Collimation Tolerances

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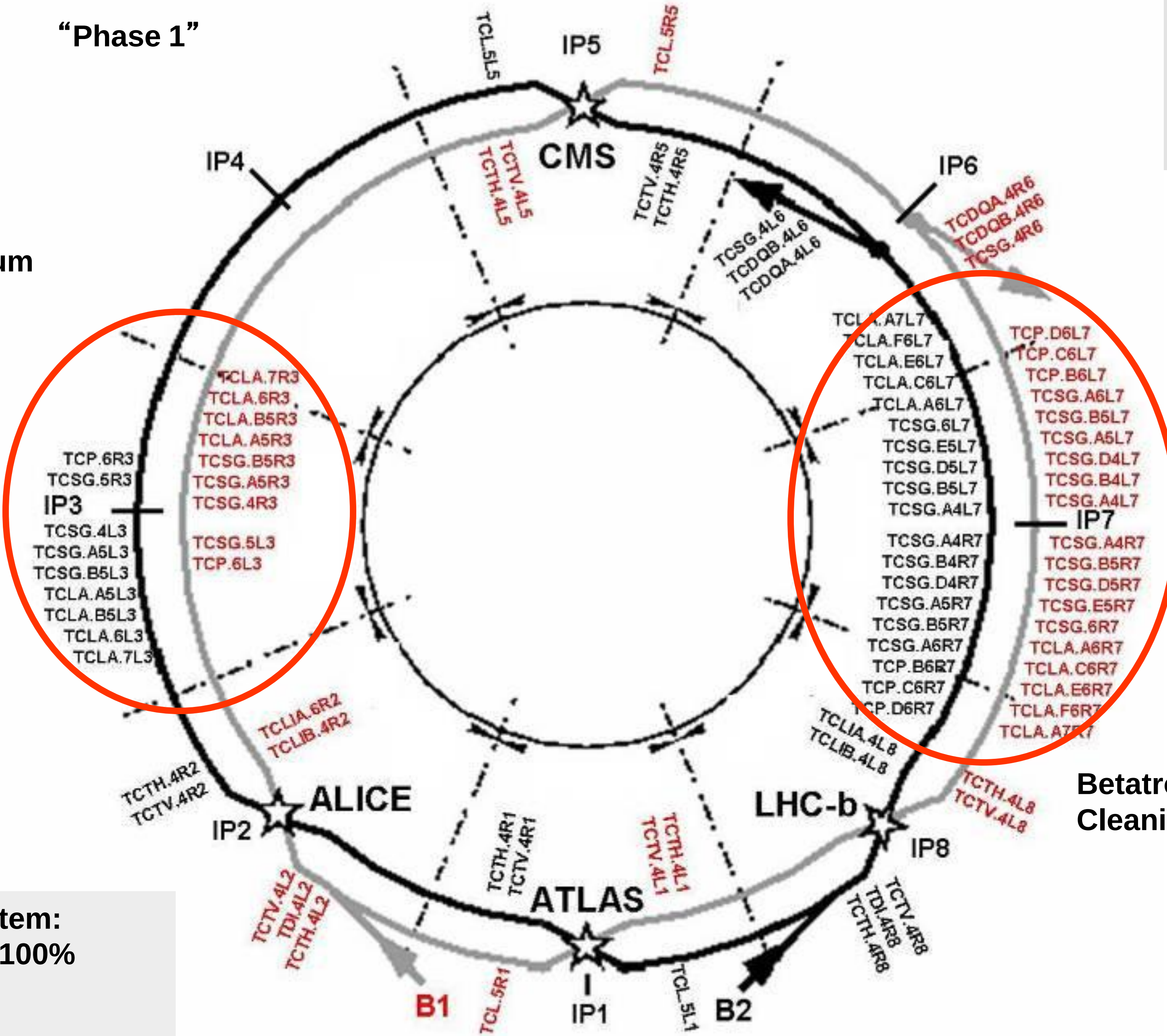
LHC Crab Cavity Workshop

Why Talk About Collimation?

- Collimation protects the machine aperture against damage and quenches.
- Any significant change in the machine must be revisited also from the collimation and machine protection view: possible impact on protection, loss distribution, activation, quench limitations, experimental background.
- Critical issues: Upgrades in several colliders were heavily affected by unforeseen problems with beam loss and background after the upgrade. Loss in overall integrated luminosity with insertion upgrade.
- Goal of this talk: **Give collimation input to the ongoing discussions for LHC upgrades such that it will be fully successful.**
- Note: MP and dump issues only mentioned as far as collimation is affected.

"Phase 1"

Momentum Cleaning



Betatron Cleaning

"Final" system: Layount is 100% frozen!

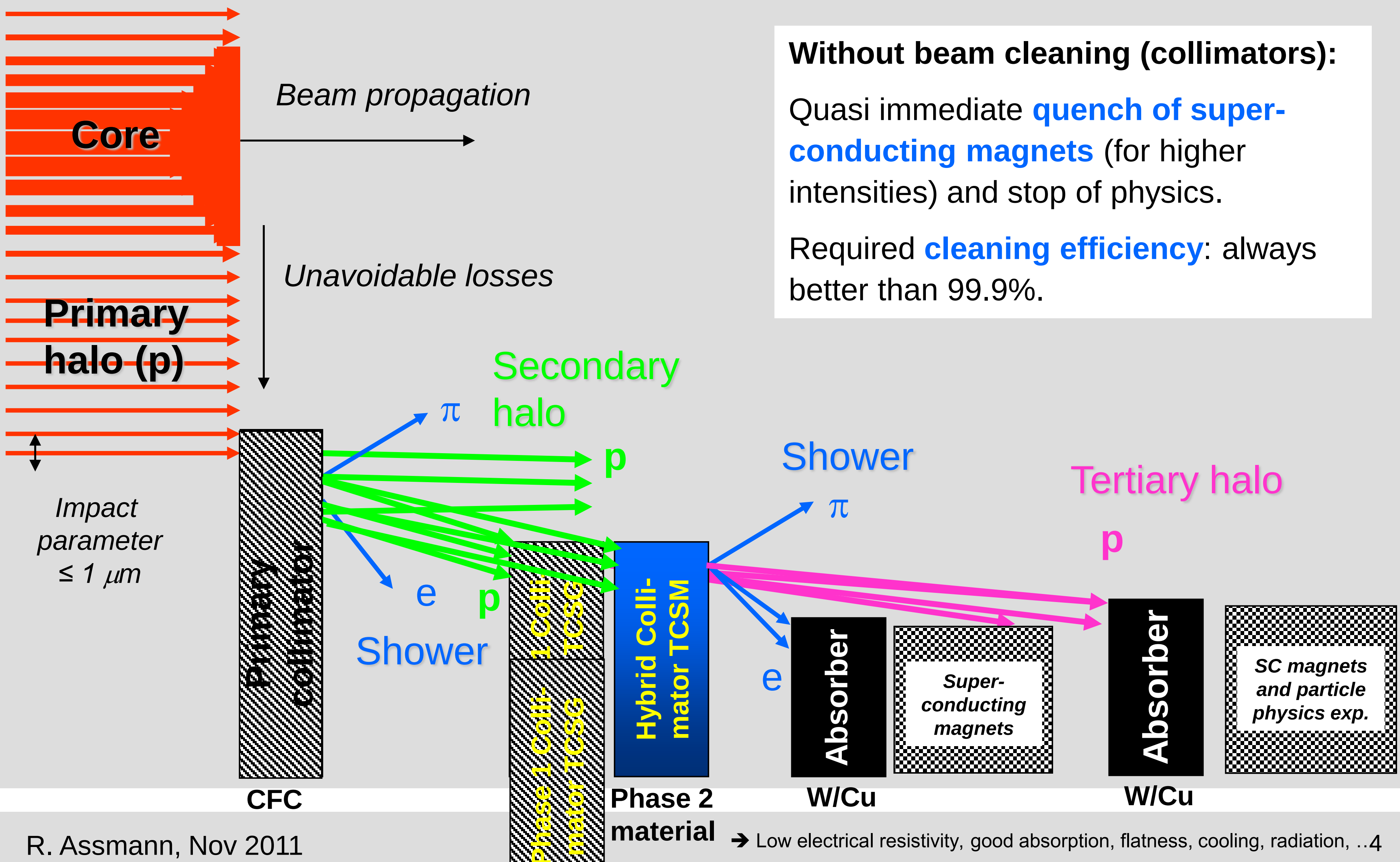
➔ **Outcome of accelerator physics + energy deposition optimization**

