Operational Experience with the LHC Collimation System

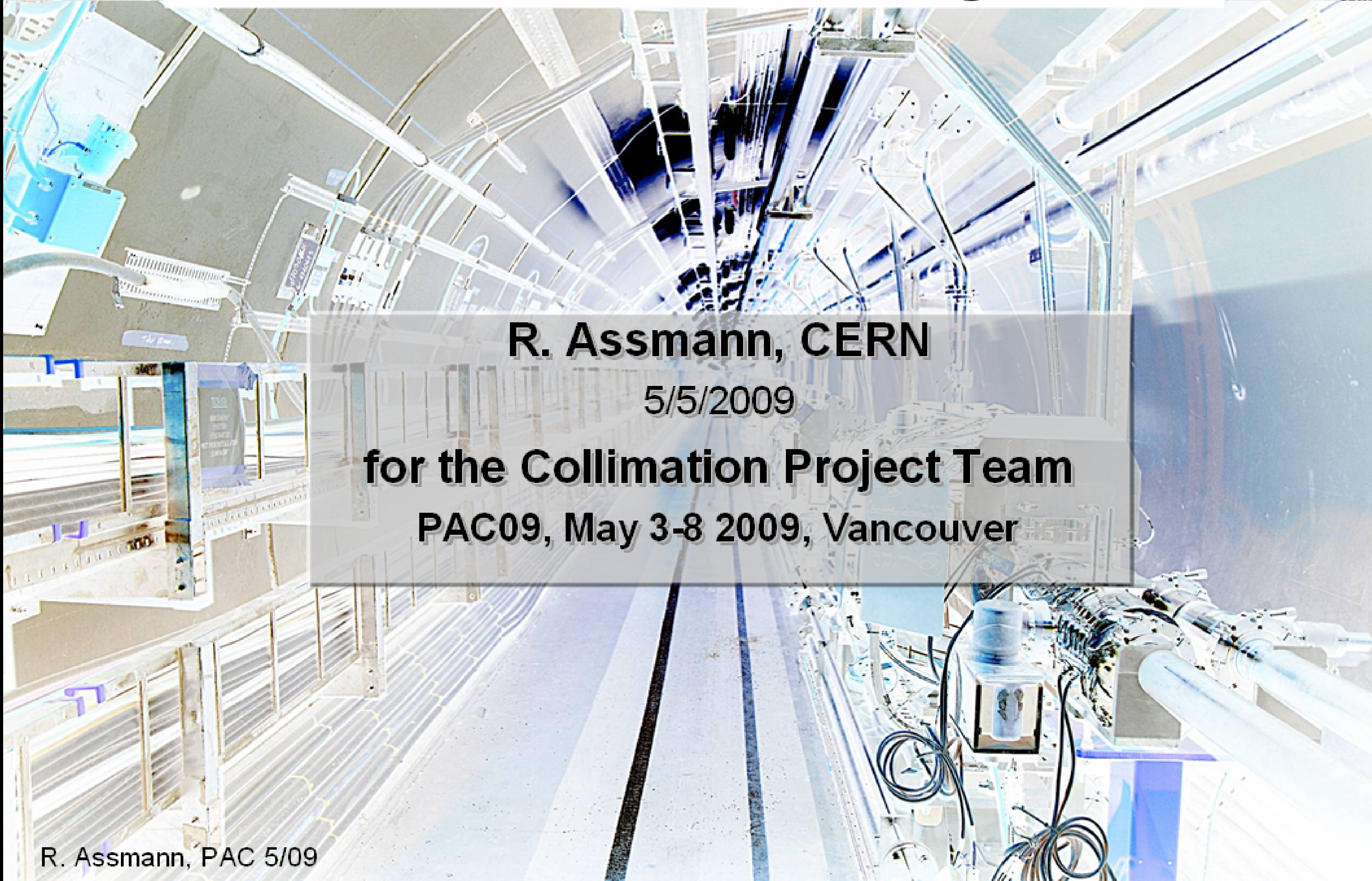
R. Assmann, CERN

5/5/2009

for the Collimation Project Team

PAC09, May 3-8 2009, Vancouver

~~Operational~~ Experience with the LHC Collimation System



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First Experience with the LHC Collimation System

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5/5/2009

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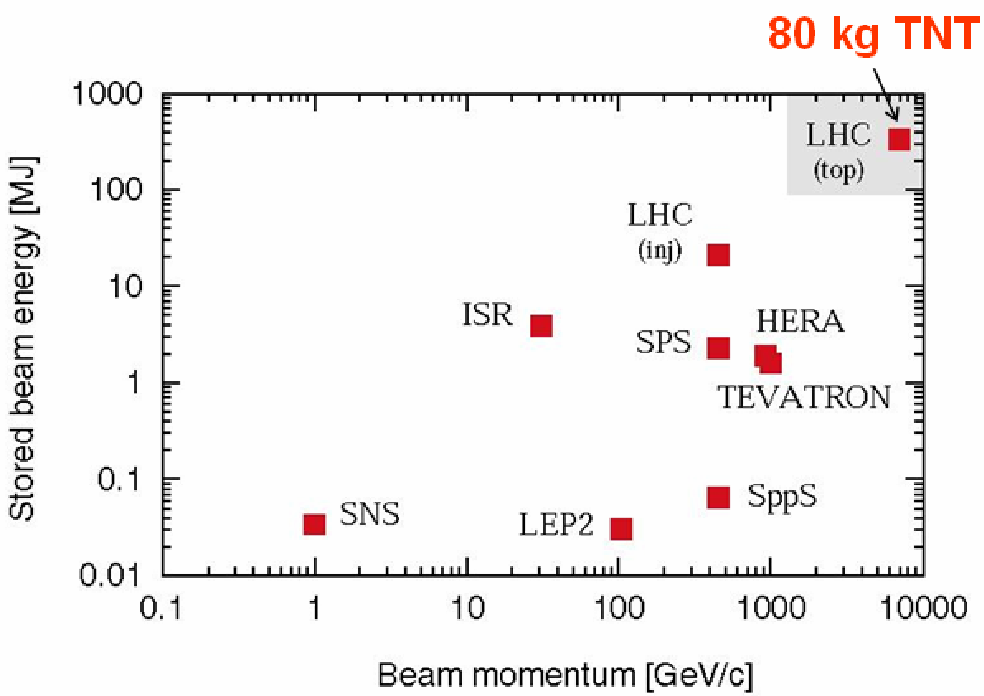
PAC09, May 3-8 2009, Vancouver

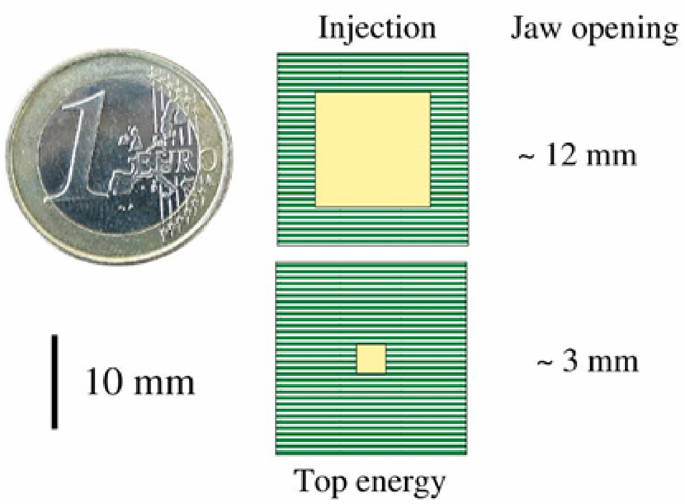
The LHC Challenge

- **LHC extrapolates stored energy by 2-3 orders of magnitude beyond state of the art**, while beam momentum is extrapolated by factor 7!

High stored energy and stored energy density!



Small collimation gaps!



Low emittance at 7 TeV!

Luminosity and Stored Energy

- Luminosity can be expressed as a **function of transverse energy** E_{stored} that is stored in each beam (*for round beams at IP*):

$$L = \frac{1}{4\pi \cdot m_0 c^2} \cdot \frac{f_{rev} \cdot N_p \cdot F}{\beta^* \cdot \varepsilon_n} \cdot E_{stored}$$

β^* = *IP beta function* ($\beta_x = \beta_y$)
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*

- To reach **10^{34} cm^{-2}s^{-1}** the LHC needs to store **360 MJ per beam**, more than 100 times the present world record in super-conducting colliders.

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constant **tunnel length**

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$$L = \underbrace{\frac{1}{4\pi \cdot m_0 c^2}}_{\text{constant}} \cdot \frac{\overbrace{f_{rev}}^{\text{tunnel length}} \cdot \overbrace{N_p \cdot F}^{\text{beam-beam limits}}}{\beta^* \cdot \varepsilon_n} \cdot E_{stored}$$

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constant — tunnel length — beam-beam limits — IR optics limits

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constant: $\frac{1}{4\pi \cdot m_0 c^2}$

tunnel length: f_{rev}

beam-beam limits: $N_p \cdot F$

IR optics limits: β^*

Injectors limits, Robustness limits: ε_n

β^* = IP beta function ($\beta_x = \beta_y$)

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

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constant → $\frac{1}{4\pi \cdot m_0 c^2}$

tunnel length → f_{rev}

beam-beam limits → $N_p \cdot F$

IR optics limits → β^*

Injectors limits
Robustness limits → ε_n

LHC luminosity is increased via stored energy! → E_{stored}

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SC Magnets: Preventing Quenches

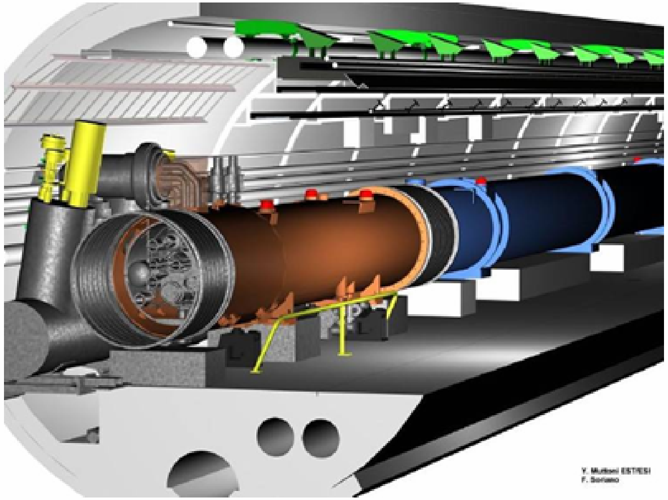
- Shock beam impact: **2 MJ/mm² in 200 ns (0.5 kg TNT)**
- Maximum **beam loss at 7 TeV**: 0.1% of beam (360 MJ) per second

  (assumed lower than Tevatron/HERA)

360 kW ➔ proportional to stored energy

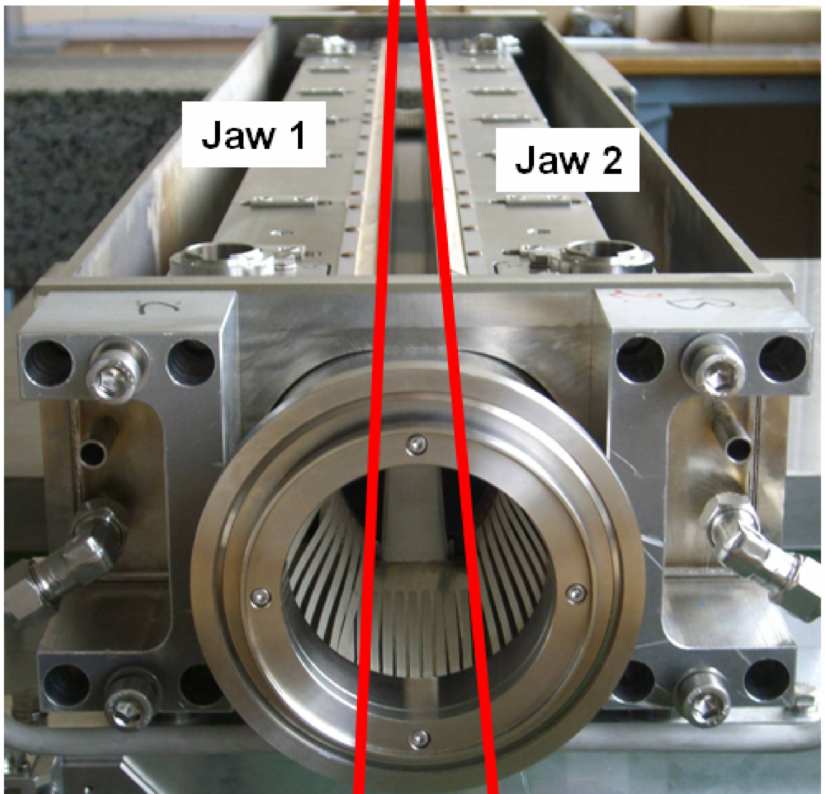
- **Quench limit** of SC LHC magnet:

~ 5 mW/cm³



LHC Collimators: Dilute and Stop

Quench limit: **~ 5 mJ/mm²** (any SC magnet)



Required "filter" factor:

1×10^{-10} = Leakage / Dilution

Leakage factor (inefficiency): **10^{-4}**

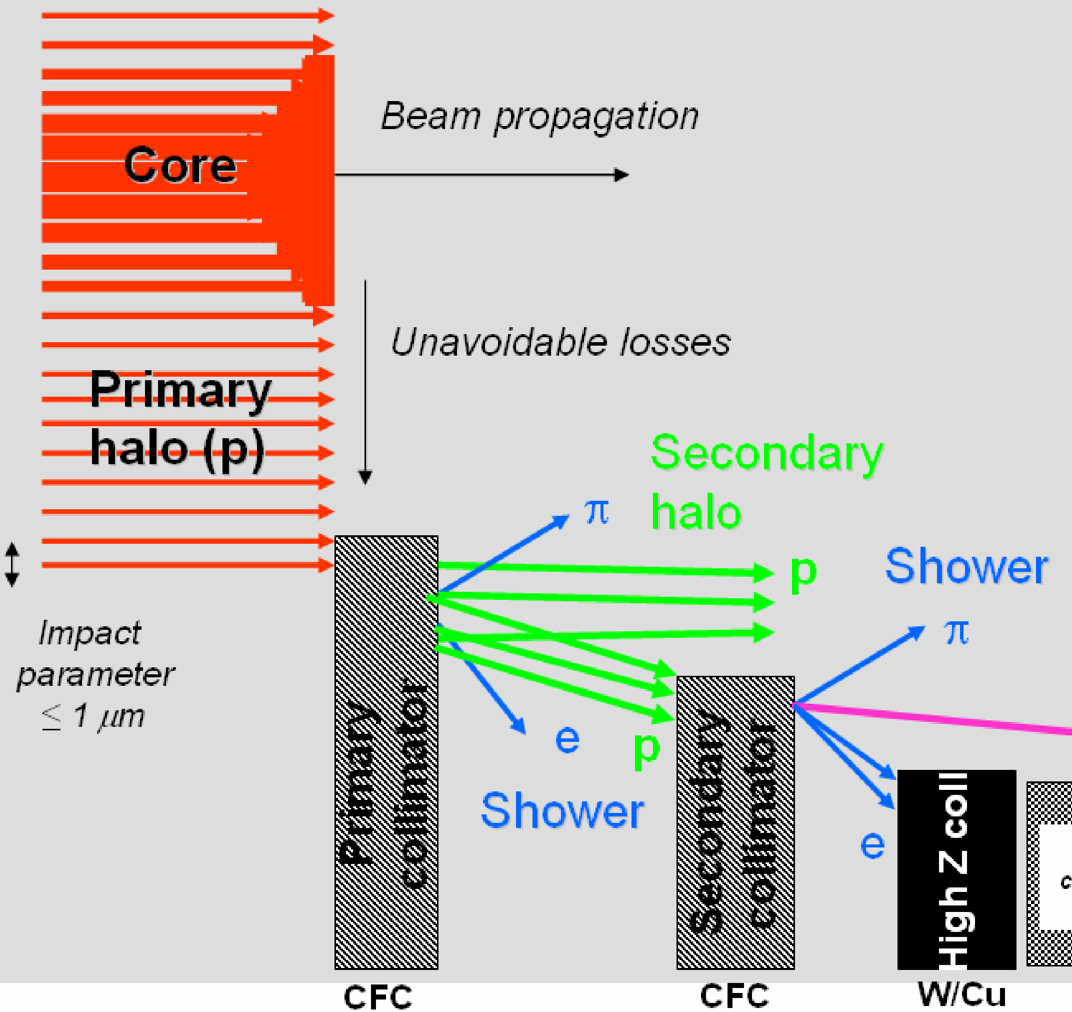
Dilution factor: **10^{6}**

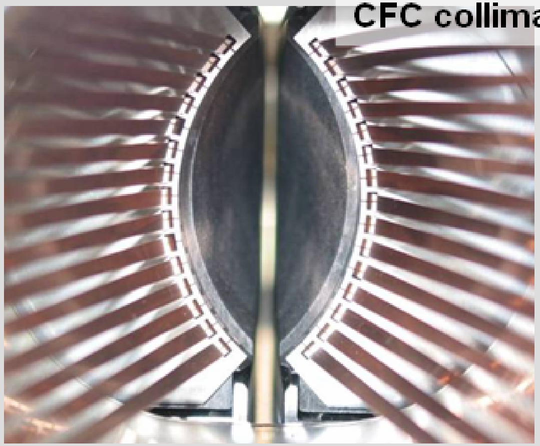
Cannot be achieved with single collimator → therefore multi-stage collimation for betatron cleaning (x, y, skew) and momentum cleaning.

