Running the LHC at low energy & high beta*

Impedance & stability

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Observations during 2018 high β^* run @ 450 GeV

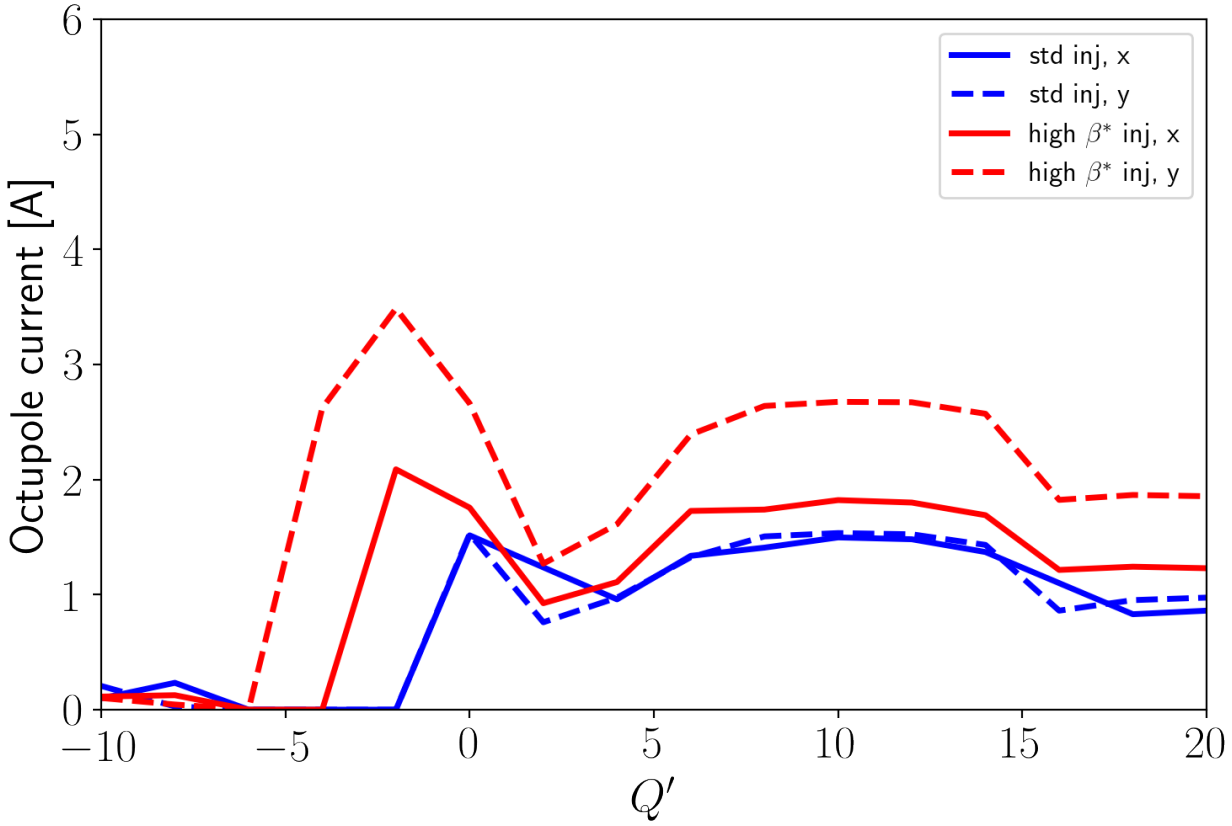
- No instability spotted by the LHC instability monitoring team during:
  - fills 7246[1] → 7250: (high beta* tests @ injection energy),
  - fills 7279 → 7291 (high beta* run @ injection energy).
- True even for the first test fills, for which octupoles were completely switched off (fills 7246 and – partly – 7247).
- In qualitative agreement with predictions, showing that a few A in the octupoles are enough for stability (see talk at the coll. working group https://indico.cern.ch/event/752722/contributions/3118632/attachments/1709447/2755384/20180903_highbeta_injection_CWG.pdf)

[1] During the first high beta* test (fill 7246), a small, rising coherent signal was observed in VB1, but:
- no blow-up nor intensity loss were observed,
- one cavity switched off right before the instability, leading to possible transient effects.

→ this is currently not thought to be an instability.

Predictions: octupole current vs. chromaticity

- In an isolated bunch & single beam situation: octupole current vs. Q′, comparing std injection to high β^* at injection, without crystal coll.:



- Despite larger impedance than in std operation, the octupole current needed to stabilize is very small: **less than 3A** for 5 < Q′ < 15**.**

Relevant (in)stability aspects

Detrimental

- ✓ Some collimators are moved very close to the beam (several vertical tungsten collimators moved to 2.5-2.7 σ, IR3 moved in by 3 σ).
- ✓ Roman pots in (~3 σ).
- ✓ Small emittance (~1mm.mrad)
- ✓ Crystal collimator sometimes in.
- ✓ Bunch tails scraped (can reduce Landau damping from oct.).

