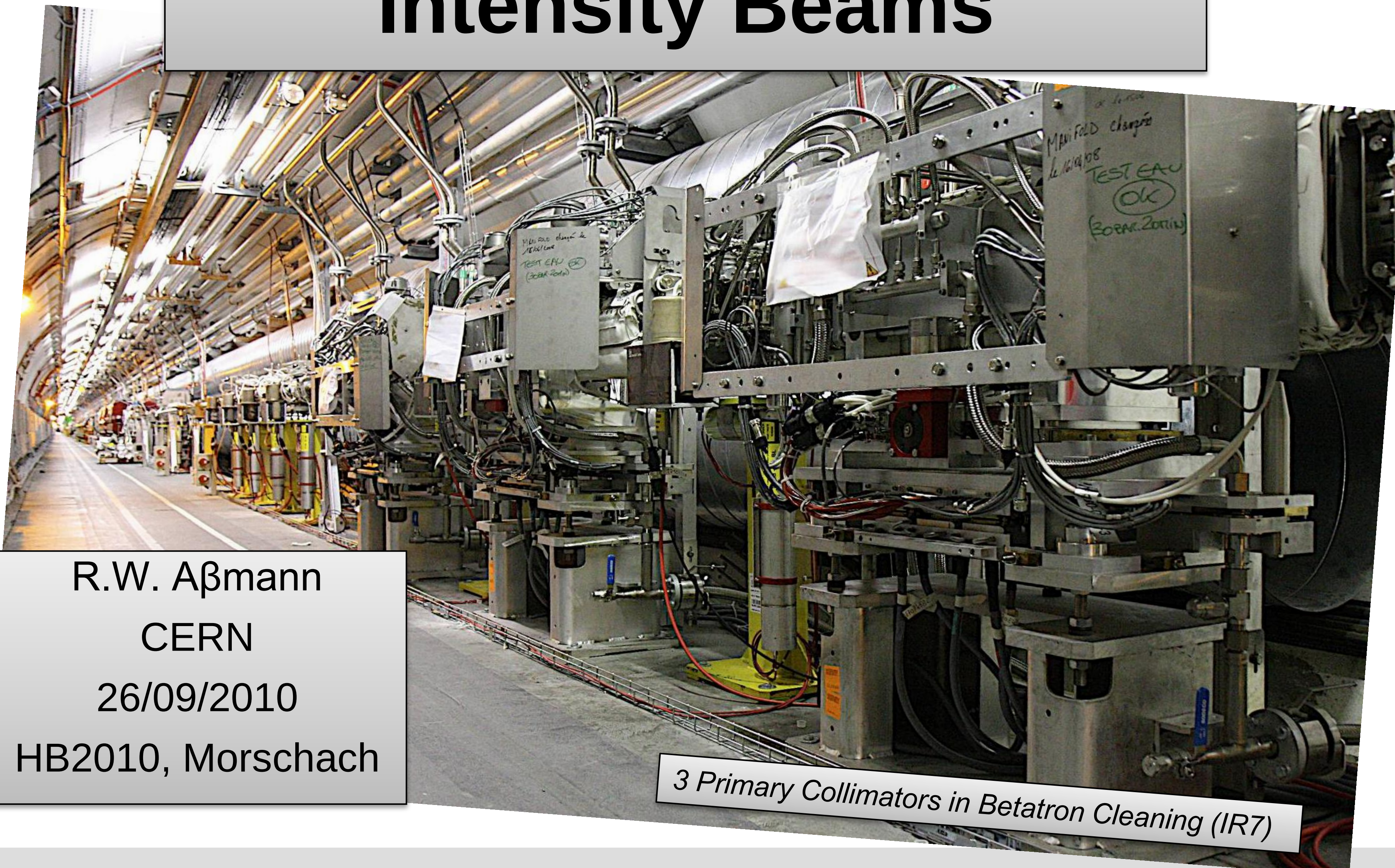
Collimation for LHC High Intensity Beams



3 Primary Collimators in Betatron Cleaning (IR7)

R.W. Aßmann

CERN

26/09/2010

HB2010, Morschach

The Collimation Project Team & Close Collaborators

- Results on phase I collimation are outcome of lot of work performed over last 8 years by the following **CERN colleagues**:

O. Aberle, J.P. Bacher, V. Baglin, G. Bellodi, A. Bertarelli, R. Billen, V. Boccone, A.P. Bouzoud, C. Bracco, H. Braun, R. Bruce, M. Cauchi, N. Hilleret, E.B. Holzer, D. Jacquet, J.B. Jeanneret, J.M. Jimenez, M. Jonker, Y. Kadi, K. Kershaw, G. Kruk, M. Lamont, L. Lari, J. Lendaro, J. Lettry, R. Losito, M. Magistris, A. Masi, M. Mayer, E. Métral, C. Mitifiot, R. Perret, S. Perrolaz, V. Previtali, C. Rathjen, S. Redaelli, G. Robert-Demolaize, C. Roderick, S. Roesler, A. Rossi, F. Ruggiero, M. Santana, R. Schmidt, P. Sievers, M. Sobczak, K. Tsoulou, G. Valentino, E. Veyrunes, H. Vincke, V. Vlachoudis, T. Weiler, J. Wenninger, D. Wollmann, …

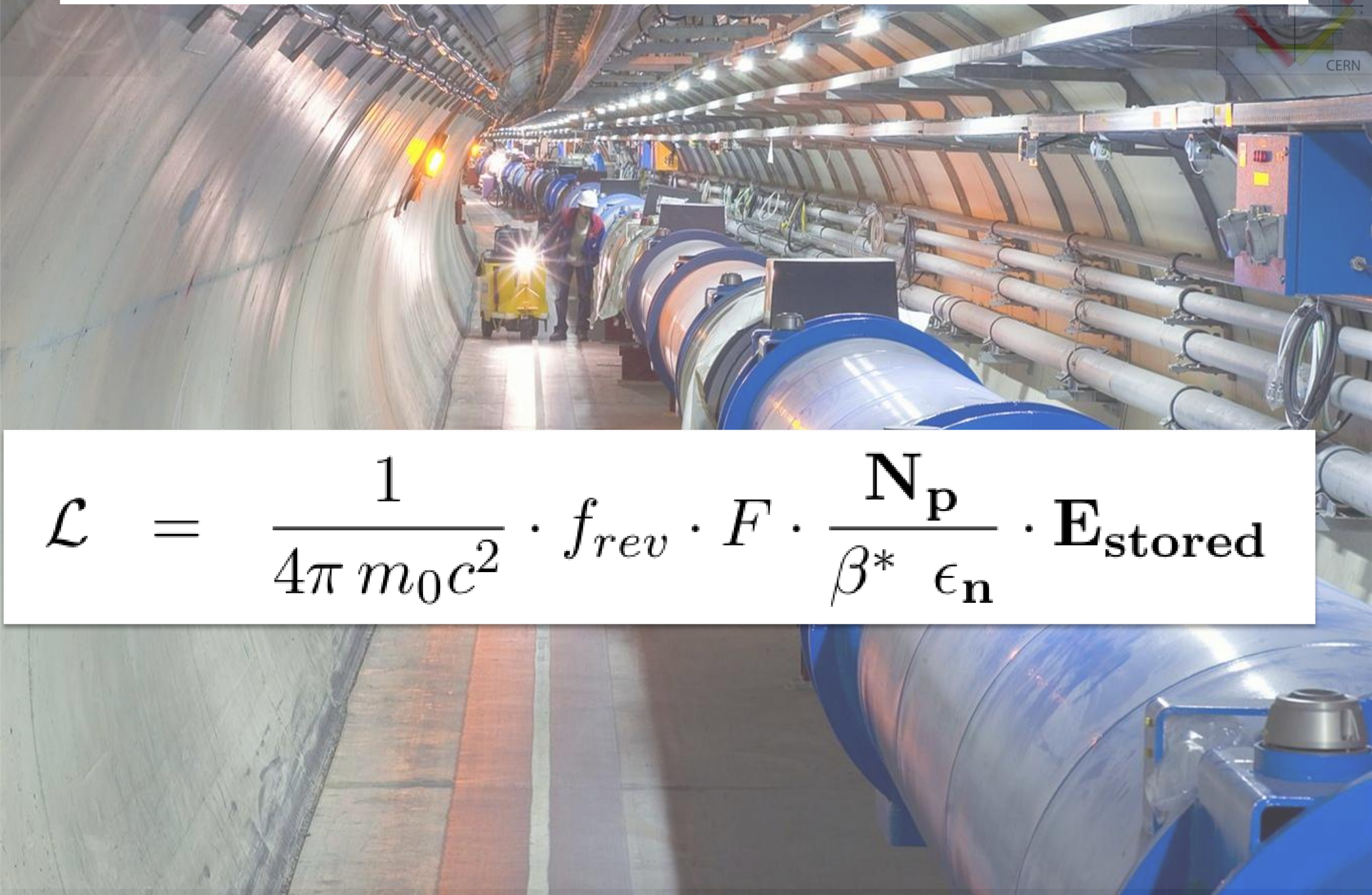
- Crucial work also performed by **collaborators** at:

EuCARD/ColMat partners, TRIUMF (D. Kaltchev), IHEP (I. Baishev & team), SLAC (T. Markiewicz & team), FNAL (N. Mokhov & team), BNL (N. Simos, A. Drees & team), Kurchatov (A. Ryazanov & team).

Outline

- **The Energy and Intensity Frontier at LHC**
- The LHC Collimation System
- Collimation Setup
- Performance: Simulation and Measurement
- Outlook: Upgrades
- Conclusion

Parameters for LHC Luminosity Production



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

Parameters for LHC Luminosity Production

Fixed tunnel length: **low LHC revolution frequency** makes it harder to produce lumi (compared to Tevatron)

Beam-beam: **Fine with nominal bunch charge**! Can put more…

LHC luminosity is increased via stored energy → 2.8 MJ!

Go up by increasing number of bunches!

Extrapolating from 2.8 MJ: No show-stopper 30 MJ (2010 goal).

Go up not too fast & not too slow...

constant

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

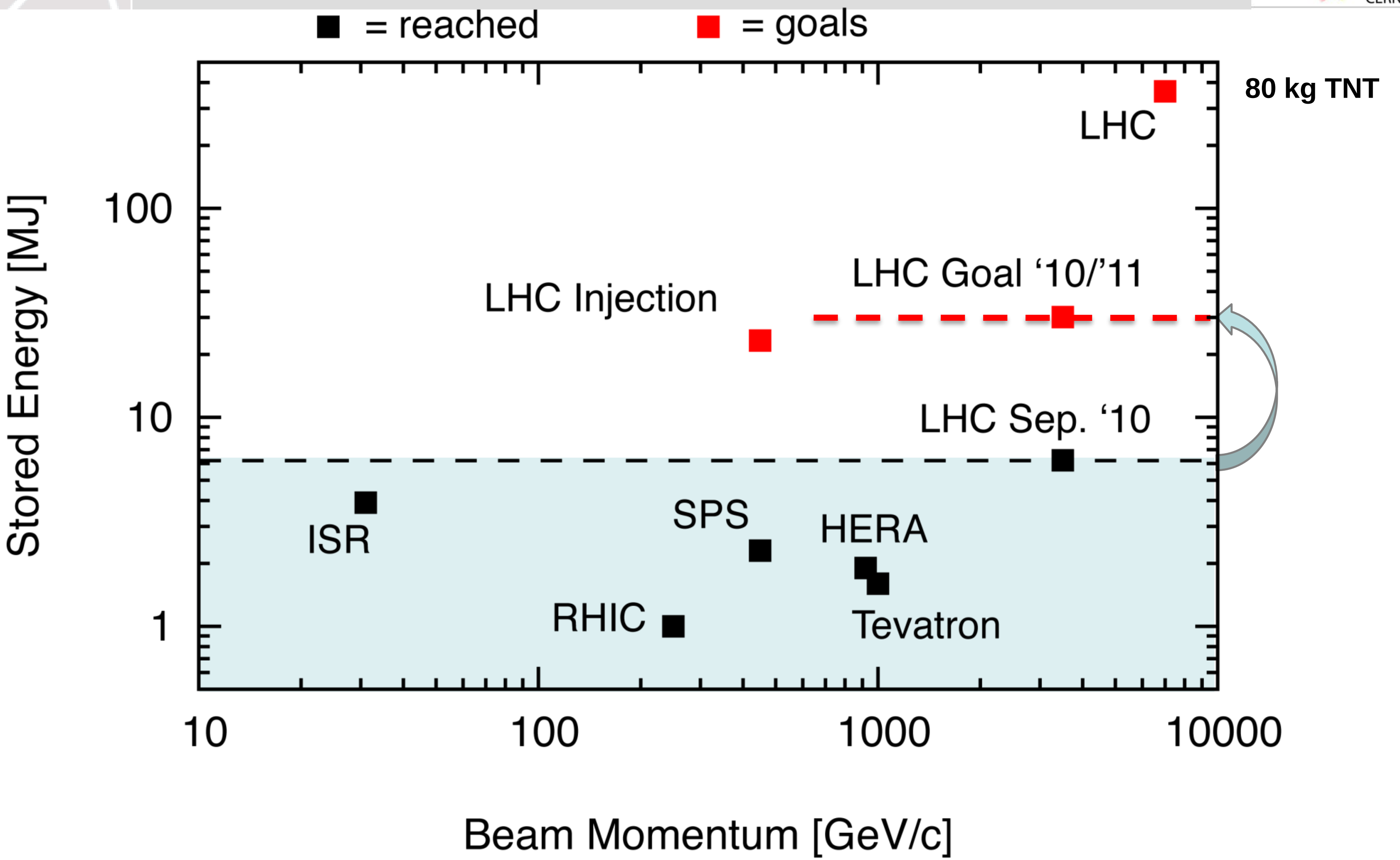
β^* = IP beta function (β_x=β_y)
ε_n = norm. transv. emittance
N_p = protons per bunch
f_{rev} = revolution frequency
F = geometrical correction
m_0 = rest mass, e.g. of proton
c = velocity of light

At the moment **set to 3.5 m in all IR’s** (2m reached): better margins for operation, collimation and protection.

Limit is ~1.2 m at 3.5 TeV. However, then very tight tolerances!

Achieved normalized **emittance** 40% below nominal!

Stored Energy (Measure of Quench Potential)



LHC Parameters

(for Reference)

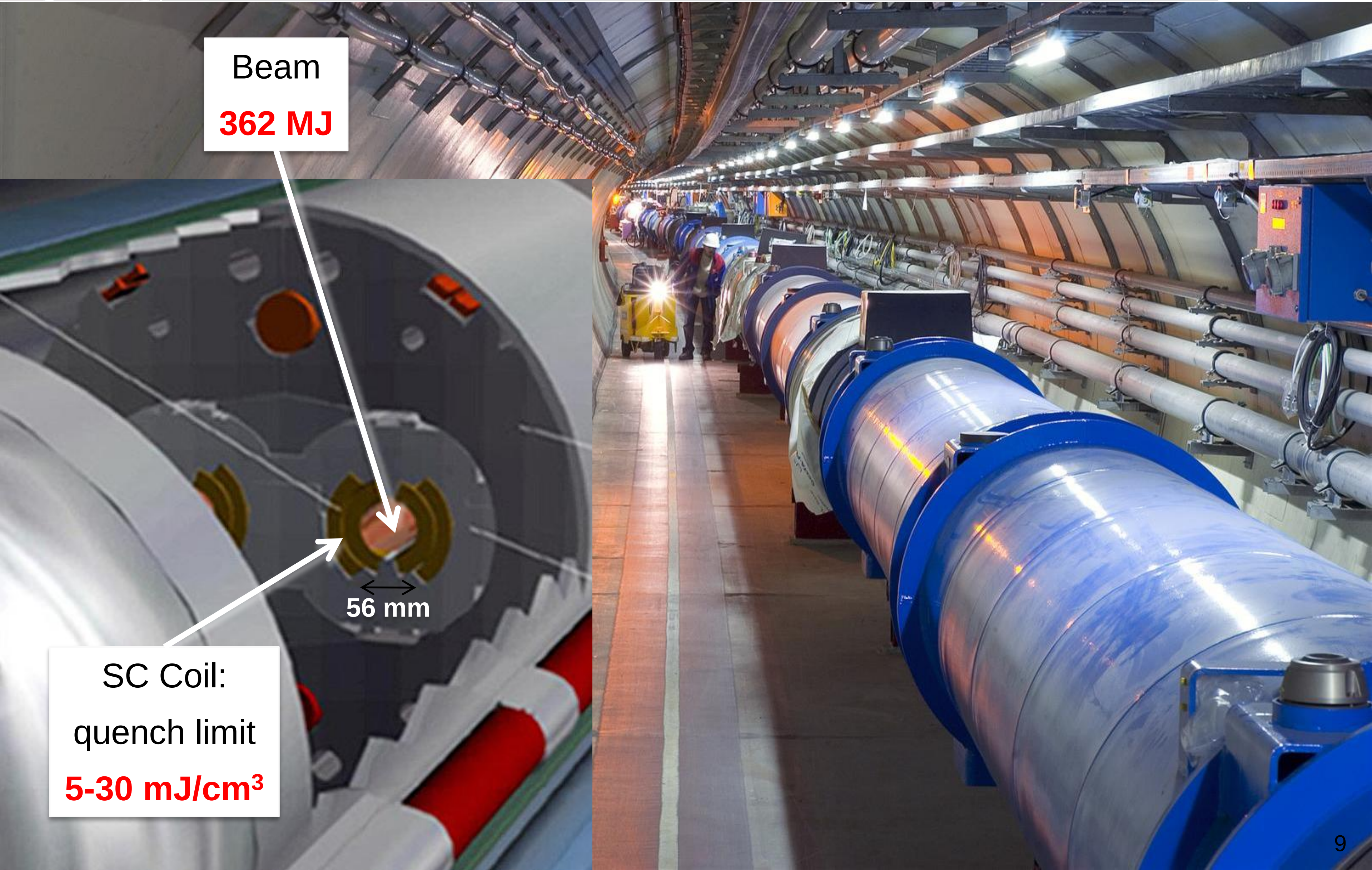
• Beam energy:	**3.5 TeV**	**frontier**, 7 TeV in 2013
• Bunch intensity:	1.1e11	nominal, can put more
• Number of bunches:	104	
• Norm. emittance:	2.2 μm	60% of nominal
• IP beta value:	3.5 m	limited for larger margins
• Stored energy:	**6.2 MJ**	**frontier**, 30 MJ in 2010/11
• Peak luminosity:	**3.5 x 10^{31} cm^{-2} s^{-1}**	factor 3 to go in 2010
• Luminosity lifetime:	~25 h	
• Availability:	**~85 %**	(max. weekly)
• Time in physics:	**40.2 %**	(max. weekly)

