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External Review of LHC Collimation Project

LHC Aperture
and
Collimator Settings

Stefano Redaelli, Ralph Assmann,
Jean-Bernard Jeanneret, Guillaume Robert-Demolaize

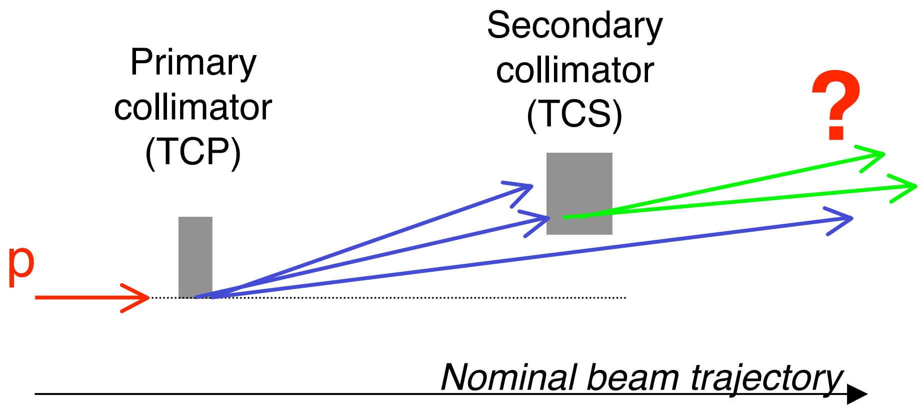
Input from many colleagues (S. Chemly, C. Rathjen, …) and various WGs

CERN
AB - ABP - LOC
Switzerland

Overview of my talk:

1. **Introduction**
   - The aperture of the LHC - motivation
   - How do we set the movable elements?
2. **The LHC aperture bottlenecks**
   - Calculation of APL code
   - Aperture restrictions in various cases (injection, low β, …)
3. **Proposed settings of movable elements**
   - Requirement from accelerator physics
   - Collimation tolerances (flatness, tilt, β -beat,…)
4. **More detailed calculations of aperture restrictions**
   - Detailed aperture model with < 1 metre spatial resolution
   - Preliminary results - loss paterns vs. quench limits
5. **Conclusions**

Introduction - motivation for the aperture model



LHC: Two stage collimation system

Where are the halo particle lost?

⇒ Allow for a *maximum loss rate* to prevent quenches!

$$\frac{R_{\rm loss}}{R_{\rm Q}} = \frac{L_{\rm dil}}{\eta_c}$$

Allowed loss rate [p/s] → $R_{\rm loss}$

Quench limit [p/m/s] → $R_{\rm Q}$

Cleaning inefficiency → η_c

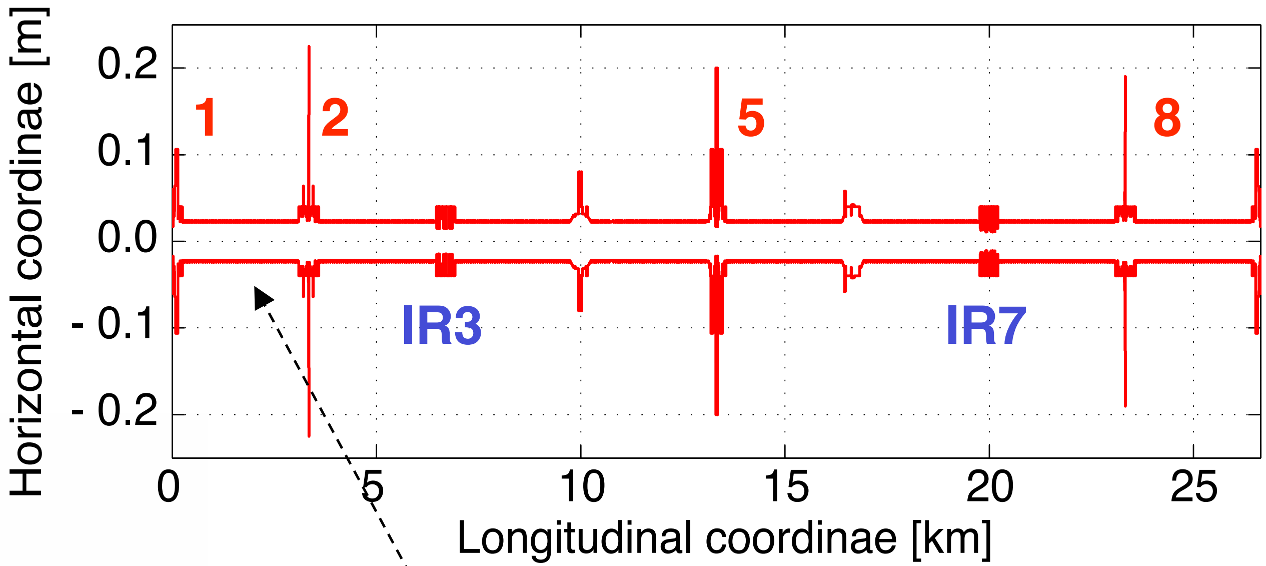
Dilution length [m] → $L_{\rm dil}$

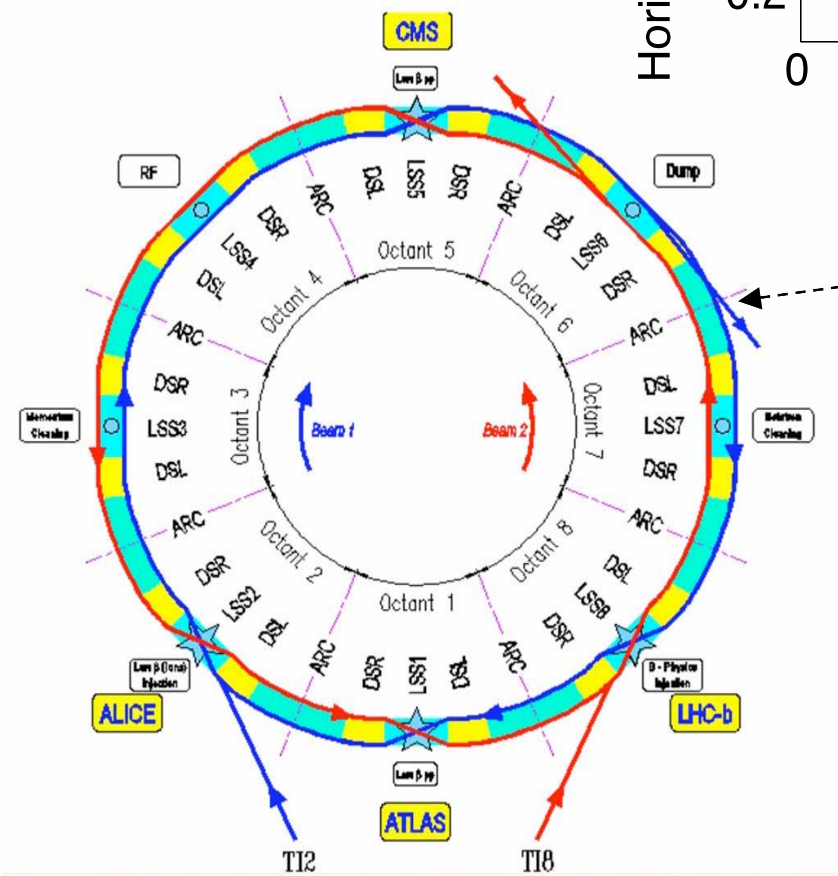
Depends on the aperture vs longitudinal coordinate!

