Collimation Issues for the Two LHC+ Scenarios and Future Plans

R. Assmann, CERN, AB/ABP

Acknowledgements to the colleagues in the LHC Collimation Working Group which worked out and presented most of the results shown here:

http://www.cern.ch/lhc-collimation

BEAM´07

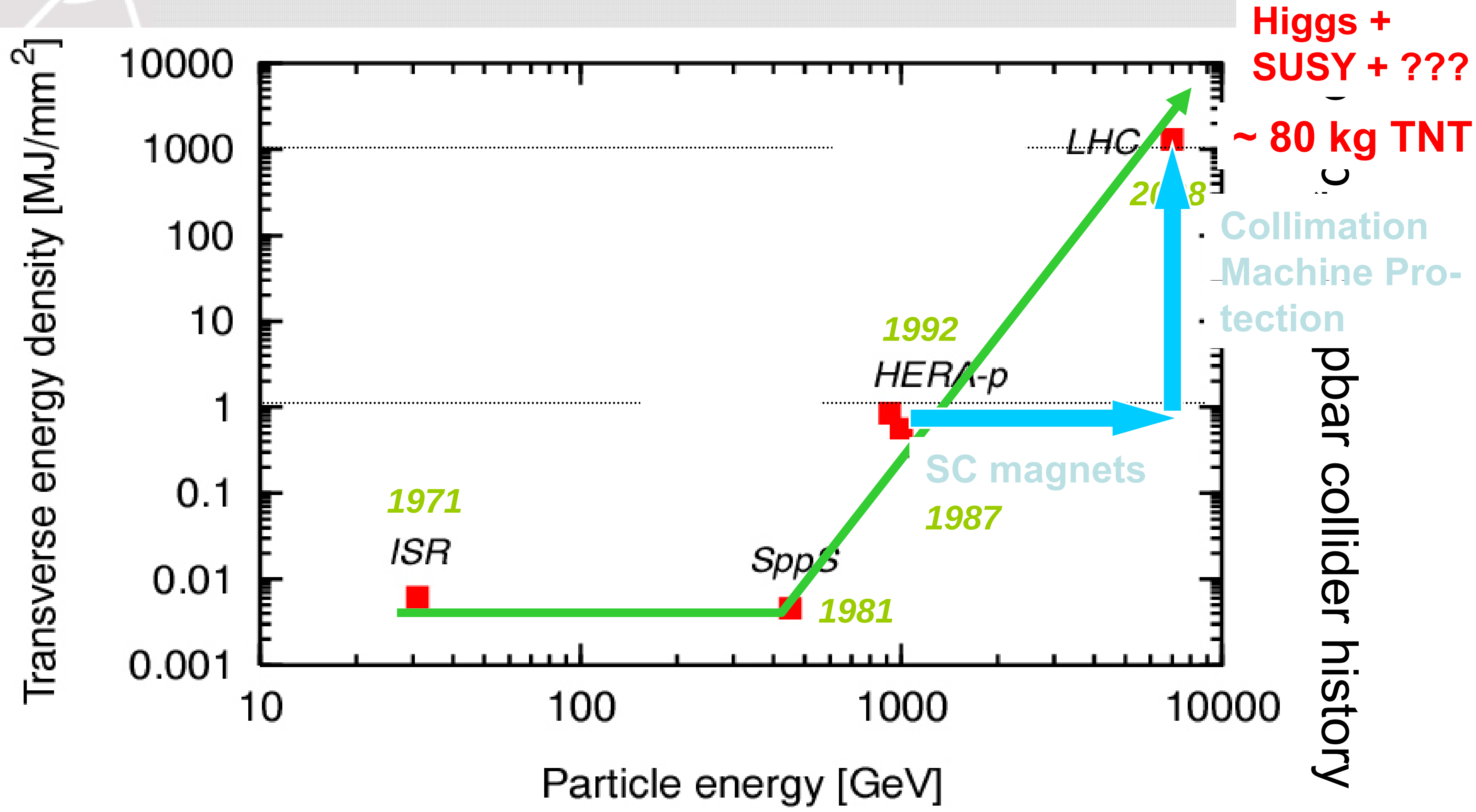
CERN, Switzerland

October 1st, 2007

Collimation Design Goals

- High power, high intensity accelerators use collimators always to **intercept and concentrate beam losses in well defined locations**.
- Depending on the accelerators several different design goals can apply:
  - **Background control:** Improve signal to noise ratio in particle and nuclear physics experiments (classical role in colliders).
  - **Cleaning:** Protect super-conducting magnets against direct beam losses and beam-induced quenches (e.g. LHC).
  - **Protection:** Shield sensitive equipment against beam-induced damage (instantaneous shock and long-term radiation damage).
  - **Radiation control:** Localize and shield beam-induced radiation such to provide hands-on maintenance for rest of accelerator (e.g. SNS), control environmental impact, ….
- For every accelerator all of these issues must be analyzed in detail.
- Has been done for the LHC over the last years!

CERN: Full Exploitation of the LHC



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

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

➔ Collimation. Machine Protection.

LHC Type Collimators

Collimators/absorbers are the sunglasses of an accelerator!

Intercept and absorb unavoidable slow beam losses: >99.95% efficiency goal (LHC, FAIR).

