LHC Project Workshop
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LHC Aperture and Commissioning of the Collimation System

Stefano Redaelli

with

Ralph Assmann and Guillaume Robert-Demolaize

CERN
AB - ABP - LOC
Switzerland

Motivation

LHC beams, 7 TeV:
2 x 350 MJ stored energy!

High damage potential
"failure scenarios"

Protection system

Quench SC magnets
"regular losses"

Collimation system

Local losses in cold magnets ***< 10^{-7}-10^{-9}*** *of beam intensity!*

How do we prevent particles from touching the aperture?

1. **Good aperture design!** → *Leave enough space to the beam!*
2. **Efficient collimation system!** → *Clean-up the beam halo!*
3. Additional local protection → *Shade sensitive equipment!*

The cleaning system is not perfect and hence we must understand:

- ⇒ *How many particle escape?*
- ⇒ *Where are they lost in the ring?*
- ⇒ *Can they quench the magnets?*

Take correction actions before it is too late…

Overview of my talk

1. The LHC aperture

- Design criteria for the LHC aperture
- Aperture bottlenecks
- Dependence on optics parameters

2. Loss maps around the LHC ring

- Tools for halo tracking and loss maps
- Loss maps for a perfect optics
- Effect of optics imperfections

3. Collimator test at the SPS

- Measurement with beam at the SPS
- What have we learnt?

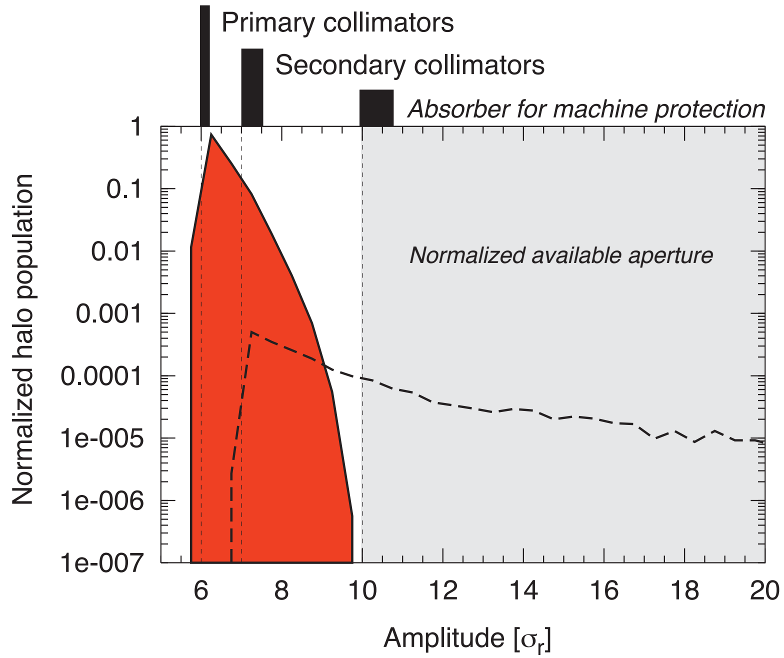
4. Conclusion

The design of the LHC aperture:

Secondary beam halo should not touch the mechanical aperture inner wall!
JB.Jeanneret et al, LHC Proj Note 111, 1997

LHC design values: X / Y aperture (1D) = **8.4 σ**
Radial aperture = **9.8 σ**

*… this ensures a geometrical acceptance of **10 σ** for the circulating beams!*



R. Assmann, ChamonixXII, 2003

Design of ring aperture takes into account
(simplified linear model based on the Twiss functions):

Mechanical tolerances (manufacturing + alignment) → **1.0 - 2.5 mm**

Allowance δ*p/p* (chromatic sweep, on top of bucket width) → **0.05 %**

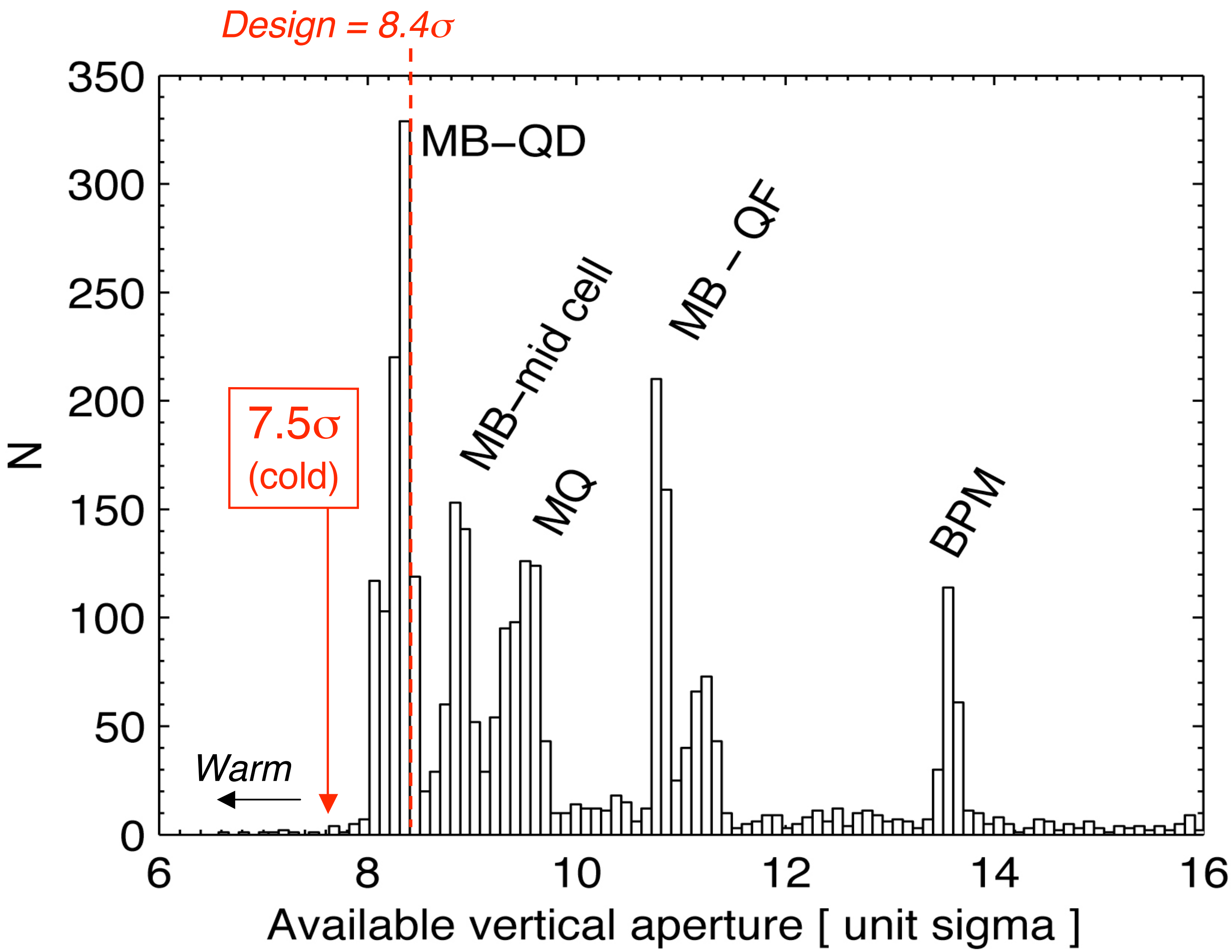
Separation/crossing schemes (IR's only) → **≤ 15 mm (D1)**

Spurious dispersion → **27% of spurious normalized D_x**

Closed orbit (radial) → **4 mm (3 mm at triplets)**

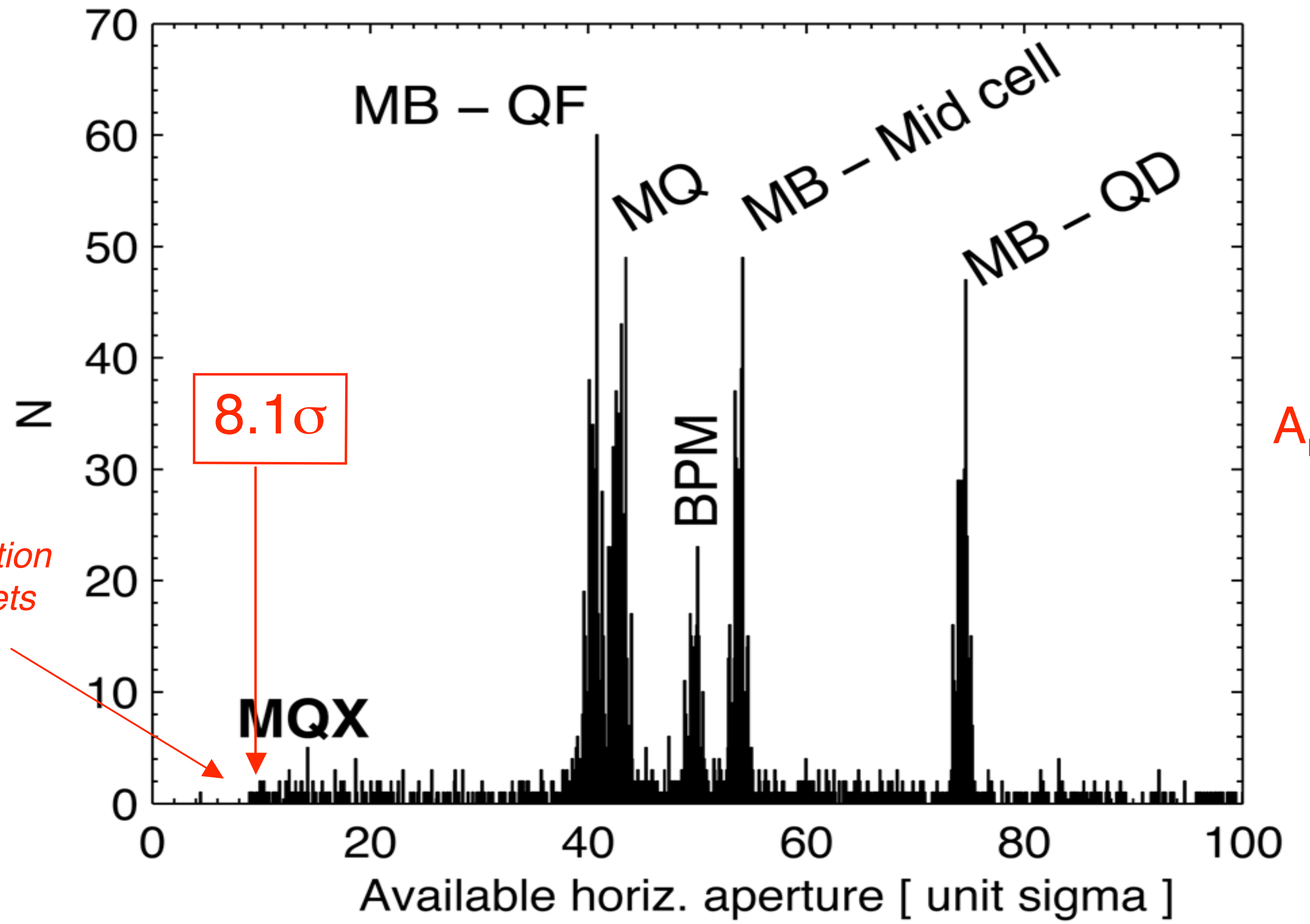
Beta beating (δβ/β) → **20 %**

Distribution of available aperture at injection (450 GeV)



The **ARCs** are the aperture bottlenecks at injection: $\mathbf{A_{mech}^{min} \approx 7.5\ \sigma}$

Distribution of available aperture at collision (7 TeV)



Similar available aperture as at injection (smaller aperture sets the scale…)

$A_{mech}^{arc} \approx 40\ \sigma$

The triplets ($\beta \approx 4500$ m) are the aperture bottlenecks at 7 TeV: **$A_{mech}^{min} \approx 8.1\ \sigma$**

(only for $\beta^* = 0.5$ m)