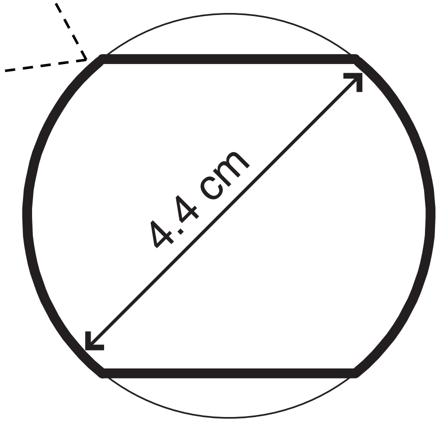
Need for an **aperture model**:

1. *Aperture bottlenecks → collimator settings*
2. *How many protons are lost in which cold elements?*
3. *Which is the longitudinal distribution of losses?*

The LHC aperture
(more details later)







Beam screen of main bending dipoles (ARC)

*Various **movable elements** to be adjusted for tuning collimation performance…*

Setting of movable elements within the LHC aperture

LHC ring mechanical aperture sets scale a_{mech}

➔ *tight LHC aperture (SC magnets!)*

Protection devices must protect ring aperture $a_{prot} < a_{ring}$

➔ *protect against injected beam / bump errors*

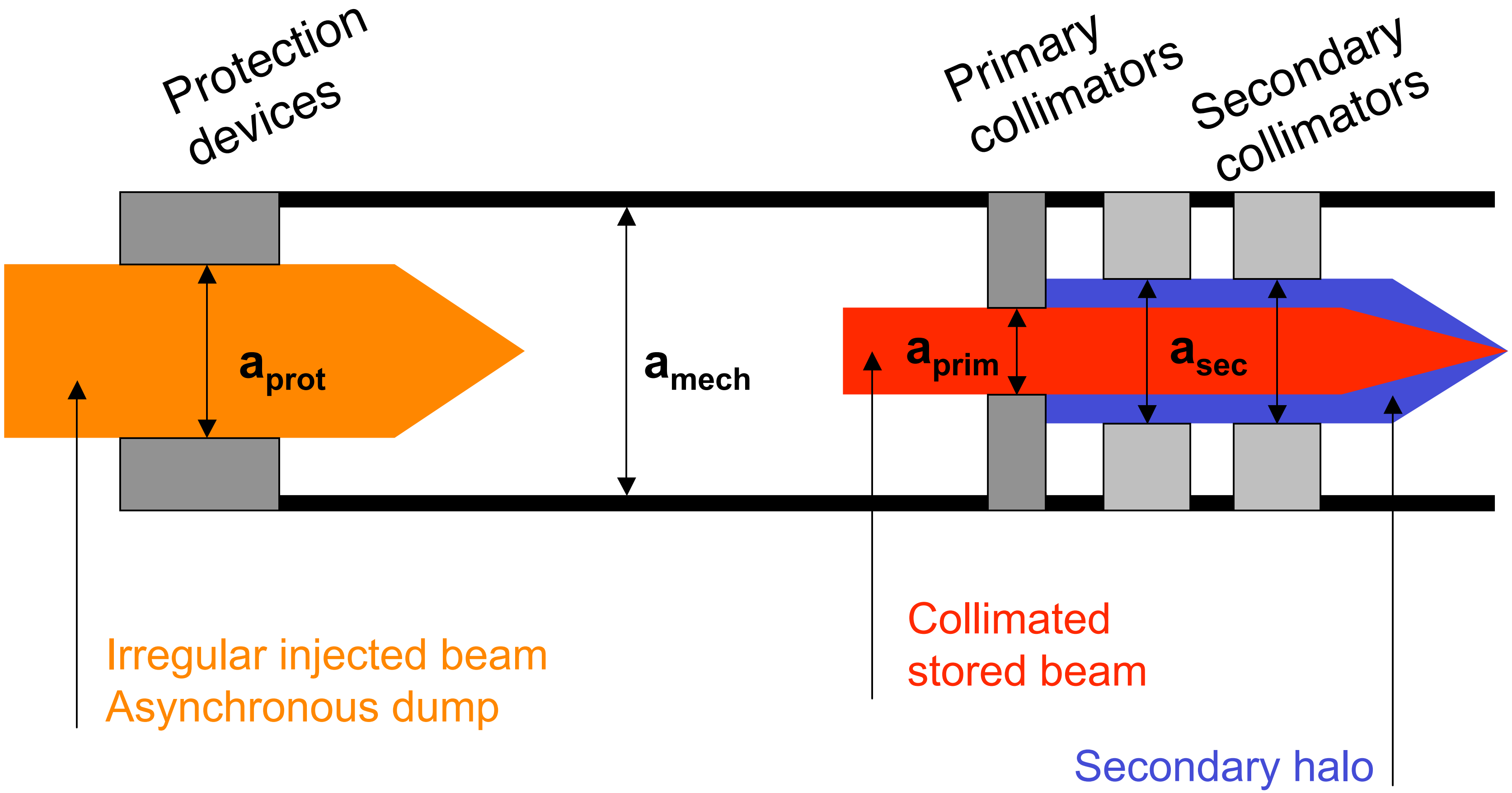
Secondary collimators tighter than protection $a_{sec} < a_{prot}$

➔ *avoid too much secondary halo hitting protection devices*

Primary collimators tighter than secondary $a_{prim} < a_{sec}$

How does this look likes?

