LHC Collimation – Too Good or Too Bad?

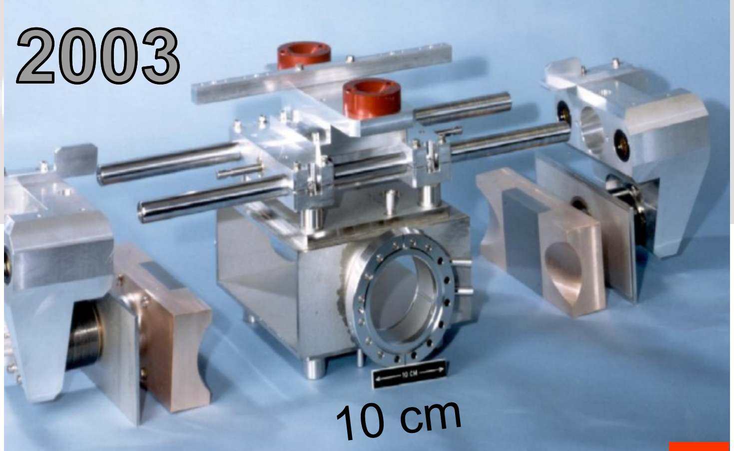
Chamonix 2011

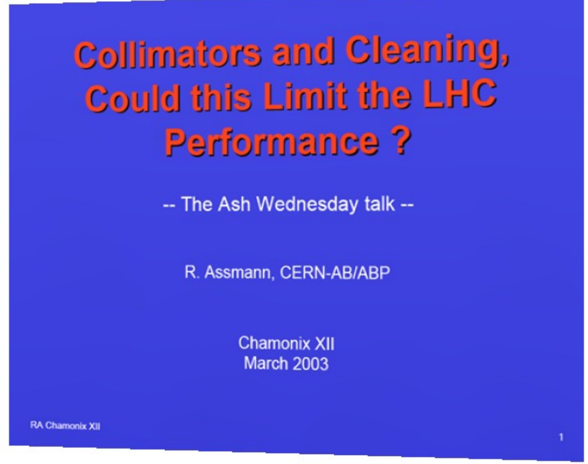
R. Assmann for the Collimation Project Team (Phase 1)

O. Aberle, R. Assmann, J.P. Bacher, V. Baglin, G. Bellodi, A. Bertarelli, P. Bestmann, V. Boccone, A.P. Bouzoud, C. Bracco, H. Braun, R. Bruce, M. Brugger, S. Calatroni, F. Caspers, M. Cauchi, F. Cerruti, R. Chamizo, A. Cherif, E. Chiaveri, A. Dallochio, D. Deboy, B. Dehning, M. Donze, 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, M. Santana, R. Schmidt, P. Sievers, M. Sobczak, K. Tsoulou, G. Valentino, E. Veyrunes, H. Vincke, V. Vlachoudis, T. Weiler, J. Wenninger, D. Wollmann, CERN, Geneva, Switzerland.

D. Kaltchev et al, TRIUMF, Canada. I. Bayshev, IHEP, Russia. T. Markiewicz et al, SLAC, USA. N. Mokhov et al, FNAL, USA. A. Ryazanov et al, Kurchatov, Russia. N. Sammut et al, University Malta, Malta. N. Simos et al, BNL, USA.

LHC Collimation Project CERN




Collimators and Cleaning, Could this Limit the LHC Performance ?