Proton Losses

- LHC: Ideally no power lost (protons stored with infinite lifetime).
- 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**

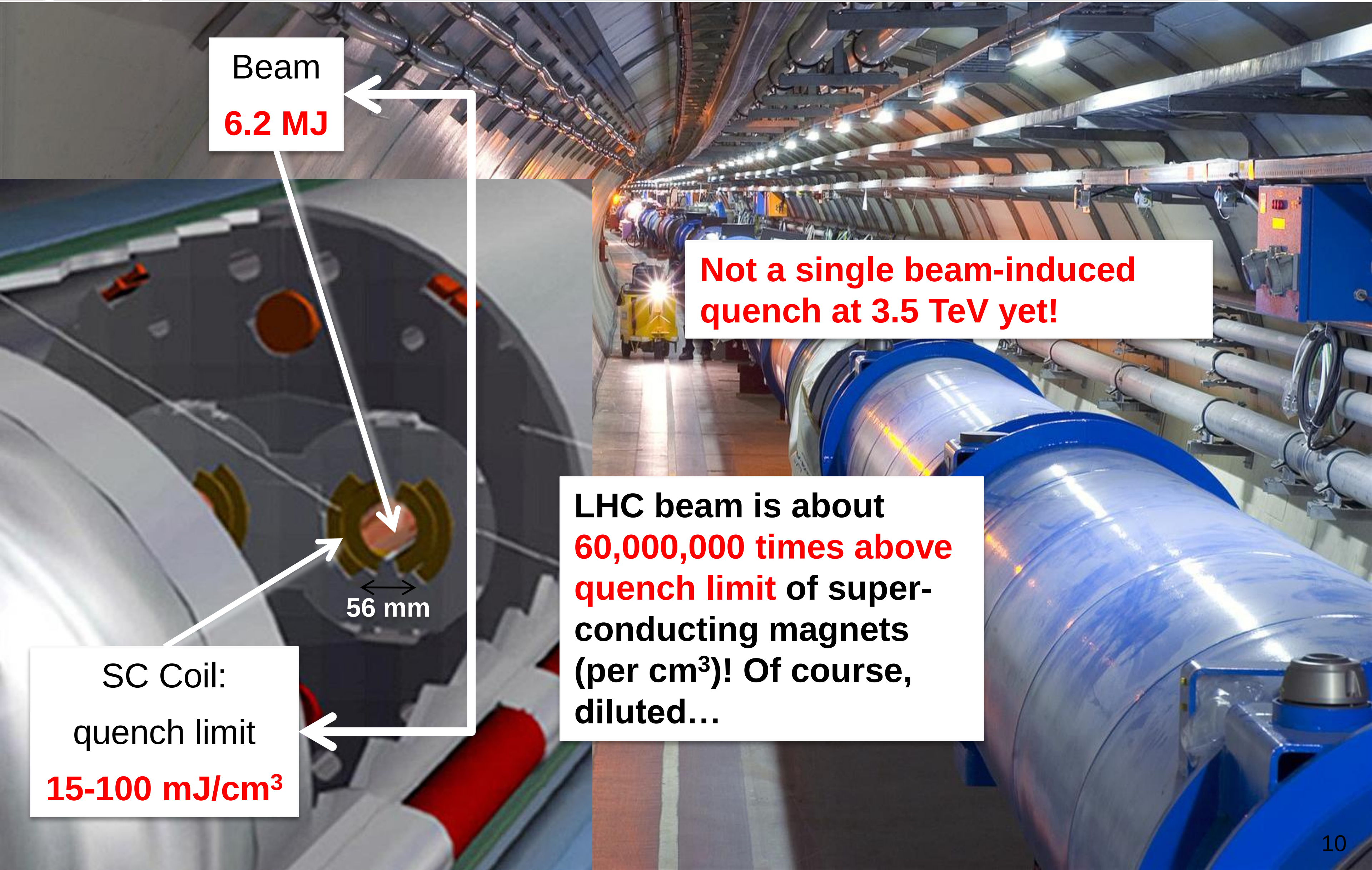
Quench Limit of LHC Super-Conducting Magnets

Nominal design at 7 TeV

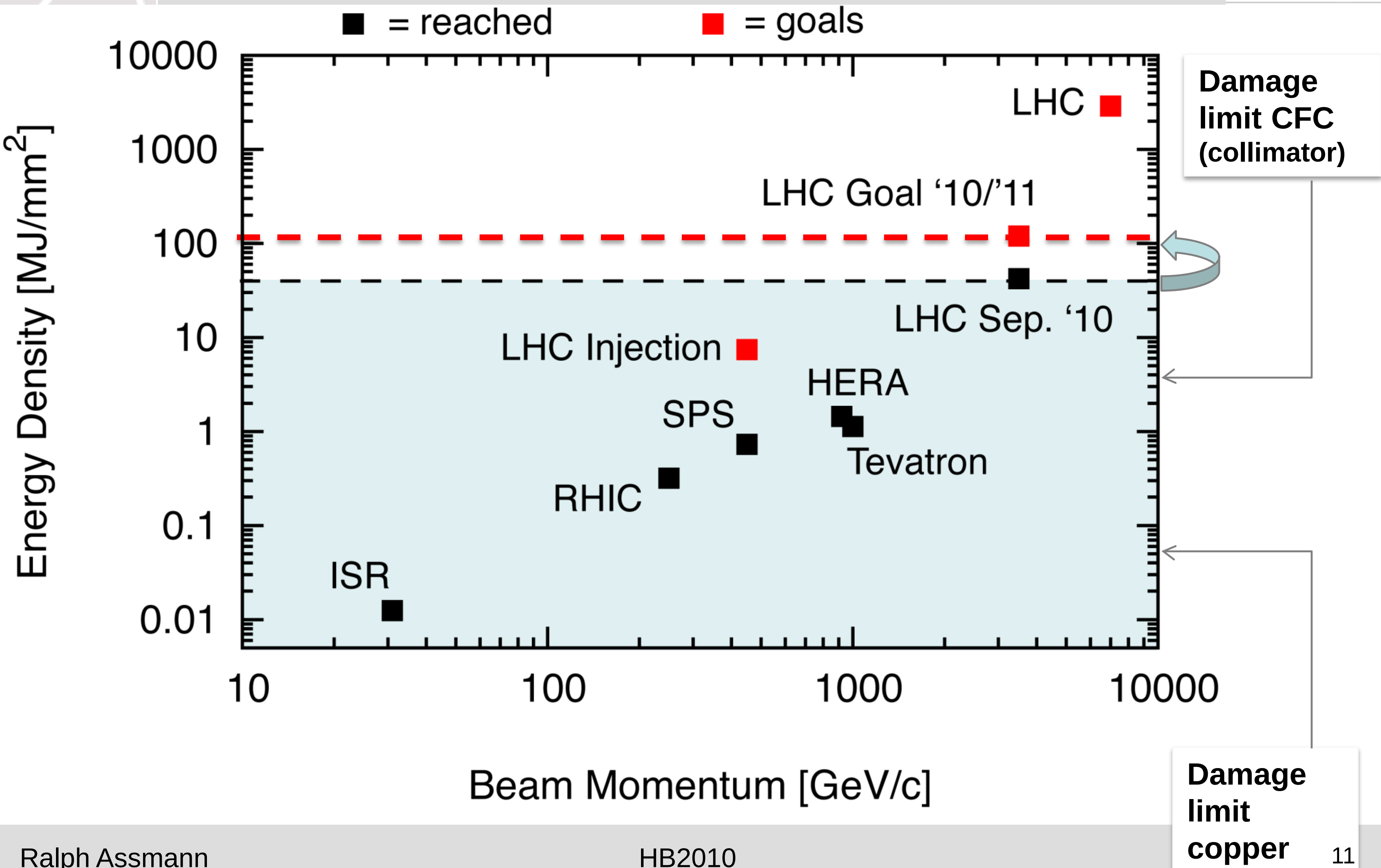


Quench Limit of LHC Super-Conducting Magnets

Situation at 3.5 TeV (on September 26, 2010)



Energy Density (Measure of Damage Potential)

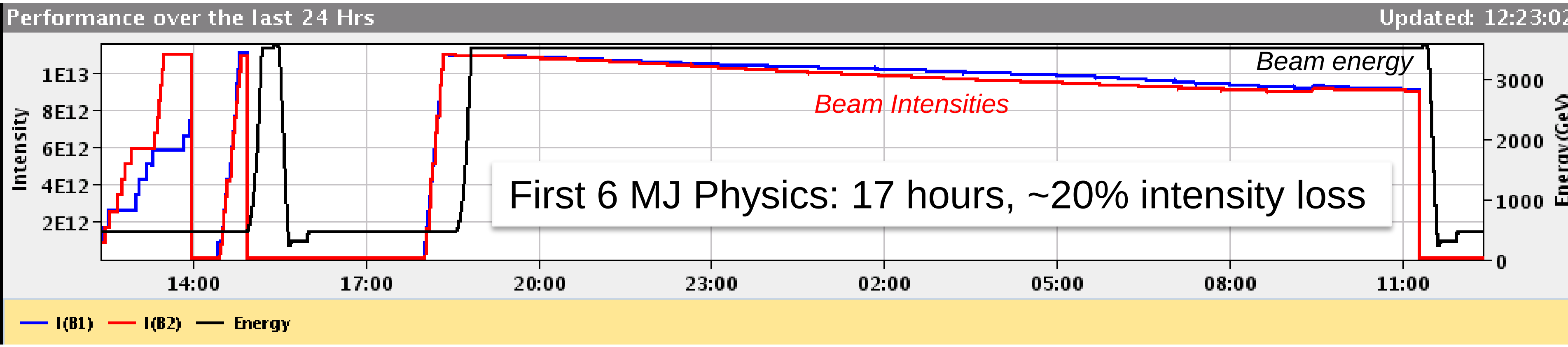


Intensity Frontier at LHC: Role of Collimation

- All other SC proton colliders had an important number of beam-induced quenches while pushing up to the MJ regime.
- LHC reached 3 times the world record in stored energy per beam within 6 months and without a beam-induced quench with stored beam.
- How was this achieved?
  - Highly efficient, 4 stage collimation system in the LHC.
  - Tight collimation all through injection, ramp, squeeze and collision.
  - Catches safely all losses that occur while intensity is increased.
  - This includes "normal" losses (scattering, emittance growth, diffusion, …) and losses with equipment failures.

A Look at Record Fill This Weekend

- Intensity increased by factor 2 to **1.11e13 protons per beam**.



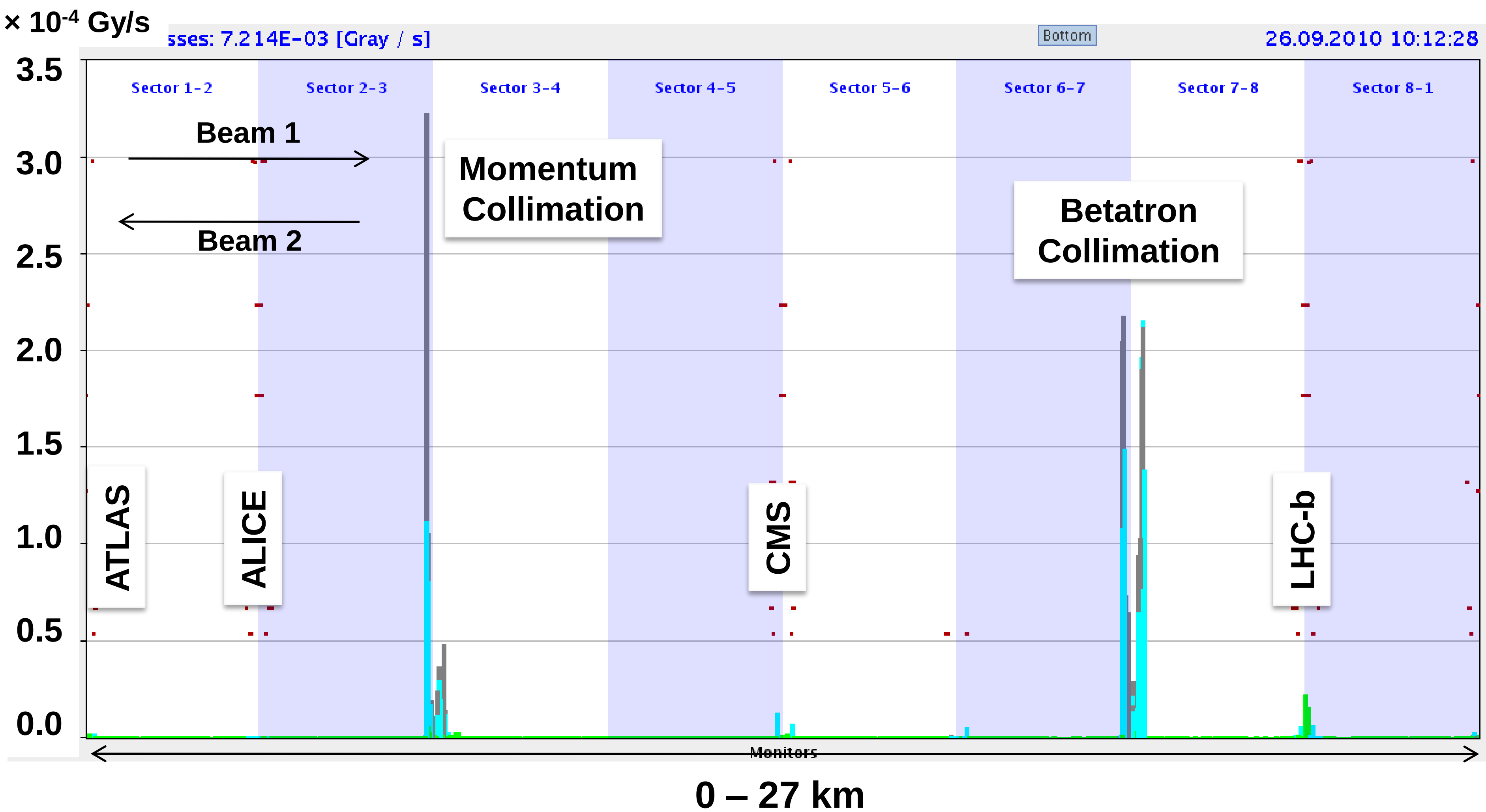
25-Sep-2010 19:36:45 Fill #: 1372 Energy: 3500 GeV I(B1): 1.11e+13 I(B2): 1.10e+13

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	NOT READY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	34....	0.082	34.714	0.426
BRAN Luminosity (ub.s)^-1	33.003	0.096	125.709	24.661

- Peak luminosity: **3.5×10^{31} cm^{-2} s^{-1}**

Losses Around the Ring

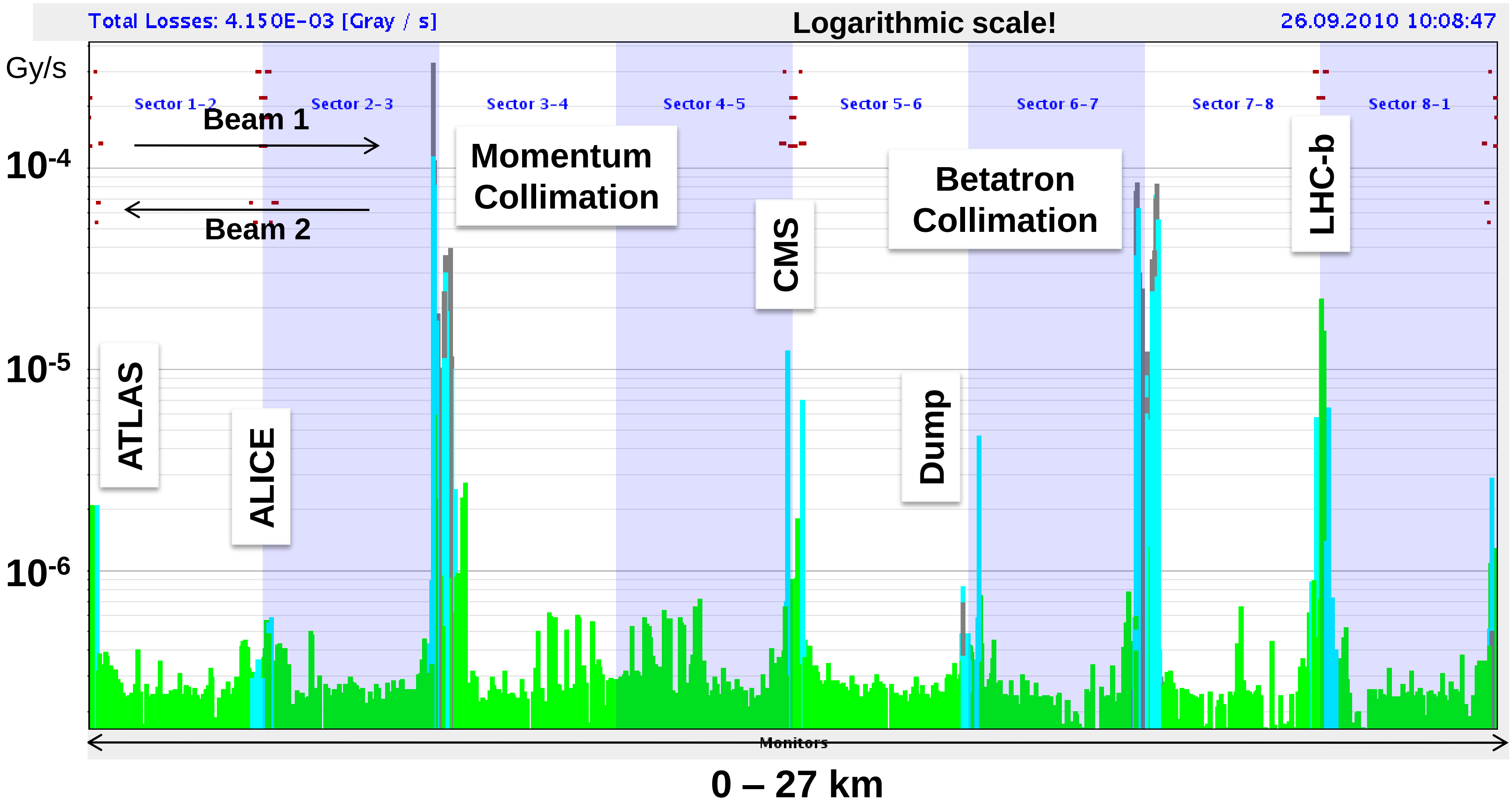
(3.5 TeV, End Record Fill 26.9.2010, τ > 75 h)



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

Losses Around the Ring

(3.5 TeV, End Record Fill 26.9.2010, τ > 75 h)



→ *Details can be seen in logarithmic scale!*

Cleaning All the Time…

- With high LHC beam intensity we see unavoidable beam losses constantly (see example for lifetime > 75 hours).
- We can characterize losses. E.g. losses for beam 1 mostly in momentum cleaning → had a few RF cavity trips. Losses for beam 2 mostly in betatron cleaning → no RF trips for beam 2.
- **Essentially all losses intercepted at primary collimators in betatron and momentum cleaning insertions!**
- Very small leakage to outside cleaning insertions.
- Some local losses occur in the experimental insertions (visible on logarithmic scale): luminosity-driven losses, p-p collisions.
- In addition: rare beam dumps due to tiny, fast losses in middle of arc (10 events so far → rare dust particles?). Not discussed here…

How Does Collimation Work and Does it Work as Predicted?

