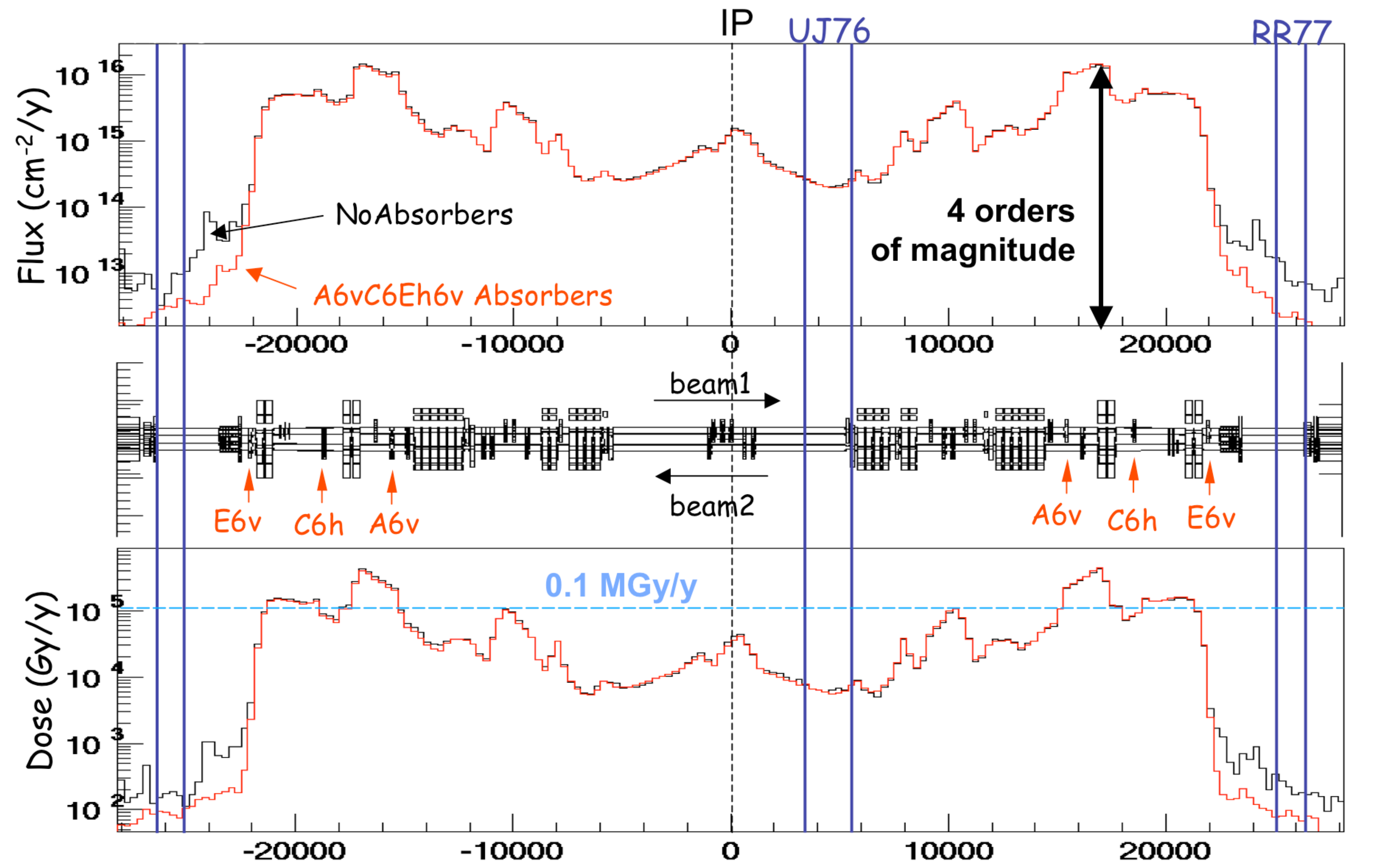
V. Vlachoudis et al

Line input file for FLUKA generated from collimation halo tracking program.
Automatic generation of FLUKA geometry with dynamic placement of collimators.
Powerful tool ➔ Automatic generation of full LHC FLUKA geometry on the horizon?

Studies on absorbers ➔ Similar outcome as in IR3 – factor 200 improvement needed!

Dose in IR7

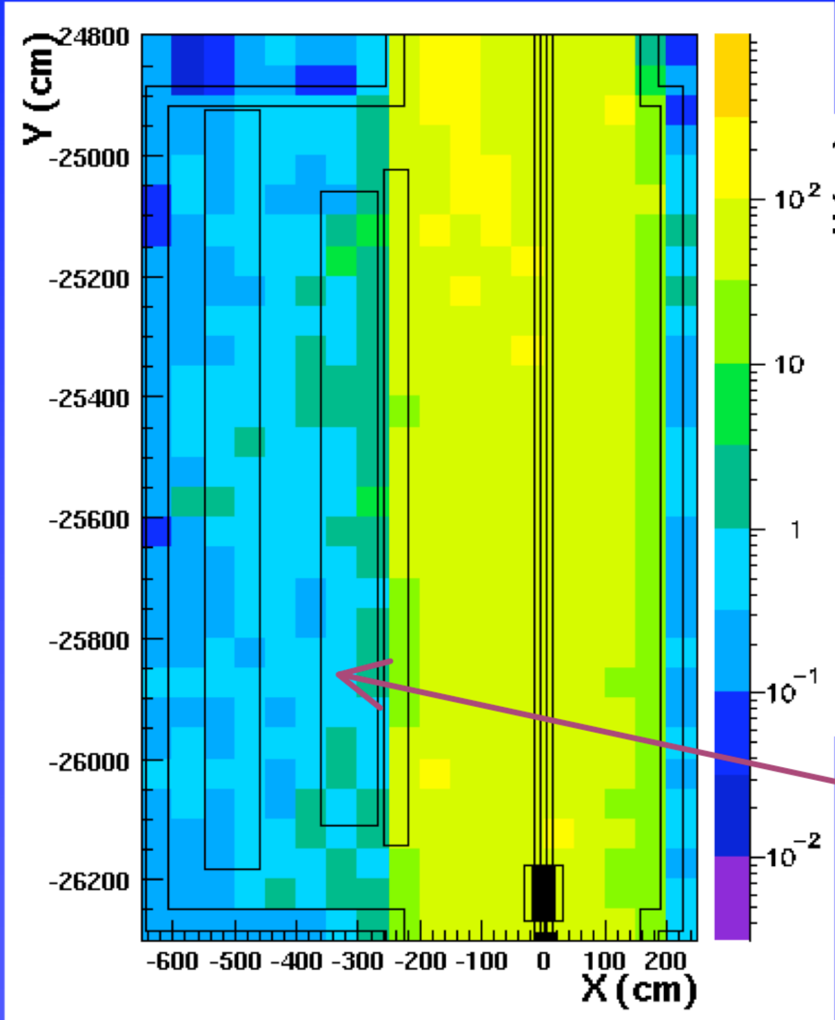
K. Tsoulou et al



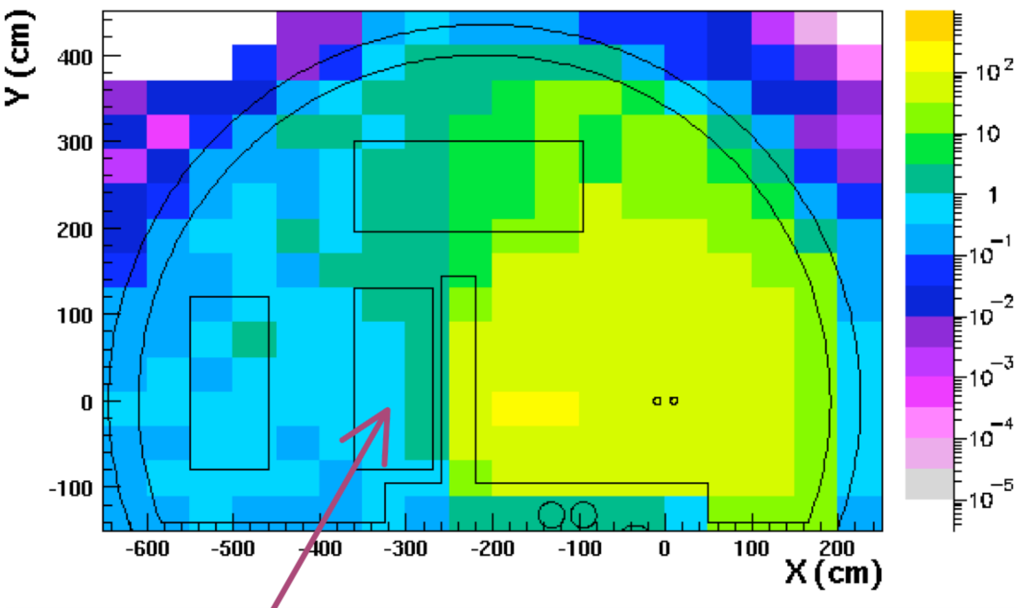
Mean values ± 2m horizontally and ± 1m vertically.

Radiation to electronics

Dose (Gy/y)



Dose (Gy/y)



Doses in racks ≤ 5 Gy/y

~ 1 order of magnitude less than without active absorbers but still factor 10 too high!