-- The Ash Wednesday talk --

R. Assmann, CERN-AB/ABP

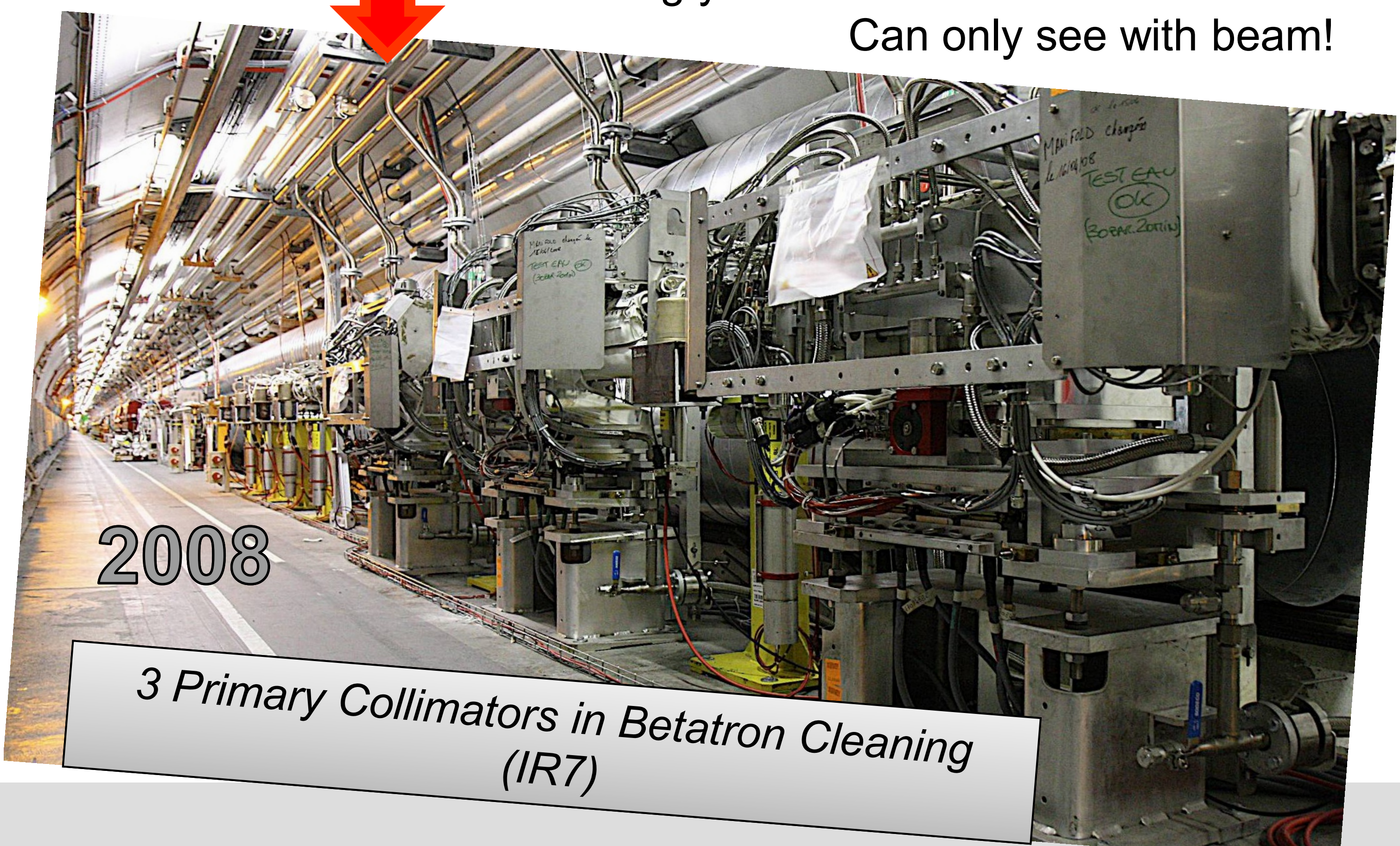
Chamonix XII
March 2003

RA Chamonix XII

1

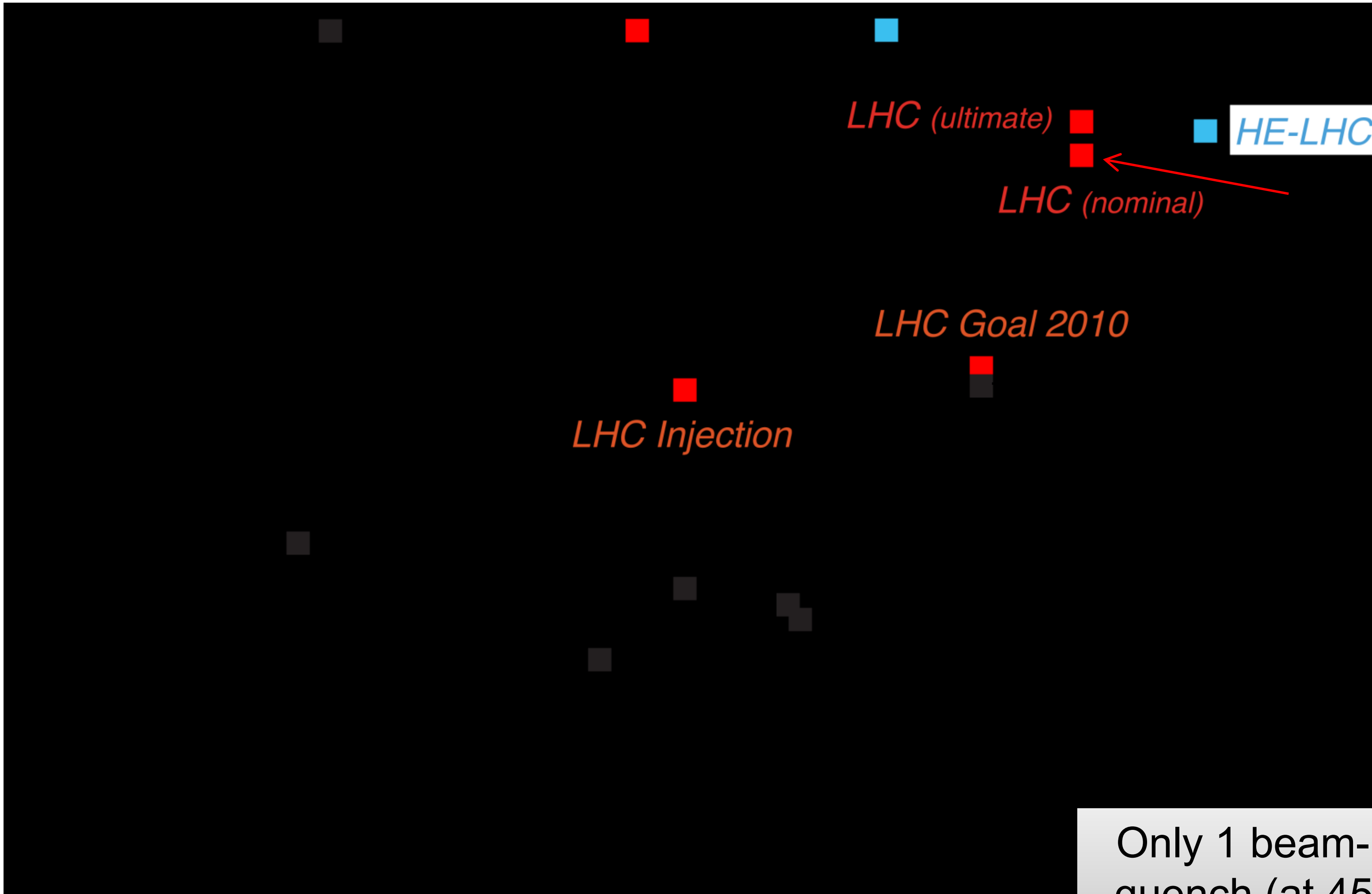
… the 2003 Ash Wednesday talk!

Exciting year 2010 for us! Would it work?
Can only see with beam!



3 Primary Collimators in Betatron Cleaning (IR7)

LHC Beam Momentum: x 3.5 WR
LHC Stored Energy: x 15 WR*



But now [redacted]

Only 1 beam-induced quench (at 450 GeV), except quench test.

* *Here taking world record in **super-conducting** accelerators.*

Content

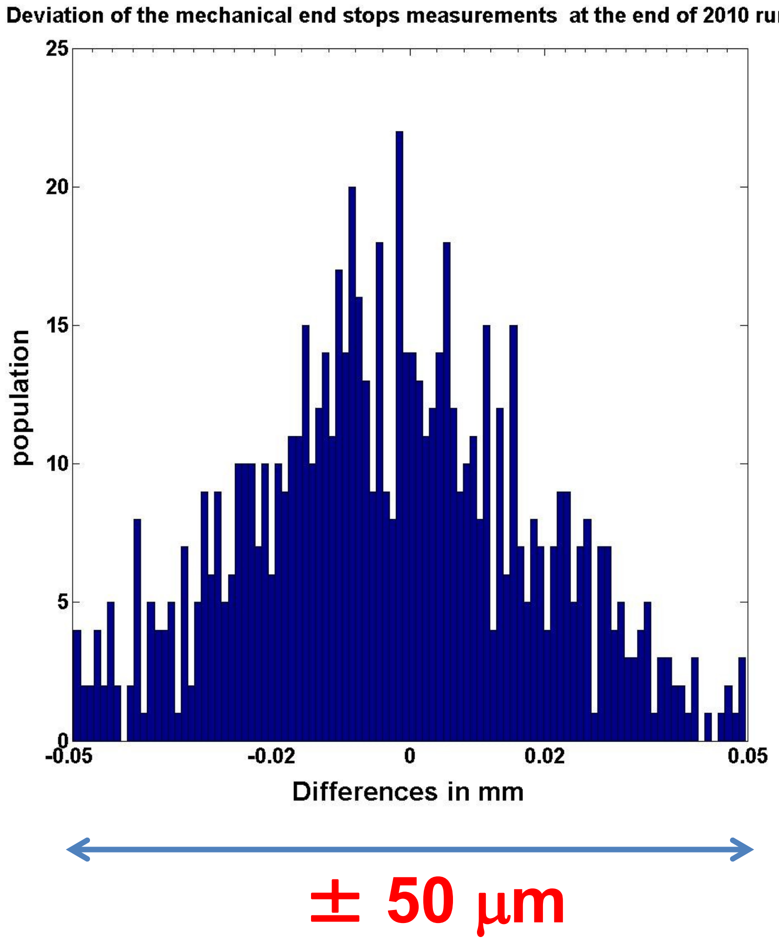
- **Hardware performance, collimation setup, impedance and verification**
- Intensity reach from collimation
- β^* reach from orbit & collimation
- Luminosity reach at 3.5 TeV from collimation
- Conclusion

See also Evian talks in “Beam Loss” session, in particular Daniel Wollmann and Roderik Bruce!

Includes short synthesis and summary of these Evian presentations!

LHC Collimators Position sensors performance: drift evaluation over 1 year operation

Analysis A. Masi
EN-STI



Differences between end-stops measurements (both inner and outer) performed with LVDT in January 2011 and reference values used in 2010 operational calibrations

The 2011 measurements of the mechanical end stops are averages of 5 repeated measurements

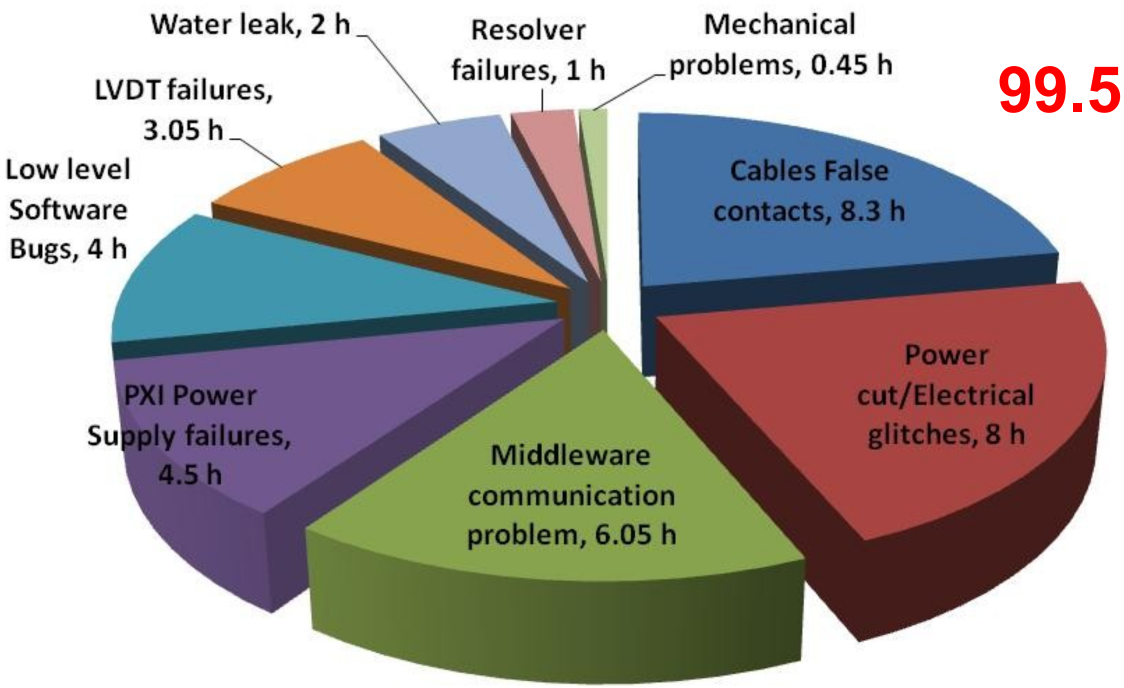
Only few axes have shown deviations above 20-30 um. Accurate investigations have shown that these are caused by a higher uncertainty on the mechanical end stops approaching experienced on some calibrations and not by a higher drift of the sensor reading over the year

