Parameters and tolerances for aperture margin evaluation at injection

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Acknowledgement: P. Baudrenghien, R. de Maria,
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Outline

- Introduction
- Updated tolerances
- Updated criterion for allowed aperture
- Summary

Introduction

- Available aperture in experimental insertions defines reach in β*
- Aperture calculations traditionally carried out with n1 model, including different tolerances
- Aperture measurements and beam measurements (orbit, optics,...) in running machine allows to refine tolerances
  - Done last year for collision (CERN-ACC-2014-0044)

Injection calculation

- Injection aperture also to be evaluated for LHC and HL-LHC
- Applications:
  - Global aperture: Calculation to be used to determine whether an optics (globally) gives enough aperture margin
  - Injection at smaller β*: Updated aperture calculations to be used to determine triplet aperture and β* for injection – similar calculation as in collision
- To update calculation parameters, need
  - Updated error tolerances
  - Updated criterion of allowed aperture

Previous parameters

- During design, used same parameters at injection and collision except closed orbit and momentum offset

Parameter	Unit	Design value @ injection	Design value @ collision
Primary halo	σ	6.0	6.0
Sec. halo, H/V	σ	7.3	7.3
Sec. halo, R	σ	8.4	8.4
Normalized emittance	μm	3.75	3.75
Closed orbit	mm	4.0	3.0
Momentum offset	-	1.5e-3	8.6e-4
β-beat (beam size)	-	1.1	1.1
Parasitic dispersion	-	0.27	0.27

- Criterion: n1≥7

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Updated error tolerances

- Discussions with various experts based on Run 1 experience and expectations for HL-LHC
- Concerned parameters:
  - Halo shape
  - Emittance : only overall scaling factor as long as other constraints (impedance, machine protection margins) limit the collimator settings
  - Optics (β-beat, parasitic dispersion)
  - Orbit
  - Momentum offset

Halo and emittance

- Old halo definition: Very rough assumption of secondary halo without tail, not accounting for tertiary halo - not adequate for the modeling of the real cleaning bottlenecks in the DS
- Proposal: use round halo={6,6,6} so that the calculation gives the aperture and not n1
  - As done for collision
- Emittance: overall scaling factor in aperture calculation. Either
  - keep present design emittance of 3.5 μm => Easy comparison with present machine (done so far for HL-LHC collimation), or
  - Use the HL-LHC design emittance of 2.5 μm => Consistency within HL-LHC (all collimator settings in sigma would then need to be rescaled)

Optics

- Philosophy to base parameters for future machines on what has been achieved so far in the LHC. Include any expected worsening on top
- Run 1: achieved about 10% beta-beat and 14% spurious dispersion at injection.
  - Reduced to half of the design parameters!
- Similar philosophy used at collision: better beta-beat than nominal achieved, but correction expected to be worse for HL due to high β-functions in the arcs
    - Kept design parameter of 20%
- Proposal: 10% beta-beat (bbeat=1.05) and 14% spurious dispersion

Orbit

- So far used 4 mm closed orbit tolerance
- Could be decreased to 2 mm, but need to add 1.75 mm for injection oscillations
  - Closed orbit tolerance could be decreased to 1 mm but at the expense of availability
    (need of immediate corrector repair if not all available)
  - transfer line re-steering needed above 1.75 mm
- Proposal: Keep 4 mm orbit tolerance