K. Tsoulou et al

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Personnel Dose IR7

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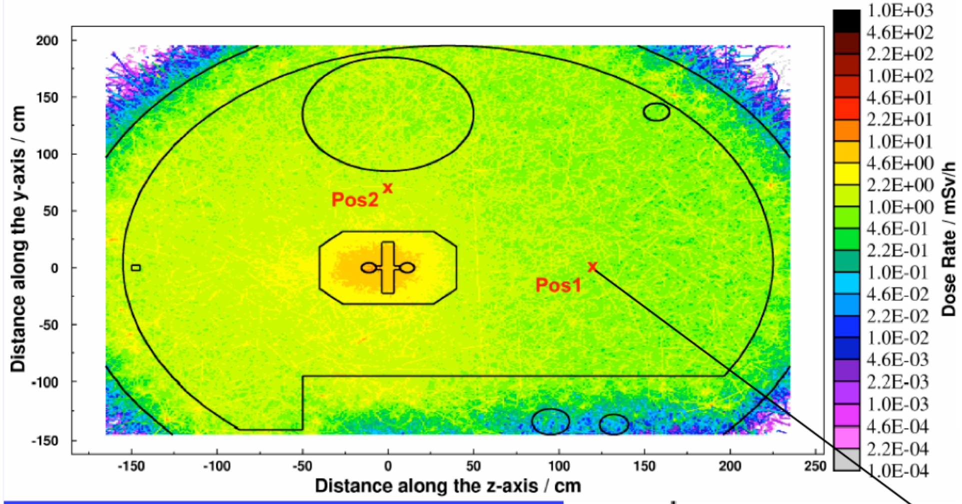
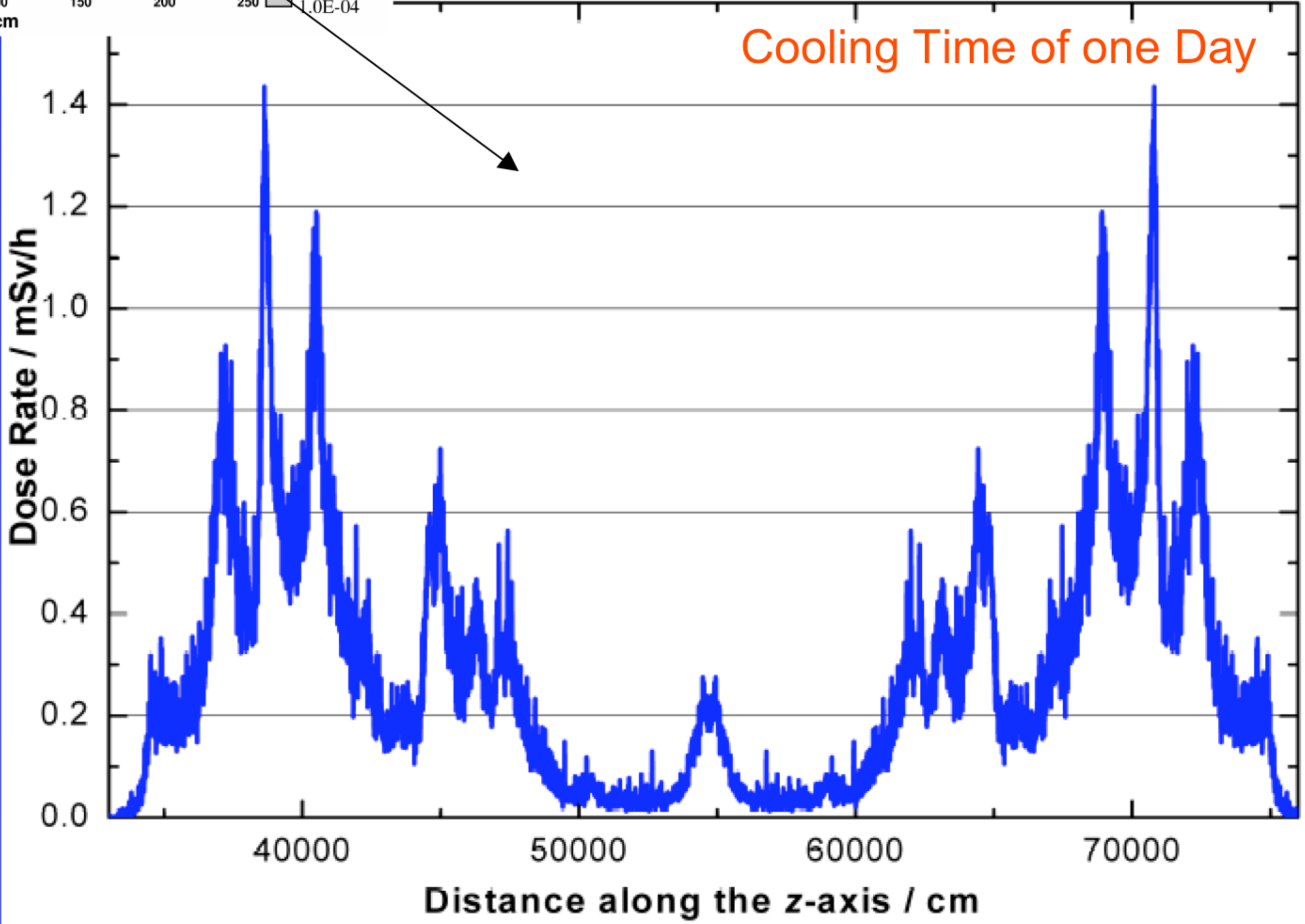
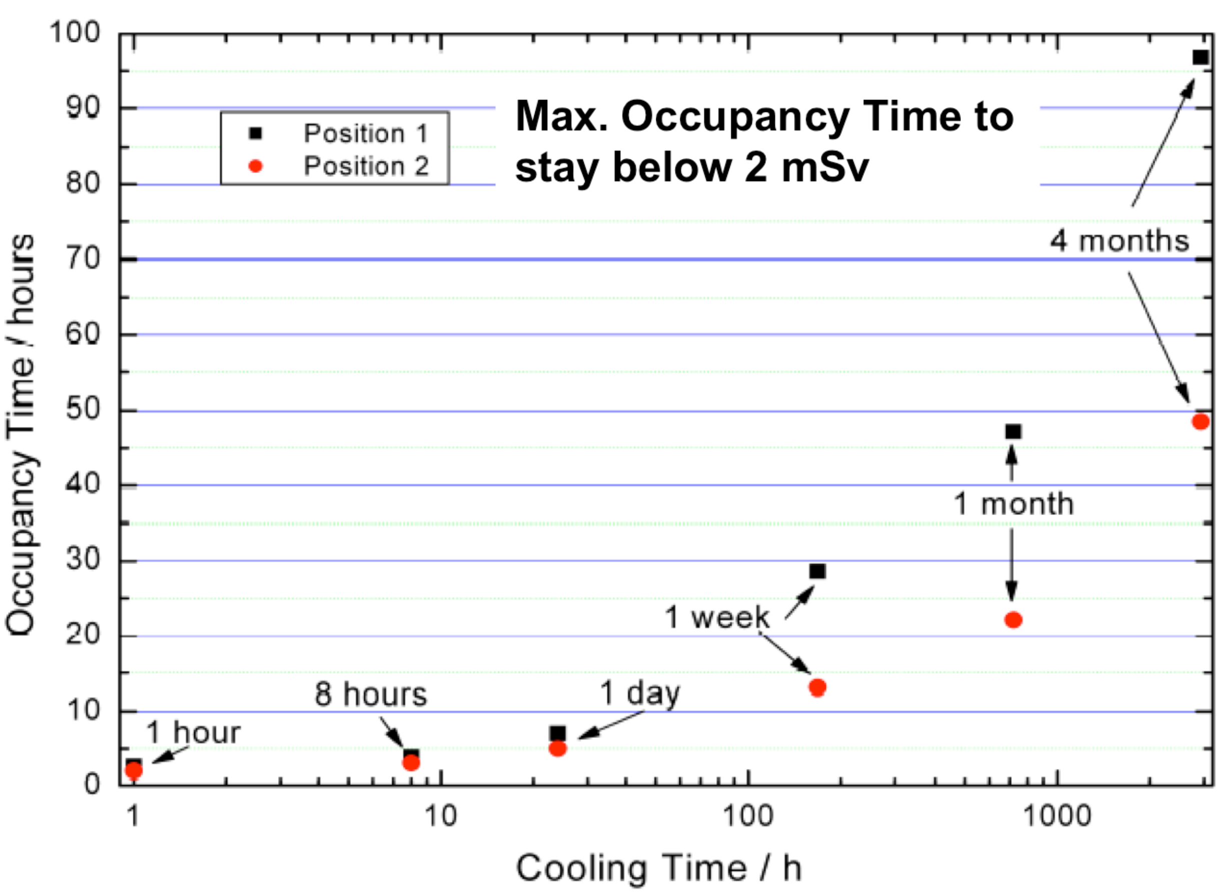


M. Brugger
S. Roesler
et al





LHC Collimation Project

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S. Roesler
et al

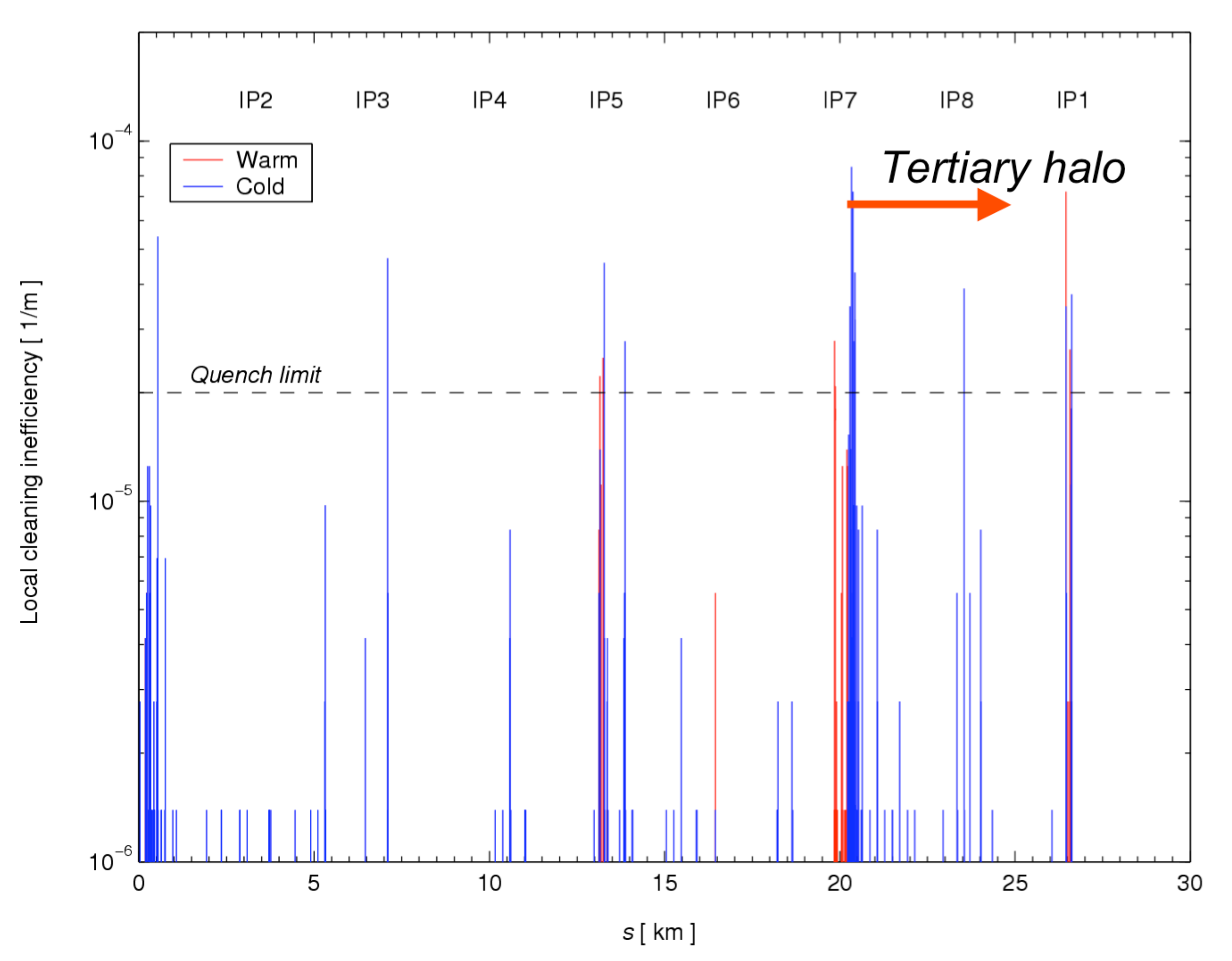
Collimator exchange in IR7 (simple scenario)							
Actions	**Time required (min)**	**1h**	**8h**	**1d**	**1w**	**1m**	**4m**
Access	4 min	0.03	0.02	0.01	0.003	0.002	0.001
Exchange	1 h	4.7	3.4	2.7	1.6	0.9	0.4
Return	10 min	0.03	0.02	0.01	0.003	0.002	0.001
	Sum	**4.8**	**3.4**	**2.7**	**1.6**	**0.9**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

R. Assmann

Cleaning Efficiency

- Cleaning is the **main functionality** of the collimation system!
- Layout designed for **optimal cleaning efficiency** (not for passive machine protection)!
- If efficiency of cleaning is lost then **beam abort**:
  - Imminent quench is detected at magnets through increased beam loss rate.
  - Beam dump.
- **Understanding and fast optimization of cleaning inefficiency** is crucial for achieving integrated luminosity!
- Beam tracking studies moved to detailed loss patterns!
- More on efficiency in a realistic environment tomorrow!

Halo Beam Loss Patterns



Ideal cleaning.
Ideal aperture.
0.2h beam lifetime.

Peaks in all triplets:

Cure with tertiary collimators!

Massive computing effort:

5 _ 10^6 p tracked over 200 turns through each LHC element (full chromatic and non-linear treatment)! 27,000 loss points checked in aperture!

IR8: Nominal optics with β^* = 10 m

More tomorrow!

