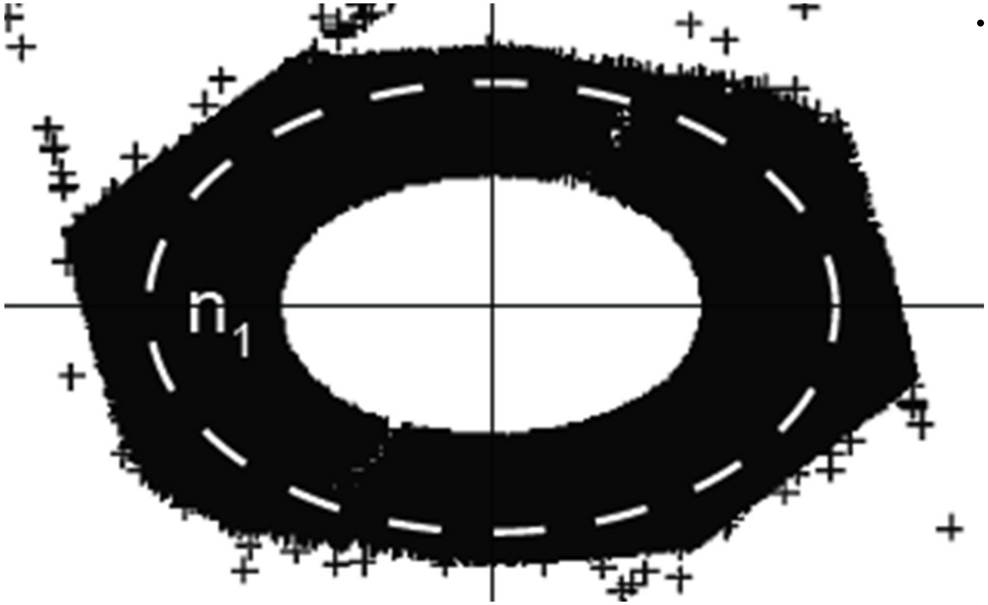
Advanced Modeling and Measurements of LHC Beam Halo and Collimation



R.W. Aβmann
CERN
22/08/2012
ICAP2012, Rostock

- **Results on phase I collimation are outcome of lot of work performed over last 10 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, N. Mounet, R. Perret, S. Perrolaz, V. Previtali, C. Rathjen, S. Redaelli, G. Robert-Demolaize, C. Roderick, S. Roesler, A. Rossi, F. Ruggiero, B. Salvachua, 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), UK colleagues (see ICAP 2012 talk).


Phase I Production
TCSG
COLLIMATION PROJECT
CERN

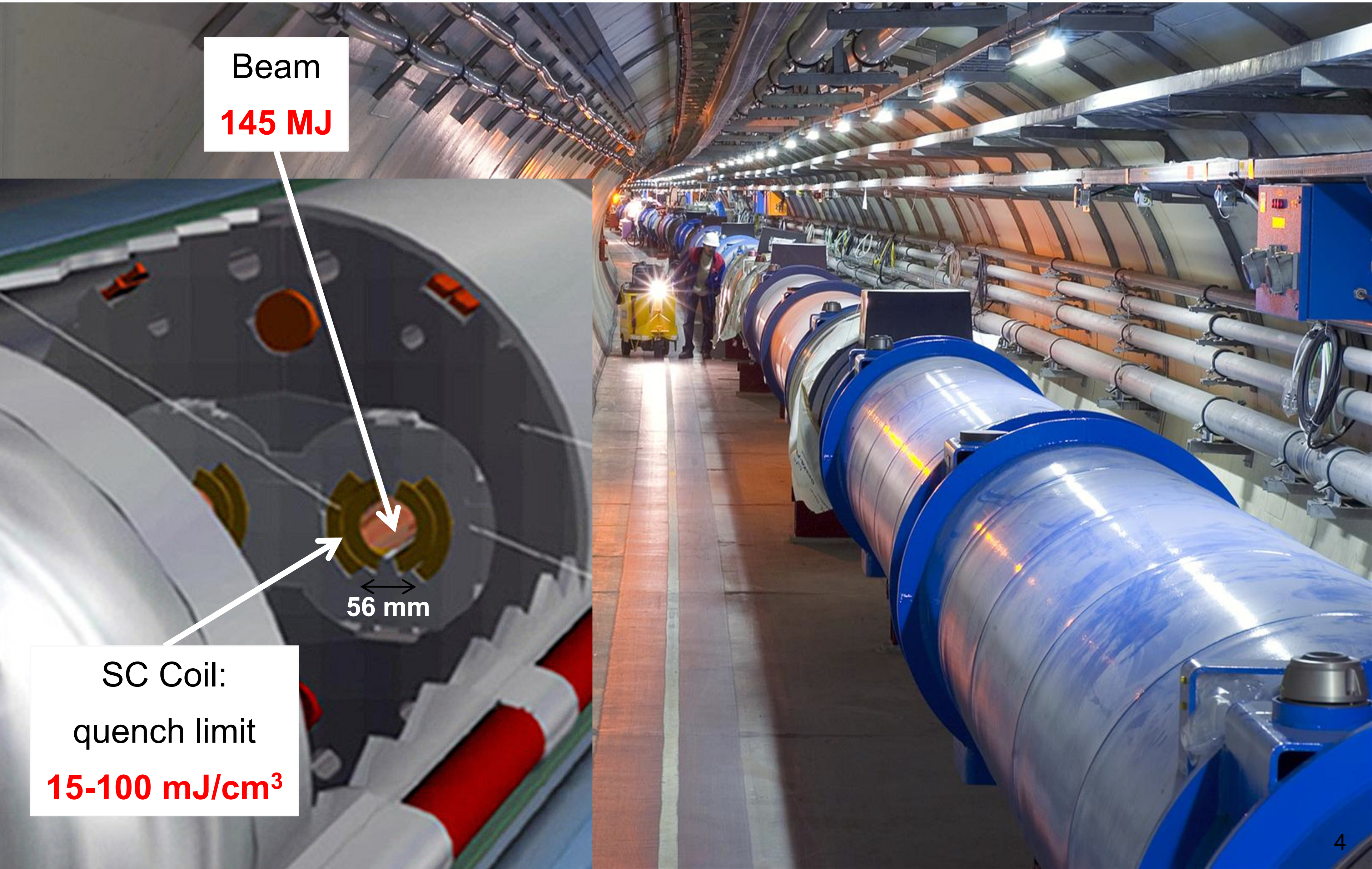
LHC Parameters

(for Reference)

Beam energy:	**4.0 TeV**	**frontier**, 6.5 TeV in 2015
Bunch intensity:	1.53e11	nominal × 1.33
Number of bunches:	1374	nominal / 2
Norm. emittance:	2.6 μm	nominal / 1.44
IP beta value:	0.6 m	nominal × 1.1
Stored energy:	**145 MJ**	**frontier**, 2 MJ in Tevatron
Peak luminosity:	**7.4×10^{33} cm^{-2} s^{-1}**	nominal / 1.35
Luminosity lifetime:	~12 h	
Availability:	**~85 %**	(max. weekly)
Time in physics:	**55 %**	(max. weekly)

Quench Limit of LHC Super-Conducting Magnets

Situation at 4.0 TeV (in August 2012)



Beam

145 MJ

SC Coil:

quench limit

15-100 mJ/cm^3

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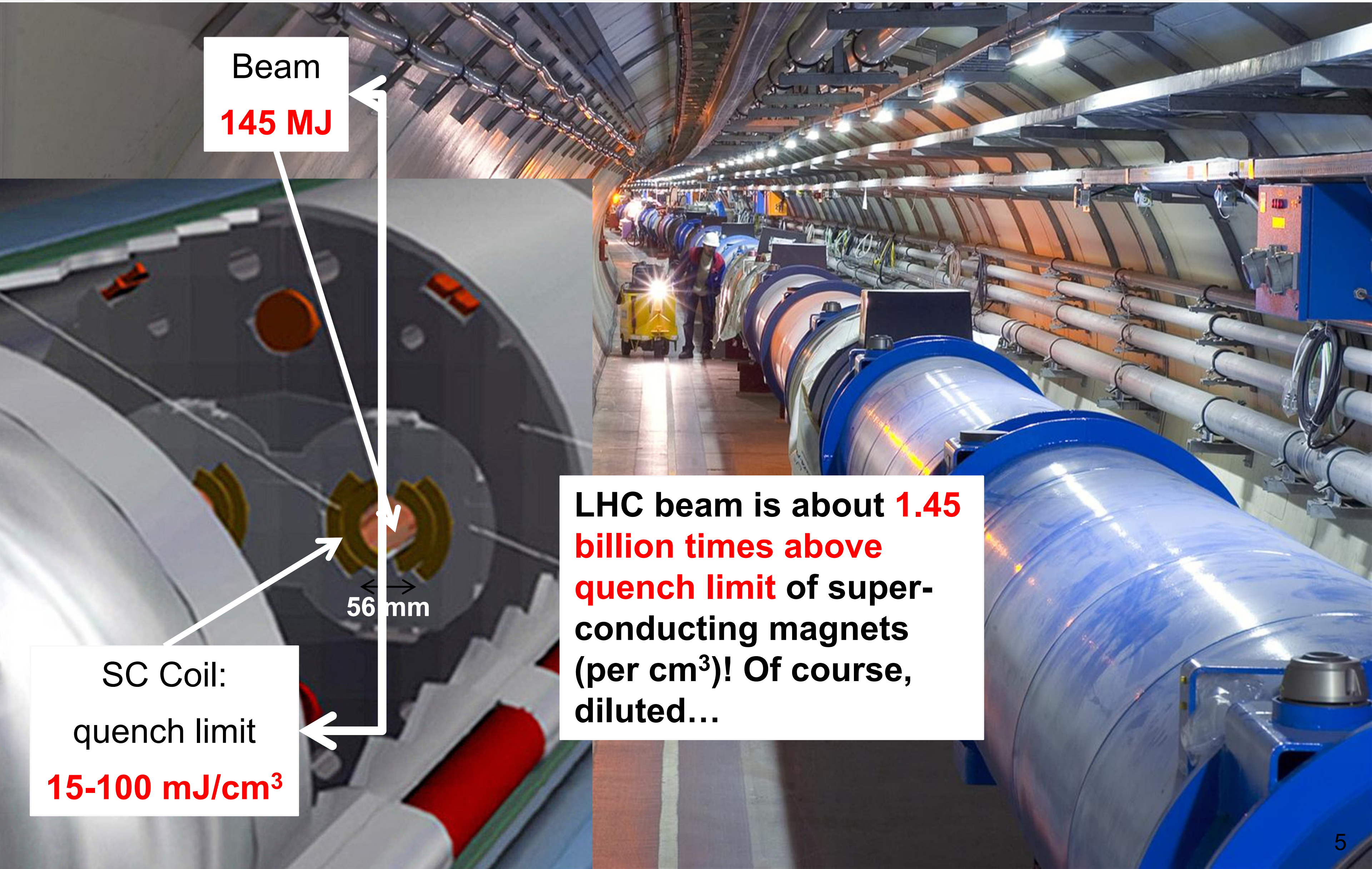

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145 MJ

SC Coil:

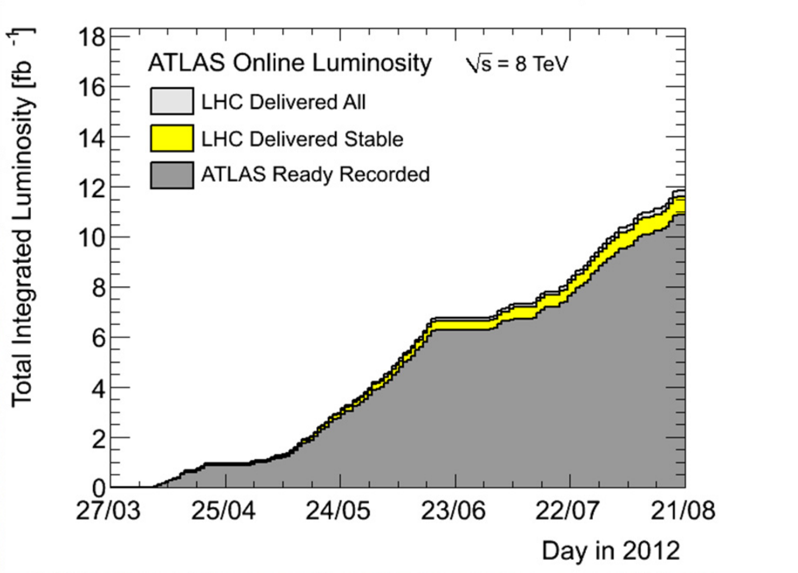
quench limit

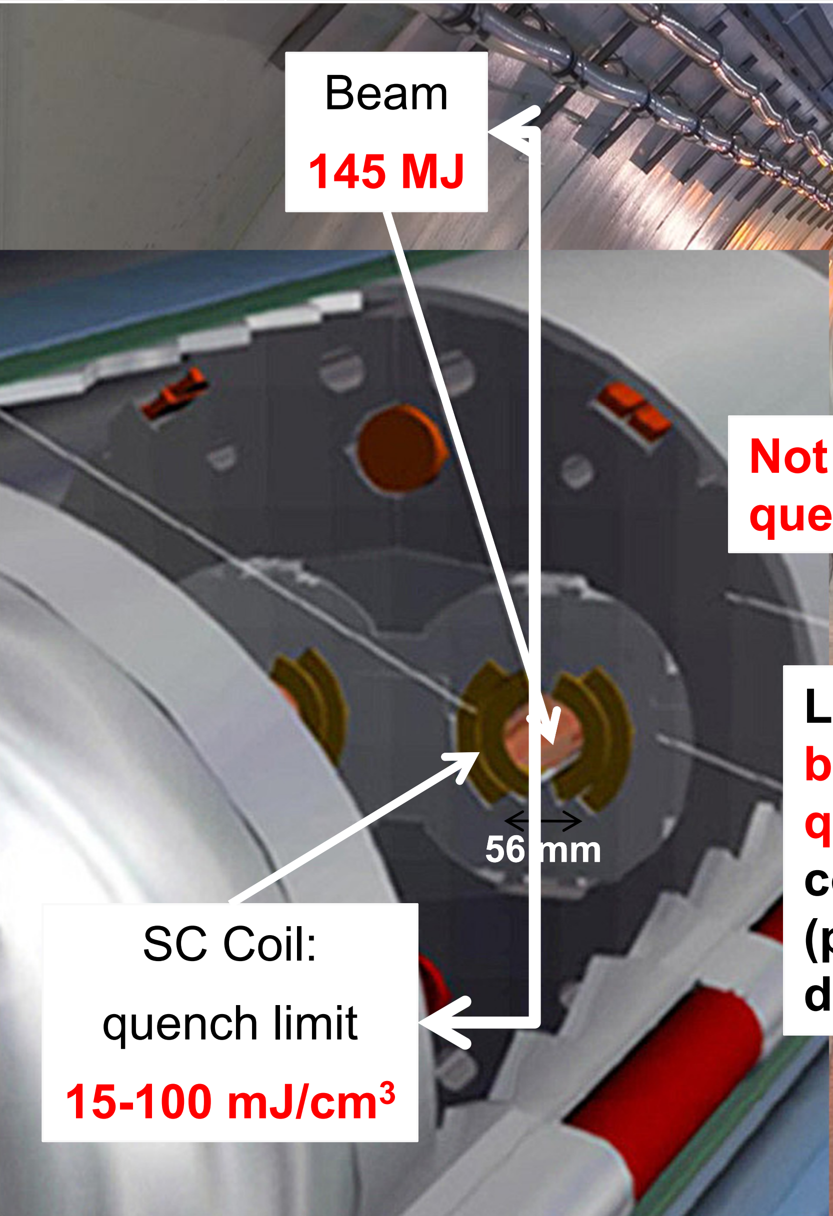
15-100 mJ/cm^3

LHC beam is about 1.45 billion times above quench limit of super-conducting magnets (per cm^3)! Of course, diluted…

