Muon collider ring:
Sensitivity Study - Impact of β^* on momentum acceptance

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International MUON Collider Collaboration

Goals and requirements

Goals

$\epsilon_L = \gamma \sigma_z \sigma_\delta$

❖ $\boldsymbol{\beta^*_{x,y} = 1.5mm}$

❖ $\alpha_c \sim 0$

❖ Circumference ~10 km

Beam constraints

❖ $\boldsymbol{\delta = 0.1\%}$

❖ $\epsilon_N = 25\mu m$

Required performance:

→ Transverse dynamic aperture: $\sim$ **3-4$\boldsymbol{\sigma}$**

→ Momentum acceptance: $\sim$**2-3 $\boldsymbol{\sigma}$**

Other constraints

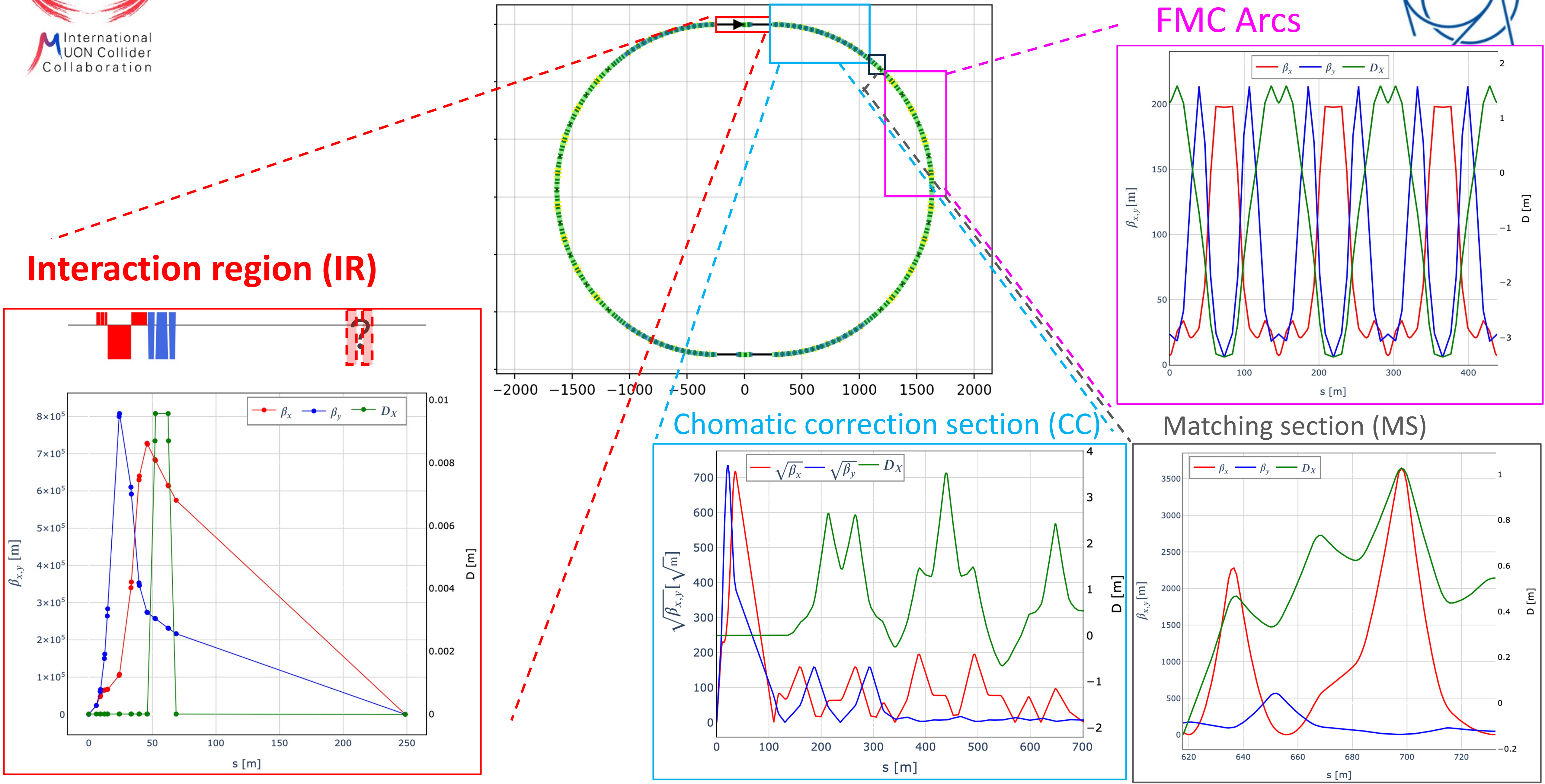
- **Maximum field** of 16 T for dipoles and **20 T** for combined-function and quadrupole magnets (to be adapted later with current magnet constraints)
- **Thickness of the radial shielding** inside the magnets: **4 cm**
- Aperture set to 5 times rms beam size + radial shielding.

Current performances

Sufficient dynamic aperture for on-momentum particles, but **requirements not yet met** for the **entire momentum range** (momentum acceptance ~ $1\sigma_\delta$ for DA ~2.5σ).

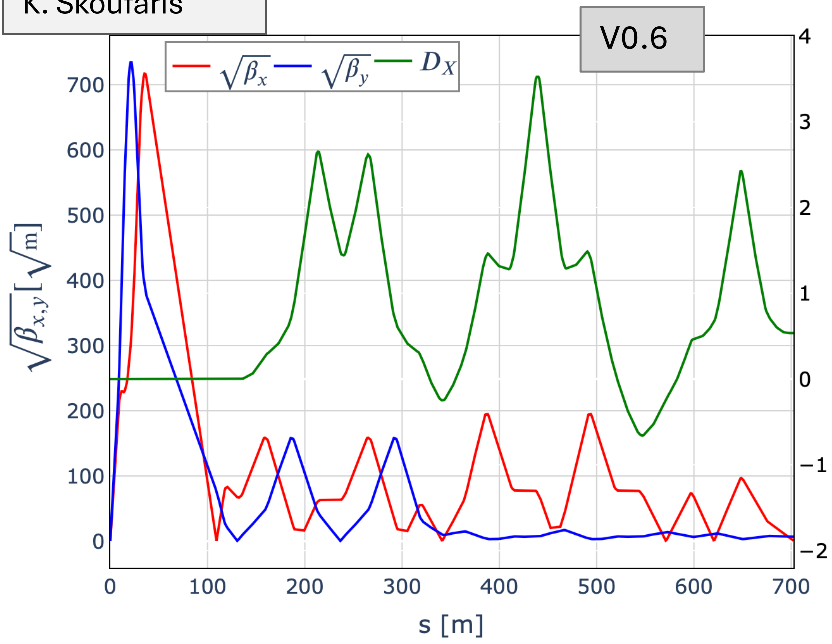
➔ Sensitivity study: Relax the β^* to evaluate the **impact of $\boldsymbol{\beta^*}$ on the dynamic and momentum acceptance.**

Reminder of last meeting



Reminder of last meeting : CC versions

v.06 – v0.7 from K. Skoufaris



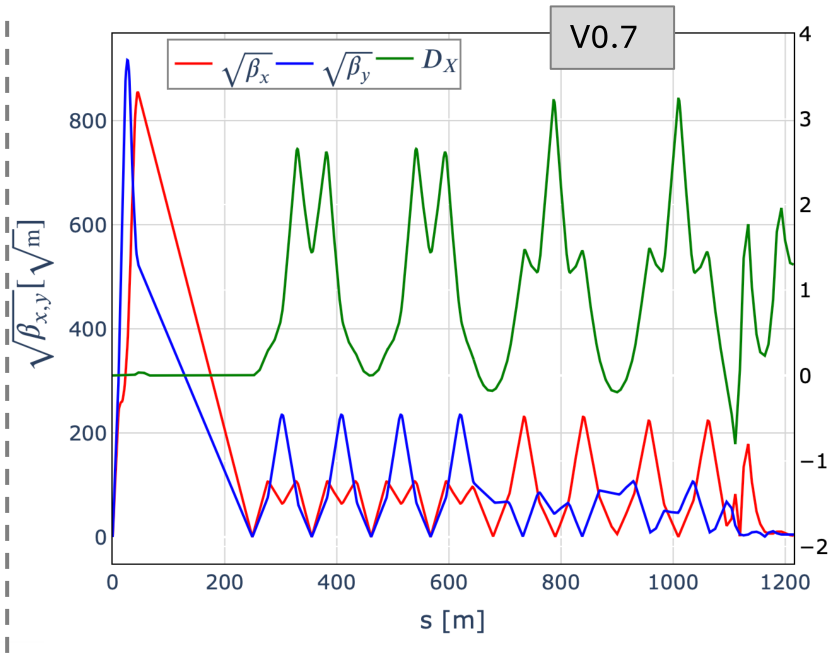
IR: **2cm of W shielding**; No chicane

CC: No Q' control in the CC

Performances:

DA~2.5σ for $\delta = -10^{-3}$

→ Most promising version

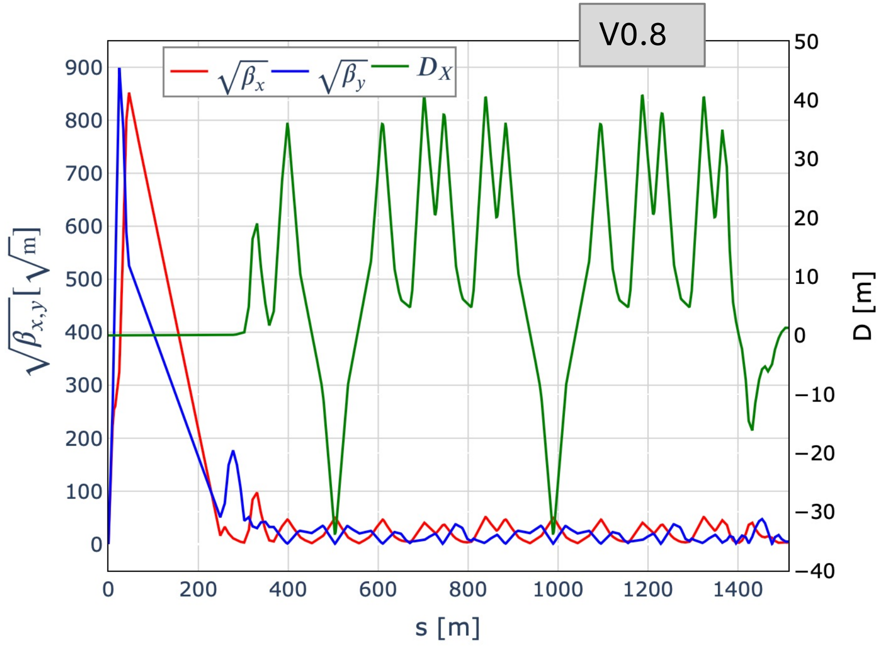


IR: **4cm of W shielding** + chicane

CC: No Q' control in the CC and huge sensitivity to the phase advance

Performances:

Particles lost for $\delta = 7 * 10^{-4}$



IR: **4cm of shielding** + chicane + no-combined function FF quads

CC: smaller β-functions; W and Q' control

Performances:

Particles lost for $\delta = 7 * 10^{-4}$;

Much less mature than other versions.

Sensitivity study for β^*

Sensitivity study

Goal

→ Obtain a **lattice** with slightly **reduced performance** (or luminosity) **working** at least **without imperfections**

→ Start **other relevant studies** (e.g. impact of imperfections and machine wobbling to mitigate the neutrino radiation issue).

- *Increase in β^* by a factor of X :*
  - → Decrease in luminosity by a factor of X.
  - → Reduction of the maximum β (in the FF triplet) by more than the factor X.
  - → Reduction of the FF quadrupoles apertures → Higher achievable gradients with smaller quadrupoles.
  - → Increase of bunch length and decrease of momentum spread by factor X.
  - → Reduction of the chromatic effects that must be compensated in the local chromatic correction section.
  - → Possible increase in momentum acceptance.

$$\mathcal{L} = \frac{1}{4\pi}\frac{N_p^2}{\varepsilon\beta^*} f_r\, f_{hg}\, \frac{\gamma T_\mu}{T_{rev}}$$

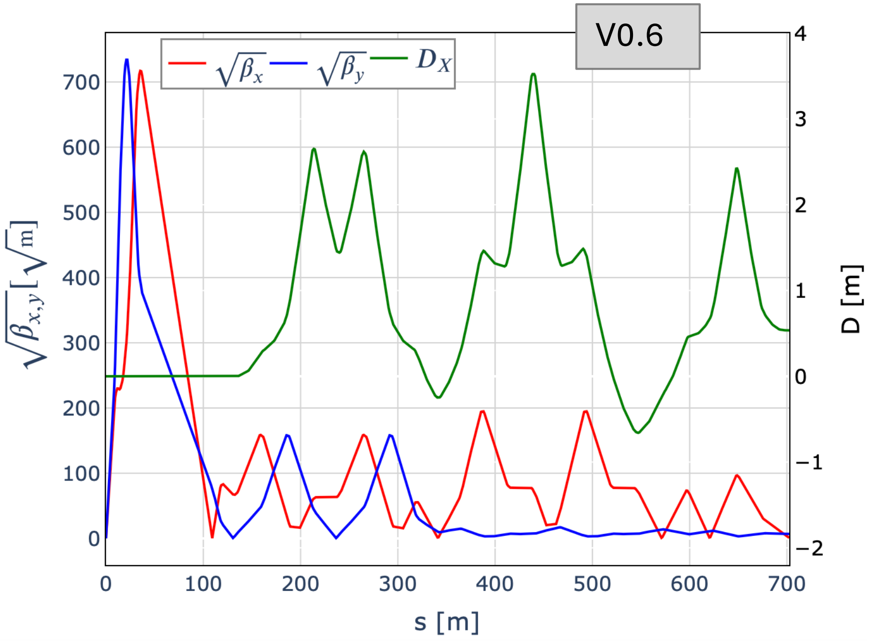
$$\beta(s) \sim \frac{s^2}{\beta^*}$$

$$\sigma = \sqrt{\beta\epsilon + \left(D\delta_p\right)^2}$$

App. = 2*(5σ + shielding)

$$\epsilon_L = \gamma\sigma_z\sigma_\delta,\ \sigma_z = \beta^*$$

Sensitivity study – Improved CC



IR: **2cm of W shielding**; No chicane

CC: No Q' control in the CC

Performances:

DA~2.5σ/ 4.5σ for $\delta = -10^{-3}/+10^{-3}$

→ Most promising version

First step: Implement recent changes in the IR in v.06: **4cm of radial W shielding** in the IR magnets and addition of a **chicane** in the IR for BIB mitigation.

→ Larger **maximum beta functions** in the FF quadrupoles with **larger chromatic effects.**

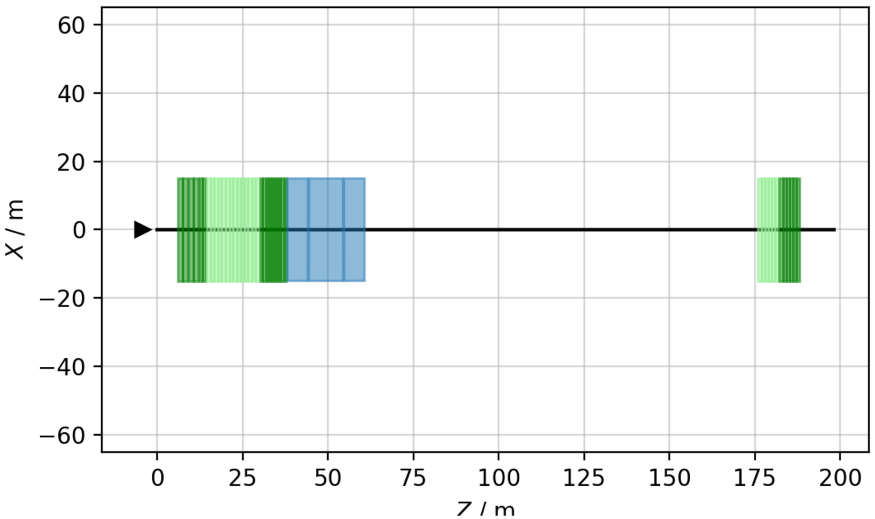
2cm shielding: $\beta_{y,max} \sim 540km$, $\beta_{x,max} \sim 514\ km$
4cm shielding: $\beta_{y,max} \sim 800km$, $\beta_{x,max} \sim 550\ km$

→ **Small changes in the optics** caused by the weak focusing of the bends in the **chicane**.

→ **Performances:** DA $\sim 2\sigma$ for $\delta = \pm 10^{-3}$ $(1\sigma_\delta)$

→Still **too large magnetic field in the CC** for 4cm shielding.

Sensitivity study – Procedure for each $\boldsymbol{\beta}^*$



Adaptation of the IR:

- Set the FF **quadrupole field to the maximum** (20T at magnet aperture) and reduce slightly the quad lengths.
- Slightly adjust the quad gradients to match the **same conditions at the beginning of the CC for all $\boldsymbol{\beta}^*$**.

