Aperture in case of an asynchronous beam dump with ATS optics

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With valueable input from:

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Outline

- Considerations for aperture calculations
- Asynchronous beam dump
- Studies of halo and allowed aperture from asynchronous beam dump
  - Injection
  - Top energy
- Conclusions

Aperture calculations

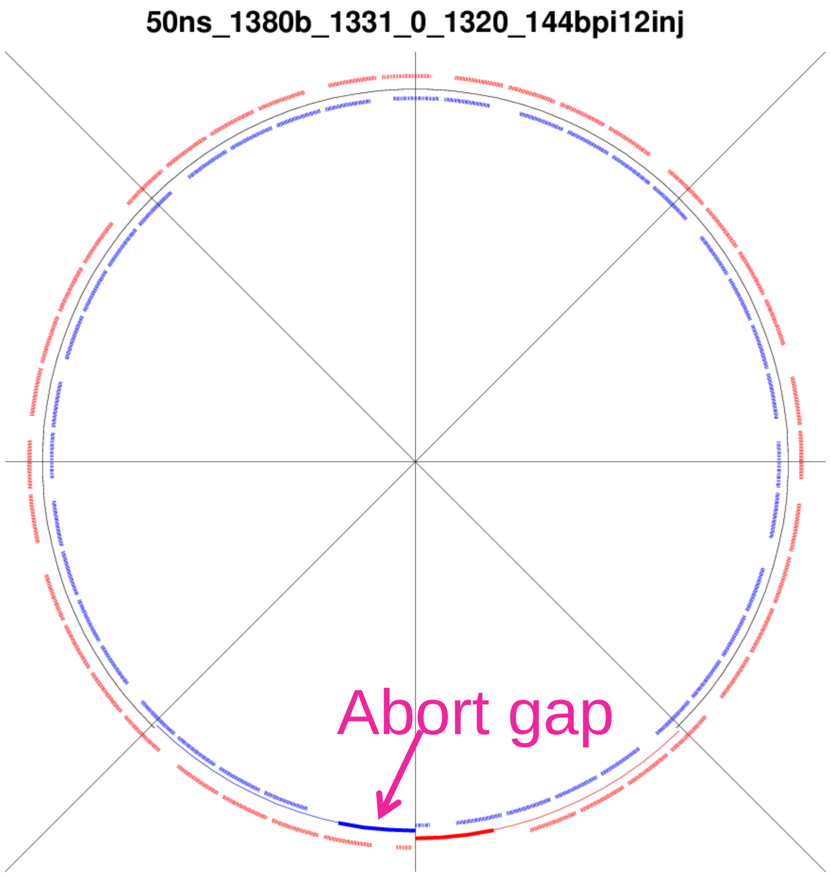
- Collimation hierarchy defines a minimum protected normalized aperture
- Important for safety and smooth functioning of LHC that any element in the ring should not have smaller aperture than this
- Available aperture in experimental IRs constrains β*-reach
  - When squeezing β* to smaller values for higher luminosity, normalized aperture in triplet goes down
  - Allowed aperture sets limit on β*
- Aperture calculations on design stage traditionally carried out with n1 model in MAD-X. Need two ingredients:
  - Tolerances to apply. Discussed in the past (CERN-ACC-2014-0044)
  - Criterion for minimum allowed aperture – topic for today

Limiting factors on aperture

- In Run I, risk of damage during asynchronous beam dumps was limiting factor for aperture
  - Not included in initial approximated n1 criterion. Continuously improved over the years
  - Allowed aperture and the resulting reach in β^* determined by calculating margins between collimators to make sure aperture is always shadowed by collimators
- Need to investigate the effects of asynchronous beam dump for HL-LHC and define a minimum allowed aperture
  - New tracking studies can complement the model used in Run I