Outline

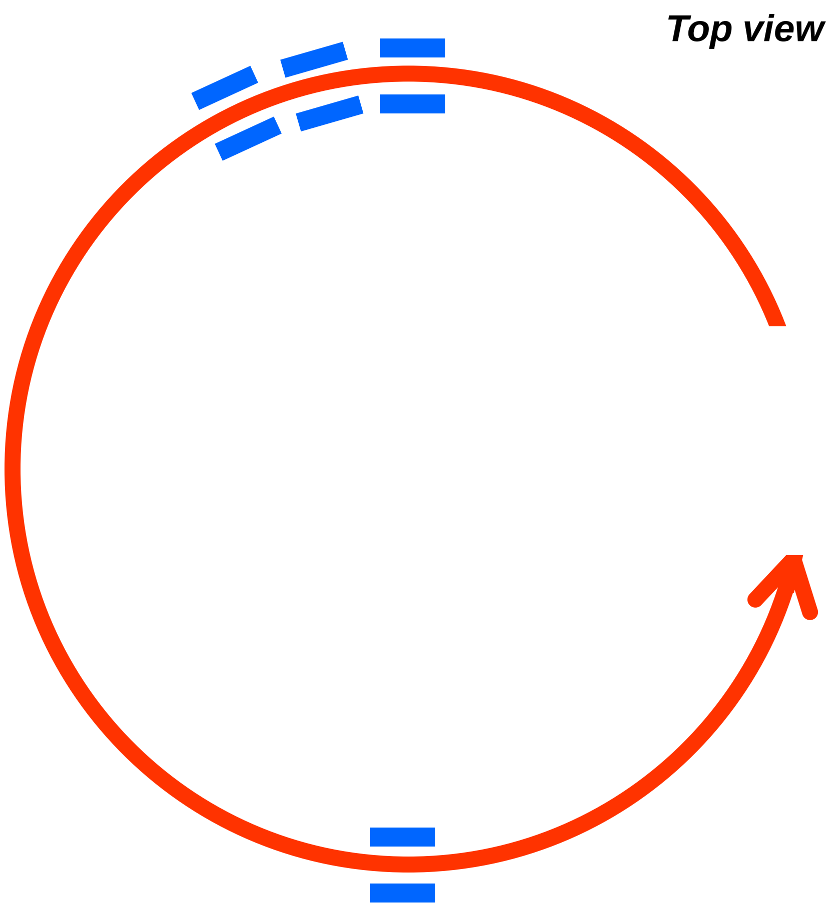
- The Energy and Intensity Frontier at LHC
- **The LHC Collimation System**
- Collimation Setup
- Performance: Simulation and Measurement
- Outlook: Upgrades
- Conclusion

The LHC Collimation System

- Collimators must intercept any losses of protons such that the rest of the machine is protected („the sunglasses of the LHC“):

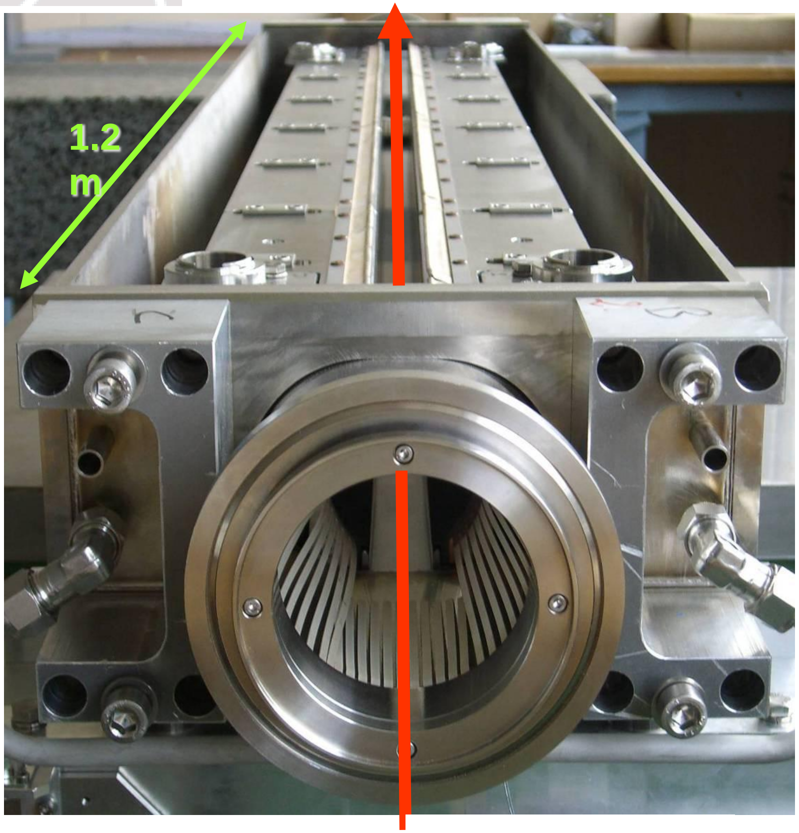
  > 99.9% efficiency!

- 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.

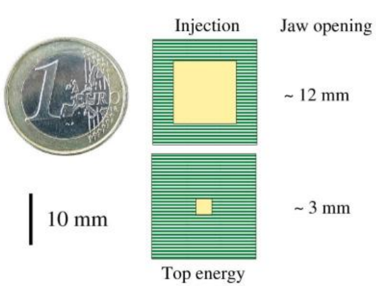


The Carbon Fiber Collimator

closest to beam: primary (TCP) and secondary (TCS) collimators



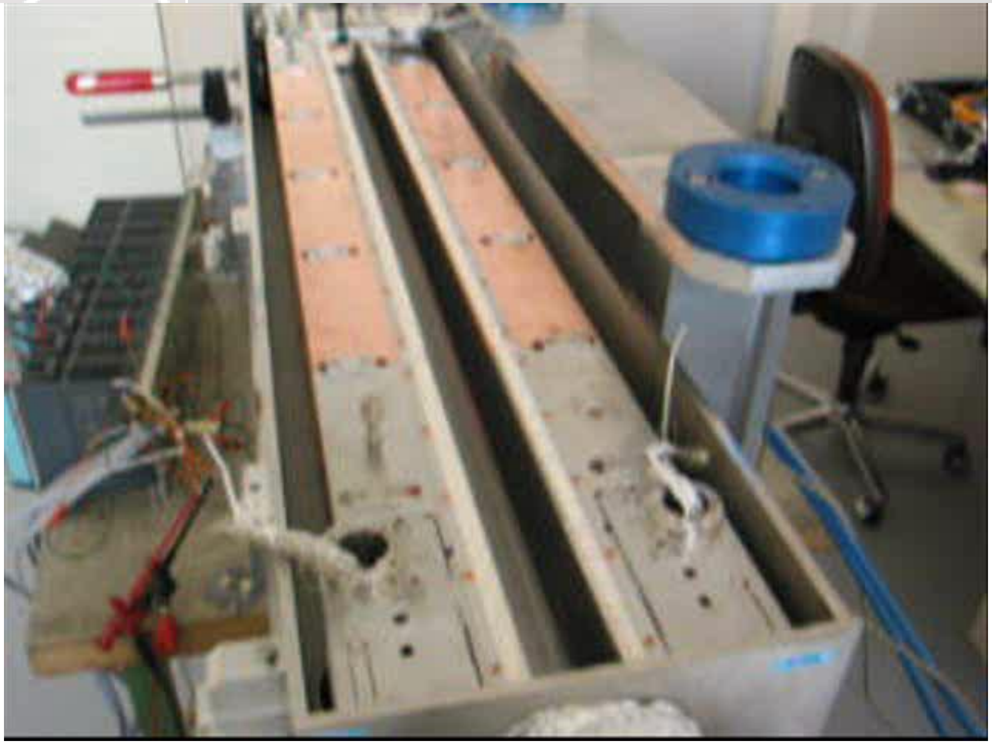
360 MJ proton beam



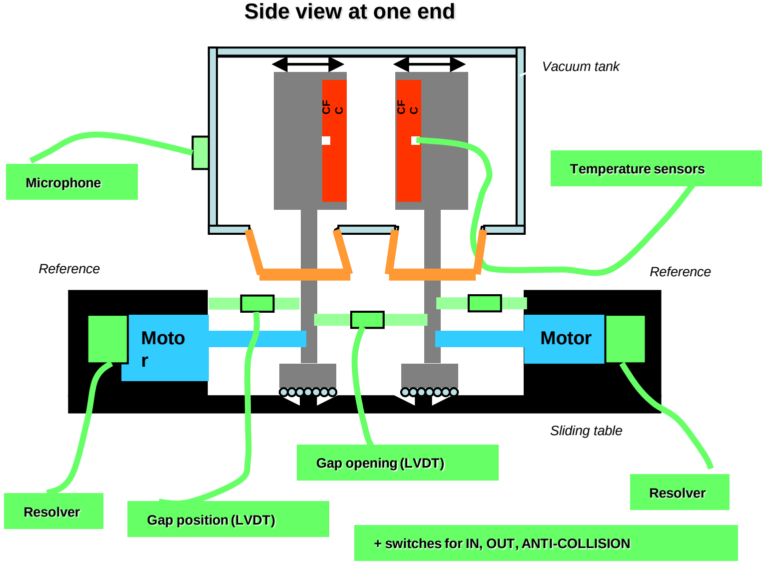
Parameter		Unit	Specification
Jaw material			CFC
Jaw length	TCS TCP	cm cm	100 60
Jaw tapering		cm	10 + 10
Jaw cross section		mm^2	65 × 25
Jaw resistivity		μΩm	≤ 10
Surface roughness		μm	≤ 1.6
Jaw flatness error		**μm**	**≤ 40**
Heat load		kW	≤ 7
Jaw temperature		°C	≤ 50
Bake-out temp.		°C	250
Minimal gap		**mm**	**≤ 0.5**
Maximal gap		mm	≥ 58
Jaw position control		μm	≤ 10
Jaw angle control		μrad	≤ 15
Reproducibility		**μm**	**≤ 20**

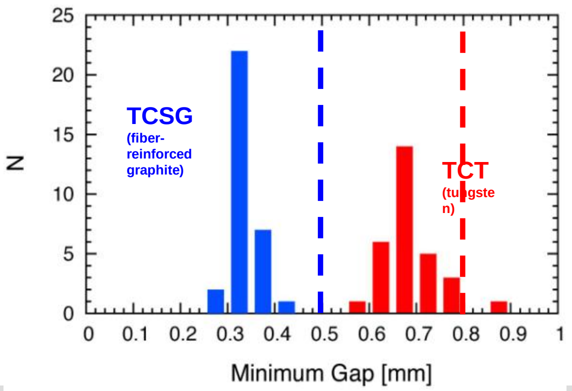
2003 Specification

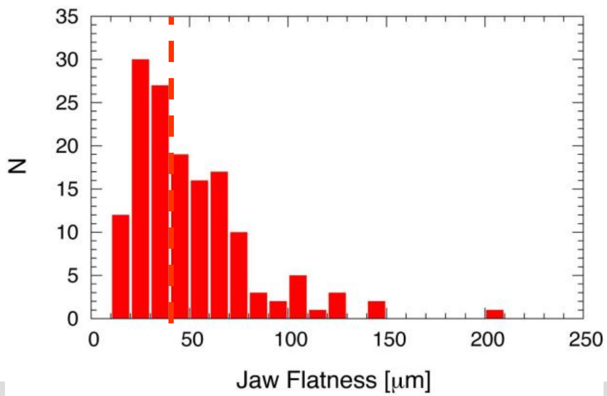
Precisions Control & Movements

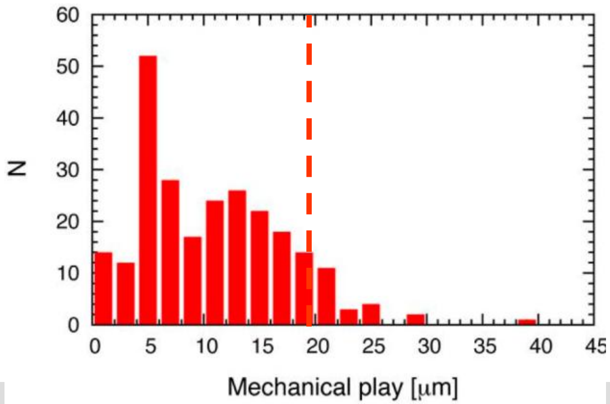


Accurate stepping motors control jaw positions versus time!

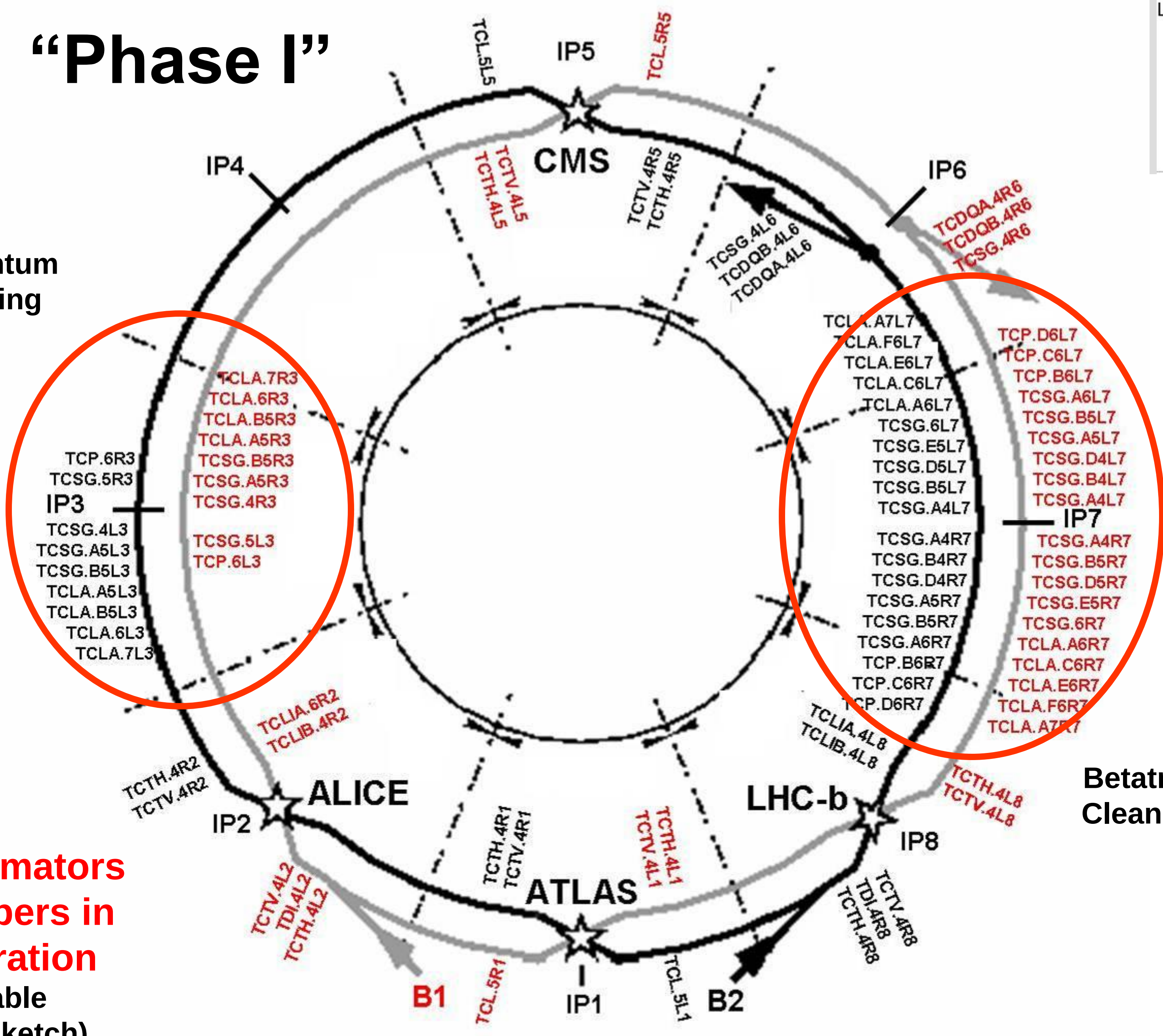








"Phase I"

