FCC-ee IR Tuning Knobs

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With inputs from Frank Zimmermann, Michael Hofer & Leon Van Riesen-Haupt

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Introduction

- FCC-ee foreseen to target **unprecedented luminosity**

$$L = \frac{N_1 N_2 \, f \, n_b}{4\pi \, \sigma_x^* \, \sigma_y^*}$$

- **Field errors or alignment** issues cause differences in the optics parameters at the IP
- As a consequence, it is critical to achieve the desired target
- Essential to introduce **knobs** that would help in the **fine-tuning** of the IR optics
- Studies carried out on **z-lattice** whose operating energy is 45.6GeV (Radiation and RF turned off)

The term “Tuning knobs”

- Magnet excitations in specific linear combinations forming the so-called “**Tuning Knobs**”
- The term tuning knob is commonly used for one or several magnets which are used to **tune one variable**
- Find out which **magnet groups/combinations** can be used to achieve the desired value of the IP parameters
- Linear changes in the magnet strengths correspond to the target parameter

Implementation: $\beta^*_{x,y}$ and $w_{x,y}$ knobs

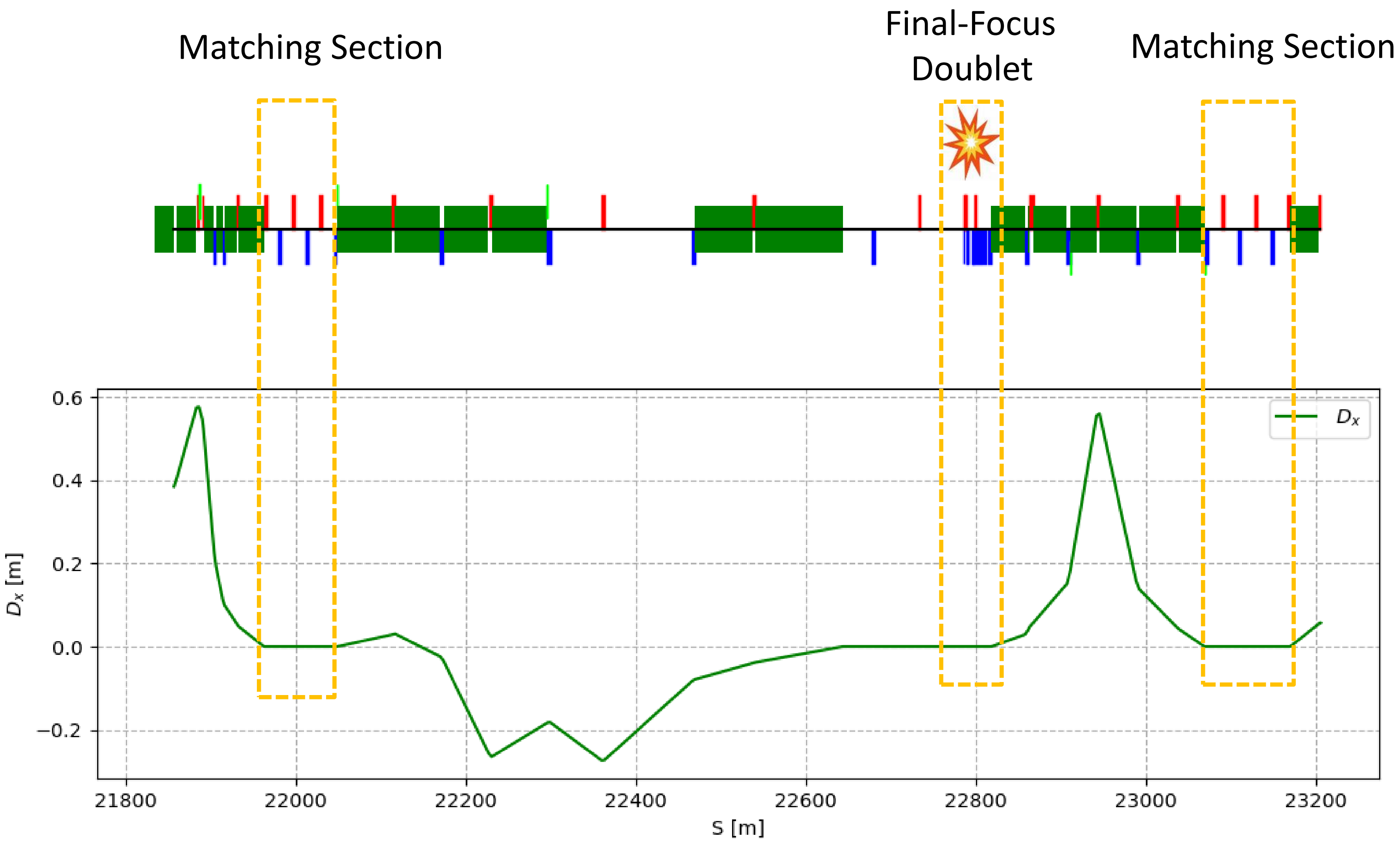
- Can be constructed using the Final-Focus Doublet magnets and Matching section
- Idea motivated by Leon Van Riesen-Haupt at FCC-ee optics tuning and correction workshop, 2023 https://indico.cern.ch/event/1242395/
- Generate Response matrix (M) by varying the individual magnet strengths (k_i)

$$\Delta(\beta^*_{x,y}\,, w_{x,y} \ldots \ldots)_j \;=\; M_{ji} * \Delta k_i$$

- Construct Pseudo inverse of response matrix (M^{-1}) using SVD decomposition, which will be useful to find the correct setting of k_i for a desired change in $\beta^*_{x,y}\,, w_{x,y}$

$$\Delta k \;=\; M^{-1} * \Delta(\beta^*_{x,y}\,, w_{x,y} \ldots \ldots)$$

$\beta^*_{x,y}$ and $w_{x,y}$ knobs



Lattice with Errors

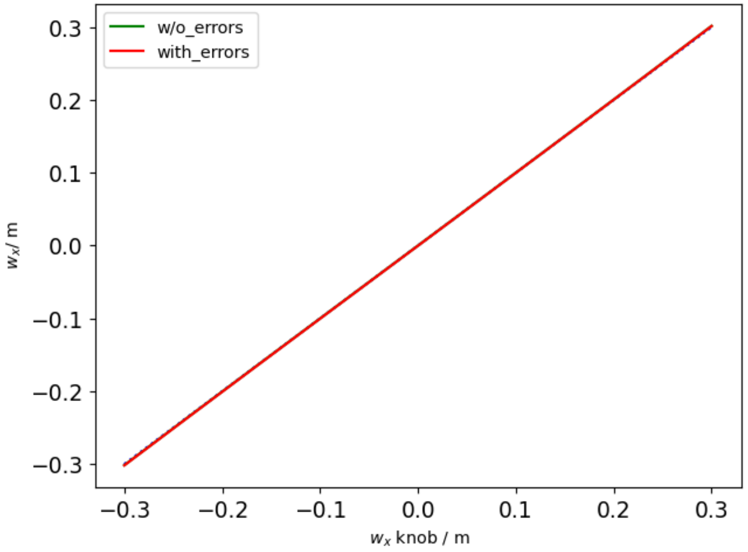
- Demonstrated the effectiveness of knobs on the ideal lattice
- Examine the functionality of knobs on an error lattice
- Include random distribution of alignment errors in the lattice
- Error creation routine written in Python is available

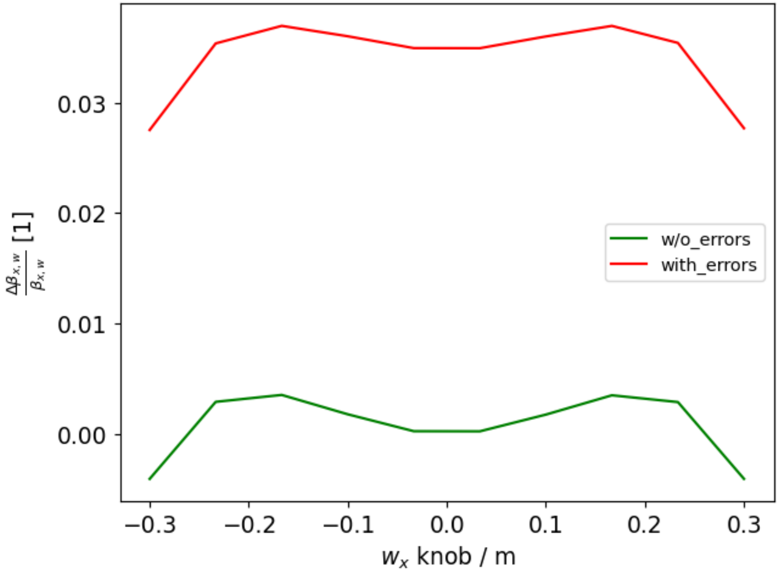
  https://gitlab.cern.ch/mihofer/fccee_xample_longrange_alignment
- Applied to the arc quadrupoles only

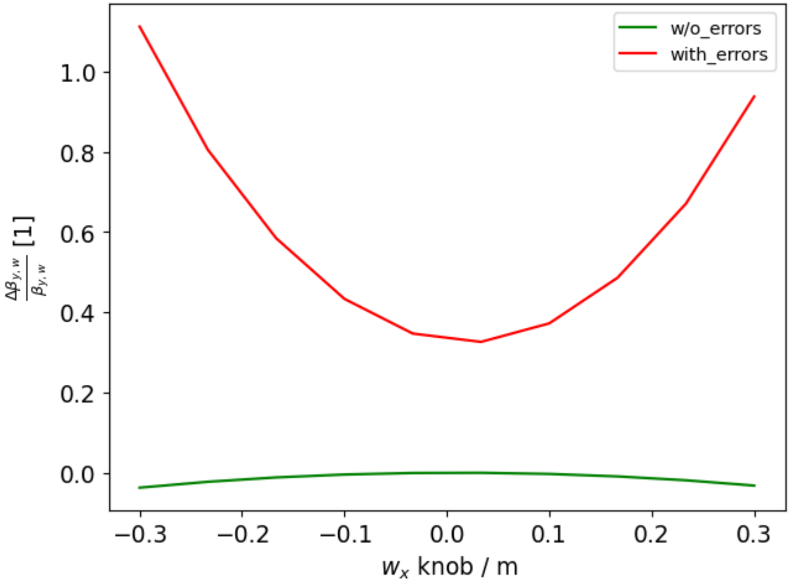
```
# call error creation routine using loaded twiss as input
error_df = cet.main(
    twiss_df=twiss_df, # twiss file to get list of elements and their location
    errors_dict={'Reference_radius': 0.01, 'Q[FD]\d\..*':{ 'dX_rand':10e-6,'dY_rand':10e-6 },},
    full_table=False
)
```

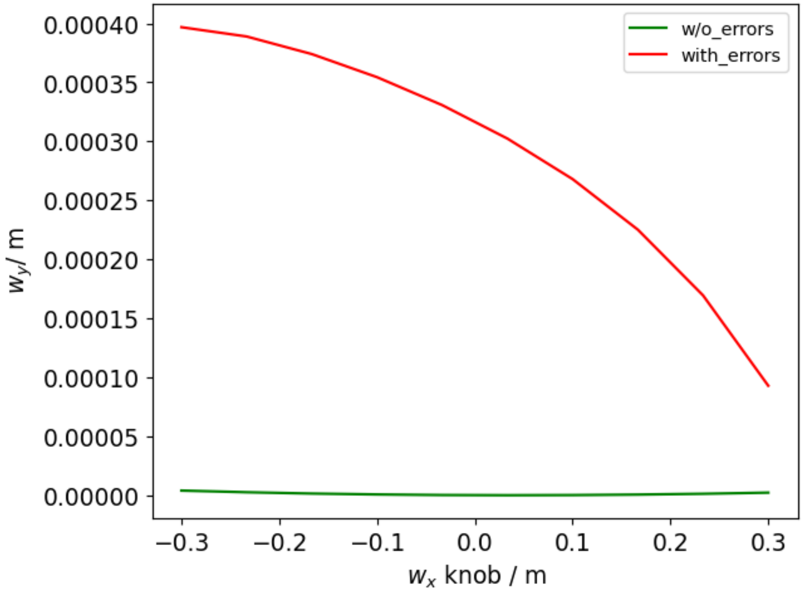
$\mathbf{w_x}$ knob robustness: Ideal vs Error Lattice

- Performance of $\mathbf{w_x}$ knob on the other linear parameters for both the ideal & error lattices is demonstrated
- Working range seems to be **0.3m**
- **Expecting the curves (ideal & error case) to be identical**
- **Non-linear aberrations** noticed on $\boldsymbol{\beta}_{\mathbf{y}}^{*}$ and $\mathbf{w_y}$ when the knob is applied on error lattice



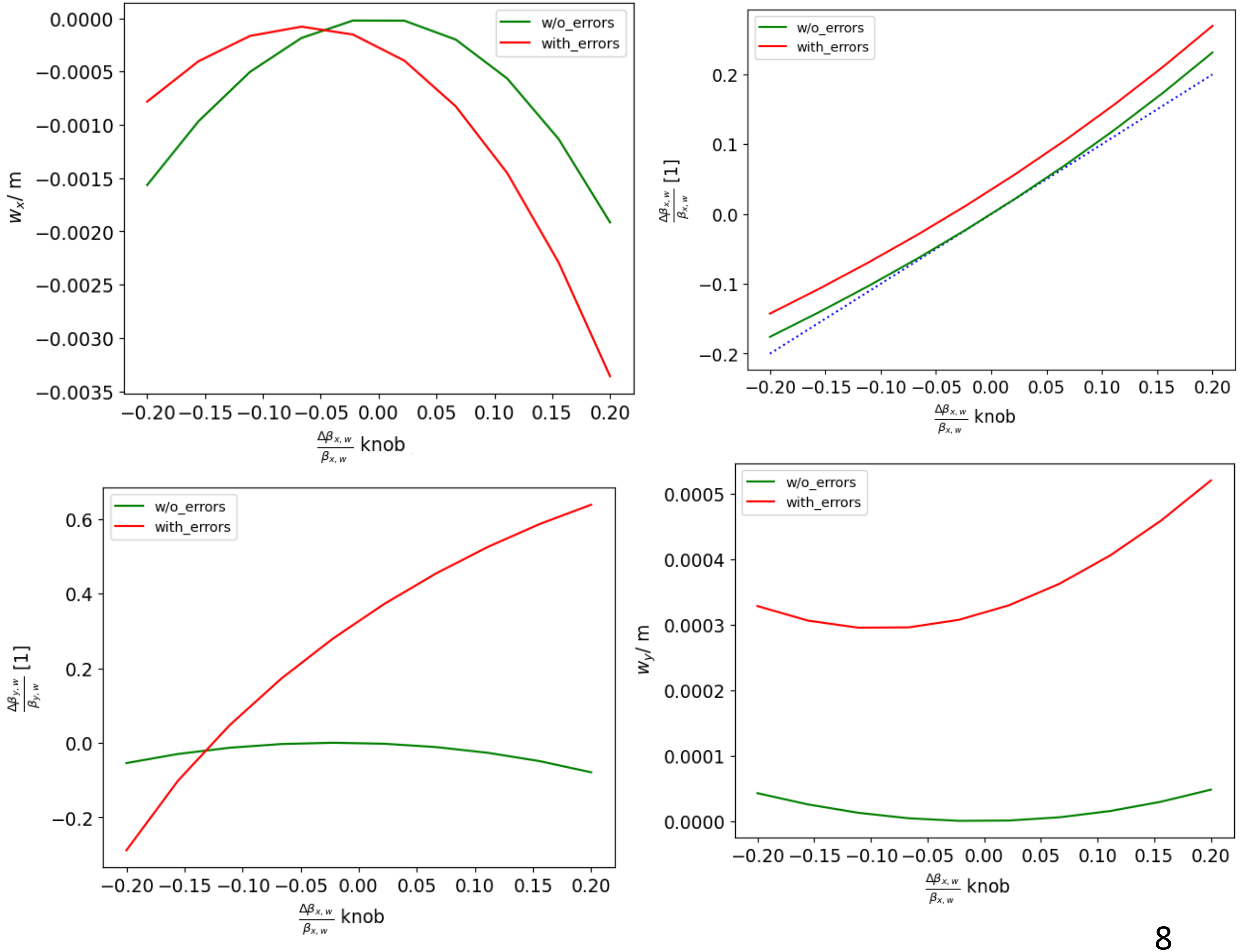






β_x^* knob robustness: Ideal vs Error Lattice

- Performance of β_x^* knob on the other linear parameters for both the ideal & error lattices is demonstrated
- Tuning range appears to be **20%**
- Knob impacts β_y^*, w_y and w_x in a **non-linear fashion**