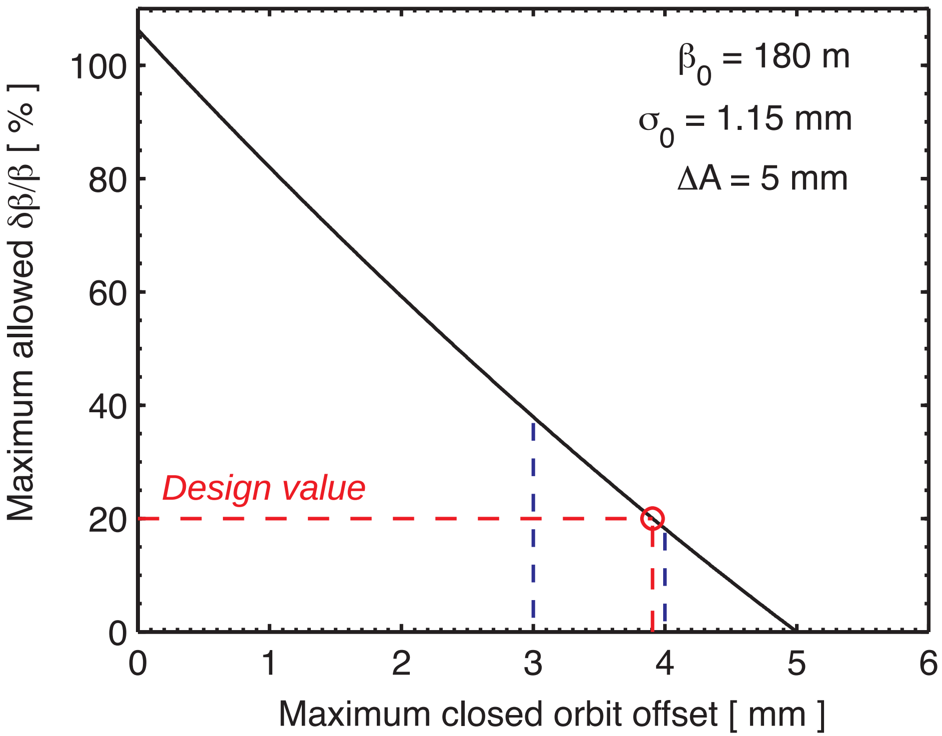
β -beat versus closed orbit

$$\Delta A = n_c \Delta\sigma^{\beta-\mathrm{beat}} + \Delta^{\mathrm{CO}}$$

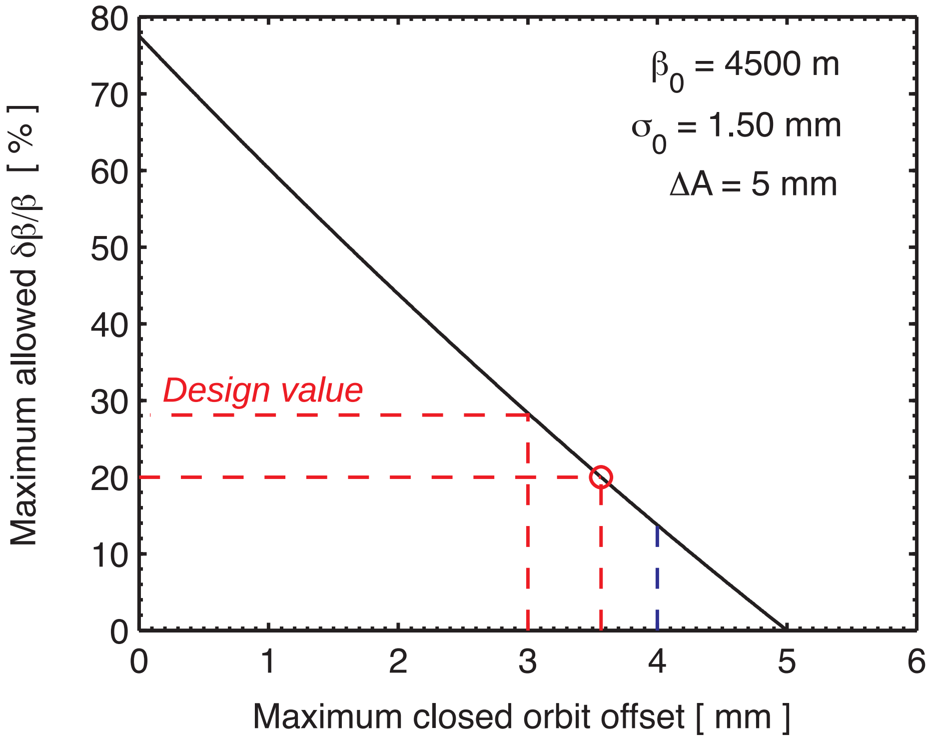
$$\left(\frac{\Delta\beta}{\beta_0}\right)_{\mathrm{allowed}} = \left[\frac{\Delta A - \Delta^{\mathrm{CO}}}{n_c} + \sigma_0\right]^2 \frac{1}{\sigma_0^2} - 1$$

ΔA	*allocated margin*
$\Delta\sigma^{\beta}$	*size variation from $\delta\beta/\beta$*
Δ^{CO}	*local closed orbit error*
n_c=10	*number of sigma*

At 450 GeV: ***ARCs*** (Δ^{CO} = 4 mm)



At 7 TeV: ***Triplets*** (Δ^{CO} = 3 mm)



1. **The LHC aperture**
   - Design criteria for the LHC aperture
   - Aperture bottlenecks
   - Dependence on optics parameters

2. **Loss maps around the LHC ring**
   - **Tools for halo tracking and loss maps**
   - **Loss maps for a perfect optics**
   - **Effect of optics imperfections**

3. **Collimator test at the SPS**
   - Measurement with beam at the SPS
   - What have we learnt?

4. **Conclusion**

Tools for halo tracking and loss maps

Halo generation and tracking done with SixTrack + K2 (R. Assmann, G.Robert-Demolaize)

⇒ *Halo production in the two stage collimation system (LHC optics V6.5) and multi-turn tracking of secondary and tertiary halos (δE/E, …)*

⇩

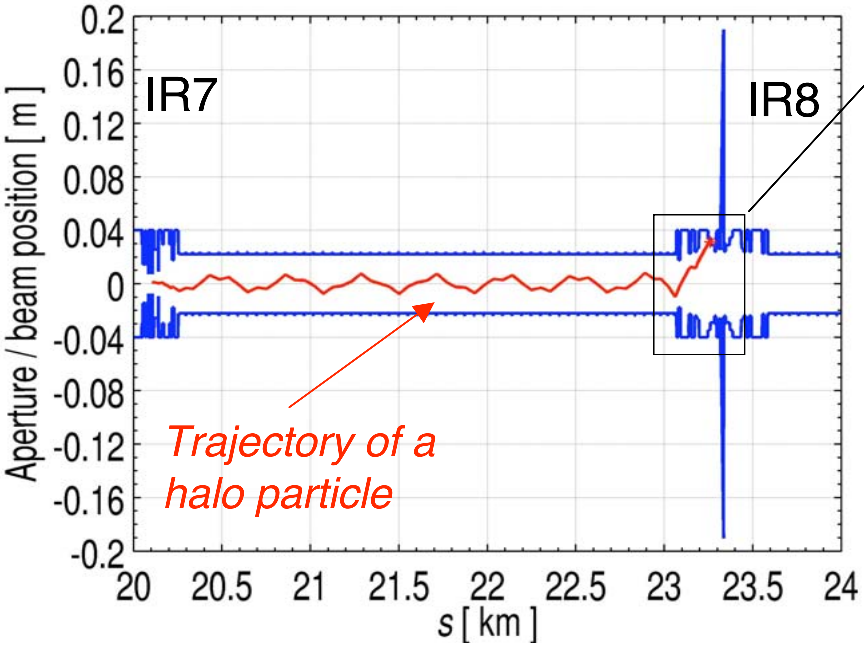
Trajectories of secondary and tertiary halo part's

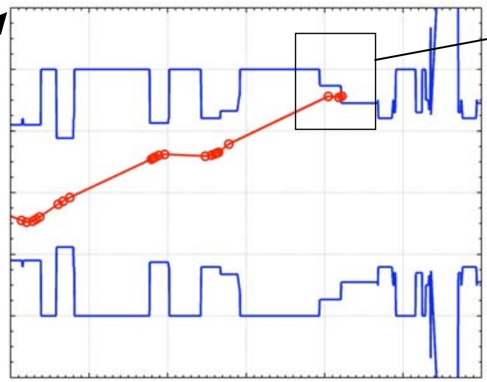
⇩

Aperture model for the full LHC ring, 10 cm longitudinal spatial resolution.

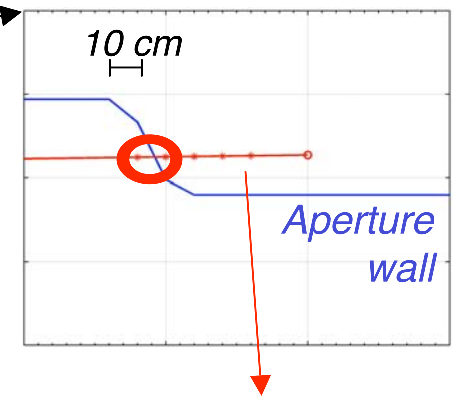
⇒ *Reconstruction of beam trajectory provides longitudinal and transverse distributions of losses*

Off-line treatment of effects such as closed orbit, misalignments, kicks from D1… D4 magnets





Magnets locations (*thin lenses*): **$\Delta s \leq$ 100m**



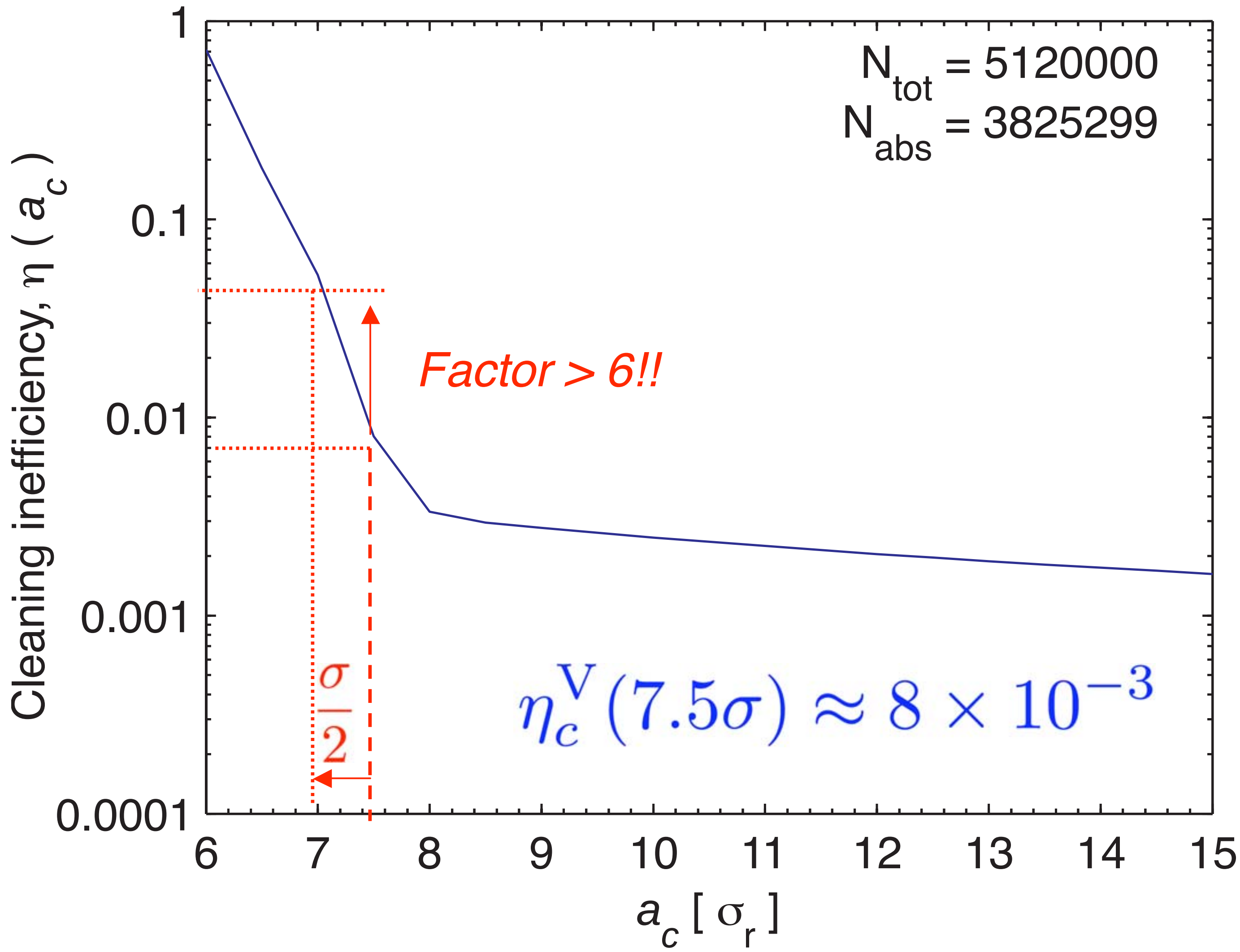
Interpolation: **Δs=10 cm**
(**270'000** points!)

Goals of our study: *1. How many particles escape the cleaning insertion?*
2. Where are they actually lost? Can they quench magnets?

How many particles are lost? → *Cleaning inefficiency*

$$\eta_c(A_0) = \frac{N_p(A > A_0)}{N_{\rm abs}}$$

Reduce aperture by 0.5σ
⇒ 6 times more losses!



The collimation system must ensure that $N_{loss} < N_{quench}$!

Local cleaning inefficiency at the quench [1/m]

$$\tilde{\eta}_c(A_0) = \frac{\eta_c(A_0)}{L_{\mathrm{dil}}}$$

L_{dil} = 50 m

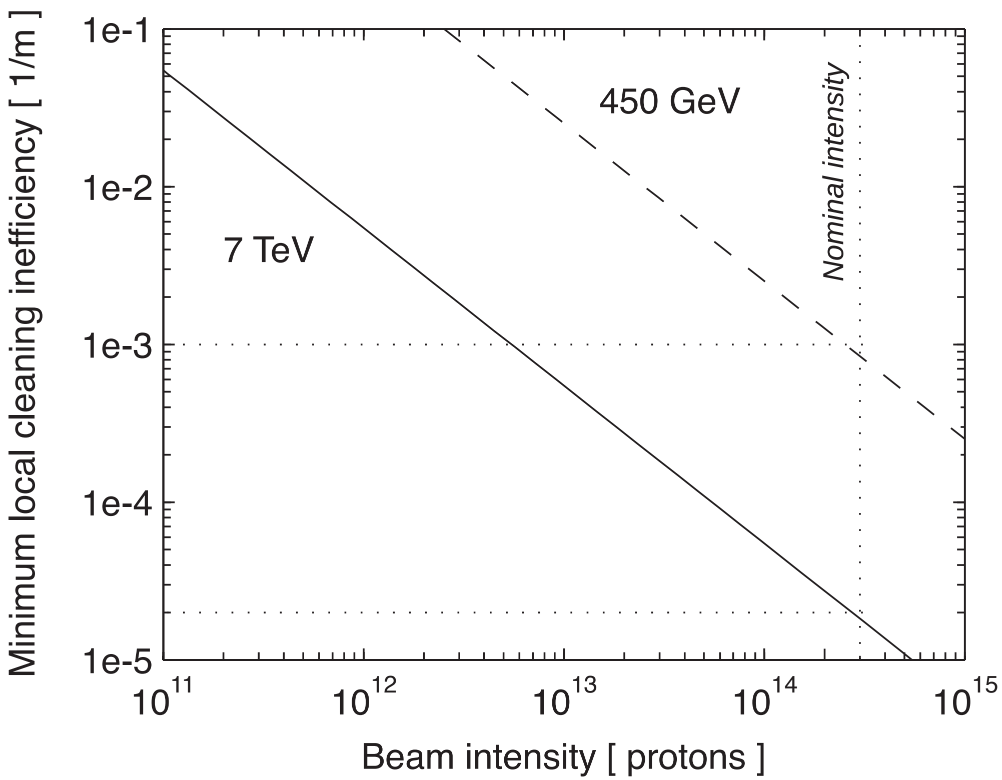
OP → Beam lifetime [s]

$$\tilde{\eta}_c^{\mathrm{quench}} = \frac{\tau R_{\mathrm{quench}}}{N_{\mathrm{tot}}}$$