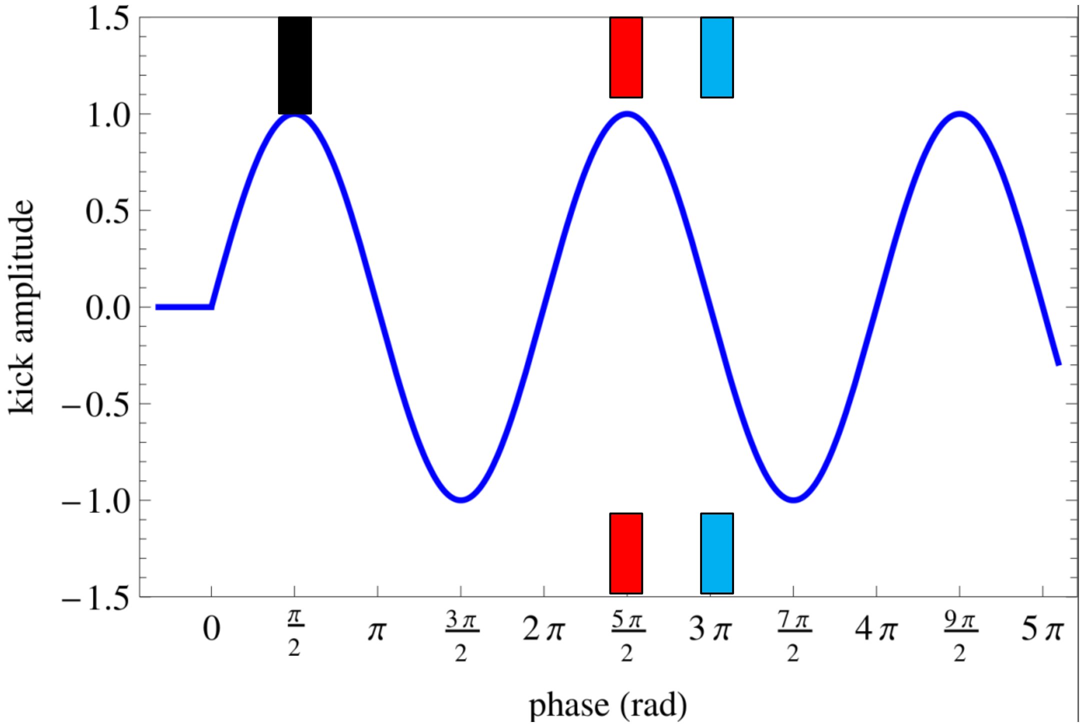
Asynchronous beam dump

- LHC filling scheme has “hole” – abort gap – to allow rise of the 15 extraction kickers (MKD) from zero to full field.
- Possible failure mode: Kickers could fire at the wrong moment, when beam is passing
  - 1-3 failures per year could be expected
- Could give intermediate kicks to some bunches and send beam directly onto sensitive equipment (TCTs / aperture)
- Dump protection (TCDQ / TCSP) installed to protect against this



Effects of asynchronous beam dumps

- Bunches kicked to different oscillating orbits, local dump protection at about 90 deg from kickers
- What escapes risks to go to aperture bottlenecks in the experimental IRs
  - Direct impacts on triplet and other bottlenecks in the IRs could be very harmful
  - TCTs for protection: also not robust against high-intensity impacts



Phase advance in HL-LHC v1.2

- Phase advance from dump kicker to sensitive equipment important for the likelihood of high-intensity hits
  – Close to zero phase advance between TCTs and triplets in squeezed optics.

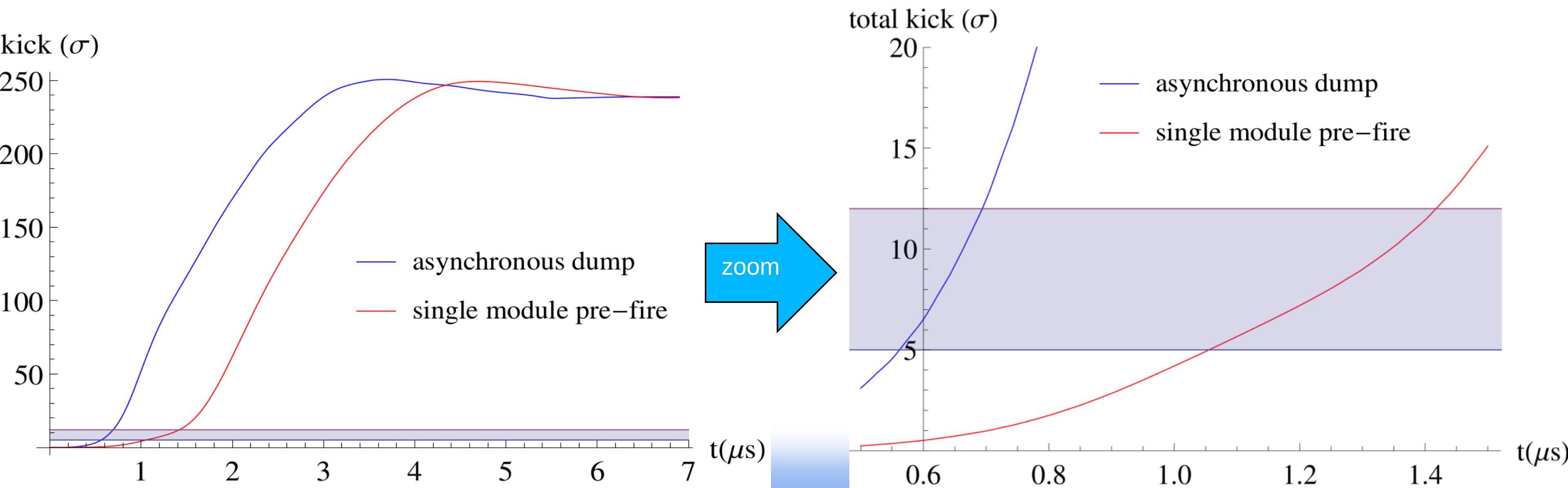
element	Fractional phase advance B1	Fractional phase advance B2
TCDQ	92	92
TCT6 IR1	106	101
Triplet IR1	109	104
TCT6 IR5	142	138
Triplet IR5	145	140

Tracking studies

- Detailed estimates of loss distribution during asynchronous dump from tracking simulations
- Using SixTrack with collimation
  - Standard tool used for collimation cleaning simulations
  - Tracking with full collimation system in place.
  - Monte-Carlo simulation of proton-matter interaction in collimators
  - Output: loss distribution around the ring
- Special setup for asynch. dump
  - Simulating Gaussian bunches, not only halo as for cleaning
  - On turn 2: intermediate kicks from dump kickers. On turn 3: full field kicks that extract the beam
  - Including the real rise of the kickers

Received kicks

- Kicker waveforms provided by B. Goddard and M. Fraser
- Two failure modes
  - Asynchronous dump: all 15 kickers fire simultaneously at the wrong moment
  - Single module pre-fire: one kicker fires first, the others re-triggers after some delay
- Only a limited number of bunches risk to hit TCTs
- Single module pre-fire more dangerous: stay longer time at small kicks => more bunches potentially affected