Orbit correction

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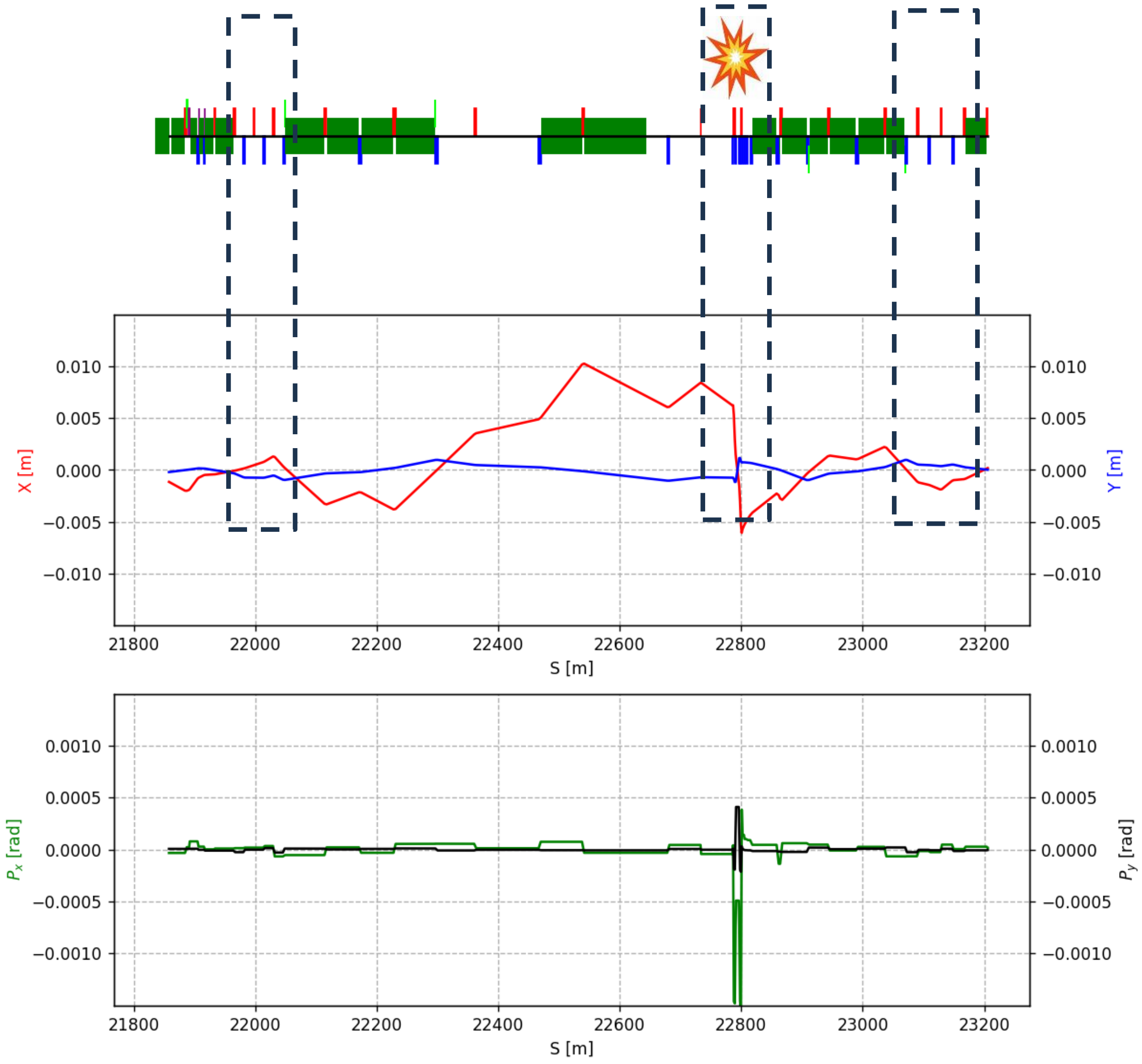
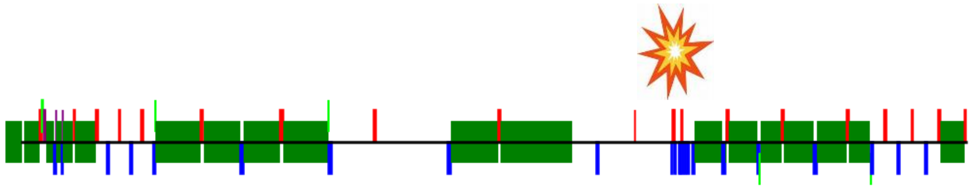
- This arises from the **distortion of the orbit** within the knob region



Orbit correction



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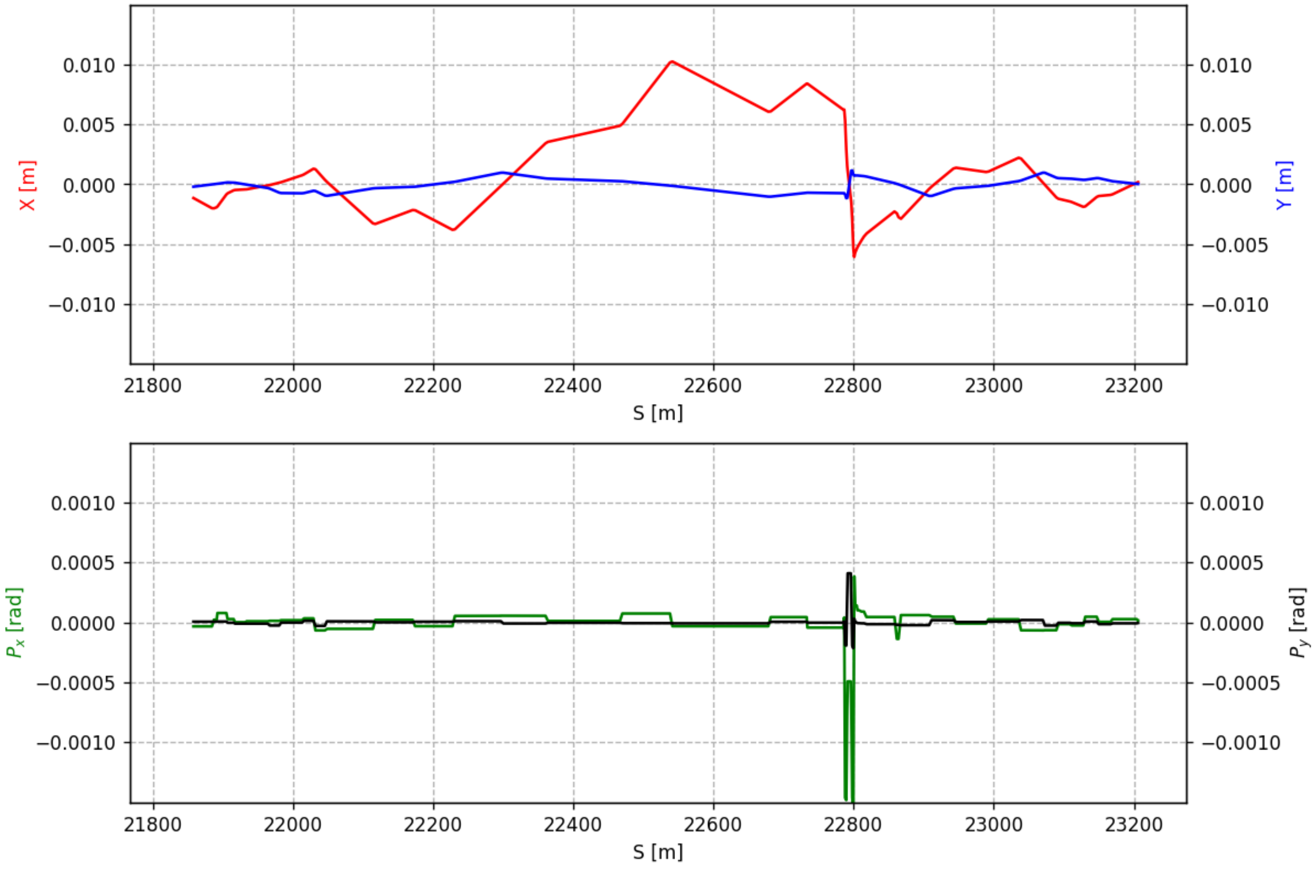
- The remedy is to **correct the orbit**



Orbit correction

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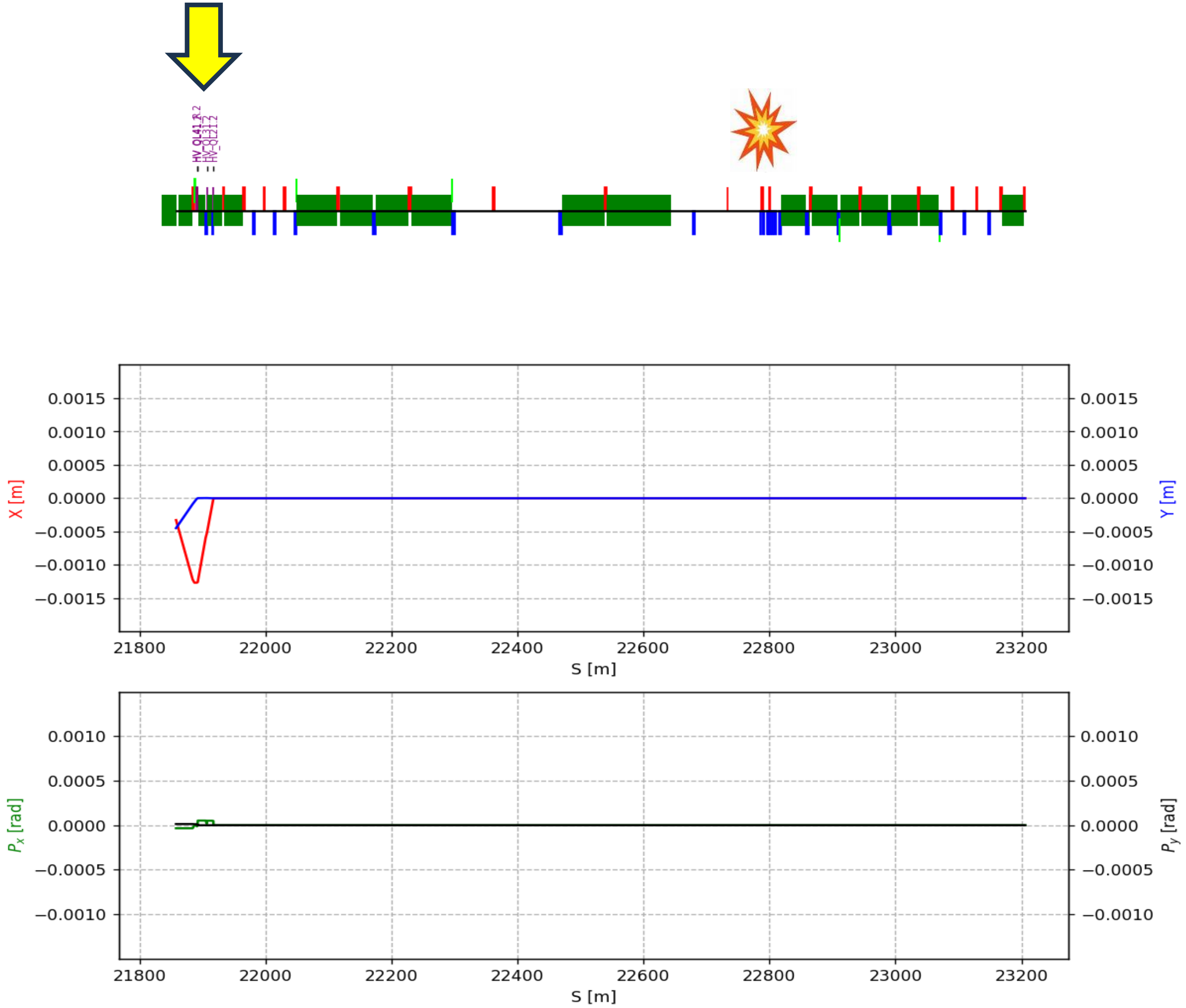
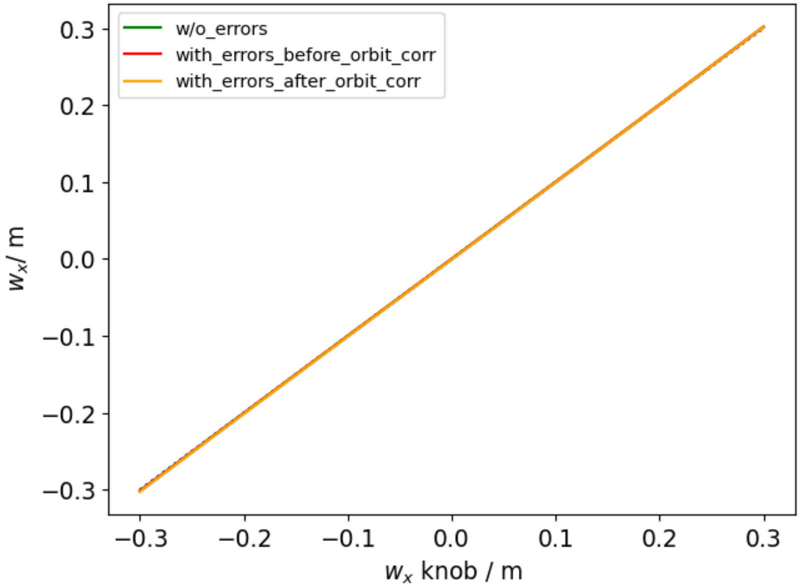
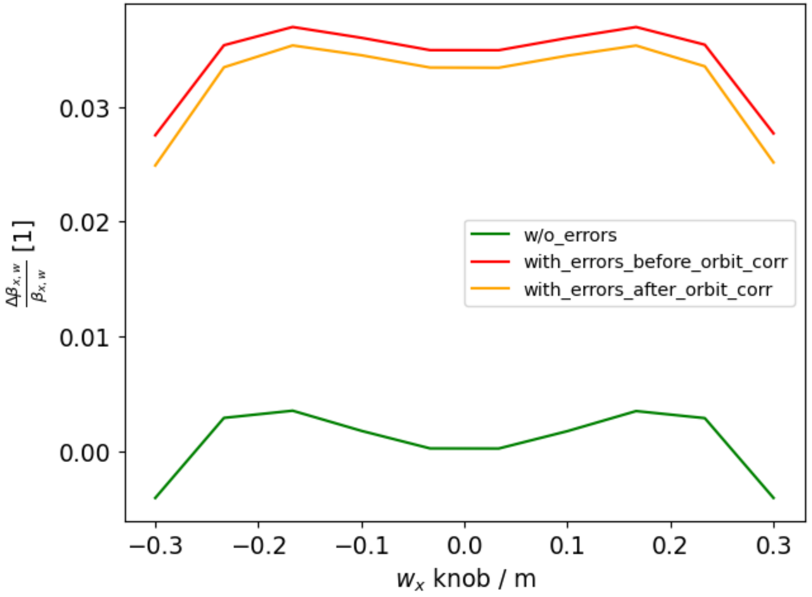
- This arises from the **distortion of the orbit** within the knob region
- The remedy is to **correct the orbit**
- **Install orbit correctors** upstream of matching section

