Status of the Muon Collider Lattice design

Marion Vanwelde

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Challenges of the Muon Collider Ring

10TeV Muon collider

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

Parameter	**Symbol**	**Value**
Beam energy	E	$5000\ GeV$
Luminosity per IP	$\mathcal{L}$	$\sim 20 * 10^{34} cm^{-2}\ s^{-1}$
Bunch population	N_p	$1.8\ *\ 10^{12}$
Repetition rate	f_r	$5\ Hz$
Normalized transverse rms emittance	$\varepsilon_{nx} = \varepsilon_{ny}$	$25\ \mu m$
Geometric transverse rms emittance	$\varepsilon_{gx} = \varepsilon_{gy}$	$0.528\ nm$
Longitudinal geometric rms emittance	ε_L	$70\ mm$
Rms bunch length	σ_z	$1.5\ mm$
Relative rms energy spread	$\delta = \frac{\sigma_E}{E}$	$0.1\ \%$
Beta function at IP	$\beta_x^* = \beta_y^*$	$1.5\ mm$
Circumference	C	$\sim 10\ km$

Muon collider: Challenges

Relative rms energy spread	δ	$0.1\ \%$
Beta function at IP	$\beta_x^* = \beta_y^*$	$1.5\ mm$

- Very **small $\boldsymbol{\beta}^*$** at IP → β of ~700-800 km in the Final Focusing (FF) quadrupoles
- **Large** relative **energy spread**

FF quadrupoles introduce large chromaticity effects that must be corrected with sextupoles in a **local chromatic correction section**:

- W (Montague functions): describe variations of Twiss α and β for (small) momentum offsets. Q' (Chromaticity): Variation in tune with respect to momentum.

Large $\boldsymbol{\beta}$ in the FF quadrupoles:

→ Significant magnet aperture and sensitivity to unwanted multipolar components.

→ Very high magnetic field required (HTS technology) with good field quality.

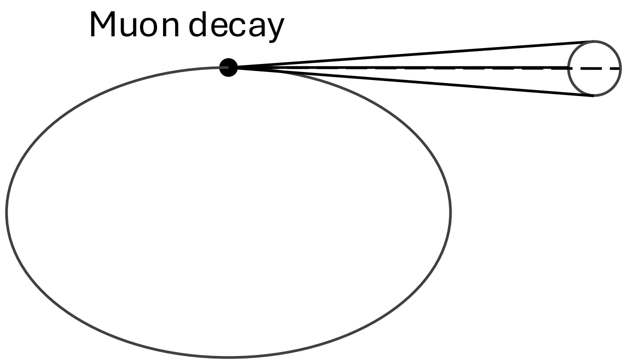
Muon collider: Challenges

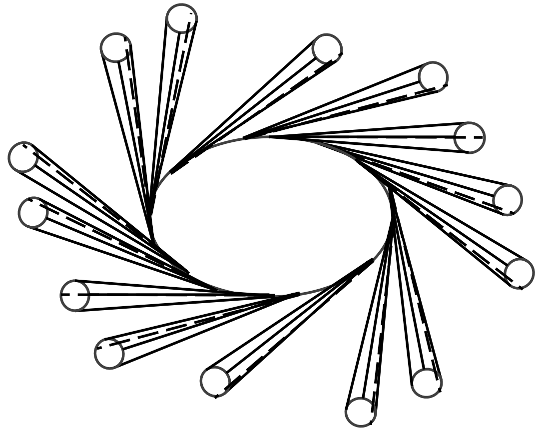
Short bunch length (1.5mm) to be kept for ~>1000 turns: $\eta = 0; \alpha_c \sim 0$

→ **Flexible momentum compaction (FMC) arc cells**

Short muon lifetime → Muon decay

- Ring **circumference** should be as **small** as possible → High magnetic field
- **Neutrinos** emitted in a small cone tangential to the collider ring





Muon collider: Challenges

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→**Fewest possible straight sections** in the lattice: **small drifts** for the element interconnections and **long straight sections** in the **Interaction Region (IR)**

→**"Geoprofiler":** Tool to place the ring close to CERN so that the **exit points** from the long straights in the IR are in the **Mediterranean** Sea and in sparsely populated areas of the **Jura**.

Muon collider: Challenges

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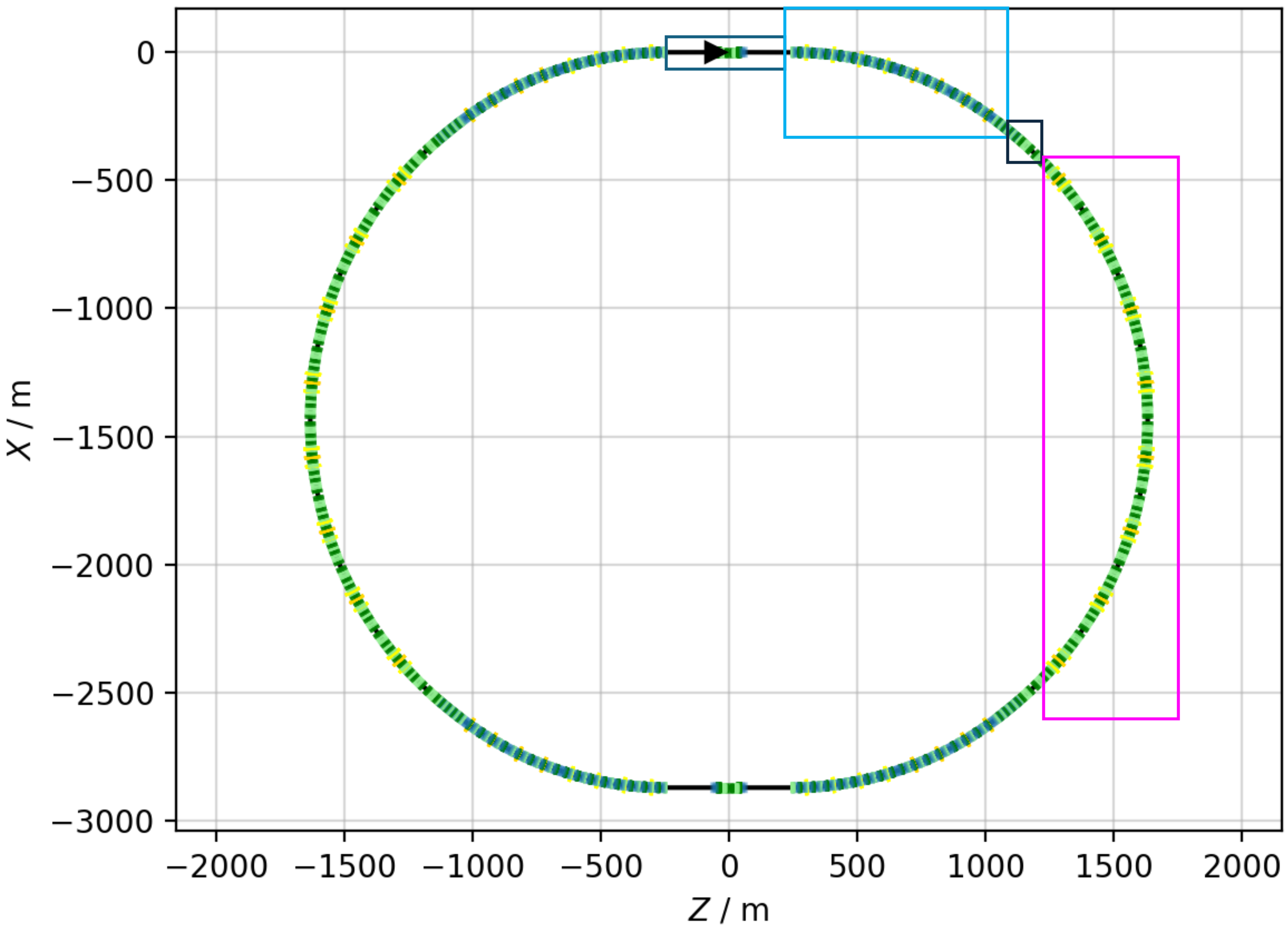
- Ring **circumference** should be as **small** as possible → High magnetic field
- **Neutrinos** emitted in a small cone tangential to the collider ring
  →**Fewest possible straight sections** in the lattice: **small drifts** for the element interconnections and **long straight sections** in the **Interaction Region (IR)**
  →**"Geoprofiler":** Tool to place the ring close to CERN so that the **exit points** from the IR are in the **Mediterranean** Sea or in the **Jura**.
- **Beam-induced background** to be mitigated and **W shielding** (~30-40mm) inside the magnets to absorb shower generated by e+/e-

Overview of the Collider Ring

Muon collider

<u>Assumptions & aims</u>

- ❖10 km collider ring
- ❖Maximum 10 m long magnet
- ❖Maximum field of 16 T for dipoles and 20 T for combined-function magnets
- ❖30 cm drift for interconnection



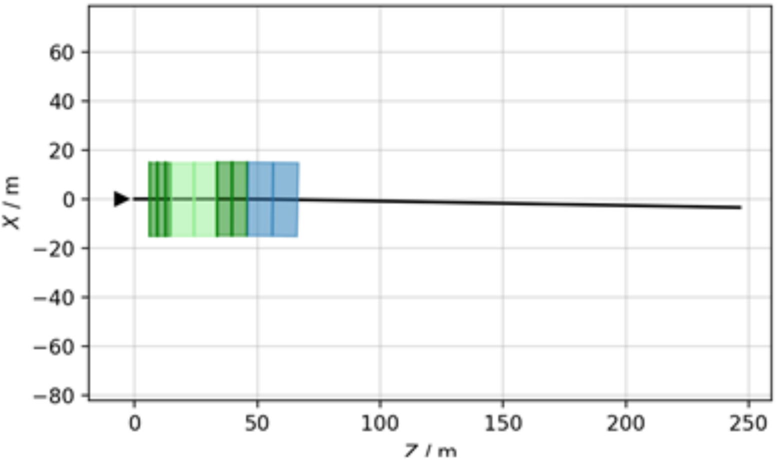
Interaction region (IR)

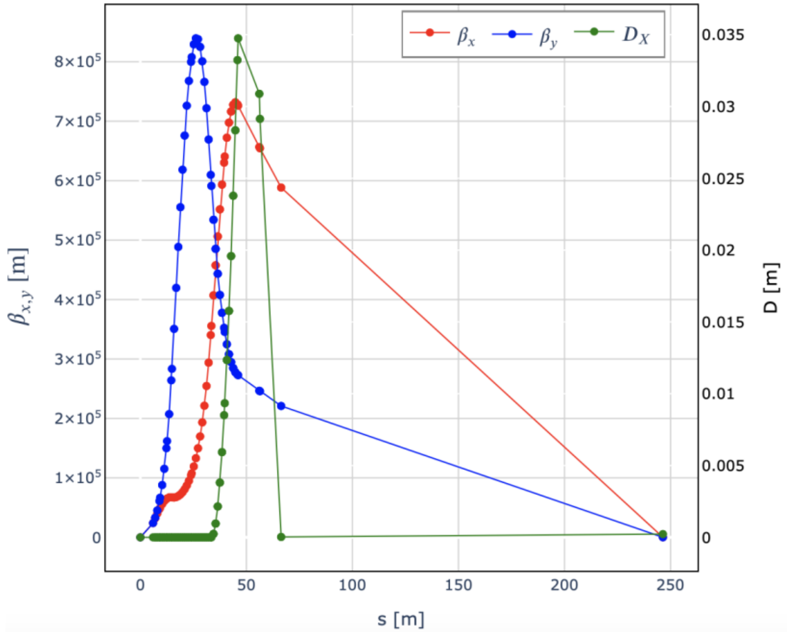
Local Chomatic correction section (CC)

Matching section (MS)

Arcs (FMC cells)

Interaction region - FF scheme v07





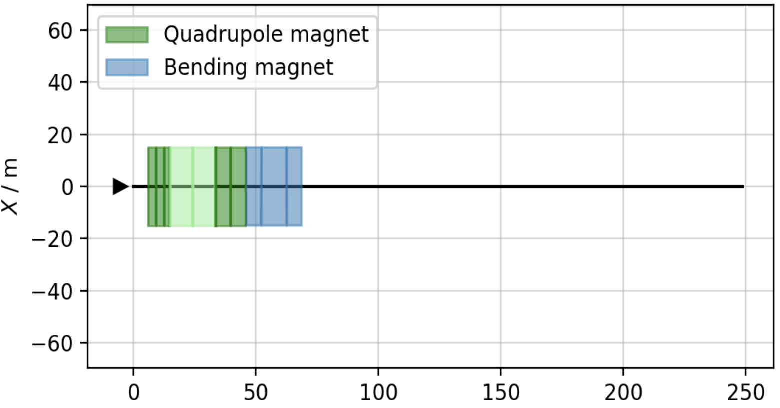
- **Long drift** for IP ($L^* = 6m$), **triplet** for the final focusing, **chicane** to reduce Beam-Induced Background (BIB), **long straight section** to smoothly reduce the beta functions without increasing W functions.

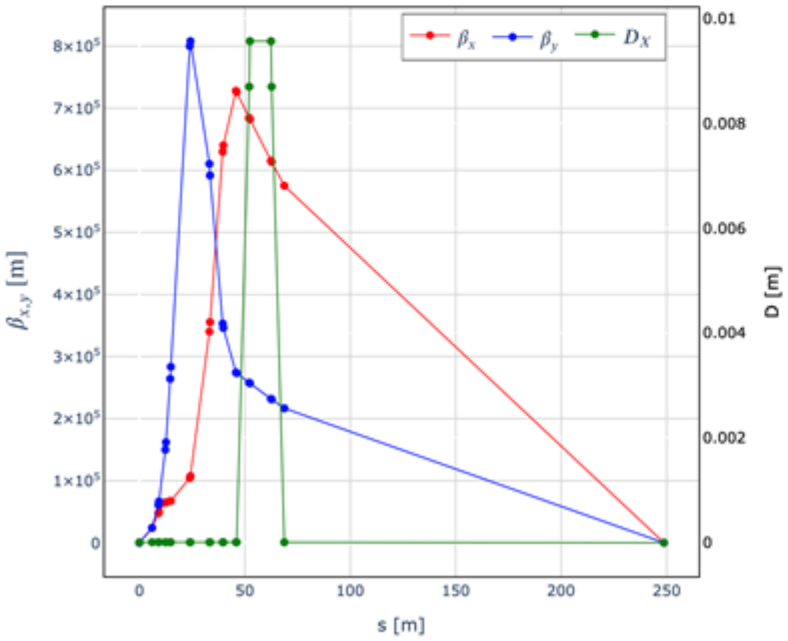
- The **first quadrupole** is divided into **three magnets** with different field gradients (maximum field set to 20 T at the magnet aperture).

- Last **FF quadrupole combined** with the first **bend of the chicane** (combined-function magnet) → small residual deflection after the chicane (0.7 mrad).

- The IR **long straight sections** result in many secondary particles from muon decay that accumulate. A **chicane** before the FF helps remove these particles as much as possible before reaching the nozzle.

Interaction region - FF scheme v08





- **Long drift** for IP ($L^* = 6m$), **triplet** for the final focusing, **chicane** to reduce Beam-Induced Background (BIB), **long straight section** to smoothly reduce the beta functions without increasing W functions.

- The **first quadrupole** is divided into **three magnets** with different field gradients (maximum field set to 20 T at the magnet aperture).

- **No combined-function magnet** in FF triplet (the 3 dipoles of the chicane separated from the FF quads). **No residual deflection & dispersion** after the chicane.

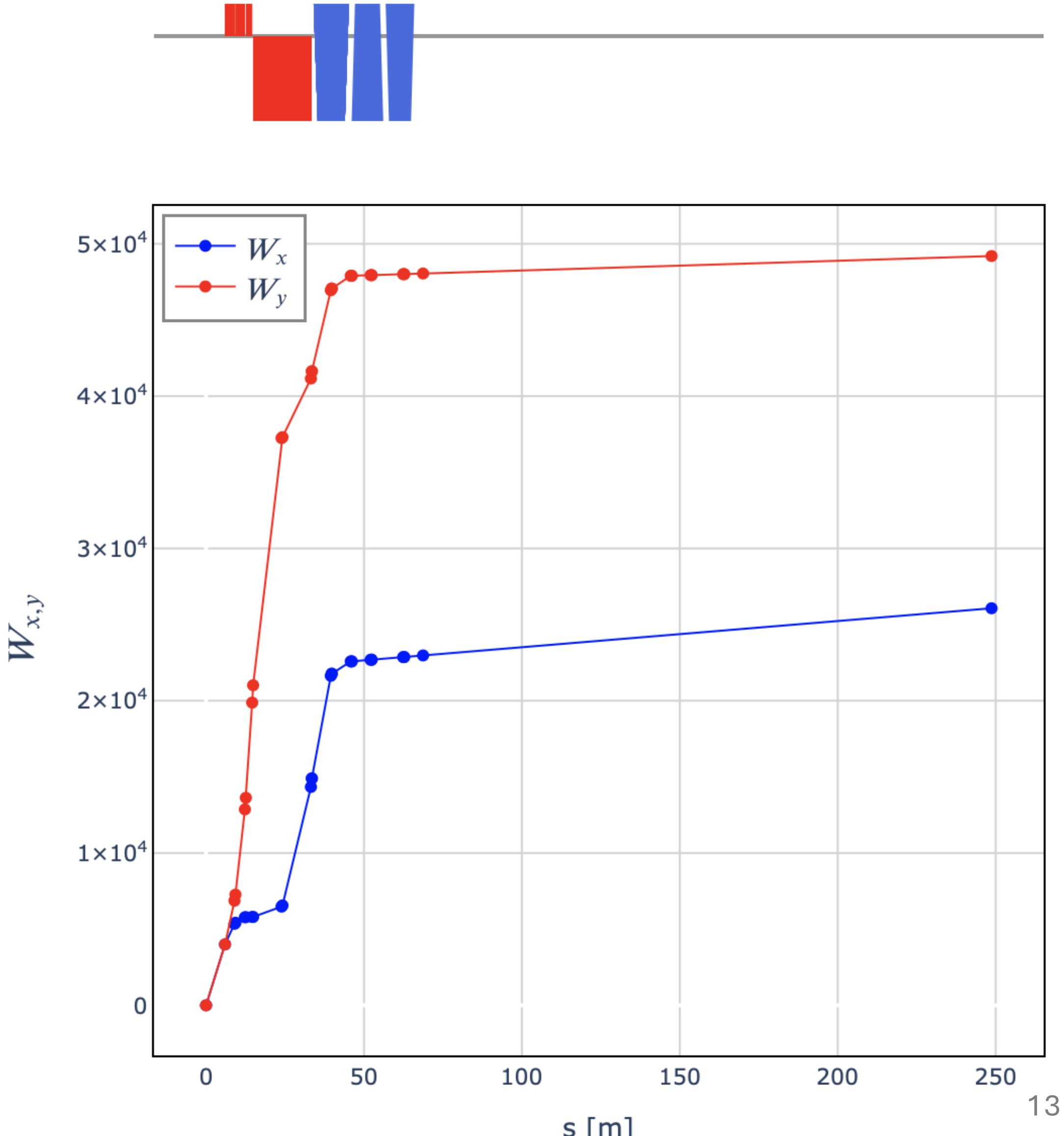
- The IR **long straight sections** result in many secondary particles from muon decay that accumulate. A **chicane** before the FF helps remove these particles as much as possible before reaching the nozzle.

IR – Montague functions

Montague chromatic functions:

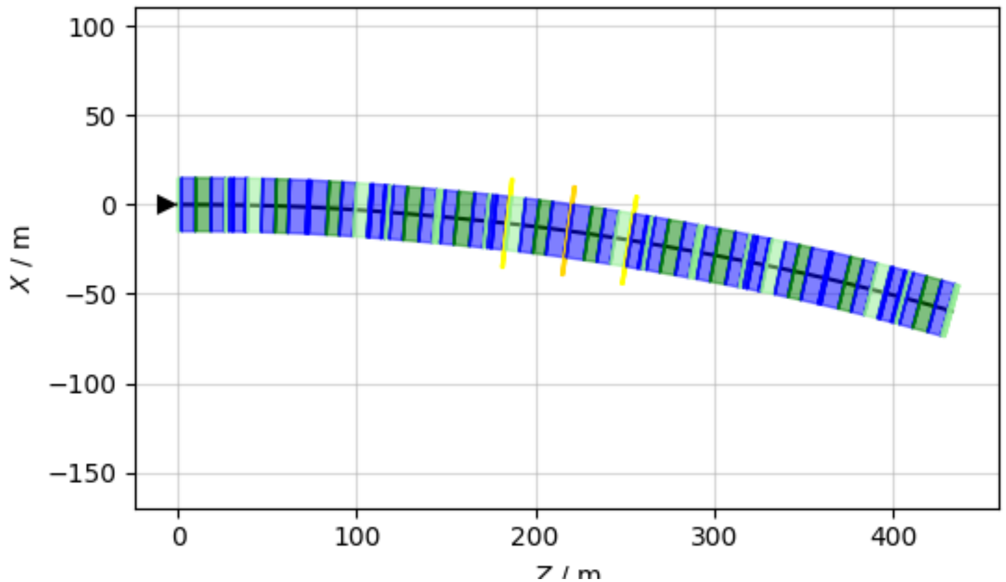
$$W = \sqrt{A^2 + B^2} \quad A = \frac{d\alpha}{d\delta} - \frac{\alpha}{\beta}\frac{d\beta}{d\delta} \quad B = \frac{1}{\beta}\frac{d\beta}{d\delta}$$

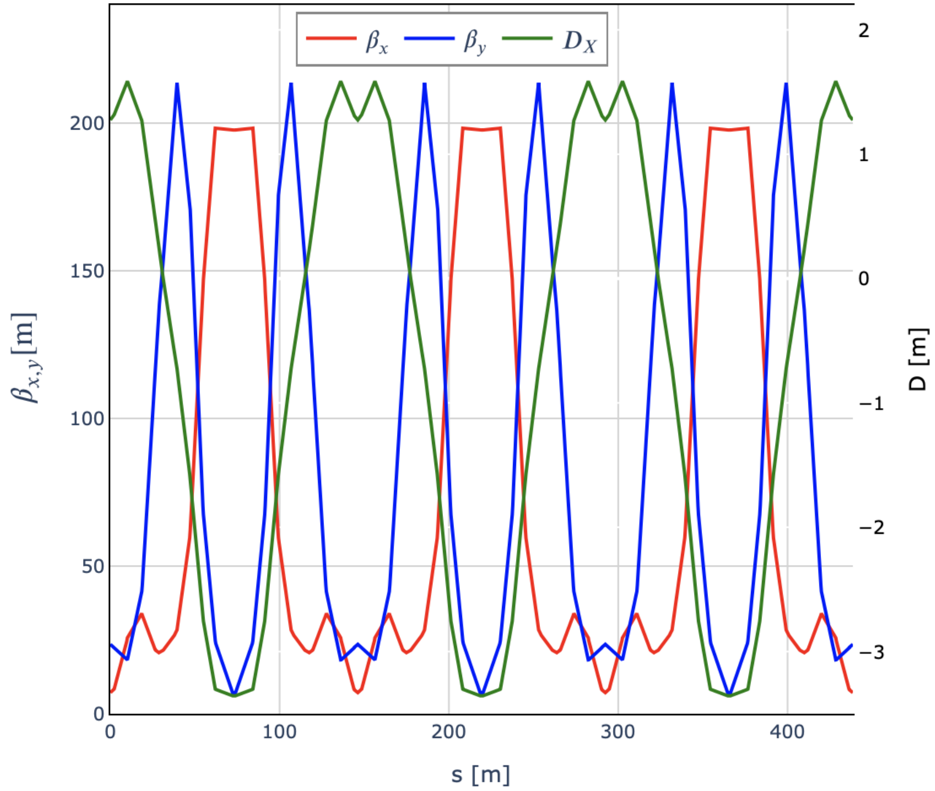
- The very small β^* at the IP induce very large β-function in the strong focusing FF quadrupoles, resulting in **significant chromatic effects**.
- **Very large W functions** at the end of the interaction region.
- Need for a **local chromatic correction section**



Muon collider: Arcs

- **Short bunch length** (1.5mm) to be kept for ~>1000 turns: $\alpha_c = 0$ → **Flexible momentum compaction (FMC) arcs.**
- The closing of the trajectory on the entire ring is controlled by the dipoles in the arcs.