Loss rate at the quench limit [p/m/s], as for ***LHC Proj. Rep. 44,1996***

Total beam intensity [p]

(R. Assmann, Chamonix XII)



Minimum allowed local cleaning inefficiency to prevent quenches:

Injection $(\tau^{\mathrm{inj}} = 0.1\ \mathrm{h})$

$$\tilde{\eta}_c^{\mathrm{inj}} = 10^{-3} m^{-1}$$

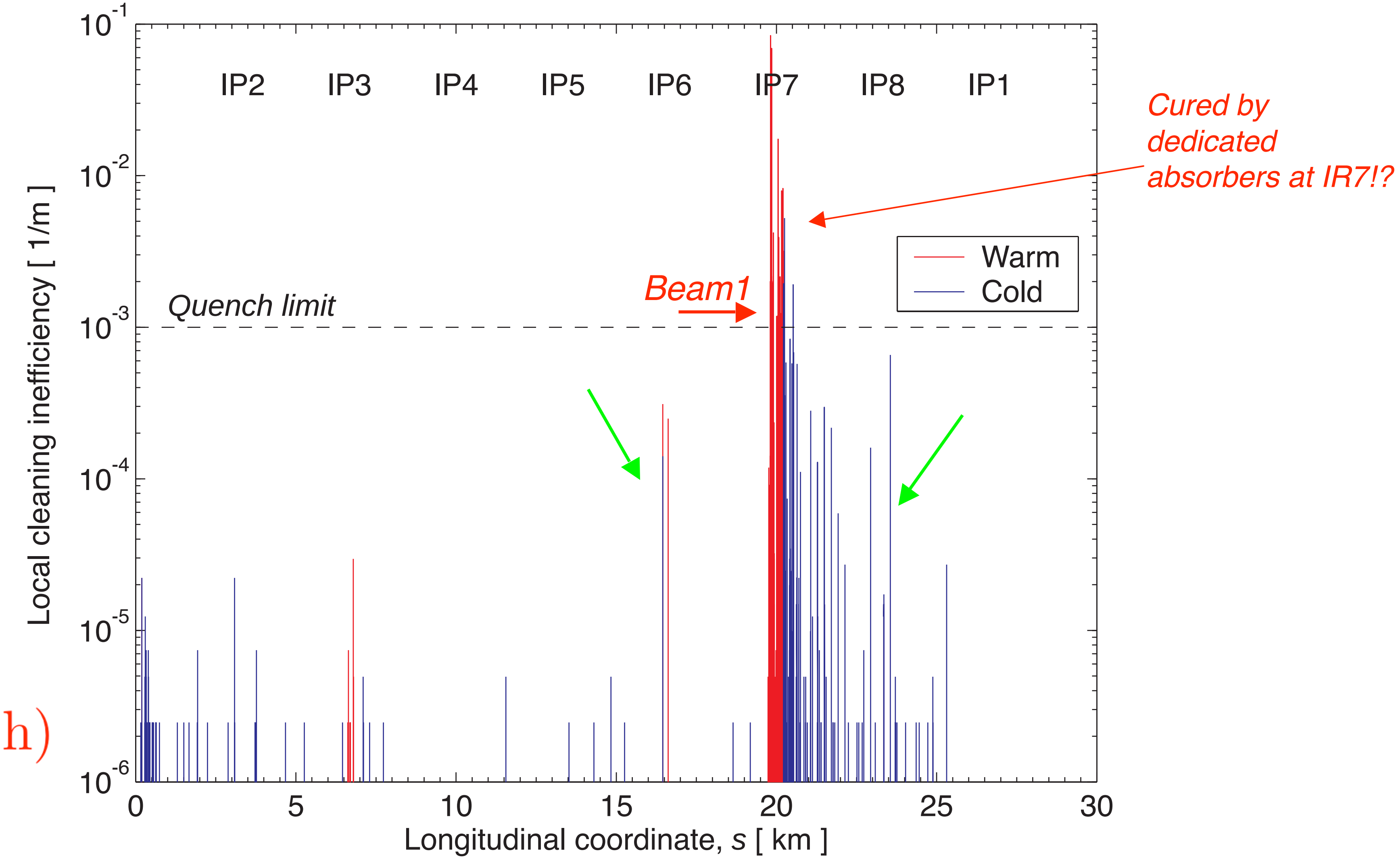
Top energy $(\tau^{\mathrm{lowb}\beta} = 0.2\ \mathrm{h})$

$$\tilde{\eta}_c^{\mathrm{low}\beta} = 2 \times 10^{-5} m^{-1}$$

See talk by A. Siemko…

Loss maps at injection (450 GeV) - perfect machine

Horizontal

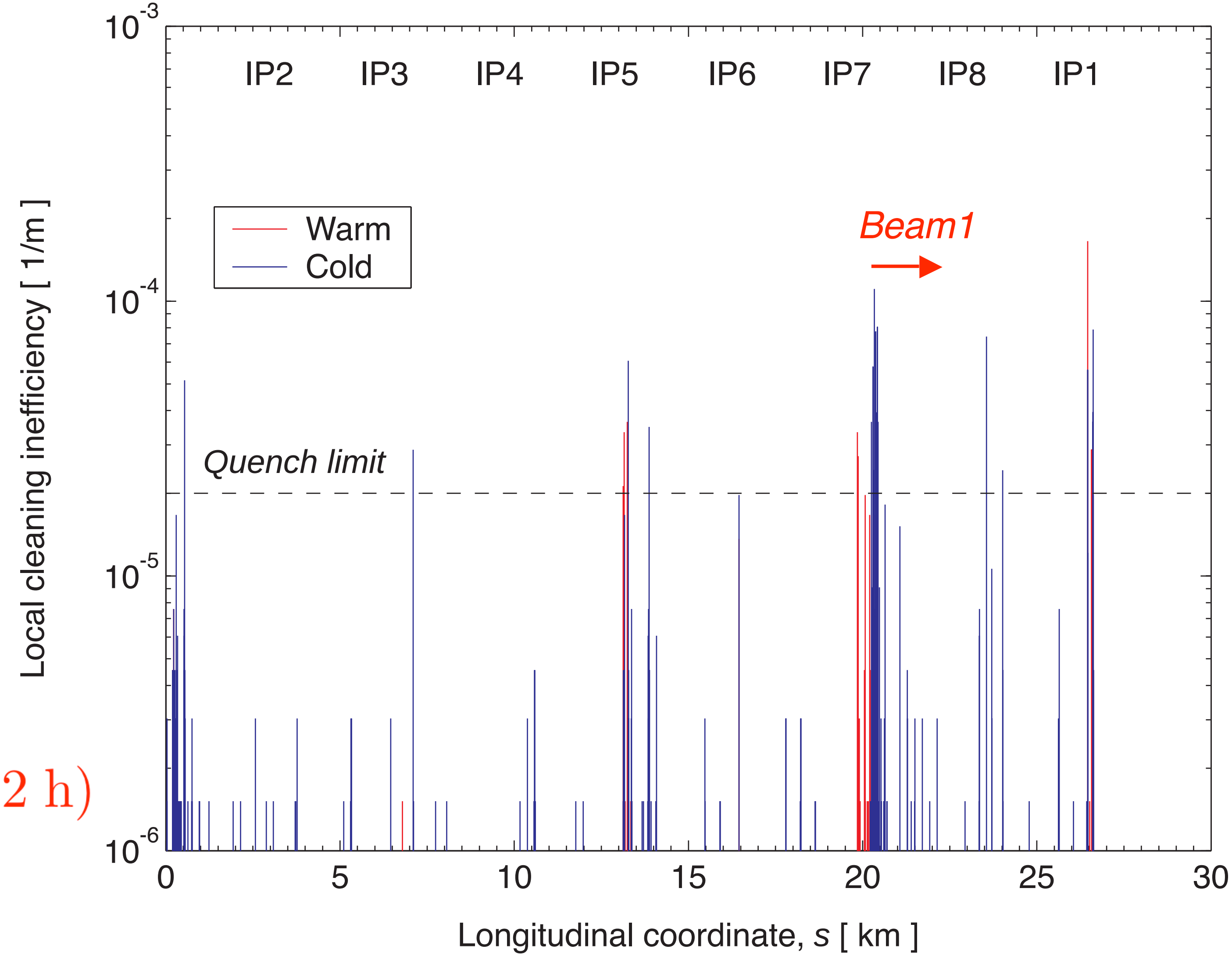


$(\tau^{\mathrm{inj}} = 0.1\ \mathrm{h})$

A few locations above Q limit in the DS 7-8 should be cured by our absorbers!

Some losses at unexpected locations (IP8, IP6)

Loss maps at top energy (7 TeV) - perfect machine
Horizontal



$(\tau^{\mathrm{lowb}\beta} = 0.2\ \mathrm{h})$

Many locations above quench limit, even for perfect machine!

List of elements above, or close to, the quench limit

Injection - perfect machine

Horizontal halo

Element	S pos [m]	ineff/l
DFBAN.7R7.B1	20253.01	5.26e-03
MQTLH.A6R7.B1	20217.88	2.01e-03
MQTLH.B6R7.B1	20221.11	1.94e-03
MB.C13R7.B1	20523.71	1.90e-03
MQTLH.A6R7.B1	20217.79	8.96e-04
MQ.11R7.B1	20427.42	8.34e-04
MQTLH.A6R7.B1	20217.19	7.09e-04
MQT.13R7.B1	20535.63	6.84e-04
MCBCH.6R8.B1	23553.23	6.57e-04
MQ.8R7.B1	20295.15	5.85e-04
MQT.12R7.B1	20482.07	5.78e-04
MQT.15R7.B1	20642.46	5.73e-04
DFBAN.7R7.B1	20256.00	3.56e-04
MQY.5L6.B1	16450.66	3.11e-04
MO.31R7.B1	21497.68	2.96e-04
MQS.23R7.B1	21070.07	2.81e-04
MQTLH.A6R7.B1	20218.03	2.32e-04
MO.33L8.B1	21711.53	2.17e-04
MQML.10L8.B1	22939.30	1.60e-04
MQY.5L6.B1	16450.86	1.41e-04
MQS.27R7.B1	21283.92	1.28e-04
MQTLH.F6L7.B1	19759.96	1.19e-04
MQT.17R7.B1	20749.39	1.11e-04

Vertical halo

Element	S pos [m]	ineff/l
MQS.27R7.B1	21284.64	1.88e-03
DFBAN.7R7.B1	20252.97	9.12e-04
MQTLH.A6R7.B1	20217.85	5.97e-04
MQ.8R7.B1	20295.06	5.94e-04
MQT.12R7.B1	20482.07	3.57e-04
MQTLH.F6L7.B1	19760.04	3.57e-04
MQ.11R7.B1	20427.38	3.02e-04
MQY.5L6.B1	16450.87	2.29e-04
MQTLH.A6R7.B1	20217.75	2.29e-04
MB.A8R7.B1	20277.49	2.21e-04
MB.B12R7.B1	20464.31	2.13e-04
MQT.15R7.B1	20642.49	2.02e-04
MQML.10L8.B1	22939.31	1.97e-04
MCBCH.6R8.B1	23553.17	1.66e-04
MQS.23R7.B1	21070.13	1.45e-04
DFBAN.7R7.B1	20256.04	1.18e-04
MQY.5L6.B1	16450.69	1.18e-04
MB.A9R1.B1	321.40	1.16e-04
MQTLH.A6R7.B1	20218.03	1.03e-04

List of elements above, or close to, the quench limit
Top energy - perfect machine

Horizontal halo

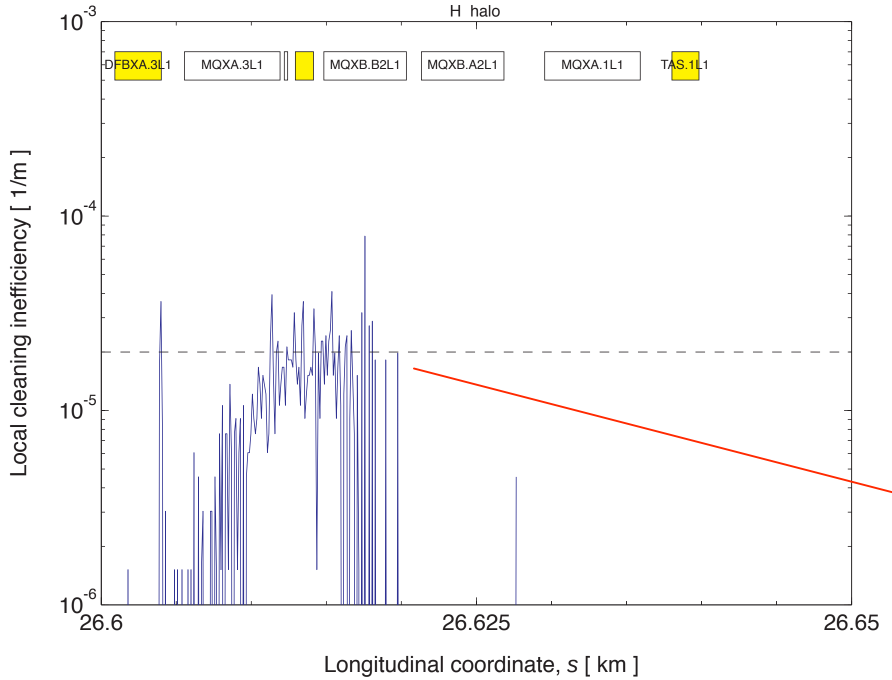
Element	S pos [m]	ineff/l
MCBCV.5L1.B1	26458.26	1.65e-04
MQ.9R7.B1	20334.09	1.11e-04
MQ.11R7.B1	20427.37	8.04e-05
MQXB.B2L1	26617.56	7.89e-05
MQ.10R7.B1	20374.64	7.74e-05
MCBCH.6R8.B1	23553.22	7.43e-05
DFBXE.3L5	13274.48	6.07e-05
MQ.8R7.B1	20295.15	5.77e-05
MCBCV.5L1.B1	26458.38	5.61e-05
MQT.13R1.B1	541.36	5.16e-05
MQXB.B2L1	26615.37	4.10e-05
MQXA.3L1	26611.37	3.94e-05
MB.B11R7.B1	20411.39	3.94e-05
DFBXE.3L5	13274.38	3.79e-05
DFBXA.3L1	26603.98	3.64e-05
MB.A12R7.B1	20442.15	3.64e-05
DFBAN.7R7.B1	20253.00	3.64e-05
MQT.13R5.B1	13870.67	3.49e-05
MB.A12R7.B1	20441.45	3.34e-05
MQY.4L5.B1	13156.98	3.34e-05
MQXB.B2L1	26617.36	3.19e-05
MB.A12R7.B1	20441.65	3.03e-05
MQXB.B2L1	26618.06	2.88e-05
MB.A12R7.B1	20441.95	2.88e-05
MQ.11R3.B1	7097.86	2.88e-05
MQXB.B2L1	26617.86	2.73e-05
TASB.3L1	26613.37	2.73e-05
MQXB.B2L1	26614.97	2.43e-05
MB.C16R8.B1	24017.09	2.43e-05
MB.A9R7.B1	20312.92	2.43e-05
MQXB.B2L1	26614.67	2.28e-05
MQXA.3L1	26611.27	2.28e-05
MQXB.B2L1	26616.27	2.12e-05
MQSX.3L1	26612.37	2.12e-05
MQML.5L5.B1	13129.78	2.12e-05
		....