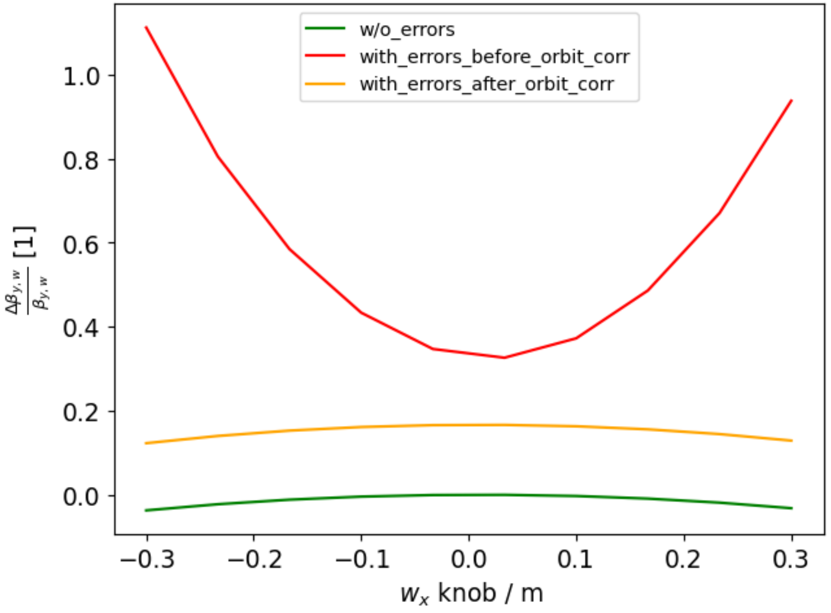


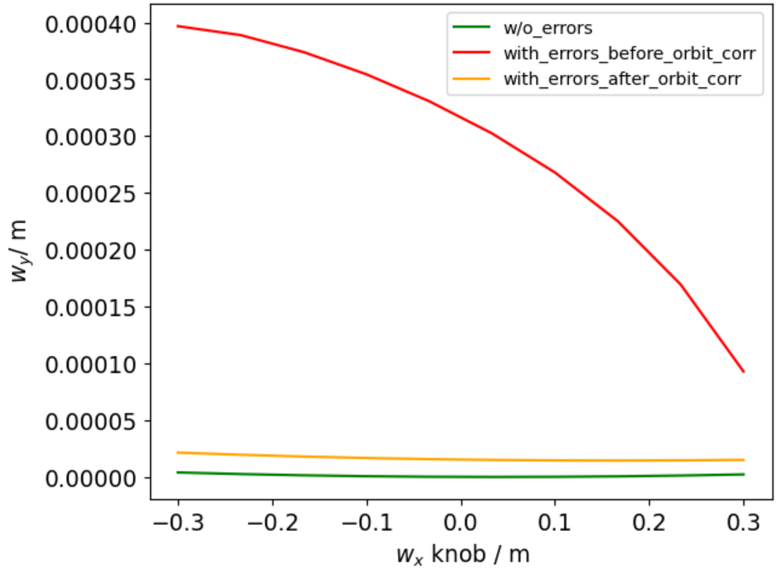
w_x knob post orbit correction

- Following the orbit correction, a consistent behavior is noticed
- Curves are parallel, differing only in the magnitude of error
- Please review the additional slides provided in the backup that illustrate the performance of the w_y knob



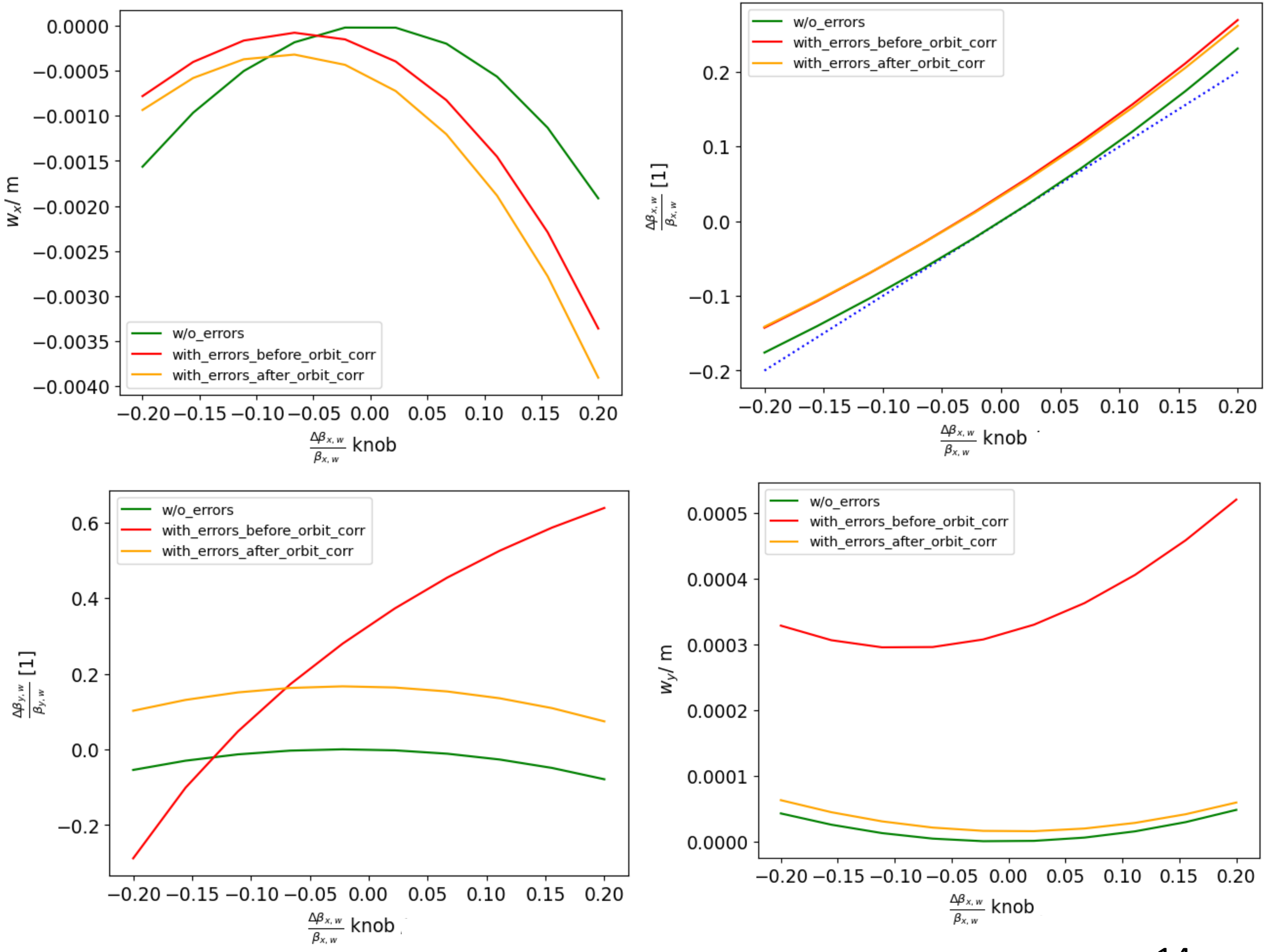






β_x^* knob post orbit correction

- Following the orbit correction, a consistent behavior is noticed
- Need to comprehend the behavior of w_x
- For β_y^* knob, kindly have a look at the end of the presentation



Motivation (Vertical Dispersion & Coupling knobs)

- Tuning knobs are necessary to correct optics errors at the IP to achieve the desired luminosity
- misalignment error/source of coupling leads to spurious $\mathrm{D_y}$ & coupling, in turn affecting the beam size, which explains that developing tuning knobs are essential
- $\sigma_y^* = \sqrt{\beta_y^* \epsilon_y + D_y^{*2} \delta_p^2}$ $\quad \sigma_y^* = \sqrt{\beta_y^* \epsilon_y + \beta_y^* \epsilon_x |F_{1001}^*|^2}$ Terms to be vanished in σ_y^*
- The idea was originally motivated by K.Oide at the FCC-ee tuning meeting, on 9 June 2022 https://indico.cern.ch/event/1167740/

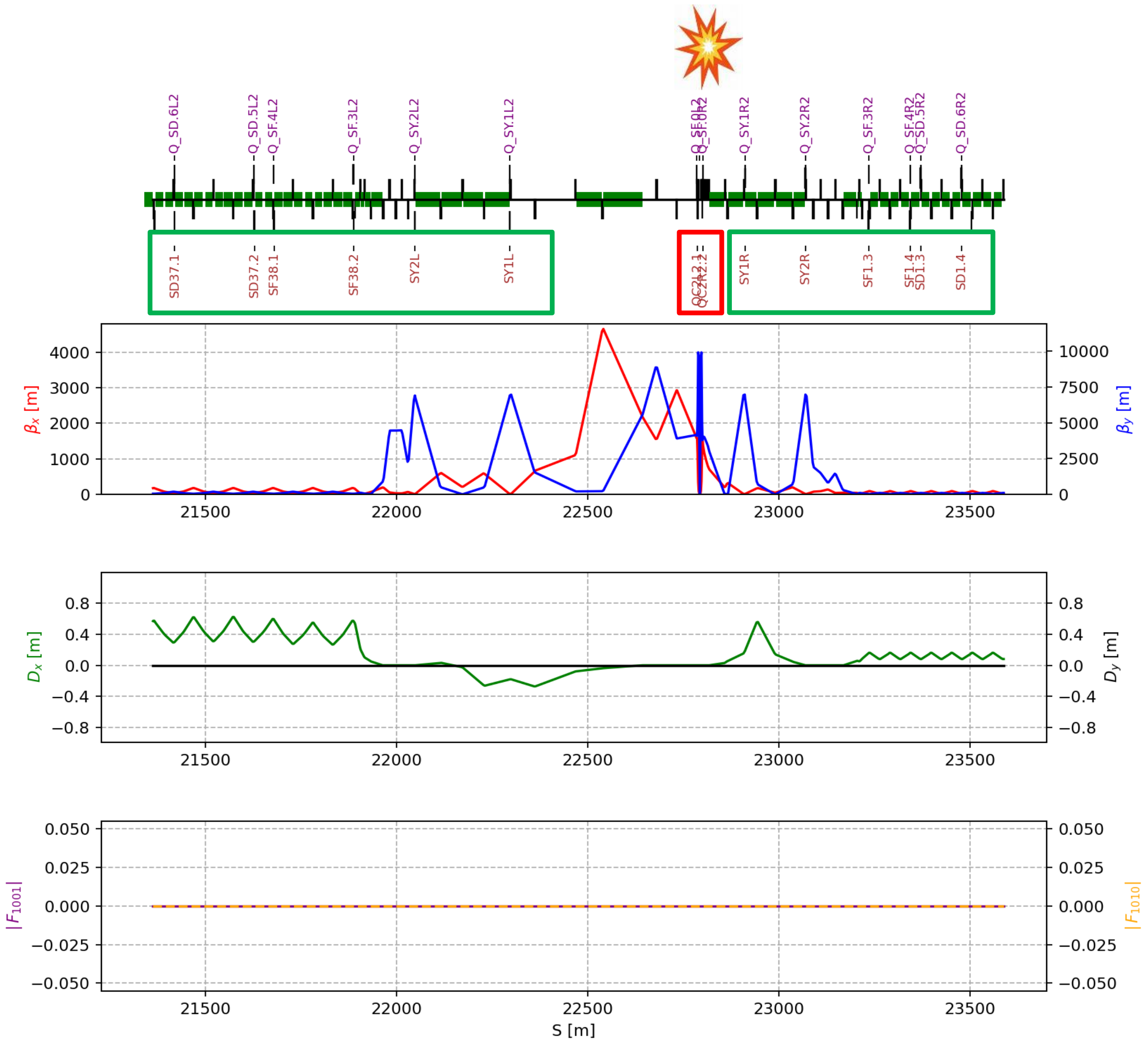
Motivation

- Extra skew windings at the **Final-Focus doublet** and at least the nearest **6 sextupoles** on each side of IP, which eventually helps in controlling vertical dispersion & coupling at the IP

Skew quads

Final doublet

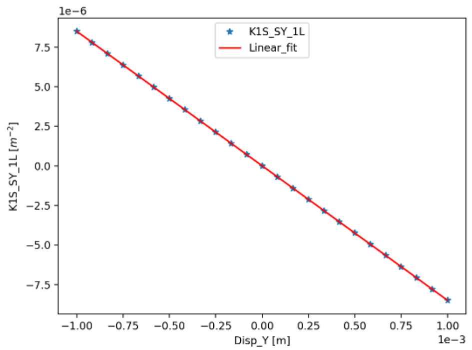
Sextupoles



Implementation

- MADx “**matching**” technique
- Match the constraint in such a way that changes in the observables (parameters other than constraints) must be minimized
- The dispersion is matched in small steps of the range of application
- For coupling, MADx matches a combination of two skew quadrupolar terms $\mathbf{F_{1001}}$(**real**) and $\mathbf{F_{1001}}$(**imaginary**)
- Strengths of the tuning skew quads are plotted as a function of dispersion/coupling
- The components of the knob vector are computed by fitting the slope of these plots