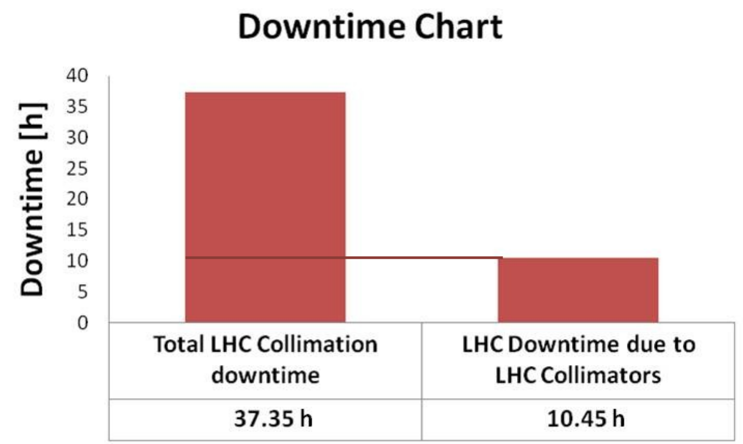
The typical value of the position sensors reading drift over the entire 2010 operation year is lower than 30 um

LHC Collimators downtime analysis over 1 year operation (1.11.2009-6.12-2010)

Analysis A. Masi
EN-STI

99.5 % uptime.





• The LHC collimators system downtime over an operation period of 8184 h ... only 37.55 hours. Only 10.45 h of these ones provoked a ... interlocks activated). The other failure ... and/or several LHC collimators

• M ... peration have been definitively fixed:

... ation problems have been fixed by the RDA team thanks to an accurate ... operator clients (slow clients) and the installation of a proxy to limit the connections toward the FESA gateways

Comment (RA): Work on maximum robustness and reliability of collimators paid off!
Excellent work on mechanics, actuation, sensors, controls, quality control.

Thanks a lot to BE/CO for the precious support

• A proper recovery tool has been developed and tested to recover LHC collimators operation after a power cut in only 20 minutes

Settings End of 2010 p Run

Condition	Unit	Plane	Set 1 Injection	Set 2 Top energy	Set 3 Crossing angle	Set 4 Squeeze	Set 5 Collision
Energy	[GeV]	n/a	450	**3500**	3500	3500	3500
IP beta function β^*	[m]	n/a	10-11	10-11	10-11	**3.5**	3.5
Crossing angle α_c	[μrad]	n/a	**170**	170	**100-110**	100-110	100-110
IR separation	[mm]	n/a	2	2	2	2	**0**
Primary cut IR7	[σ]	H. V, S	5.7	**5.7**	5.7	5.7	5.7
Secondary cut IR7	[σ]	H, V, S	6.7	**8.5**	8.5	8.5	8.5
Quartiary cut IR7	[σ]	H, V	10.0	**17.7**	17.7	17.7	17.7
Primary cut IR3	[σ]	H	8.0	**12.0/10.0**	12.0/10.0	12.0/10.0	12.0/10.0
Secondary cut IR3	[σ]	H	9.3	**15.6**	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H, V	10.0	**17.6**	17.6	17.6	17.6
Tertiary cut experiments	[σ]	H, V	15-25	40-70	**40-70+**	**15.0**	**15.0+**
Physics debris collimators	[σ]	H	out	out	out	out	out
TCSG/TCDQ IR6	[σ]	H	7-8	**9.3-10.6**	9.3-10.6	9.3-10.6	9.3-10.6
TDI/TCLIA/TCLIB	[σ]	V	7.0	**out**	out	out	out
Protection margin W coll	[σ]	H, V	1.5	7.6	7.6	5.0	5.0
Protection margin W coll	[mm]	H, V	0.8	1.5	1.5	1.5	1.5

A **few 100,000 values drive and control system**.

Settings verified with loss maps!

Generate low intensity beam losses with H, V and energy errors (induced).

Check that response of system is correct. If incorrect then fix. Only then declare system operational.

Stringent approach caught a few mistakes without impact on operation.

Time for Beam-Based Setup & Check

- LHC collimation operates very differently from other previous systems:
  - Tevatron, RHIC: Collimators adjusted at start of each physics.
  - LHC: Not possible for high power. **Infrequent but very precise setups which are then kept for months (reliability & precisions allows this).** Requires special fills.
- Each change of orbit, energy and/or optics requires new setup:

Activity	Shifts	Total
450 GeV setup:	3 x 8 h	16 h
450 GeV check:	1 x 8 h	8 h
High energy setup:	5 x 8 h	40 h
High energy check:	6 – 10 fills	30 – 50 h
Total		**94 – 114 h**

- Several measures to speed up under way but no miracles → Stefano!

Content

- Hardware performance, collimation setup, impedance and verification
- **Intensity reach from collimation**
- β^* reach from orbit & collimation
- Luminosity reach at 3.5 TeV from collimation
- Conclusion

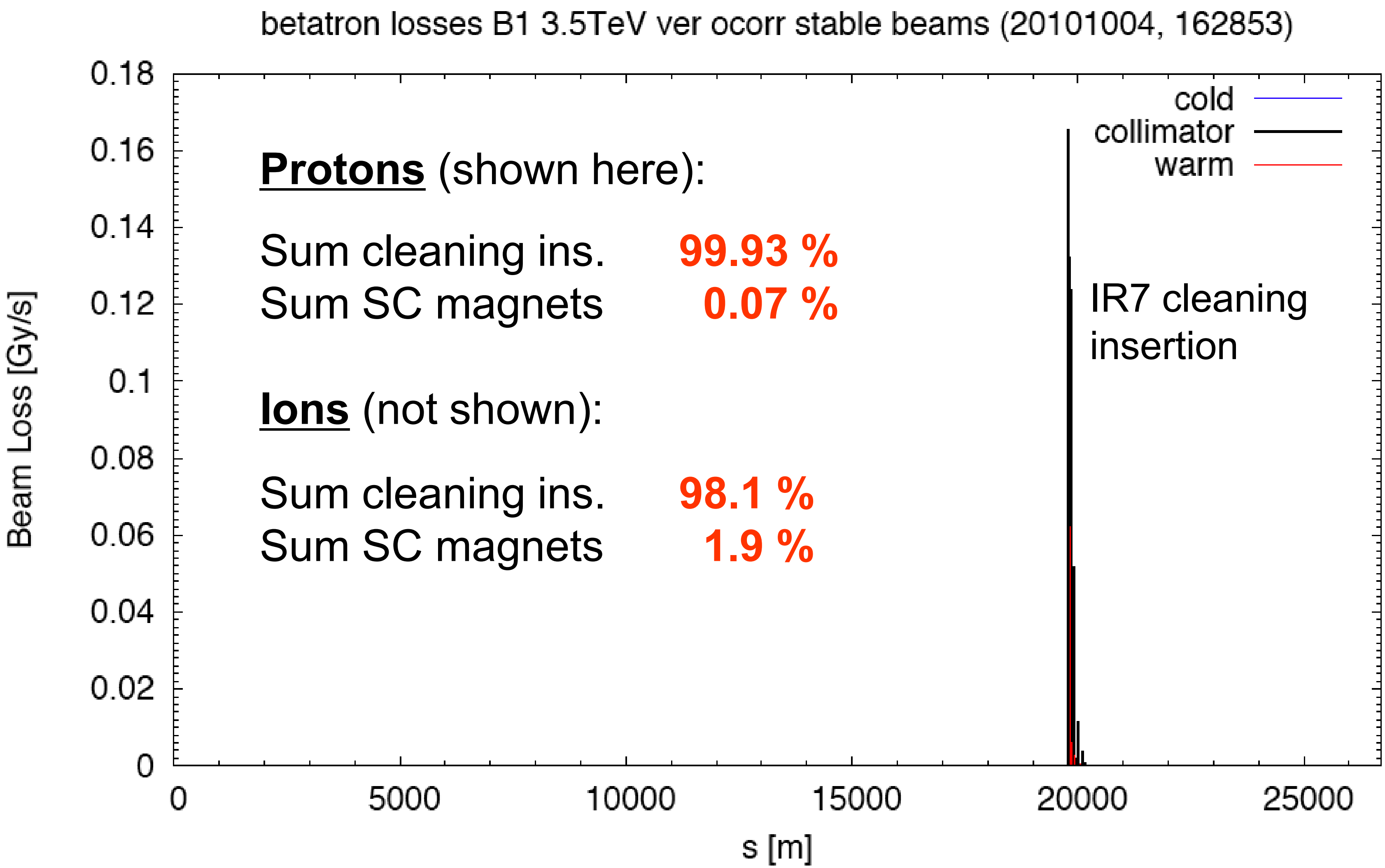
Measured Cleaning Efficiency
(linear scale, overall sums)