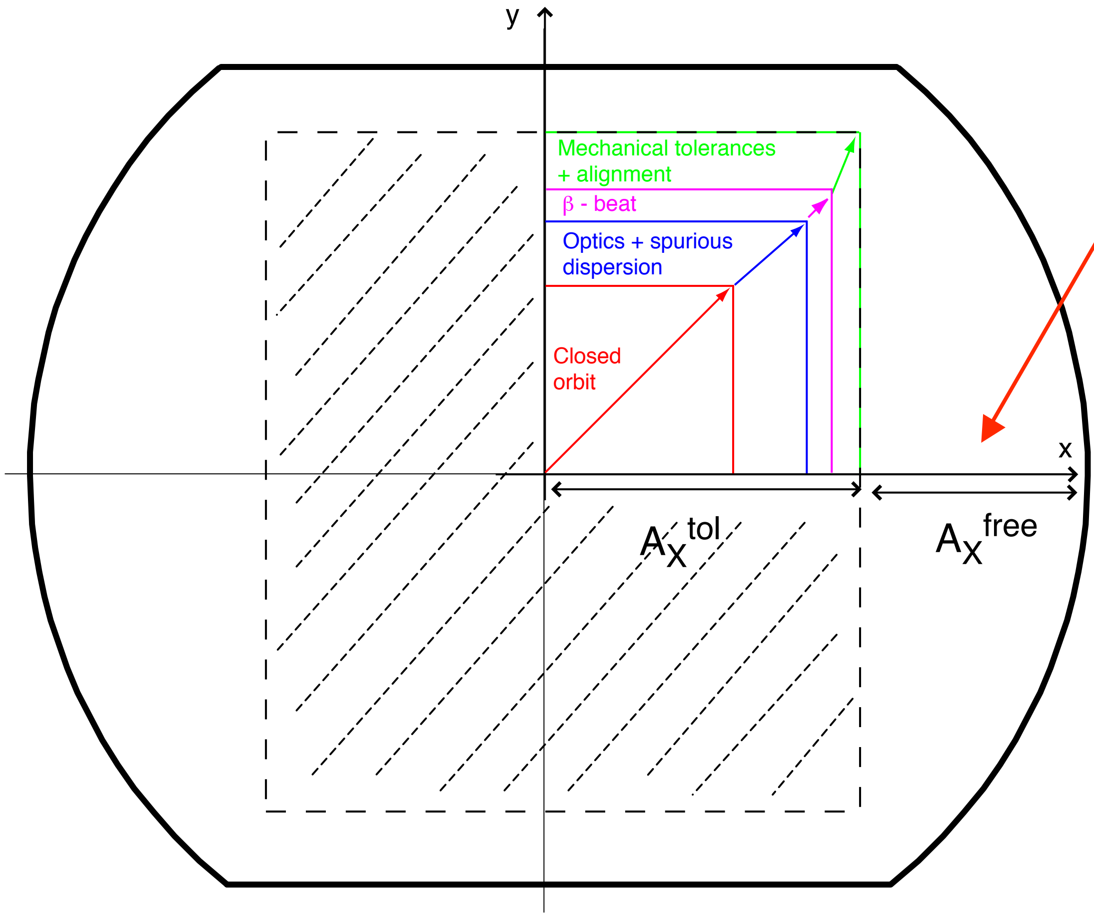
Settings of movable elements - schematic view



$$a_{prim} < a_{sec} < a_{prot} < a_{ring}$$

Chosen to fit the aperture bottlenecks - other elements set accordingly!

Calculation of the LHC available aperture



$$A_x^{\mathrm{Available}} = \frac{(A_x^{\mathrm{mech}} - A_x^{\mathrm{tol}})}{\sigma_x}$$

Design criteria for LHC aperture:
The secondary halo should not touch the beam pipe!

Top energy

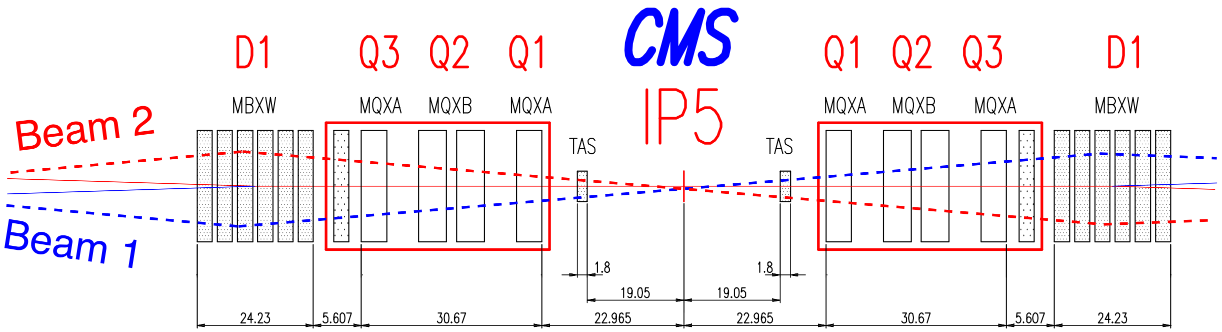
$$A_{x,y}^{\mathrm{Avail}} > 1.22 \times 6 \times \sigma_{x,y}$$
$$A_{\mathrm{skew}}^{\mathrm{Avail}} > 1.4 \times 6 \times \sigma_{\mathrm{skew}}$$

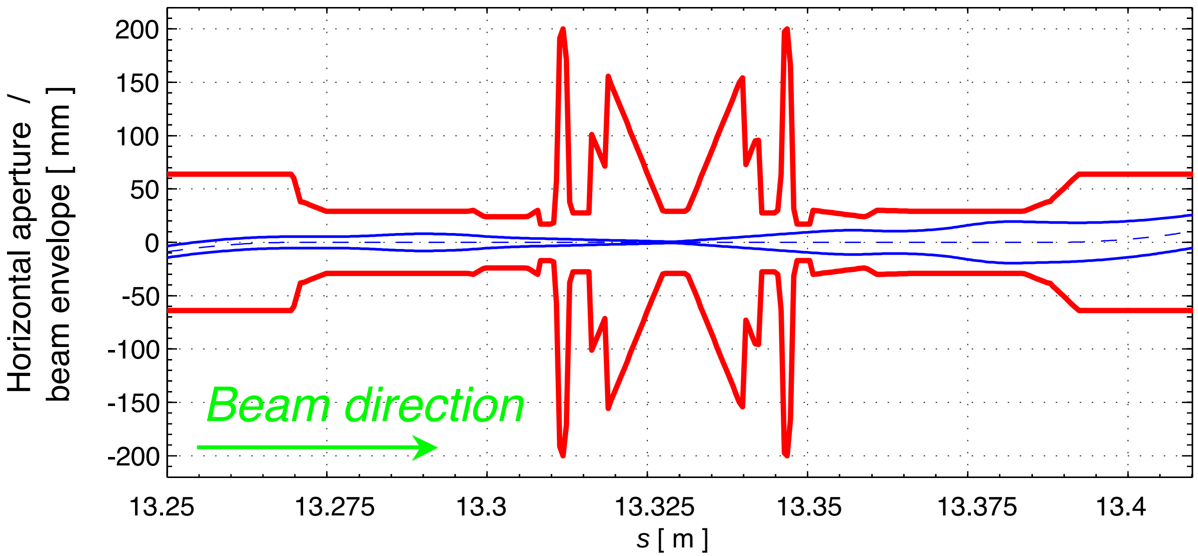
(J.B. Jeanneret, Phys. Rev. ST Accel. Beams **1** (1998) 081001)