Incoming: up to **~ 50 MJ/mm²** (primary collimator)

Multi-Stage Cleaning & Protection

3-4 Stages





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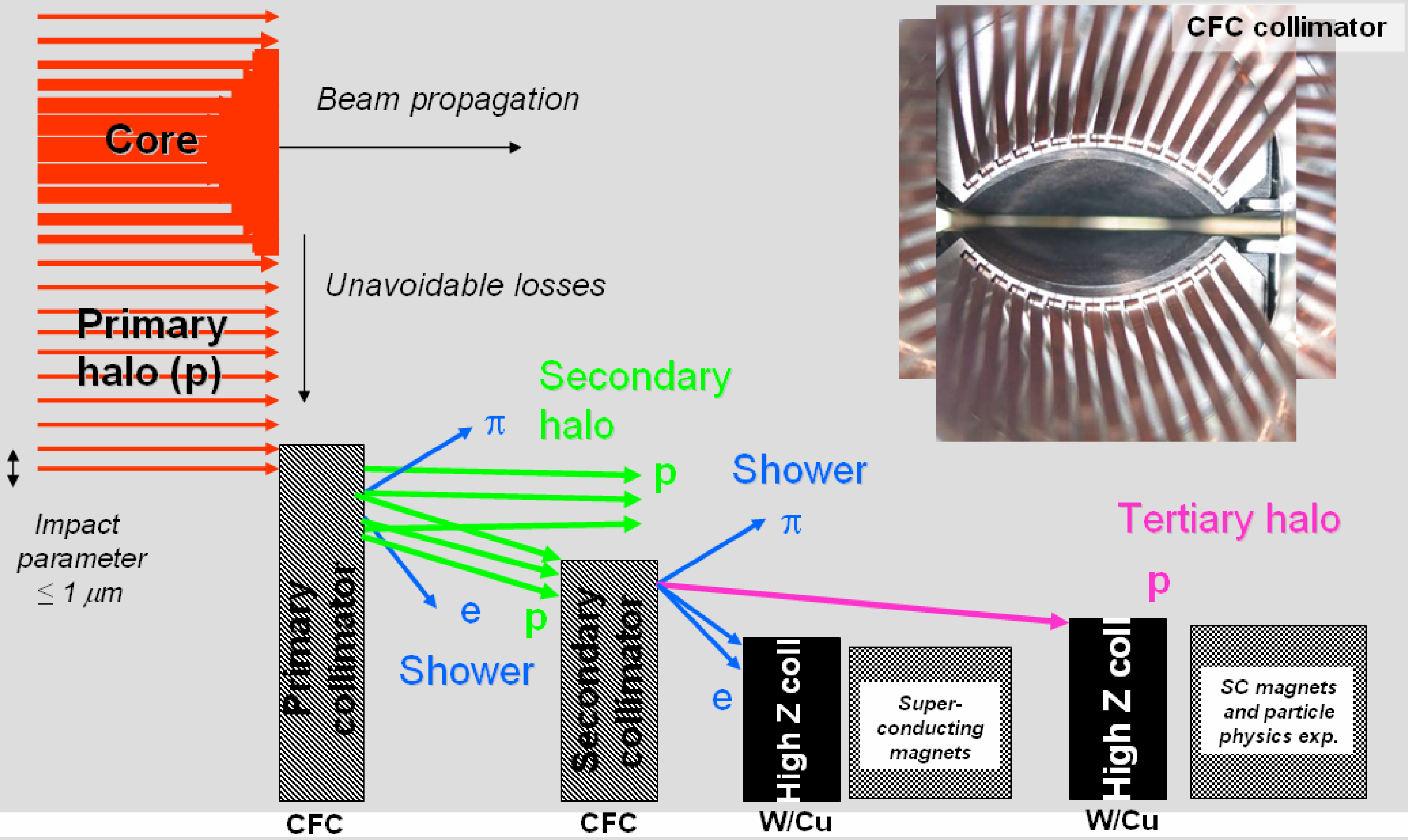

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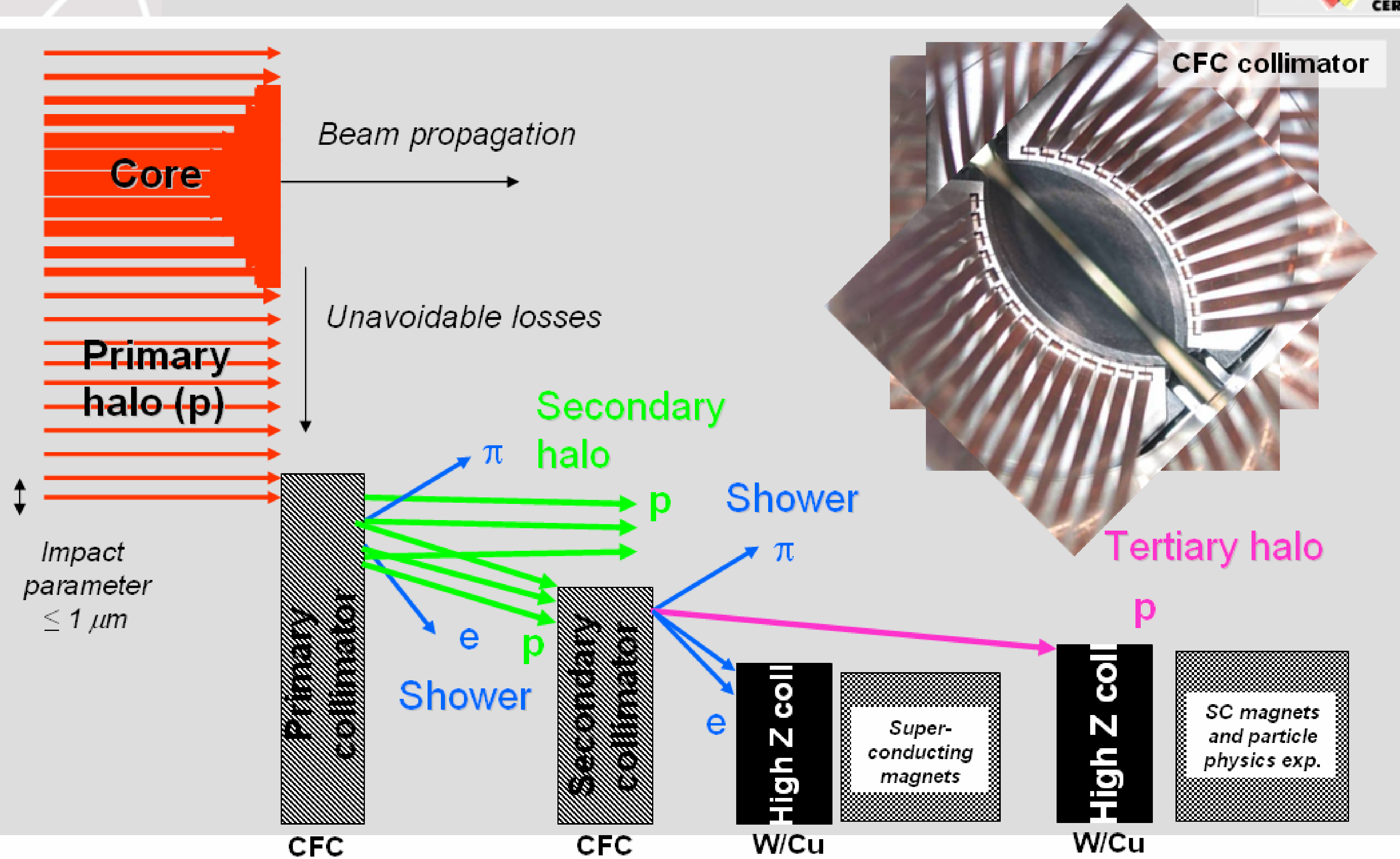

Multi-Stage Cleaning & Protection

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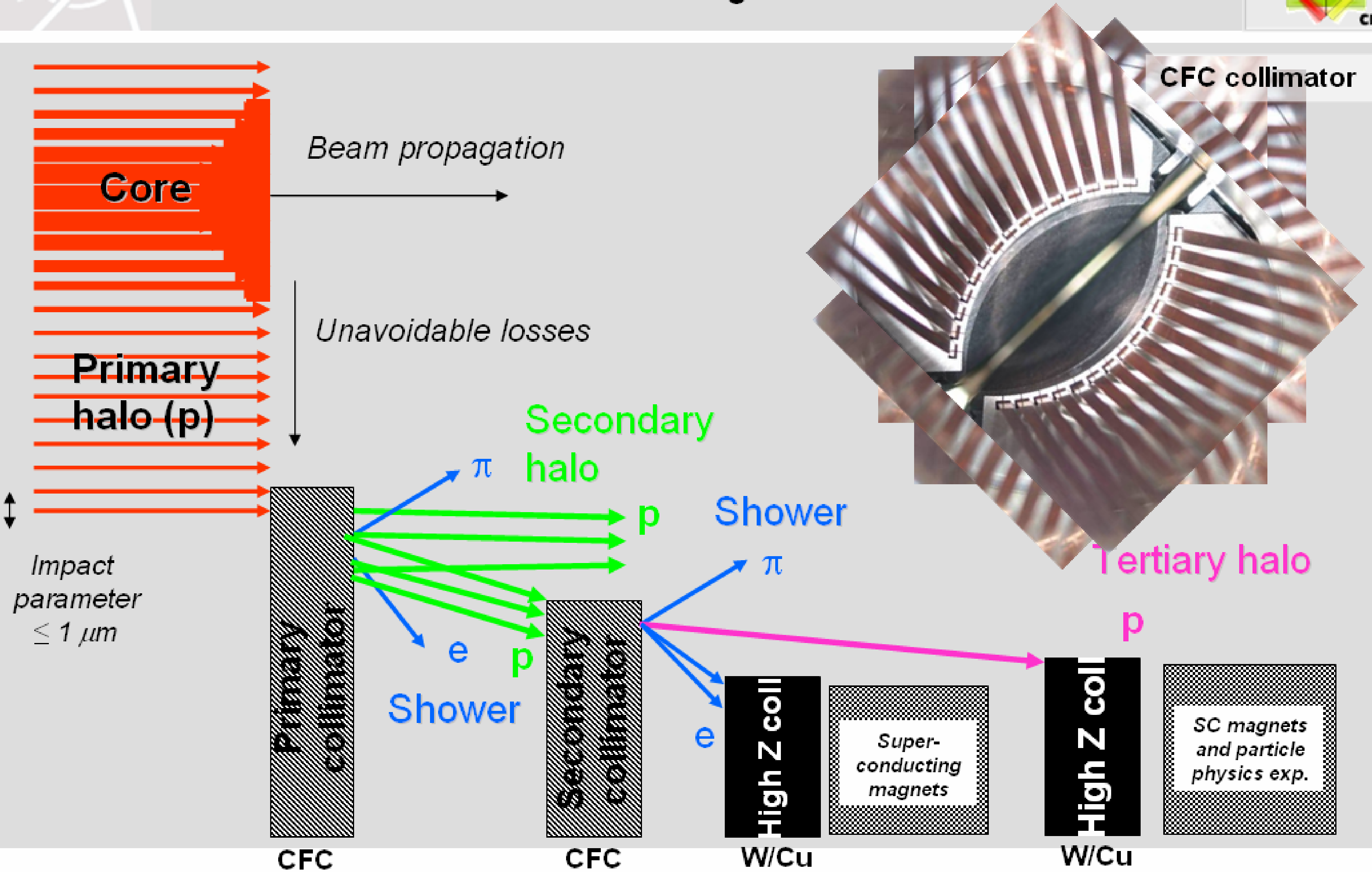
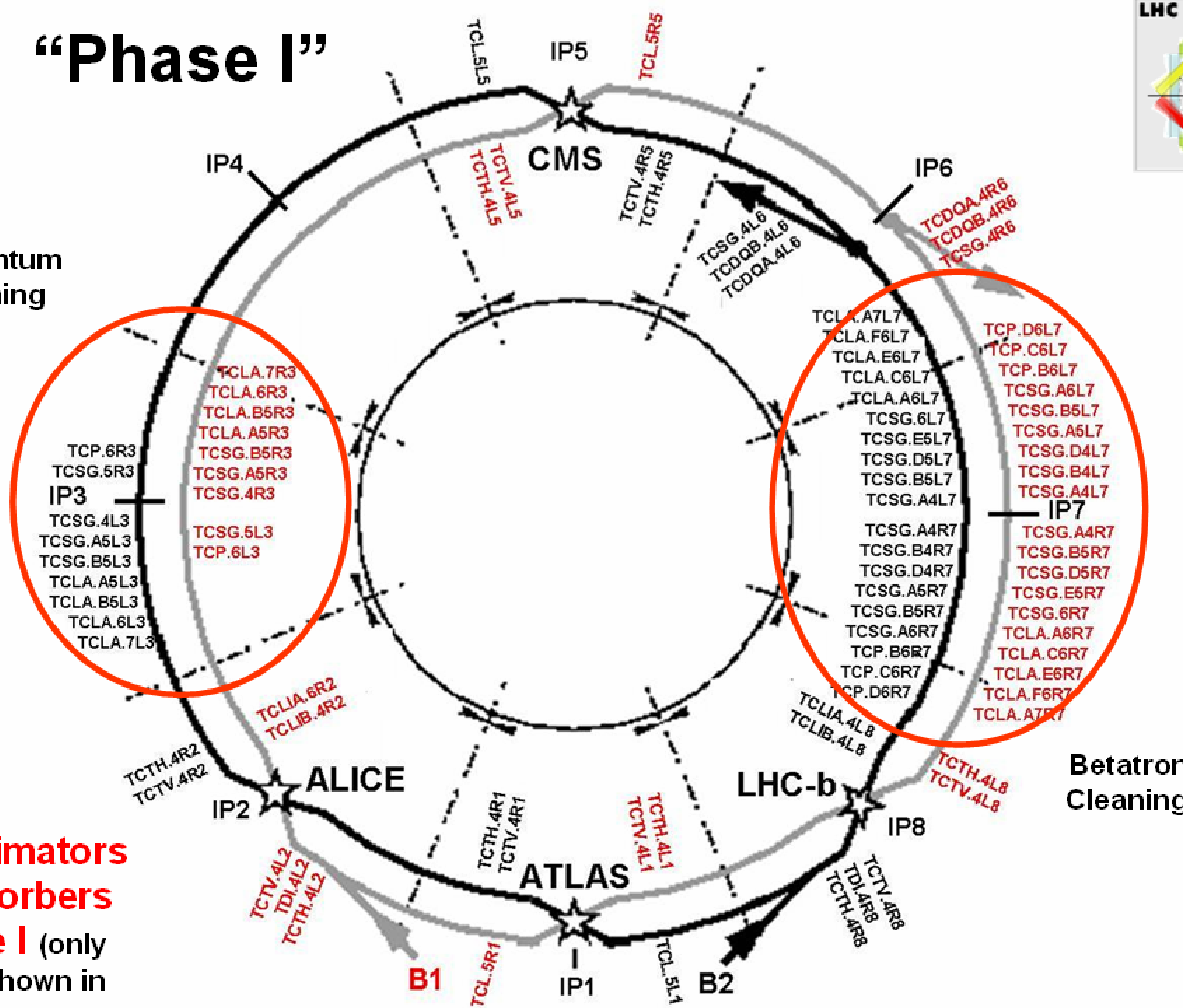


"Phase I"



108 collimators and absorbers in phase I (only movable shown in sketch)

Precision Requirements

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

Gaps: **± 6/7 σ**

2-3 mm

LHC collimators must work as precision devices!