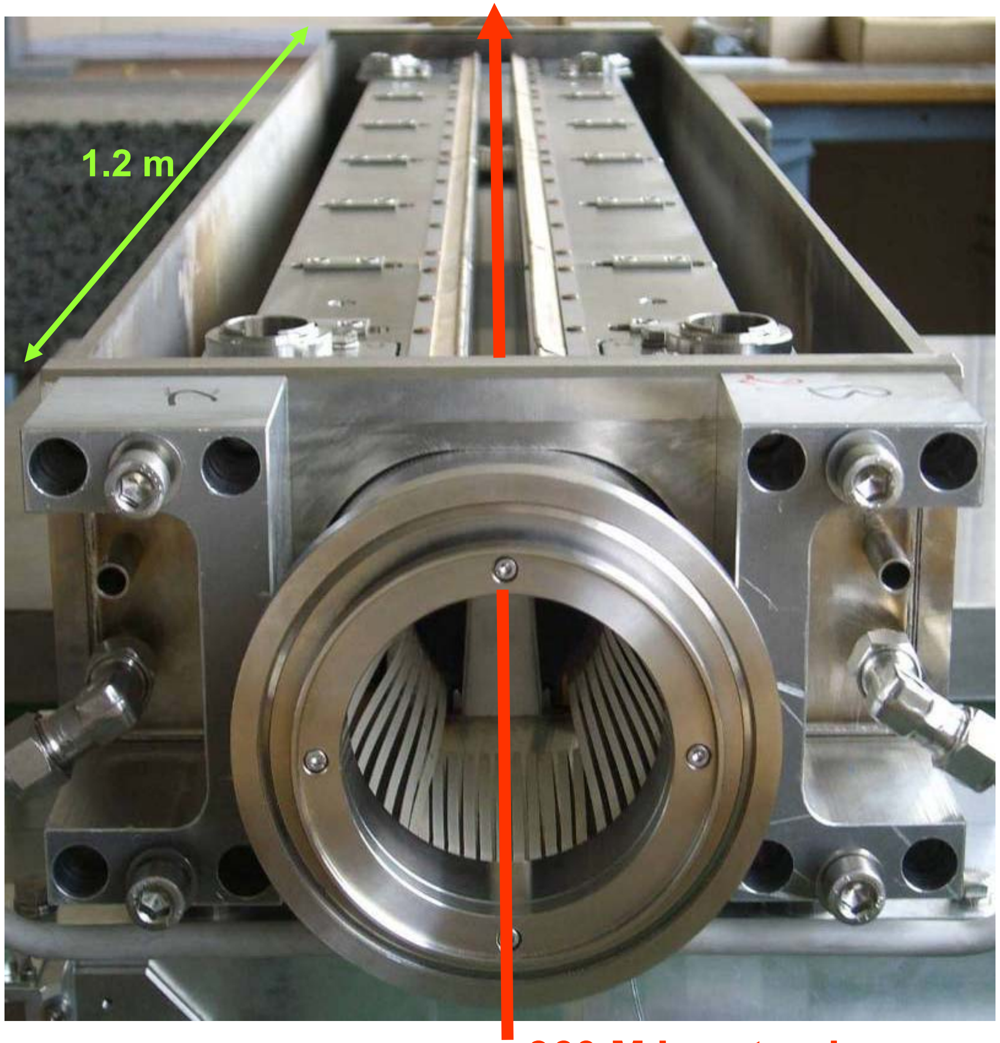
Protect against failures (protection).

Robustness: Collimators to **survive the intense beams** (shock impacts, radiation damage) and allow good beam vacuum.

Material questions are crucial!

The 99.99% challenge!

Pretty good sun-glasses (filter factor >1000)…



The Staged LHC Path

	Energy density at collimators (nominal 7 TeV)	**Stored energy in beams**	**Number of LHC collimators**
State-of-the-art in SC colliders (TEVATRON, HERA, …)	**1 MJ/mm²**	**2 MJ**	
Phase 1 LHC collimation	**400 MJ/mm²**	**150 MJ**	**88**
Nominal LHC	**1 GJ/mm²**	**360 MJ**	**122**
Ultimate & upgrade scenarios	**~2 GJ/mm²**	**800 MJ**	**≤ 138**
Limit (avoid damage/quench)	**~50 kJ/mm²**	**~10-30 mJ/cm³**	