Matching of the CC:

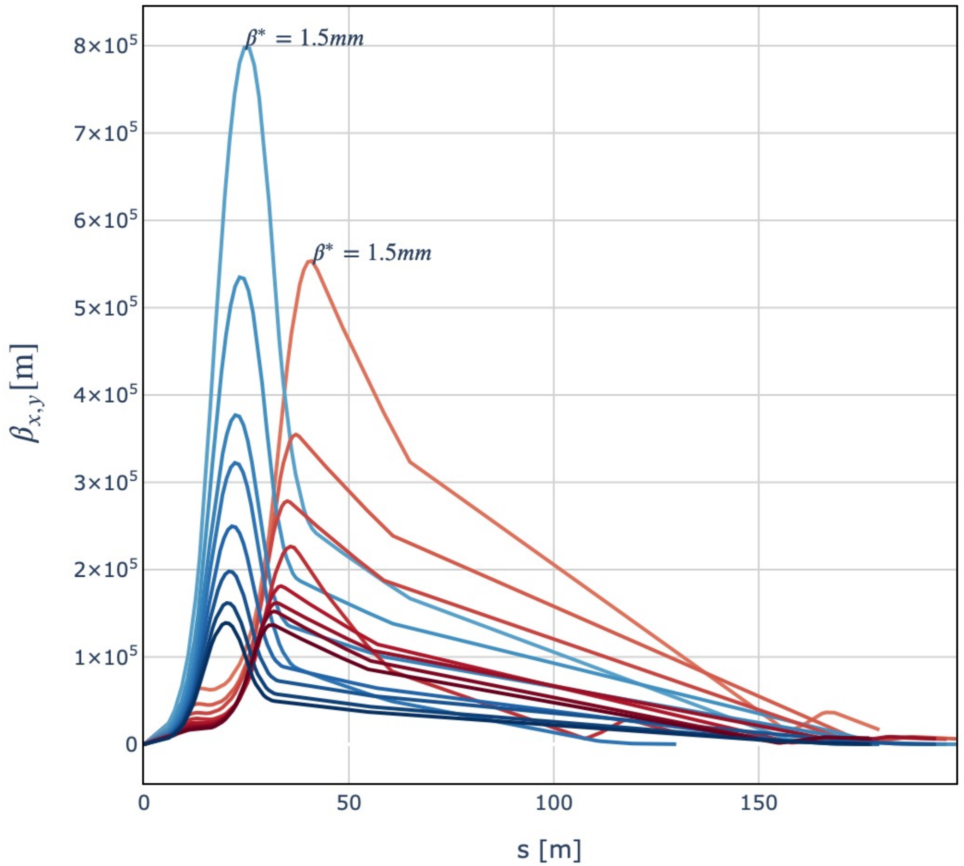
- **Similar CC for all $\boldsymbol{\beta}^*$**, same conditions on the phase advances in SD and SF sextupoles pairs.
- Optimisation of the CC to reduce the non-linearities in β vs. δ.

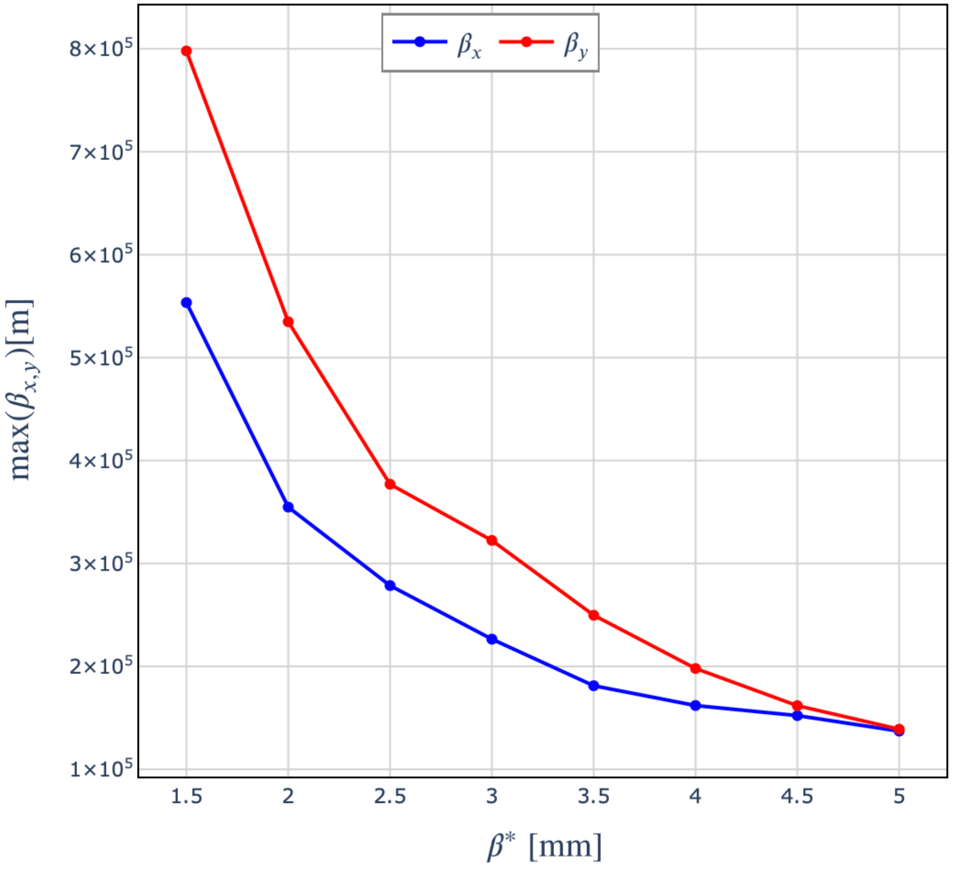
Matching of the arcs and entire ring:

- Tunes adapted in the matching section between the CC and the arcs → **Same tunes** for all β^*.

Sensitivity study: IR lattice functions

Adaptation of the IR: Larger β^* gives smaller maximum β and aperture allowing higher gradients →The reduction of the maximum β in the triplet is more than linear

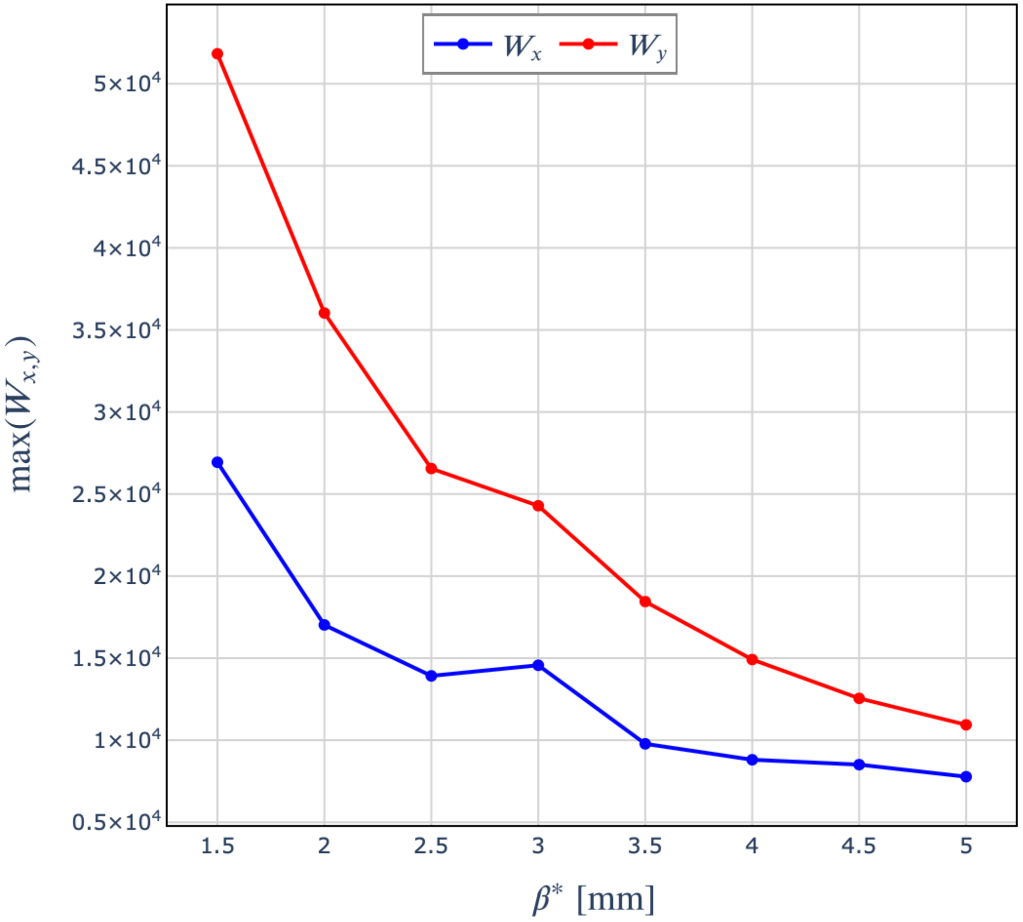




Sensitivity study: IR lattice functions

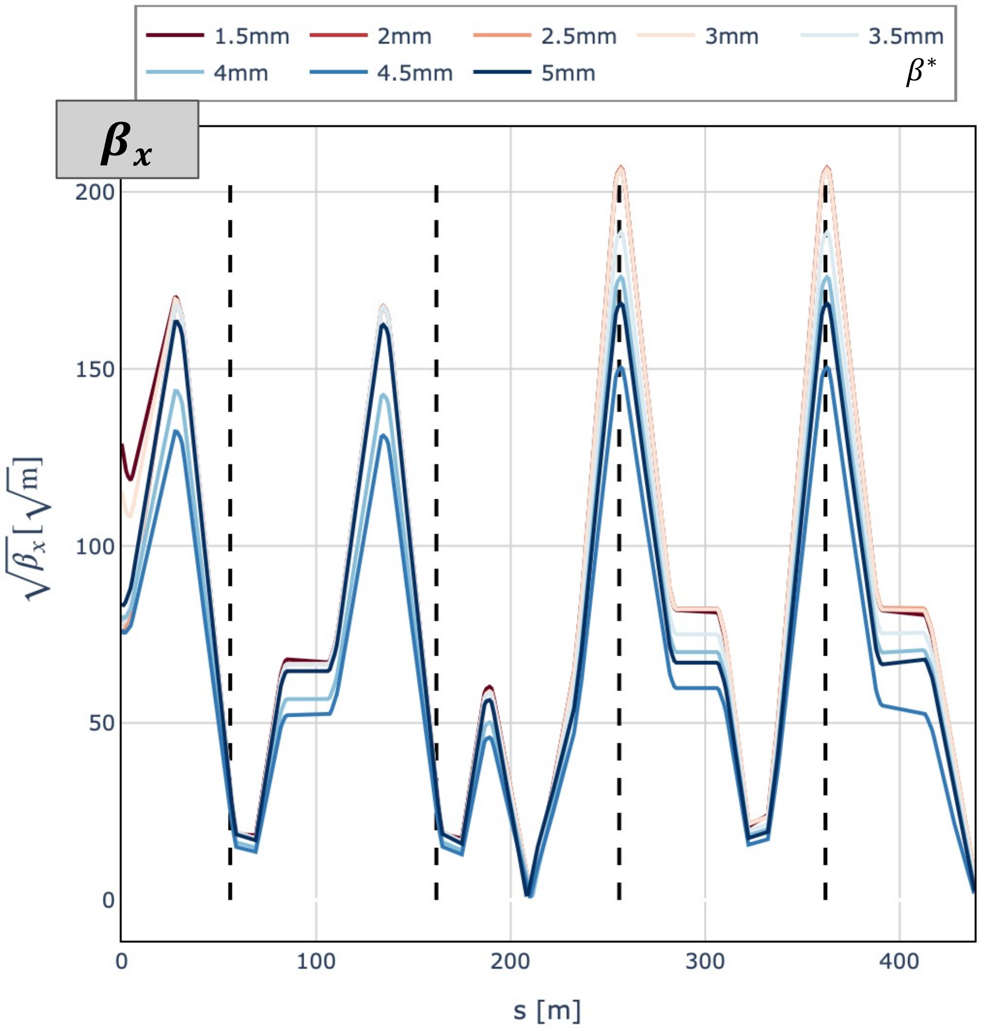
Adaptation of the IR:

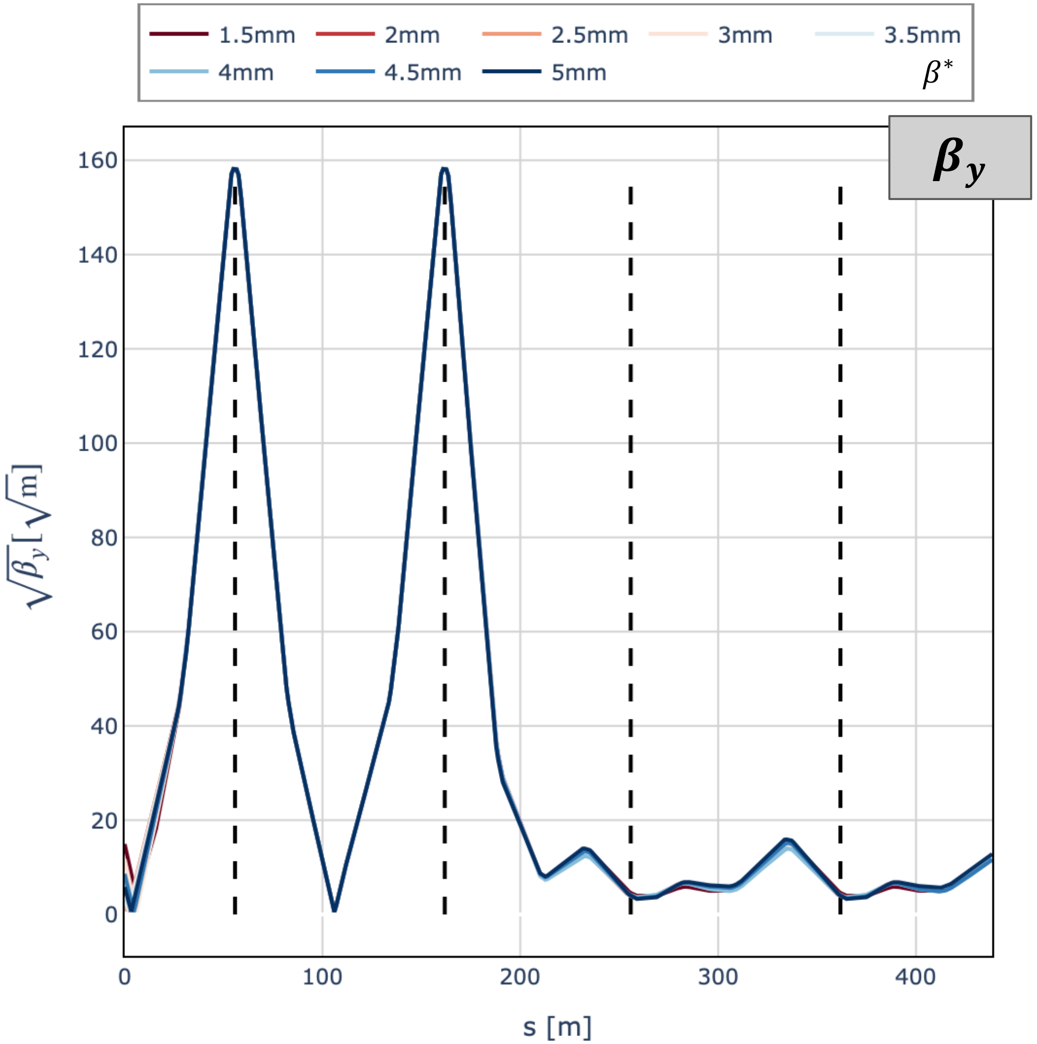
- The maxima of Montague functions decrease accordingly.
- Smaller chromatic effects for larger β^*.
- The outlier at $\beta^* = 3mm$ will also be visible in momentum acceptance results → Some improvements are needed for specific β^*



Sensitivity study: CC lattice functions

CC: Similar lattice functions in CC for all β^*.



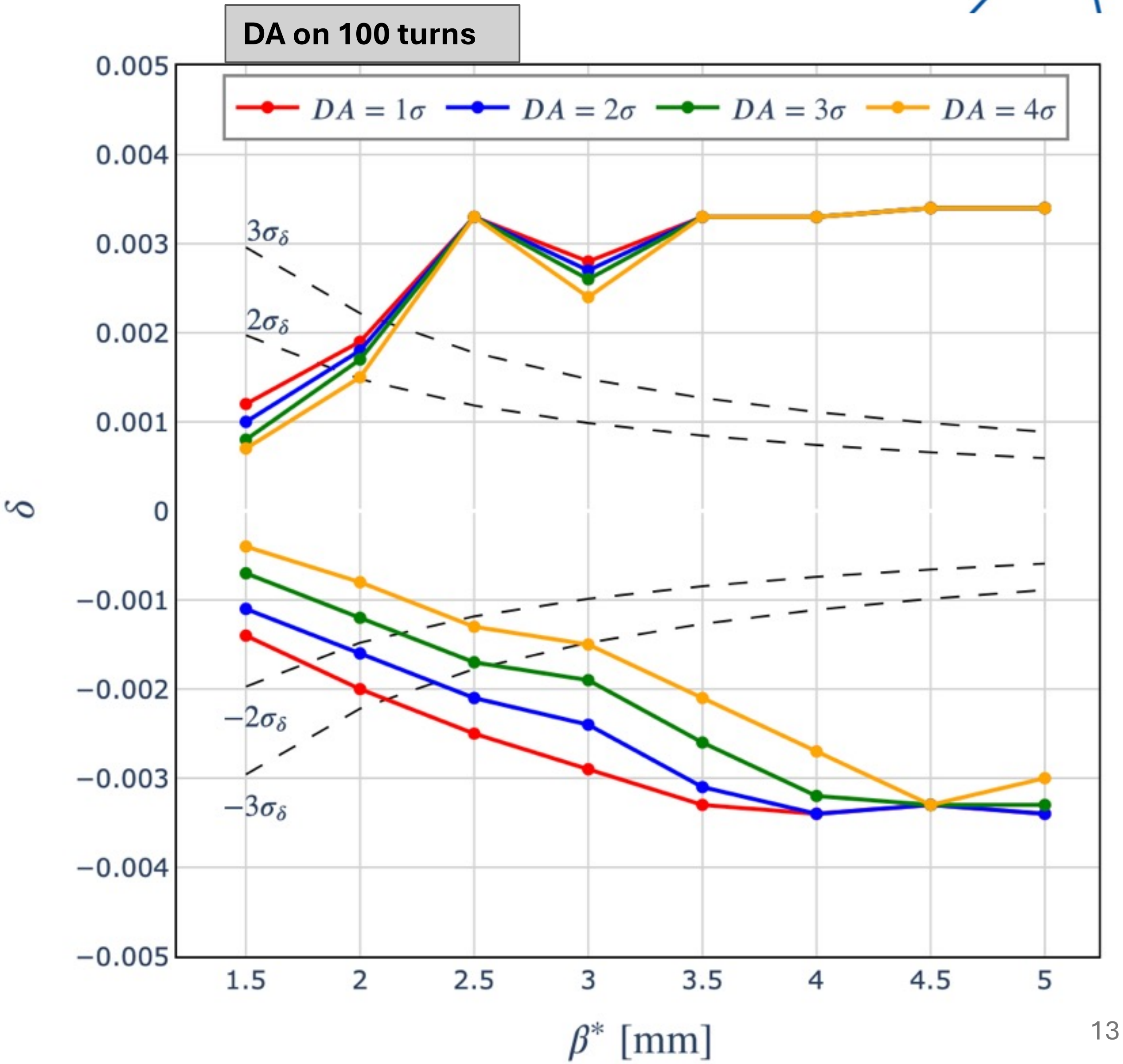


Sensitivity study - Momentum acceptance

- Transverse DA computed over 100 turns to observe the trend.
- Sufficient momentum acceptance ($\sim 3\sigma_d$) with DA $\geq 4\sigma$, for $\beta^* = 3mm$
  - **Reduction of the luminosity by** a factor of **2**.
  - Margins are still needed, particularly **to reduce the magnetic field in the CC and the arcs**.
- Some outliers for 3 and 5 mm → Better optimisation required for each β^*.
- No further increase in momentum acceptance from 4 mm onwards

  →The sextupole strength decreases.

