Intensity Issues and Machine Protection

R. Assmann, CERN

HE – LHC Workshop

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Picture of Copper-Dimanod Collimator Material
EuCARD/ColMat, GSI

Parameters HE-LHC

	nominal LHC	HE-LHC	
beam energy [TeV]	7	16.5	
dipole field [T]	8.33	20	
dipole coil aperture [mm]	56	40	
beam half aperture [cm]	2.2 (x), 1.8 (y)	1.3	
injection energy [TeV]	0.45	>1.0	
#bunches	2808	1404	
bunch population [10^{11}]	1.15	1.29	1.30
initial transverse normalized emittance	3.75	3.75 (x), 1.84 (y)	2.59 (x & y)
initial longitudinal emittance [eVs]	2.5	4.0	
number of IPs contributing to tune shift	3	2	
initial total beam-beam tune shift	0.01	0.01 (x & y)	
maximum total beam-beam tune shift	0.01	0.01	
beam circulating current [A]	0.584	0.328	
RF voltage [MV]	16	32	
rms bunch length [cm]	7.55	6.5	
rms momentum spread [10^{-4}]	1.13	0.9	
IP beta function [m]	0.55	1 (x), 0.43 (y)	0.6 (x & y)
initial rms IP spot size [μm]	16.7	14.6 (x), 6.3 (y)	9.4 (x & y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})	188.1 (12
Piwinski angle	0.65	0.39	0.65
geometric luminosity loss from crossing	0.84	0.93	0.84
stored beam energy [MJ]	362	478.5	480.7
SR power per ring [kW]	3.6	65.7	66.0
arc SR heat load dW/ds [W/m/aperture]	0.17	2.8	2.8
energy loss per turn [keV]	6.7	201.3	
critical photon energy [eV]	44	575	
photon flux [10^{17}/m/s]	1.0	1.3	
longitudinal SR emittance damping time [h]	12.9	0.98	
horizontal SR emittance damping time [h]	25.8	1.97	
initial longitudinal IBS emittance rise time	61	64	~68
initial horizontal IBS emittance rise time [h]	80	~80	~60
initial vertical IBS emittance rise time [h]	~400	~400	~300
events per crossing	19	76	
initial luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0	
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0	
beam lifetime due to *p* consumption [h]	46	12.6	
optimum run time t_r [h]	15.2	10.4	
integrated luminosity after t_r [fb^{-1}]	0.41	0.50	0.51
opt. av. int. luminosity per day [fb^{-1}]	0.47	0.78	0.79

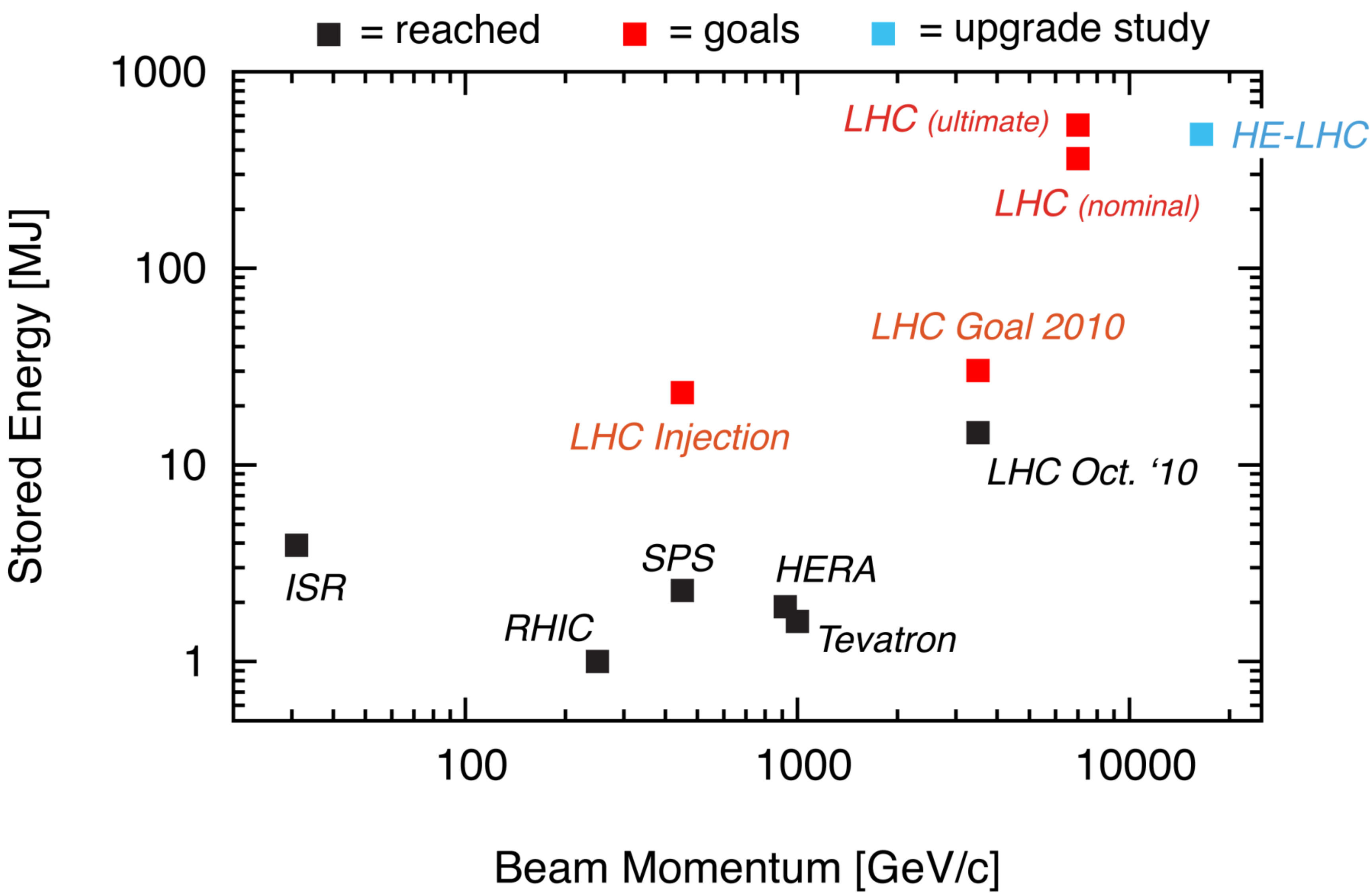
Consider:

Round case
Compare to nominal LHC
Typical collimator location β = 80m

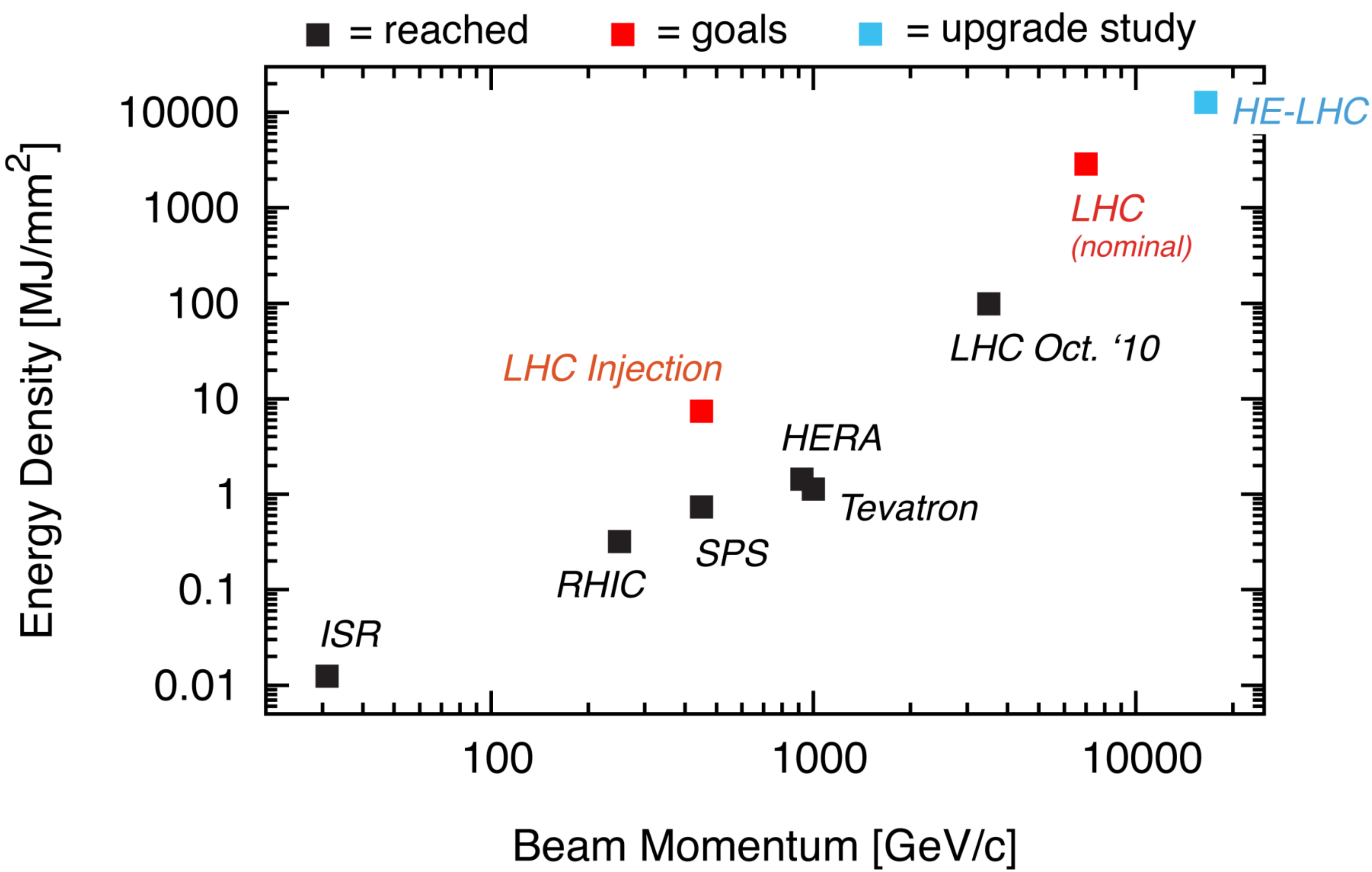
Main issues:

	Nominal	Upgrade
E	7.0 TeV	16.5 TeV
γ	7461	17587
ε	0.5 nm	**0.15 nm**
E_{stored} (tot)	362 MJ	482 MJ
ρ_e (tot)	2.9 GJ/mm^2	15.4 GJ/mm^2
E_{stored} (1b)	128 kJ	242 kJ
ρ_e (1b)	1.0 MJ/mm^2	**7.7 MJ/mm^2**

Stored Energy



Energy Density



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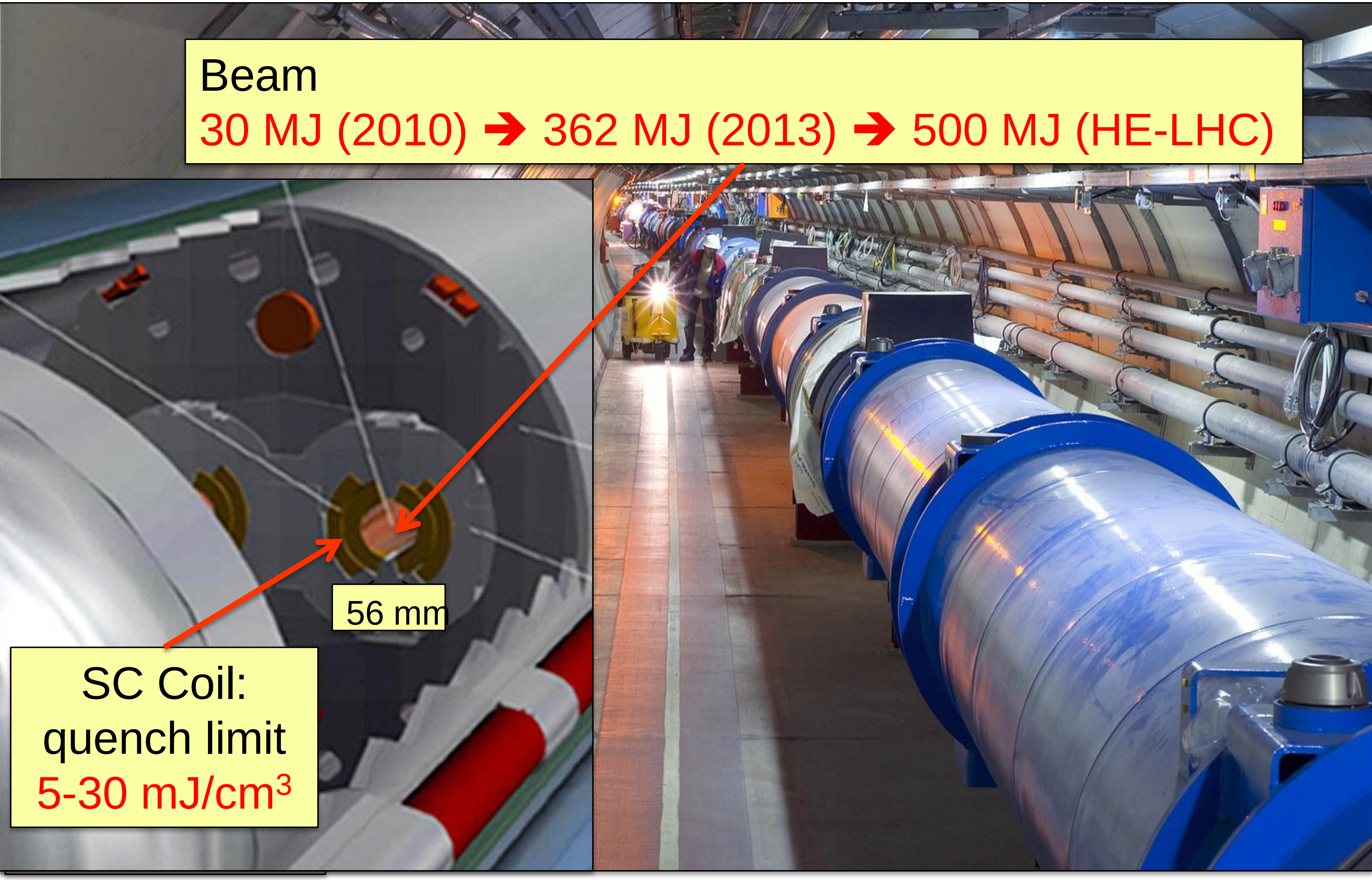
Issues to be Discussed

1. **Collimation Efficiency**
2. Machine Robustness
3. Issues due to Smaller Gaps
4. Comments on MP
5. Comments on Cleaning Insertions