Protons (shown here):

Sum cleaning ins. 99.93 %
Sum SC magnets 0.07 %

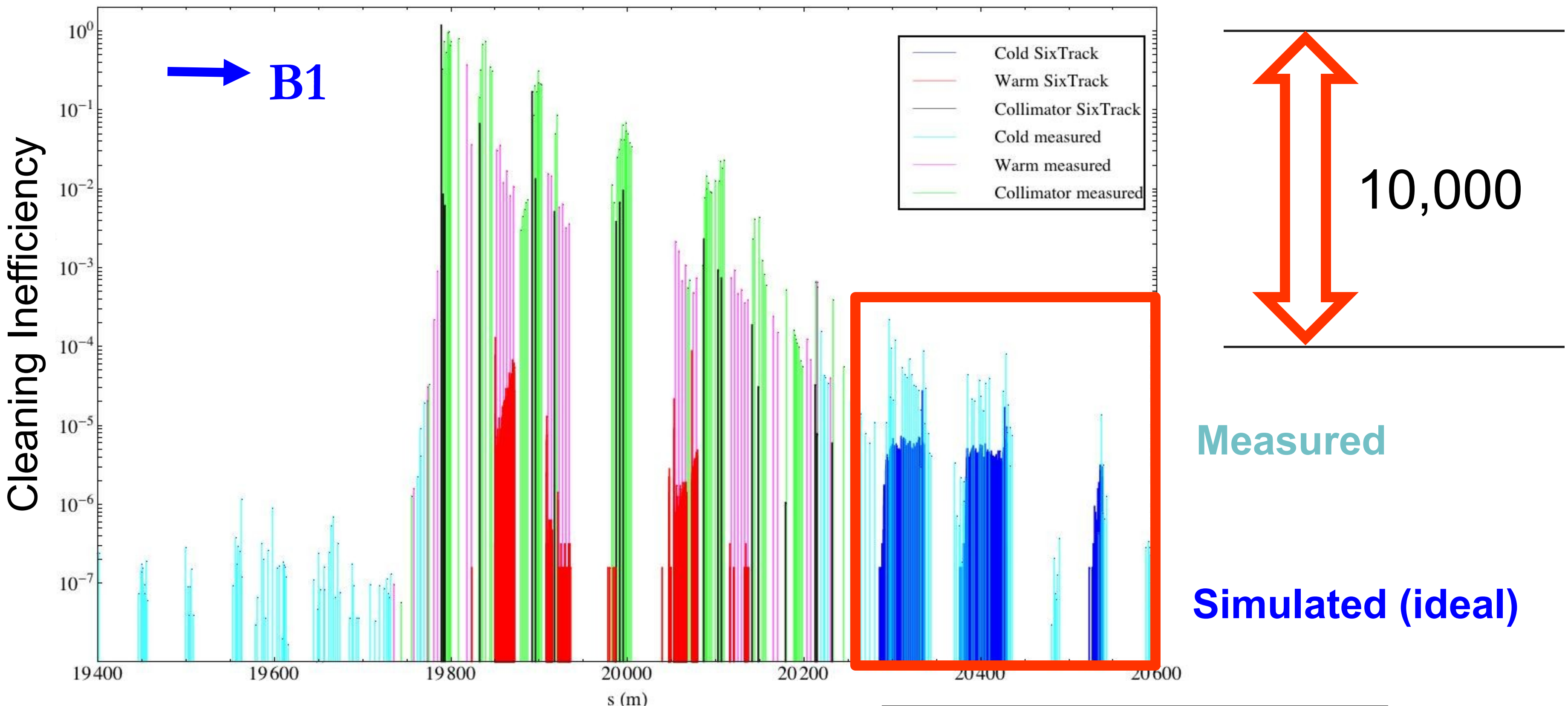
Ions (not shown):

