Optics Tuning Challenges at SuperKEKB

Y. Ohnishi / KEK

Thanks to
H. Sugimoto, A. Morita, H. Koiso, D. Zhou, K. Ohmi, K. Oide,
P. Raimondi, M. Biagini, C. Milardi,
A. Bogomyagkov, J. Keintzel, R. Tomas,
and all members of SuperKEKB International Task Force

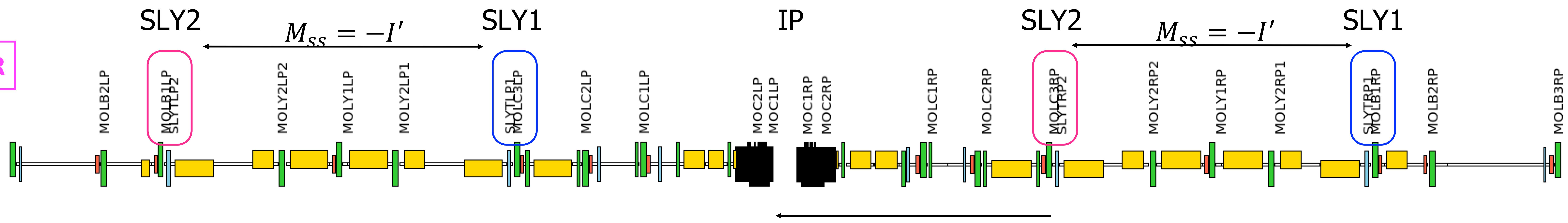
SuperKEKB ITF

Please join !

The invitation link of ITF is as follows:
https://skb-itf-chat.kek.jp/signup_user_complete/?id=dwcachrpqpgbfnqgdcrcbda68h&md=link&sbr=fa

Challenge of Optics Tuning at SuperKEKB

LER



$$K_2 = \frac{1}{2\tan\phi_x}\frac{1}{\beta_y^s\beta_y^*}\sqrt{\frac{\beta_x^*}{\beta_x^s}}$$

$$\tilde{K}_2 = -\frac{K_2}{\cos\Delta\psi_x \sin^2\Delta\psi_y}$$

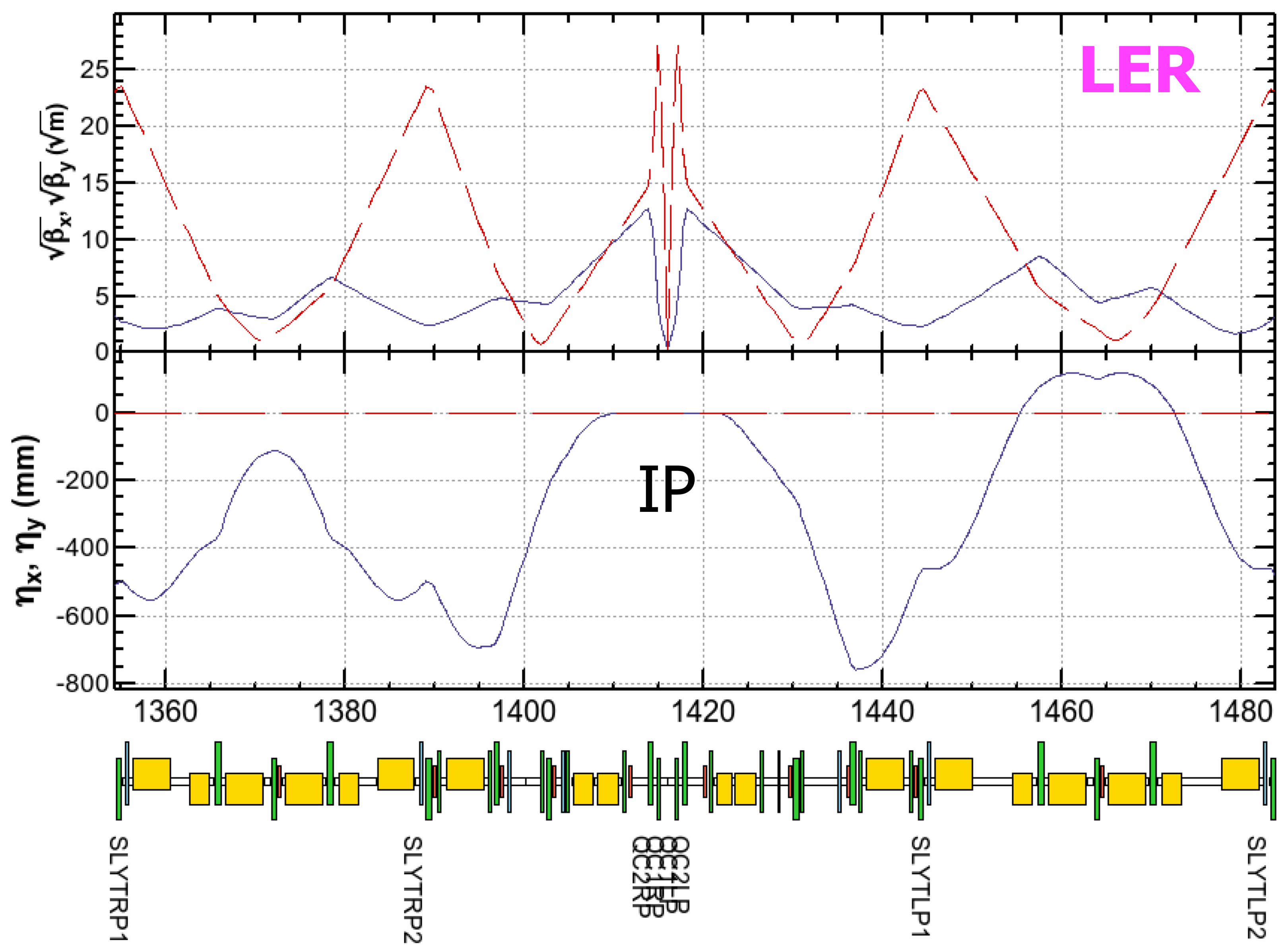
$$\Delta\psi_x = \psi_x^s - \psi_x^* \quad \sim \pi$$
$$\Delta\psi_y = \psi_y^s - \psi_y^* \quad \sim \frac{3}{2}\pi$$

positron

SLY1 and SLY2 are strong sextupoles. They make local chromaticity correction and also play a role of crab sextupoles.