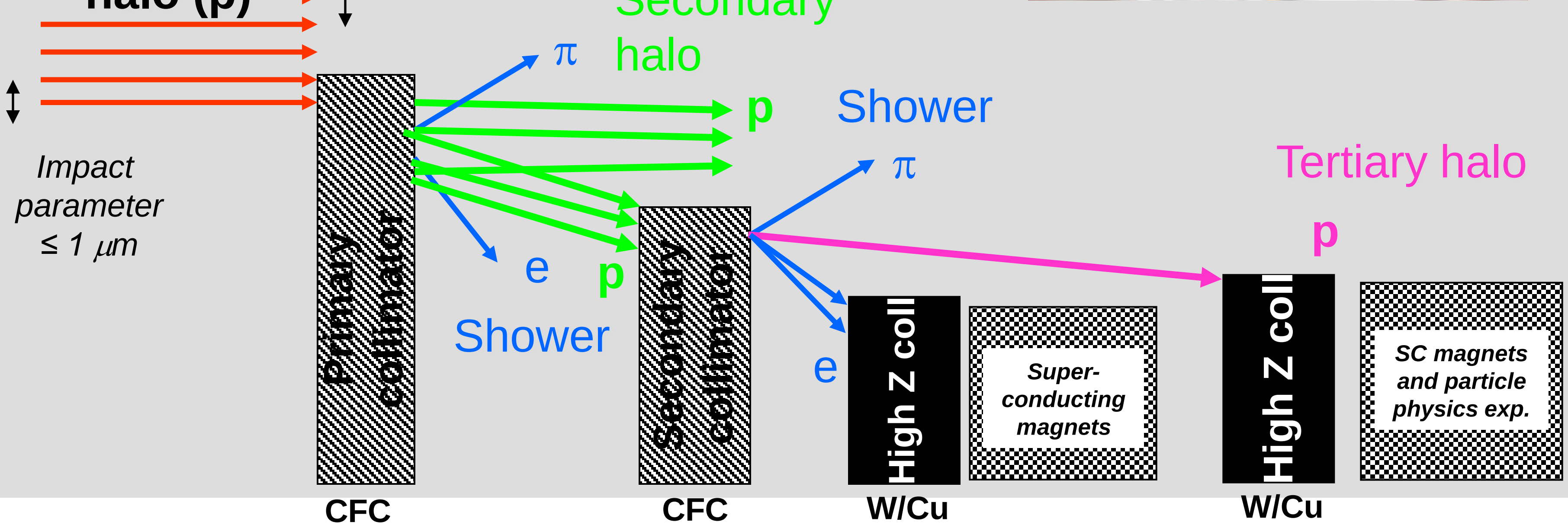


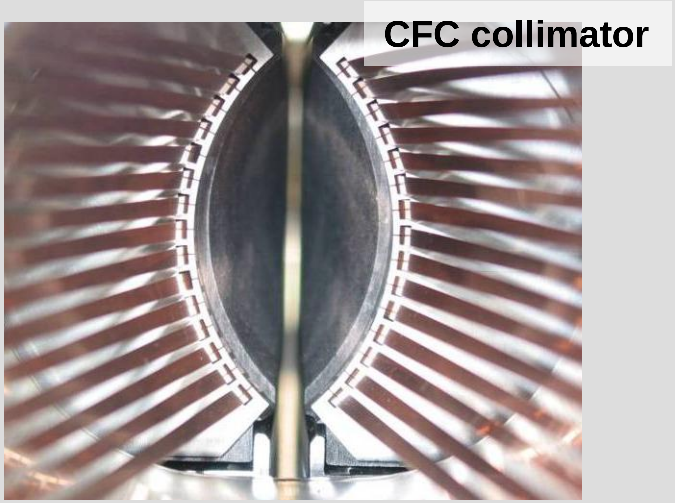
108 collimators & absorbers in 1st generation

(only movable shown in sketch)