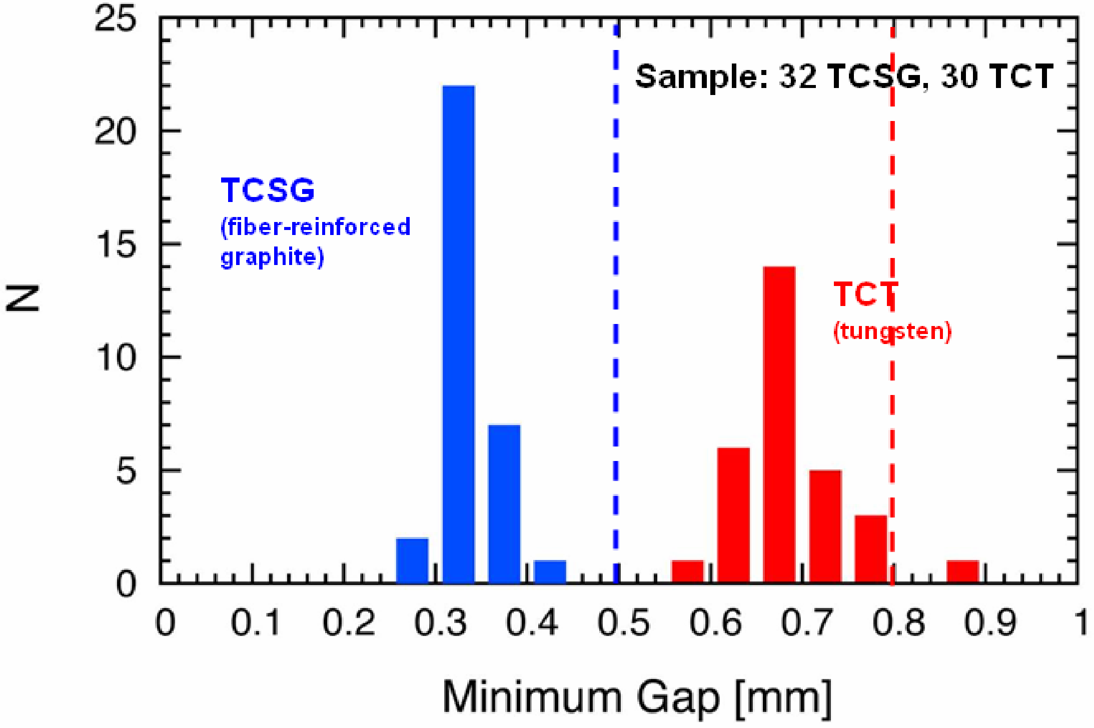
Parameter		Unit	Specification
Jaw material			CFC
Jaw length	TCS TCP	cm cm	100 60
Jaw tapering		cm	10 + 10
Jaw cross section		mm^2	65 x 25
Jaw resistivity		μΩm	≤ 10
Surface roughness		μm	≤ 1.6
Jaw flatness error		**μm**	**≤ 40**
Heat load		kW	≤ 7
Jaw temperature		°C	≤ 50
Bake-out temp.		°C	250
Minimal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

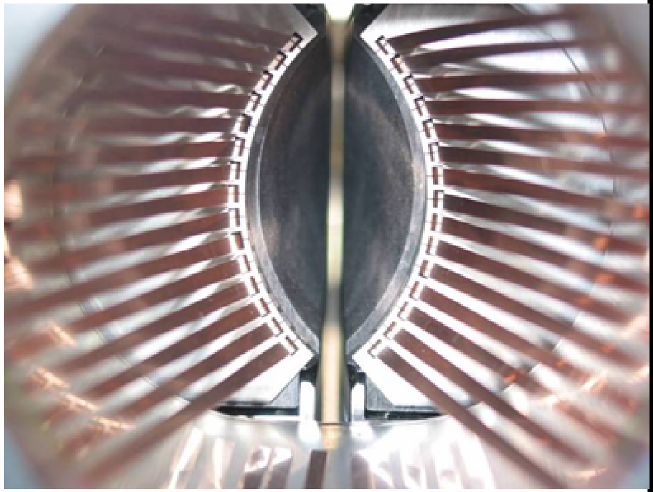
2003 Specification

The LHC Collimation System

- The **by far largest and most precise system of its kind** that has been built to this date:
  - 130 phase I collimators and absorbers produced with specifications and control at 10 μm level (including spares).
  - **Phase I:** In total **108 devices** installed (~210 m length occupied). 97 movable collimators with a total of 194 jaws and > 450 degrees of freedom for positioning. **All ready for LHC startup. Results shown here…**
  - **Phase II:** In total **158 devices** installed (~ 310 m length occupied). 147 movable collimators. Majority approved and infrastructure installed.
  - **Maximum possible:** In total **168 devices** installed (~ 330 m length occupied). Only space reservations at this time.
- Investment (cost & manpower) comparable to a small accelerator.
- Design, R&D, prototyping, series production, installation and commissioning has been managed since late 2002 through the **CERN LHC collimation project**.

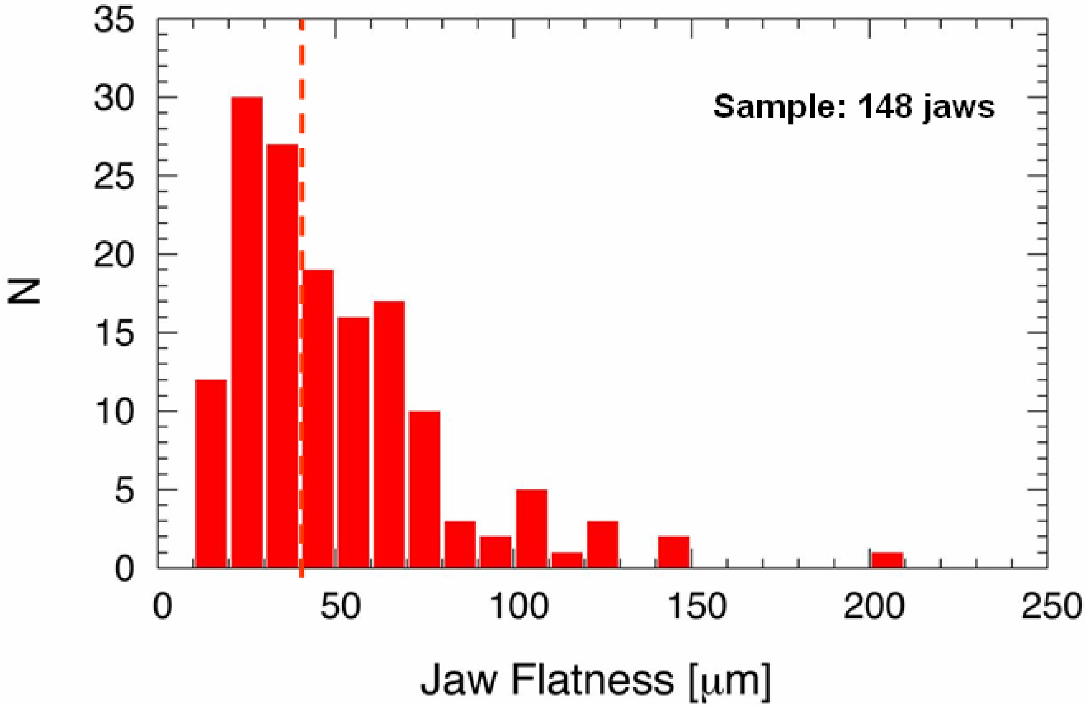
Production: Minimum Collimation Gap (Ring)

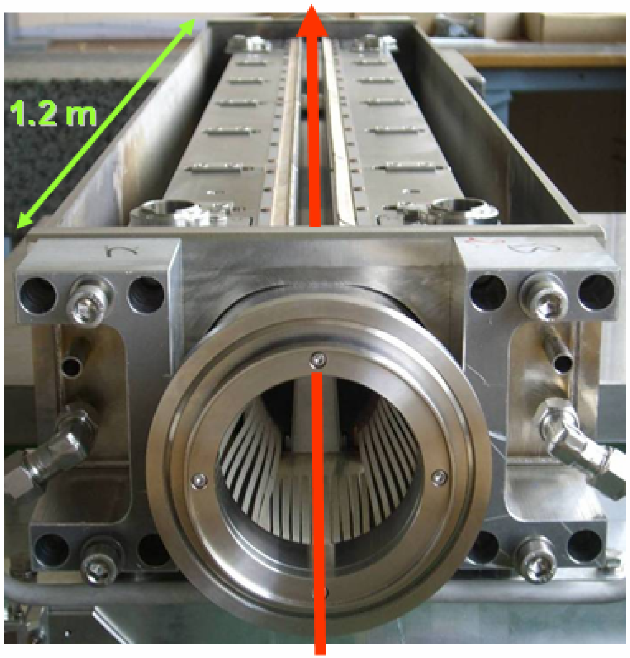




High precision collimators produced adequate for LHC conditions!

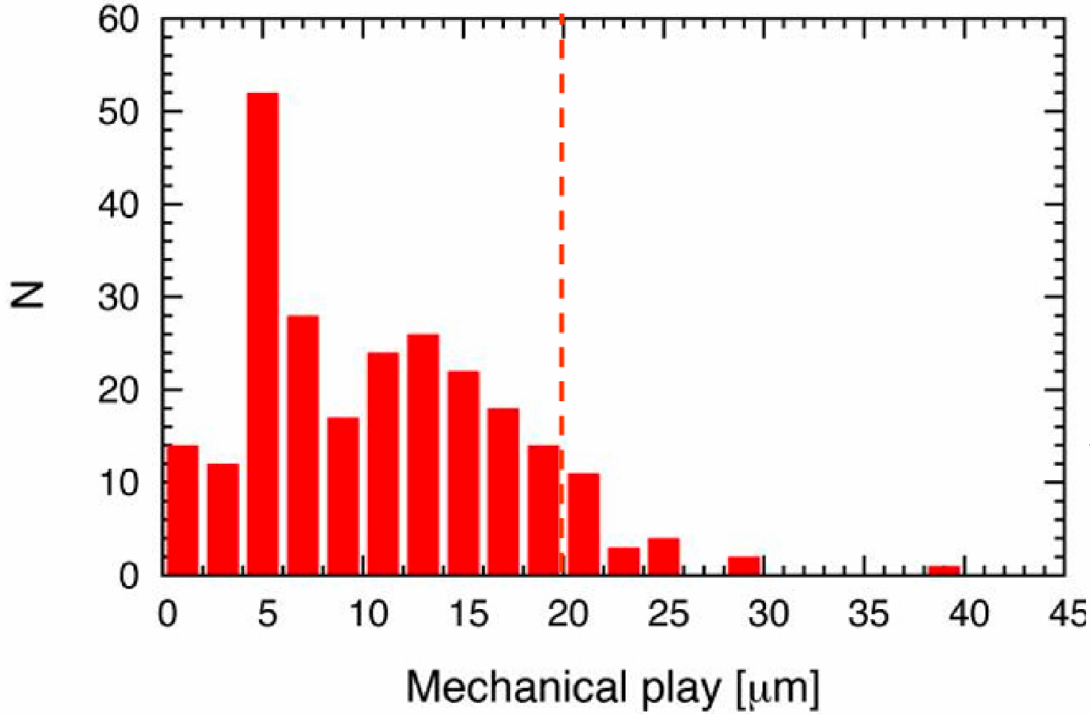
Production: Jaw Flatness (Ring & TL)

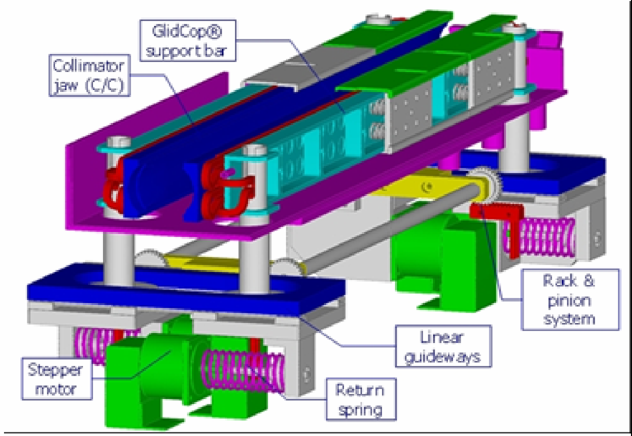




Flatness better than many feared. Out of tolerance collimators were placed in locations with more relaxed tolerances, meaning larger beta (limited sorting). Enough collimators for tightest places (40 μm).

Production: Mechanical Play (Ring & TL)

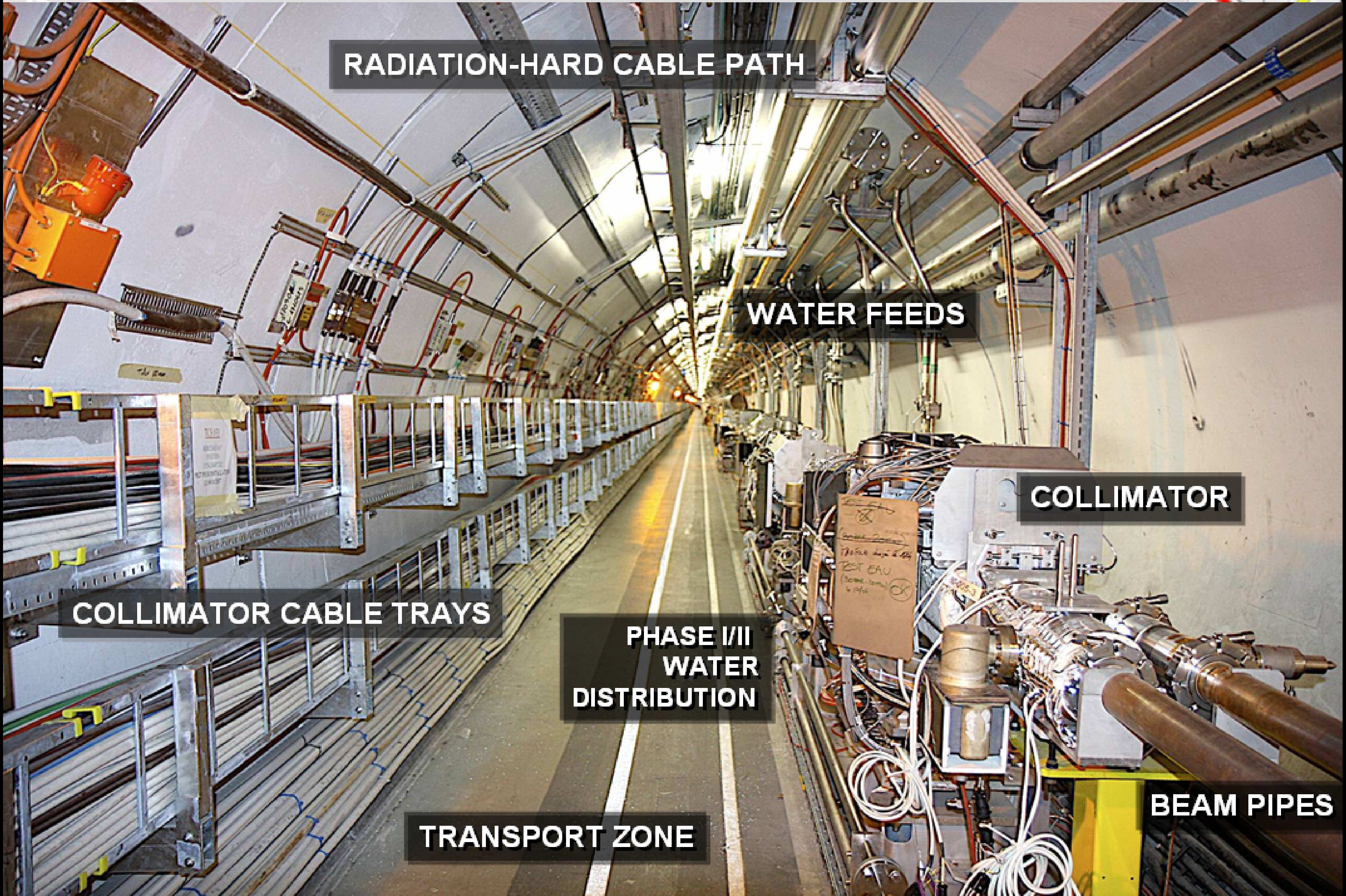




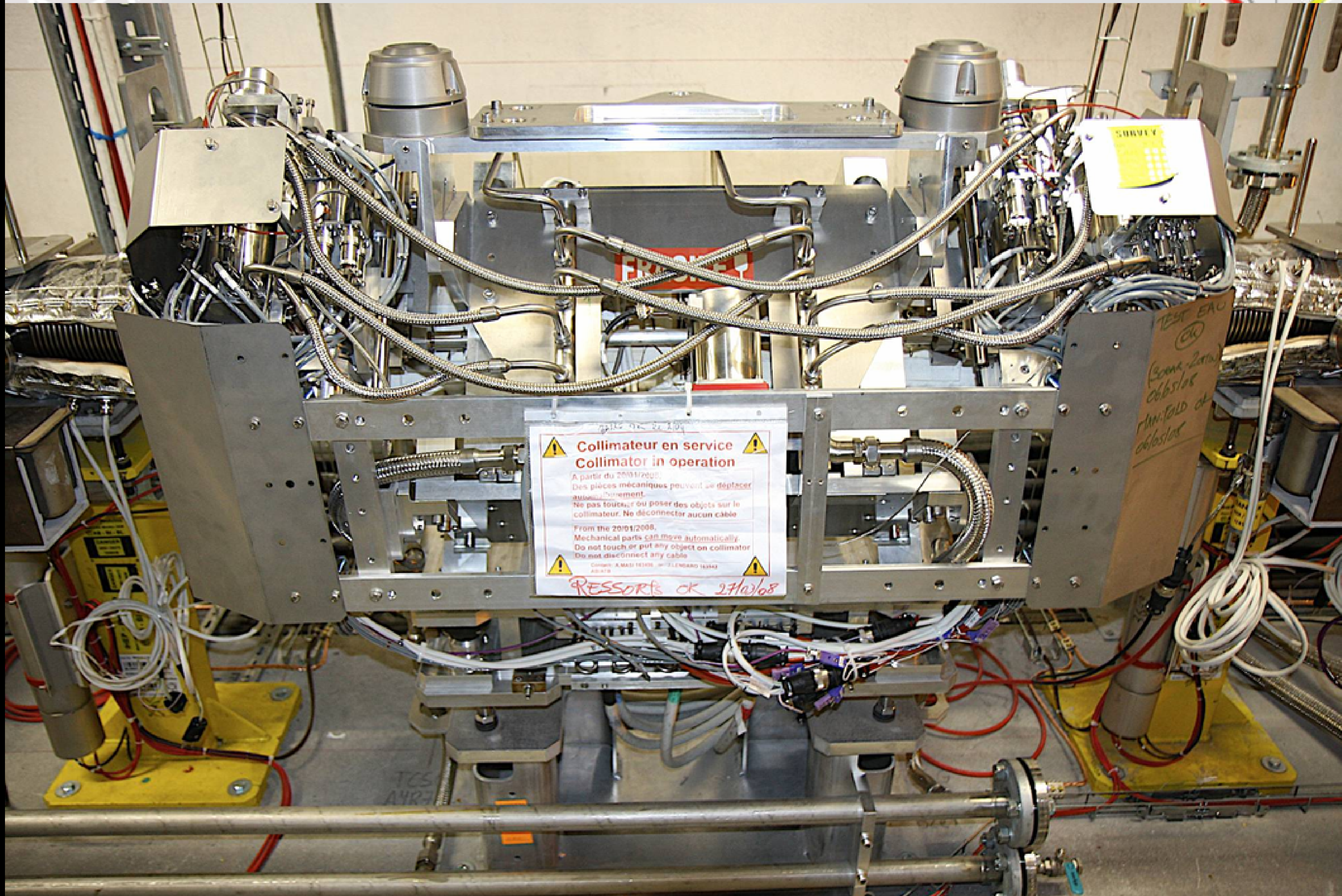
Mechanical play in movement system when reversing direction.

