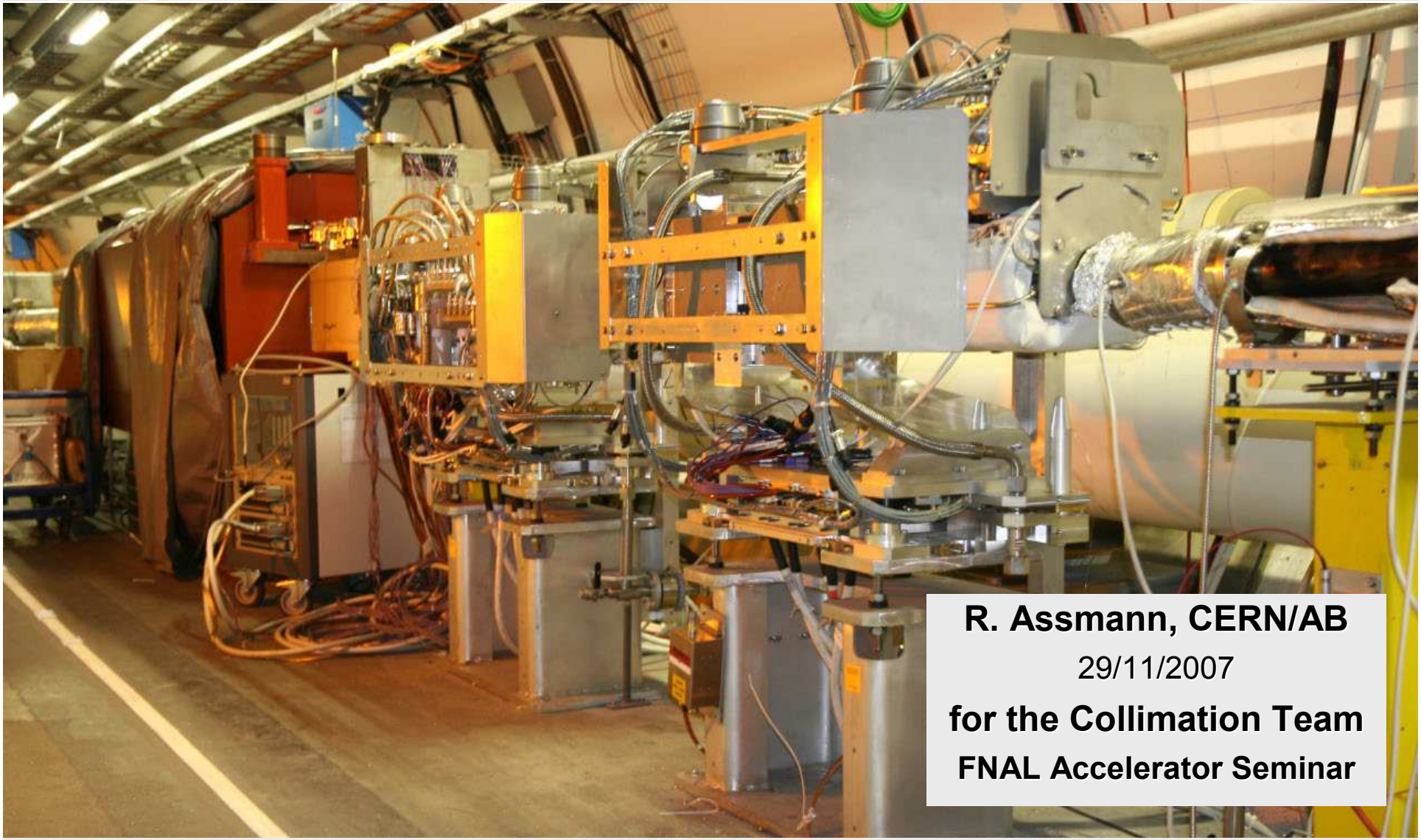
Beam Loss and Collimation at the LHC



R. Assmann, CERN/AB

29/11/2007

for the Collimation Team

FNAL Accelerator Seminar

… history …

my special history with Fermilab

–

the first physics laboratory I ever entered

Public outreach works and even reaches some German high school students participating high school exchange programs…

1) Introduction: The LHC Challenge

The Large Hadron Collider:

Circular particle physics collider with 27 km circumference.

Two colliding 7 TeV beams with each 3×10^{14} protons.

Super-conducting magnets for bending and focusing.

Start of beam commissioning: **May 2008**.

Particle physics reach defined from:

1) Center of mass energy **14 TeV**

➔ super-conducting dipoles

2) Luminosity **10^{34} cm^{-2} s^{-1}**

LHC nominal parameters

Number of bunches:	**2808**
Bunch population:	**1.15e11**
Bunch spacing:	25 ns
Top energy:	
Proton energy:	**7 TeV**
Transv. beam size:	**~ 0.2 mm**
Bunch length:	8.4 cm
Stored beam energy:	**360 MJ**
Injection:	
Proton energy:	450 GeV
Transv. Beam size:	~ 1 mm
Bunch length:	18.6 cm

The Super-Conducting Arcs

- The super-conducting arcs occupy about 90% of the total LHC tunnel.
- Important success on **November 7th**:

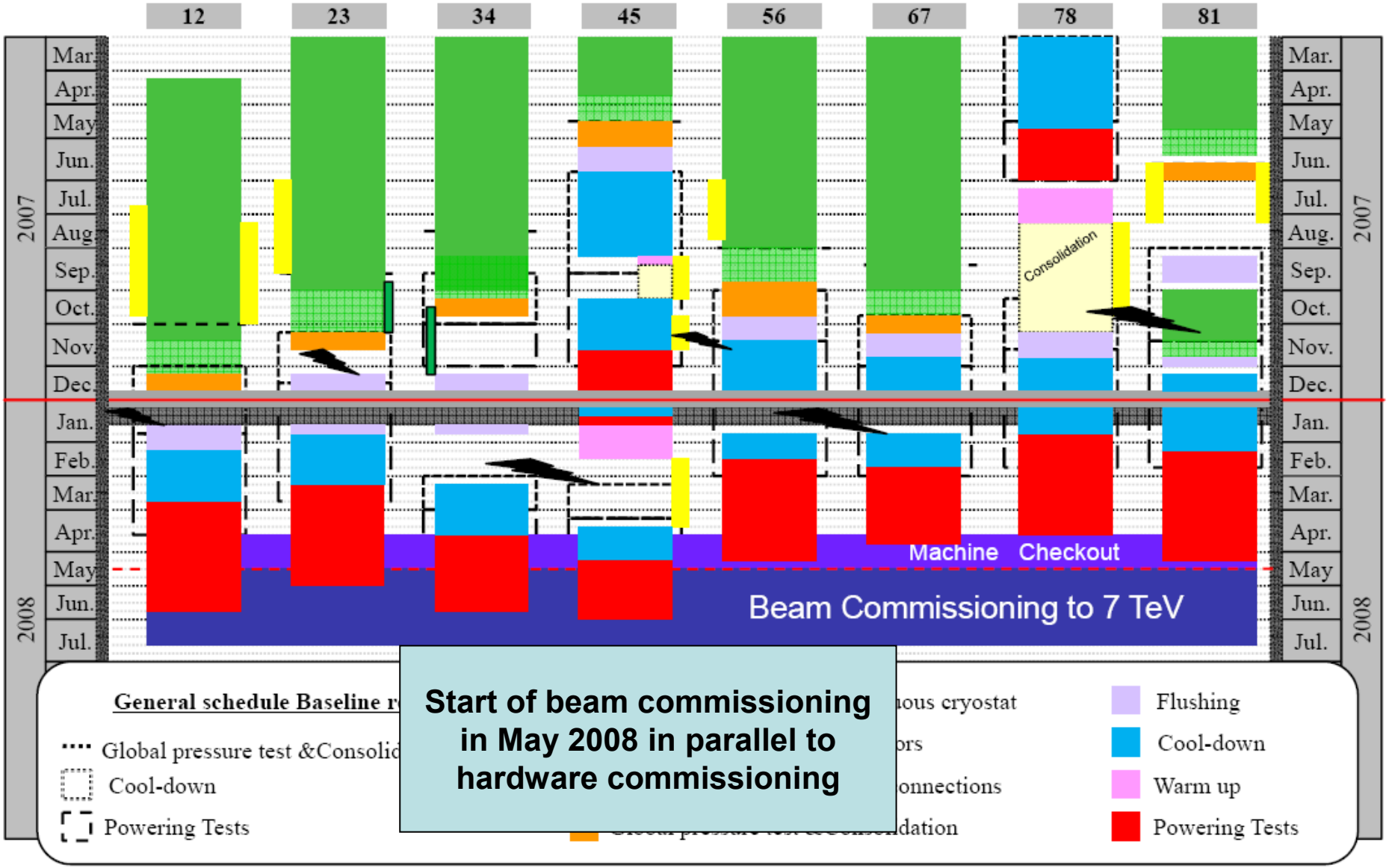
  Installation complete:

  - **1700 super-conducting magnets were installed and connected**.
  - About **40.000 leak-tight weldings were performed** (~10 km length).
  - About **65.000 superconducting cables were spliced.**

The Last Bolt (Arcs)

The LHC SC Magnets

LHC Planning (October 2007)



Start of beam commissioning in May 2008 in parallel to hardware commissioning

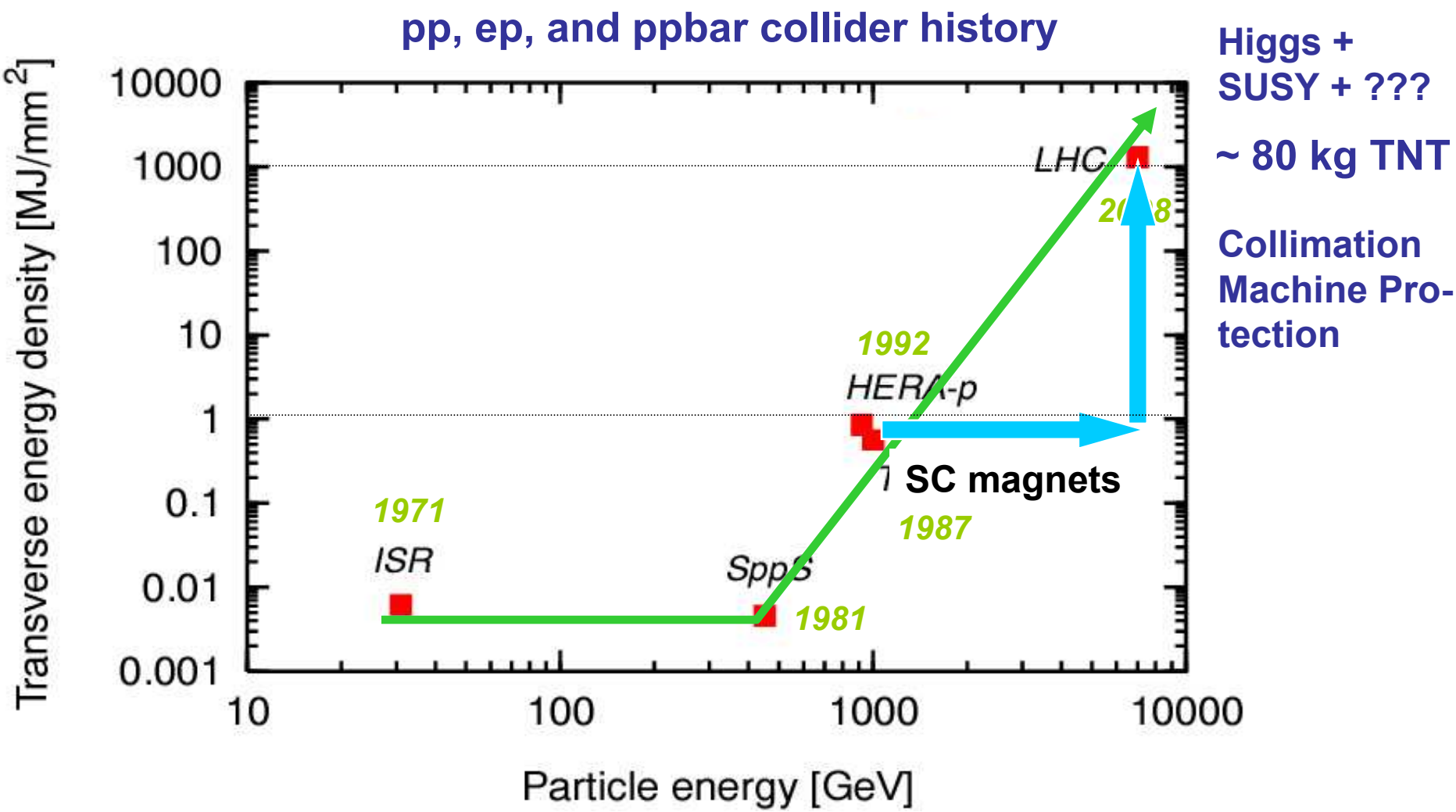
LHC Luminosity

- Luminosity can be expressed as a function of transverse energy density ρ_e in the beams at the collimators:

$$L = \rho_e \frac{f_{rev} N_p}{4E_b} \sqrt{d_x d_y}$$

d = demagnification (β_{coll}/β^*)
N_p = protons per bunch
f_{rev} = revolution freq.
E_b = beam energy

- Various parameters fixed by design, for example:
  - Tunnel fixes revolution frequency.
  - Beam-beam limit fixes maximum bunch intensity.
  - Machine layout and magnets fix possible demagnification.
  - Physics goal fixes beam energy.
- **Luminosity is increased via transverse energy density!**



The “new Livingston plot“ of proton colliders: Advancing in unknown territory!

A **lot of beam** comes with a **lot of garbage** (up to 1 MW halo loss, tails, backgrd, ...)

➔ <u>Collimation. Machine Protection.</u>

LHC Need for Collimation

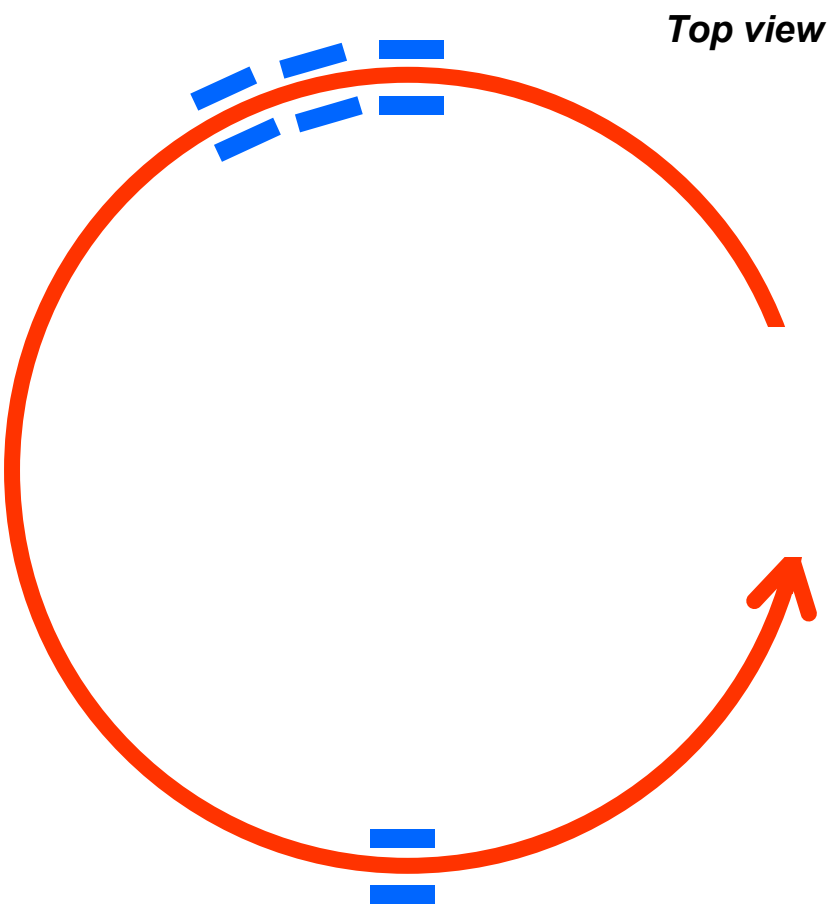
- Ideally, stored proton beams would have infinite lifetime and no protons would be lost.
- However, a multitude of physical processes will limit the lifetime of the beams and unavoidable proton losses must be taken into account.
- Conditions for quenching a SC magnet:
  - Transient loss of **10^{-9}** fraction of beam (within 10 turns)
  - Slow loss of **3×10^{-8}** fraction of beam per s and per m (< 10000 h lifetime)
- Proton losses must be **intercepted and absorbed by specifically designed devices, namely collimators**. These constrain the aperture.
- Multi-turn process: protons diffuse to limiting aperture bottleneck. Process also called beam cleaning.
- 2 out of 8 straight sections in the LHC are dedicated to collimation!

Specified Allowed Proton Losses with Collimation

- Collimators are the LHC defense against unavoidable losses:
  - Irregular fast losses and failures: Passive protection.
  - Slow losses: Cleaning and absorption of losses in super-conducting environment.
  - Radiation: Managed by collimators.
  - Particle physics background: Minimized.
- Specified 7 TeV peak beam losses (maximum allowed loss):
  - Slow: 0.1% of beam per s for 10 s **0.5 MW**
  - Transient: 5×10^{-5} of beam in ~10 turns (~1 ms) **20 MW**
  - Accidental: up to 1 MJ in 200 ns into 0.2 mm^2 **5 TW**

The LHC Collimators…

- Collimators must intercept any losses of protons such that the rest of the machine is protected („the sunglasses of the LHC“):
  > 99.9% efficiency!
- To this purpose collimators insert diluting and absorbing materials into the vacuum pipe.
- Material is movable and can be placed as close as 0.25 mm to the circulating beam!
- Nominal distance at 7 TeV: ≥ 1 mm.
- Presently building/installing phase 1!



Preventing Quenches

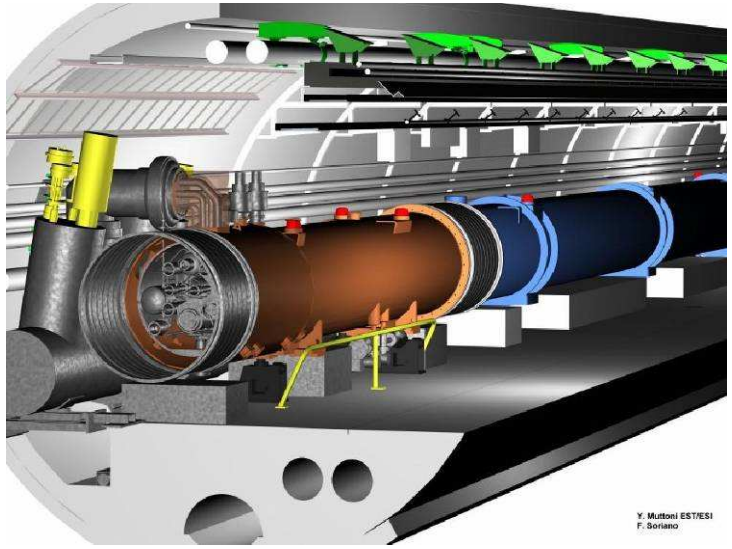
- Shock beam impact: **2 MJ/mm^2 in 200 ns (0.5 kg TNT)**

- Maximum **beam loss at 7 TeV**: 1% of beam over 10 s

500 000 W

- **Quench limit** of SC LHC magnet:

8.5 W/m



The LHC Collimation Project

- 2002: Conclusion that the originally foreseen LHC collimation system would not withstand the LHC intensities and not provide sufficient cleaning and protection.
- 2003: Start of LHC collimation project to urgently provide:
  - robust collimator hardware design.
  - suffcient cleaning efficiency and protection.
  - hardware R&D and prototyping.
  - prototype testing without and with beam.
  - industrial production and installation.
- In view of technical challenge and short time available, implementation of staged approach. Collaborative approach to include world-wide expertise.
- Total investment cost of ~30 M$ plus about 90 man-years CERN staff.
- Quite a strong effort over the last 5 years! Thanks for help from FNAL.