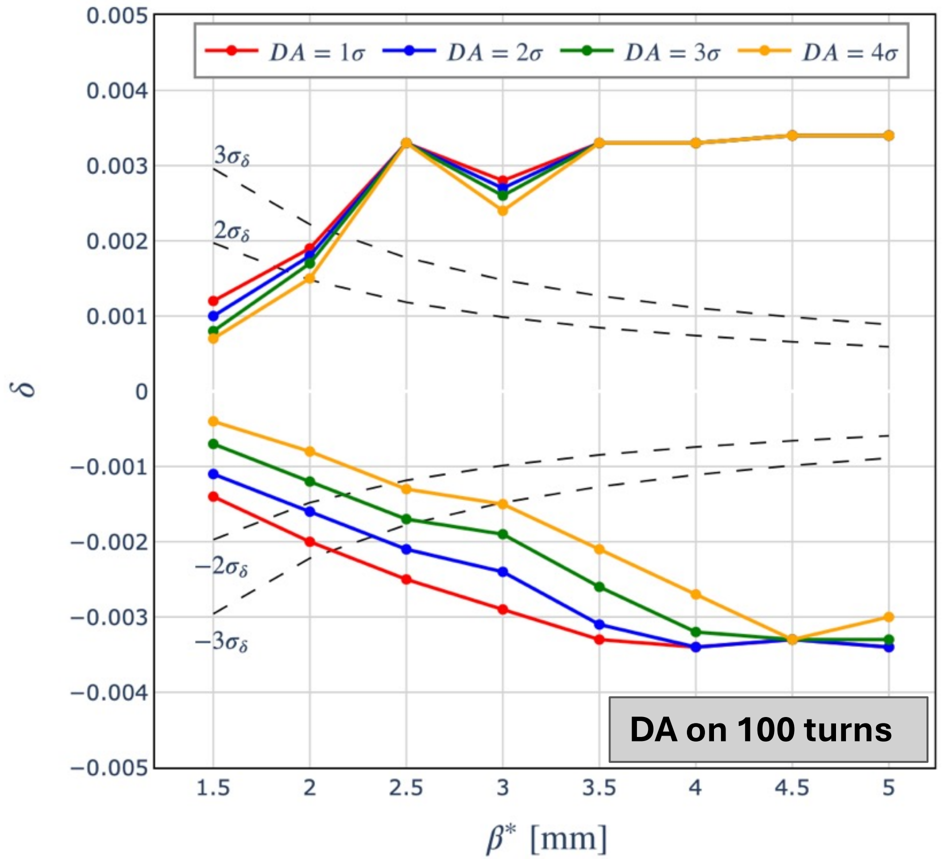
  → Increase in the transverse DA.

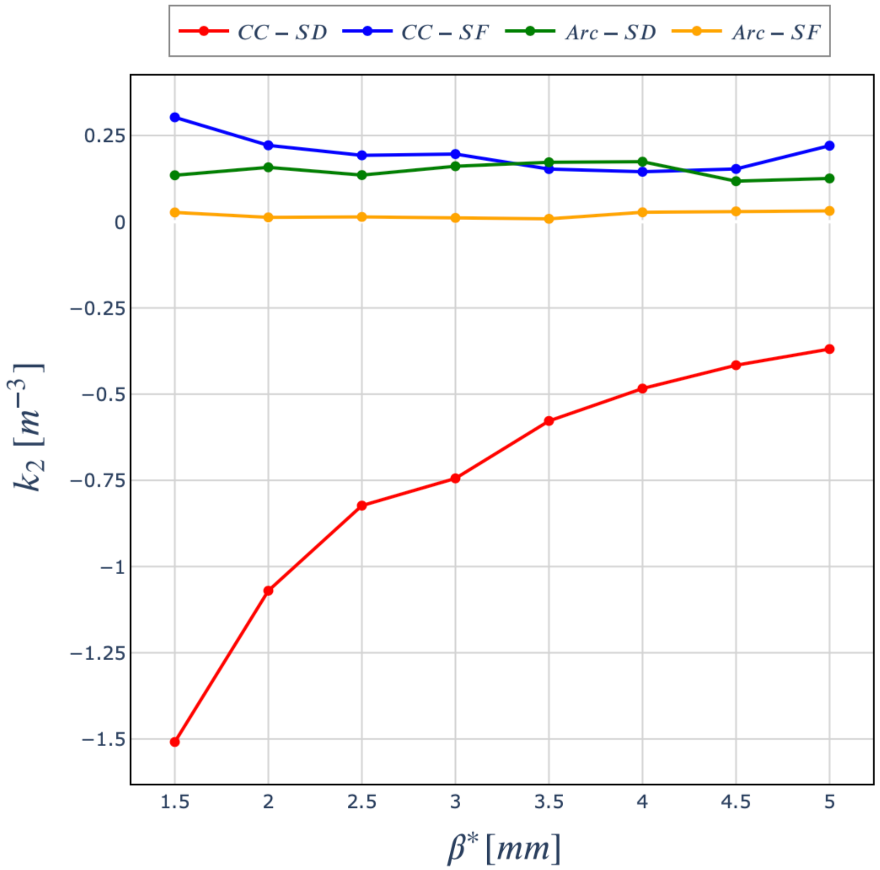


Sensitivity study – Sextupole strengths

Sextupole strengths in the CC decrease for larger β^*(chromatic effects decrease):

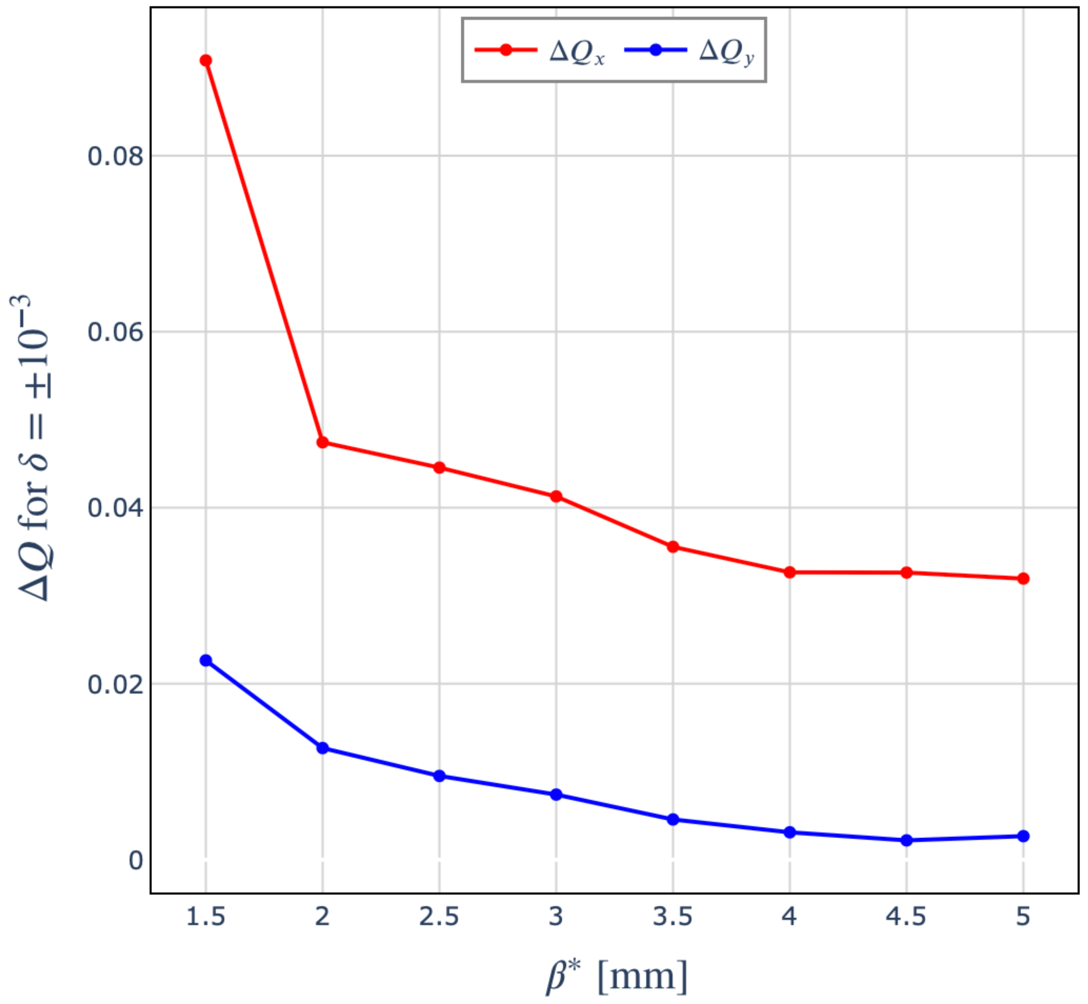
- Smaller magnetic field in sextupole magnets, smaller feed-down;
- Lattice probably less sensitive to errors.