Multi-Stage Cleaning & Protection

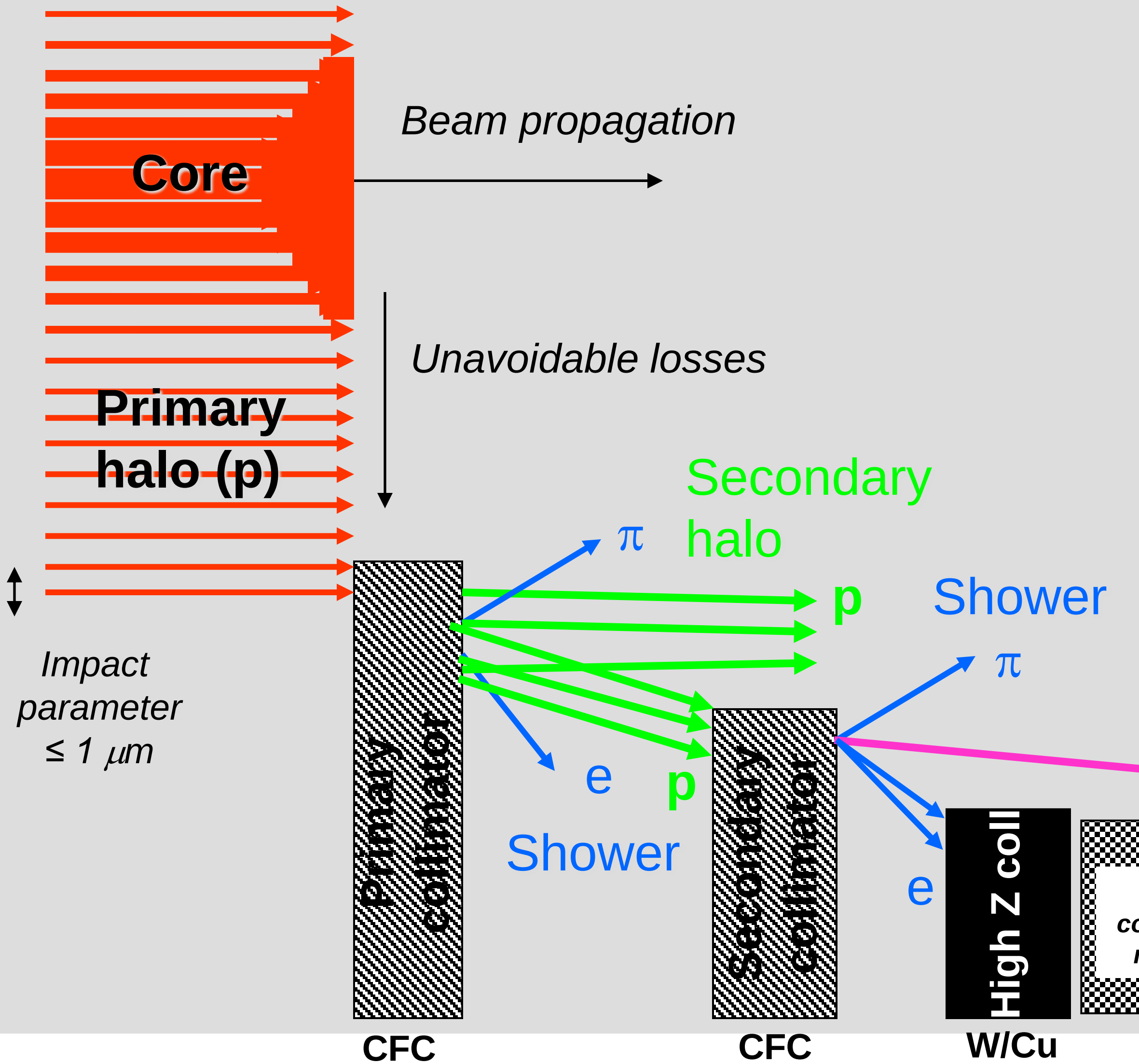
3-4 Stages

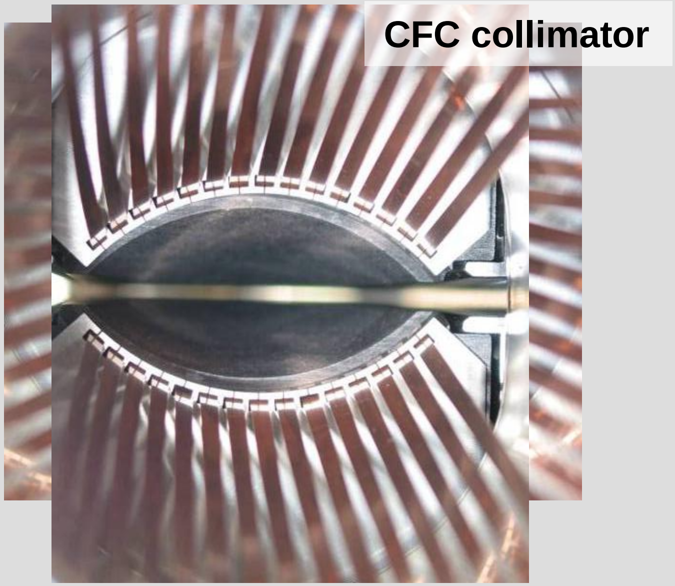




Multi-Stage Cleaning & Protection

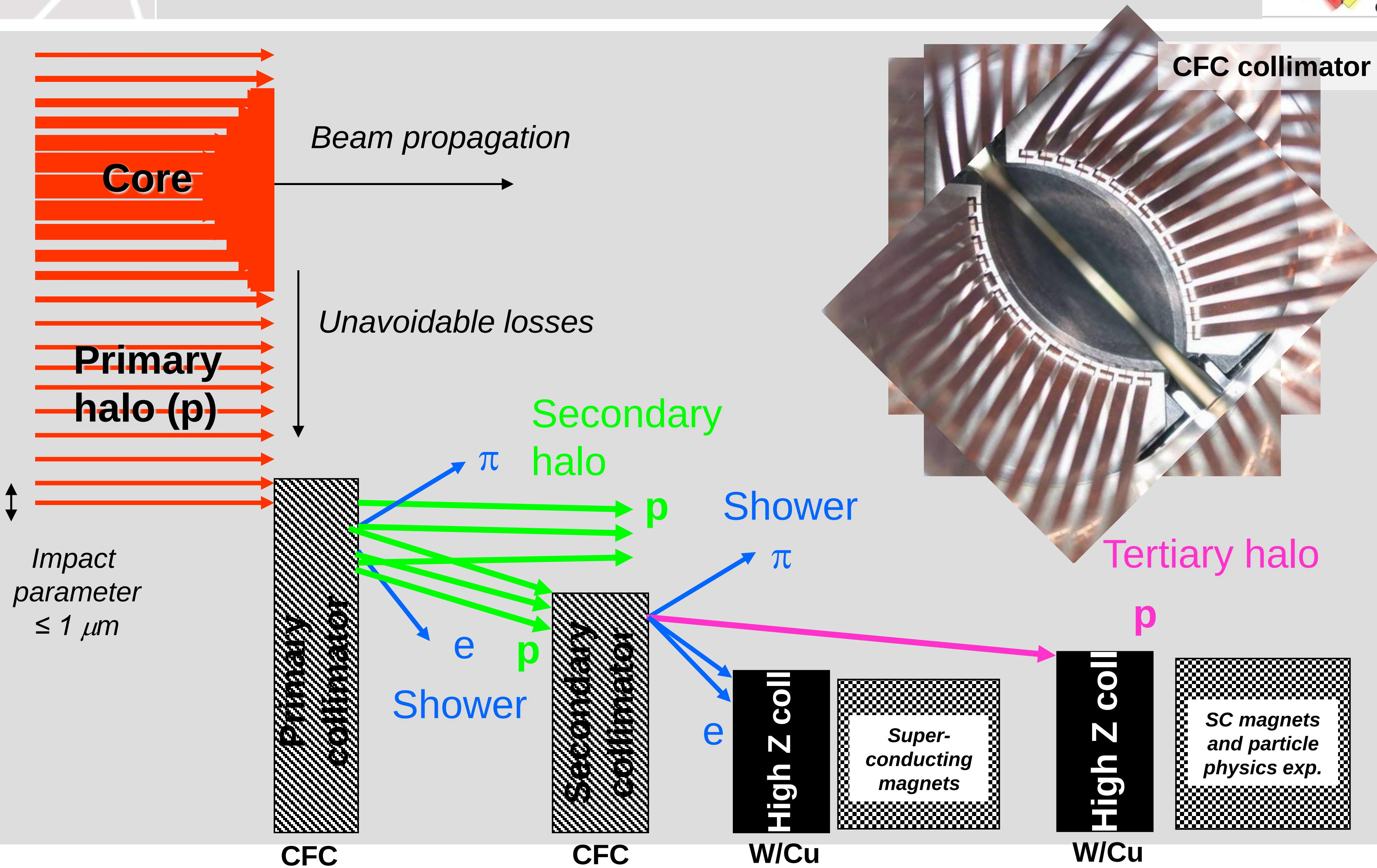
3-4 Stages





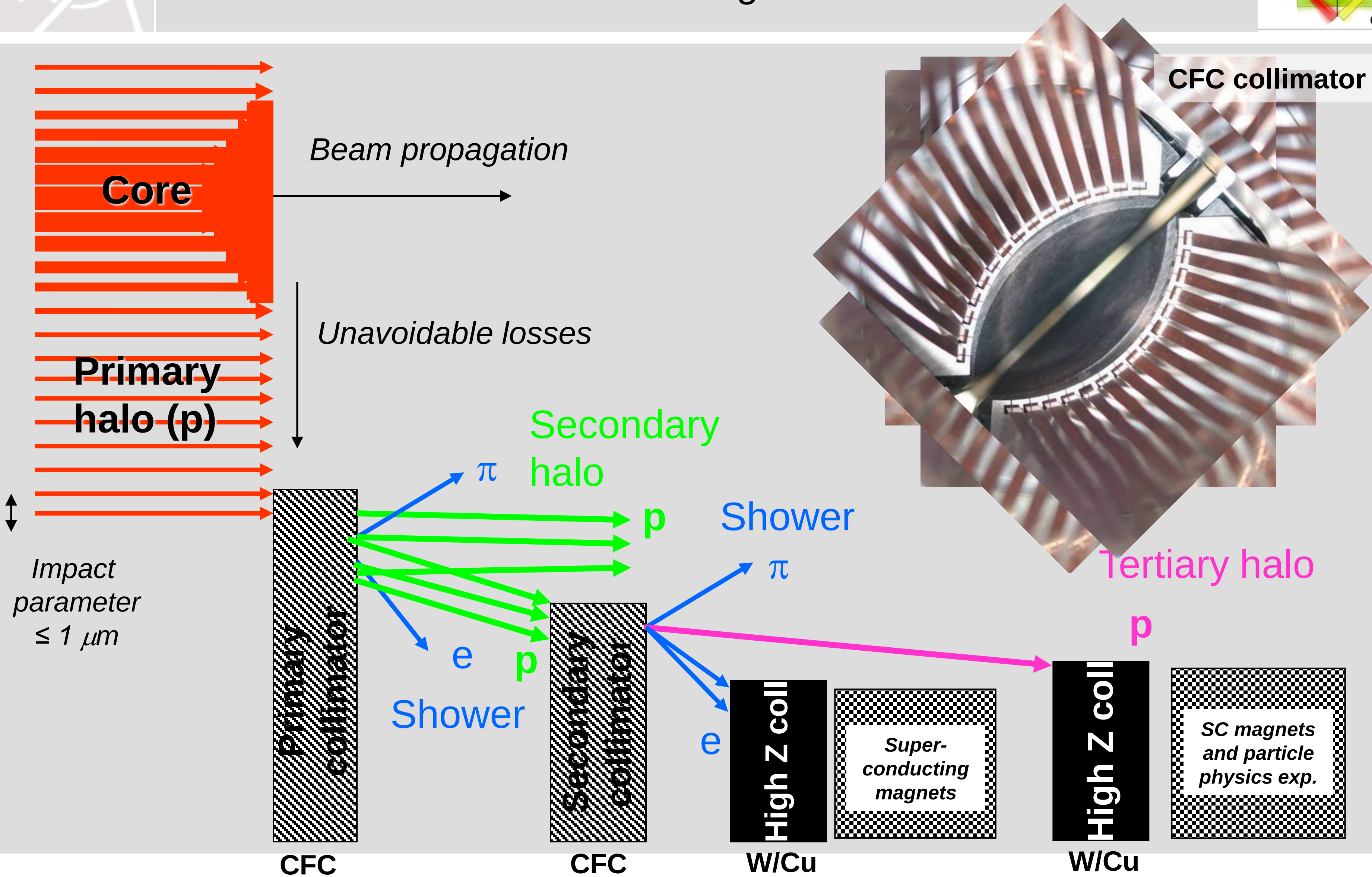
Multi-Stage Cleaning & Protection

3-4 Stages

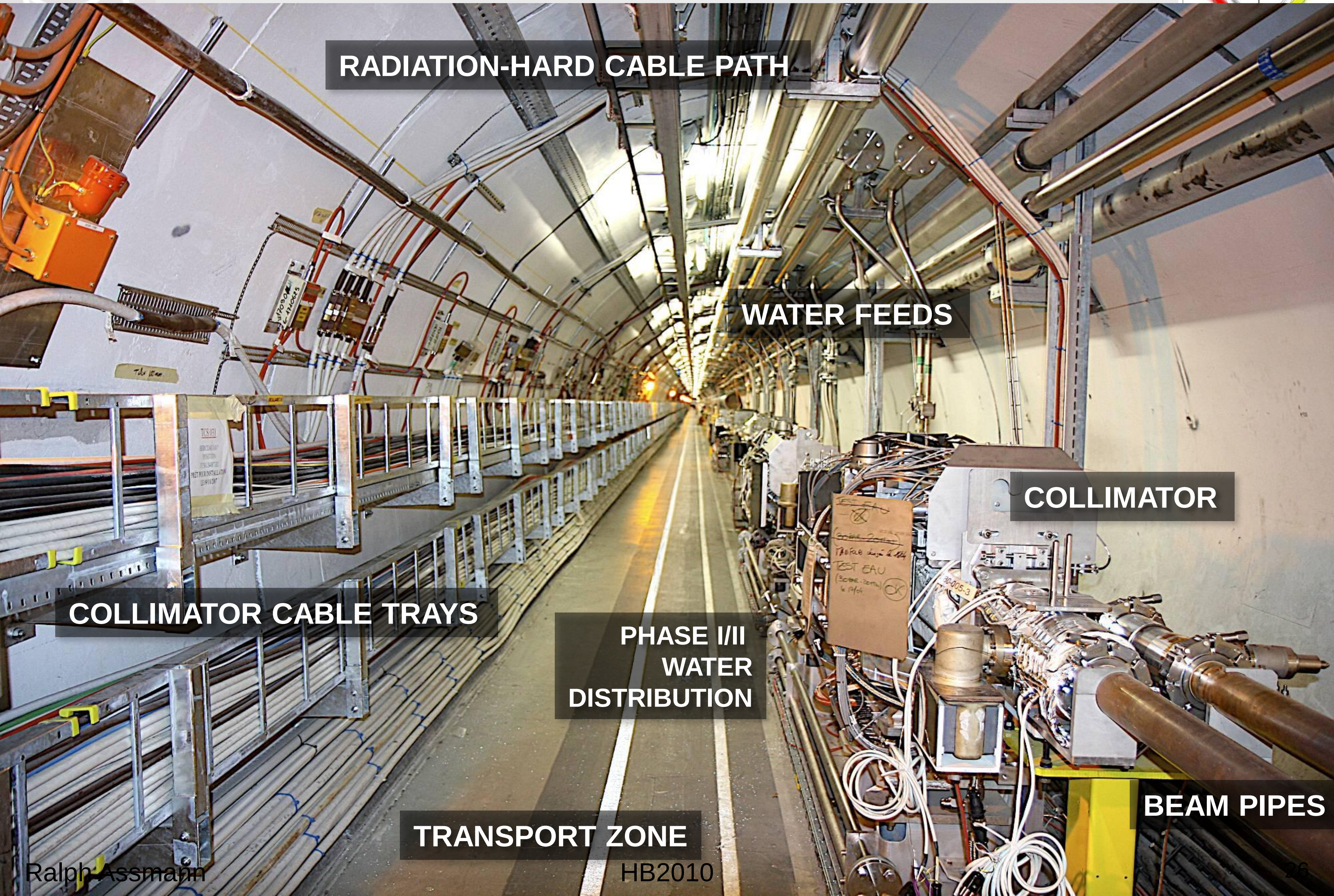


Multi-Stage Cleaning & Protection

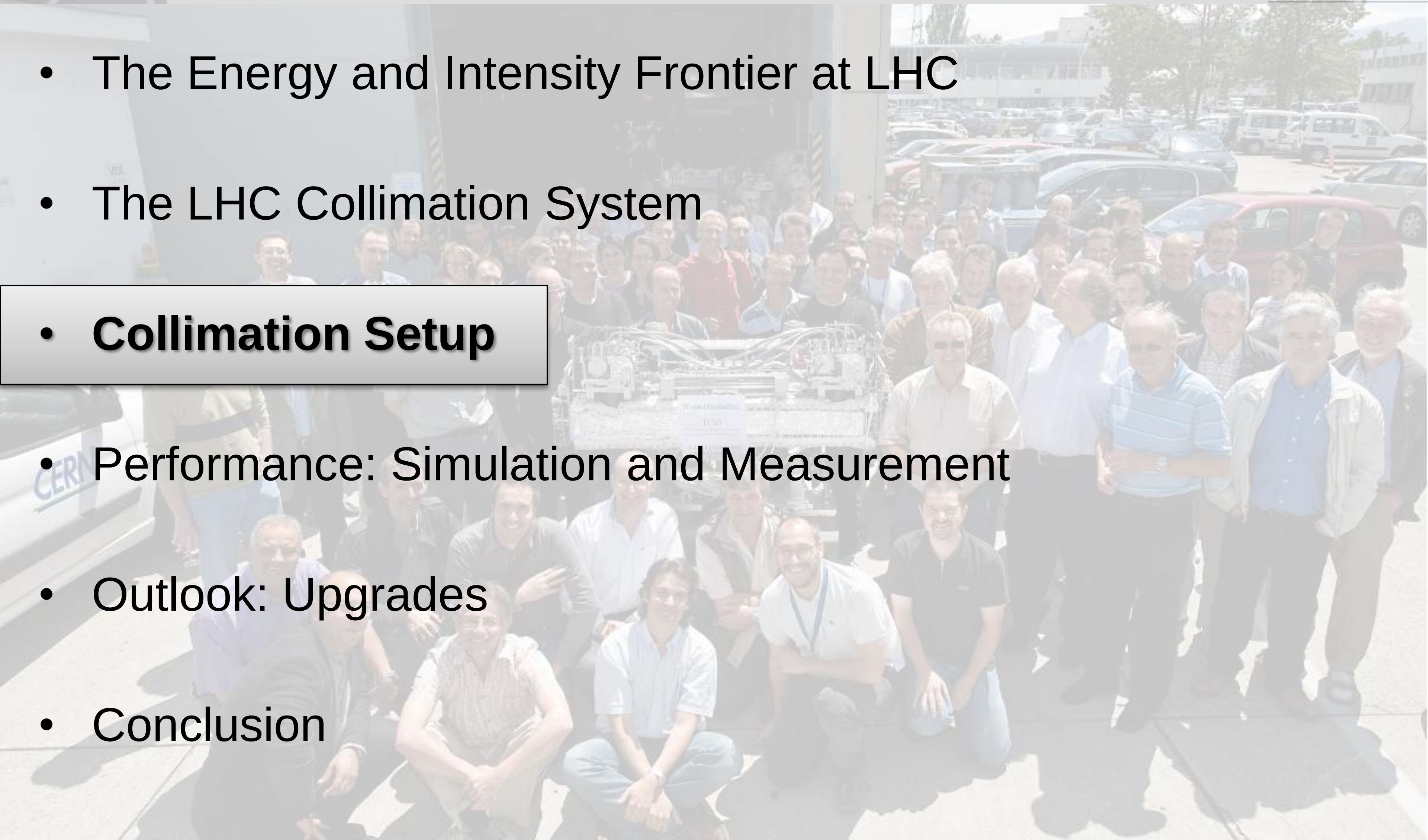
3-4 Stages



Phase I in Tunnel (Radiation-Optimized)



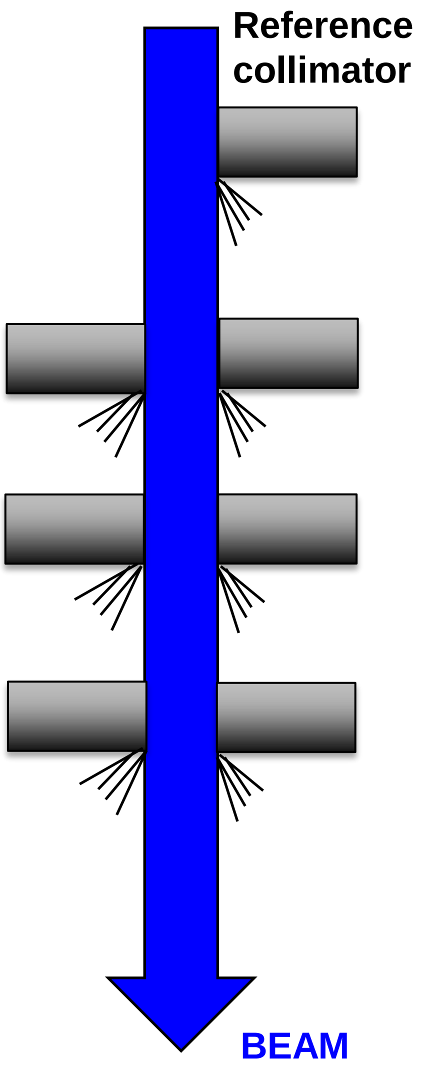
Outline



- The Energy and Intensity Frontier at LHC
- The LHC Collimation System
- **Collimation Setup**
- Performance: Simulation and Measurement
- Outlook: Upgrades
- Conclusion

Collimation Setup

- Collimation setup: Jaws are moved symmetrically around the beam until jaws create ~equal beam loss. Halo-based adjustment.
- Info from beam-based calibration: Beam center, beam size variation from collimator to collimator.
- **<u>Injection</u>**: beam center and calibrated beam size used to move collimators to +- N sigma around the beam.
- **<u>Top energy</u>**: beam center and nominal beam size (beta beat < 20%) used to move collimators to +- N sigma around the beam.
- Target settings determined from simulations (see table).



Collimation Setting Overview

(in terms of β beam size, valid 12.6. – 30.8.2010)

	Unit	Plane	Set 1	Set 2	Set 3	Set 4
Condition			Injection optics	Injection optics	Collision optics, separated	Collision optics, colliding, crossing angle
Energy	[GeV]		450	3500	3500	3500
Primary cut IR7	[σ]	H. V, S	5.7	5.7	5.7	5.7
Secondary cut IR7	[σ]	H, V, S	6.7	8.5	8.5	8.5
Quartiary cut IR7	[σ]	H, V	10.0	17.7	17.7	17.7
Primary cut IR3	[σ]	H	8.0	12	12	12
Secondary cut IR3	[σ]	H	9.3	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H, V	10.0	17.6	17.6	17.6
Tertiary cut experiments	[σ]	H, V	15-25	40-70	15	15
TCSG/TCDQ IR6	[σ]	H	7-8	9.3-10.6	9.3-10.6	9.3-10.6

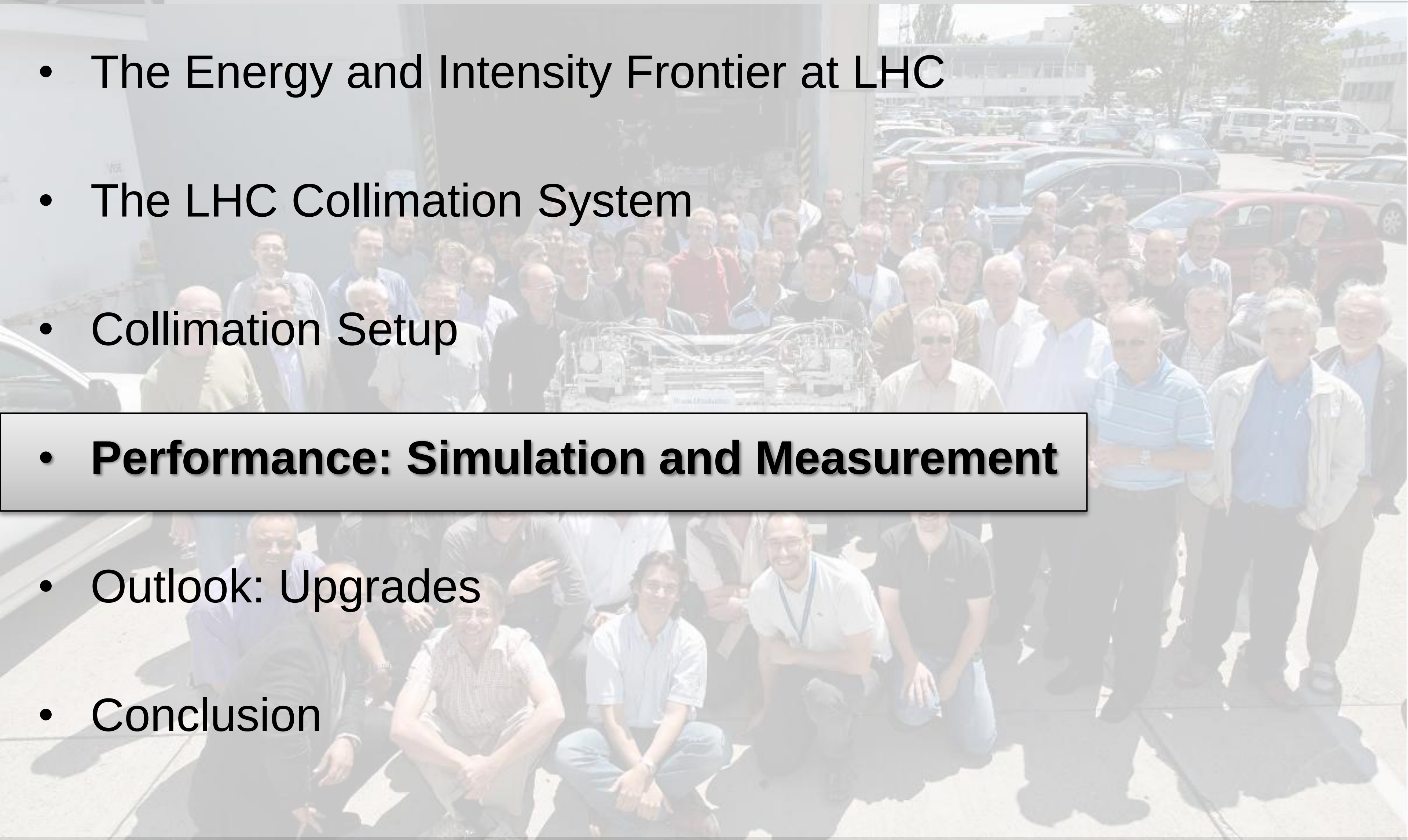
Ramp functions move smoothly from set 1 to set 2 during energy ramp!

3.5 TeV setup took ~30 h of beam time with single bunch of 1e11 p. Time distributed over 10 days with ~1 collimation shift per day.

Settings Calculation

- The collimator settings are calculated (based on beam-based data) to:
  - Provide good efficiency.
  - Provide the correct collimator hierarchy (slow primary losses at primary collimators).
  - Protect the accelerator against the specified design errors.
  - Provide continuous cleaning and protection during all stages of beam operation: injection, prepare ramp, ramp, squeeze, collision, physics.
  - Provide maximum tolerances to beam and various collimator families.
  - Provide warning thresholds on all collimator axis positions versus time.
  - Provide interlock thresholds on all collimator axis positions versus time.
  - Provide interlock thresholds on all collimator gaps versus beam energy.
- Complex problem with some 100,000 numbers to control the system.
- Redundant calculation: time-dependent (ABP), energy-dependent (OP)

Outline



- The Energy and Intensity Frontier at LHC
- The LHC Collimation System
- Collimation Setup
- **Performance: Simulation and Measurement**
- Outlook: Upgrades
- Conclusion

Performance: Simulation and Measurement

- First step for redesign of LHC collimation system: Setup of parallel simulation program and CPU cluster to numerically optimize the system.
- Maximum runs: **20,000,000 protons tracked over 200 turns**
  108 billion proton-km
- Imagine: **Simulating a proton that travels 700 times the distance sun-earth in an accelerator!**
- Simulation included all magnetic elements and an aperture model with a resolution of 0.1 m!
- Simulation includes halo proton generation, halo transport, proton-matter interaction and aperture checks for each proton every 0.1m!
- Decisions taken based on simulations: material, length of jaws, reduced number of primary collimators by 20%, reduced number of secondary collimators by 25%, added tertiary collimators, …
- AP simulations complemented by FLUKA energy deposition!

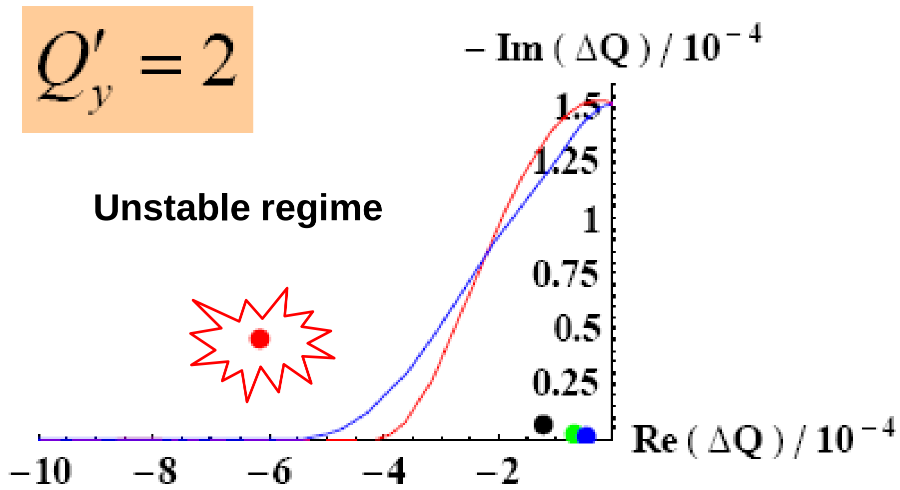
Side Remark: Impedance Issue

- Review LHC collimator-induced impedance (not thought to be problem).
- Surprise in 2003: LHC impedance driven by collimators, even metallic collimators.
- LHC has an impedance that depends on the collimator settings!
- Predicted in detailed simulations (E. Metral et al) and found as predicted. Stabilized with transverse damper and octupoles!

Third look at impedance in Feb 03 revealed a problem:

$$\frac{Z_\perp^{\mathrm{coll}}}{Z_\perp^{\mathrm{arc}}} \sim \frac{(L^{\mathrm{coll}}/L^{\mathrm{arc}})\times\sqrt{\rho^{\mathrm{coll}}/\rho^{\mathrm{arc}}}}{(a^{\mathrm{coll}}/a^{\mathrm{arc}})^3} \sim \frac{(20\,\mathrm{m}/20\,\mathrm{km})\times\sqrt{\mathrm{RRR}\sim 30}}{(1.8\,\mathrm{mm}/18\,\mathrm{mm})^3} \sim \frac{10^{-3}\times 5}{10^{-3}} \sim 5!$$

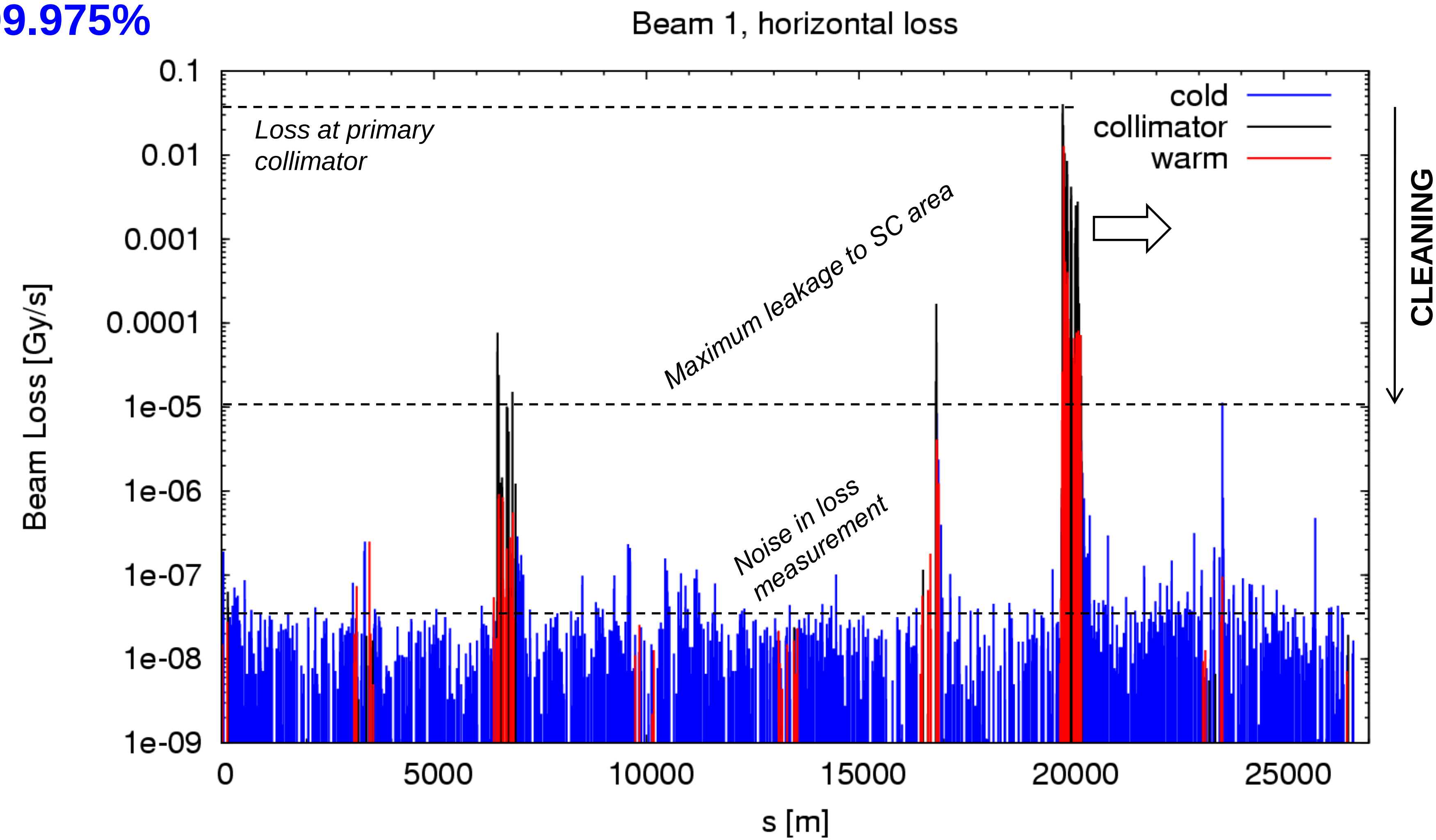
F. Ruggiero



450 GeV: Cleaning Measurement

Beam 1 – Horizontal (Q_x crossing of 1/3 resonance)