LHC Cleaning & Protection

Without beam cleaning (collimators):

Quasi immediate **quench of super-conducting magnets** (for higher intensities) and stop of physics.

Required **cleaning efficiency**: always better than 99.9%.



➔ Low electrical resistivity, good absorption, flatness, cooling, radiation, ..

Functional Description

- Two-stage cleaning (**robust CFC primary and secondary collimators**).
- Catching the cleaning-induced showers (**Cu/W collimators**).
- Protecting the warm magnets against heat and radiation (**passive absorbers**).

- Local cleaning and protection at triplets (**Cu/W collimators**).
- Catching the p-p induced showers (**Cu collimators**).

- Intercepting mis-injected beam (**TCDI, TDI, TCLI**).
- Intercepting dumped beam (**TCDQ, TCS.TCDQ**).

- Scraping and halo diagnostics (**primary collimators and thin scrapers**).

Setting Strategy for Collimation and Protection Elements

- **Clear requirements for settings:**

LHC ring aperture sets scale — a_{ring}

➔ ***tight LHC aperture***

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

➔ ***protect against injected beam; take into account accuracies***

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

➔ ***avoid too much secondary halo hitting protection devices***

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

➔ ***primary collimators define the aperture bottleneck in the LHC for cleaning of circulating beam!***

- **These conditions should always be fulfilled:**

Not allowed to use protection devices (or warm aperture limits) as a single-stage cleaning system!

R. Assmann, Chamonix 2005

7 TeV Settings at (in σ_β ,δ=0, nominal β^*)

a_{abs}	=	~ 20.0 σ	Active absorbers in IR3
a_{sec3}	=	18.0 σ	Secondary collimators IR3 (H)
a_{prim3}	=	15.0 σ	Primary collimators IR3 (H)
a_{abs}	=	~ 10.0 σ	Active absorbers in and IR7
a_{ring}	=	8.4 σ	Triplet cold aperture
a_{prot} triplet	=	8.3 σ	TCT protection and cleaning at
a_{prot}	≥	7.5 σ	TCDQ (H) protection element
a_{sec}	=	7.0 σ	Secondary collimators IR7
a_{prim}	=	6.0 σ	Primary collimators IR7

➔ "Canonical" 6/7 σ collimation settings are achievable! *R. Assmann, Chamonix 2005*

Collimator Hierarchy

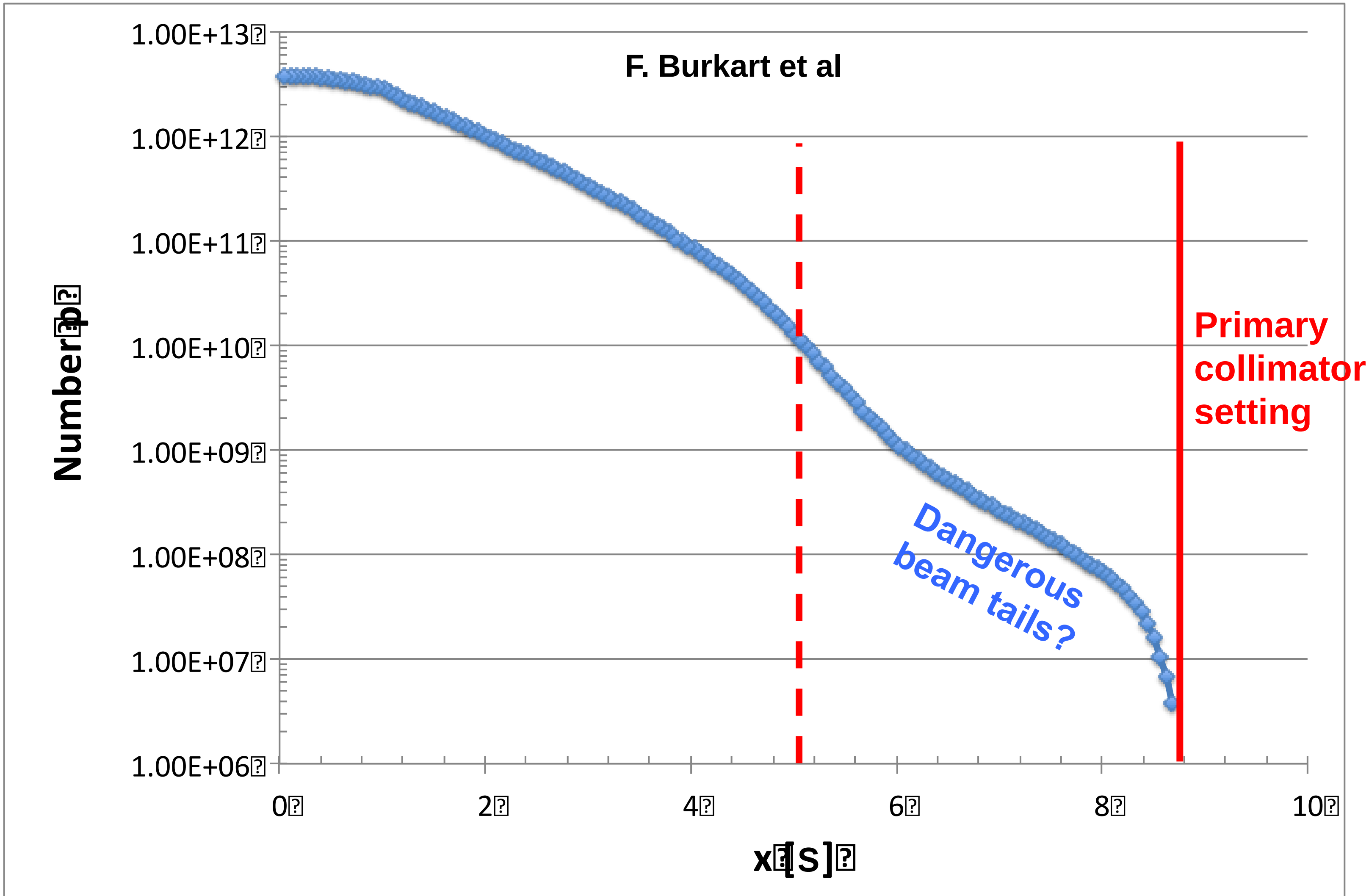
- Collimators must **respect a very strict setting hierarchy**. Not useful to explain here. Just sketching it:
  - Primary collimators (TCP) must always be closest to the beam.
  - Secondary collimators (TCSM) must always be second-closest to the beam.
  - Protection collimators (TCLA) must always be closer to the beam than local magnet or vacuum pipe aperture. They shall, however, never act as primary or secondary collimators.
- Optics perturbations can lead to violations of this hierarchy. In particular beta beat is dangerous (changes of machine beta functions).
- The upgrade optics faces a special problem: **off-momentum beta-beat** ➔ head and tail of beam collimated at different places from the core!
- Off-momentum beat beat mixes up the 6D phase space and can corrupt collimation performance (secondary collimator becomes a primary collimator for off-momentum particles).