- Dispersion oscillations to obtain a negative momentum compaction factor in the arcs → $\alpha_c \sim 0$ on the entire ring.
- Linear chromaticities controlled with sextupole pairs.

Local Chromatic Correction section (CC)

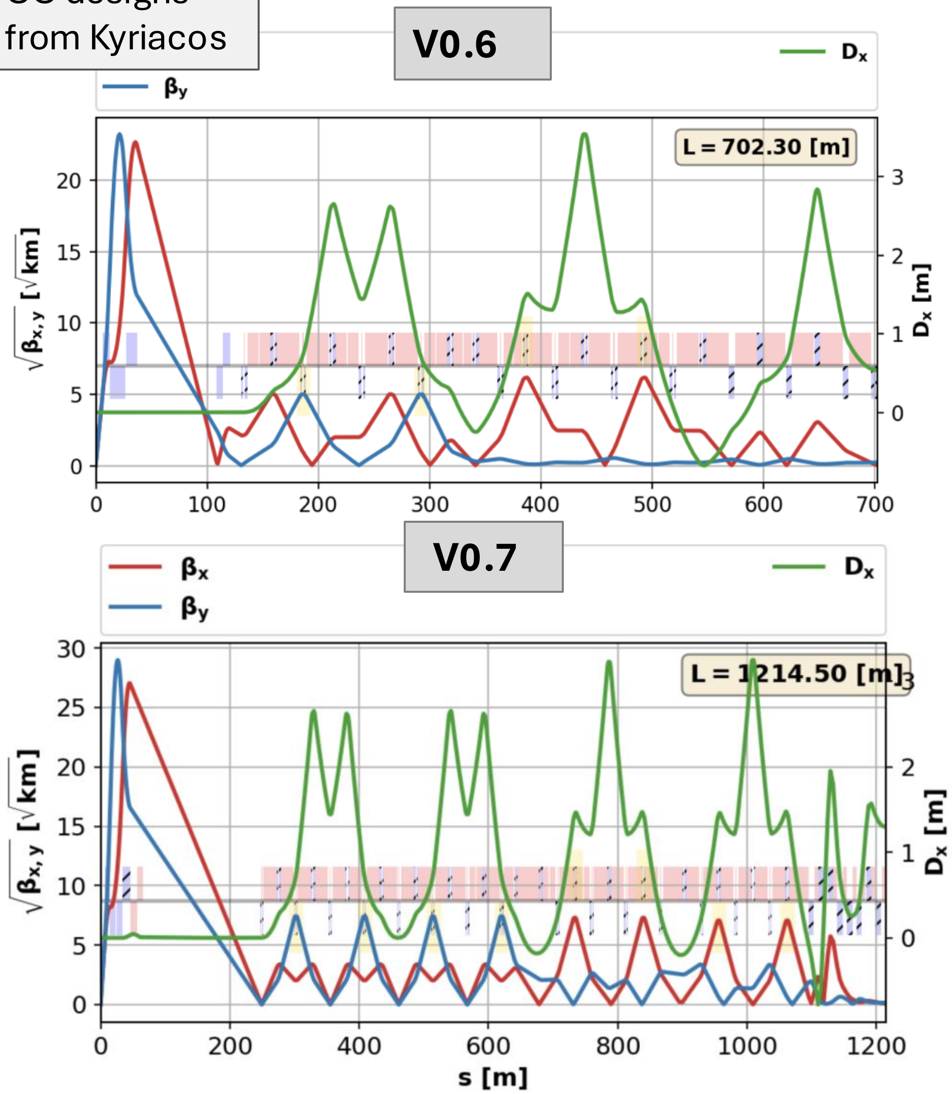
General considerations

- Model used for the sextupoles: **Thin sextupoles** surrounded by dipoles.
- Code used: **XSUITE** based on initial MAD-X files from Kyriacos:
  - *Configure_bend_model* with sufficient number of **multipolar kicks** for long **combined-function magnets** (set the number of Yoshida steps).
  - Choose carefully the **finite difference step in energy** to ensure convergence of the (second order) chromaticities: ***delta_chrom.***
  - Manually set **h = k0** in bends, otherwise change in the orbit and unwanted effects in the lattice.
  - **Footprint** plots: XSUITE does not yet make the difference between Q and 1-Q

Local Chromatic correction section

Multiple iterations: work in progress

CC designs from Kyriacos

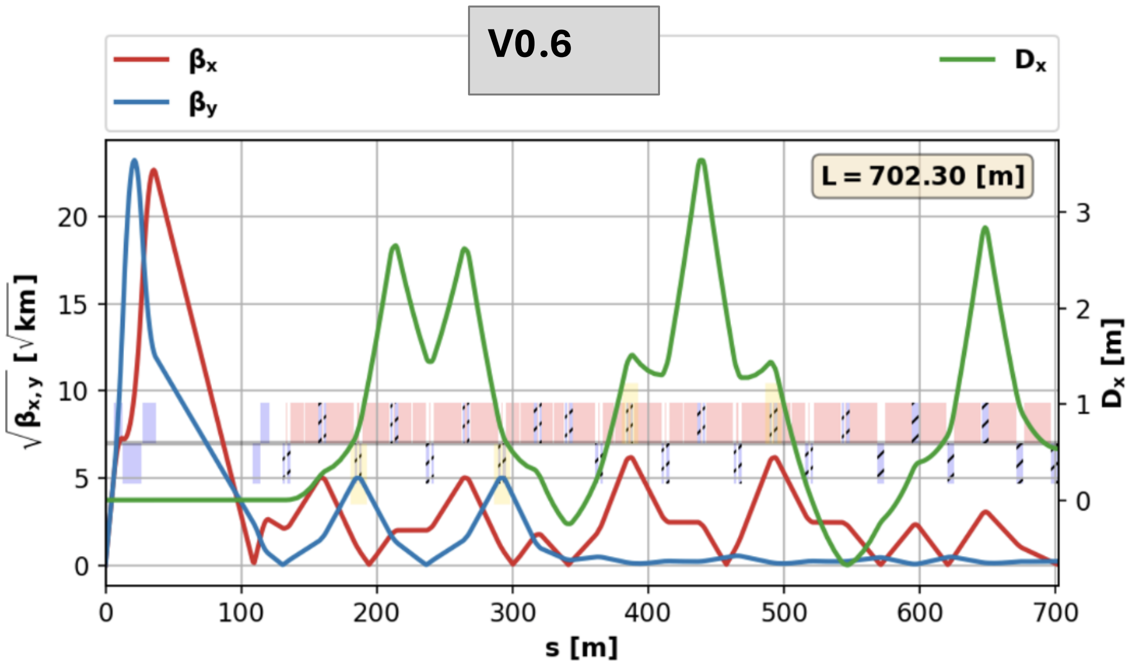


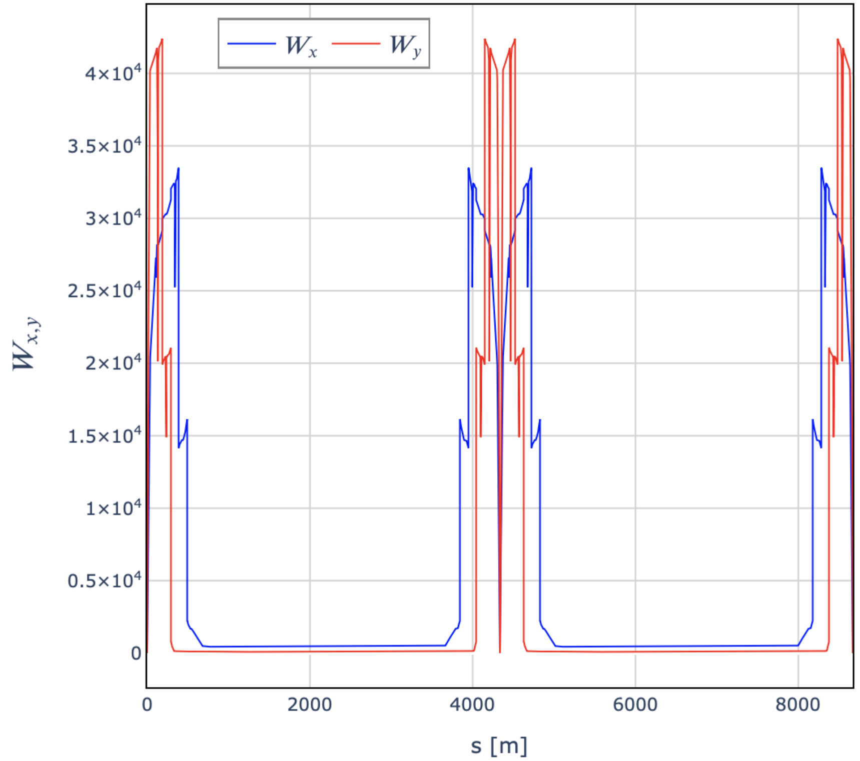
- **Sextupoles** at **non-zero dispersion** locations to correct linear chromaticity: Wy is first corrected then Wx.
- The sextupoles come **in pairs** to cancel non-linearities, with the π phase advance controlled by the in-between quads.
- **Adjust the phase at the entrance of the first sextupole** in each pair to be in phase (π) with the main error sources (triplet) – $\mu_y = 0.75$ from IP to SD and $\mu_x = 2.25$ from IP to SF.
- **Reduction** by an **order of magnitude of the β functions** between the IR and the CC: trade-off between the sextupoles strength, β, and dispersion.
- Using the end of one section to match the desired optics in the following section (no periodic conditions).

CC – v0.6

Chromatic correction section – v0.6

- Dependence between the CC section and the arcs, as there is **no Q' control in the CC**. Rematch of the entire ring required by imposing $W_x = W_y = 0$ and $Q'_x = Q'_y = 0$ → Check that W in the arcs are not too large (small $W * 10^{-3}$)

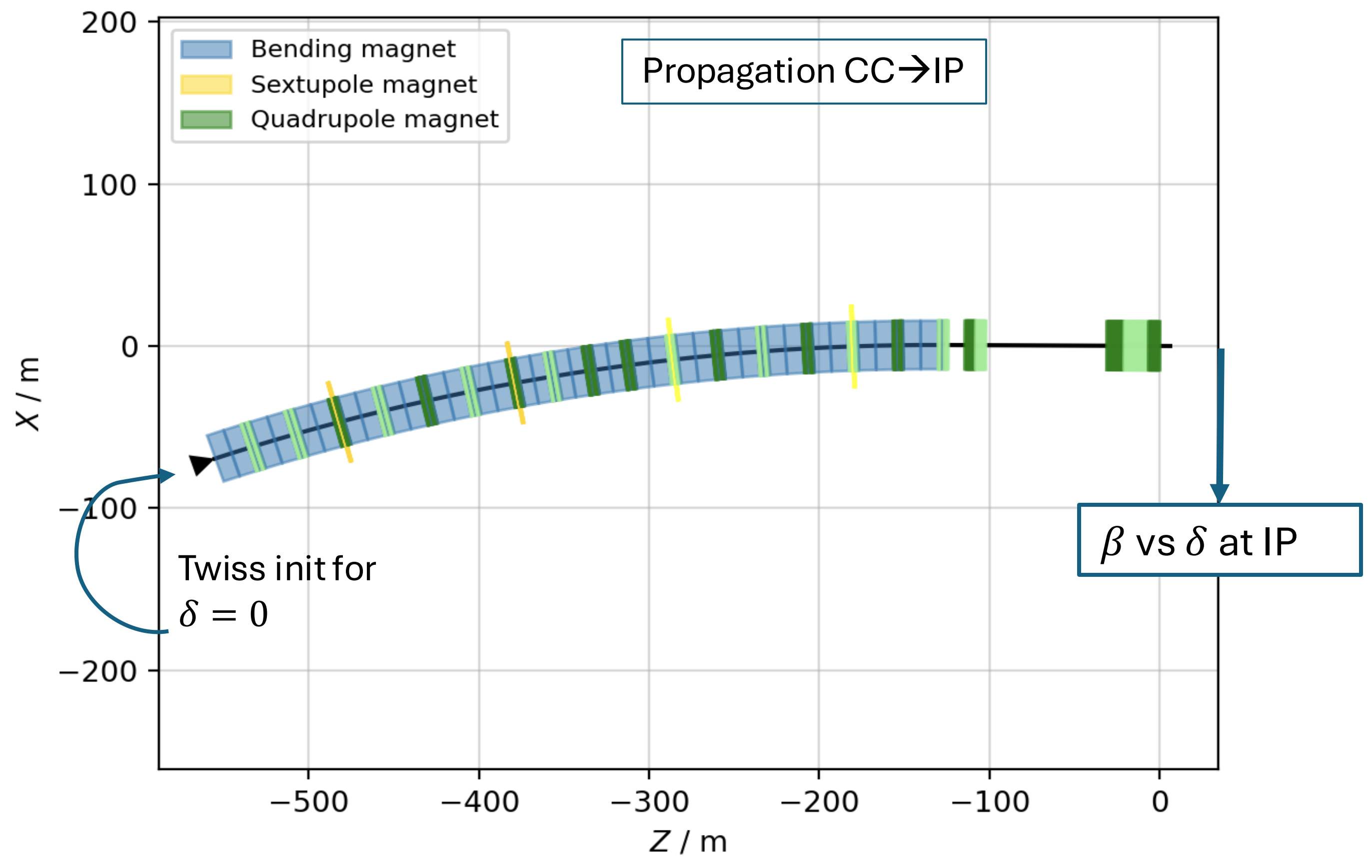




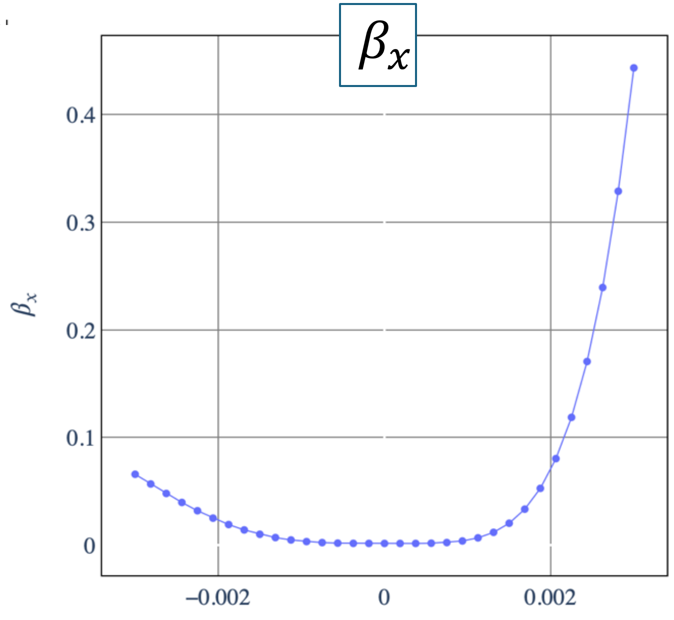
Chromatic correction section – v0.6

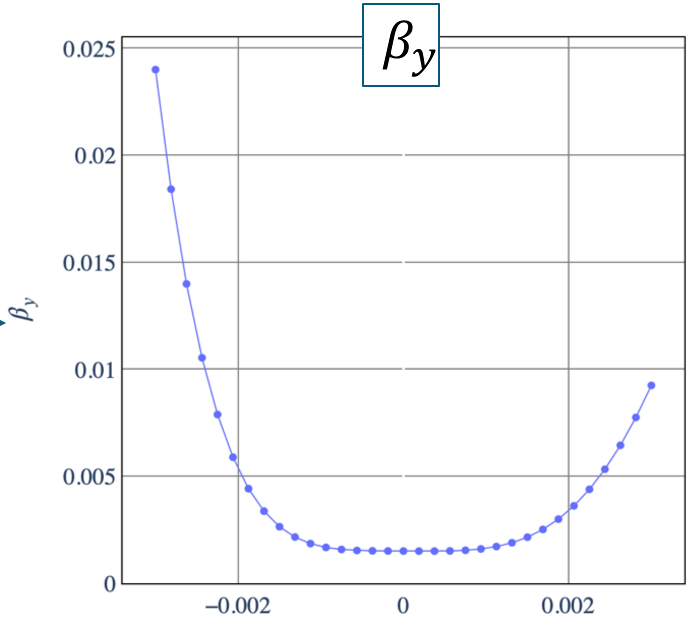
Slight phase shift at the sextupoles helps reduce the non-linearities in β vs. δ:

- Can be done manually or in a more automated way



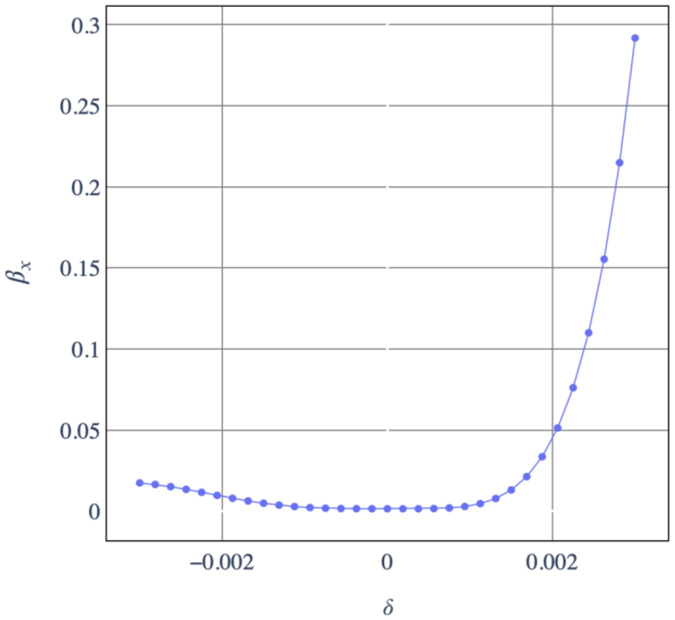
Chromatic correction section – v0.6



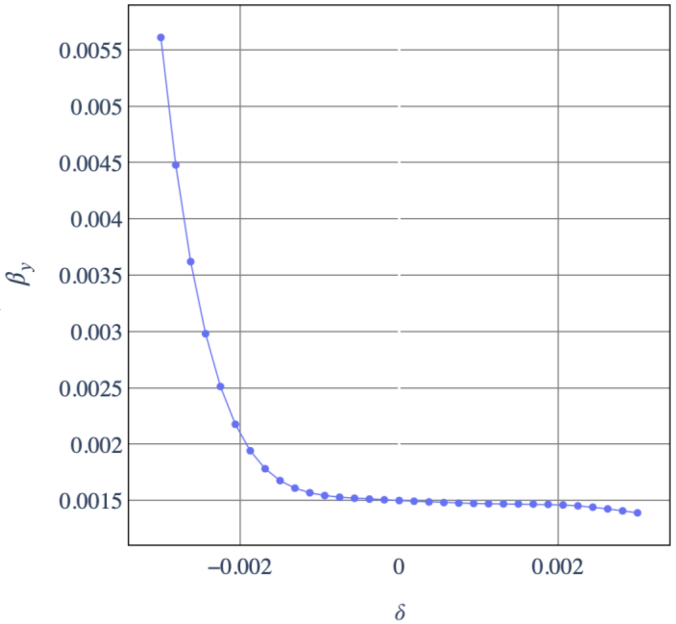


$$\mu_{y_{SD1}} = 0.75; \quad \mu_{x_{SF1}} = 2.25$$

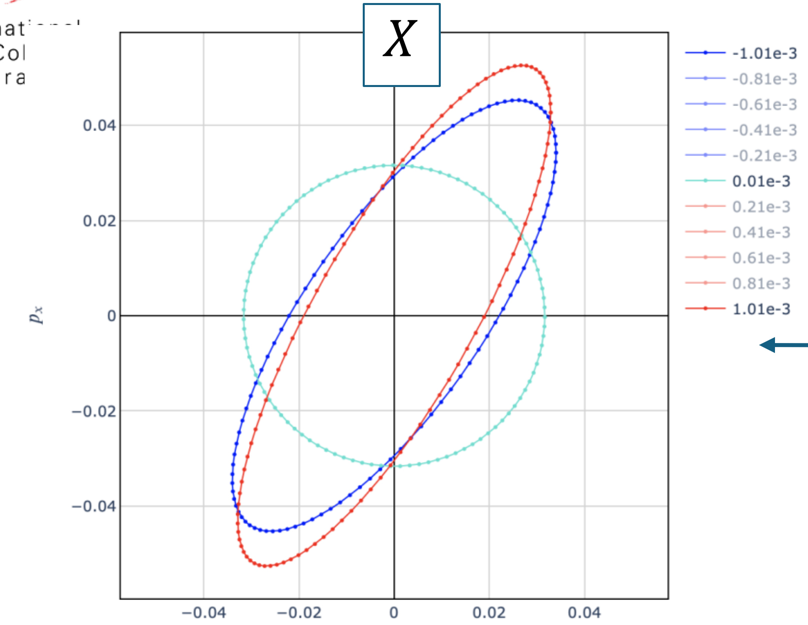
β vs δ

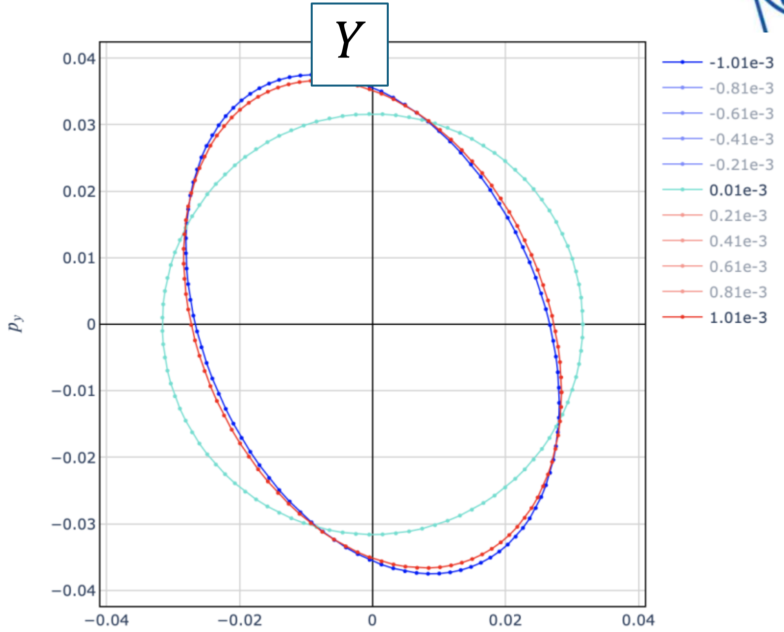


$$\mu_{y_{SD1}} = 0.75 - 0.0000225; \quad \mu_{x_{SF1}} = 2.25 + 0.000055$$



Chromatic correction section – v0.6





$\mu_{y_{SD1}} = 0.75;$
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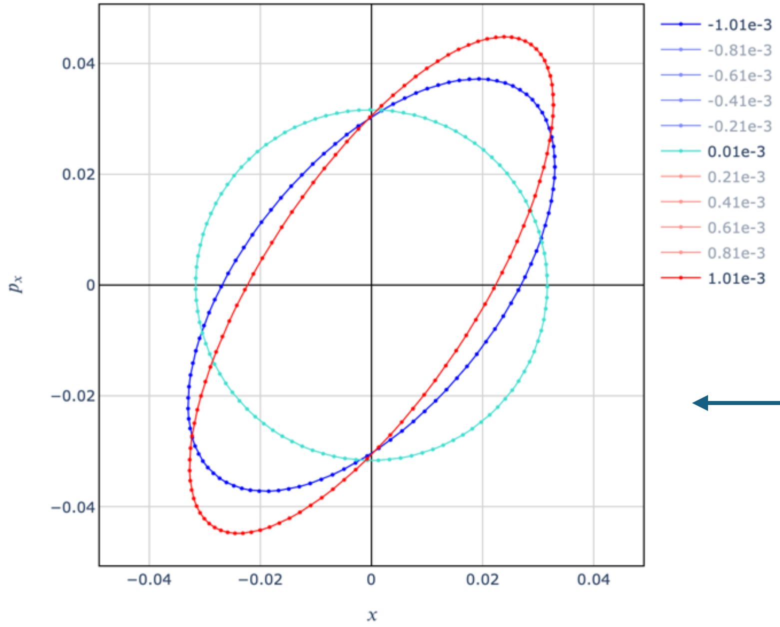
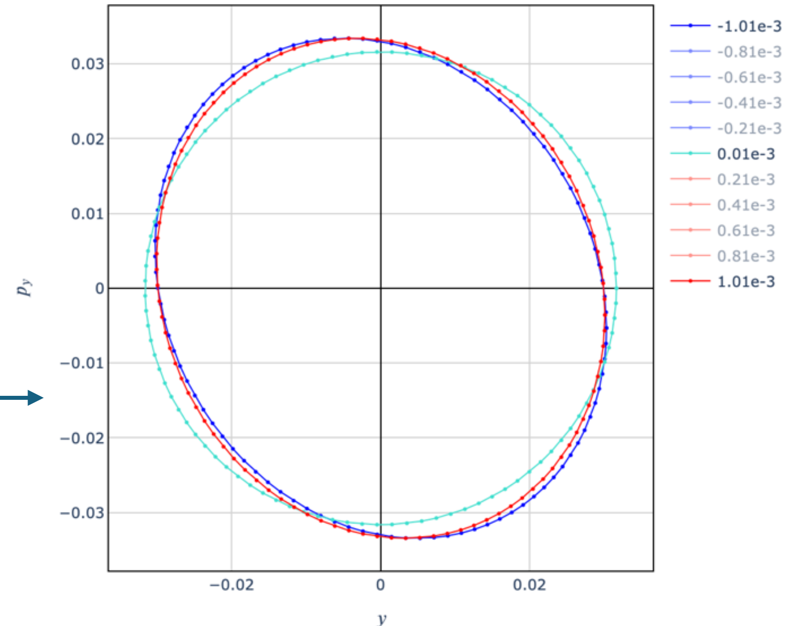
Ellipses at the end of CC