Dp/p

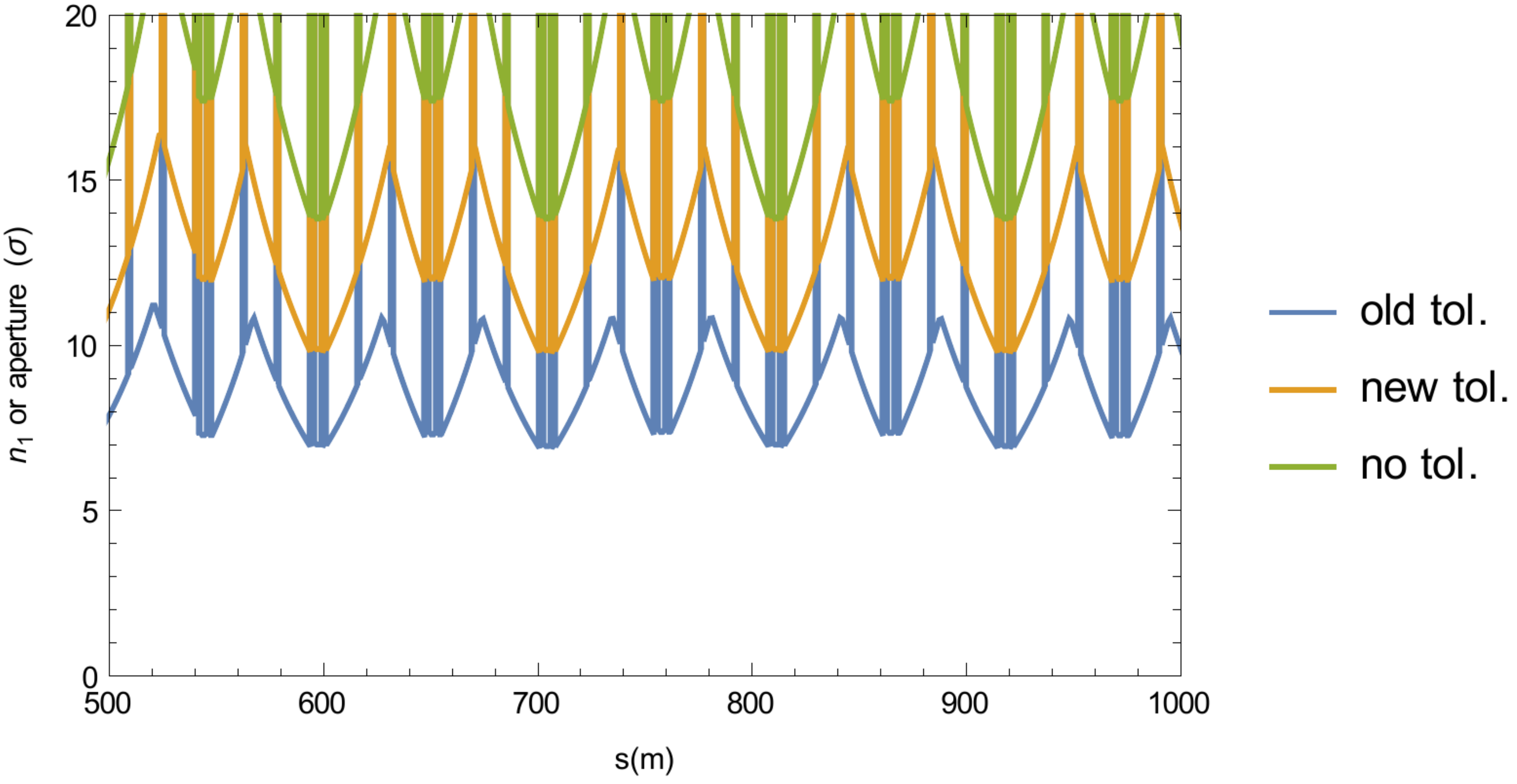
- Dp at collision decreased from 8.6e-4 to 2e-4 : no chromaticity measurements with full beam
  - Using 3 twiss evaluations for +δ, -δ, 0 and taking the minimum
- For injection (previously: dp was set to 1.5e-3):
  - Also no chromaticity measurements – do not need full bucket height
  - Take 1 σ momentum spread ≈ 4e-4
  - Add 2e-4 for energy oscillations
- Proposal: Decrease dp/p to 6e-4

Summary of parameters

Parameter	Unit	New value @ injection
Primary halo	σ	**6.0**
Sec. halo, H/V	σ	**6.0**
Sec. halo, R	σ	**6.0**
Normalized emittance	μm	**3.5 (2.5?)**
Closed orbit	mm	**4.0**
Momentum offset	-	**6e-4**
β-beat (beam size)	-	**1.05**
Parasitic dispersion	-	**0.14**