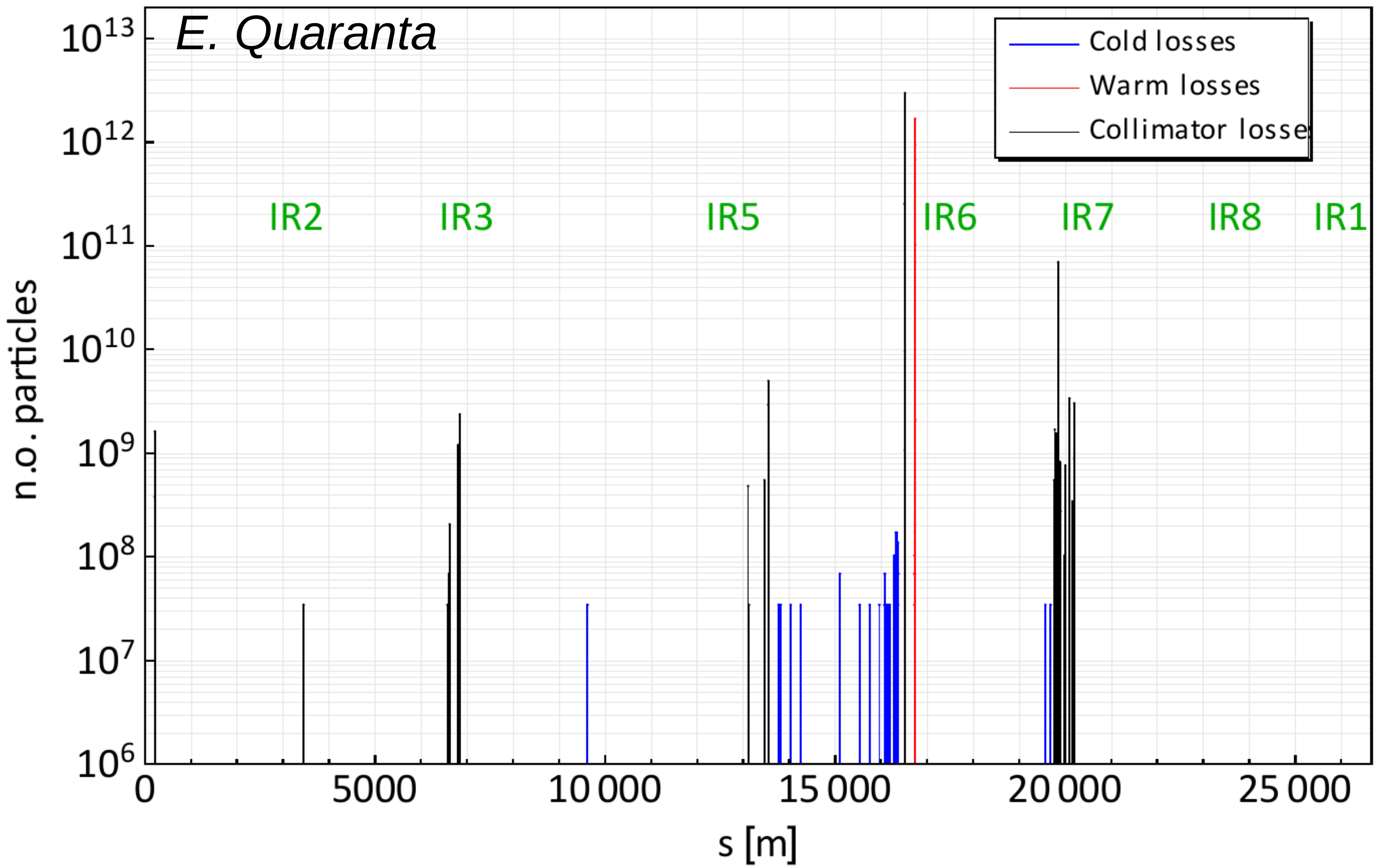
Simulation setup

- Single module pre-fire, type 2 (M. Fraser)
- 25 ns bunch structure, several bunches simulated separately
  - Each receives different kicks: sum of 15 MKDs sampled each 25 ns
- Standard collimator settings for HL-LHC
- Studying several different cases: injection 450 GeV, 7 TeV β*=15 cm, B1 &B2, variations in tail population

For β*=15 cm	Setting [σ with ε=3.5μm]	Setting [σ with ε=2.5μm]
TCP IR7	5.7	6.7
TCSG IR7	7.7	9.1
TCSG IR6	8.5	10.1
TCDQ IR6	9.0	10.6
TCT IR1/5	10.9	12.9
Protected aperture	12.2	14.4