Tolerances to Beam Loss

- The robust LHC collimators (primary and secondary CFC collimators) can stand the following maximum beam impact at 7 TeV:
  - **1 MJ within 150 ns**
  - **0.5 MW on the ≥ 1s time scale** (≈ 0.1% of beam stored per s)
- The non-robust collimators (W and Cu) can withstand much less beam. To be safe a factor ≈ 100 should be respected:
  - **10 kJ within 150 ns**
  - **5 kW on the ≥ 1s time scale** (≈ 10^{-5} of beam stored per s)
- These limits depend on detailed bunch properties (emittance, beta functions, …).
- Crab cavity failures should respect these limits to avoid damage to collimators, including impact on other collimators due to distortions of phase space.

Note: Highly Populated Beam Tails

(B1H, 450 GeV, total intensity 1e14p, real σ)



Tolerances: Orbit & Beta Beat

(transient, equivalent also for “slice” orbit – crab cavity)

- Orbit worst case:
  - No orbit shift at primary collimator
  - Maximum orbit shift 90° downstream
  - This reduces retraction between primary collimator and downstream collimator.
  - If loss of retraction is too big: Downstream collimator can become primary collimator.
- Orbit tolerance defined: **30 μm at 7 TeV**
  (transient, for collimation at 6 σ at 7 TeV, 0.15 σ)
- Beta beat tolerance: **5% at 7 TeV**
  (transient, for collimation at 6 σ at 7 TeV, 0.3 σ)
- Takes almost half of overall tolerance budget (1 σ). Details depend on settings, location, …

Tolerances: Effect from Off-Momentum Beta Beat, Dispersion, …

$$x_{cut}(i_{coll}) = n_{\beta_x cut}(i_{coll},\delta)\sqrt{\varepsilon_x \beta_x(i_{coll},\delta)} + D_x(i_{coll},\delta)\delta$$

$$\Downarrow$$

MADX

$$n_{\beta_x cut}(i_{coll},\delta) = \frac{\pm x_{cut}(i_{coll}) - D_x(i_{coll},\delta)\delta}{\sqrt{\varepsilon_x \beta_x(i_{coll},\delta)}}$$