Propagation IP→CC





$\mu_{y_{SD1}} = 0.75 - 0.0000225;$
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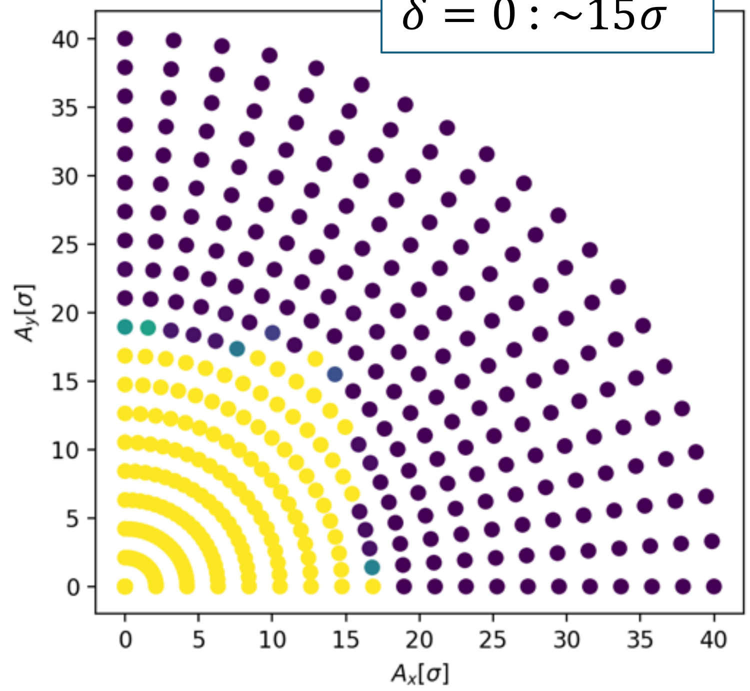
Chromatic correction section – v0.6

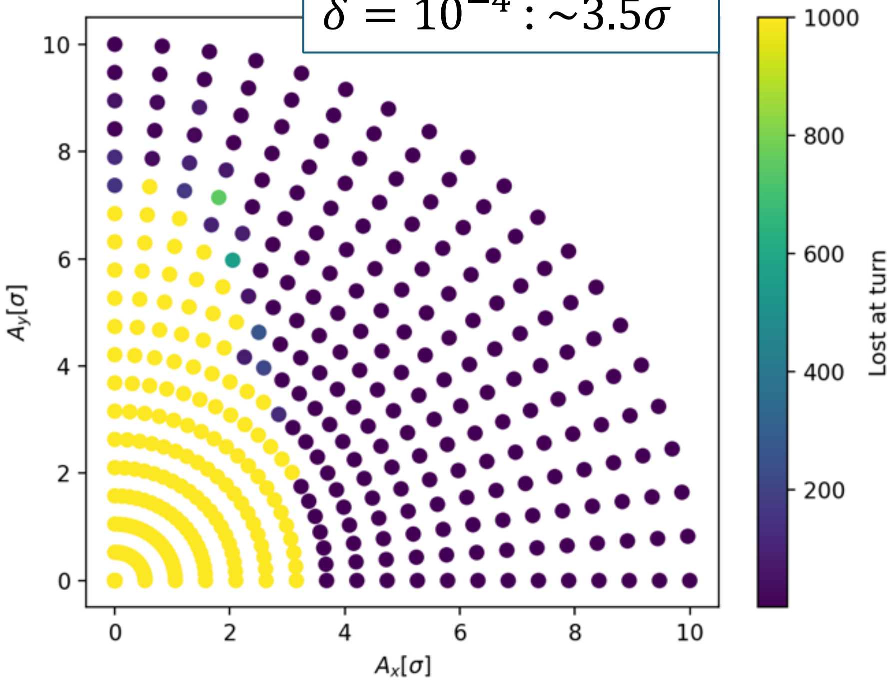
- Slight phase shift at the sextupoles helps reduce the non-linearities in β vs. δ:
  - Can be done manually or in a more automated manner
  - Increase the DA for several deltas

$\mu_{y_{SD1}} = 0.75;$
$\mu_{x_{SF1}} = 2.25$

$\delta = 0 : \sim 15\sigma$



$\delta = 10^{-4} : \sim 3.5\sigma$



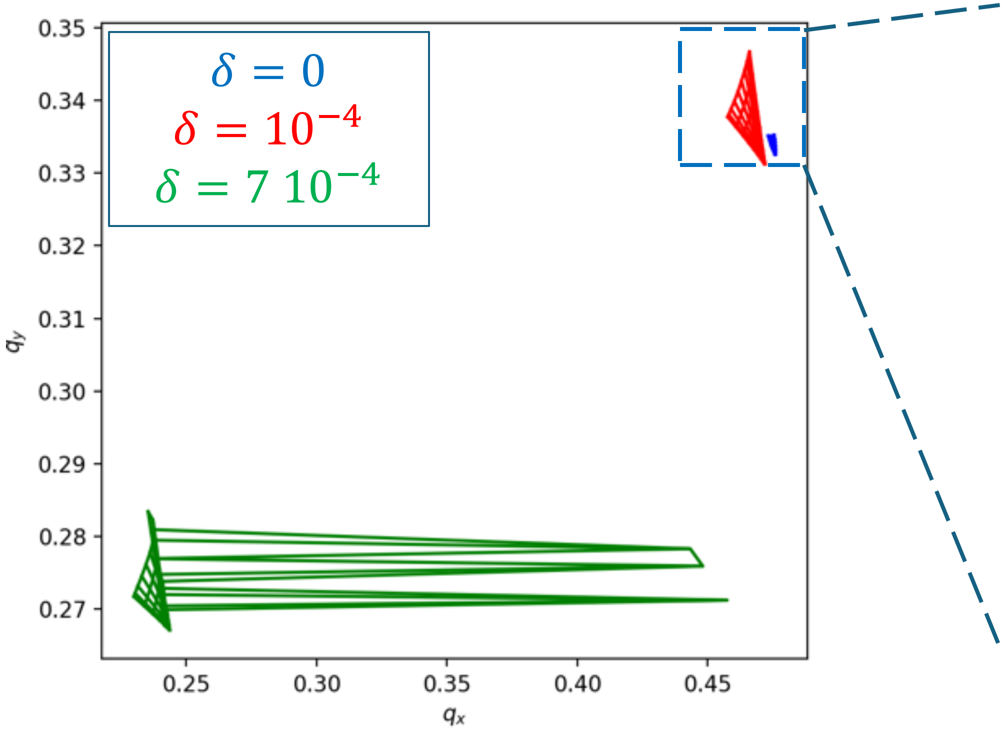
$\delta = 10^{-3} : 0\sigma$

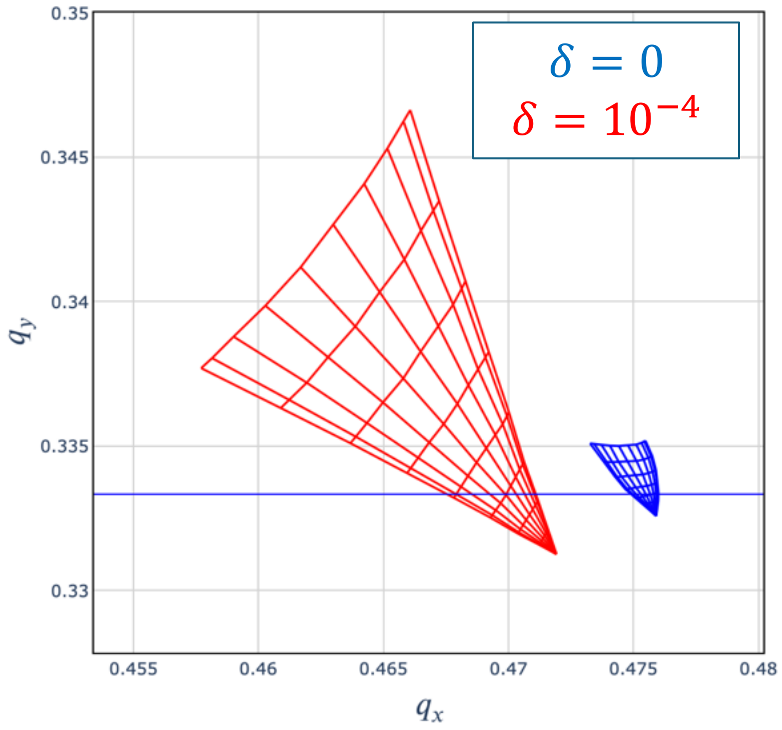
X

Chromatic correction section – v0.6

- Reduced DA for off-momentum particles: Footprint
  - XSUITE does not yet make the difference between nu and 1-nu.
  - Large **tune shifts** in tune space **for off-momentum particles.**
  - Difference in detuning with amplitude for off-momentum particles.

$\mu_{y_{SD1}} = 0.75;$
$\mu_{x_{SF1}} = 2.25$





Chromatic correction section – v0.6

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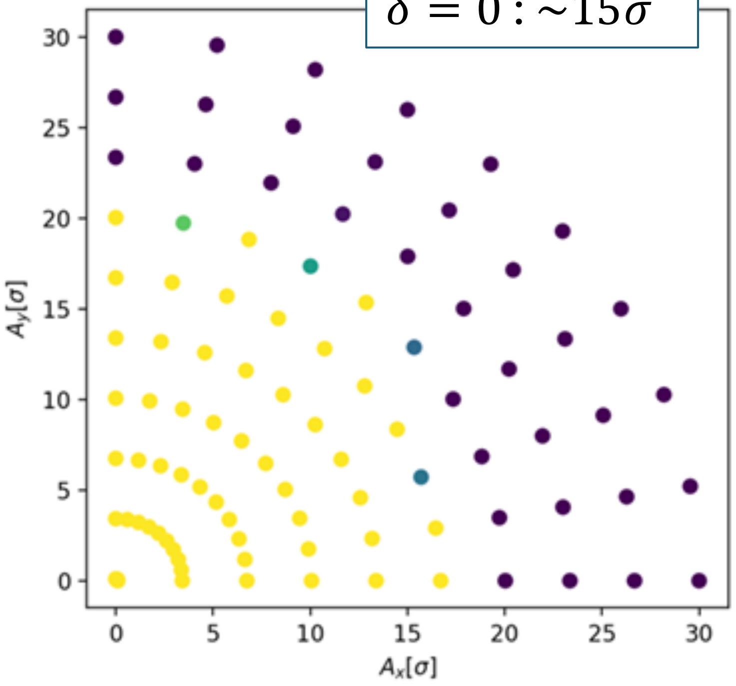
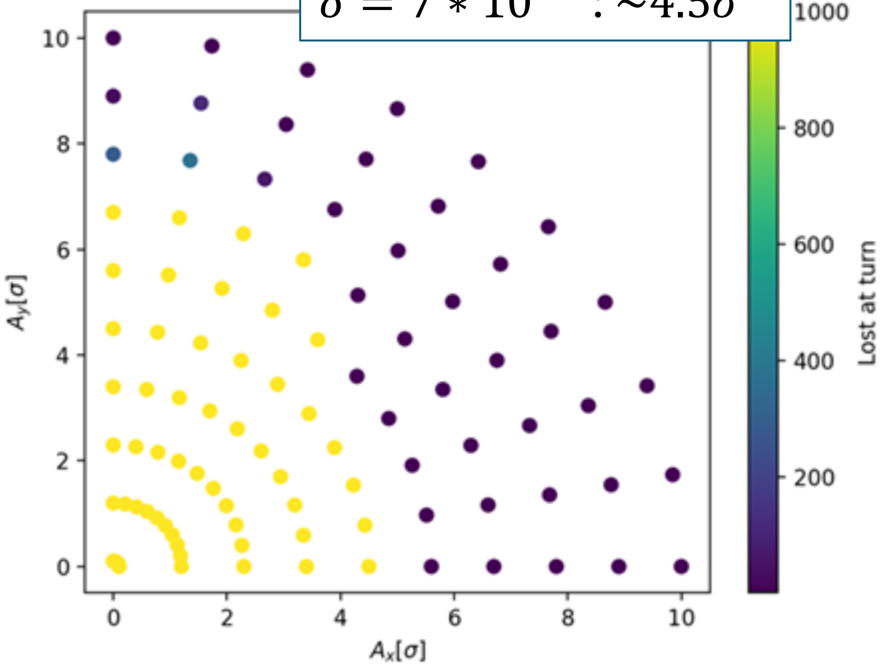


$\delta = 7 * 10^{-4} : \sim 4.5\sigma$



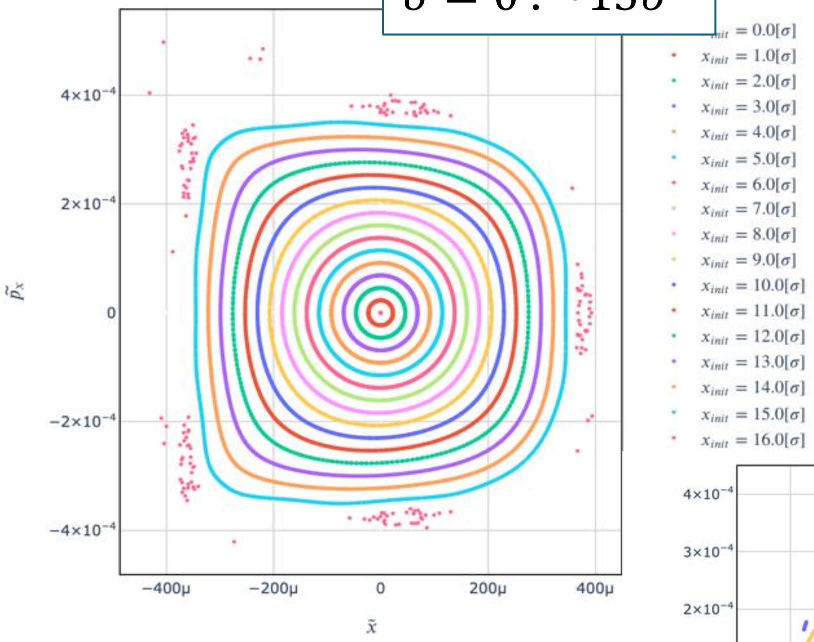
$\delta = 10^{-3} : 0\sigma$

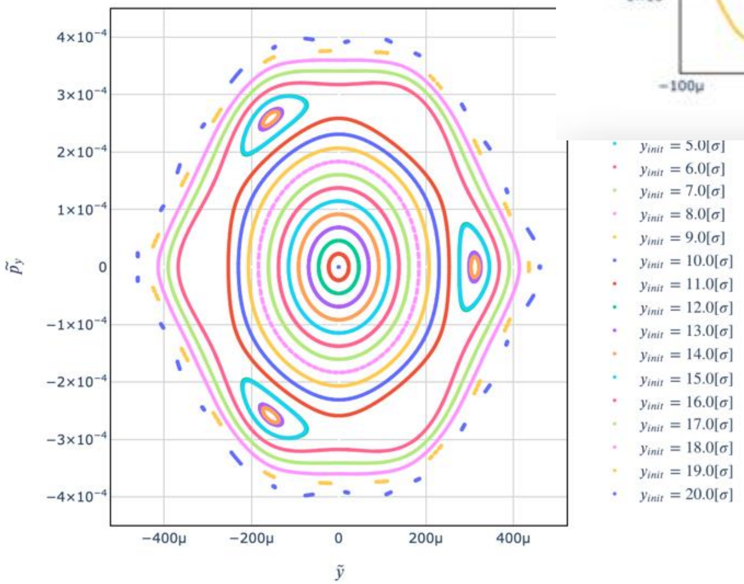
X

Chromatic correction section – v0.6

- Reduced DA for off-momentum particles: phase space plots

$\delta = 0 : \sim 15\sigma$





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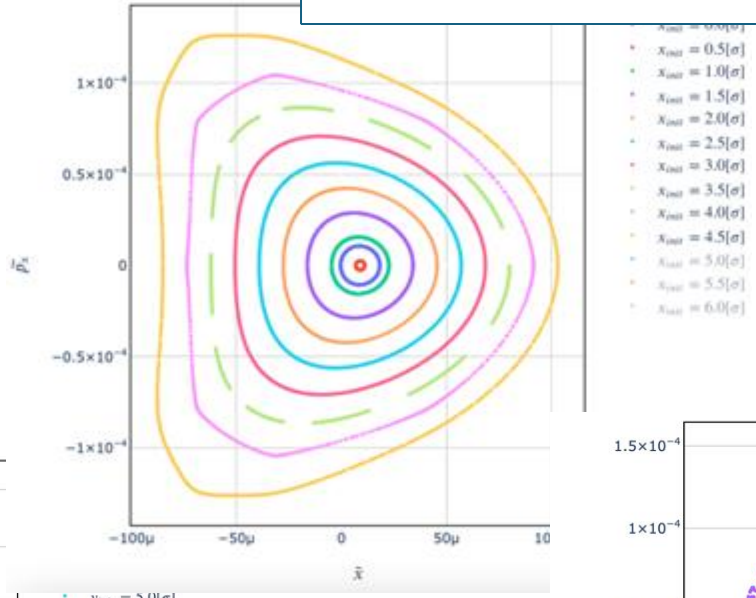

$$\mu_{y_{SD1}} = 0.75 - 0.0000225;$$
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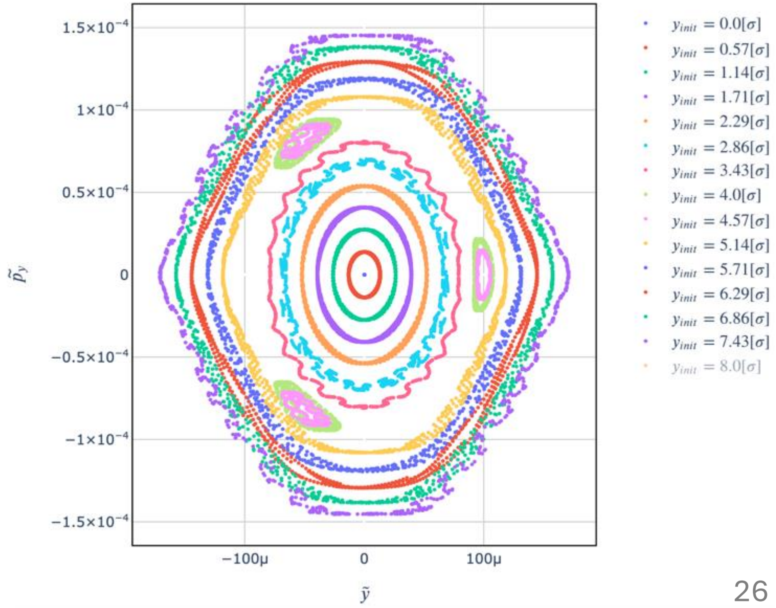
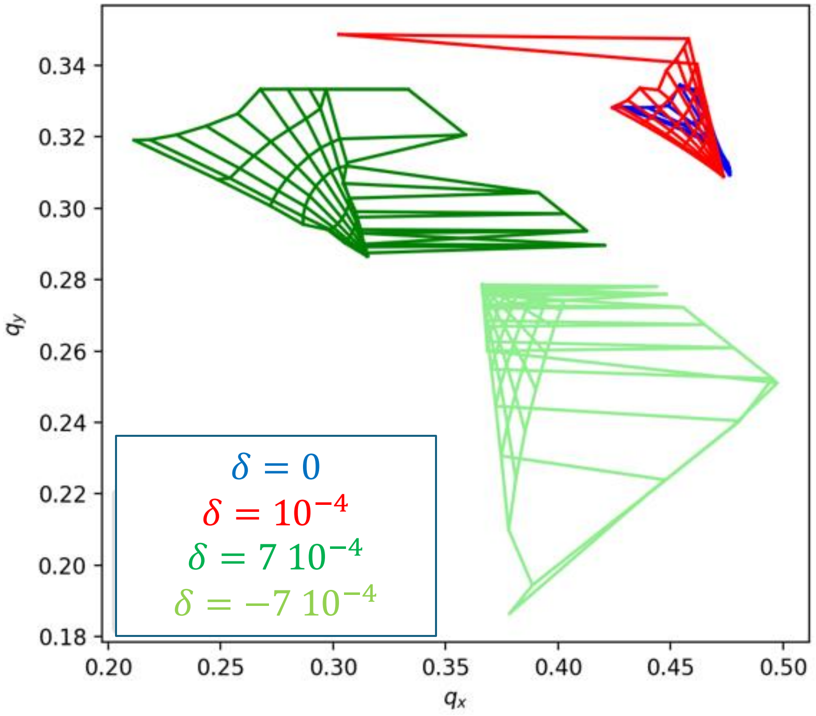
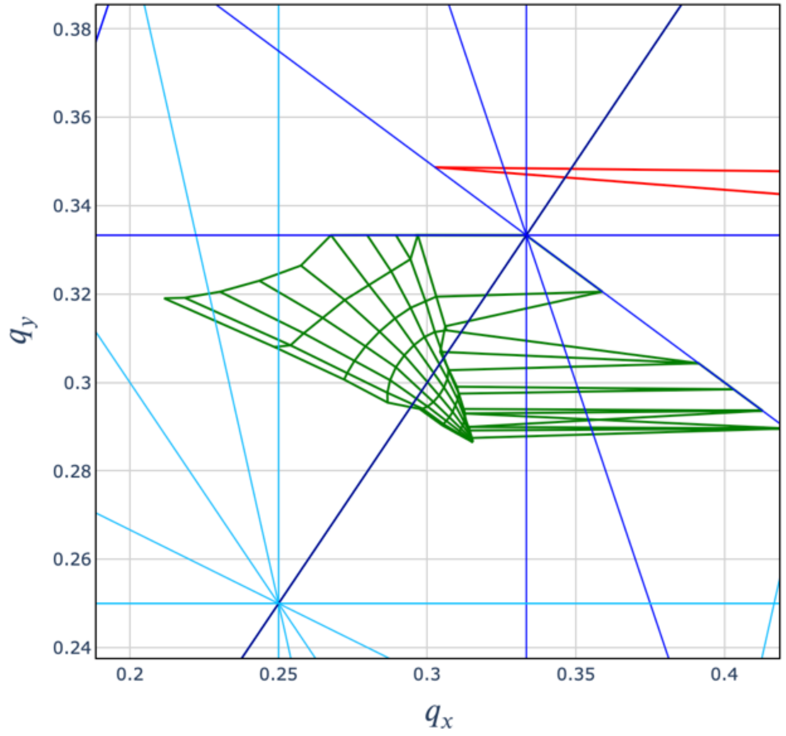


Chromatic correction section – v0.6

- Reduced DA for off-momentum particles: Footprint
  - XSUITE does not yet make the difference between nu and 1-nu
  - Tune shifts for off-momentum particles **reduced thanks to the optimized phase** at sextupoles (but **still large tune shifts**).
  - Larger amplitude detuning for off-momentum particles.