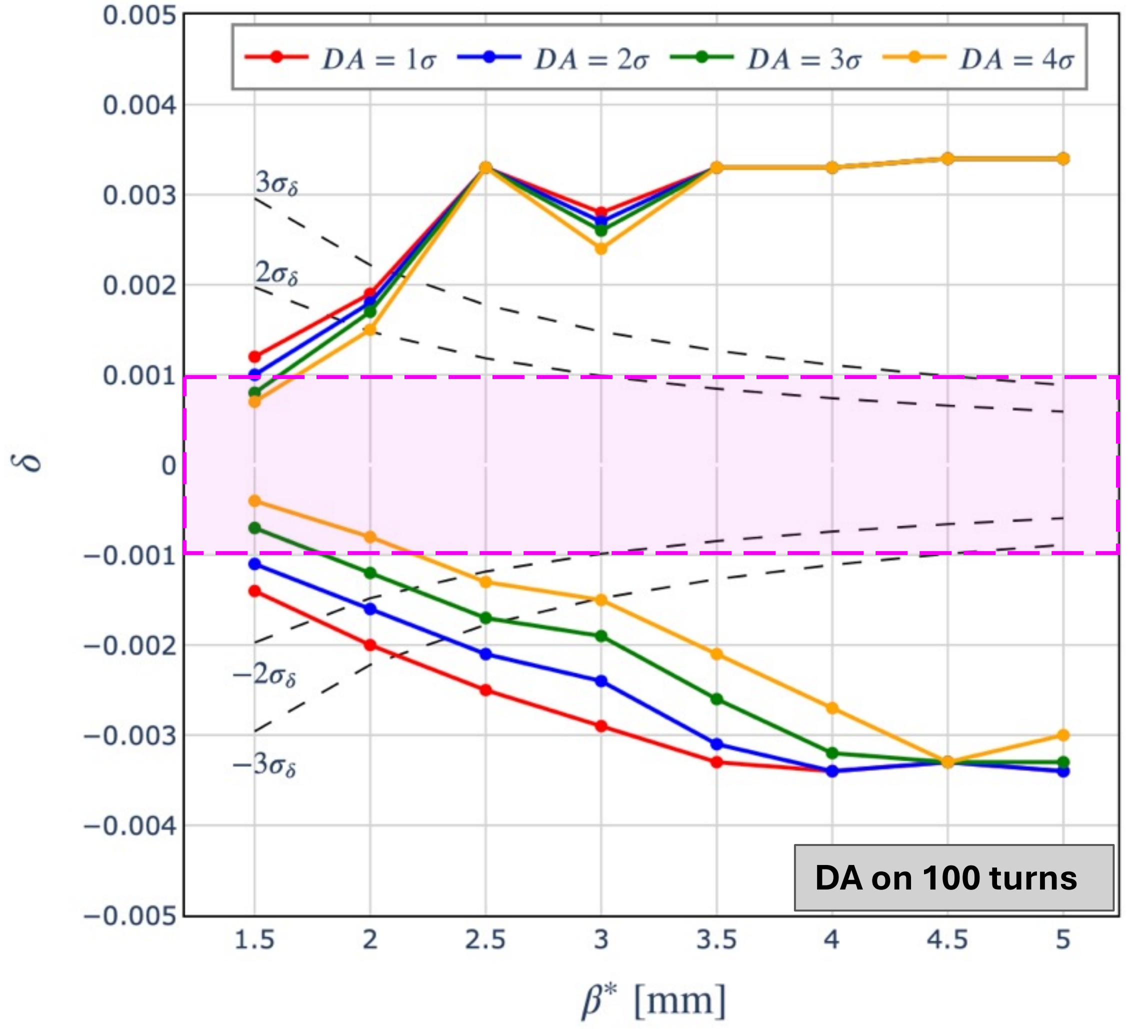




Sensitivity study - Tune spread

Difference in tunes for particles with $\delta = \pm 10^{-3}$

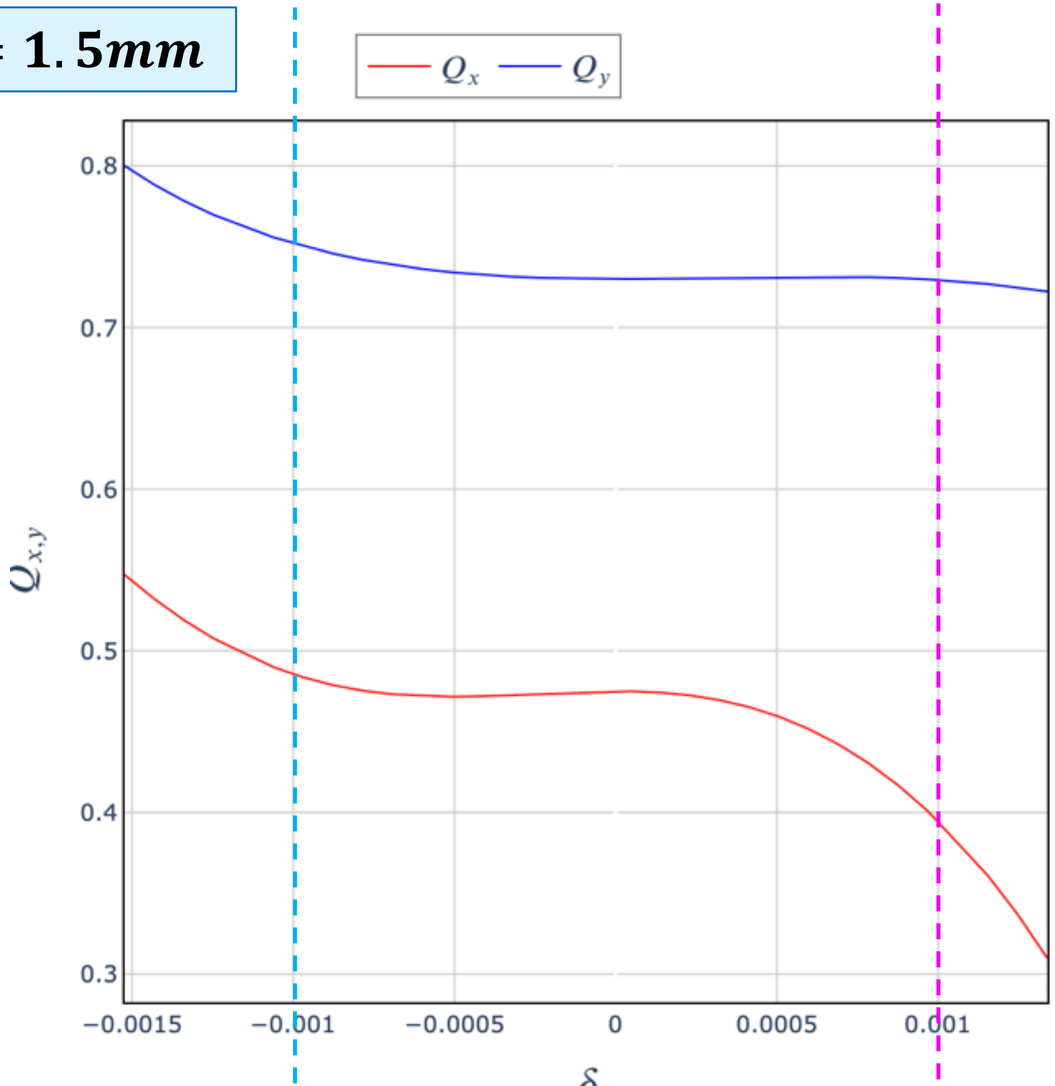


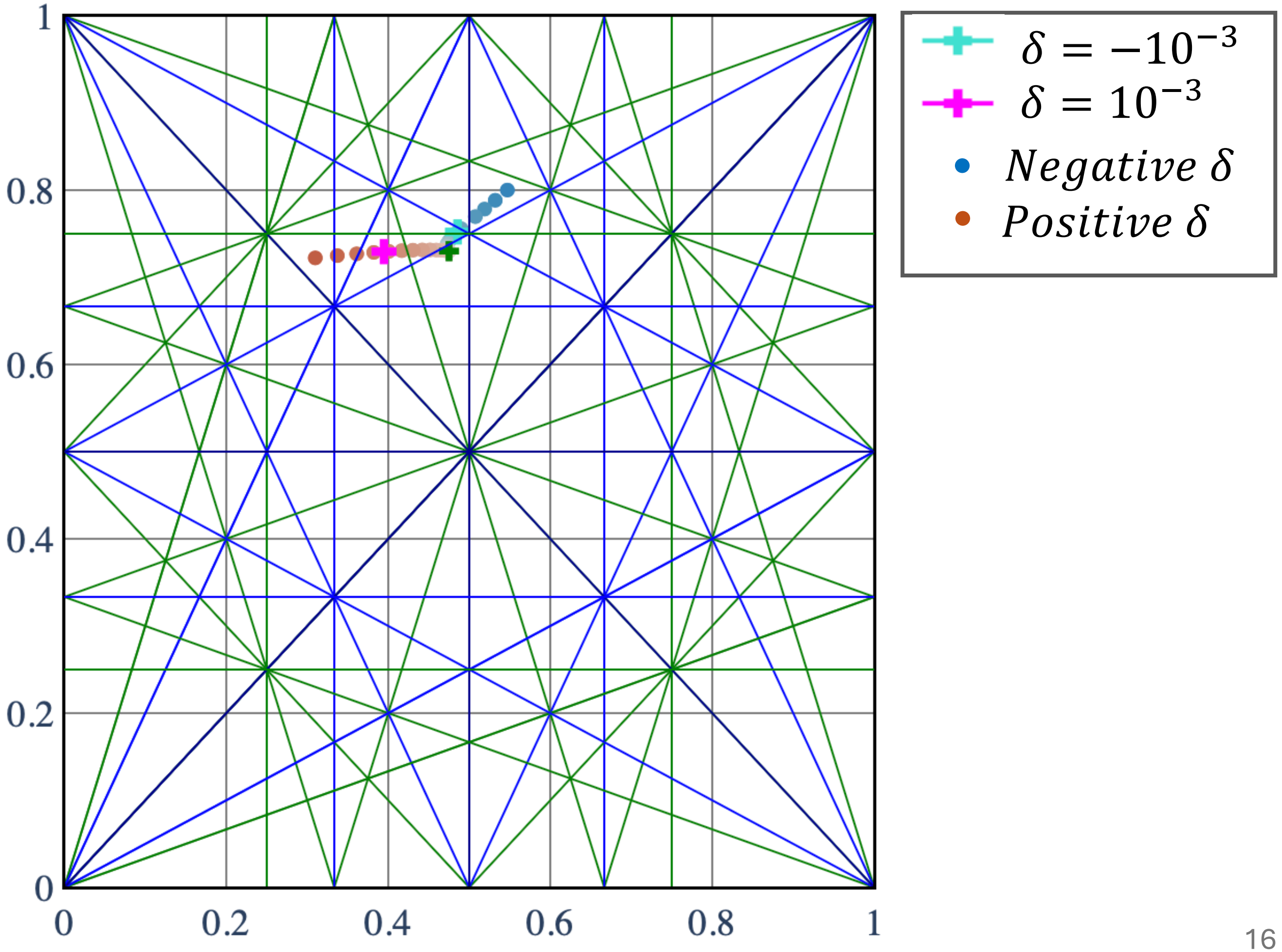


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 1.5mm$

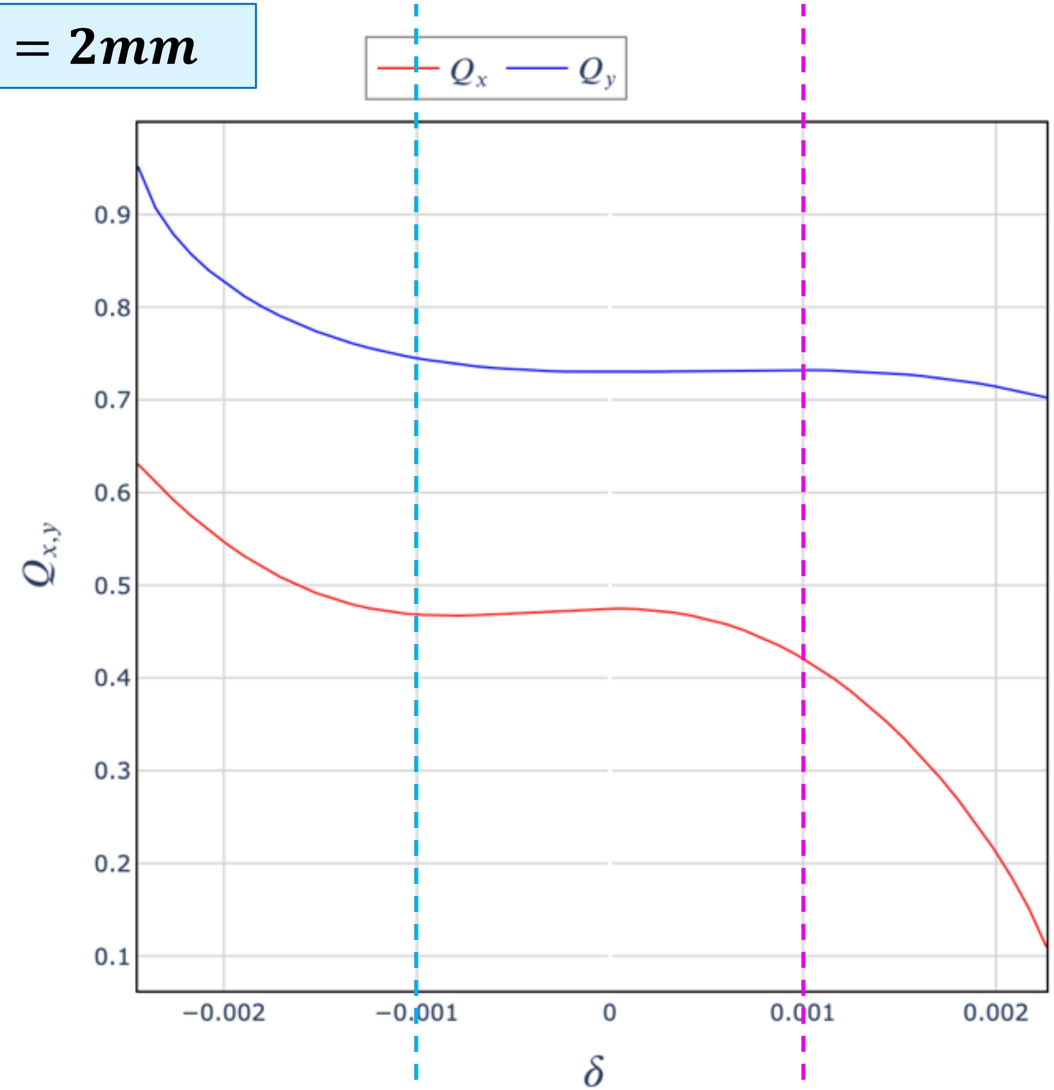


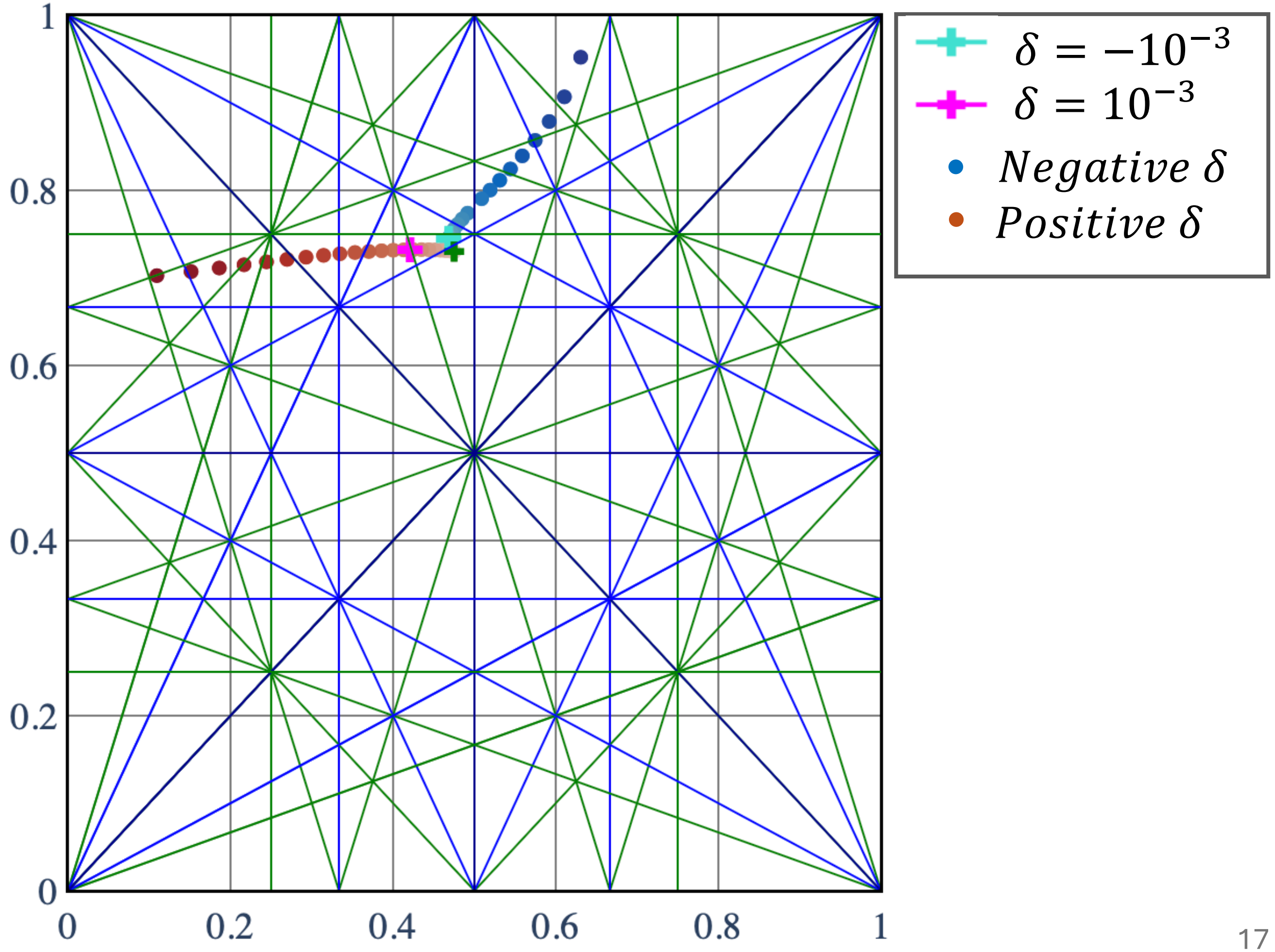


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 2mm$

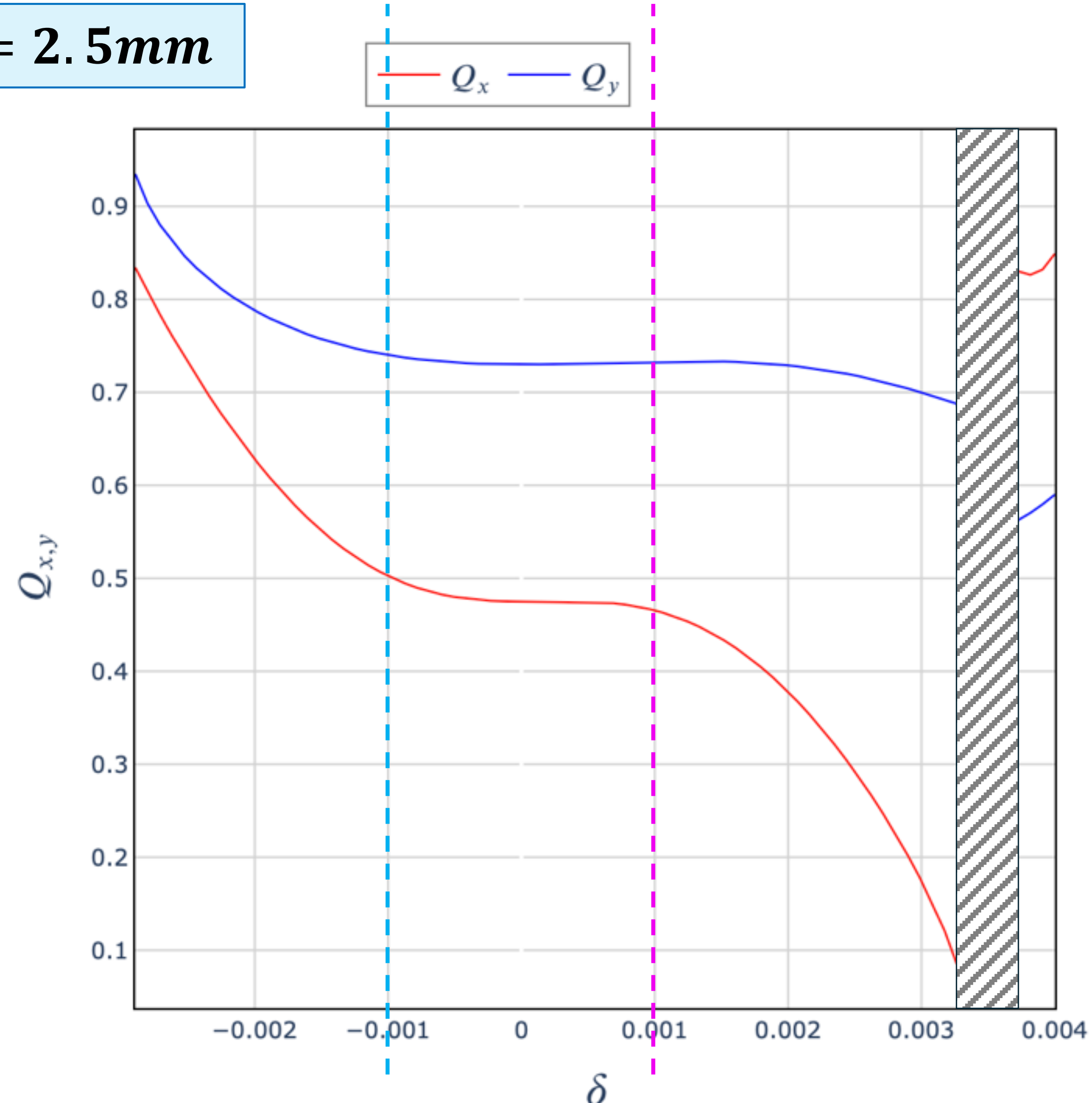


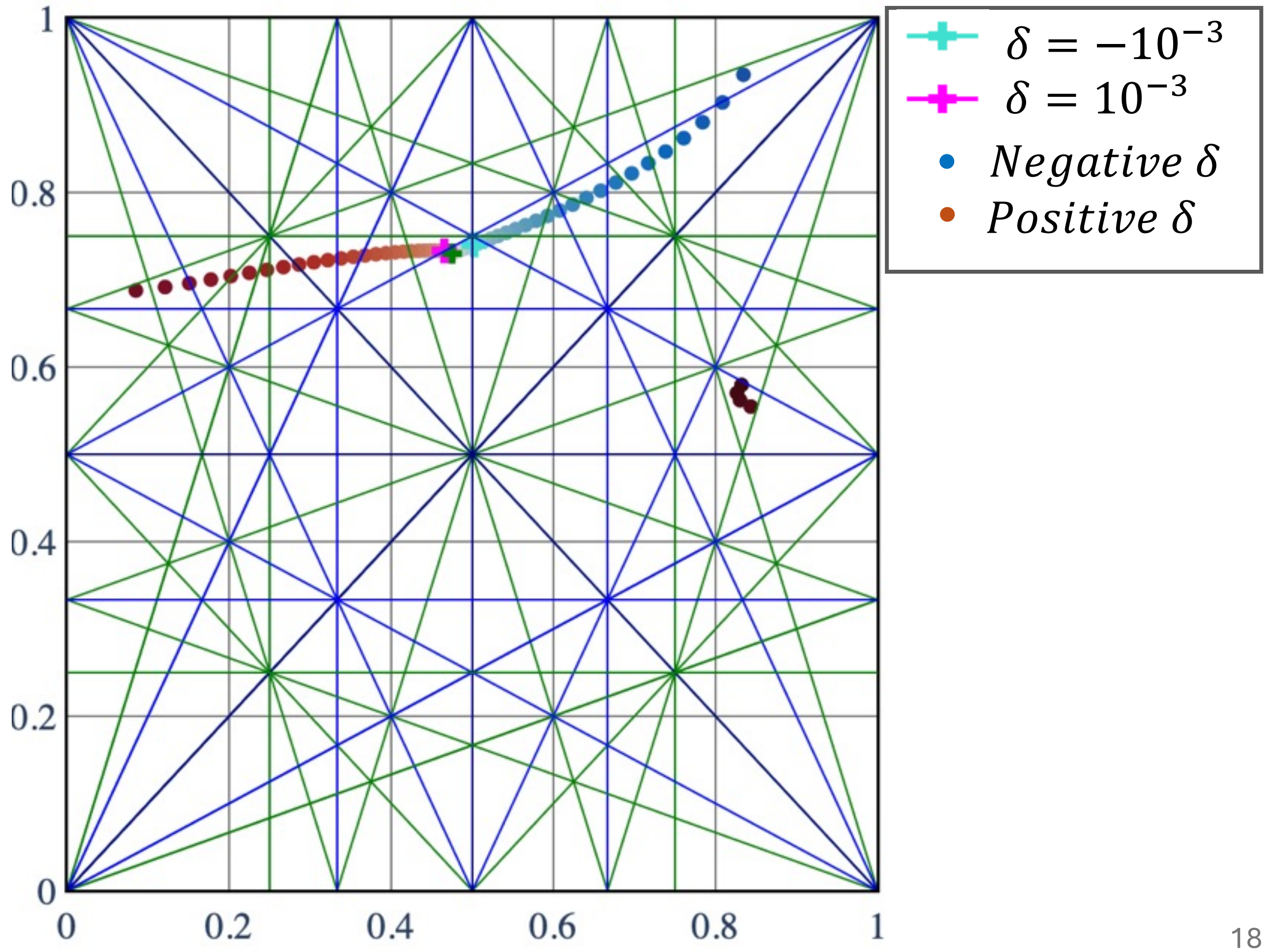


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 2.5mm$

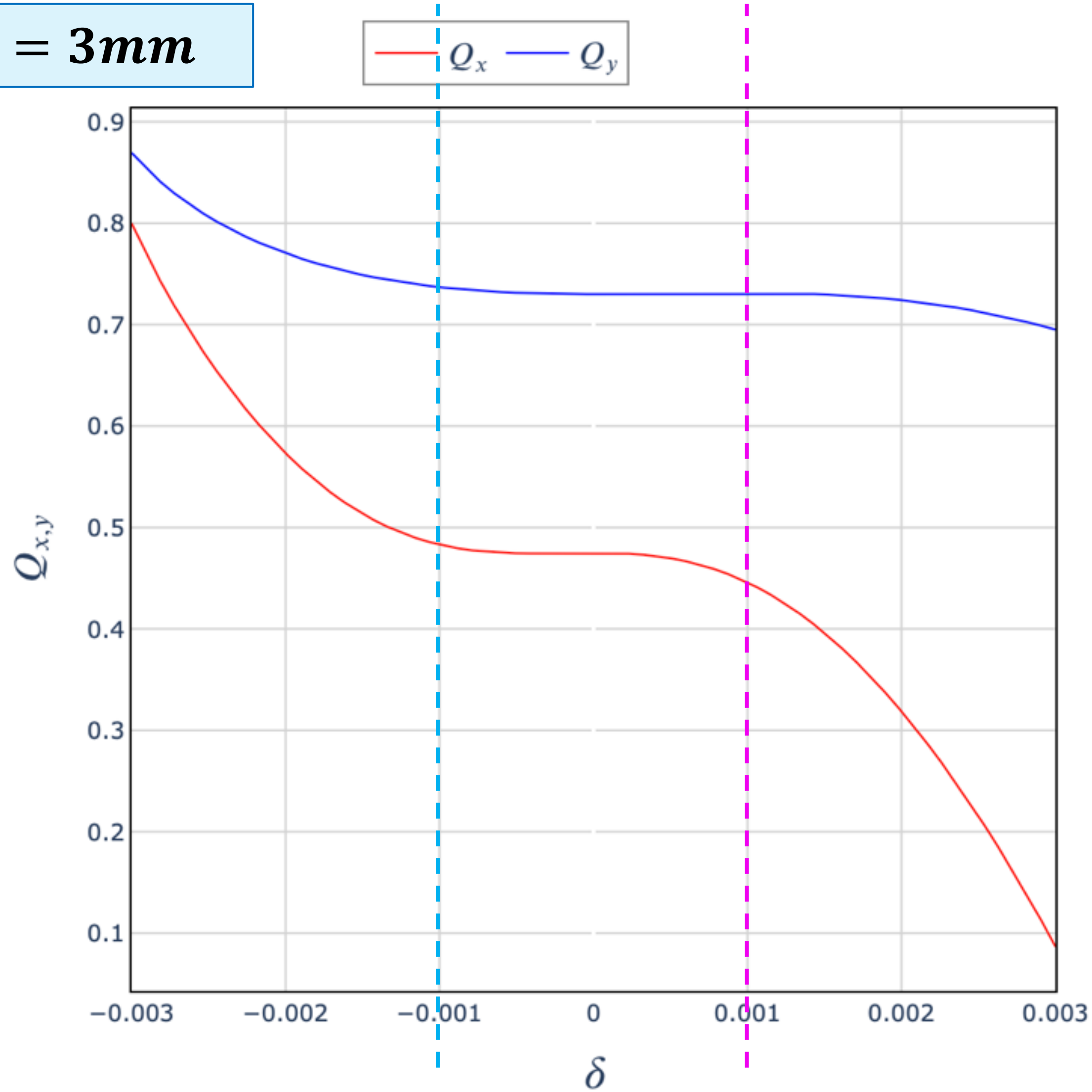