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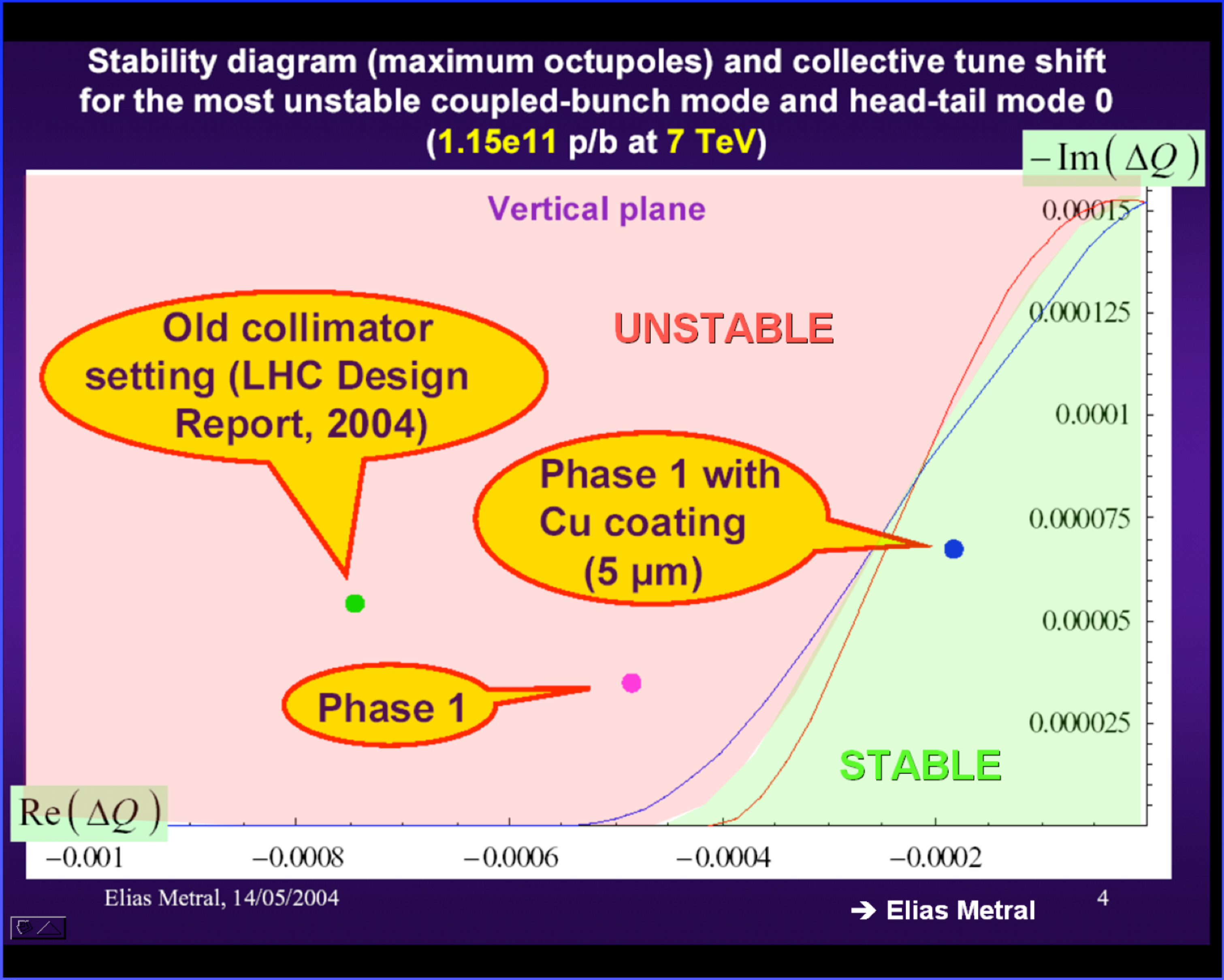
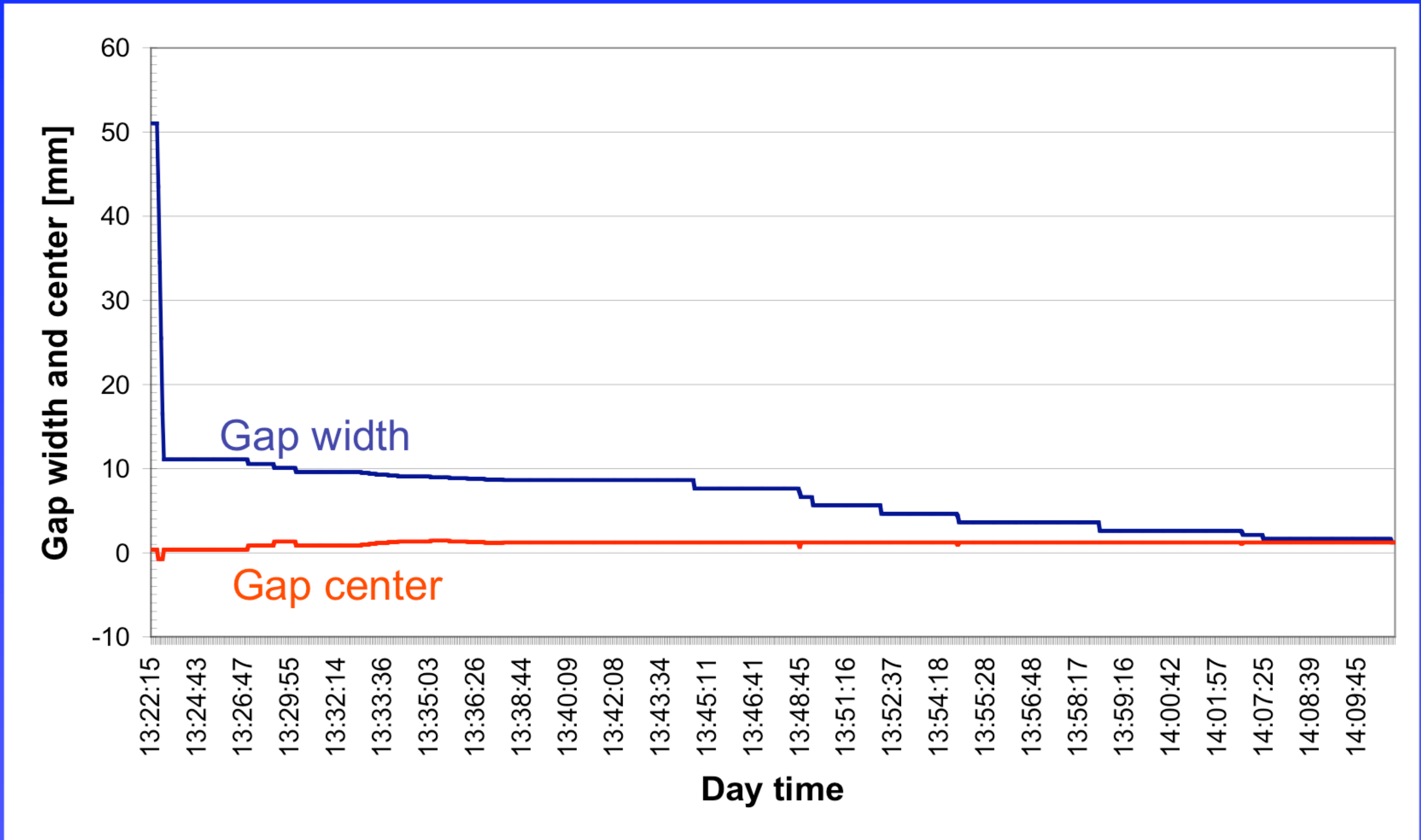
Impedance Limitation



Verification with Beam Test

- Two prototype collimators installed.
- SPS ring:
  - Functional test
  - Beam-based alignment with small gaps
  - Measurement of impedance, HOM, vacuum, e-cloud, ...
- TT40:
  - Robustness test with 2.4 MJ/mm^2

Beam-Based Collimator Alignment



Down to 1 mm with stored beam ➔ **Gaps smaller than required in LHC achieved!**

Absolute gap: ~ 100μm. **Reproducibility:** ~ 20 μm

Beam-based alignment with 50-100 μm accuracy!

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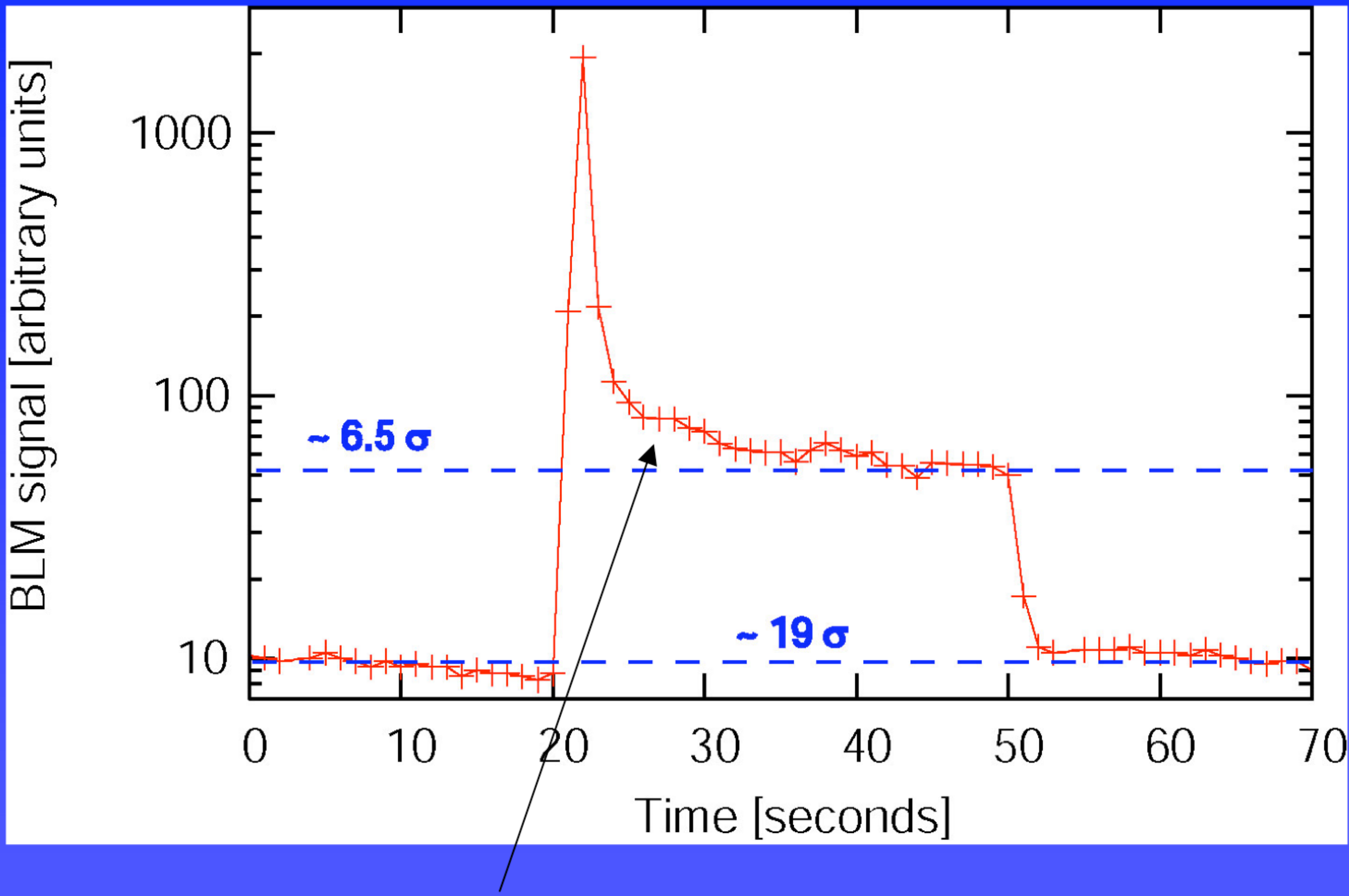
Typical BLM signal for move of jaw



Observation of BLM signal tails: Up to 10-20 seconds in length

BLM team: Many measurements → Beam related true signal!