$\mu_{y_{SD1}} = 0.75 - 0.0000225;$
$\mu_{x_{SF1}} = 2.25 + 0.000055$



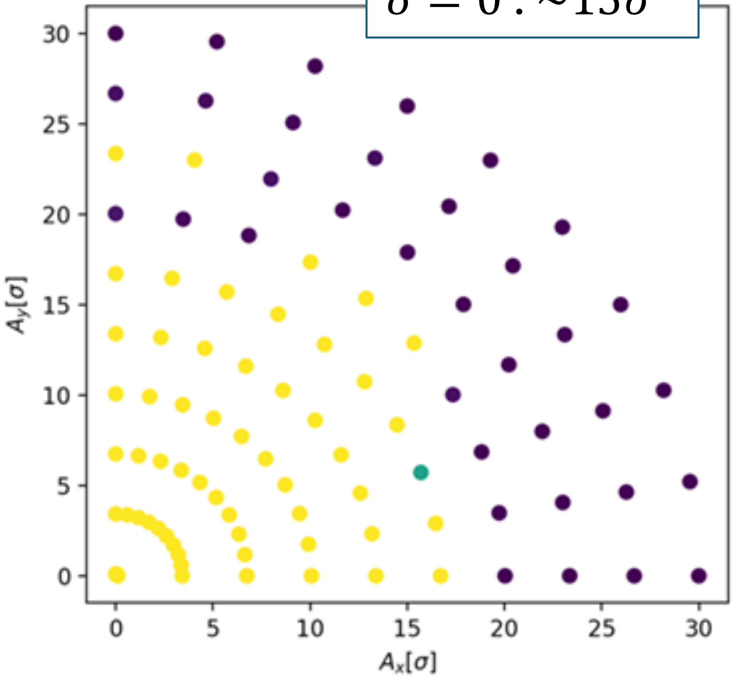


Chromatic correction section – v0.6

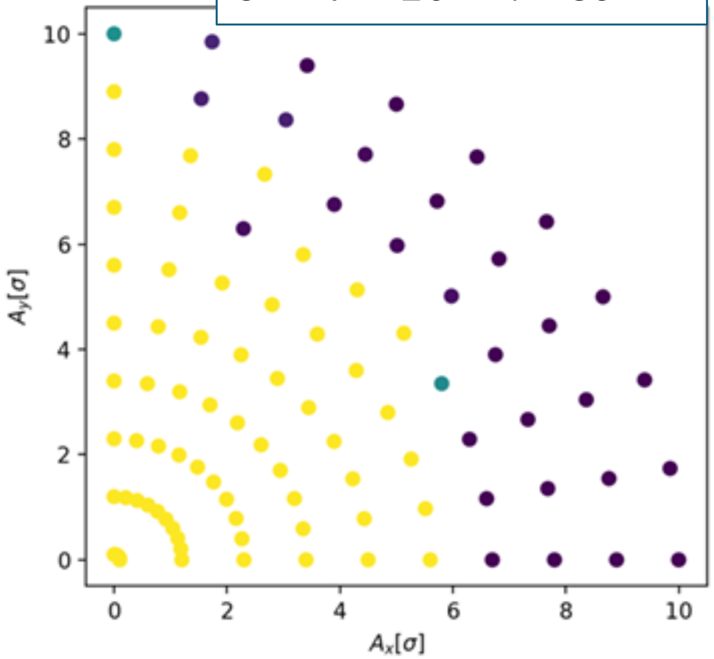
- Slight phase shift at the sextupoles helps reduce the non-linearities in β vs. δ:
  - Can be done manually or in a more automated manner
  - Increase the DA for several deltas

Optimized phase with automated cost

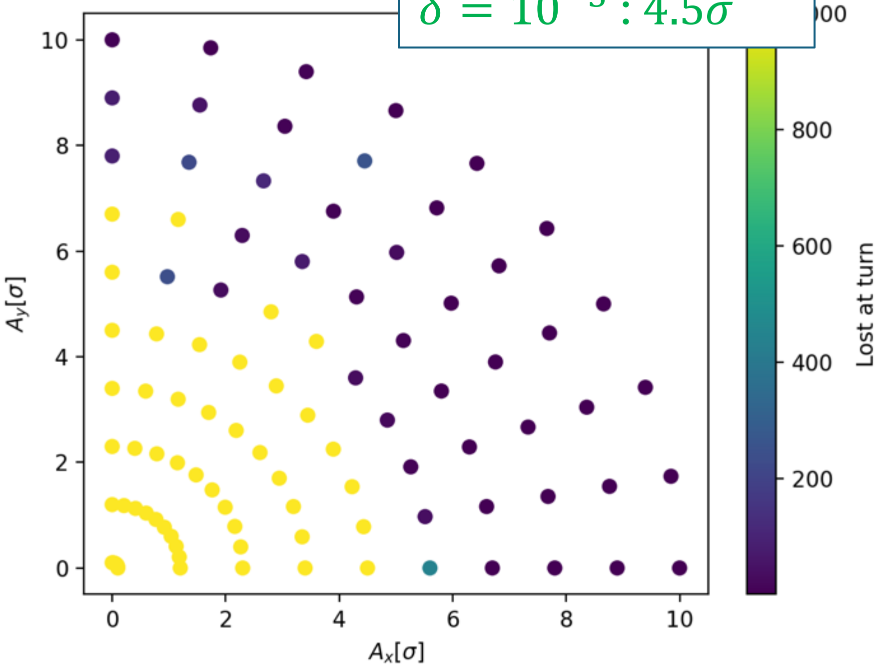
$\delta = 0 : \sim 15\sigma$



$\delta = 7 * 10^{-4} : \sim 6\sigma$



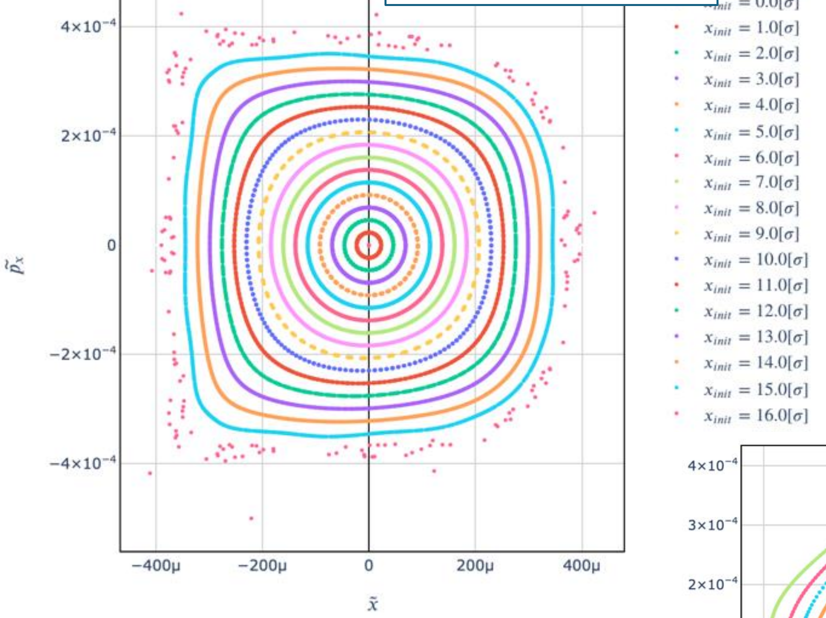
$\delta = 10^{-3} : 4.5\sigma$

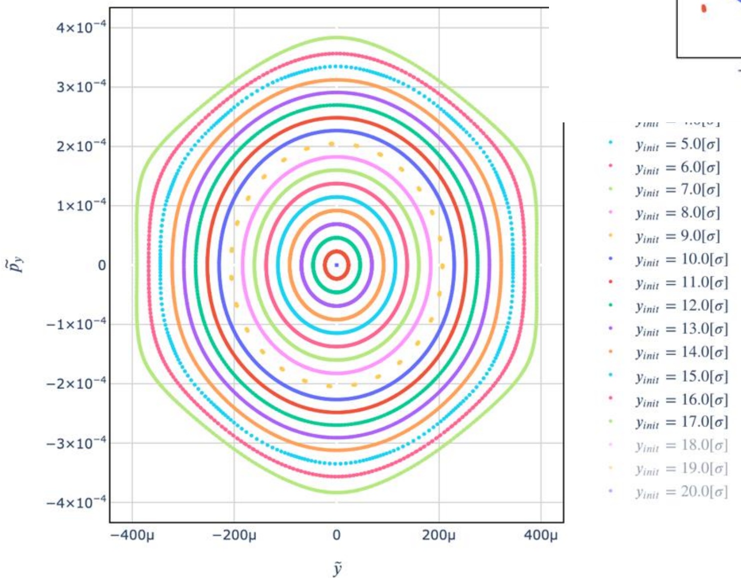


Chromatic correction section – v0.6

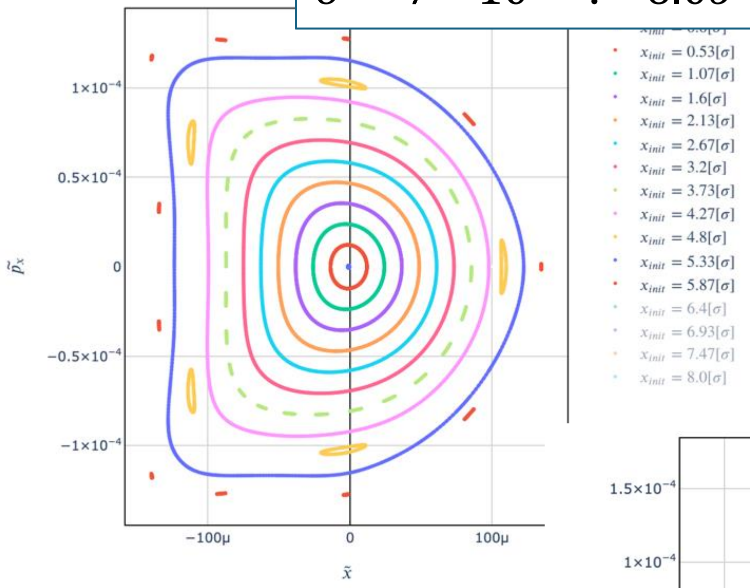
- Reduced DA for off-momentum particles: phase space plots

$\delta = 0 : \sim 15\sigma$

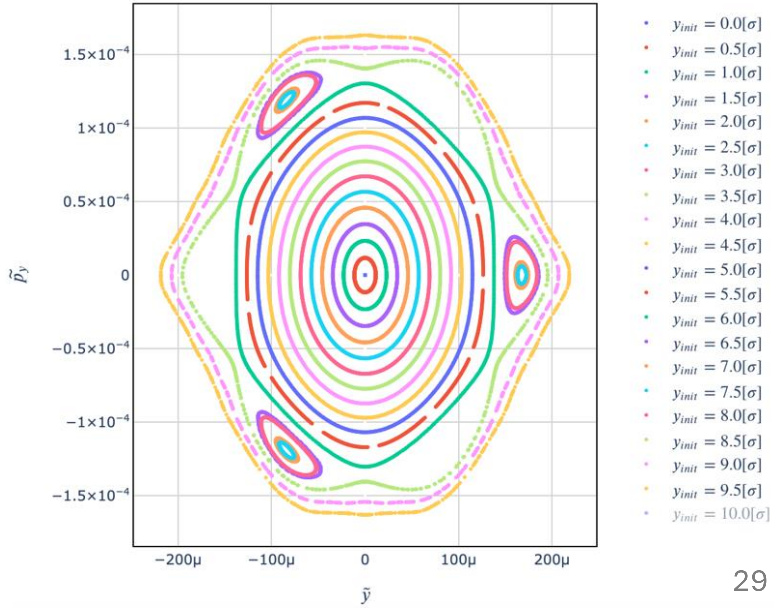




$\delta = 7 * 10^{-4} : \sim 6.0\sigma$



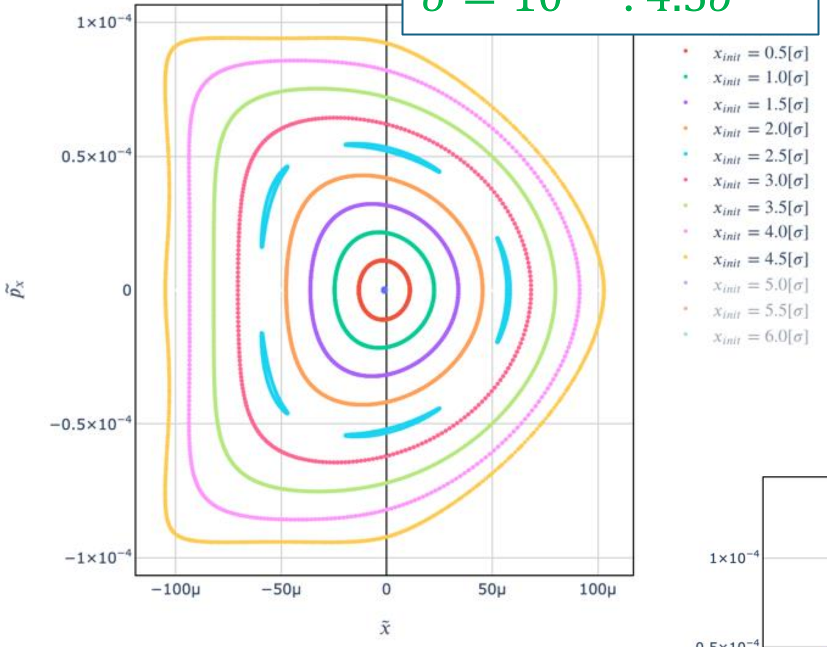
Optimized phase with automated cost

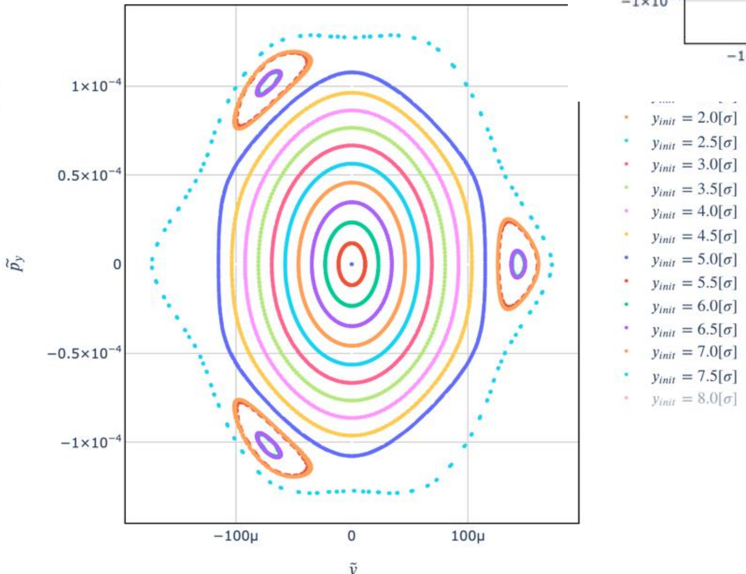


Chromatic correction section – v0.6

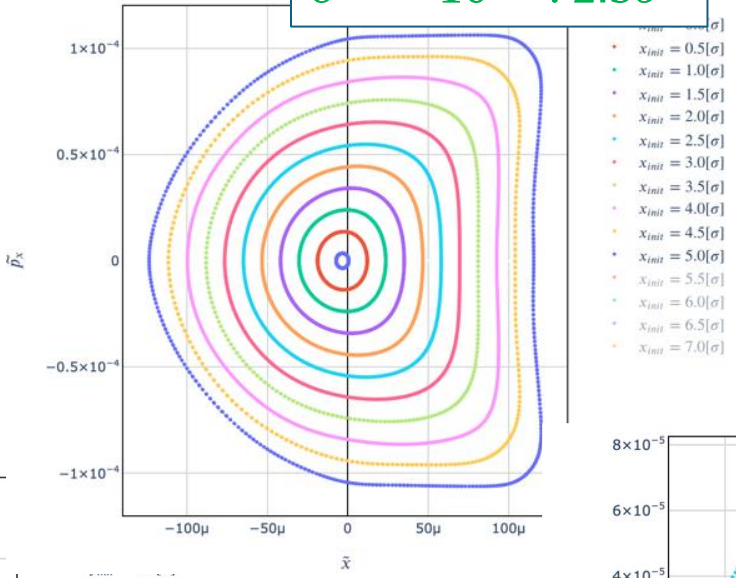
- Reduced DA for off-momentum particles: phase space plots

$\delta = 10^{-3} : 4.5\sigma$

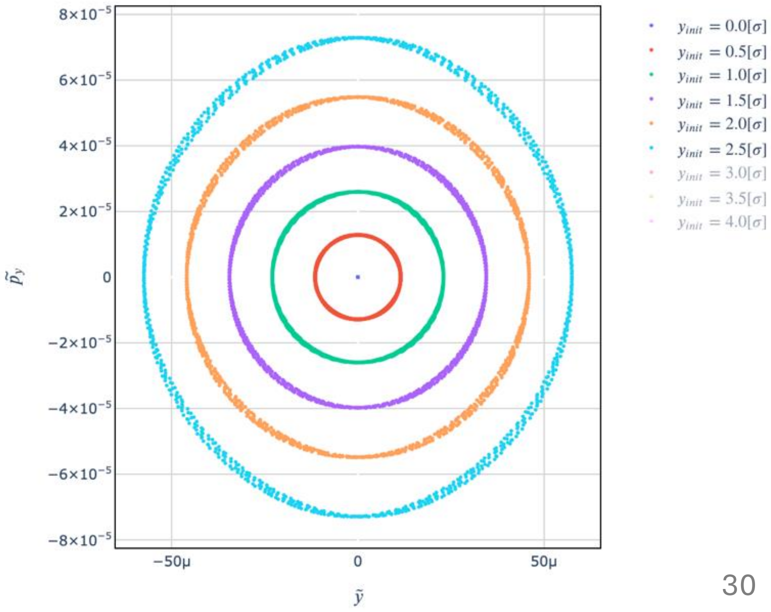




$\delta = -10^{-3} : 2.5\sigma$



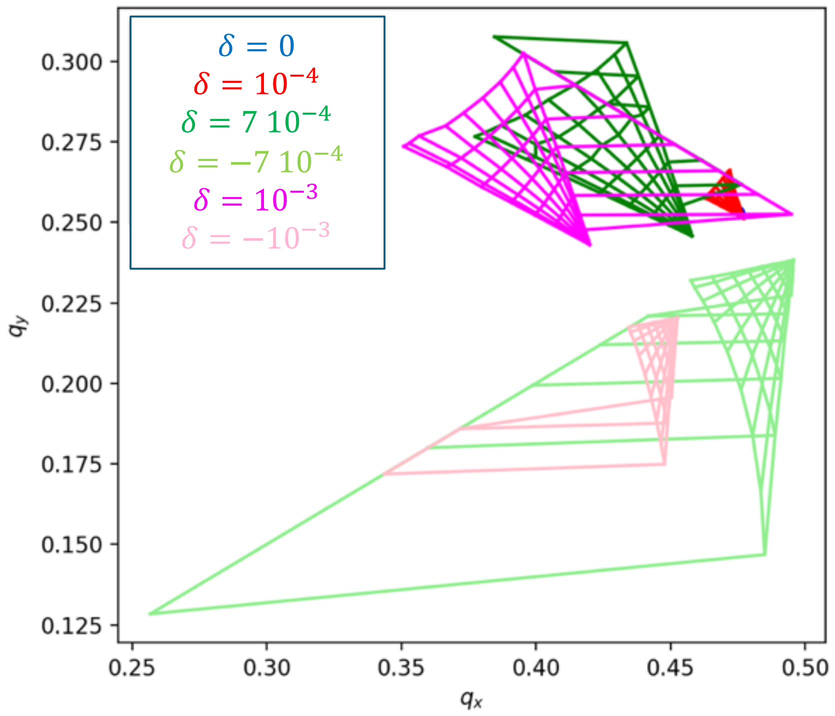
Optimized phase with automated cost

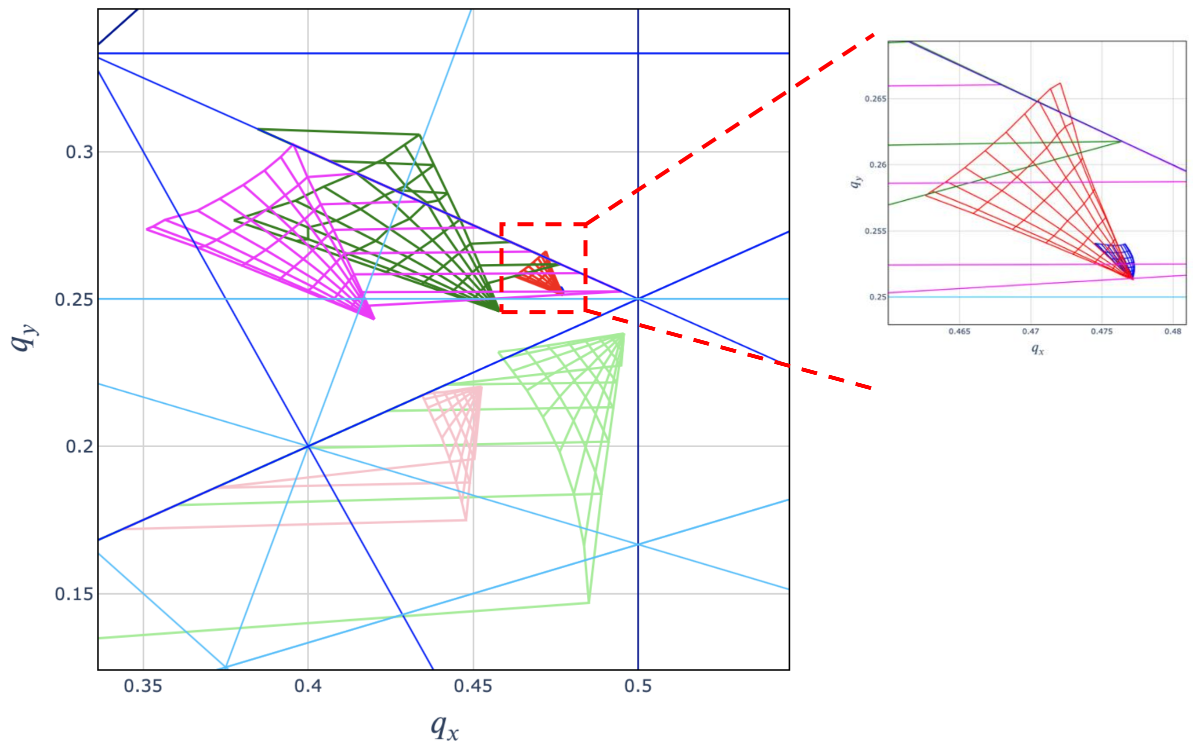


Chromatic correction section – v0.6

- Reduced DA for off-momentum particles: Footprint
  - XSUITE does not yet make the difference between nu and 1-nu
  - Tune shifts for off-momentum particles **reduced thanks to the optimized phase** at sextupoles (but still large tune shifts).
  - Larger amplitude detuning for off-momentum particles.