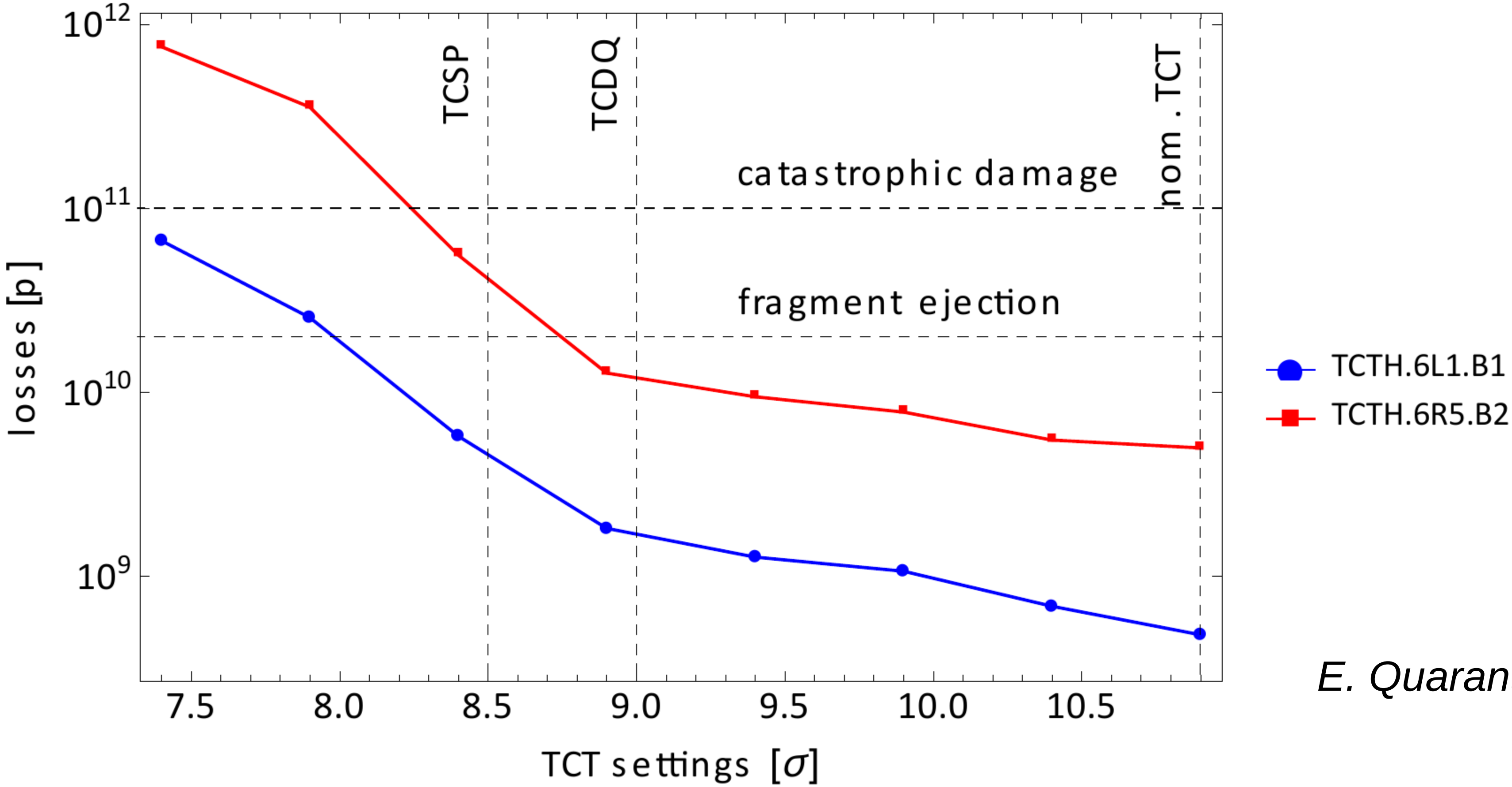
Loss distribution around the ring, β*=15cm

- Example loss distribution summed over simulated bunches
- Normalized to 2.2e11 p/bunch



Sensitivity of losses to TCT setting

- To account for imperfections, study impacts on TCTs at different settings
- TCT damage limit taken from P. Gradassi, CWG 8/6/2015



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TCT/triplet protection

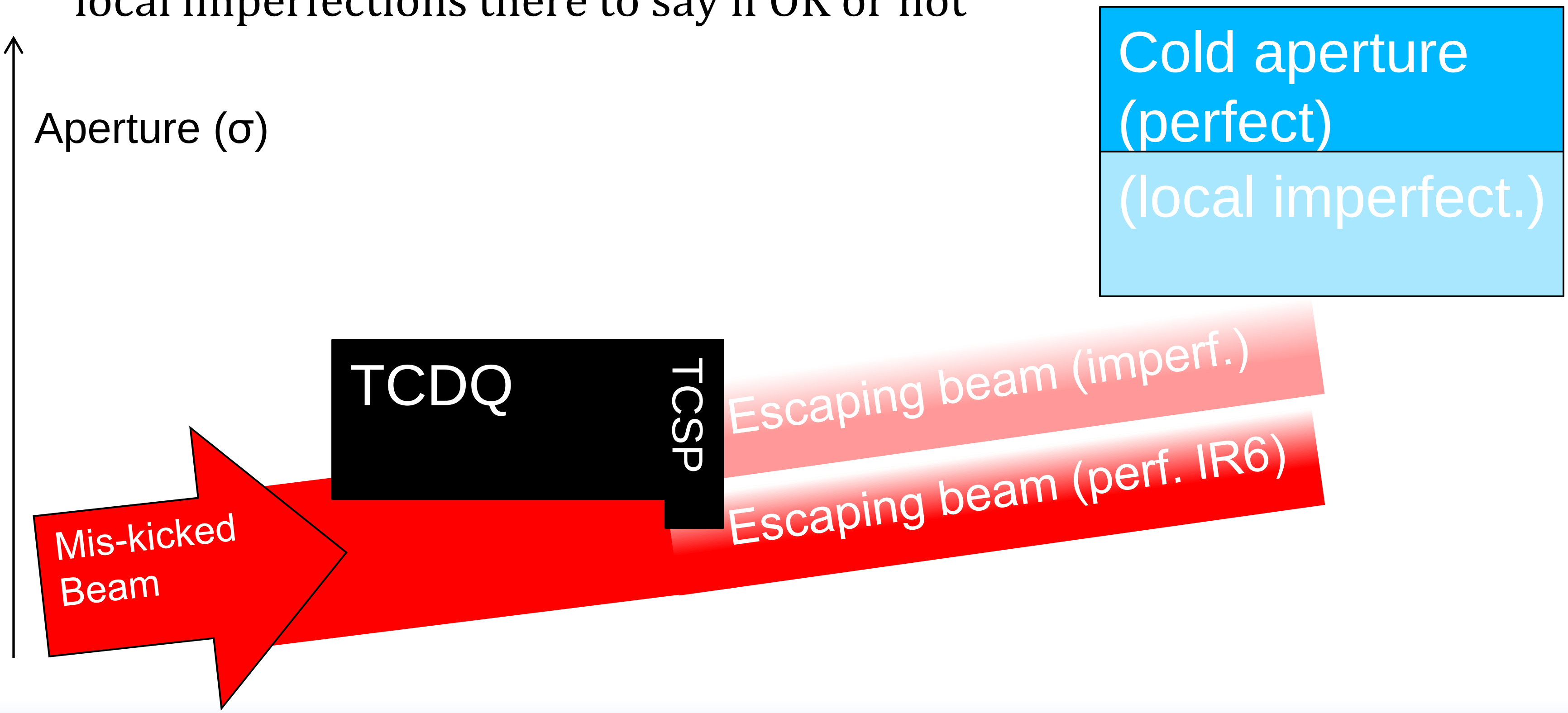
- Baseline TCT setting of 10.9 σ OK without any further error assuming a loss of 2 σ margin (based on Run I-II)
  - But uncomfortably small margin to damage. Cannot guarantee safety
  - Hope that BPM buttons can improve needed margin
  - Flat part at large TCT settings has secondary halo with factor ~20 higher damage limit – not a worry
- More robust TCT under study for HL
  - Candidate material: copper-diamond. Expected factor 10-15 higher damage level. Triplet protection and background to be studied
    - First case study for LHC: P. Ortega, Coll. Working Group 8/6/2015
- No hits in simulations on triplet or matching section. Assume IR aperture safe with sufficient retraction behind TCT
  - Allowed IR aperture inside sacrificial TCTs: 12.2 σ.