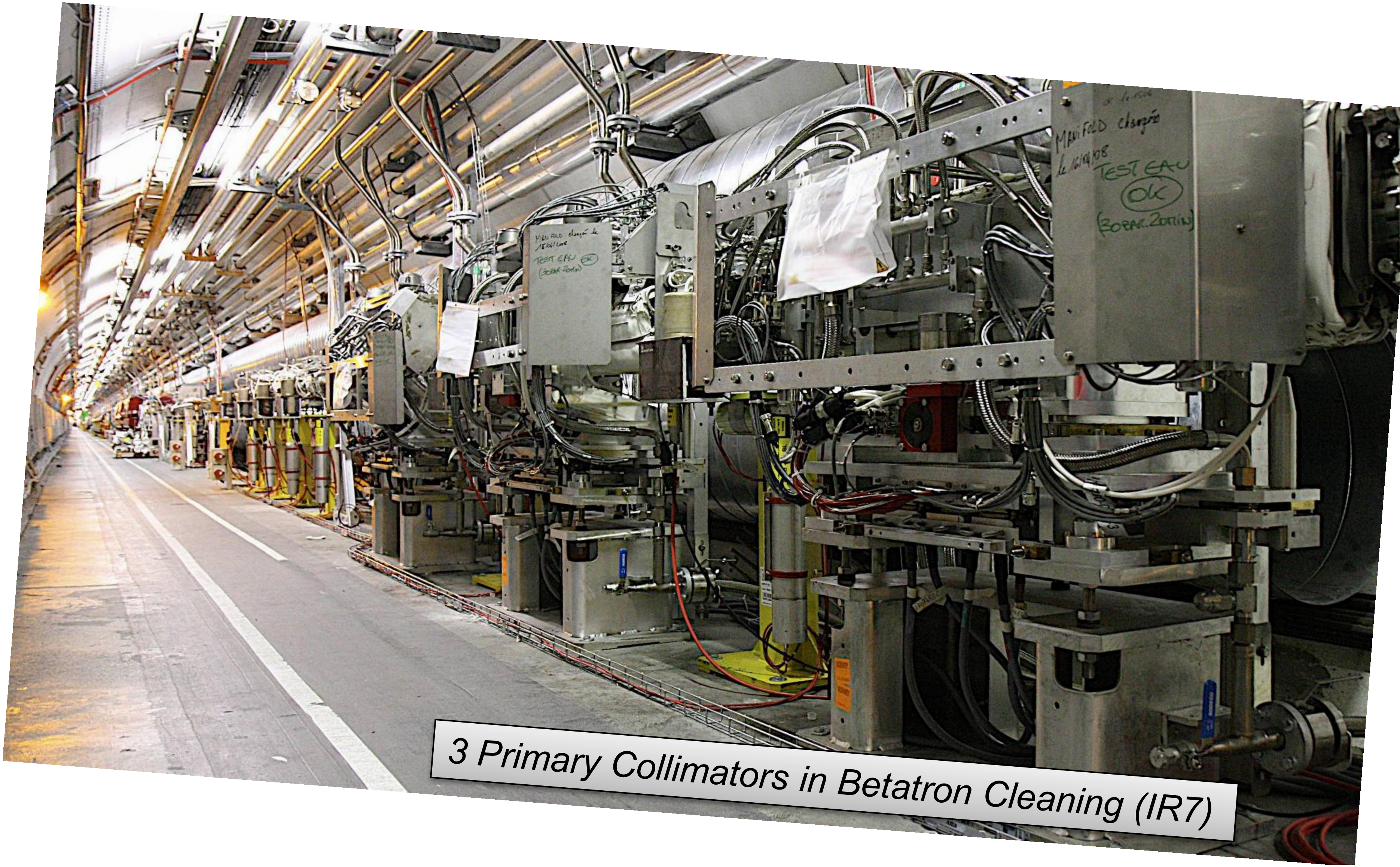
Collimation and Cleaning

- LHC has a sophisticated collimation system.
- This system **intercepts and absorbs stray beam particles with ultra-high efficiency**.
- It is located in the two cleaning insertions (IR3, IR7).
- The system had been optimized for 7 TeV by:
  - proper choice of 138 collimator locations
  - 4-stage collimation hierarchy
  - 3 different collimator jaw material types
  - 2 different lengths of jaws
  - 4 different orientations in x, y, skew plane
- **Involved nuclear physics processes depend strongly on energy.**
- System behaves differently at higher energies.

Quench Limit versus Stored Energy

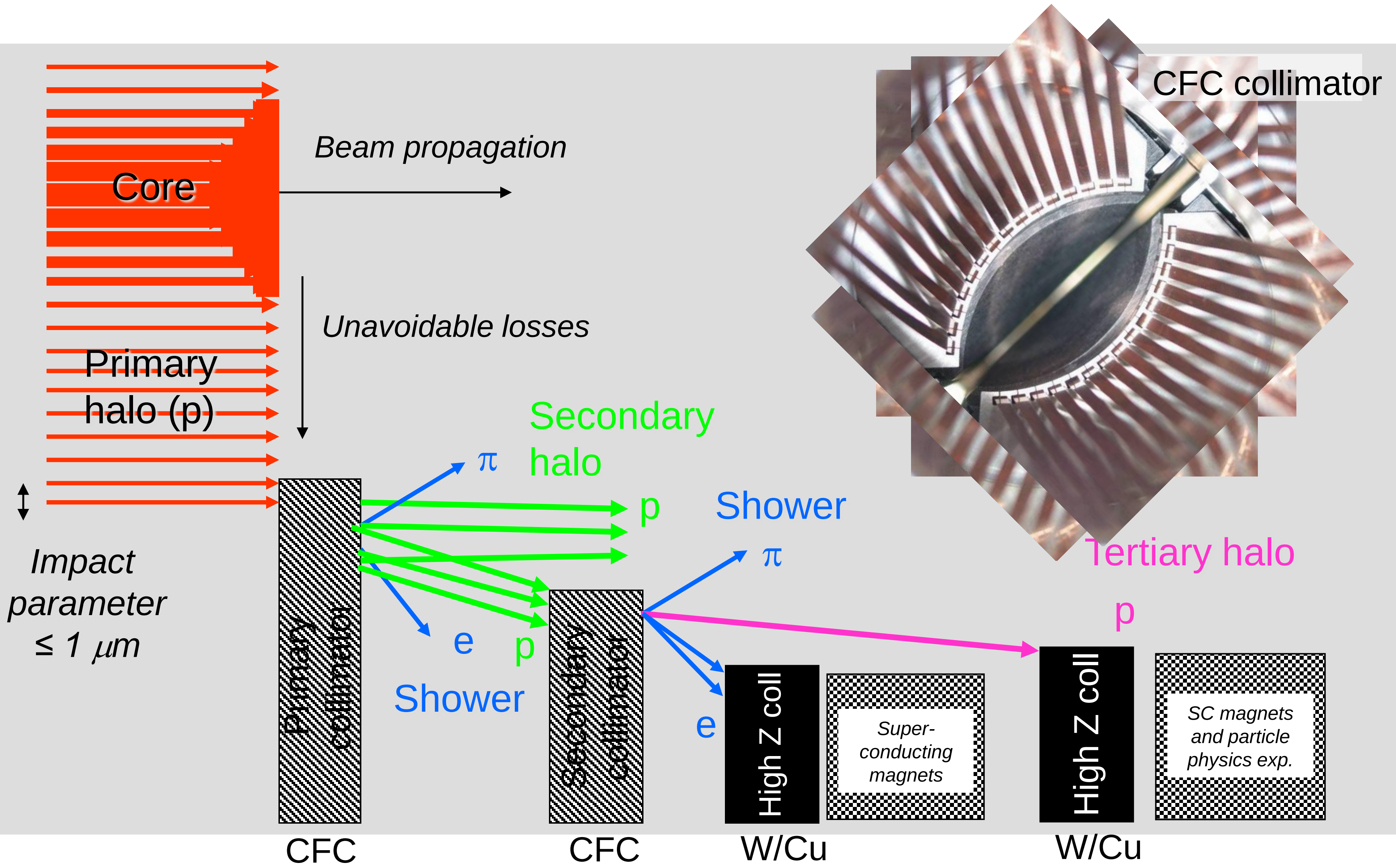


Three Primary Collimators (x, y, skew)



3 Primary Collimators in Betatron Cleaning (IR7)

Multi-Stage Cleaning & Protection *3-4 Stages*



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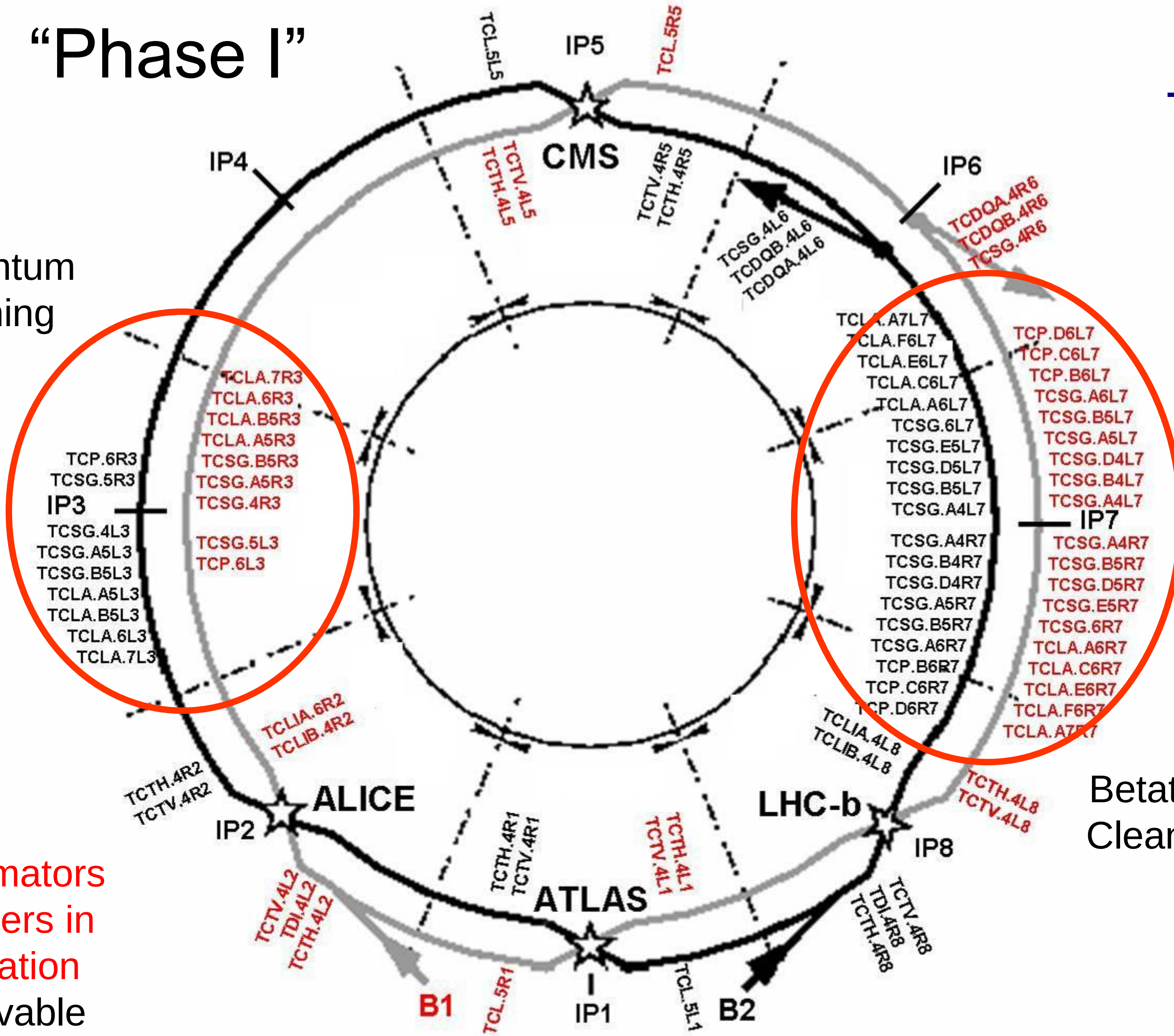
"Phase I"