Quench Limit of LHC Super-C

Situation at 4.0 TeV (in August 2012





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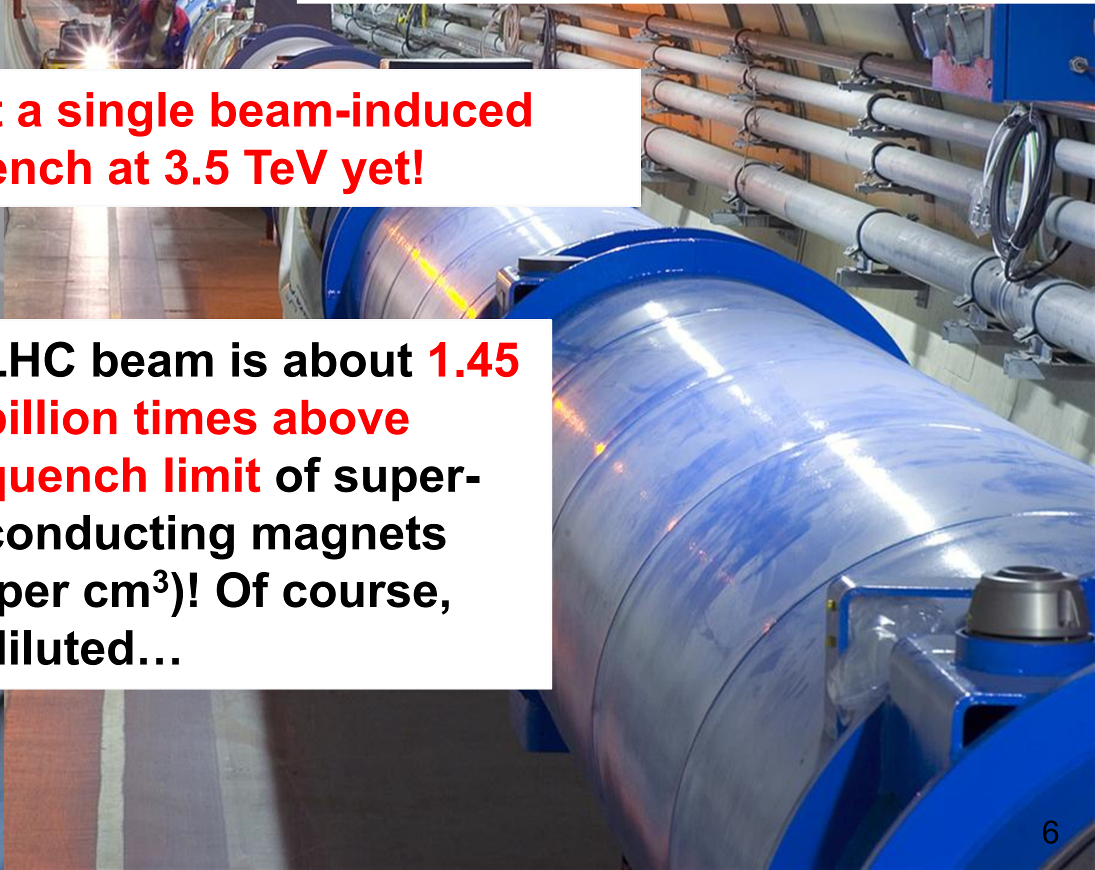


Not a single beam-induced quench at 3.5 TeV yet!

LHC beam is about 1.45 billion times above quench limit of super-conducting magnets (per cm^3)! Of course, diluted…

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**

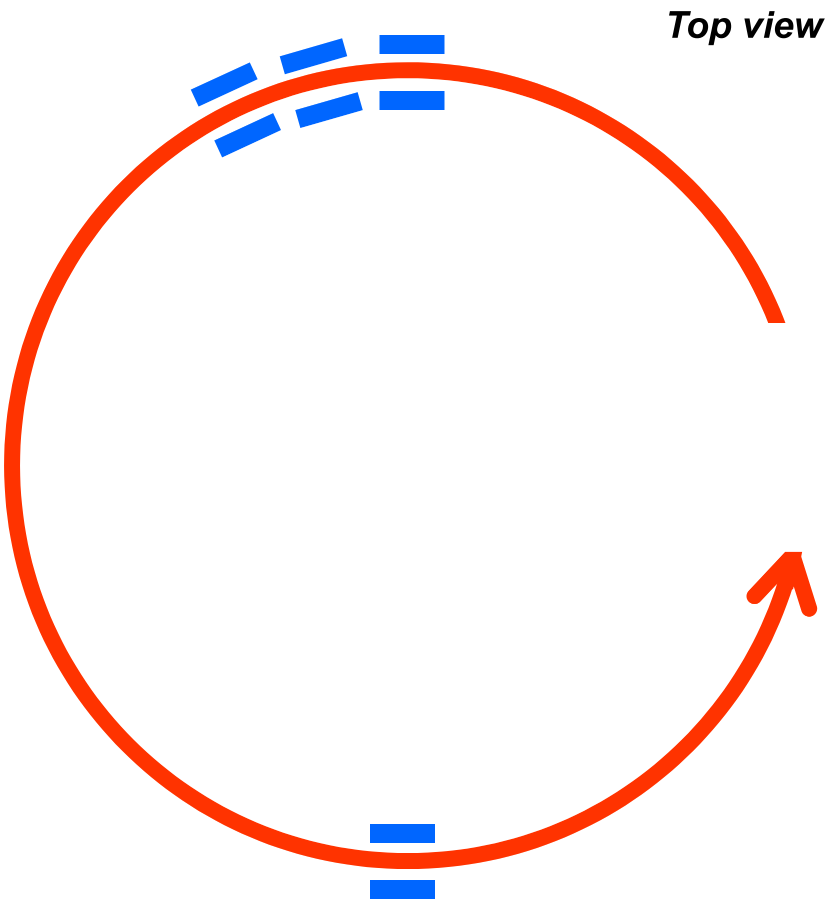
The LHC Collimation System

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

  > 99.9% efficiency!

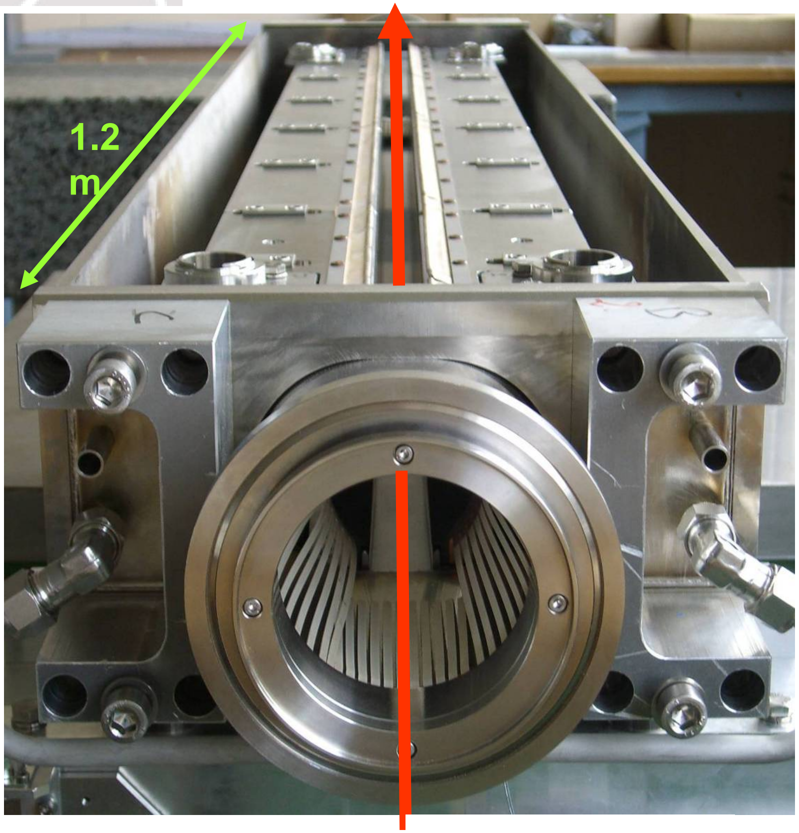
- To this purpose collimators insert diluting and absorbing materials into the vacuum pipe.
- Material is movable and can be placed as close as 0.25 mm to the circulating beam!
- Nominal distance at 7 TeV: ≥ 1 mm.

➔ <u>optimized in years of modeling and simulation…</u>

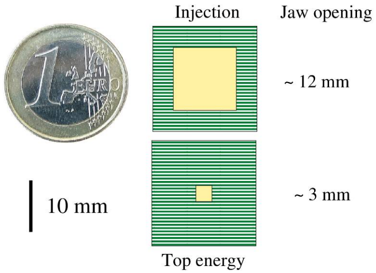


The Carbon Fiber Collimator

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



360 MJ proton beam

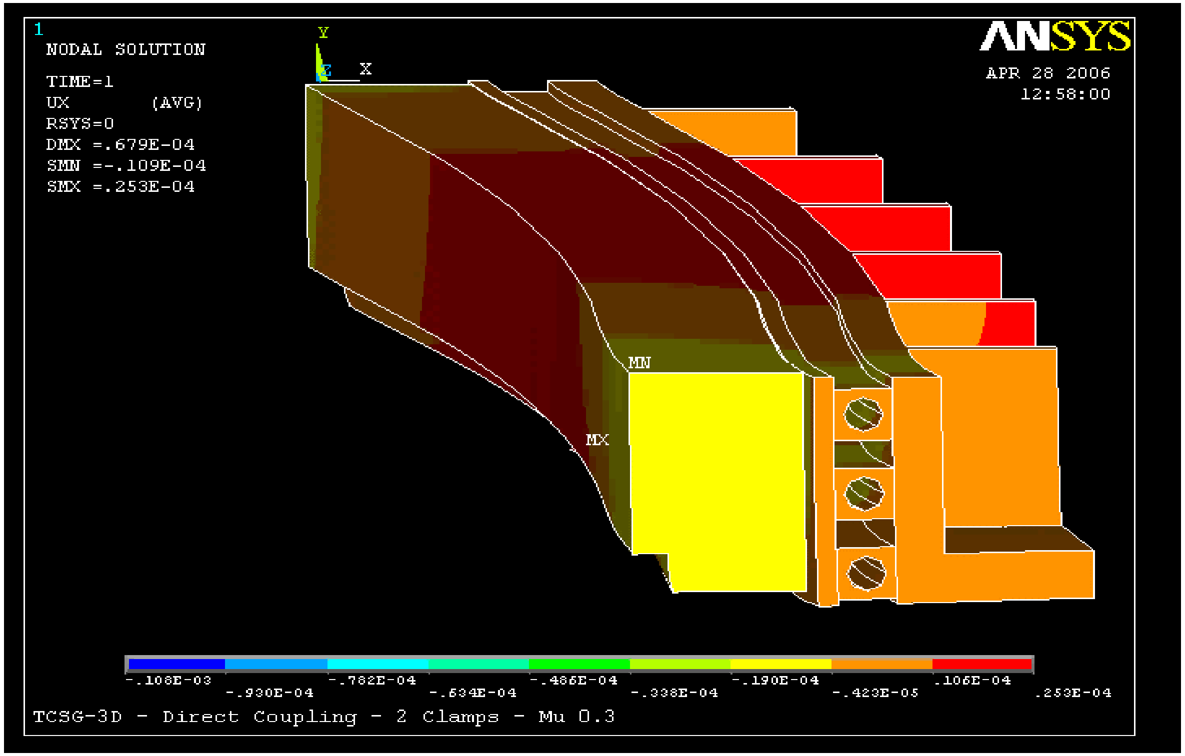


Parameter	Unit	Specification
Jaw material		CFC
Jaw length TCS TCP	cm cm	100 60
Jaw tapering	cm	10 + 10
Jaw cross section	mm^2	65 × 25
Jaw resistivity	μΩm	≤ 10
Surface roughness	μm	≤ 1.6
Jaw flatness error	**μm**	**≤ 40**
Heat load	kW	≤ 7
Jaw temperature	°C	≤ 50
Bake-out temp.	°C	250
Minimal gap	**mm**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

2003 Specification

Other System Simulations & Measurements (Except Cleaning)

- **Many simulations not covered here but crucial to design system.**
- Energy deposition and radiation – FLUKA, MARS, …
- Shock waves – ANSYS, AUTDYN, GSI, Kurchatov, …
- Radiation damage
- HiRadMat tests
- Integration & handling
- Impedance effects



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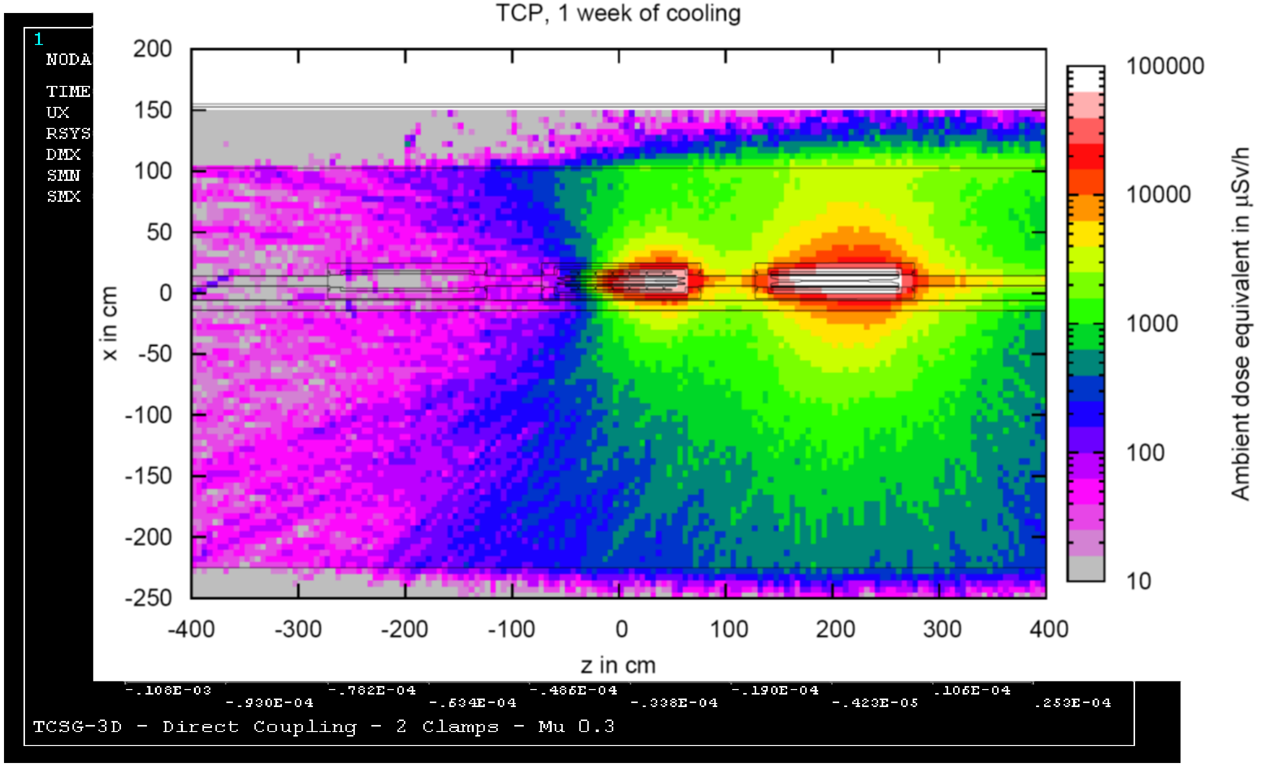

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Analysis of Radiation Induced Erosion in Graphite Composite Material AC Irradiated by Carbon Ions with the Energy 5 MeV at Irradiation Dose: 1x10 E17 p/cм 2