Available mechanical aperture around the *full LHC ring* calculated with the **APL code** by J.-B. Jeanneret (See *LHC-Project-Note 111*)

Example: Beam envelope at the interaction point 5 (CMS)

Collision energy, squeezed optics.

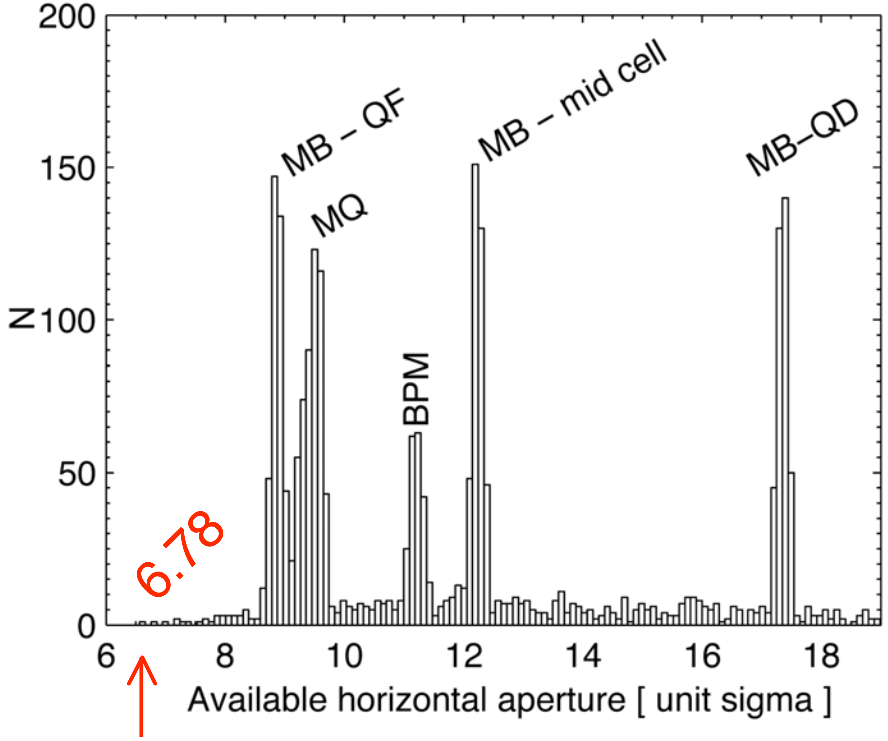




Available aperture calculated for the full LHC ring in various cases (inj, lowβ)

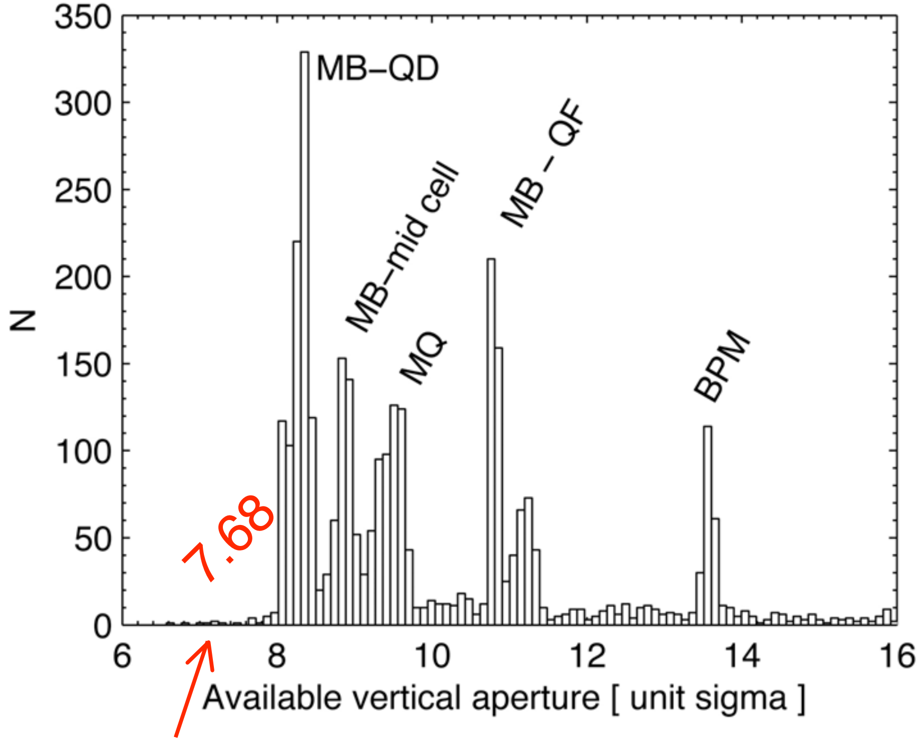
Distribution of available aperture at injection (450 GeV)

Horizontal



Aperture limit (unit sigma)

Vertical



Aperture limit

The smallest available mechanical aperture defines the settings of primary collimators!

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

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

What are the corresponding collimator openings?