Sum cleaning ins. 98.1 %
Sum SC magnets 1.9 %



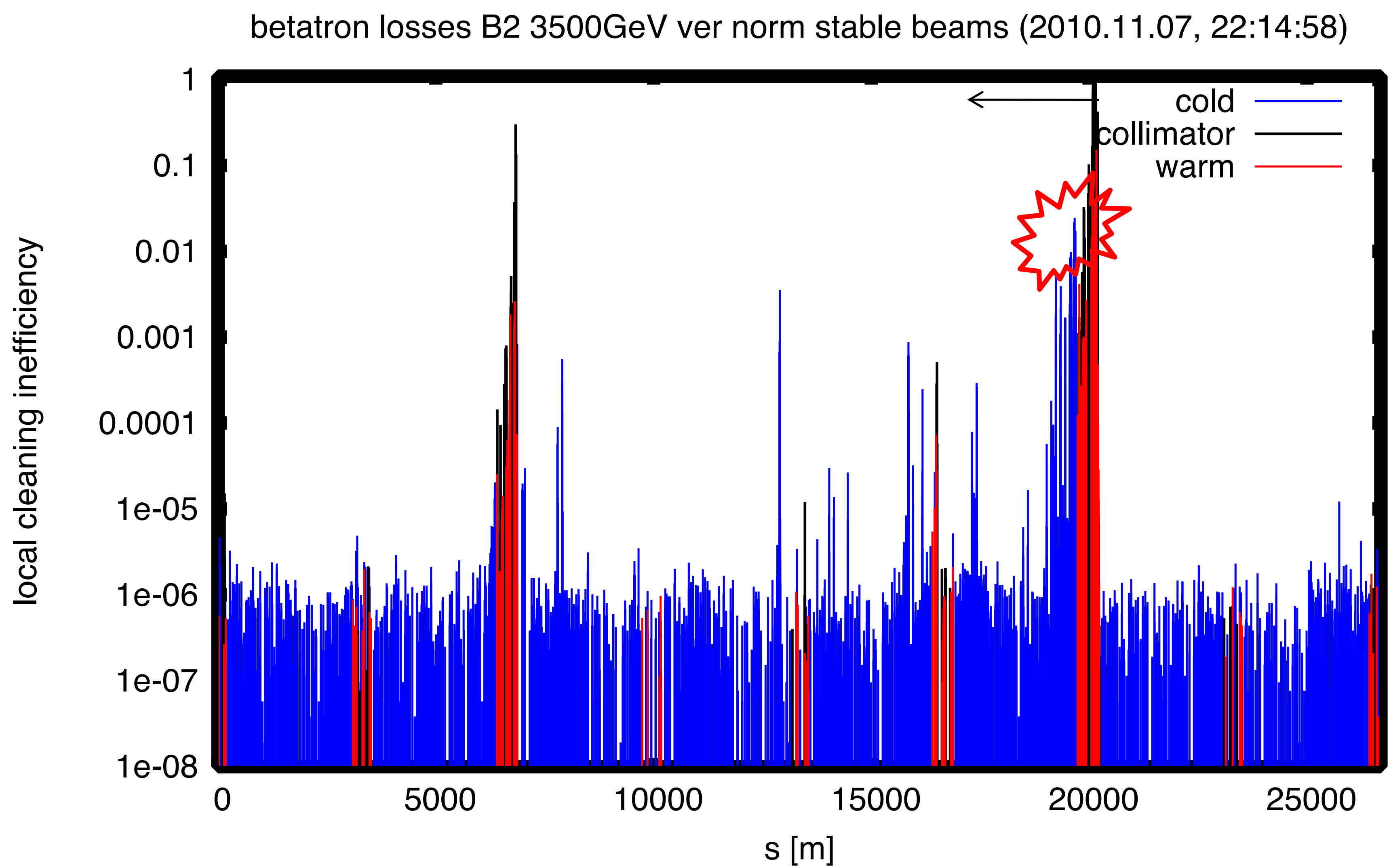
Protons: Simulations vs Measurement

B1v, 3.5TeV, β=3.5m, IR7*



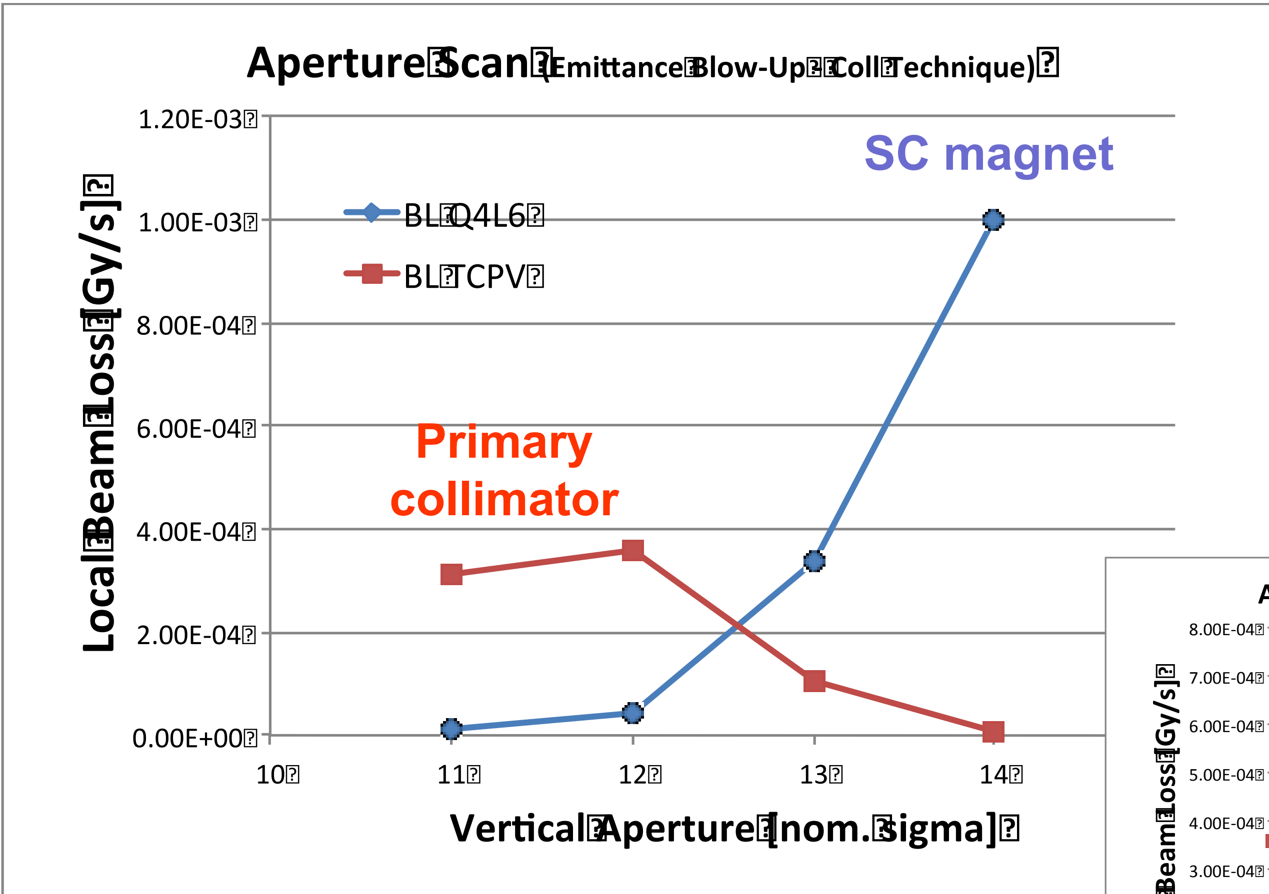
Losses in SC magnets understood: location and magnitude

Ions: Beam 2 Leakage from IR7 Collimation (much worse, as expected)



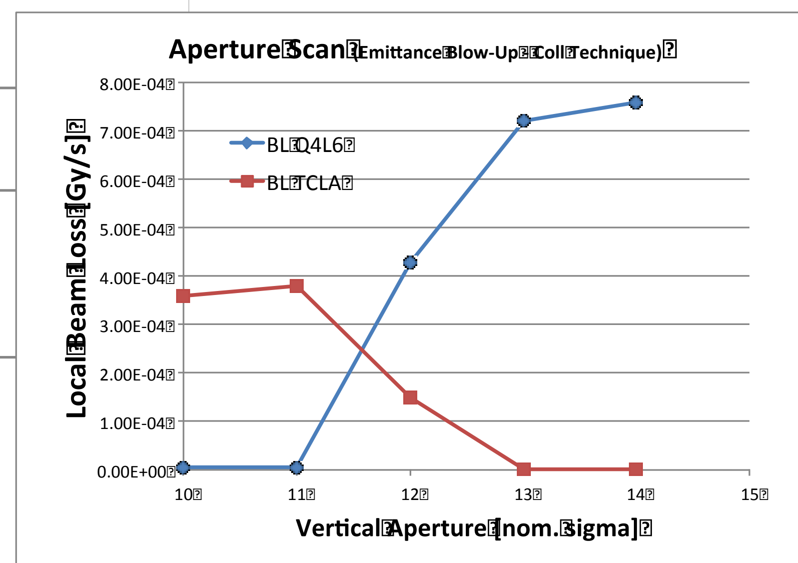
R. Assmann

Correction of Cleaning Inefficiency:
Reduce by Factor 2 (BLM Response)



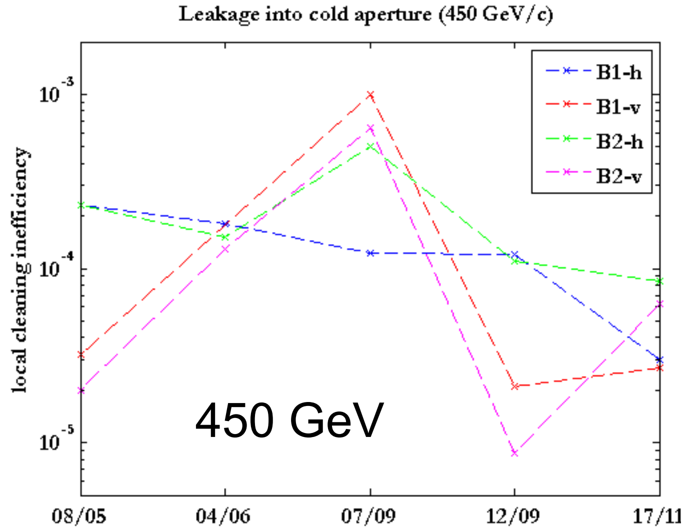
Factor 2 better performance reach!

Included now.