Factor > 1000 energy density

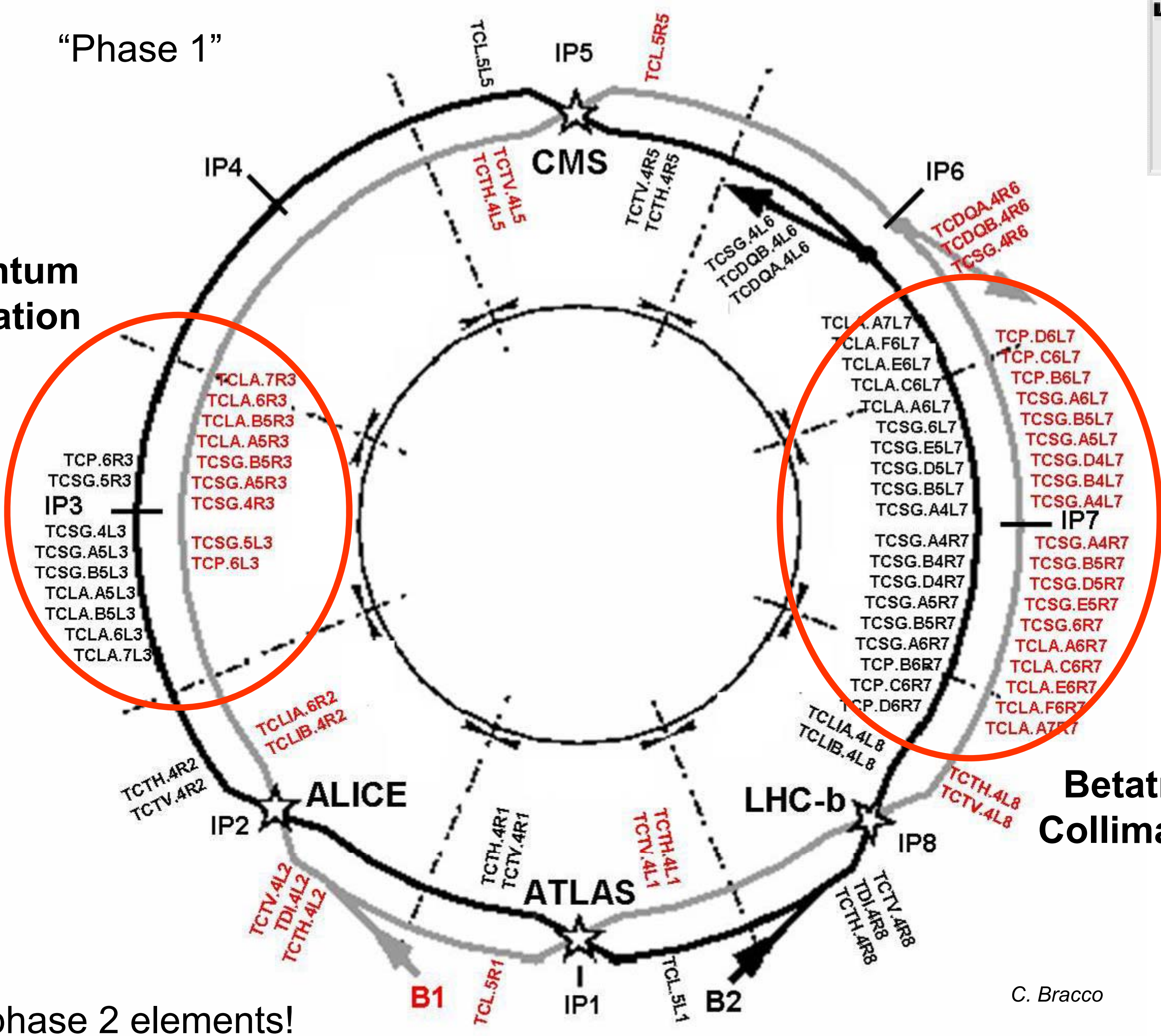
Equivalent 80 kg TNT explosive

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 radiation 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.

“Phase 1”