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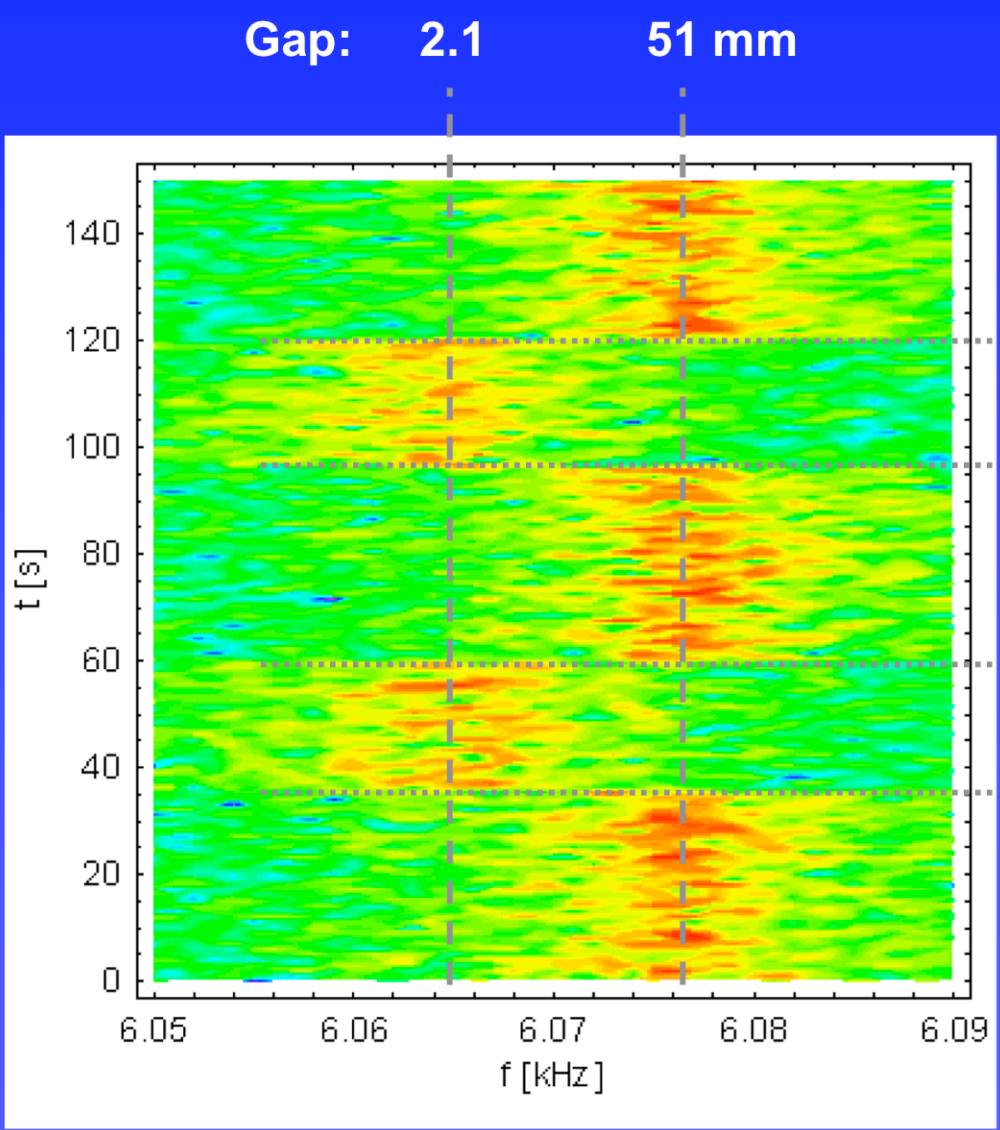
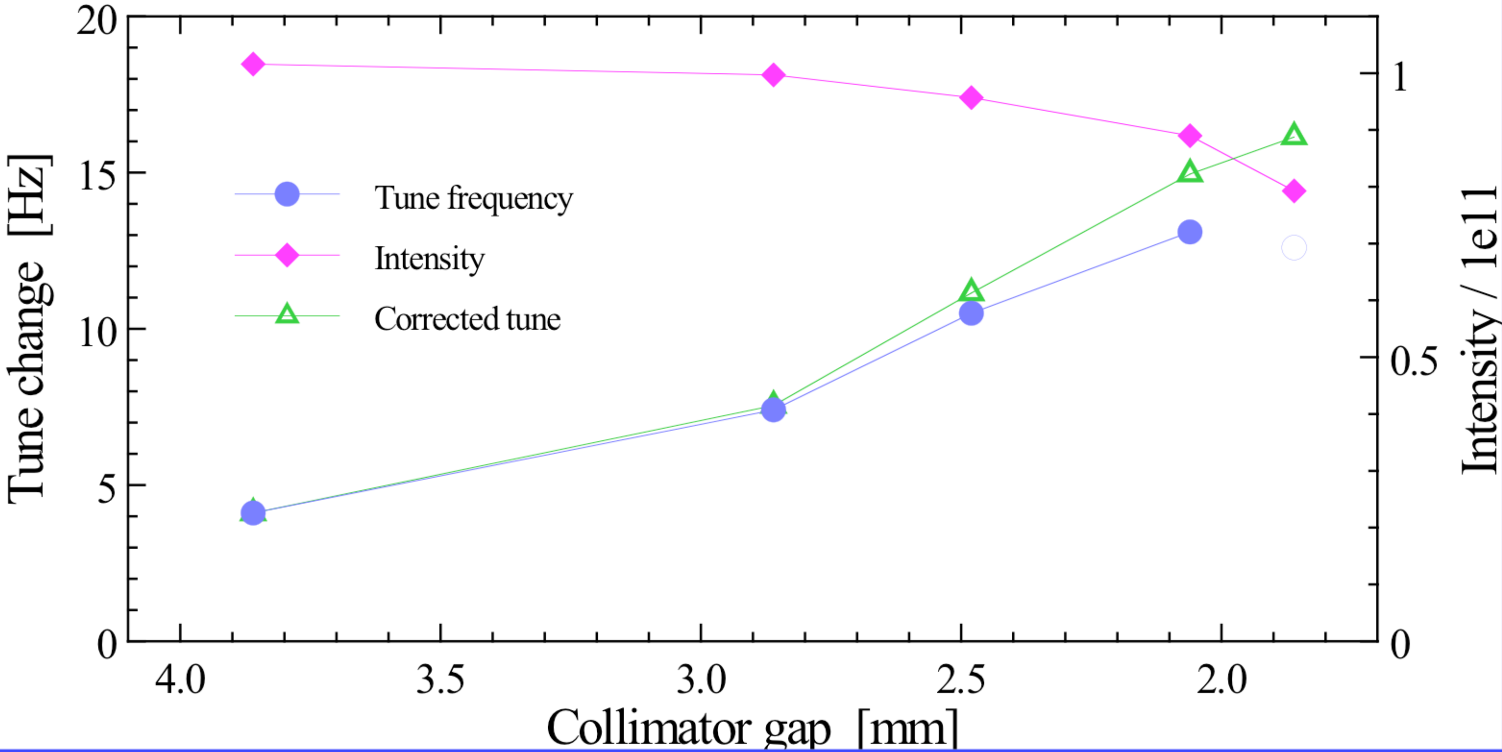
Tune While Changing LHC Collimator Gap



So-called BBQ device (M. Gasior & R. Jones)

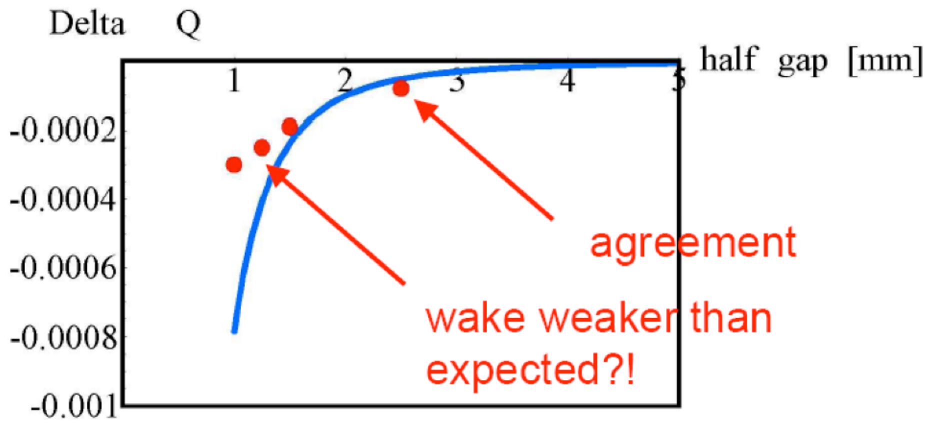
SPS tune depends on collimator gap!

M. Gasior, R. Jones et al



M. Gasior, R. Jones et al

comparison of measured & predicted ΔQ



Expected tune shift of a pencil beam of constant intensity of 8.5x10[10] protons, on which the measured data (from Marek Glasior's APC talk) are superimposed.

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Robustness Test

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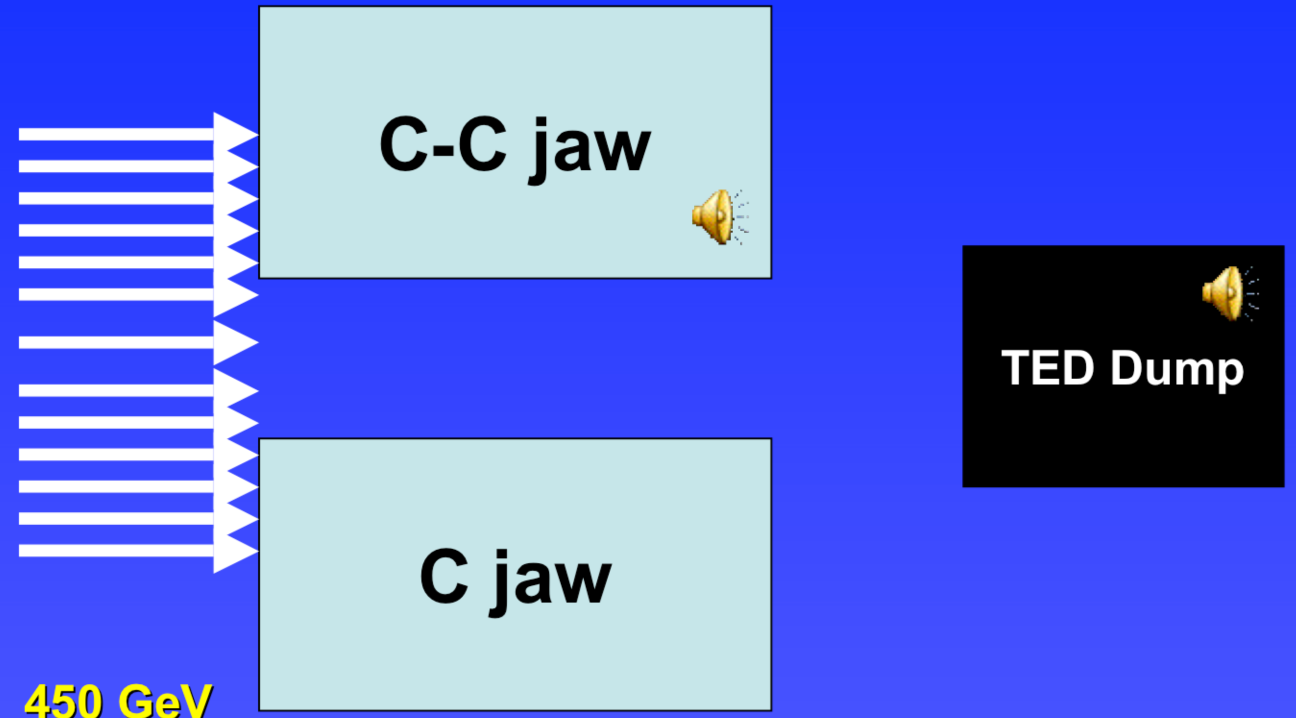
Microphone



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

~ Tevatron beam

~ _ kg TNT

- **Jaw impact could be measured during all expected hits: no change in jaw dimensions (nothing fell off)**
- **Closure of two jaws to 1mm gap after test (no large debris).**
- **Take out collimator in January and inspect.**
- **Analyzing measurements of temperature, vibration and sound.**