Slopes from the linear fitting



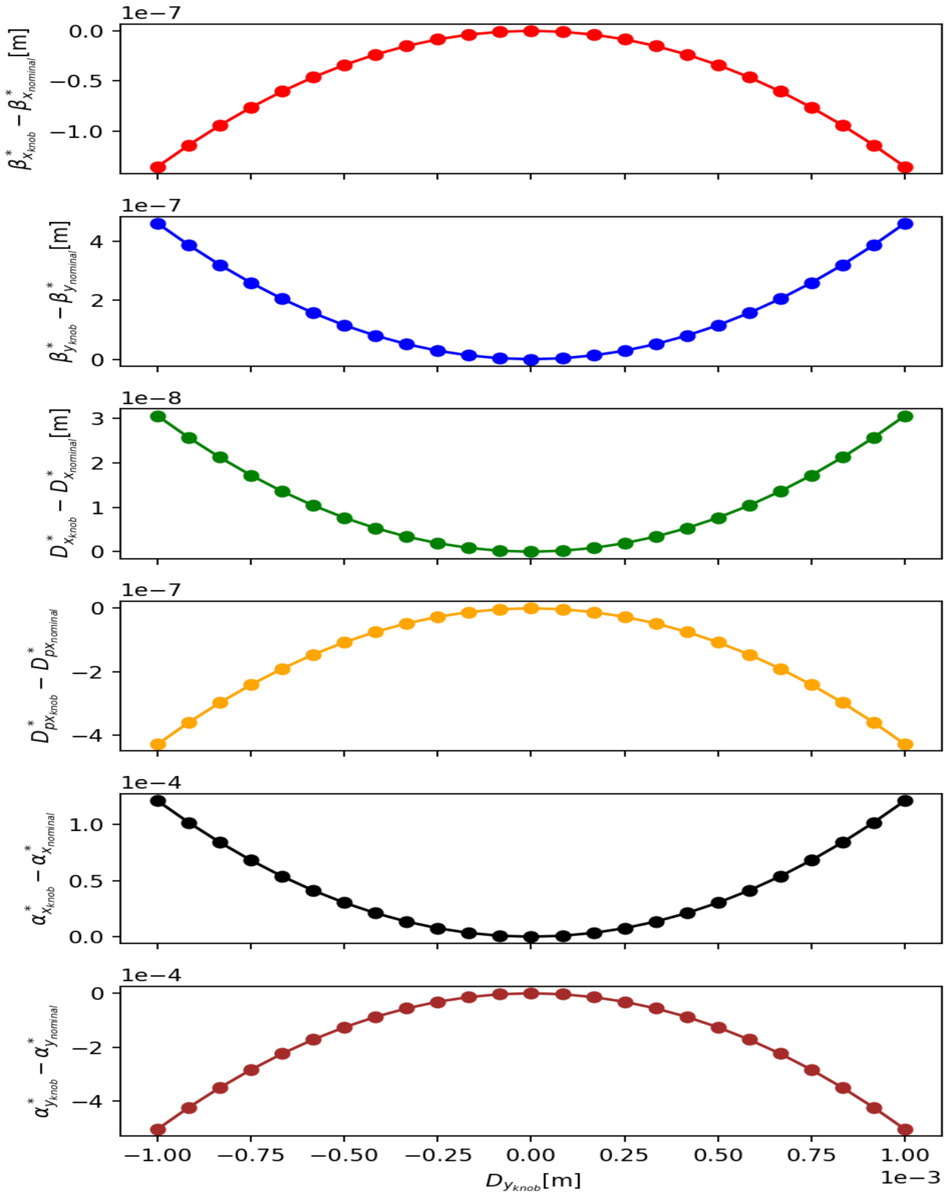
Equation of a linear function, $y = mx + c$

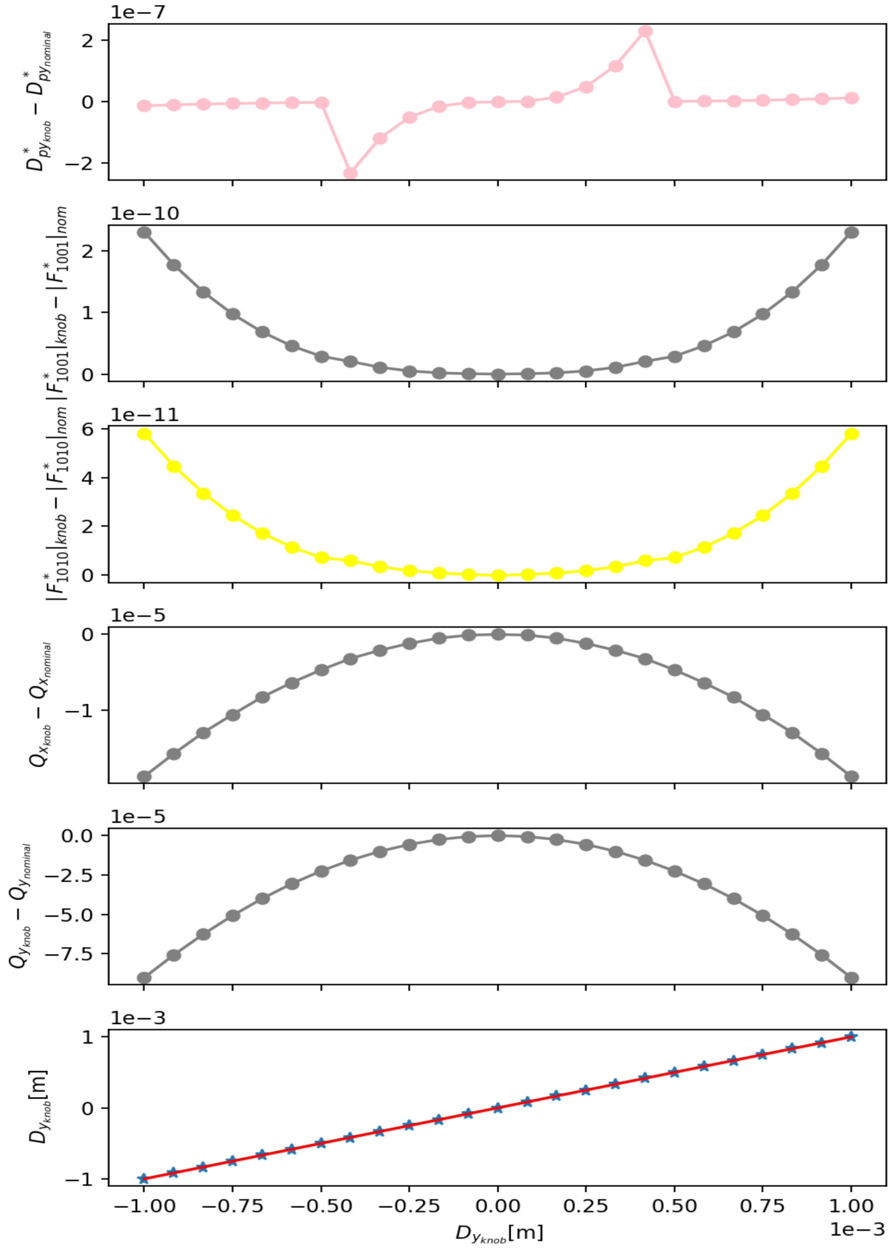
where slope, $m = \frac{y_2 - y_1}{x_2 - x_1}$

Knob_setting $* \begin{bmatrix} K1S_1^I \\ K1S_2^I \\ K1S_3^I \\ . \\ . \\ . \\ . \\ K1S_n^I \end{bmatrix} \longrightarrow \begin{bmatrix} K1S_1 \\ K1S_2 \\ K1S_3 \\ . \\ . \\ . \\ . \\ K1S_n \end{bmatrix}$

Cross talk of D_y^* Knob

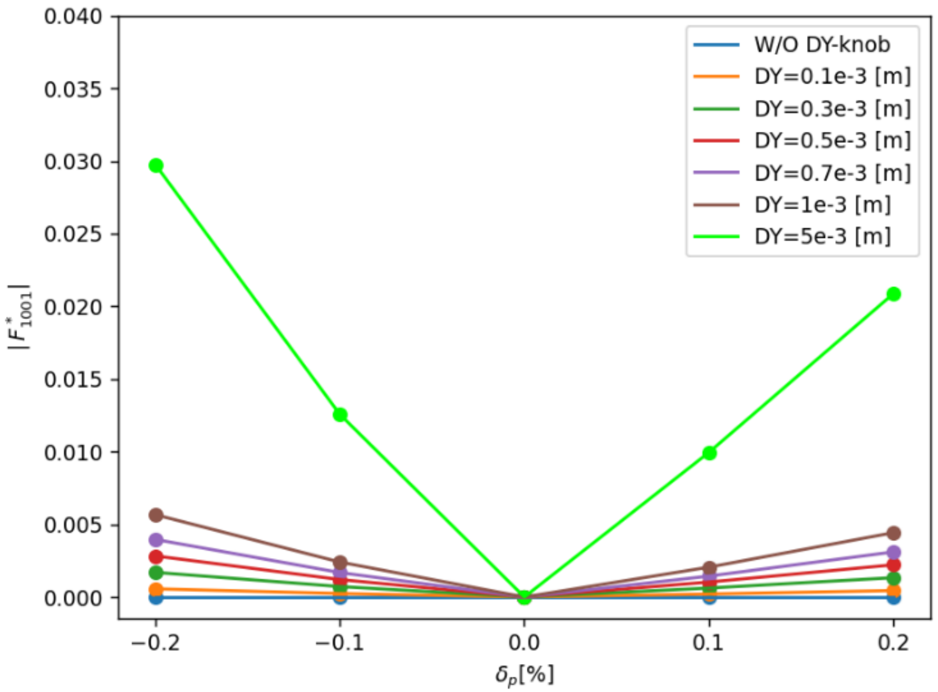
- Aberrations are quadratic being the impact on other IP parameters negligible
- Tuning range is simulated to be **1mm**

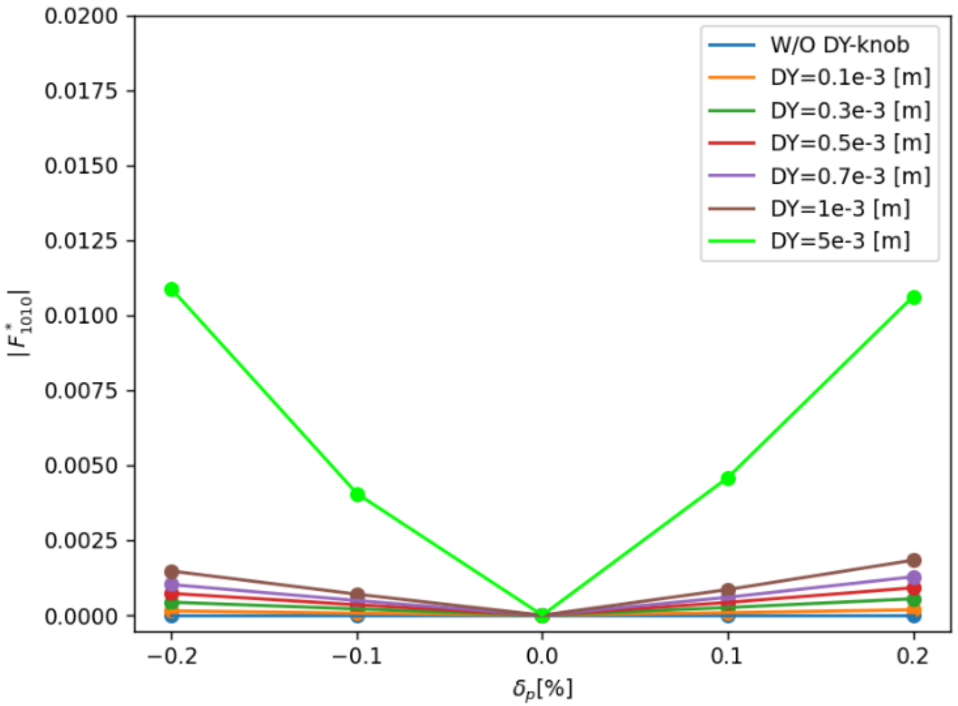




Chromatic variations of β, α, tune and Coupling

- Knob influence on chromatic behavior mirrors that of an ideal lattice
- knob setting of 5mm has a significant impact