Ambient dose equivalent in µSv/h

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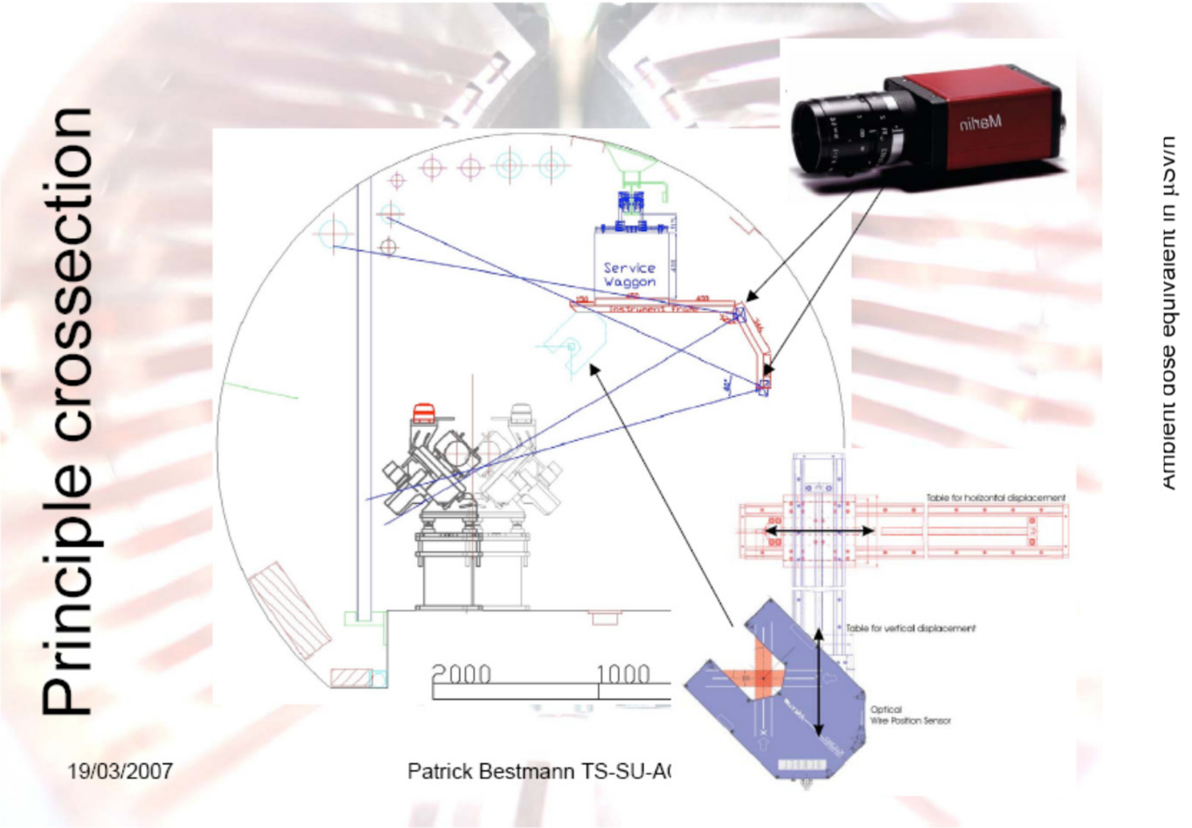

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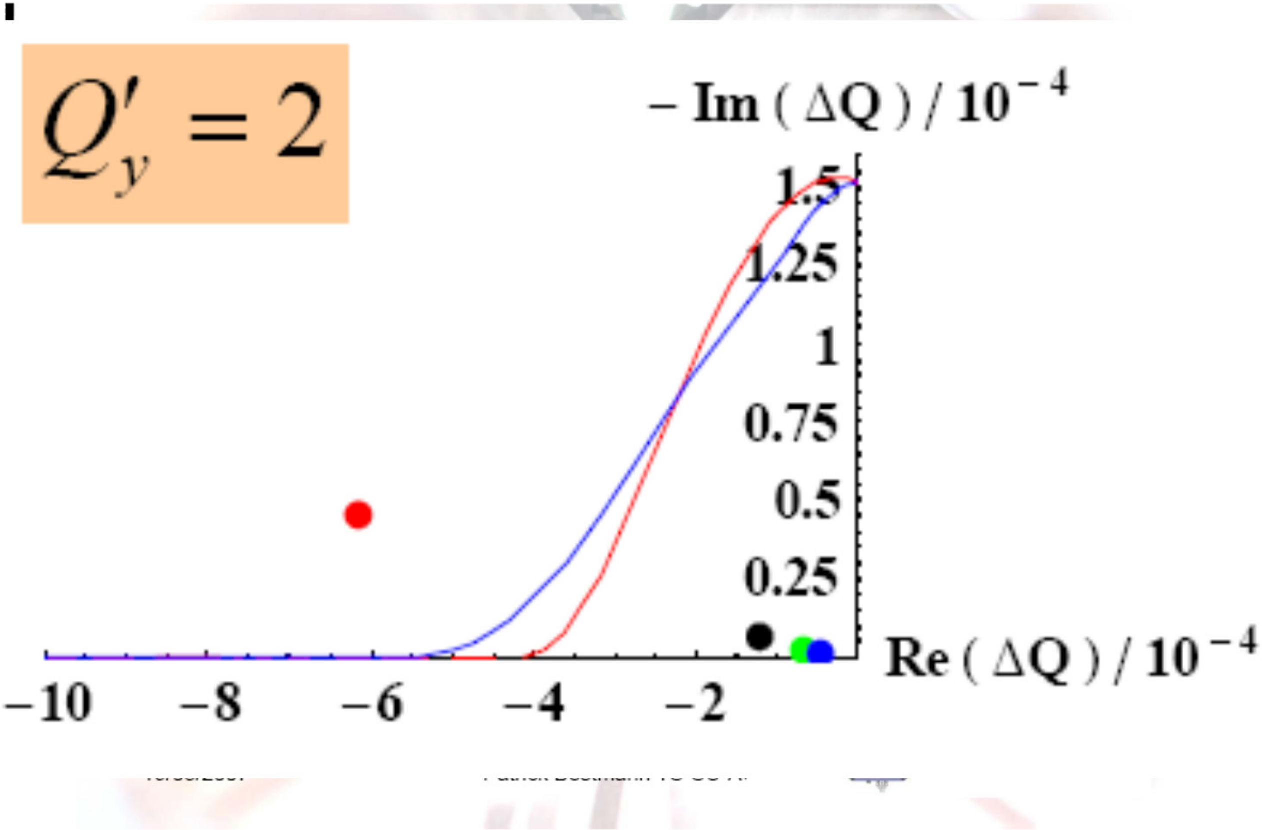
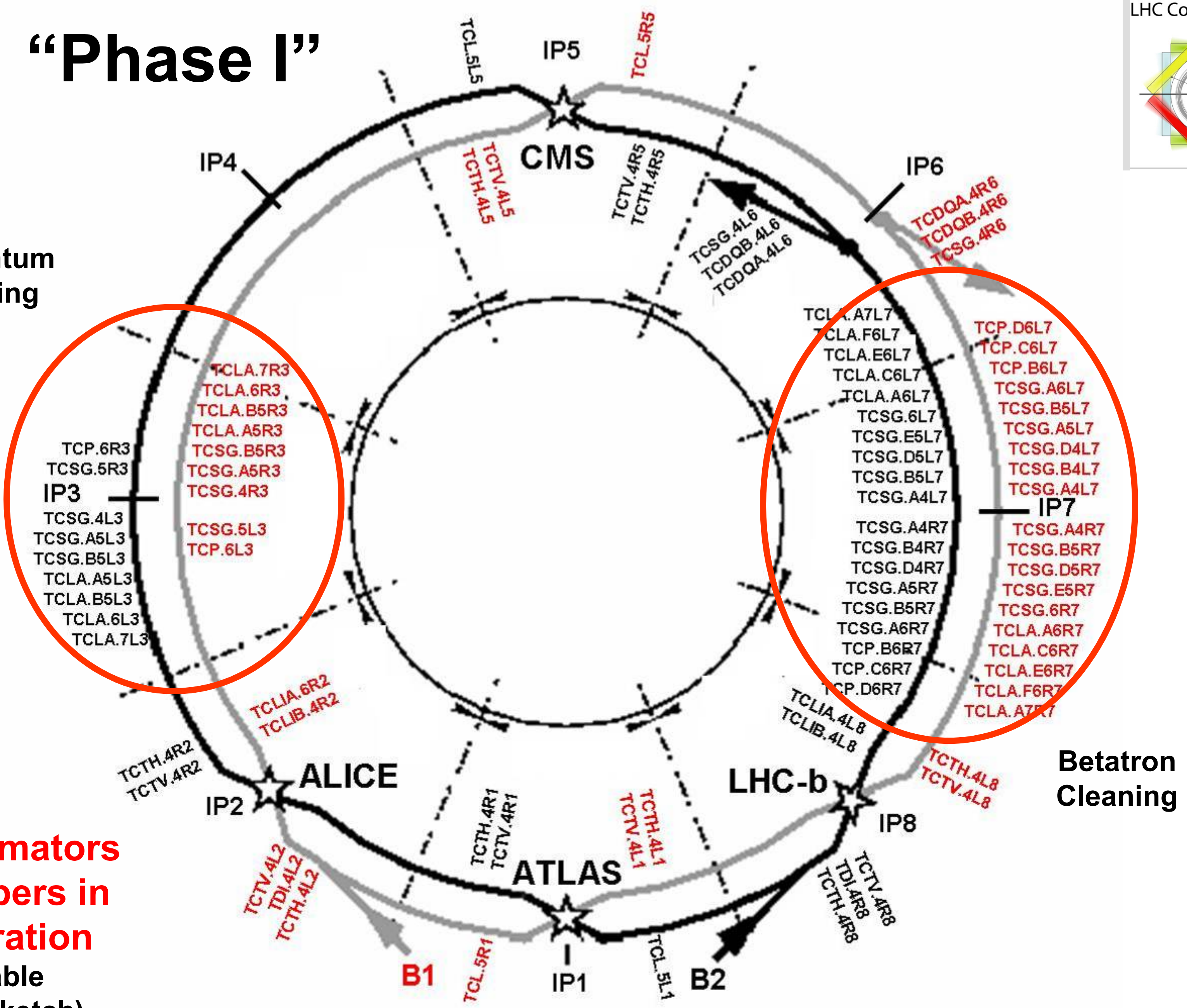


“Phase I”



Momentum Cleaning

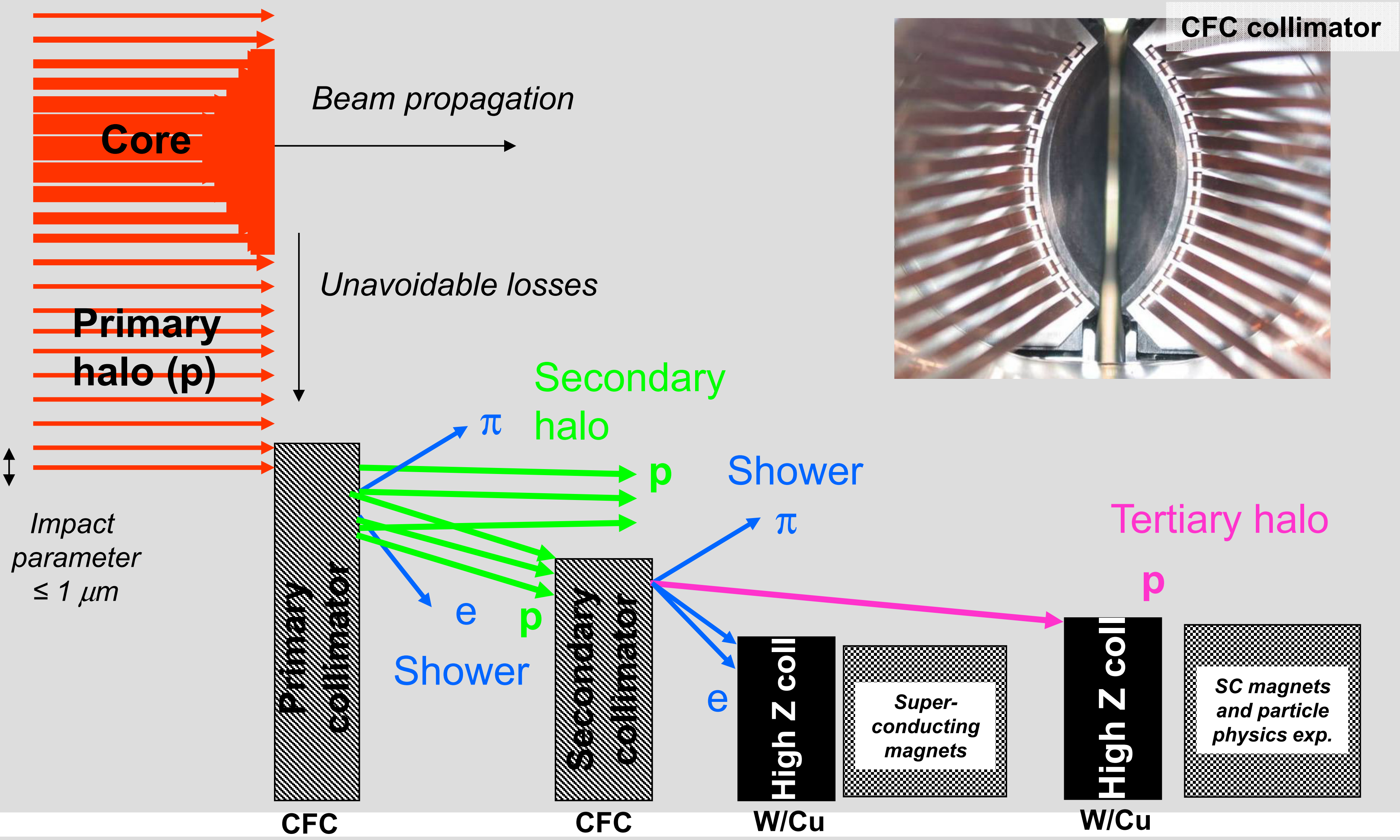
Betatron Cleaning

108 collimators & absorbers in 1st generation

(only movable shown in sketch)

Multi-Stage Cleaning & Protection

3-4 Stages



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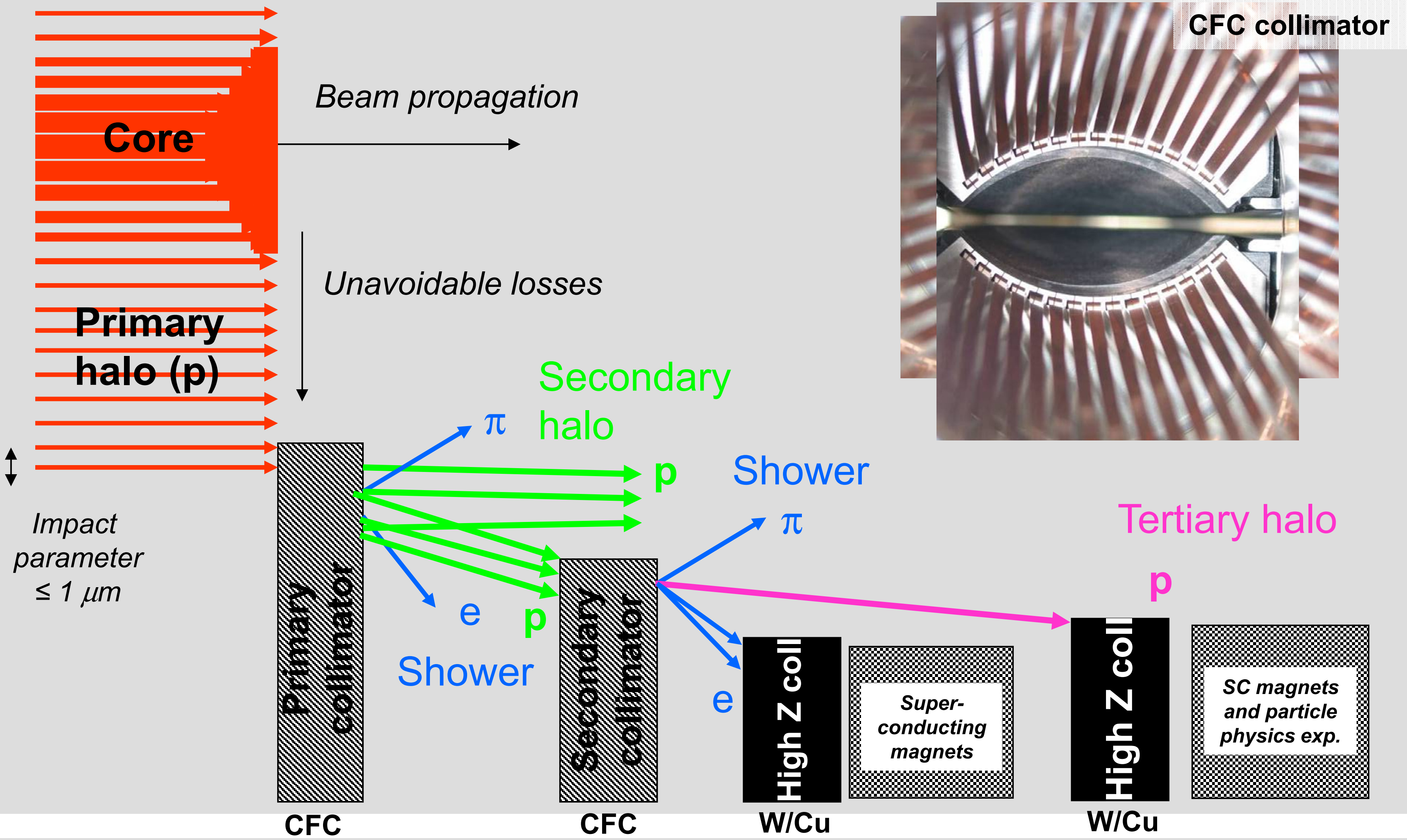

