Geneva, 12 April 2005
LHC Machine Protection Review

Beam losses
versus
BLM locations at the LHC

R. Assmann, S. Redaelli, G. Robert-Demolaize

AB - ABP

Acknowledgements: B. Dehning

Motivation - Are the proposed BLM locations suitable for detecting *slow* beam losses at the LHC?

Design Philosophy for BLM locations

(see next talk by B. Dehning)

1. BLM at each **collimator** → Where largest losses occur!
2. BLM at each **quadrupole** → Maximum β functions!
3. Additional special locations (e.g., dispersion suppressor and separation dipoles, …) → Large dispersion, aperture restrictions…

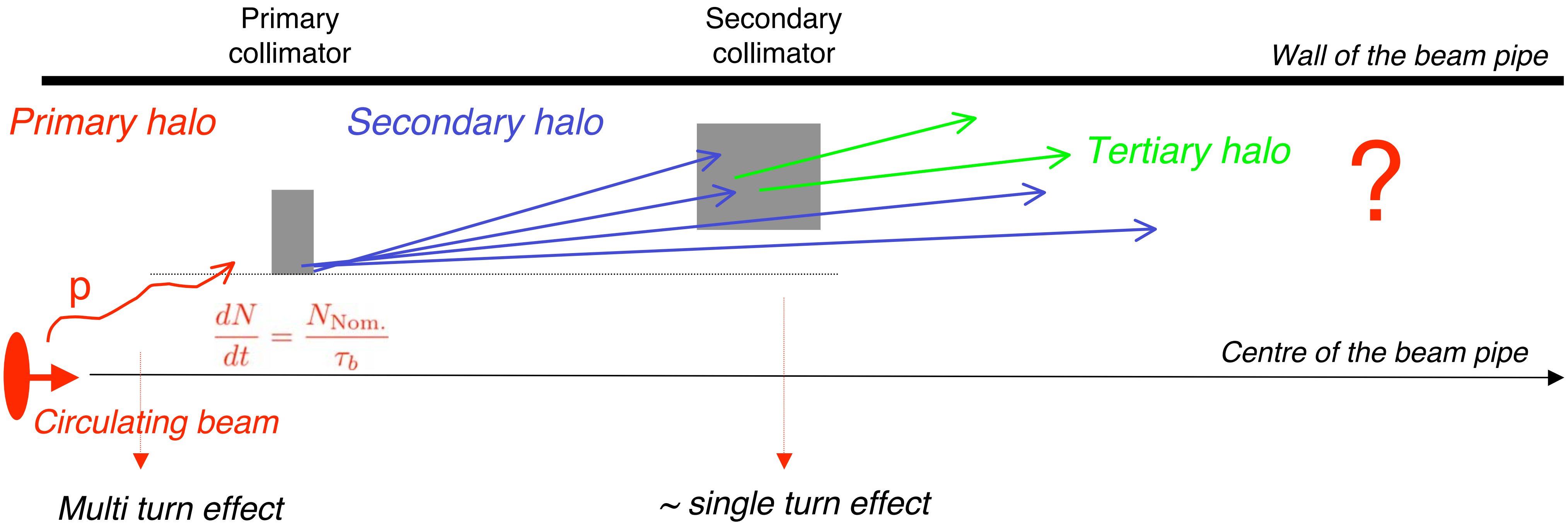
Goal of this study:

- Assess these design criteria with tracking results
- Find if there are unexpected loss locations

Overview of my talk:

1. **Slow losses from the collimators**
2. **Simulation tools**
3. **Beam loss patterns**
4. **Conclusions**

Mechanism to produce *slow losses* in a two-stage collimation system



Well tuned machine with collimators at nominal settings and a stable circulating beam.

Beam proton diffuse outwards with a rate fixed by the beam lifetime (τ_b): $\frac{dN}{dt} = \frac{N_{\mathrm{Nom.}}}{\tau_b}$

Slow "regular" losses → No other aperture bottlenecks are hit before the primary collimators. Loss rate of beam protons in the cleaning insertion determined by the beam lifetime. Time scale: some seconds.

(no failures!)

Some secondary and tertiary halo particles escape from the cleaning insertion can be lost around in the ring!

1. Large betatron kicks
2. Large energy errors

Requires detailed tracking of particle's trajectories

Precise distribution of losses

Requires aperture model for the full ring

The appropriated TOOLS have been setup in the framework of the Accelerator Physics collimation studies (AB-ABP) to understand:

- How many particles are lost?
- *Where are they lost in the ring?*
- How does the losses compare with the quench limits?

Main focus for this talk…

ABP collimation team:
R. Assmann
S. Redaelli
G. Robert-Demolaize

Tools for halo tracking and loss maps

Halo generation and tracking
done with SixTrack + K2

⇨ *Halo production in the two stage collimation system and multi-turn tracking of secondary and tertiary halos (δE/E, field errors, correction schemes, …)*

⇩

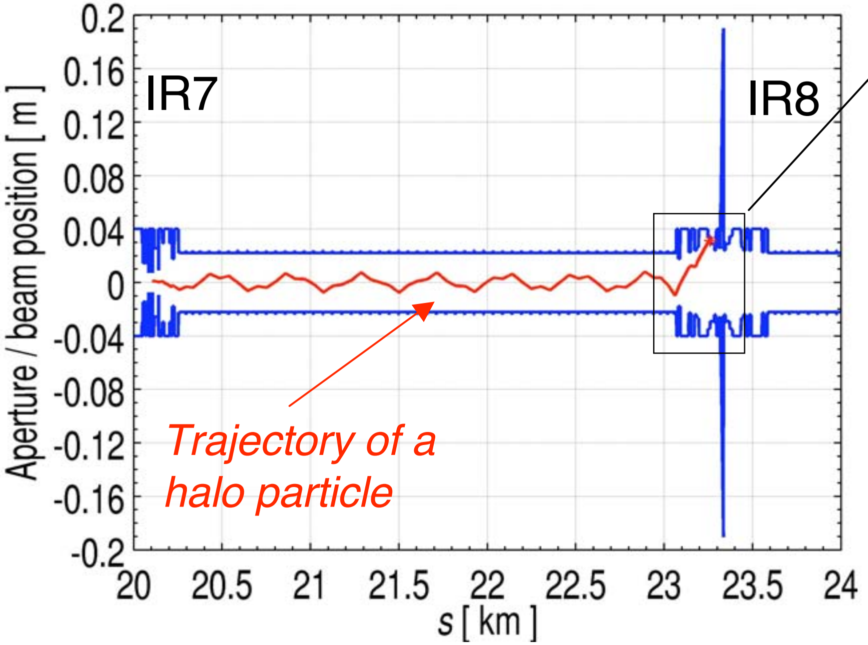
Trajectories of secondary and tertiary halo part's

⇩

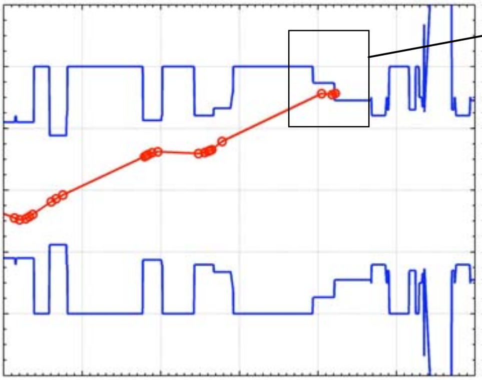
Aperture model for the full LHC ring,
10 cm longitudinal spatial resolution.

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

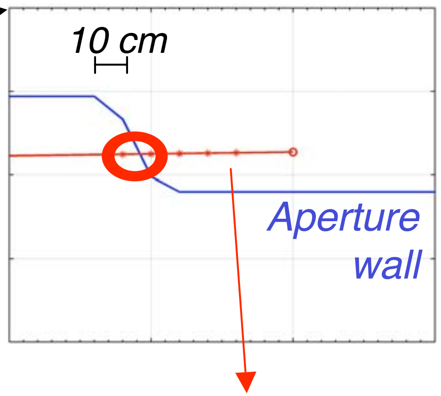
Off-line treatment of effects such as closed orbit, misalignments, kicks from D1… D4 magnets