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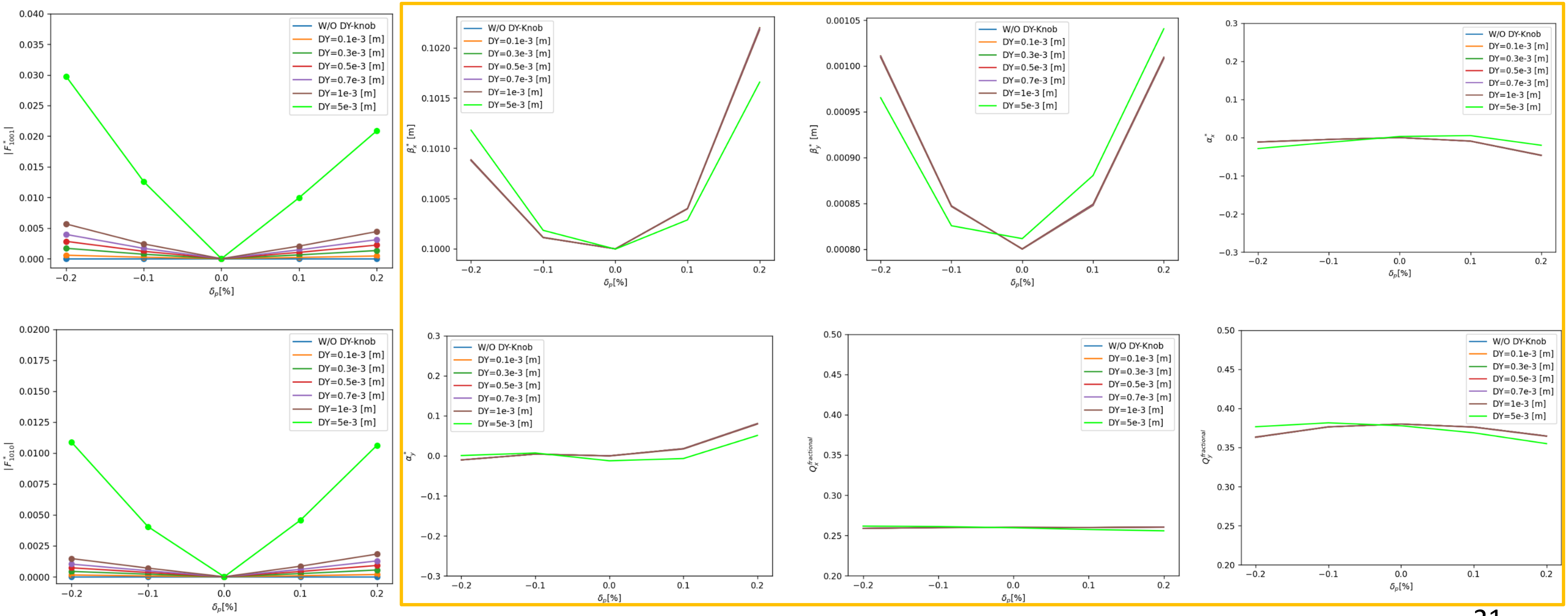
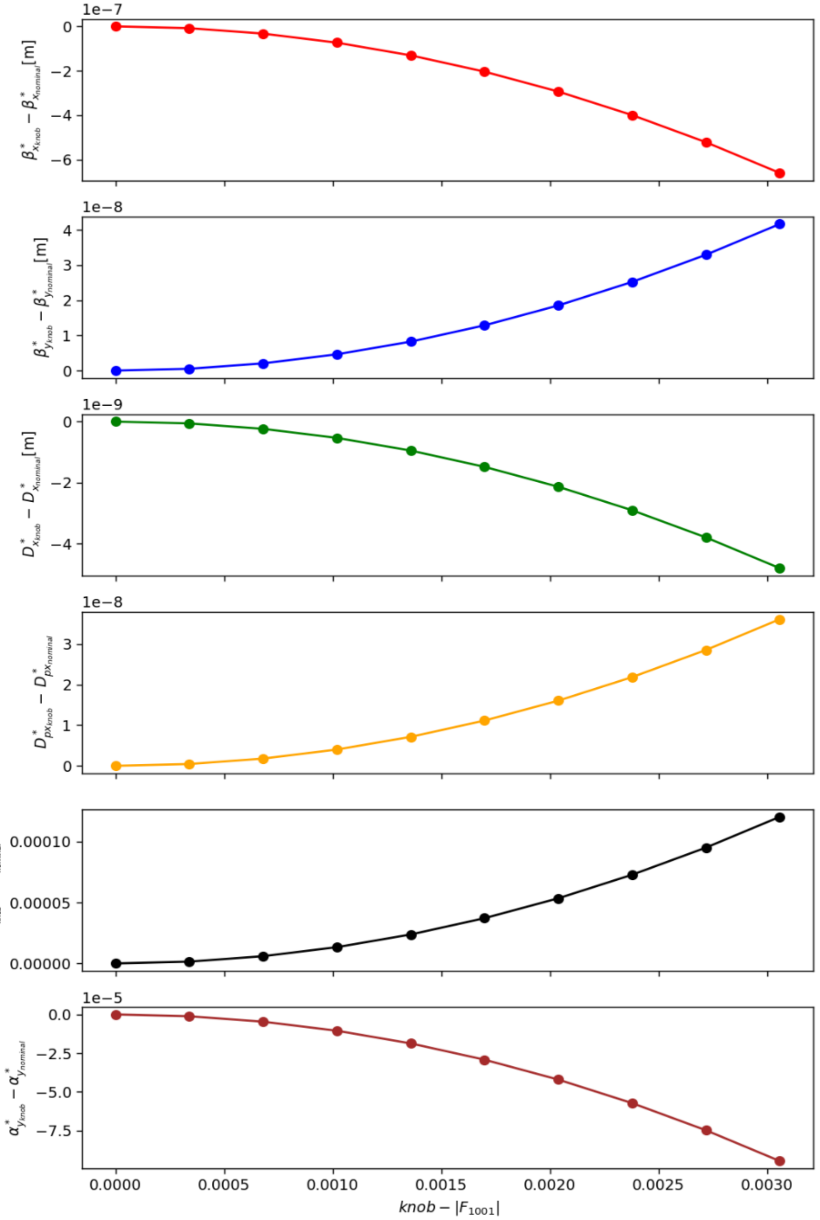
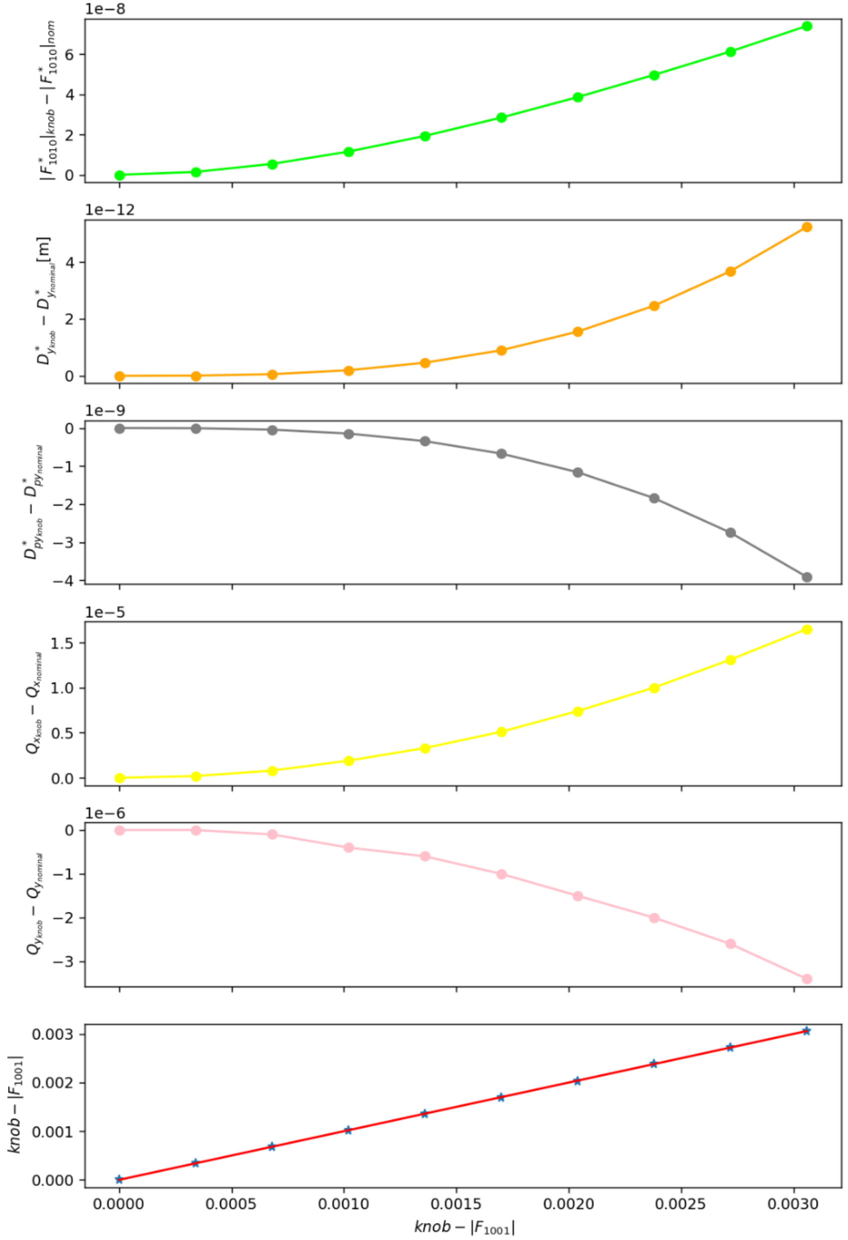


Cross talk of $|F^{*}_{1001}|$ Knob

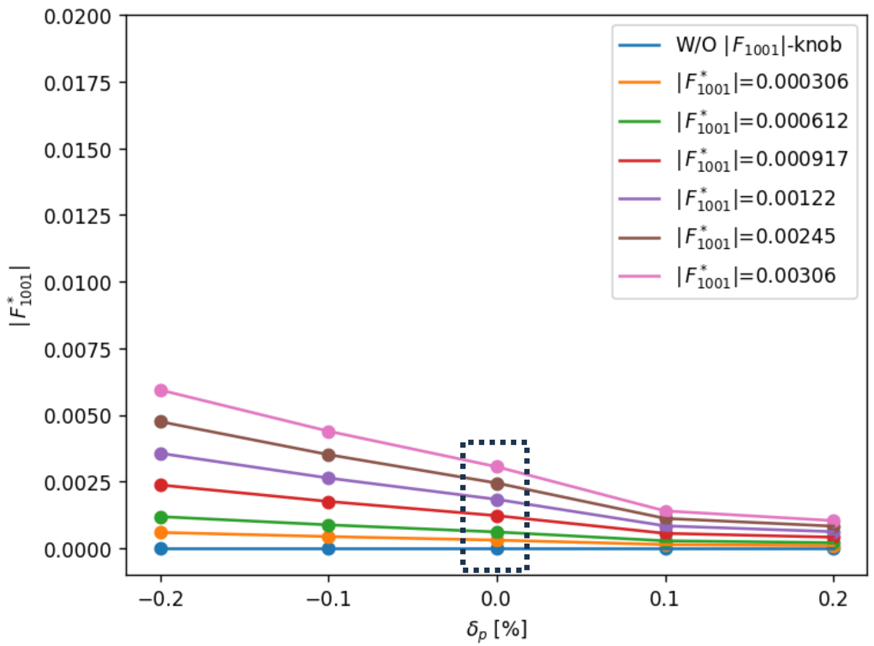
- Knob created has no potential to influence other linear optics
- Kindly review the backup slides provided for the replicated studies concerning the **$|F^{*}_{1010}|$ knob**

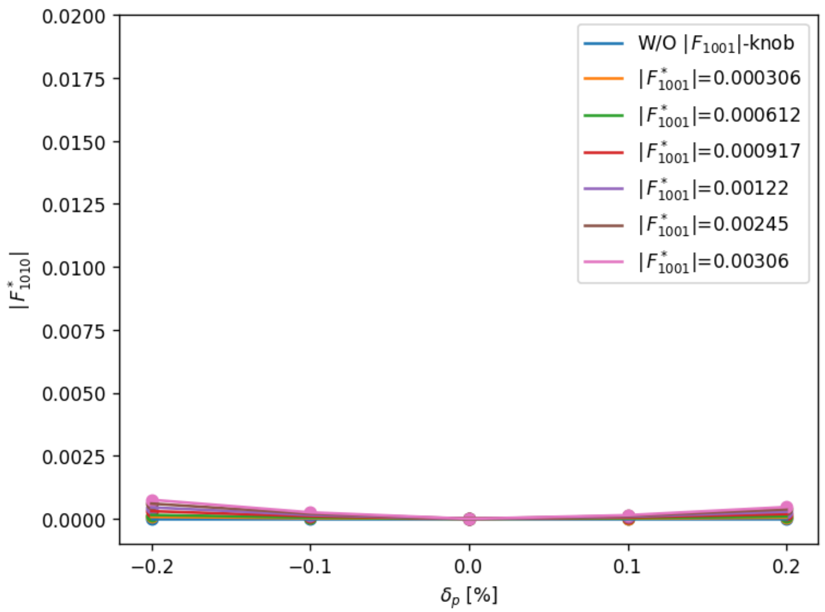




Chromatic variations of β, α, tune and Coupling

- Chromatic coupling in various situations runs similarly, with the only distinction being the specific value we assign with the knob
- The chromatic pattern remains consistent in both the ideal scenario and with the knob





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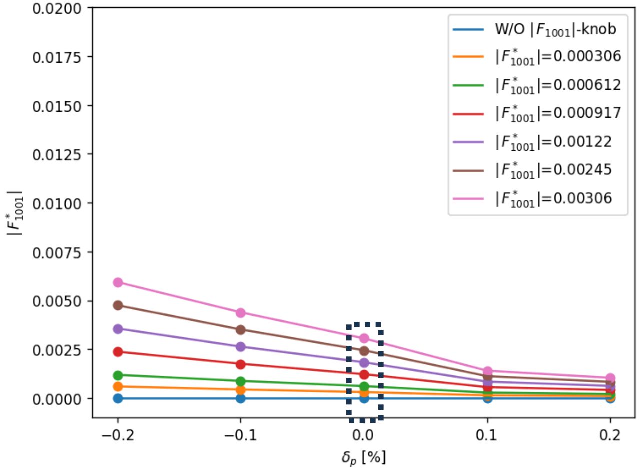
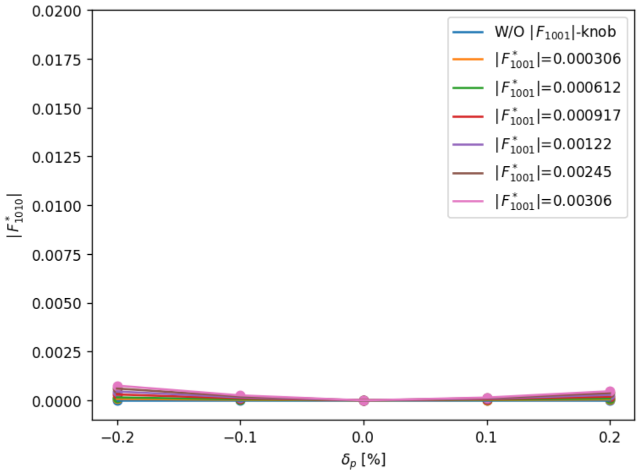
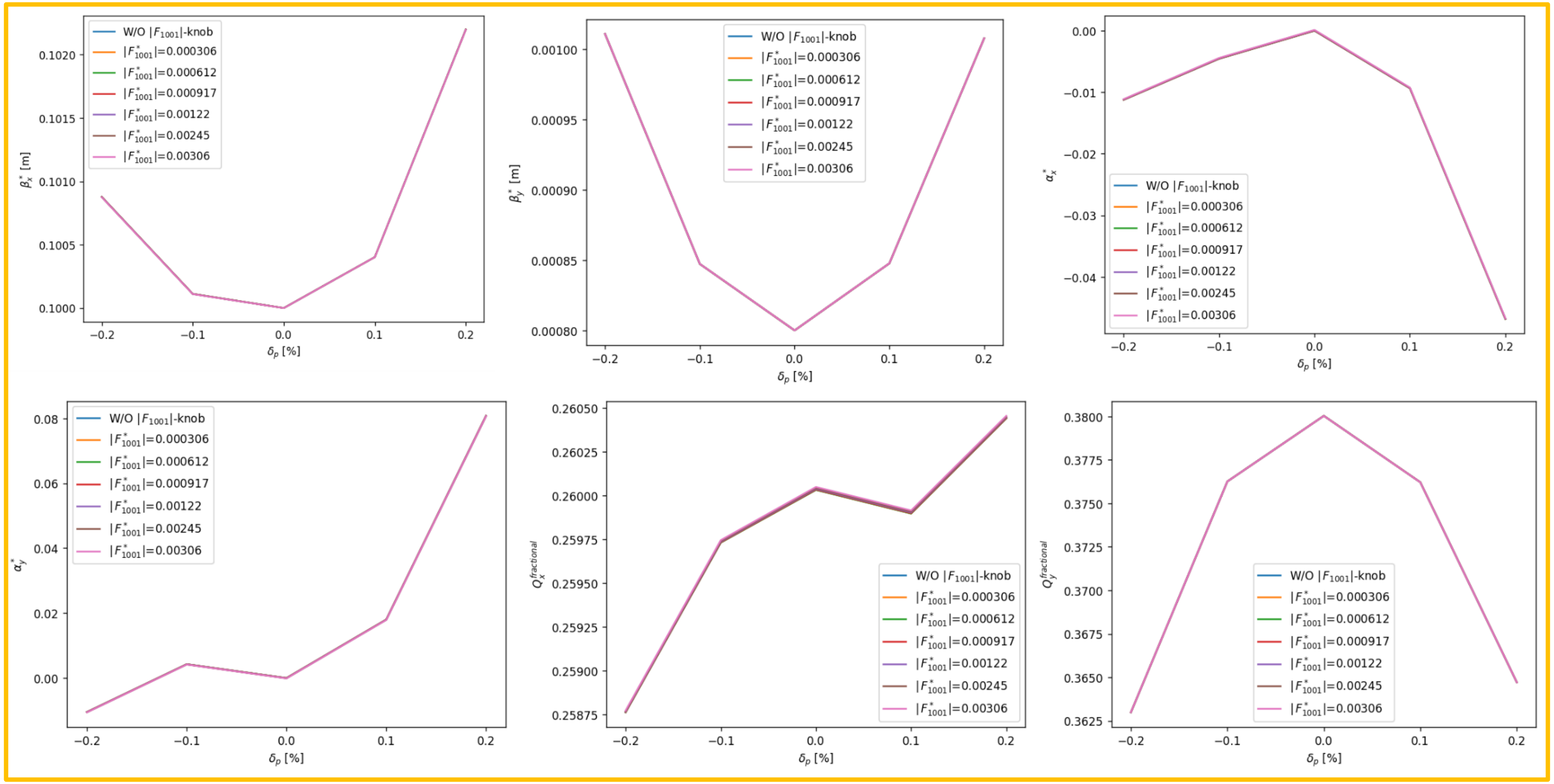






Conclusions & Further Work

- IP tuning knobs are necessary for precise tuning of optics
- Studied linear optics knobs for Z-lattice
  - Orbit distortion made it critical for the knobs to work in a lattice with errors
  - Performed orbit correction by placing the appropriate correctors
- Developed D_y^* & coupling knobs for the ideal lattice
  - Vertical dispersion knob setting of **5mm or above** demonstrates an influence on the chromatic behavior