Example comparison of obtained apertures

- Example: 500m of the arc



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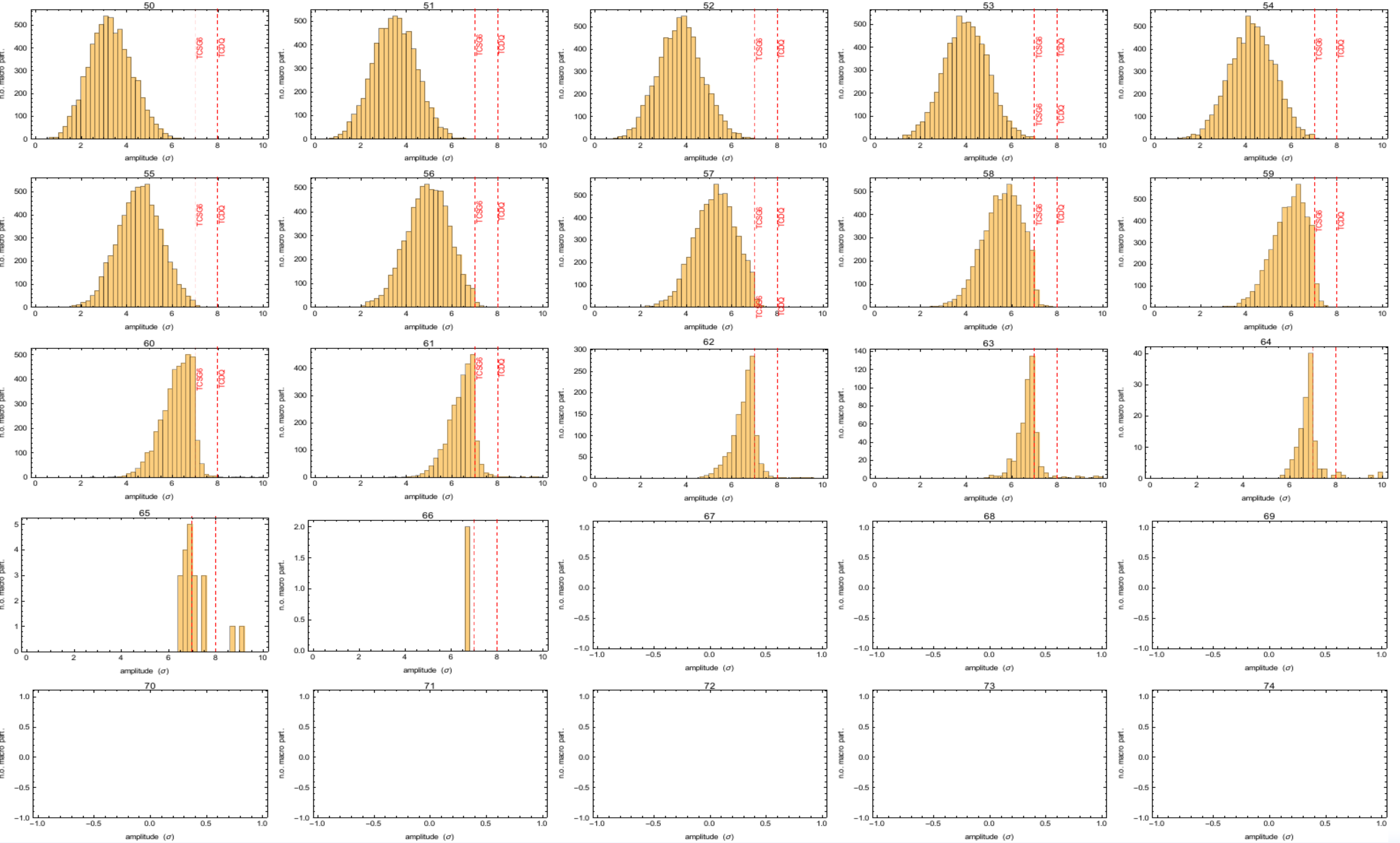
Estimating allowed aperture

- Aperture must be protected by collimation system during all relevant loss scenarios
- In the past, considered only halo cleaning in n1 model
- At top energy, potential damage during asynchronous dumps was driving the allowed aperture
- At injection: evaluate minimum allowed aperture for different loss scenarios, and take the maximum
  - Asynchronous beam dumps
  - Injection failure (talk F. Velotti)
  - Halo cleaning

Asynchronous beam dump

- Single-module pre-fire simulated with SixTrack at injection with full collimation system in place
- 25 ns bunch structure, each bunch in train simulated
- Assuming 3.5 um emittance, 7 TeV: worse case than 2.5 um
- Standard nominal collimator settings for injection
- Studying several different cases: HL-LHC B1 &B2, nominal LHC, using a perfect Gaussian and measured tails, error on TCDQ retraction
- Example illustration on next slide
  - bunch-by-bunch distribution of normalized betatron amplitude of particles escaping dump protection in IR6 for HL B1 with perfect Gaussian