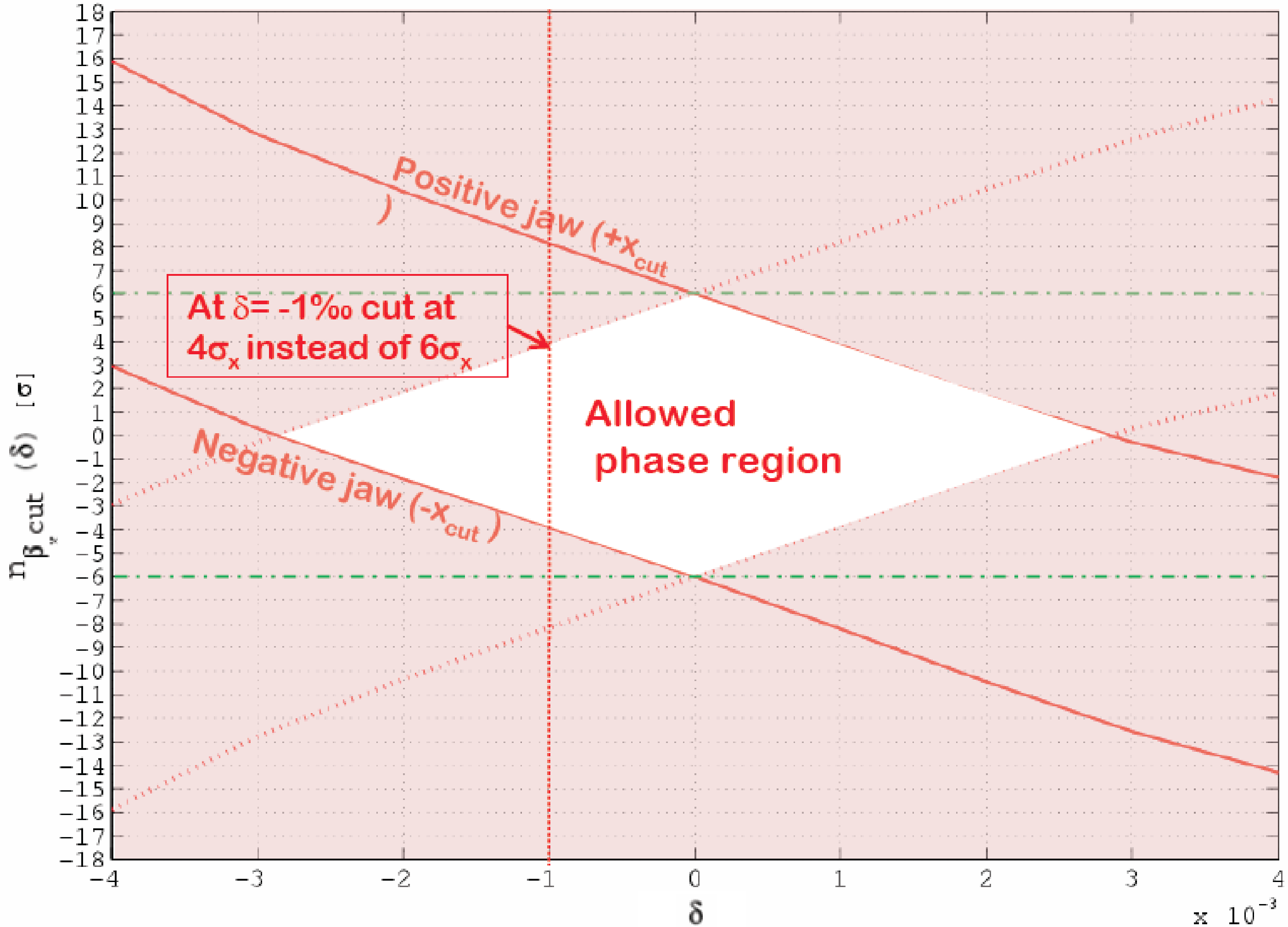
positive and negative x jaws

MADX

Allowed phase space region

TCP.C6L7.B1

(Horizontal primary betatron collimator, beta beat IP1→IP5)

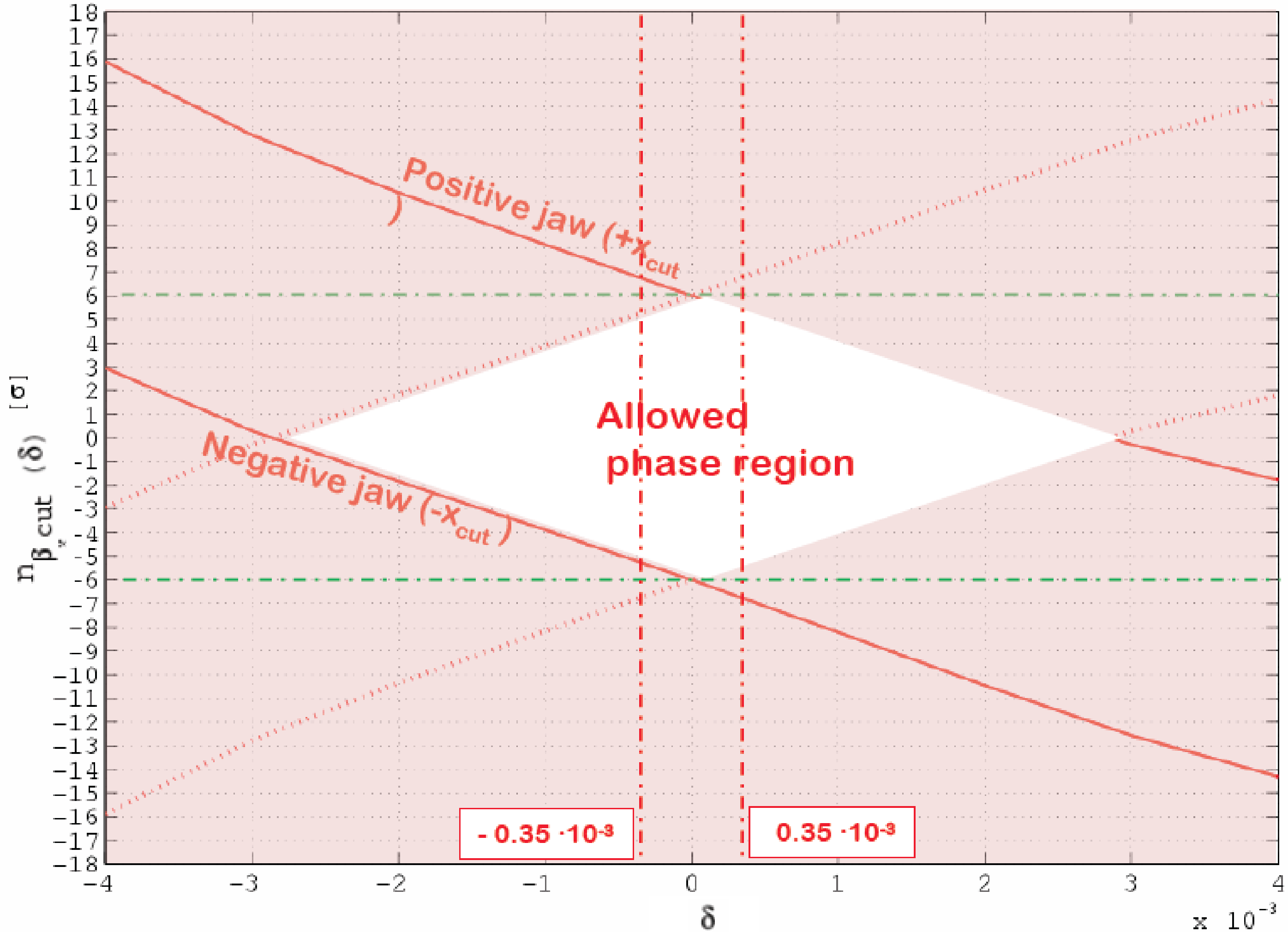


Reflecting each point with respect to the $n_{\beta x cut}$=0 line an "allowed phase space region" is defined. (single turn amplitude jumps of many σ_x are excluded)

Allowed phase space region

TCP.C6L7.B1

(Horizontal primary betatron collimator, beta beat IP1→IP5)