Trajectory of a halo particle

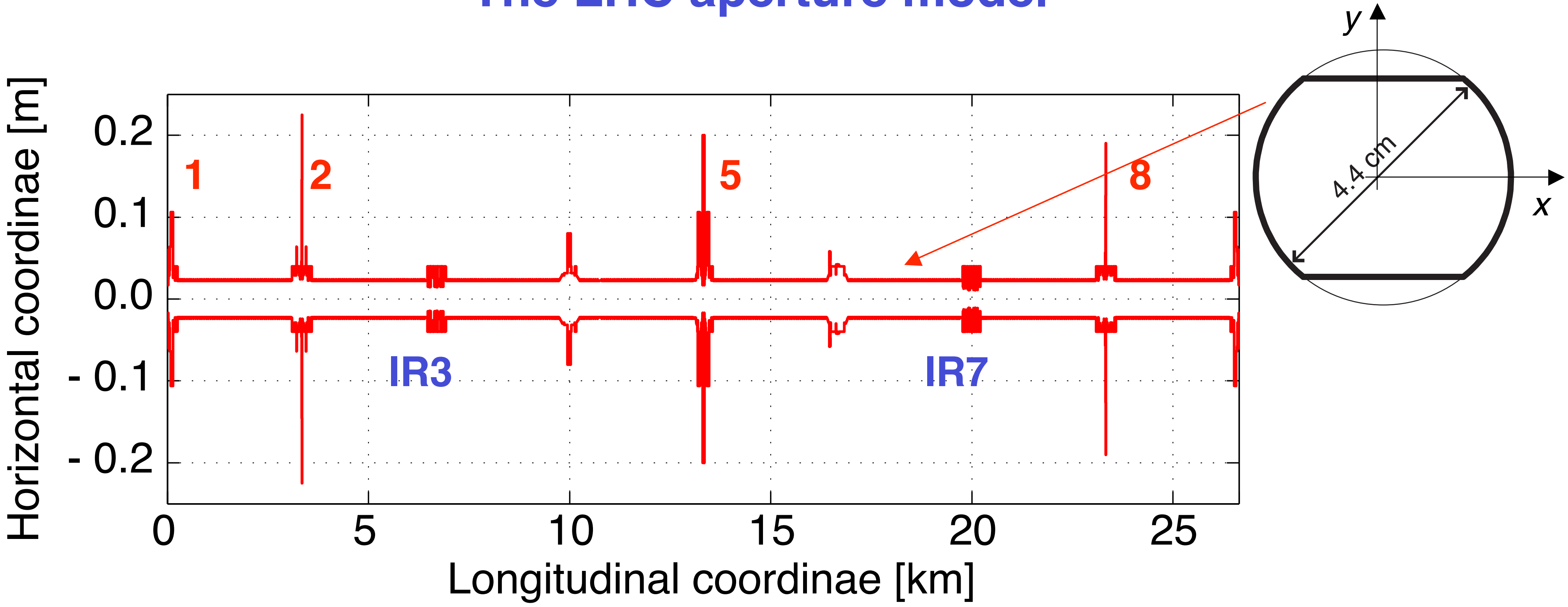


Magnets locations (*thin lenses*): **Δs ≤ 100m**



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

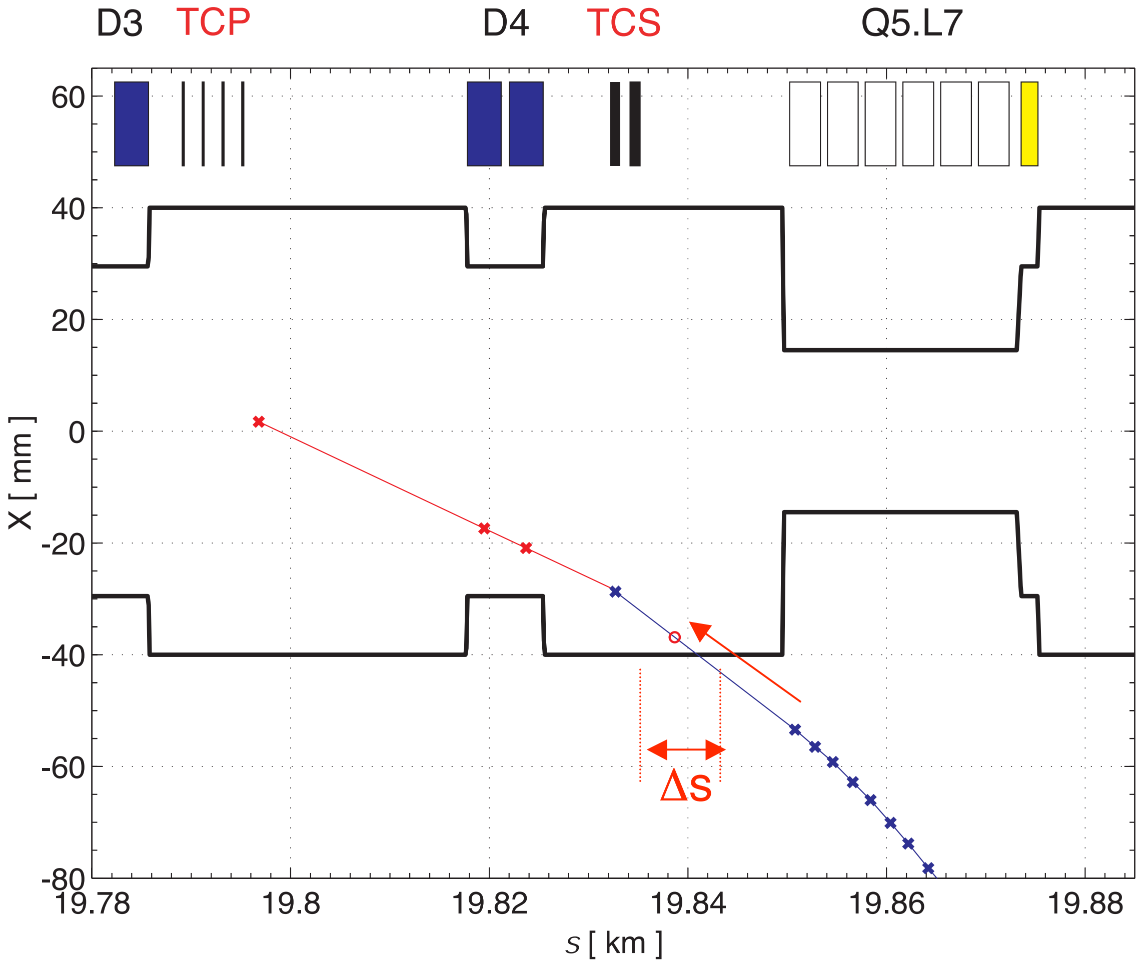
The LHC aperture model

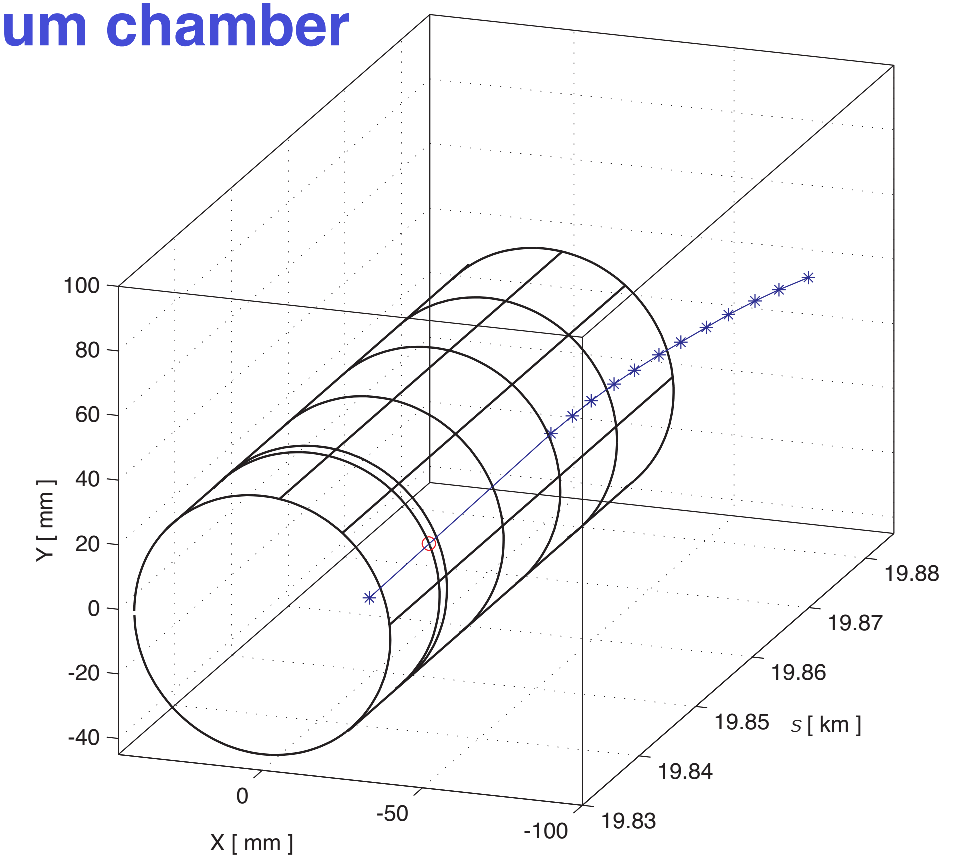


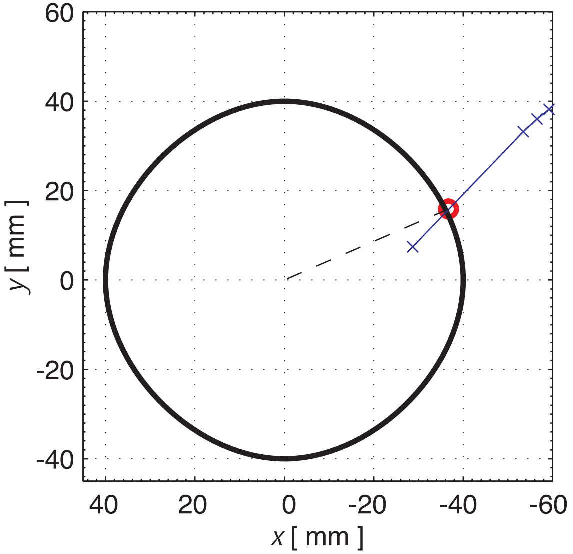
The aperture model includes

- Beam screen of all superconducting magnets (different size, tilts)
- Aperture of warm magnets
- BPM aperture
- Detector region aperture
- Linear interpolation for the transitions
- Kick of separation magnets (D1, D2, …)

Example of halo particle lost in the vacuum chamber







- Trace back trajectory until the loss point is found (5D)
- Count the number of lost particles in the bin Δs = 0.1 m
- Look at *x*, *y*, *x'*, *y'* distributions

Calculation of the proton loss rate per unit length

$$\boxed{\frac{dN}{dt\,ds} = \frac{1}{ds}\frac{dN(ds)}{\tau_b}\frac{N_{\text{Nom.}}}{N_{\text{Abs.}}}}$$

From aperture model **dN(ds)** : number of particles lost around the full ring

From tracking **N_{abs}** : number of particles lost in the cleaning insertion (*dN(ds)/N_{abs}* is the cleaning inefficiency!)

For *slow losses*, all the particles that drift out of the beam core interact first with the primary collimators: ⇨ $\frac{dN}{dt} \propto \frac{N_{\text{Nom.}}}{\tau_b}\frac{1}{N_{\text{Abs.}}}$

Assumptions on:

1. Total beam intensity → $N_{\text{Nom.}} = 3\times10^{14}\ \text{p}$
2. Beam lifetime → $\begin{cases} \tau_b^{\text{inj}} = 0.1\ \text{h} \\ \tau_b^{\text{top}} = 0.2\ \text{h} \end{cases}$

Quench limit of superconducting magnets:

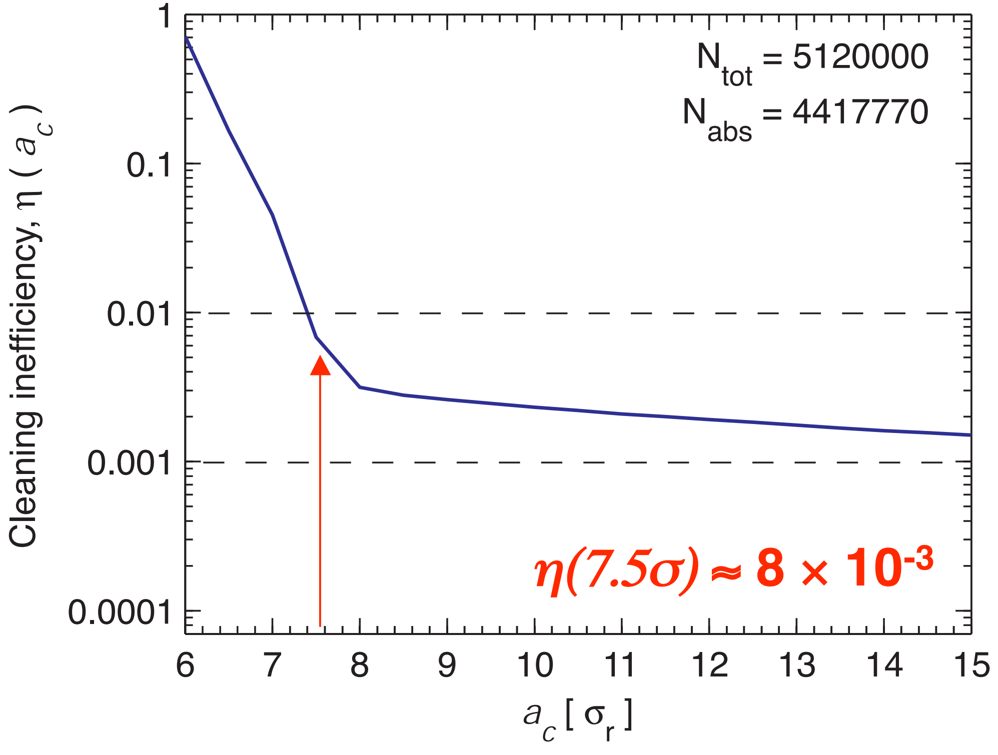
$$\boxed{\begin{aligned} R_{\text{Q}}^{\text{inj}} &= 7\times10^{8}\ \text{p/m/s} \\ R_{\text{Q}}^{\text{top}} &= 7.6\times10^{6}\ \text{p/m/s} \end{aligned}}$$

Performance of the collimation system → **Cleaning inefficiency**

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

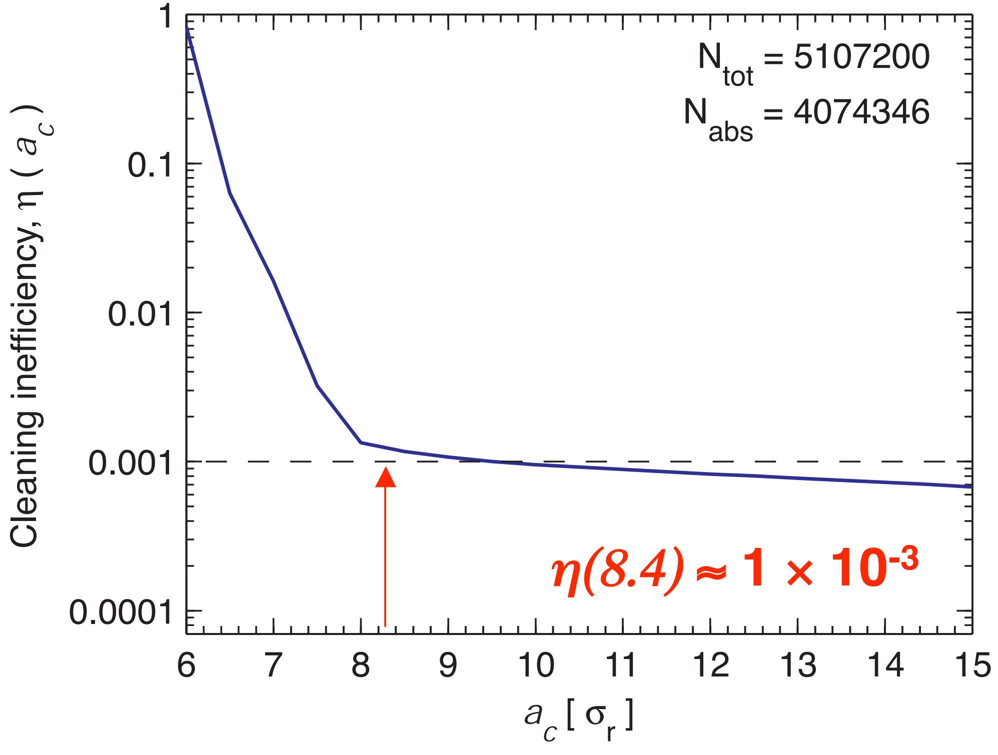
Particle leakage: fraction of particles that escape from the cleaning insertion

Injection (450 GeV/c)