Specification of 20 μm well achieved. Will be corrected for in operational use.

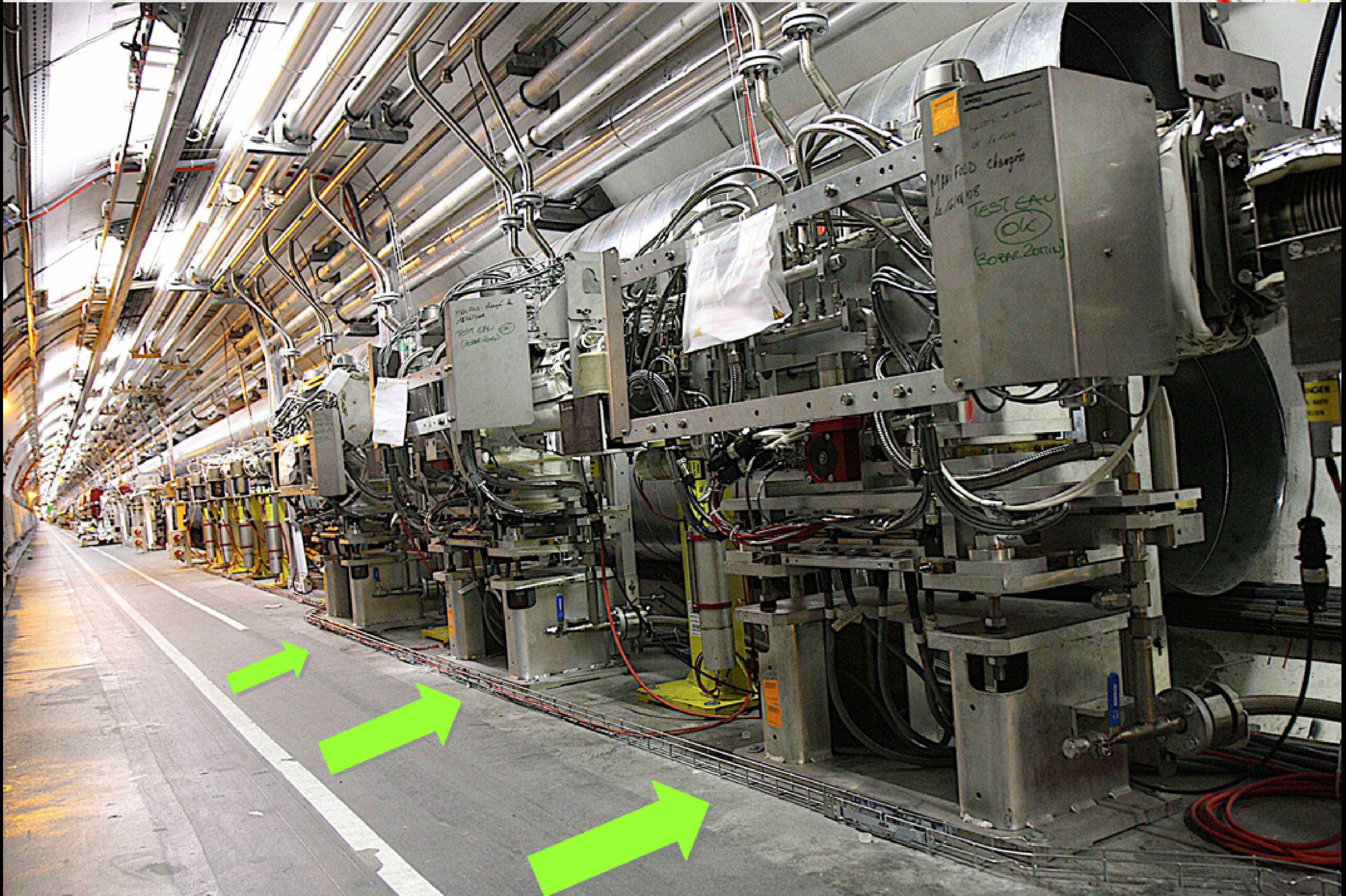
Tunnel: Cleaning Insertion IR7



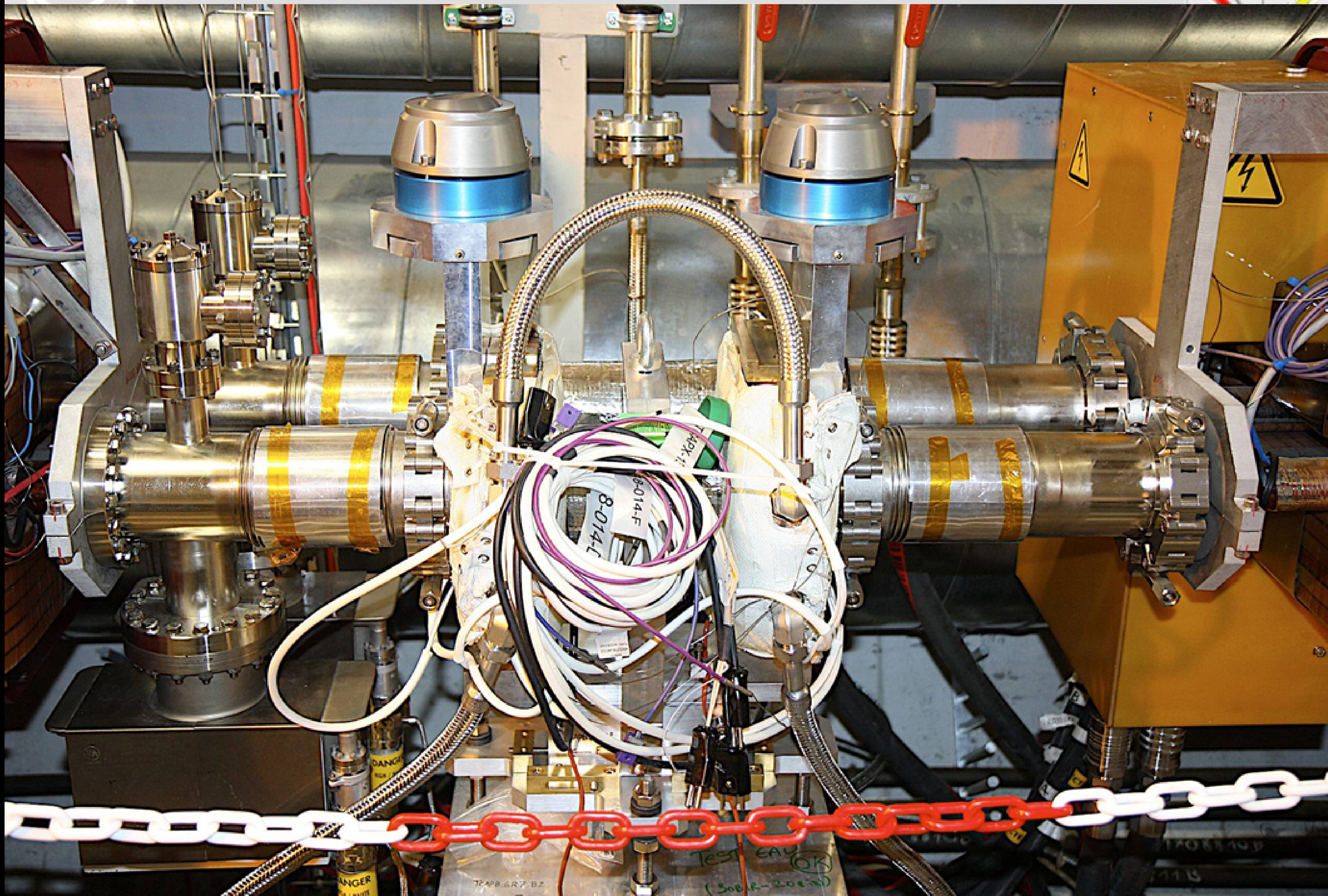
Tunnel: Side View Phase I Collimator



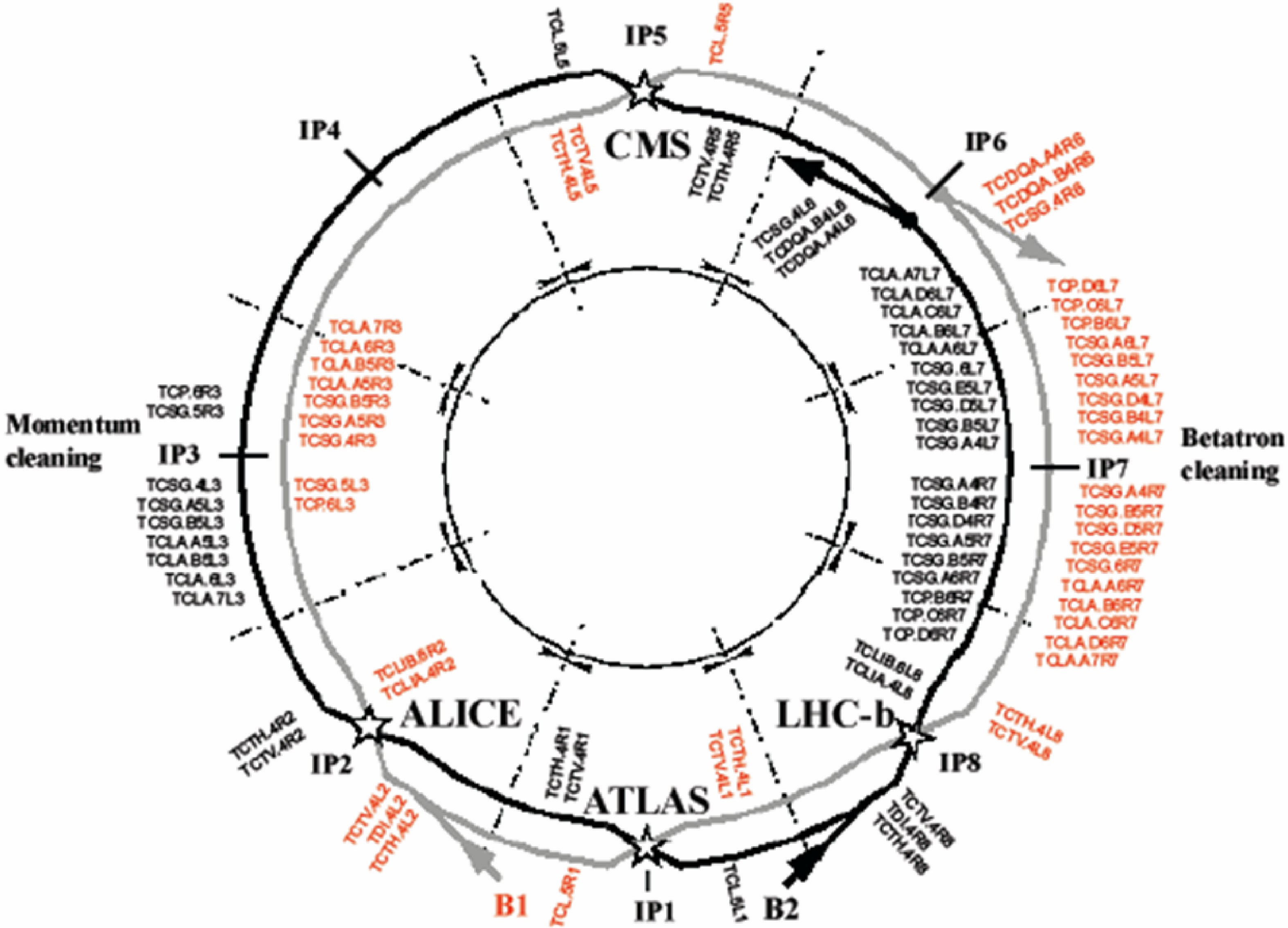
Tunnel: 3 Primary Betatron Collimators



Tunnel: Passive Absorber TCAPA



First Beam Day: 10 Sep 2008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TCL.6L5
TCL.5R5
TCTV.4L5
TCTH.4L5
TCTV.4R5
TCTH.4R5
IP4
IP6
TCDQA.A4R6
TCDQA.B4R6
TCSG.4R6
TCSG.4L6
TCDQA.B4L6
TCDQA.A4L6
TCLA.A7L7
TCLA.D6L7
TCLA.C6L7
TCLA.B6L7
TCLA.A6L7
TCSG.6L7
TCSG.E5L7
TCSG.D5L7
TCSG.B5L7
TCSG.A4L7
TCP.D6L7
TCP.C6L7
TCP.B6L7
TCSG.A6L7
TCSG.B5L7
TCSG.A5L7
TCSG.D4L7
TCSG.B4L7
TCSG.A4L7
Betatron
cleaning
IP7
TCSG.A4R7
TCSG.B4R7
TCSG.D4R7
TCSG.A5R7
TCSG.B5R7
TCSG.A6R7
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TCP.C6R7
TCP.D6R7
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TCSG.B5R7
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TCSG.6R7
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TCLA.D6R7
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TCLA.7R3
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TCLA.A5R3
TCSG.B5R3
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TCSG.4R3
TCP.6R3
TCSG.5R3
Momentum
cleaning
IP3
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TCSG.B5L3
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TCLA.6L3
TCLA.7L3
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TCP.6L3
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TCLIA.4R2
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TCTV.4R2
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TDI.4L2
TCTH.4L2
B1
TCL.5R1
ATLAS
TCTH.4R1
TCTV.4R1
TCTH.4L1
TCTV.4L1
IP1
TCL.6L1
B2
LHC-b
TCLIB.6L8
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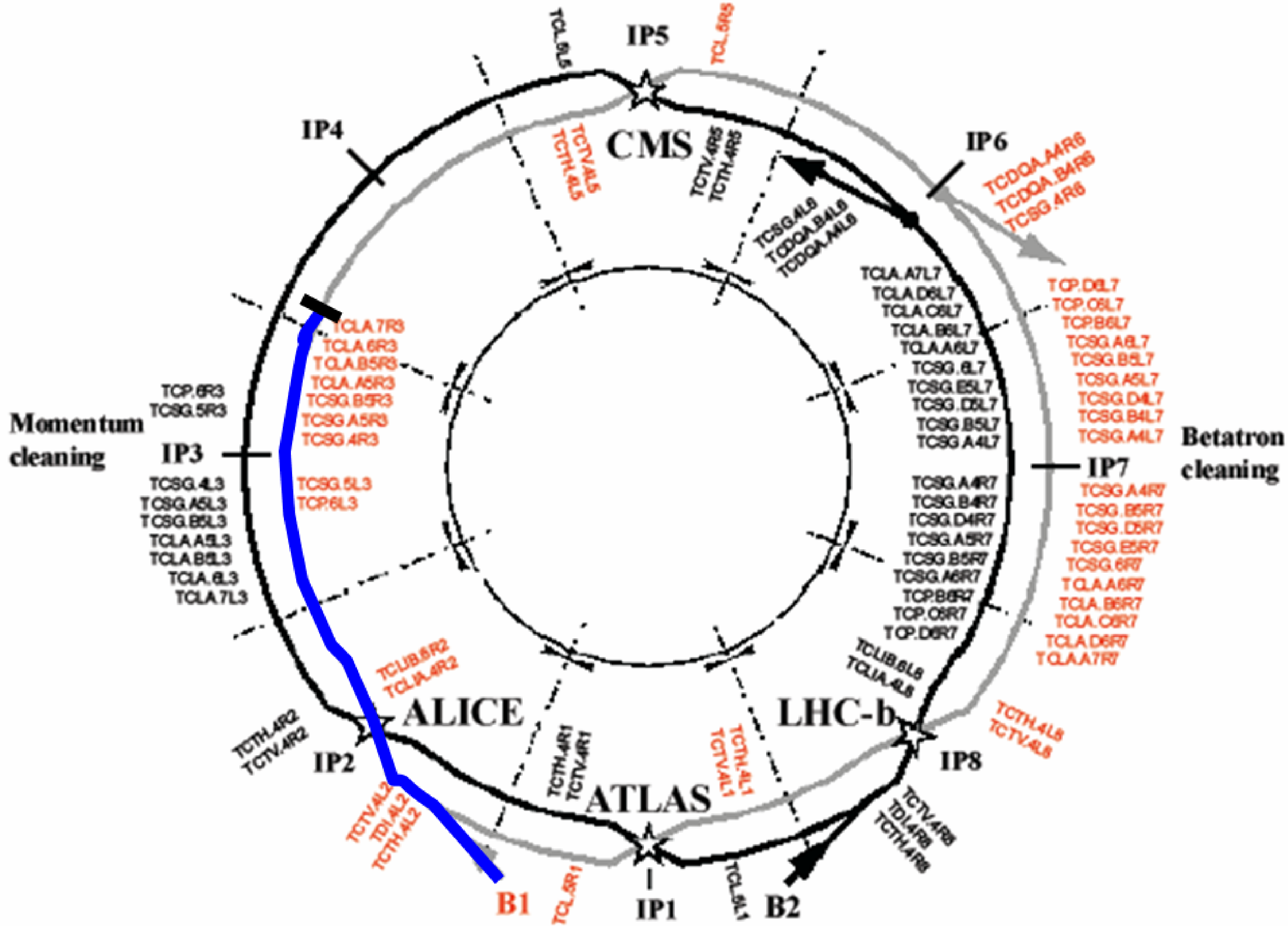
TCTH.4R8