Momentum Collimation

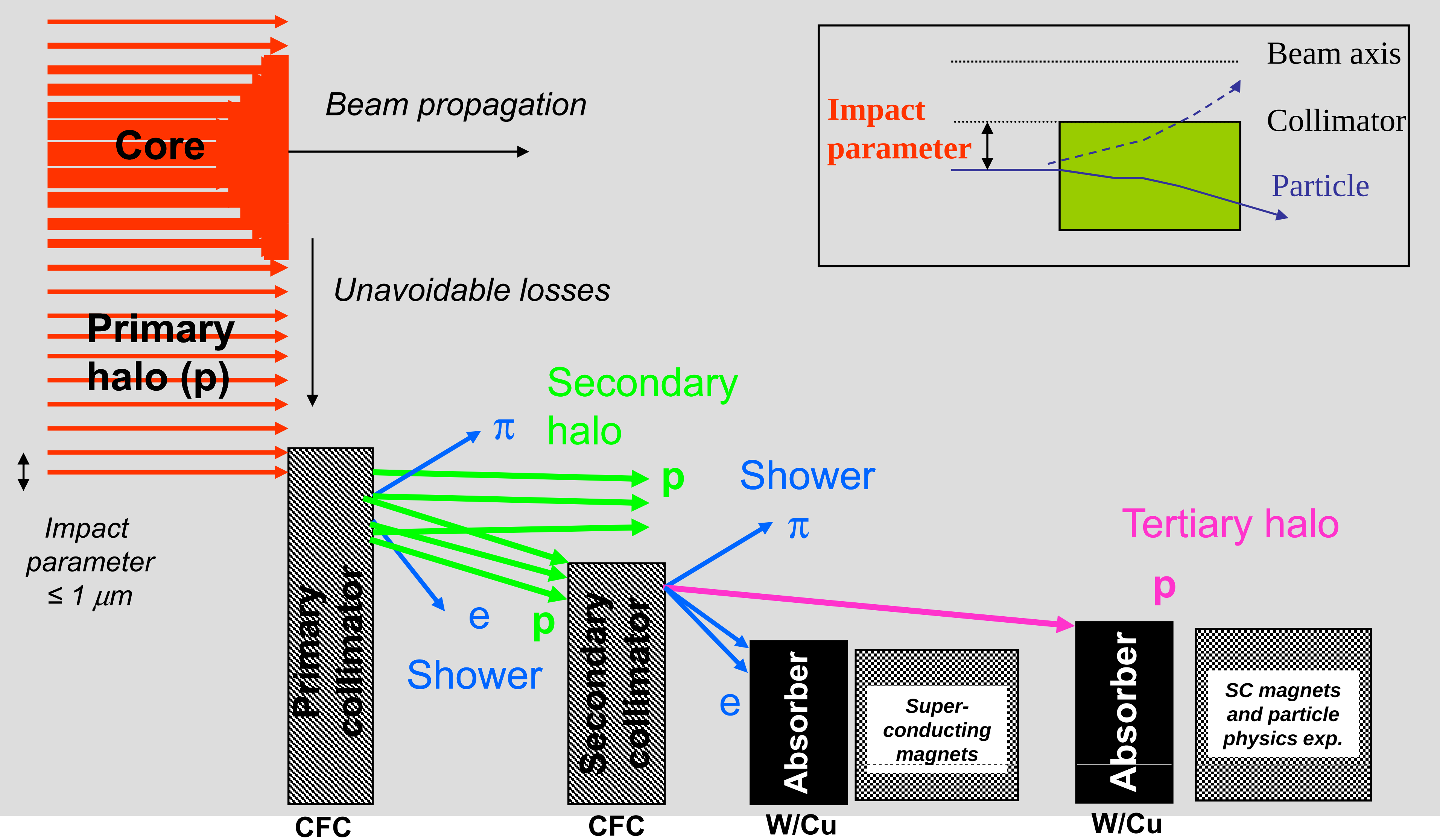


Betatron Collimation

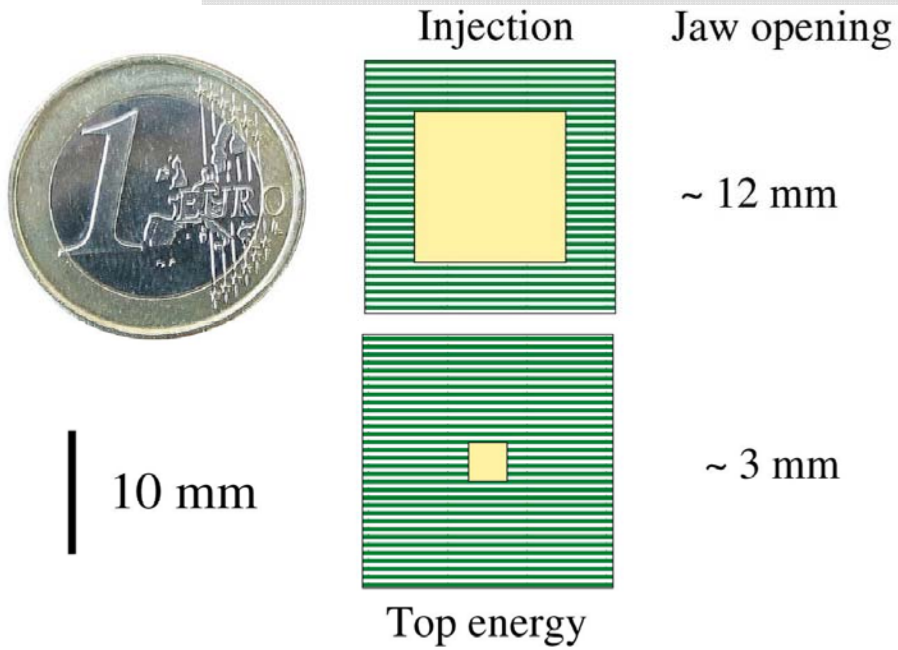
C. Bracco

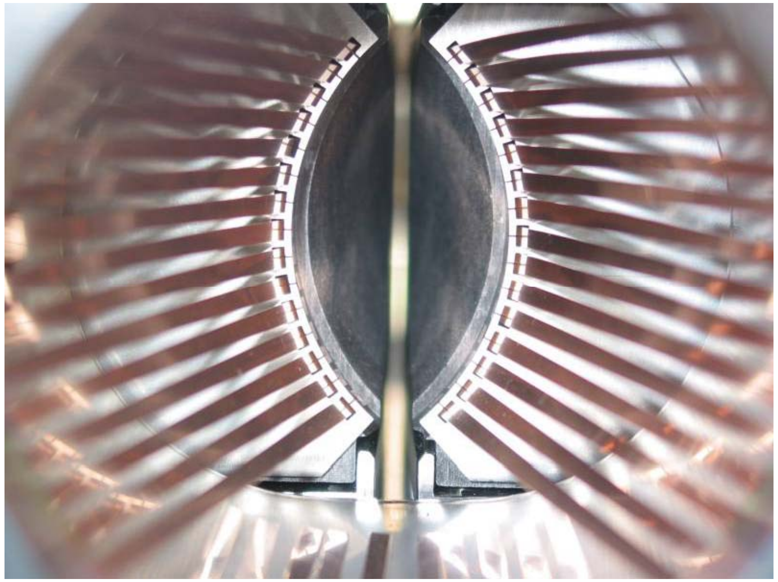
Without phase 2 elements!

Multi-Stage Cleaning & Protection



LHC Collimator Gaps





Collimator settings:

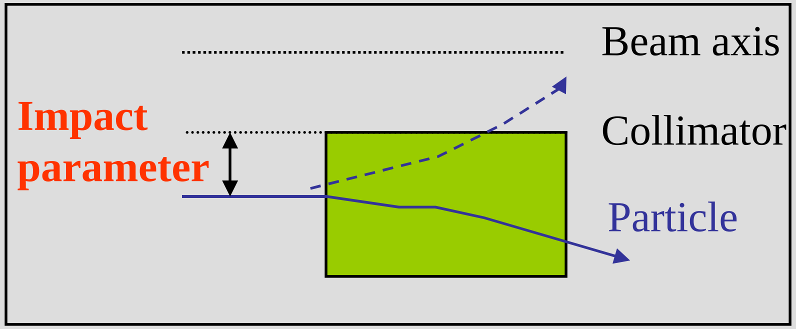
5 - 6 σ (primary)
6 - 9 σ (secondary)

σ ~ 1 mm (injection)
σ ~ 0.2 mm (top)