$\eta(7.5\sigma) \approx$ **8 × 10^{-3}**

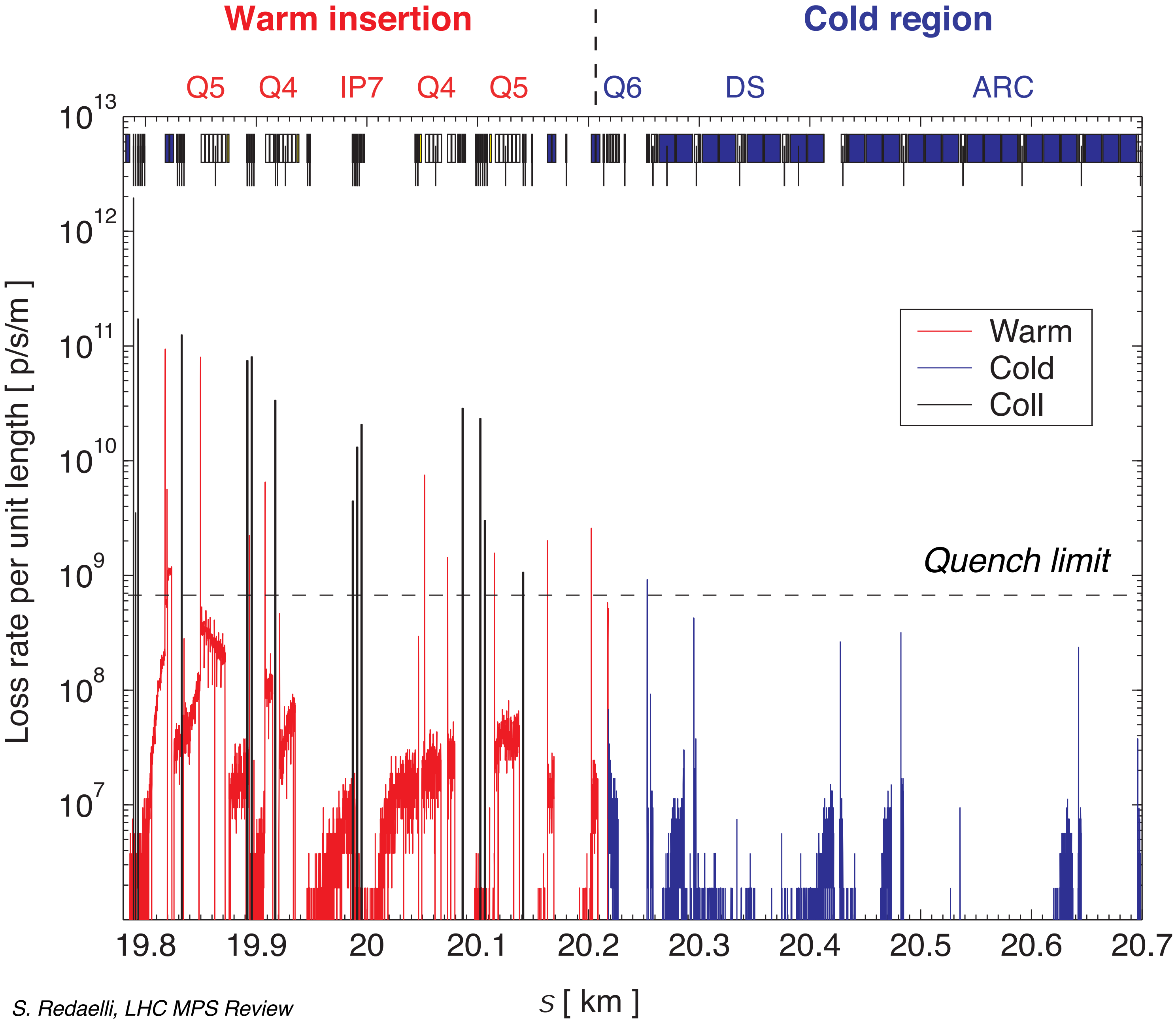
Top energy (7 TeV/c)



$\eta(8.4) \approx$ **1 × 10^{-3}**

System designed to perform better at 7 TeV.

Loss maps at injection (450 GeV/c)



Losses in collimators / warm magnets are up to 100-1000 times larger than in the cold section!

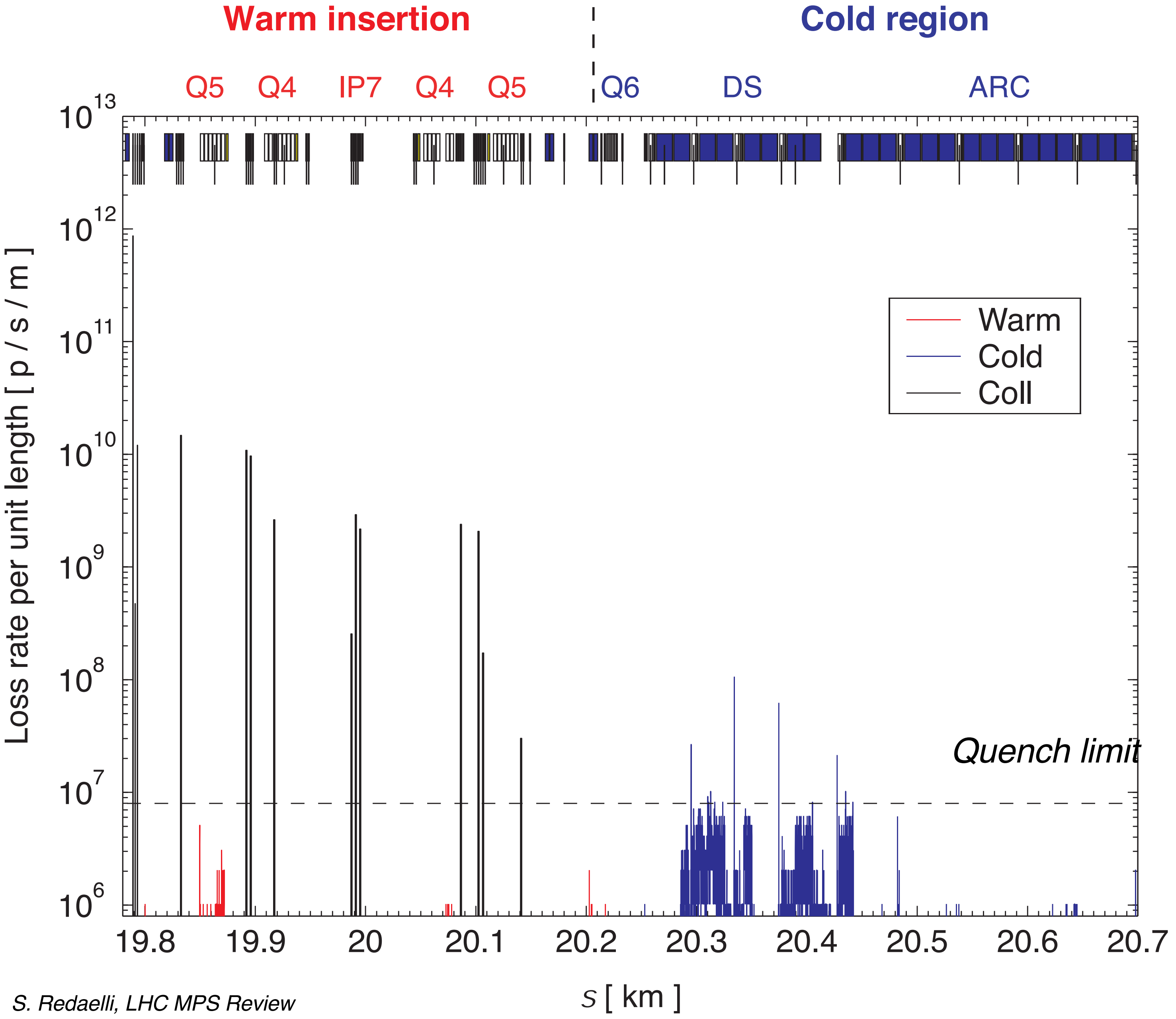
Preliminary results for perfect machine/cleaning

TCP (6σ) and TCS (7σ) only

$$N_{\mathrm{Nom.}} = 3\times 10^{14}\ \mathrm{p}$$

$$\tau_b^{\mathrm{inj}} = 0.1\ \mathrm{h}$$

Loss maps at top energy (7 TeV/c)



Less losses at the quadrupoles: beam size smaller at 7 TeV/c!

Slow losses are easier to detect at the collimators!

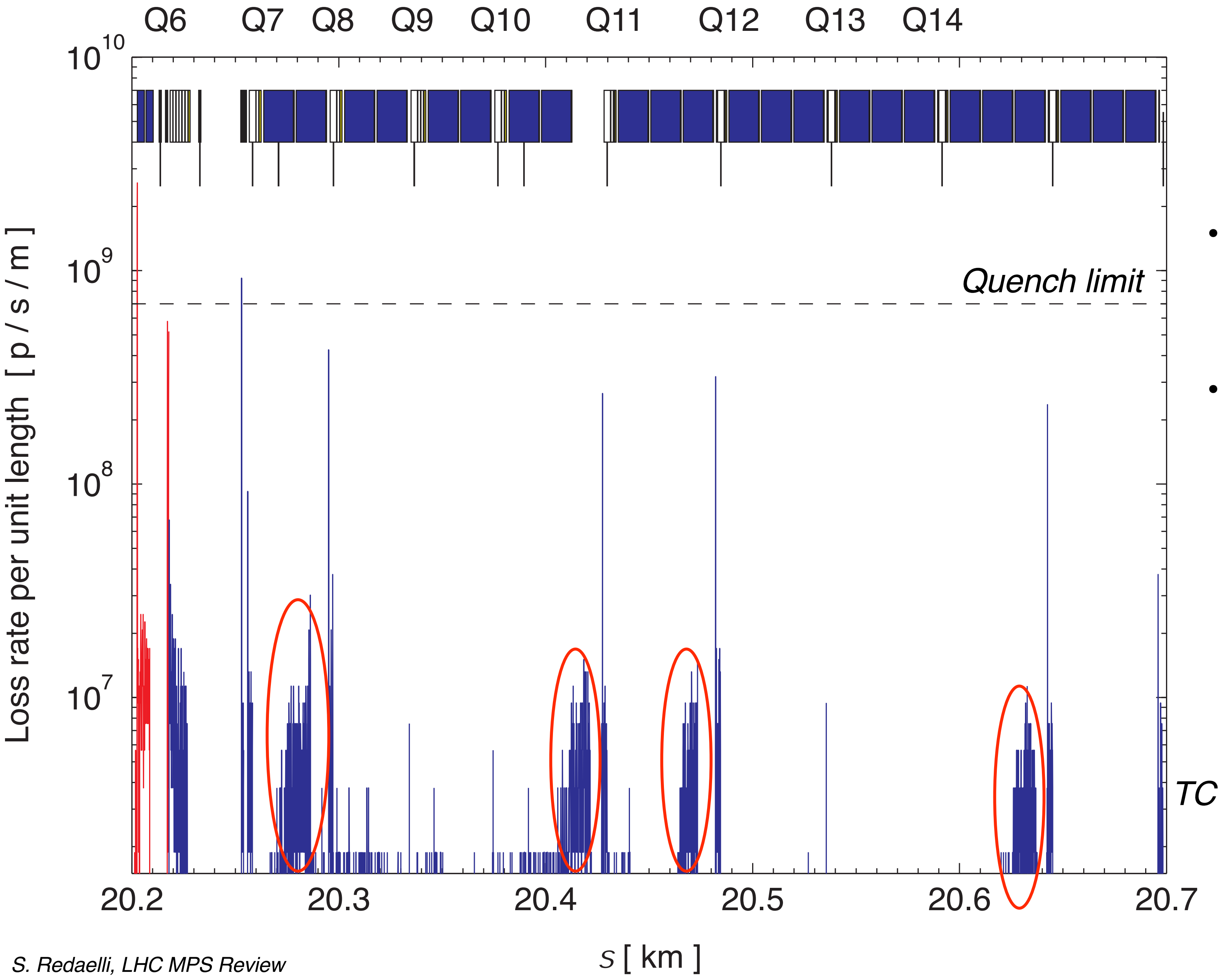
Mandatory to have BLM's for EACH collimators, as foreseen.

Perfect machine/cleaning

TCP (6σ) and TCS (7σ) only

$$N_{\mathrm{Nom.}} = 3\times10^{14}\ \mathrm{p}$$
$$\tau_b^{\mathrm{top}} = 0.2\ \mathrm{h}$$

Losses in the cold region - Injection energy (450 GeV/c)



- Loss peaks at the quadrupoles, where β is largest
- Losses in dispersion regions! BLM **not** foreseen everywhere!