Possible improvements

- A smaller allowed aperture might be possible if
  - We install robust TCTs (increase damage limit).
    - Ongoing studies (Coll. Team, EN-STI, EN-MME)
  - We profit from better orbit control with BPM buttons (to be demonstrated at LHC)
  - We can change the optics and put phase advance from dump kickers to TCTs/IRs further away from 90 deg
    - Ongoing studies (S. Fartoukh)
  - We reduce margins between primary and secondary collimators in IR7
    - Need low-impedance collimators. Exact limit not well known
  - Move in the whole collimation hierarchy, including primary collimator
    - Watch out with impedance and loss spikes / beam lifetime

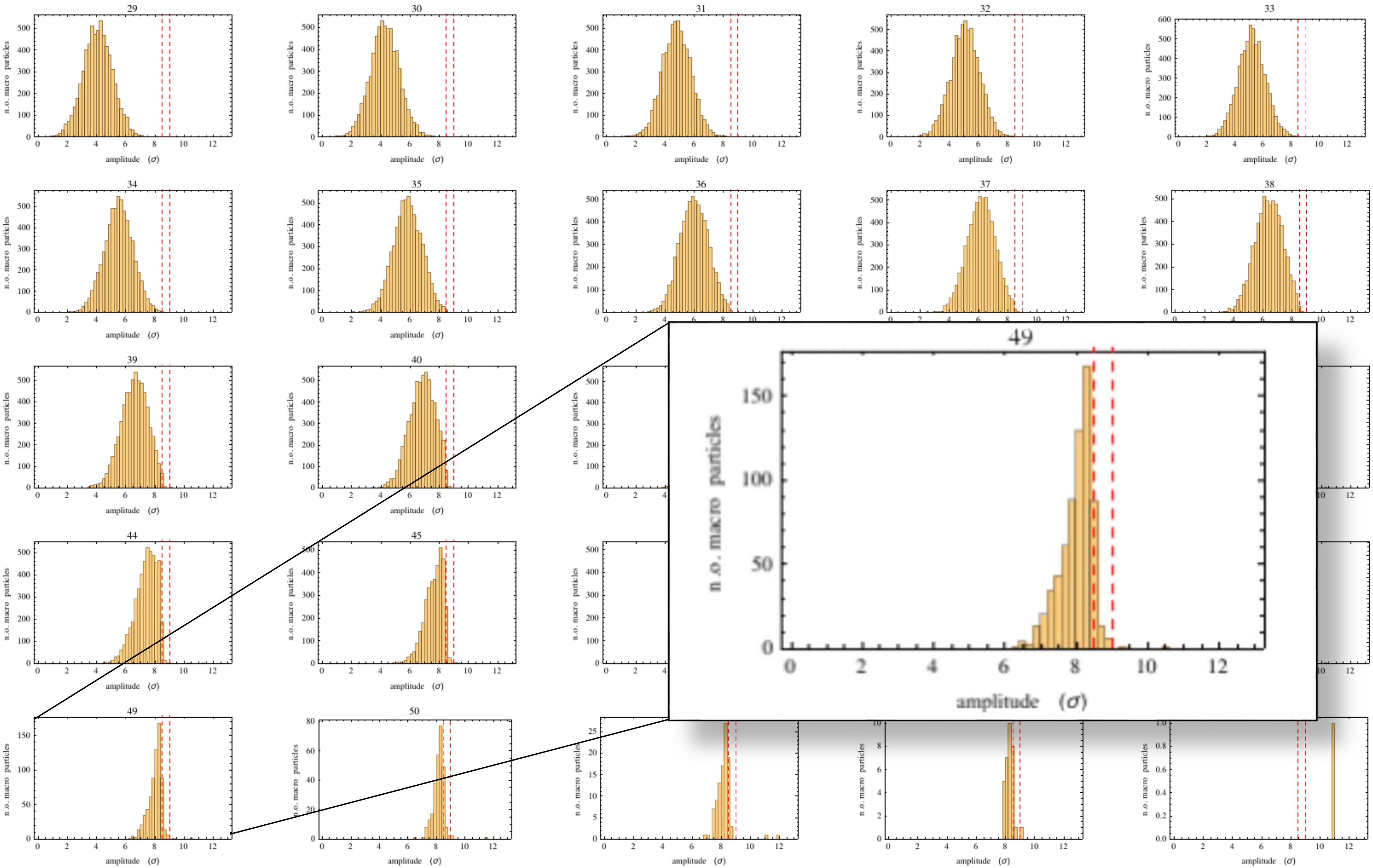
Apertures outside experimental IRs

- For any apertures in the ring, not protected by TCTs, need to rely on TCDQ/TCSP only
- 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