99.975%



Measured 6 days after beam-based setup of collimators – no retuning…

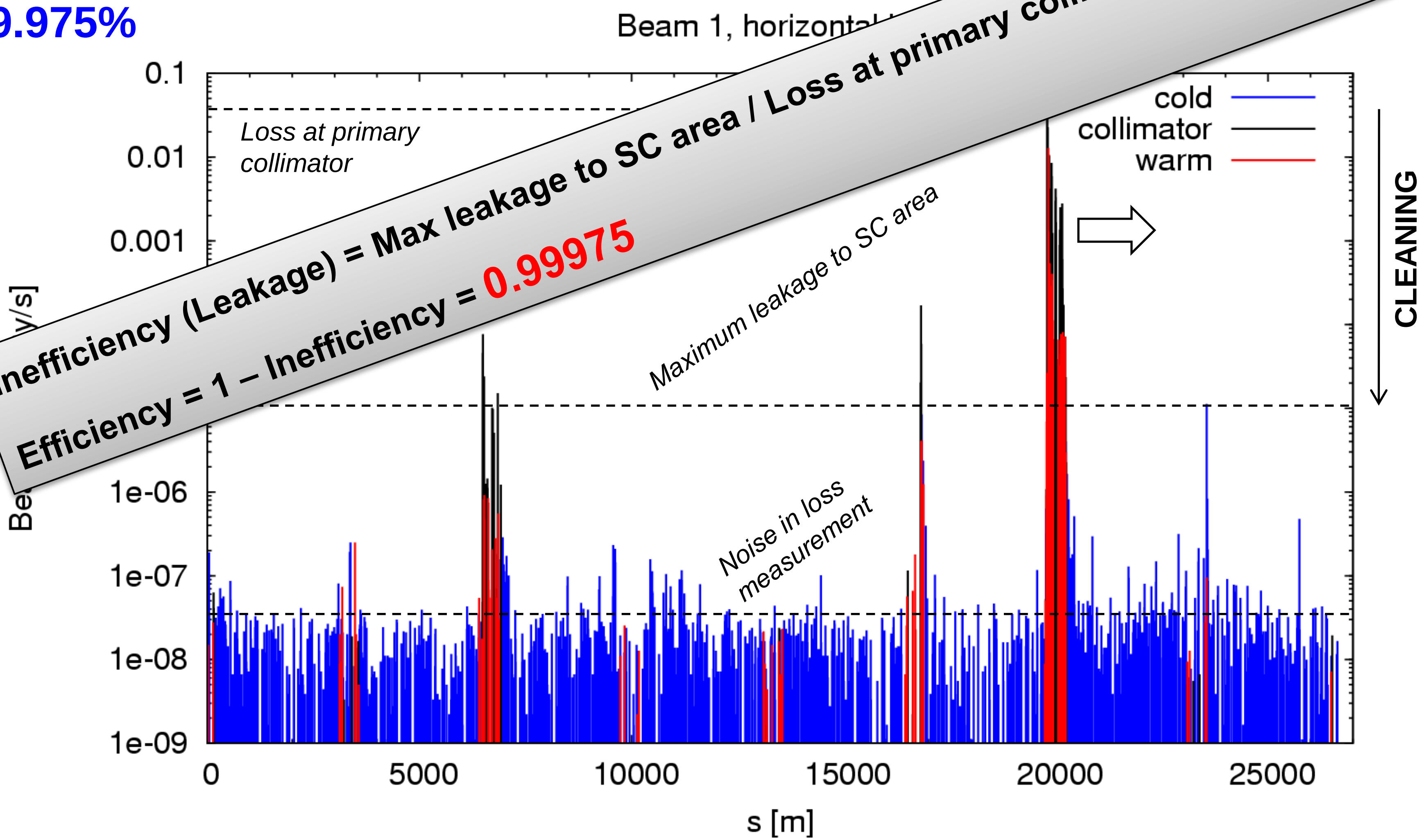
450 GeV: Cleaning Measurement

Beam 1 – Horizontal (Q_x crossing of 1/3 resonance)

99.975%

Inefficiency (Leakage) = Max leakage to SC area / Loss at primary collimator = 2.5e-4

Efficiency = 1 – Inefficiency = 0.99975



Measured 6 days after beam-based setup of collimators – no retuning…

450 GeV: Cleaning Measurement

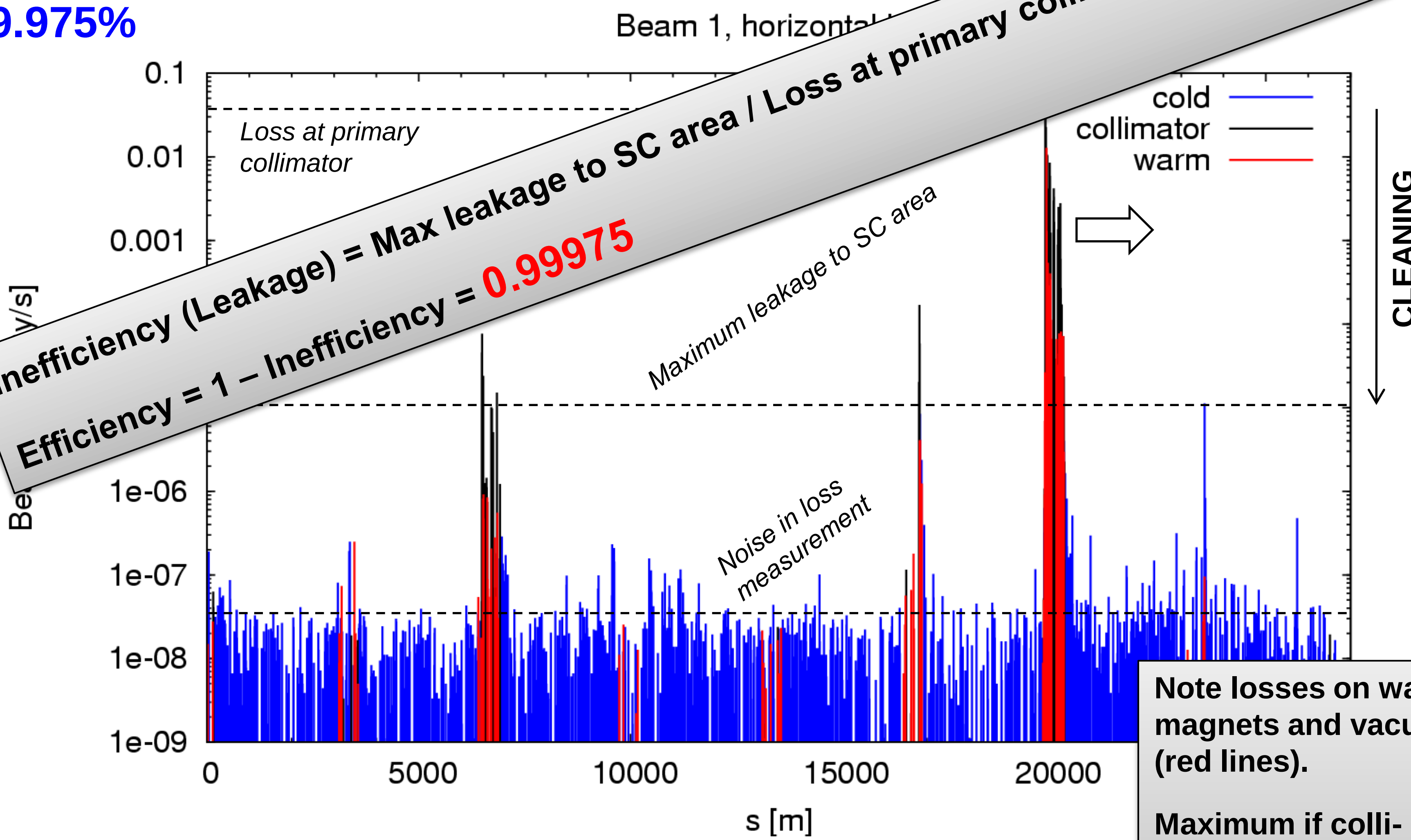
Beam 1 – Horizontal (Q_x crossing of 1/3 resonance)

LHC Collimation Project CERN

99.975%

Inefficiency (Leakage) = Max leakage to SC area / Loss at primary collimator = 2.5e-4

Efficiency = 1 – Inefficiency = 0.99975



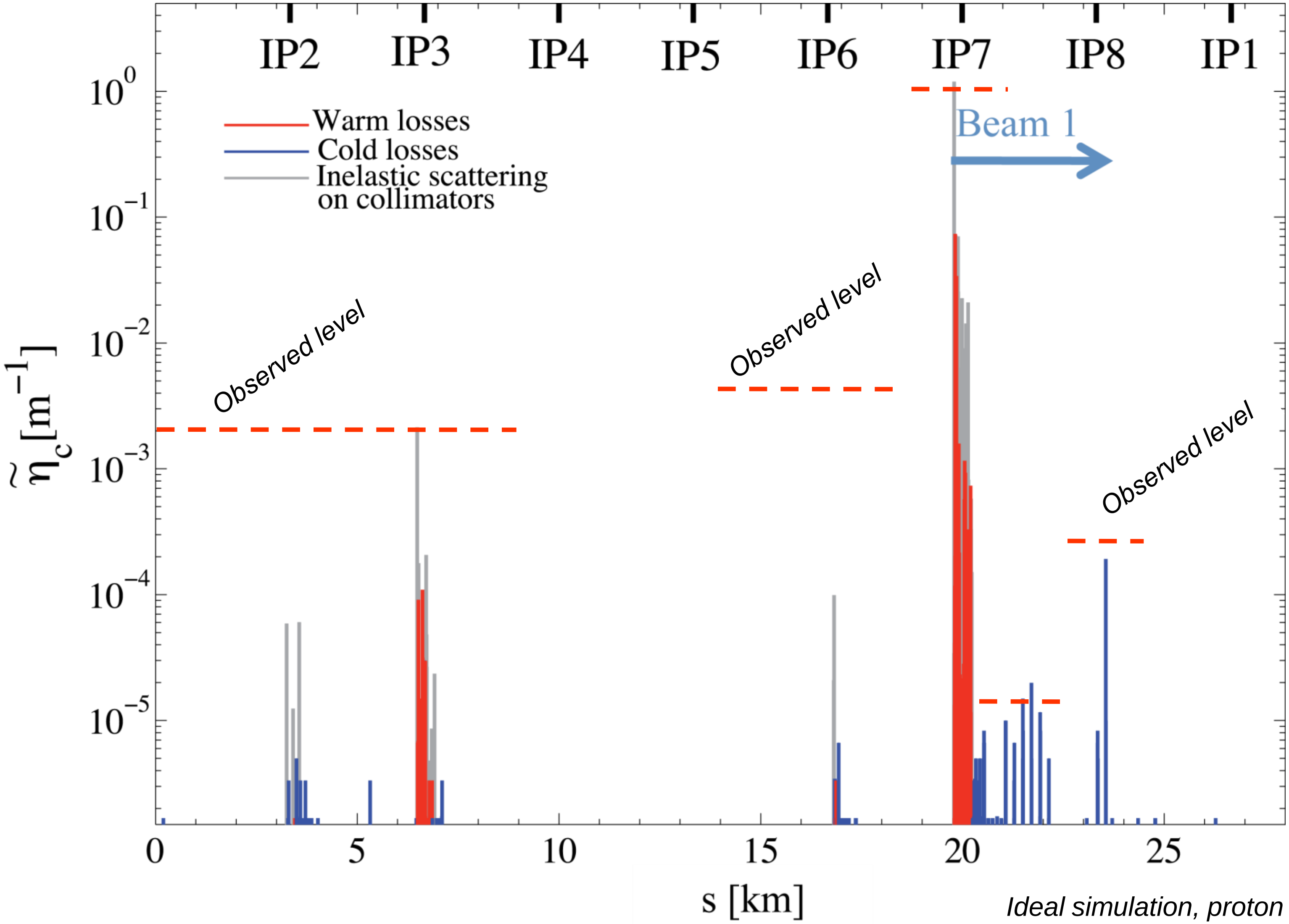
Measured 6 days after beam-based setup of c

Note losses on warm magnets and vacuum (red lines).

Maximum if colli-mation works well! ~ 1/3 of beam ends here!

450 GeV: Simulation

(PhD C. Bracco 2008, p. 74)

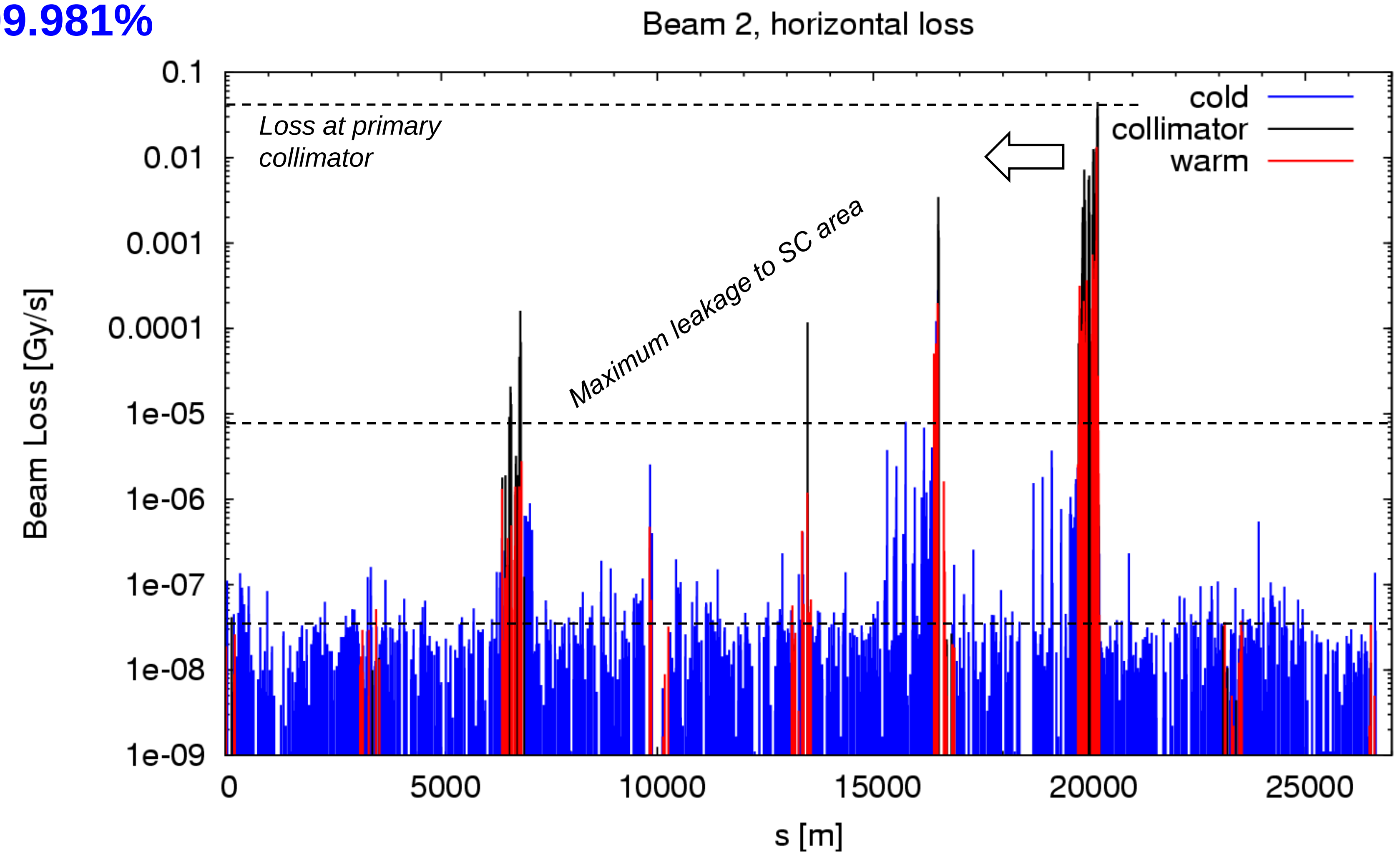


Ideal simulation, proton tracking, no showers

450 GeV: Cleaning Measurement

Beam 2 – Horizontal (Q_x crossing of 1/3 resonance)

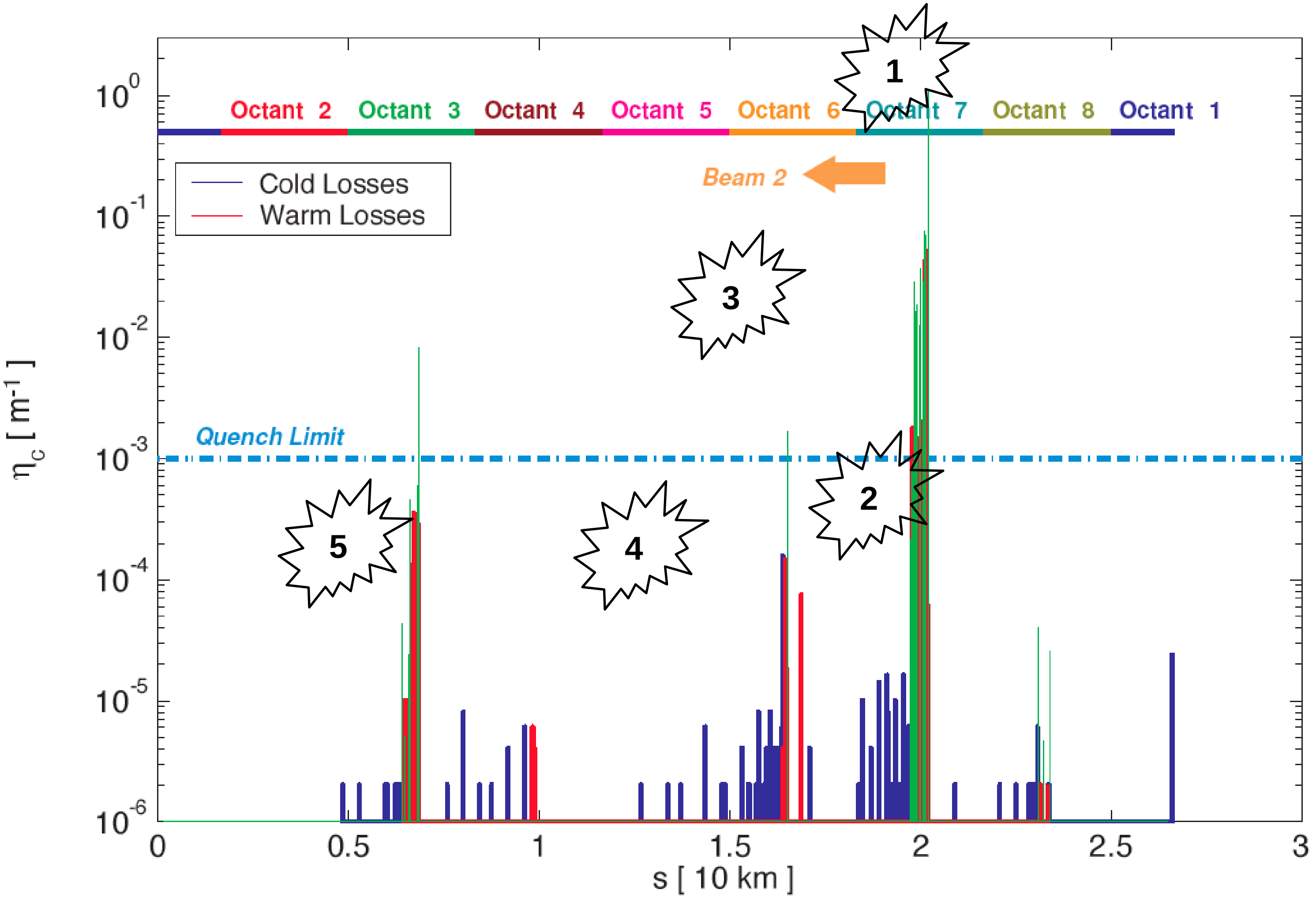
99.981%



Measured 6 days after beam-based setup of collimators – no retuning…

450 GeV: Simulation vs Measurement

(Data 2009 - PhD G. Robert-Demolaize 2006, p. 114)



Notes:

(1) As expected, additional losses from showers behind primary collimators.