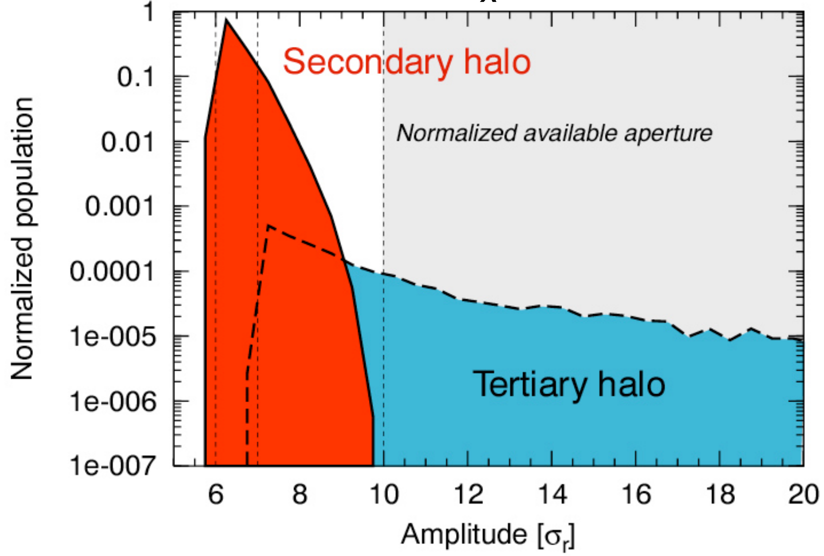
Perfect machine/cleaning

TCP (6σ) and TCS (7σ) only

$$N_{\mathrm{Nom.}} = 3\times10^{14}\ \mathrm{p}$$

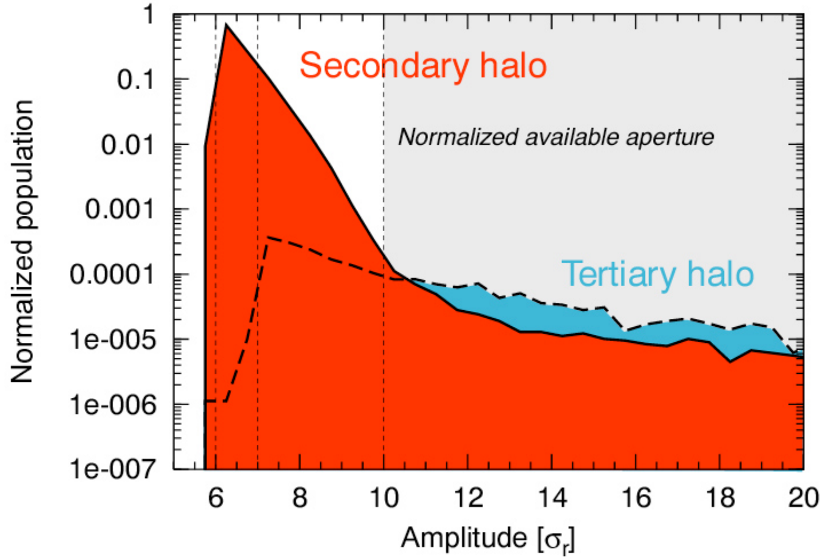
$$\tau_b^{\mathrm{inj}} = 0.1\ \mathrm{h}$$

$D_x = 0$



Losses in dispersion regions are expected because secondary halo particles can experience ***large energy errors!***

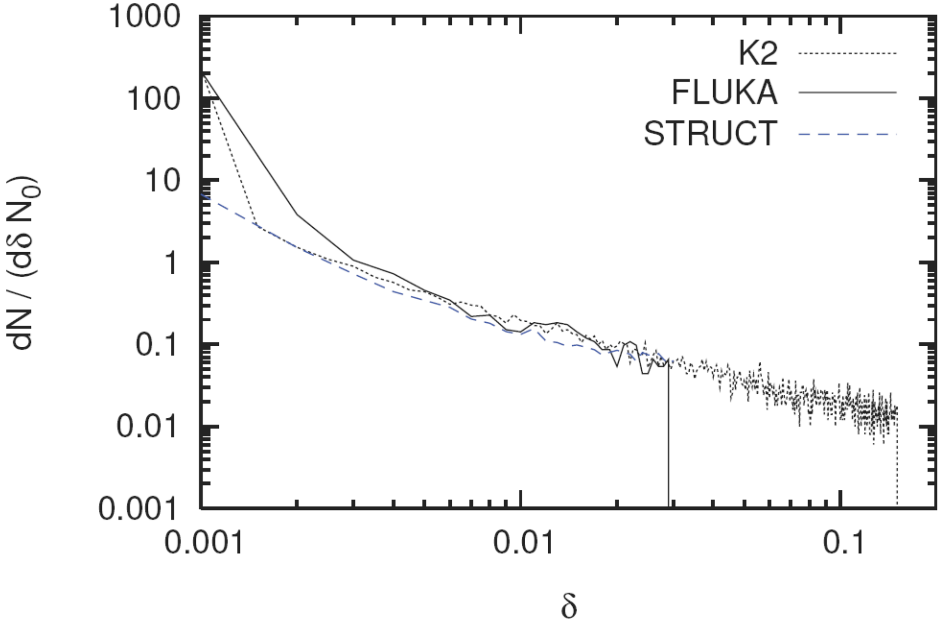
$D_x = D_x^{arc}$

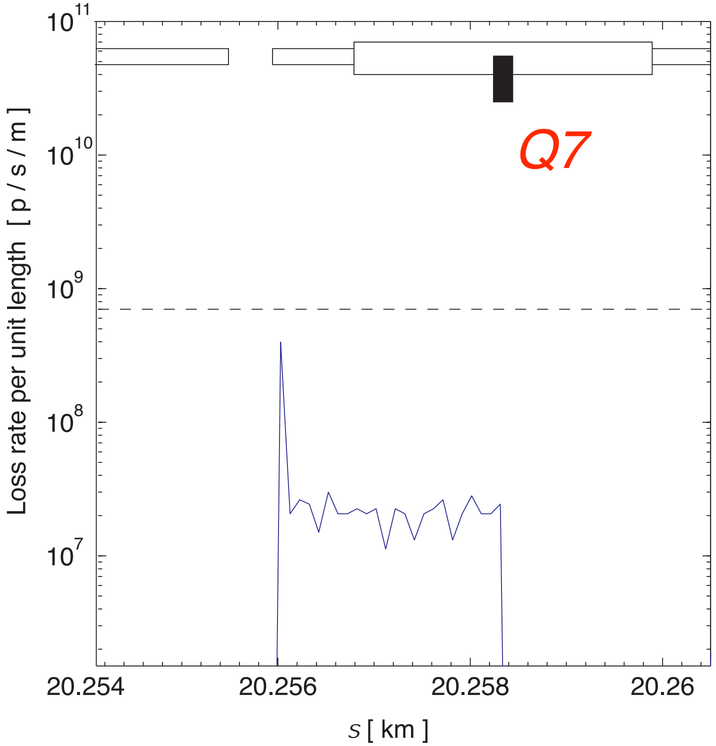


See R. Assmann's talk.

Energy distribution for protons impinging on a 50 cm Copper block

Energy errors due to single-diffractive scattering!





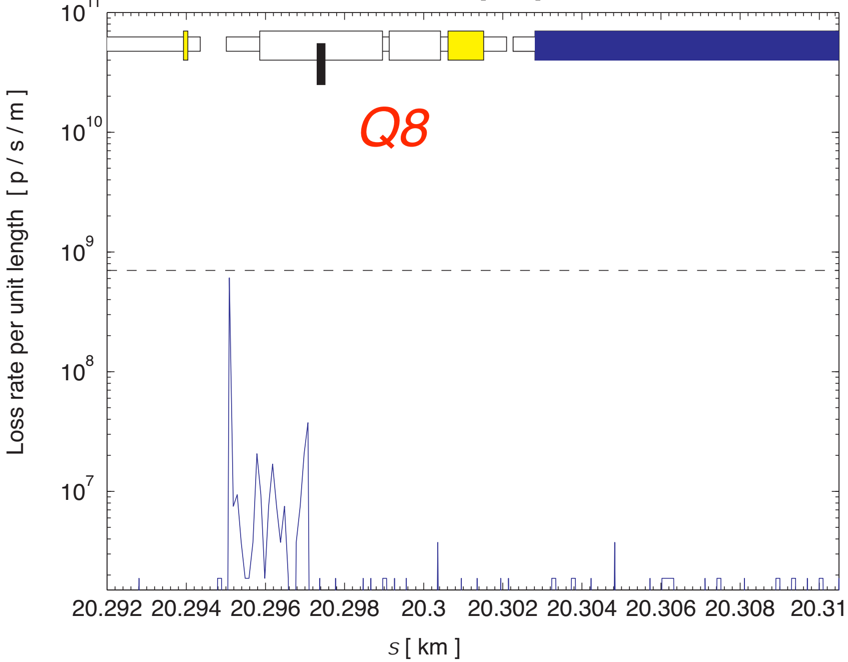
As expected, for all quadrupoles:

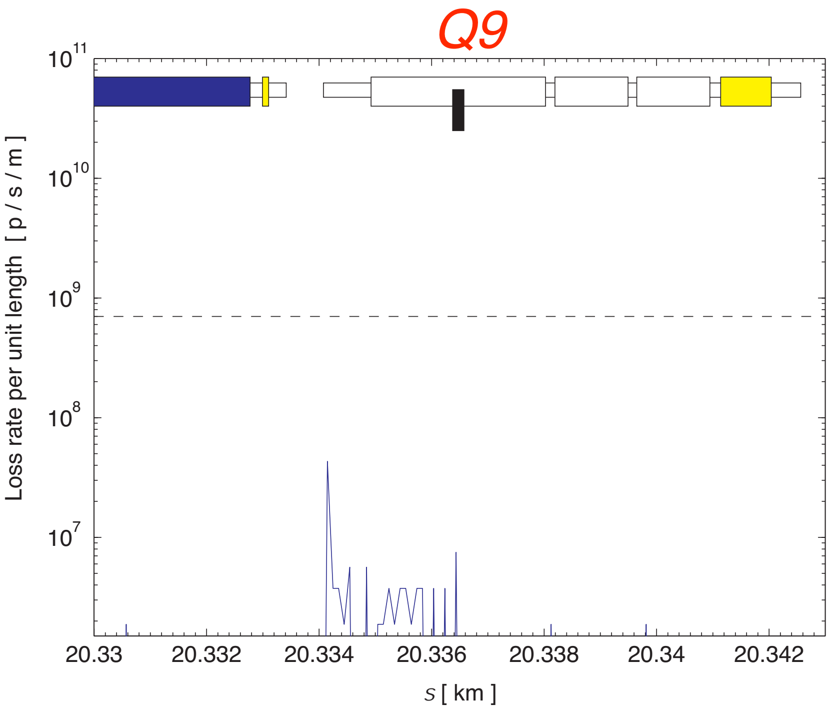
- Loss peaks at the warm/cold transition!