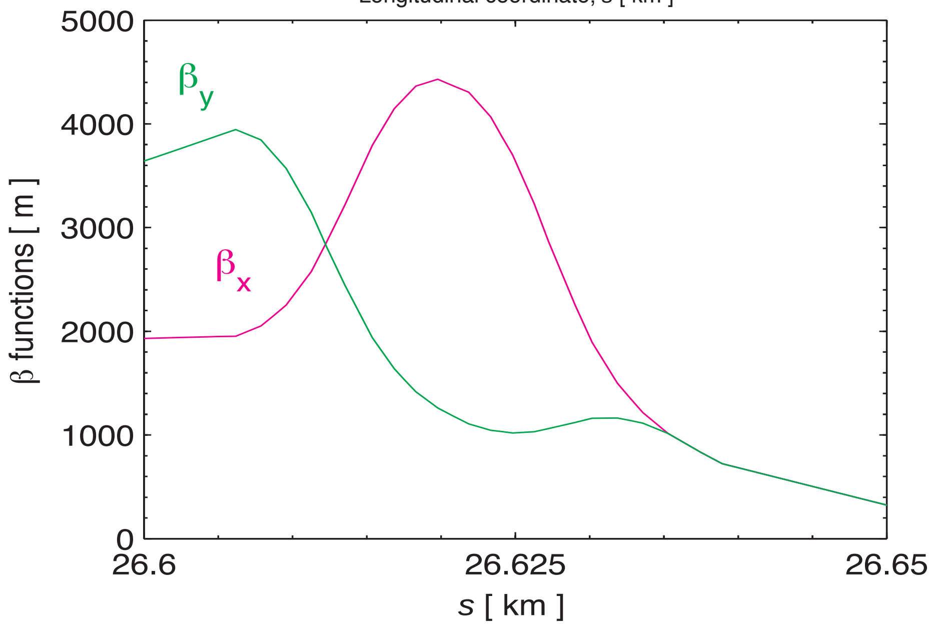
Pick a few examples…

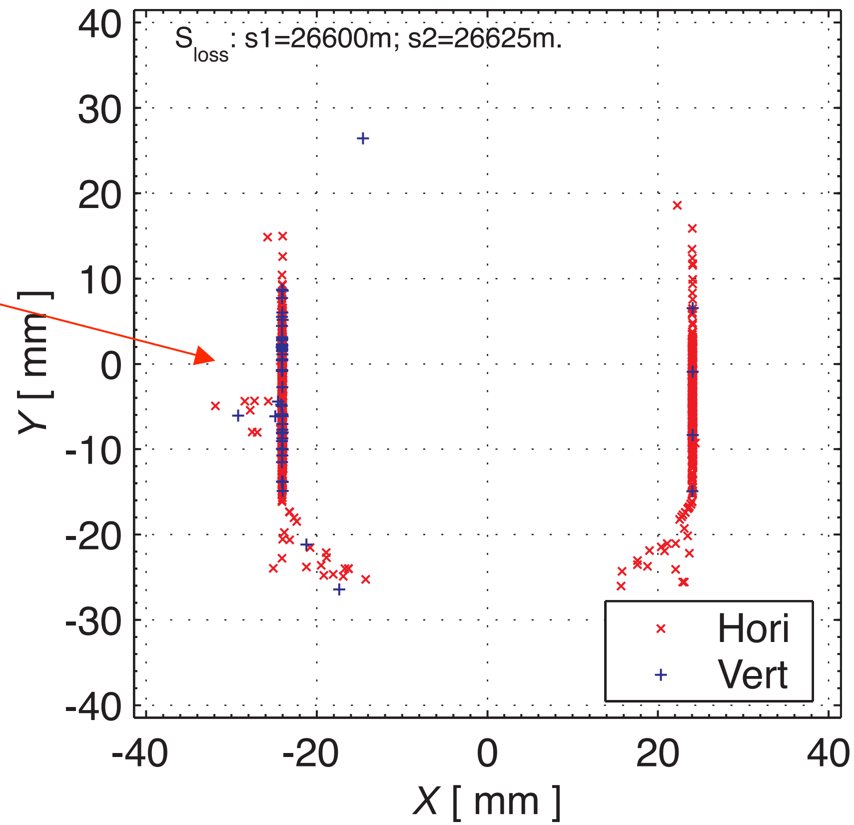
Vertical halo

Element	S pos [m]	ineff/l
MQ.10R7.B1	20374.64	1.00e-04
MQ.9R7.B1	20334.10	8.98e-05
DFBXE.3L5	13274.47	7.13e-05
MQT.13R1.B1	541.38	7.13e-05
MQ.11R7.B1	20427.37	4.75e-05
MQT.13R5.B1	13870.68	4.75e-05
MQ.11R3.B1	7097.87	4.75e-05
MQT.14R4.B1	10591.43	3.17e-05
MO.28L3.B1	5316.54	2.64e-05
MQT.12R7.B1	20482.10	2.38e-05
MQ.11R1.B1	433.22	2.11e-05
MQY.4L5.B1	13156.97	1.85e-05
MQT.15R7.B1	20642.49	1.58e-05
MB.A12R7.B1	20437.36	1.58e-05
MO.25L6.B1	15474.25	1.58e-05
MCBCV.5L1.B1	26458.25	1.58e-05
MB.A12R7.B1	20436.46	1.32e-05
MQ.11R7.B1	20430.07	1.32e-05
MB.B11R7.B1	20405.00	1.32e-05
MB.A11R7.B1	20392.92	1.32e-05
MBRC.4L5.B1	13166.11	1.32e-05
MQMC.9R1.B1	340.05	1.32e-05
MB.A12R7.B1	20435.56	1.06e-05
MCBH.11R7.B1	20433.76	1.06e-05
MS.11R7.B1	20432.97	1.06e-05
MB.B11R7.B1	20398.41	1.06e-05
MB.A11R7.B1	20390.82	1.06e-05
MB.A10R7.B1	20348.88	1.06e-05
MQ.9R7.B1	20335.49	1.06e-05
MB.B9R7.B1	20319.32	1.06e-05
MQXB.B2R5	13367.95	1.06e-05
MQXB.A2R5	13365.95	1.06e-05
MCBCH.6L3.B1	6458.02	1.06e-05
		....

Longitudinal and transverse distribution of losses at IP1



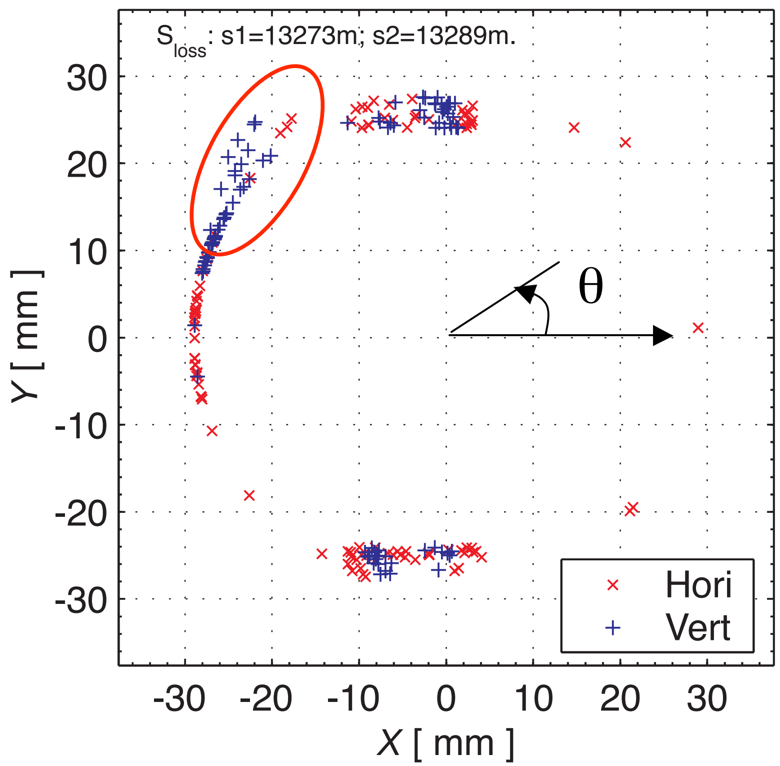




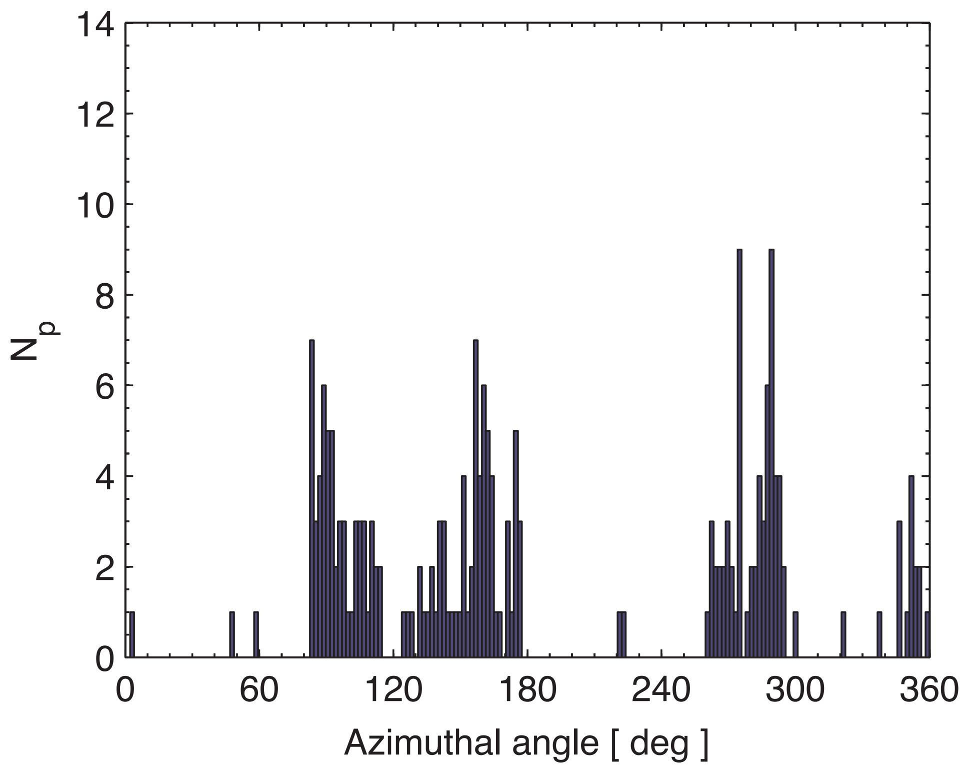
*Losses at the **triplets**: protected by local tertiary collimators (TCT's)!*

*At **IP5**, **skew losses** at the triplets, at top energy!*
How can we protect them with TCT's?