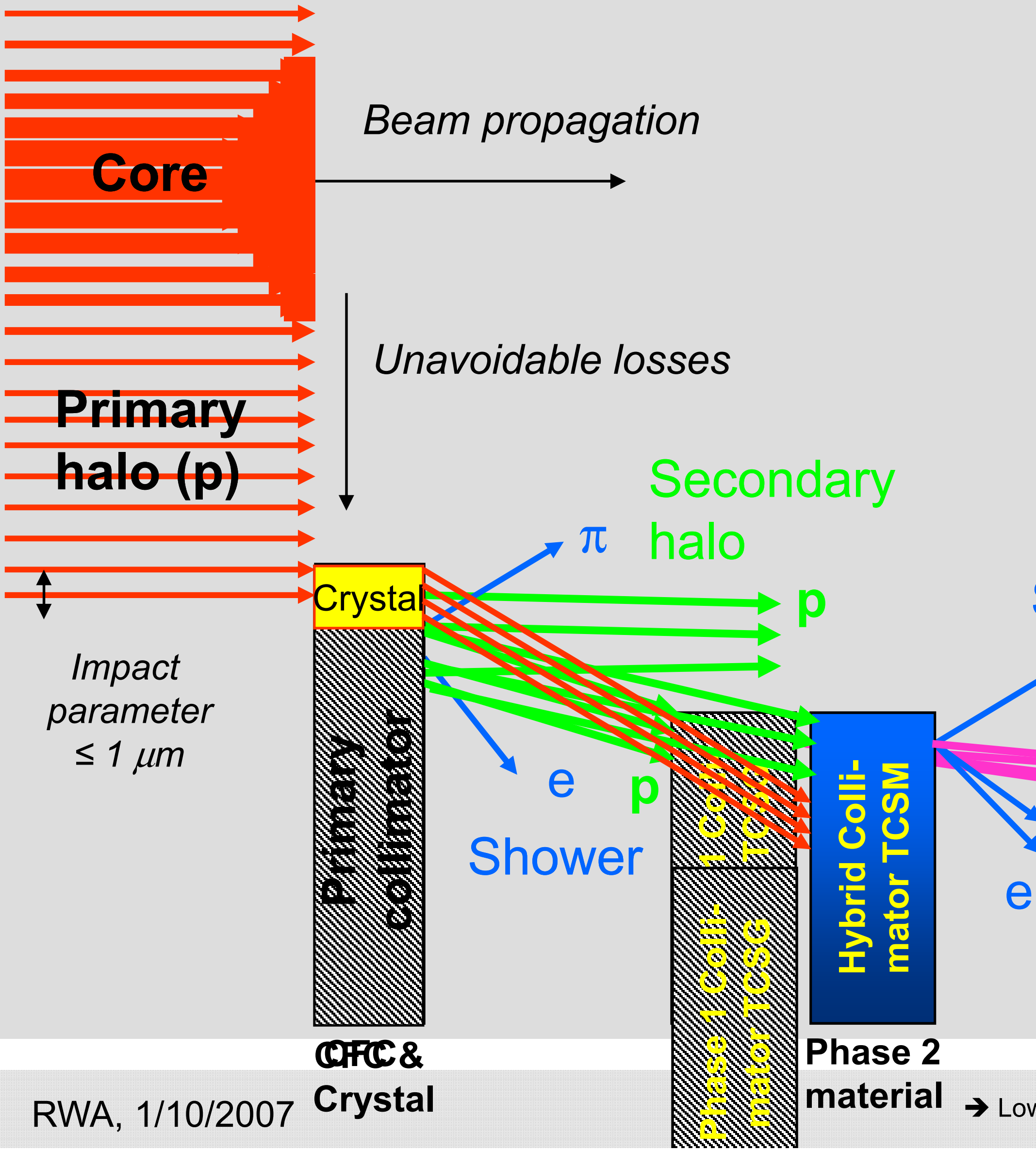
Small gaps lead to:

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

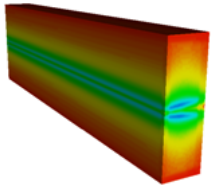
Phase 2 Cleaning & Protection



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…

Preventing Quenches

- Quench limits of SC magnets given by design.
- Overall criterion for preventing quenches:

$$\frac{dN}{N_0 dt} \times \eta_{ineff} \times \frac{1}{L_{dil}} \leq 2.4\times10^{-8}(\text{ms})^{-1}$$

$\frac{dN}{N_0 dt}$	η_{ineff}	$\frac{1}{L_{dil}}$		$2.4\times10^{-8}(\text{ms})^{-1}$
Fractional loss rate	*Leakage rate*	*Dilution length*		*Fractional quench limit (w/o BLM threshold)*
⇩ Minimize losses	⇩ Minimize inefficiency	⇩ Spread losses		
Example 0.1% per s	1/5,000	1/(10 m)	➔	2.0×10^{-8} (ms)$^{-1}$

Recipe for Avoiding Beam Loss Limitations in the LHC

1. Optimize stability of the collider!

2. Optimize cleaning efficiency of the collimation system!

3. Spread residual beam losses over large distances!

The LHC Upgrade Scenarios

Scenario	Protons stored	Energy stored	Energy in 200 ns	β*	Peak luminosity
Phase 1 collimation	1.4×10^{14}	**150 MJ**	**0.4 MJ**	0.55 m	0.4×10^{34}
Nominal	3.2×10^{14}	**360 MJ**	**1.0 MJ**	0.55 m	1.0×10^{34}
Ultimate	4.8×10^{14}	**532 MJ**	**2.2 MJ**	0.50 m	2.3×10^{34}
Scenario I	4.8×10^{14}	**532 MJ**	**2.2 MJ**	0.08 m	15.5×10^{34}
Scenario II	6.9×10^{14}	**767 MJ**	**2.3 MJ**	0.25 m	10.7×10^{34}

Improve stability and efficiency!

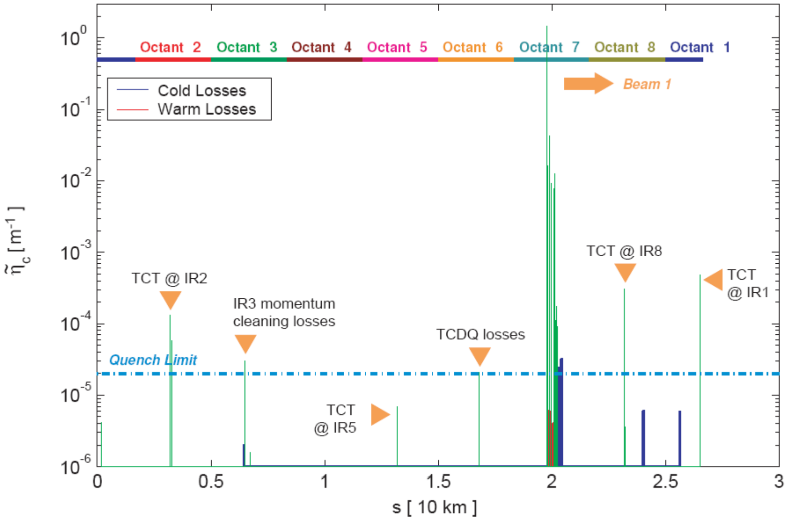
Address collimator robustness or upgrade beam dump!