  (confirm simulations by R.Assmann, B.E. Holzer, V.Kain)

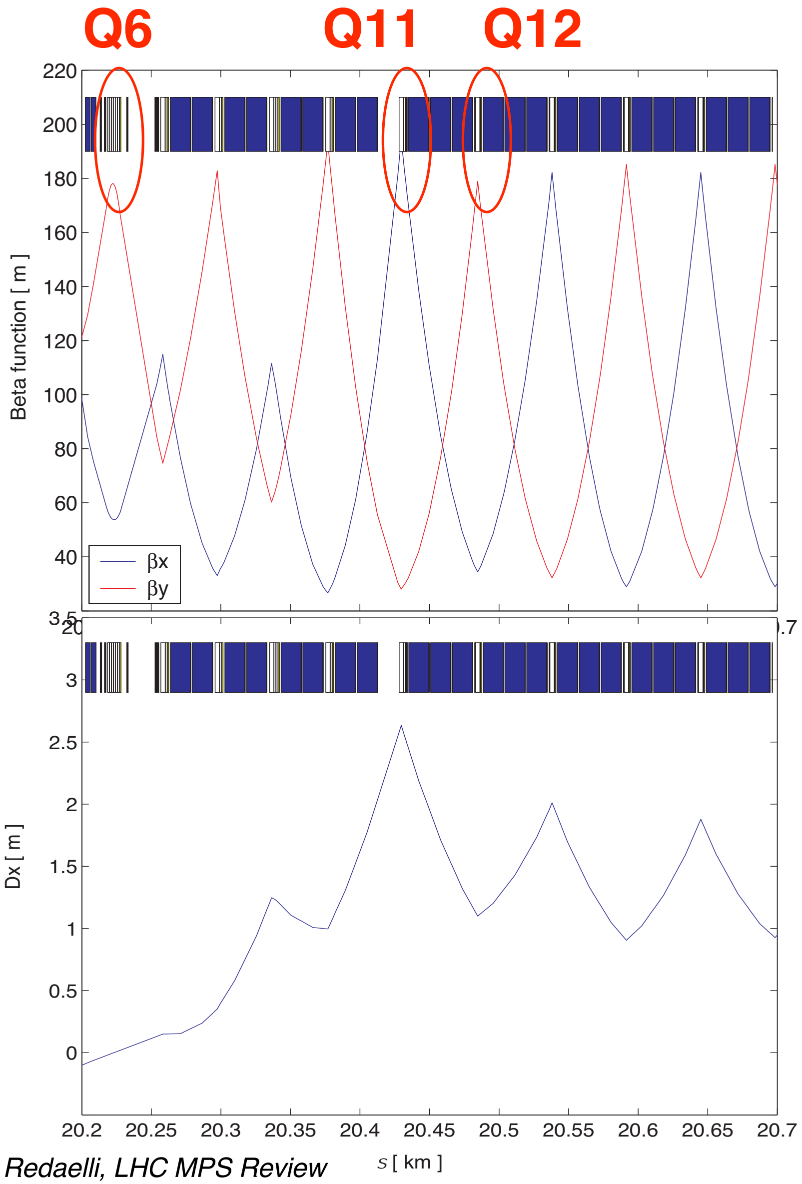
- Losses in the first half of the magnet

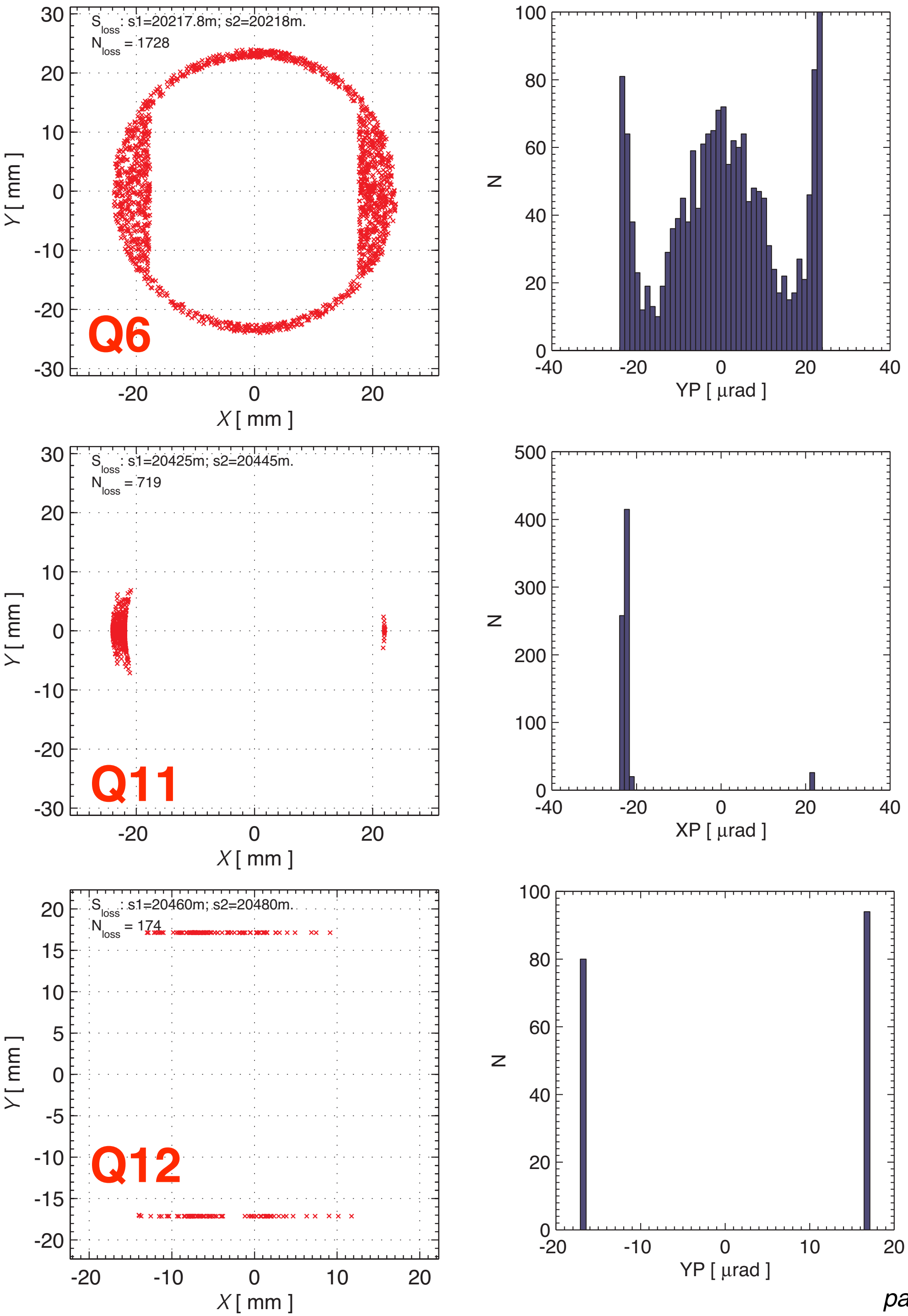
  (peak of β in the middle)



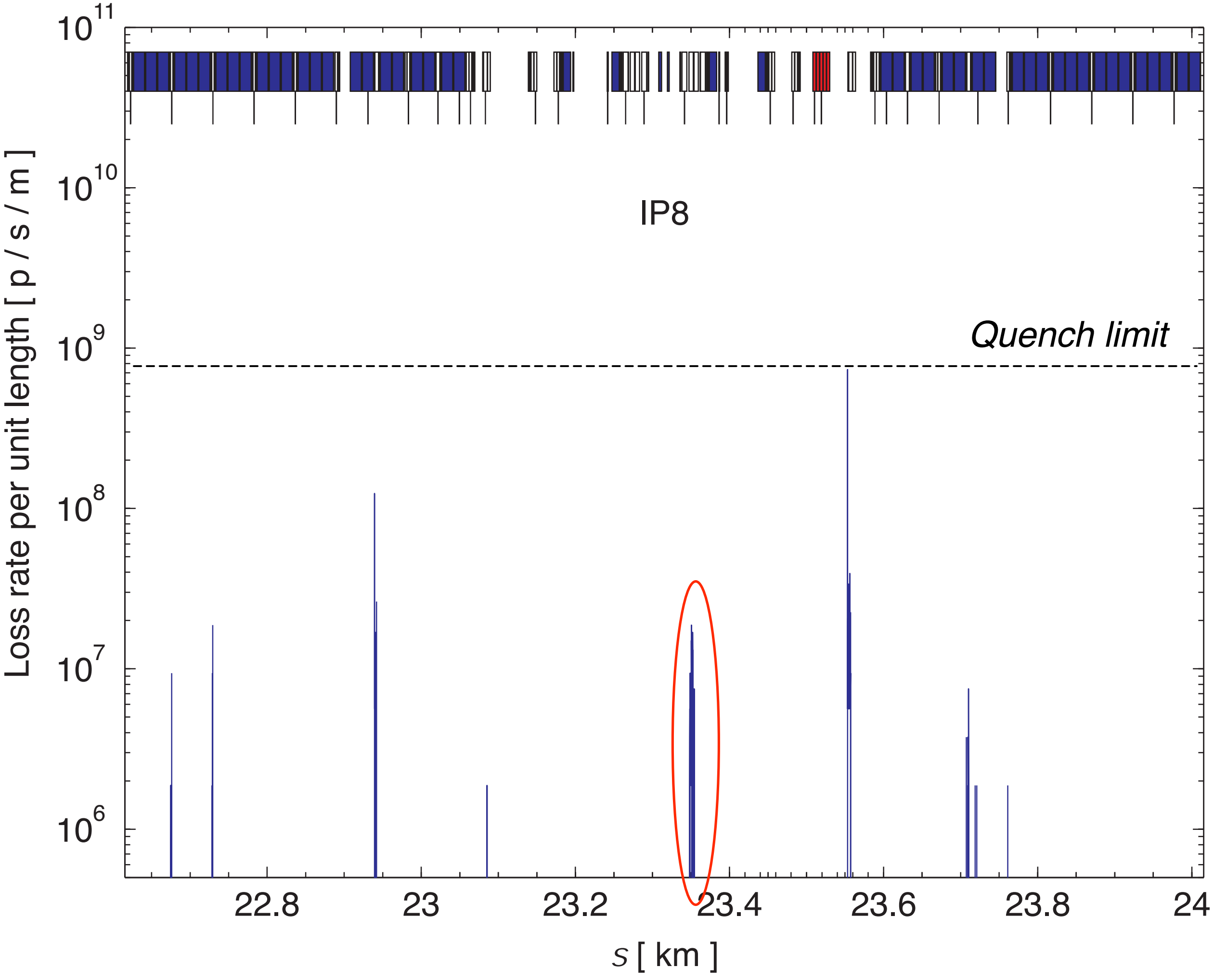


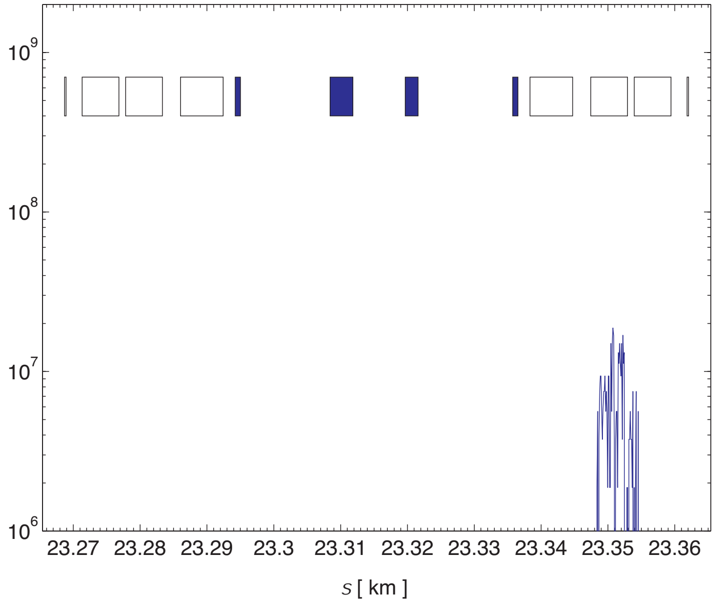
Transverse distributions of losses depend on the location!

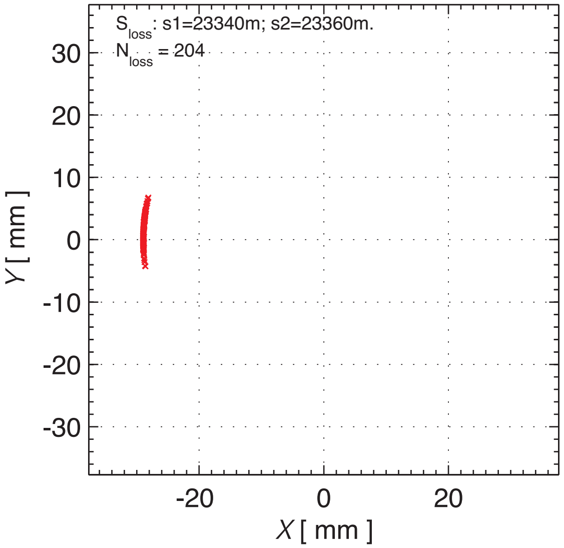




Losses also further downstream of the arc 7-8!