(2) 3x higher than simulated losses in LSS7L SC magnets.

(3) 50x higher than simulated TCDQ losses ➔ setup.

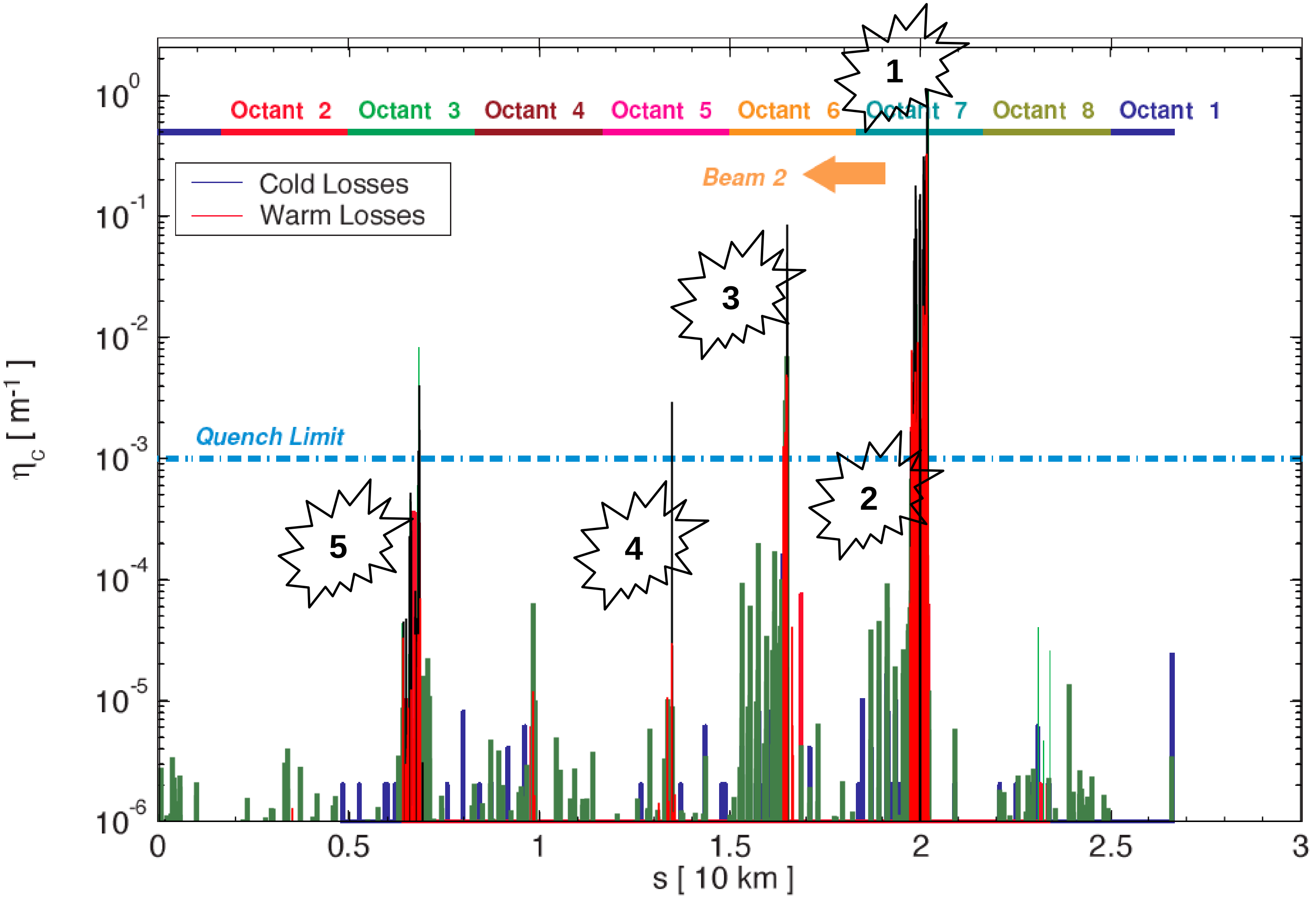
(4) Additional loss on TCT in IR5: simulations at 450 GeV had TCT out.

(5) As expected losses in IR3 ➔ correct simulation of energy loss in IR7 collimators.

Simulation with worst case design orbit error, proton tracking, no showers

450 GeV: Simulation vs Measurement

(Data 2009 - PhD G. Robert-Demolaize 2006, p. 114)



Notes:

(1) As expected, additional losses from showers behind primary collimators.

(2) 3x higher than simulated losses in LSS7L SC magnets.

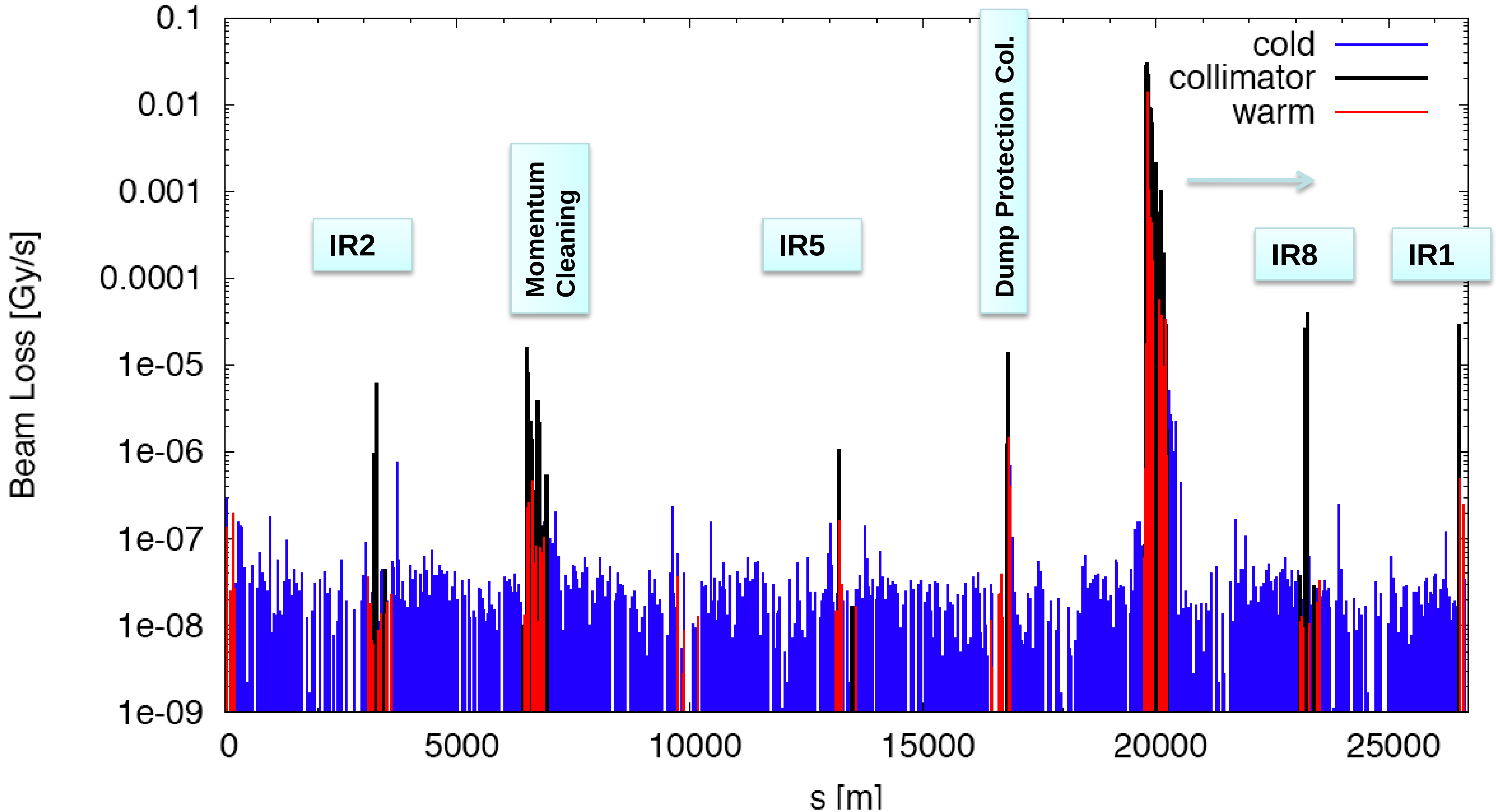
(3) 50x higher than simulated TCDQ losses ➔ setup.

(4) Additional loss on TCT in IR5: simulations at 450 GeV had TCT out.

(5) As expected losses in IR3 ➔ correct simulation of energy loss in IR7 collimators.

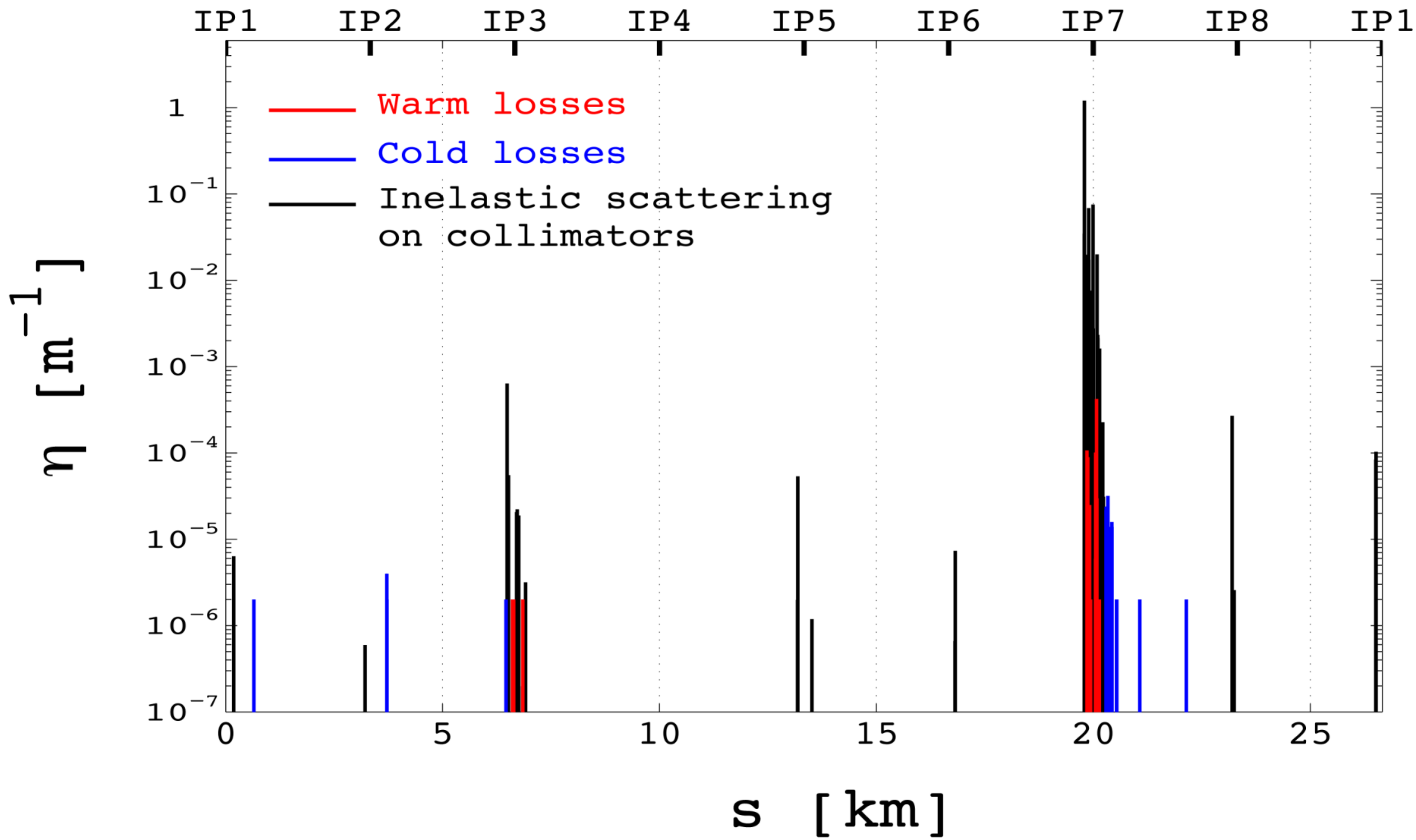
Simulation with worst case design orbit error, proton tracking, no showers

Measured Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)

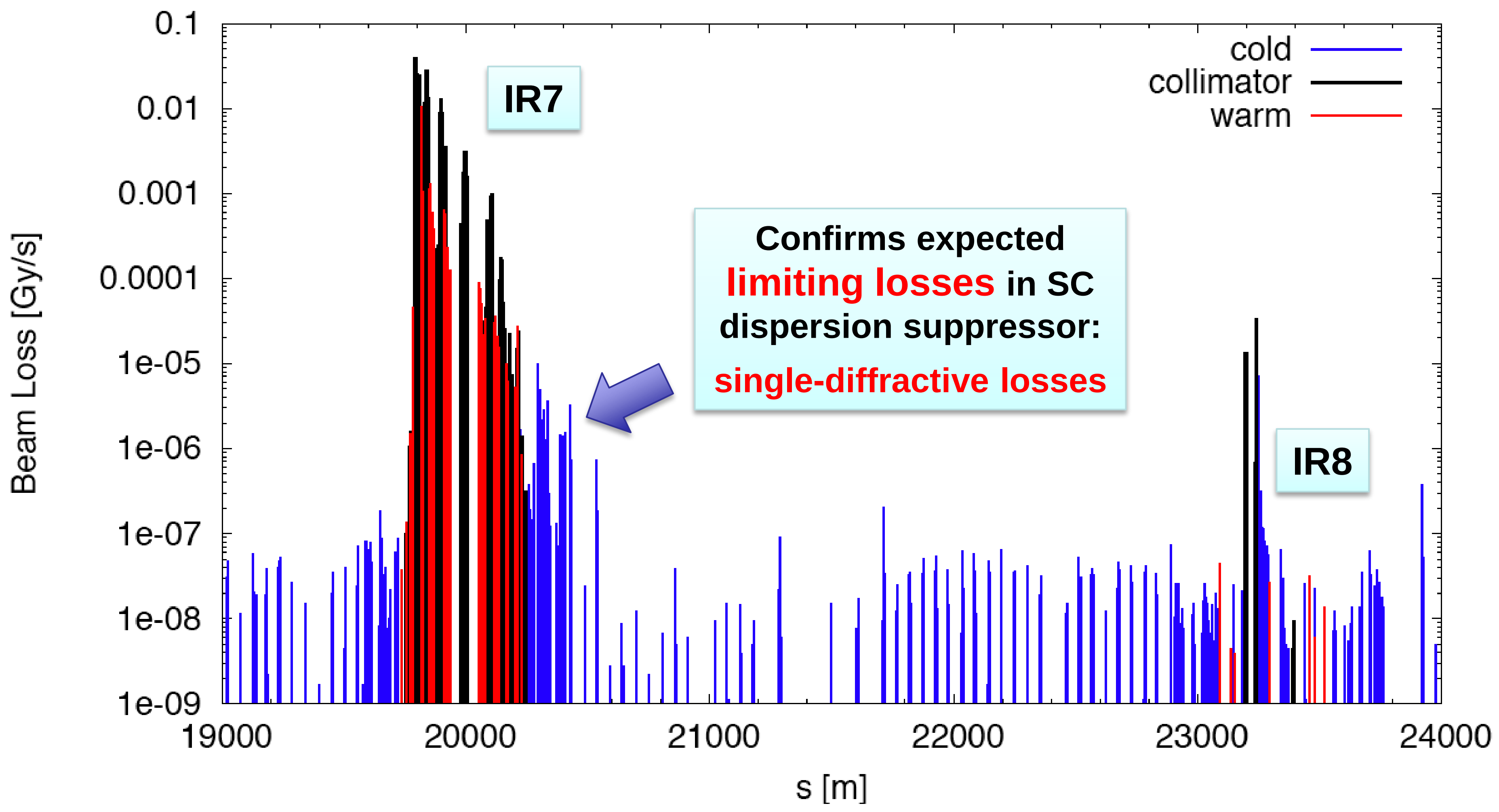


2m optics exposes IR's as expected! Protected by tertiary collimators.