The Collimation Team…

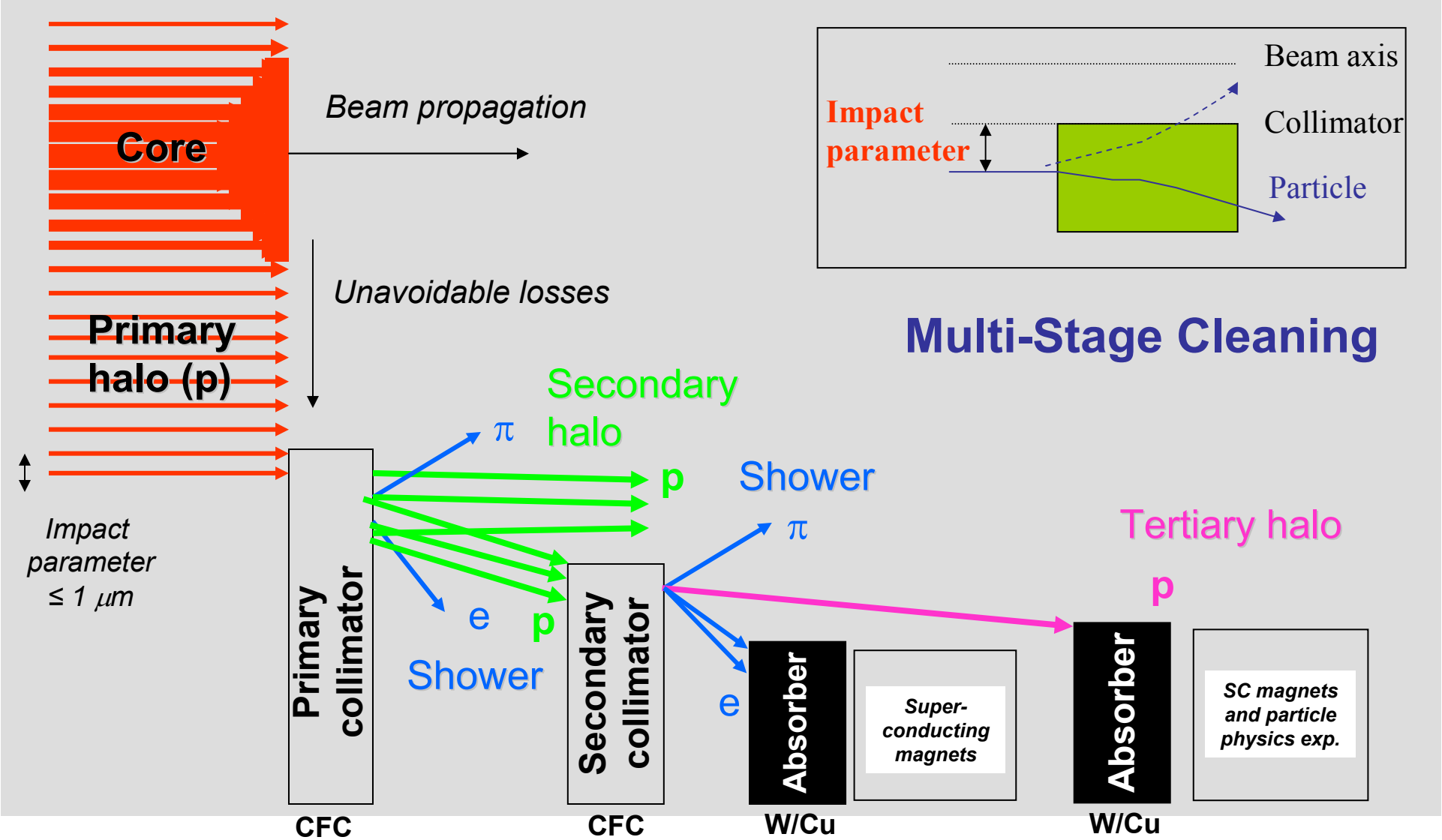
Collimation team:

About 60 CERN technicians, engineers and physicists… in various groups and departments.

+ many friends in connected areas (BLM's, MP, …)

+ collaborators in various laboratories (SLAC, FNAL, BNL, Kurchatov, …)

2) LHC Collimation Basics



Diffusion Process & Impact Parameter

Slow loss:

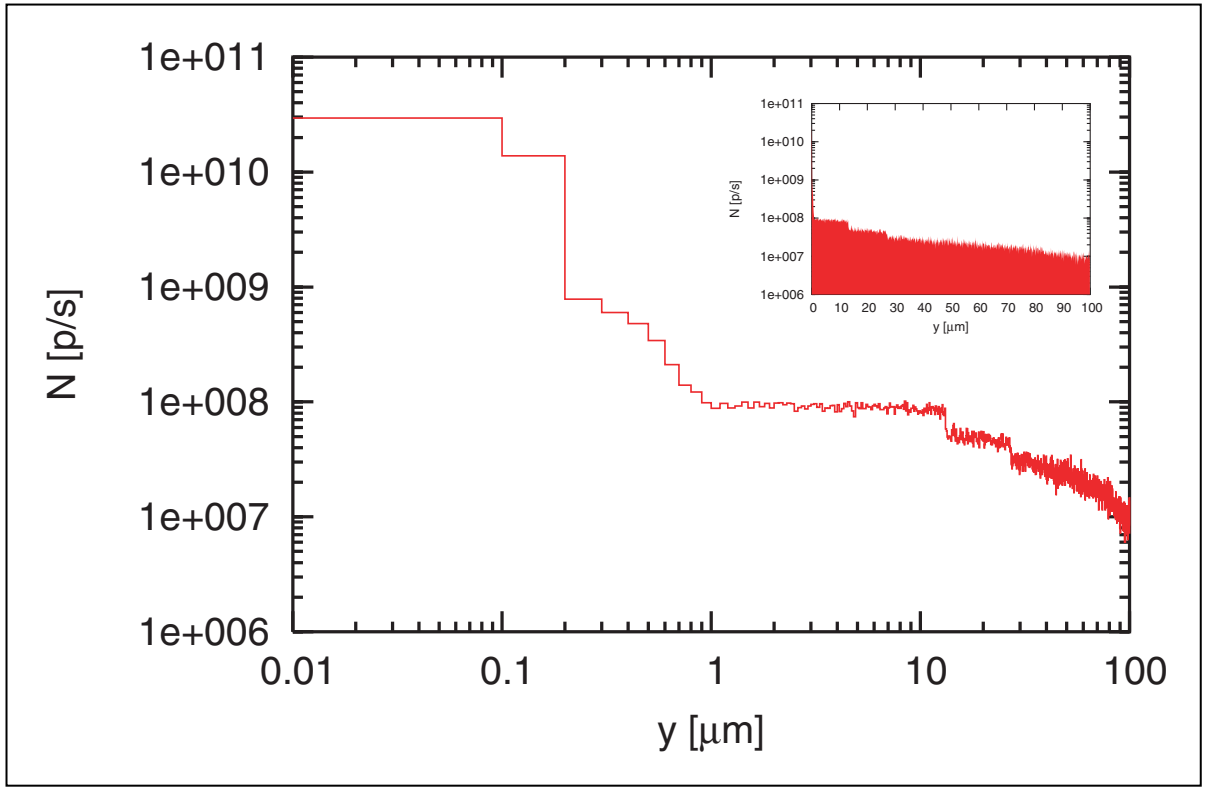
Uniform "emittance" blow-up

Beam lifetime: **0.2 h**

Assume drift: 0.3 sig/s
5.3 nm/turn

Loss rate: 4.1e11 p/s
Loss in 10 s: 4.1e12 p (**1.4 %**)
(~ 40 bunches)

(sigma = 200 micron)



Transverse impact parameter

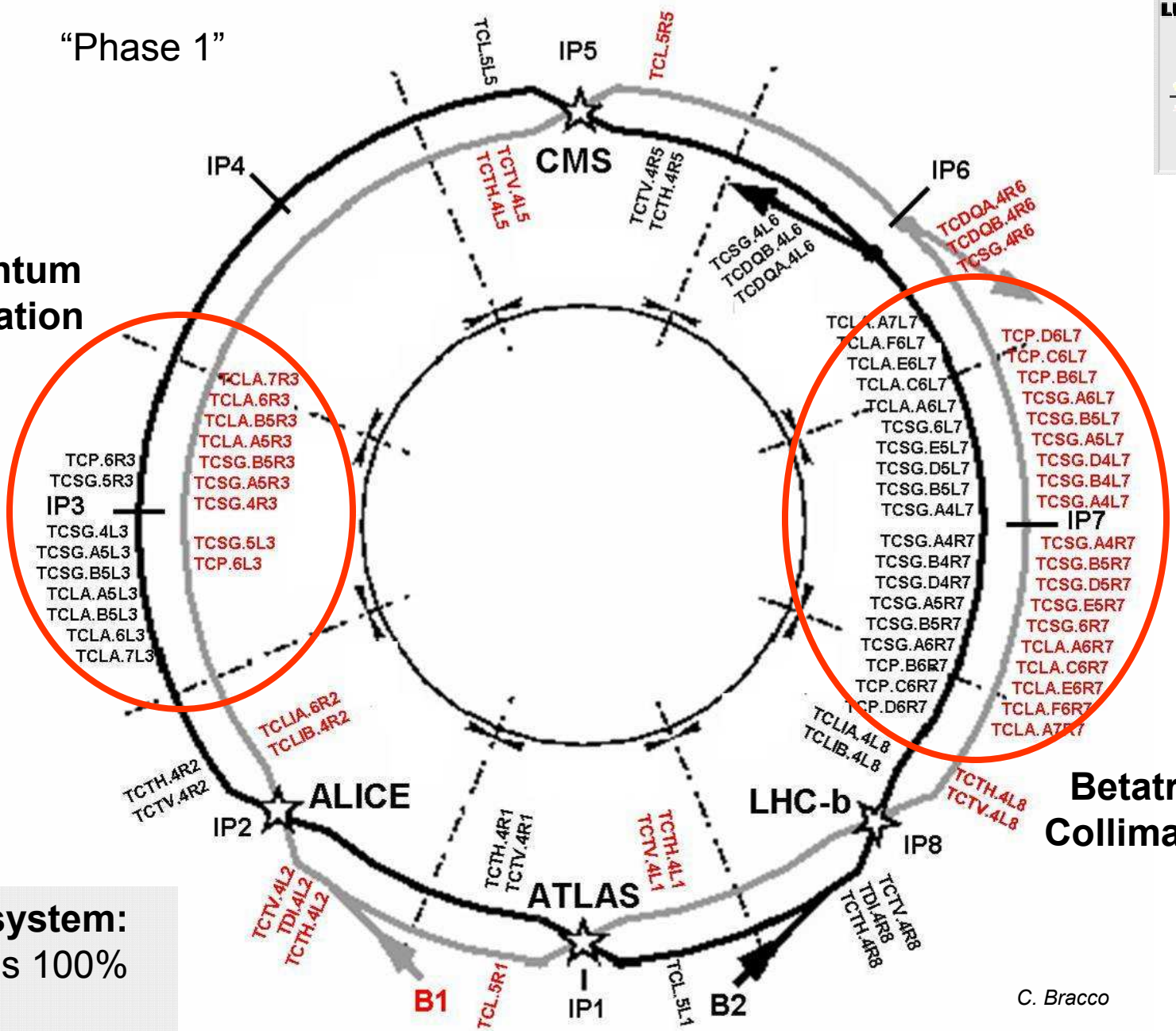
Almost all particles impact with

y ≤ 0.2 µm

Surface phenomenon!

“Phase 1”

Momentum Collimation



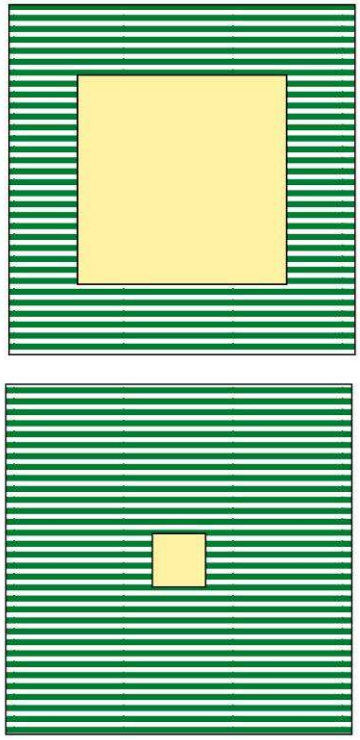
Betatron Collimation

C. Bracco

“Final” system:
Layount is 100% frozen!

LHC Collimator Gaps

10 mm



Collimator settings:

5 - 6 σ (primary)
6 - 9 σ (secondary)

σ ~ 1 mm (injection)
σ ~ 0.2 mm (top)

Small gaps lead to:

1. Surface flatness tolerance (40 μm).
2. Impedance increase.
3. Mechanical precision demands (10 μm).

Required Efficiency

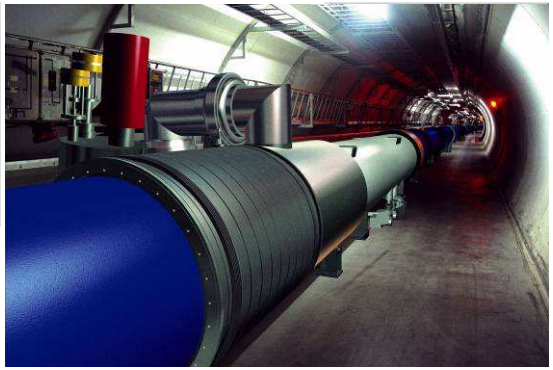


Illustration of LHC dipole in tunnel

Allowed intensity

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

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

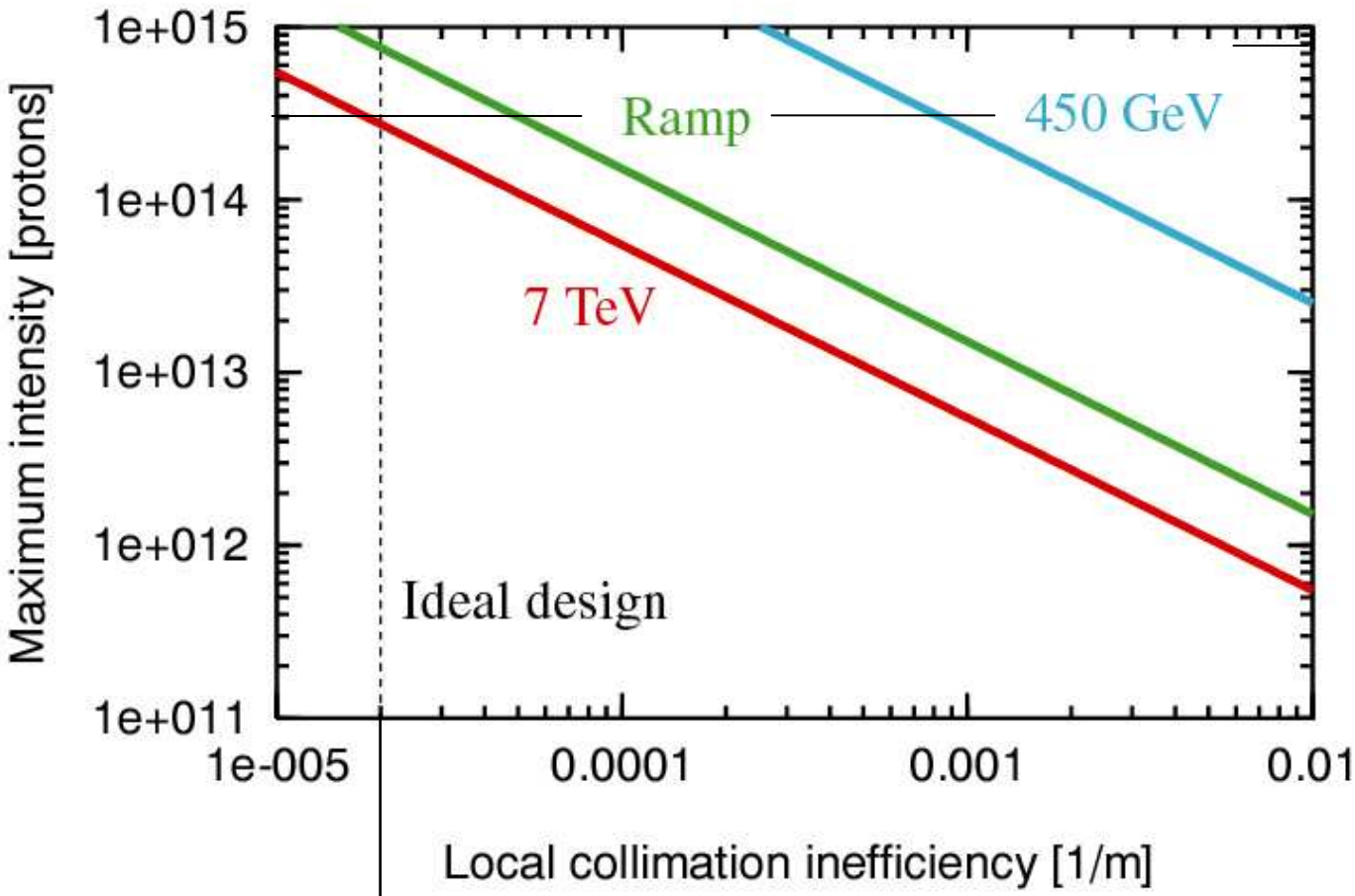
Cleaning inefficiency
=
$$\frac{\text{Number of escaping p } (>10\sigma)}{\text{Number of impacting p } (6\sigma)}$$

Beam lifetime
(e.g. 0.2 h minimum)

Dilution length
(~10 m)

Collimation performance can limit the intensity and therefore LHC luminosity.