Large betas + separation induce losses in the triplet also at injection

Same longitudinal profile for the other MQ's

Losses at top energy - cold region

Same loss patterns as at injection

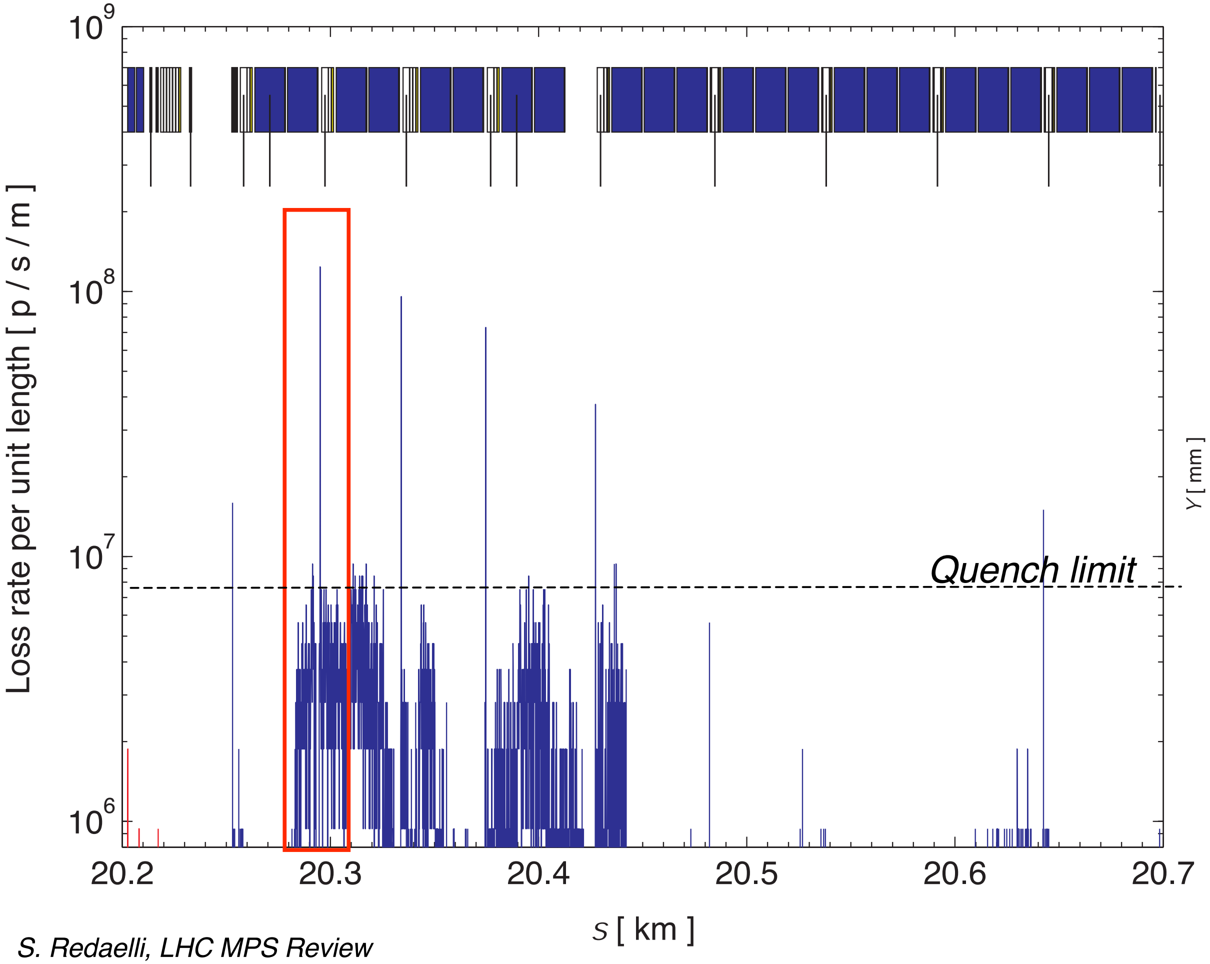
However, in some locations longitudinal and transverse distribution of losses is different *(betatron losses smaller, energy errors dominate!)*

Perfect machine/cleaning

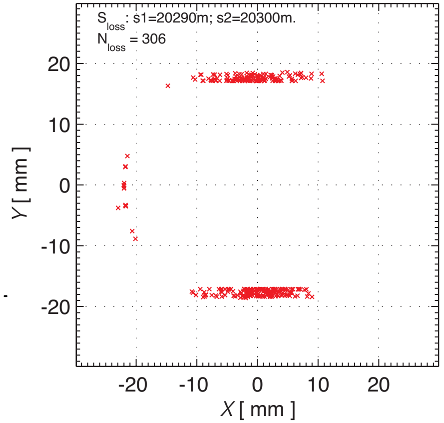
TCP (6σ) and TCS (7σ) only

$$N_{\mathrm{Nom.}} = 3\times10^{14}\ \mathrm{p}$$

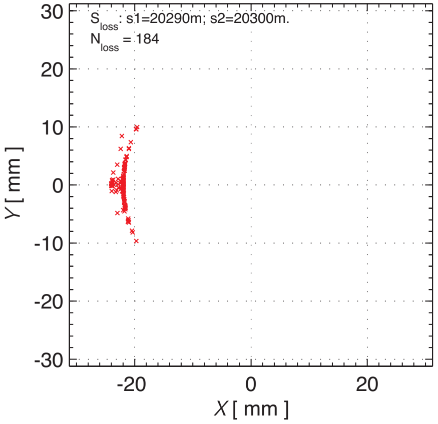
$$\tau_b^{\mathrm{top}} = 0.2\ \mathrm{h}$$



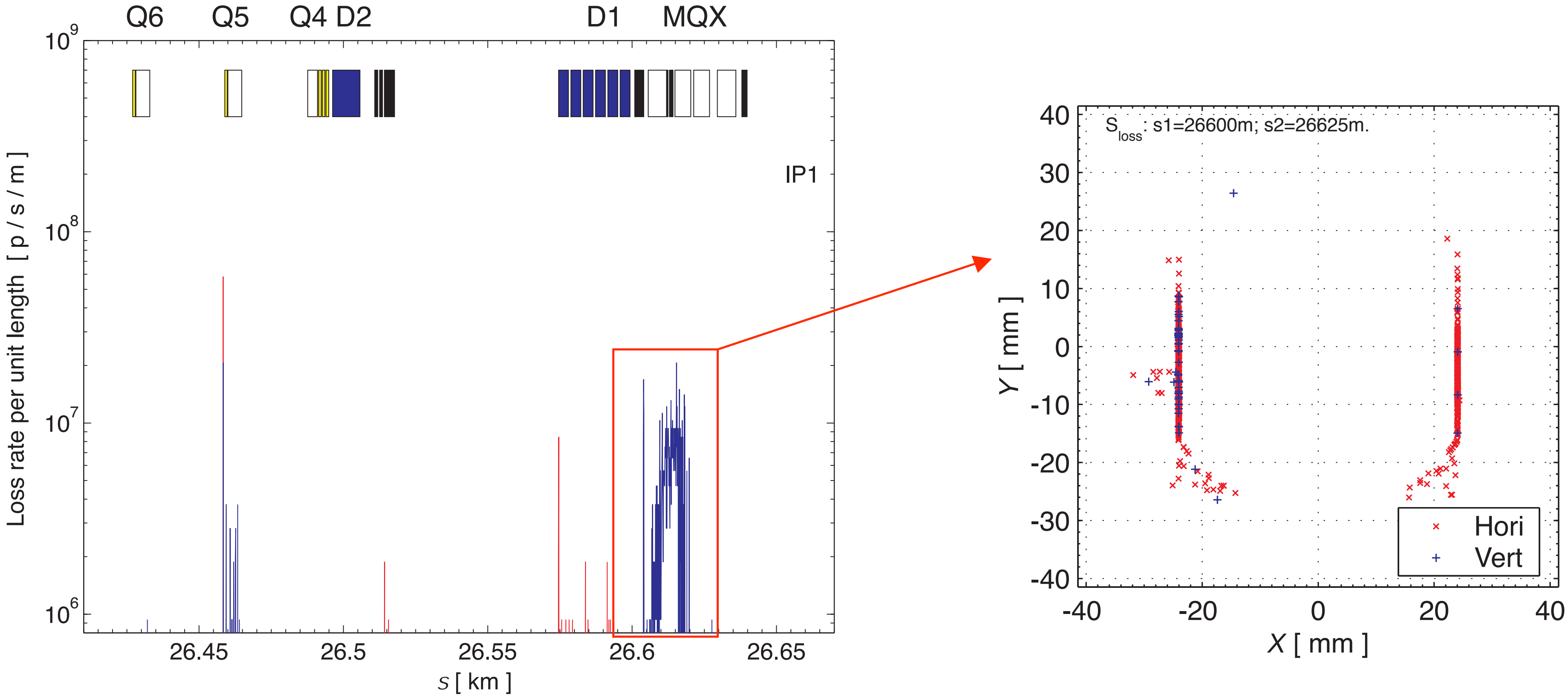
Q8 - injection



Q8 - top energy



Losses at the superconducting triplets are induced by the large beta functions (> 4000m) and by the crossing schemes.



Tertiary collimators have been added to shield the triplets….

Conclusions

- ✓ Loss patterns around the full LHC ring can now be precisely calculated!
  Simulations: Tracking of particle halo trajectory and aperture model (Δs = 10 cm!)
  Preliminary results (primary and secondary collimators only, no absorbers)

- ✓ *As expected:* Largest losses arise in the cleaning insertions
  Large loss peaks at the quadrupoles (warm/cold transitions)
  Large losses at local aperture restrictions

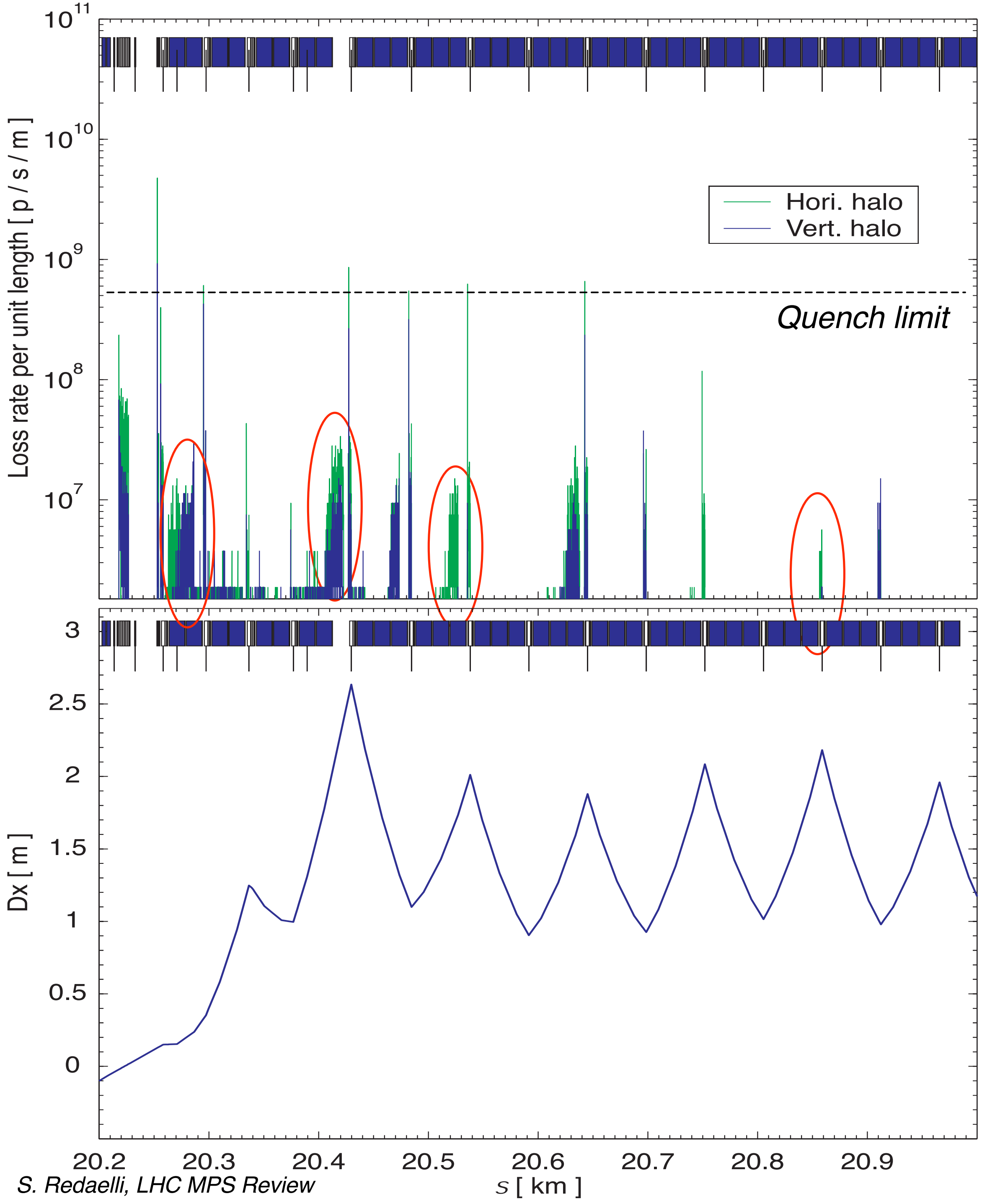
- ✓ *However:* Losses at unforeseen locations (e.g., dipoles with high D_x)
  Longitudinal and transverse loss distributions change during energy ramping!