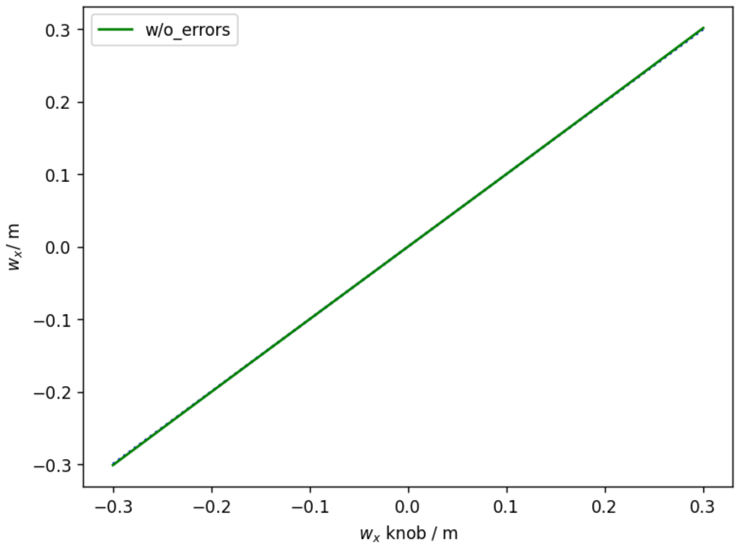
<u>Next Steps</u>:

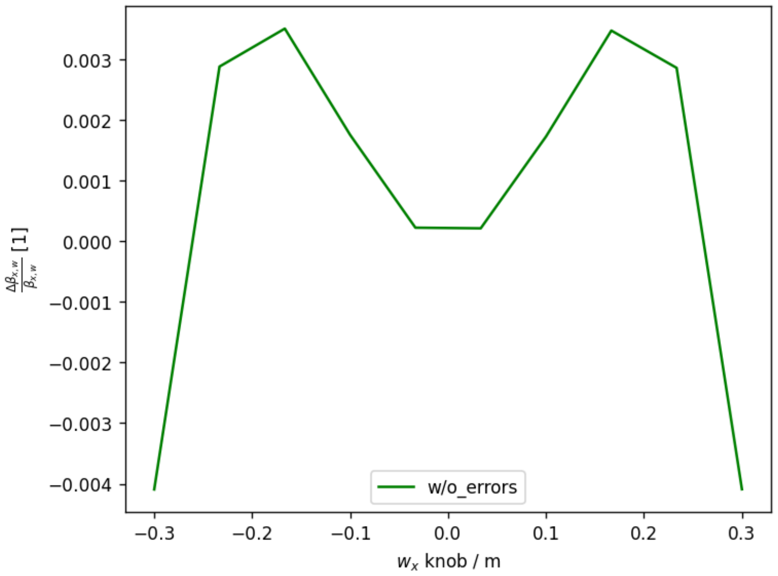
- Orbit adjustment in the arc section may also be necessary, as the D_y^* and coupling knobs extends over the arc
- Include errors in the straight sections (IR) as well and examine any further corrections are required to enhance the effectiveness of knobs
- Need to implement D_x^* knob