Intensity Versus Cleaning Efficiency



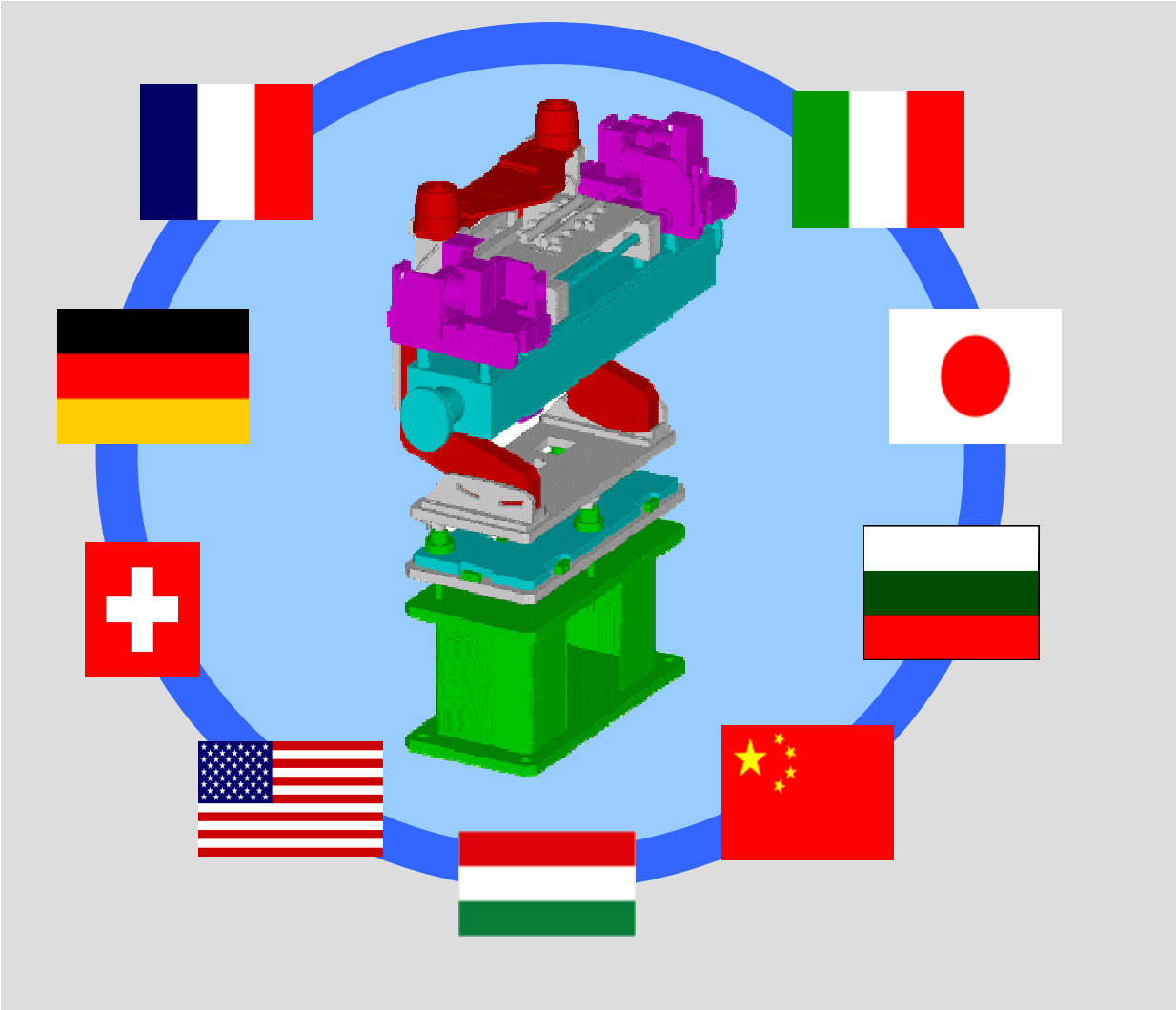
For a 0.2 h minimum beam lifetime during the cycle.

99.998 % per m efficiency

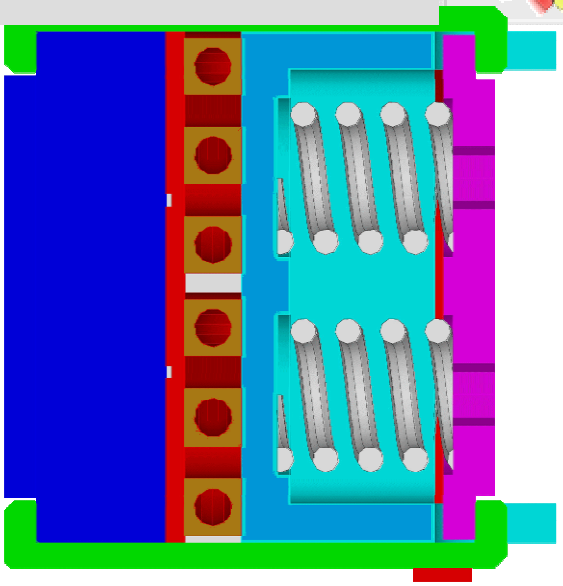
The LHC Phase 1 Collimation

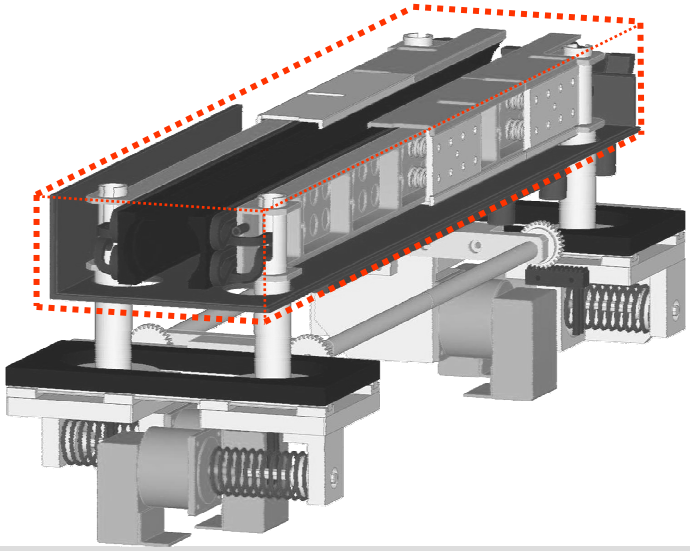
- Low Z materials closest to the beam:
  - **Survival** of materials with direct beam impact
  - Improved **cleaning efficiency**
  - High **transparency**: 95% of energy leaves jaw
- Distributing losses over ~250 m long *dedicated* cleaning insertions:
  - Average load **≤ 2.5 kW per m** for a 500 kW loss.
  - No risk of quenches in **normal-conducting magnets**.
  - Hot spots protected by passive **absorbers** outside of vacuum.
- Capturing residual energy flux by high Z absorbers:
  - Preventing losses into **super-conducting region** after collimator insertions.
  - Protecting expensive magnets **against damage**.
- No shielding of collimators:
  - As a result **radiation spread more equally** in tunnel.
  - Lower **peak doses**.
  - Fast and **remote handling possible** for low weight collimators.

3) Collimator Hardware



Hardware: Water Cooled Jaw

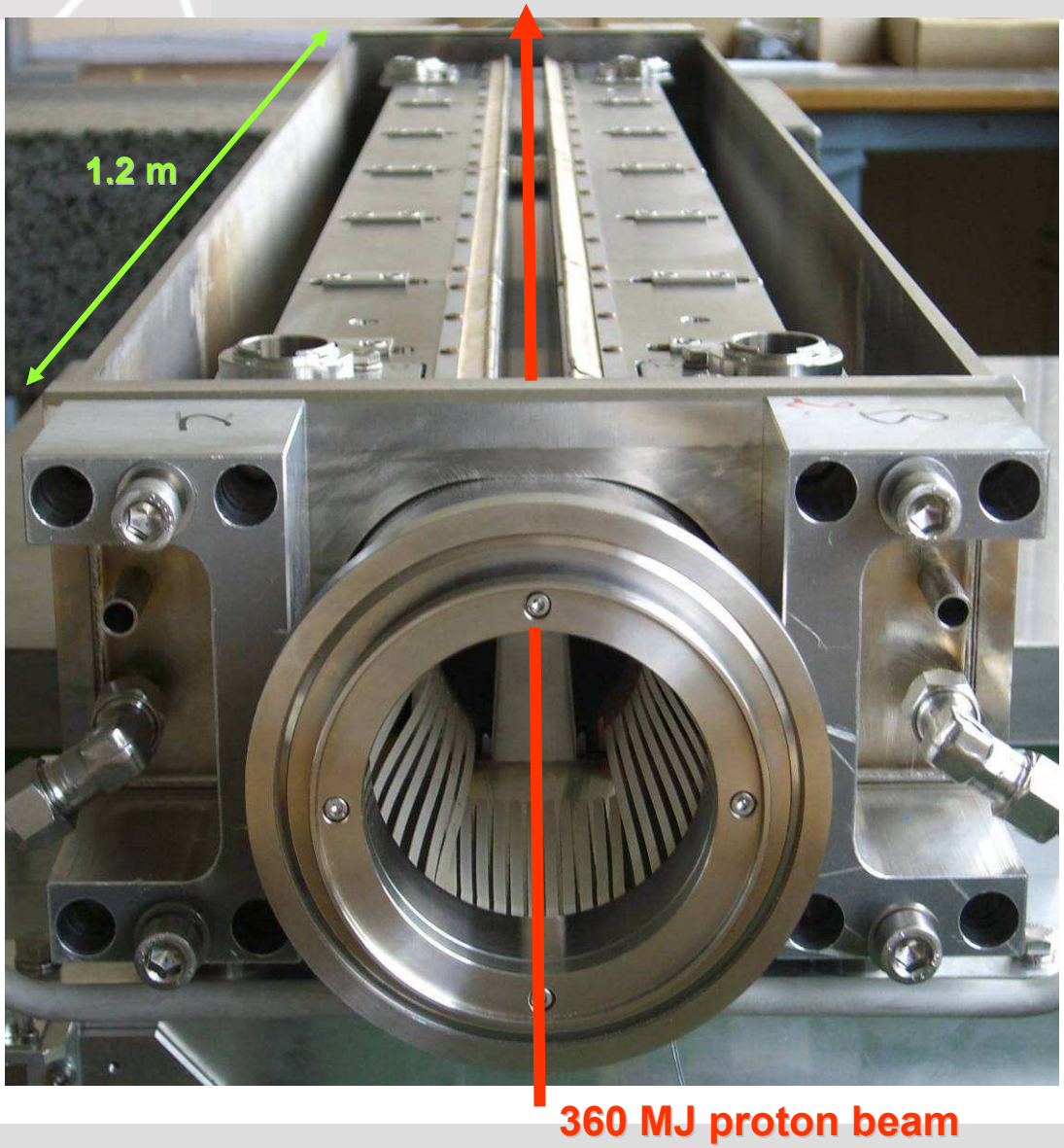


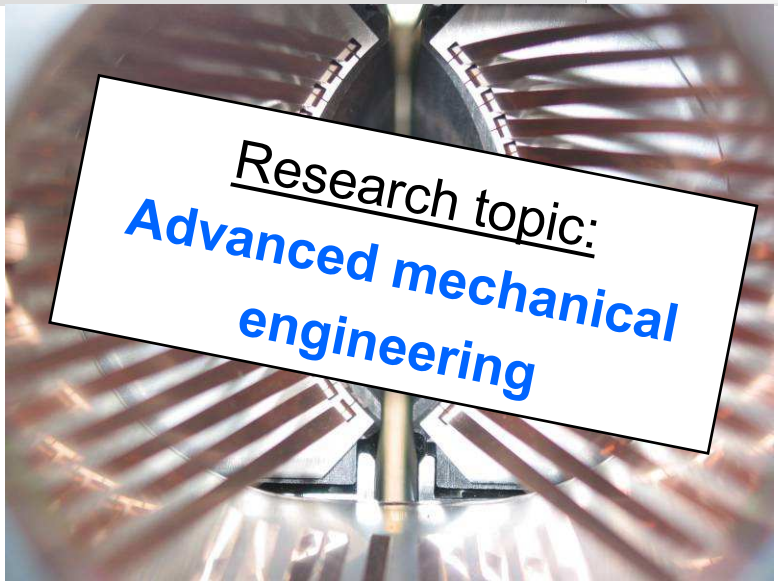


➔Up to 500 kW impacting on a jaw (7 kW absorbed in jaw)…

Advanced material: Fiber-reinforced graphite (CFC)

The LHC "TCSG" Collimator





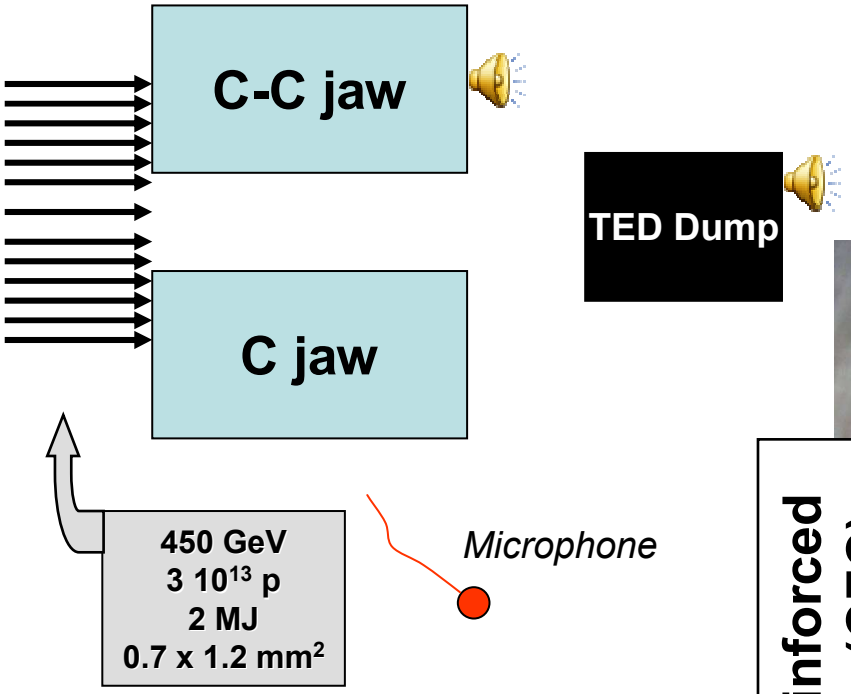
3 mm beam passage with RF contacts for guiding image currents

Designed for maximum robustness:

Advanced CC jaws with water cooling!

Other types: Mostly with different jaw materials. Some very different with 2 beams!

Robustness Test with Beam



~ Tevatron beam

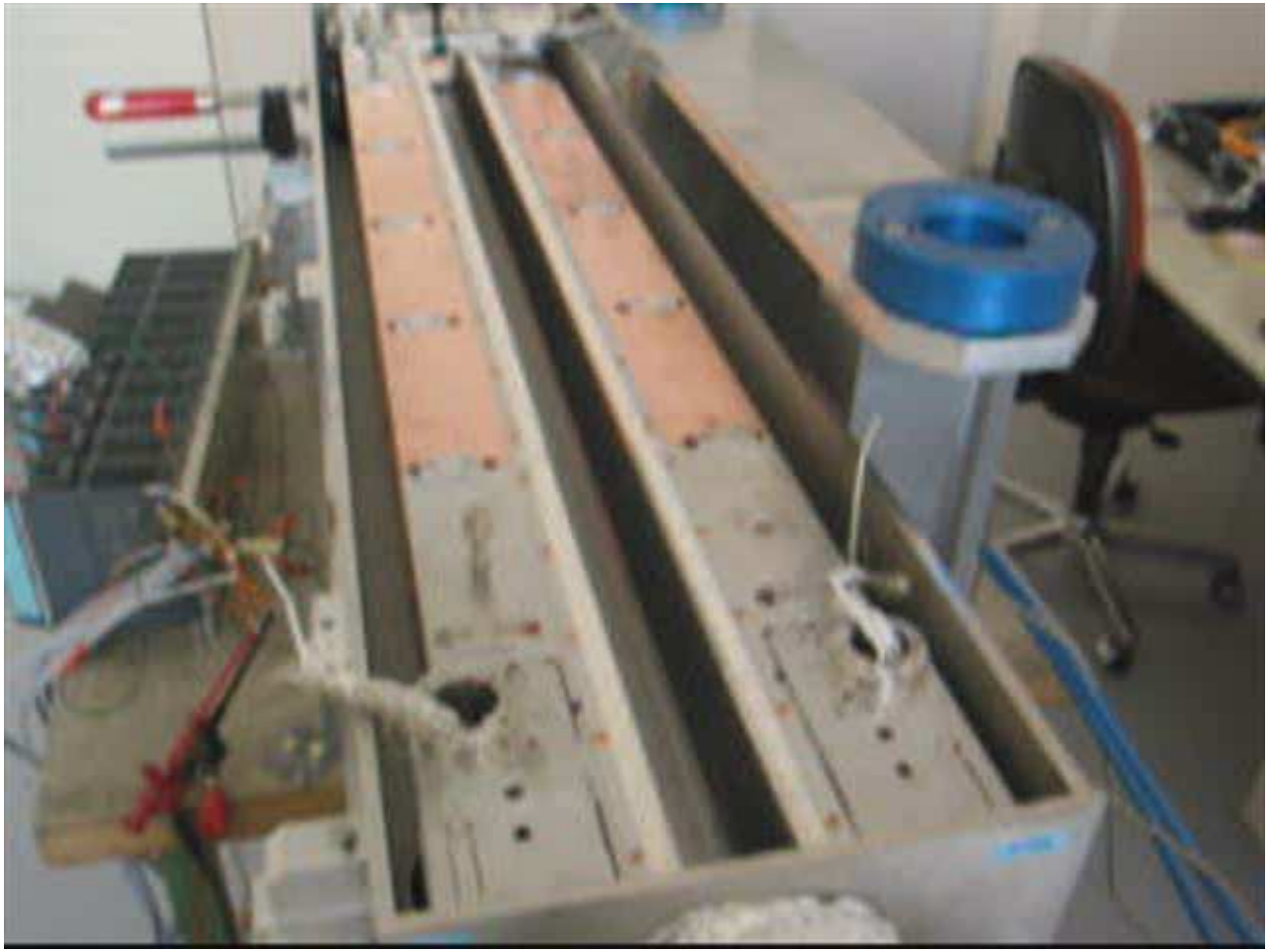
~ ½ kg TNT

Research topic:
Advanced materials and extreme shock waves

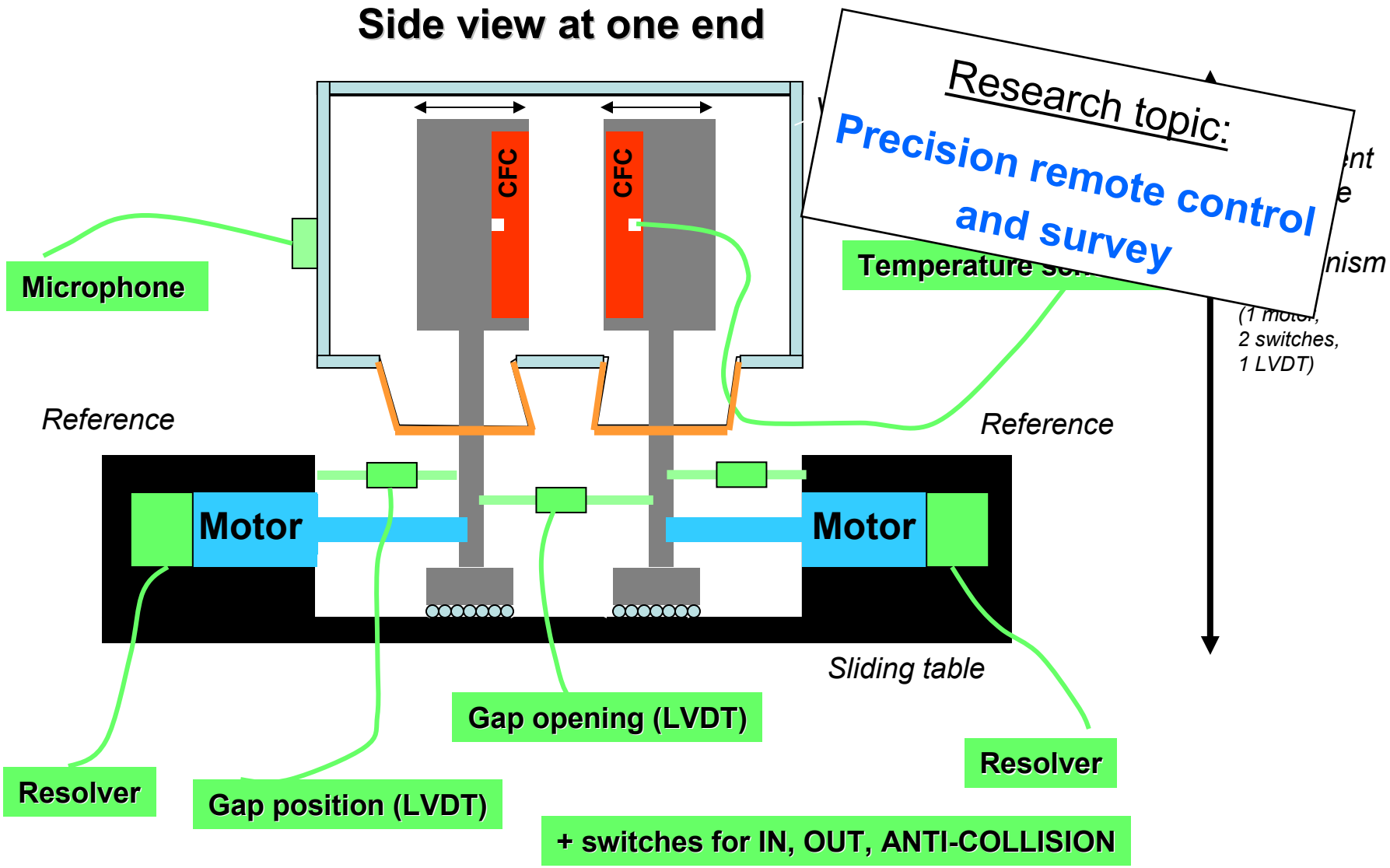
Fiber-reinforced graphite (CFC)