K. Oide, FCC-ee style crab waist

$$\Delta\psi_x = \psi_x^s - \psi_x^* \quad \sim \pi$$
$$\Delta\psi_y = \psi_y^s - \psi_y^* \quad \sim \frac{3}{2}\pi$$



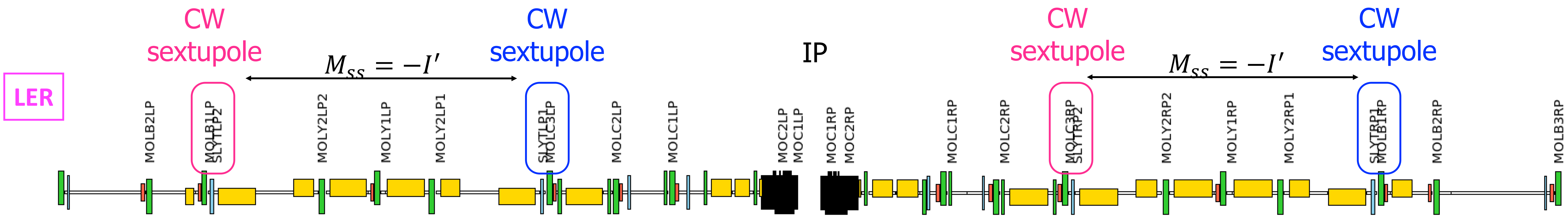
P. Raimondi, The first crab sextupole in the world (DAFNE).

c_r is crab-waist ratio and
K_2^{SLY} is the original setting (CW 0%);

$$K_2^{SLY1} = -c_r\frac{\tilde{K}_2}{2} + K_2^{SYL}$$

$$K_2^{SLY2} = c_r\frac{\tilde{K}_2}{2} + K_2^{SYL}$$

The difference of K2 between SLY1 and SLY2 makes crab waist effect.
The crab waist ratio, c_r is defined by the difference between them.

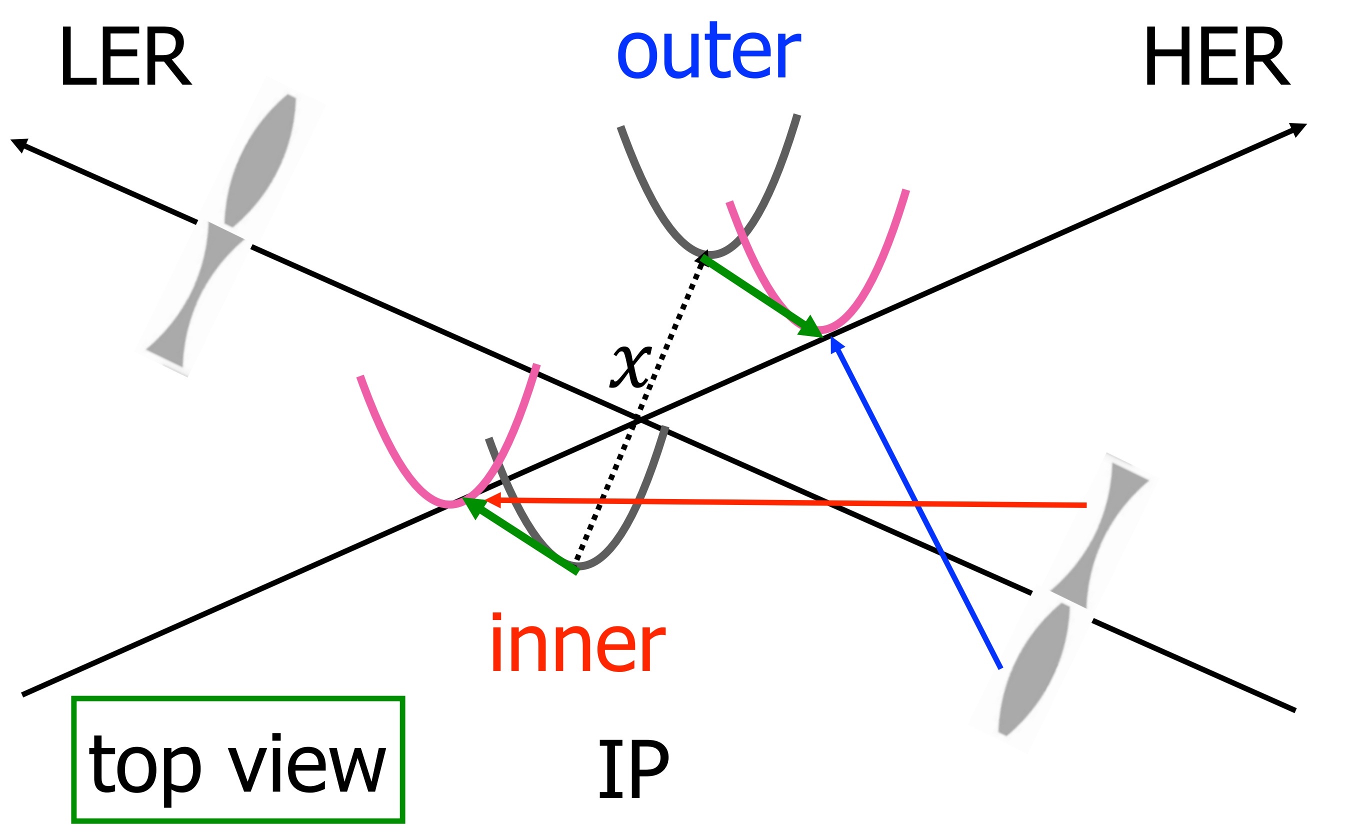


$$\Delta\psi_x = \psi_x^s - \psi_x^* \quad \sim \pi$$
$$\Delta\psi_y = \psi_y^s - \psi_y^* \quad \sim \tfrac{3}{2}\pi$$

Crab Waist

Crab waist scheme creates α_y^* according to x at the IP. The sextupole makes vertical focusing and defocusing for outer and inner particles of the horizontal direction, respectively.