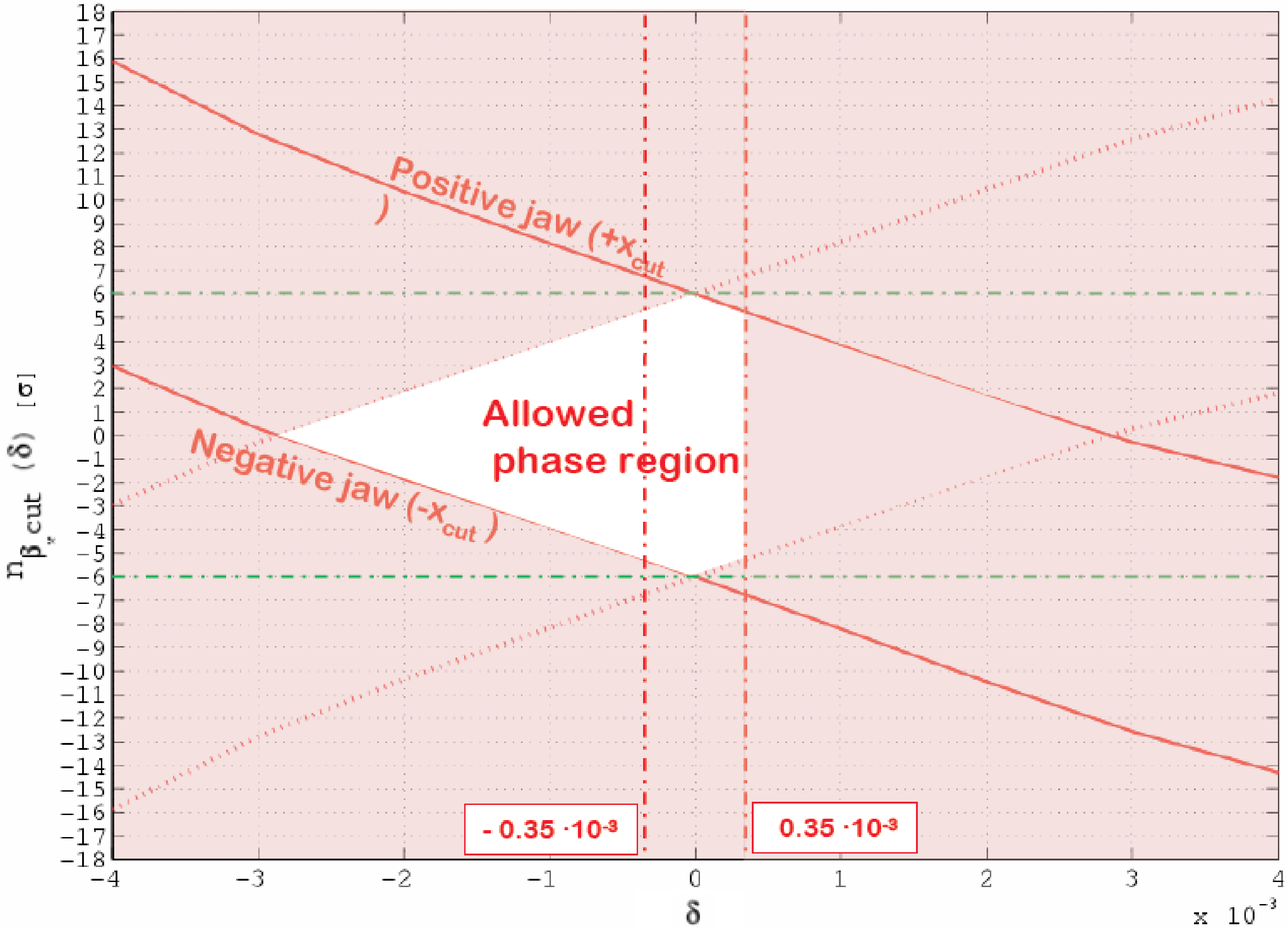
Momentum aperture in the ring: $\pm 7\cdot 10^{-3}$ [δ] (mechanical aperture, tolerances, orbit, 3σ beam)

Half height of the bucket : $\pm$ 0.35 $\cdot 10^{-3}$[δ] [E. Shaposhnikova, S. Fartoukh, B. Jeanneret "LHC abort gap filling by proton beam"; *LHC project report t 63*]

Allowed phase space region

TCP.C6L7.B1

(Horizontal primary betatron collimator, beta beat IP1→IP5)



Momentum aperture in the ring: ±7·10⁻³ [δ] (mechanical aperture, tolerances, orbit, 3σ beam)

Half height of the bucket : ± 0.35 ·10⁻³[δ]

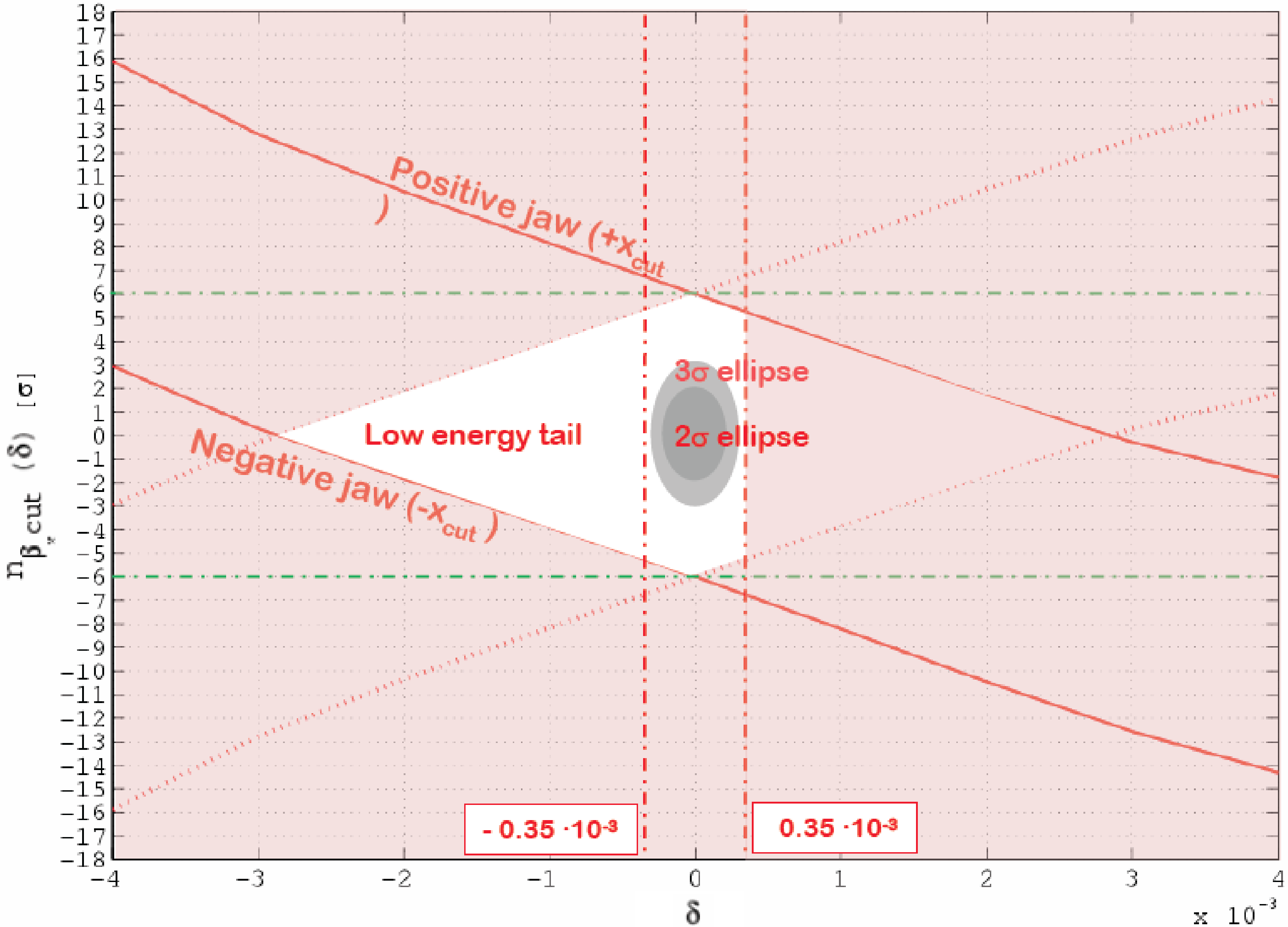
Particles cannot have δ> +0.35 ·10⁻³[δ].