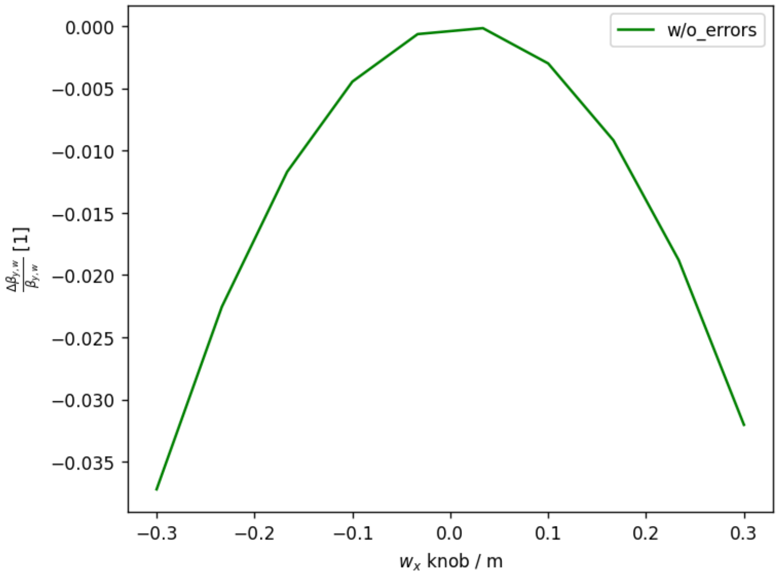
Thank you for your attention

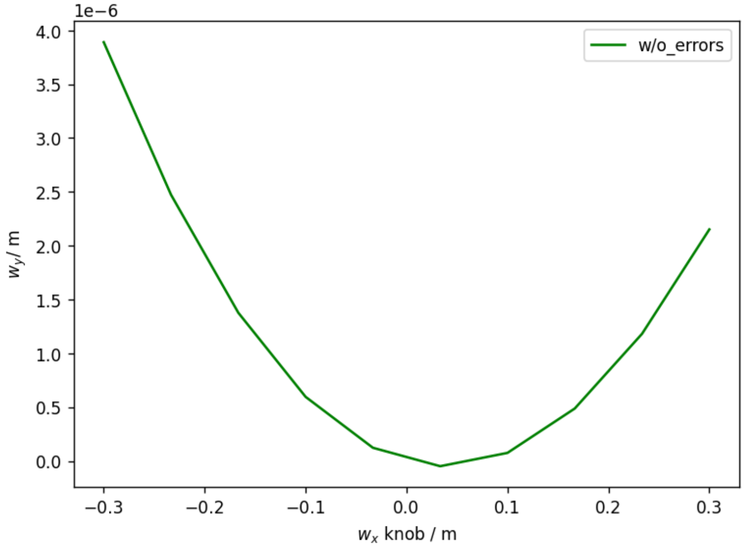
Backup Slides

w_x knob on ideal lattice

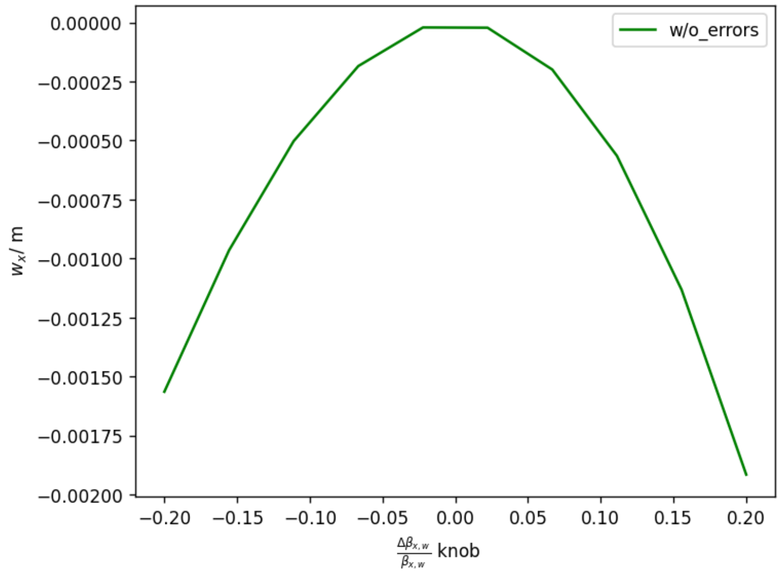


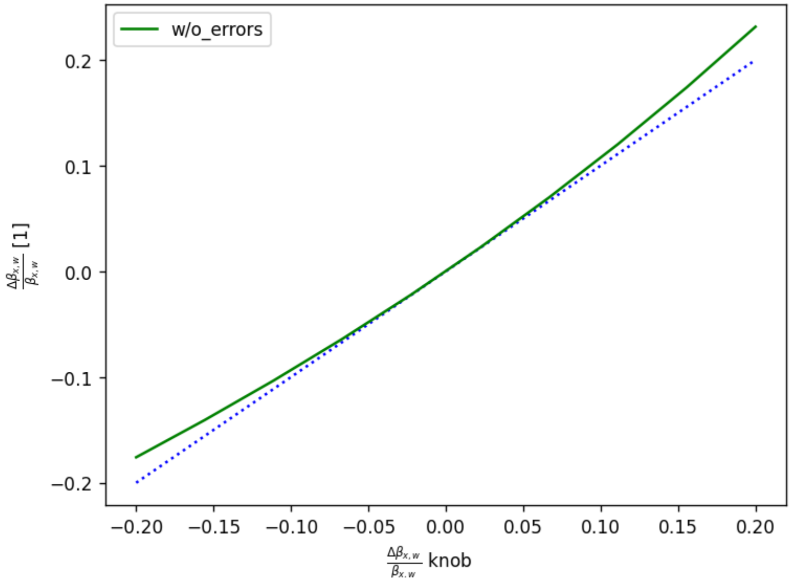


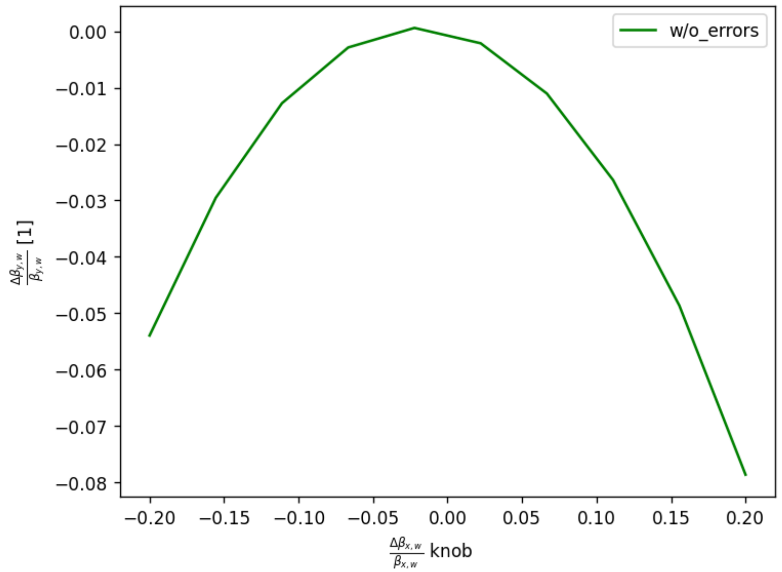


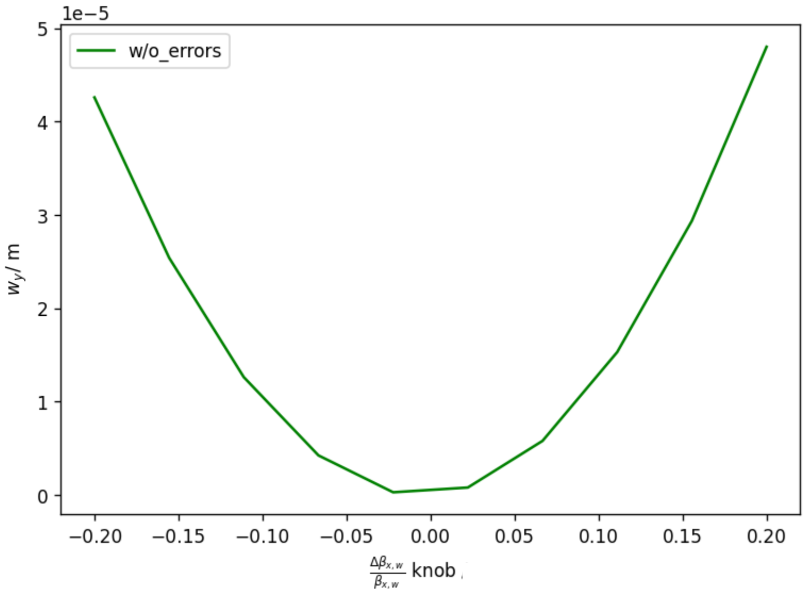


β_x^* knob on ideal lattice

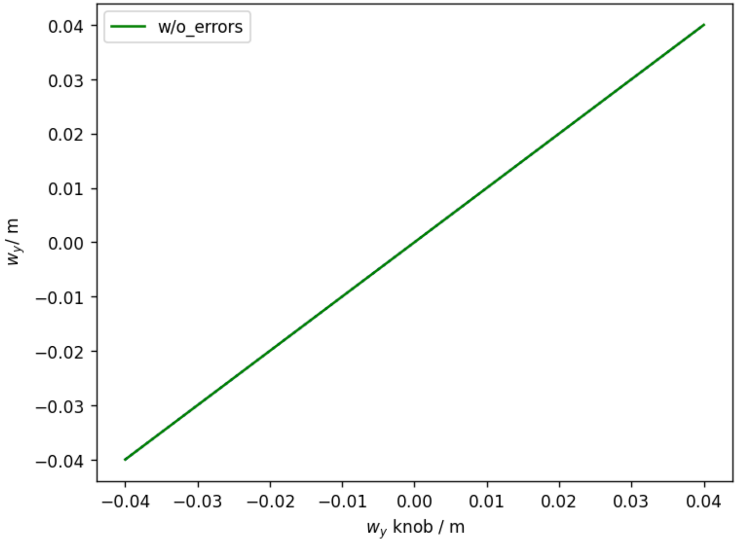


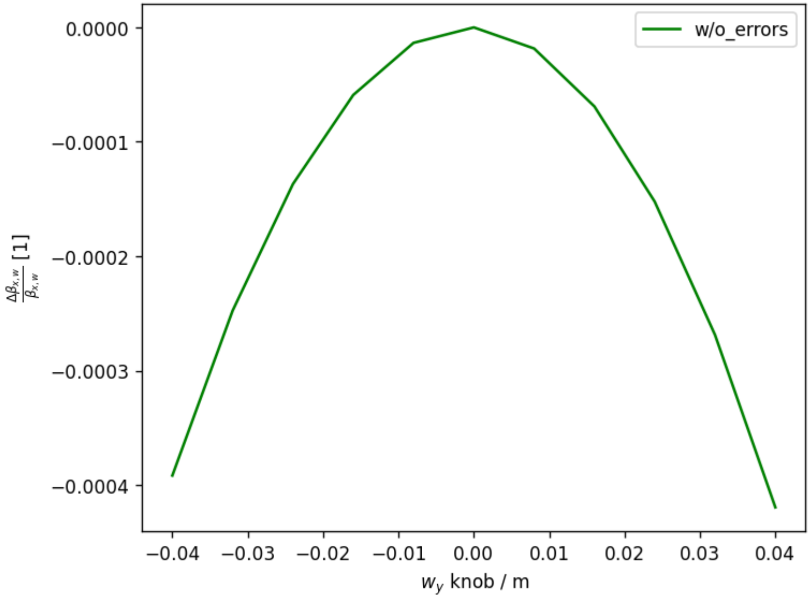


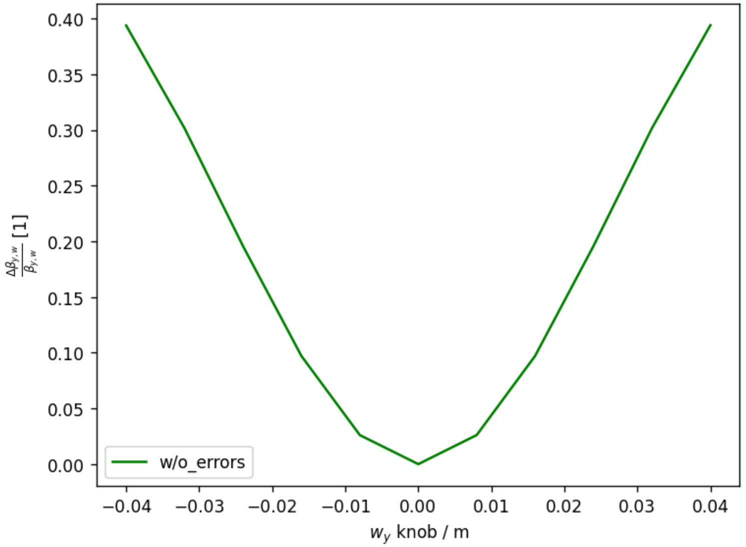


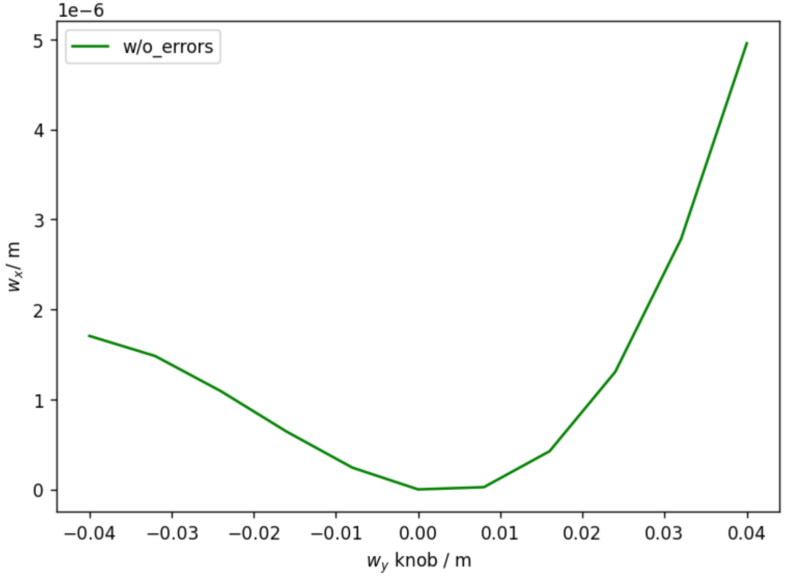


w_y knob wrt linear optics parameters

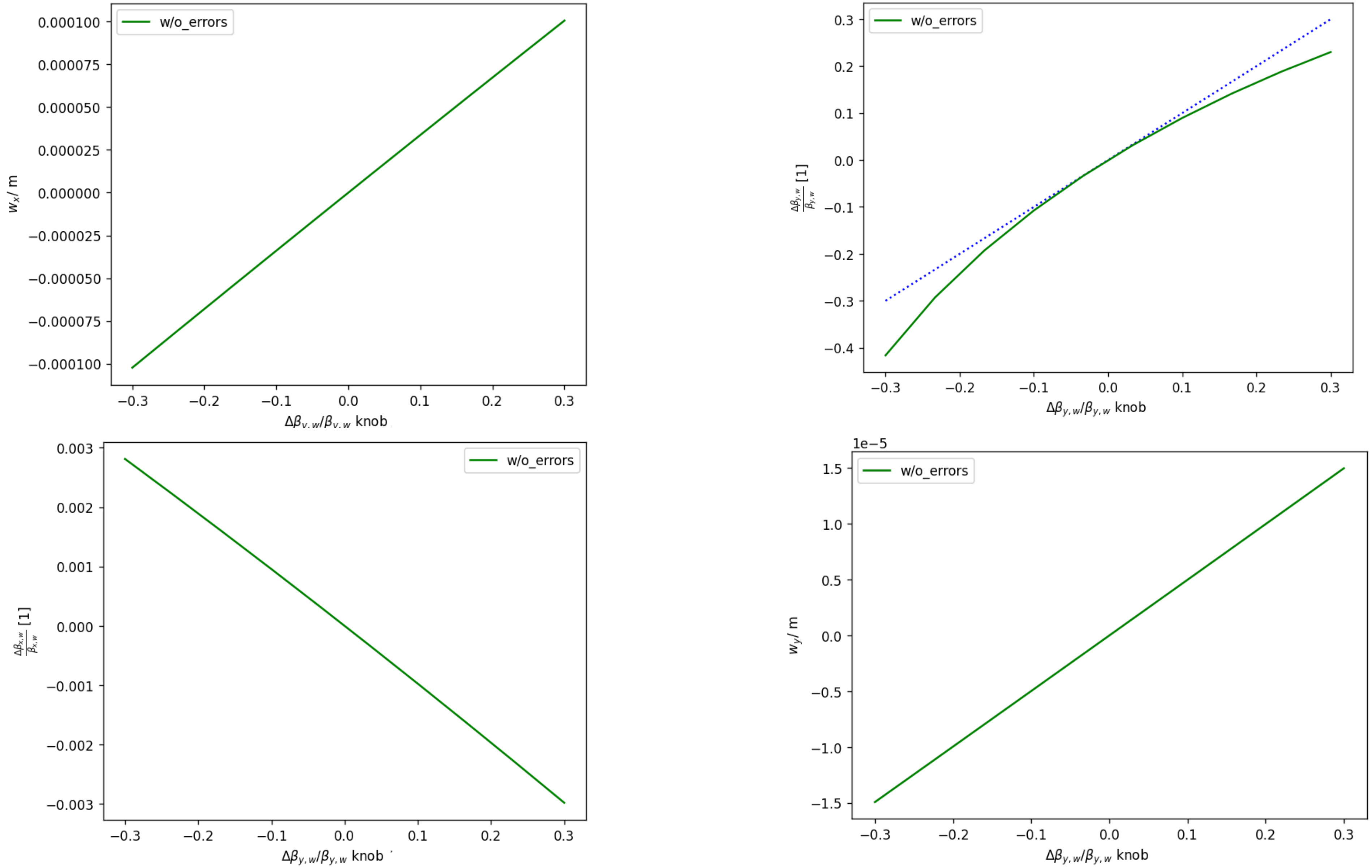




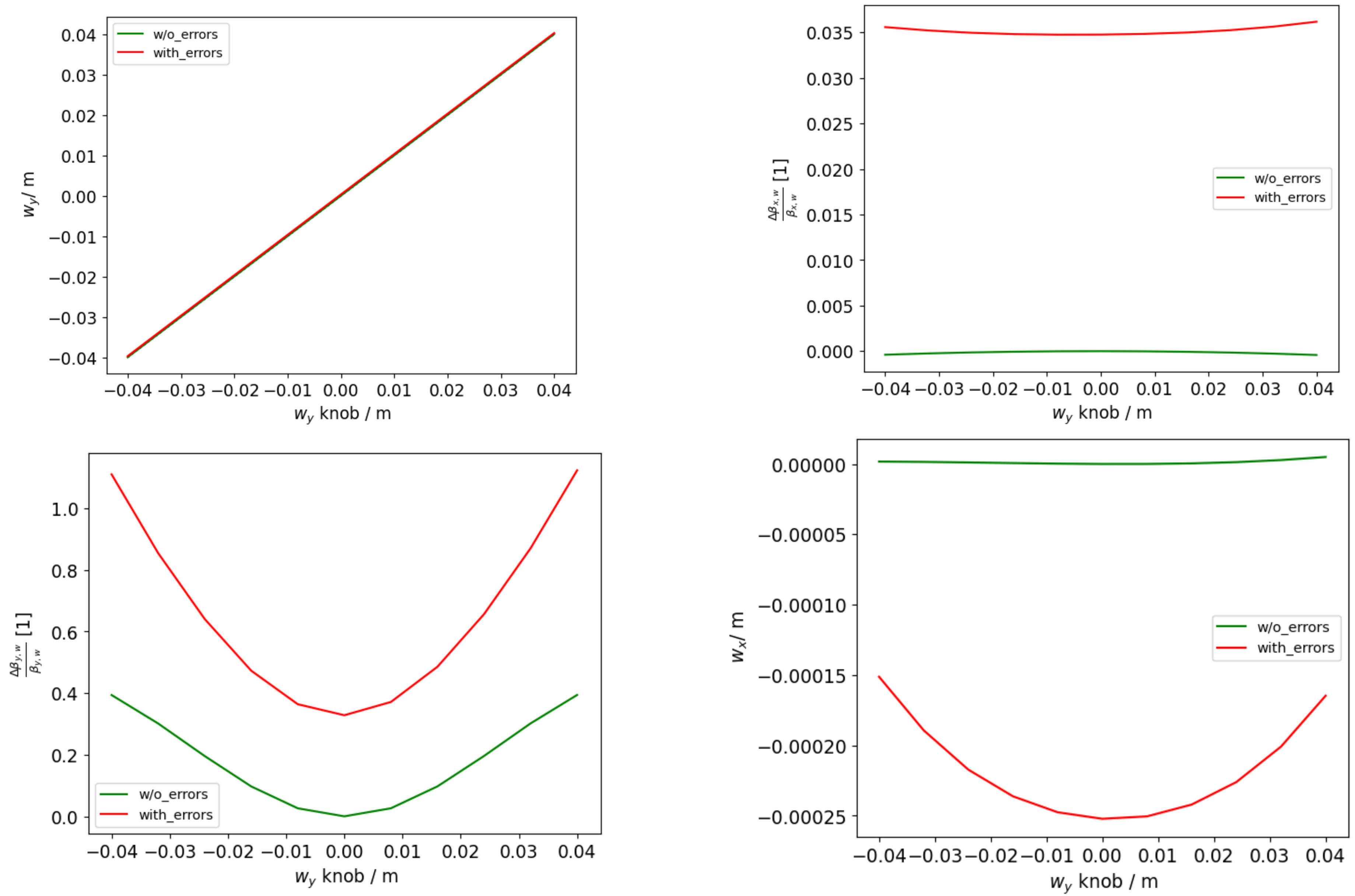




β_y^* knob wrt linear optics parameters



w_y knob robustness: Ideal vs Error Lattice



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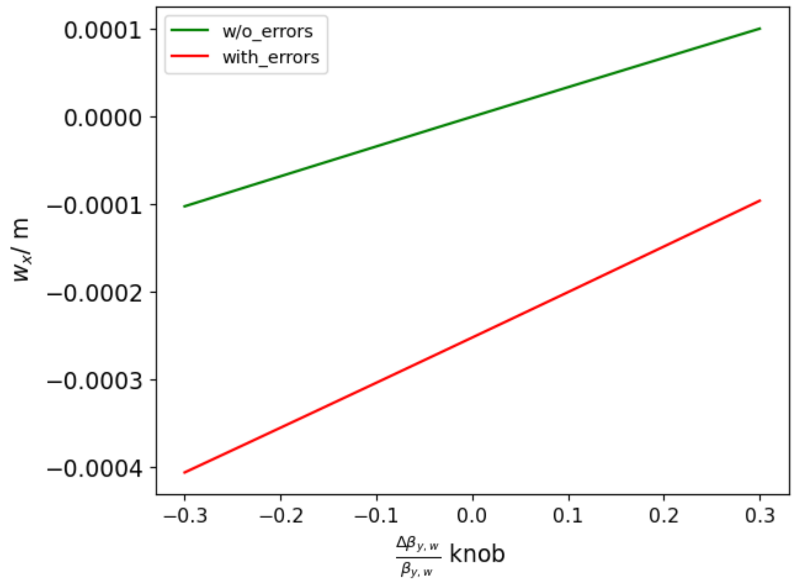
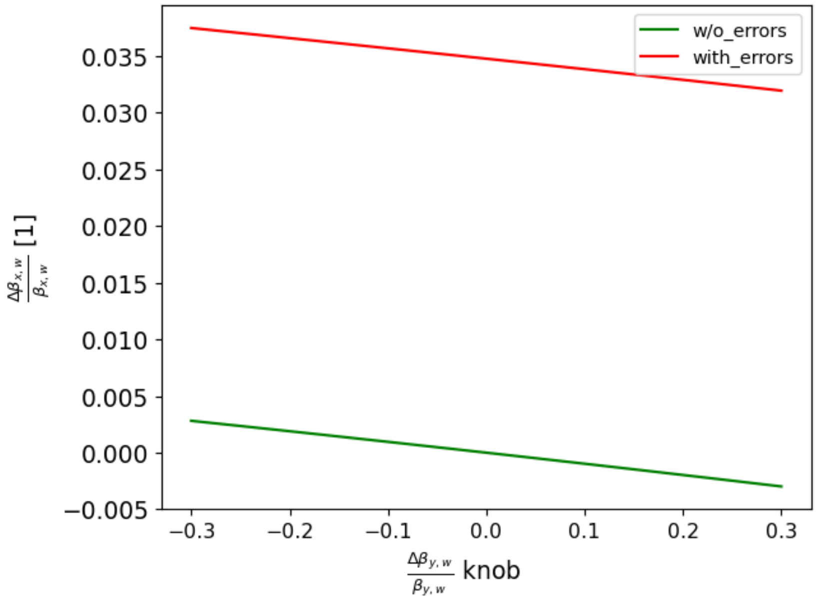
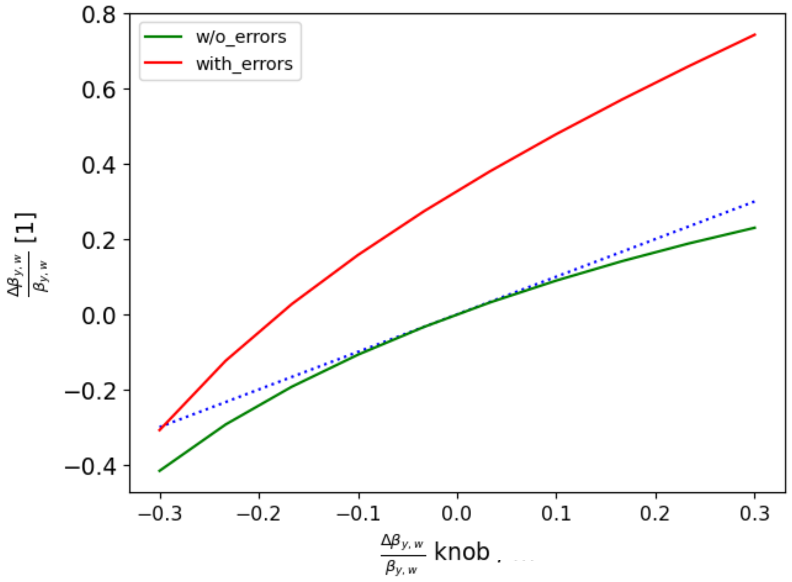
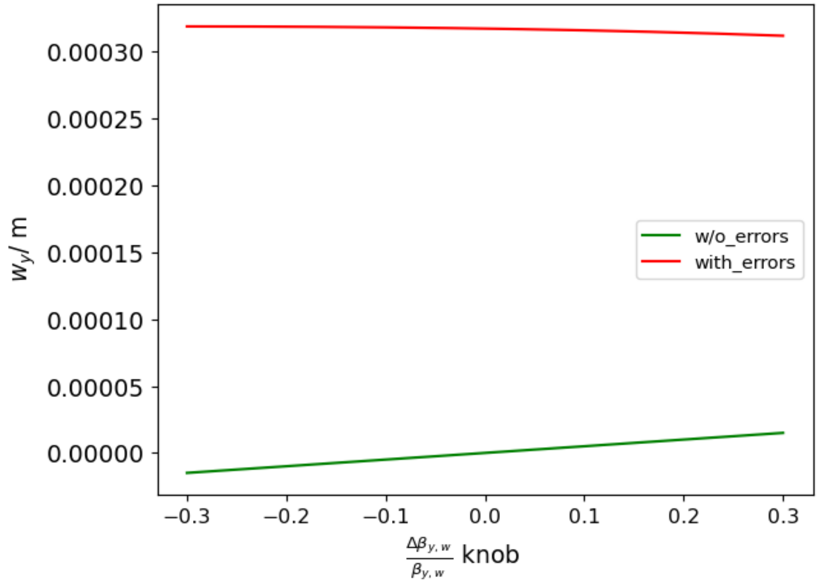
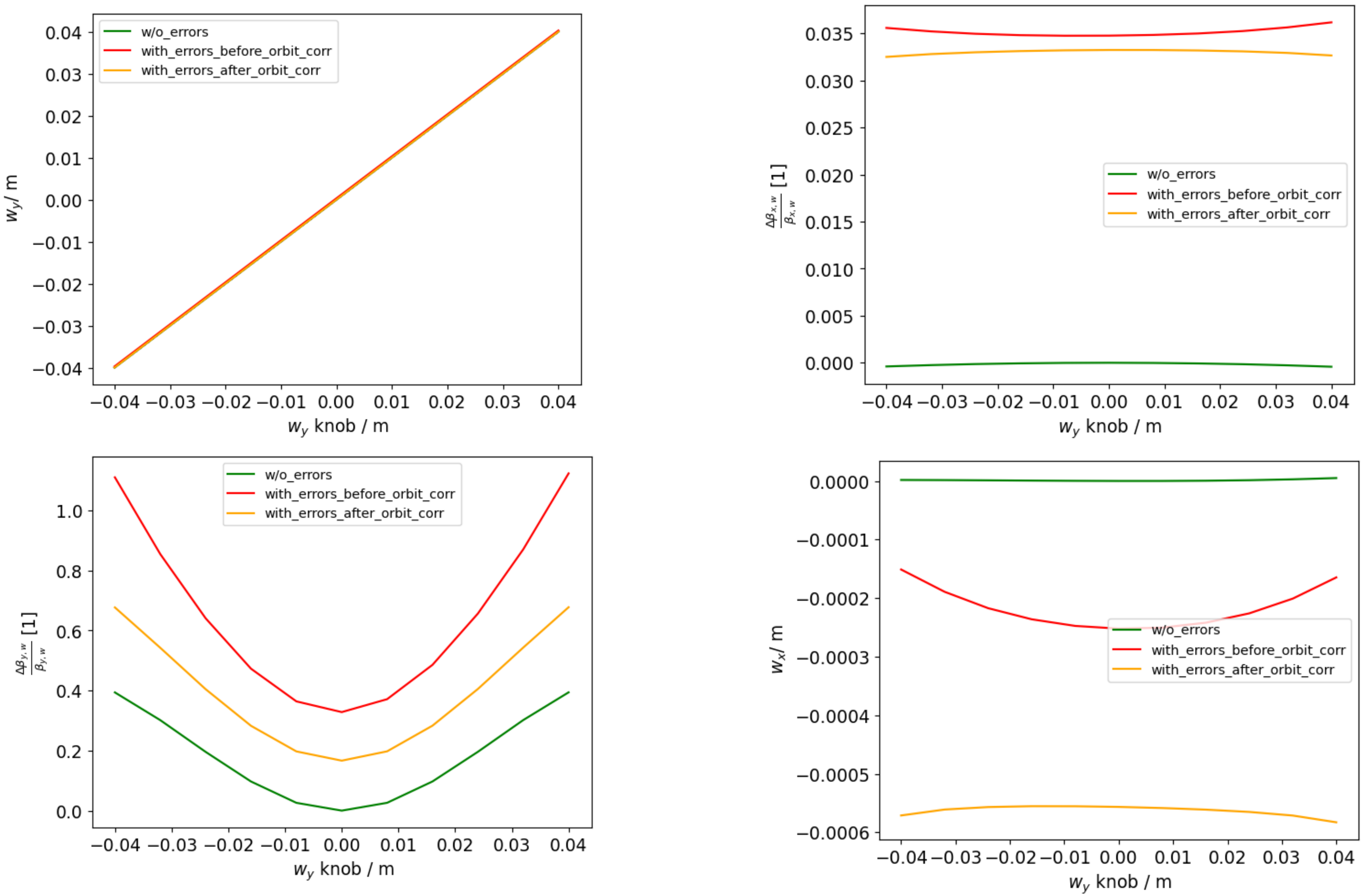