Scatter plot of losses



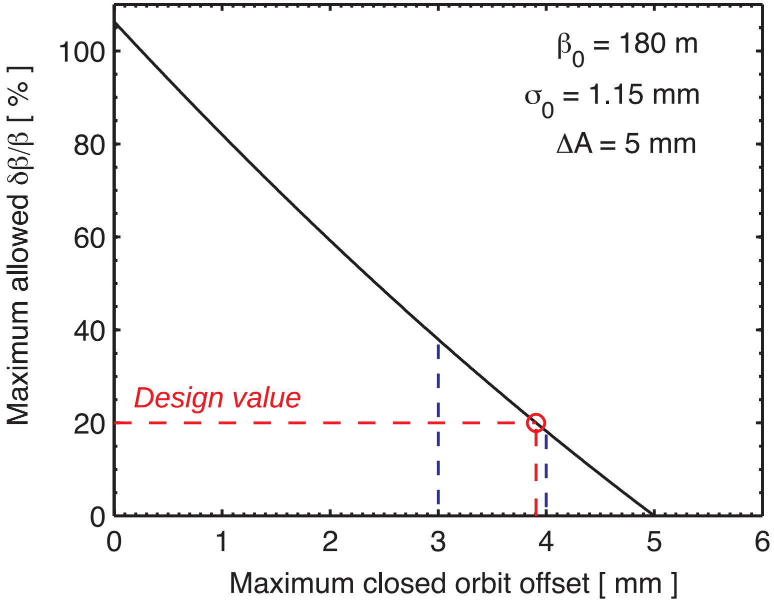
Azimuthal distribution of losses

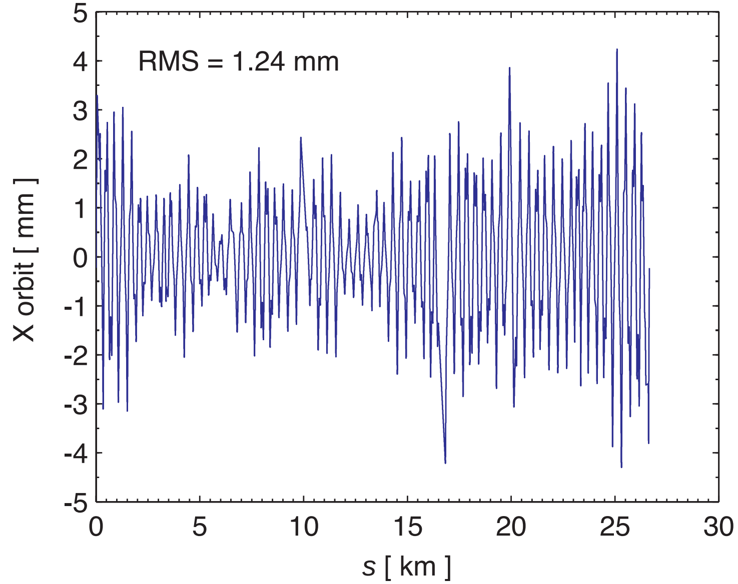


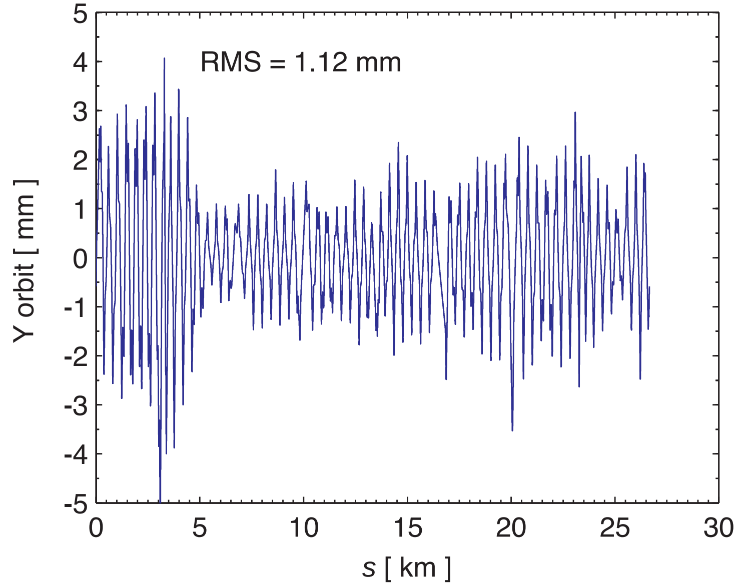
Perfect machine considered so far…

Effect of optics imperfections - Closed orbit

CO dominates!







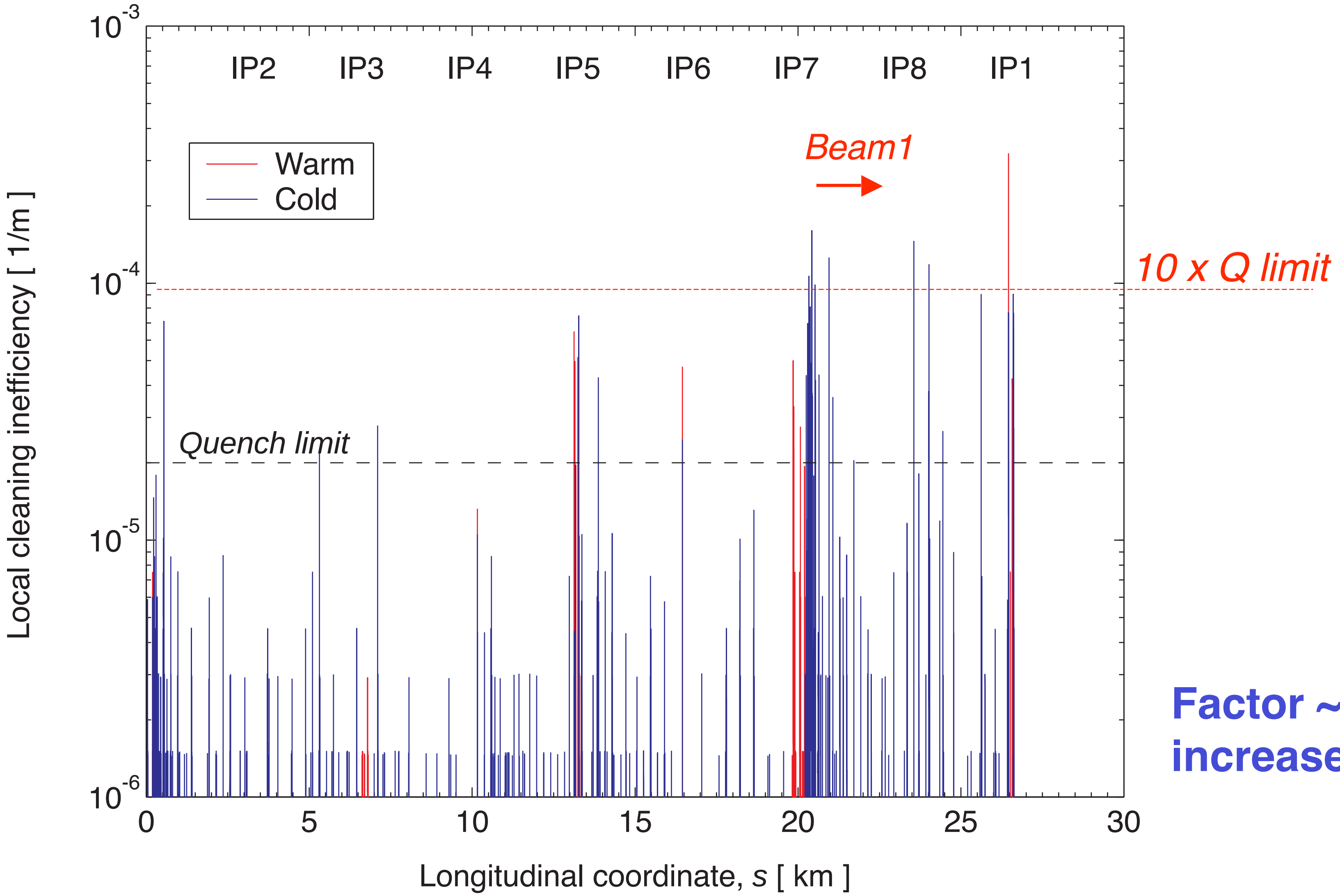
10 seed of realistic closed orbits, V+H, generated with MADX.
Added offline to the trajectories of halo particles!

RMS orbit ≈ 1 mm

Peak-to-peak ≈ ± 4 mm

Effect of closed orbit at top energy (Max of 11 seeds)

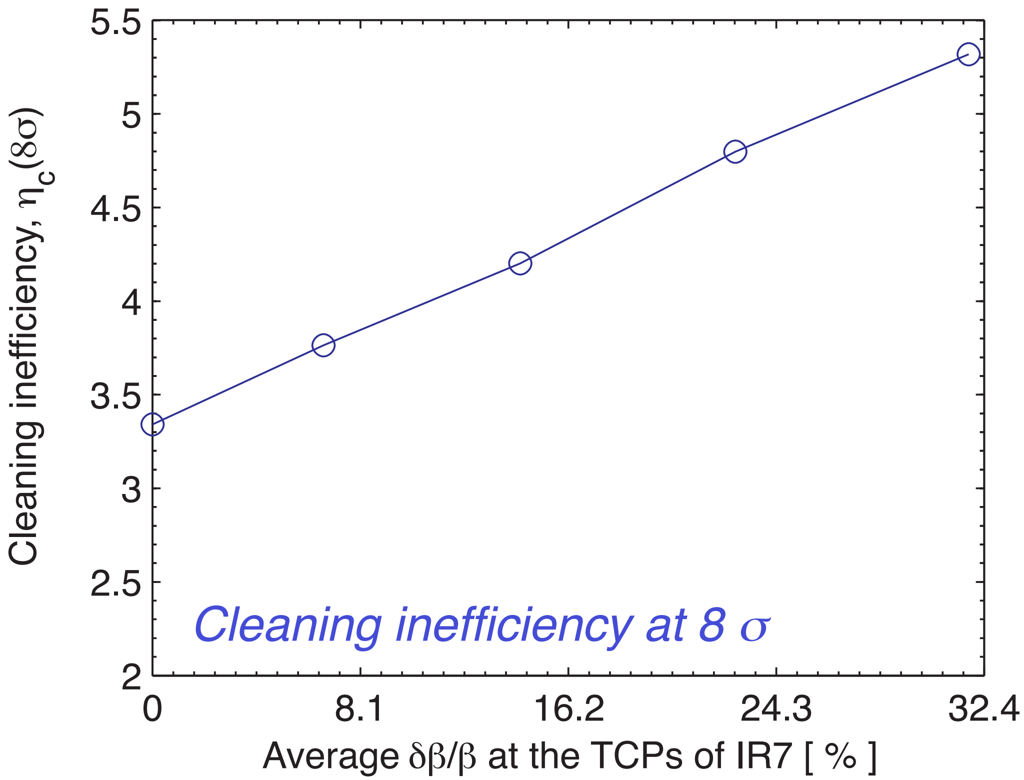
Perfect cleaning…

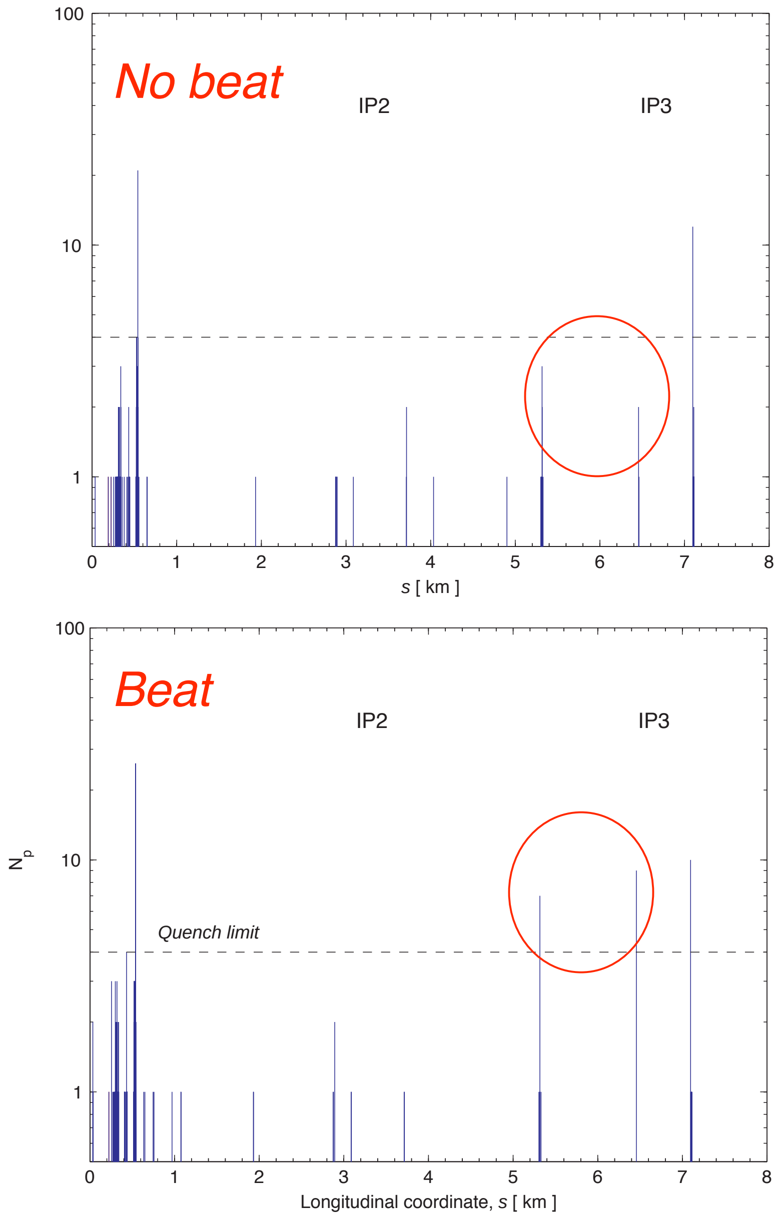


Factor ~10 increase!