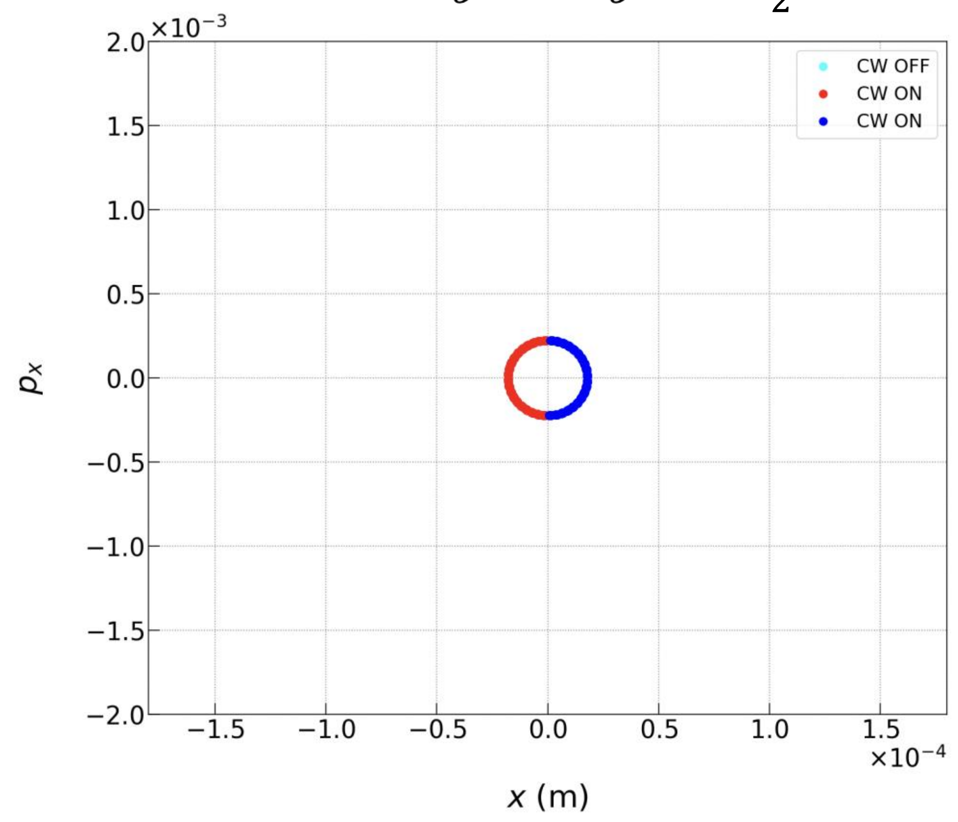
$$\Delta s = \beta_y^w \alpha_y^*$$

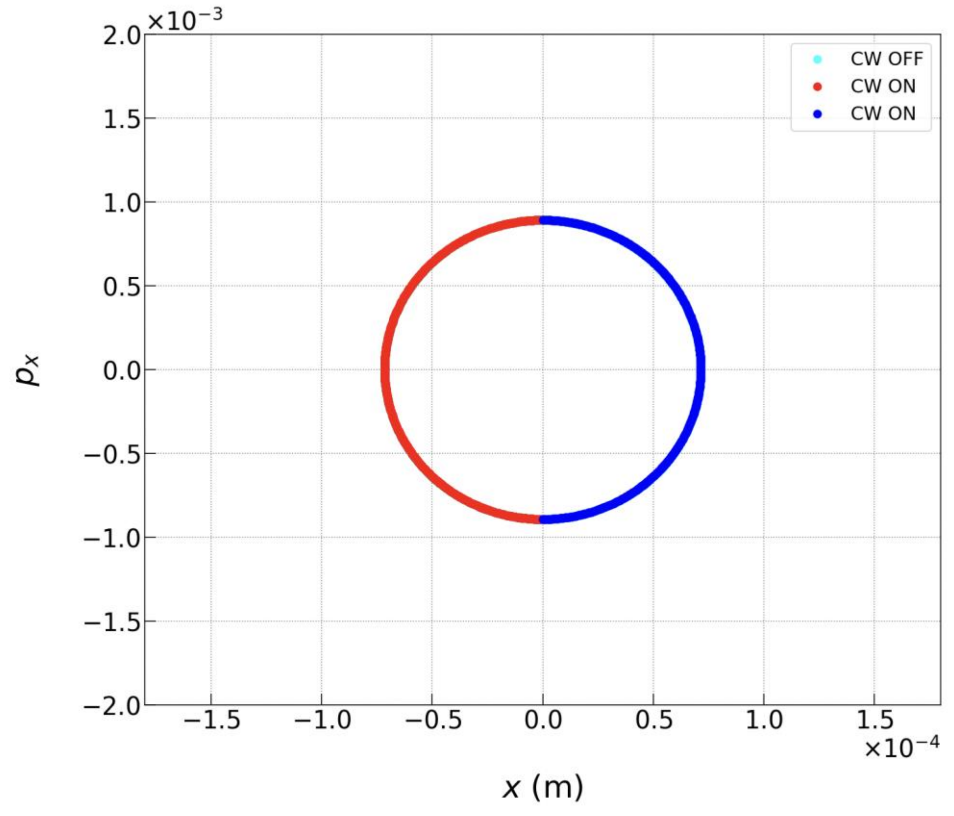


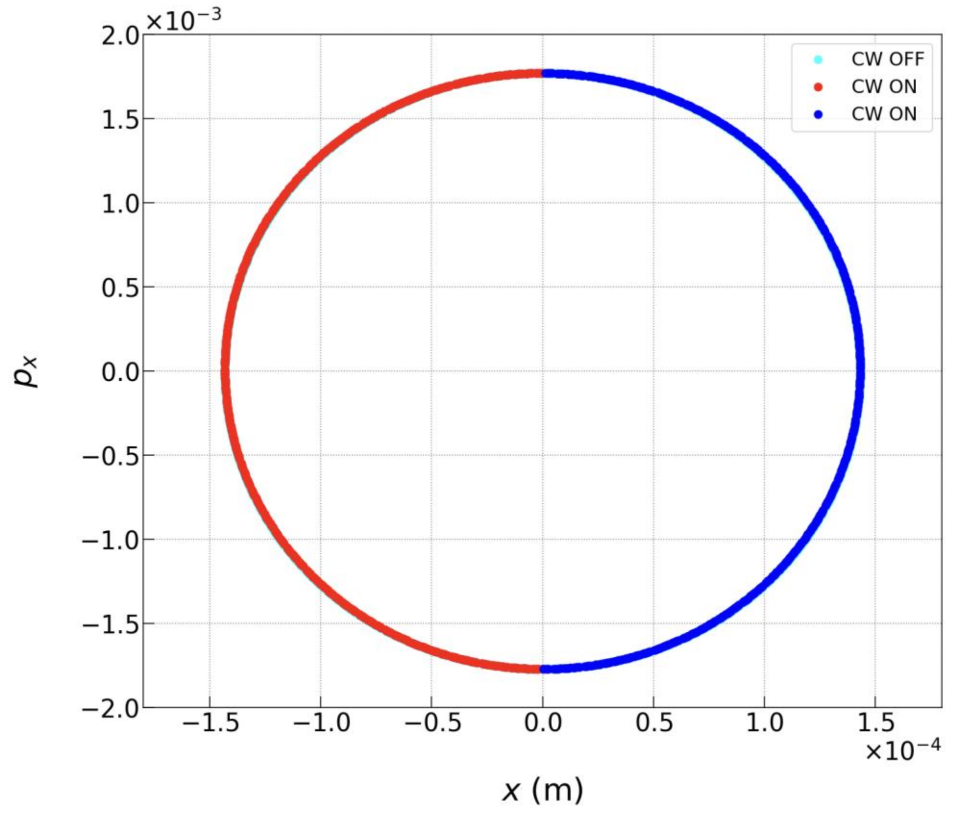
It is expected to reduce resonance lines and bean-tail due to beam-beam.