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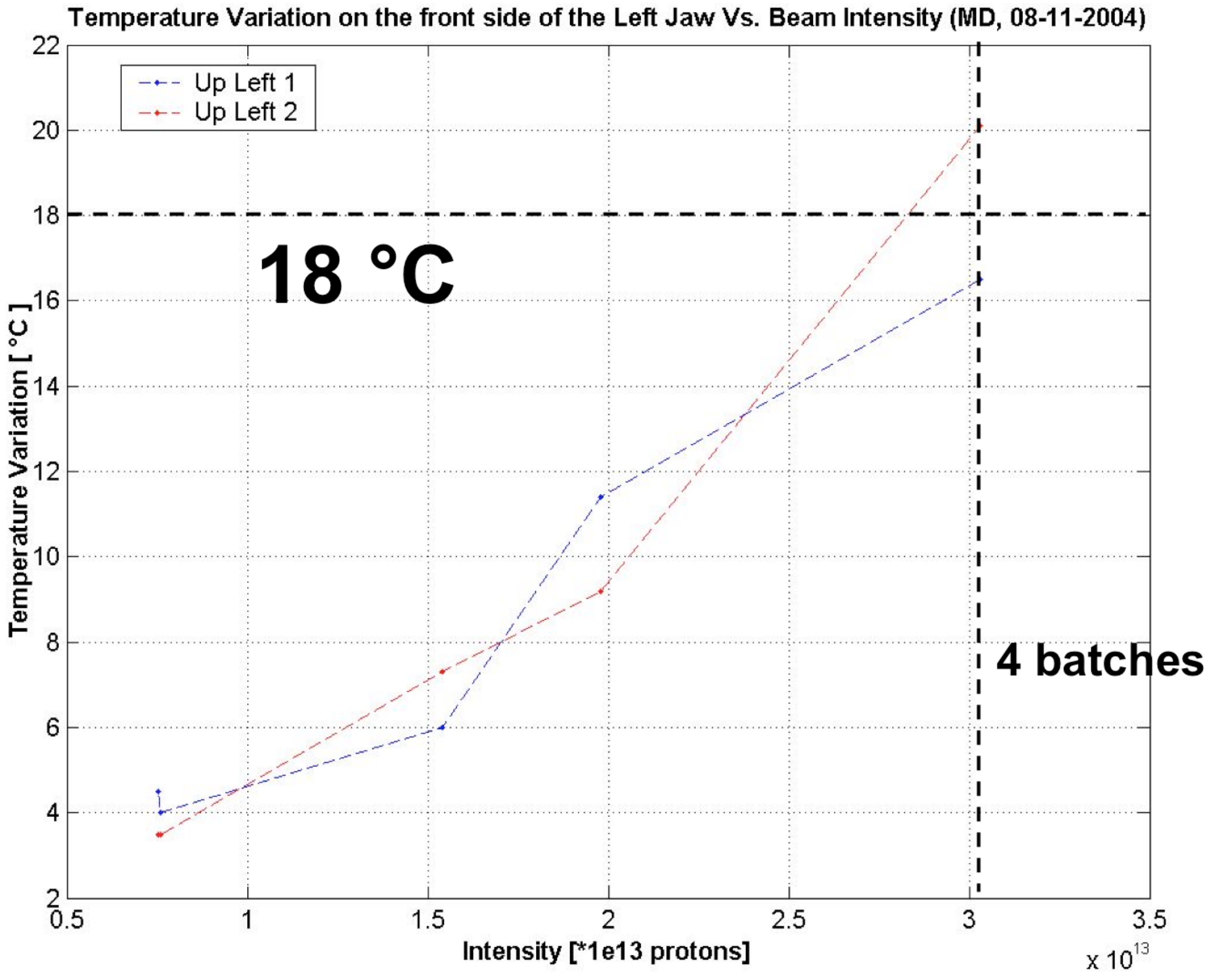
ΔT after Impact Versus Intensity



Peak T higher (**350 °C**)!

Here: T at back of jaw!

Expected: **28 °C**

Lost all temperature sensors!

Unexpected decay of T!

G. Robert-Demolaize et al

Conclusion

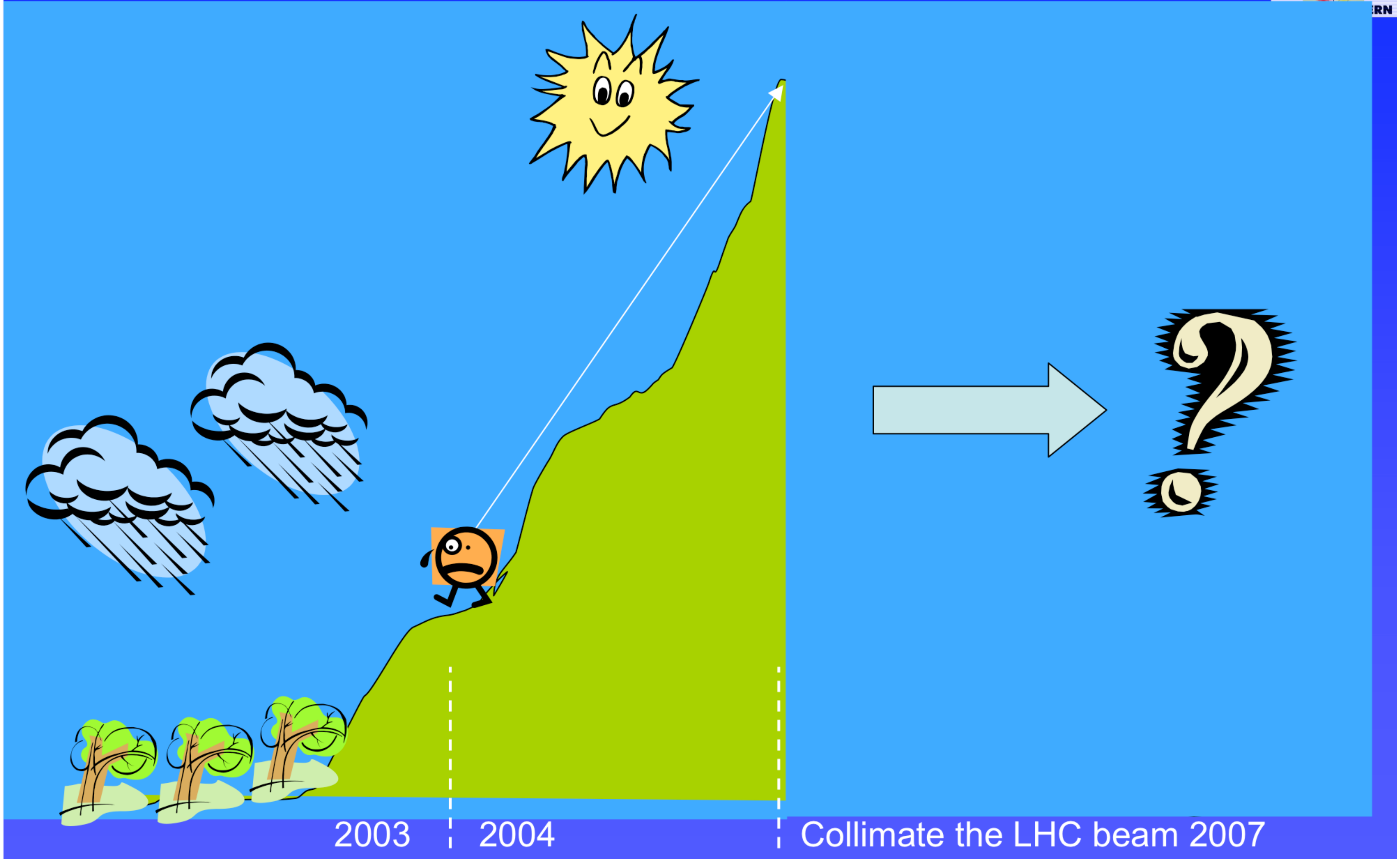
- Collimation is one of the most **challenging issues in LHC**.
- Many **detailed studies** have been completed. Difficult problems encountered but basic solutions have been established.
- Layout **IR3 and IR7** has strongly advanced.
  - All collimator positions have been frozen, absorbers are still being placed. Found need for factor 200 improvement with absorbers!
  - General optimization for quench protection, lifetime of components, radiation impact is essential.
  - Remaining layout worries: SC link cable in IR3 – Absorbers in IR7 – Dose to electronics in IR7 – Final layout of ventilation and cabling in IR7.
  - Should be finalized in the next months...
- Successful **external review of the collimation project** in July 2004.
- Completed most of **phase I collimator design and prototyping**. Hope to achieve up to 50% of nominal intensity with it!
- Many **design choices verified in beam tests**, now preparing for series production.

➔ Many achievements but also still concerns...

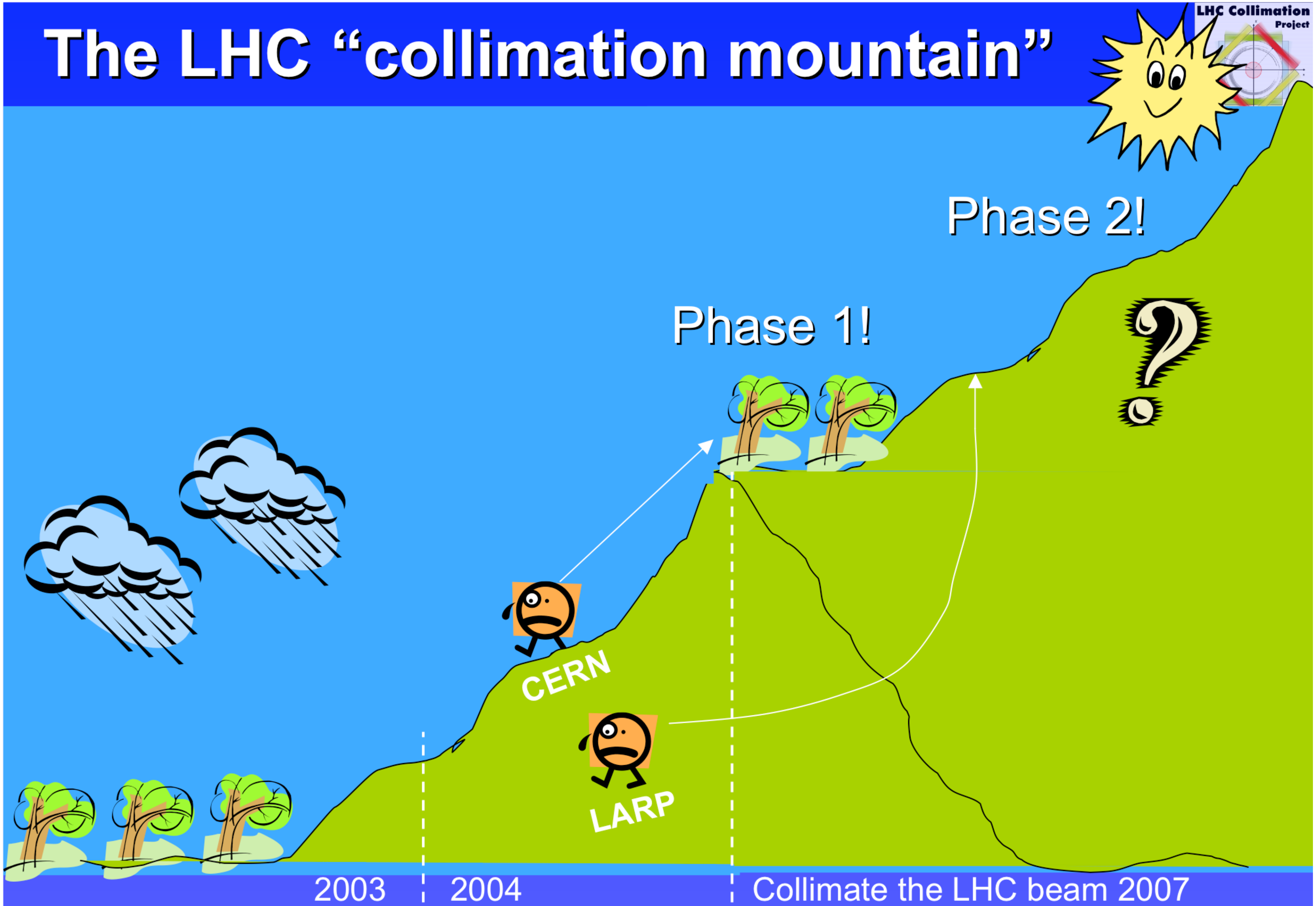
Concerns

- Get **series production** on its way and have collimators, supports, vacuum interconnects, infrastructure ready for 2007!
- **Collimator control** and interface to BLM system and machine protection:
  - Need fast optimization of efficiency (hundreds of DOF).
  - Need high flexibility and excellent safety.
  - Need good robustness against beam-induced noise.
- **Cleaning efficiency**:
  - Completely solve energy deposition by showers with absorbers (factor 200)!
  - Robustness of multi-turn halo cleaning against imperfections (easily another factor 10 lost).
  - Include beam-gas scattering in IR7!
  - Predict detailed situation at experimental insertions (background).
- **General conditions** in and close to cleaning insertions (radiation, access, Ozone, ...).
- No solution for nominal **ion collimation**. Early ion scheme is OK.
- Prepare for nominal performance: R&D on **advanced phase 2 collimation** now (with US colleagues).

The LHC "collimation mountain"



The LHC “collimation mountain”



R. Assmann

The LHC Collimation Team

Excellent AB, TS, AT, SC collaboration inside CERN!