Escaping population bunch by bunch

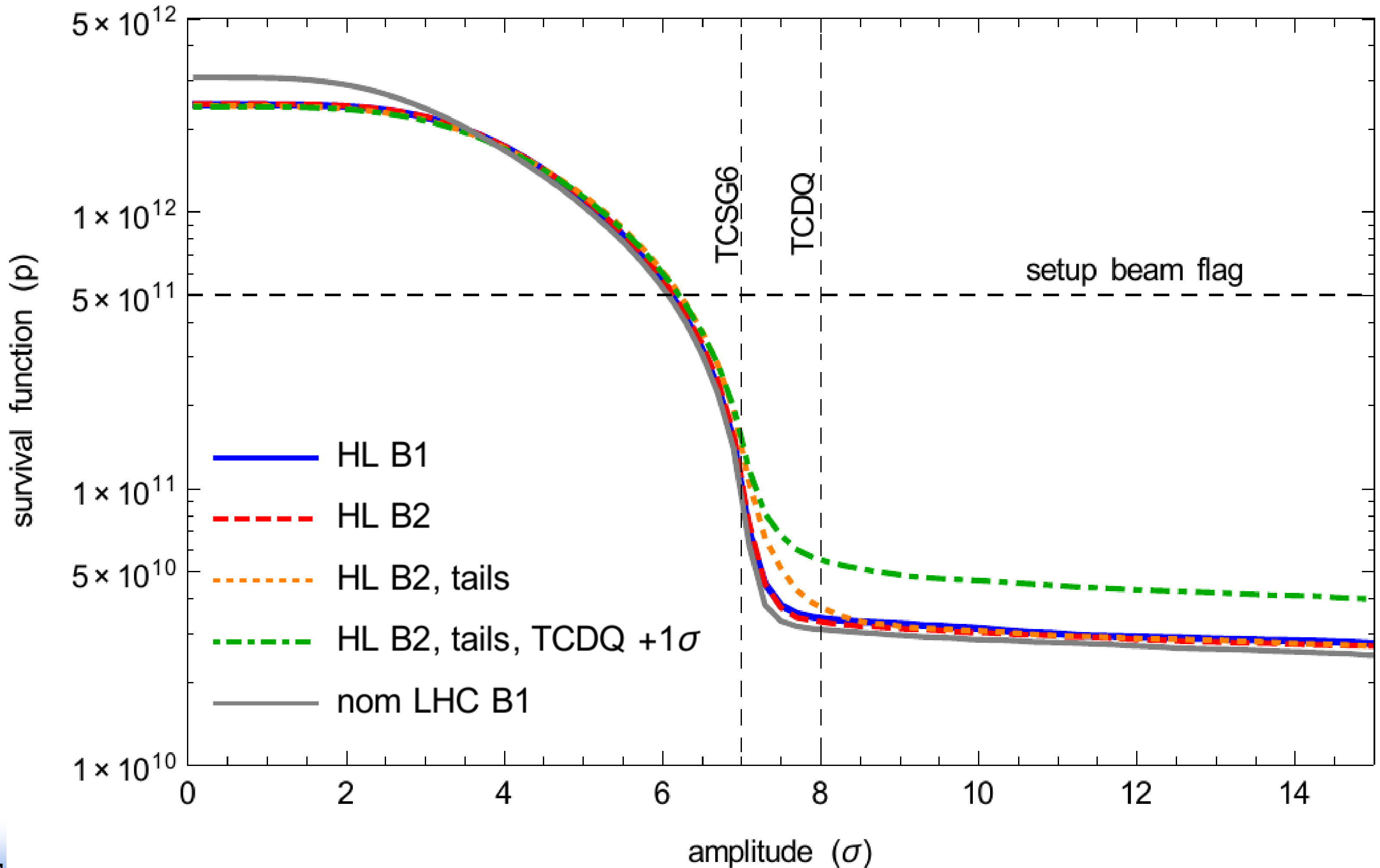


Quantifying allowed aperture

- Idea:
  - Study distribution of escaping betatron amplitudes out of IR6, summed over all bunches
  - Study as survival function: Integrate escaping population from *N* σ to infinity. This is the maximum number of impacting protons that is possible at an aperture at level *N*
    - This is a pessimistic estimate – most likely the losses will be distributed
  - Normalize to HL bunch population of 2.2e11 p/bunch
  - Compare with damage level used for setup beam flag
  - If integrated population is below, the aperture is allowed

Integrated population above given aperture cut

- Survival function equals setup beam flag at ≤6.5σ for all studied cases
- Differences between cases seen mainly in the tail