*Additional **factor ~ 2** in cleaning inefficiency expected from error in collimator settings…*

Effect of static β-beat - top energy





Efficiency of the overall system is affected by STATIC β-beat:

δη/η=30% for δβ/β=20%

Variations of loss patterns depending on the local beat (CO dominates, though…)

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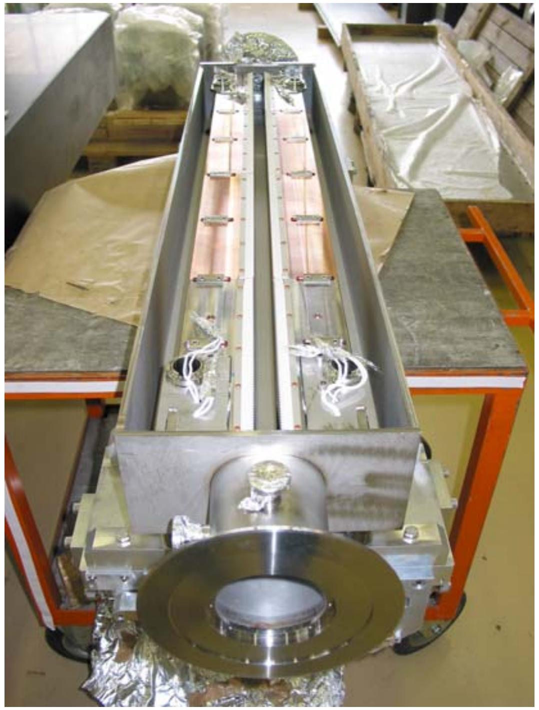
3. **Collimator test at the SPS**
    - **Measurement with beam at the SPS**
    - **What have we learnt?**
4. **Conclusion**

The collimator test with beam at the SPS

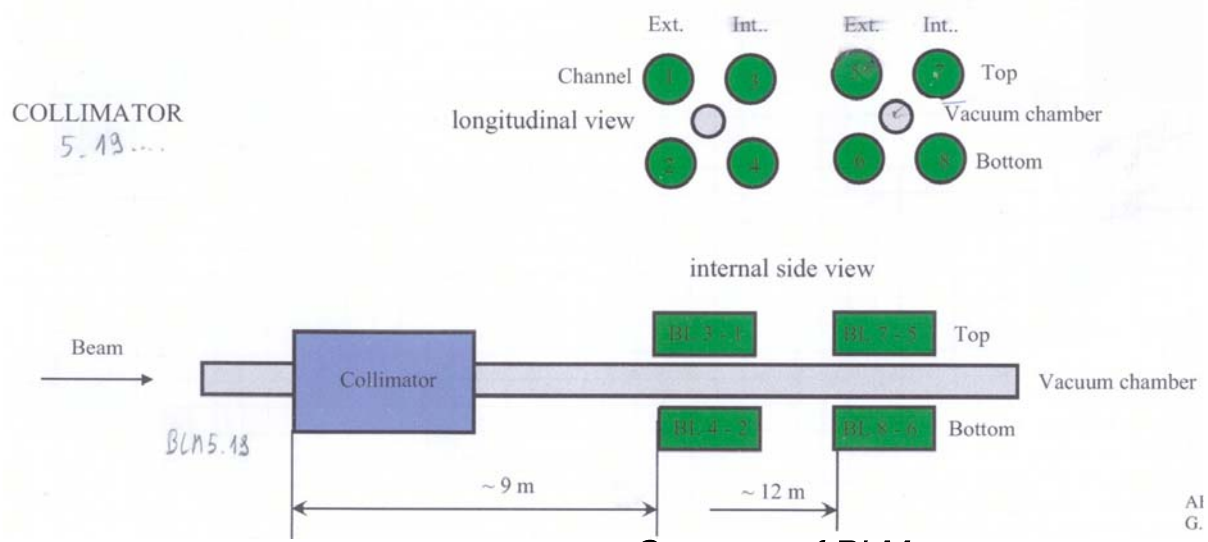
Goal of the test: Demonstrate the required functionalities of the LHC collimator prototype (mechanical movements, impedance, vacuum, …)

Low intensity test:	E_b = 270 GeV	$N_b \approx 1.1\text{x}10^{11}$p	I_b = (1-16) x N_b
(TOTEM beam)	$\varepsilon_x \approx$ 1 μm	$\sigma_x \approx$ **0.4 mm**	
High intensity test:	E_b = 270 GeV	$N_b \approx 1.1\text{x}10^{11}$p	I_b = 4 x 72 x N_b
(LHC beam)	$\varepsilon_x \approx$ 3.75 μm	$\sigma_x \approx$ **0.7 mm**	

Horizontal collimator *prototype in the SPS (18/08/04)*



*Dedicated **BLM system** used for beam-based alignment (plotting in PCR + logging for off-line analysis)*



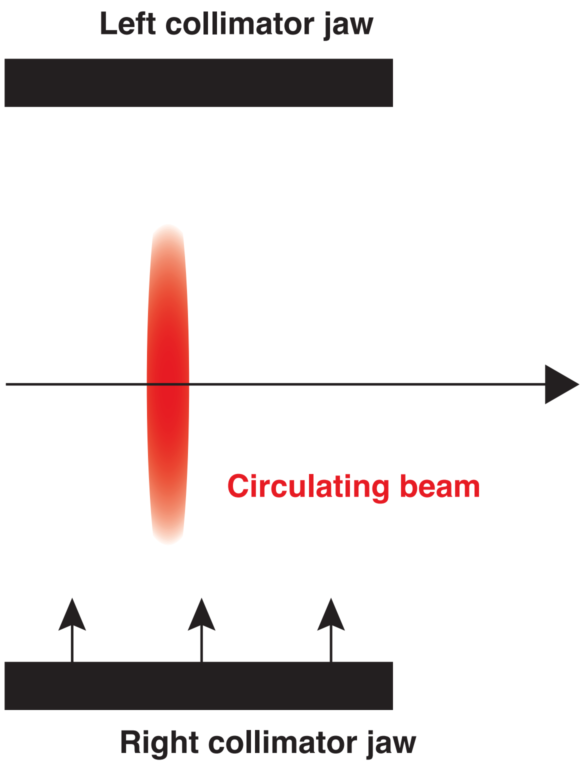
Courtesy of BLM team

List of performed measurements:

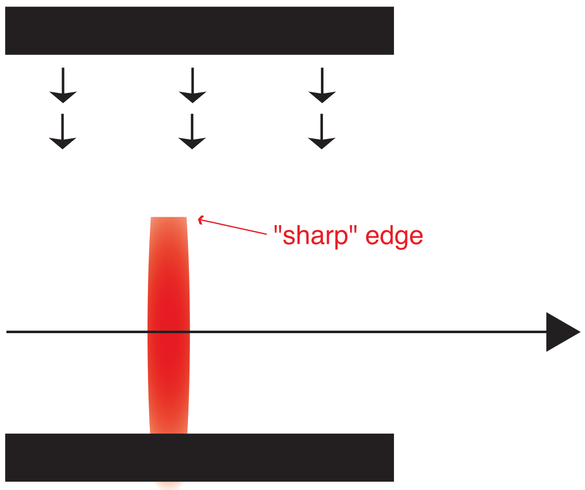
1. Functionality and basic control
2. Beam-based centring and alignment
3. Halo dynamics / beam shaping
4. Heating of collimator jaw / cooling water
5. Systematics of BLM system
6. Impedance and trapped modes
7. Tune vs collimator opening (various methods)
8. Vacuum / outgassing (e-cloud)

Procedure for beam-based alignment of the collimator jaws with BLM's

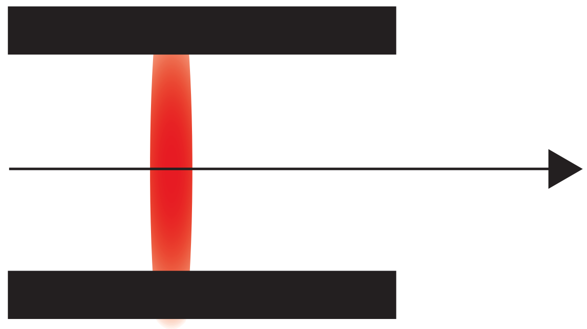
1. Move one jaw in



2. Scape the beam (sharp edge)



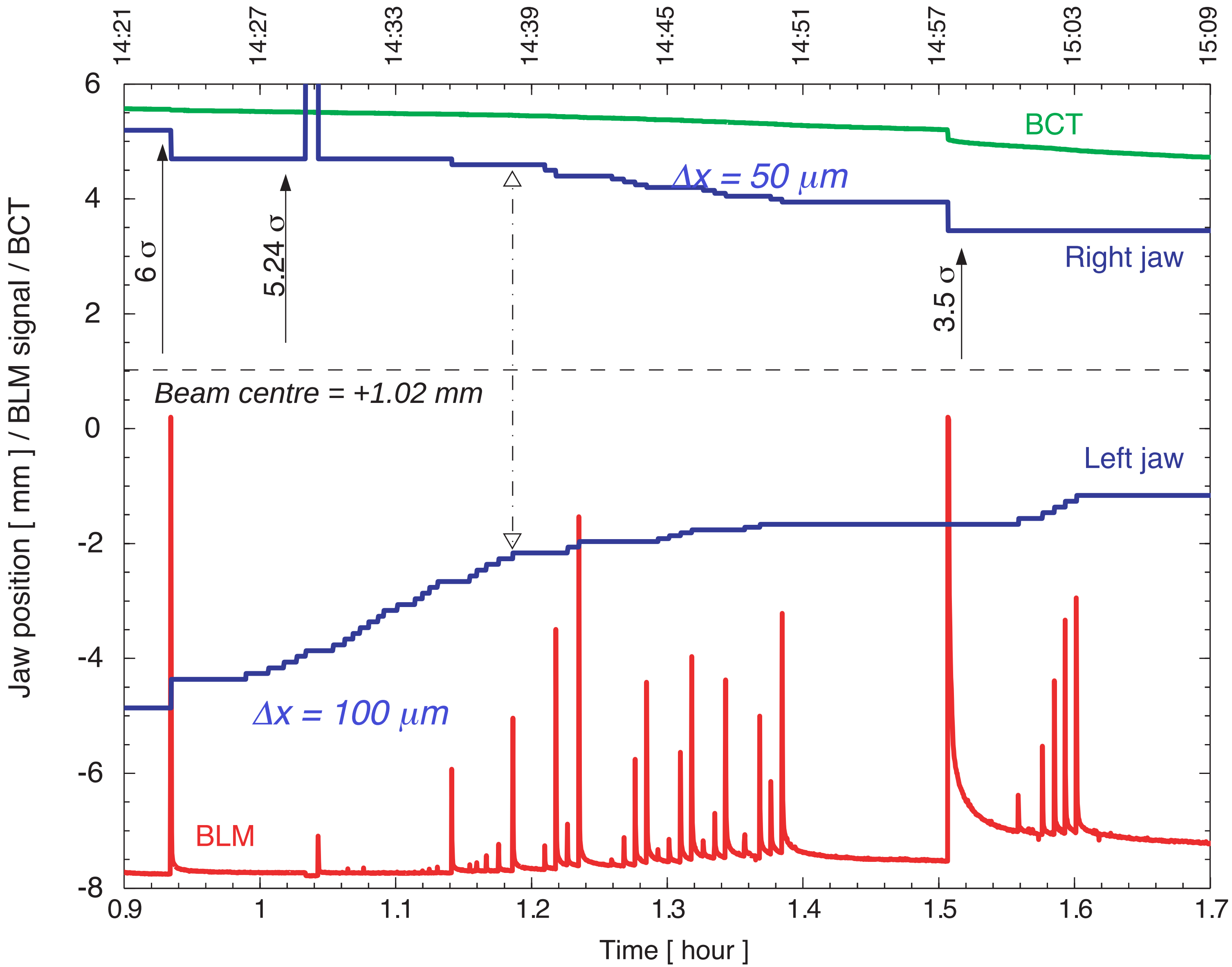
3. Move the other jaw until you see a signal on the BLM



- *The step size Δx sets the precision of the final alignment!*
- *Move one jaw corner at the time to adjust angles?*

Alignment with LHC-type beam (E_b = 270 GeV, $I_b \approx 3 \times 10^{13}$ p)

$\sigma_x \approx 0.7$ mm



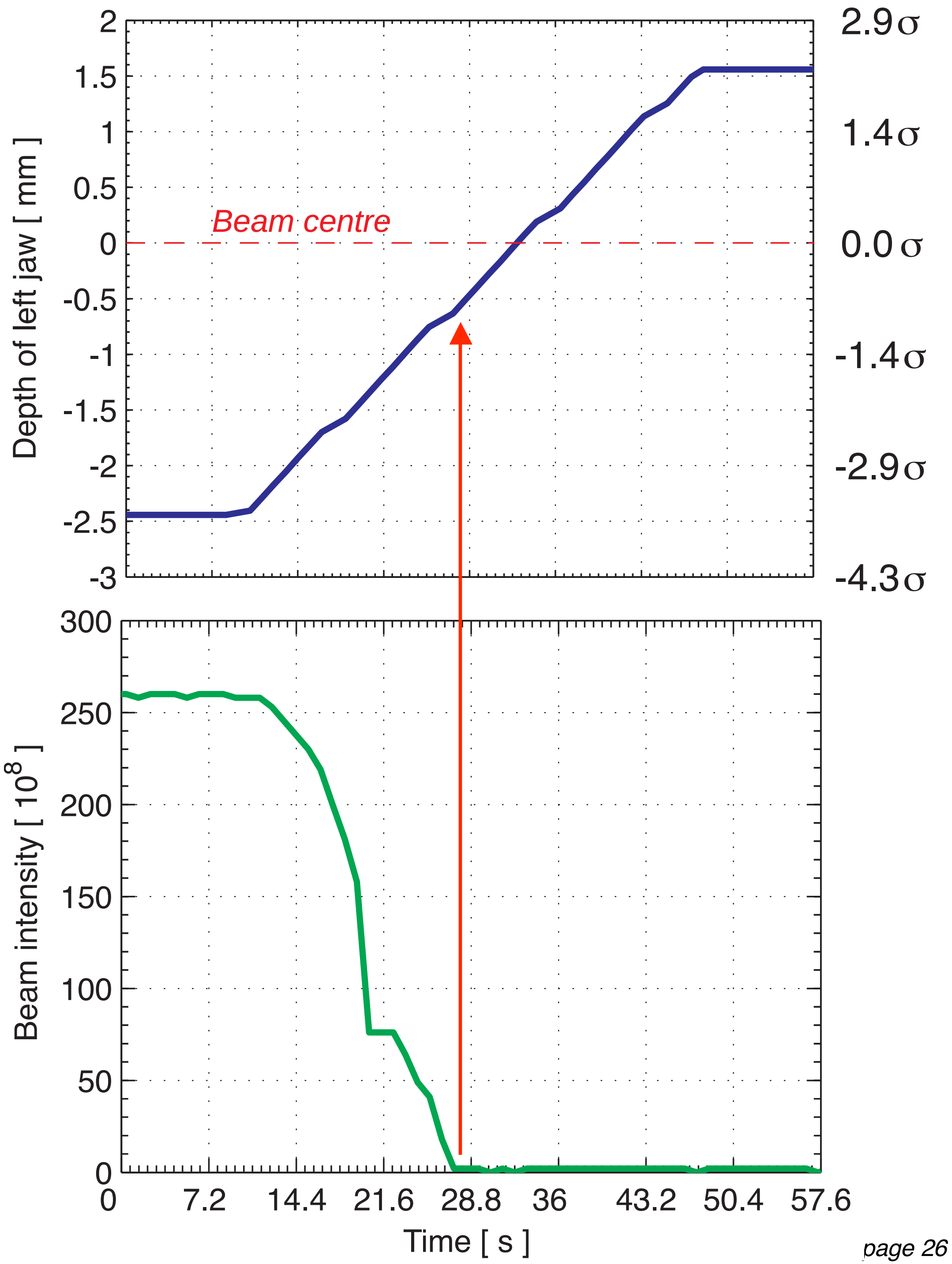
*Required time **< 1h**; Centring repeated at every new coast: ~15 minutes*

Finding the beam centre by *slowly* scraping the beam:

BCT signal must go to zero at when the jaw reaches the beam centre!