Collimator settings at injection (450 GeV)

(based on discussions with WGs involved)

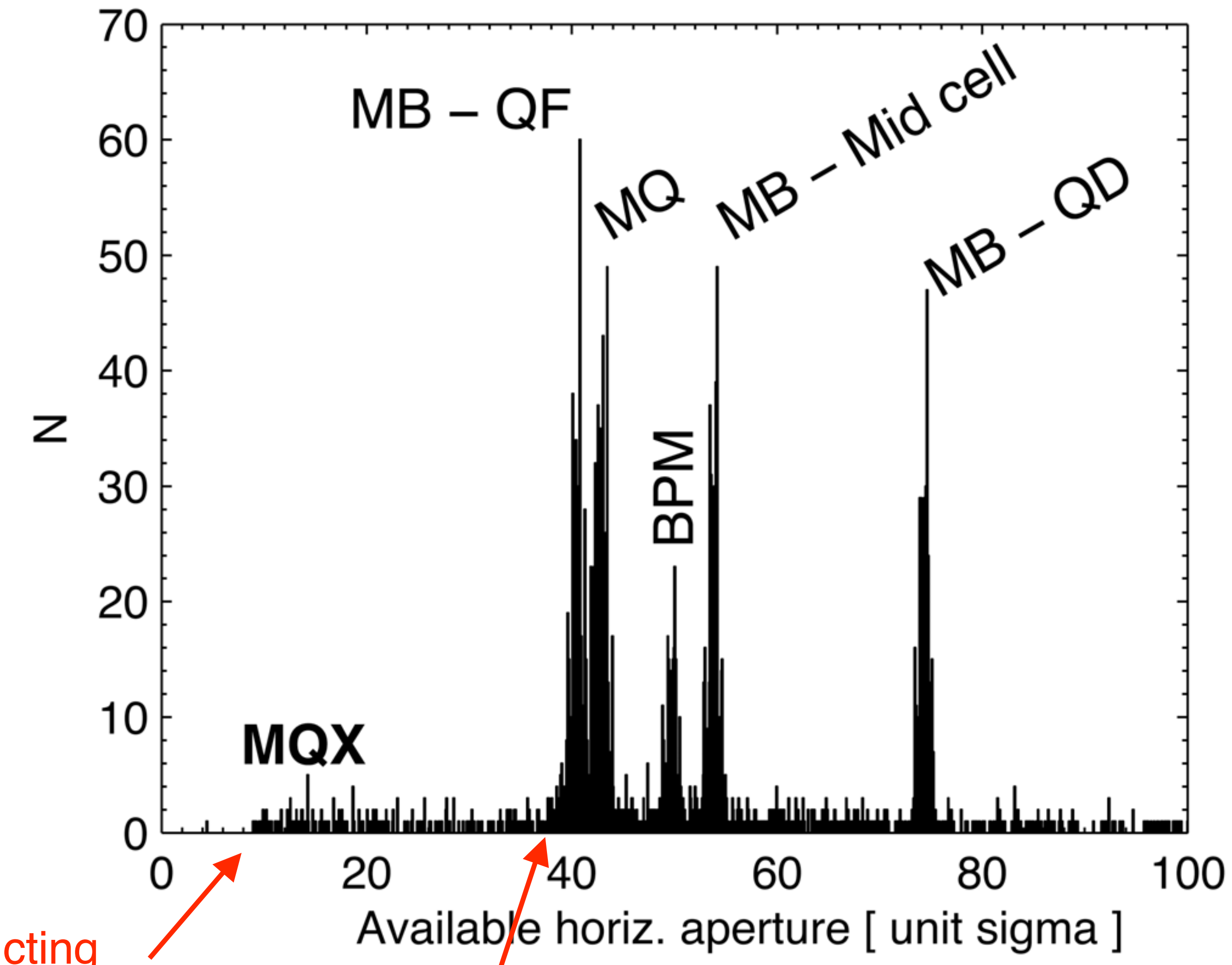
a_{mech}	=	**7.5 σ**	Available mechanical aperture
a_{prot}	=	**7.2 σ**	Protection devices
a_{sec}	=	**6.7 σ**	Secondary collimators
a_{prim}	=	**5.7 σ**	Primary collimators

In millimetres…

For $\sigma \approx 1\ mm$ at injection ⇒ collimator half-gap: $\mathbf{A_x^{Prim} \approx 6\ mm}$

Distribution of available aperture at collision (7 TeV)

(squeezed optics)



Superconducting triplets ($\beta \approx 4$ Km)

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

Minimal available aperture (collision, nominal β*)

Physical available space in unit sigma

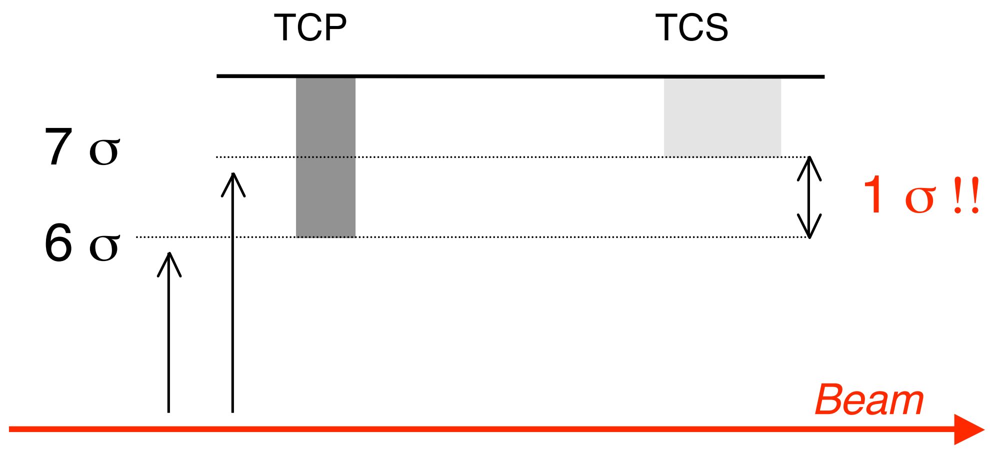
Beam 1	Warm	Cold	
Horizontal	28.1	8.90	σ_x
Vertical	8.34	8.43	σ_y

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

$\Rightarrow$ We take $A_{mech} = 8.0\ \sigma$ as the available mechanical aperture

Primary collimators at ≈ *6 σ = 6 x 200 μm* $\Rightarrow$ A_x^{Prim} ≈ 1.2 mm

Why collimator tolerances?



Two-stage collimation:

secondary collimators
should never
act as a primary!

Primary: 6 σ

Secondary: 7 σ

$\Delta_{retraction}$: **1 σ**

The beam size sets scale:
(collision energy)

$\sigma \approx 200\ \mu m$

Jaw surface flatness
Orbit excursions
β-beat
Position error
Angular alignment
...