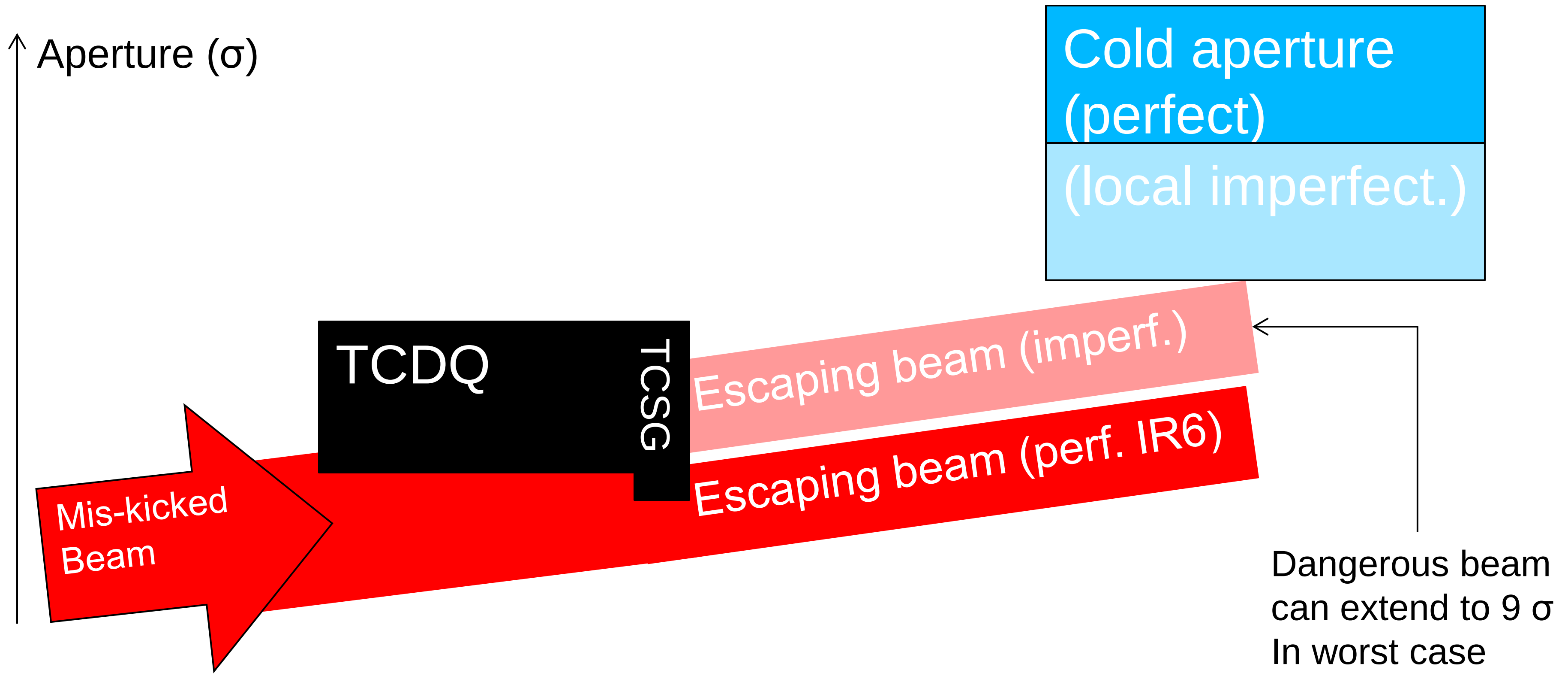


Adding errors

- Could thus allow ~6.5 σ aperture with perfect IR6. Should on top account for imperfections
- Orbit drifts at the dump protection=> TCSG/TCDQ could be at a larger effective setting than simulated:
  - Use 3.5 mm as worst case: it is the allowed excursion by the BPMS interlock. Translates to about 1.8 σ for all studies optics
- Account for additional errors:
  - 10% β-beat => 0.4 σ
  - Setup and positioning errors negligible at injection (<0.03σ)
- Conclusion: accounting for imperfections, allowed aperture for asynch. dump goes to ~8.7 σ. Round to 9 σ => additional safety