Graphite

Operational Control

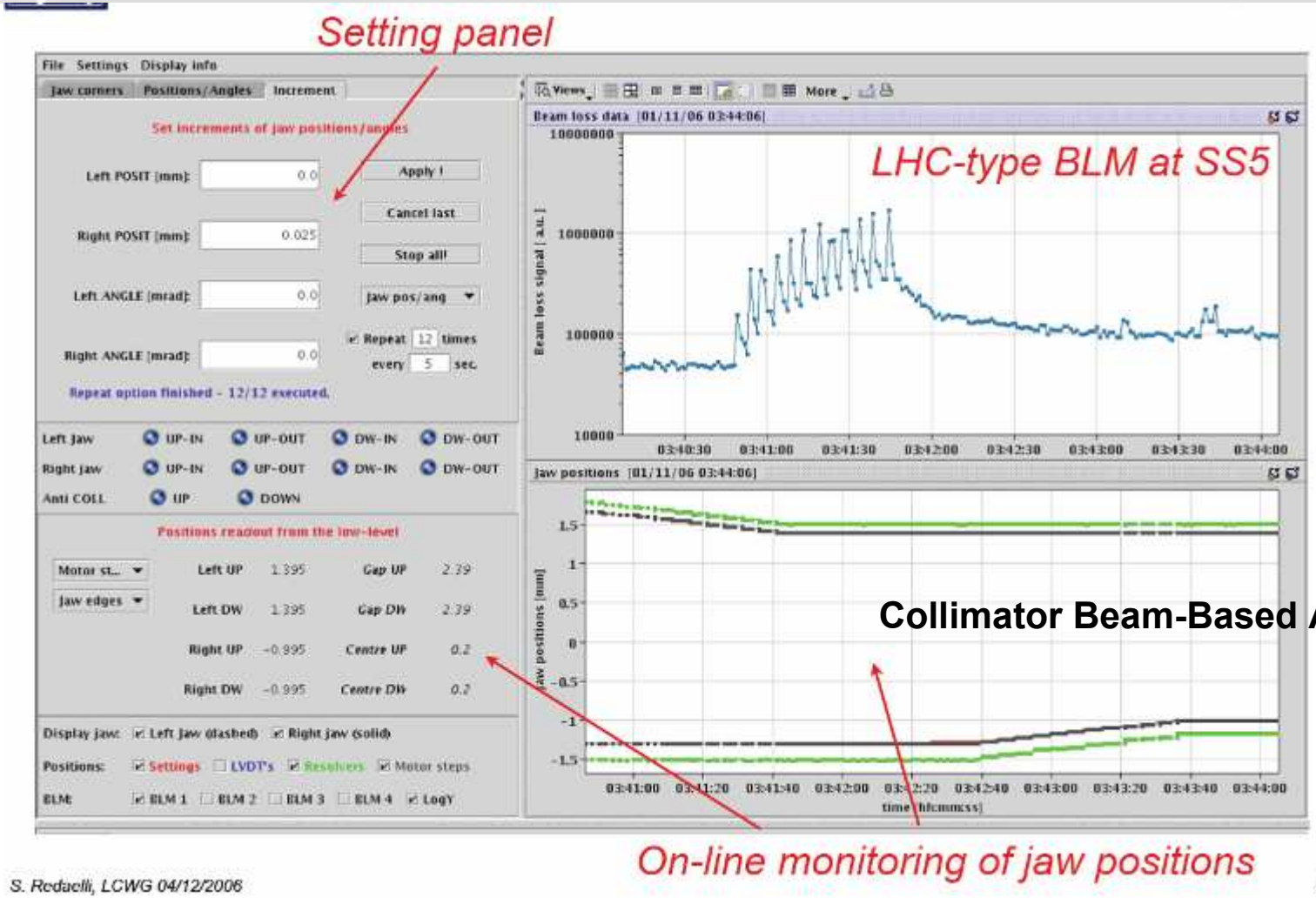


Using Sensors to Monitor LHC Jaw Positions



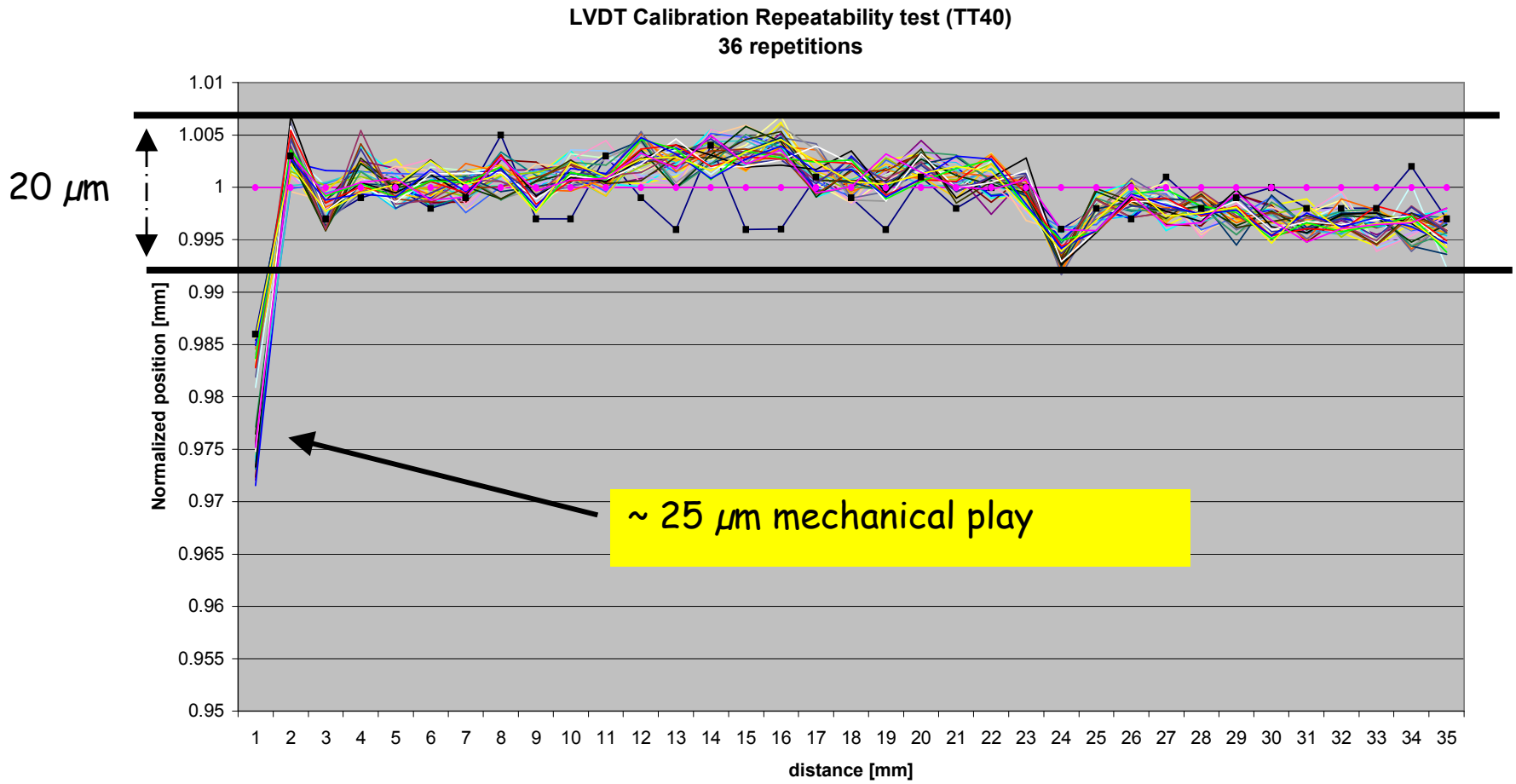
Collimator Controls

S. Redaelli et al



Successful test of LHC collimator control architecture with SPS beam (low, middle, top level)

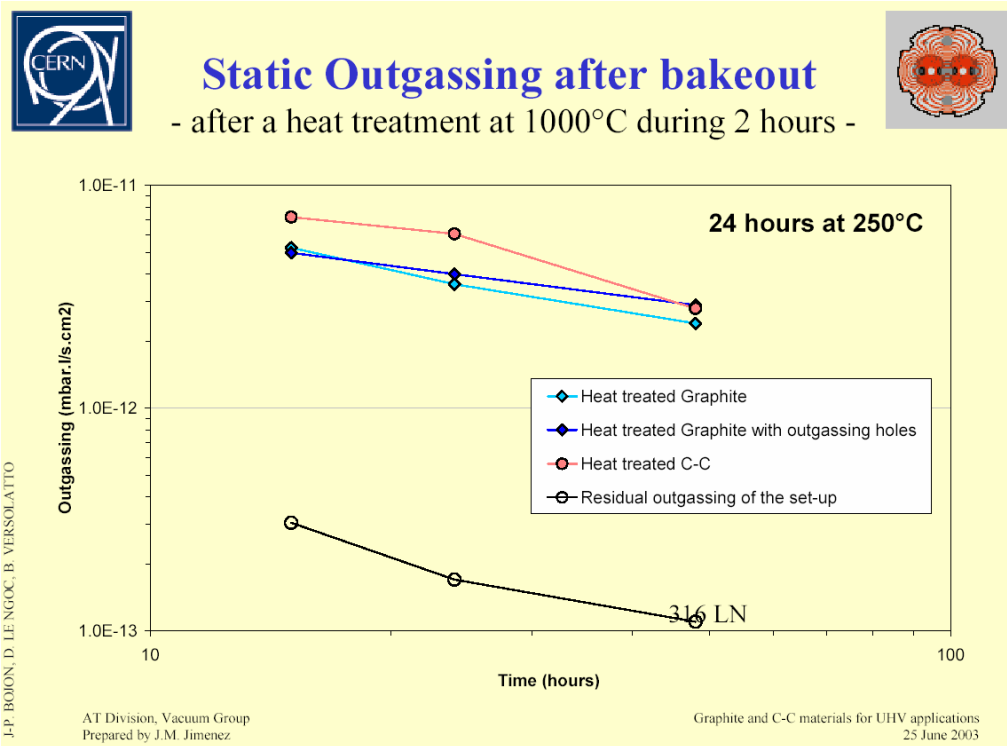
Position Measurement and Reproducibility

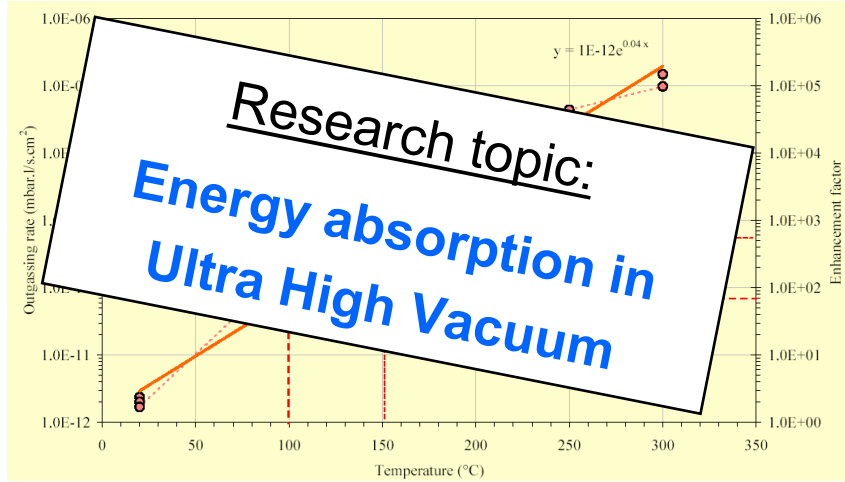


R. Losito et al

- Measured during test in TT40 (Oct. 31st) in remote!!!!

Compatibility with LHC UHV





J-P. BOJON, J.M. JIMENEZ,
D. LE NGOC, B. VERSOLATTO

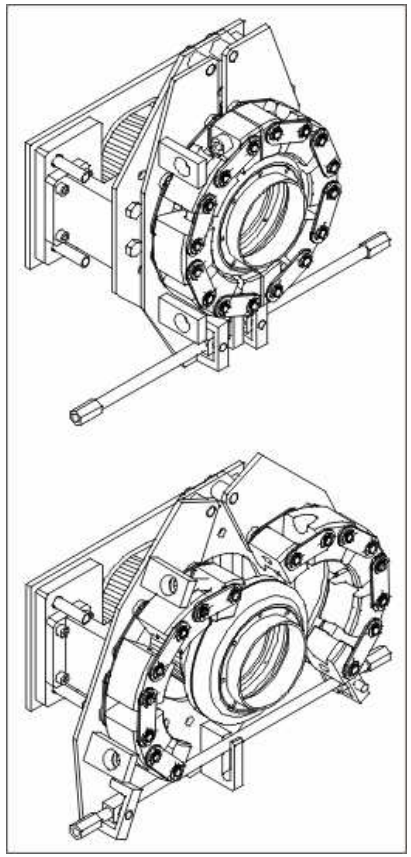
Conclusion: **Graphite-based jaws are compatible** with the LHC vacuum.

The outgassing rates of the C jaws will be optimized by **material and heat treatment under vacuum, an in-situ bake-out and a proper shape design**.

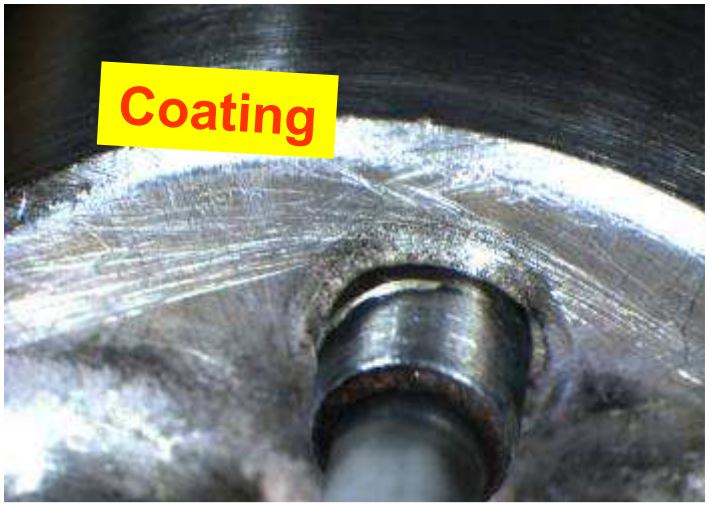
No indication that **graphite dust** may be a problem for the LHC.

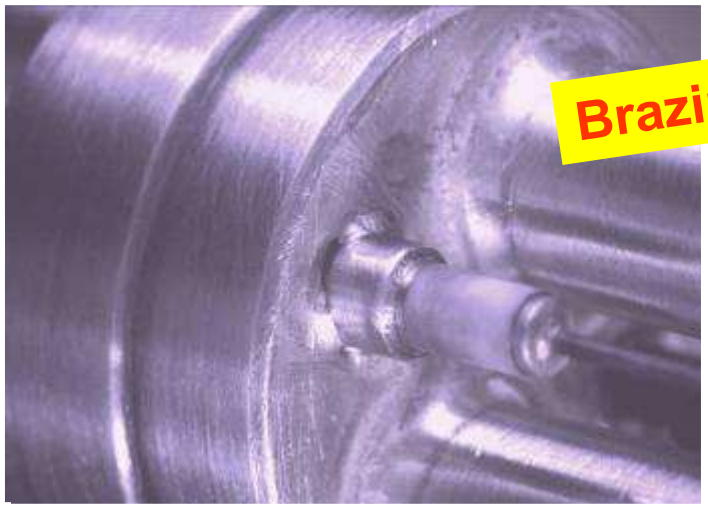
Other collimator features

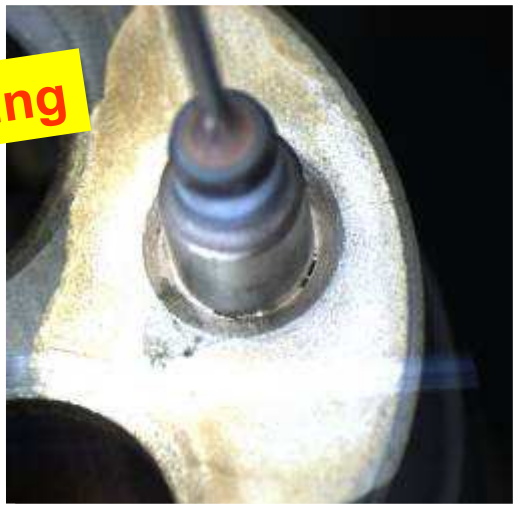
- In-situ **spare concept** by moving the whole tank (move to fresh surface if we scratch the surface with beam)
- Direct **measurements of jaw positions and absolute gap** (we always know where the jaws are)
- Precision **referencing system** during production
- Measurements of jaw **temperature**
- **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



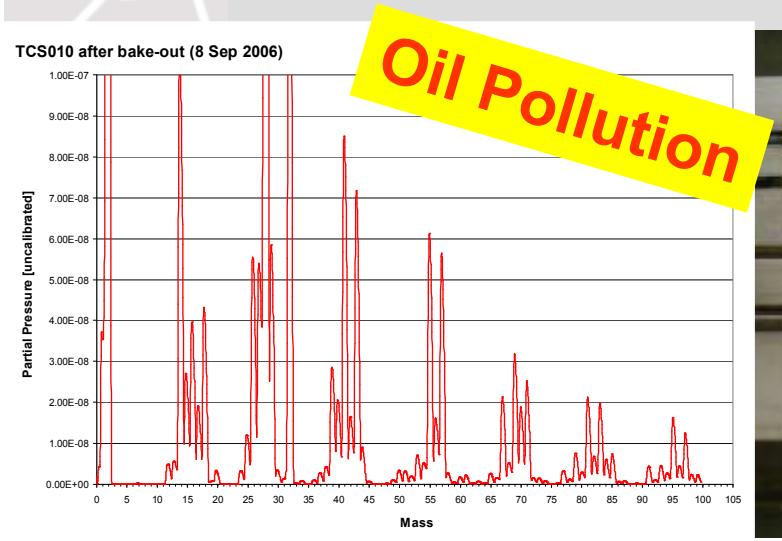
Problem Collection Industrial Production I