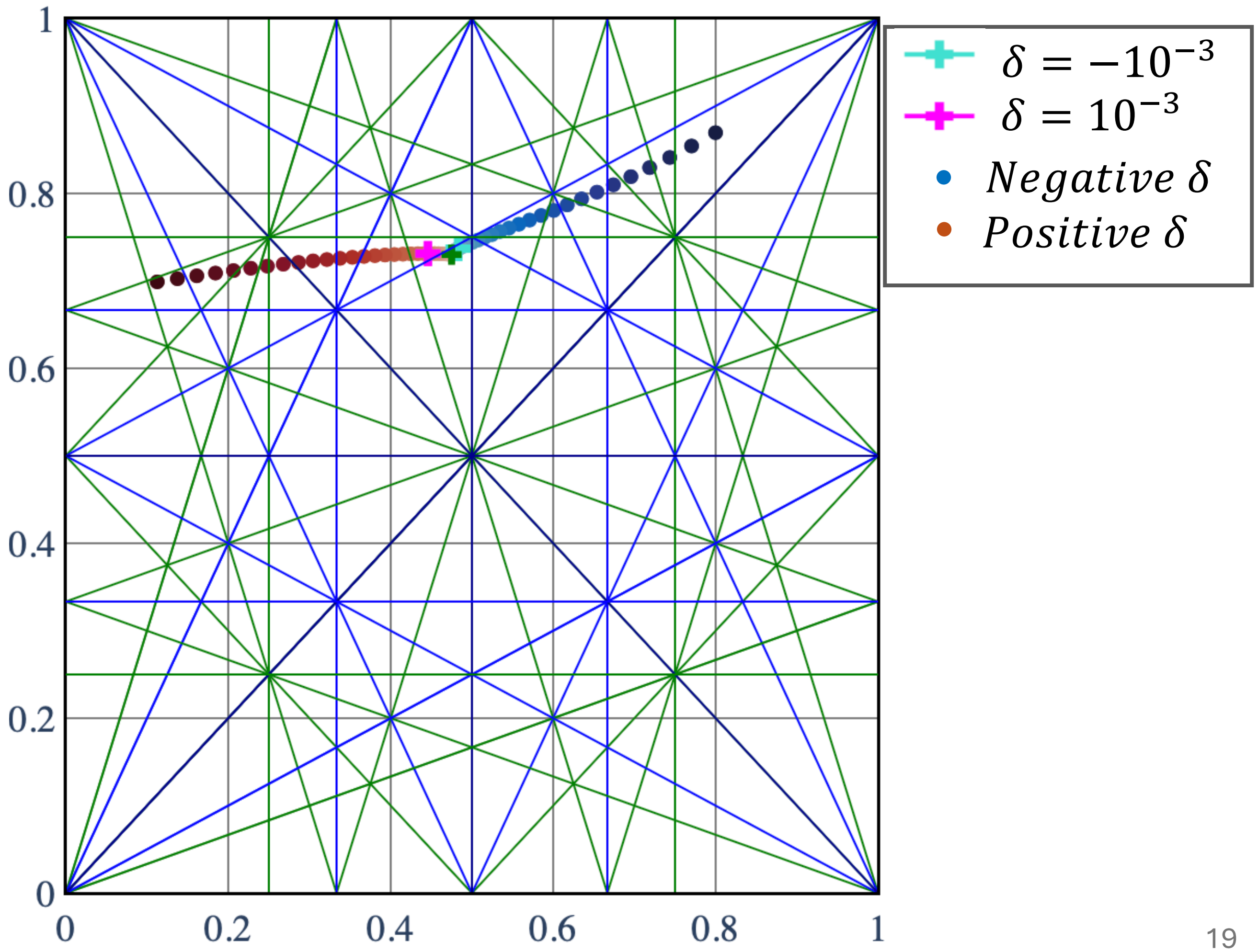


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 3mm$

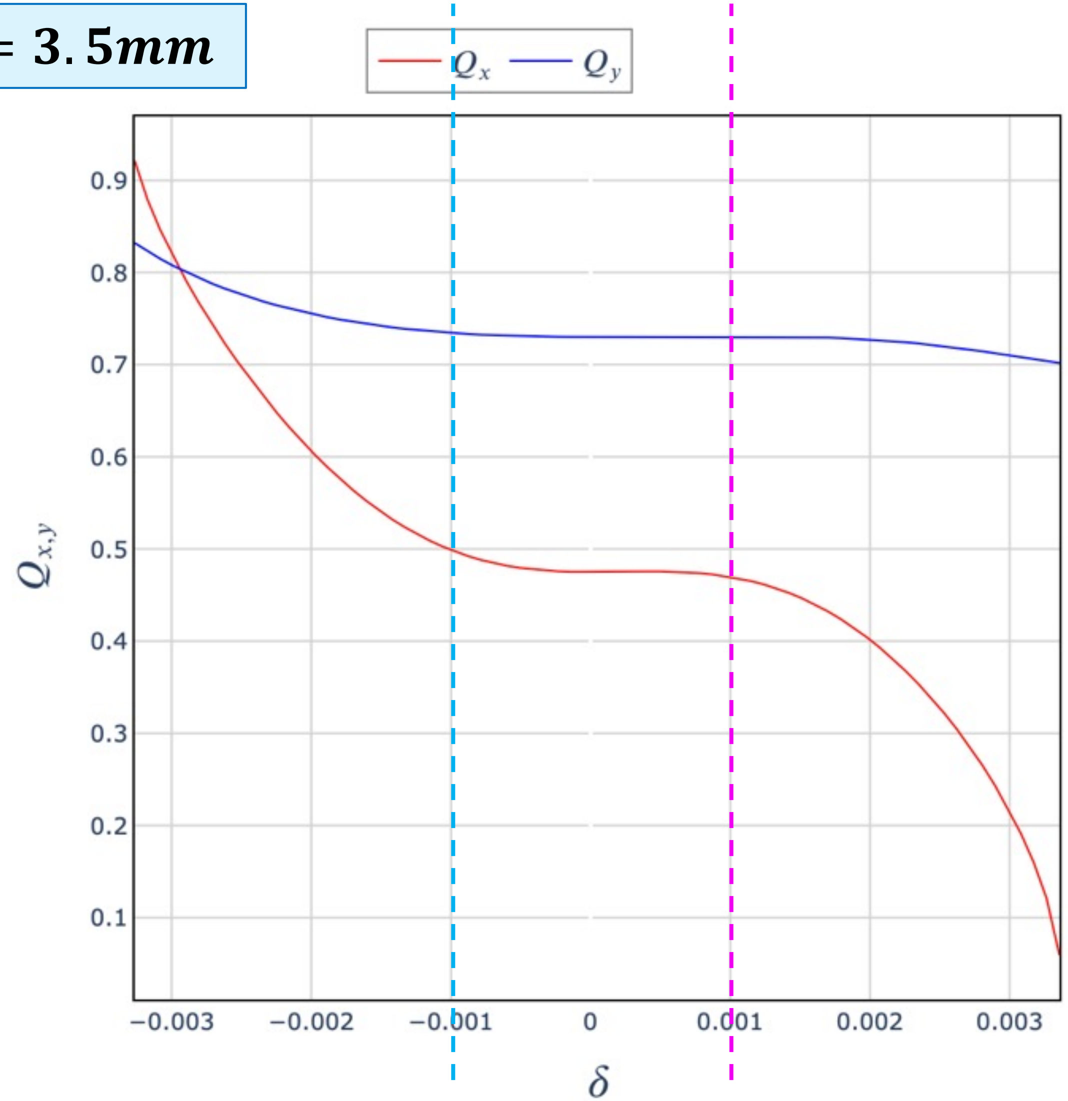


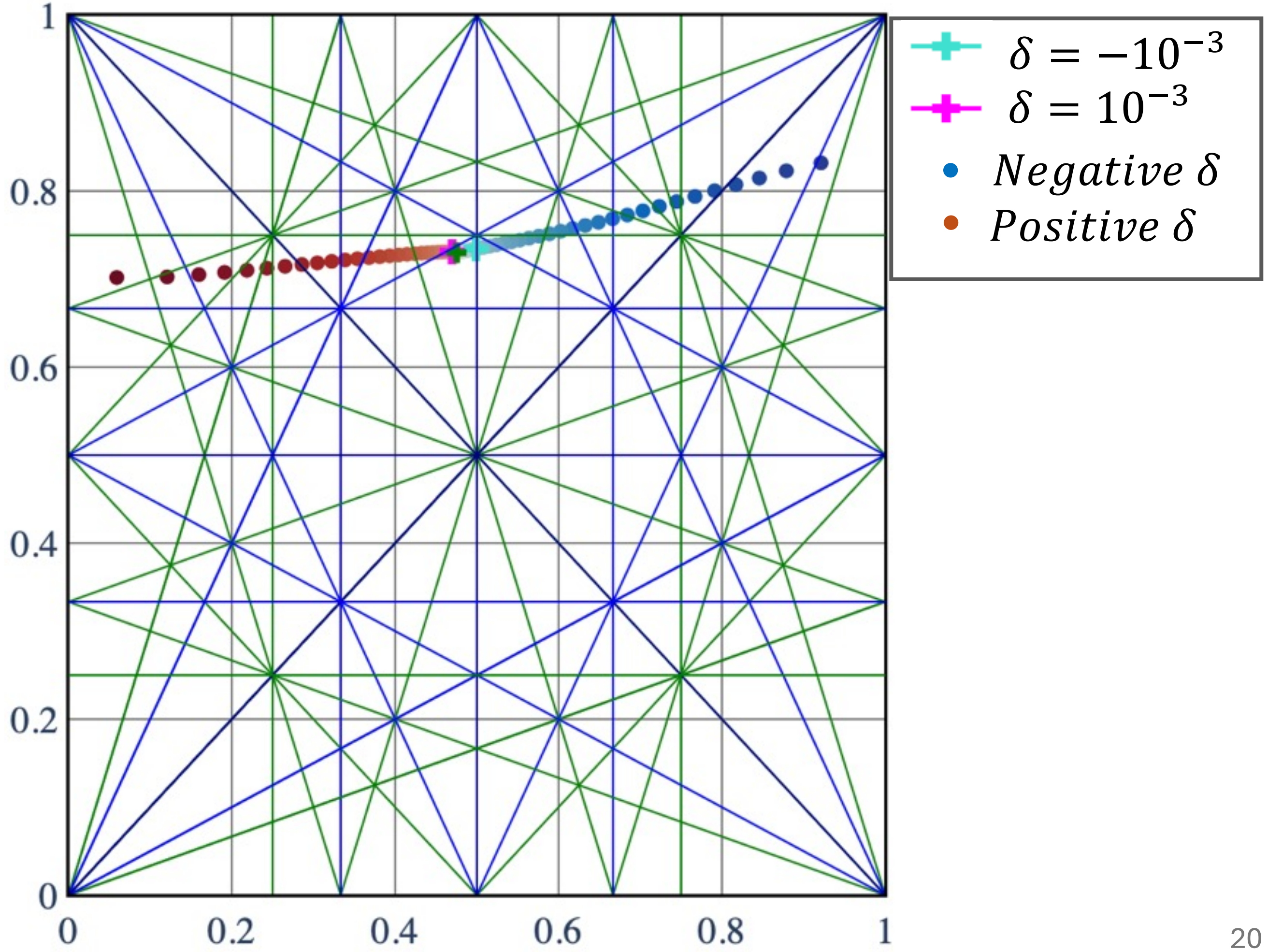


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 3.5mm$

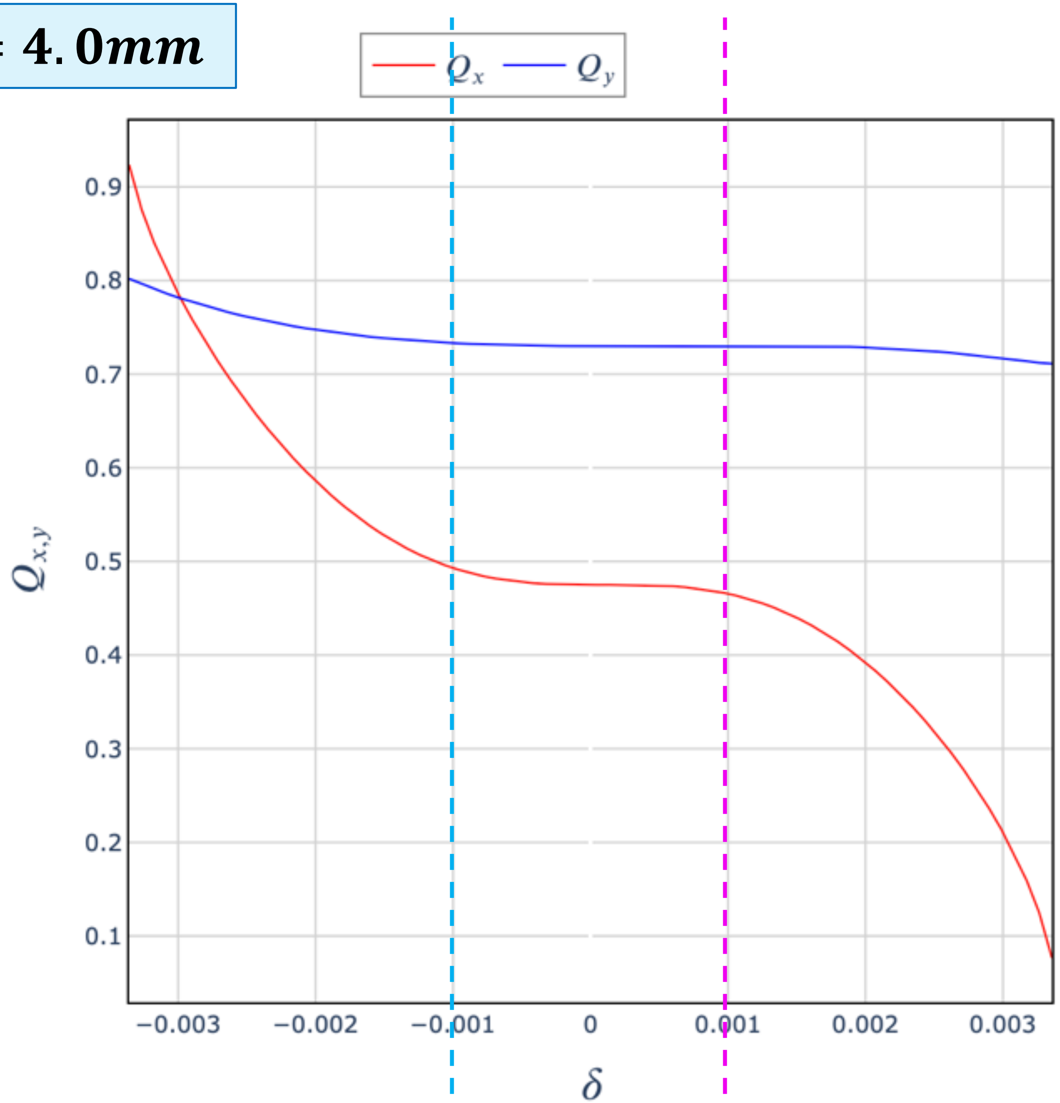


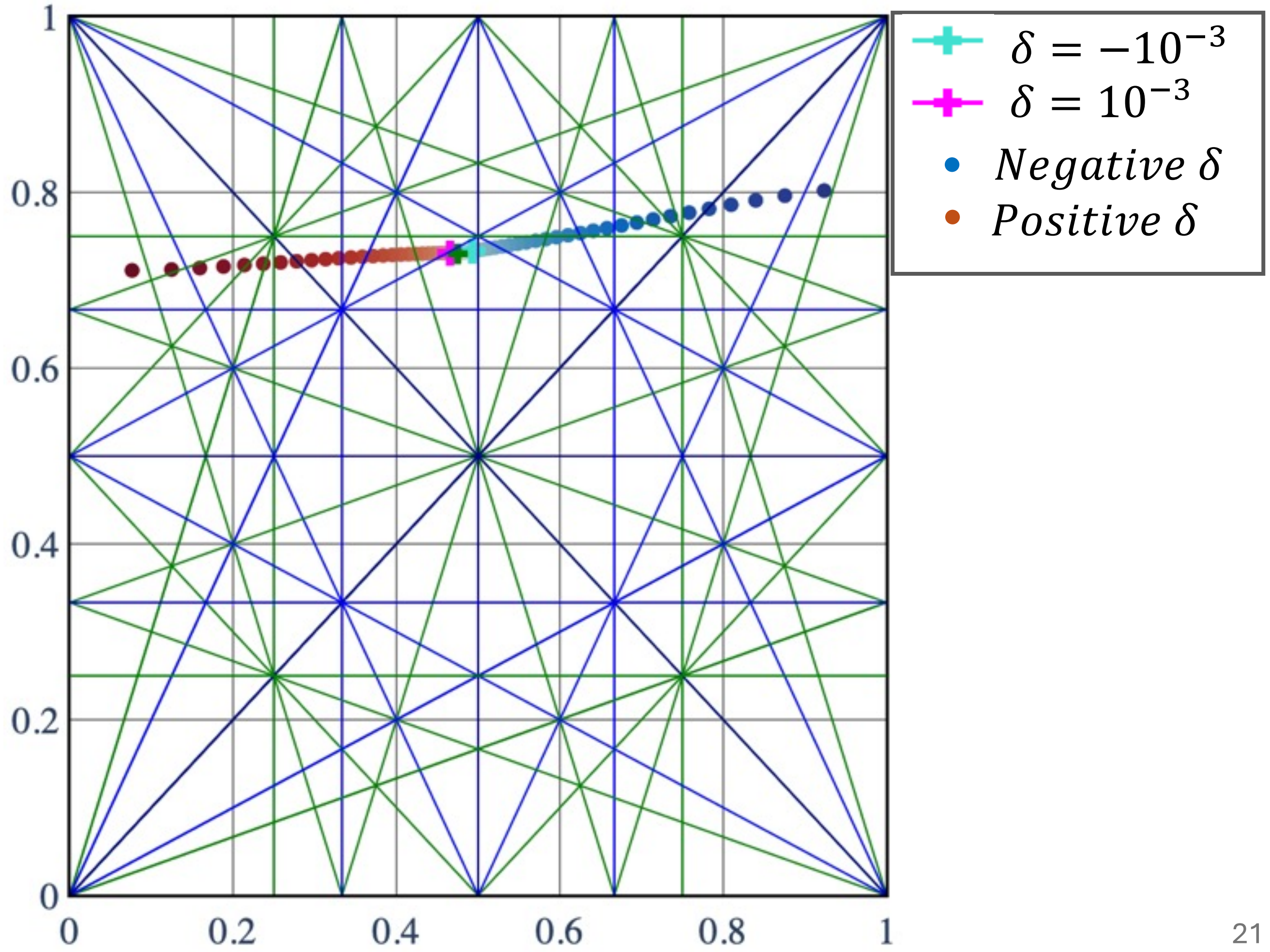


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 4.0mm$

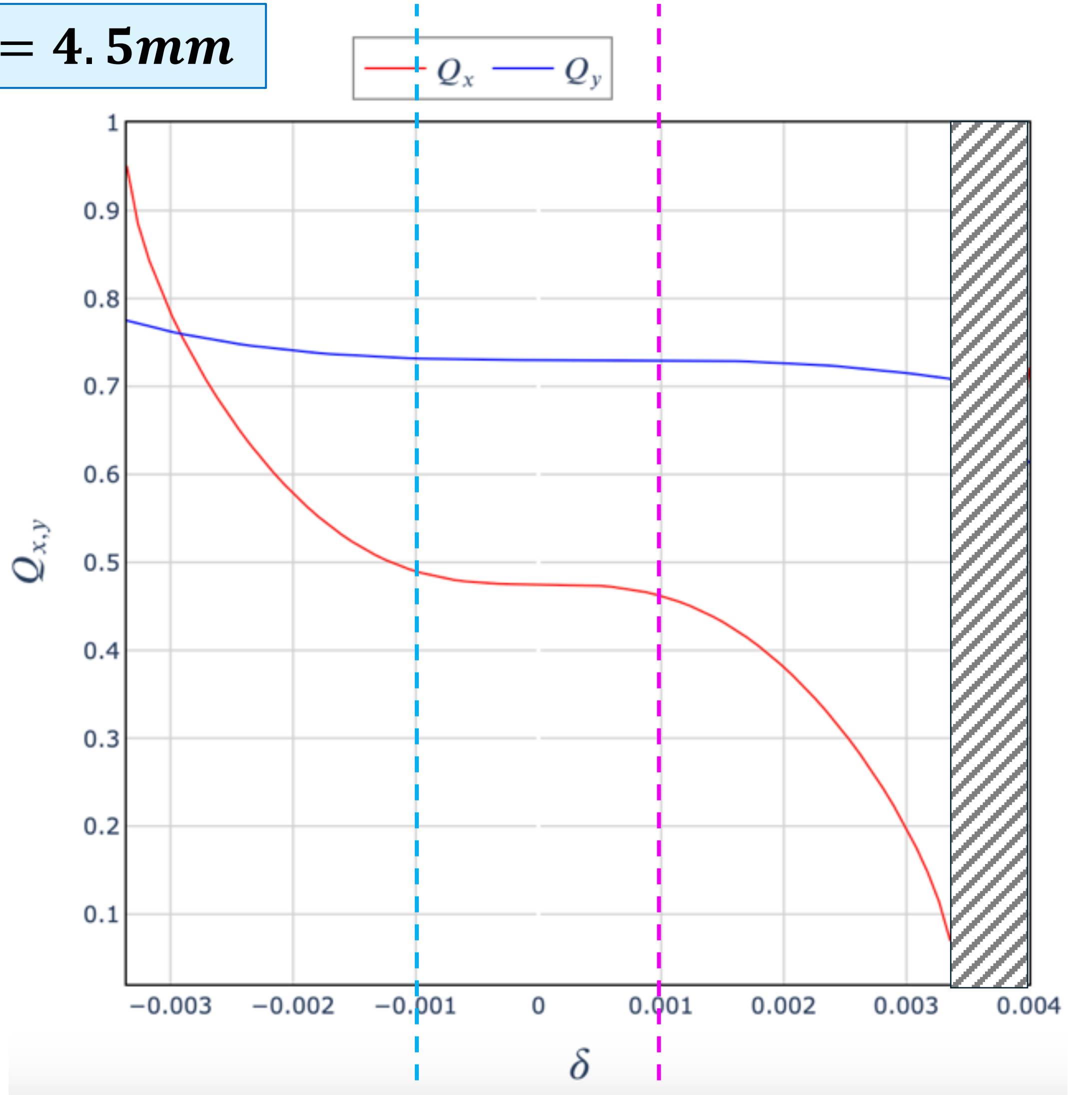


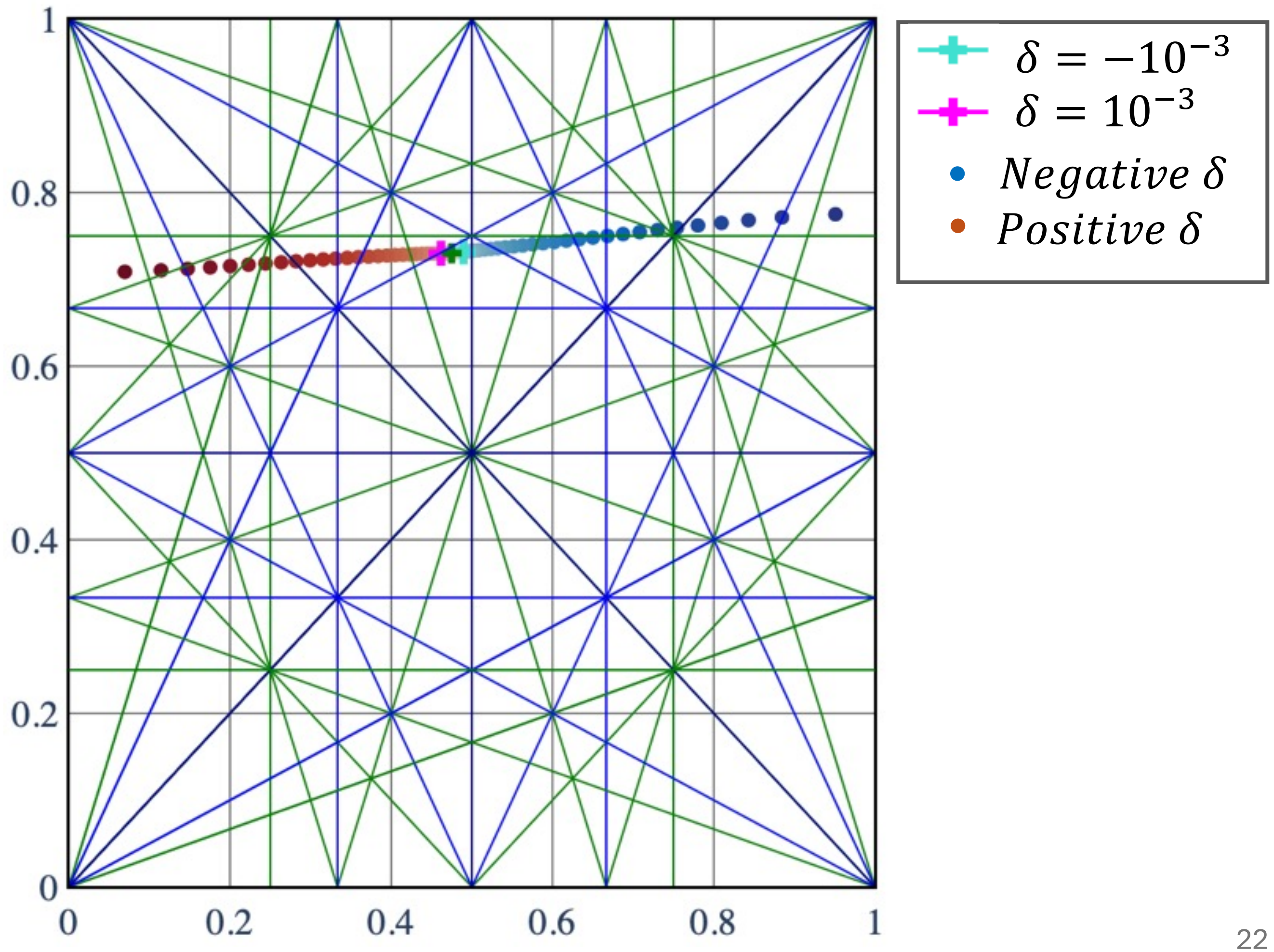


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 4.5mm$

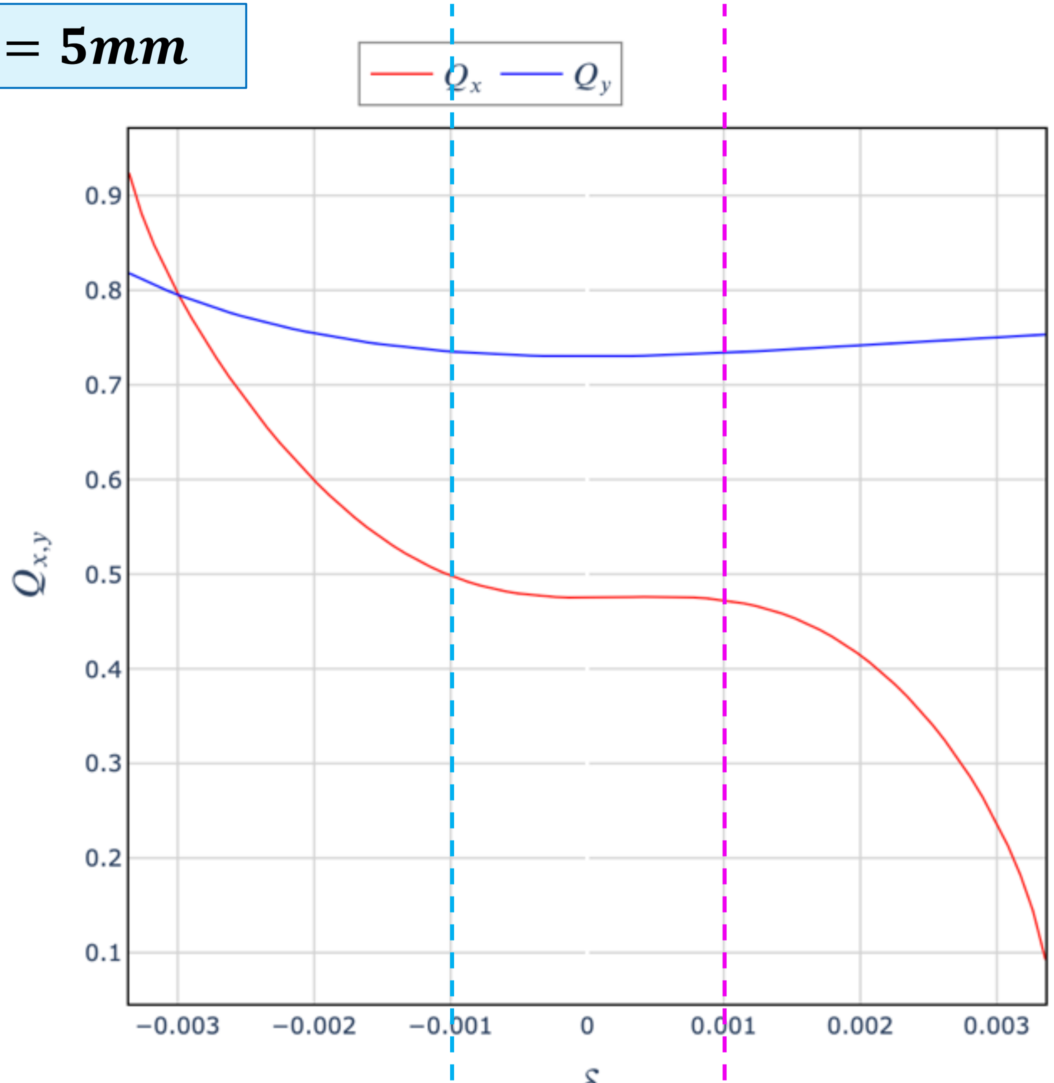


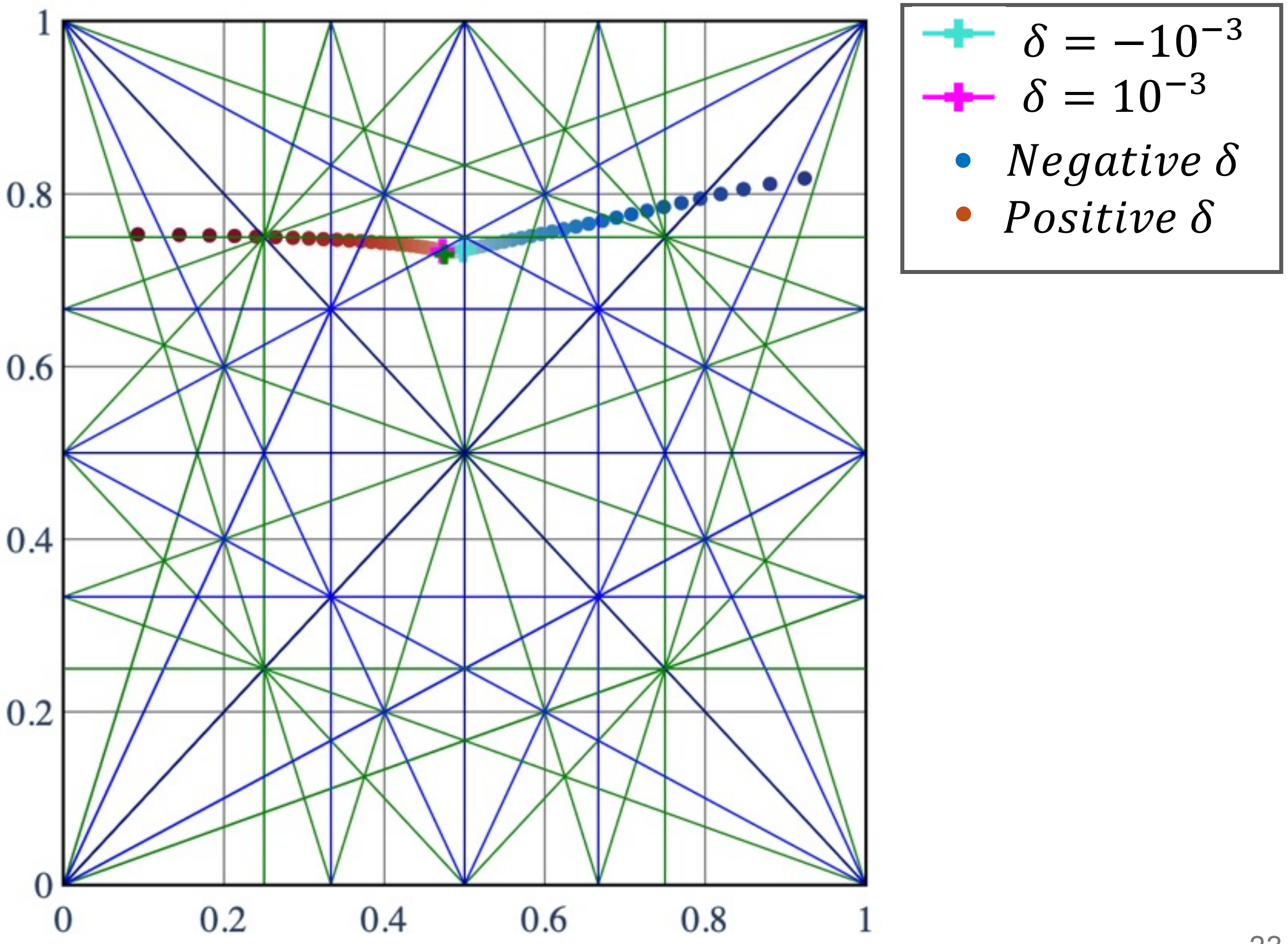