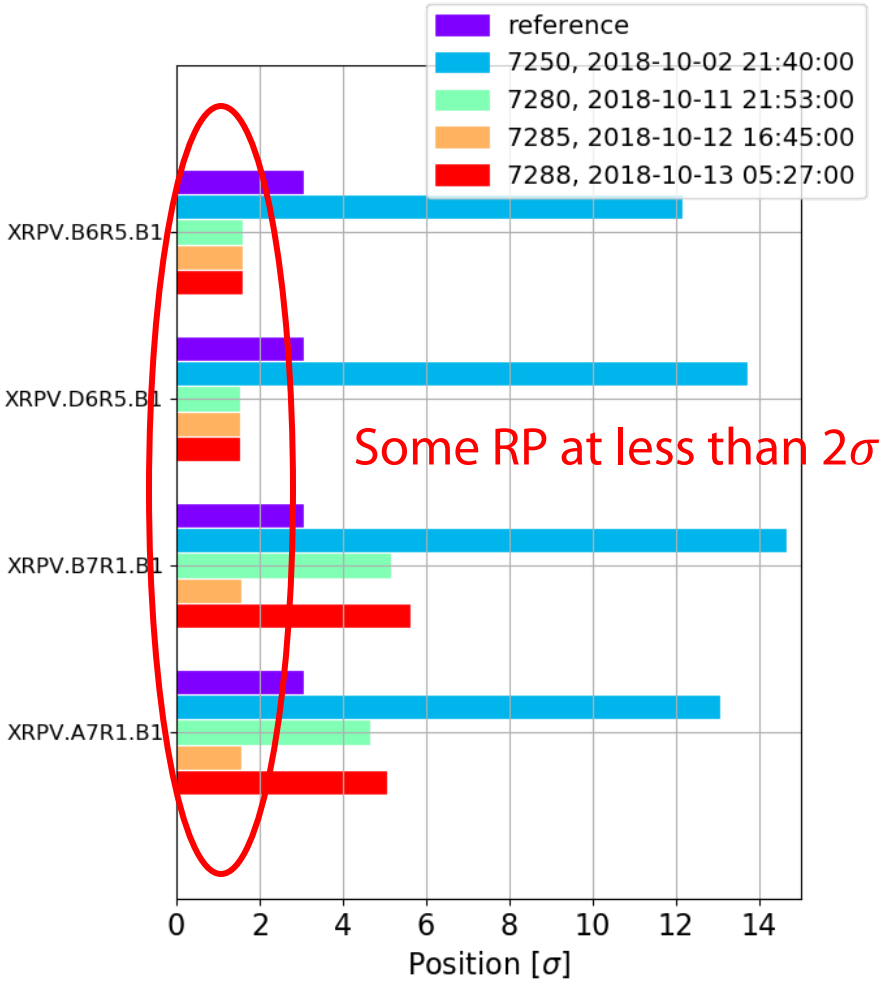
- ✓ Intensity close to nominal (~8.10^{10} p+/bunch).
- ✓ Bunch length close to standard (~1.1 ns).

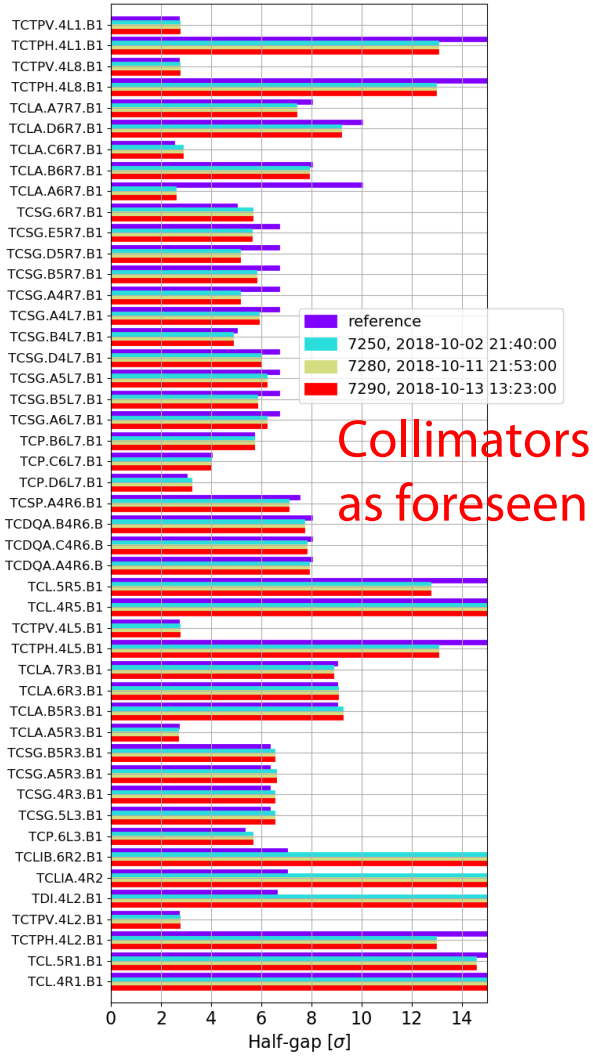
Beneficial

- ✓ Energy (450 GeV).
- ✓ Isolated bunches (typically 6 bunches with lot of space in-between).
- ✓ Beam-beam head-on tunespread (Landau damping).