Optimized phase with automated cost

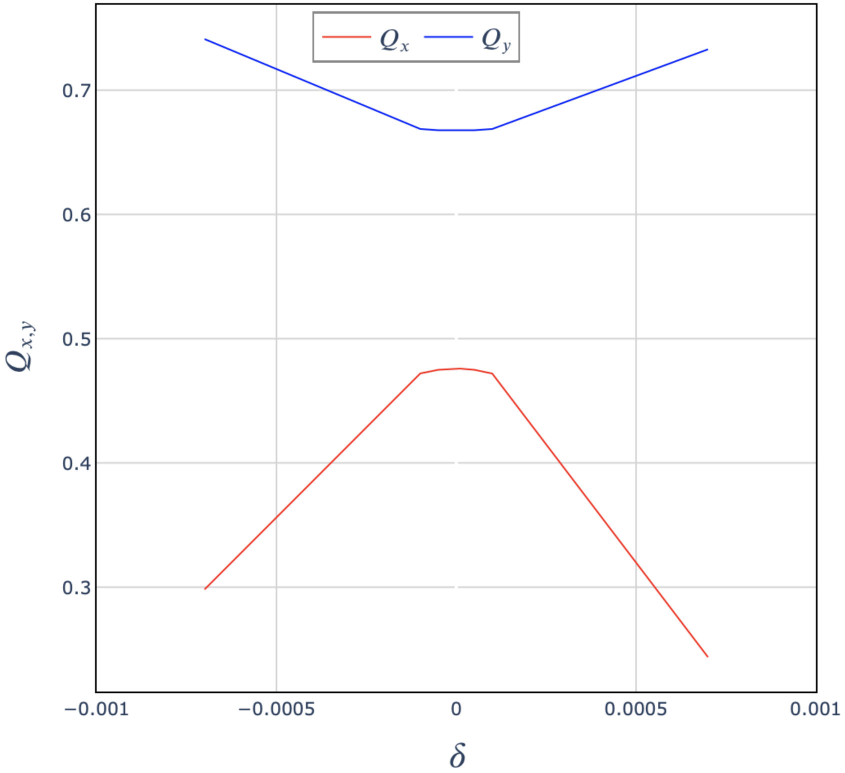




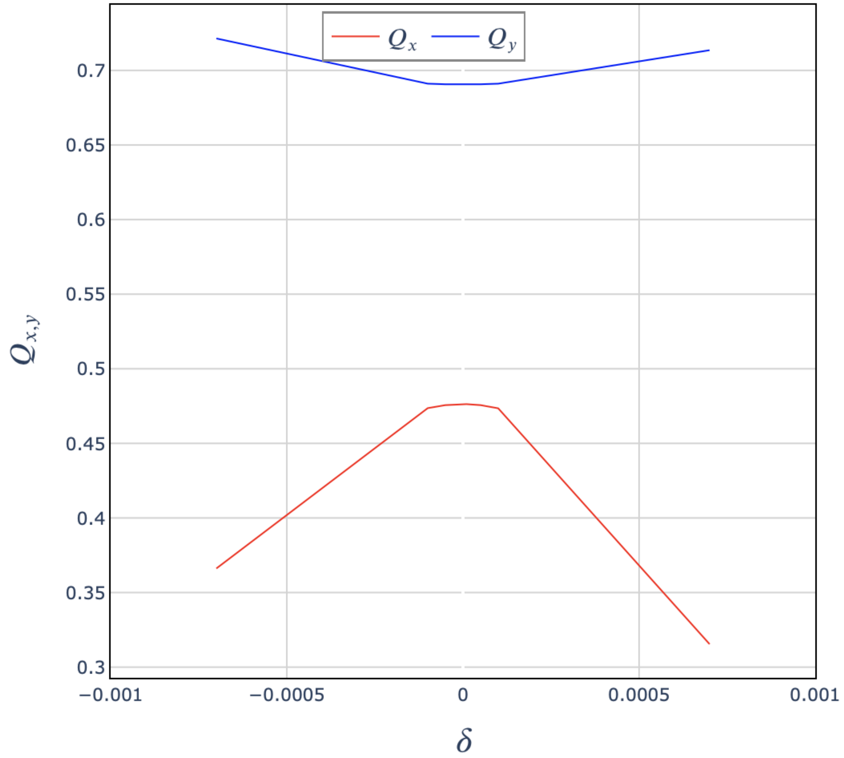
Chromatic correction section – v0.6

Dependence of the tunes on δ

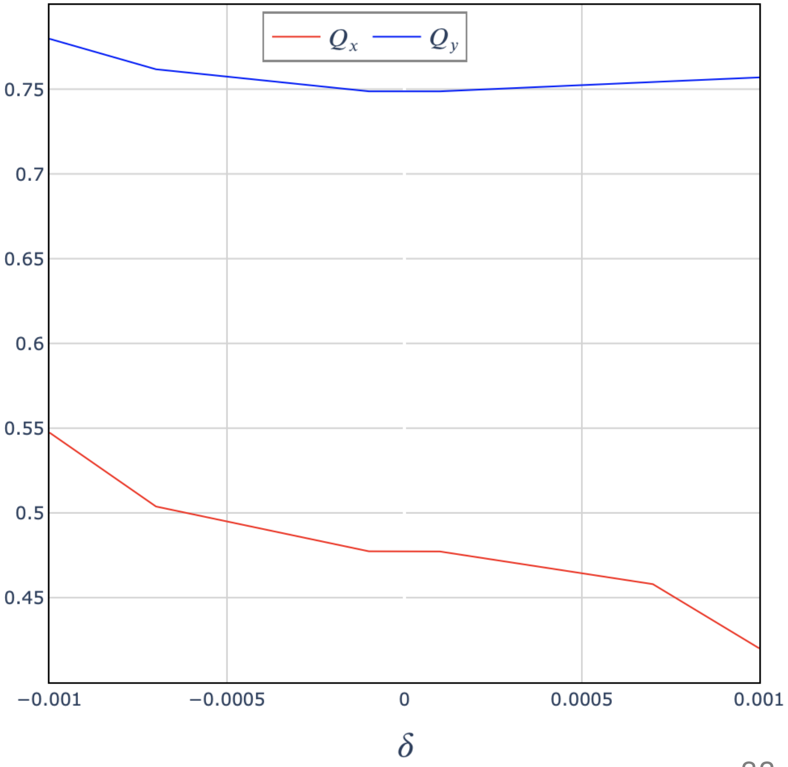
$\mu_{y_{SD1}} = 0.75;$
$\mu_{x_{SF1}} = 2.25$



$\mu_{y_{SD1}} = 0.75 \ - 0.0000225;$
$\mu_{x_{SF1}} = 2.25 + 0.000055$



Optimized phase with automated cost

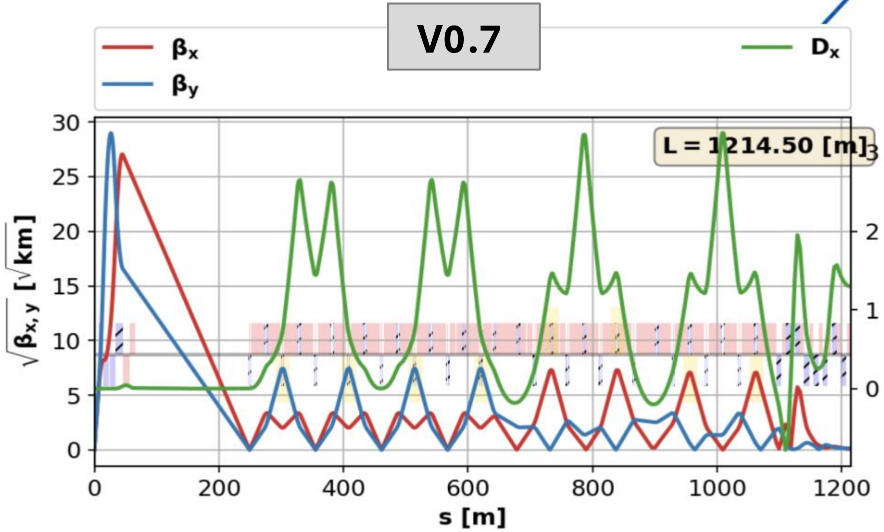


CC – v07

Chromatic correction section – v0.7

Main **differences** with v0.6:

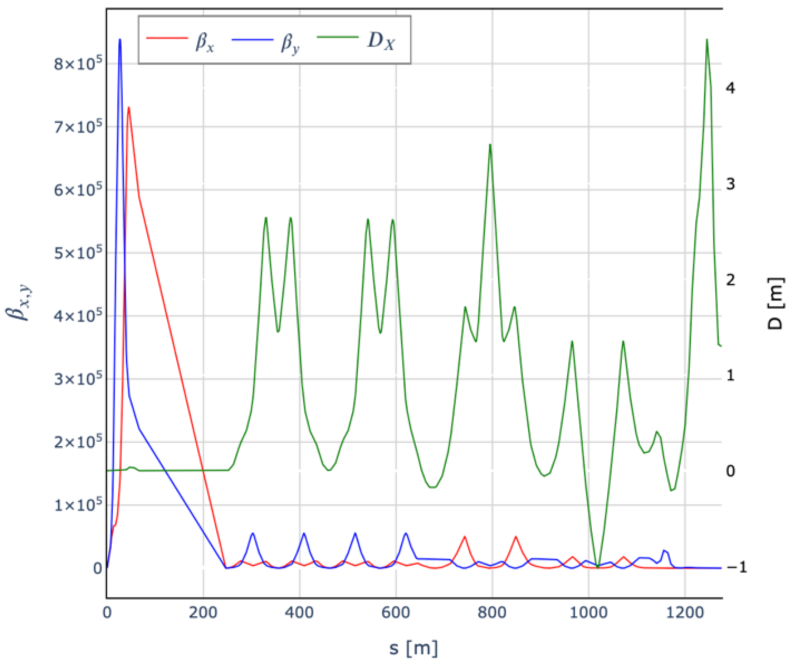
Double pair of sextupoles to try to control the chromaticities and the matching of $W = \sqrt{A^2 + B^2}$ in the CC (independence of the CC and the arcs)

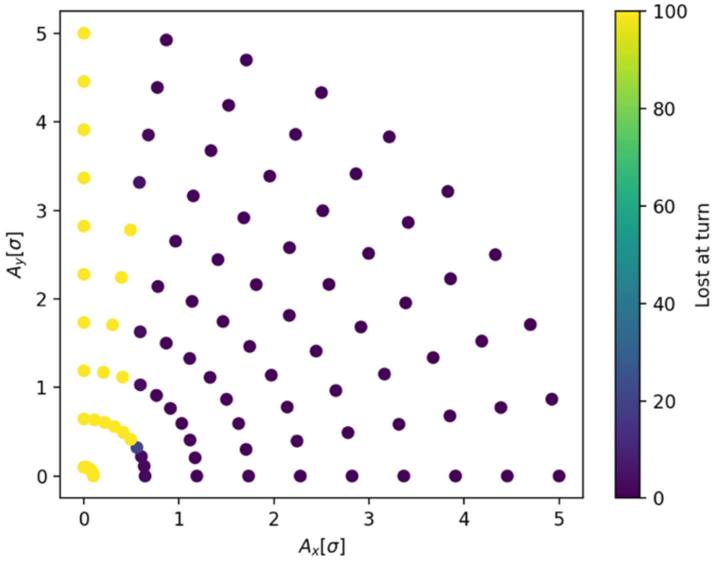


Main **issues/problems** in Kyriacos version:

- **Magnetic field of 50T** in the matching section
  → Better results by **limiting the quadrupole strength** in the matching of the MS (B<20T with shielding of 3cm).
- **Matching of A&B and chromaticities** not possible at the same time
  → Need 4 variables (double pair of sextupoles with slightly different phase advances at sextupoles) to correctly match (Ax, Bx), (Ay, By) but **impossible to match W AND Q'**
  → Dependence between the CC section and the arcs (**no Q' control in the CC)**
- **D and β not the same in both sextupoles of each pair**

Chromatic correction section – v0.7





D and β not the same in both sextupoles of each pair

- Adapt the quadrupole and dipole strengths to find a suitable solution
- Lattice strongly constrained (almost all quad strengths used for matching purposes).
- The DA is very small, even for $\delta = 0$
  - The limitation came from a 3rd order resonance ($\nu_1 + 2\nu_2 = 2$), which should have been canceled out by the second sextupole of the pair.
  - **HUGE sensitivity of the lattice to the phase advance** (max error of 5e-5 on the π phase advance between two sextupoles of a pair).

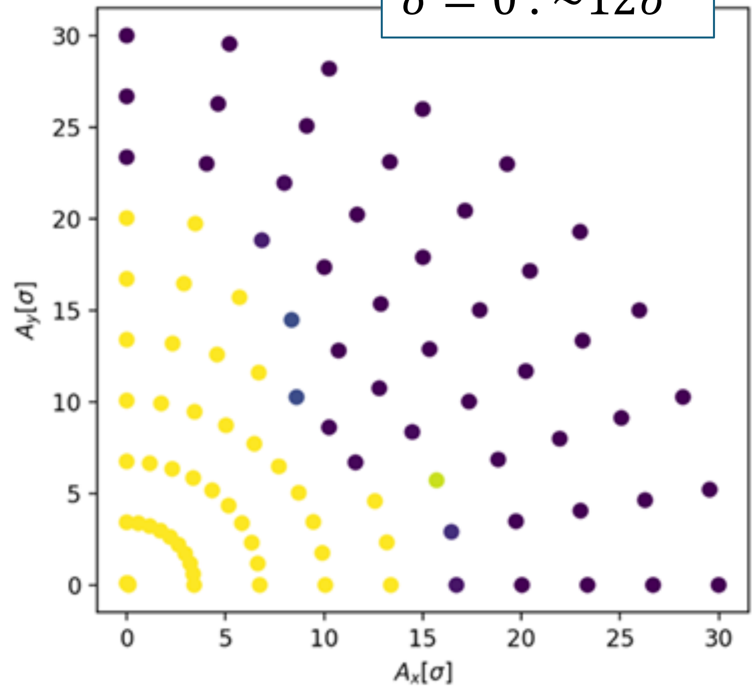
→Doesn't seems well for future error studies!

Chromatic correction section – v0.7

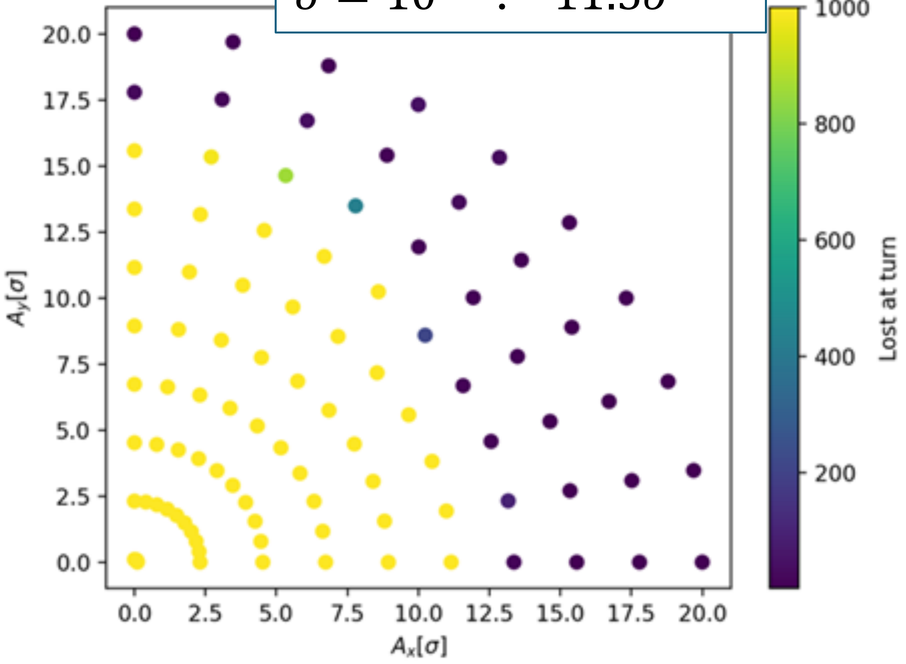
<u>DA on the v0.7 </u> with the correct MS and best chromaticity achived without re-matching of the entire ring:

- DA **much smaller than for v0.6** (and probably the previous version of v7 as well?)
- The off-momentum DA is not sufficiently large → **Really bad DA** starting from $\boldsymbol{\delta = 7\ 10^{-4}}$; even for the « baseline lattice », without any changes.

$\delta = 0 : \sim 12\sigma$



$\delta = 10^{-4} : \sim 11.5\sigma$



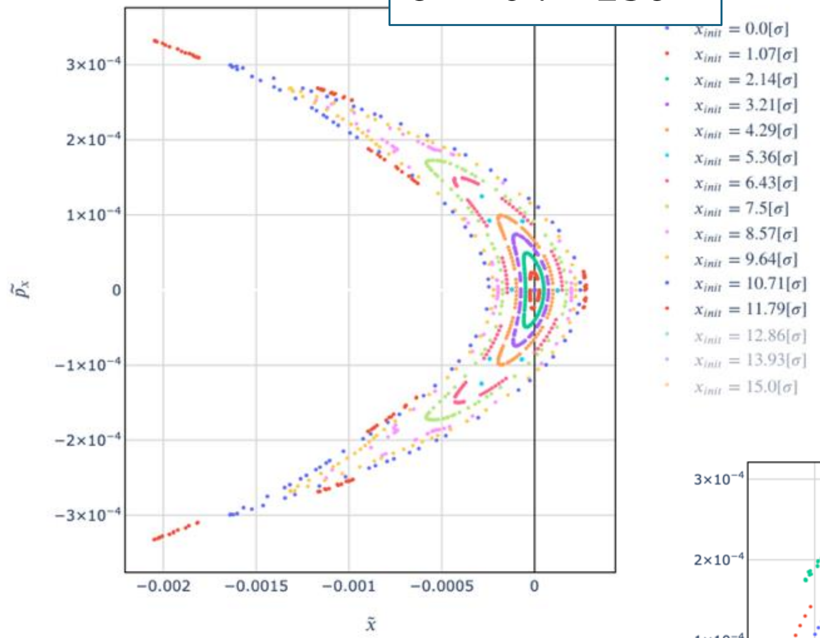
$\delta = 7 * 10^{-4} : 0\sigma$

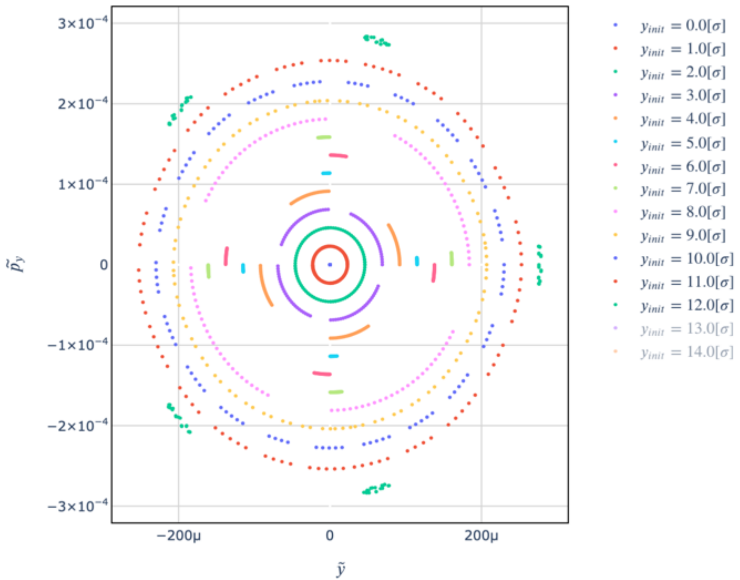
X

Chromatic correction section – v0.7

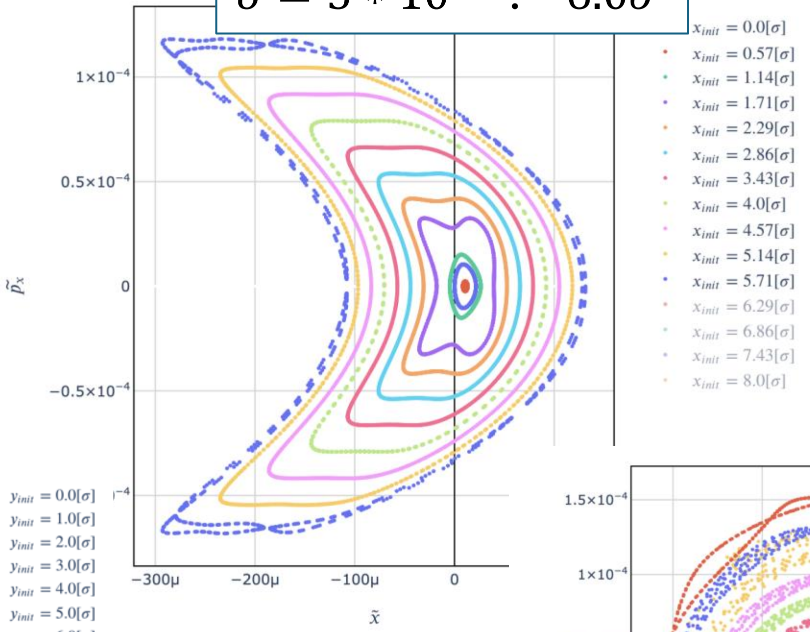
- Reduced DA for off-momentum particles: phase space plots