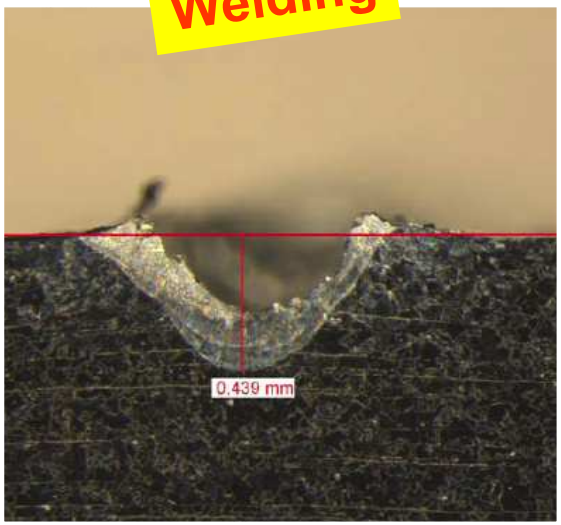


Problem Collection Industrial Production II



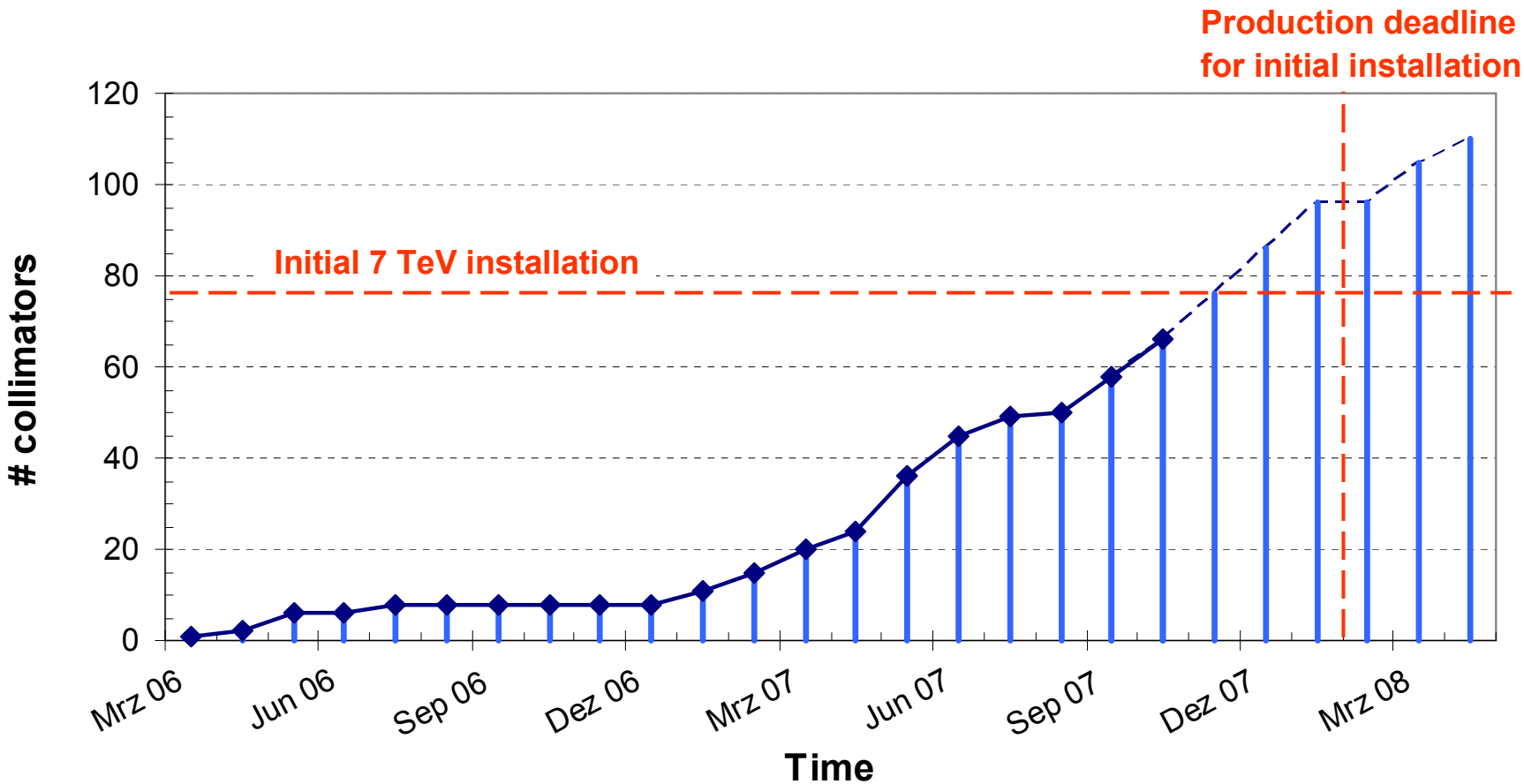
Oil Pollution

Welding



RF fingers

Collimator Deliveries



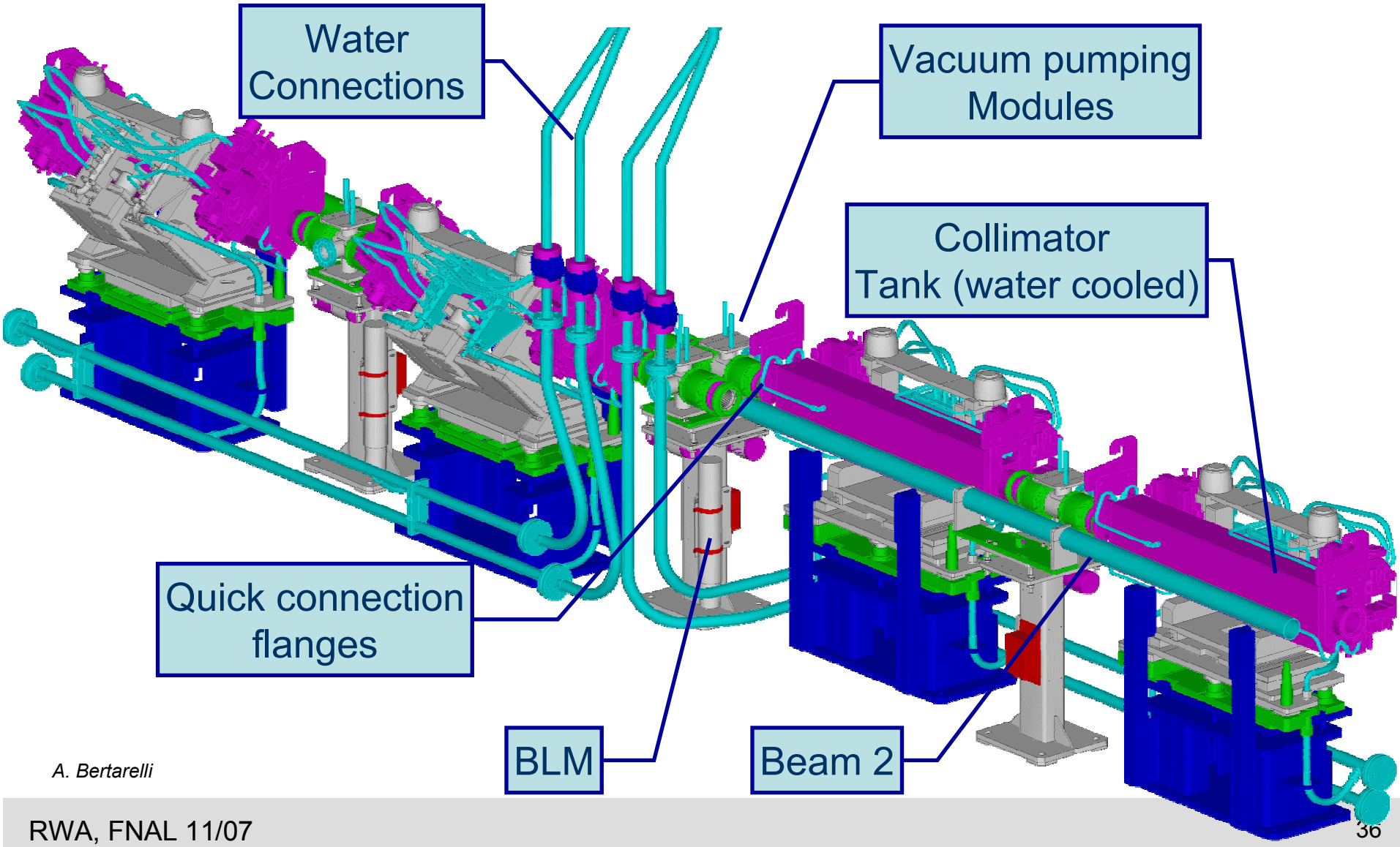
Industry: 87% of production for 7 TeV initial ring installation has been completed (66/76).

All collimators for first run should be at CERN by end of the year.

Total production should be completed in April.

4) Tunnel Installations

(vertical and skew shown)



A. Bertarelli

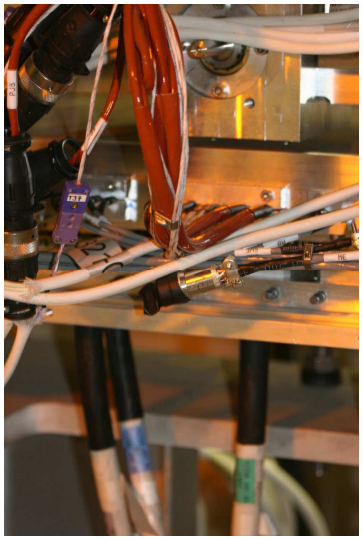
Tunnel Preparations IR7

Collimator Installation

Quick plug-in support (10 min installation)

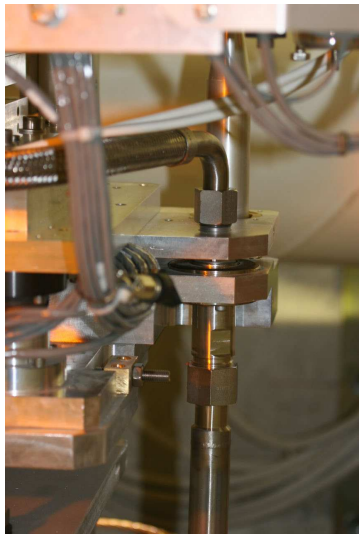
Installed Collimator on Plug-In

Collimator



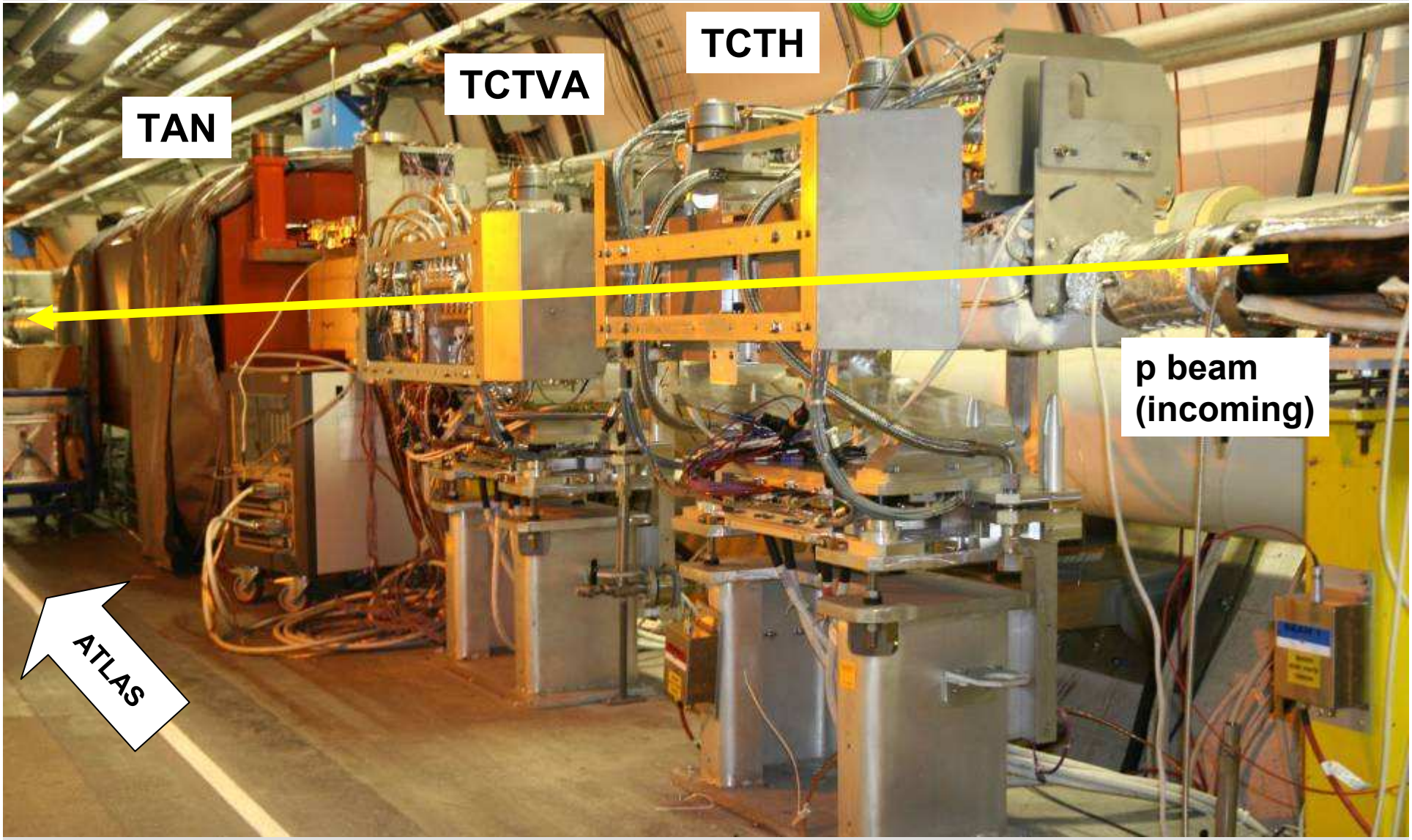
Upper plug-in

Lower plug-in



Base support

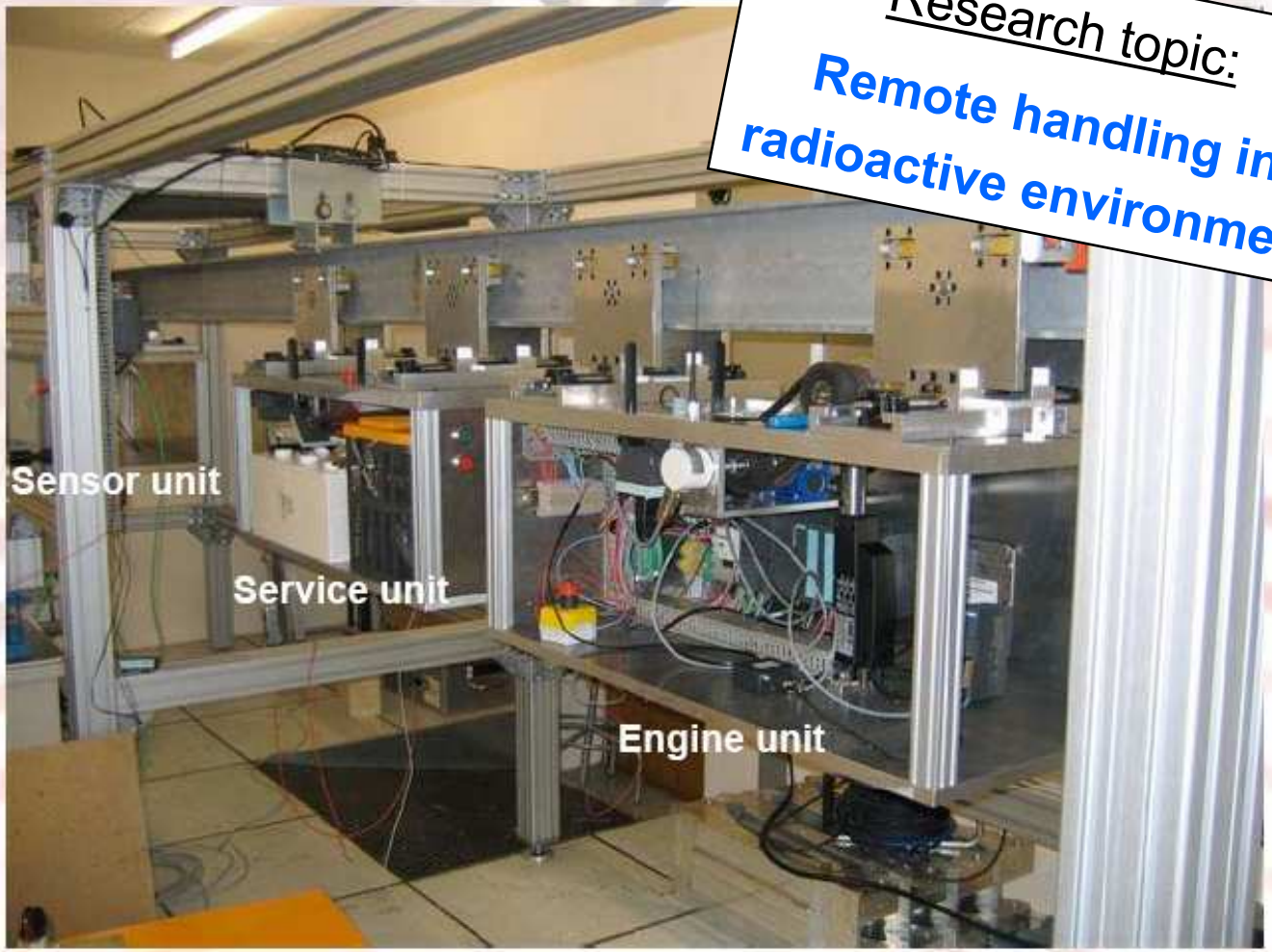
Example: Collimation for ATLAS



2 out of more than 100 collimators

Remote Train

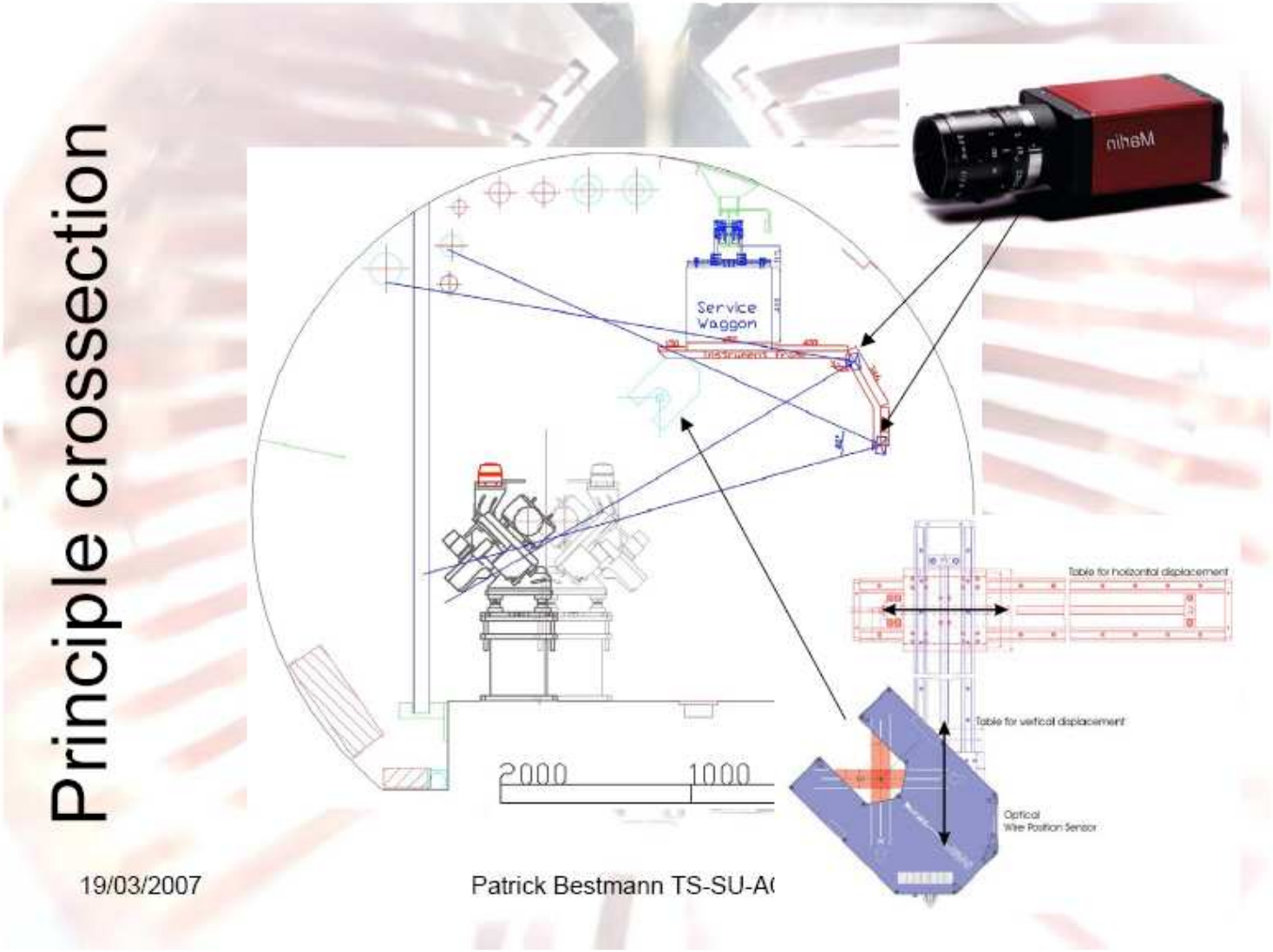
Train concept



Research topic:

Remote handling in radioactive environment

Remote Survey



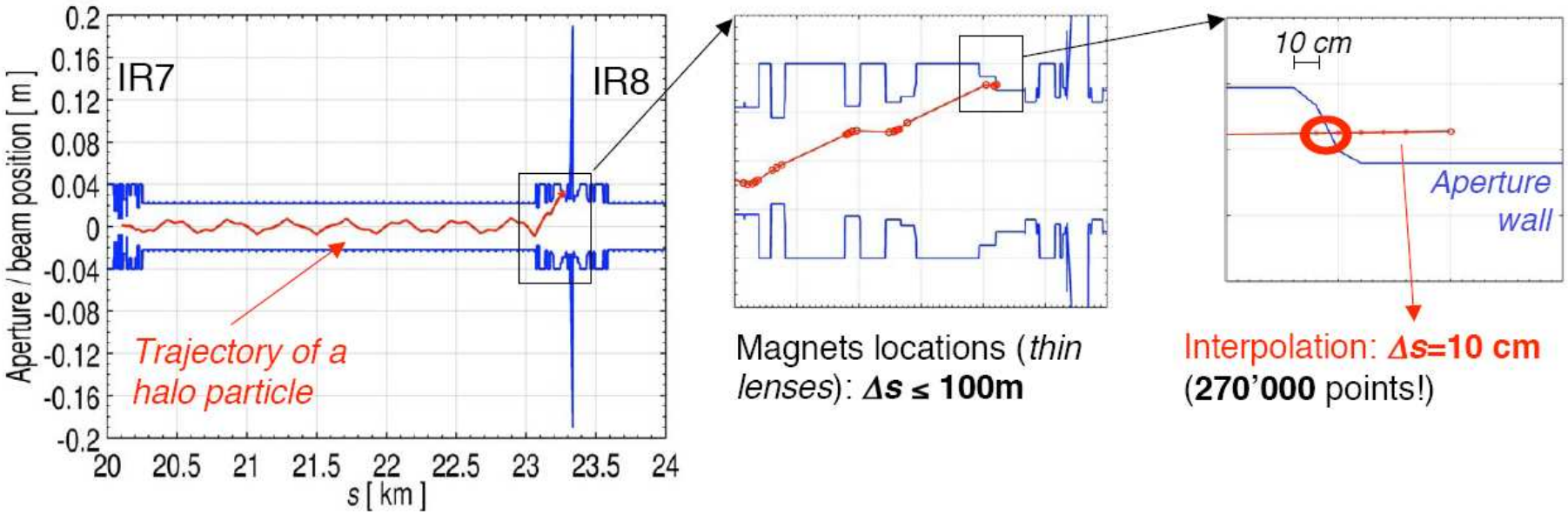
4) Collimation Performance

Simulations: **5 million halo protons**

200 turns

realistic interactions in all collimator-like objects

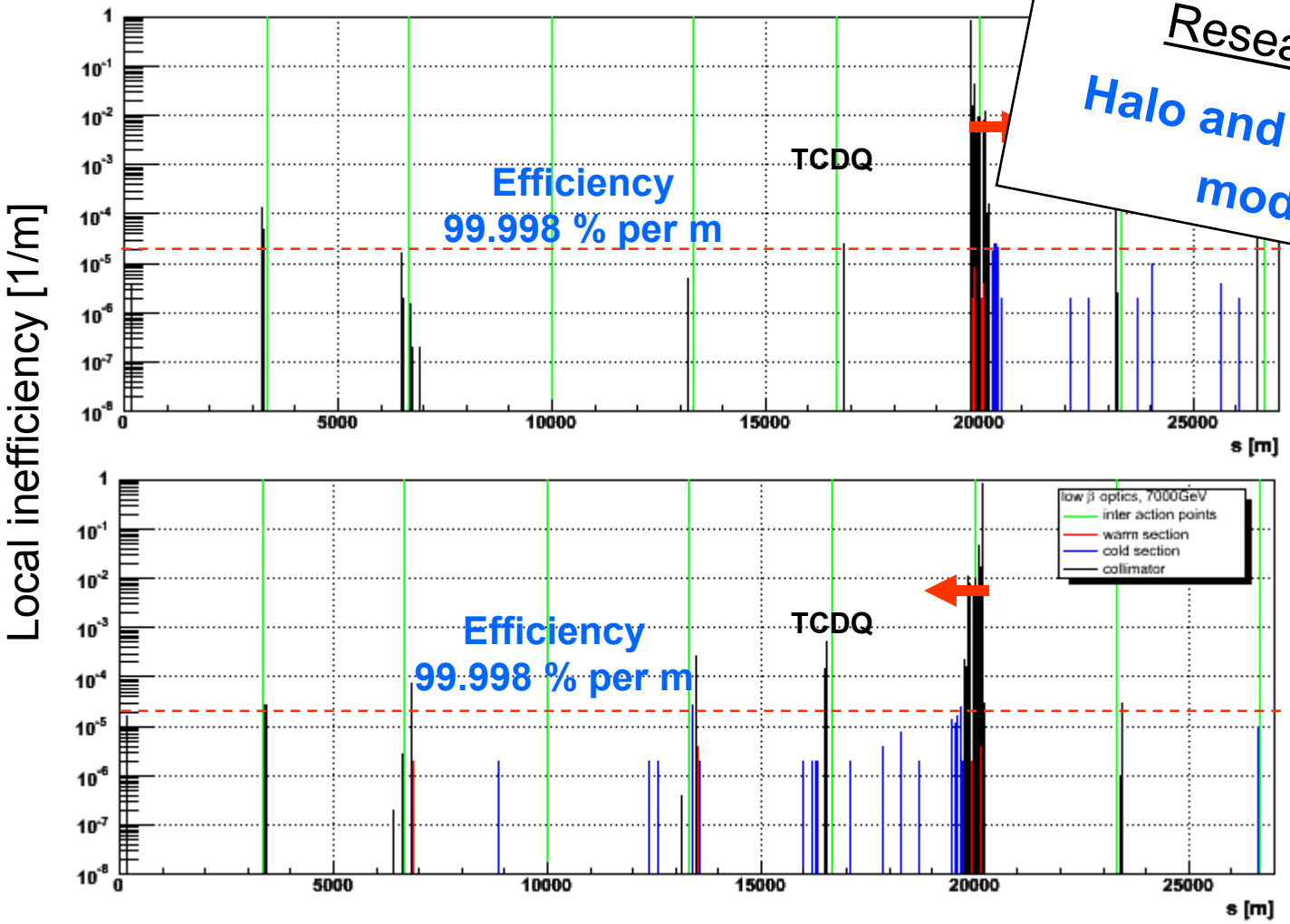
LHC aperture model



➔ **Multi-turn loss predictions**

Efficiency in Capturing Losses

Research topic:
Halo and collimation modeling



Beam2, 7 TeV
Betatron cleaning
Ideal performance

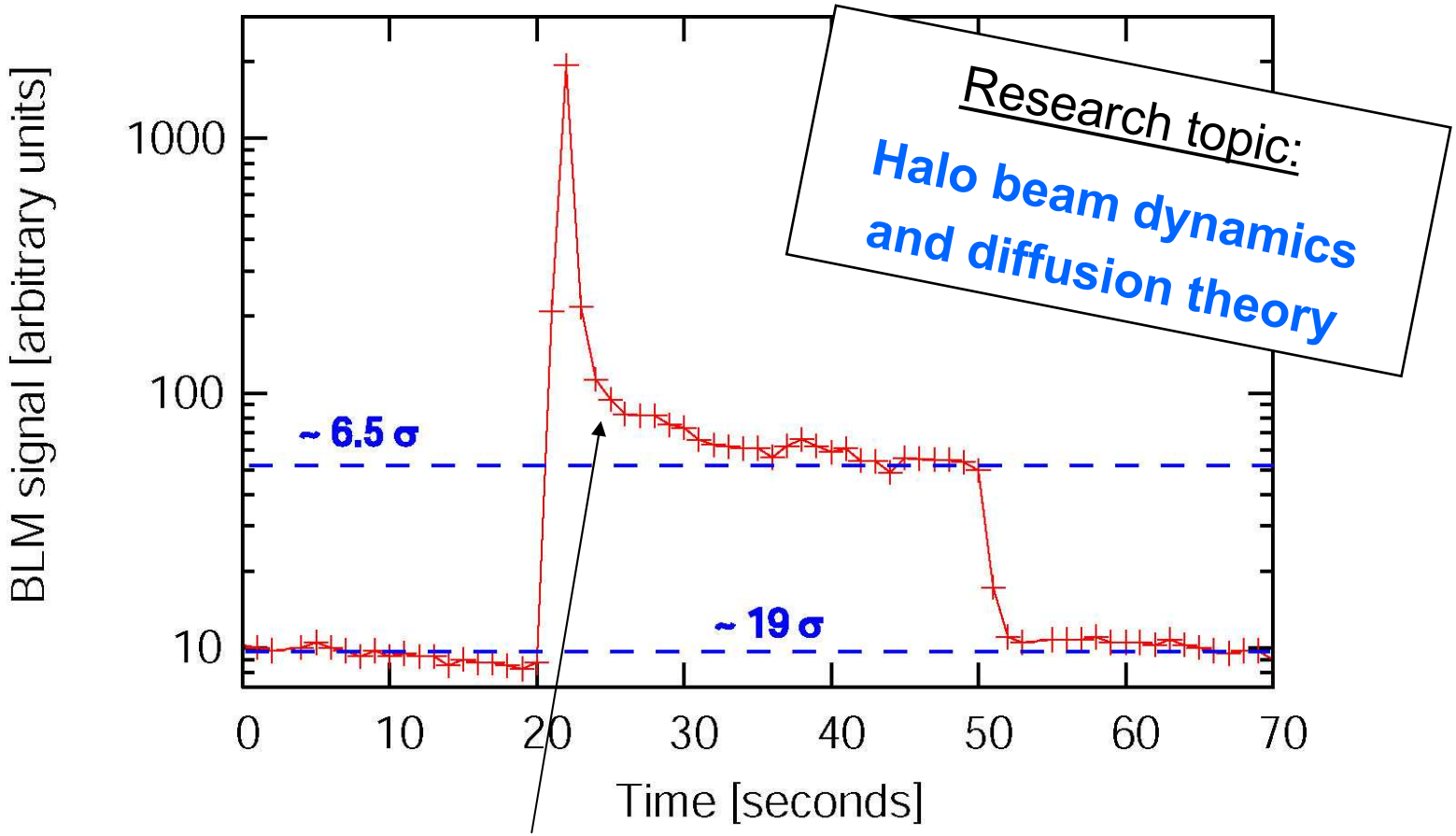
Quench limit
(nominal I, τ=0.2h)

99.998 % needed

99.995 % predicted

Local inefficiency: #p lost in 1 m over total #p lost = leakage rate

Problem: Beam loss tails?



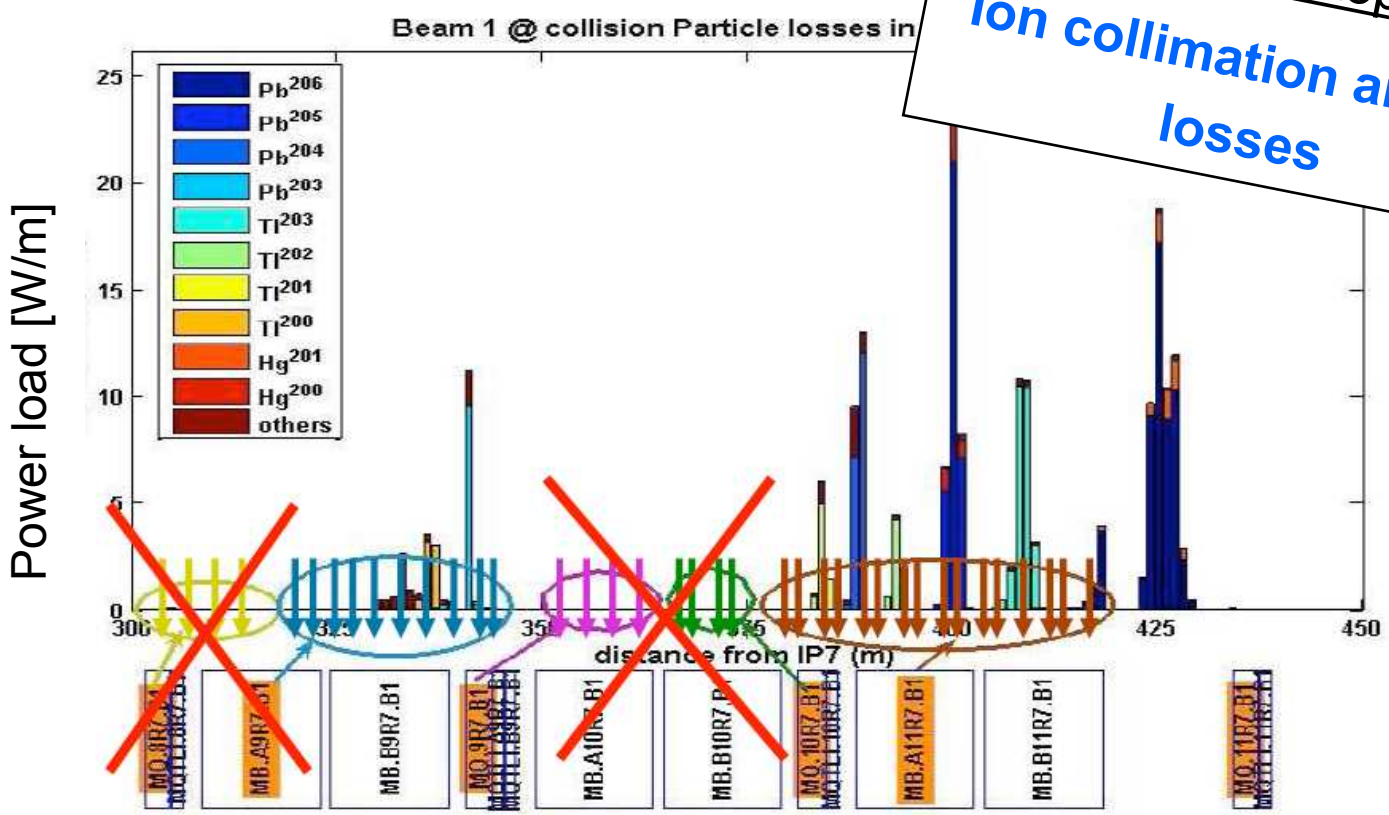
Observation of BLM signal tails: Up to 10-20 seconds in length

BLM team: Many measurements ➔ Beam related true signal!

Collimation for Ions

Different physics! Two-stage β cleaning not workin… …tion to **~50% of nominal ion intensity**.

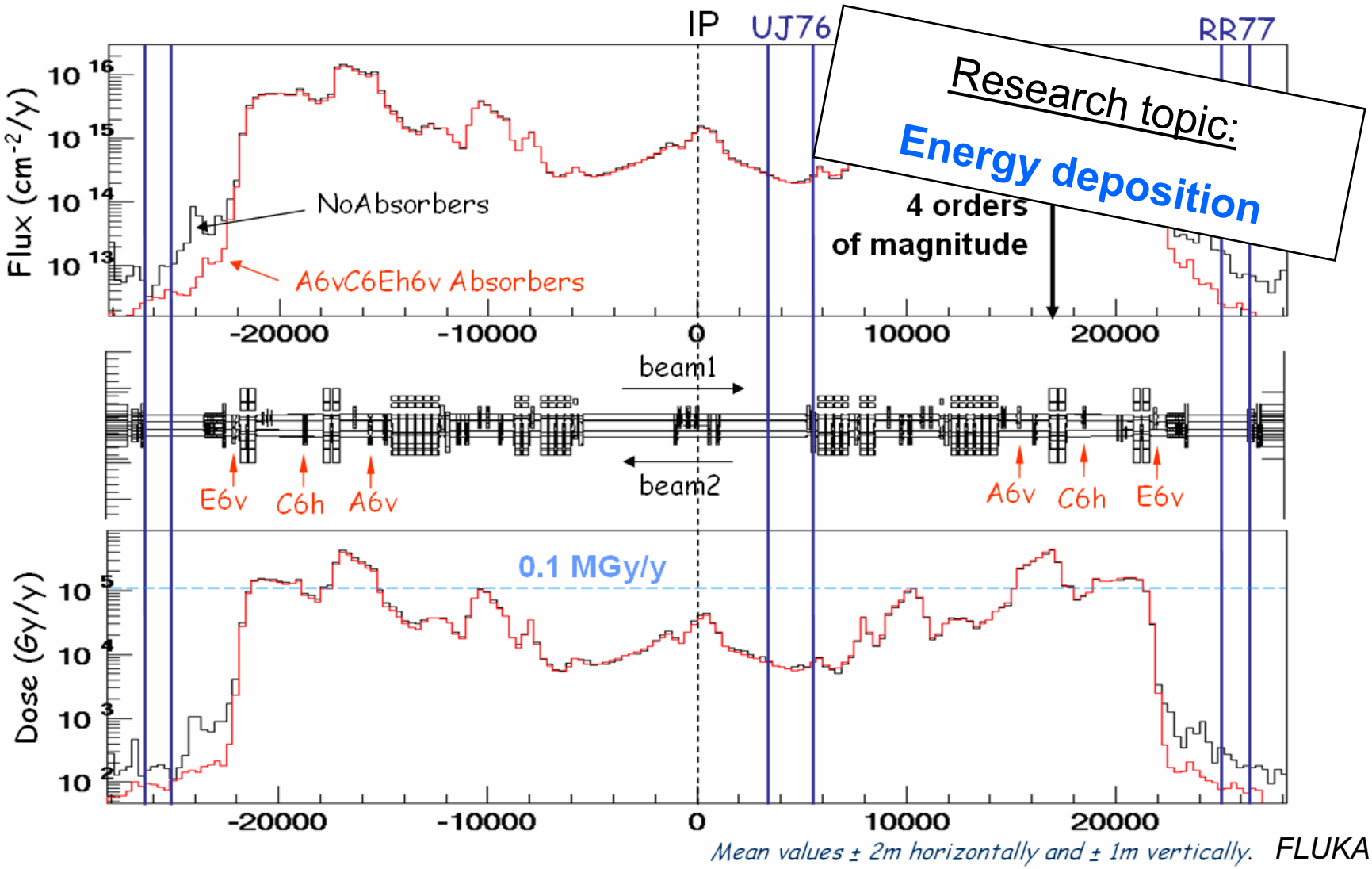
Research topic:
Ion collimation and ion losses



➔ Loss predictions used for allocation of additional BLM's for ions!