Collimation Issues for LHC Upgrade I

- **<u>Higher stored energy</u>** (higher peak losses, higher annual losses, higher activation):
  - Better or same beam stability (upgrade must not reduce beam stability – should be a decision criterion).
  - Better spreading of losses ➔ Operational procedures to avoid local hot spots.
  - Improved collimation efficiency ➔ White paper, LARP, FP7 work.
  - Improved radiation hardness of collimators ➔ White paper, LARP, FP7 work.
  - Improved power absorption ➔ White paper, LARP, FP7 work.
  - Improved local protection or more radiation-hard warm magnets ➔ Experience will show whether needed (less leakage with phase 2).
  - Improved shielding of electronics ➔ Experience will show whether needed.
  - Radiation impact study.
  - Upgrade of beam dump and protection devices.
  - Upgrade of super-conducting link cable in IR3.

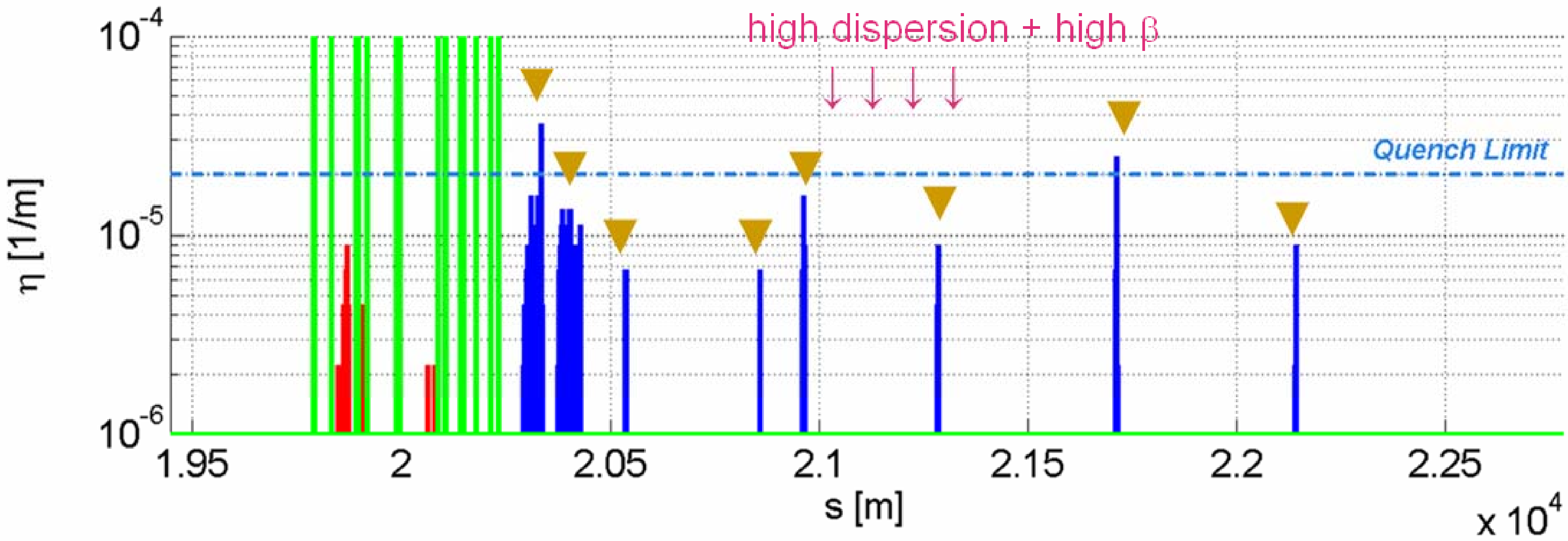
7 TeV Proton Loss Prediction

Ideal case



G. Robert-Demolaize et al

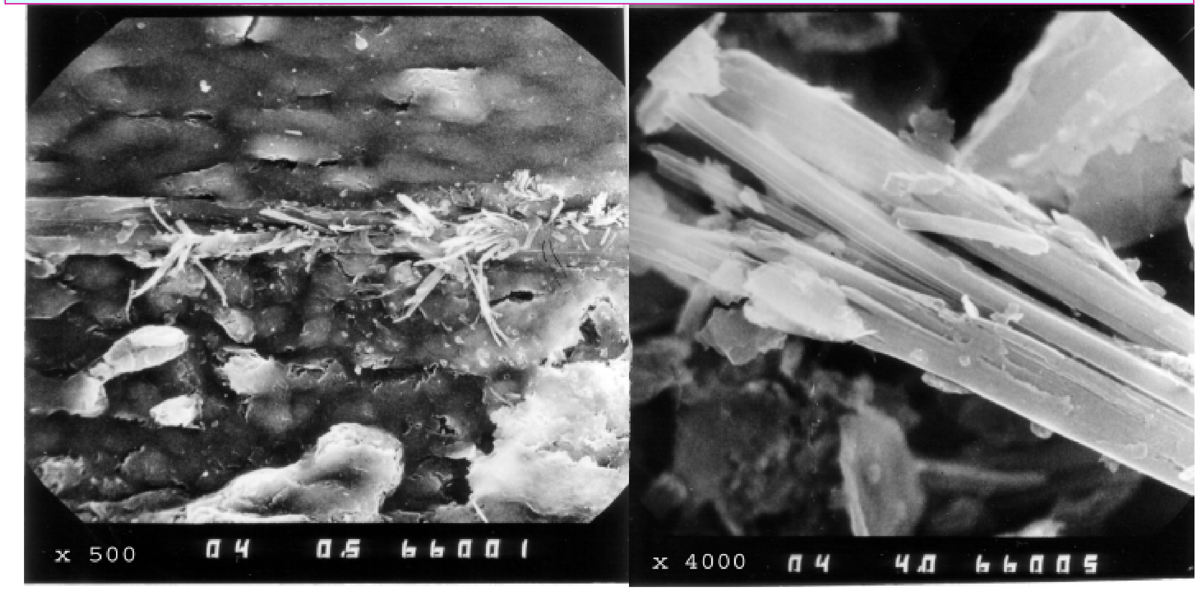
With design orbit



Irradiation Studies of CFC Material Used in LHC Collimators

BNL: N. Simos

Analysis of Radiation Induced Erosion in Graphite Composite Material AC Irradiated by Carbon Ions with the Energy 5 MeV at Irradiation Dose: 1x10 E17 p/cм 2