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
Knowlegde of gap	50 μm
Jaw position control	≤ 10 μm
Reproducibility of settings	20 μm

See talk by A. Bertarelli (Surface flatness - TCP, - TCS)

See talk by F. Decorvet (Knowlegde of gap, Jaw position control, Reproducibility of settings)

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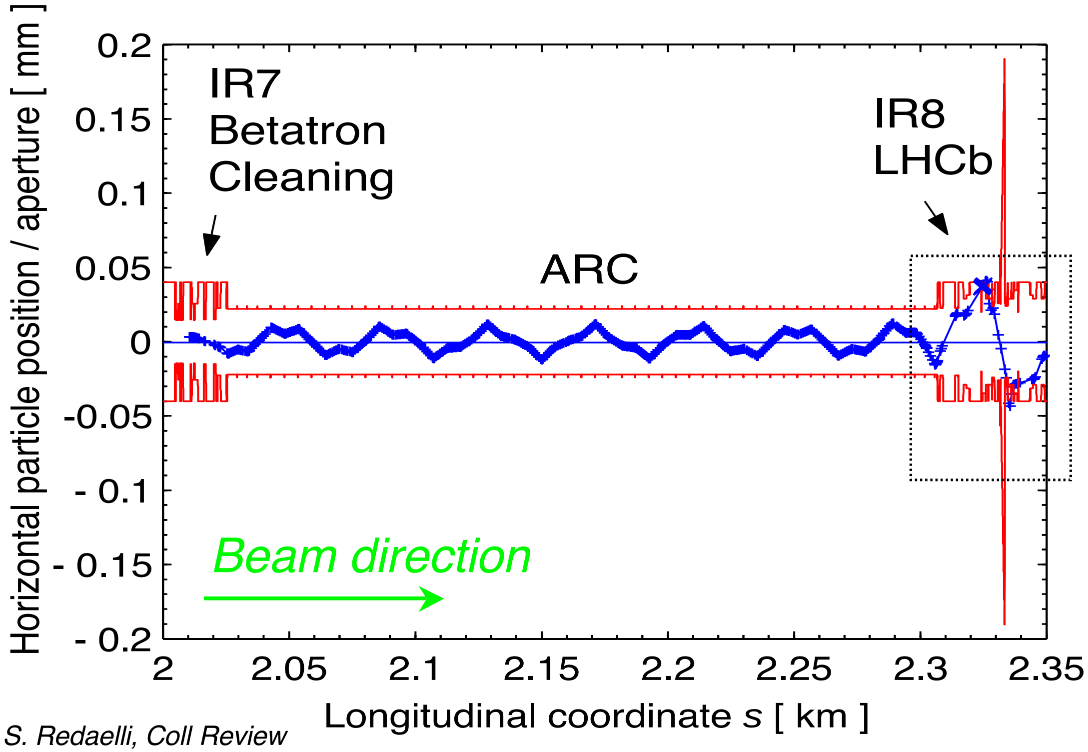
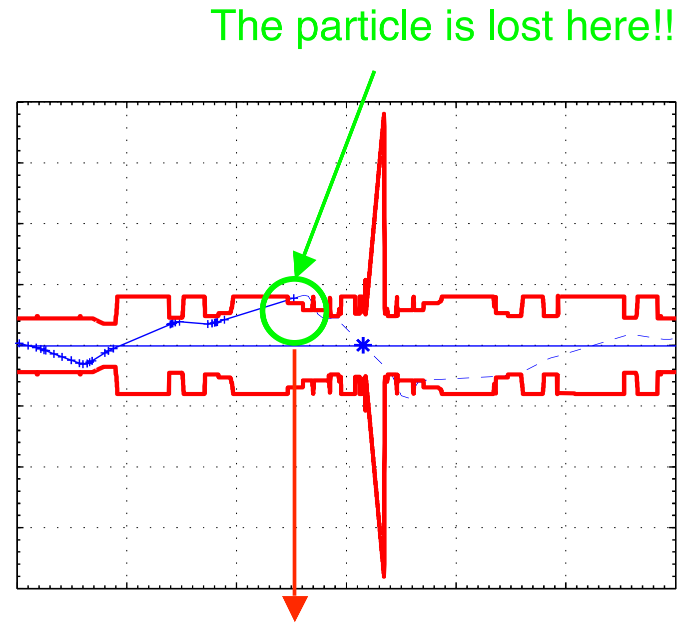
Detailed calculations of beam loss patterns

Calculation of beam envelope based on linear optics ($\beta_i \rightarrow \sigma_i$) does ***not*** allow estimating in detail the *proton loss rate*!

Need for:

- Exact **tracking** of secondary and tertiary beam **halo** with **collimators** (multipole errors, chromatic effects, …) ← *CollTrack*
  R.Assmann
  G. Robert-Demolaize
- Detailed **aperture model** of the LHC aperture (full ring, with accuracy ≈ 0.1 metre)





Spatial resolution of ≤ 0.1 m!

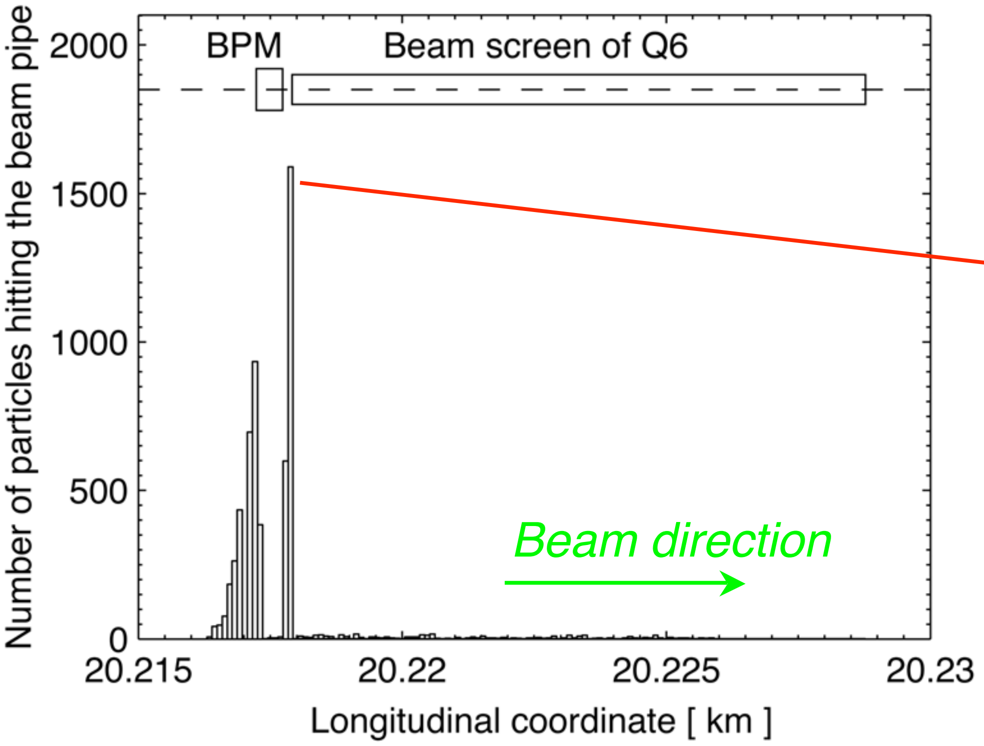
Simulations of *distribution of lost particles* around the ring.