Sensitivity study - Tune spread

Still quite large differences in tunes for off-momentum particles

$\beta^* = 5mm$

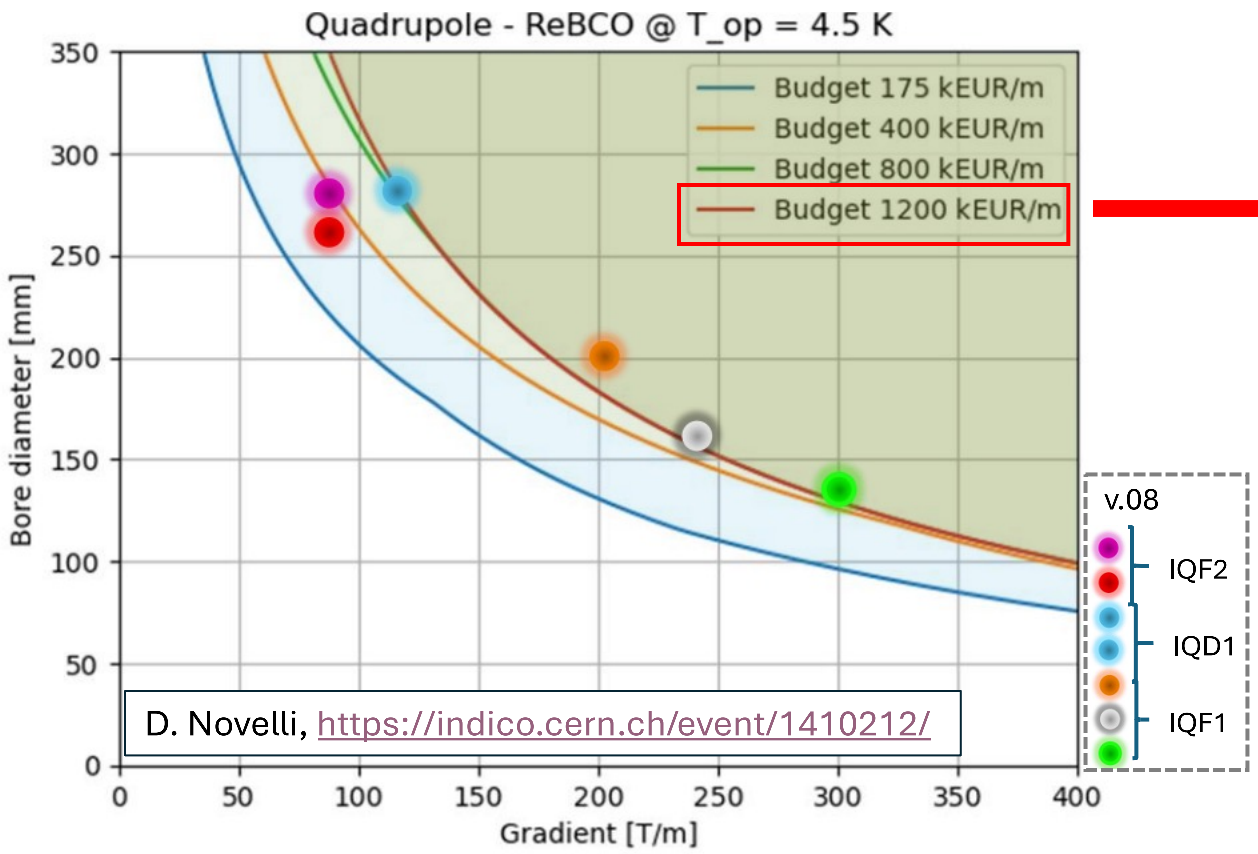


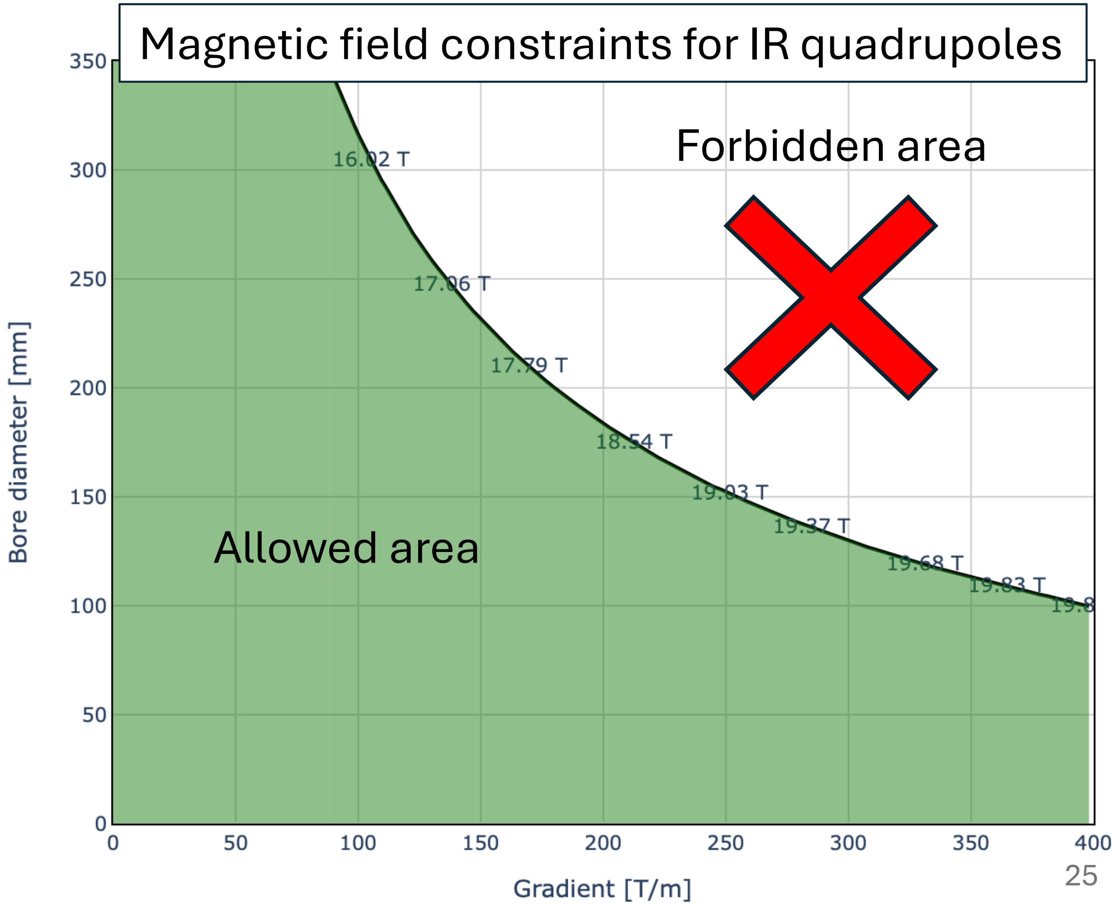


Sensitivity study for updated magnetic field

Updated magnetic field for IR quads

- **Goal:** Adapt the design such that the magnetic field at the magnet aperture is in the allowed area of the “A-B plots” for HTS quadrupoles provided by the magnet team.

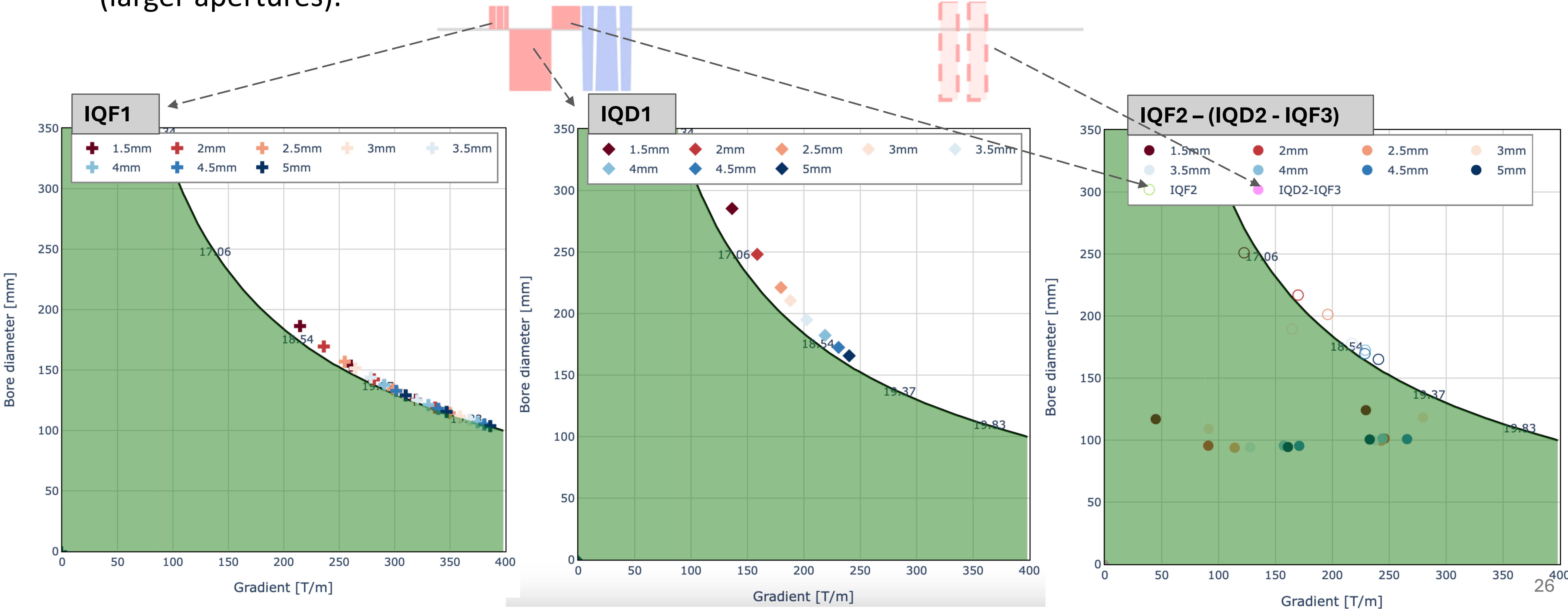




Updated magnetic field for IR quads

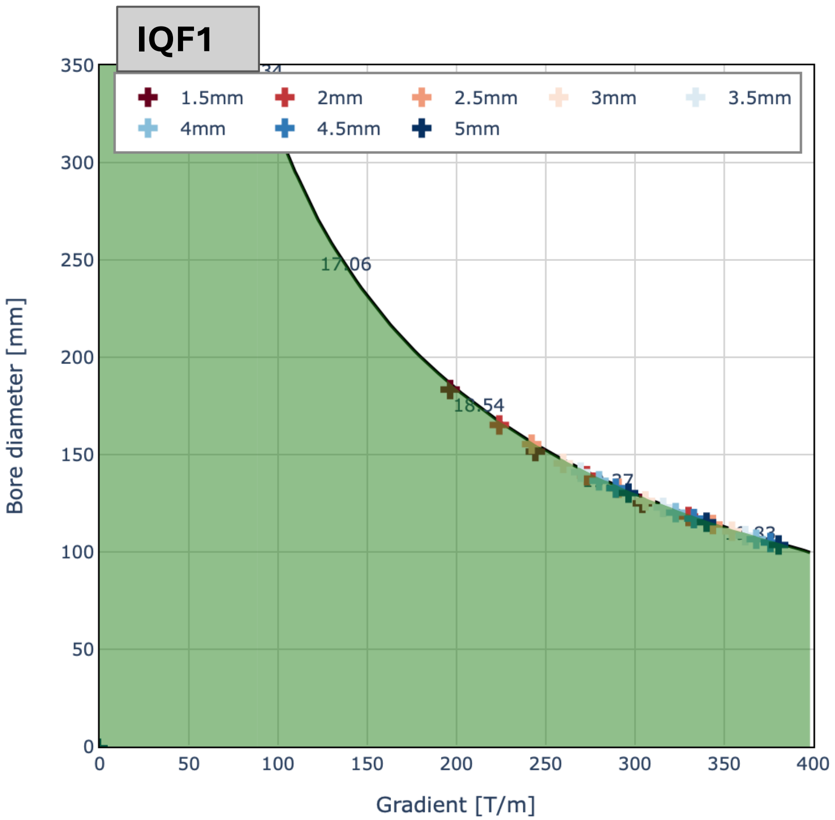
IR quads for the sensitivity study :