IP5
CMS
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IP6
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Momentum cleaning
IP7
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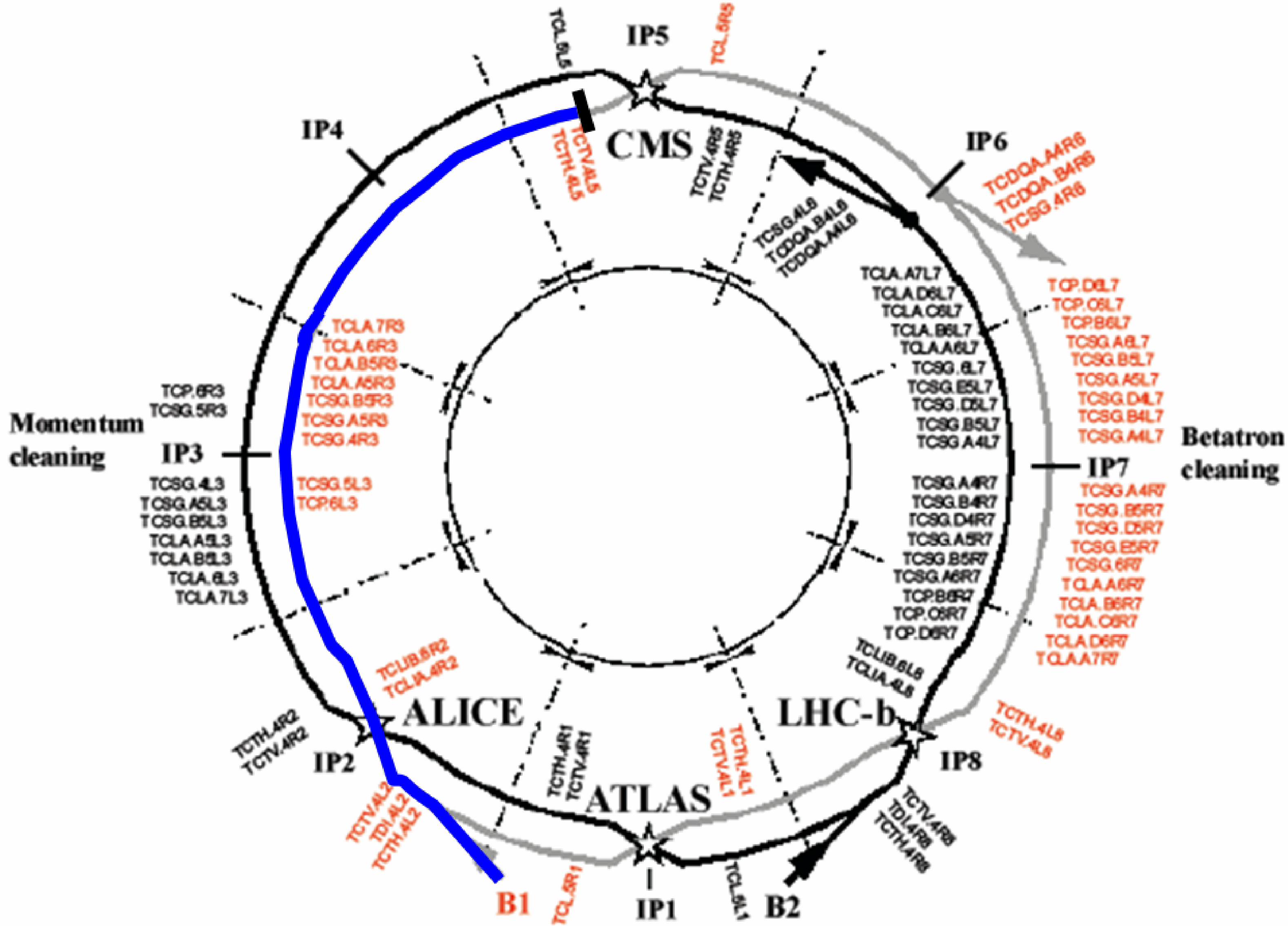
TCP.6L3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TDI.4L2
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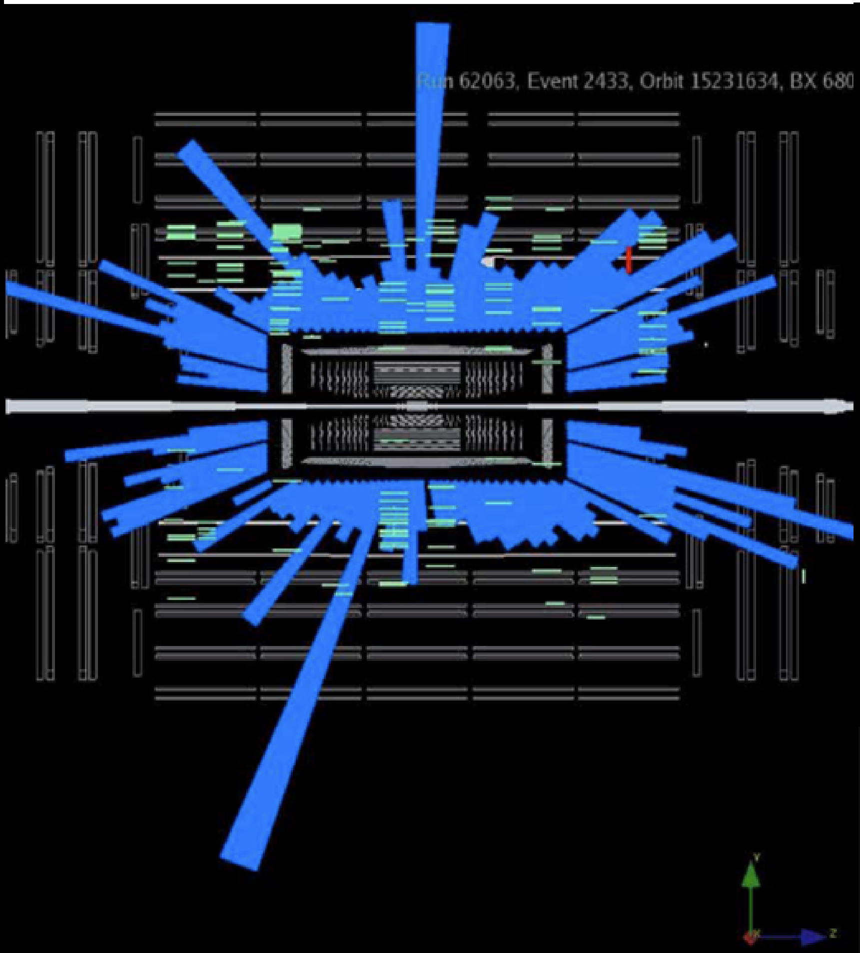
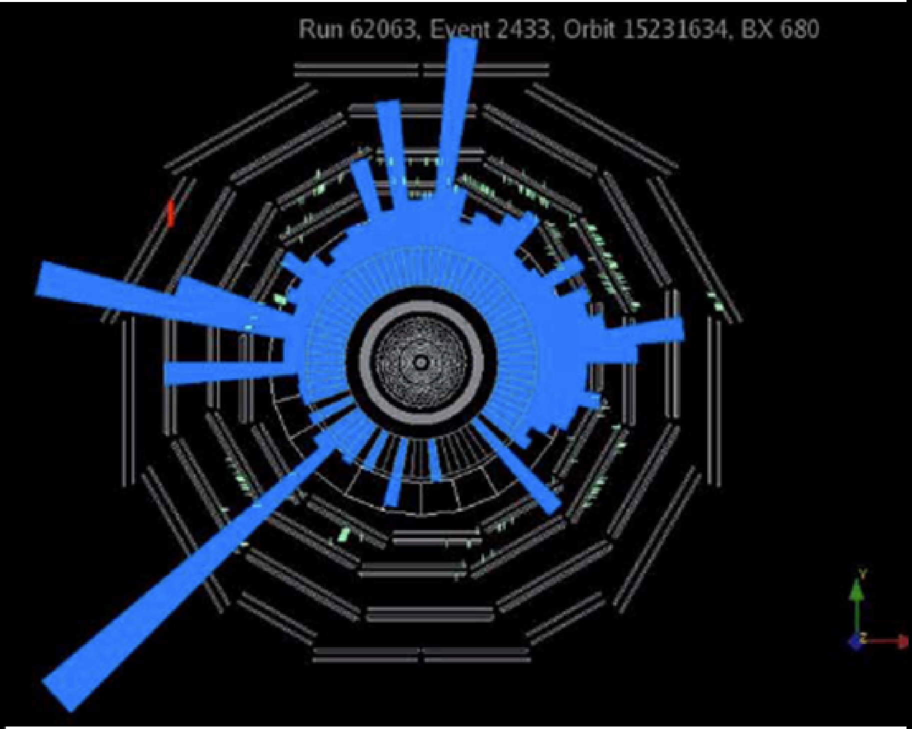
TCL.5L1
TCLIB.6L8
TCLIA.4L8
TCTH.4L8
TCTV.4L8
TCTV.4R8
TDI.4R8
TCTH.4R8

Tertiary Collimator "Splash" Events



CMS view of beam hitting collimator

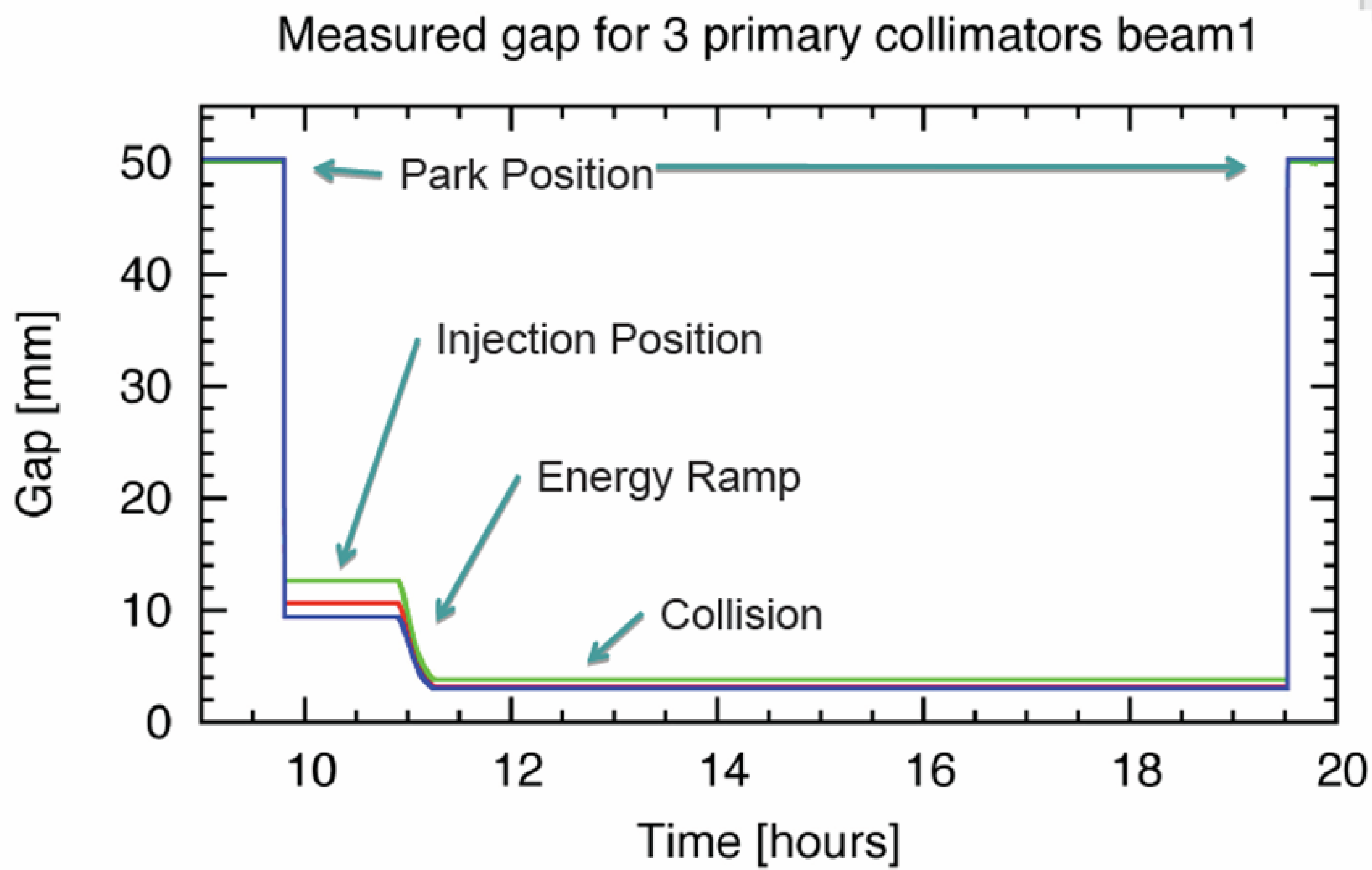


Events now, background later…

Performance Highlights

- Collimators **used very successfully as stoppers and fixed targets** during September 10 first beam day (collimator events) and earlier injection tests. Unforeseen but entertaining use of tertiary collimators at experiments…
- Machine **protection functionality completely checked** (interlocks from temperature and position sensors activated by violating limits). Few residual sensor issues identified. **System was fully safe** (ready for higher intensities/energies).
- **No opportunity to set up with beam as collimators.**
- Collimators kept operational since August, except **IR3 collimators** which were **switched off after incident in 3-4**. All 18 collimators in IR3 fully OK.
- Used time after incident to perform **reproducibility test over 10 days with all 28 collimators in IR7**.