Momentum Cleaning



Betatron Cleaning

108 collimators & absorbers in 1st generation (only movable shown in sketch)

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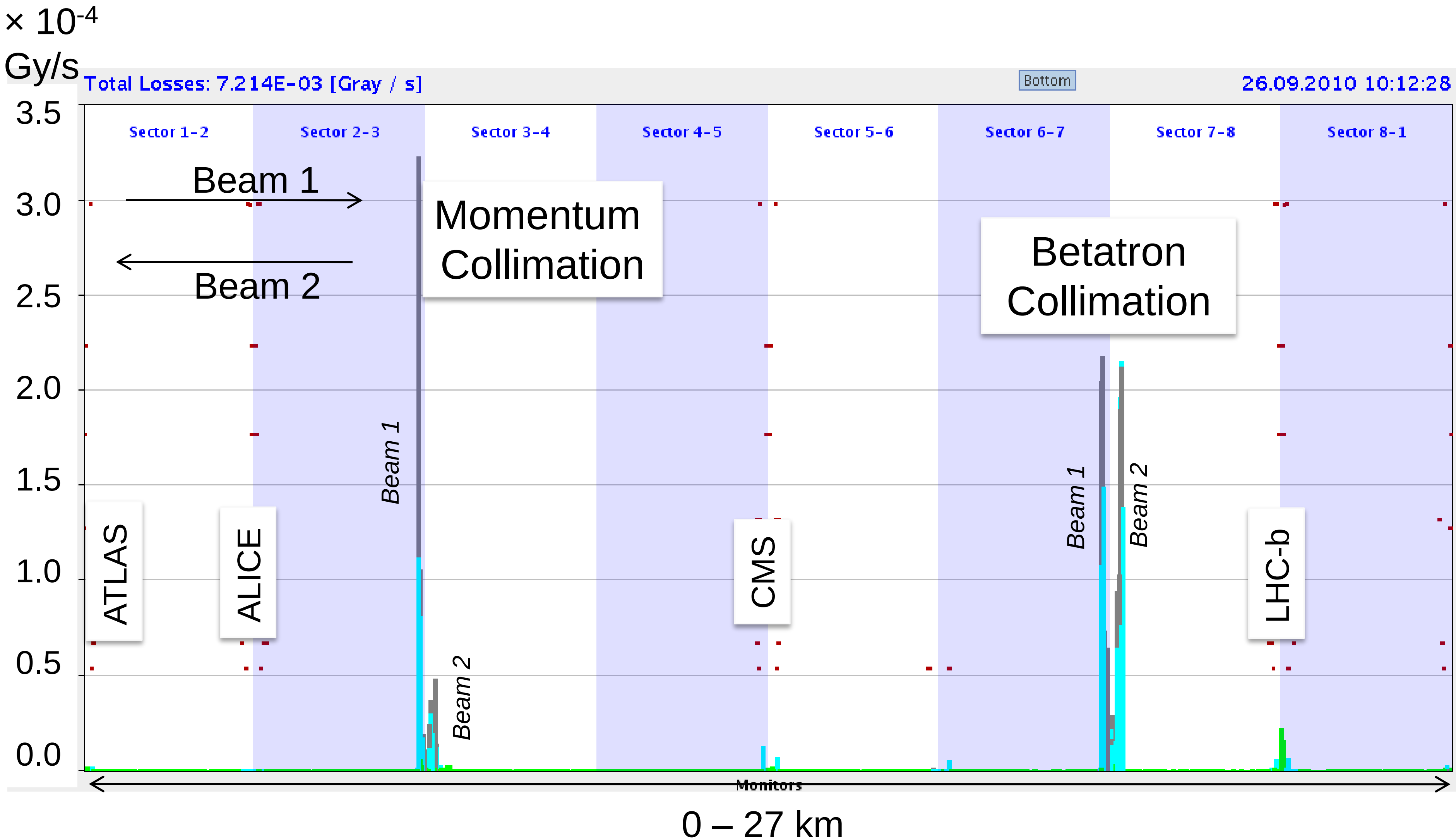
Losses in the Ring *(3.5 TeV, End Fill 26.9.2010, $\tau > 75$ h)*



Essentially all losses at collimators → No beam dump or quench!

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Multiple Coulomb Scattering

$$\theta_{MCS} \approx \frac{13.6\,\mathrm{MeV}\cdot Z}{E}\cdot\sqrt{\frac{s_{trav}}{X_0}}$$

Material	X_0 [cm]
Beryllium	35.28
Graphite	18.80
Alluminium	8.90
Copper	1.43
Tungsten	0.35
Lead	0.56

Z = Atomic number
X_0 = Radiation length
E = Beam energy
s_{trav} = Length traversed

- **MCS scattering angles decrease with the energy.**
- Particles get less kicks and return for multi-turn traversals.
- Kick goes with the square root of total length traversed.
- Collimator material (Graphite) has weak MCS.

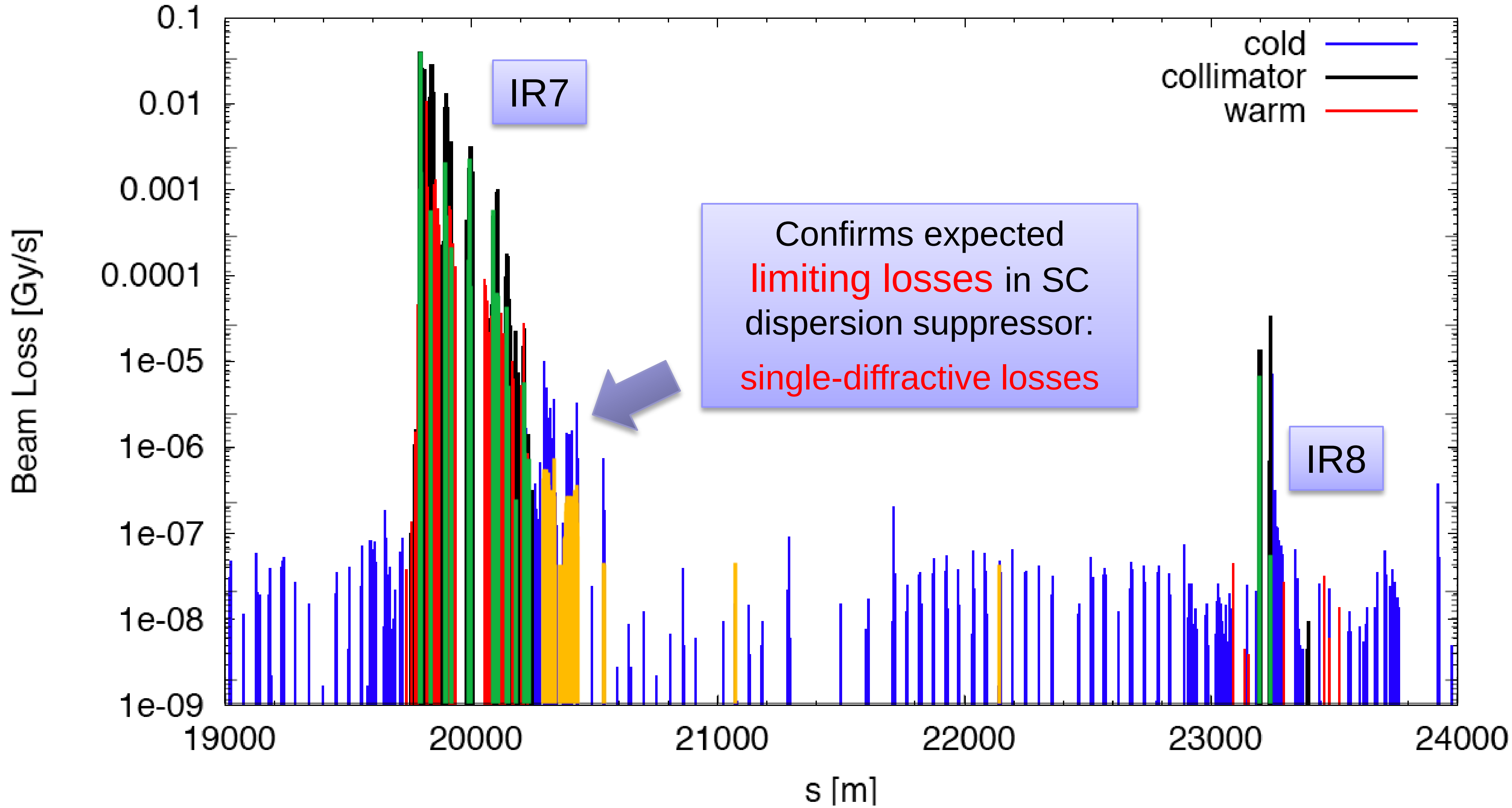
Single-Diffractive (SD) Scattering

- Single-diffractive scattering creates off-energy protons.
- These are the **limiting losses in the LHC at higher energy and lost in the dispersion suppressors** of the LHC.
- Cross section:

$$\sigma_{SD} = 0.68\,\mathrm{mb} \cdot \ln\left(0.3 \cdot E\right)$$

- SD scattering cross section increases slowly with beam energy E.
- Indeed we do see losses in the predicted dispersion suppressor locations at 3.5 TeV.