O. Aberle, R. Assmann, I. Baishev, A. Bertarelli, 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, V. Kain, M. Lamont, 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, 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)

Collimation Performance with Ions

(H. Braun)

Two-stage betatron cleaning system was designed for protons ➔ low energy loss, large betatronic kick!

The relative weight of energy loss and transverse kicks is very different for ions (much stronger energy loss).

Additional physics processes change q/m for ions.

➔ **LHC betatron cleaning system does not work for ions as a two-stage cleaning system**.

➔ Loss in efficiency with single-stage cleaning compensates lower intensities.

➔ Nominal intensities violate quench limit downstream of betatron cleaning system (assuming same operating range as for protons).

Detailed studies performed by H. Braun.

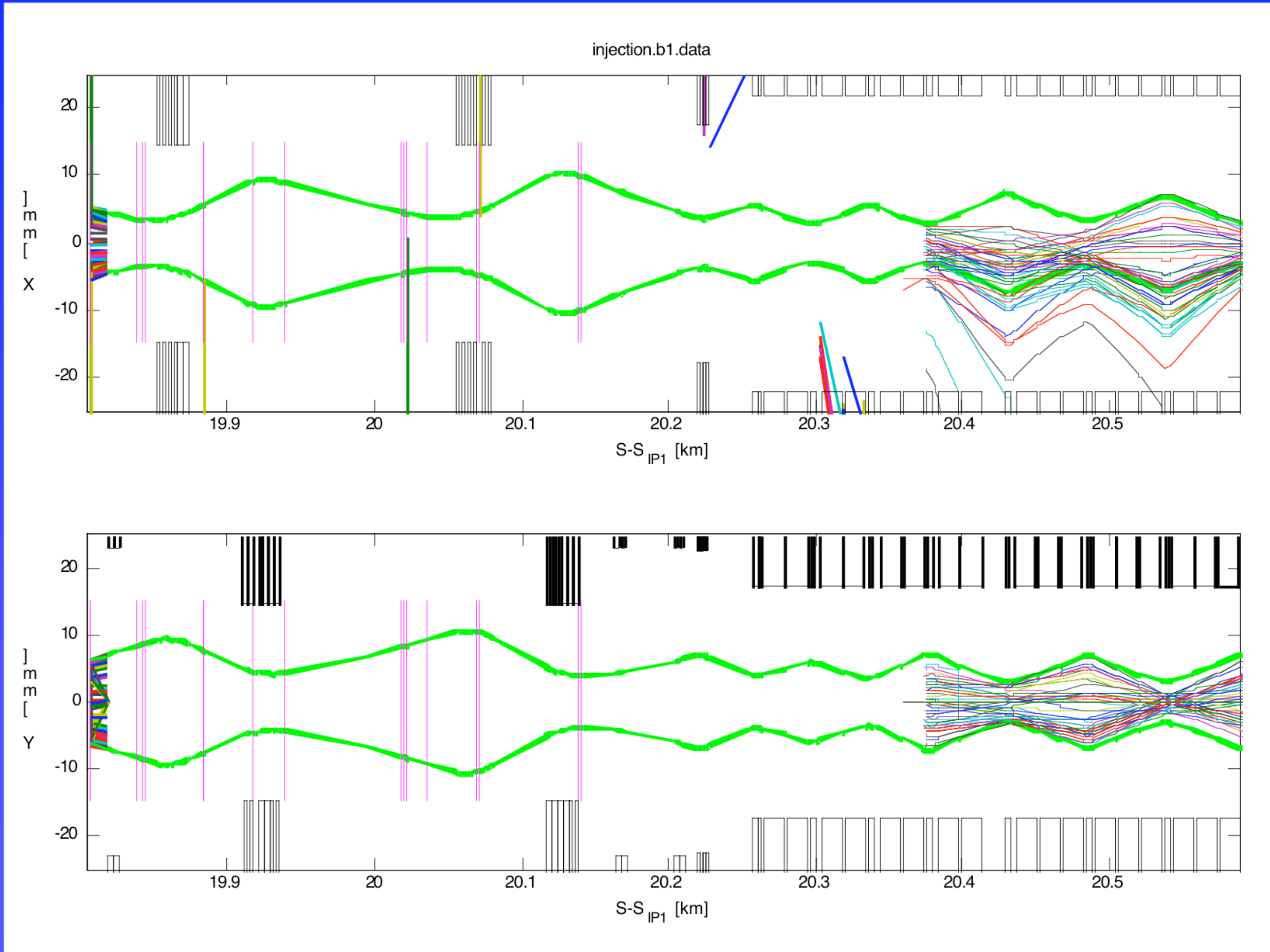
^{208}Pb-ion/matter interactions in comparison with proton/matter interactions.

(values are for particle impact on graphite)

Physics process	p injection	p collision	^{208}Pb injection	^{208}Pb collision
Ionisation energy loss $\frac{dE}{E\,dx}$	0.12 %/m	0.0088 %/m	9.57 %/m	0.73 %/m
Multiple scattering projected r.m.s. angle	$73.5\mu rad/m^{1/2}$	$4.72\mu rad/m^{1/2}$	$73.5\mu rad/m^{1/2}$	$4.72\mu rad/m^{1/2}$
Electron capture length	-	-	20 cm	312 cm
Electron stripping length	-	-	0.028 cm	0.018 cm
ECPP interaction length	-	-	24.5 cm	0.63 cm
Nuclear interaction length (incl. fragmentation)	38.1 cm	38.1 cm	2.5 cm	2.2 cm
Electromagnetic dissociation length	-	-	33.0 cm	19.0 cm

H. Braun

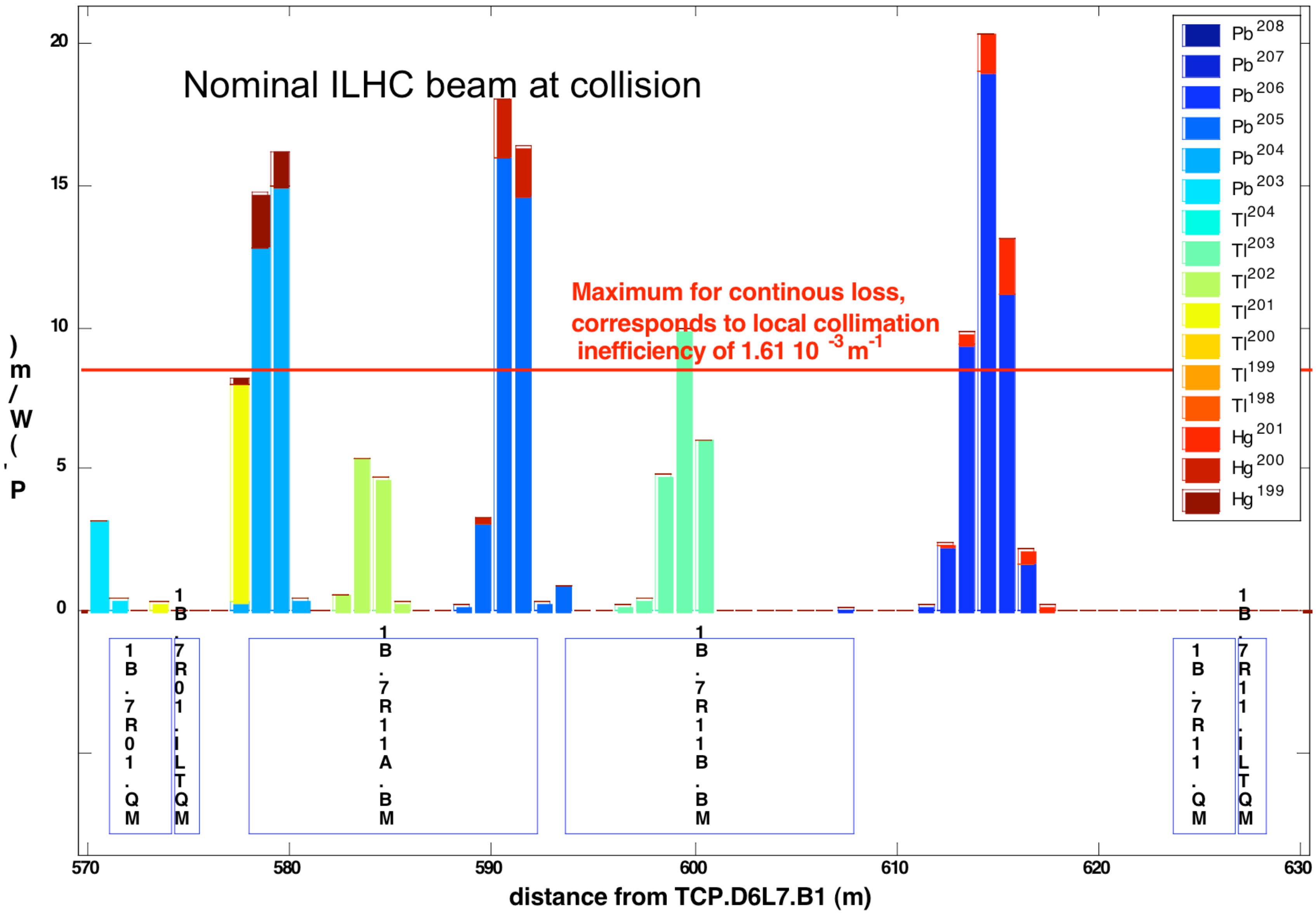
Trajectories around collimation in IR7 as computed by ICOSIM
(computed for injection energy)



H. Braun

R. Assmann

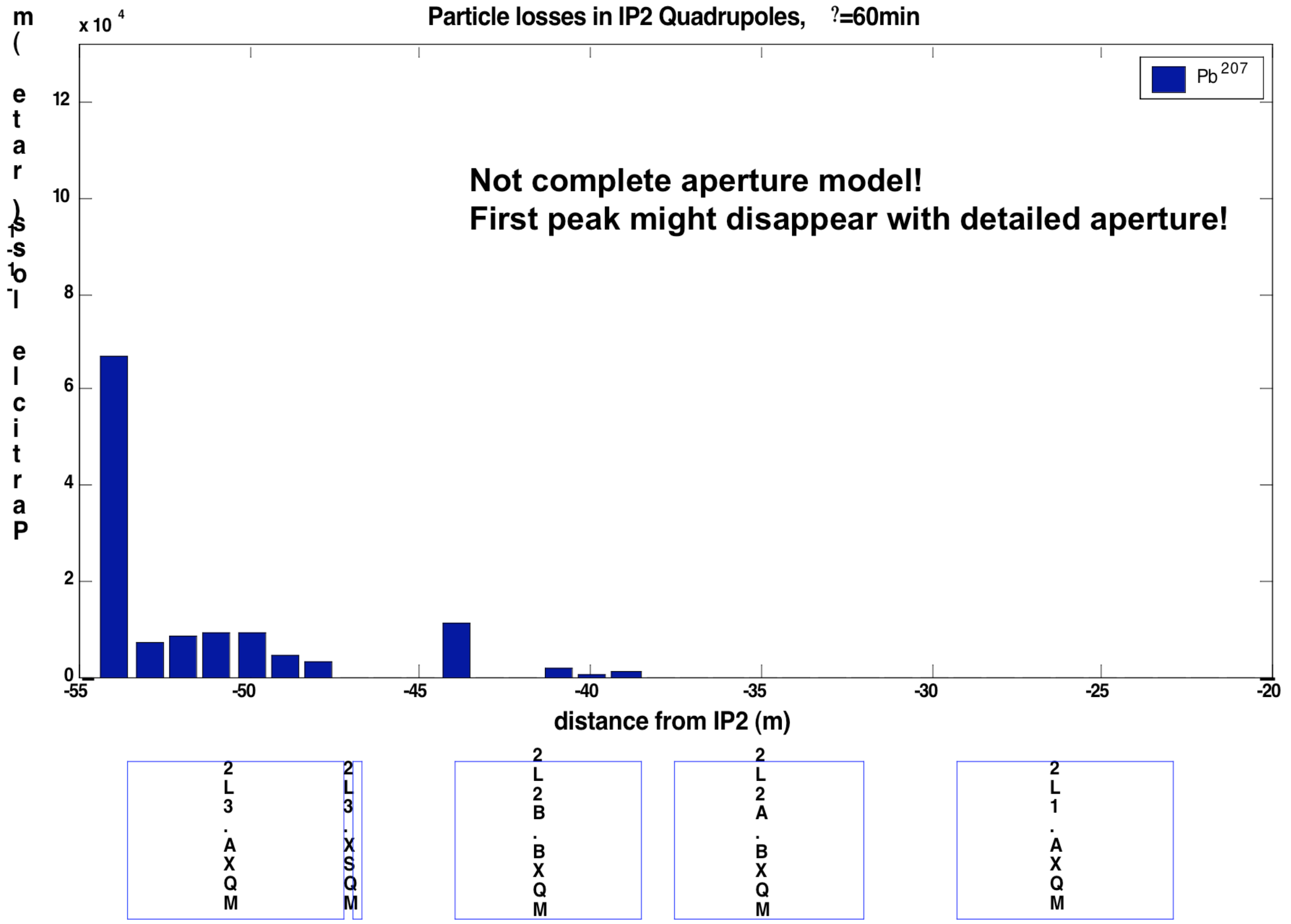
Fractional heat load in dispersion suppressor, ?=12min