Particles can have a lower energy than the bucket due to:
- Synchrotron radiation
- Impedance

Allowed phase space region

TCP.C6L7.B1

(Horizontal primary betatron collimator, beta beat IP1→IP5)



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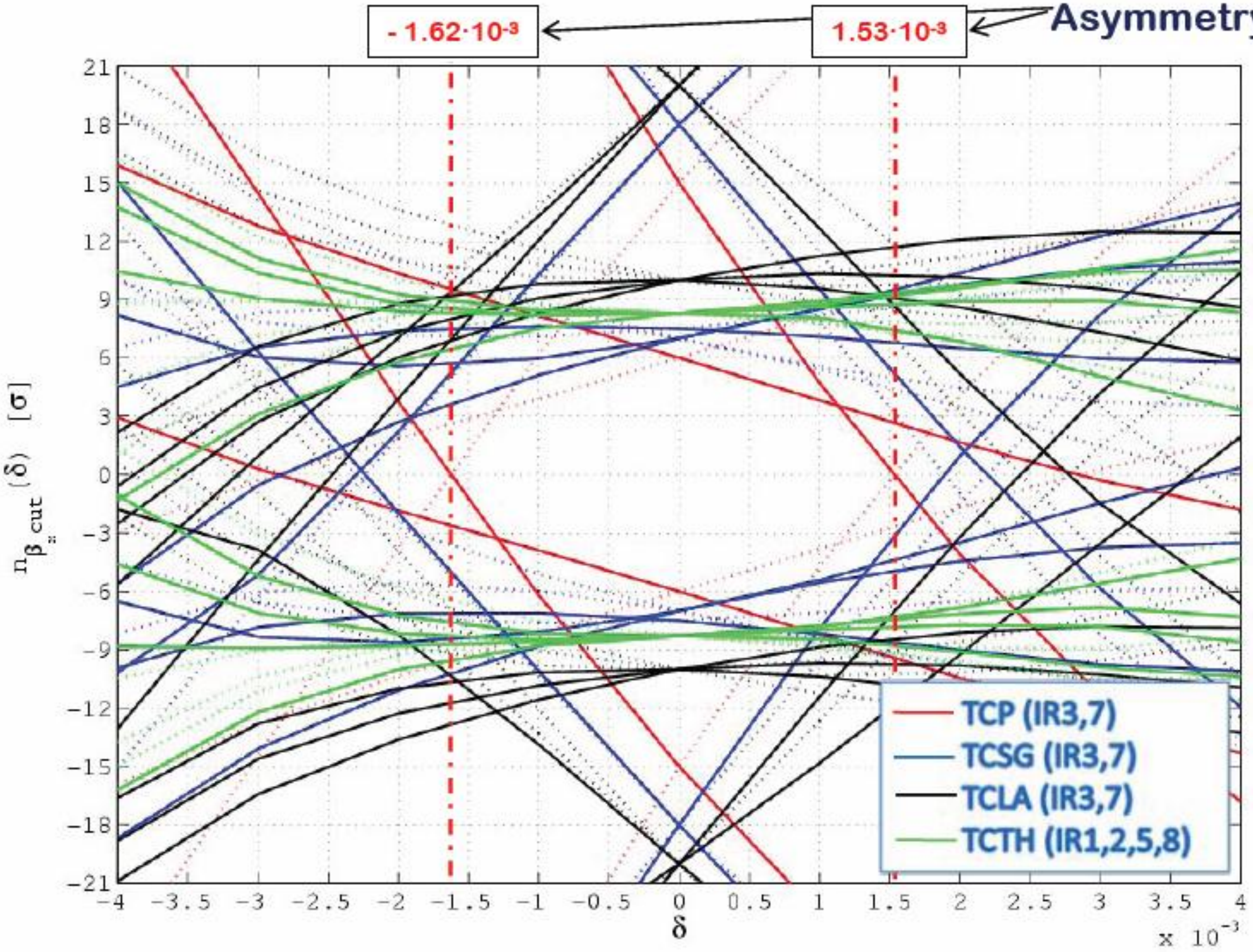
- **Synchrotron radiation**
- **Impedance**

Off momentum Beta beat IP1→IP5

Overlapping all the horizontal collimators:

Asymmetry due to dispersion



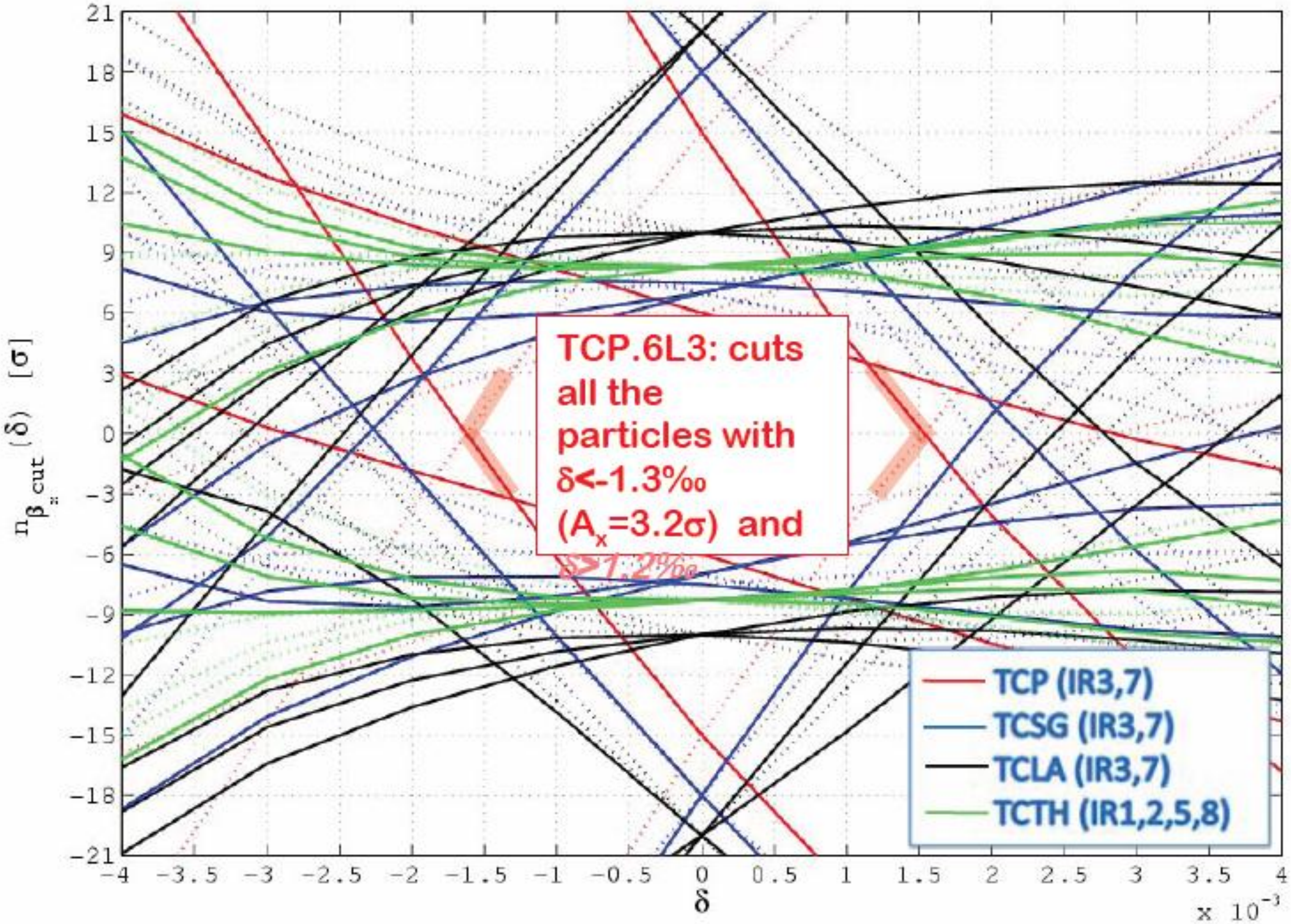
Each solid line represent one collimator jaw.