Collimators & roman pots

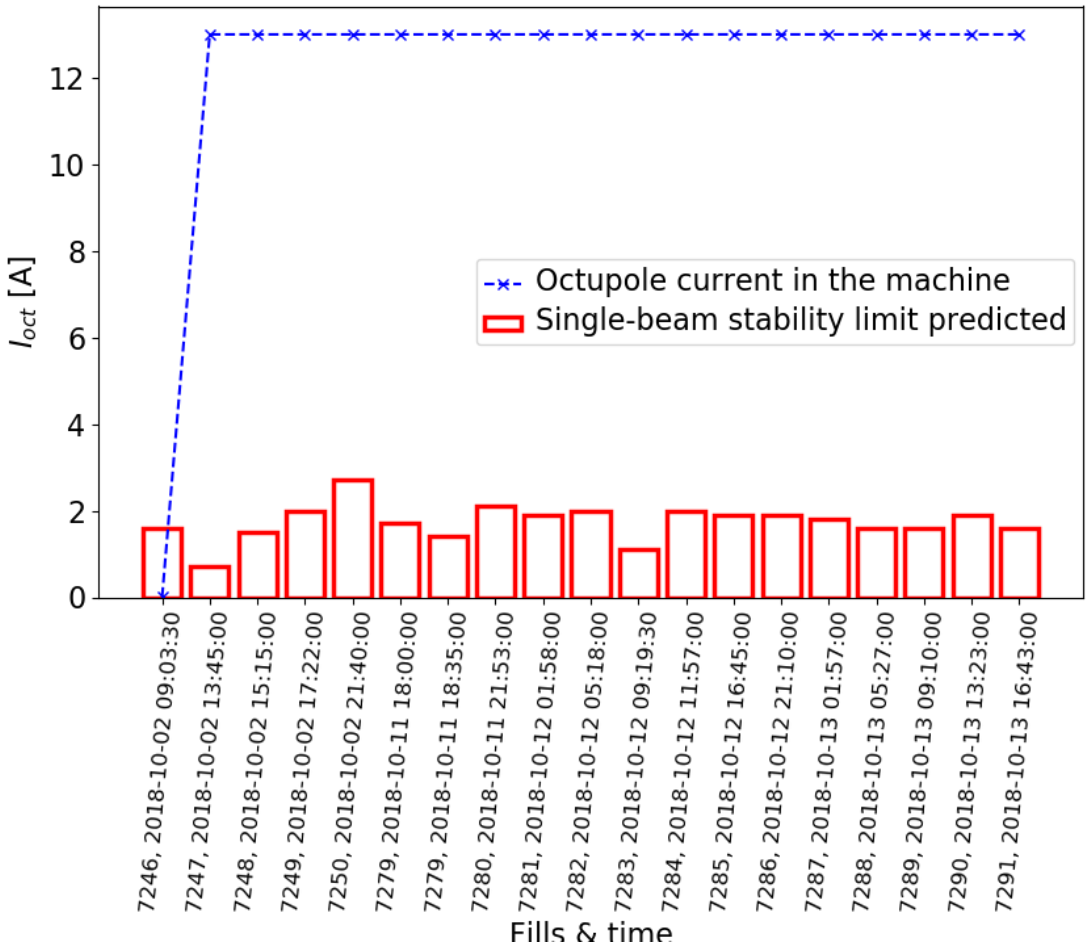
- Comparison between what was foreseen ("reference") and what really happened during the run:





Octupole currents computed for the real machine settings

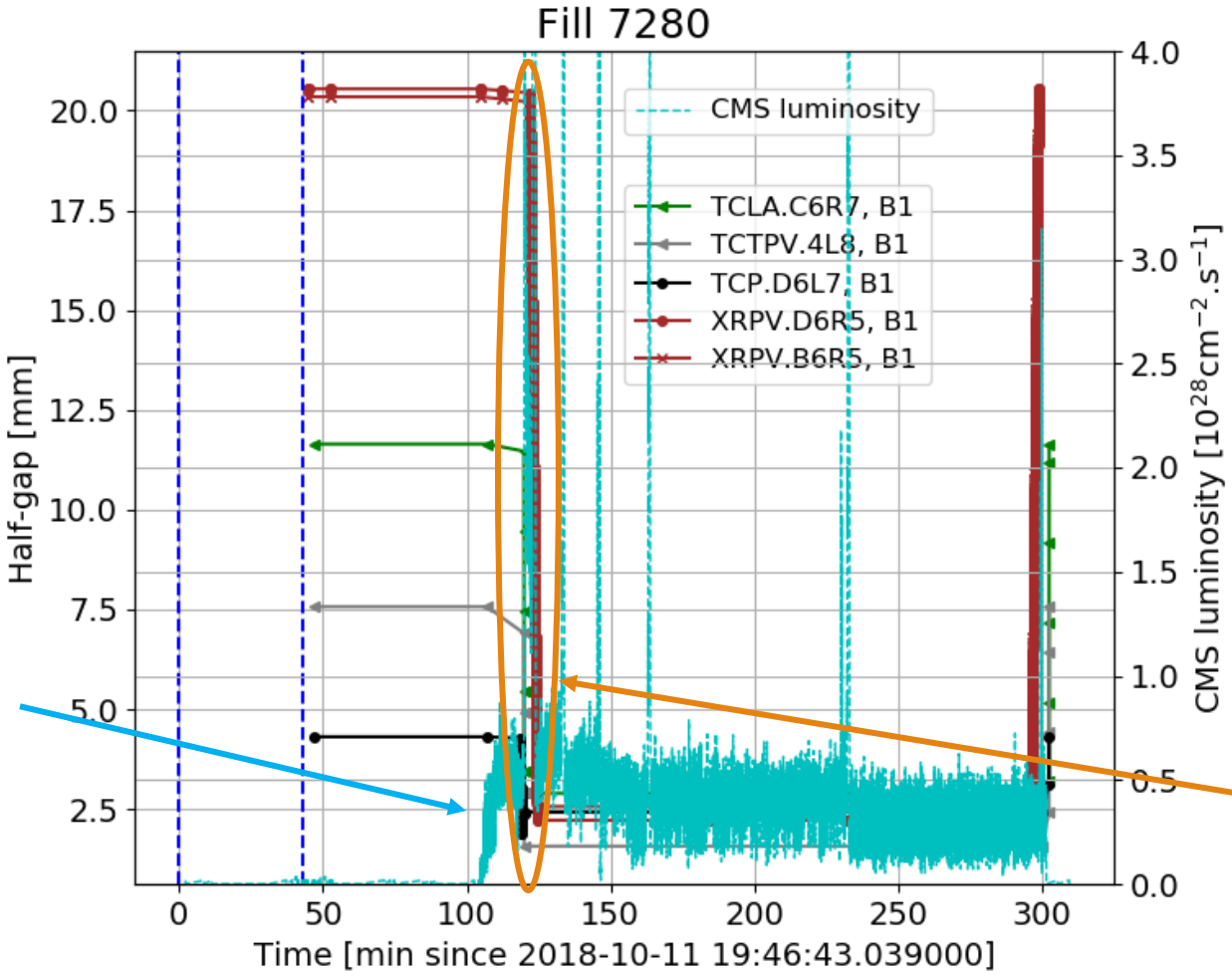
- Octupole current needed to stabilize each fill, for a single-beam, right after collimators are closed (without crystall coll.):



$\Rightarrow$ we were always well below the stability limit.