LHC Collimation Project
CERN

H. Braun

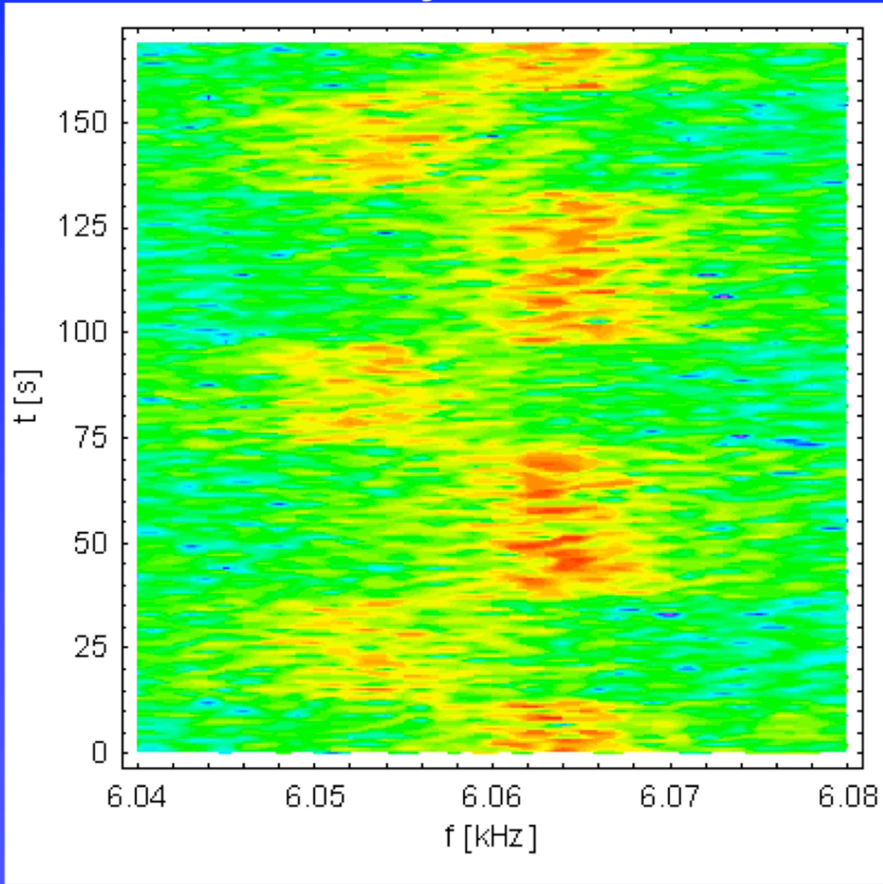
R. Assmann


Particle losses in IP2 Quadrupoles, ?=60min
x 10 4
Particle loss rate (s-1 m-1)
Pb 207
Not complete aperture model!
First peak might disappear with detailed aperture!
0
2
4
6
8
10
12
-55
-50
-45
-40
-35
-30
-25
-20
distance from IP2 (m)
MQXA.3L2
MQSX.3L2
MQXB.B2L2
MQXB.A2L2
MQXA.1L2

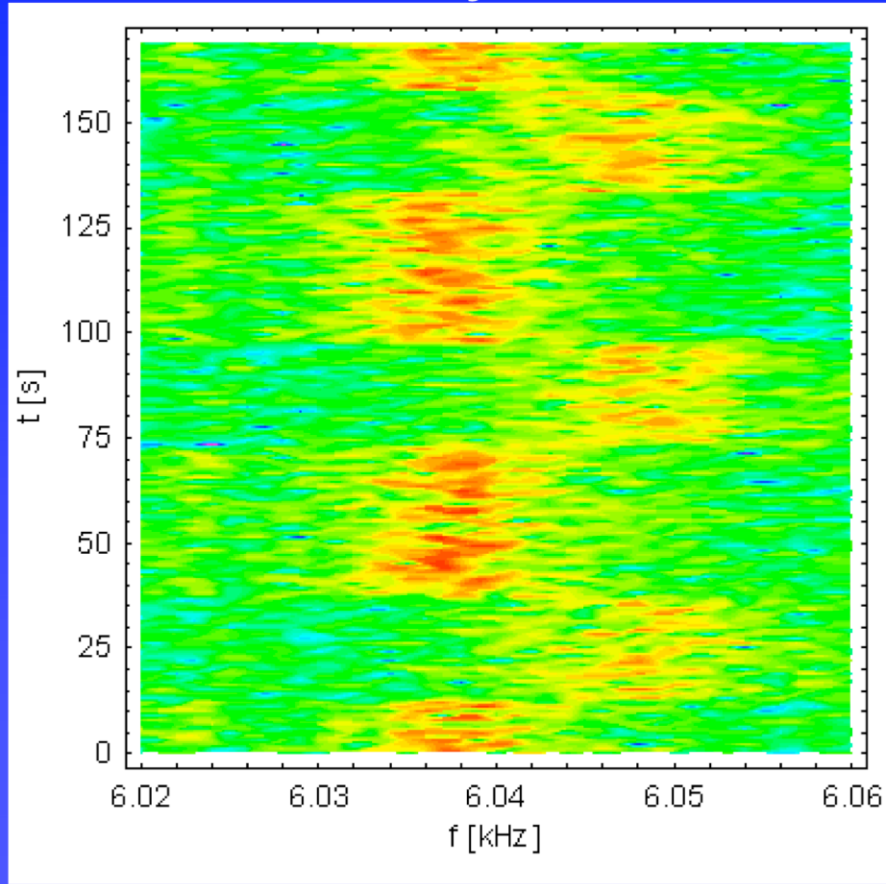
H. Braun

Tune Cross-checks

BBQ system



245 MHz system



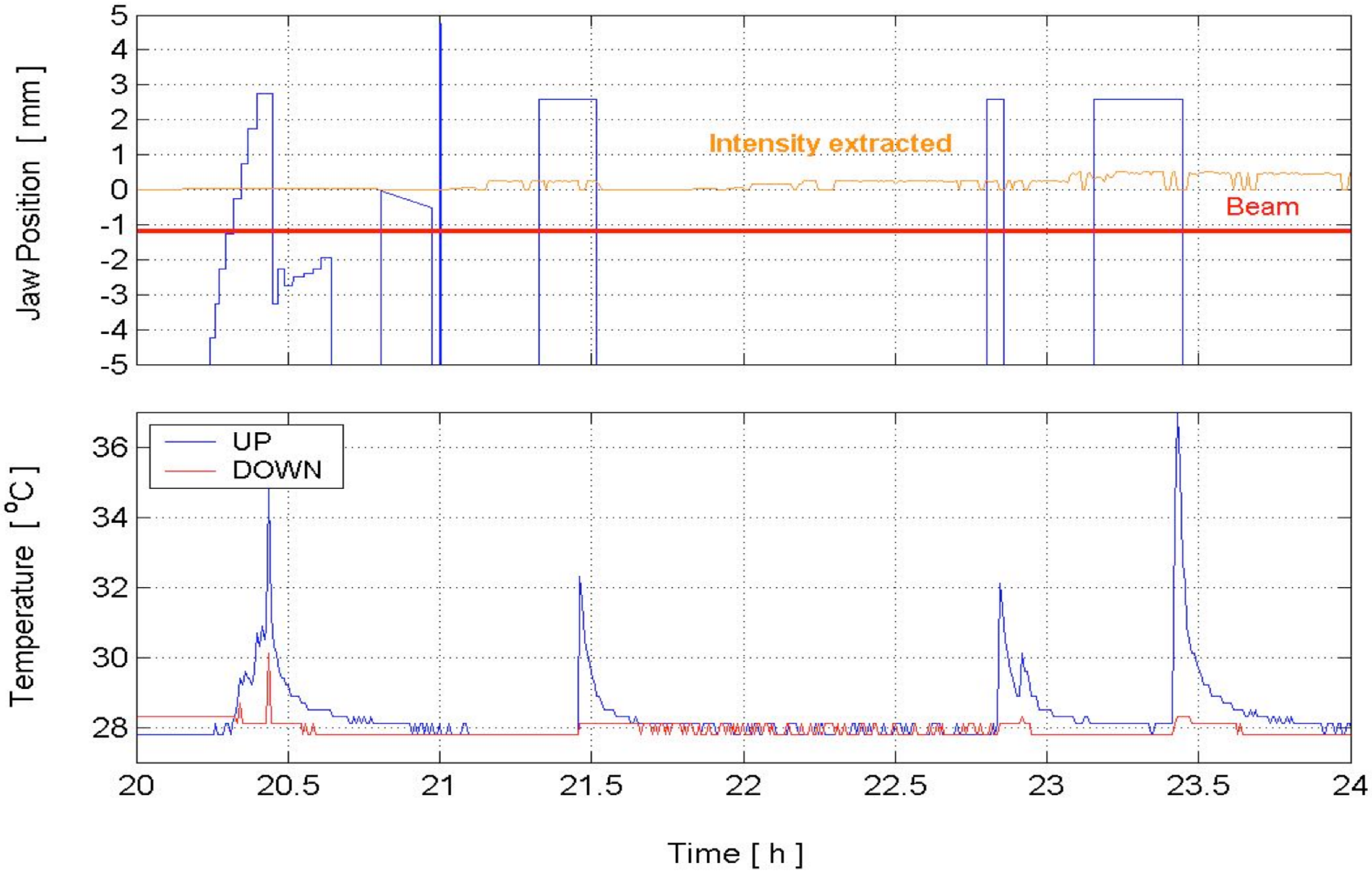
- Collimator cycled (at ca 4h33) between the gap of 51 mm and 2 mm.
- Tune frequency was changing by 10 Hz, i.e. 2.3×10^{-4} ($\times f_{rev}$)

245 MHz system confirms data (F. Caspers/T. Kroyer)

Also: Standard tune measurments (H. Burkhardt)