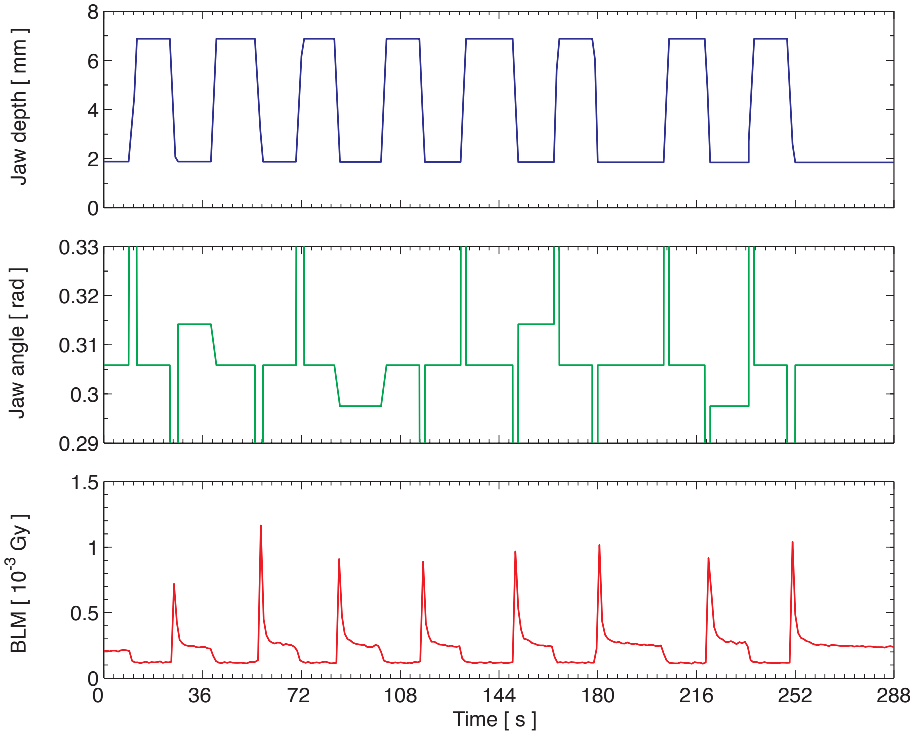
Centring agrees with jaw procedure of ~2 h before within **~0.5σ**

BCT (transmission measurements) also used to align the collimator jaws in the transfer lines (single passage)
→V. Kain, Session 5

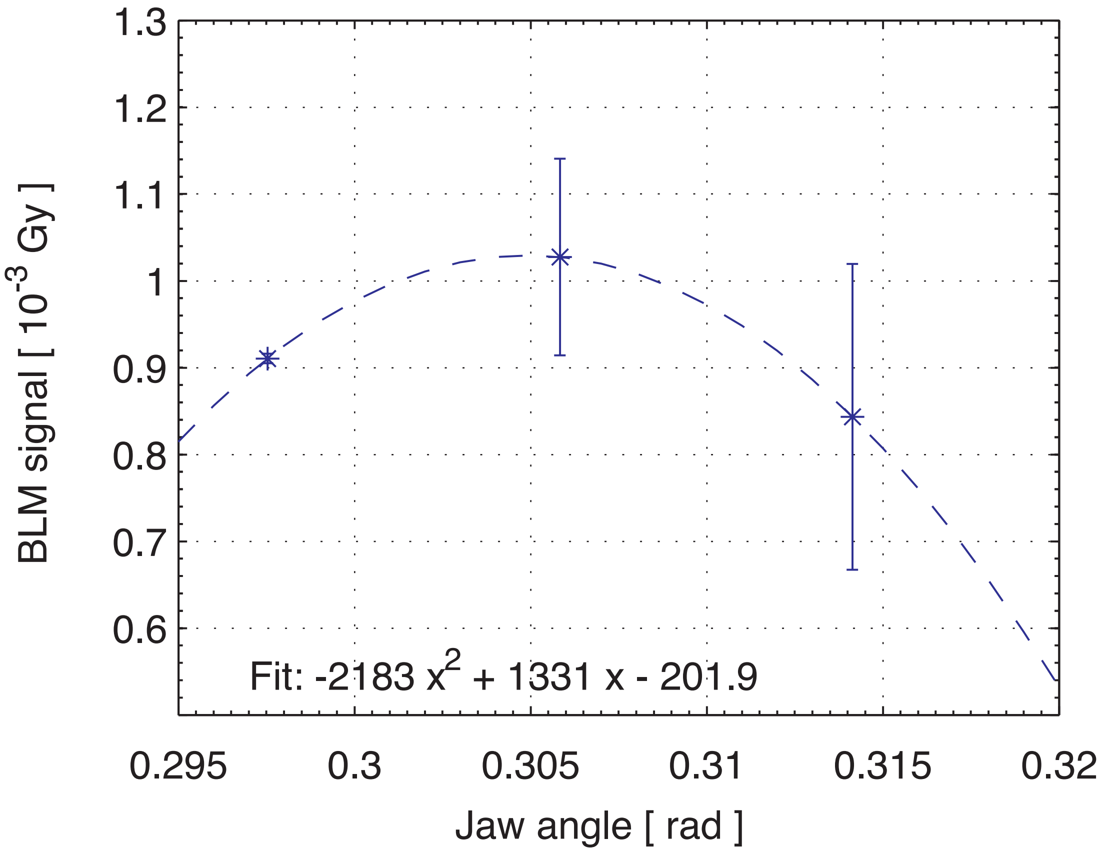


Adjusting jaw angle with respect to the beam envelope?

*Tolerance for the LHC: **~20 μrad** (TCS)*



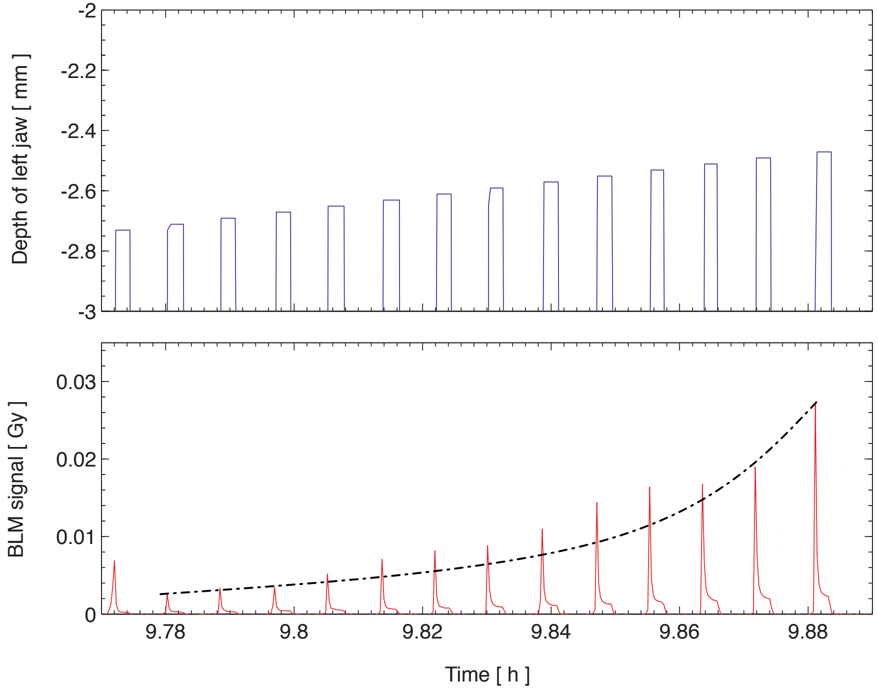
Different BLM signals if the jaw scrapes the beam tail with different angle!

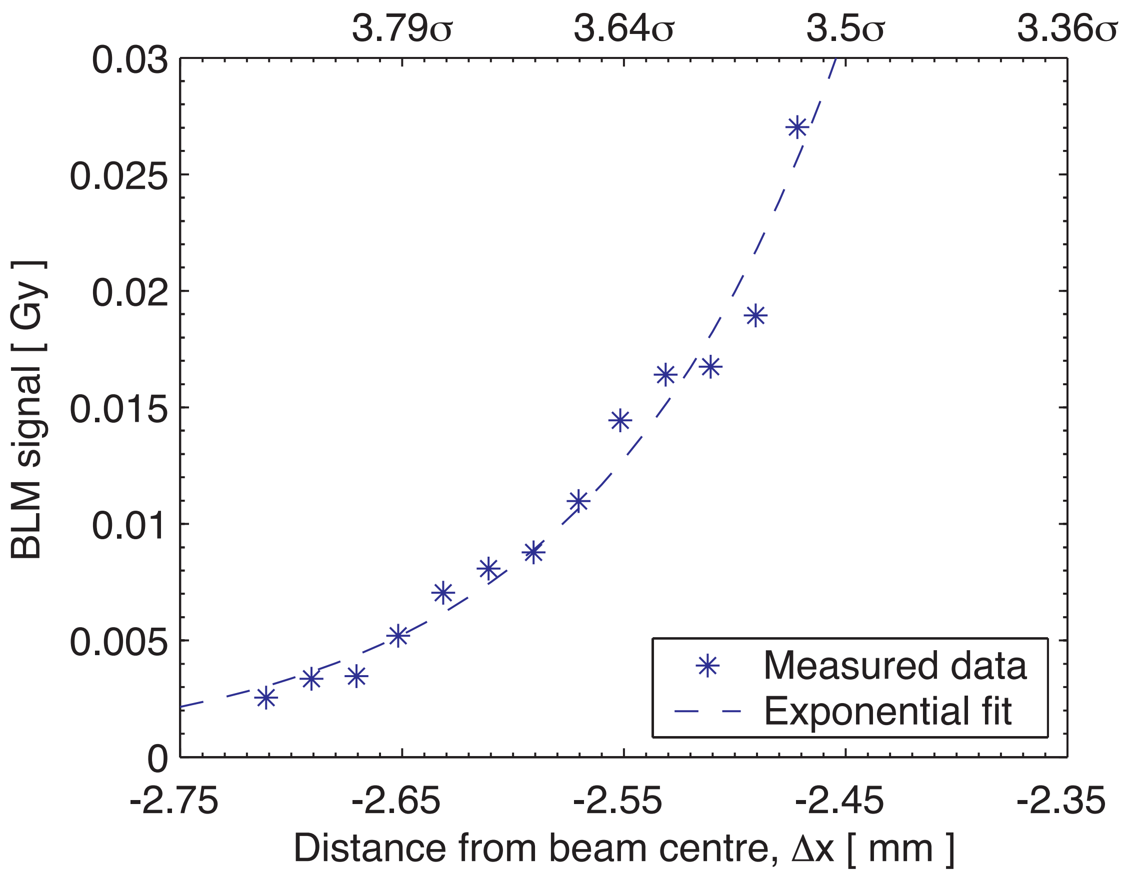


Poor statistics, more understanding is required…

Scans of tail population:

The "sharp" edge is not as sharp as expected!
Tail scans measured with depths ≤ 10σ.
Same exponential trend both at low and high intensity.
Prevented alignment to within better than < 50 μm!





Can we use this to calculate to jaw depth in unit sigma?
… would be very useful for the setup of the full system!

What have we learnt?

Main functionalities/tolerance for the LHC were demonstrated at the SPS!
No mechanical problem for motors (~2000 cycles)

Beam-based centring of collimator jaws to the **~50 μm** level achieved!

First alignment took **≤ 1 h**; then **~15 min** per collimator for each new beam

Vacuum worked as expected - No sign of e-cloud!

No measurable effect on BPM orbit feedback

Impedance in fair agreement with simulations

Lessons:

β functions at the collimator and beam emittance must be know well to adjust the collimator gap to the desired number of sigmas

Additional investigation would help in understanding:

Can we do better than 50 μm?
Halo dynamics - could it help in adjusting the jaw depth?
How to precisely can we set the jaw angle?

Conclusions

- ✓ *By design*, the aperture of the LHC is tight: **Inj → 7.5 σ (arcs)**
  Top → 8.1 σ (triplets)
- ✓ Good **orbit stability** and **control of β-beat** are necessary for achieving required beam cleaning - very limited operational margins
- ✓ Analysis of loss maps around the ring shows **critical locations for quenches**
- ✓ **Imperfections** increase the losses in cold elements by up to a **factor ~10!**
- ✓ When will we be limited? Serious problems above **≈10%** of nominal intensity
  Experience should tell us where the limitations come from… and how to deal with them!
- ✓ SPS tests with beam showed that the **collimator prototype works PROPERLY**
  Our expectations for the **Phase I collimation** are basically **confirmed**
- ✓ **Additional beam time in 2006** would help in better understanding critical aspects of the collimator commissioning!