CFC collimator

Multi-Stage Cleaning & Protection

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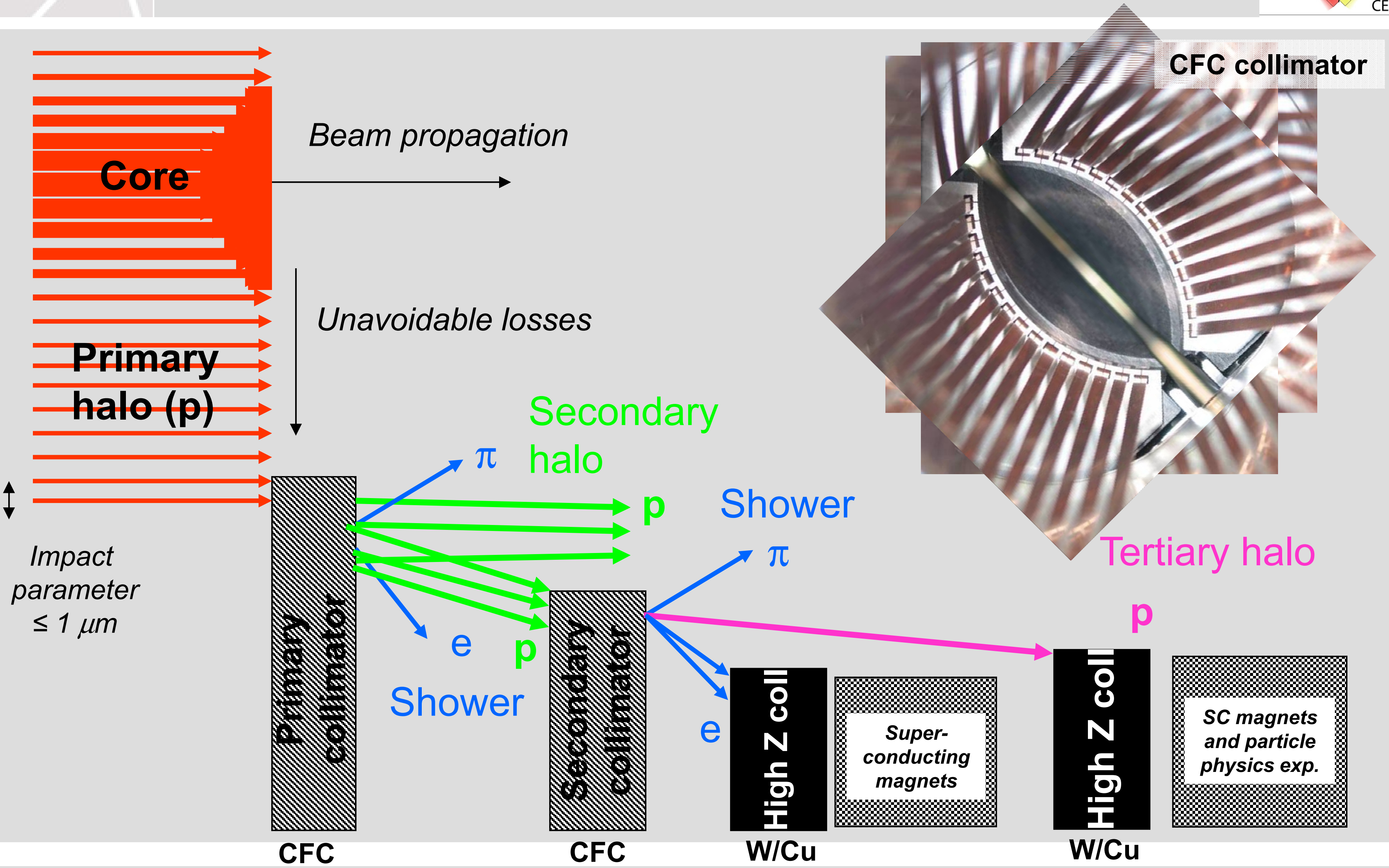

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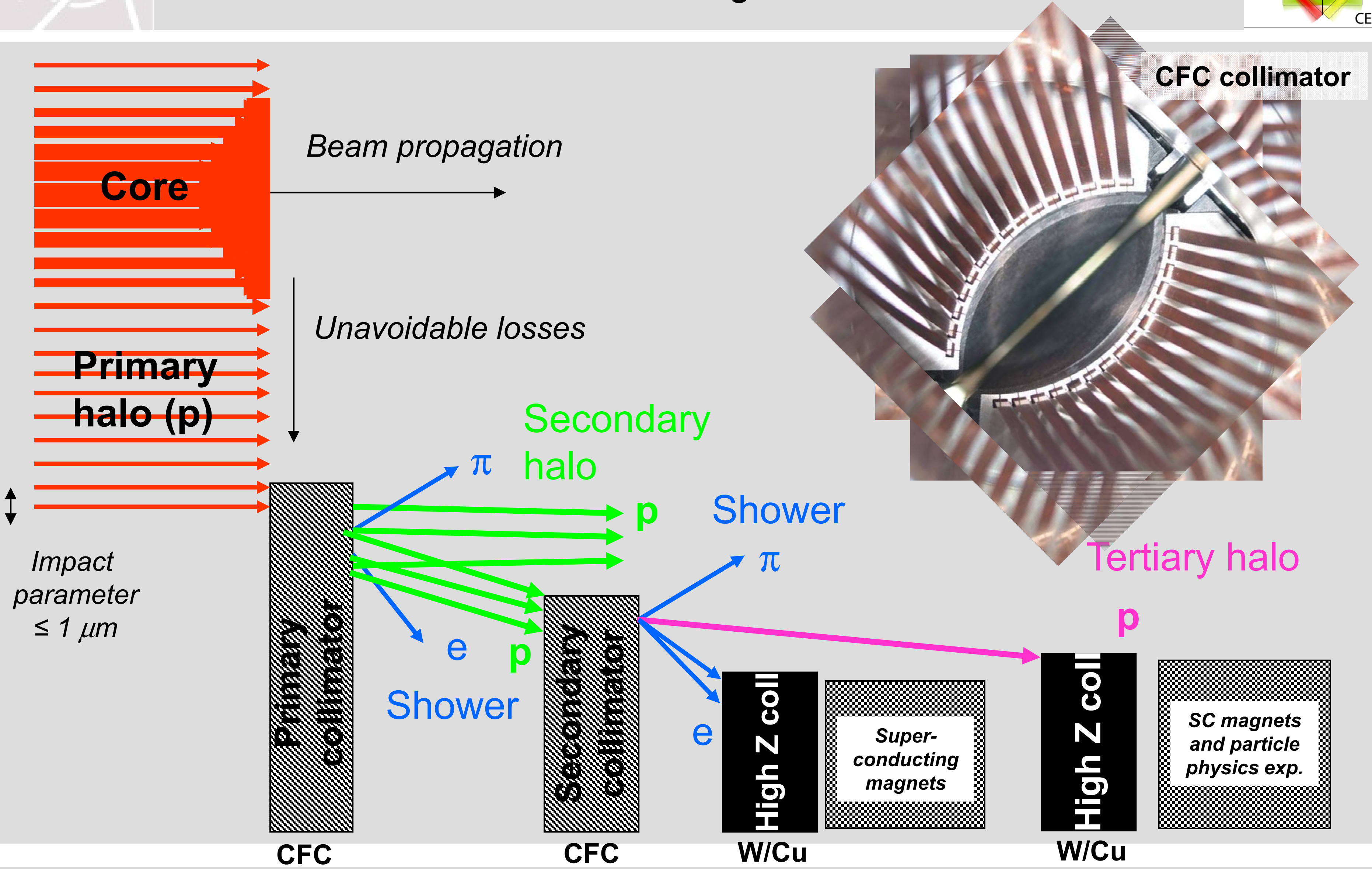


CFC collimator

Core

Beam propagation

Primary halo (p)

Unavoidable losses

Impact parameter ≤ 1 µm

Primary collimator

CFC

Secondary halo

π

p

e

p

Shower

Secondary collimator

CFC

Shower

π

e

High Z coll

W/Cu

Super-conducting magnets

Tertiary halo

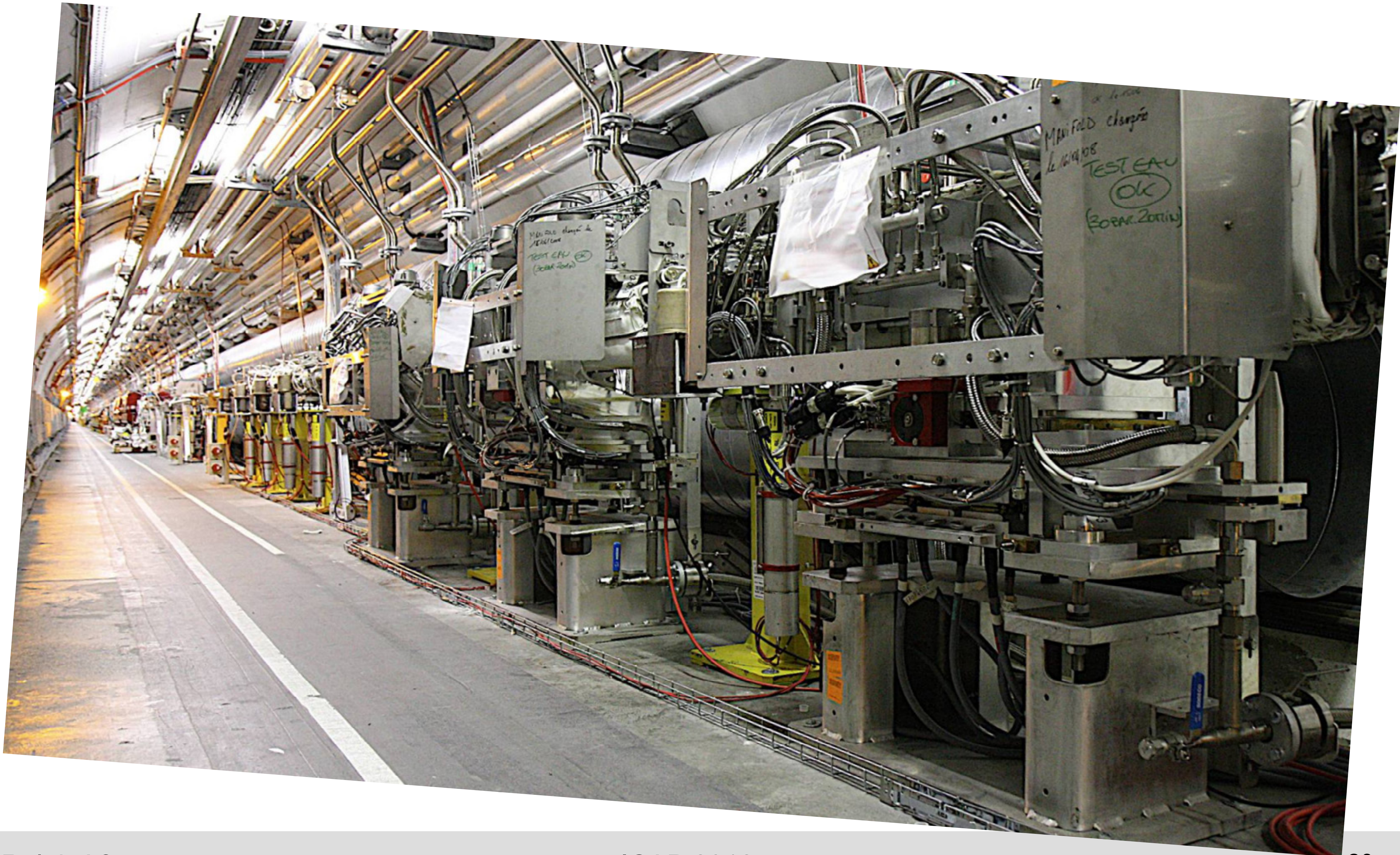
p

High Z coll

W/Cu

SC magnets and particle physics exp.

Installed Collimators…



What is Cleaning Inefficiency?

- Collimation is acting in the normalized phase space. With $z = x$ or $z = y$, the Twiss functions β_z and α_z, and the emittance ϵ_z we define the normalized coordinates z_n and z'_n as:

$$\begin{aligned} z_n &= \frac{z}{\sqrt{\epsilon_z \beta_z}} \\ z'_n &= \frac{\alpha_z z + \beta_z z'}{\sqrt{\epsilon_z \beta_z}} \end{aligned}$$

- An unperturbed particle describes a circle in normalized phase space with amplitude:

$$a_z = \sqrt{z_n^2 + z_n'^2}$$

For collimation it is convenient to define inefficiency or leakage[3]. We first introduce inefficiency and then connect it to efficiency. The inefficiency η_c of a collimation system with a primary collimation cut at n_1 is defined as the ratio between the number N_{leak} of particles that leak out and reach a normalized transverse amplitude a_z^{cut} and the number N_{impact} of impacting particles:

$$\eta_c = \frac{N_{leak}(a_z > a_z^{cut})}{N_{impact}}$$

Efficiency η can then be defined as $\eta = 1 - \eta_c$

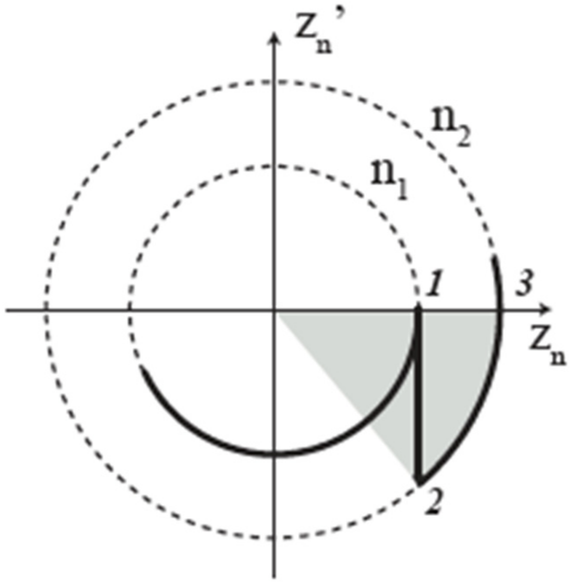
Collimation in Phase Space

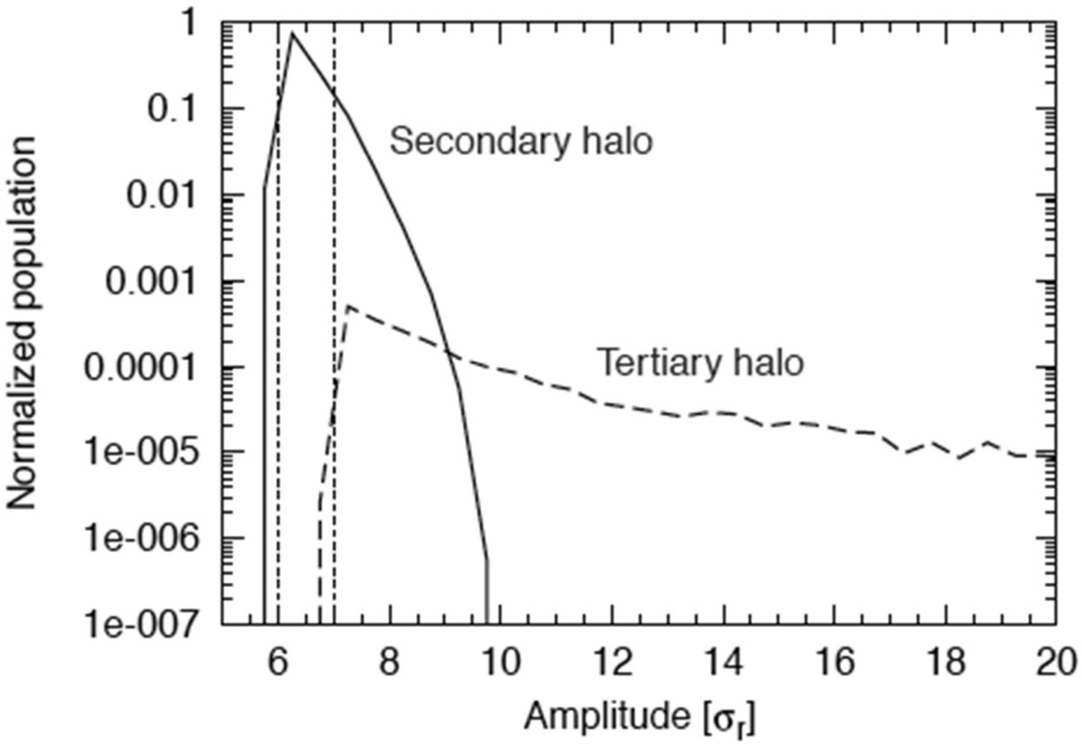
Primary collimator (1, set at n1) intercepts particle from <u>primary</u> halo