Horizontal

Phase space plot at the IP



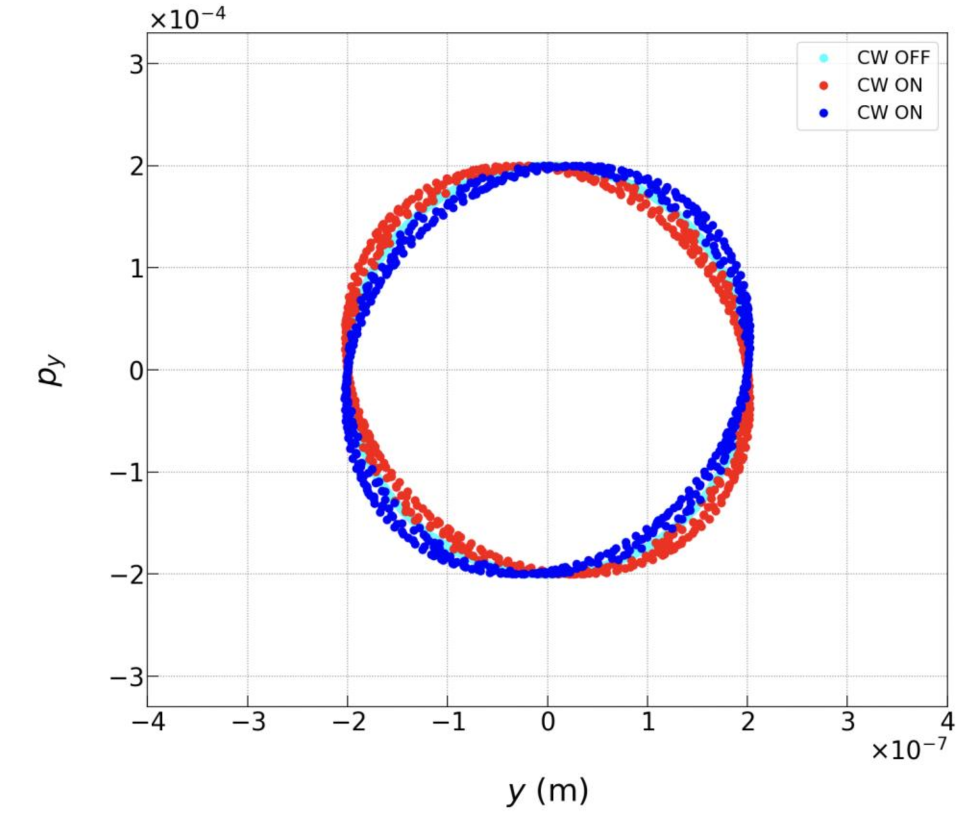


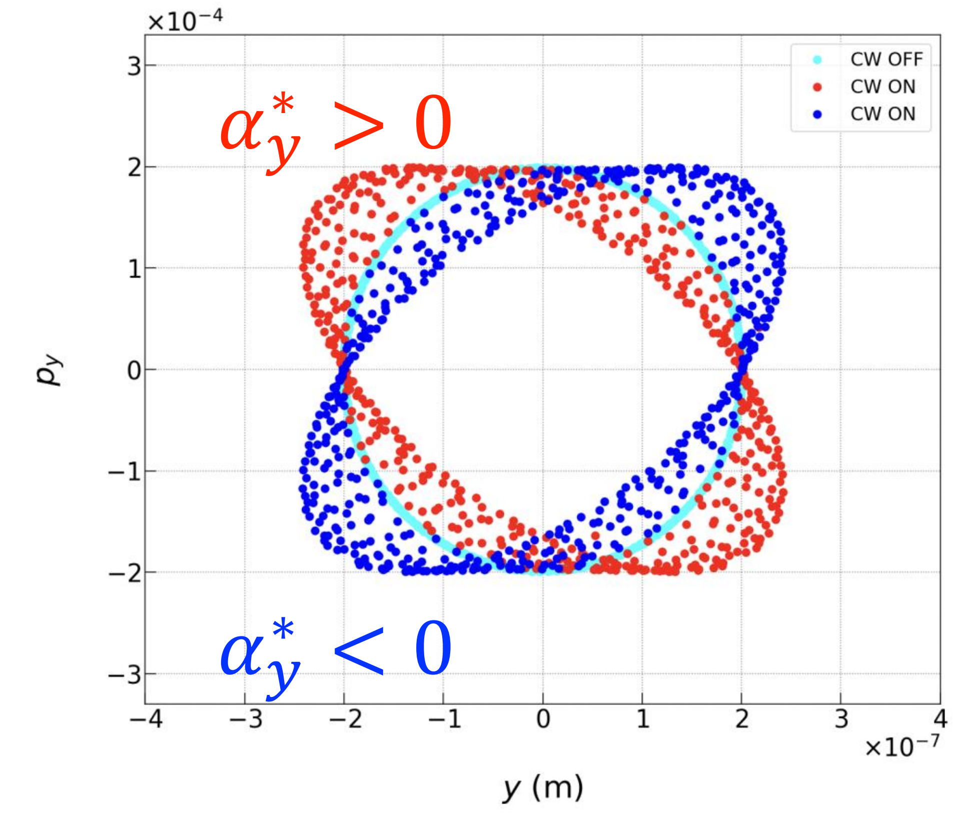


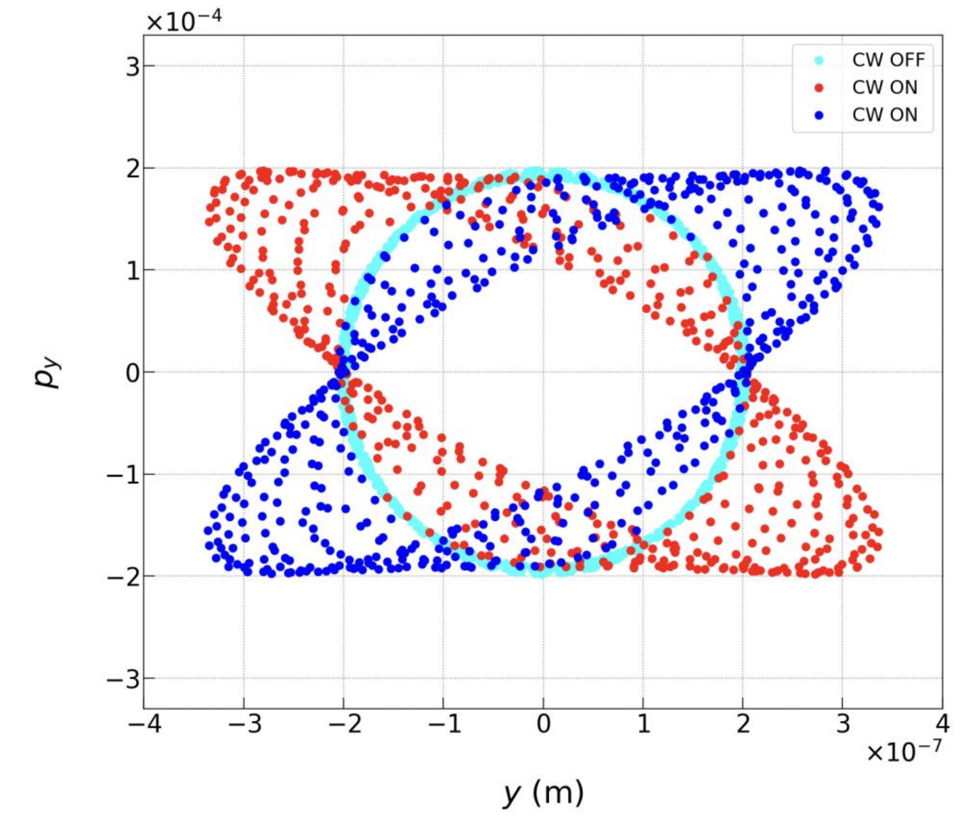
$$H_{CW} = -\frac{1}{2\tan 2\phi_x} x^* p_y^{*2}$$