Kurchtov: A. Ryazanov

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

… in addition shock wave models…

Collimation Issues for LHC Upgrade II

- **Higher beam intensity** (intensity dependent effects from collimator-driven LHC impedance):
  - Operation with increased chromaticity.
  - Upgrade of transverse feedback.
  - Operational collimator gaps opened, if efficiency/protection/halo allows to do this.
  - Better conducting collimator jaw material ➔ White paper, LARP, FP7 work.
- **Higher shock beam impact** from irregular dumps:
  - Upgrade of the LHC beam dump to reduce amount of escaping beam.
  - Address collimator robustness ➔ White paper, LARP, FP7 work.

Reminder: 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: F. Ruggiero, E. Metral, F. Caspers, L. Vos, ...

Third look at impedance in Feb 03 revealed a problem:

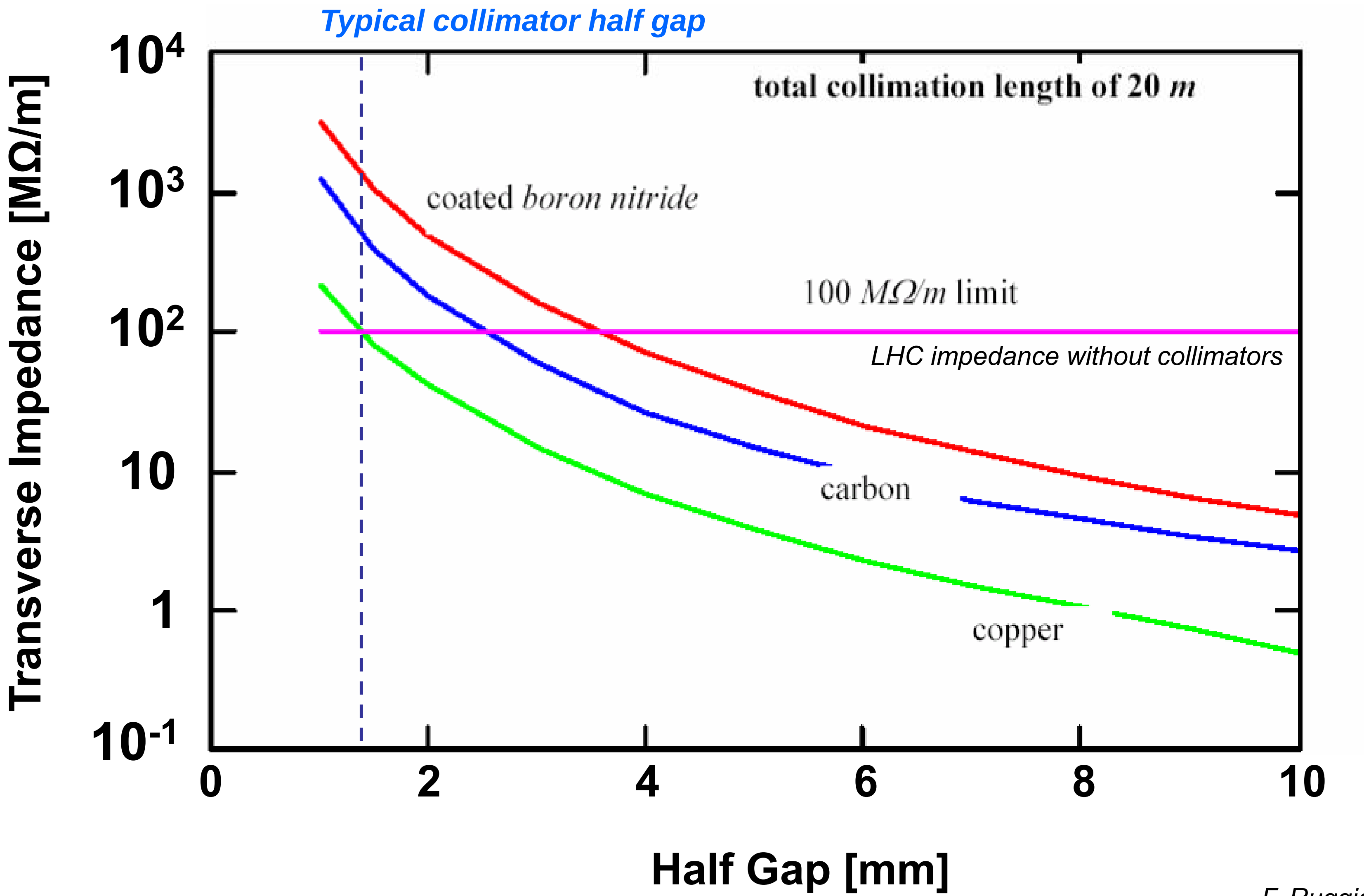
$$\frac{Z_\perp^{\rm coll}}{Z_\perp^{\rm arc}} \sim \frac{(L^{\rm coll}/L^{\rm arc}) \times \sqrt{\rho^{\rm coll}/\rho^{\rm arc}}}{(a^{\rm coll}/a^{\rm arc})^3} \sim$$

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

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

F. Ruggiero

First Impedance Estimates 2003



F. Ruggiero, L. Vos

Collimation Issues for LHC Upgrade III

- **<u>Layout, aperture and optics changes</u>** in experimental insertions:
  - Local collimation and protection must be re-evaluated in detail such that tertiary collimation (effect on background) is kept functional.
  - Probably need to rebuild tertiary collimators for ATLAS and CMS.
  - Full simulation of multi-turn halo losses in local aperture, power loads, machine protection and energy deposition is absolutely essential.
  - Full study of halo dynamics with potentially increased off-momentum beta-beat.
  - Collimation request: local triplet masks also for the incoming beam (best possible protection and cleaning)!
- Important not to underestimate the overall effects from local changes in the experimental insertions!