Particle has some probability to escape (no inelastic interaction) and to become member of the secondary halo with increased amplitude

Secondary collimator (2, set at n2) intercepts particle from secondary halo

…

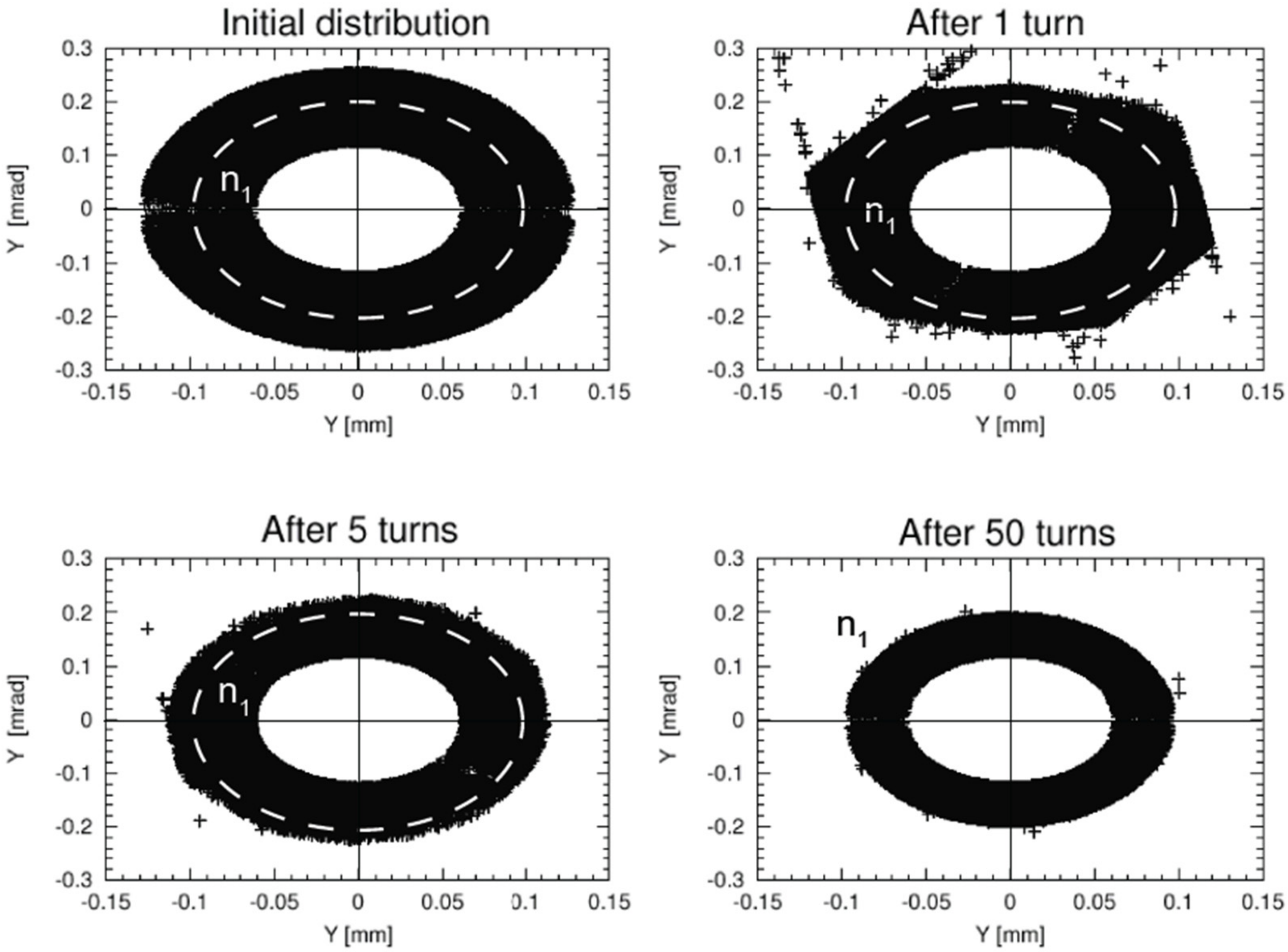




This we can simulate by using nuclear scattering routines which describe the collimator blocks!

CERN LHC → <u>K2 routine</u> from the 1990's and <u>CollTrack/SixTrack</u> tracking code for acc.!

Example of Beam Shaving with Collimators…



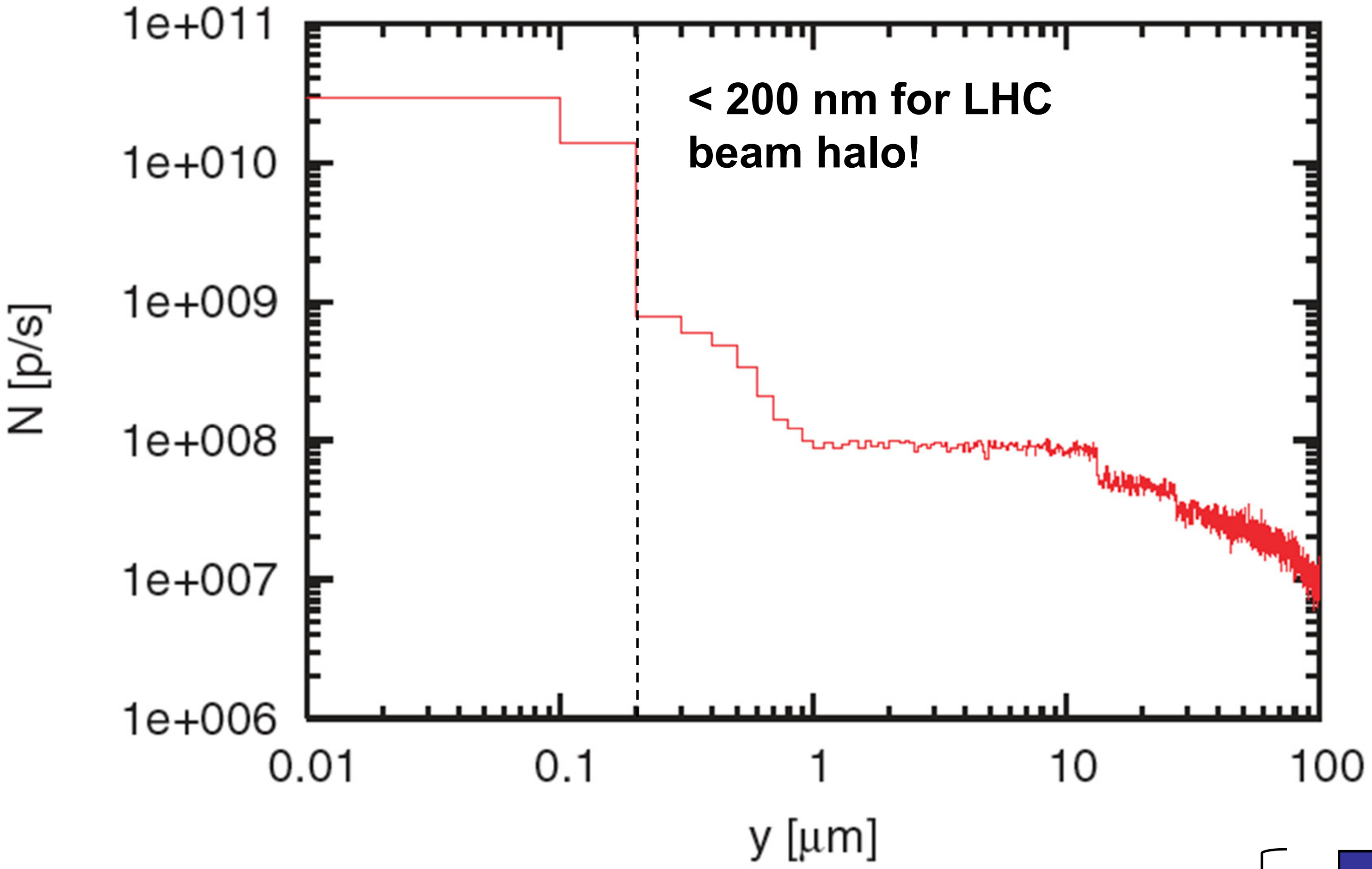
Collimation is an Edge Effect…

Slow losses

Beam lifetime: **0.2 h**	Loss rate:	4.1e11	p/s
		3.6e7	p/turn
	Loss in 10 s:	4.1e12	p
		1.4	**%**

Assume drift:	0.3	sig/s	*(uniform “emittance” blow-up)*
	2.7e-5	sig/turn	
	5.3	**nm/turn**	(sigma = 200 micron)
Simulate:	10	s	
	112360	turns	(1.1e5)
	1.1e5	turns	
	4.1e12	p	
Representation:	360	p/turn	(1p represents 1e5 real p)
	40e6	p*turn	(if 360 generated just-in-time per turn)

Transverse Offset (Impact Parameter) from Collimator Edge when Hitting



< 200 nm for LHC beam halo!

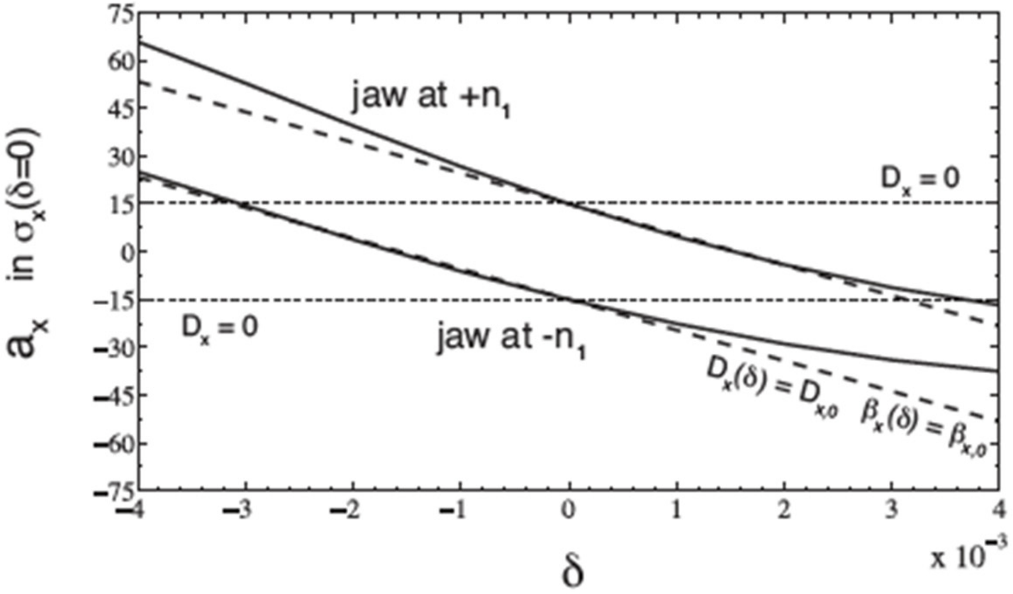
Major Simulation Effort for LHC

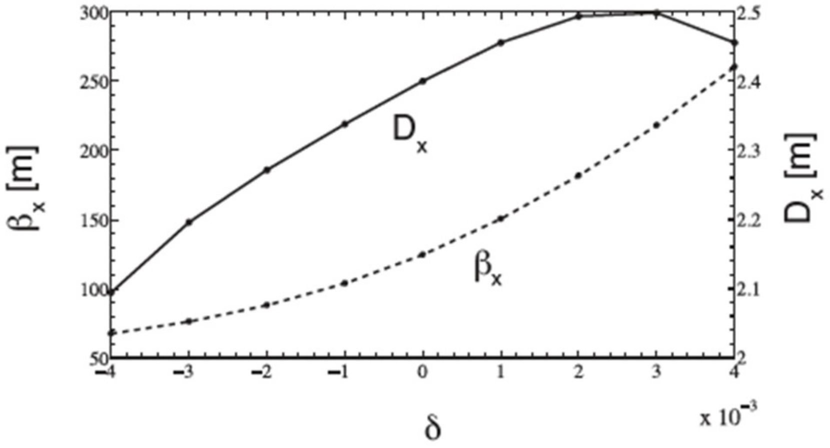
(started in 2001, several PhD students + Post Doc's)

- Goal: Correct description of small impact parameters and edge effects!
- Previous simulations:
  - Assume a few micron diffusion per turn (~1000 times too high) to create beam halo in non-chromatic tracking. Forced by limited CPU power.
  - Price to pay: Artificially high impact parameters and biased efficiency results.
- Major programming effort went into edge effect for LHC collimation, much less effort in modernizing K2 nuclear scattering routines (→ they have much less importance for results). Our solution:
  - Go to large particle ensembles (**20 million halo protons** in tracking).
  - Simulate halo **WITHOUT diffusion**: 5 nm/turn neglected over 200 turns.
  - Instead create **halo particles at the collimator edge with correct impact parameter** (requires precise tracking).
  - Include **chromatic effects** and **local tracking** through accelerator elements.