Escaping population bunch by bunch

(at Q4 downstream of TCSP, 7 TeV 15cm)

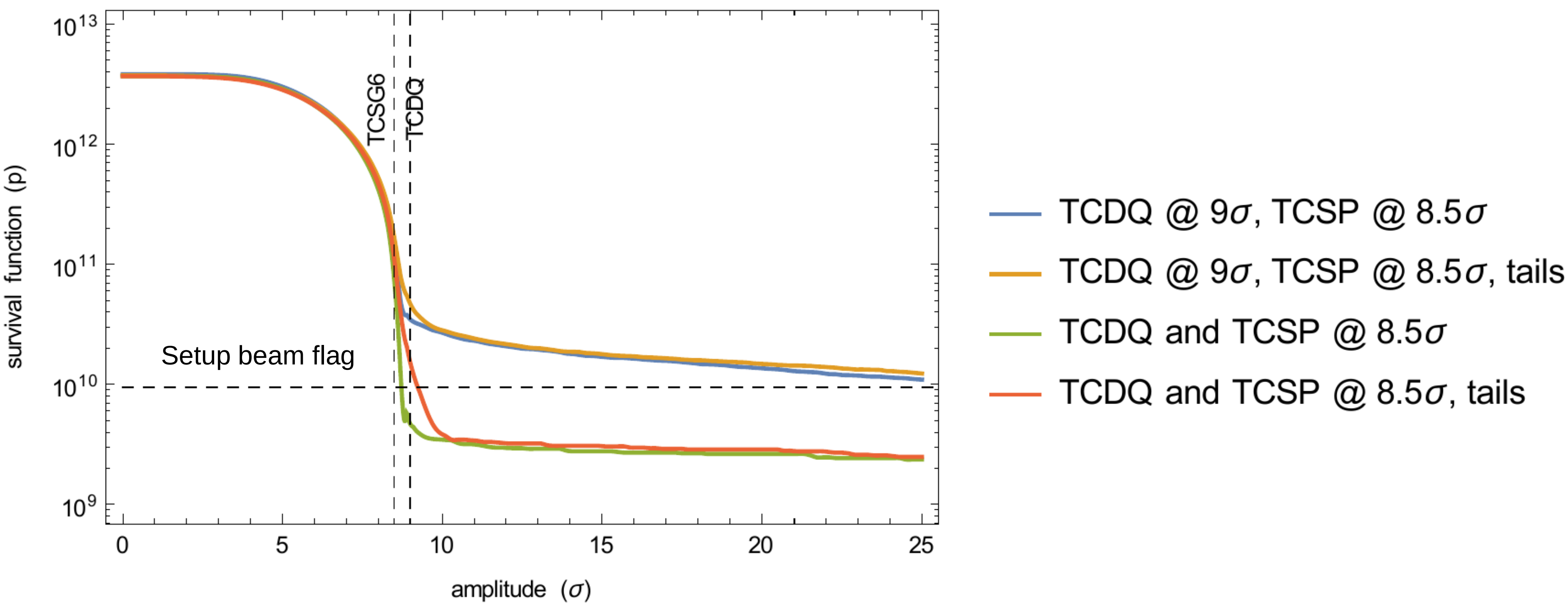


Quantifying allowed aperture

- Idea:
  - Sum distribution of escaping betatron amplitudes out of IR6 over all bunches
  - Study as survival function: Integrate escaping population from $N\sigma$ 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 setup beam flag as damage limit (9.4e9 for 7 TeV, 5e11 for 450 GeV)
  - If integrated population is below, the aperture is allowed