Each color represent one collimator family (legend)

The phase space is limited by the jaws of the two horizontal TCP (TCP.6L3, TCP.C6L7)

Off momentum Beta beat IP1→IP5

Overlapping all the horizontal collimators:



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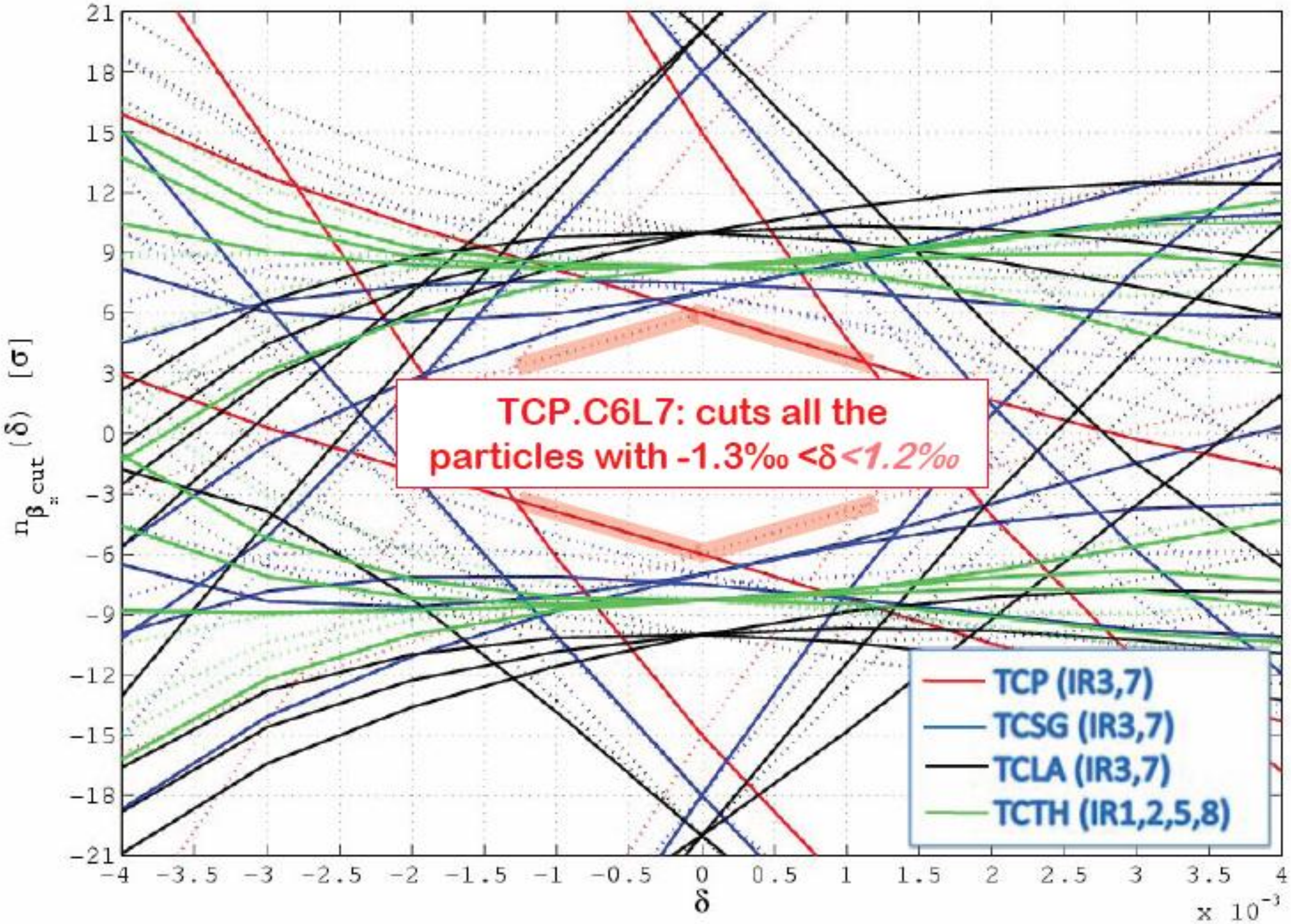