Meas. & Sim. Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



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Comparing MCS and SD processes I

Parameter	MCS	SD
Energy E	$\sim 1/E$	$\sim \ln(E)$
Length L	$\sim \sqrt{L}$	$\sim L$

MCS brings p from primary to secondary collimator:

- Imagine going from E0 to E1 in energy.
- Typical scattering angle: $\theta_1 = \theta_0 * E_0 / E_1$
- Required scattering angle: $\theta_{1,req} = \theta_{0,req} * \sqrt{(E_1 / E_0)}$
- For required scattering angle travel longer length:

$$L_1 = L_0 * E_0 / E_1$$

Comparing MCS and SD processes II

Now SD scattering:

- Length traversed: $L_1 = L_0 * E_0 / E_1$ (from MCS)
- Cross section: $\sigma_1 = \sigma_0 * \ln(0.3*E_1) / \ln(0.3*E_0)$
- Probability for SD scattering with MCS scaling:

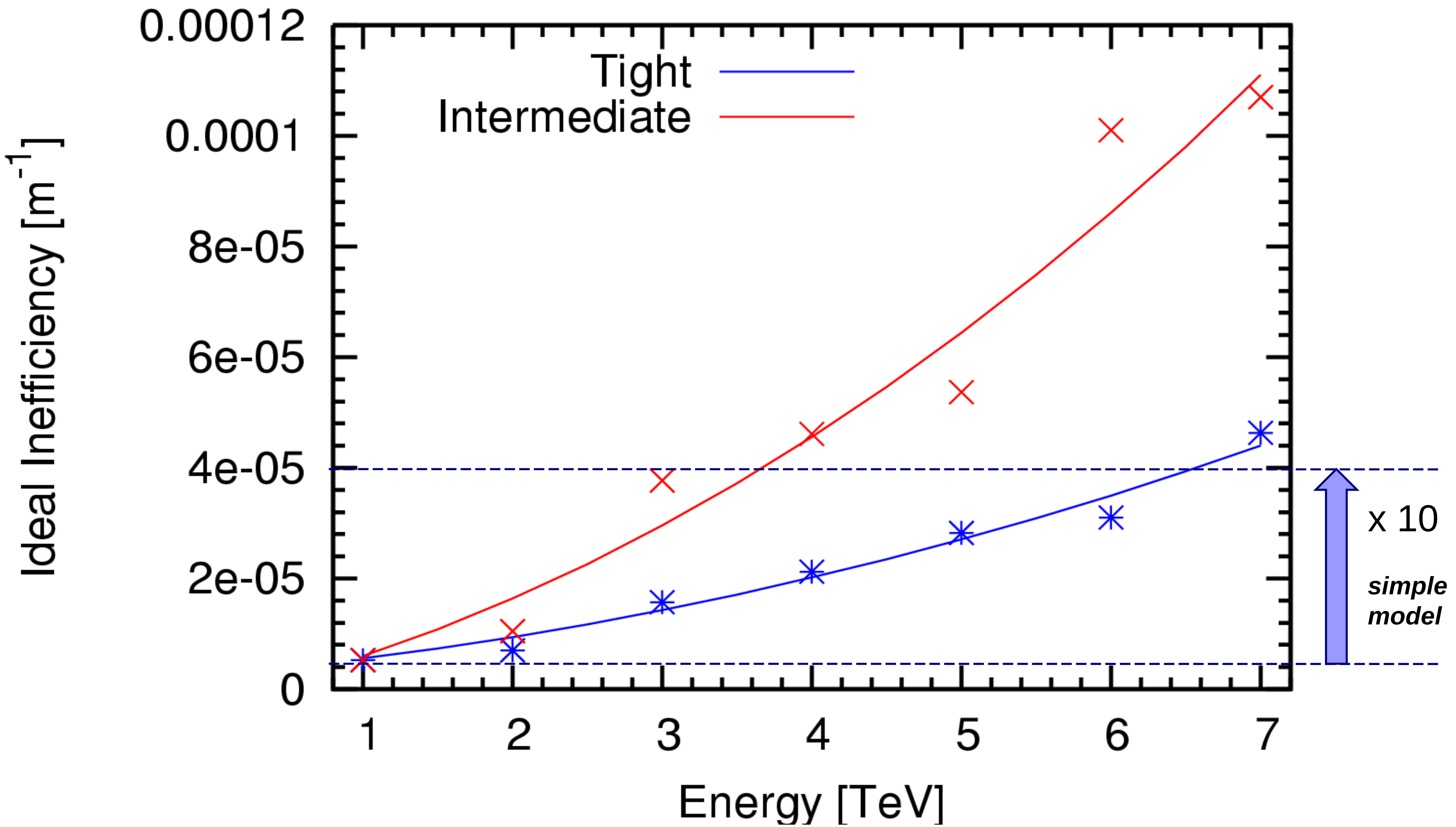
$$P_1 = P_0 \cdot \frac{E_1 \cdot \ln(0.3 \cdot E_1)}{E_0 \cdot \ln(0.3 \cdot E_0)} \qquad \text{with } E_1 > E_0$$

- Effects from SD scattering become stronger with higher beam energy.
- Loss from 7 TeV to 16.5 TeV: **factor 2.6**

Situation More Complicated (of course)

- Multi-turn behavior not so simple to just linearly add up kicks (as assumed before).
- It is not fully correct to express the transport from primary to secondary collimator by a required kick (diffusion process).
- Single-diffractive scattering and MCS produce combined effects.
- Other processes play into the game.
- **Still a very useful analytical estimate…**

Compare Simple Model to Simulations



… quite reasonable agreement…

Impact Collimation Efficiency

- Beam energy increase: 7 TeV → 16.5 TeV
- We **loose a factor 2-3 in cleaning efficiency due to energy dependence of nuclear processes**.
- Single-diffractive losses in dispersion suppressors will become more and more pronounced.
- Can easily loose another factor 10 if aperture in dispersion-suppressor magnets would be smaller.
- Could be compensated by higher Z collimator materials but these would be less robust.
- Our cryo(DS)-collimators for LHC will also help for HE-LHC.
- Must be assessed in detailed collimation simulations with detailed aperture model, quench limits, …
- **Strong impact but I believe solutions can be found.**

Issues to be Discussed

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2. **Machine Robustness**

3. Issues due to Smaller Gaps

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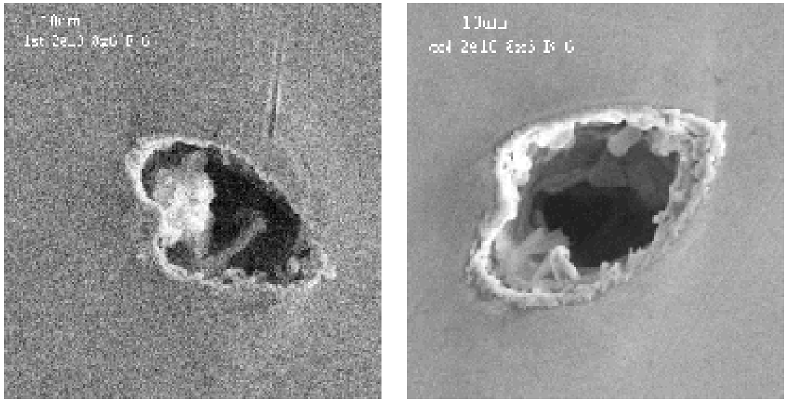
Limit on Bunch Density

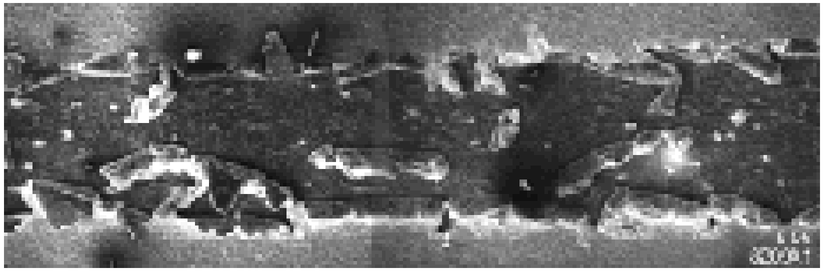
- **Damage is a matter of beam density** (this is why low power electron beams with a very small beam size can drill holes).
- To guide the extrapolation we consider a simple model.
- Assumption:
  - Ultimate bunch intensity (1.7e11 p) and nominal beam emittance (0.5 nm at 7 TeV) are OK.
  - Survival of accelerator elements (collimators, dumps, absorbers) OK.
  - Here focus on collimators.
- Model can also be used to define valid phase space for operation of the collider.