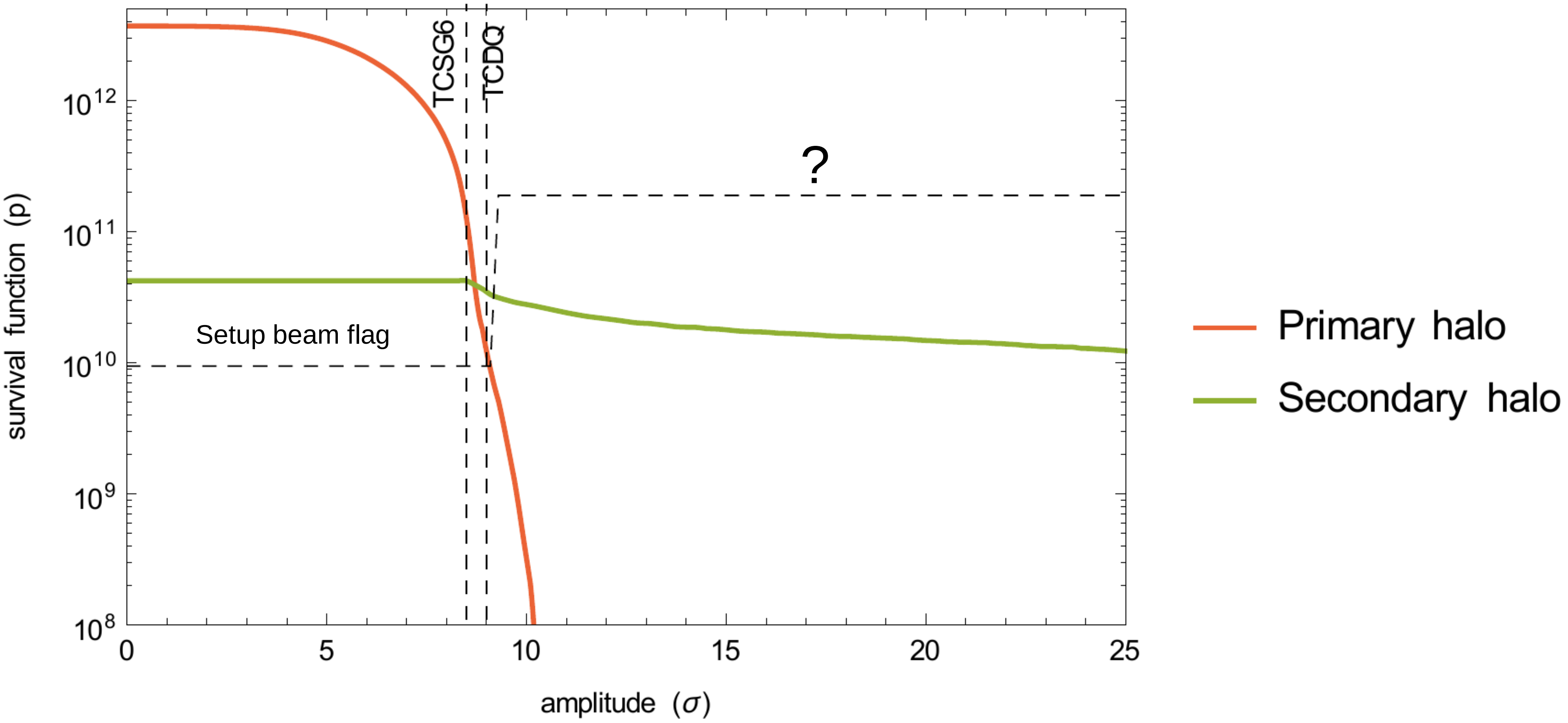
Escaping beam from IR6, 7 TeV 15 cm

- Flat tail of losses: secondary losses scattered out of IR6 collimators?
- Position where survival function equals setup beam flag is very sensitive to TCDQ setting



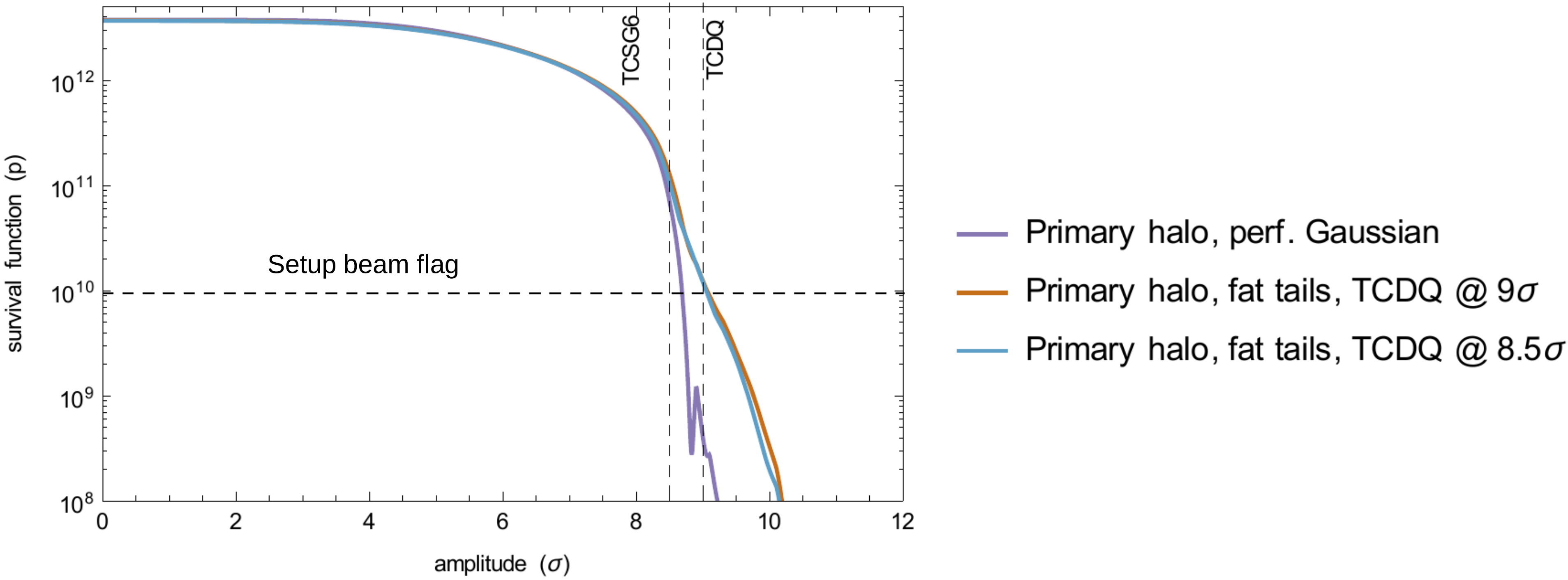
Primary and secondary losses

- Tail consists only of secondary losses. Steep falloff of primary beam (has not hit any collimator) outside cut of IR6 collimators as expected
- TCT: damage level is factor ~20 higher with secondary halo (*P. Gradassi CWG 8/6/2015*) since beam is more spread out. What about magnets?