Future Plans

- Powerful LHC collimation system is being installed. Should allow extrapolation in stored energy by factor 100.
- Nevertheless, it can well be that nominal and ultimate LHC intensities already are limited due to beam loss and collimation.
- Work already ongoing or being prepared for phase 2 collimation with support from CERN white paper, LARP and FP7 (if approved):
  - Better efficiency
  - Better radiation hardness
  - Better power absorption
  - Better conducting jaws
  - More robust jaws or in-situ handling of damage
  - Improved operational setup with jaw-internal diagnostics
- No magic bullet ➔ Several improvements together will get us ready for LHC upgrade scenarios!

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) – Crystal implementation & engineering

<u>Options:</u>

Option1 (FP7) – Absorbers for machine protection

Option2 (FP7) – Magnetic collimators

Working Together to Develop Solutions…

- Many if not most new accelerators are loss-limited in one way or another!
- Collimation has become a core requirement for success. The LHC upgrade program is or will be just one example.
- Collimation is so challenging in modern accelerators that it warrants a full collaborative approach to extend the present technological limits.
- Collaborations exist or are under discussion with presently 17 partners:

  Alicante University, Austrian Research Center, BNL, EPFL, FNAL, GSI, IHEP, INFN, JINR Dubna, John Adams Institute, Kurchatov Institute, Milano University, Plansee company, Protvino, PSI, SLAC, Turin Polytechnic

- The importance and intellectual potential is reflected by the strong support from the international community.
- Operational and design challenges impose fascinating technological and physics R&D.

Conclusion

- Collimation predictions are difficult and assumptions have uncertainties: peak loss rate, quench limit, imperfections, BLM thresholds, impedance, …
- Only the machine will give us the real picture.
- All performance studies indicate intensity limitations below nominal LHC intensity. Reality is usual worse.
- A factor ≥ 10 improvement is desirable to be prepared for LHC upgrades.
- Draft work packages have been shown. Studies have started or are starting now:
  - CERN effort through **white paper**.
  - **LARP/SLAC effort** on LHC collimation upgrade.
  - Preparation of **FP7 program** with European collaborators.
- Goal: Respond to LHC machine limitations quickly with hardware solutions!
- Request triplet-masks for incoming beam as part of upgrade!
- In parallel, **any insertion upgrade requires a detailed halo, beam loss, collimation, protection and energy deposition study** to ensure its feasibility!

Thanks for your attention…

Collimation: LHC Intensity Limitations I

Issue for protons	Prediction	Consequences
Collimator impedance	LHC impedance determined by collimators	≤ 40% of nominal intensity
Dispersion suppressors IR7	Losses of off-momentum p (single-diffractive scattering)	≤ 30-40% of nominal intensity for ideal cleaning
Unavoidable imperfections	Efficiency reduced to less than ideal	Set up time versus reduced efficiency
Efficient BLM thresholds	Factor 3-10 uncertainty from BLM reading on knowledge of beam loss	Thresholds at least factor 3 below intensity limit for quench
Radiation dose IR7 magnets (MBW, MQW)	2-3 MGy per year	Limited lifetime of magnets (specified for 50 MGy)
SC link in IR3	Risk of quench for losses of uncaptured beam	≤ 3.5% of nominal intensity in uncaptured beam
Dose on personnel	High remanent radiation	Limited access for modifications and upgrades in cleaning insertions
Environmental impact	OK for ultimate intensity	Review needed for any upgrade above ultimate ➔ bypass galleries

Collimation: LHC Intensity Limitations II

Issue for protons	Prediction	Consequences
Vacuum equipment (chambers, heating jackets)	Up to 8.5 MGy per year and up 500 W/m heating	Limited lifetime
Collimator robustness against failures	OK for accident cases with nominal intensity (450 GeV and 7 TeV), including water circuit in vacuum (up to 2 MJ)	Review for any upgrade in intensity, beam brightness, bunch structure, …
Collimator jaw damage	Under preparation	Limited lifetime of LHC collimators
Radiation to electronics close to cleaning insertions	OK for nominal intensity (0.5 Gy/y)	Review needed for any upgrade
Quench downstream of local dump protection (TCDQ)	MQY at 60% of quench limit for nominal intensity (beam 2).	Upgrade of TCDQ should be envisaged.

Issue for ions	Prediction	Consequences
Fragmentation and dissociation in primary collimator	Two-stage cleaning does not work.	Intensity limited to ~ 30% of nominal.

Issues Summary and Plan

Limitation:	Beam intensity for protons and ions *(limit at ~½ of nominal LHC intensity?)*	
Problem:	Losses in dispersive, super-conducting arc regions (LHC and FAIR) *impedance limitation with initial collimators, issues with multi-stage cleaning efficiency, single-diffractive scattering, ion fragmentation, dissociation*	
Hardware:	WP4-I, WP6	(scrapers/primary collimators with crystal feature)
	WP4-II	(improved secondary collimators, phase 2)
	WP5	(cryogenic collimators at loss locations – FAIR, LHC upgrade)
	Option 2	(magnetic collimators for additional deflection of halo particles)

Limitation:	Maximum ion luminosity *(limit at > ½ nominal LHC ion luminosity?)*	
Problem:	Losses of collision products in super-conducting arcs (physics).	
Hardware:	WP5	(cryogenic collimators at loss locations – FAIR, LHC upgrade)

Limitation:	Protection, availability, component lifetime.	
Problem:	Absorption efficiency and robustness of absorber.	
Hardware:	Option 1	(improved absorber design)