What about beam-beam effects?

- The collimators and roman pots were actually closed AFTER the beams were put in collision - example of fill 7280

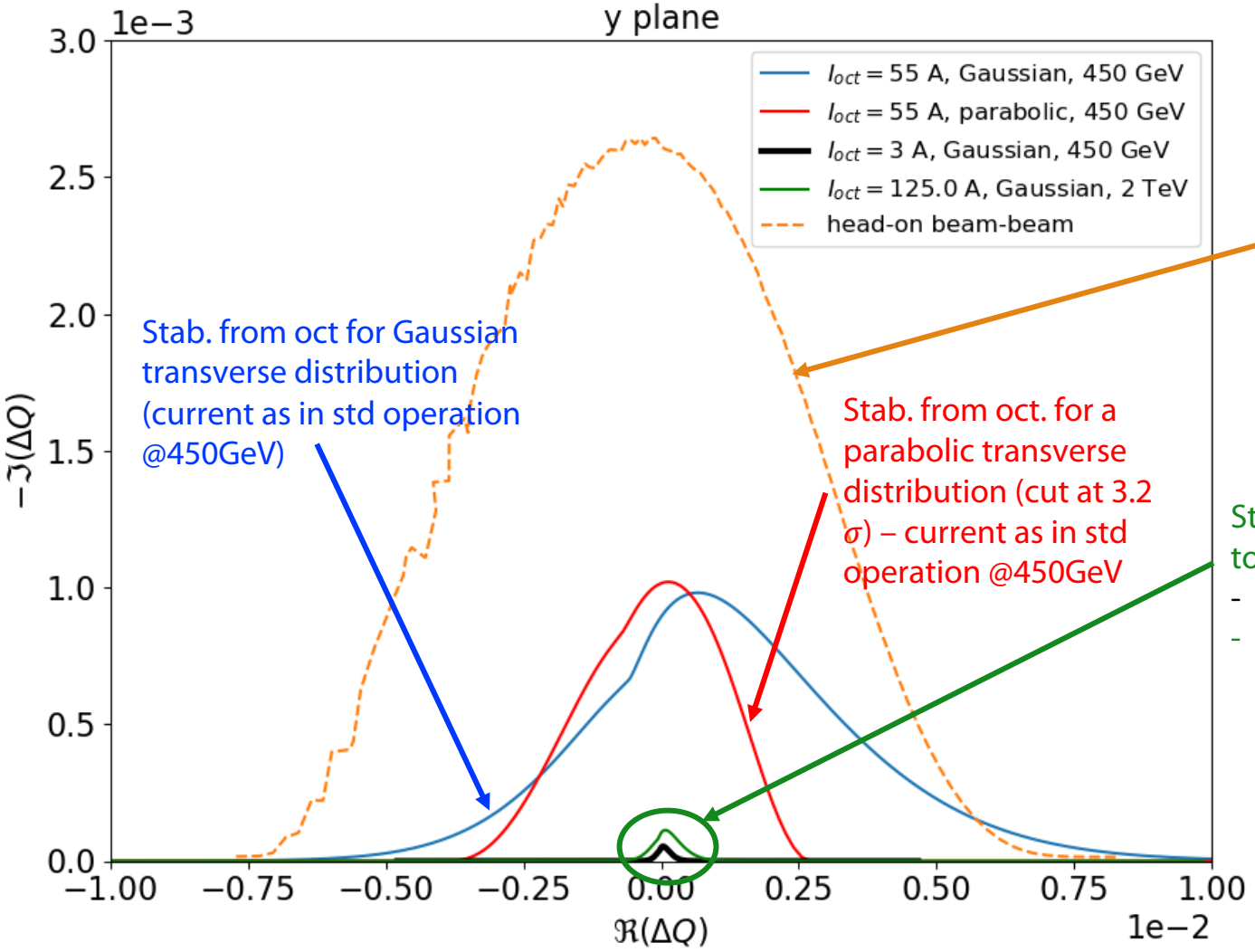


CMS luminosity increase

Collimators & RP closed

Stability diagrams with head-on beam-beam

- Tunespread from head-on beam-beam (ξ~0.02) dominates everything else:



Stab. from head-on-beam-beam tunespread (~independent of energy)