Aperture criterion for primary halo

- In the assumption that secondary halo is not a concern, define allowed aperture with respect to primary halo
- With tails, reach damage limit at 9.1 σ
  - Take 9.5 σ to be on the safe side, accounting for possibly worse tails
  - Steep distribution of primary halo – not so sensitive to distribution and damage limit



Adding errors

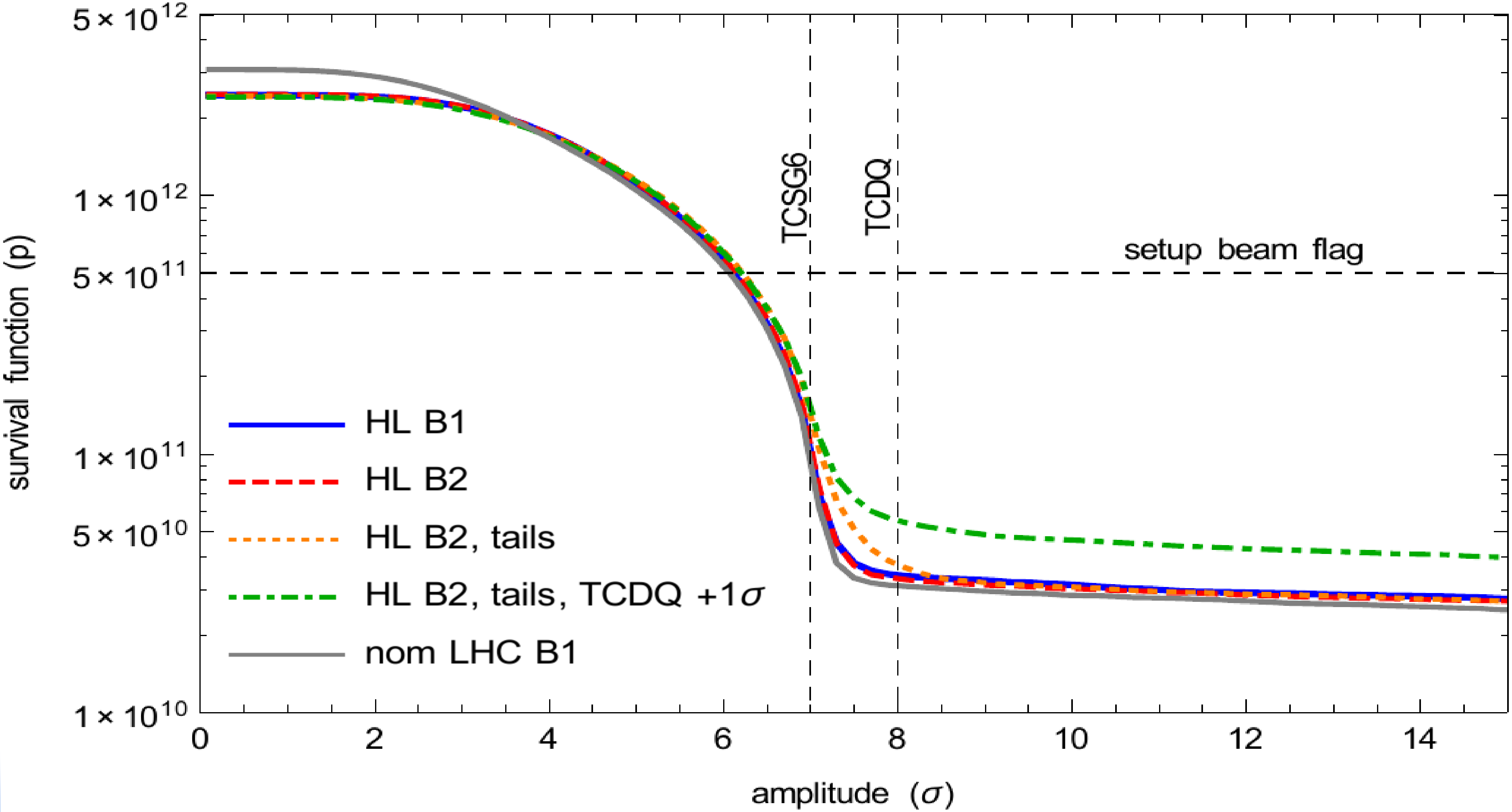
- Could thus allow ~9.5 σ aperture with perfect IR6. Should on top account for imperfections
- Orbit drifts at the dump protection => TCSP/TCDQ could be at a larger effective setting than simulated:
  - Use 3.5 mm as worst case: it is the allowed excursion by the BPMS interlock. Translates to 6.2 σ
- Account for additional errors:
  - 10% β-beat => 0.7 σ
  - Setup and positioning errors small: (~0.2 σ)

Allowed aperture at 7 TeV, 15 cm

- Adding up all imperfections, allowed aperture for asynch. dump goes to ~16.6 σ. Round to 17 σ => additional safety
- Underlying assumptions
  - Pessimistic assumption that all escaping particles could be lost at one location
  - Probably pessimistic assumption of damage level at 9e9. Damage levels for magnets not well known but detailed studies ongoing in WP7
    - But: Assumption that secondary losses have much higher damage limit and can be neglected should be verified.
    - To reduce uncertainty: propose baseline with TCDQ at TCSP level
  - Pessimistic assumption of 3.5 mm orbit shift

Escaping population, injection

- Repeating same study at injection
- Survival function equals setup beam flag at ≤6.5σ for all studied cases
- Tail of secondary losses not important at injection



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

Summary

- Asynchronous beam dump has in Run 1 been the limiting factor determining allowed aperture
- Tracking studies for HL-LHC show that allowed aperture for asynchronous beam dump is
  - 17σ at 7 TeV if accounting for no local protection
    - Caveat: assumes that secondary losses are not important
  - 12 σ inside the TCTs of IR1 and IR5 at squeeze (β^*=15 cm)
  - 9 σ at injection
- The 12 σ aperture at β^*=15 cm could possibly be reduced if for example
  - Robust TCTs are installed, and we profit from BPM buttons
  - We can change phase advance from IR6 dump kickers to TCTs
- For complete picture of aperture: study also cleaning losses and other failures (injection, crab cavity…)