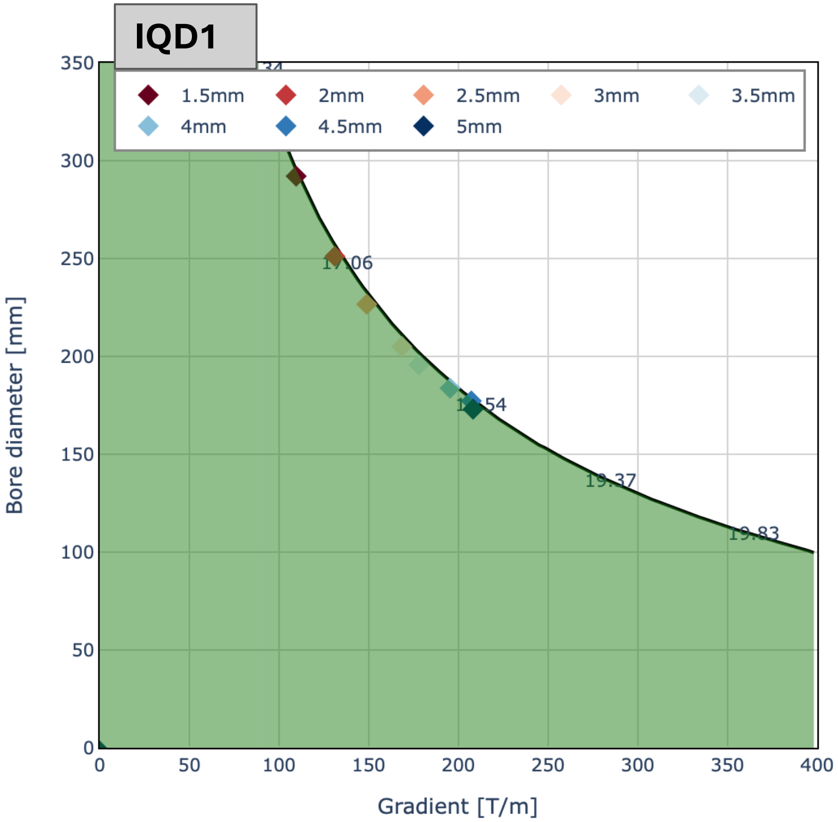
First quadrupole (divided into 3 pieces – IQF1) and second quadrupole (IQD1) of the FF triplet always in the forbidden zone → Less realistic field for $\beta^* = 1.5mm$ because of the larger β in the FF triplet (larger apertures).

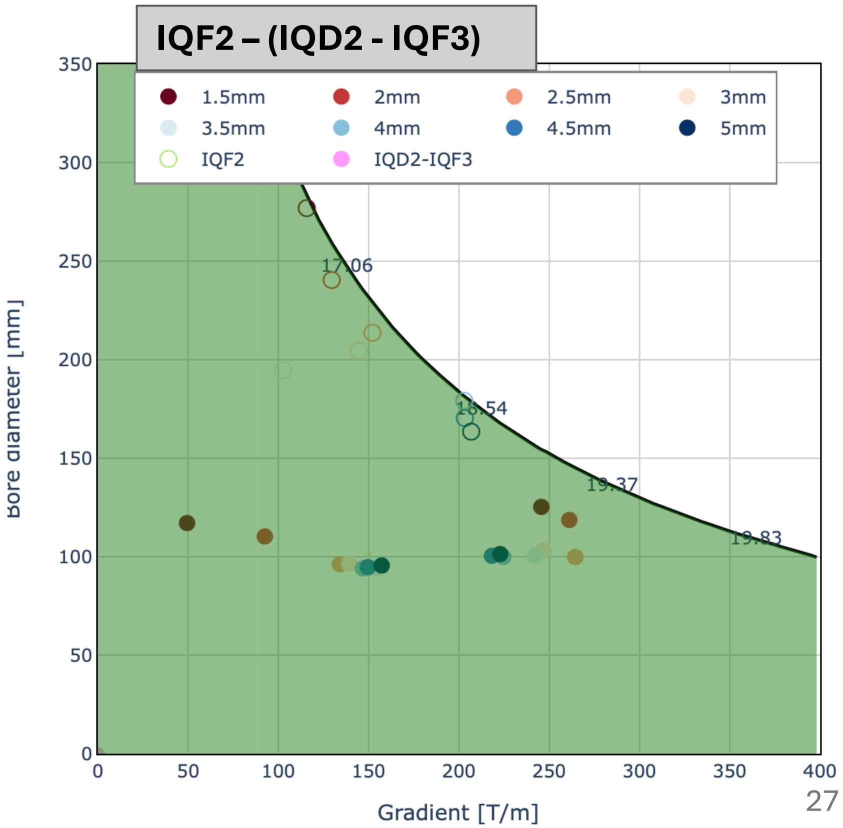


Sensitivity study for updated IR quads

- The same procedure was used with the maximum **magnetic field of IR quadrupoles** adjusted to be in the **allowed area**.
- *Note:* the magnetic field is still **too strong in the CC and in the arcs** with **4 cm W** shielding (A-B plots not yet available for the combined function magnets).