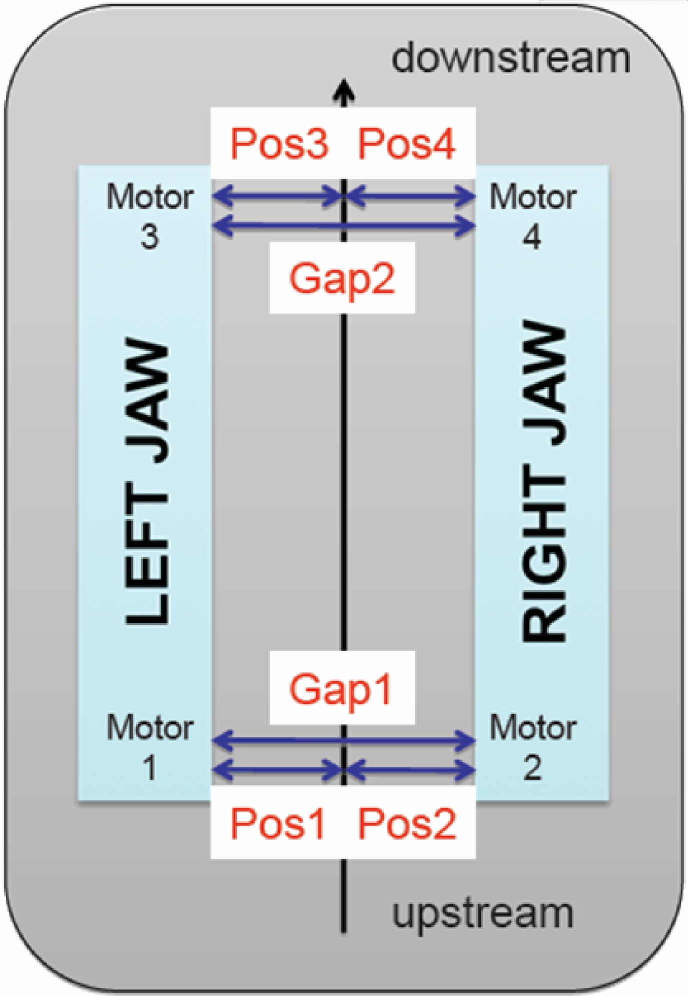
Nominal Collimator Cycle



Real functions for 28 collimators generated in collimator control. **Executed by operation crew on shift (thanks!).**

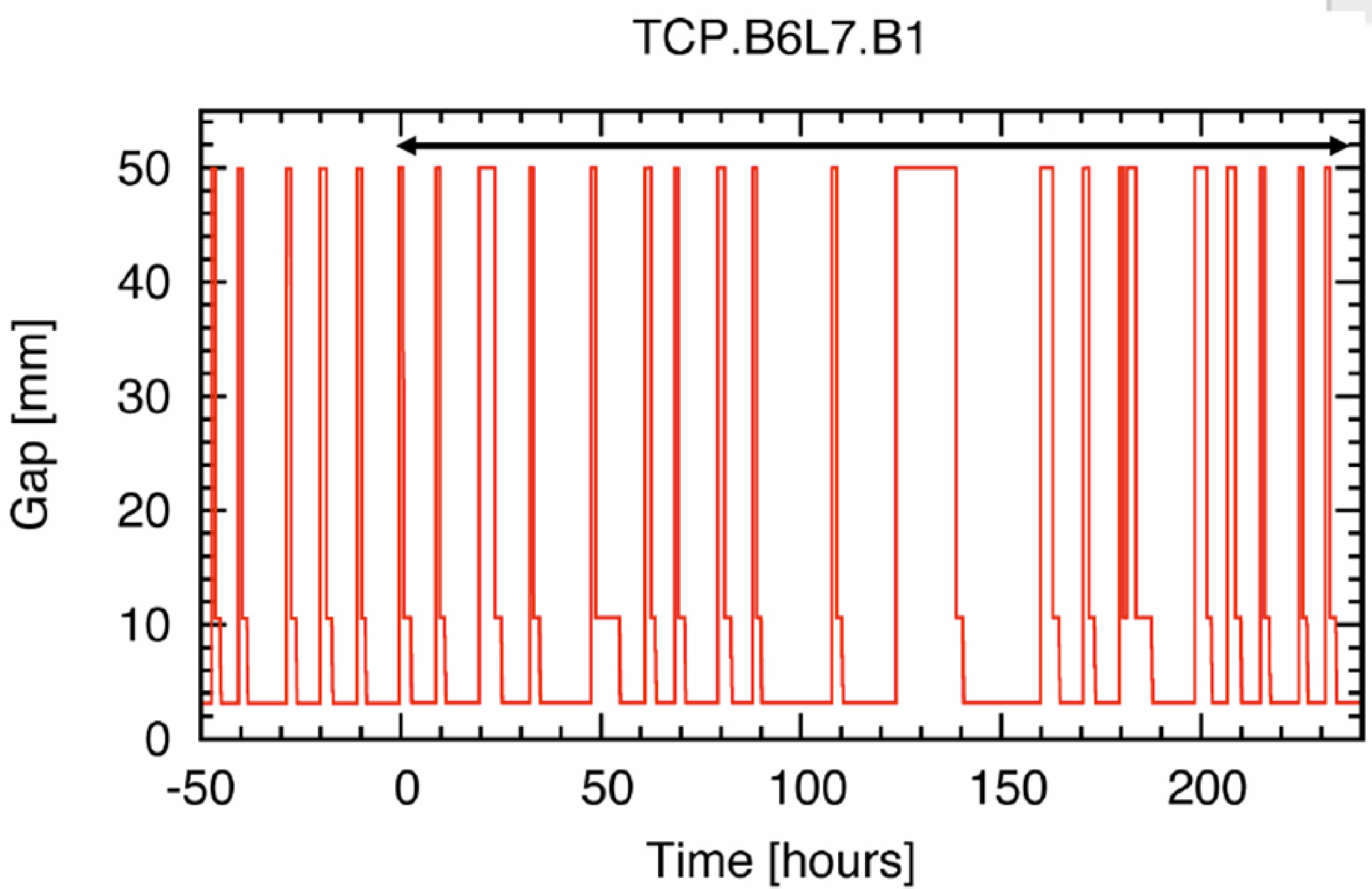
Test Procedure

- Each collimator has 6 position sensors: **4 jaw corners and 2 gaps measured independently**.
- Redundancy for 6 sensors and 4 DOF.
- **Stepping motors are driven through the collimator cycle without any feedback from measured positions.**
- Position monitoring implemented completely independent (safety) and used for measuring the jaw position and the gaps.
- Jaw positions used for operational interlocks (time driven).
- Gap sensors used for independent MP interlock (energy driven).
- **How well do we control collimators?**



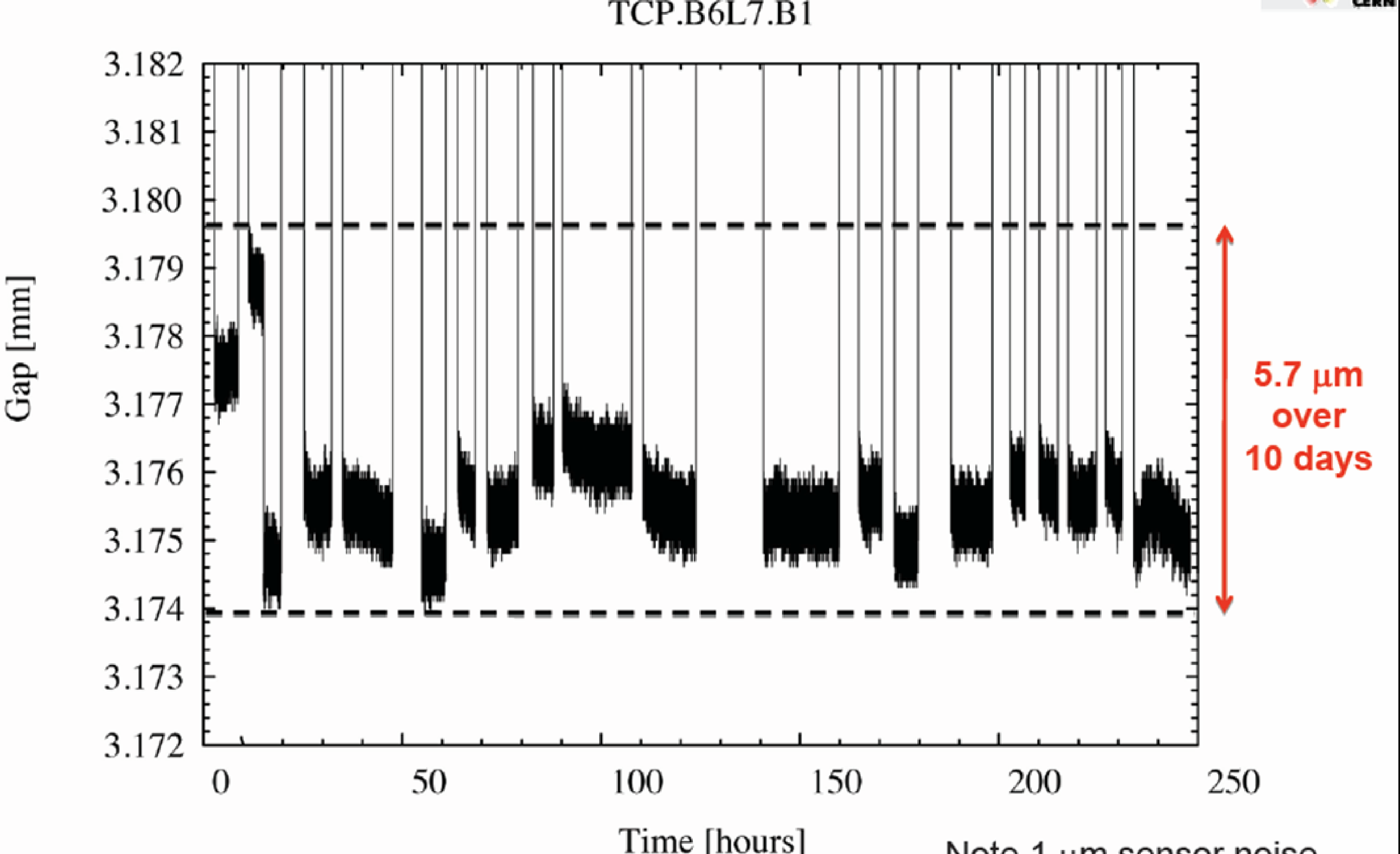
Top view for horizontal collimator.

Reproducibility Run



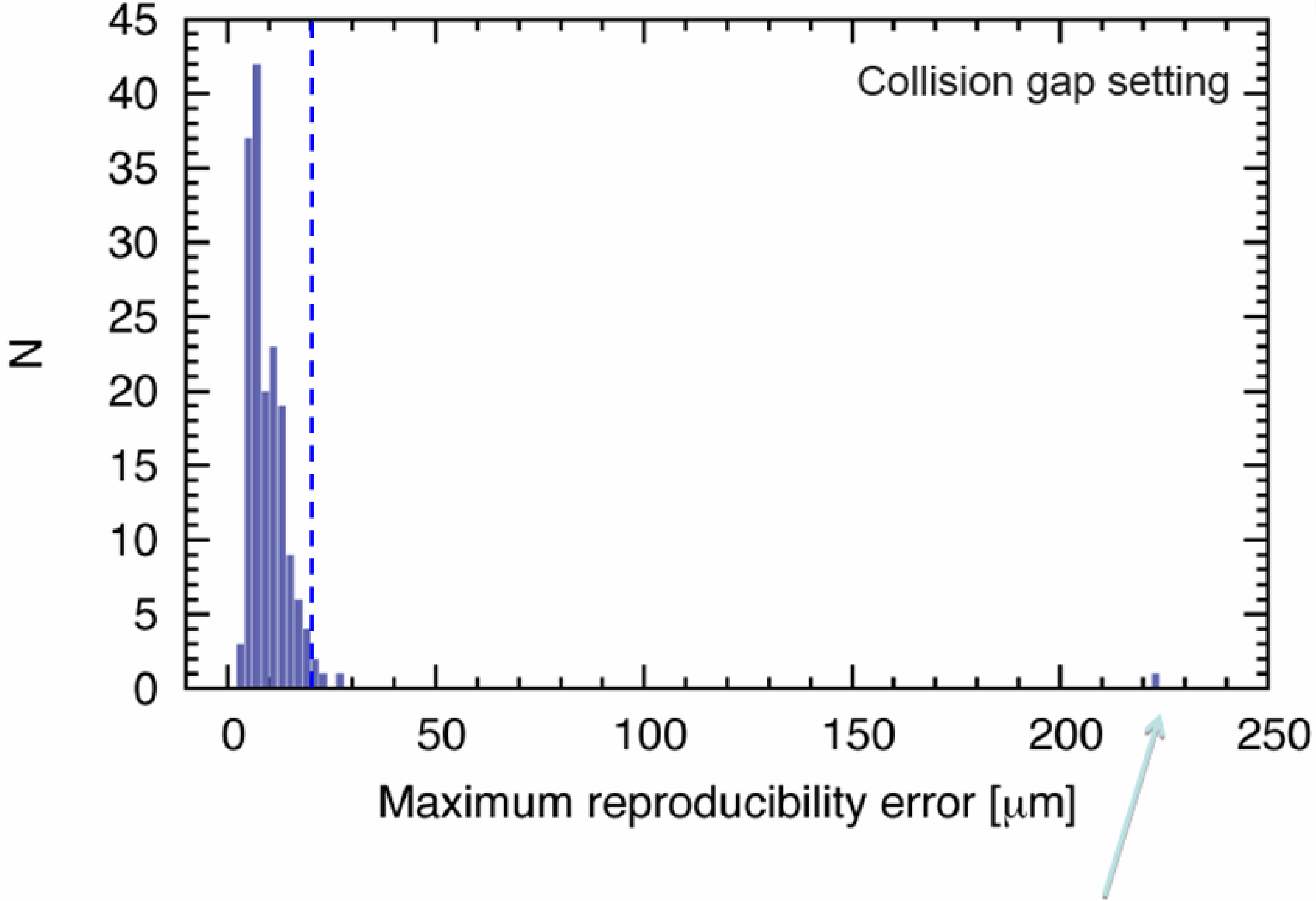
Analyzing 19 cycles after T=0 (reset of collimator sensor calibrations).

Zoom into Collision Gaps



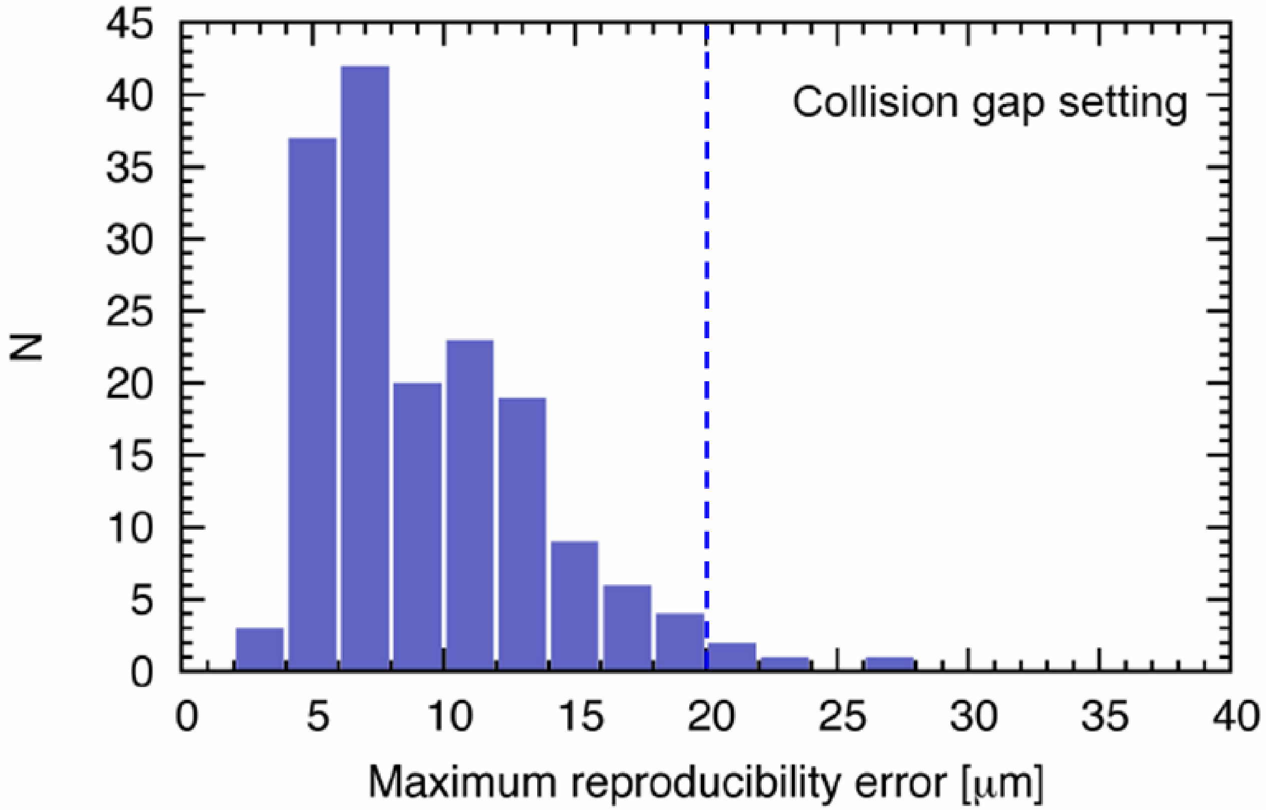
Note 1 μm sensor noise.