Beam-Induced Damage is Possible



Entry and exit holes of an electron beam impacting on a spoiler

(courtesy P. Tenenbaum)



Damage of coating of a SLC collimator

Tungsten collimator in the SPS

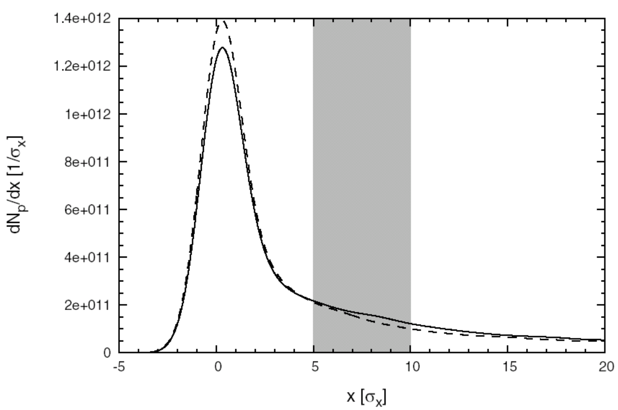
Lead block accidentally put into a p beam

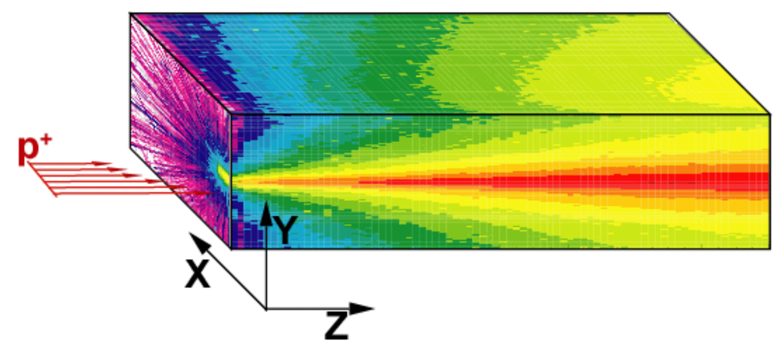
(courtesy G. Stevenson)

Irregular Beam Impact

Irregular condition	Beam energy [TeV]	Intensity deposit [protons]	Energy deposit [kJ]	Transverse dimensions [mm×mm]	Impact duration [ns]	Affected plane
Injection error	0.45	2.9×10^{13}	2073	1.0×1.0	6250	H/V/S
Asynchronous beam dump	0.45	6.8×10^{11}	49	***5.0*** $\times 1.0$	150	H
(all modules)	7.00	4.8×10^{11}	538	***1.0*** $\times 0.2$	100	H
Asynchronous beam dump	0.45	10.2×10^{11}	74	***5.0*** $\times 1.0$	225	H
(1 out of 15 modules)	7.00	9.1×10^{11}	1021	***1.0*** $\times 0.2$	200	H

R. Assmann et al





A. Ferrari,V. Vlachoudis

Relevant Robustness Parameter

$$\mathcal{L} = \frac{1}{4\pi\, m_0 c^2} \cdot \frac{f_{rev} \cdot F}{\gamma \cdot \beta^*} \cdot \frac{\mathbf{N_p}}{\epsilon} \cdot \mathbf{E_{stored}}$$

$$5.3 \times 10^8\, \mathrm{J}^{-1}$$

$$\frac{\mathbf{N_p}}{\epsilon} \leq 3.4 \times 10^{20}\, \mathrm{m}^{-1}$$

$$\begin{aligned}
m_0 &= \text{Proton rest mass} \\
c &= \text{Light velocity} \\
f_{rev} &= \text{Revolution frequency} \\
F &= \text{Geometric correction factor} \\
\beta^* &= \text{IP beta function} \\
E_{stored} &= \gamma\, N_p\, N_{bunch}\, m_0 c^2 = \text{Stored energy} \\
N_{bunch} &= \text{Number of bunches per beam} \\
N_p &= \text{Number of protons per bunch} \\
\gamma &= \text{Relativistic Lorentz factor} \\
\epsilon &= \text{Transverse (round) emittance (geom)}
\end{aligned}$$

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Present LHC Collimation Robustness

- Respect absolutely the following condition:

$$\frac{\mathbf{N_p}}{\epsilon} \leq 3.4 \times 10^{20}\,\mathrm{m}^{-1}$$

- Luminosity reach is then:

$$\mathcal{L} \;\; \lesssim \;\; \frac{10^{40}\;(\mathrm{cm\;s})^{-1}}{\gamma \cdot \beta^*} \cdot \frac{E_{stored}}{500\,\mathrm{MJ}}$$

Example 1: Performance Reach 3.5 TeV

- Best performance reach parameters while respecting robustness limit:
  - Bunch intensity: 1.7e11 p (ultimate)
  - Norm. emittance: 1.9 μm (half nominal)
  - Geom. emittance: 0.5 nm (nominal value at 7 TeV)
  - Number of bunches: 1404 (50 ns)
  - β^*: 2.5 m
- We then get:
  - Stored energy: 133 MJ
- Luminosity reach:

  … have to add F correction …

  - Luminosity limit: **2.9×10^{33} cm^{-2} s^{-1}**

$$\mathcal{L} \lesssim \frac{10^{40}\ (\mathrm{cm\ s})^{-1}}{\gamma \cdot \beta^*} \cdot \frac{E_{stored}}{500\,\mathrm{MJ}}$$

Example 2: Performance Reach 3.5 TeV

- Best performance reach parameters while respecting robustness limit:
  - Bunch intensity: 1.15e11 p (nominal)
  - Norm. emittance: 1.3 μm (half nominal)
  - Geom. emittance: 0.34 nm (nominal value at 7 TeV)
  - Number of bunches: 2808 (25 ns)
  - β^*: 2.5 m
- We then get:
  - Stored energy: 180 MJ
- Luminosity reach:

… have to add F correction …

  - Luminosity max: **3.9×10^{33} cm^{-2} s^{-1}**

$$\mathcal{L} \lesssim \frac{10^{40}\ (\mathrm{cm\ s})^{-1}}{\gamma \cdot \beta^*} \cdot \frac{E_{stored}}{500\,\mathrm{MJ}}$$

HE-LHC Situation for Robustness

- Respect absolutely the following condition:

$$\frac{\mathbf{N_p}}{\epsilon} \leq 3.4 \times 10^{20}\,\mathrm{m}^{-1}$$

- Present design parameters HE-LHC at 16.5 TeV:

$$\mathrm{HE\text{-}LHC} \longrightarrow \quad \frac{\mathbf{N_p}}{\epsilon} = 8.7 \times 10^{20}\,\mathrm{m}^{-1}$$

→ **Not a priori OK!**

Comparison assumes similar kicker rise times, leakage, failure scenarios,…

HE-LHC with Present Technologies

- **Bunch density factor 2.6 above limit.**
- Possibility 1 (this works for sure):
  - Increase emittance: **0.15 nm → 0.38 nm**
  - Feasible with present technologies.
  - Luminosity reach: 9.4×10^{33} cm^{-2} s^{-1} (~ half)
- Possibility 2 (can be good or bad news):
  - Review damage limits.
  - Further simulations.
  - Experimental studies: HiRadMat
- Possibility 3 (looks quite promising):
  - **New collimator and absorber technology**
  - Studies are underway → EuCARD/ColMat

No showstopper

Mechanical Stresses: Present LHC Coll.

(a) Injection

Material	Jaw length [cm]	Max. temperature [°C]	Stress σ_{equiv} [MPa]	σ_{allow} [MPa]	Suitability
Carbon-Carbon	20	335	4.4	86	yes
	100	345	12.7	86	yes
Graphite	20	335	3.1	18	yes
	100	345	6.2	18	yes
Beryllium	20	168	334	[illegible]	[illegible]
	100	200	[illegible]	[illegible]	[illegible]

Calculated: **82 MPa** → Allowed: **86 MPa**
Not much margin, even for nominal intensity!