Tracking of many particle (20 x 450000)

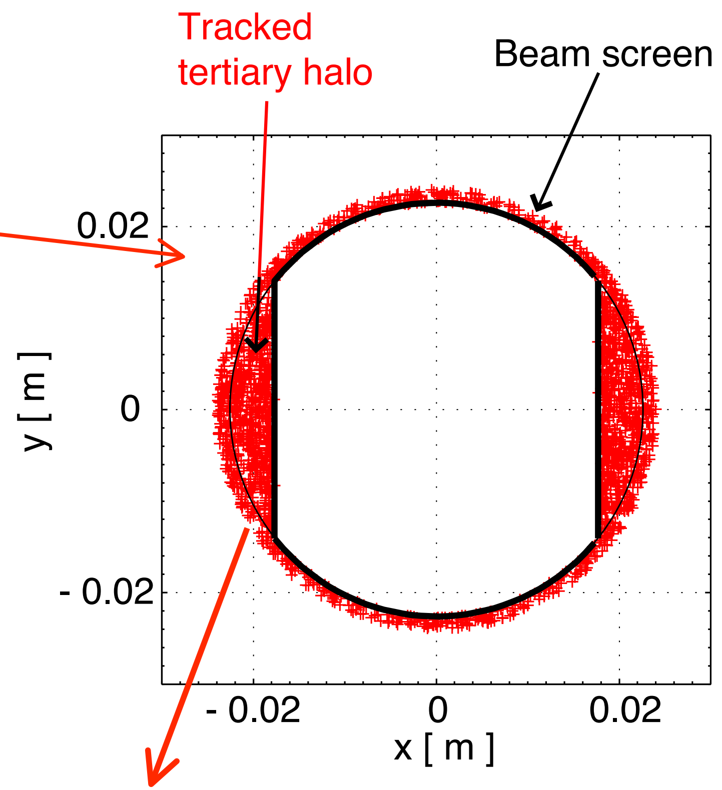
Example:

First superconducting magnet downstream of momentum cleaning (IR7)