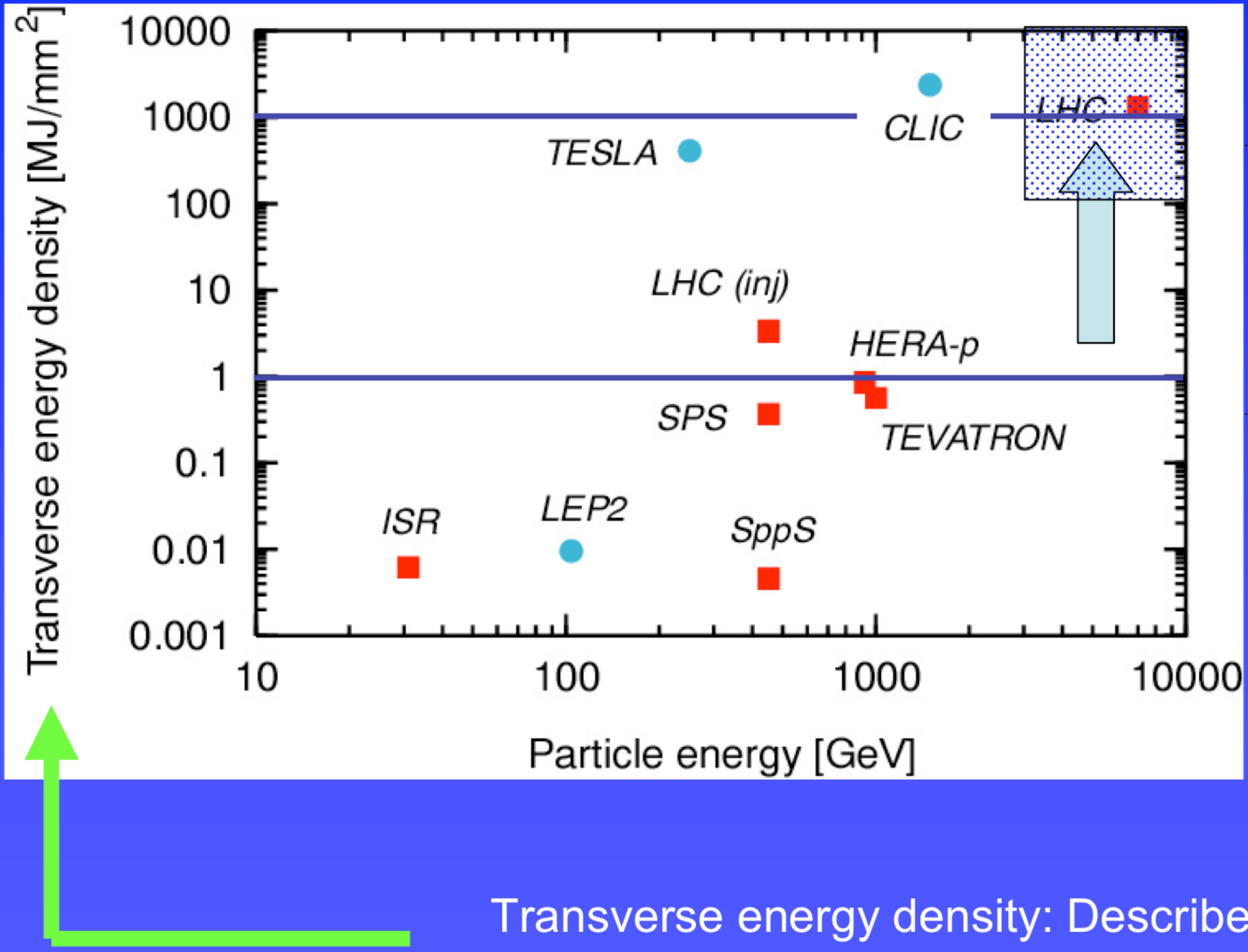
Jaw Temperature After Impact

LHC Collimation Project CERN



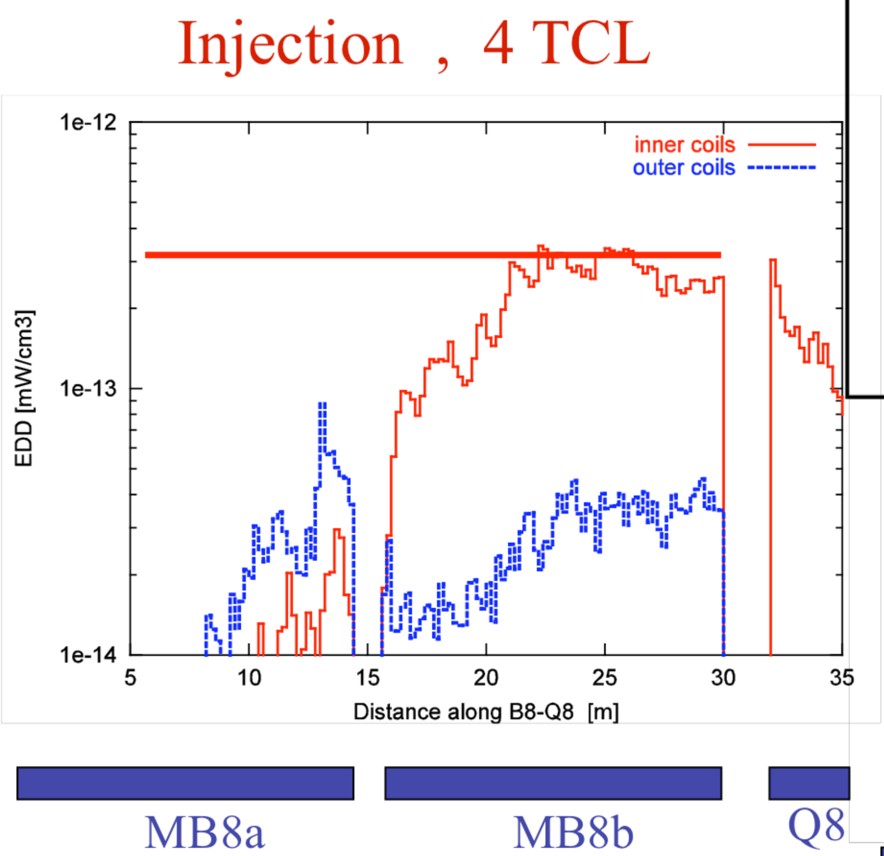
G. Robert-Demolaize et al

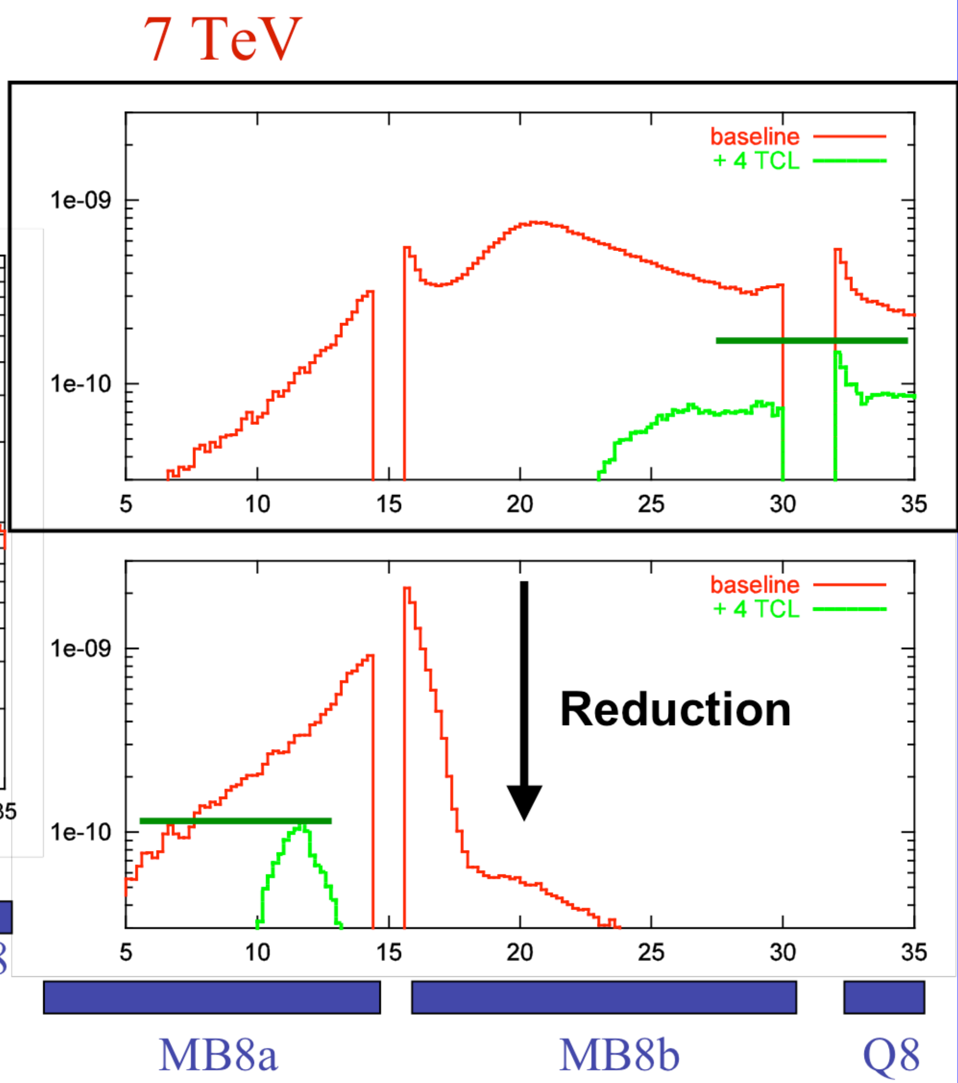
“Destructive” LHC Beams



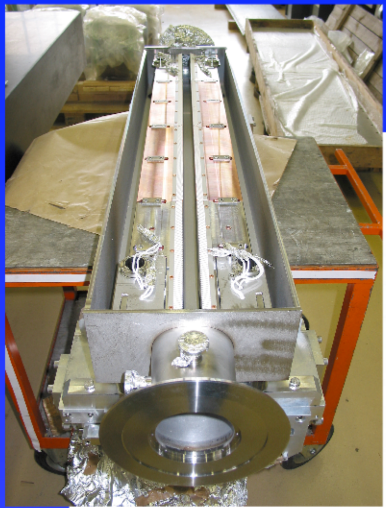
Transverse energy density: Describes damage potential of the LHC beam (3 orders of magnitude more dangerous than present beams)

Peak Energy Deposition in coils [mW/cm³/proton]

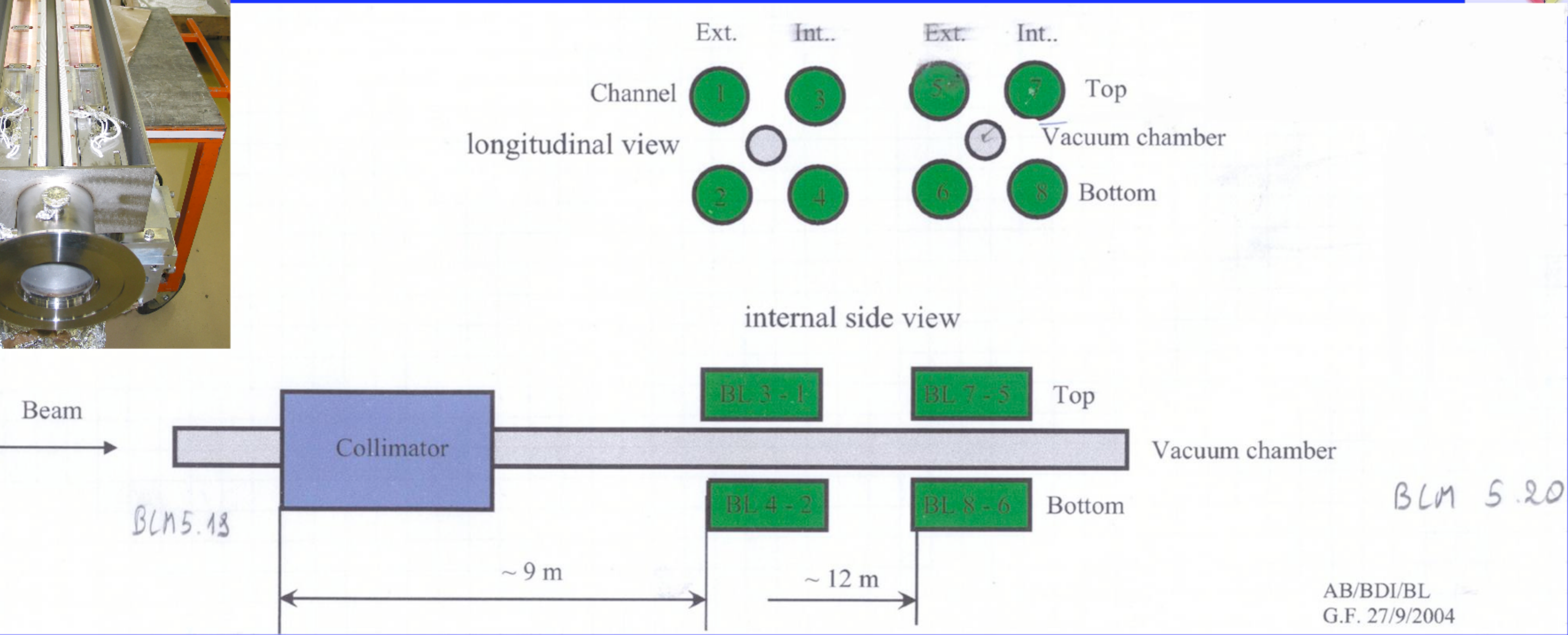




J.B. Jeanneret, I. Baishev



Configuration



L. Ponce et al

Collimation team: Collimator in P5 of SPS

BLM team: 8 downstream BLMs

Together: 1 Hz DAQ and plotting in control room