(b) 7 TeV

Material	Jaw length [cm]	Max. temperature [°C]	Stress σ_{equiv} [MPa]	σ_{allow} [MPa]	Suitability
Carbon-Carbon	20	212	20.8	86	yes
	100	551	82.0	86	yes
Graphite	20	212	4.4	18	yes
	100	551	17.8	18	yes
Beryllium	20	116	584	160	no
	100	168	1248	160	no

O. Aberle, L. Bruno

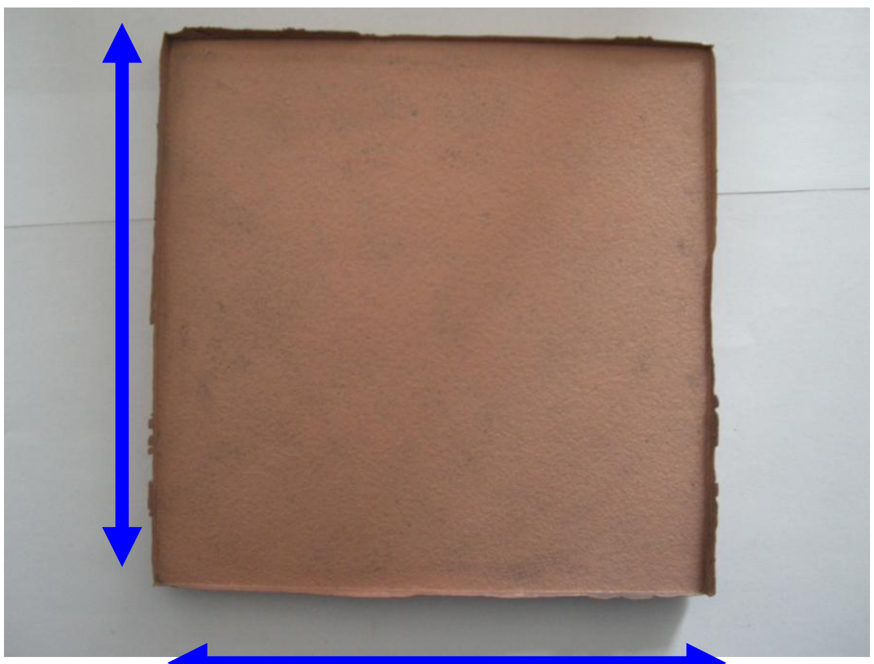
… being reviewed …

Collimator R&D

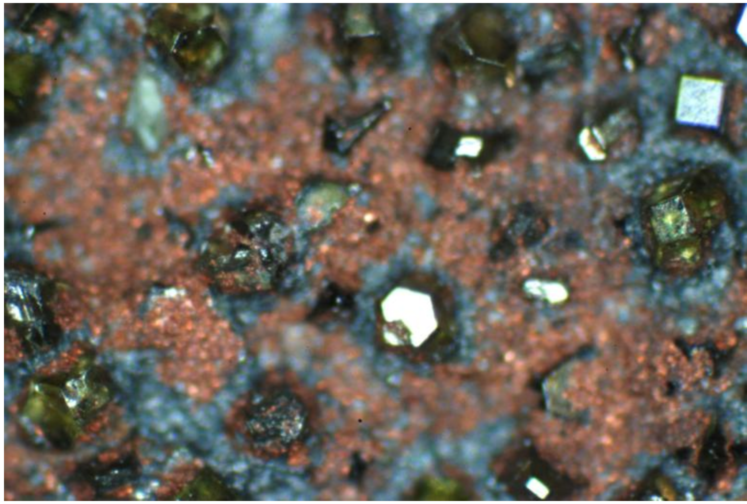
- Collimator R&D is done in a European/US collaboration.
- Supported by EU FP7 and LARP.

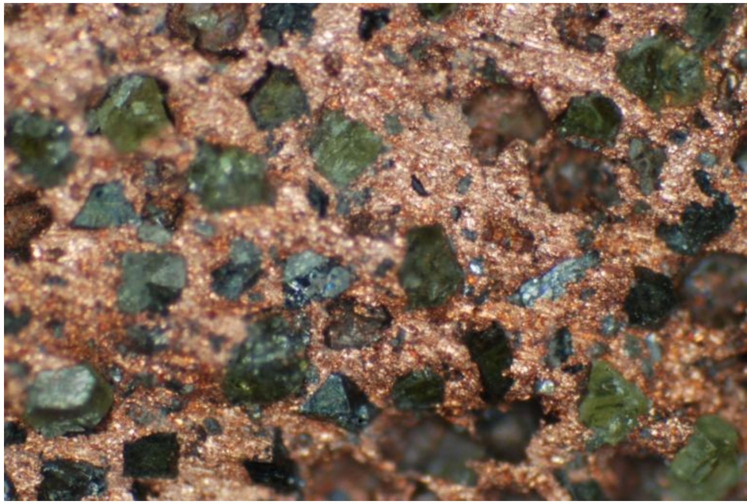
Manufacturing of Cu-diamond composite

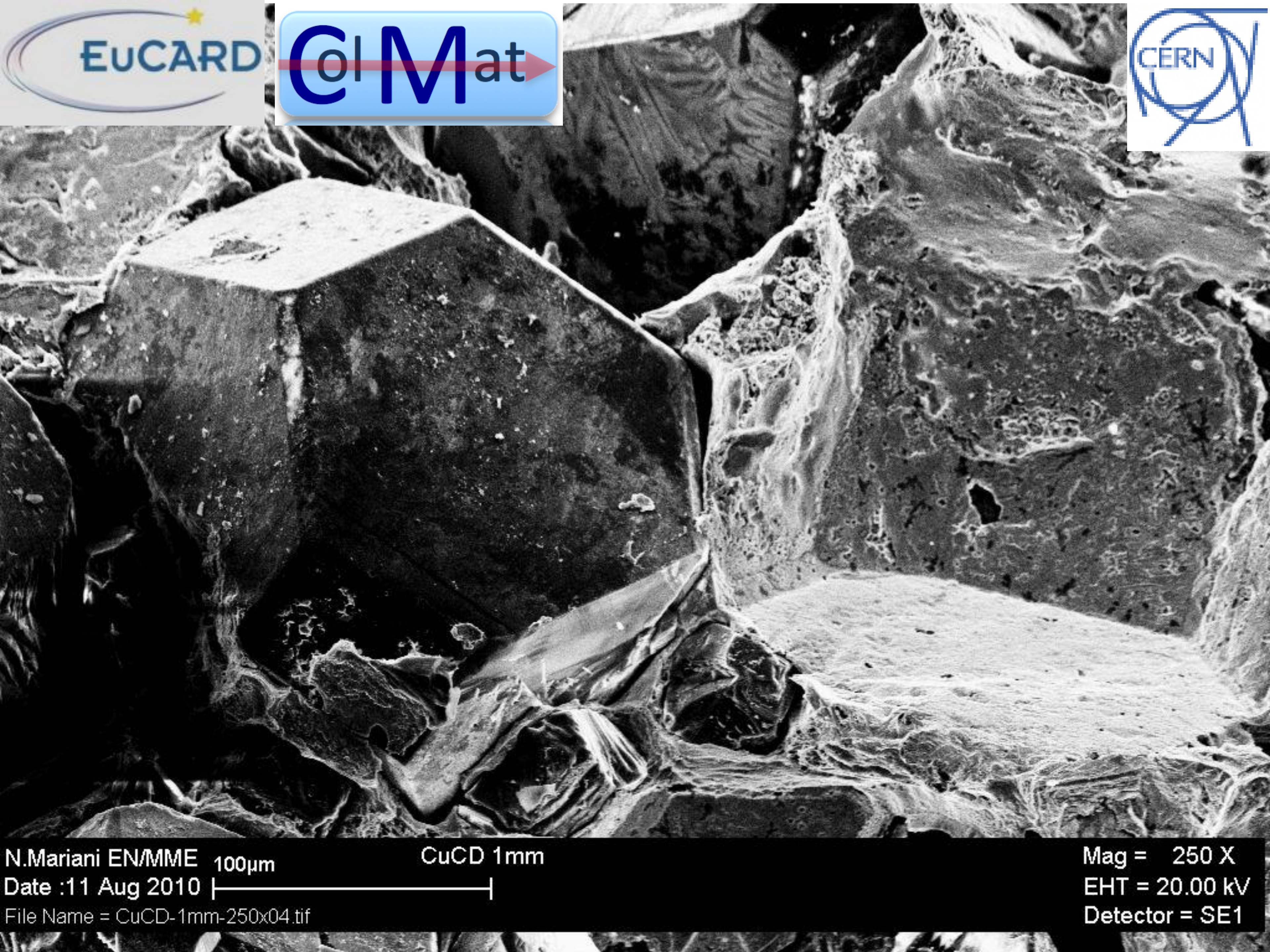
- Manufacturing of Cu-diamond plates with 60 vol.%
- Water jet cutting of samples for:
  - Thermal Diffusivity
  - CTE
  - Mechanical Testing
  - Meas. of mech. properties at high T