Chromatic Phase Space Cuts

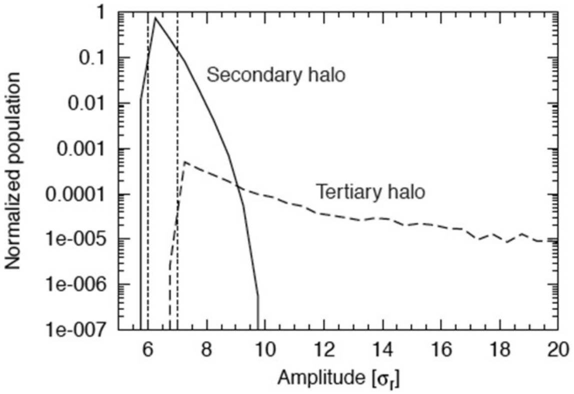
$$\pm n_1 = a_z \sqrt{\frac{\beta_z(\delta)}{\beta_{z,0}}} + \delta \frac{D_z(\delta)}{\sqrt{\beta_{z,0}\epsilon_z}}$$



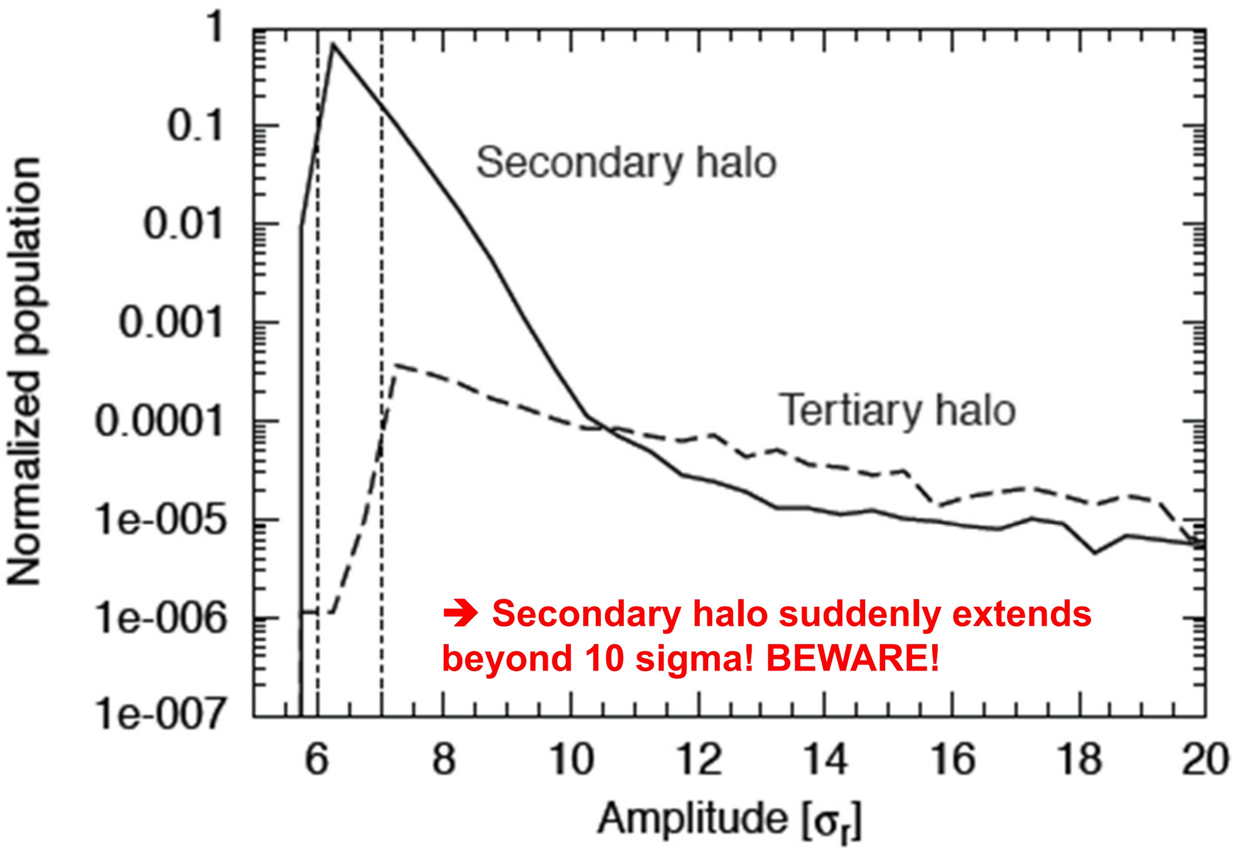


- ➔ **Minimizing chromatic deviations in the LHC guarantees clean phase space cuts!**
- ➔ **Another crucial ingredient for success!**

Importance of Fully Chromatic Codes



➔ Secondary halo constrained to below 10 sigma without chromatic effects!



➔ Secondary halo suddenly extends beyond 10 sigma! BEWARE!

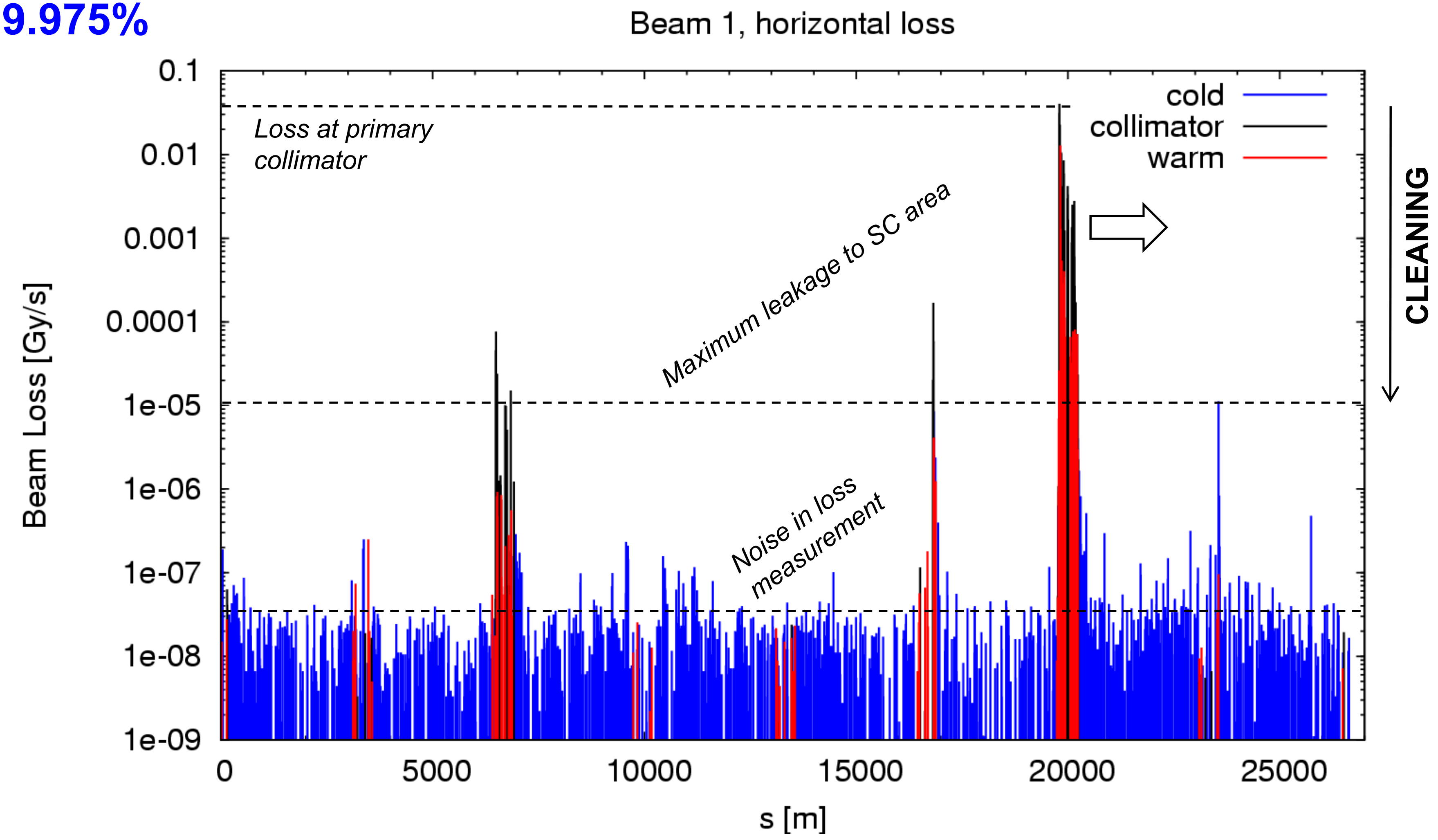
System Cleaning Efficiency Optimized in Simulation

- 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 full set of FLUKA energy deposition!

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

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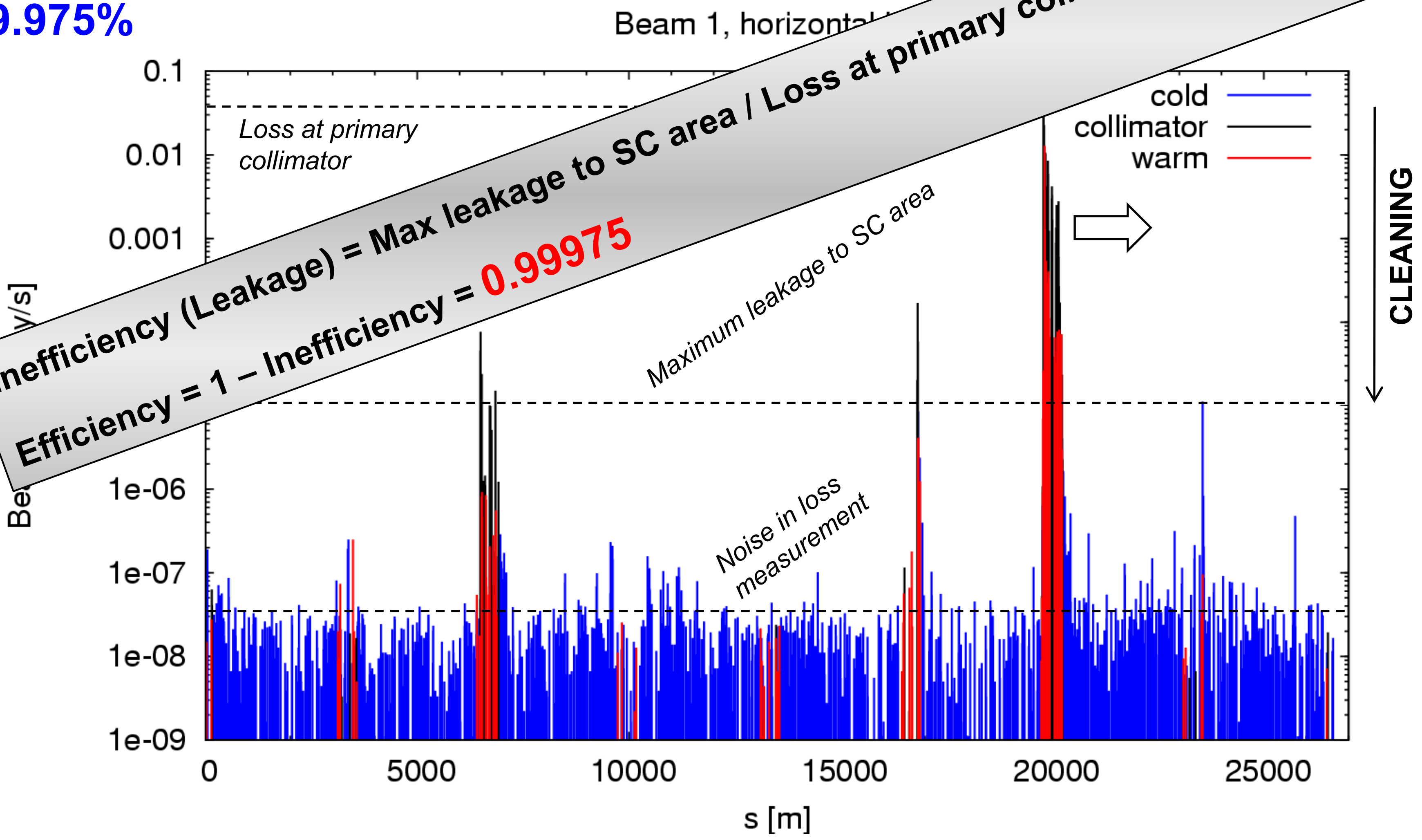

Inefficiency (Leakage) = Max leakage to SC area / Loss at primary collimator = 2.5e-4

Efficiency = 1 – Inefficiency = 0.99975

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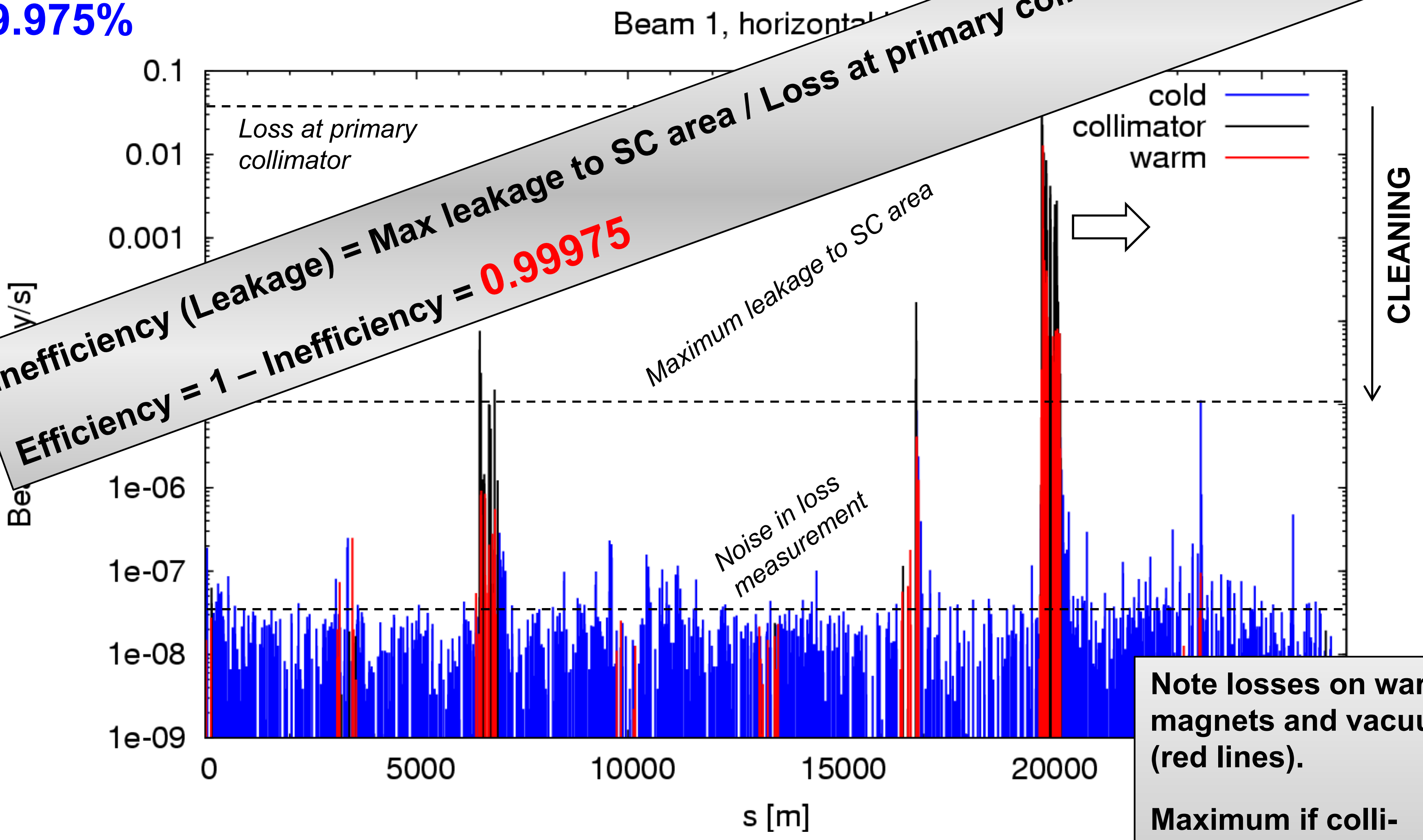

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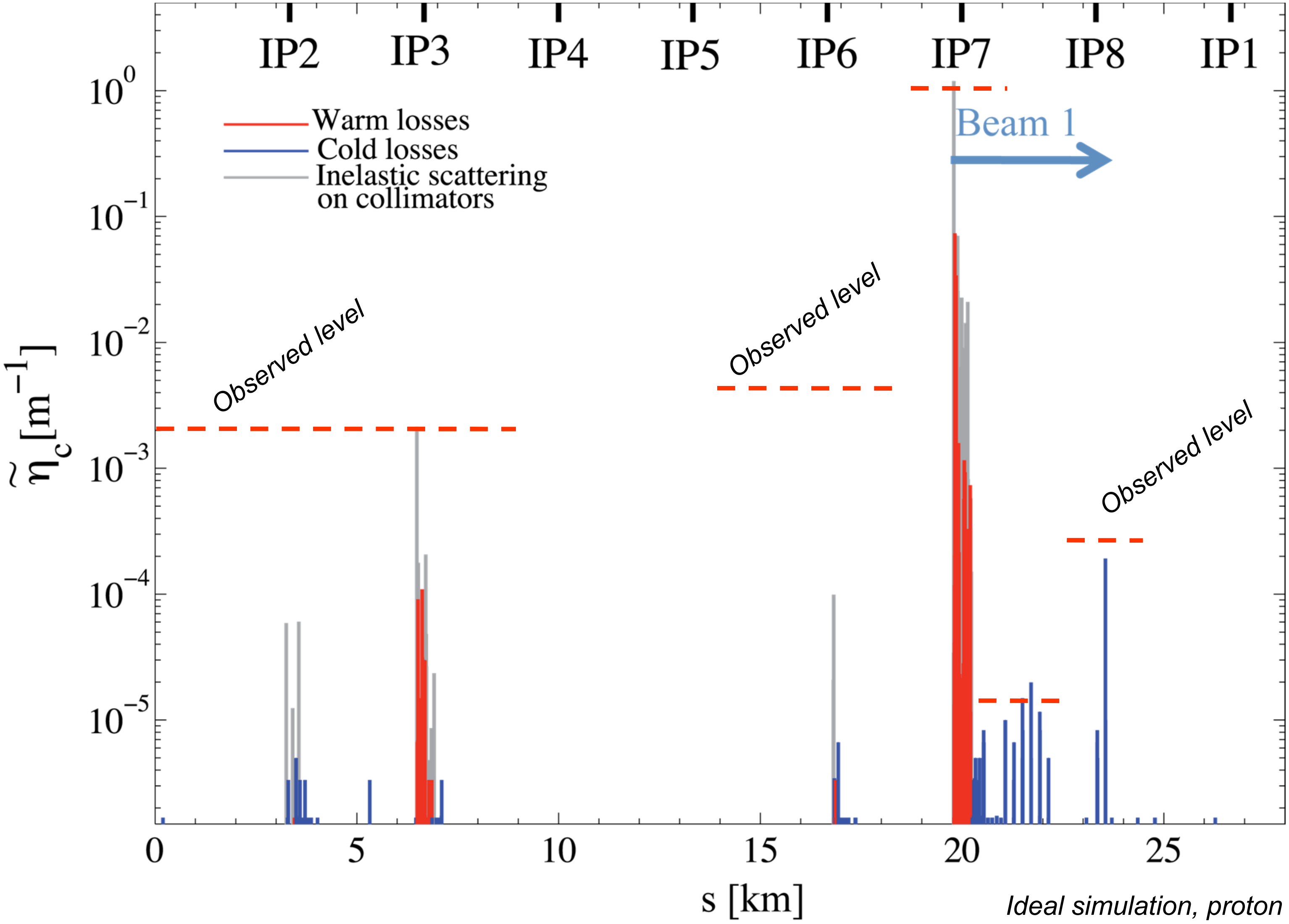
Measured 6 days after beam-based setup of c

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

Maximum if collimation works well! ~ 1/3 of beam ends here!