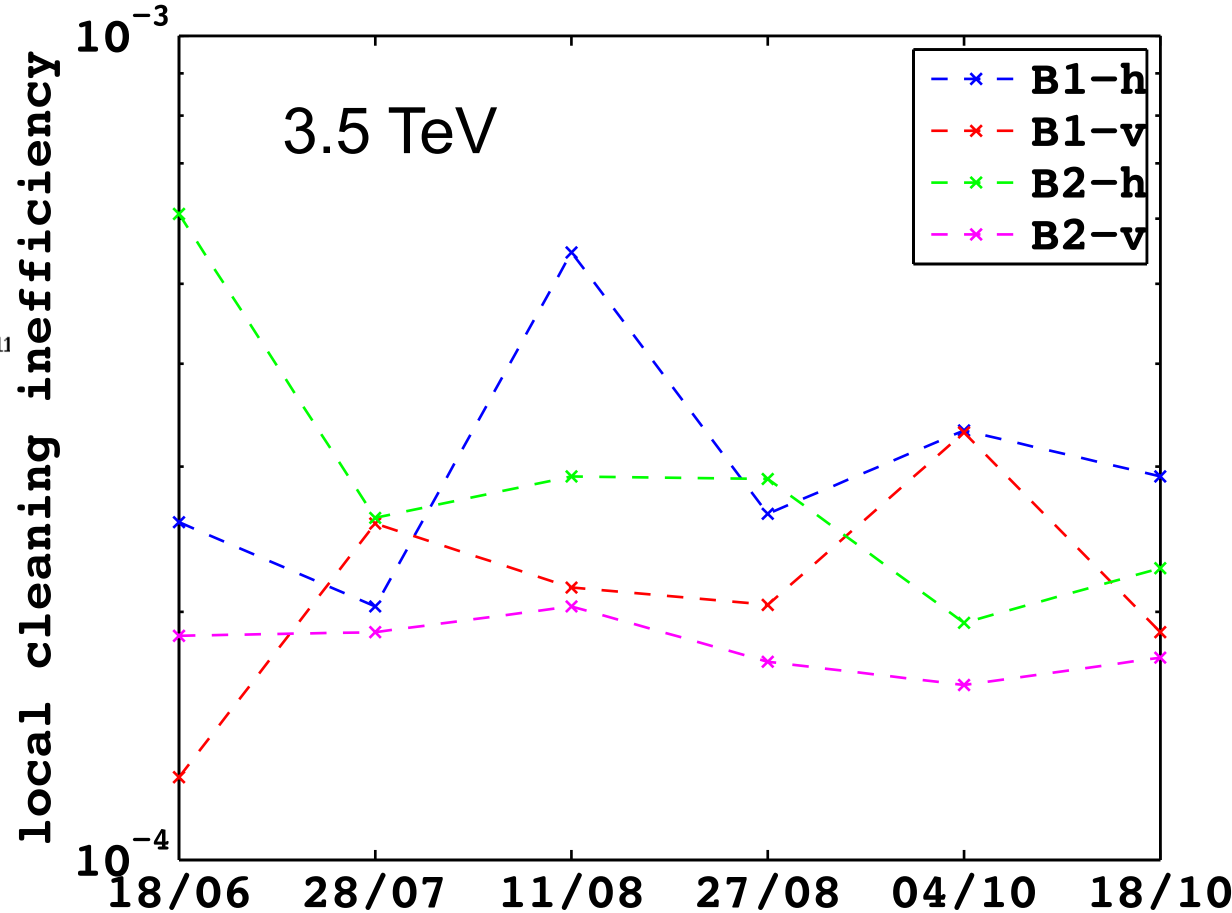


Data show BLM response for full beam lost, while collimator is being closed

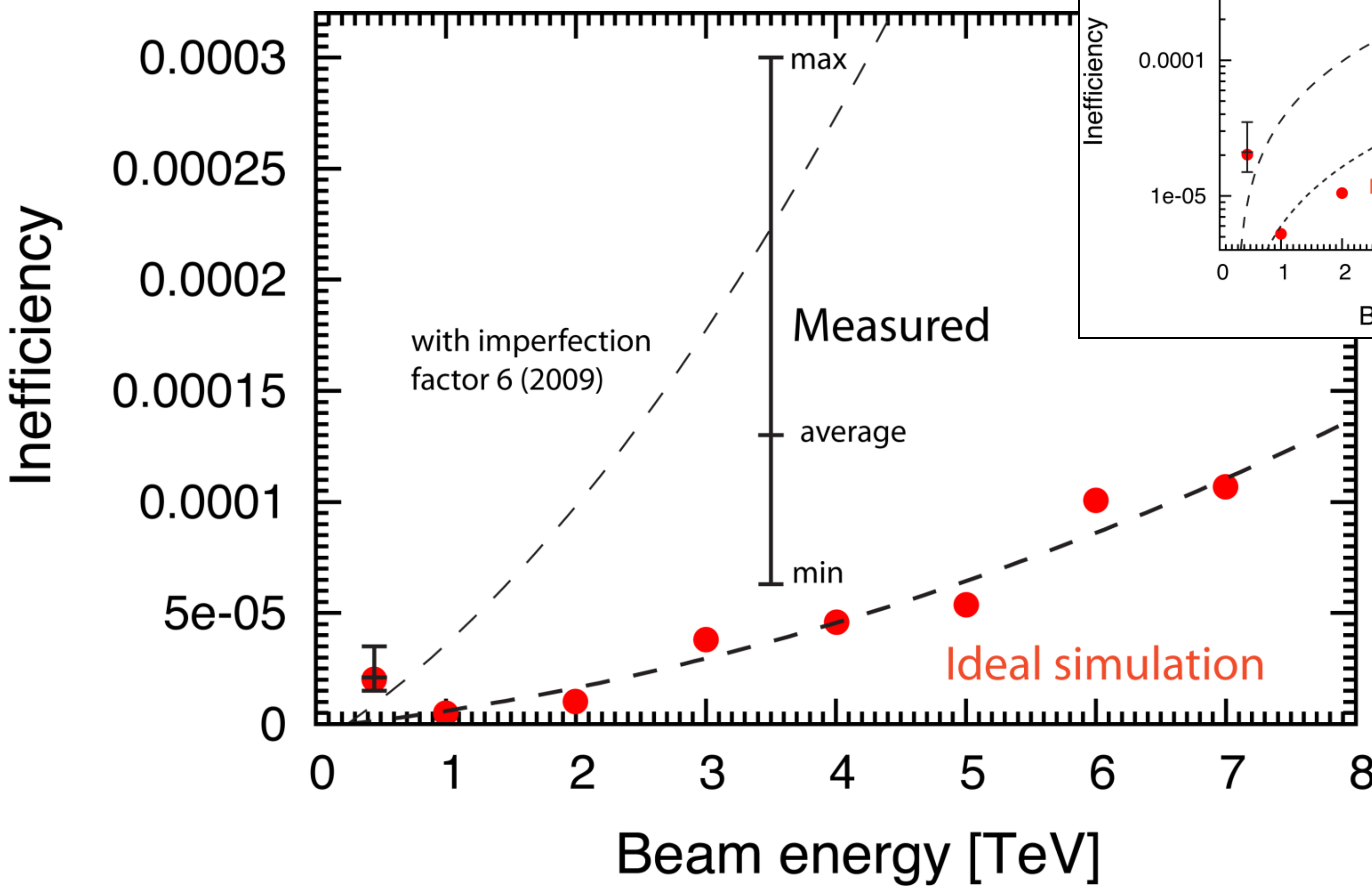
Stability Versus Time

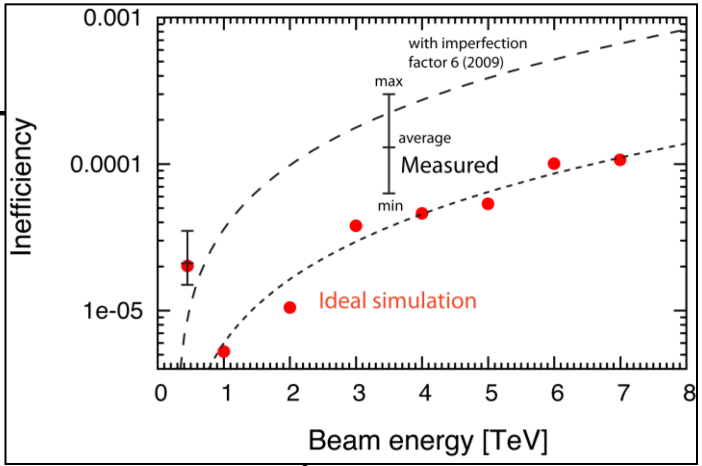


Analysis: Daniel Wollmann, see Evian talk!