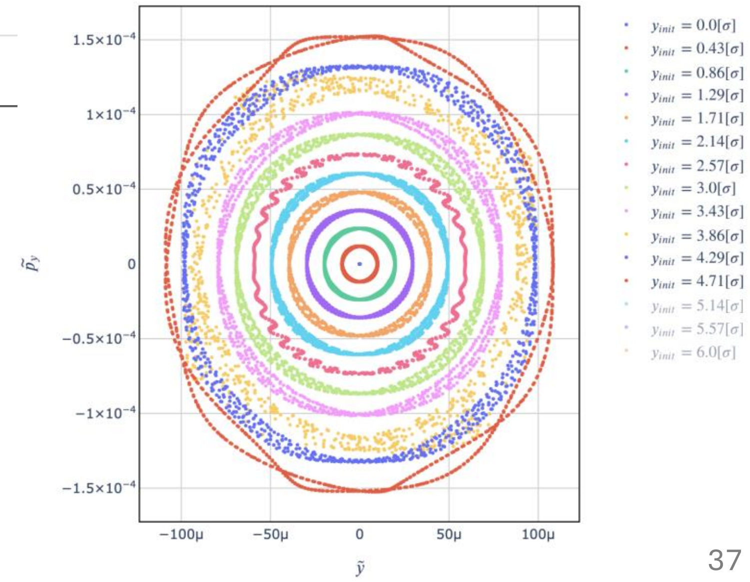
$\delta = 0 : \sim 15\sigma$





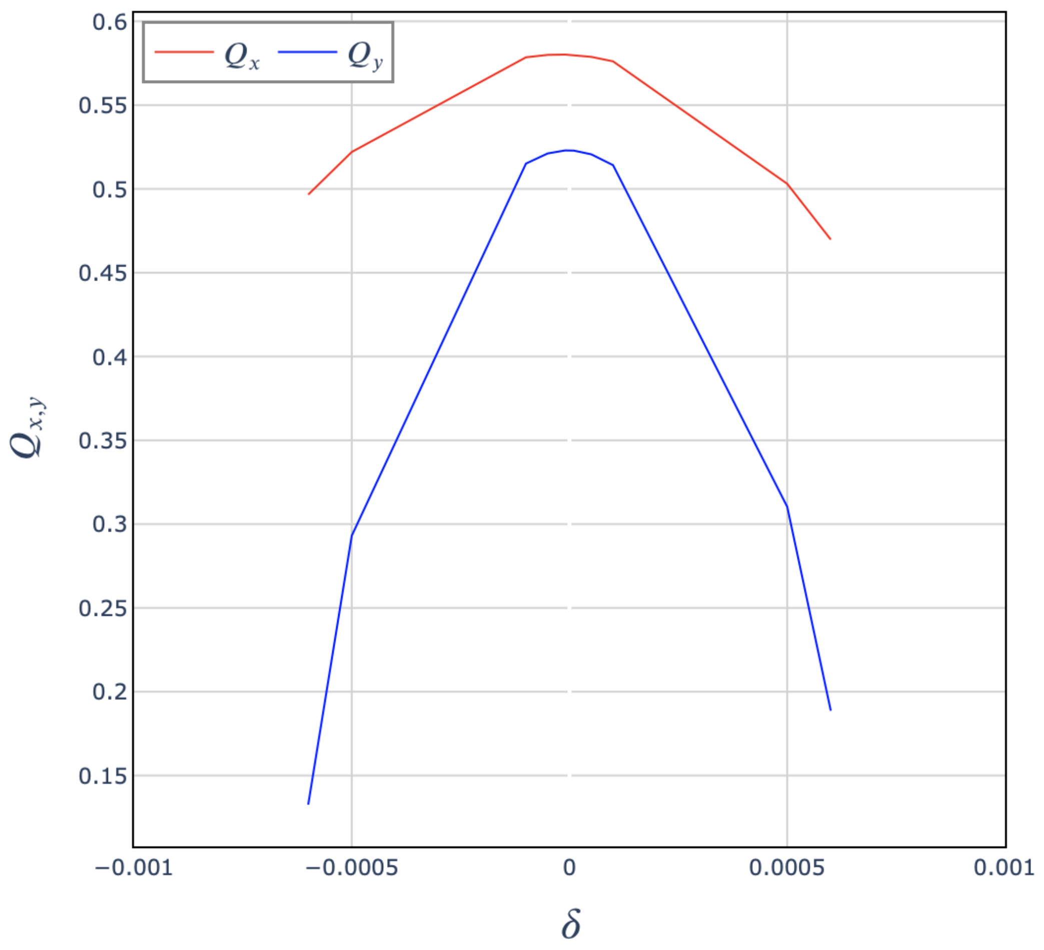
$\delta = 5 * 10^{-4} : \sim 6.0\sigma$





Chromatic correction section – v0.7

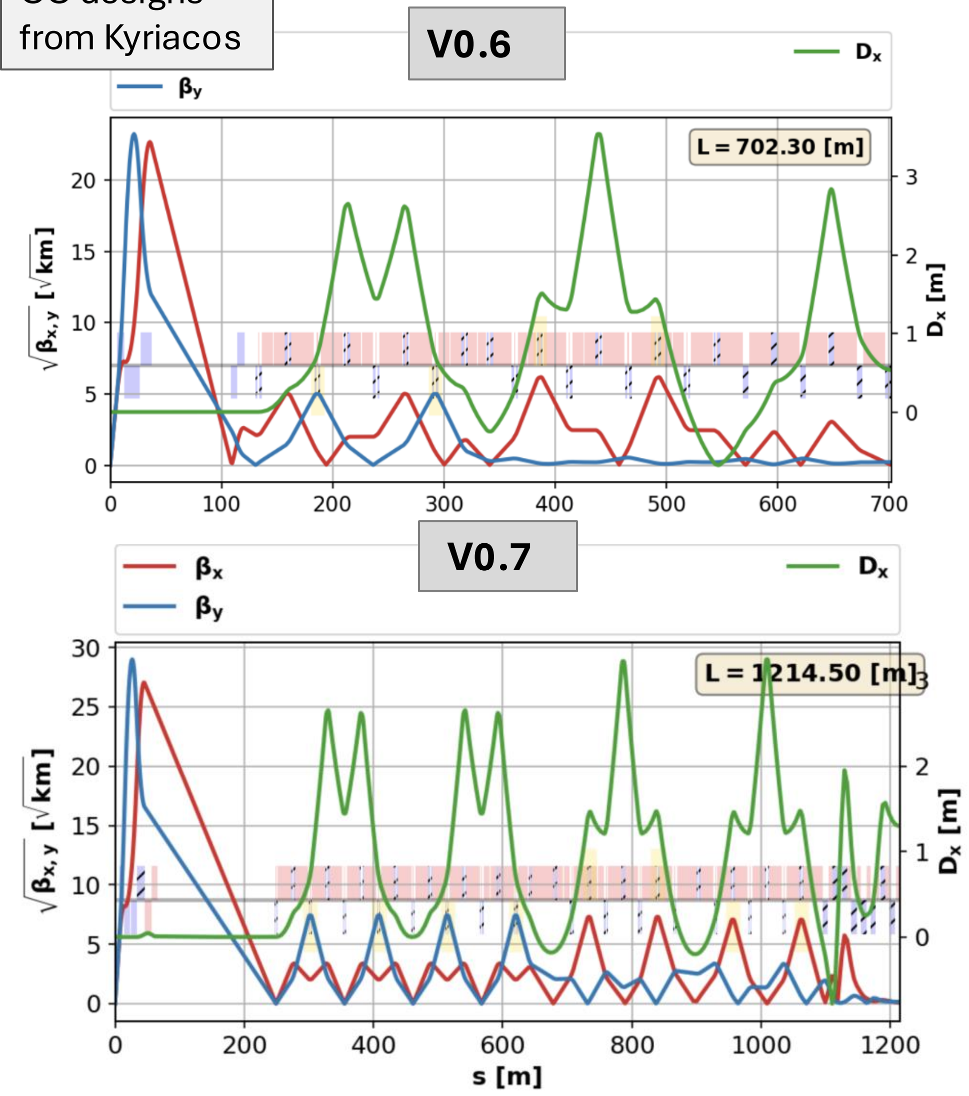
Dependence of the tunes on δ:



Local Chromatic correction section

Remaining issues of v0.6 & v0.7

CC designs from Kyriacos



- Sufficient dynamic aperture for on-momentum particles, but **requirements not yet met** for the **entire momentum range**.
- **Huge sensitivity to phase advance** error between the sextupoles of a pair → poor DA for small errors.
- Beta remains very high in the CC (compared to a circumference of 10 km) → The lattice will probably be very sensitive to alignements/field errors.
- **No** clear knobs to **control the working point** in the current lattice.
- The sextupoles are placed on the slope of the dispersion. Ideally, we would like to place them at a maximum of the dispersion (D' = 0).
- Matching section between CC and arcs not easy to match

New optics attempt: « v0.8 »

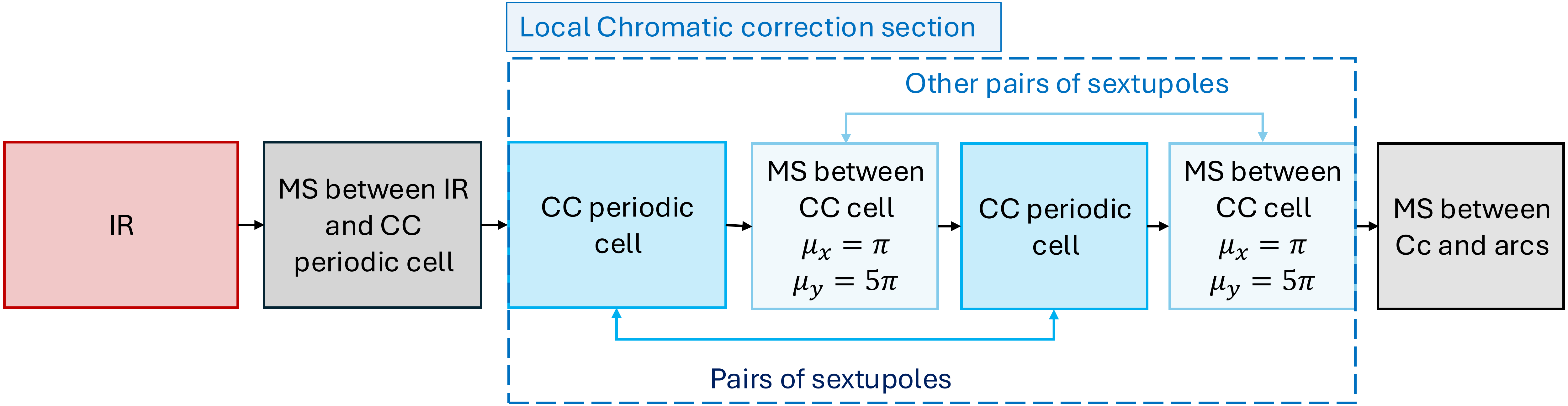
Goals of the "new optics"

Change the optics in order to have:

- **Lower sextupole strengths** and smaller $\boldsymbol{\beta}$ **functions** in CC (less sensitive to small errors).
- A **periodic and symmetric cell** for the CC that could be **repeated** as needed, without having to adjust all the quad strengths in each part (less constrained lattice); We automatically have the **same** $\boldsymbol{\beta}$ **and D in the sextupoles of a pair**.
- **Maximum dispersion** at the **sextupoles** ($\widetilde{D}' = 0$).
- **More sextupoles** to have more variables to match all the required quantites (Wx, Wy, Q'_x, Q'_y); all sextupoles in a same cell.

→ CC with **dispersion oscillation** to take advantage of a **larger dispersion** and reduce the beta functions and sextupole strengths.

V0.8 - Structure of the CC



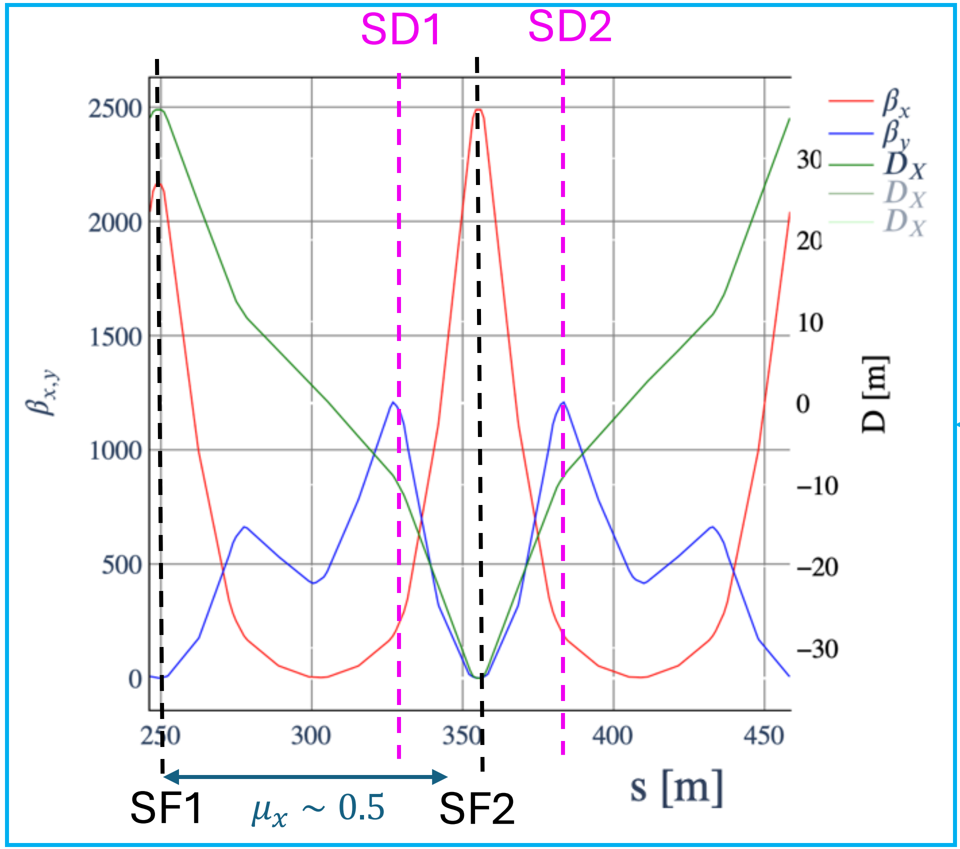
V0.8 - Structure of the CC

International MUON Collider Collaboration

CERN

Other pairs of sextupoles

IR → MS between IR and CC periodic cell → CC periodic cell → MS between CC cell $\mu_x = \pi$ $\mu_y = 5\pi$ → CC periodic cell → MS between CC cell $\mu_x = \pi$ $\mu_y = 5\pi$ → MS between Cc and arcs



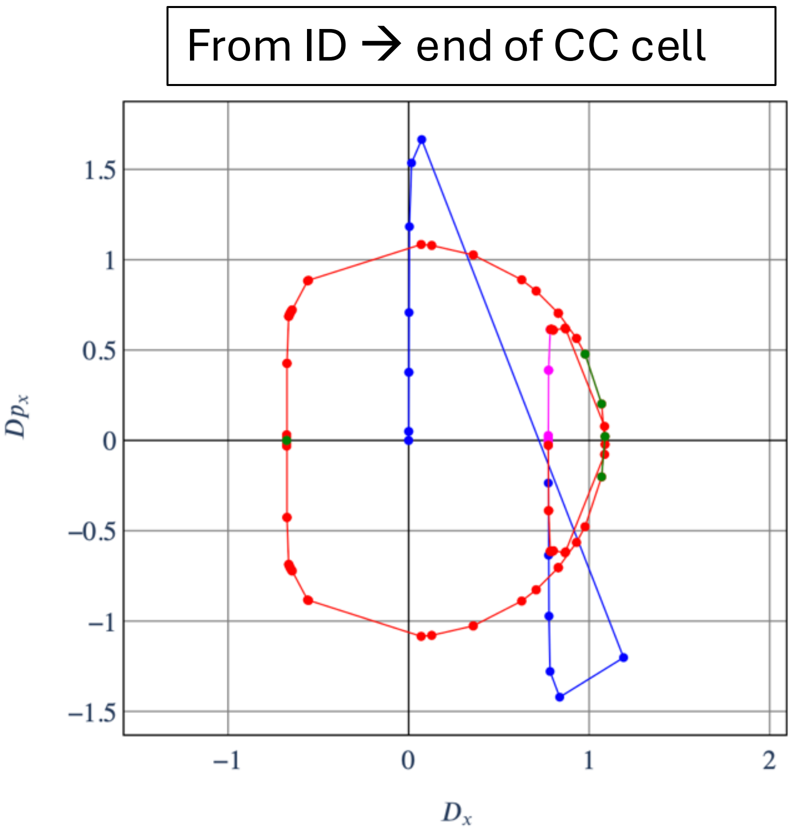
Pairs of sextupoles

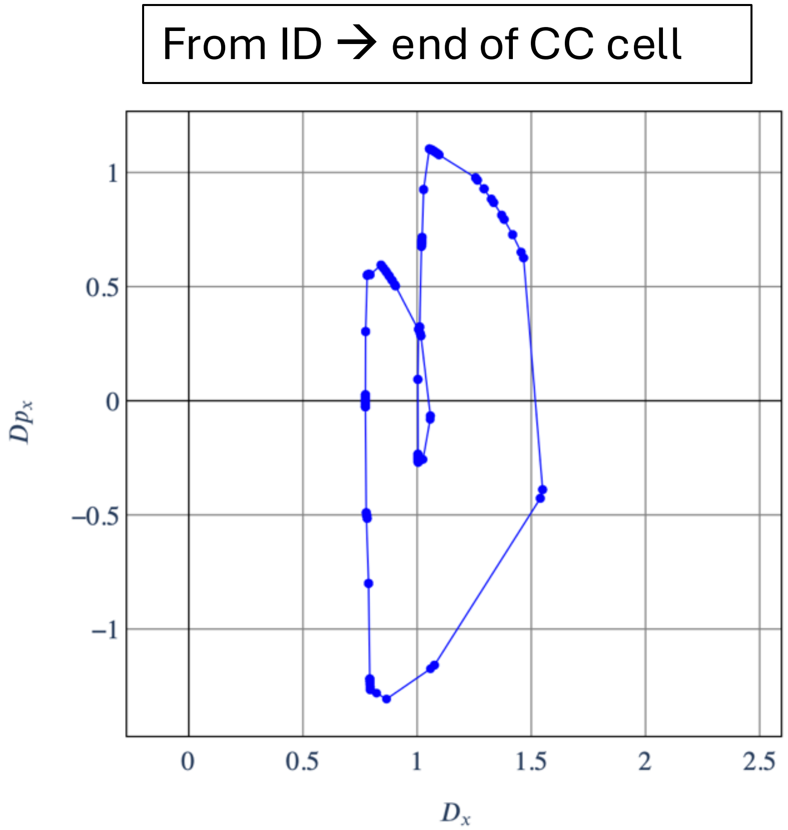
- The **maximum of β_x** corresponds to the **maximum of dispersion** → Sextupoles to correct chromaticity errors in X.
- The **maximum of β_y** corresponds to $D \sim -8m$ → Sextupoles to correct chromaticity errors in Y.
- Periodic cell: $\mu_x \sim \mu_y \sim 2\pi$ $(q_1 = 0.985, q_2 = 0.994)$.
- **Need for a second cell**, shifted by π in μ_x and μ_y to have sextupole pairs and **cancel the non-linear kicks**.

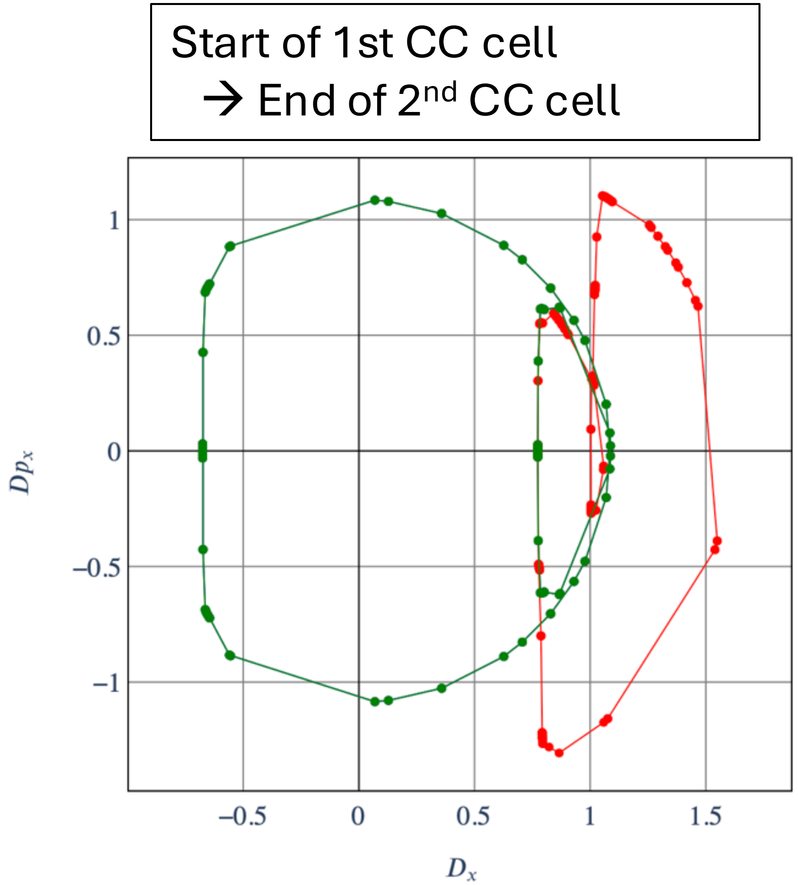
→Need for a **matching section between 2 CC cells** with $\mu_x = (2n+1)\pi, \mu_y = (2n+1)\pi. s$

V0.8 - Matching section between 2 CC cells

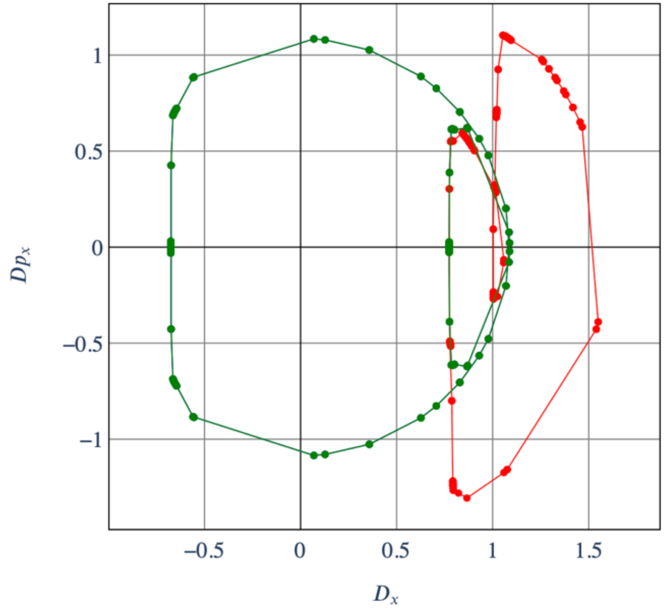
- Matching section done manually based on the plots of the normalized dispersion: $\mu_x = \pi, \mu_y = 5\pi$.