Energy Deposition (FLUKA)

K. Tsoulou et al



FLUKA team

CERN Mechanical Simulations

Displacement analysis – Nominal conditions (100 k… …ad Case 2
10s Transient (500 kW) – Loss rate 4×10^{11} p/s (Be…

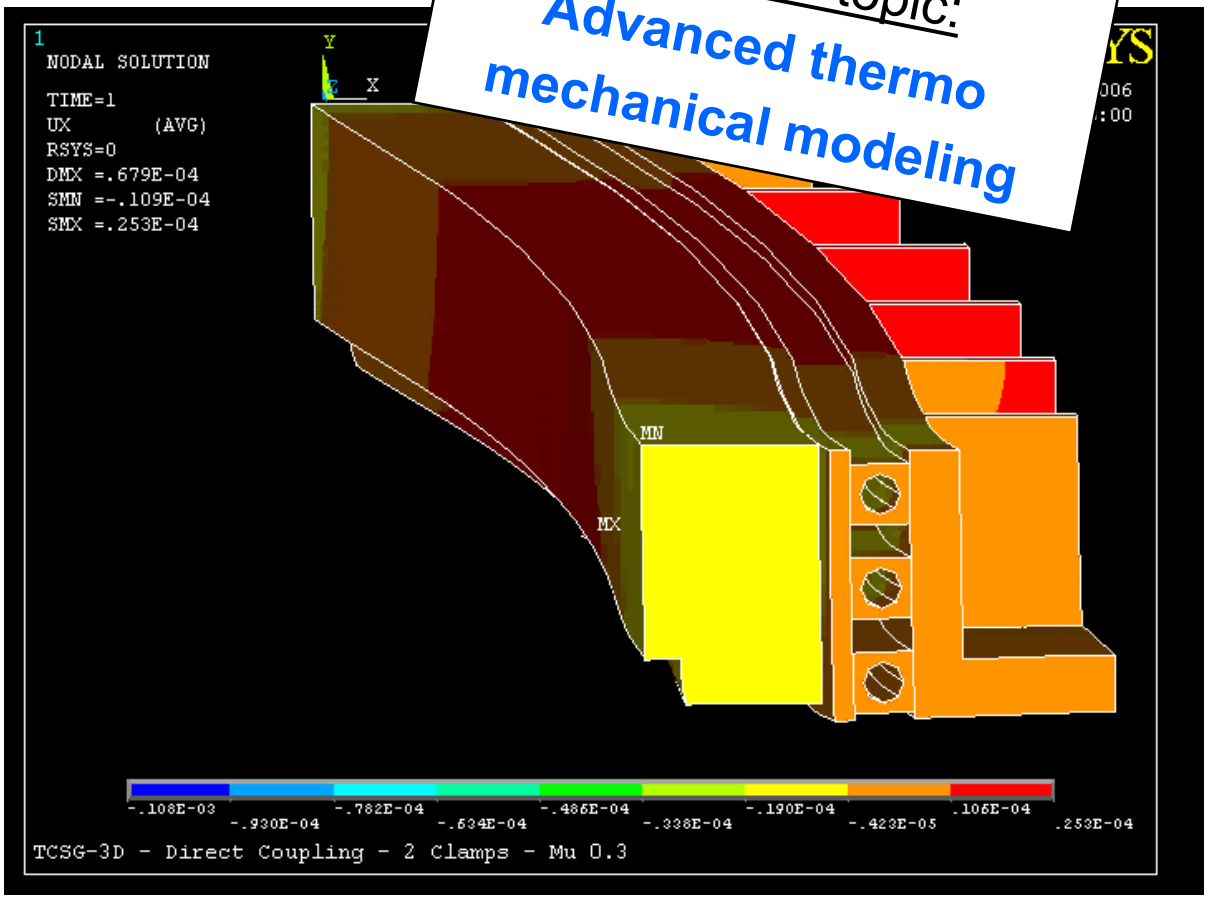
Research topic:
Advanced thermo mechanical modeling

Initial loss 8e10p/s Max. deflect. ~20μm

Transient loss 4e11p/s during 10s

Max deflect. -108μm

Back to 8e10p/s situation!



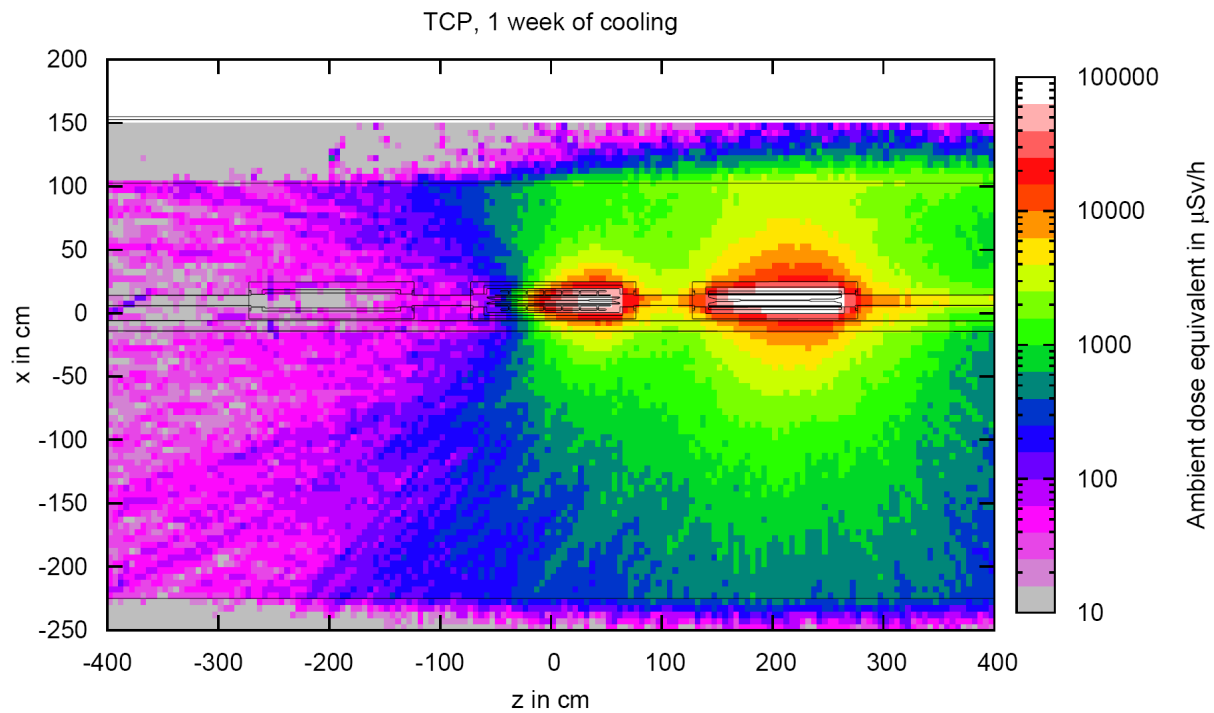
A. Bertarelli & A. Dallochio

Local Activation

- Losses at collimators generate local heating and
- Local heating: On average **2.5 kW/m**.
- Activation: Up to **20 mSv/h** on contact (better not to
- Fast handling implemented. Remote handling being developed.

Research topic:
Radiation impact

Residual dose rates
One week of cooling

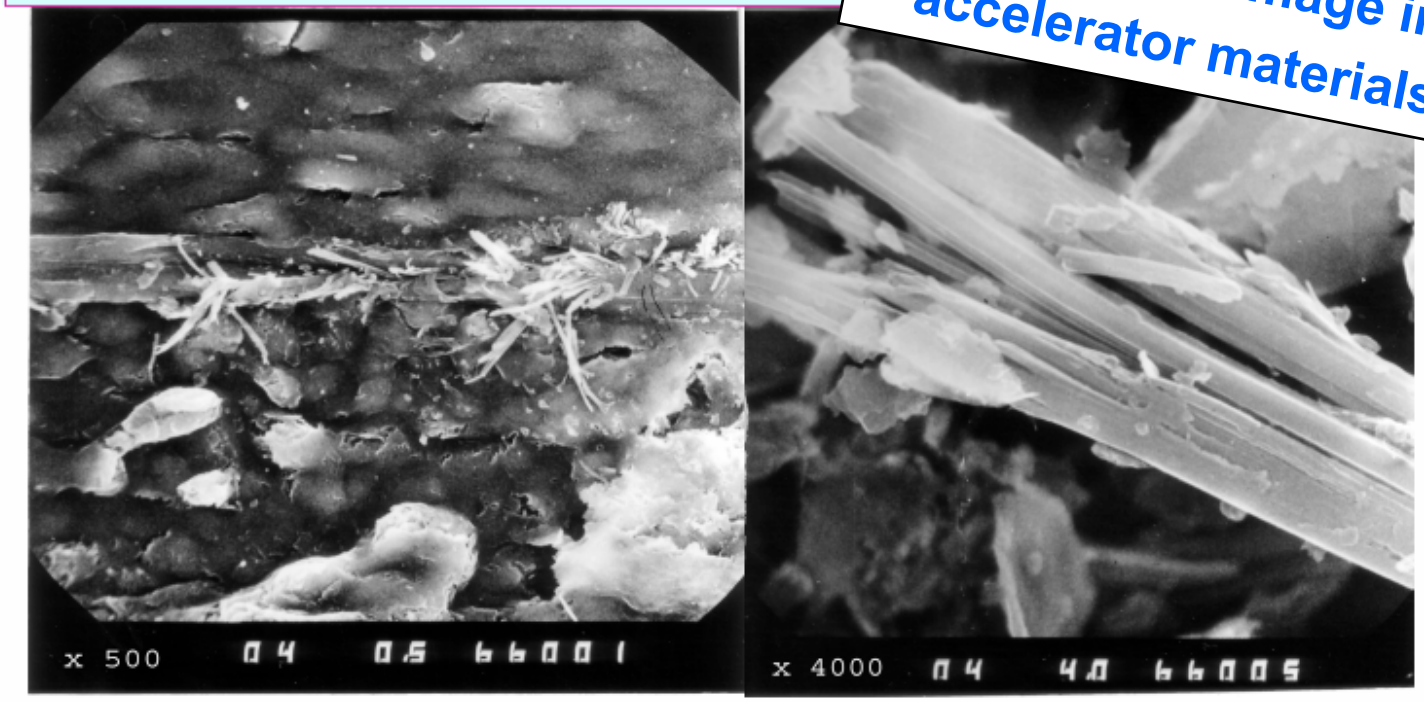


S. Roesler et al

Kurchatov Collaboration Studies of CFC Material Used in LHC Collimators

Analysis of Radiation Induced Erosion … osite Material AC Irradiated by Carbon Ions at Irradiation Dose: 1x10

Research topic:
Radiation damage in accelerator materials



A. Ryazanov

➔ **Working on understanding radiation damage to LHC collimators from 10^{16} impacting protons of 7 TeV per year. Also with BNL/LARP…**

… in addition shock wave models…

Impedance Problem

- Several reviews of LHC collimator-induced impedance (originally not thought to be a problem).
- Surprise in 2003: LHC impedance driven by collimators, even metallic collimators.
- LHC will have an impedance that depends on the collimator settings!
- Strong effort to understand implications…

Third look at impedance in Feb 03 revealed a problem:

$$\frac{Z_\perp^{\rm coll}}{Z_\perp^{\rm arc}} \sim \frac{(L^{\rm coll}/L^{\rm arc}) \times \sqrt{\rho^{\rm coll}/\rho^{\rm arc}}}{(a^{\rm coll}/a^{\rm arc})^3} \sim$$

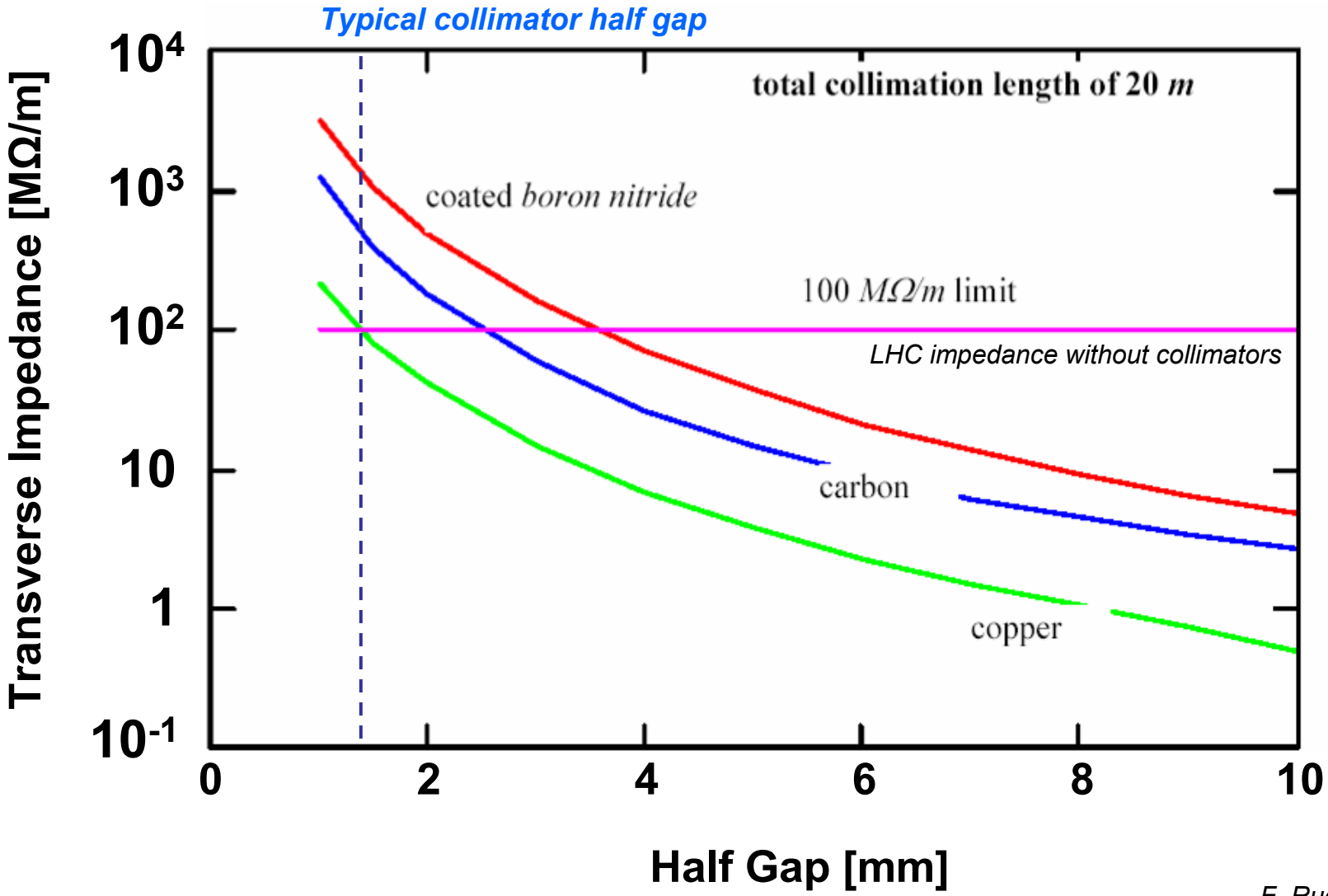
$$\sim \frac{(20\,{\rm m}/20\,{\rm km}) \times \sqrt{{\rm RRR} \sim 30}}{(1.8\,{\rm mm}/18\,{\rm mm})^3} \sim$$