Reproducibility IR7 collimators in 10 days



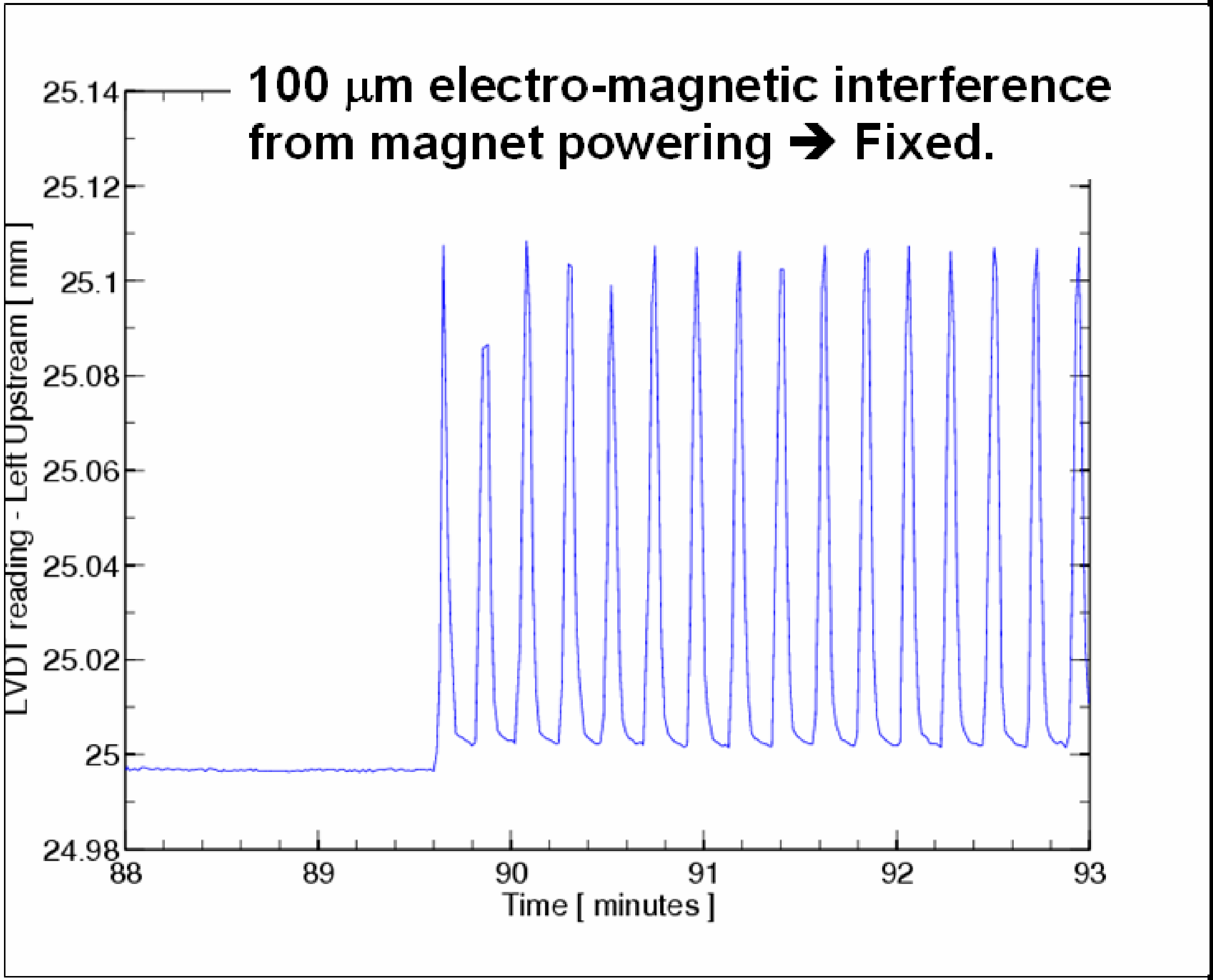
168 position sensors for 28 collimators. Only 1 sensor above 30 μm!

Reproducibility IR7 collimators in 10 days

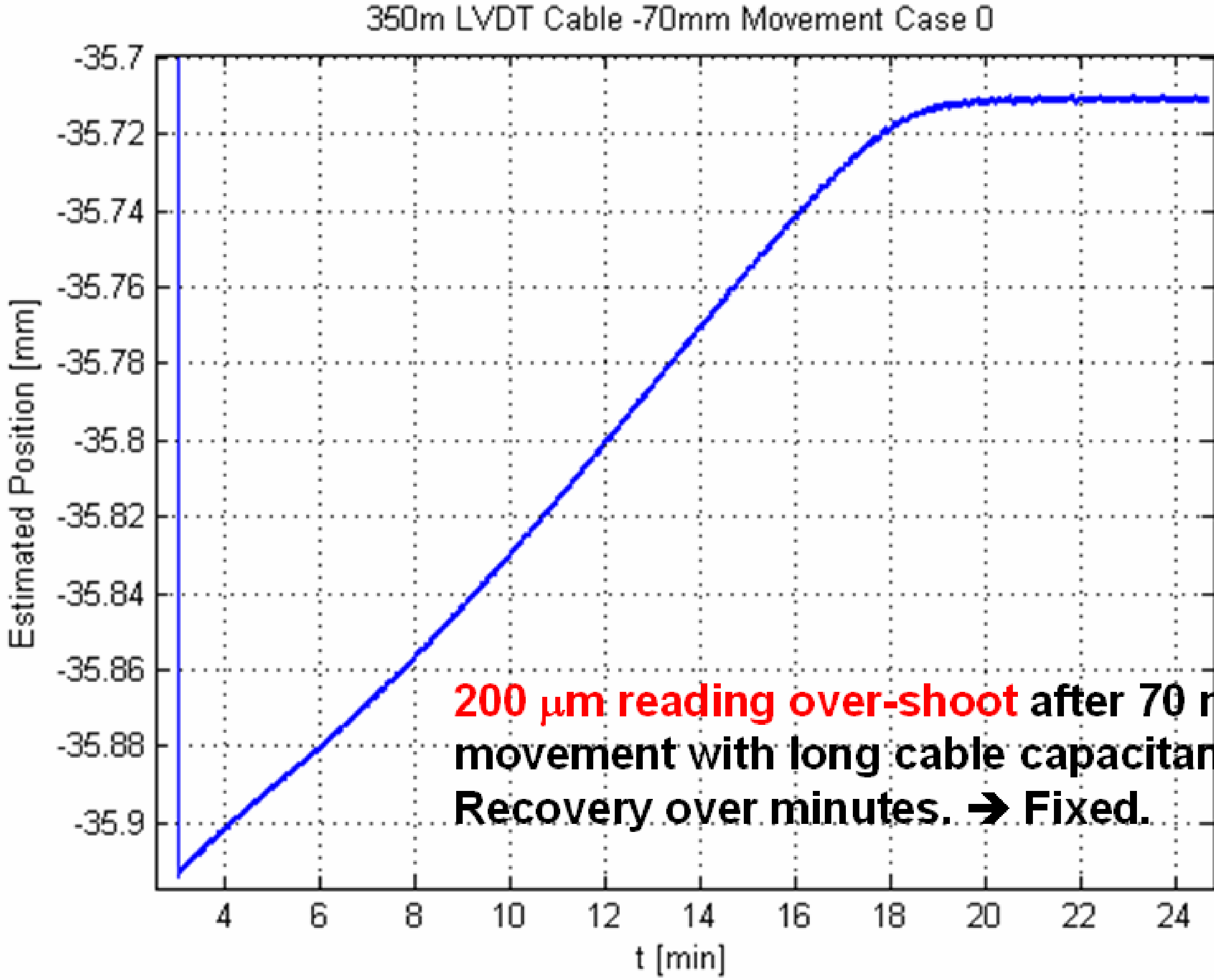


Includes mechanical, motor and sensor stability! Specification is surpassed: major success for all involved! Possible to control at **better than 30 μm level**!

Issues Learnt and Fixed

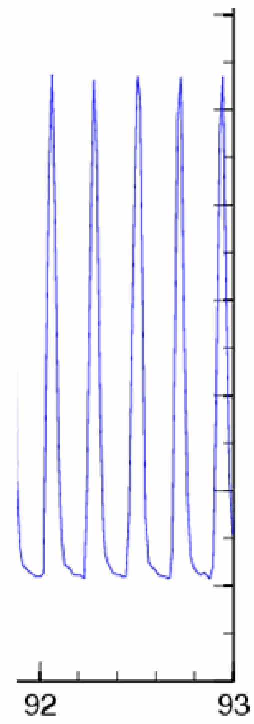


Issues Learnt and Fixed

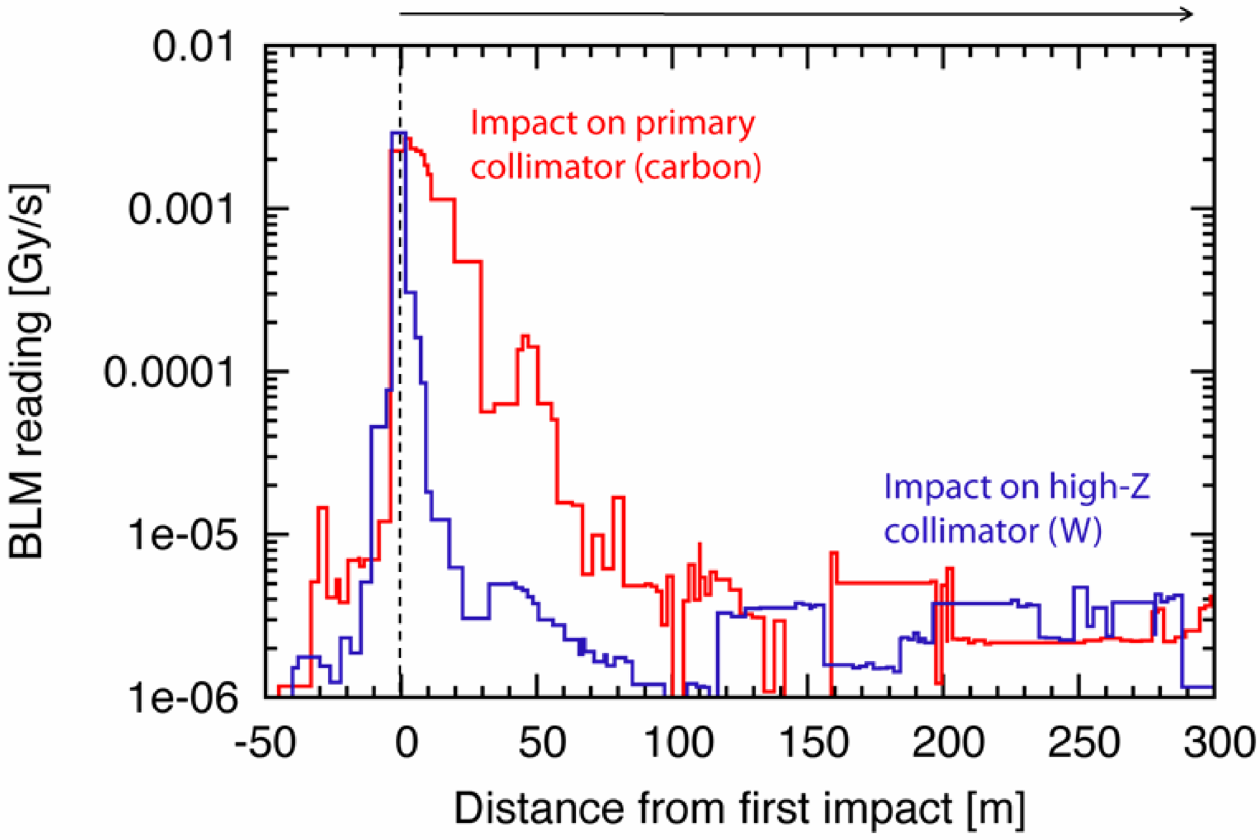


200 μm reading over-shoot after 70 mm movement with long cable capacitance. Recovery over minutes. ➔ Fixed.

terference
ixed.



First Beam Loss Maps with LHC Beam



BLM system fully reacting to beam loss and showers from collimators.

Expected feature: <u>Carbon much more transparent than tungsten!</u>

Carbon used for diluting, tungsten for absorbing!

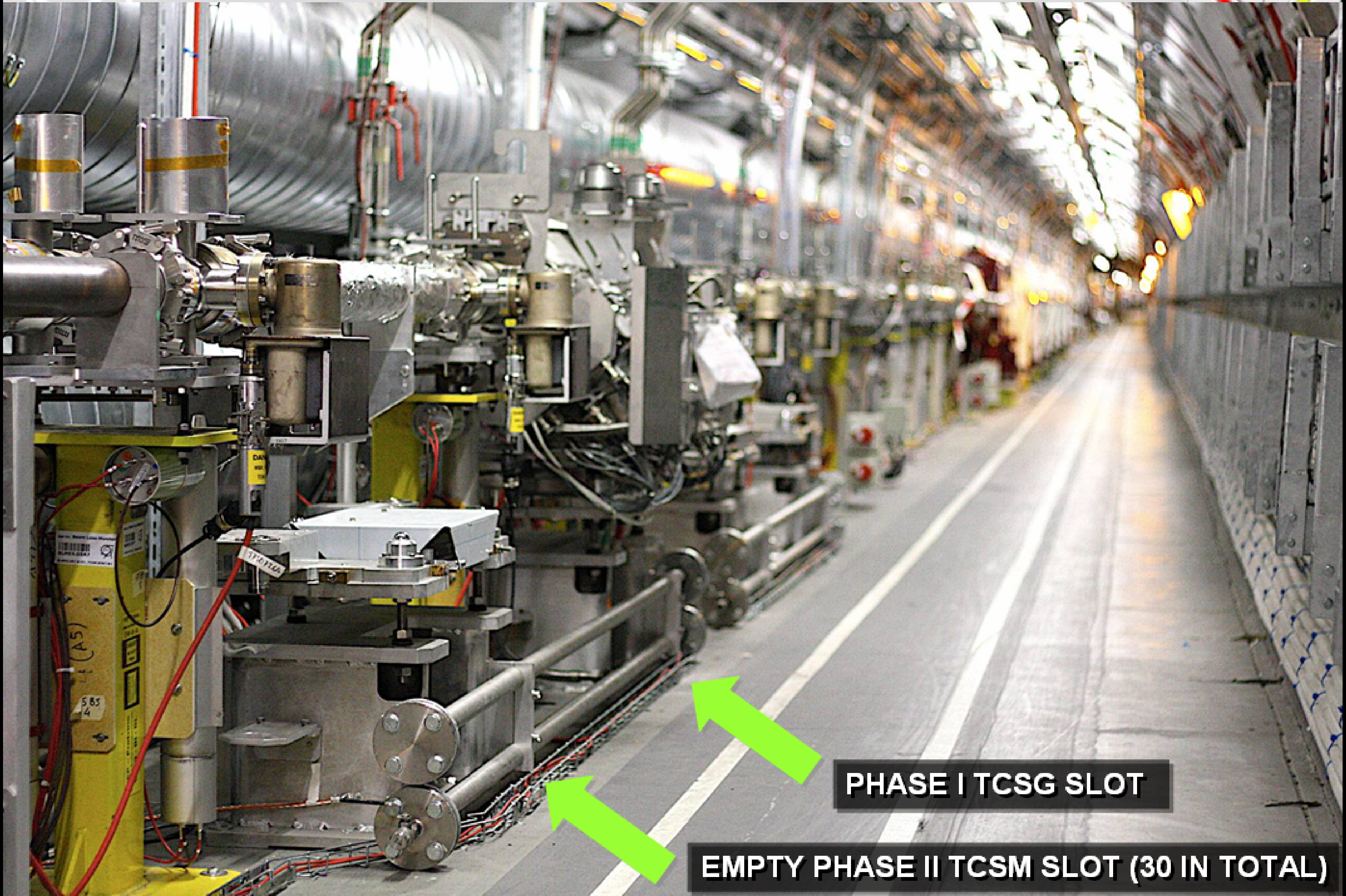
<u>Exponential decay of loss signals</u>