Acknowledgements

AB-ABP: O. Brüning, S. Fartoukh, M. Giovannozzi, JB Jeanneret, T. Risselada, F. Schmidt G. Arduini

AB-OP: J. Wenniger

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TS-IC/AT-VAC: for setup of aperture model

AB-CO: M. Jonker, …

IT: E. McIntosh, H. Renshall, …

… and many others…

Reserve slides

Minimal available aperture (injection)

Physical available space in unit sigma

Beam 1	Warm	Cold	
Horizontal	6.78	7.88	σ_x
Vertical	7.68	7.79	σ_y

Beam 2	Warm	Cold	
Horizontal	6.68	7.70	σ_x
Vertical	7.65	7.60	σ_y

$A_{mech} = 7.5\ \sigma$ as the *available mechanical aperture*

(superconducting magnets)

LHC optics V6.5 → *1 σ below design target*…

Minimal available aperture (collision, nominal β^*)

Physical available space in unit sigma

Beam 1	Warm	Cold	
Horizontal	28.1	8.90	σ_x
Vertical	8.34	8.43	σ_y

Beam 2	Warm	Cold	
Horizontal	27.6	**8.13**	σ_x
Vertical	8.69	8.75	σ_y

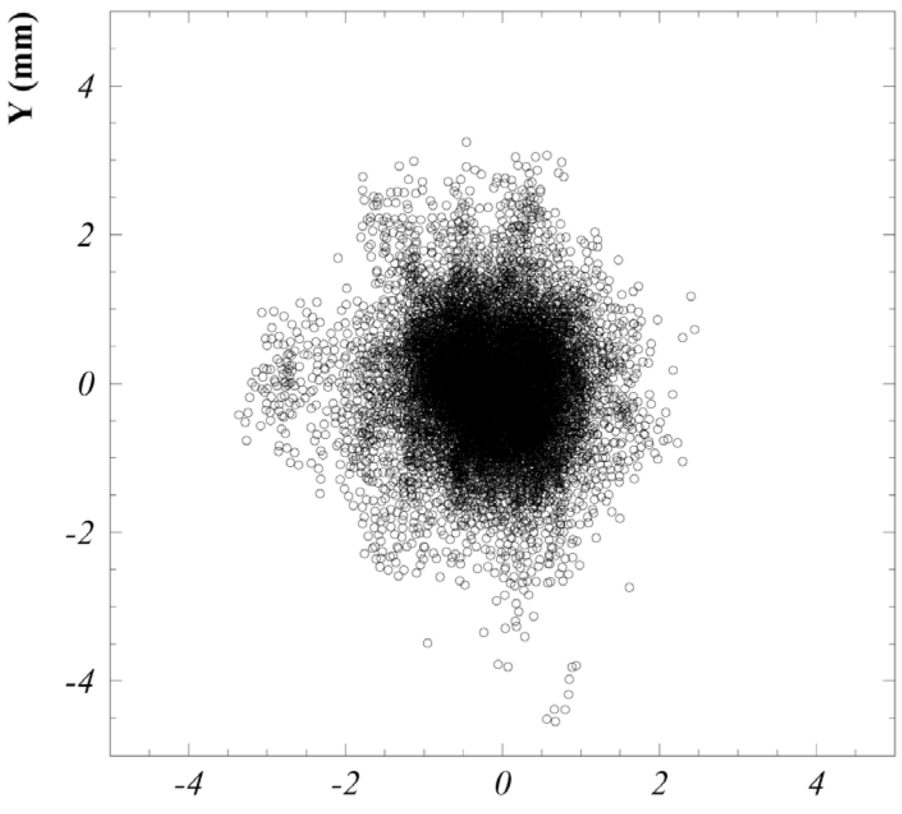
A_{mech} = 8.1 σ as the *available mechanical aperture*
(superconducting magnets)

Are the assumptions on CO errors realistic?

… LEP experience: measure X/Y orbit in the 1996 run:

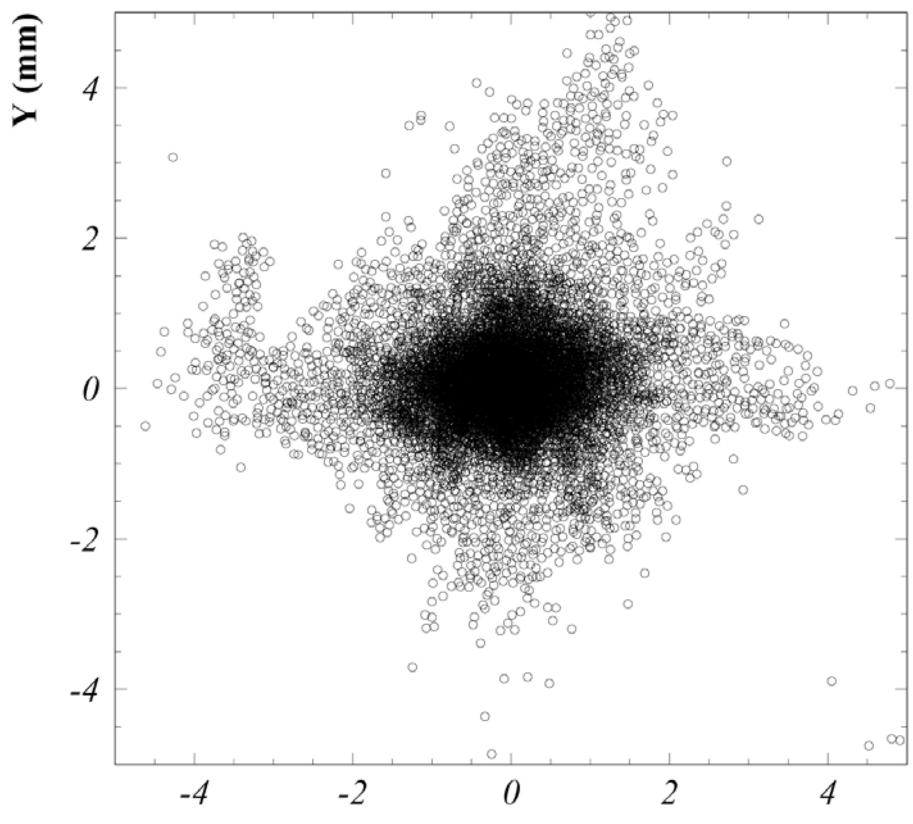
(J. Wenninger, LHC Proj Note 104, 1998)

In the ARCS:



LEP Arcs

In the INSERIONS:

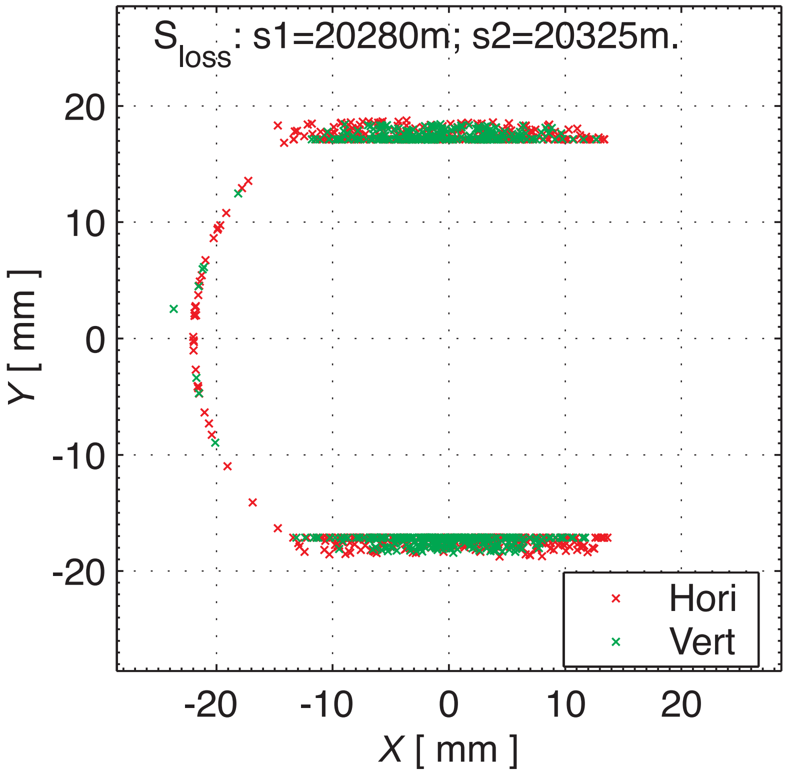


LEP Insertions

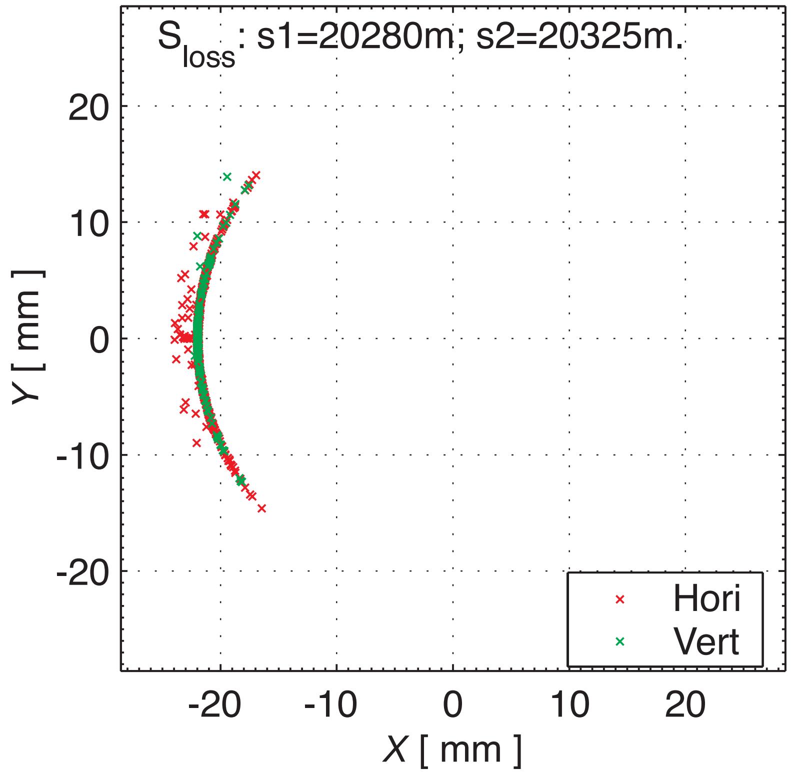
It seems difficult to increase the margin for the β-beat by controlling the CO better…

Dispersion suppressor - arc downstream of cleaning

Injection - dominated by betatron oscillations!



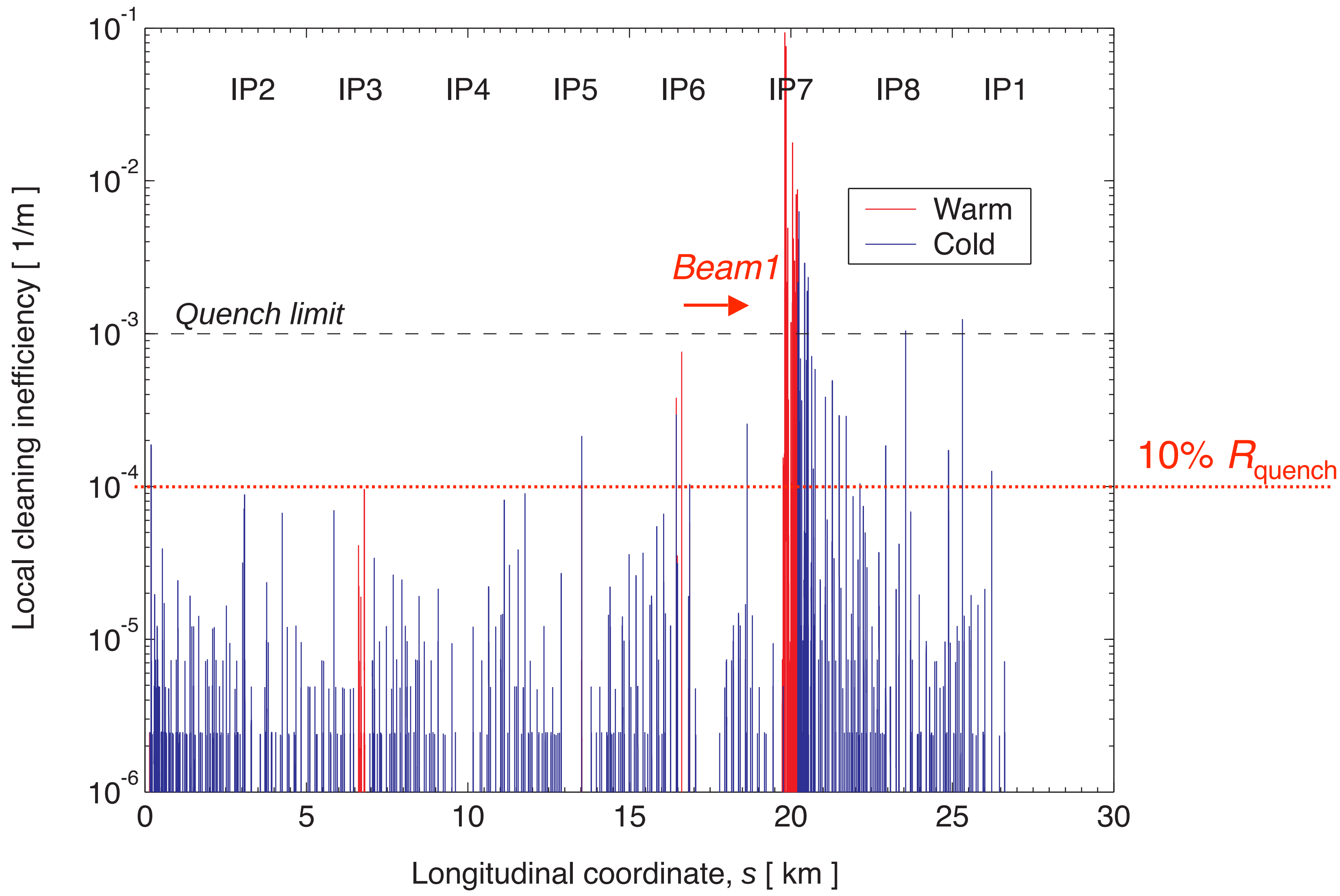
Top energy - dominated by dispersion!



How this affects the quench behaviour of SC magnets?

What is the best location for the BLM's?

Effect of closed orbit at injection *(Max of 11 seeds) - still perfect cleaning…*



Factor ~10 increase!

*Additional **factor ~ 2** in cleaning inefficiency expected from error in collimator settings…*

Review of collimator tolerances

Work done by R. Assmann *et al (Proc. EPAC2002)*

Error	Tolerance
Orbit position	0.6 σ
β-beat	8 %
Longitudinal angle (tilt) control	20 μrad
Surface flatness - TCP	10 μm
- TCS	25 μm
Knowledge of gap	50 μm
Jaw position control	$\leq$ 10 μm
Reproducibility of settings	20 μm