$$\sim \frac{10^{-3} \times 5}{10^{-3}} \sim 5!$$

F. Ruggiero

Research topic:
Impedance

First Impedance Estimates 2003

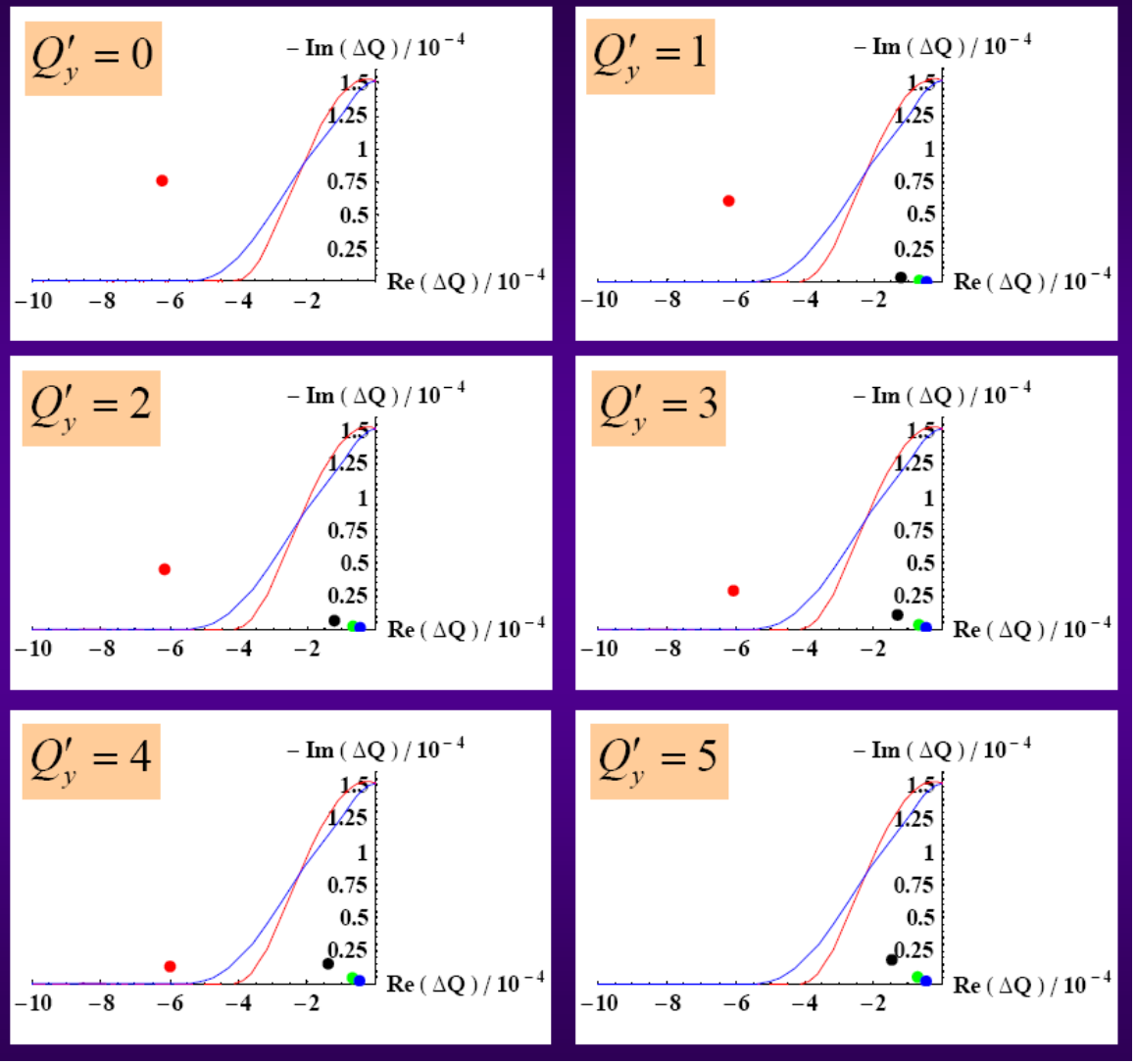


F. Ruggiero, L. Vos

Impedance and Chromaticity

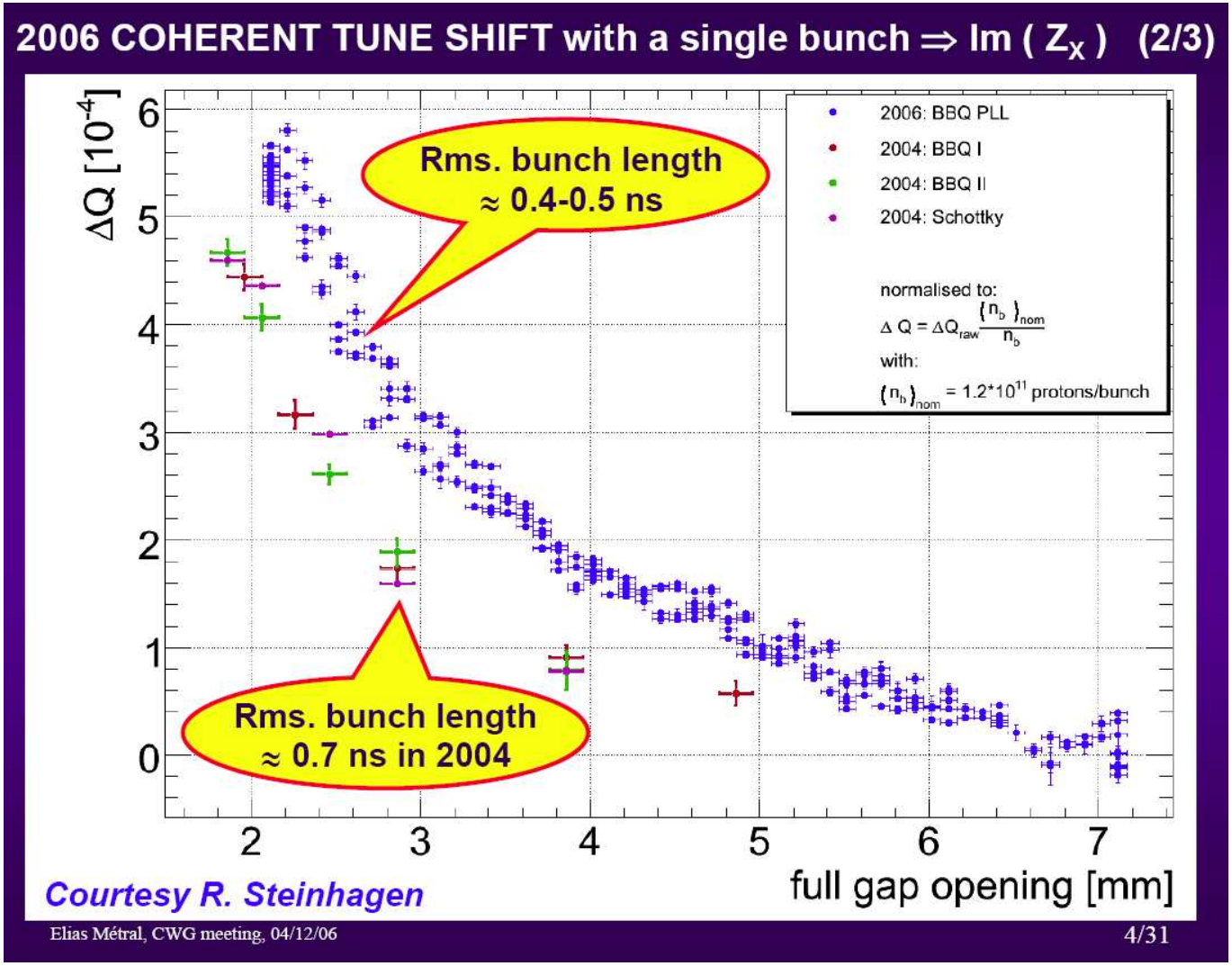
Stability diagrams (Y-plane)

Mode 0
Mode 1
Mode 2
Mode 3



E. Metral et al

2006 Collimator Impedance Measurement



Improved controls in 2006:

- Possibility of automatic scan in collimator position.
- Much more accurate and complete data set in 2006 than in 2004!

R. Steinhagen et al
E. Metral et al

Summary: The Staged LHC Path

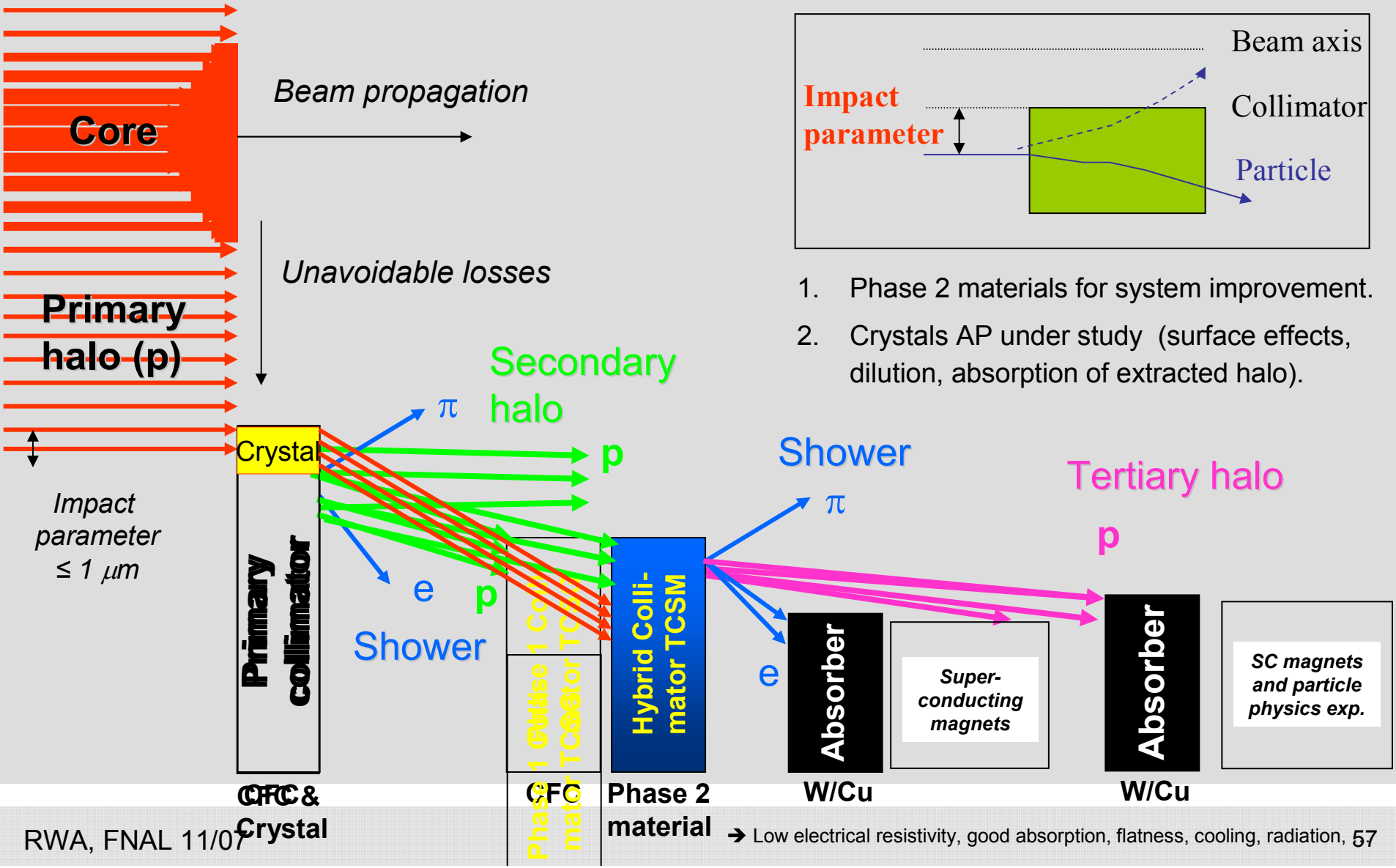
	Energy density at collimators (nominal 7 TeV)	Stored energy in beams	Number of collimators
State-of-the-art in SC colliders (TEVATRON, HERA, …)	**1 MJ/mm^2**	**2 MJ**	
Phase 1 LHC Collimation	**400 MJ/mm^2**	**150 MJ ***	**88**
Nominal LHC	**1 GJ/mm^2**	**360 MJ**	**122**
Ultimate & upgrade scenarios	**~4 GJ/mm^2**	**~1.5 GJ**	**≤ 138**
Limit (avoid damage/quench)	**~50 kJ/mm^2**	**~10-30 mJ/cm^3**	

*** Limited by cleaning efficiency (primary) and impedance (secondary)**

5) Beyond Phase 1

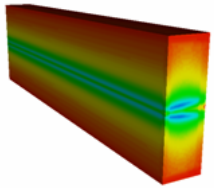
- The LHC phase 1 system is the best system we could get within the available 4-5 years.
- Phase 1 is quite advanced and powerful already and should allow to go a factor 100 beyond HERA and TEVATRON.
- Phase 2 R&D for advanced secondary collimators starts early to address expected collimation limitations of phase 1.
- Phase 2 collimation project was approved and funded (CERN white paper). Starts Jan 2008. Should aim at complementary design compared to SLAC.
- Collaborations within Europe through FP7 and with US through LARP are crucial components in our plans and address several possible problems.
- We also revisit other collimation solutions, like cryogenic collimators, crystals, magnetic collimators, non-linear schemes.

LHC Phase 2 Cleaning & Protection



1. Phase 2 materials for system improvement.
2. Crystals AP under study (surface effects, dilution, absorption of extracted halo).

➔ Low electrical resistivity, good absorption, flatness, cooling, radiation,



Workshop on Materials for Collimators and Beam Absorbers

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Home

This workshop will focus on collimators and beam absorbers for High Energy Hadron Accelerators, with the energy stored in the beams far above damage limit. The objective of the workshop is a better understanding of the technological limits imposed by mechanisms related to beam impact on materials. The issues to be addressed at the workshop are listed below.

Dates: from 03 September 2007 14:00 to 05 September 2007 18:15

Location: *CERN*
Geneva, Switzerland
Room: **40-S2-D01**

Chairs:
Ralph W. ASSMANN (CERN) - ORGANIZING COMMITTEE
Wim WETERINGS (CERN) - ORGANIZING COMMITTEE
Nikolai V. MOKHOV (Fermilab) - ORGANIZING COMMITTEE
Alessandro BERTARELLI (CERN) - ORGANIZING COMMITTEE
Peter SPILLER (GSI) - ORGANIZING COMMITTEE
Rudiger SCHMIDT (CERN) - Chairman
Małgorzata MACUDA (CERN) - Workshop Secretary
Caroline CAZENOVES (CERN) - Workshop Secretary

Additional info: A detailed agenda will soon be made available. We are planning to reserve a large fraction of the workshop time for comments and discussions.

WORKSHOP TOPICS:

- The problems encountered for systems used in different accelerators will be presented together with the solutions adopted. What materials are being used? What led to the choice of these materials? What are the limits of the present solutions?
- Why will more robust devices be needed in the future? What is the perspective in the framework of new or upgraded machines?
- The relevant parameters for beam impact on the material will be discussed, such as deposited beam energy, beam power and time structure of the beam impact.
- What material parameters are relevant, such as specific heat capacity, enthalpy, Young's modulus, yield stress, coefficient of thermal expansion, thermal conductivity? What are the relevant figures of merit? Are the bulk or microscopic parameters the relevant ones, particularly for composite and anisotropic materials?
- What materials are most suitable, e.g. robust and with low electrical resistance? Other parameters such as anisotropy of materials and secondary electron yield? Are there new materials on the horizon?
- What happens in case of shock impact (time constant ~μs or ~ns) and continuous impact (time constant ~s)? What are the relevant physics effects to be considered?
- What are the limits of the domain of application of the classical thermoelastic/plastic theory with respect to the Hydrodynamic theory of Shock Waves?
- What happens to the material beyond melting / vaporisation temperature? (example: beam tunneling through materials).
- What is the design limit based on, e.g., maximum temperature? When do we require renewable/disposable/sacrificial devices?
- What is the status of the codes for energy deposition calculations? When do calculations for shock impact with mechanical engineering codes (e.g., ANSYS, AUTODYN, LS-DYNA) break down? What are the domains of validity for simulation?
- How to compare the results from different codes, possibly for some (simple) test cases to be defined?
- What experimental evidence and experience with benchmarking exists?
- How to formulate an equation of state for materials in advanced codes?
- What are the short- and long-term effects of radiation? What is the effect of the total dose on material properties, and on equation of state? Is there an effect of the dose rate?
- DPA (displacements per atom) is a measure of the material irradiation. Is this a universal measure for different radiation fields? Is there a temperature dependence during radiation? What about annealing? Can this be used to 'repair' devices?
- What tests of materials are possible? What to test? Where to test? How to analyse test results? Test bench at SPS?

➔ September workshop provided important input and support…

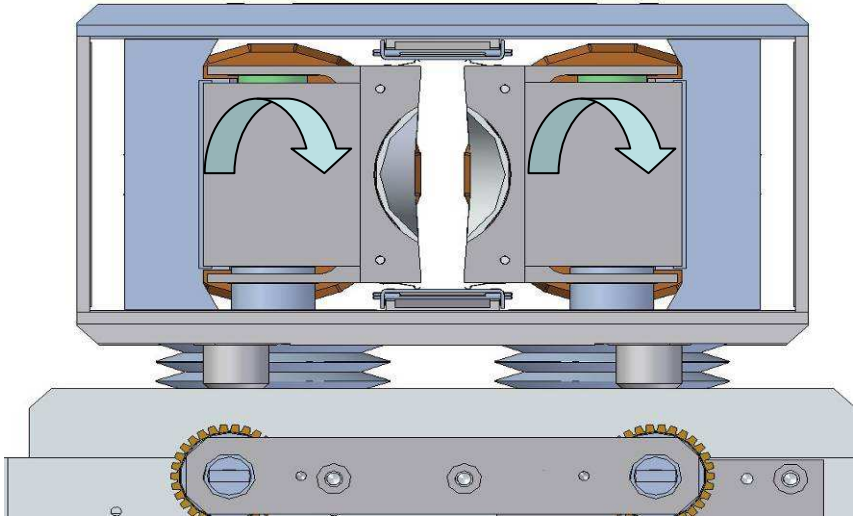
Draft Work Packages

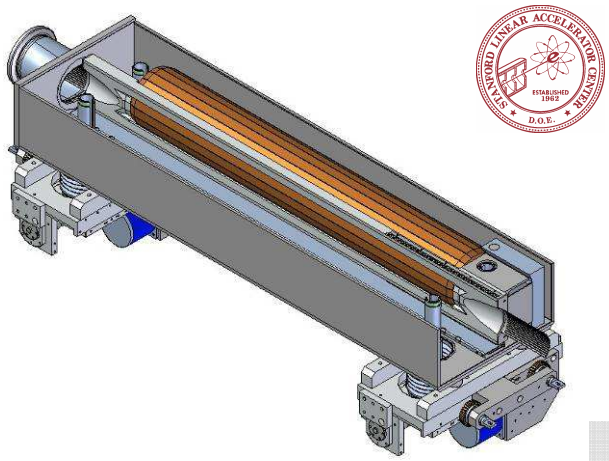
White Paper (WP), Europe (FP7), US (LARP)

WP1 (FP7)	–	Management and communication
WP2 (WP, FP7, LARP)	–	Collimation modeling and studies
WP3 (WP, FP7, LARP)	–	Material & high power target modeling and tests
WP4 (WP, FP7, LARP)	–	Collimator prototyping & testing for warm regions
Task 1	–	Scrapers/primary collimators with crystal feature
Task 2	–	Phase 2 secondary collimators
WP5 (FP7)	–	Collimator prototyping & testing for cryogenic regions
WP6 (FP7, LARP)	–	Crystal implementation & engineering

SLAC/LARP Collimator R&D + Prototyping: Rotatable LHC Collimator for Upgrade

Design with 2 rotatable Cu jaws



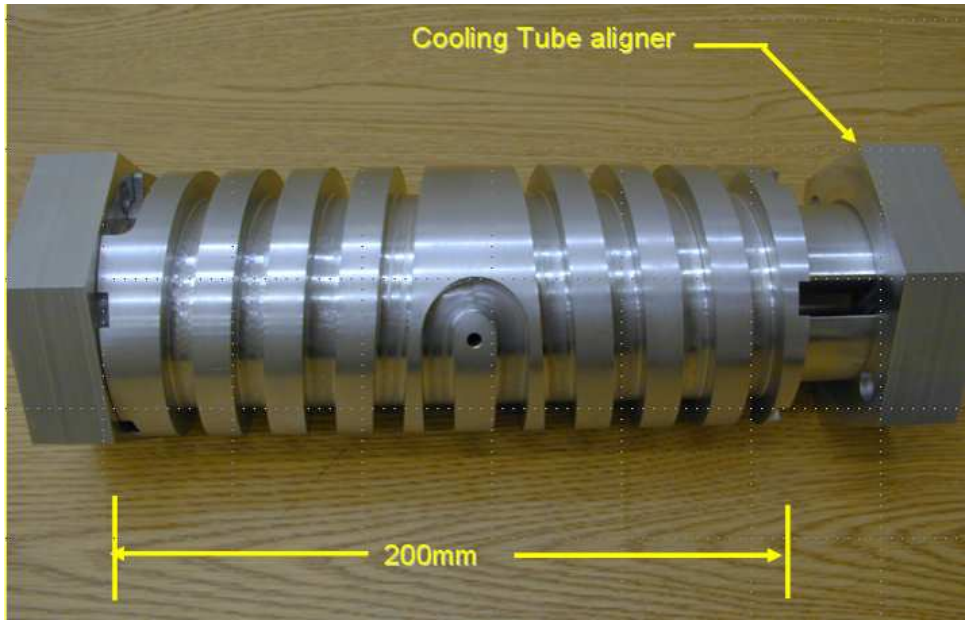


Strong US commitment and effort:

Theoretical studies, mechanical design, prototyping.

New full time mechanical engineer hired.

Looking for SLAC post-doc on LHC collimation!



First prototype with helical cooling circuit (SLAC workshop)

6) Conclusion

- LHC advances the accelerator field into a **new regime of high power beams with unprecedented stored energy** (and destructive potential).
- The understanding of beam halo and collimation of losses at the 10^{-5} level will be crucial for its success (high luminosity)!
- LHC **collimation will be a challenge and a learning experience**!
- Collimation is a surprisingly wide field: Accelerator physics, nuclear physics, material science, precision engineering, production technology, radiation physics.
- A **staged collimation approach** is being implemented for the LHC, relying on the available expertise in-house and in other labs.
- The **collaboration and exchange with other labs** is very important to design and build the best possible system (achieve our design goals)!
- Visit to FNAL to **learn maximum from TEVATRON** and discuss **additional links in beam loss and collimation**: crystals for LHC, e-lens for LHC, BLM, …

The Collimation Team…

Collimation team:

About 60 CERN technicians, engineers and physicists… in various groups and departments.

+ many friends in connected areas (BLM's, MP, …)

+ collaborators in various laboratories (SLAC, FNAL, BNL, Kurchatov, …)