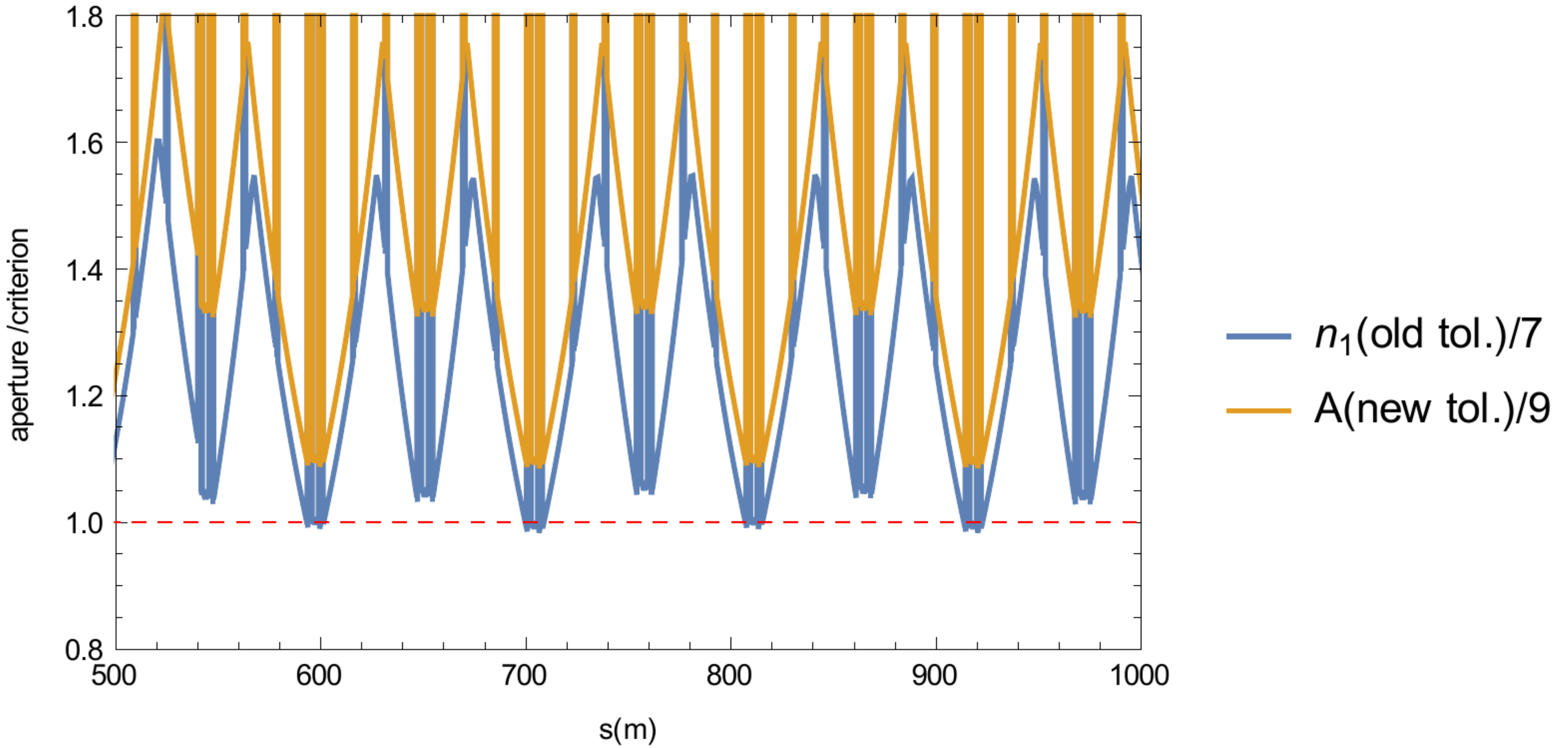
Calculation principle to qualify aperture

- Calculate worst-case aperture from imperfections (locally) with updated parameters in MAD from previous slides
- Compare with max amplitude of dangerous beam escaping IR6, including local imperfections there to say if OK or not