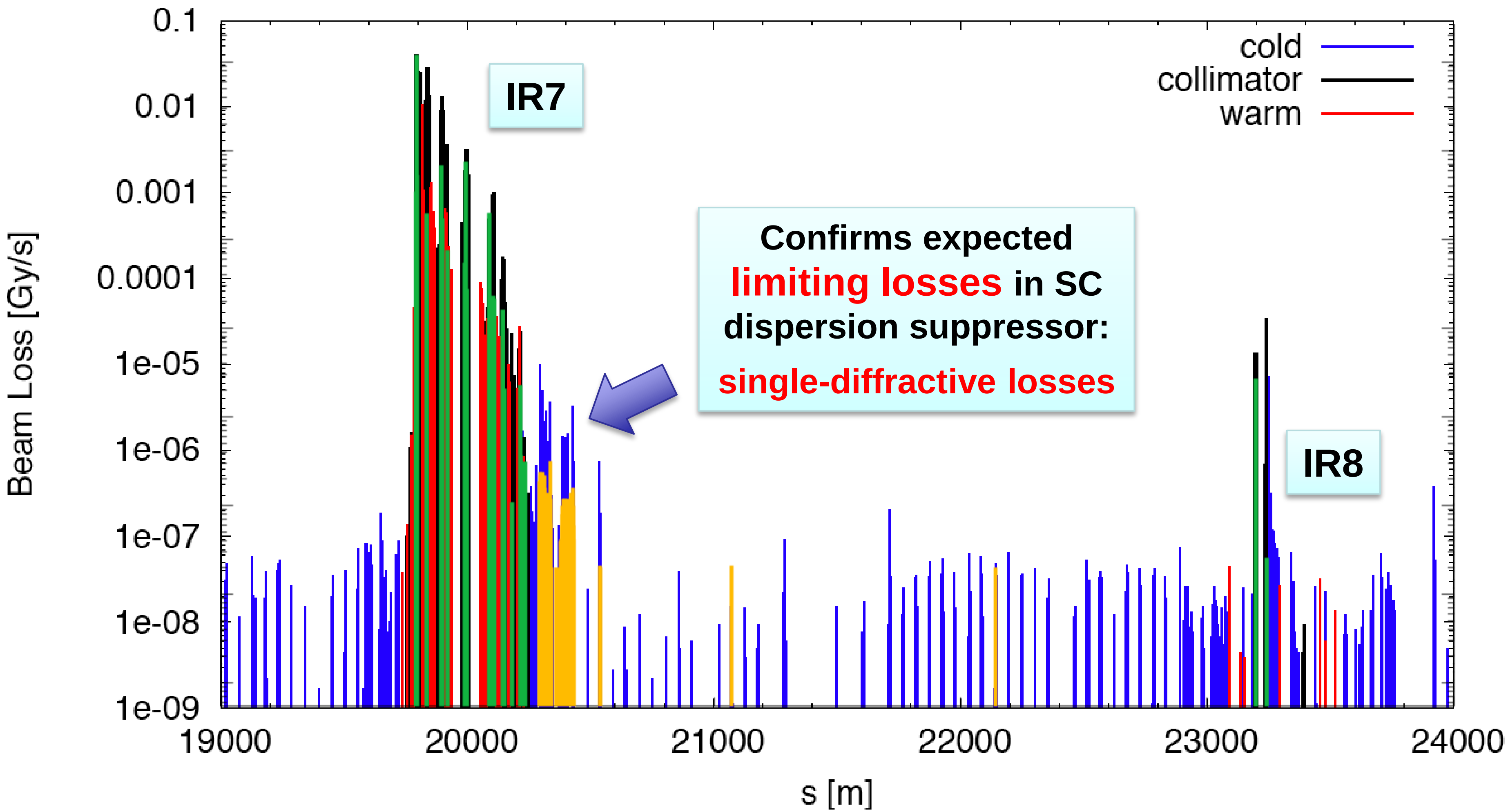
Simulated Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



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



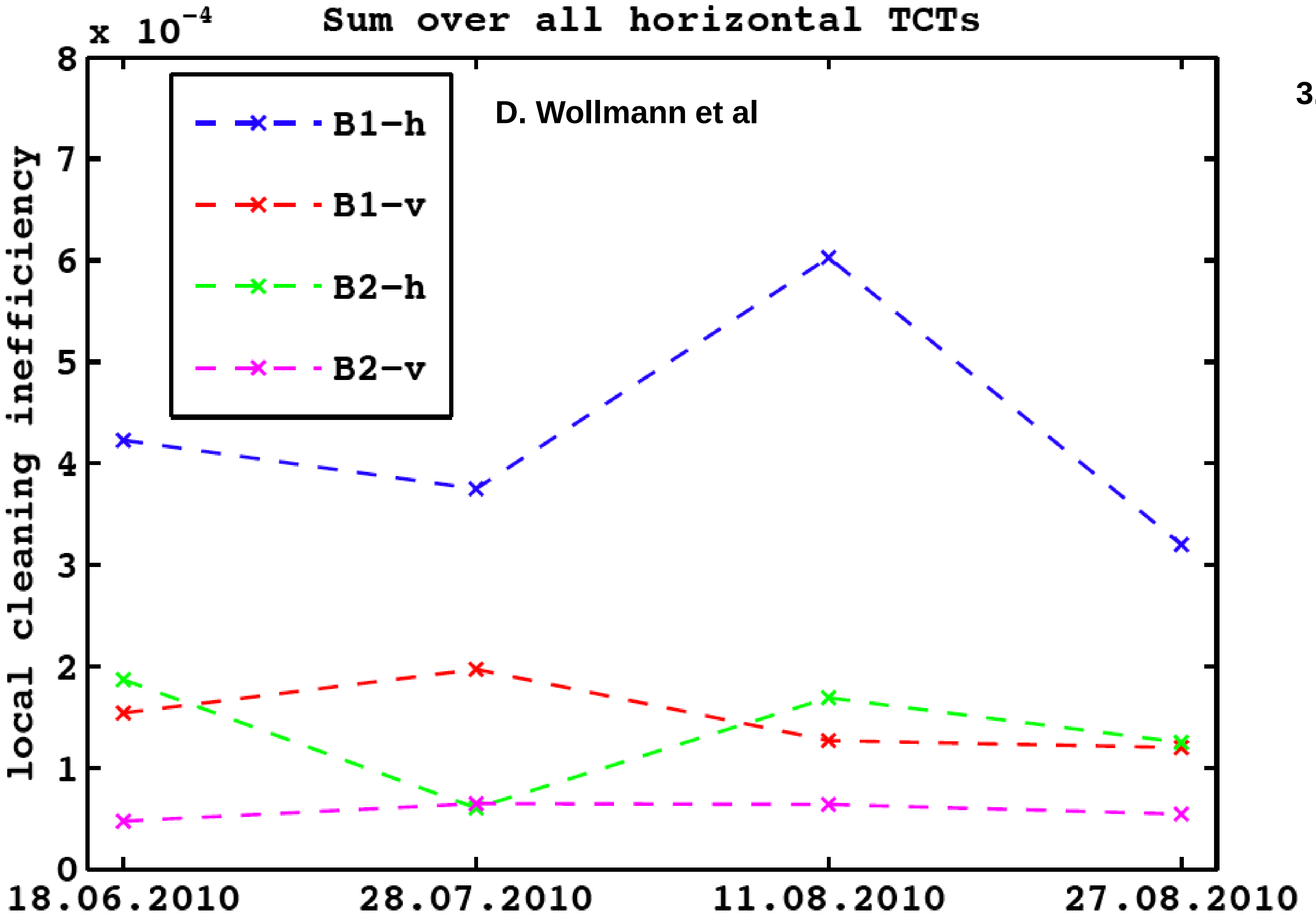
Meas. & Sim. Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



Confirms expected limiting losses in SC dispersion suppressor:

single-diffractive losses

Betatron Cleaning: Stability Over 10 Weeks



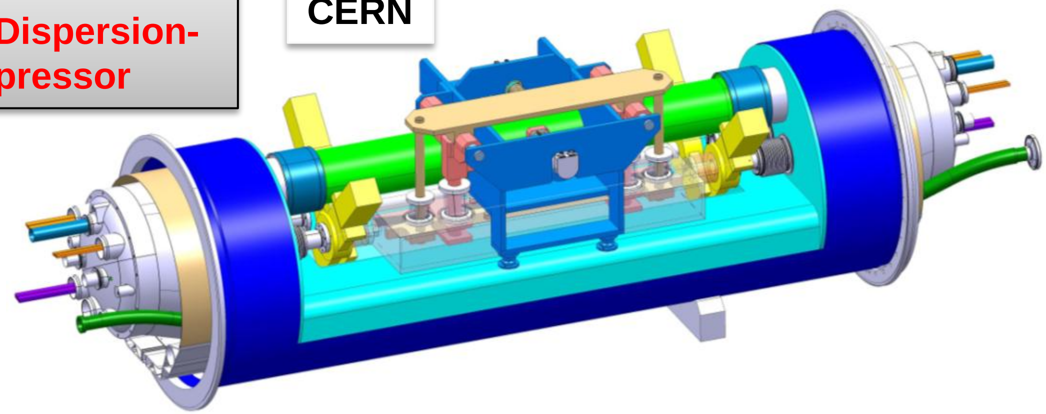
3.5 TeV

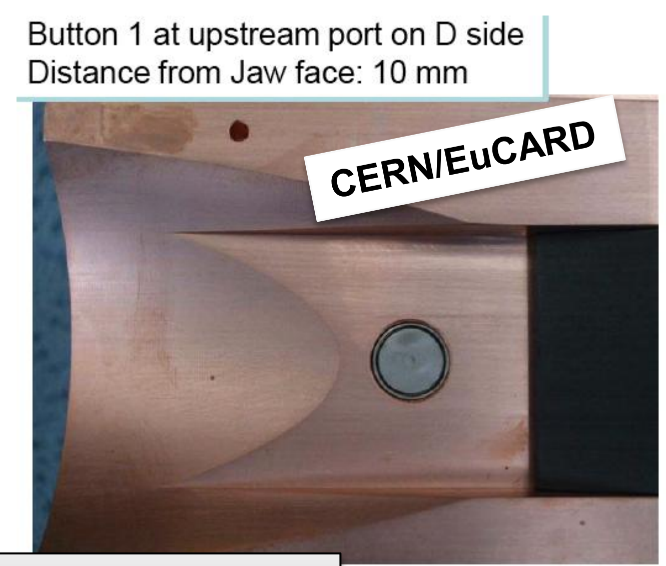
Outline

- The Energy and Intensity Frontier at LHC
- The LHC Collimation System
- Collimation Setup
- Performance: Simulation and Measurement
- **Outlook: Upgrades**
- Conclusion

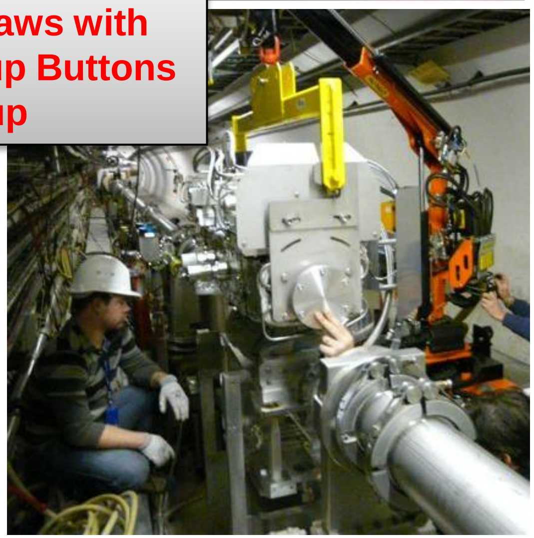
Outlook: LHC Collimation Upgrades

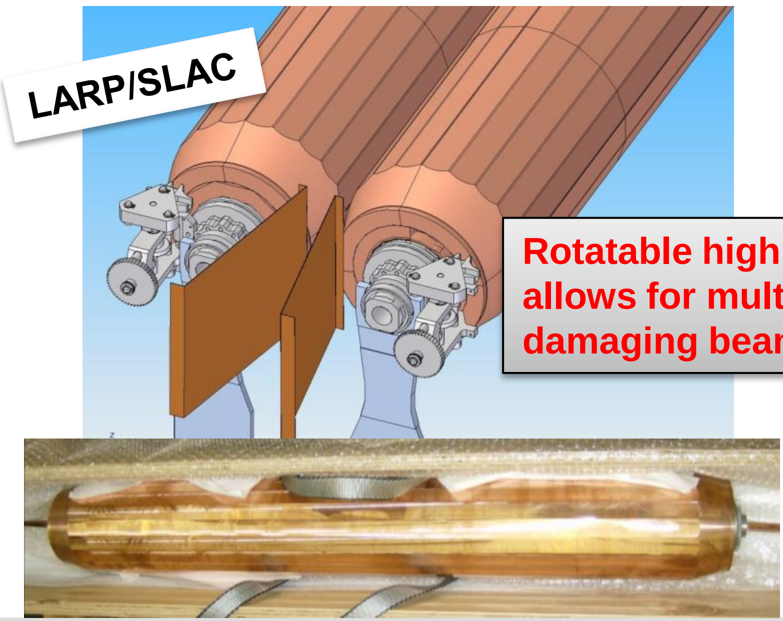
Cryo-Collimator For Dispersion-Suppressor





Collimator Jaws with In-Situ Pickup Buttons for Fast Setup

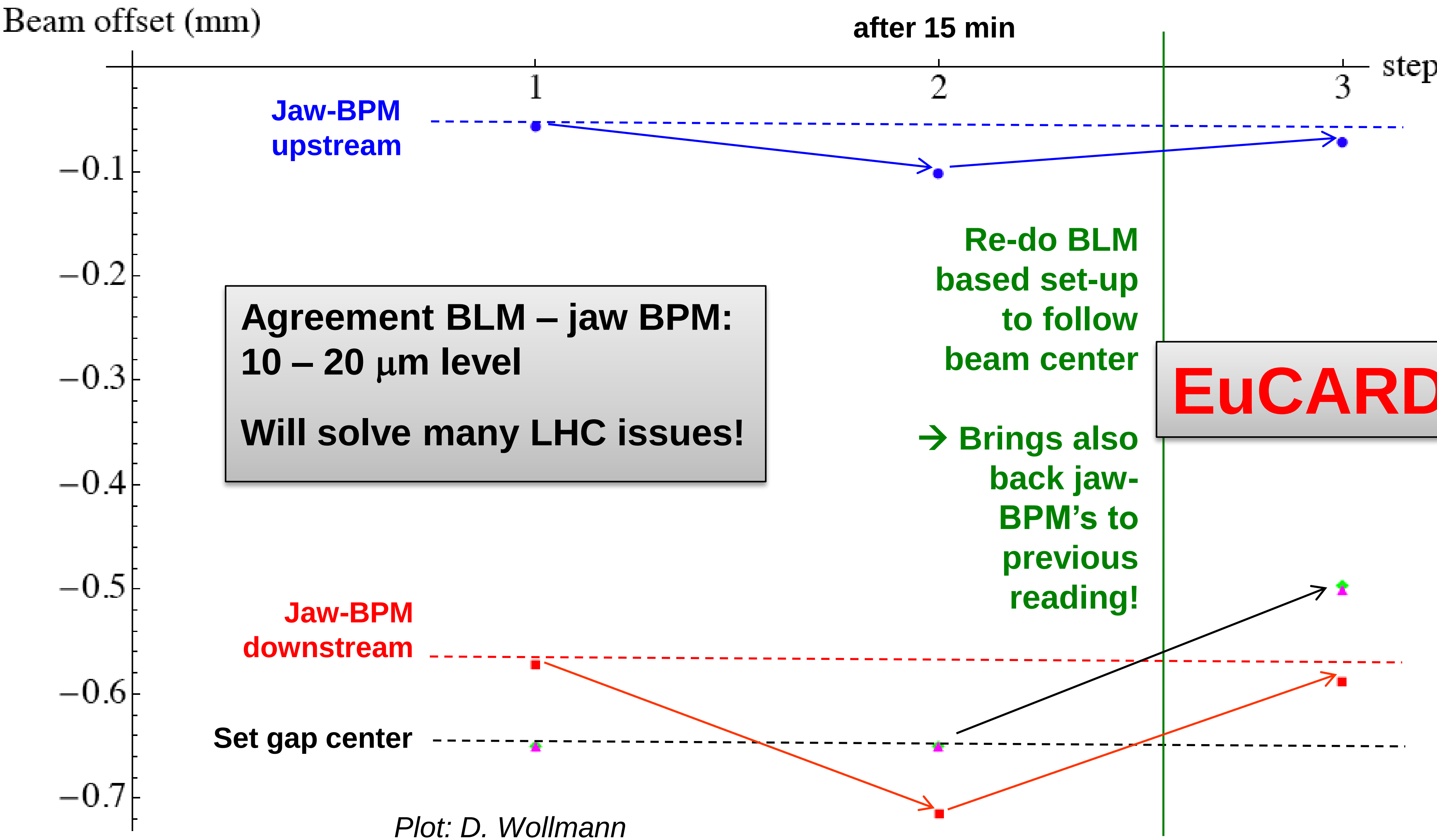




Rotatable high Z jaw allows for multiple damaging beam hits!

Phase 2 Coll. With SPS Beam Drifts

Standard BLM-based Method – Observing Jaw-BPM's



Agreement BLM – jaw BPM: 10 – 20 µm level

Will solve many LHC issues!

Re-do BLM based set-up to follow beam center

→ Brings also back jaw-BPM's to previous reading!

EuCARD

Conclusion

- The LHC collimation system has been designed, produced, installed and commissioned over the last 8 years!
- Major effort to make it right, with strong support from various CERN departments and outside collaborators. Biggest and most complex (also most expensive) system built so far.
- LHC collimation works with expected performance level and has shown an amazing stability over the last 2 months. Simulations were right!
- Collimation and beam cleaning allowed the LHC in establishing the intensity frontier in 6 months (passing Tevatron, HERA, ISR, RHIC, …).
- Not a single quench with stored beam!
- Thanks to all the world experts helping with advice and support over the years. Our success reflects the rapid progress in the field.
- Upgrades are being prepared to improve collimation by a further factor 5-10 over next years.

Pointers to Talks & Posters

Other talks/posters on LHC collimation-related topics:

S. Redaelli – Operational Performance of Collimation

D. Wollmann – Collimation Upgrade

M. Zerlauth – Machine Protection

E.B. Holzer – Beam Loss Monitors

A. Nordt – Beam Loss Monitors

V. Kain – LHC Beam Commissioning