- ✓ Re-evaluation of the BLM location is in progresses!

- ✓ Errors must be studied in detail! Alignment, closed orbit, non-linear fields

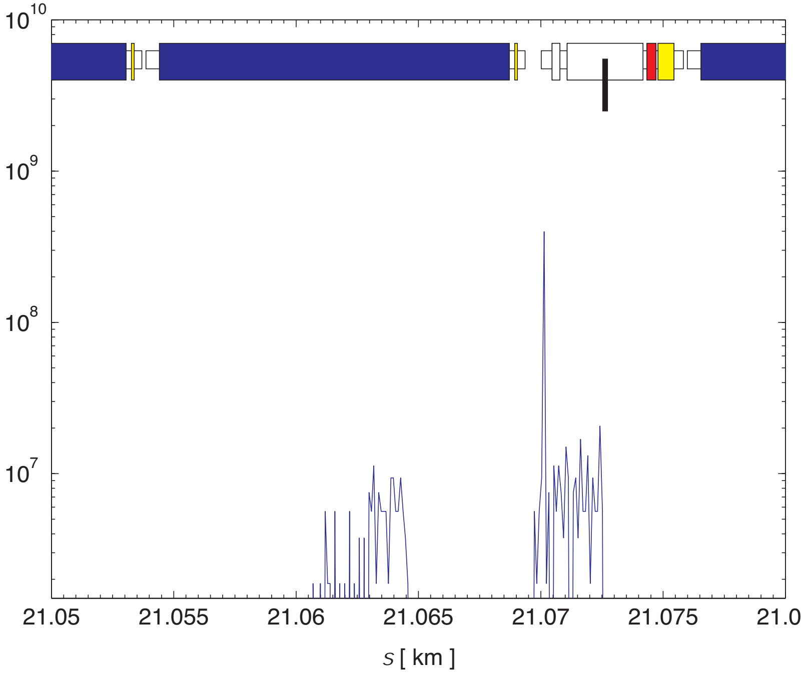
- ✓ Failure scenarios other than regular ‘slow’ losses require dedicated studies

Reserve slides



Losses due to energy errors in the dispersion suppressor but also further donwstream in the *arc*!

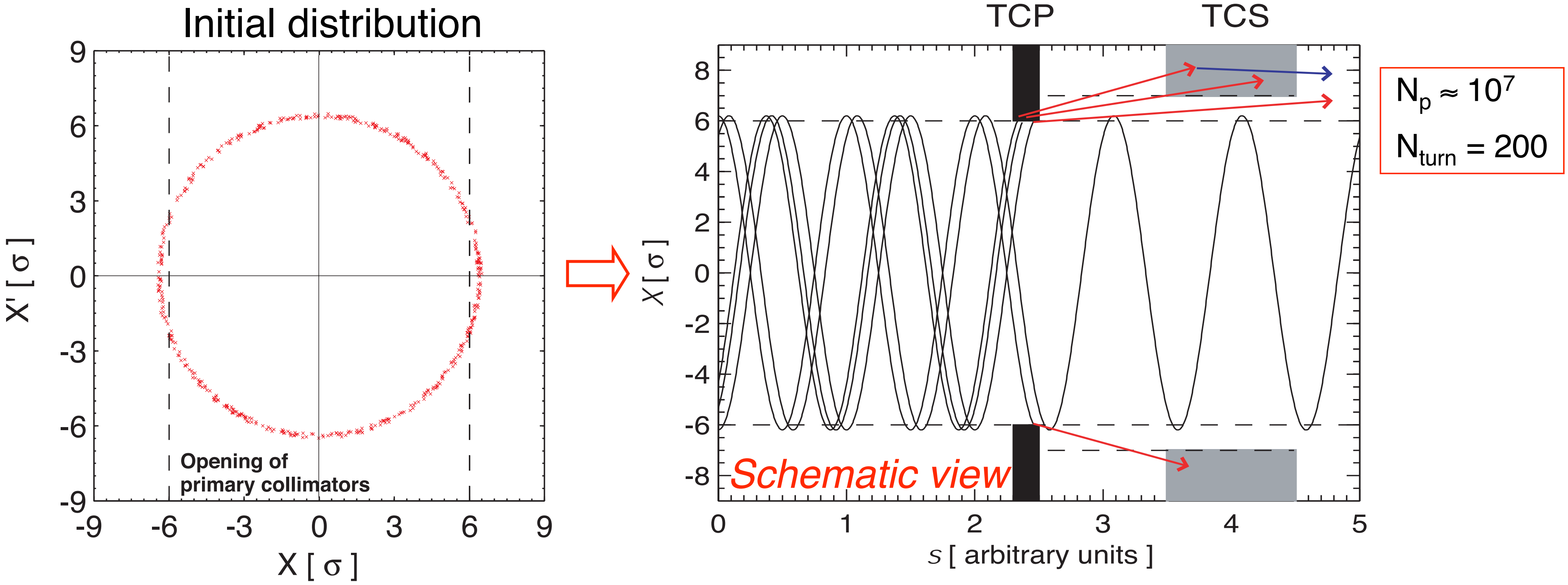
Additional BLM's should be foreseen for dipoles were the dispersion is high!



Generation and tracking of halo particles

Annulus distribution at the beginning of the ring (one plane only).
Amplitude chosen to have impacts on the primary collimators

Nominal settings:	Primary collimators (TCP)	**6 σ**
	Secondary collimators (TCS)	**7 σ**

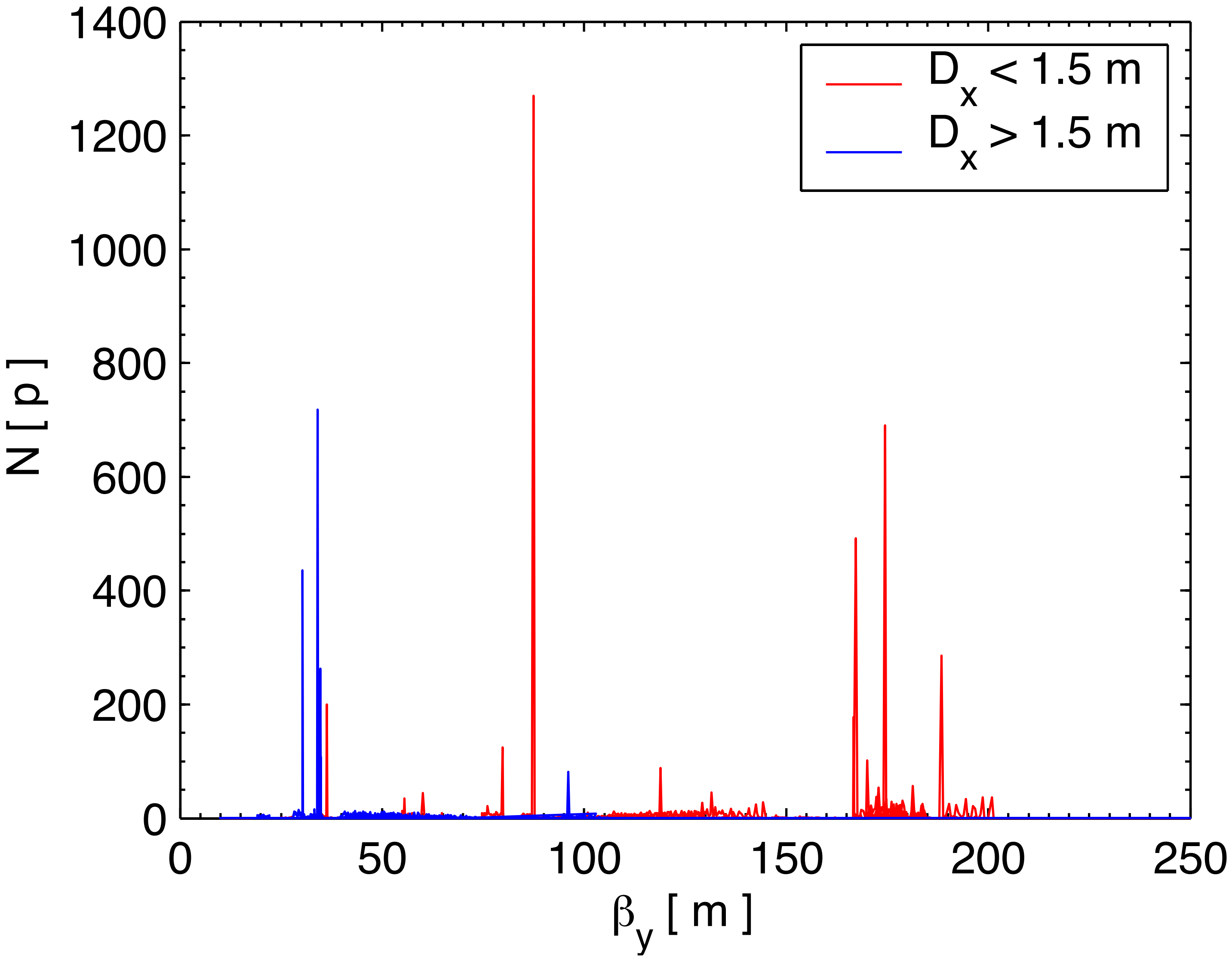


$N_p \approx 10^7$

$N_{turn} = 200$

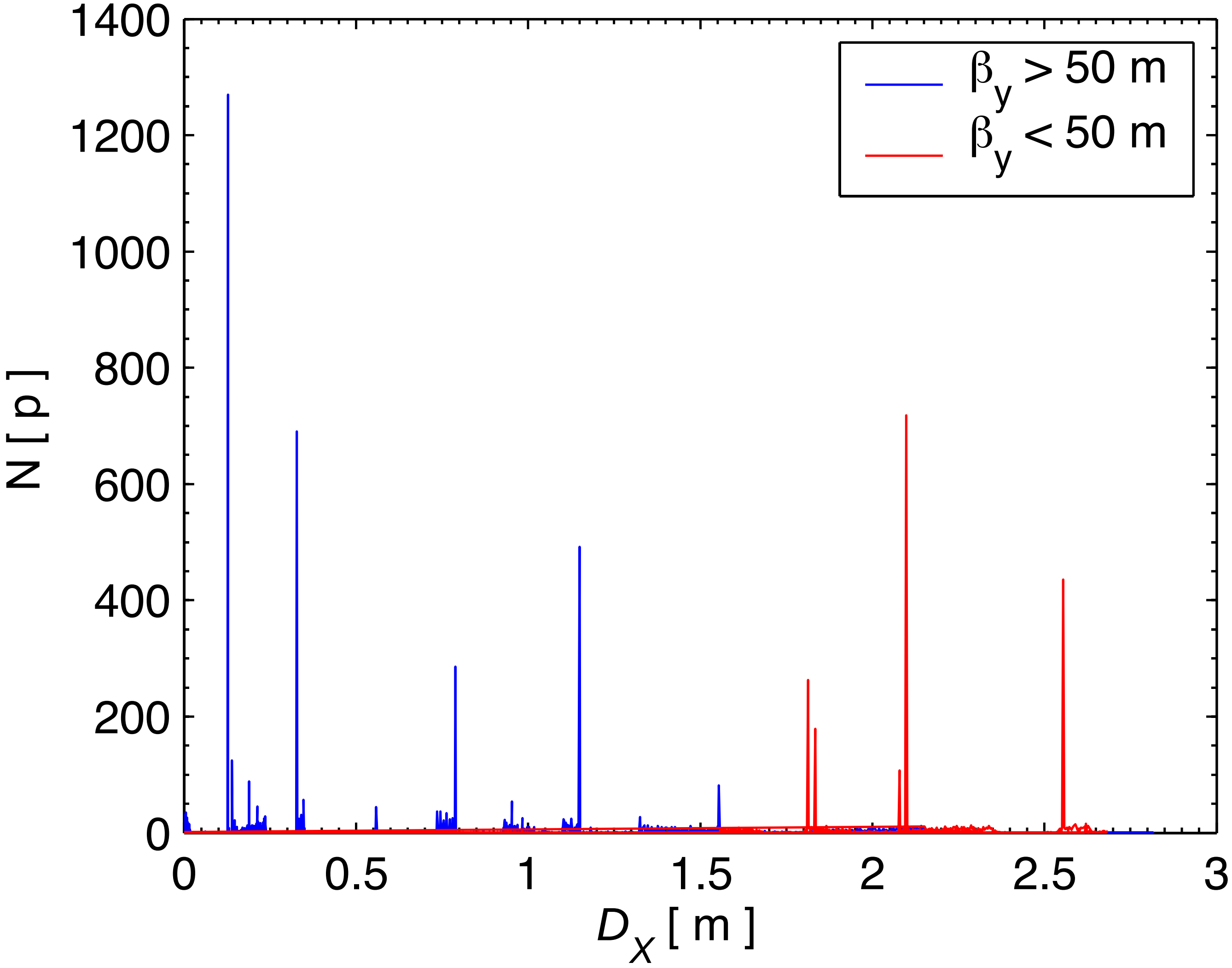
Horizontal (vert) halo ≡ Initial distribution in X (Y)
→ Interaction with horizontal (vert) primary collimators