150 mm x 150 mm



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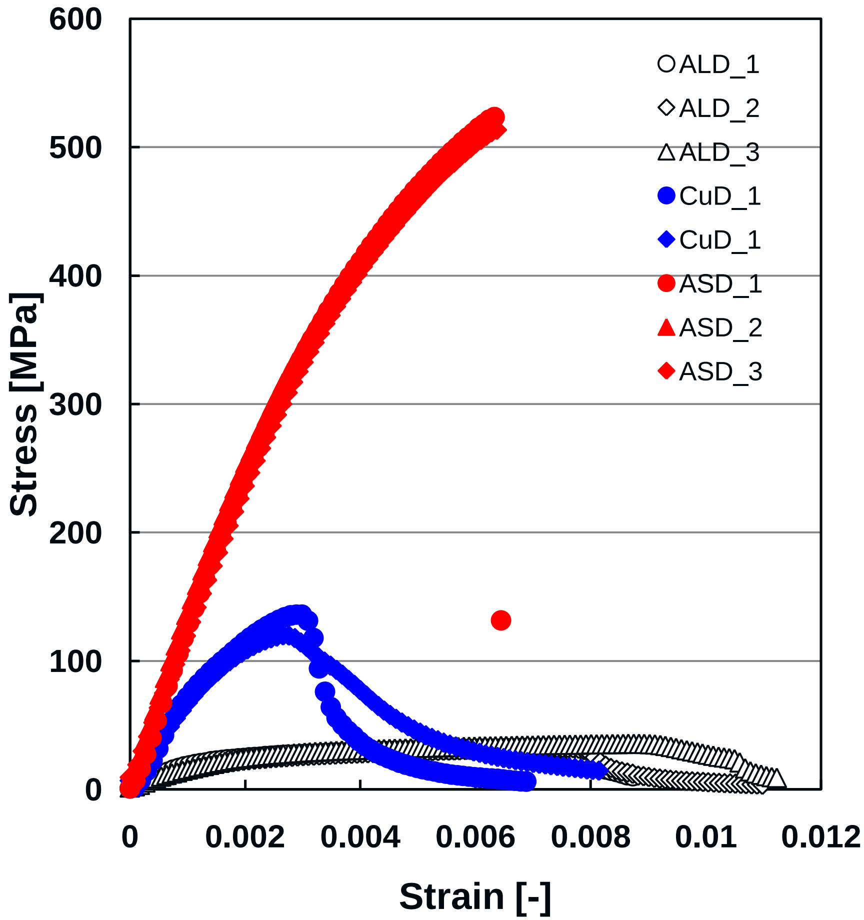
Detector = SE1

Mechanical behaviour of Diamond MMCs: Bending strength

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

L. Weber



- Ag-Si-D with **> 500 MPa bending strength** (particle size 45 µm)
- CuD with a bending strength around 130 MPa (some plasticity, elastic limit much lower). Particle size 200 µm.
- AlD bending strength <30 Mpa, large plastic defor-mation. Particle size 45 µm.

Innovative materials…

- We are producing materials with a bending strength beyond 500 Mpa!
- This is significantly beyond the strength of the fiber-reinforced graphite that we used (86 Mpa – already extremely strong material).
- This R&D might allow us to overcome the limitations that we presently must respect!

86 Mpa → 500 Mpa (?)

- Too early to conclude whether we can use these materials in the LHC.
- Tests (radiation, vacuum, …) ongoing and continued in EuCARD2!

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Collimating with Small Gaps

~ 0.15 ~ 0.6

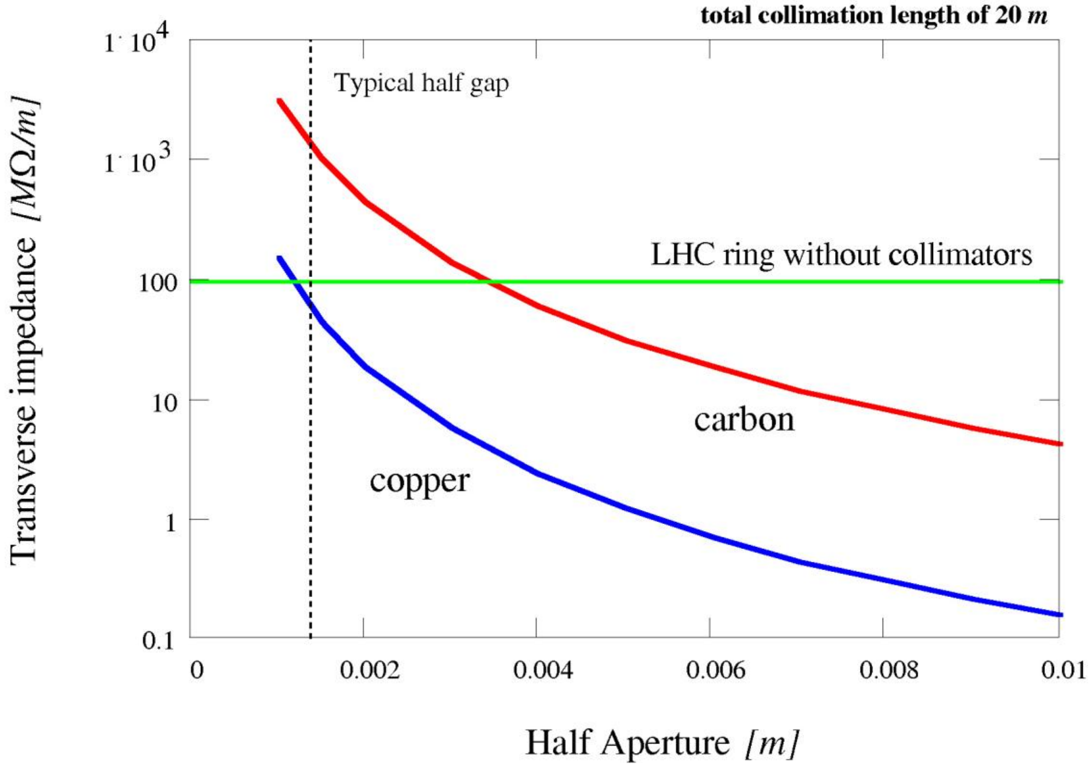
$$a_{coll} \leq 0.6 \cdot a_{sc} \cdot \sqrt{\frac{\beta_{coll}}{\beta_{sc}}} \cdot \left(\frac{A_{primary}^{max}}{A_{secondary}^{max}} \right)$$

Collimator gap must be **10 times smaller** than available triplet aperture for nominal luminosity!

Collimator settings usually defined in sigma with nominal emittance!

- The limiting super-conducting (sc) aperture is usually in the triplet during collisions.
- **If the super-conducting aperture is reduced, we might have to run with lower gaps.**
- This means: tighter tolerances for machine and collimators.
- It also means that the impedance will be larger (factor 6?).
- Half gap 5.7 σ: **1.1 mm (7 TeV)** → **0.6 mm (16.5 TeV)**

The Impedance Challenge



Machine impedance increases while closing collimators (Carbon curve).

*LHC will operate at the **impedance limit** with collimators closed!*

2003, F. Ruggiero, L. Vos

Transverse impedance ~ 1 / (half gap)^3

→ To be addressed in detailed studies with E. Metral et al

Issues with Smaller Gaps

- Must try to keep collimator gaps reasonably large.
- Ideally for available SC aperture a [σ] in collision:

a [σ] (16.5 TeV) = 1.5 × a [σ] (7 TeV)

- This costs reach in β^* or requires the same IR/DS apertures (in mm).
- Alternative (if we keep collimation at ~6 σ):
  - New LHC collimator technology for factor 2 smaller gaps and even higher precision and reproducibility.
  - Live with much higher impedance.
  - Live with operational tolerances (orbit) at the 20-30 μm level.

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Comments on MP

- Passive protection to a large extend covered by collimation aspects (see before).
- The robustness issues have been discussed before.
- Injection and dump protection to be discussed by experts (B. Goddard et al) independently. Originally next talk on this…
- MP system (interlocks, surveillance, …):
  - Instrumentation systematics (orbit changes, …).
  - Check and possibly adjust dynamic range of BLM's.
  - Energy and squeeze factors.
- Requires detailed study by machine protection team.

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Comments on Cleaning Insertions

- Cleaning insertions (warm magnets) were carefully designed for collimation:
  - Establish a three stage cleaning per insertion, in H/V/Skew/Mom.
  - Protect magnets/elements against excessive heating and radiation damage.
  - Radiation control. Remote handling.
- Important constraints:
  - Essentially, no space left (had to already move warm magnets to make space for collimators). Musty keep magnet length ~constant.
  - Phase advance is at the limit of what is required.
  - Optics must be kept similar: no way to decrease lattice strength, remove quadrupoles, increase beta functions, …
  - No way to increase inter-beam distance (w/o civil engineering): require very strong warm dogleg bends.
- Redesign for 16.5 TeV will be a MAJOR challenge.

Conclusion

- HE-LHC puts challenges for high intensity beam control.
- Cleaning efficiency:
  - Loose factor 2-3 in cleaning efficiency due to nuclear processes. Easily loose factor 10 in efficiency with smaller aperture in DS/arc.
  - Planned collimation upgrade (cryo/DS coll) will help for this.
- Material robustness:
  - HE-LHC parameters factor ~3 beyond present robustness limit.
  - Either increase emittance which is aimed for (loose factor 2 in L) or use new materials & technologies (under study in EuCARD/ColMat).
- Gaps and tolerances:
  - Should aim for 50% larger normalized aperture at 16.5 TeV.
  - Alternatively, new collimator technologies required.
- MP requires further attention but no show-stopper expected.
- Cleaning insertion re-design for 16.5 TeV a major challenge.