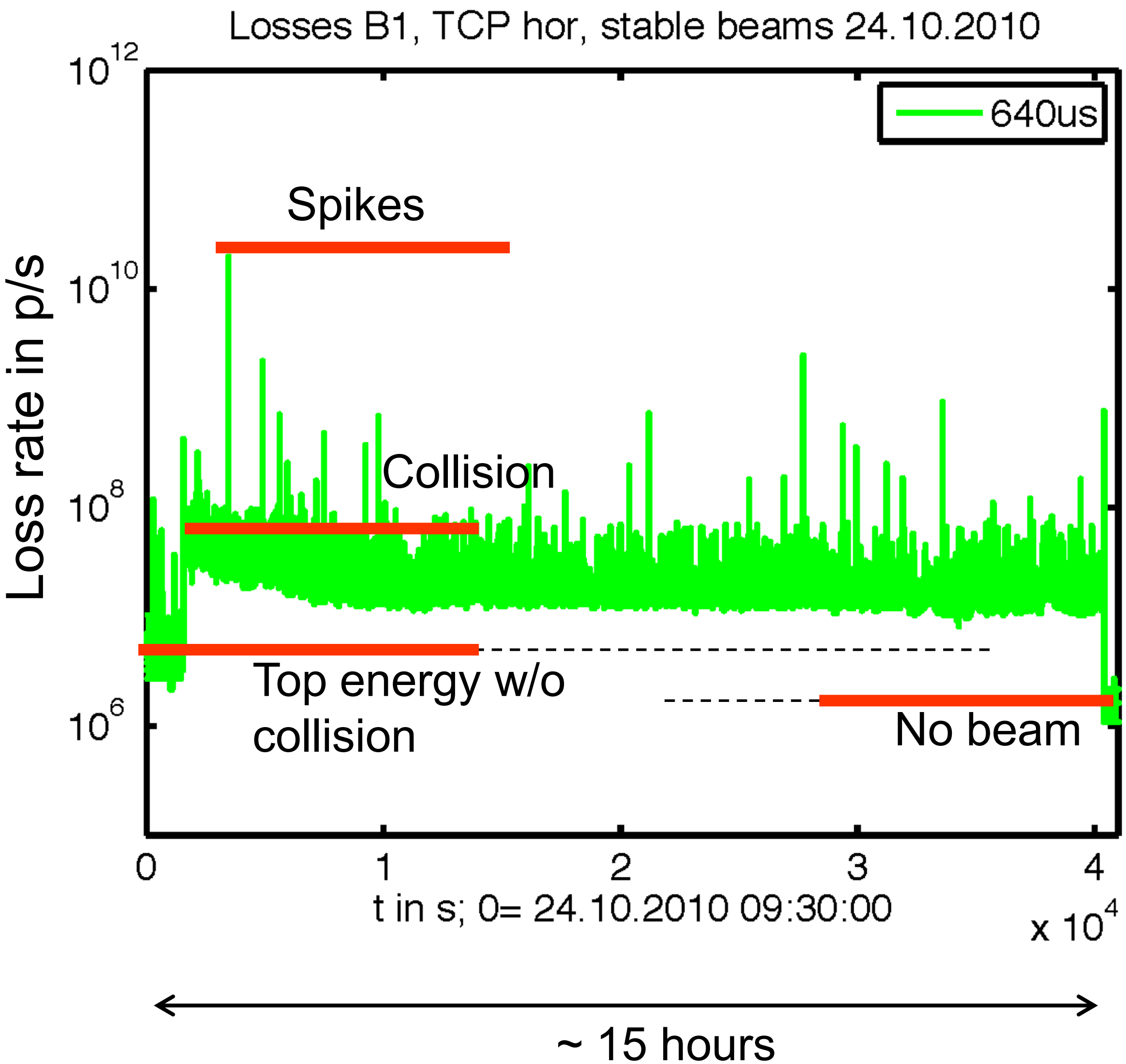
Compare Observation to Model from 2008





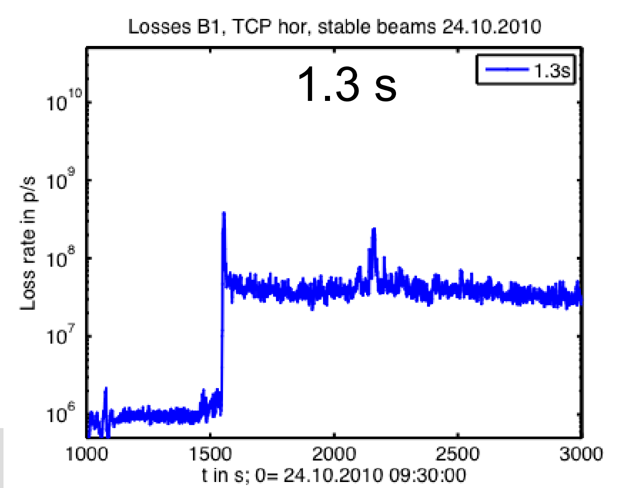
Model is OK!

Loss rate at hor. TCP in IR7 during high luminosity run, 150ns, 312b (24.10.2010)



Analysis: Daniel Wollmann, see Evian talk!

- 150ns, 312 bunches
- BLM signal RS04 (640us)
- Significant loss increase when in collisions
- Loss spike during the whole run



Loss rates and instantaneous life time for the 8 high luminosity fills

Range of highest (lowest) loss rates (life times) during high luminosity proton runs for different integration times of BLM signal:

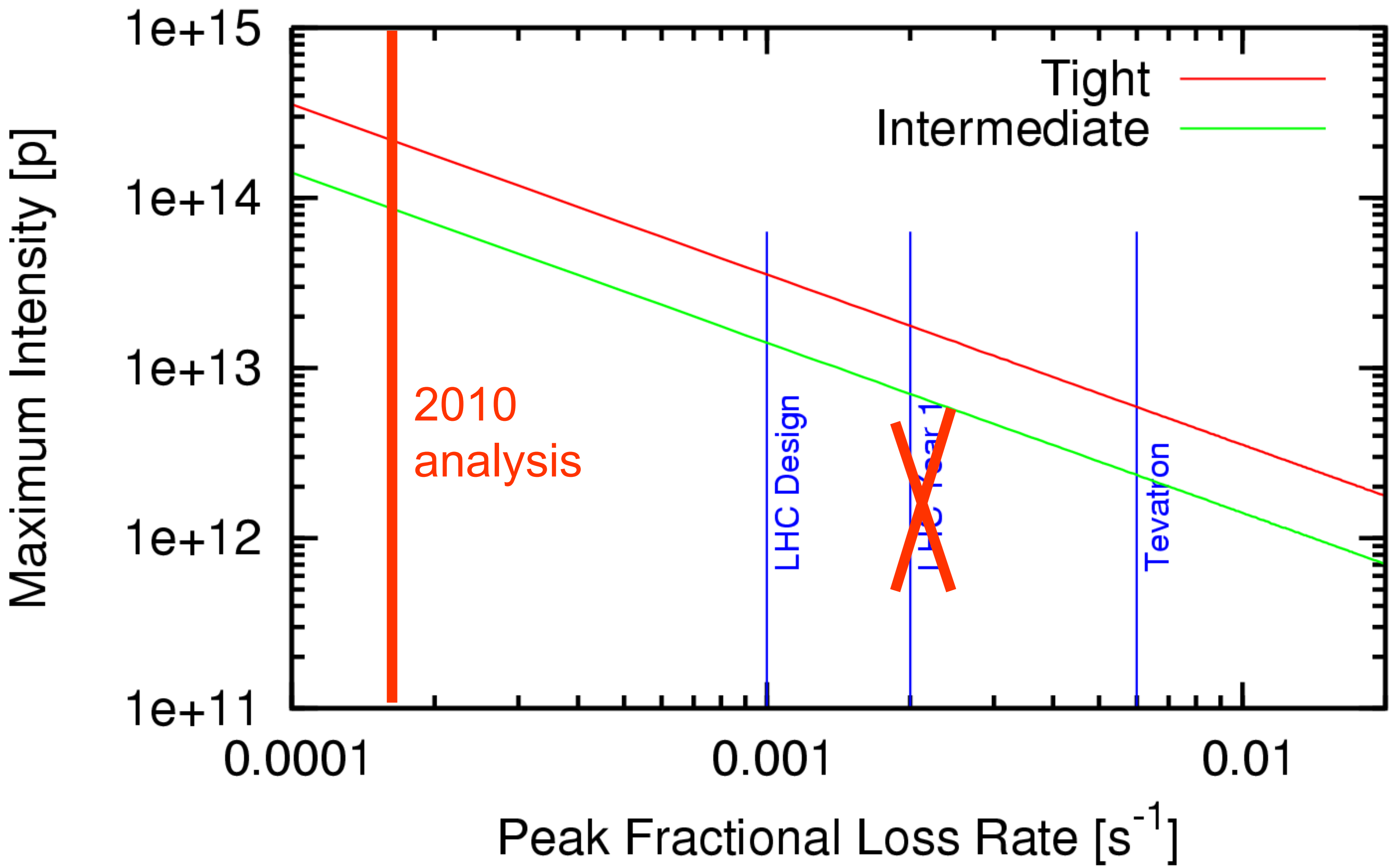
Integration times	Runs 312 bunches (3 runs)	**Runs 368 bunches (5 runs)**
RS02 (80us)-lifetime [h]	$0.3<\tau< 2.6$	$0.6<\tau< 6.8$
Loss rate [p/s]	3.3e10> R > 2.8e9	1.6e10 > R > 1.64e9
RS04 (640us)-lifetime [h]	$0.5 <\tau< 5.5$	$1.0<\tau< 7.7$
Loss rate [p/s]	2.0e10 > R > 1.3e9	1.2e10 > R > 1.4e9
RS06 (**10.24ms**)-lifetime [h]	**$2.3 <\tau< 6.2$**	**$1.3 <\tau< 21.6$**
Loss rate [p/s]	4.2e9 > R > 1.6e9	9.3e9 > R > 5.5e8
RS09 (1.3s)-lifetime [h]	$6.0 <\tau< 26.5$	$1.6 <\tau< 40.6$
Loss rate [p/s]	1.4e9 > R > 3.8e8	7.2e9 > R > 3.0e8

Remarks:

- RS02 and RS04: transient losses (1-7 turns)
- RS06 and RS09: steady state losses (115 – 14600 turns)
- B2 less loss spikes in 80us BLM signals, although the overall life time during fills is better in B1
- B2: IR7 TCSG.A6R7 at same loss level as TCPs for some fills
- Error (loss rate, life time < 20%)

Analysis: Daniel Wollmann, see Evian talk!