Amplitude of losses versus beta function values



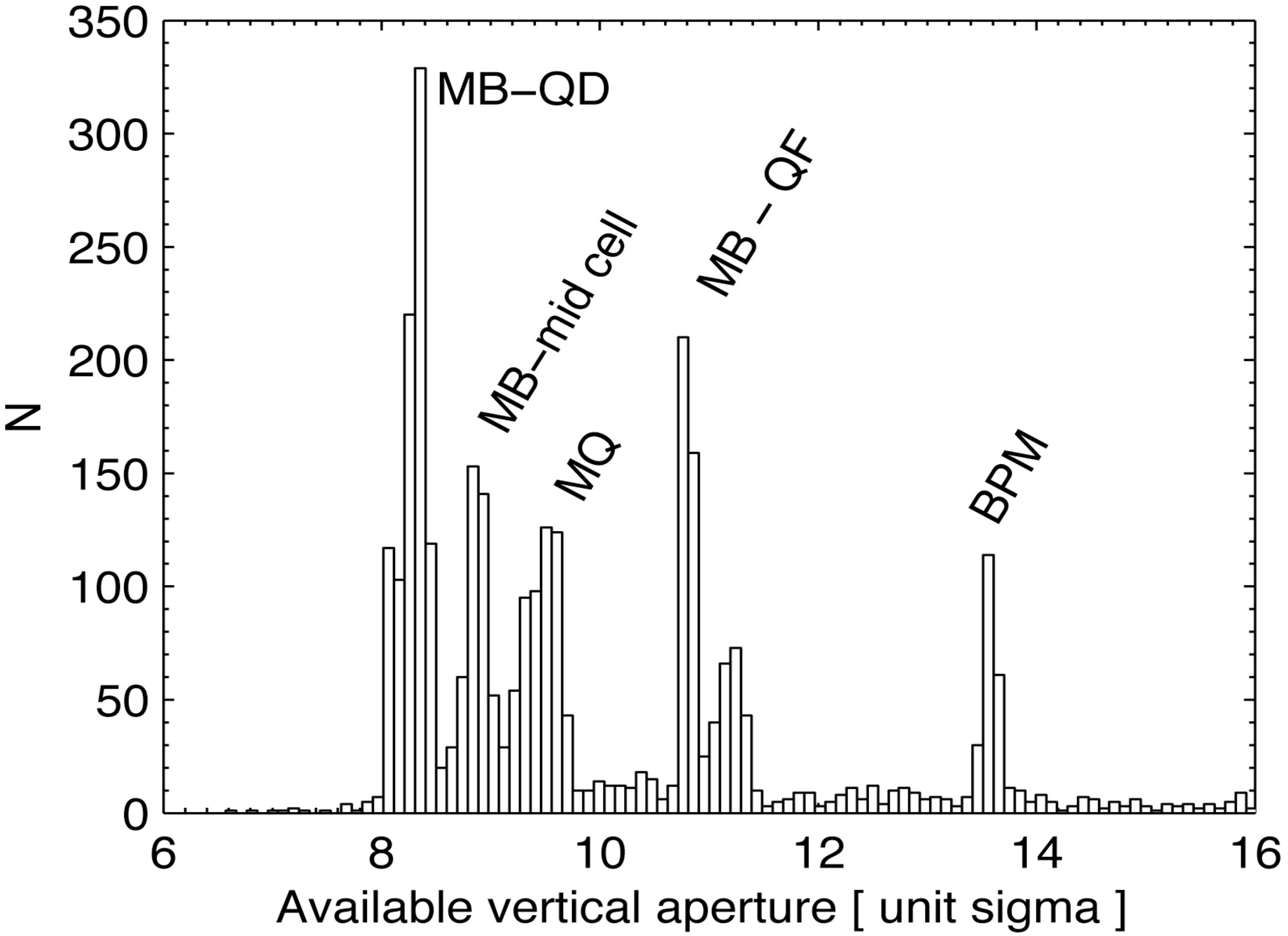
Neglecting the contribution from dispersion, losses occur at the peak values of β!

Amplitude of losses versus dispersion values

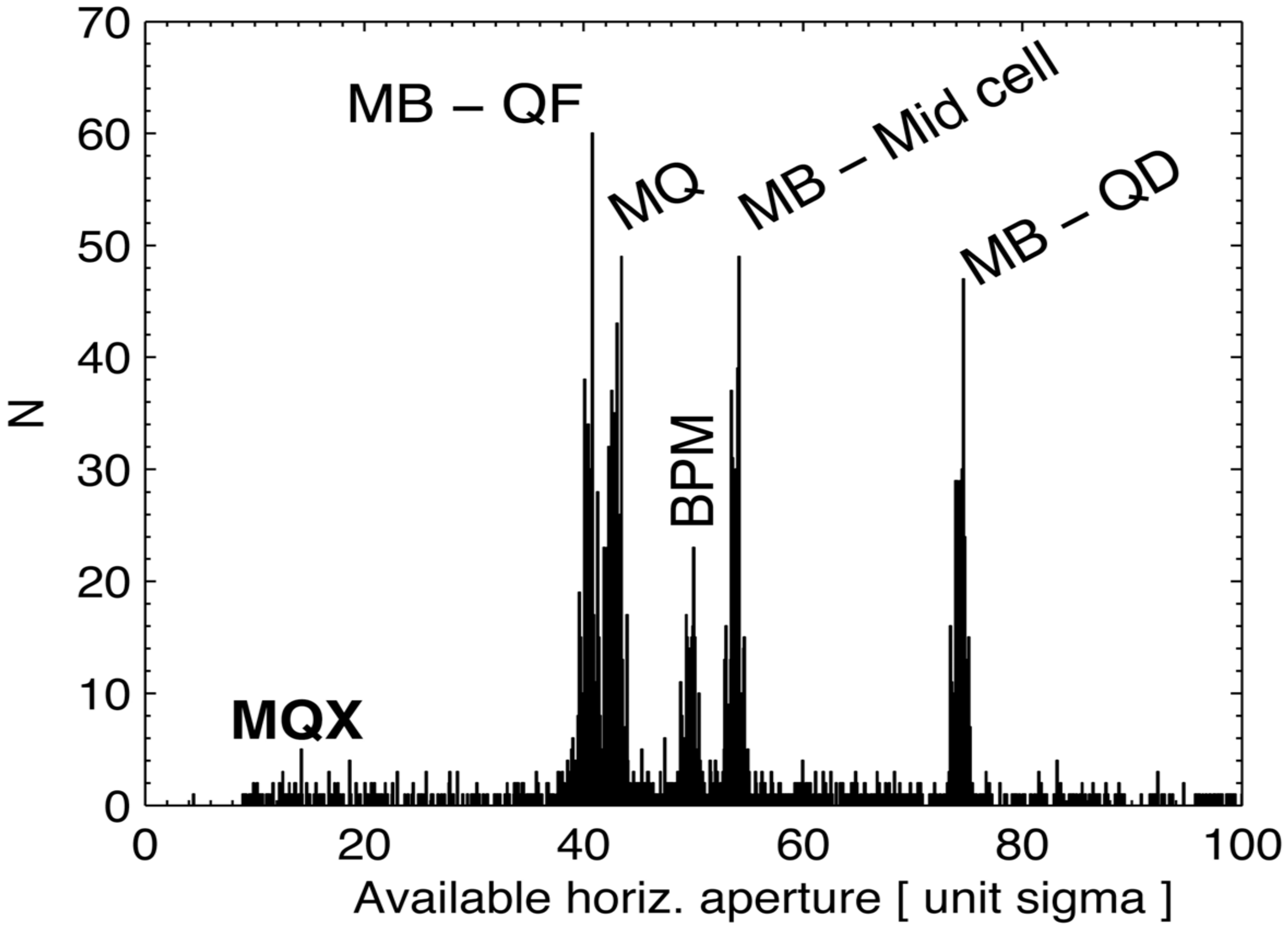


For small values of β, the losses are driven by energy error (large D_x)!

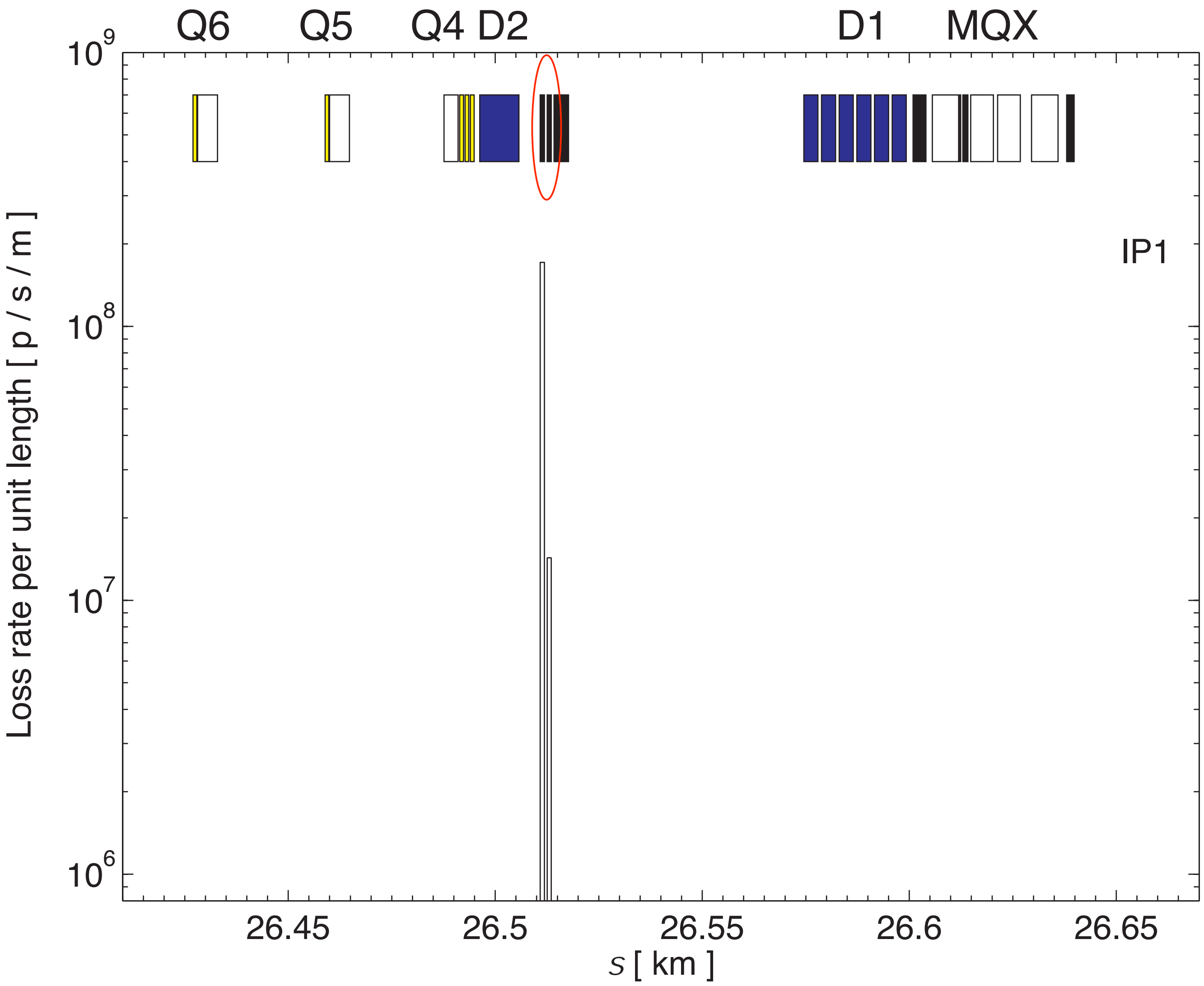
Distribution of available LHC aperture at injection (450 GeV/c)



Distribution of available LHC aperture at top energy (7 TeV/c)



Preliminary beam losses with tertiary collimators to protect the triple:



No more losses at the triplets with tertiary collimators at 8.4 σ!