Comparison: old n1 vs new aperture calculation

- Comparing ratio of obtained aperture (or n1) to the criterion

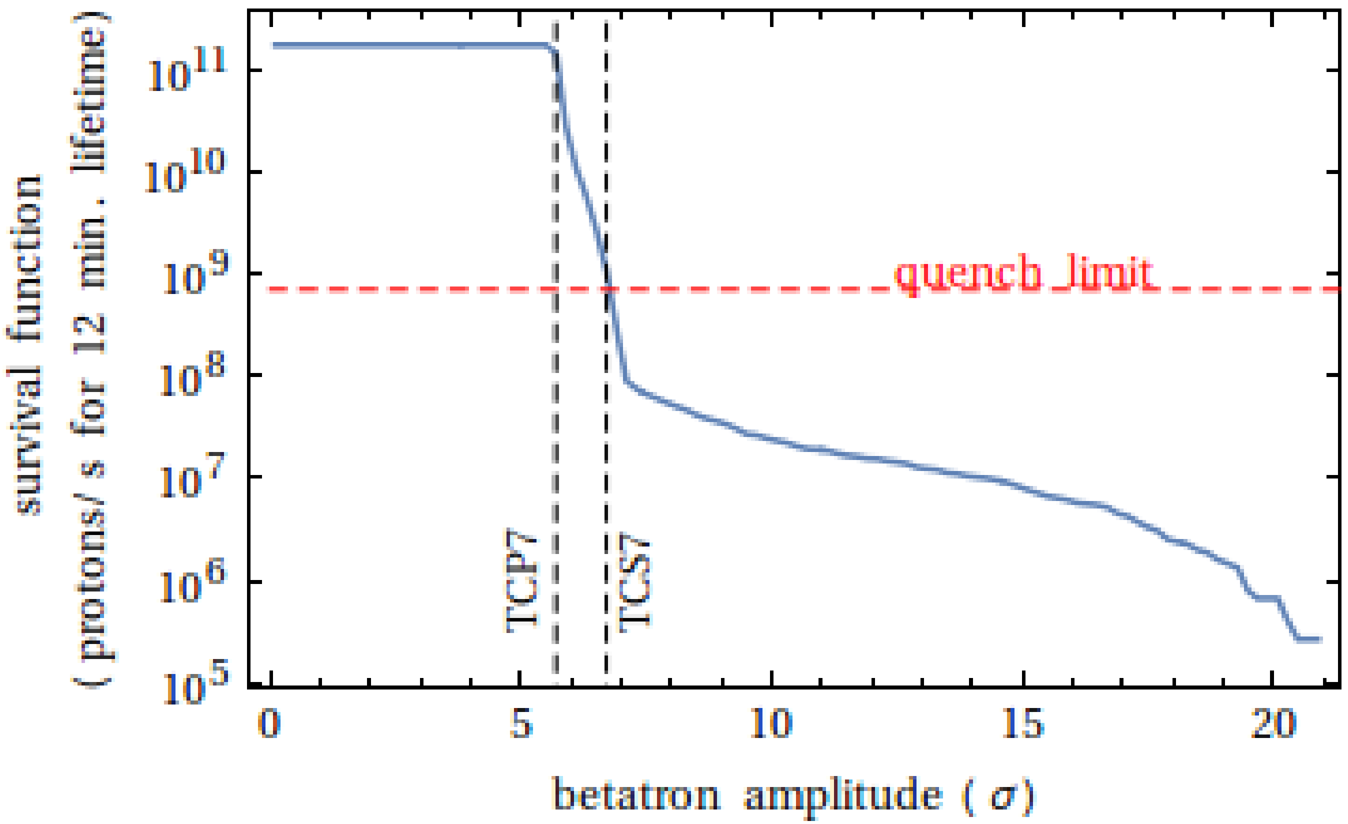


Cleaning

- Pessimistic estimate : Look at outgoing halo population downstream of IR7 simulated with SixTrack without aperture
  - Sum halo over 200 turns: Assuming a constant loss rate, this is the convolution of the losses from previous turns. Gives the instantaneous halo population at any given moment. Assume this can be lost per turn – very pessimistic!
  - Re-normalize to loss rate during lifetime drop to 12 minutes (collimation design criterion)
- Integrate halo population from any given aperture cut X to infinity: an aperture at X σ cannot intercept a higher loss rate
  - In reality, losses are distributed: not all lost on one bottleneck
  - Compare with pessimistic design quench limit – real quench limit is higher!

Survival function for cleaning

- Similar to cleaning inefficiency curves studied in the past
- IR7 secondary collimators give limit around 6.7 σ



Cleaning constraints

- Extremely pessimistic assumptions: losing on every turn the whole integrated instantaneous halo at given bottleneck
- Not straightforward to include imperfections
  - almost impossible that all TCSGs are simultaneously misaligned
  - Could nevertheless increase a bit the halo population by order of factor ~2 (peak DS losses in previous SixTrack studies with imperfections)
- However, very steep curve => almost impossible that limit goes as high as 9 σ
  - Cleaning is less critical than asynch. dumps
- In the future: look at 2D halo distribution in betatron amplitude and energy offset
- Similar studies ongoing for FCC (M. Fiascaris)

Summary

- New tolerances for aperture calculations at injection estimated based on Run 1 experience and expectations for the future
- Criterion for allowed aperture: studying several loss scenarios, and taking the most critical one
  - Asynch. dumps more critical than cleaning: allowed aperture of 9 σ
  - **Still to be compared with injection failure: see talk F. Velotti**
  - As for the case of the top-energy triplet aperture, the allowed value depends on the collimator settings
- The presented criterion is valid for all apertures in the ring but pessimistic.
  - If the injection aperture limits performance, could consider local collimation studies to qualify smaller apertures at specific locations (as done for triplets with squeezed optics)