450 GeV: Design Simulation

(PhD C. Bracco 2008, p. 74 → years before data)

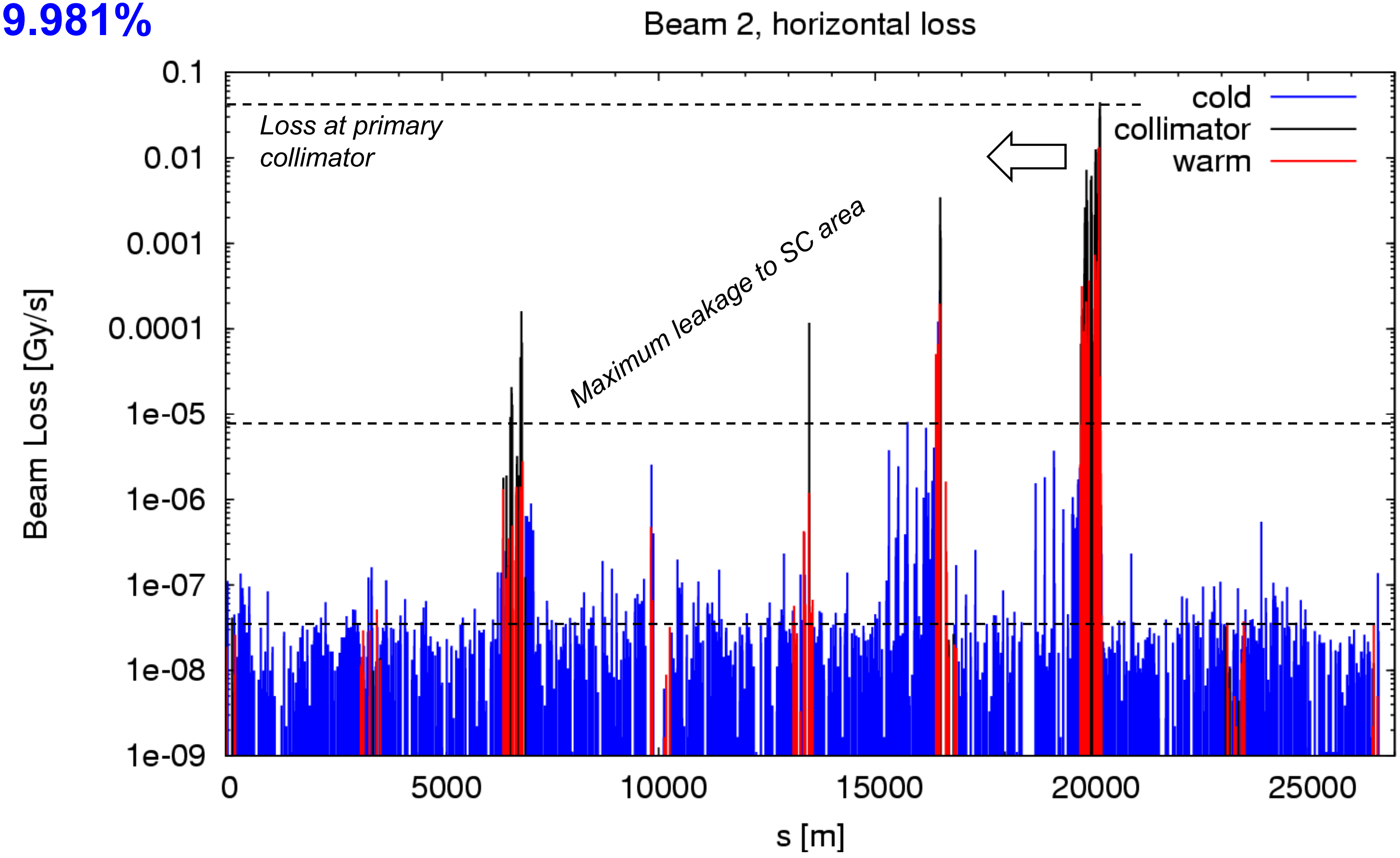


Ideal simulation, proton tracking, no showers

450 GeV: Cleaning Measurement

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

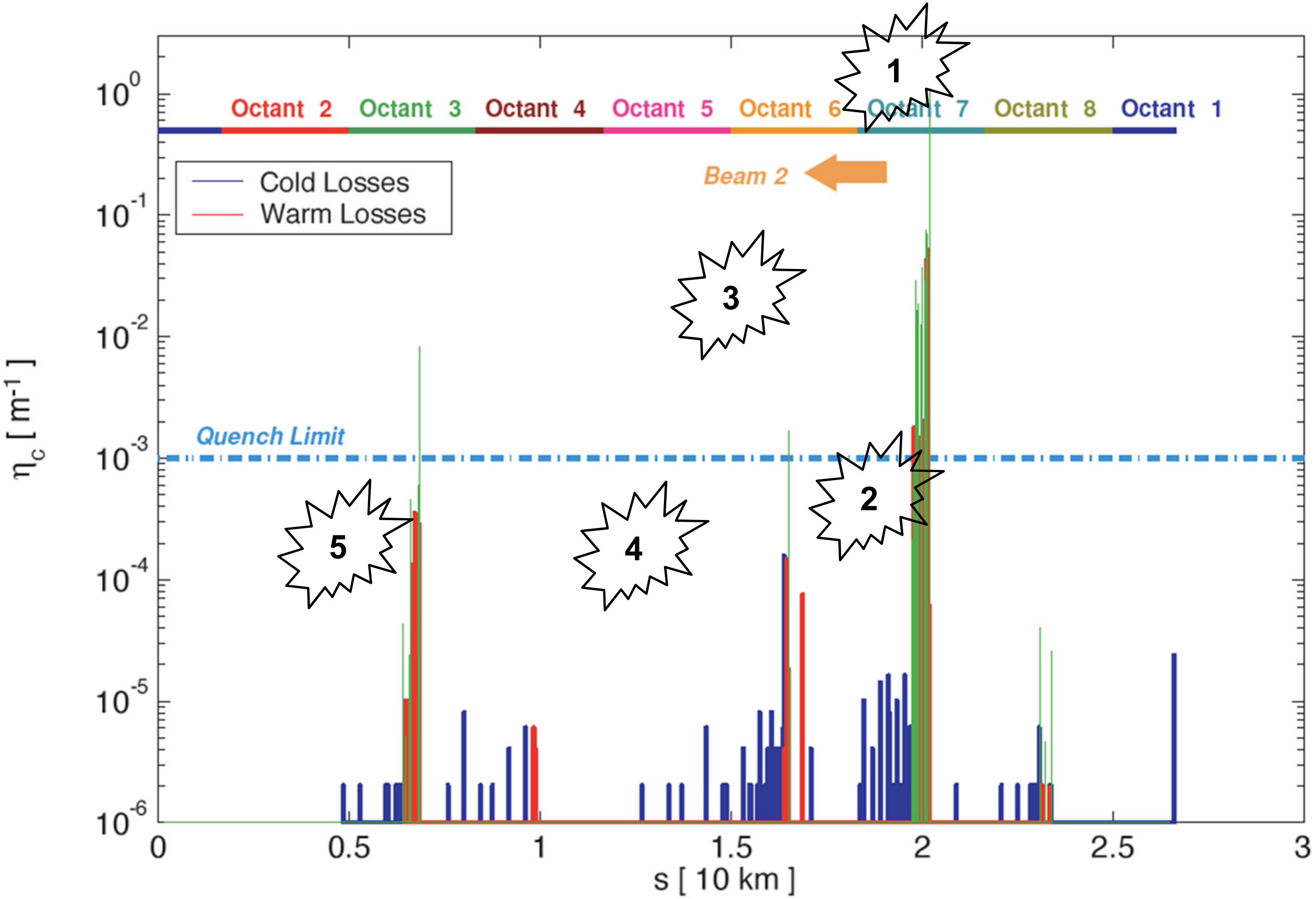
99.981%



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

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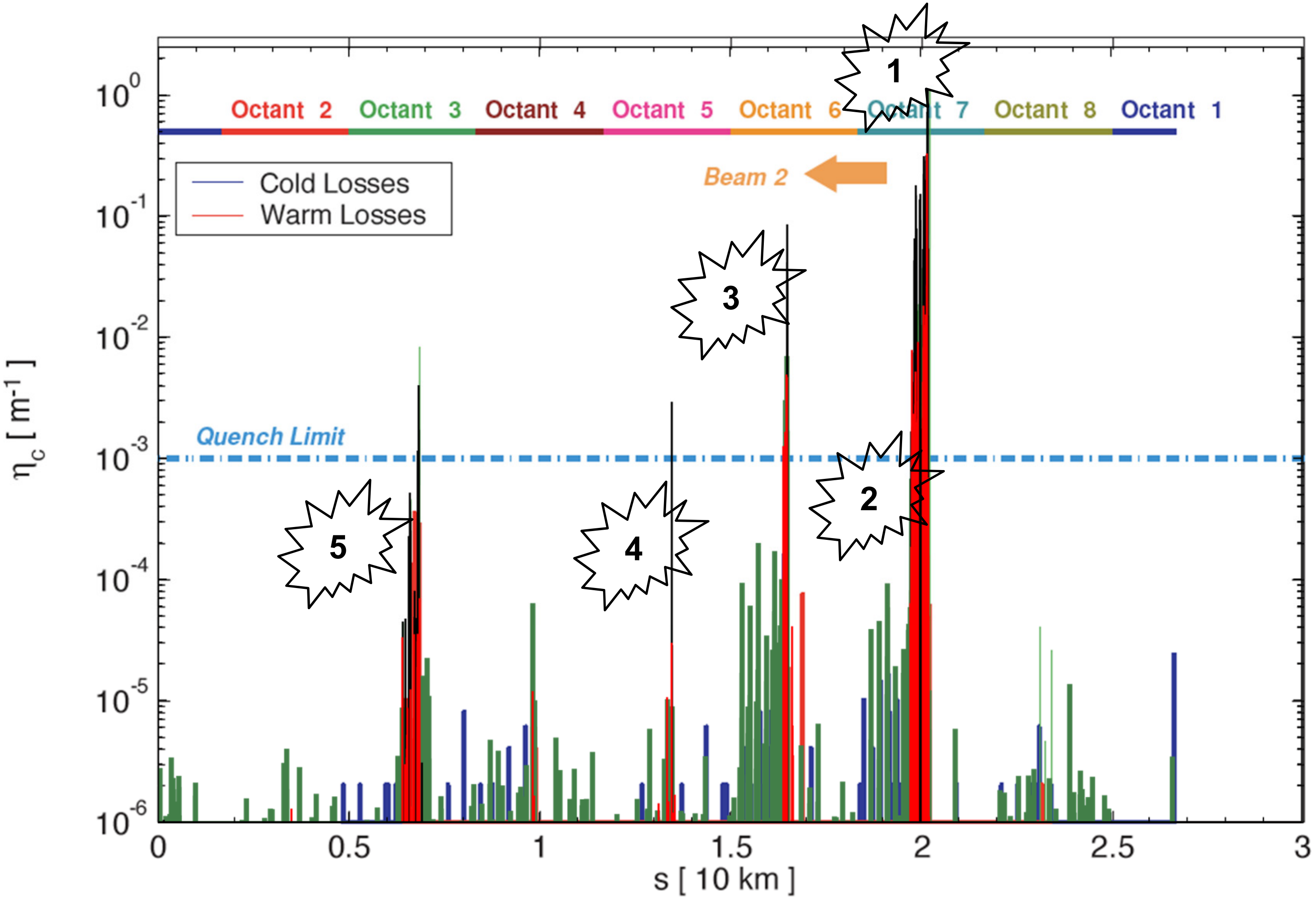
(Data 2009 - PhD G. Robert-Demolaize 2006, p. 114)