Distribution of lost particles

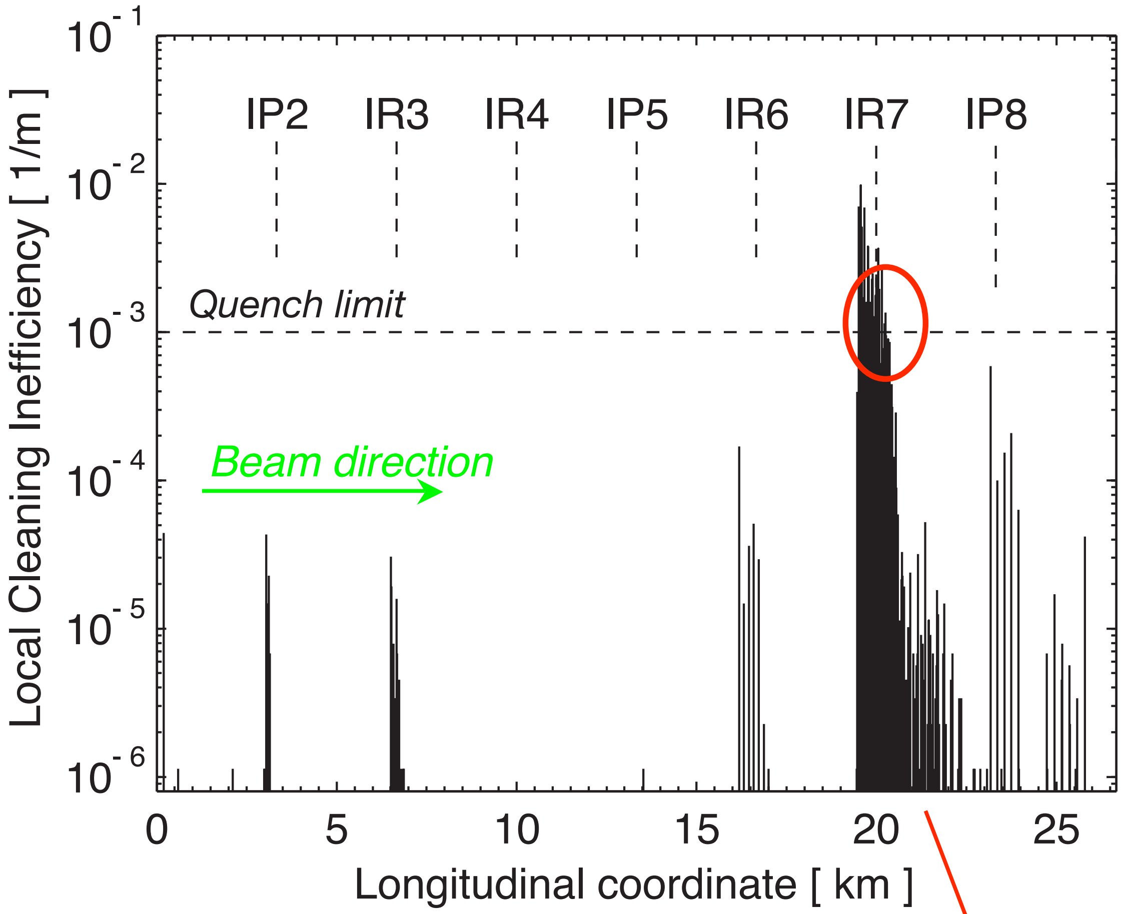


Scatter plot of lost partices

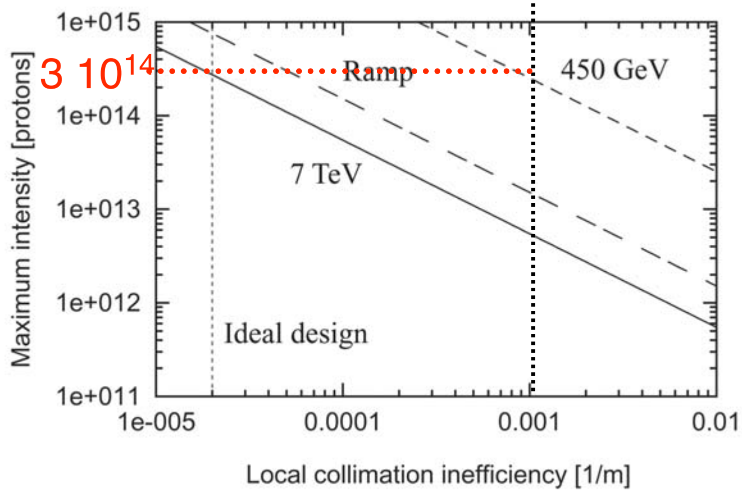


Uniform distribution!!

Loss patterns at injection



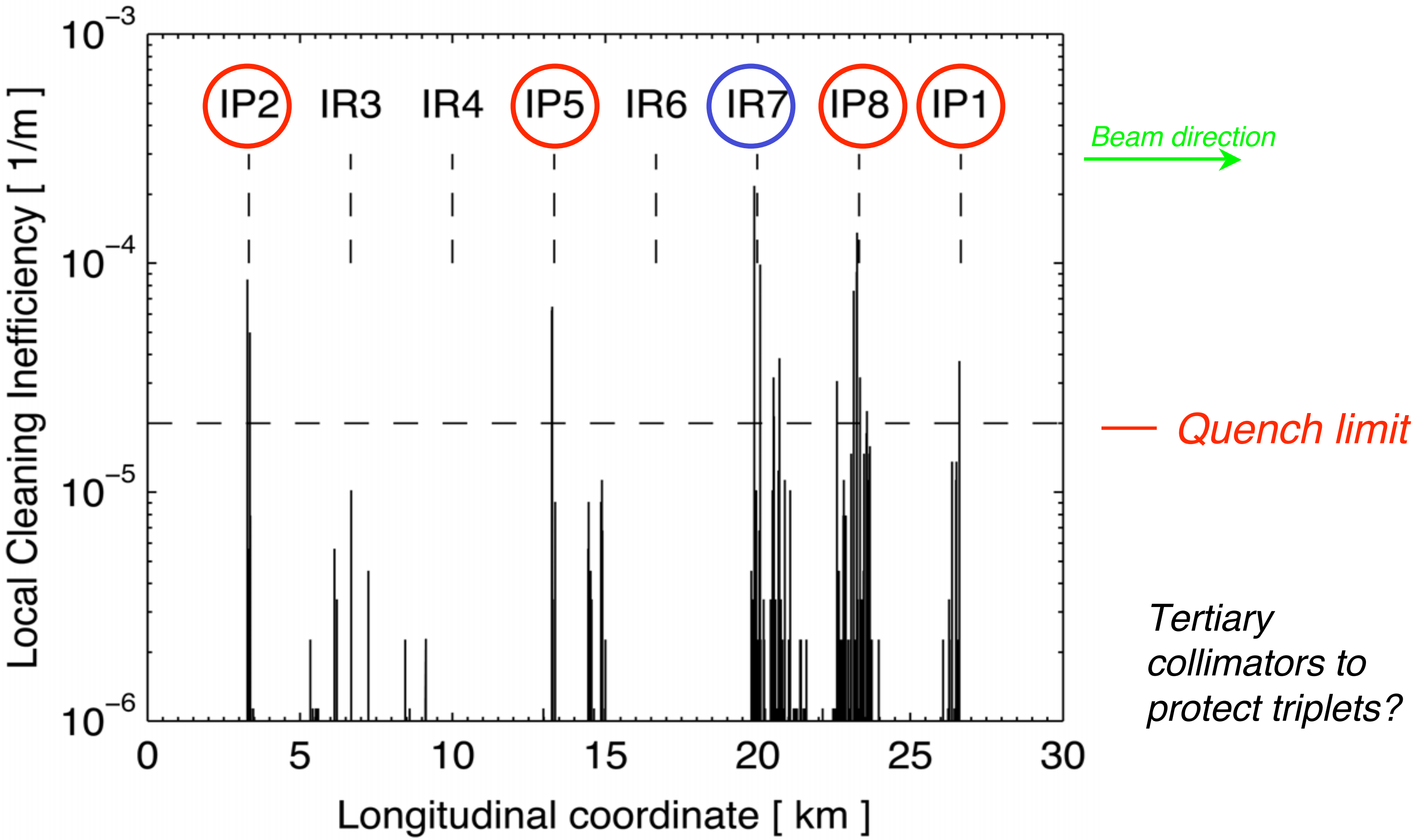
Quench limit calculated for the nominal intensity at 450 GeV of 3 x 10^{14} protons



$$R_{\text{loss}} = R_{\text{Q}} \left(\frac{L_{\text{dil}}}{\eta_c} \right)$$

Momentum cleaning

Loss patterns at collision (all IPs squeezed)



Tertiary collimators to protect triplets?

- Squeezed optics ⇒ particle lost in the SC triplets of experiments!
- Installation of **local absorbers** (TCT) will improve local clenaning
- Quench limit may be relaxed because particles are lost uniformly around pipe!

Conclusions

✓ Problem of the **LHC aperture** has been presented

✓ Model based on linear optics to estimated the *LHC aperture bottlenecks*

Definition of the settings of movable elements:

1. Tight collimator settings are required to protect the machine and to achieve the desired collimation performance (opening $\leq 6\ \sigma$, retraction $\approx 1\sigma$)
2. Correspondingly, stringent tolerances are imposed (μm range)

✓ Powerful tools for halo tracking + aperture model (10 cml have been set up

1. Patterns of lost protons around the full ring (inj + coll energies)
2. Achieved local inefficiency compared with quench limit of SC magnets

✓ Studies on-going to understand in detail loss patterns → **Imperfections!**

Acknowledgements

Collimation Working Group

Injection Working Group

Protection Working Group

AB-ABP-LOC:	O. Bruening, T. Risselada, S. Fartouhk, F. Schmidt
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AT-VAC:	C. Rathjen, G. Schneider, R. Veness, J. Knaster, …
AB-CO:	V. Kain

… and many others…