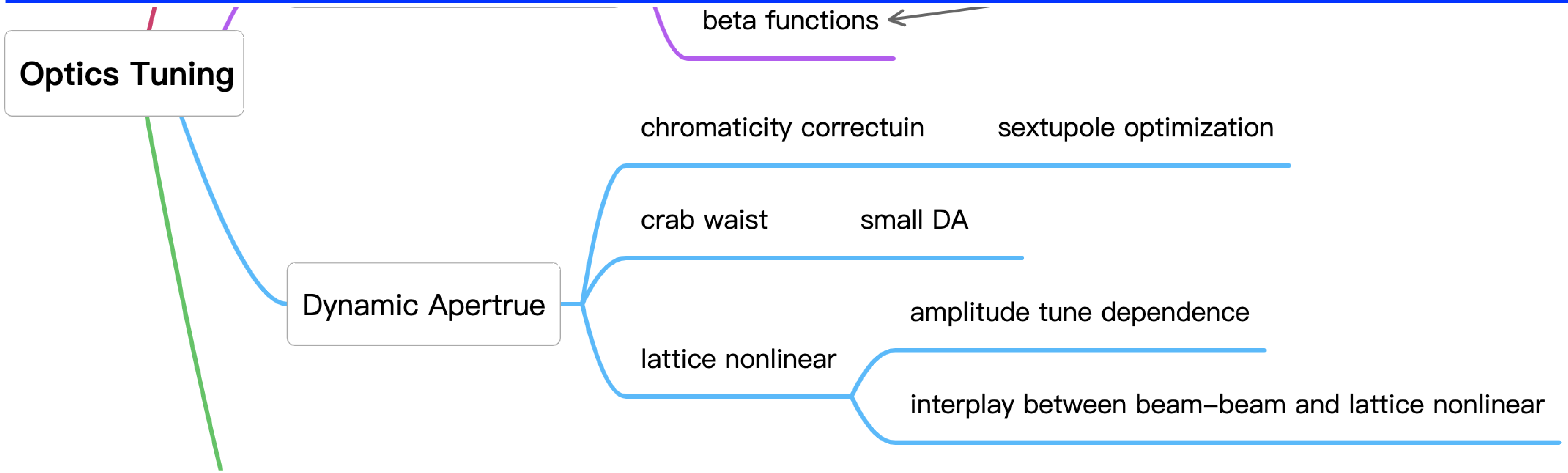
Vertical

* multi-turn tracking of single particle

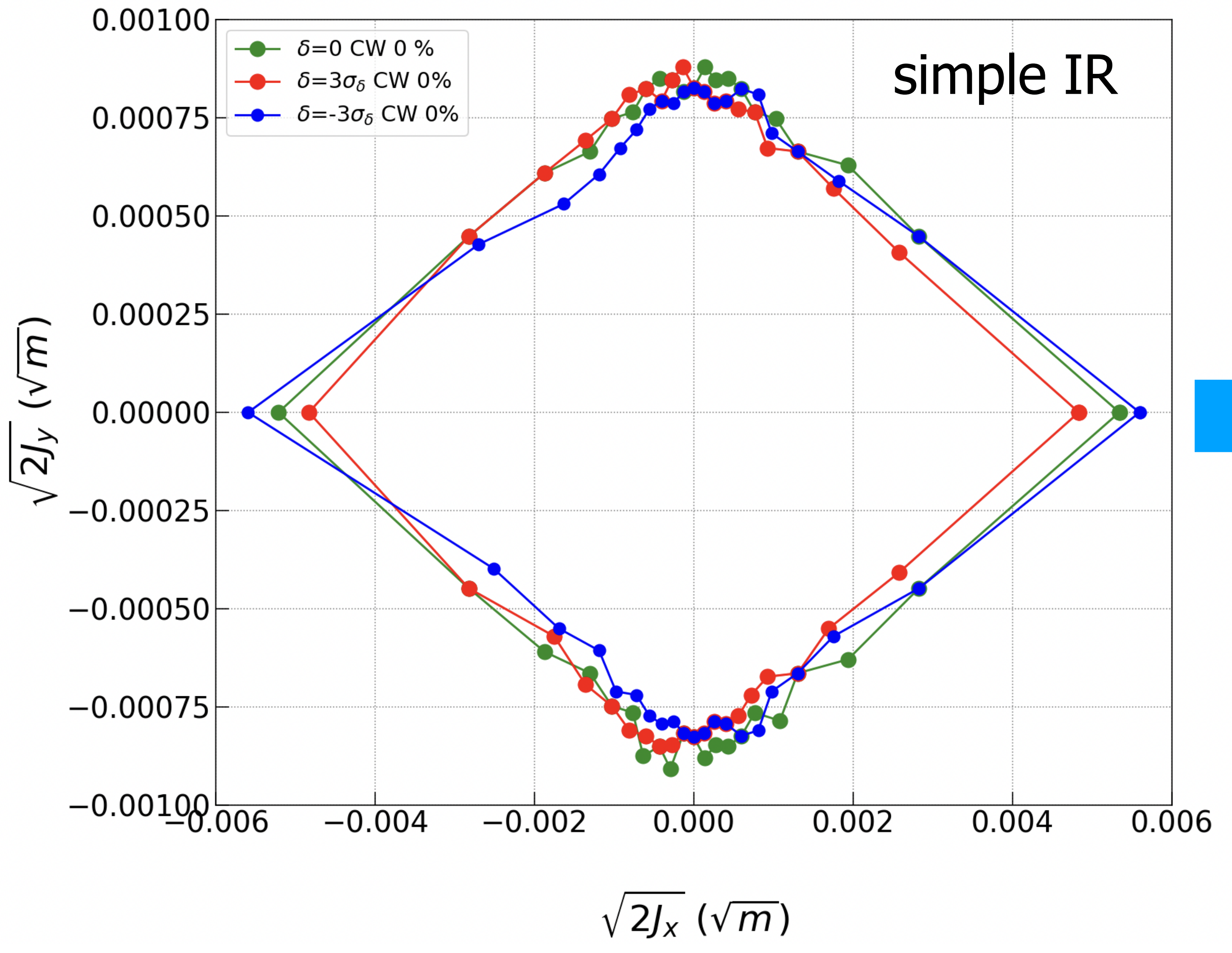




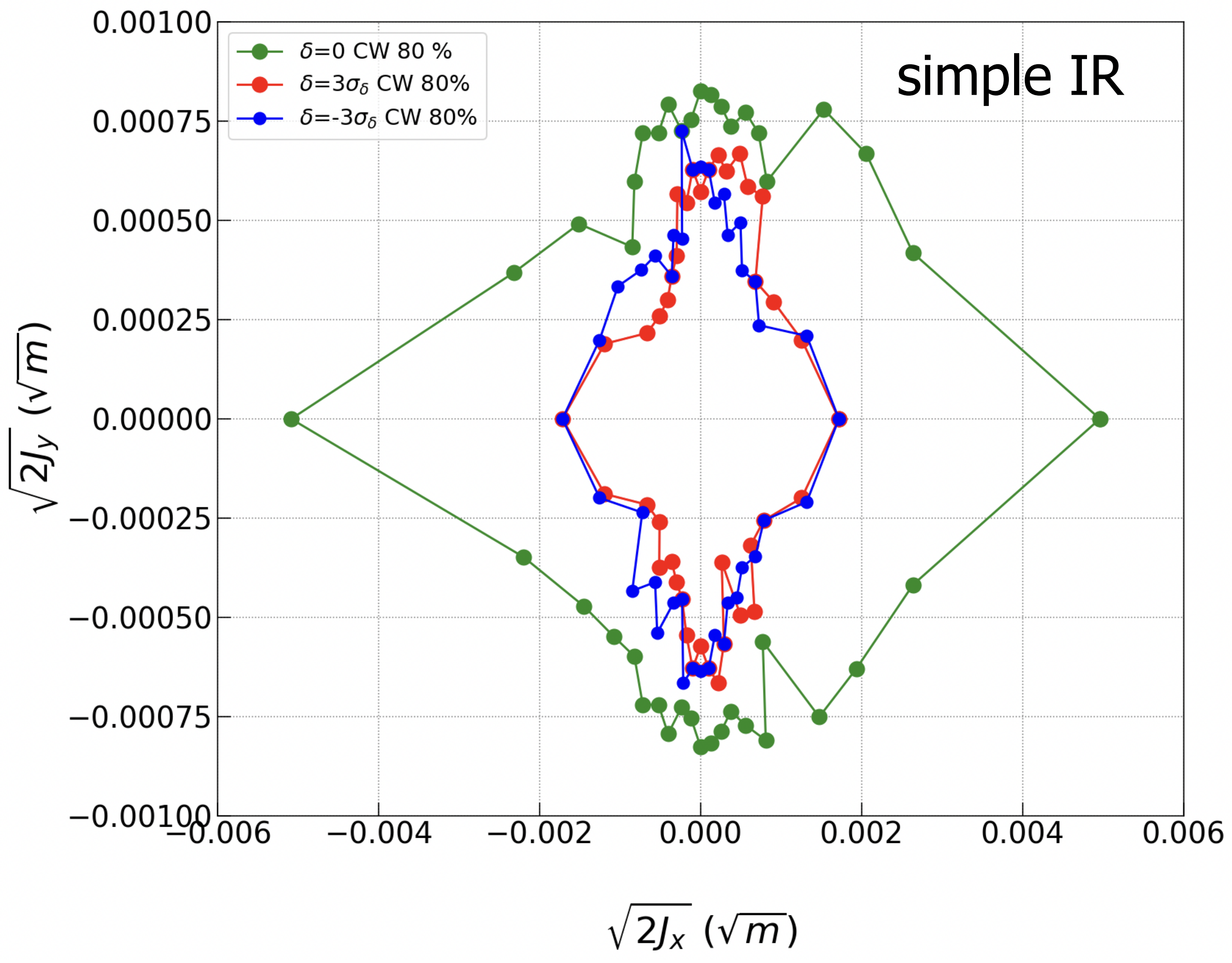




CW : 0 %



CW : 80 %



Crab waist reduces dynamic aperture significantly. (off-momentum)

How does it work ?

PA (collimator) is slightly smaller than DA in the normal operation, so far.
... to suppress beam backgrounds.

Does PA increase in conjunction with DA?

Amplitude Detuning

E.H. Maclean, T. Pugnat, B. Dalena, A. Franchi, R. Tomas, et al.

Tune expanded around the beam center:

$$\nu_{x,y}(J_x, J_y) = \nu_{x0,y0} + \left(\frac{\partial \nu_{x,y}}{\partial J_x} J_x + \frac{\partial \nu_{x,y}}{\partial J_y} J_y\right) + \cdots$$

Hamiltonian equation:

$$\begin{pmatrix} \frac{\partial \psi_{x,y}}{\partial s} \\ \frac{\partial J_{x,y}}{\partial s} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial \psi_{x,y}} \\ \frac{\partial H}{\partial J_{x,y}} \end{pmatrix}$$

Definition of the tune:

$$\nu_x = \frac{1}{2\pi} \oint \frac{\partial \psi_x}{\partial s} ds \qquad \nu_y = \frac{1}{2\pi} \oint \frac{\partial \psi_y}{\partial s} ds$$

Change of the tune within one magnet of the length L:

$$\Delta \nu_{x,y} = \frac{1}{2\pi} \int_L \frac{\partial < H >}{\partial J_{x,y}} ds$$ for over many turns