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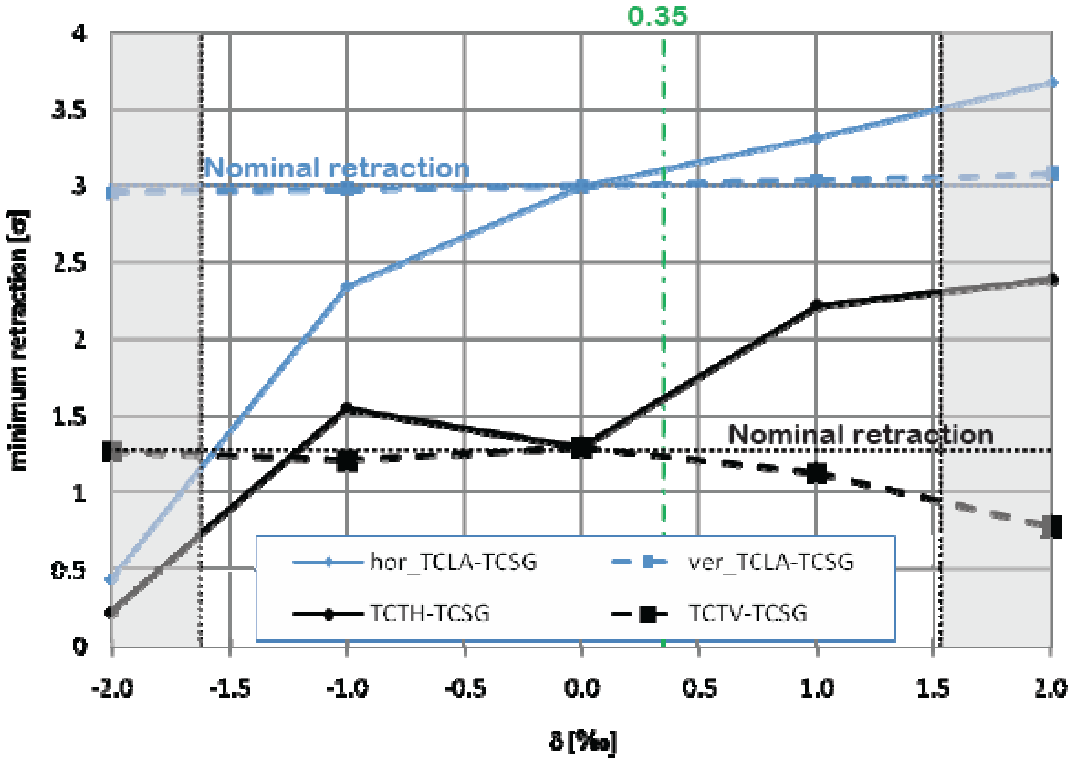
The phase space is limited by the jaws of the two horizontal TCP (TCP.6L3, TCP.C6L7)

IR7 TCLA/TCTH-TCSG retraction [σ]

Nominal half-gap ($\beta=\beta_0$) in IR7: TCSG =7σ
TCLA =10σ
TCTH/V= 8.3σ



- **Horizontal TCLA-TCSG:** 1.8σ reduction → Worrisome!
- **Horizontal TCTH-TCSG:** 0.5σ reduction

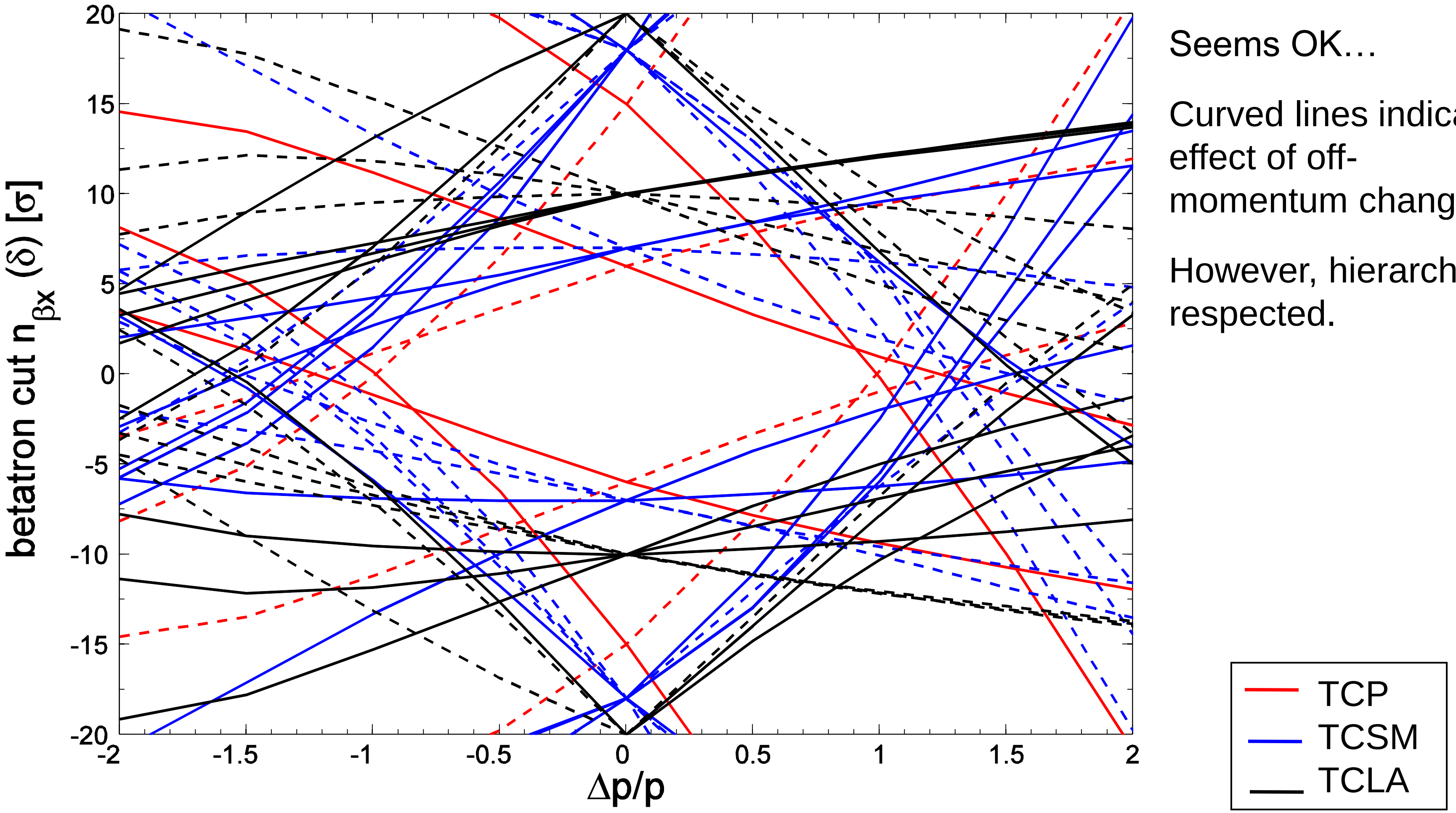
tighter tolerances!!

Conclusion

- The tolerances for LHC collimation were presented.
- Any upgrade must respect the robustness limits of LHC collimation, taking into account the beam energy stored in the tails of the LHC beams.
- We presently run in a tolerance-optimized way → 3 – 4 times the tolerances that we will have later at 7 TeV with the system (and LHC performance) pushed to its limit.
- Tolerances will become very critical by the time we will install crab cavities into LHC:
  - Almost half of the margin eaten up by transient orbit and beta beat errors.
  - Some other margin required for collimator stability.
  - Chromatic beta beat can take additional margin away.
  - Crab cavities should not reduce this further → local solution favored.
  - Impact of failures might be most critical residual issue with local crabbing.

Additional Slides

Phase Space Cut, 7 TeV, No Corrections, Separation ON



Seems OK…

Curved lines indicate effect of off-momentum changes.

However, hierarchy respected.