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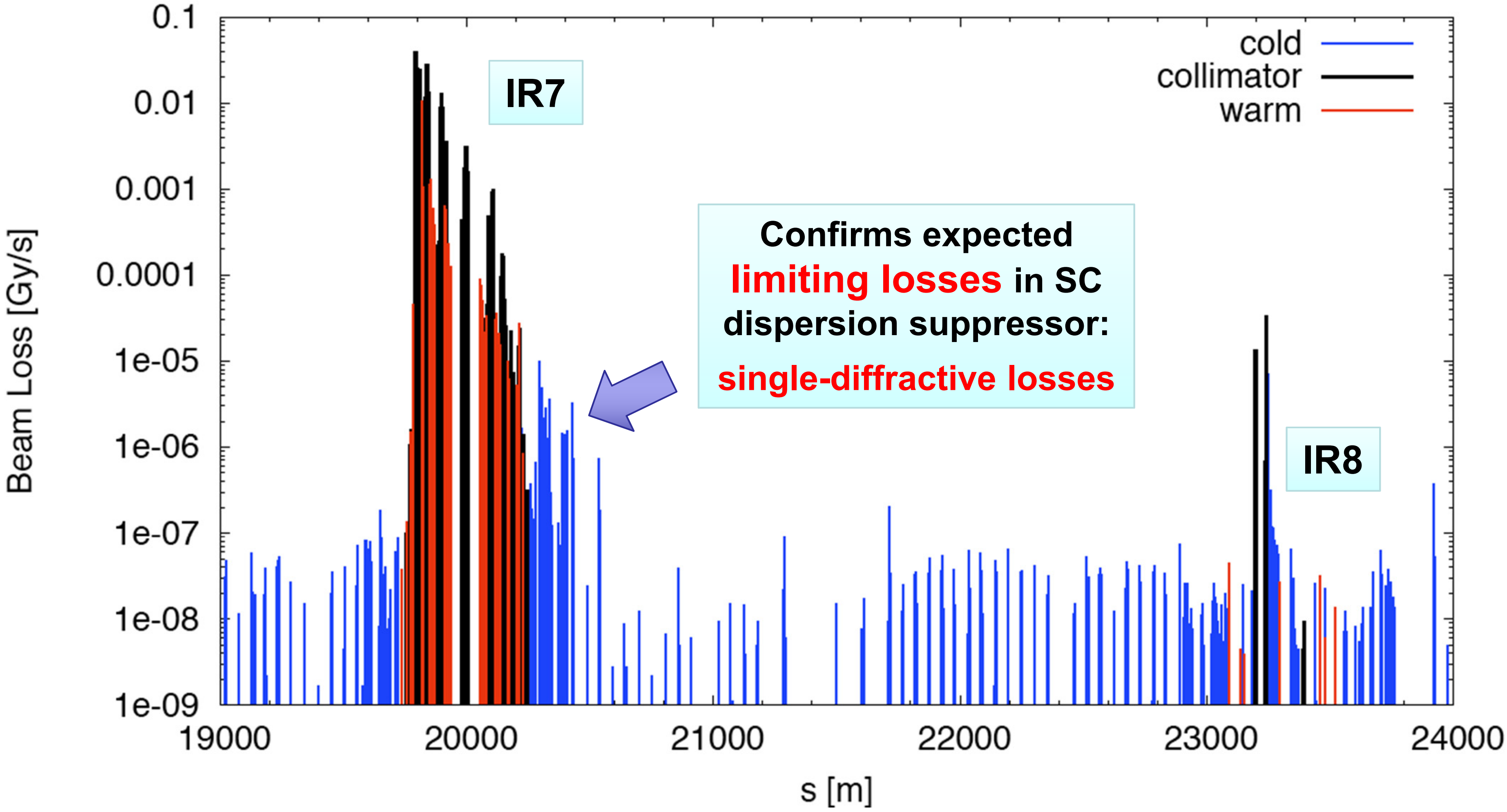
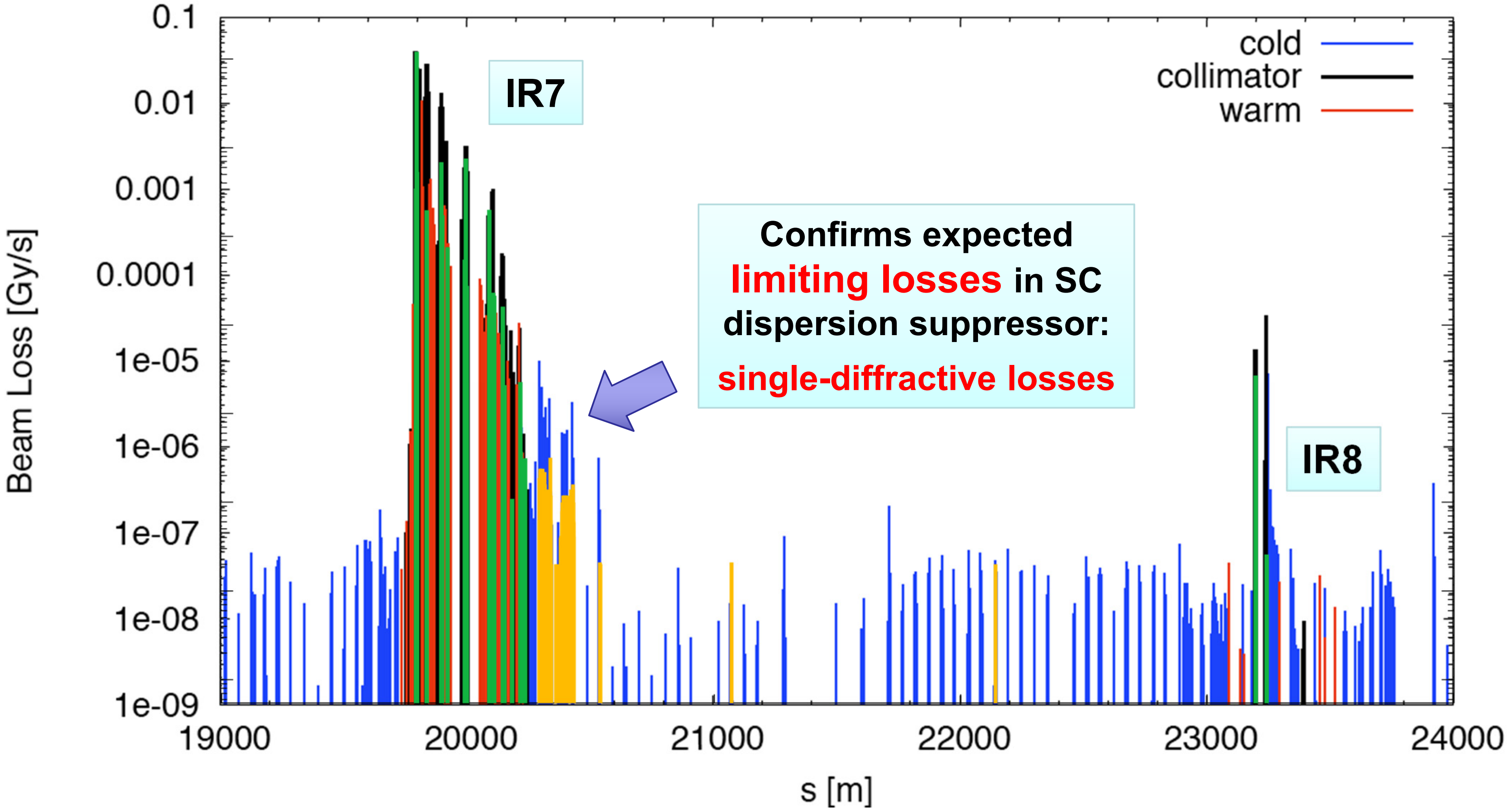
Meas. & Sim. Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



Confirms expected **limiting losses** in SC dispersion suppressor:

single-diffractive losses

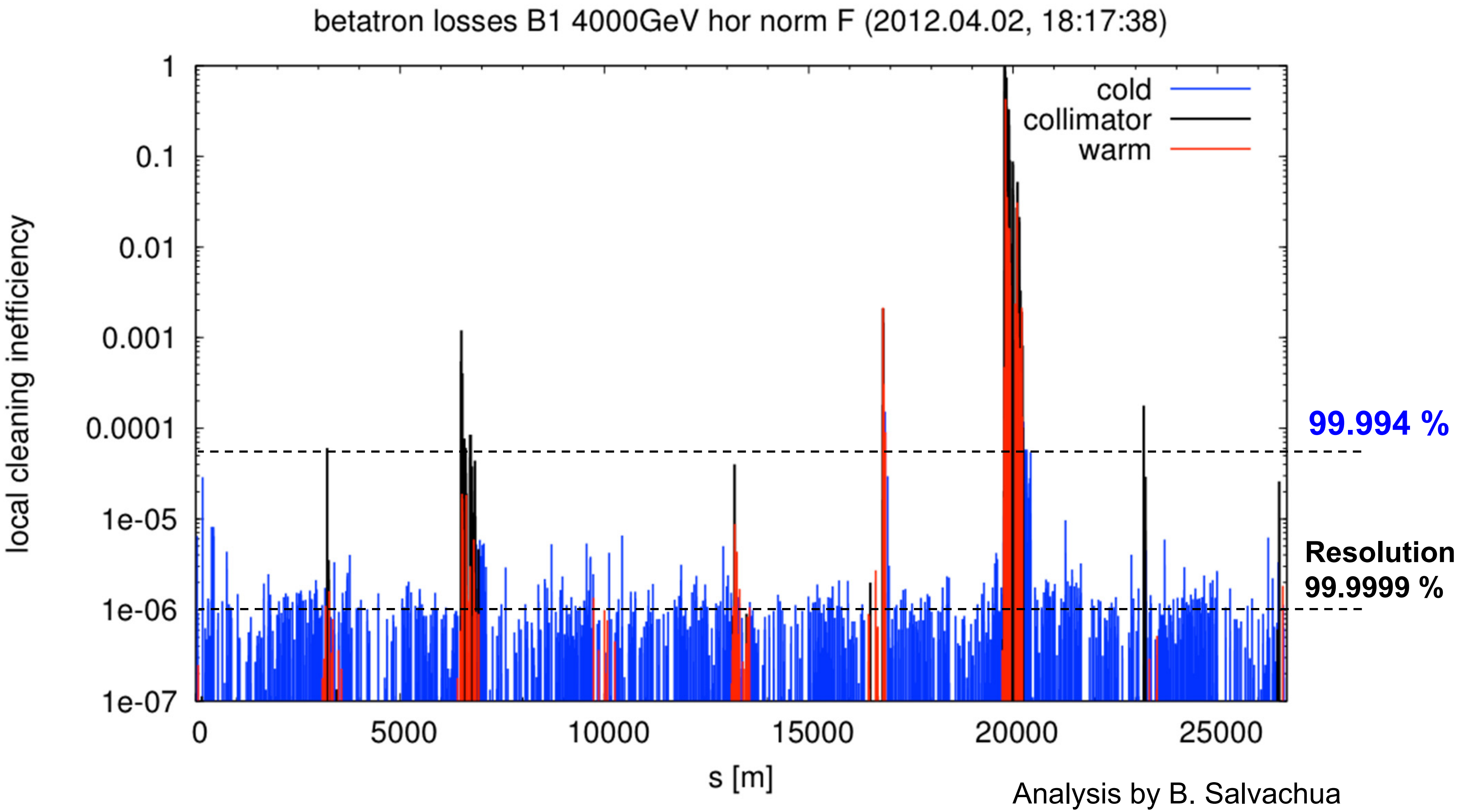
Meas. & Sim. Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



Confirms expected limiting losses in SC dispersion suppressor:

single-diffractive losses

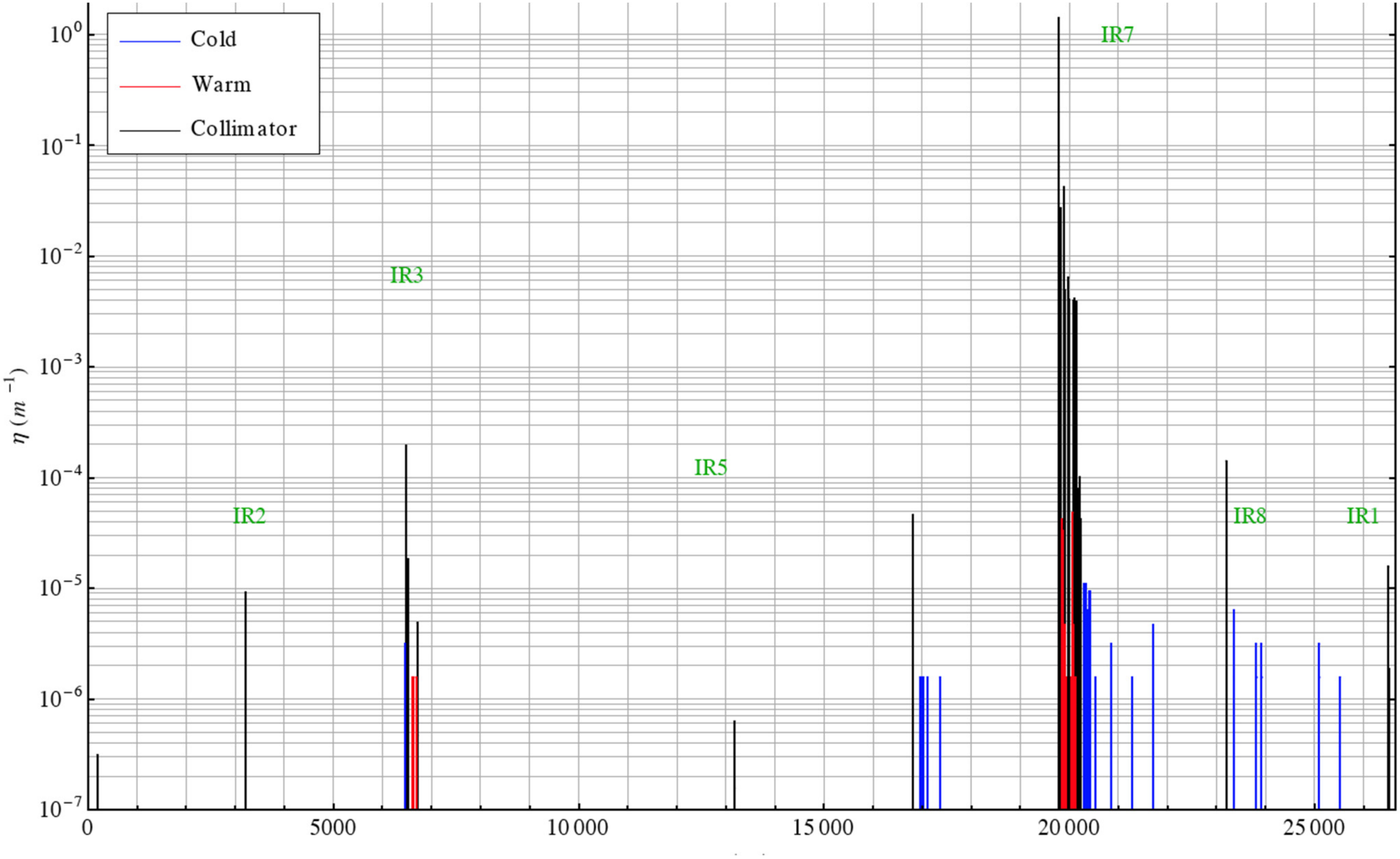
4 TeV: B1 HOR Measured



Analysis by B. Salvachua

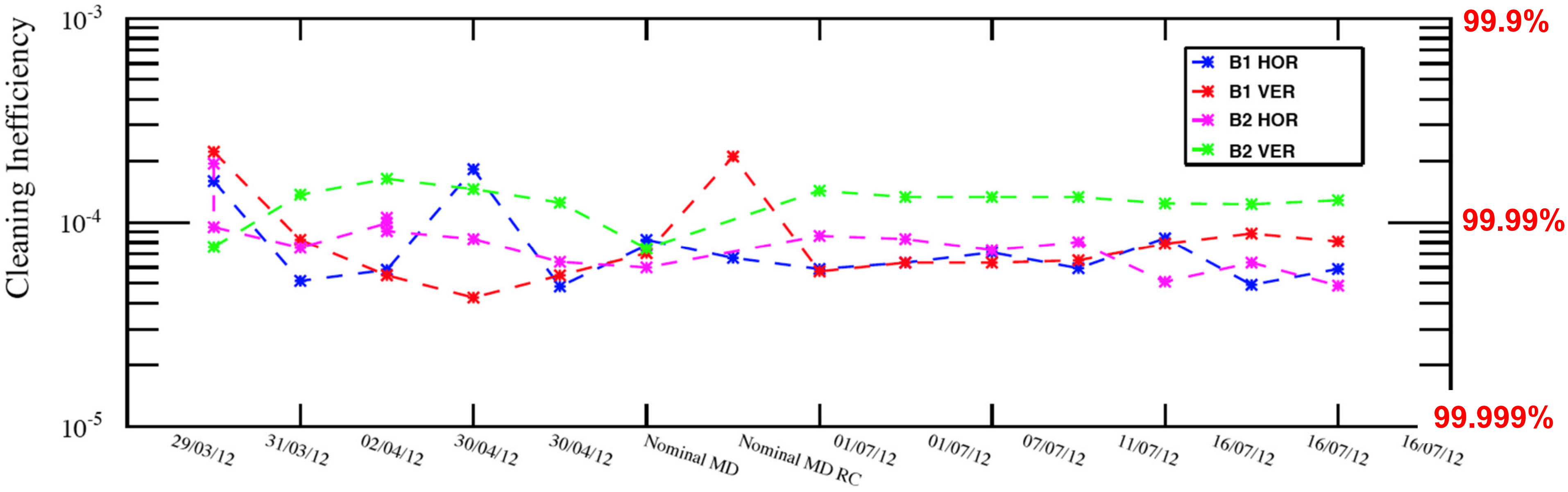
Simulation…

(preliminary work for 4 TeV)



Simulation by R. Bruce

Betatron Cleaning at 4 TeV: 2012 Stability Over 16 Weeks



Beam 1, beam 2 each HOR and VER

Analysis by B. Salvachua and D. Wollmann

→ Setup methods, qualification tools and settings: See talk by G. Valentino, one of our PhD students!

Conclusion

- The LHC collimation system has been designed, produced, installed and commissioned over the last 10 years! Advanced halo simulations have been used for all design choices.
- LHC collimation works with expected performance level and has shown an amazing stability over up to a year. Simulations are confirmed!
- Routinely collimating 145 MJ beams in SC magnets with quench limits below 100 mJ/cm^3. Not a single quench with stored beam!
- This illustrates the predictive power that advanced simulations can have nowadays. Ingredients:
  - Much more CPU power.
  - Right decisions on assumptions: no diffusion simulated, correct impact parameter, fully chromatic, orthogonal phase space cuts, …
- Upgrades will gain another factor 5-10 in efficiency.
- Proton beam halo can be predicted and simulated quite accurately!