Normal octupoles:

$$H_3(x,y) = \frac{1}{4!} k_3 (x^4 - 6x^2y^2 + y^4)$$

$$x, y = \sqrt{2J_{x,y}\beta_{x,y}} \cos \psi_{x,y}$$

$$< H_3 >= \frac{k_3}{16} (J_x^2 \beta_x^2 - 4 J_x J_y \beta_x \beta_y + J_y^2 \beta_y^2)$$

$$\frac{1}{2\pi} \int \frac{\partial < H_3 >}{\partial J_x} ds = \sum_i \frac{k_3 L_o}{16\pi} \beta_x^2 J_x - \sum_i \frac{k_3 L_o}{8\pi} \beta_x \beta_y J_y$$
$$= a_{xx} J_x + a_{xy} J_y$$

$$\frac{1}{2\pi} \int \frac{\partial < H_3 >}{\partial J_y} ds = -\sum_i \frac{k_3 L_o}{8\pi} \beta_x \beta_y J_x + \sum_i \frac{k_3 L_o}{16\pi} \beta_y^2 J_y$$
$$= a_{yx} J_x + a_{yy} J_y$$

Nonlinear Fringe Field of Quadrupole, Kinematic Term

E. Forest et al., Nucl. Inst. Meth. in Physics Research, A269 (1988)
K. Oide and H. Koiso, Phys. Rev. E, 47, 3 (1993)

A. Bogomyagkov et al., PR-AB, 19, 121005 (2016)

Quadrupole nonlinear fringe (Normal)

$$H_{f\pm} = \pm\frac{k_1}{12}(x^3p_x - 3x^2yp_y + 3y^2xp_x - y^3p_y)$$

(+: entrance, -: exit)

Average of H_f

$$< H_{f+} >= -\frac{k_1}{8}\beta_x\alpha_x J_x^2 + \frac{k_1}{4}(\beta_x\alpha_y - \beta_y\alpha_x)J_xJ_y + \frac{k_1}{8}\beta_y\alpha_y J_y^2$$

Amplitude detuning:

$$\frac{1}{2\pi}\int\frac{\partial < H_{f+} >}{\partial J_x}ds = -\sum_i\frac{k_1}{8\pi}\beta_x\alpha_x J_x + \sum_i\frac{k_1}{8\pi}(\beta_x\alpha_y - \beta_y\alpha_x)J_y$$
$$= a_{xx}J_x + a_{xy}J_y$$

$$\frac{1}{2\pi}\int\frac{\partial < H_{f+} >}{\partial J_y}ds = \sum_i\frac{k_1}{8\pi}(\beta_x\alpha_y - \beta_y\alpha_x)J_x + \sum_i\frac{k_1}{8\pi}\alpha_y\beta_y J_y$$
$$= a_{yx}J_x + a_{yy}J_y$$

$$\alpha_y = -\frac{L^*}{\beta_y^*} \quad k_1L_Q = -\frac{2}{L^* + L_Q/2}$$ (IP side)

Kinematic term

$$H_k = \frac{(p_x^2 + p_y^2)^2}{8}$$

Average of H_k

$$< H_k >= \frac{1}{16}(3\gamma_x^3 J_x^2 + 2\gamma_x\gamma_y J_xJ_y + 3\gamma_y^2 J_y^2)$$

approximation: $\gamma_{x,y}^2 = \frac{(1+\alpha_{x,y}^2)^2}{\beta_{x,y}^2} \simeq \frac{1}{\beta_{x,y}^2}$

$$\frac{1}{2\pi}\int\frac{\partial < H_k >}{\partial J_x}ds = \frac{1}{16\pi\beta_x^*}\left(L^* + \frac{L_Q}{2}\right)\left(\frac{3}{\beta_x^*}J_x + \frac{1}{\beta_y^*}J_y\right)$$
$$= a_{xx}J_x + a_{xy}J_y$$

$$\frac{1}{2\pi}\int\frac{\partial < H_k >}{\partial J_y}ds = \frac{1}{16\pi\beta_y^*}\left(L^* + \frac{L_Q}{2}\right)\left(\frac{1}{\beta_x^*}J_x + \frac{3}{\beta_y^*}J_y\right)$$
$$= a_{xx}J_x + a_{xy}J_y$$

from IP to the 1st quadrupole magnet

Thickness of Sextupole

K. Oide and H. Koiso, Phys. Rev. E, 47, 3 (1993)
A. Bogomyagkov et al., PR-AB, 19, 121005 (2016)

Sextupole: thick lens

$$H_s = -\frac{(k_2 L_S)^2 L_S}{48}(x^2+y^2)^2$$

Average of H_f

$$< H_s >= -\frac{(k_2 L_S)^2 L_S}{16}\left(\frac{\beta_x^2}{2}J_x^2 + \frac{2}{3}\beta_x\beta_y J_x J_y + \frac{\beta_y^2}{2}J_y^2\right)$$

Amplitude detuning:

$$\frac{1}{2\pi}\int \frac{\partial < H_s >}{\partial J_x} ds = -\sum_i \frac{(k_2 L_S)^2 L_S}{32\pi}\beta_x J_x - \sum_i \frac{(k_2 L_S)^2 L_S}{48\pi}\beta_x\beta_y J_y$$
$$= a_{xx}J_x + a_{xy}J_y$$