w_y knob post orbit correction



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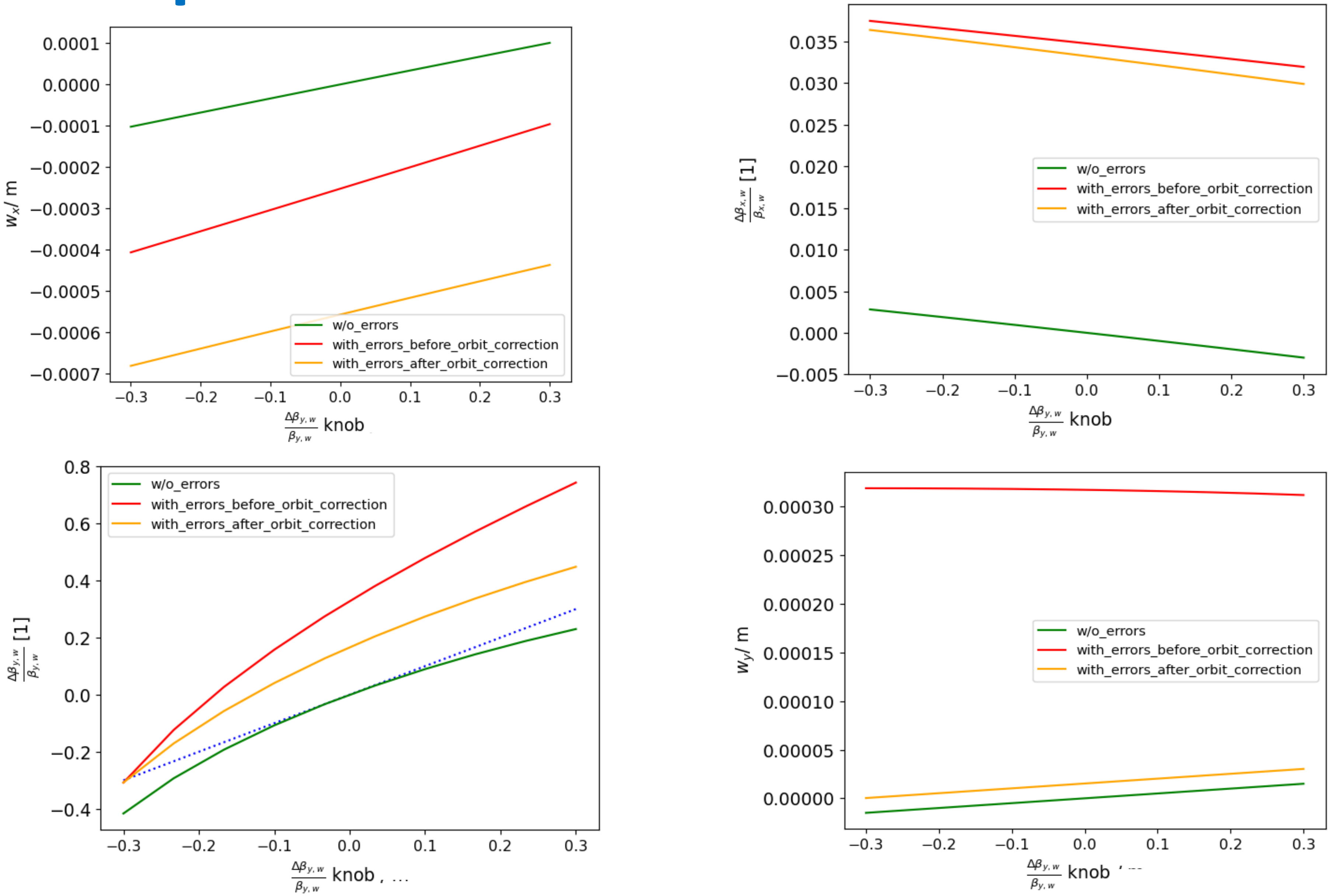
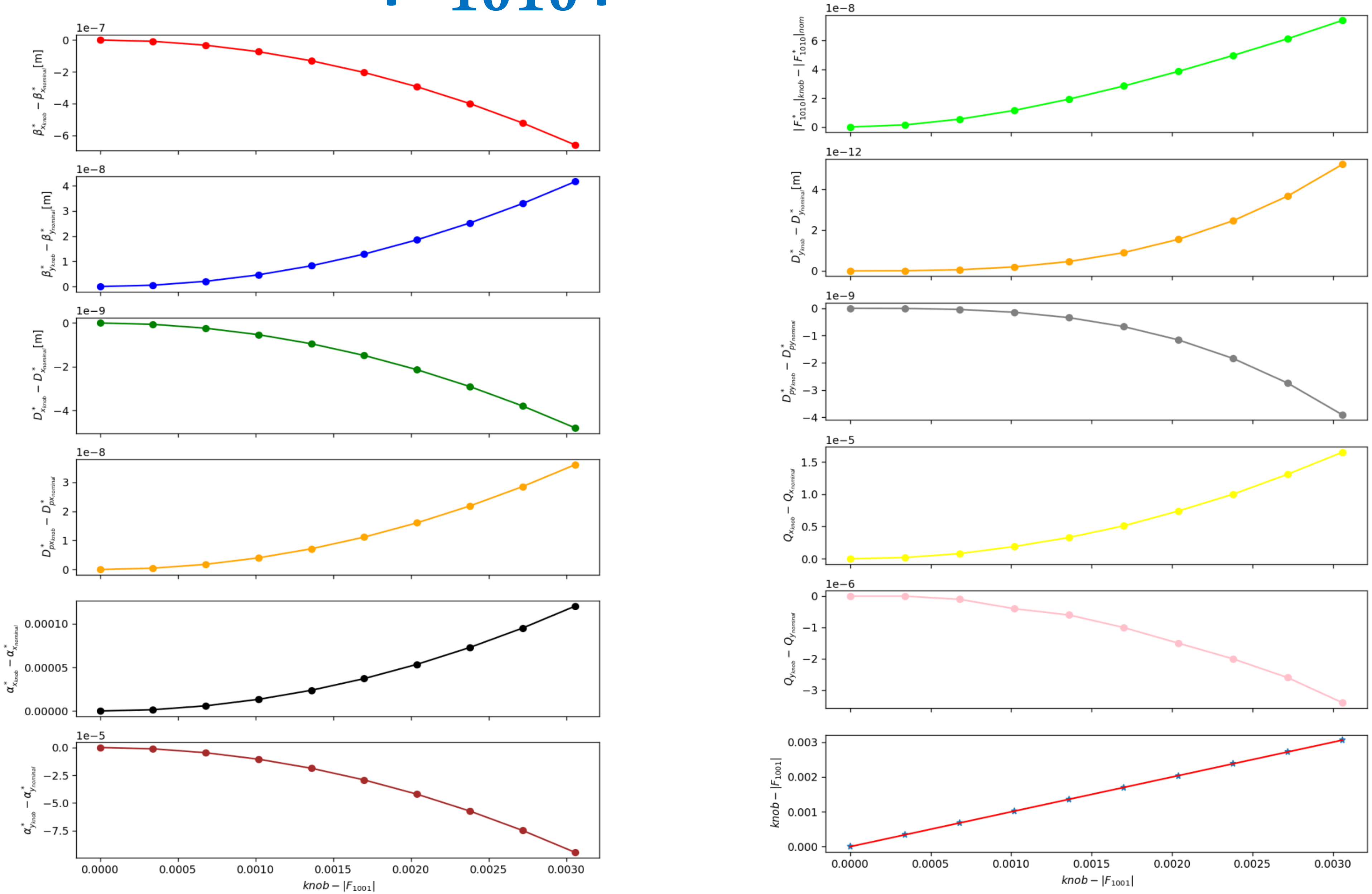
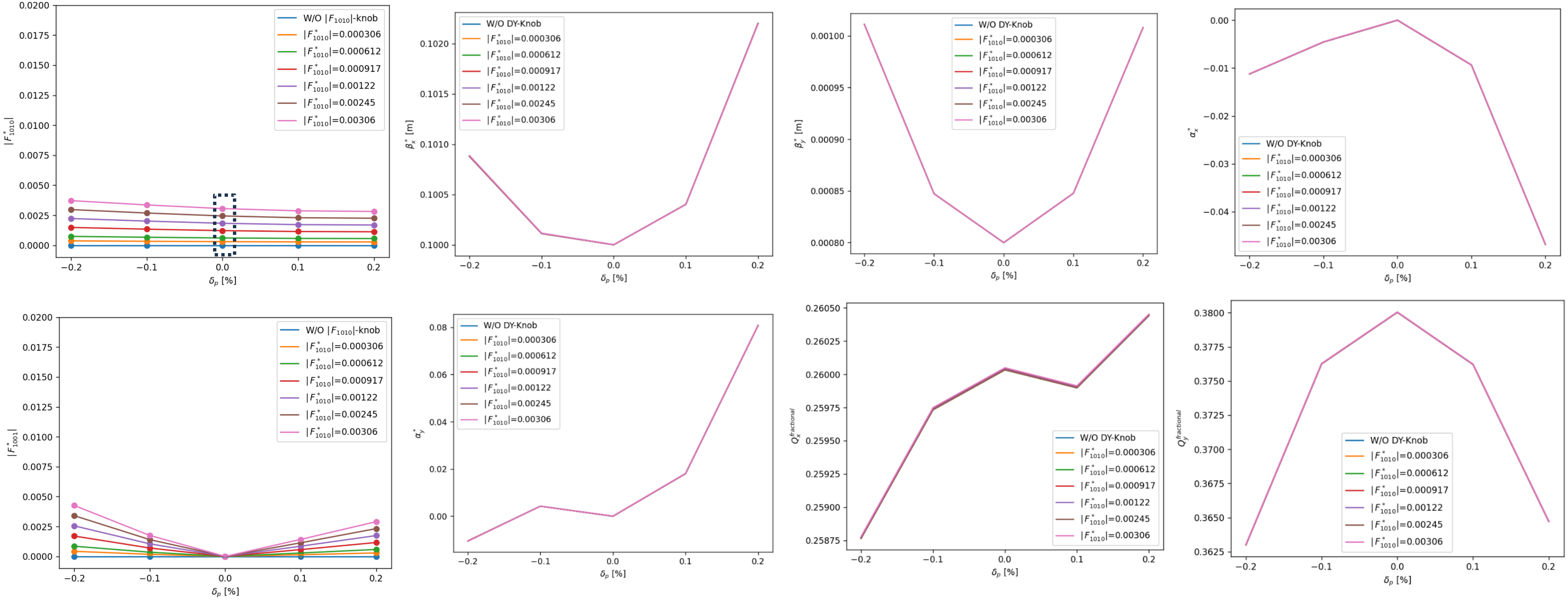


Cross talk of $|F^*_{1010}|$ Knob



Chromatic variations of β, α, tune and Coupling



$\beta^*_{x,y}$ and $w_{x,y}$ knobs