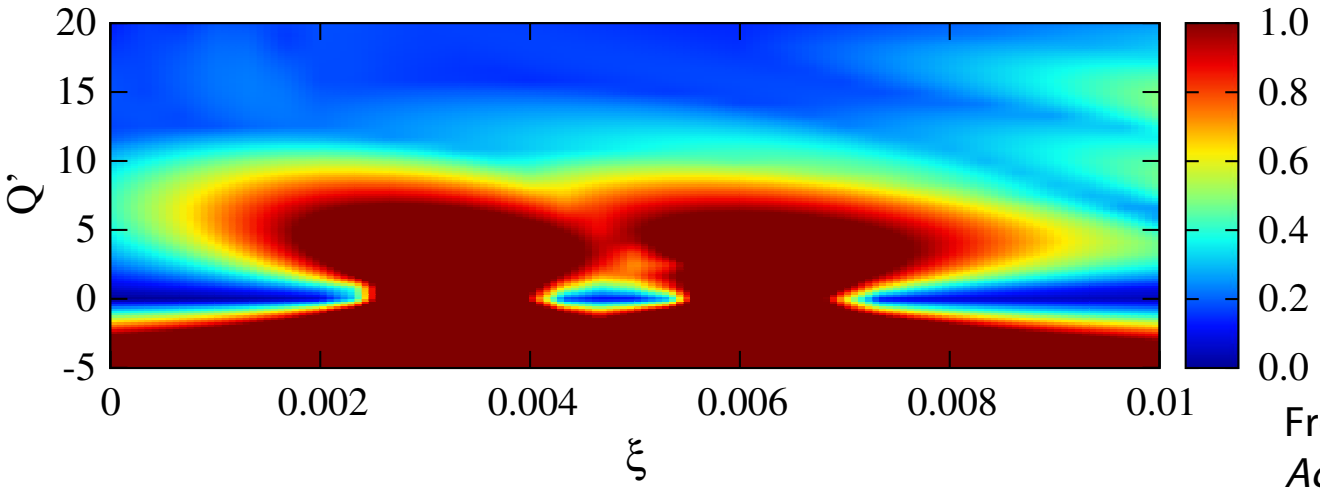
Stab. diagram we need to stabilize the beam:

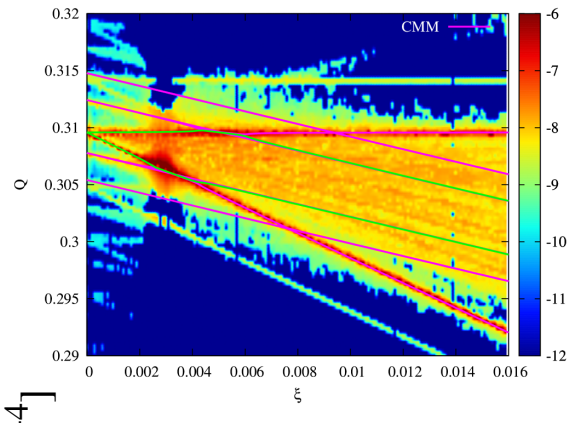
- @ 450 GeV
- @ 2TeV, assuming collimators & RP at same #σ (pessimistically) – scaling is $\gamma^{5/2}$

A few pitfalls…

- The crystal collimator impedance is not in the model yet – ongoing work by A. Passarelli, N. Biancacci, D. Amorim & M. Migliorati.
- On another ground: when the two beams are very symmetric, coherent beam-beam modes can in principle couple with headtail modes from impedance, leading to a strong, TMCI-like, instability:

Imag. tune shift vs. chromaticity Q' and beam-beam parameter ξ:





From S. White et al, *Phys. Rev. ST Accel. Beams* 17, 041002 (2014)

Conclusions

- In single-beam we were well below the stability limit during the high beta @ injection run, and we still have a comfortable margin.
- When beams are colliding, the situation is even more beneficial.

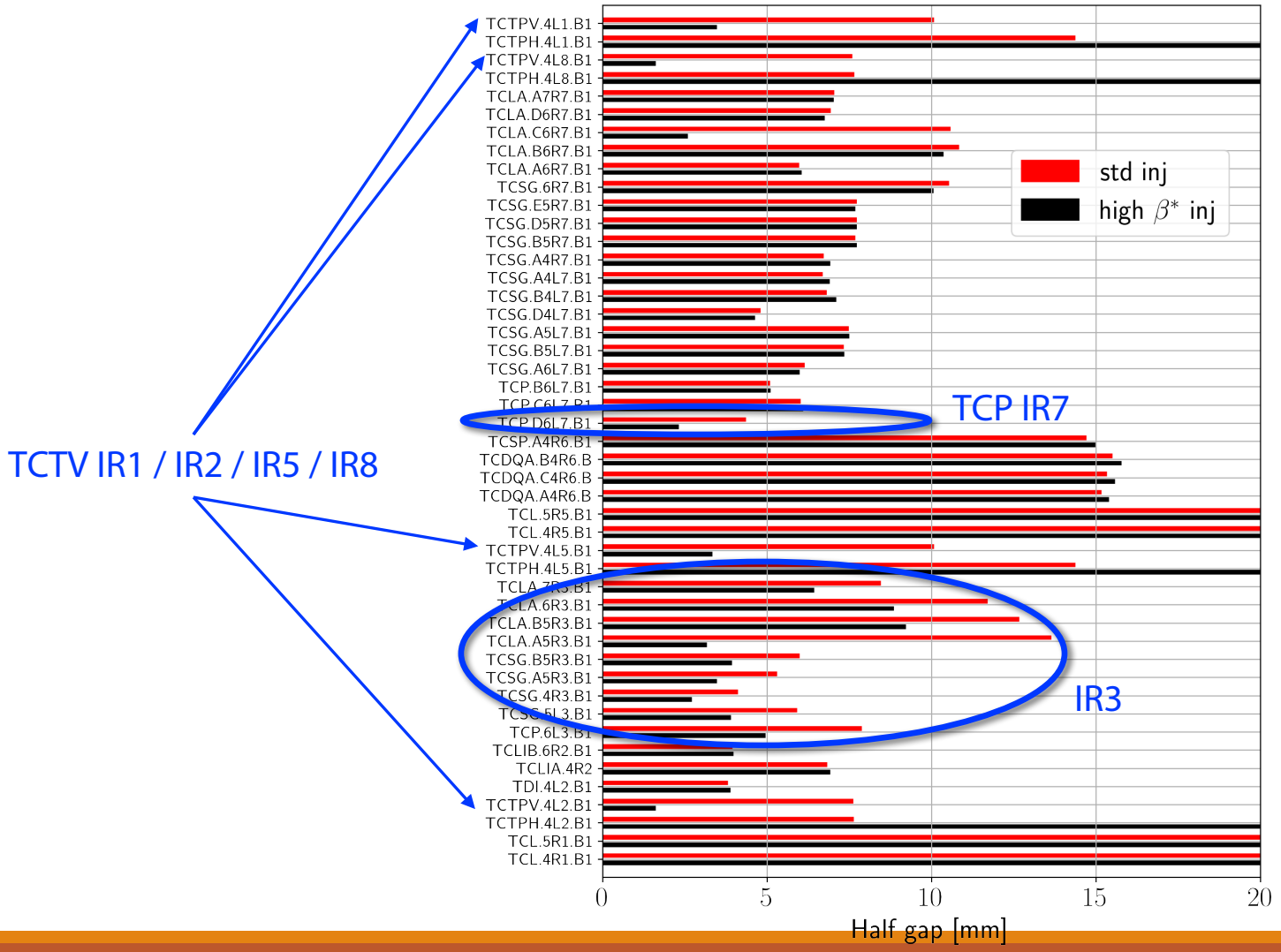
But there are also possible pitfalls, still to be checked:

- The situation could degrade if the two beams get more symmetric, as we might enter the regime where coherent beam-beam modes and headtail modes could couple, leading to a TMCI-like instability.
- The crystal collimator is not in the impedance model yet
  → ongoing work.

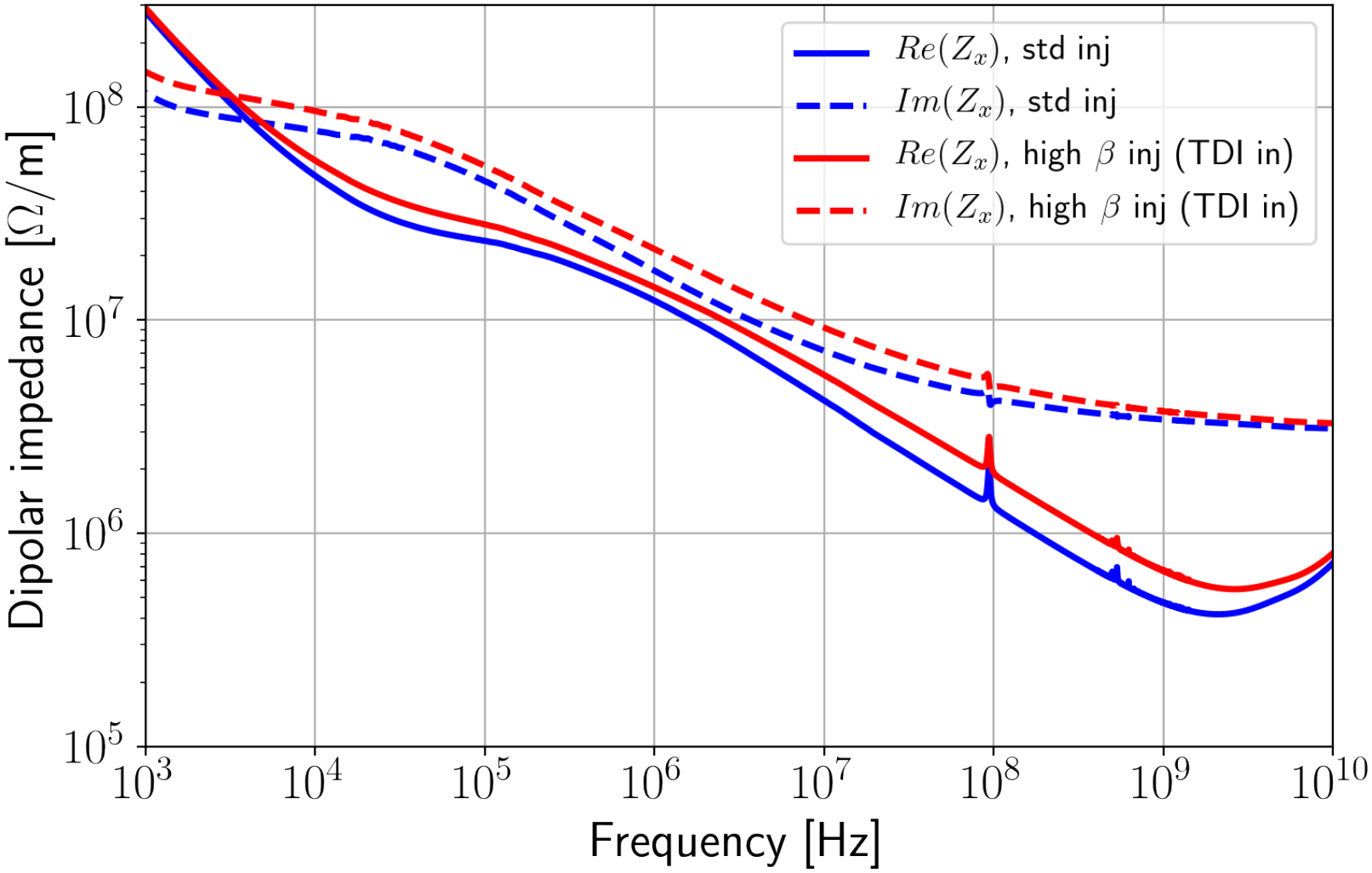
Backup slides

Collimator & roman pots

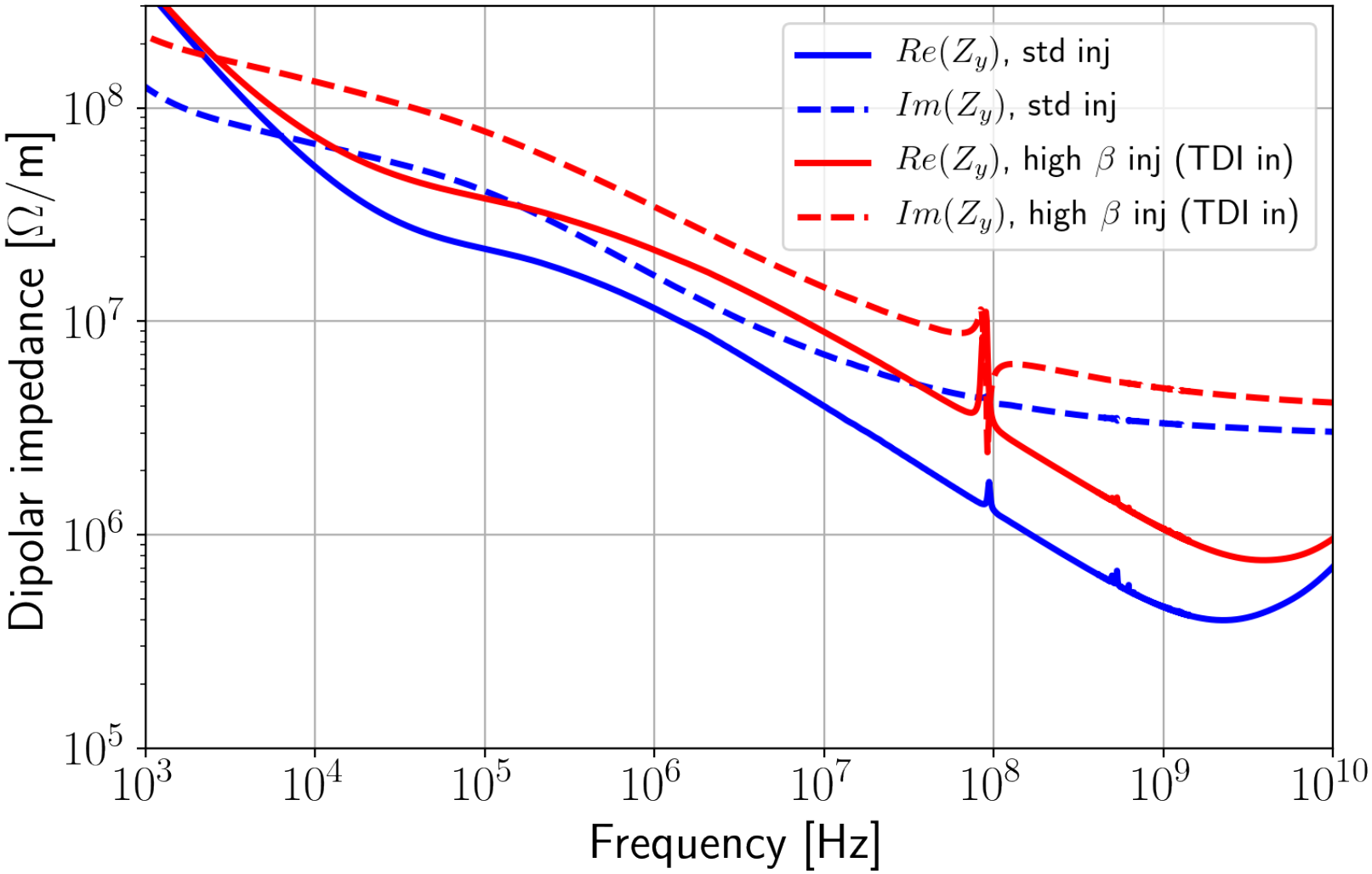
- Comparison between standard and high beta collimator half gaps:



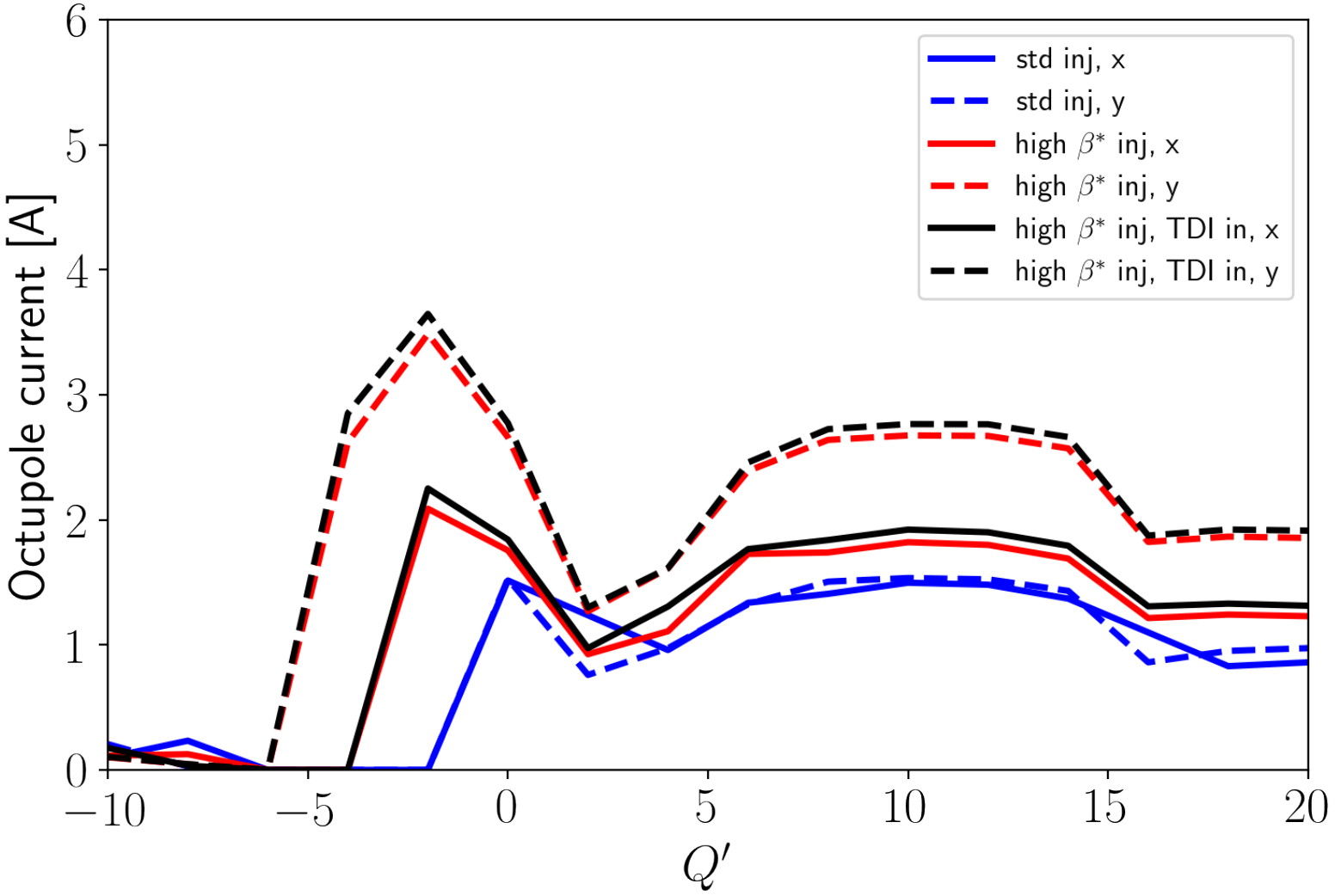
Impedance comparison - horizontal



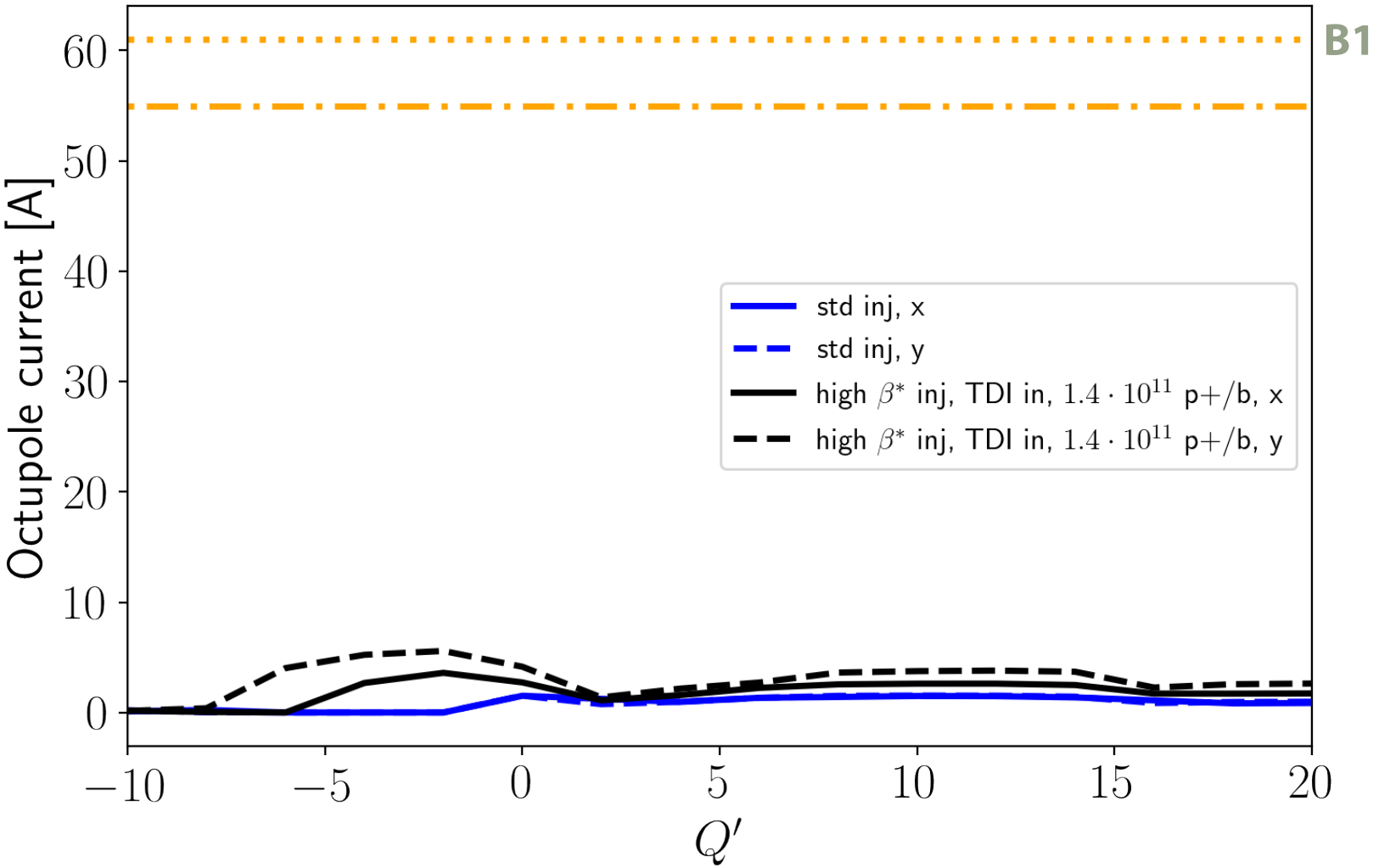
Impedance comparison - vertical



Single-bunch octupole current vs. chromaticity



Single-bunch octupole current vs. chromaticity



- … but we are still more than 10 times less than standard octupole current used at injection (indicated here for B1 & B2).