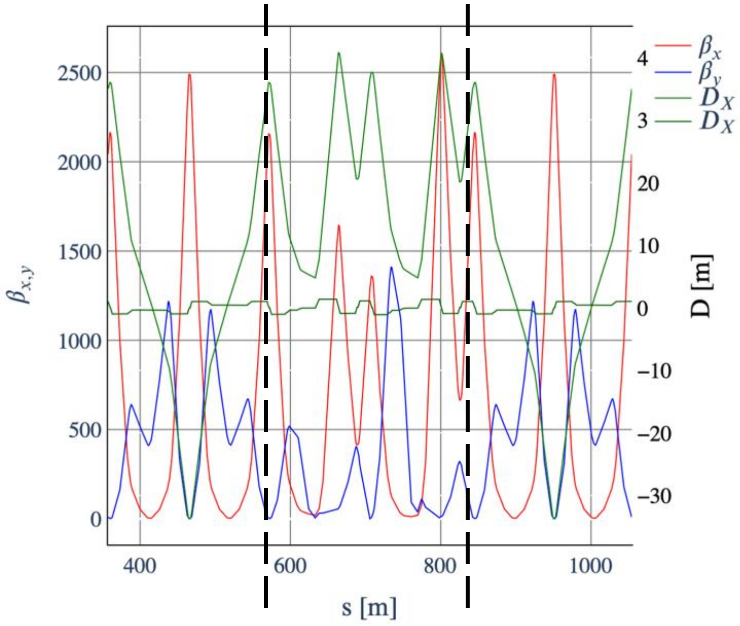




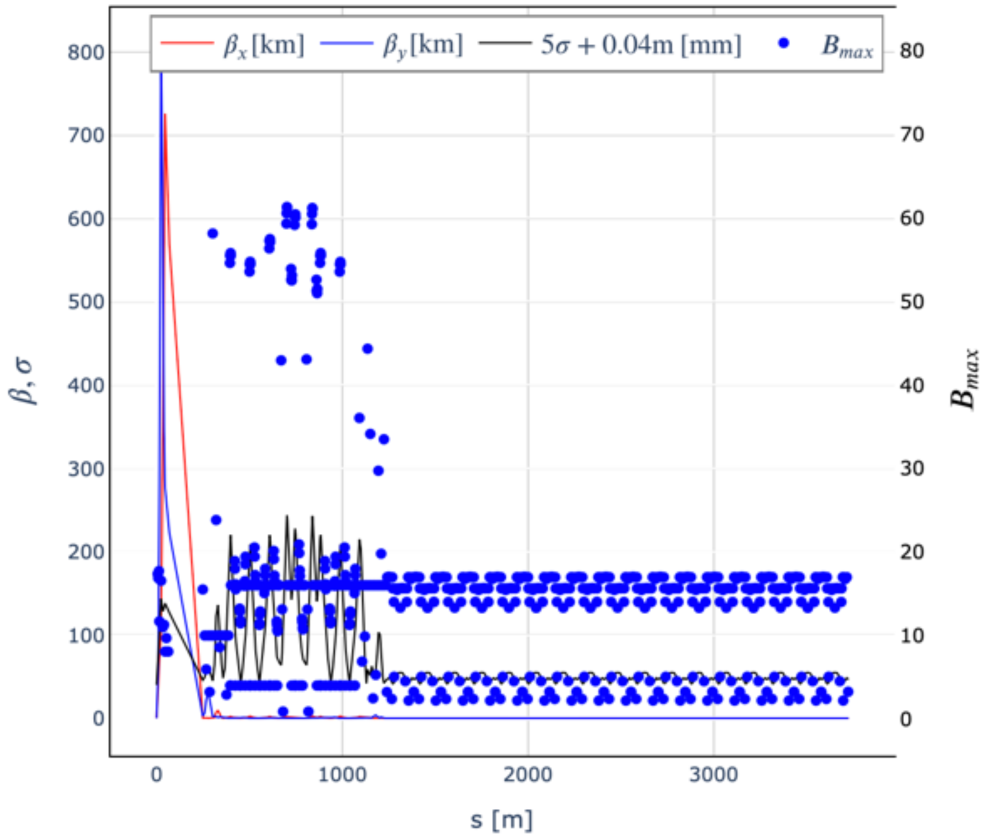


V0.8 - Matching section between 2 CC cells

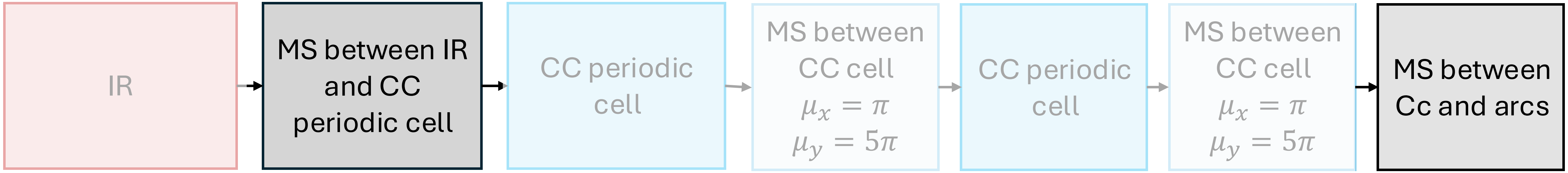




- Large dispersion → Large magnet apertures and magnetic field



Matching sections IR-CC; CC-arcs



MS between IR and CC:

- **Difficult** matching section because it requires significantly **increasing the dispersion** with not too high beta functions, while respecting the **phase constraints** : $\mu_x = 1.25$ at first SF, $\mu_y = 0.75$ at first SD.
- Magnetic field too high.

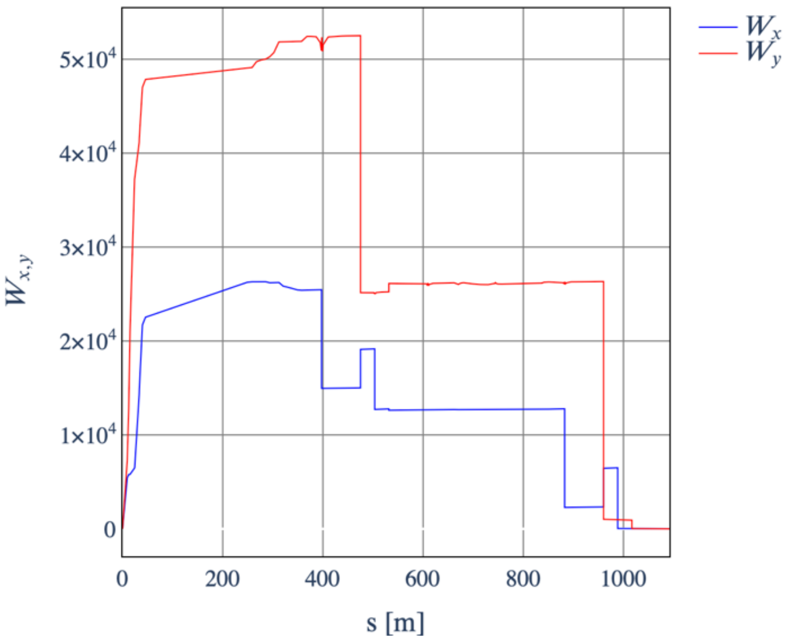
MS between CC and arcs:

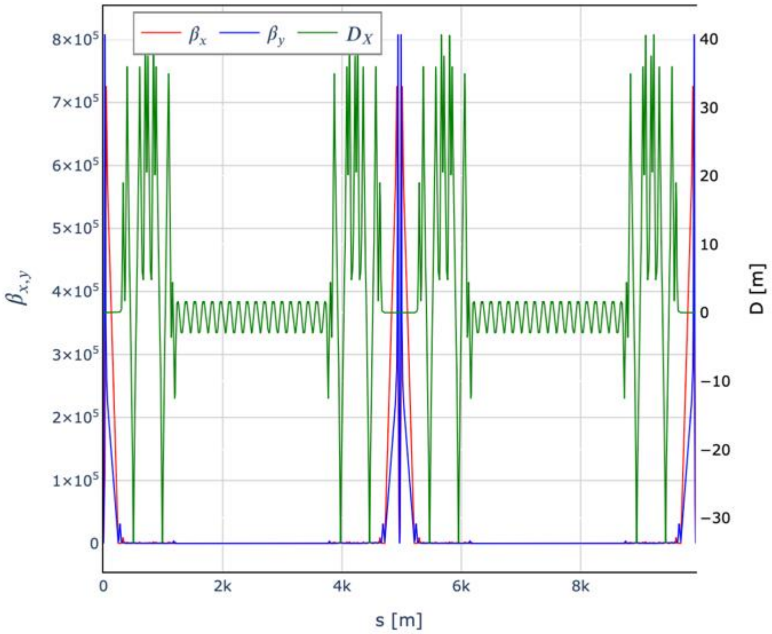
- Fairly **easy** to find a working solution, **limiting the quad strengths** to reduce the magnetic field.
- May be used later to **adjust the working point**.

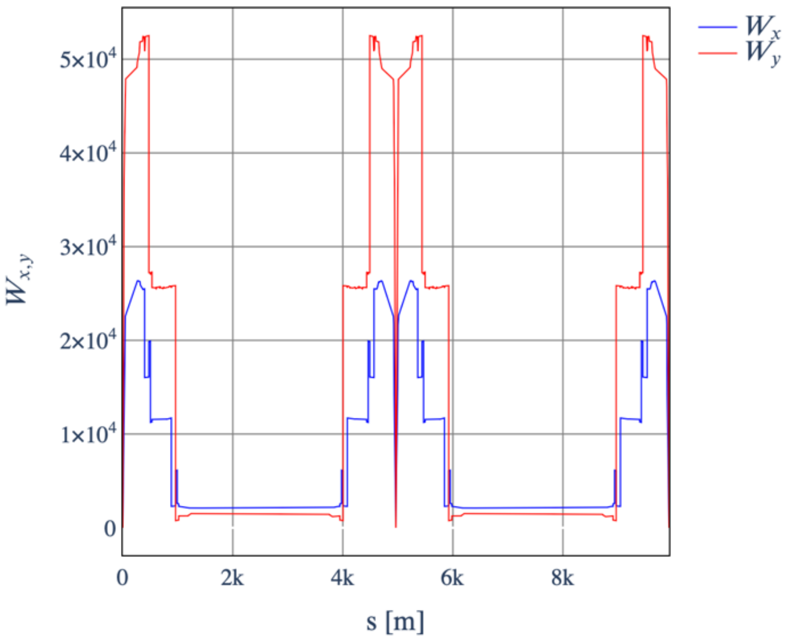
Matching of Wx, Wy

- The **sextupoles strengths** have been adjusted to correctly **match W_x and W_y** at the entrance of the arcs.
- **No control of chromaticites** → Rematch of the entire ring to achieve $W_x = W_y = 0$, and zero chromaticities → **Large W** in the arcs!

→ **Need to control the chromaticities in the CC to have W <1000 in the arcs!**







V0.8 – Q' control in CC

- **Quads in the MS** between IR and CC that **drive linear chromaticity** at $\mu_x \sim 1$
- Place SF sextupole at a phase multiple of $1[2\pi]$ to correct Q'_x not coming from the FF triplet.

There are two terms that are independent of the phase variable

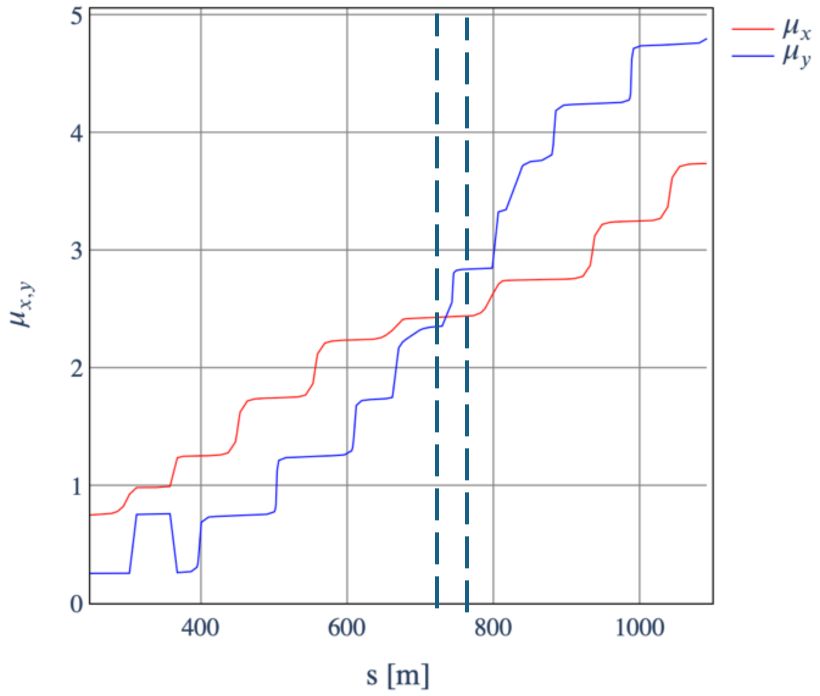
$$
\begin{aligned}
h_{11001} &= \frac{1}{4}\sum_{i=1}^{N}\left[(b_2L)_i - 2(b_3L)_i\eta_{xi}^{(1)}\right]\beta_{xi} + O\left(\delta^2\right), \\
h_{00111} &= -\frac{1}{4}\sum_{i=1}^{N}\left[(b_2L)_i - 2(b_3L)_i\eta_{xi}^{(1)}\right]\beta_{yi} + O\left(\delta^2\right)
\end{aligned} \qquad (95)
$$

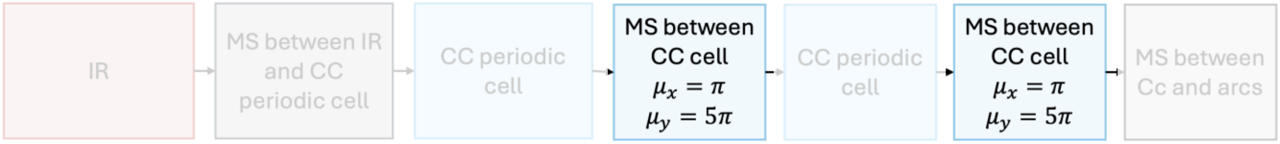
which drive the linear chromaticity, the initial reason for introducing sextupoles into the lattice. The remaining are

$$
\begin{aligned}
h_{20001} &= h^{*}_{02001} = \frac{1}{8}\sum_{i=1}^{N}\left[(b_2L)_i - 2(b_3L)_i\eta_{xi}^{(1)}\right]\beta_{xi}e^{i2\mu_{xi}} + O\left(\delta^2\right), \\
h_{00201} &= h^{*}_{00021} = -\frac{1}{8}\sum_{i=1}^{N}\left[(b_2L)_i - 2(b_3L)_i\eta_{xi}^{(1)}\right]\beta_{yi}e^{i2\mu_{yi}} + O\left(\delta^2\right), \\
h_{10002} &= h^{*}_{01002} = \frac{1}{2}\sum_{i=1}^{N}\left[(b_2L)_i - (b_3L)_i\eta_{xi}^{(1)}\right]\eta_{xi}^{(1)}\sqrt{\beta_{xi}}e^{i\mu_{xi}} + O\left(\delta^3\right) \quad (96)
\end{aligned}
$$

J. Bengtsson, *The sextupole scheme for the Swiss Light Source (SLS)- An Analytic Approach*

→Add sextupoles in the MS between 2 CC cells, at $\mu_x = 2.42$ and $\mu_x = 2.43$; need a second MS at the end of the CC to have sextupole pairs.

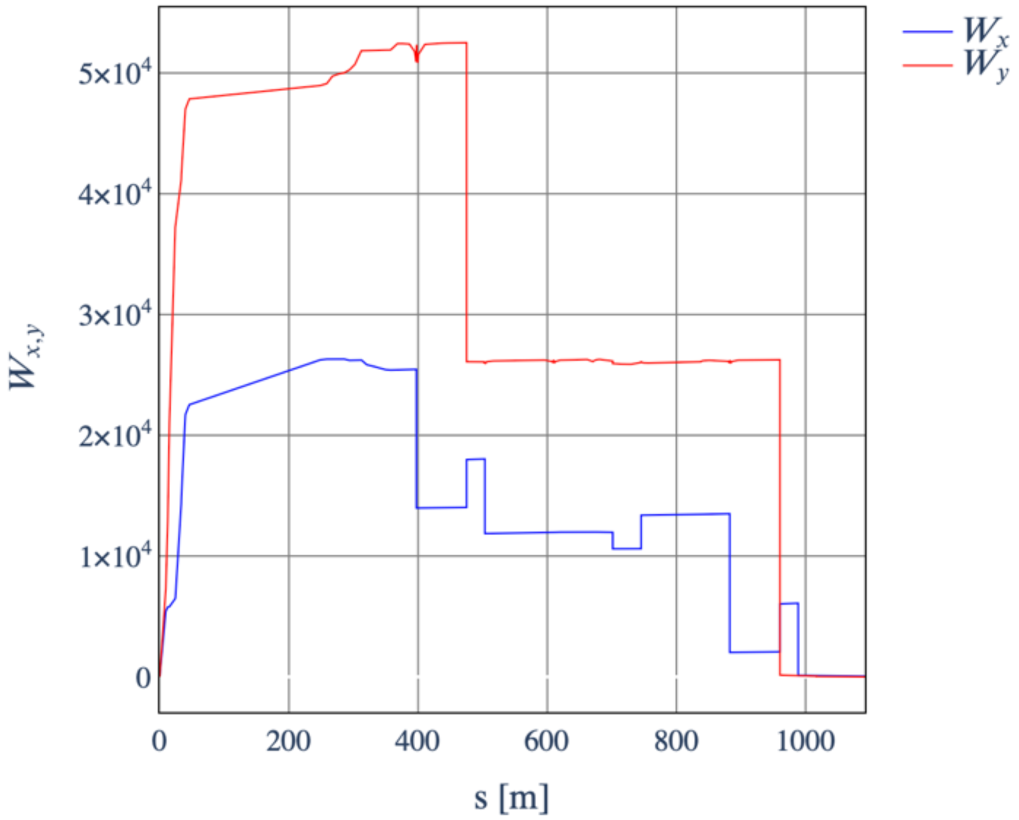




V0.8 – Q' control in CC

→Possible to **control of W and Q' in the CC**

→Independence of the CC and the arcs.

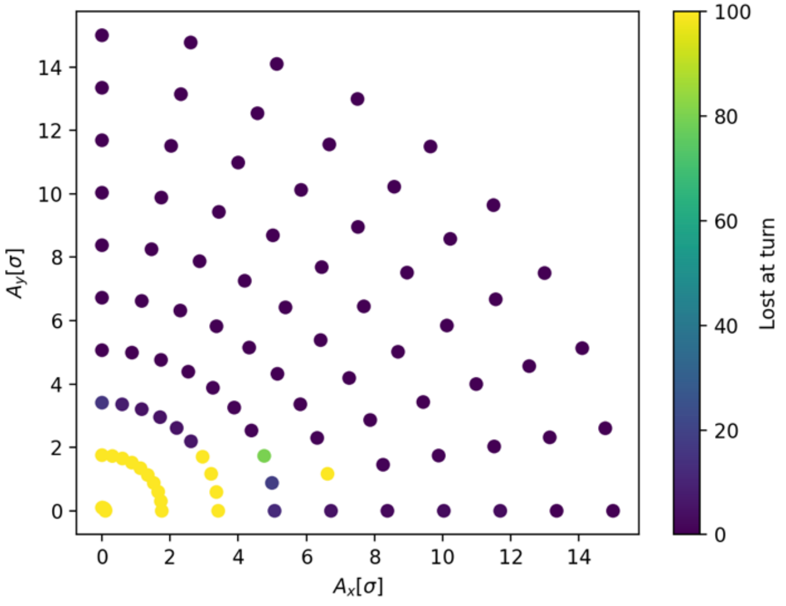


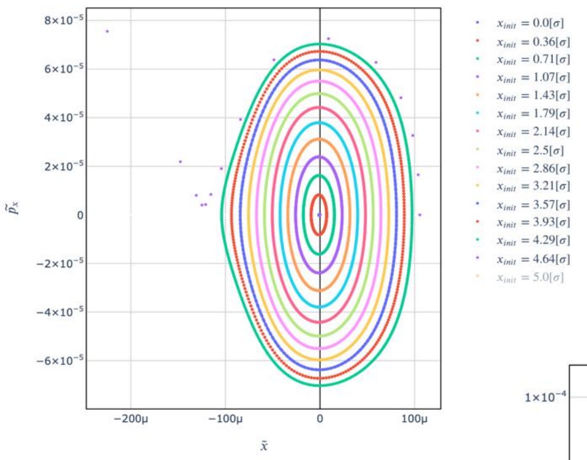
V0.8 – Dynamic apertures

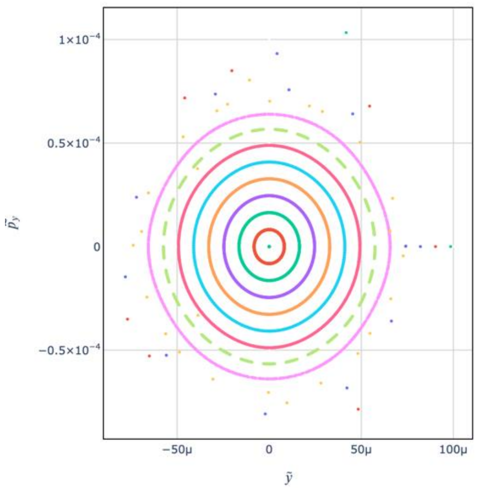
- Poor DA and momentum acceptance
  - Due to higher order chromaticities ?

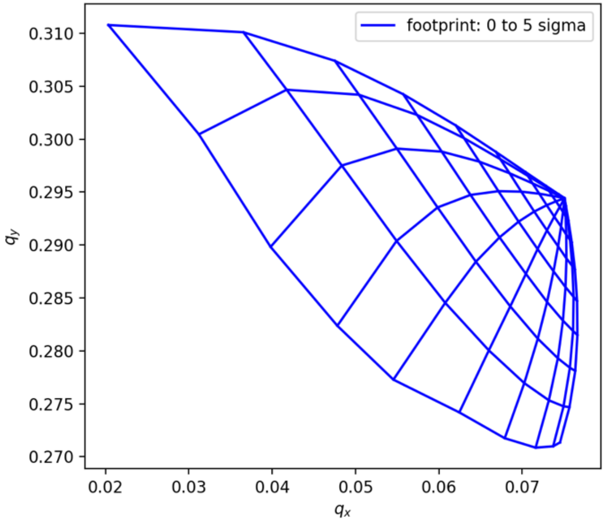
$$Q_x'', Q_y'' \;=\; 1.9\, e^5, 1.2e^7$$

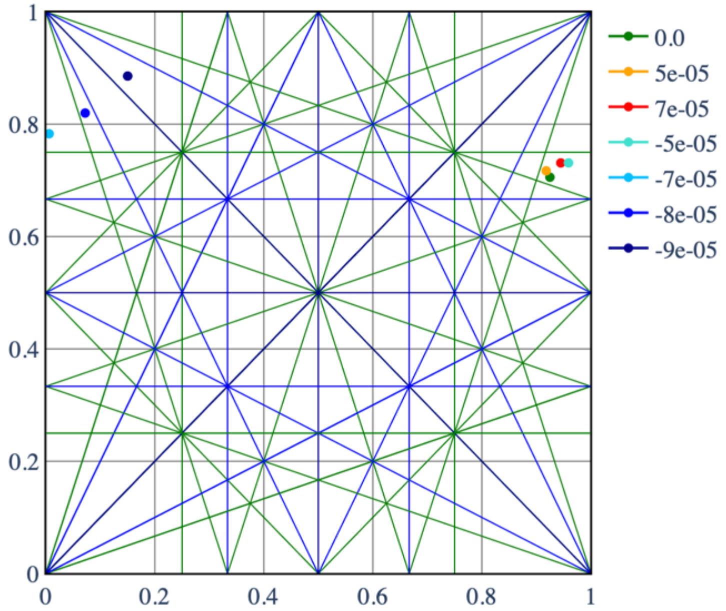
$\delta = 0 : \sim 2\sigma$











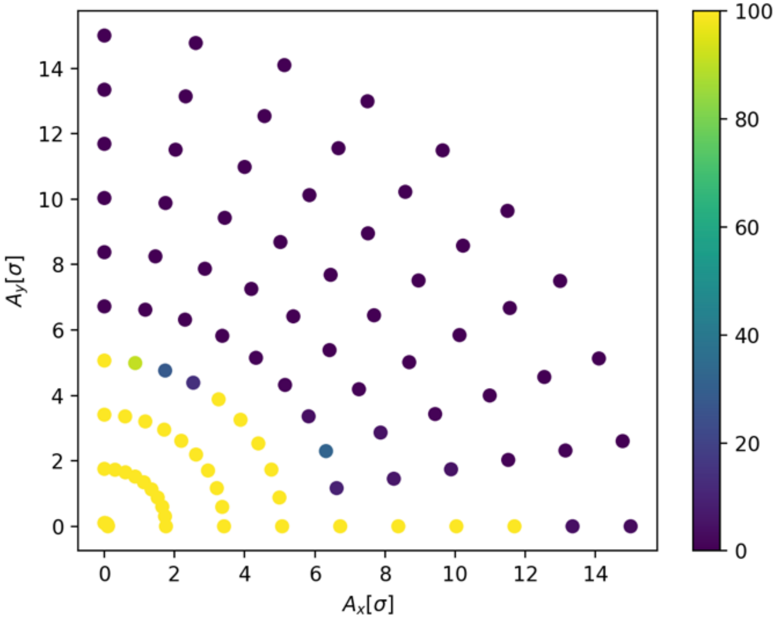
V0.8 – Dynamic apertures

- Poor DA and momentum acceptance

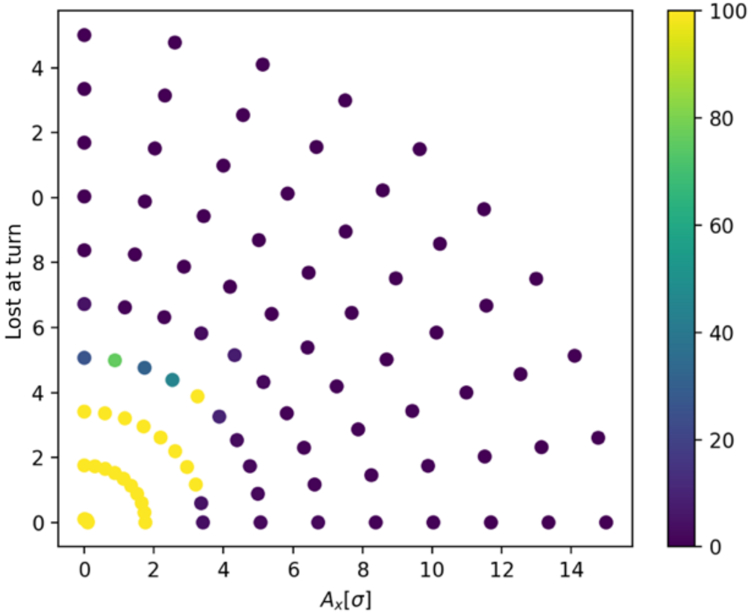
  →**Match the second order chromaticities** on the entire ring with all sets of sextupoles

  →**Increased but still small DA even for $\delta = 0$**; DA increased to 8σ if we divide all sextupole strengths by 2→ **Sextupole strengths** too high ?