Summary of parameters

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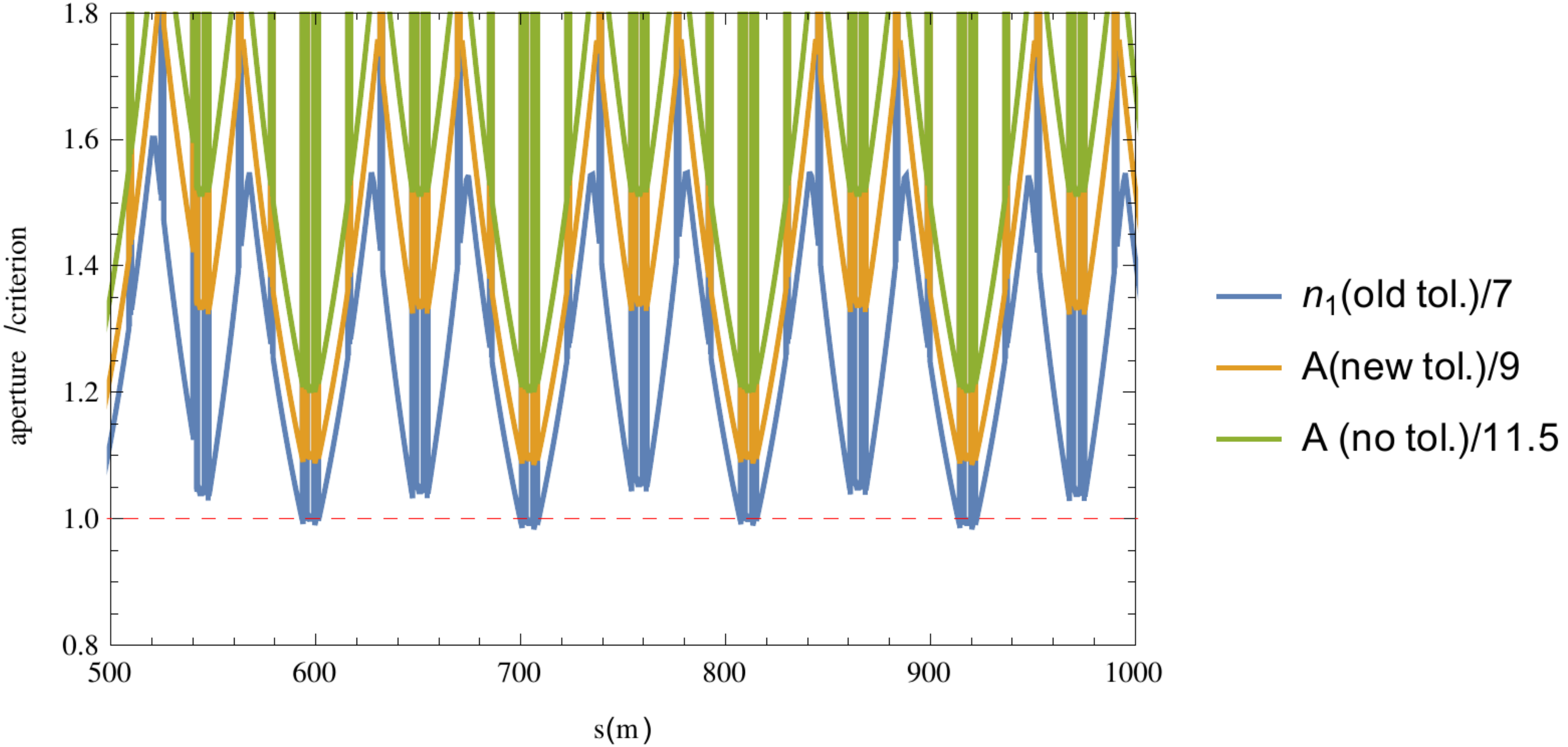
Closed orbit	mm	4.0	3.0	**4.0**	2.0
Momentum offset	-	1.5e-3	8.6e-4	**6e-4**	2e-4
β-beat (beam size)	-	1.1	1.1	**1.05**	1.1
Parasitic dispersion	-	0.27	0.27	**0.14**	0.1

Criterion: obtained aperture should be > 9 σ

(possibly to be updated based on requirements for injection failure)

Backup


1.8
1.6
1.4
1.2
1.0
0.8
500
600
700
800
900
1000
s(m)
aperture /criterion
n_1(old tol.)/7
A(new tol.)/9
A (no tol.)/11.5