Result: Intensity Limit vs Loss Rate 7 TeV

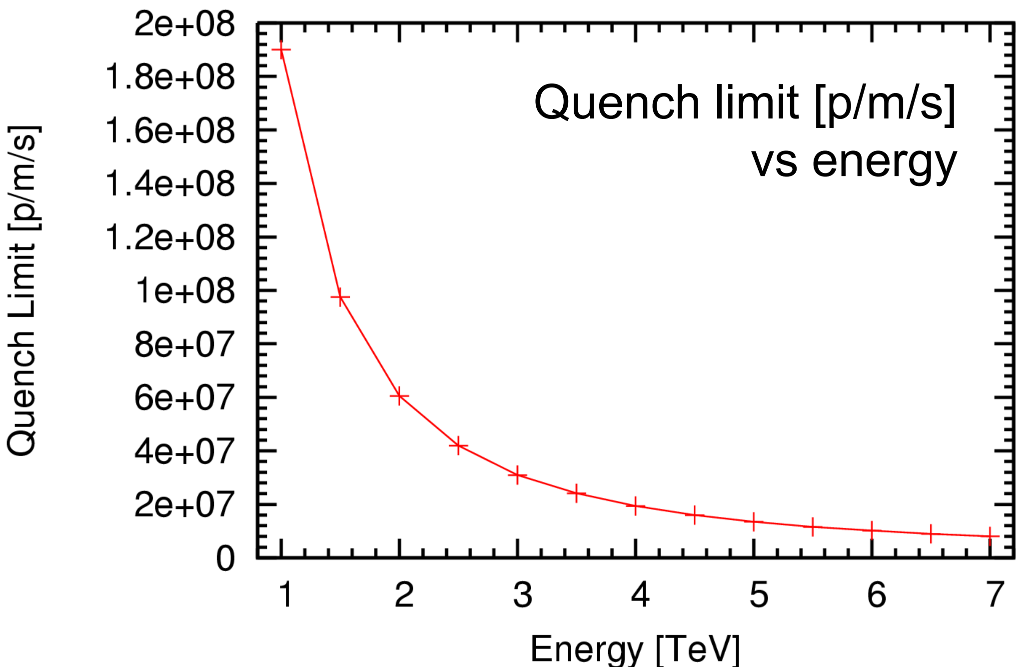


better ← → *worse*

Model LMC March 2009 – Same Plot

Intensity Reach
(from collimation)

Energy	p Intensity (max)	Ion intensity (max)
3.5 TeV	9.1e14	1.5e13 (q)
5.0 TeV	2.3e14	
7.0 TeV	0.9e14	



No predicted collimation limit on intensity at 3.5 TeV and 4 TeV!

Can imagine up to 2808 nominal or even ultimate bunches, if we only look at cleaning!

Analysis: Daniel Wollmann & Ralph Assmann,
see Daniel's Evian talk!

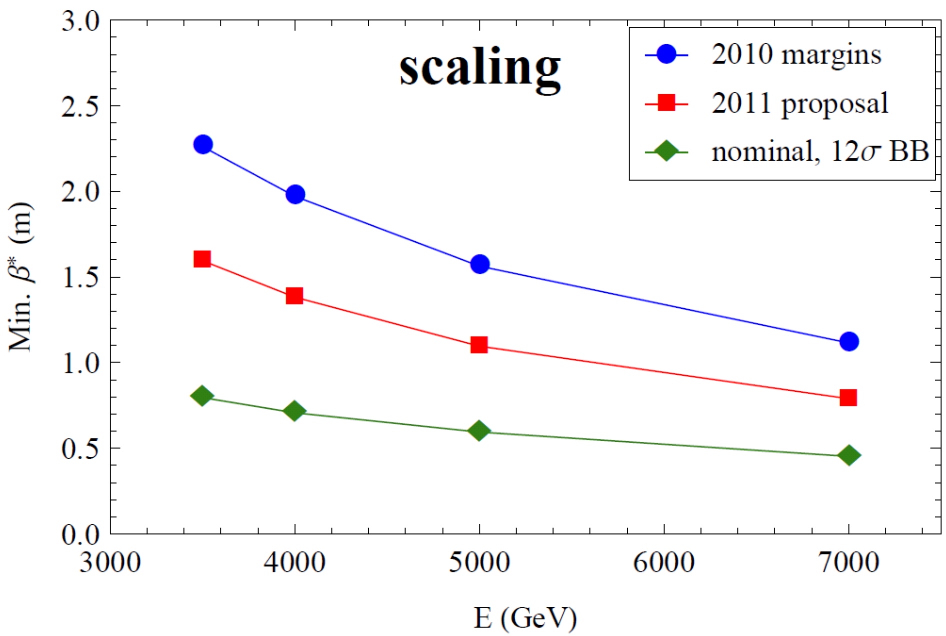
Content

- Hardware performance, collimation setup, impedance and verification
- Intensity reach from collimation
- **β^* reach from orbit & collimation**
- Luminosity reach at 3.5 TeV from collimation
- Conclusion

β* Reach from Orbit & Collimation

(accepting ≤ 1/30,000 y risk for triplet, ≤ 1/300 y for TCT)

- Reduce the separation at the IPs to its nominal value of 0.7 mm
- Measure the triplet aperture locally
- β-beating below 10%, reproducibility 5%, bias at TCTs/triplets
- Interlocks, warnings to reduce damage risk further
- New settings to be qualified with loss maps and async. dump tests. Problems => margins and β* to be increased
- Verify cleaning hierarchy on a regular basis
- Detailed study to correlate n1 calculation and measurements



Analysis: Roderik Bruce, see Roderik's Evian talk!

	3.5 TeV		4 TeV	
	β^* (m)	α (μrad)	β^* (m)	α (μrad)
2010 margins	2.3	125	2.0	125
2011 proposal	1.6	150	1.4	150

Proposed Margins and Settings

Analysis: Roderik Bruce, see Roderik's Evian talk!

- Summing *linearly* we get the margins

	2010		2011	
	(σ)	(mm)	(σ)	(mm)
triplet–TCT	2.5	0.9–2.1	2.3	1.1–2.7
TCT–TCSG IR6	5.7	3.5–4.4	2.5	1.3–1.8
TCSG IR7–TCP	2.8	0.6–1.6	2.8	0.5–1.5

- and the settings

TCP IR7	TCS IR7	TCS IR6	TCT	aperture
5.70	8.50	9.30	11.80	14.10

- Assuming IP2 remains at larger margins. Proposed settings very similar to what was used in 2010 run with β*=2.0m

Content

- Hardware performance, collimation setup, impedance and verification
- Intensity reach from collimation
- β^* reach from orbit & collimation
- **Luminosity reach at 3.5 TeV from collimation**
- Conclusion

Emittance Limit from Collimation

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

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

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

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

Conservative limit but gives peace of mind! Injectors cannot do better anyway!

Luminosity at Collimation Limit @ 3.5 TeV (50 ns)

- 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^*: 1.6 m
- We then get:
  - Stored energy: 133 MJ
- Luminosity reach with collimation limits:

… have to add F correction …

  - Theoretically: $< 4.5 \times 10^{33}$ cm^{-2} s^{-1}

…not reachable due to other limits… Thursday session!

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

Content

- Hardware performance, collimation setup, impedance and verification
- Intensity reach from collimation
- β^* reach from orbit & collimation
- Luminosity reach at 3.5 TeV from collimation
- **Conclusion**

Conclusion: Disclaimer

- **Other beam dynamics limits** do exist: fold in → Thursday session.
- Our **life is much easier at 3.5 TeV** than it will be later:
  - Operation with low emittance beams (primary collimators at 10 σ_{real} instead of 5.7 σ_{real}).
  - Losses reduced by skipping chromaticity measurements.
  - Impedance much lower than later (intermediate coll. settings & 3.5 TeV gaps).
  - Operation with 150 ns was far away from instabilities (e.g. e-cloud).
  - Long-range beam-beam much weaker than later.
  - Magnets far away from their limits (much more quench margin).
  - Efficiency of collimation is better at lower beam energy (less effect from single-diffractive scattering).
  - Transverse damper is easier.
  - Aperture might get worse with time due to ground motion.
- Be **careful with extrapolation to higher intensities and energies**!

Conclusion

- **Collimation behaves as predicted, including cleaning efficiency** → no need to change performance models.
- Good surprise: **6 times better beam lifetime than specified**.
- Collimation: N_{tot} (p) ≤ 2808 times 1.7 x 10^{11} (3.5 & 4 TeV)

  (cleaning only) N_{tot} (ion) ≤ 1.5 x 10^{13} (charges)

  N_p/ε ≤ 3.4 x 10^{20} m^{-1}

  T_{setup} ≈ 94 – 114 h

  $T_{validity}$ ≈ 4 – 5 months

  T_{uptime} = 99.5 %

  Essentially: No intensity limit from collimation at 3.5 TeV and 4 TeV!
- Orbit & coll.: β^* ≥ 1.6 m (1.4 m @ 4 TeV)
- Coll. cannot help for UFO cleaning (localized losses away from coll).
- **Limit for 7 TeV now estimated at ~ 30% of nominal intensity.**
- Ongoing upgrade program should guarantee nominal intensity @ 7 TeV.

Thank You

Microphone Detection of Unstable Beam