Carbon (low Z)	**17.4 m**
Tungsten (high Z)	**1.7 m**

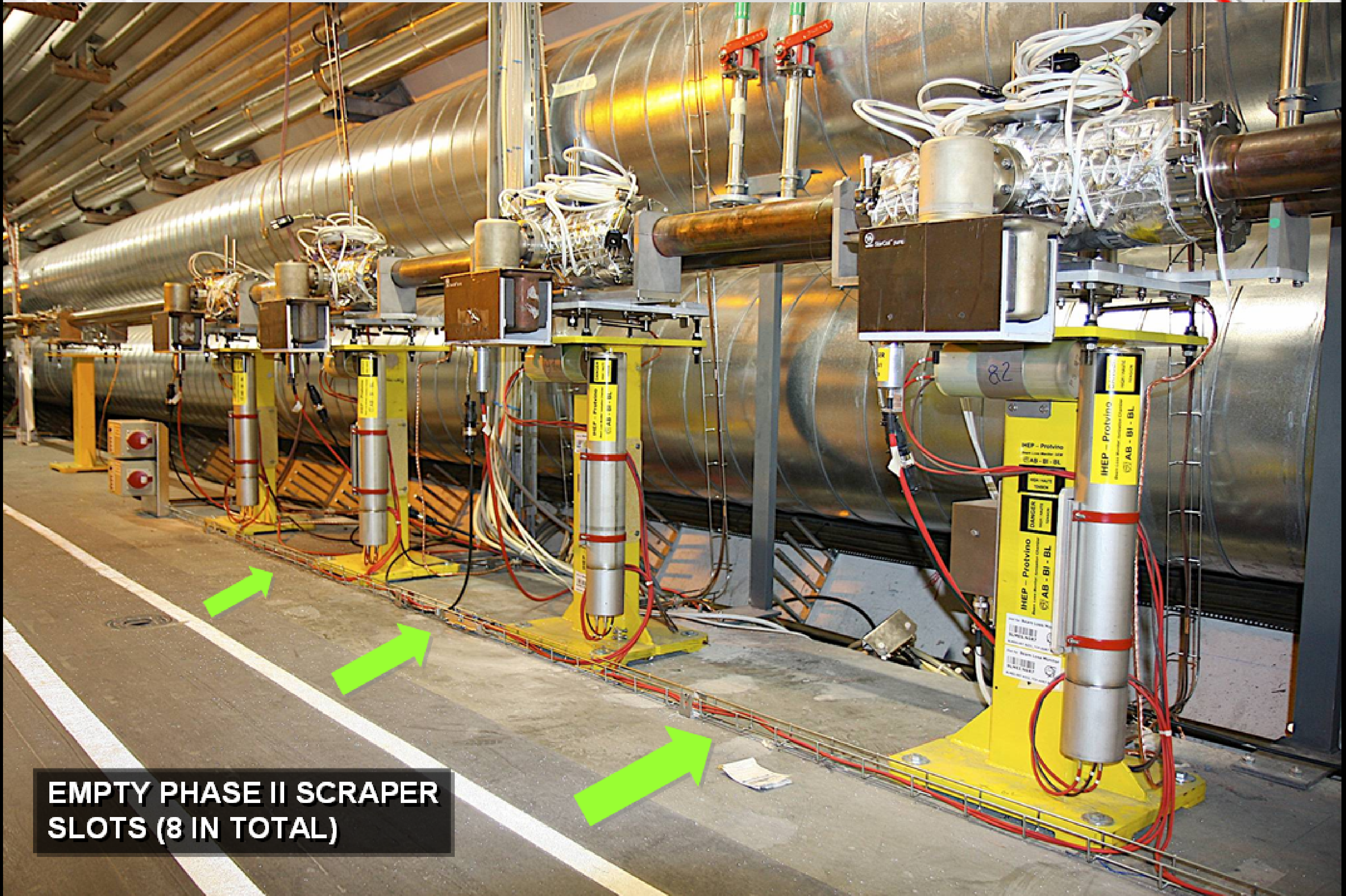
Finishing Phase I Work with Beam

- LHC **collimators used for stopping beam reliably** around the ring. As such important pre-requisite for injection tests and first turn of beam.
- Unfortunately, 2008 beam experience with collimators was quite limited. However, **system worked as specified** mechanically and electronically.
- Next run: **Set up collimators with beam for establishing passive protection and beam cleaning. Measure cleaning efficiency!**
- Completed when phase I system shows **predicted cleaning efficiency**.
- Prediction:
  - **Phase I collimation good for something around 20 MJ, ~10 times beyond present world record.**
  - Prediction depends on multiple parameters to be verified with LHC operation.
- Work on phase II collimation is ongoing with work plan until 2014.
- Phase II prepared in tunnel and will allow nominal and higher intensities.

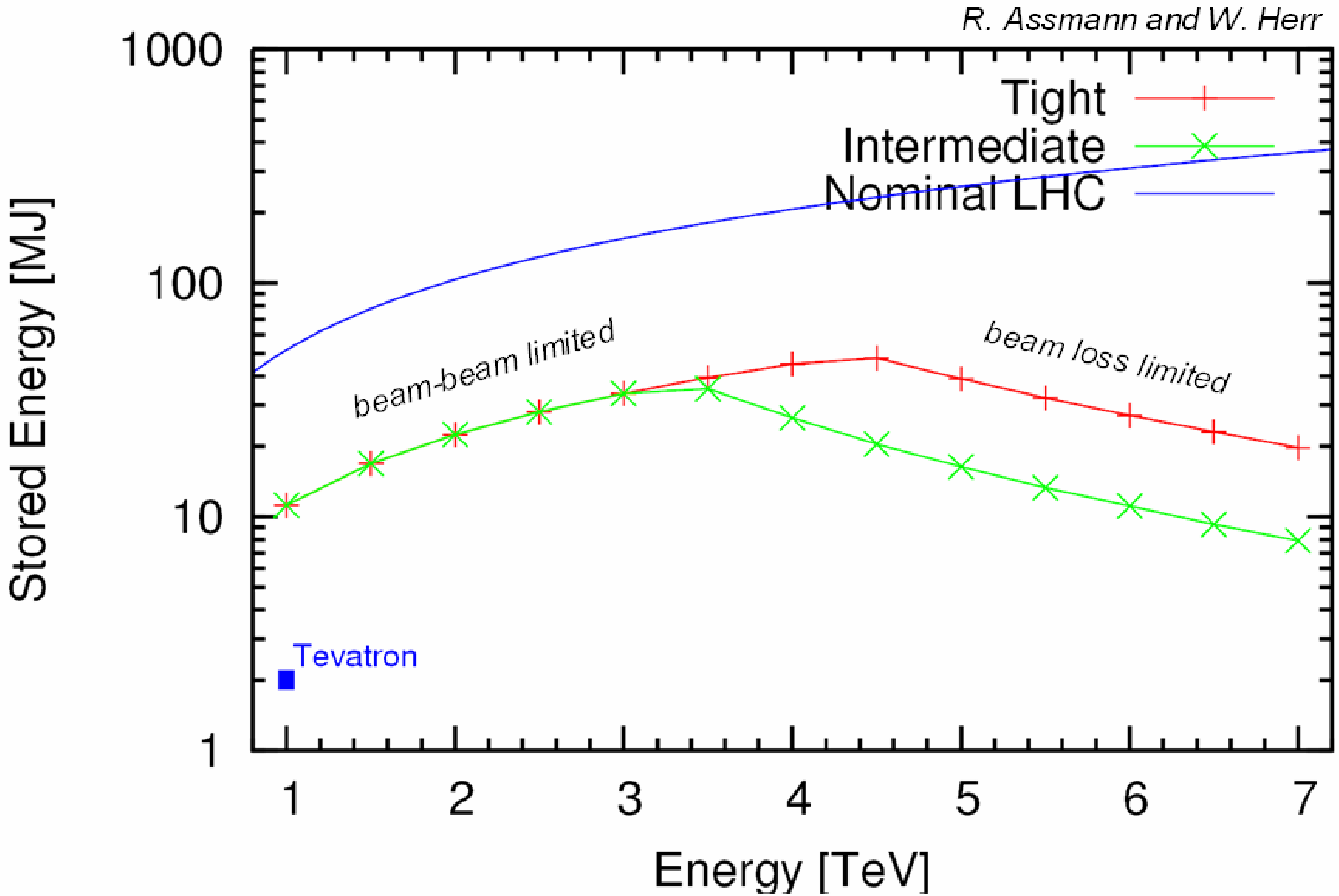
Tunnel: Phase II Secondary Collimator Slots



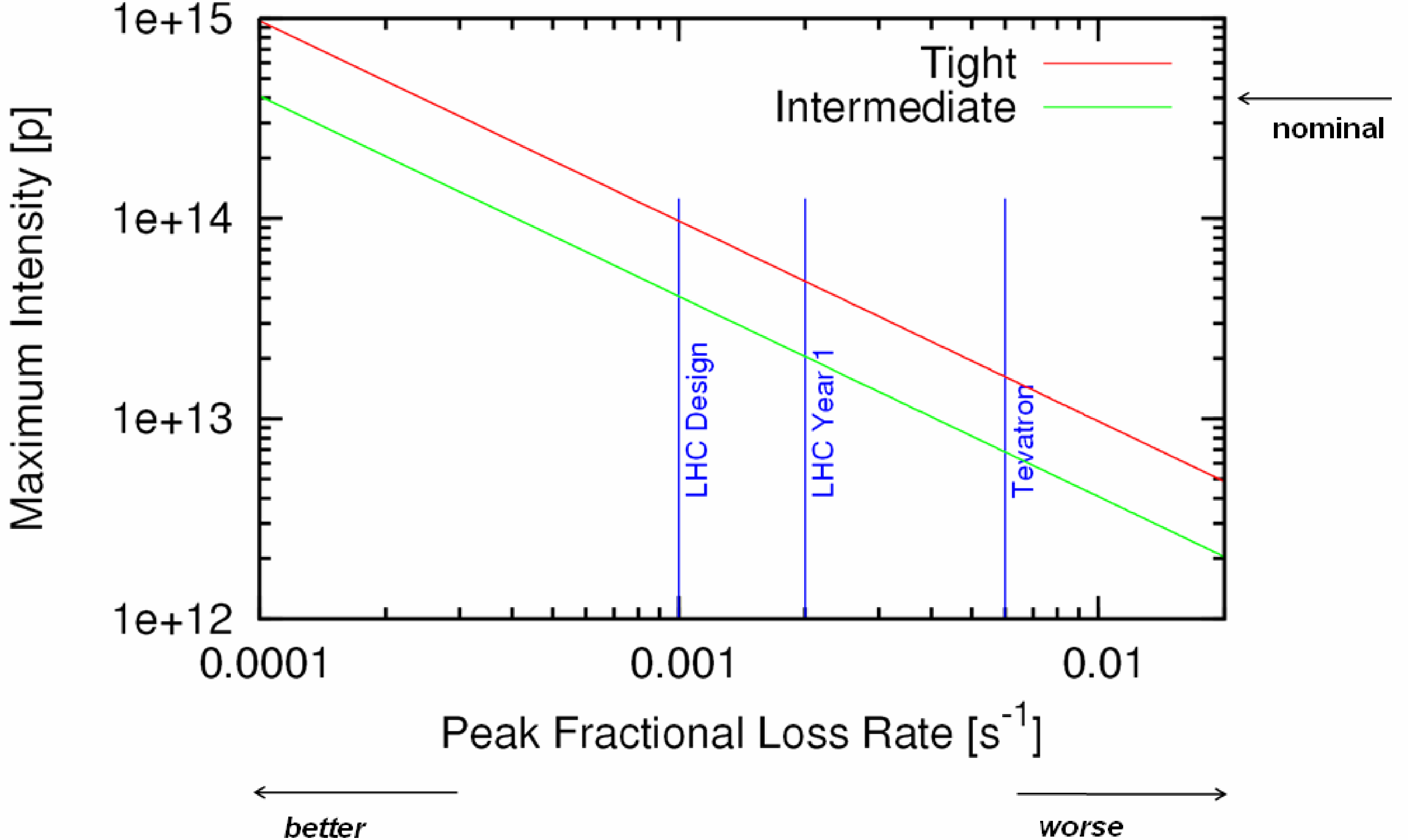
Tunnel: Phase II Beam Scraper Slots

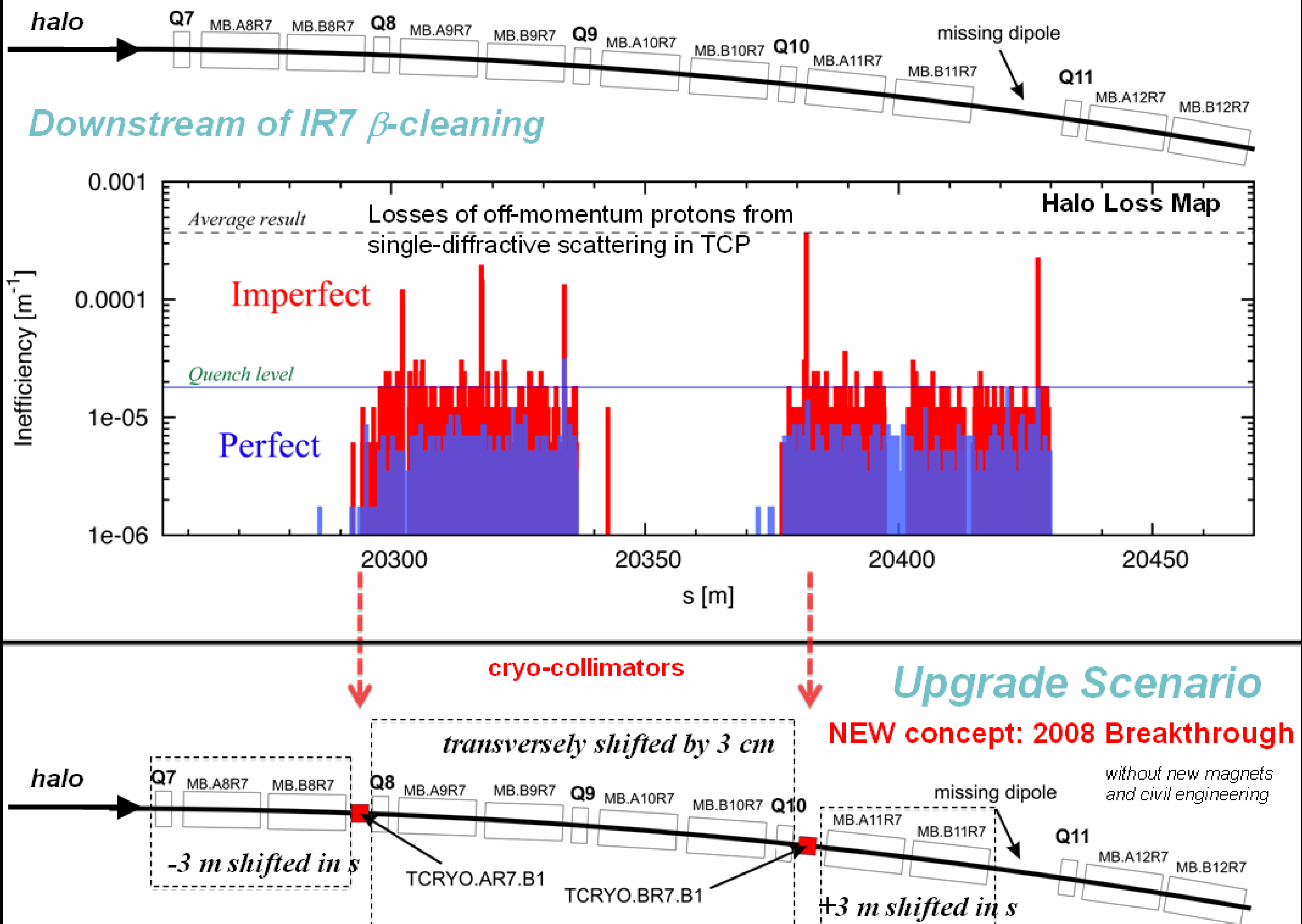


Phase I Collimation Limit for Stored Energy vs Beam Energy



Phase I Collimation Intensity Limit versus Peak Loss Rate 5 TeV





R. Assmann, PAC 5/09

Phase II Collimation Work Plan

- R&D on advanced, low impedance materials for LHC collimators.
- Design, prototyping and testing of phase II secondary collimators, implementing in-jaw pick-ups (improved operation) and various jaw materials (lower impedance). Construct 30 plus spares.
- Install HiRadMat beam test facility for beam verification of advanced collimator designs.
- Start R&D, prototyping and testing on hollow e-beam lens for LHC scraping: FNAL and CERN.
- Work out technical design for modified dispersion suppressors in IR3/7. Design and build new cryostat for missing dipole. R&D on “cryo-collimators” for modified dispersion suppressors and construction.
- Support R&D on advanced new concepts (crystal collimation, …).
- Collaboration with 12 institutes in Europe, funded by EU (FP7). Collaboration with 3 institutes in U.S., funded by DOE (LARP).

Conclusion

- LHC collimation is designed to extend the intensity frontier by more than 2 orders of magnitude. It will not be easy: staged approach.
- **Phase I is completed and already is the largest such system built to date.** Worked as specified without beam: showed control and stability to better than 30 μm (width of human hair). Loss maps well behaved.
- Once LHC beam is back, phase I system will be set up and cleaning efficiency measured. Expect to reach around 20 MJ (10 times world record) with phase I collimation, but below nominal design.
- Phase II collimation has been worked out and will be implemented in steps until 2014 to upgrade performance. It will allow nominal and higher intensities (hopefully before 2014).
- Work is performed in international collaboration, supported by EU and DOE/LARP. Thanks to all who help us in this challenge!
- Please see many LHC collimation posters at PAC09 for more detail!

The Collimation Project Team & Close Collaborators

- Results on phase I collimation that I presented are outcome of lot of work performed over last 6 years by the following **CERN colleagues**:

  O. Aberle, R. Assmann, J.P. Bacher, V. Baglin, G. Bellodi, A. Bertarelli, R. Billen, A.P. Bouzoud, C. Bracco, H. Braun, M. Brugger, S. Calatroni, F. Caspers, F. Cerutti, R. Chamizo, A. Cherif, E. Chiaveri, A. Dallochio, B. Dehning, M. Donze, A. Ferrari, R. Folch, P. Gander, A. Grudiev, 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, E. Veyrunes, H. Vincke, V. Vlachoudis, T. Weiler, J. Wenninger

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

  TRIUMF (D. Kaltchev), IHEP (I. Baishev & team), SLAC (T. Markiewicz & team), FNAL (N. Mokhov & team), BNL (N. Simos, A. Drees & team).