$\delta = 0 : \sim 4\sigma$



$\delta = 10^{-4} : \sim 3.1\sigma$



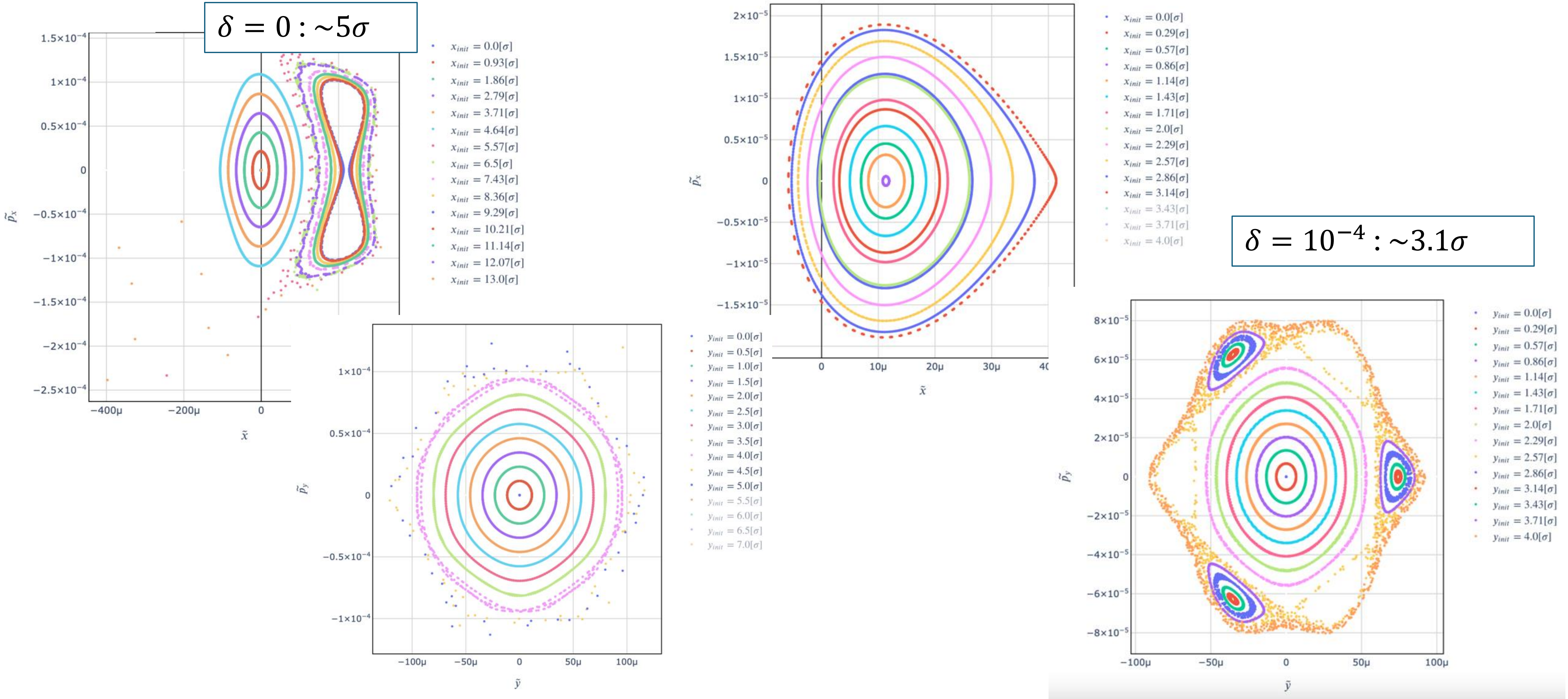
$\delta > 10^{-4} : \sim 0\sigma$

X

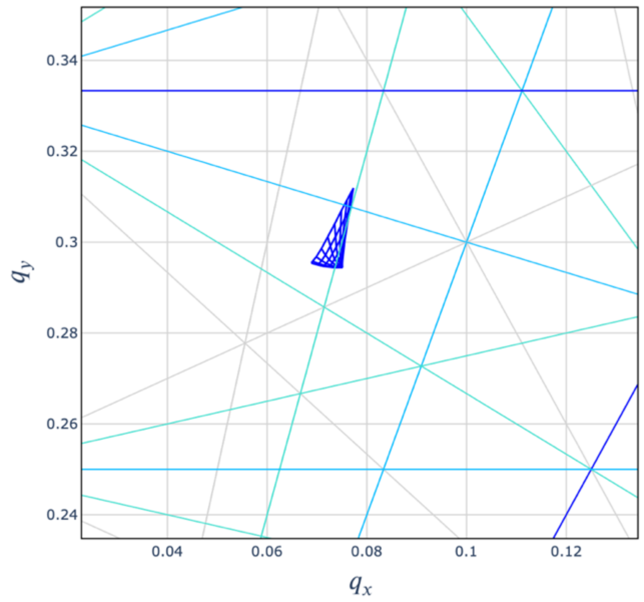
0	ON	False	0.00500132	0.00500132	0	'dqx', val=0,
1	ON	True	9.9476e-07	9.9476e-07	0	'dqy', val=0,
2	ON	False	0.792507	0.792507	0	('wx_chrom', '
3	ON	False	0.0361833	0.0361833	0	('wy_chrom', '
4	ON	False	-7.86571	-7.86571	0	'ddqx', val=0,
5	ON	False	6.62226	6.62226	0	'ddqy', val=0,

V0.8 – phase spaces

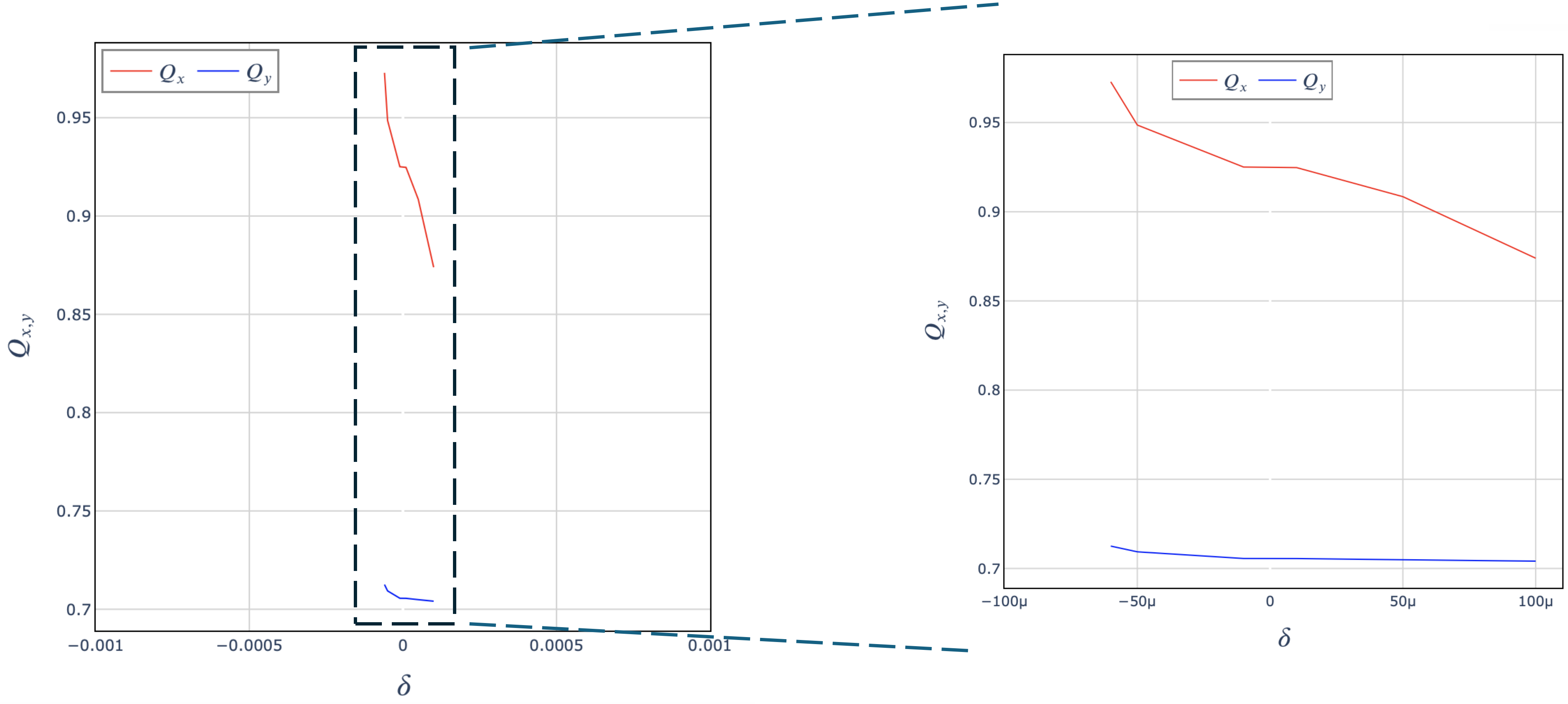
- Phase space in Y quite similar to what we had in v0.6!



V0.8 – Footprint & tune variations



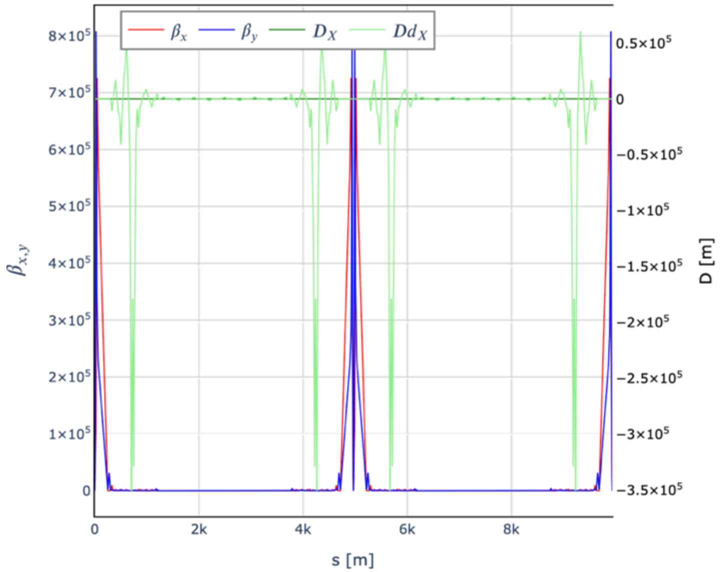
- Limitations not clear from the footprint
- **Huge tune shift** with δ even if $\boldsymbol{Q' \to 0}$ **and** $\boldsymbol{Q'' \to O(10)}$



Main Advantages/issue of v0.8

Advantages:

- Play on dispersion rather than beta and sextupole strengths → The lattice will be likely **less sensitive to errors**.
- **W and Q' control in the CC !** Seems possible to control of Q_x'', Q_y'' on the entire ring
- **Reducing β** also helps **avoid adding chromatic errors from other CC quads** that may not be in phase with the FF triplet errors.
- The **structure of the lattice** allows for **adding as many sextupoles as necessary**, with the non-linear kicks always being canceled out by the sextupoles in the second cell.
- Reducing the β in the CC helps to **minimize path length differences** due to betatron oscillations (to be compared to the approximately 10 km circumference of the ring).



Issues:

- Huge **second-order dispersion**
- Huge **magnetic field** due to the large dispersion oscillation amplitude
- Tunes not (yet) adjusted; no clear knob for **working point control**.
- SD strength still really large !
- Low DA but lattice design much less mature than the other versions.

Comparaison of v0.6, v0.7, v0.8

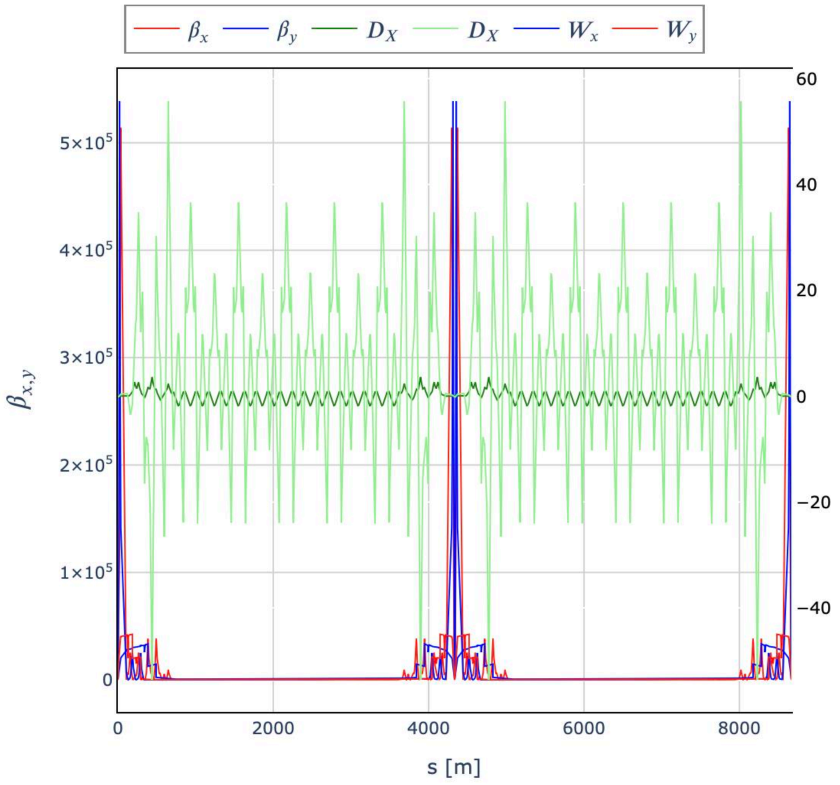
Comparaison of v06, v07 and v08

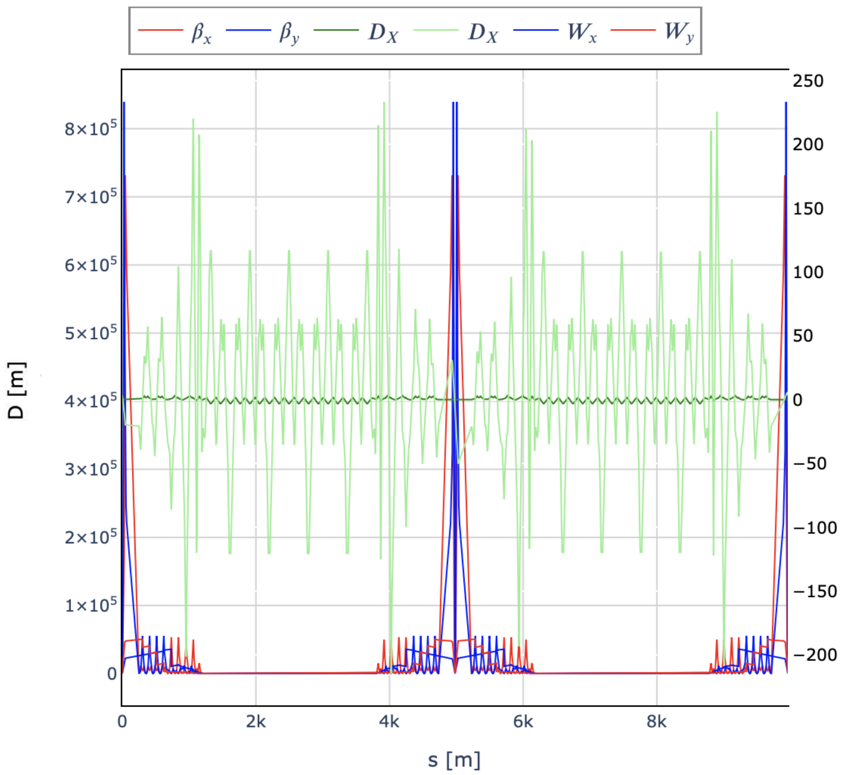
	V0.6	V0.7	V0.8
Sextupoles strengths			
SF_arcs	0.064294	-0.062492	-0.101590
SD_arcs	0.117603	0.223955	0.219194
SF_CC_1	0.345776	0.327754	0.147995
SF_CC_2	/	-0.02236	-0.076368
SD_CC_1	-1.227299	-0.300536	2.516348
SD_CC_2	/	-0.470982	-0.060867
MS_SF_1	/	/	0.163888
MS_SF_2	/	/	-0.120175
β - Functions			
β_x max in CC	~25km	~50km	~2.5 km
β_y max in CC	~38km	~50km	~1.2 km
Max Dispersion in CC	~3.5	~5.77	~40.6
Dispersion in sextupoles	~0.77 - ~1.4	0.77 – 1.44	~35.9

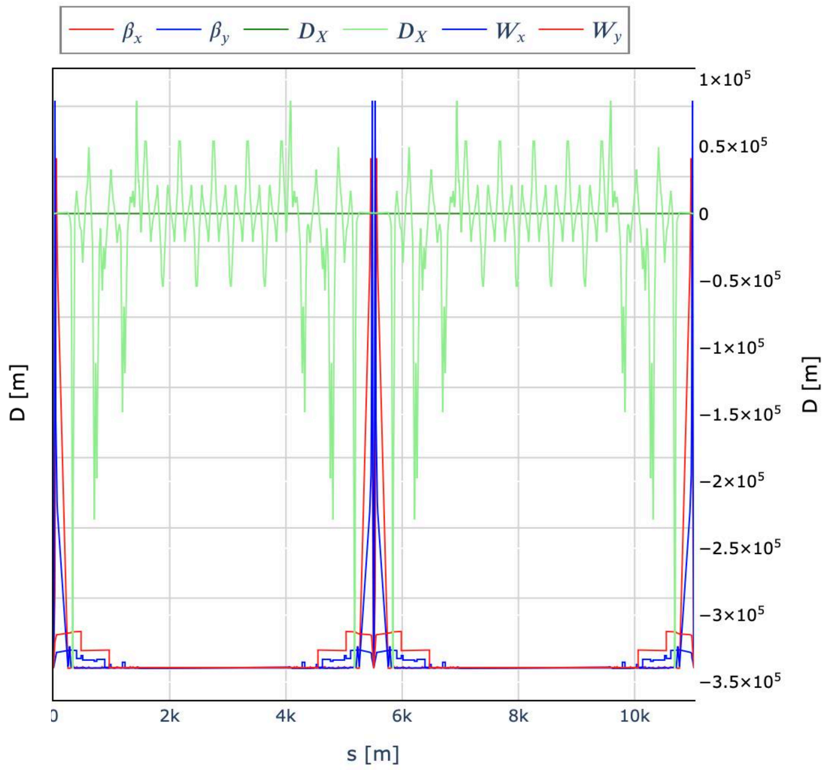
Comparaison of v06, v07 and v08

	V0.6	V0.7	V0.8
DA (Best)			
$\delta = 0$	$\sim 15\sigma$	$\sim 10\sigma$	$\sim 4\sigma$
$\delta = 10^{-4}$	$\sim 12.4\sigma$	$\sim 12\sigma$	$\sim 3.7\sigma$
$\delta = 7 * 10^{-4}$	$\sim 6\sigma$	X	X
$\delta = 10^{-3}$	$\sim 2.5\sigma - 4.5\sigma$	X	X
$\delta = 2 * 10^{-3}$	X	X	X
Q_x	44.4759 – 44.4763 – 44.4772	49.5801	45.924904
Q_y	39.6674– 39.6905 – 39.7485	47.523	62.705569
Q'_x	$3.8e^{-4}$– -$3.4e^{-6}$ – -$1.4e^{-4}$	-11.7408	$5e^{-3}$
Q'_y	$8.1e^{-8}$ – -$1.5e^{-8}$ – -$2.8e^{-8}$	-5.4623	$9.9e^{-7}$
Q''_x	-$7.9e^{5}$ – $5.5e^{5}$ – $1.7e^{4}$	-$5.5e^{5}$	-7.87
Q''_y	$2.6e^{5}$ – $1.1e^{5}$ – $3.8e^{4}$	-$1.6e^{6}$	6.62
Circumference	8.668km	9.959km	~ 11 km

Comparaison of v06, v07 and v08







Comparaison of v06, v07 and v08

	V0.6	V0.7	V0.8
	- DA **up to 4.5σ for $\delta = 1 * 10^{-3}$** with phases optimized at the sextupoles	**-** More compact arcs and slightly changed IR but no advantages in the CC	- **W and Q' control in the CC !** - **Smaller β** in CC (less sensitive to errors?) - **Control of Q''_x, Q''_y** on the entire ring - All sextupole pairs automatically separated by $\mu_x = \pi, \mu_y = \pi$
		- **Smaller DA than v06 and** poor momentum acceptance (Bad DA from $\delta = 7 * 10^{-4}$) - Everything is constrained→ Not enough degrees of freedom to optimize anything else - **Huge sensitivity to phase advance** error between the sextupoles of a pair	- Huge **B** due to large dispersion oscillations. - Huge **second order dispersion** - Particle loss for $\boldsymbol{\delta > 7 * 10^{-4}}$ - Larger circumference of the ring - Poor DA but also less mature lattice
	- Beta remains very high in the CC - Dependence between the CC section and the arcs (**no Q' control in the CC).** - The sextupoles are placed on the slope of the dispersion		

Remaining issues and Next steps

Main design choices to discuss & issues

- **Which version** should we keep ?
  - V0.6 with new IR ? But what are the remaining possibilities for improvements in this version?
  - If v0.7: Adding a third pair could help (3 sextupole variables for 3 parameters to match in each plane)?
  - What could be the limitations for the DA for v0.8 ?
- How can we handle the remaining **tune shift with momentum** and the dependence of footprint with momentum ?

Remaining issues (to keep in mind)

- High **magnetic field value** → probably not possible to have magnets of 20T (FF) or 16T (arcs). We should try to reduce the field or to relax the collider requirements (increase the β^*).
- The **distance for element interconnection** still very small (30cm). We can try to increase it, at the expense of the dose due to neutrinos.
- **No** clear knobs to **control the working point** (transverse tunes) in the current lattice.

Next steps

- Sensitivity study of the momentum acceptance as a function of β^*
- **Implement** the capability to have a combined function **dipole-sextupole magnet in Xsuite**; Evaluate the effects of thick sextupoles.
- Improve the lattice design for momentum acceptance:
  - Any ideas ?
  - Look more closely at the RDTs
  - Second order dispersion ?
  - Add other multipolar components
- …