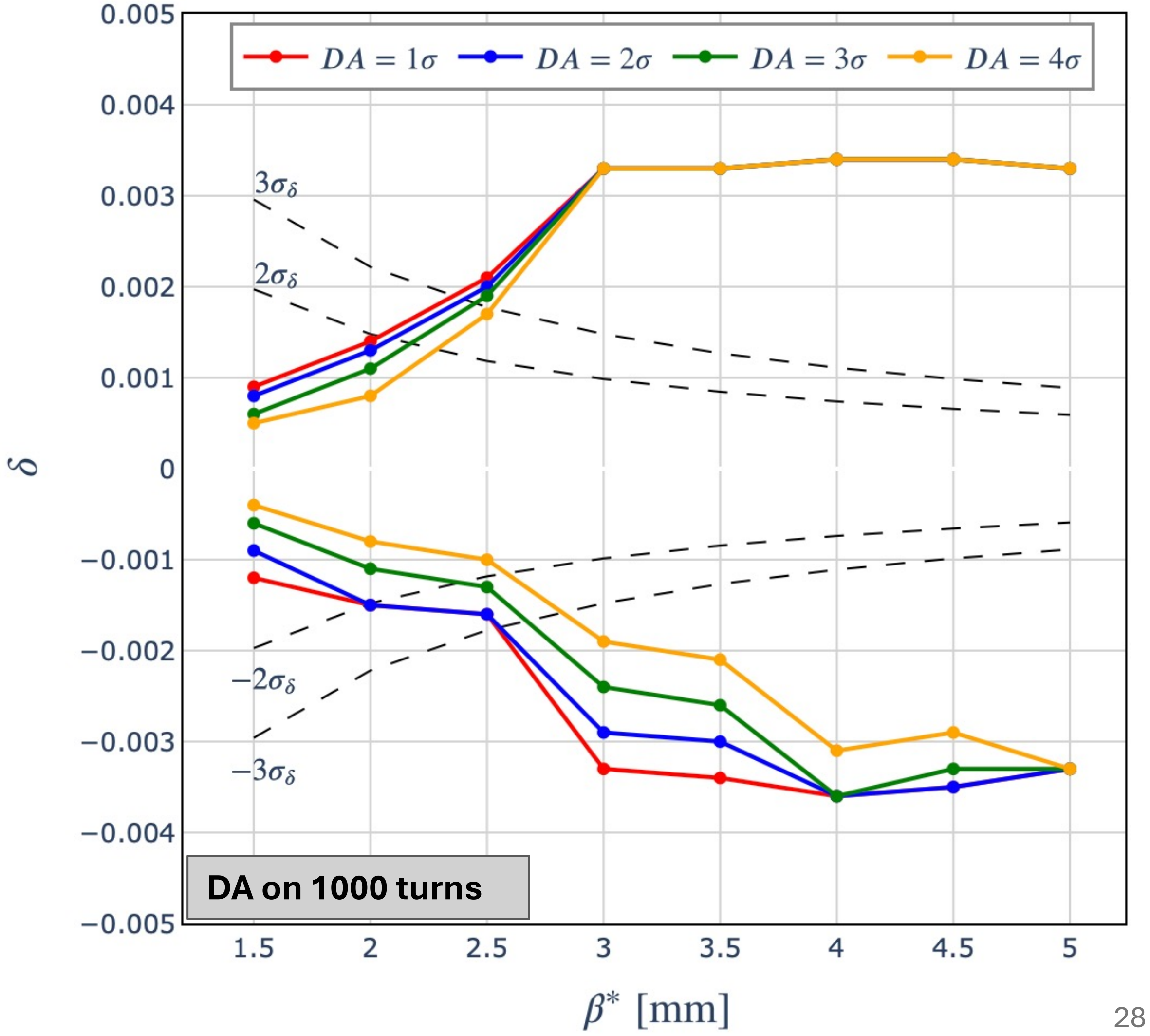






Sensitivity study for updated IR quads

- Similar conclusions than before: Sufficient momentum acceptance ($\sim \boldsymbol{3\sigma_d}$) with DA $\geq 4\sigma$, for $\boldsymbol{\beta^* = 3mm}$ (even though the magnetic field is still too high in the CC and in the arcs).
- No significant changes between the DA computed for 100 turns and the DA computed for 1000 turns.



Sensitivity study for updated IR quads

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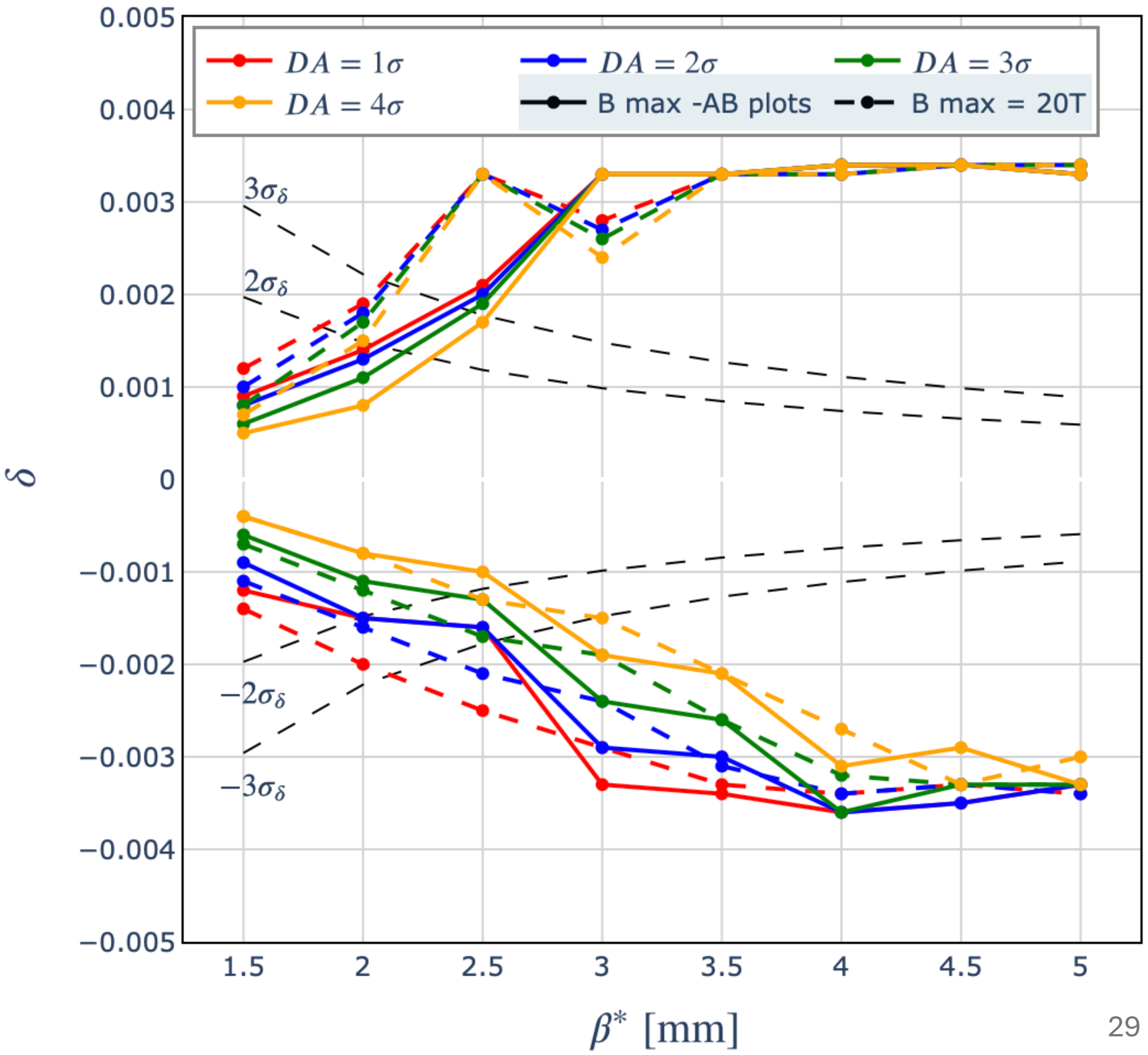
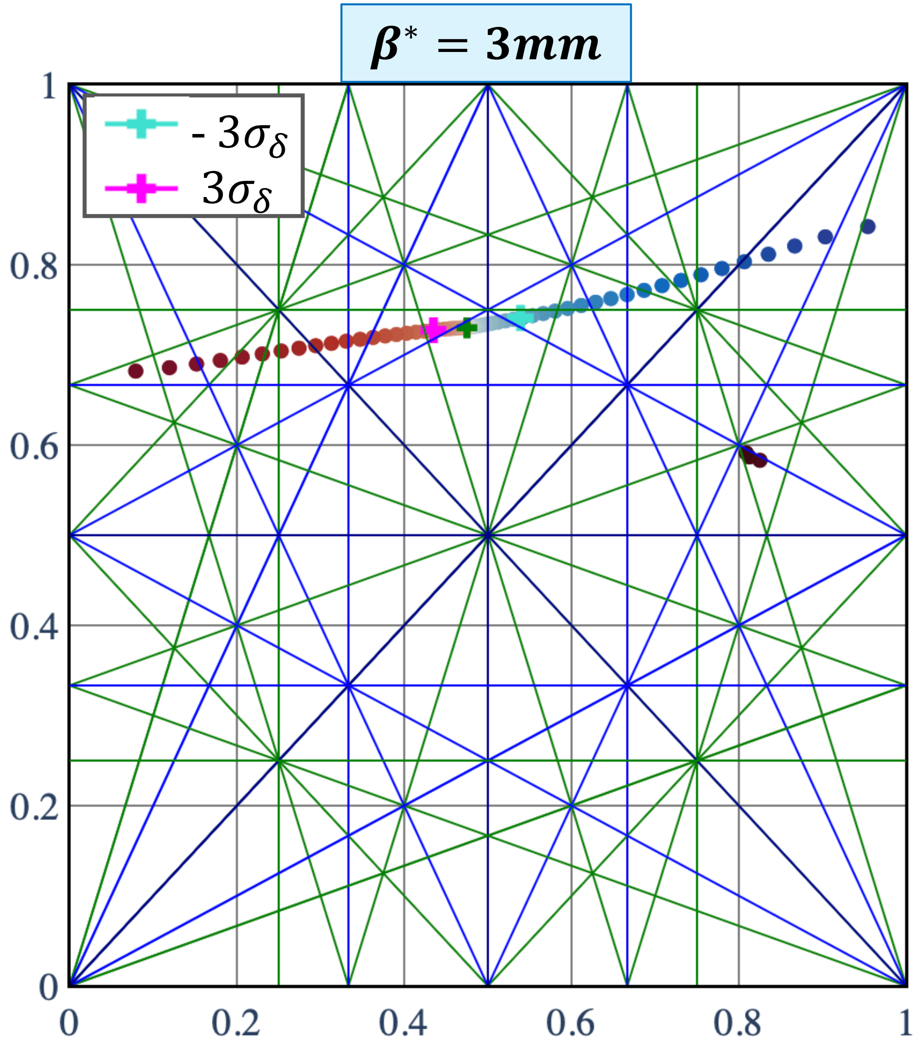
- No significant changes between the DA computed for 100 turns and the DA computed for 1000 turns.

- *General trend:* as expected, slightly reduced momentum acceptance compared to the study with 20T maximum field for very small β^*.



Other considerations

- Performances for the different β^* strongly depend on small optimizations and phase advances in the machine:
  - β_x must reach a minimum before the last two IR quads
  - Influence on the second-order dispersion
- The **tune spread** with energy offset remains **significant**, covering a large area of the tune diagram:
  - Possible **particle loss** when crossing resonance (perhaps not observed here due to the **discretization** used for momentum acceptance computations).
- Tune spread seems to be dominated by **third-order chromaticity** → Best practices for setting elements at the correct phases to control this chromaticity?

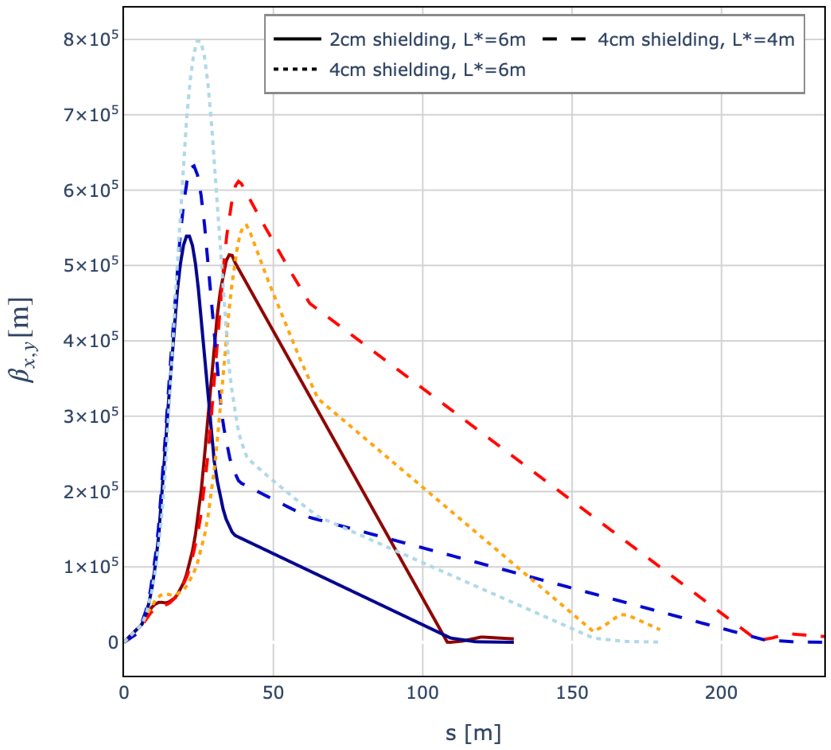


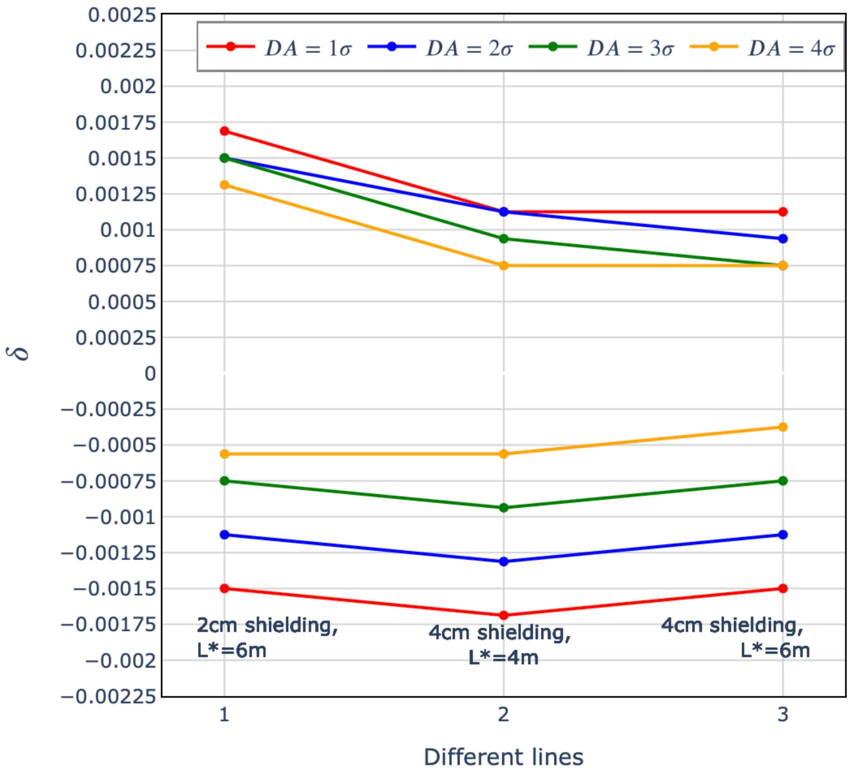
Influence of L*

Influence of L*

<u>Adaptation of the IR:</u> Set the L* to 4m instead of 6m (20T for maximum field; $\beta^* = 1.5mm$)

- Reduction of the maximum beta (increase of ~15-20% of the maximum β-functions compare to the lattice with 2cm shielding in the IR).
- **No significant momentum acceptance improvement by reducing L*** (L* small compared to triplet length); small reduction of sextupole strengths in the CC.





Next steps

Next steps

In parallel

Improvements of the lattice for $\beta^* = 1.5mm$

- Modify the CC to achieve true –I transformation between both sextupoles of a pair.
- Enough elements at the correct phase to correct higher-order chromaticities; multi-point matching
- Explore the lattice with MAD-NG to see the limitating RDT

Study other effects on (a working) lattice ($\beta^* > 1.5mm$)

- **Implement** the capability to have a combined function **dipole-sextupole** magnet in Xsuite; Evaluate the **effects of thick sextupoles** and compensate for the abberations.
- Preliminary (alignment and field) **error studies**
- Starfish plots to monitor geometric aberrations

To keep in mind

- High (unrealistic) **magnetic field values in CC and arcs**→ Try to limit the magnetic field for the lattice with 4 cm W shielding.
- Input needed from the magnet team regarding the **element interconnection length** (impact on **neutrino radiation**).
- **No** clear knobs to **control the working point** (transverse tunes) in the current lattice.

Thank you for your attention

The lattice presented is still a work in progress and subject to change in the future