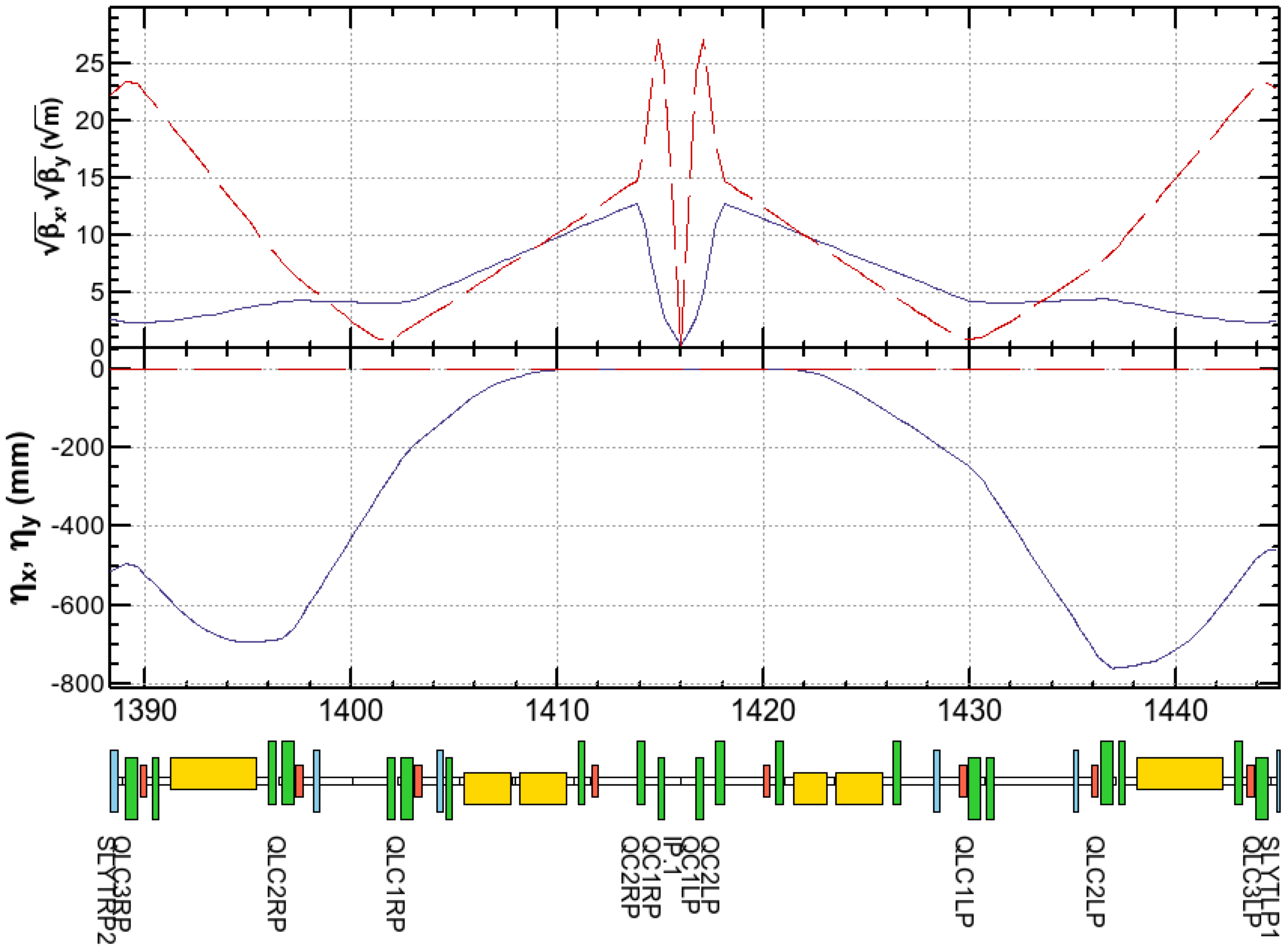
$$\frac{1}{2\pi}\int \frac{\partial < H_s >}{\partial J_y} ds = -\sum_i \frac{(k_2 L_S)^2 L_S}{48\pi}\beta_x\beta_y J_x - \sum_i \frac{(k_2 L_S)^2 L_S}{32\pi}\beta_y J_y$$
$$= a_{yx}J_x + a_{yy}J_y$$

We can turned OFF and ON for each items in the tracking simulations.

case	1	2	3	4	5
Kinematic term	x	o	x	x	x
QC1 fringe	x	x	o	x	x
QC2 fringe	x	x	x	o	x
Sextupole thick lens	x	x	x	x	o

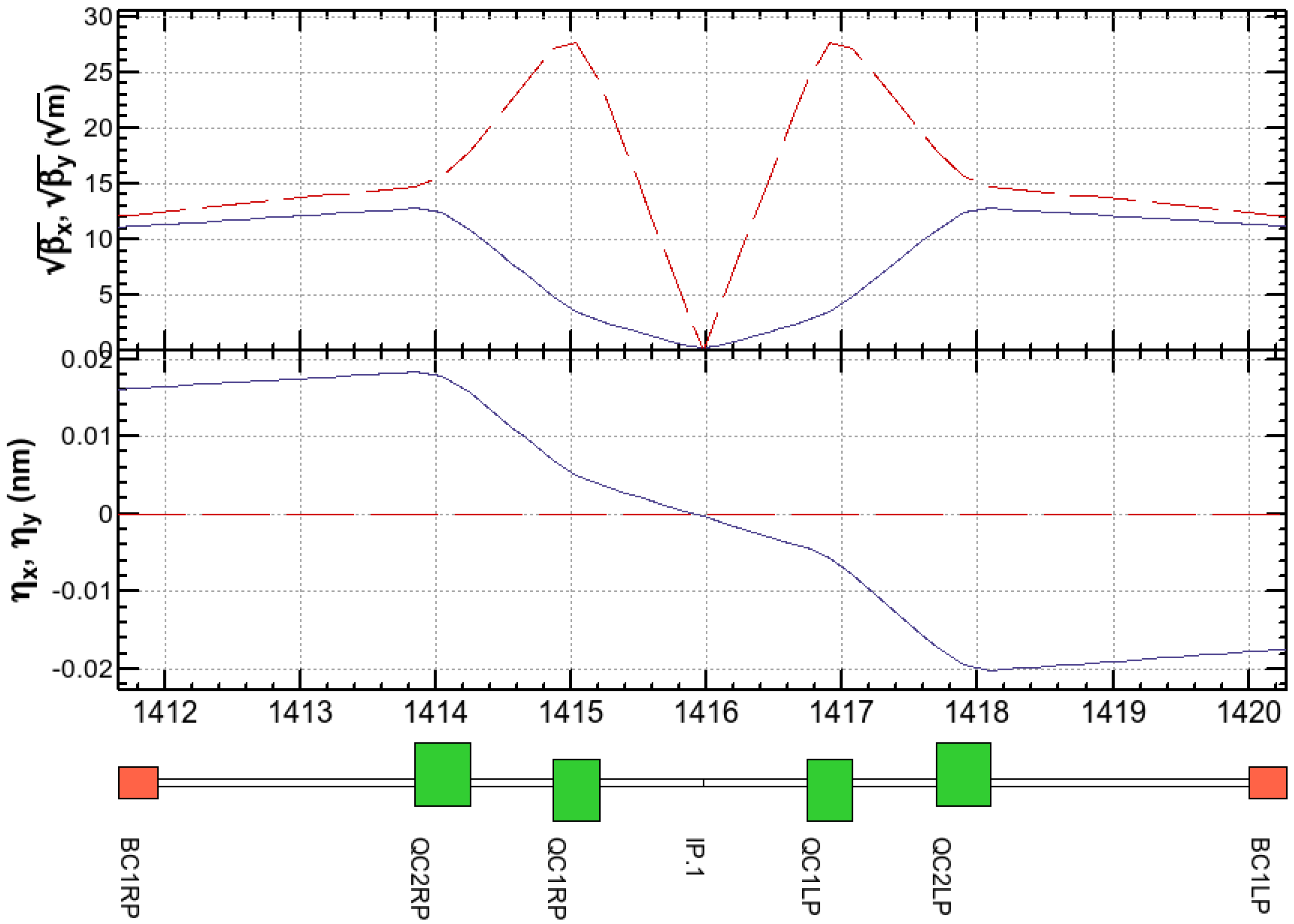
No solenoid, no higher order multipole fields, no X-Y couplings, no offset of magnets

$$\beta_x^* = 80mm \qquad \beta_y^* = 1mm$$



SLY1
(crab sextupole)

SLY1
(crab sextupole)



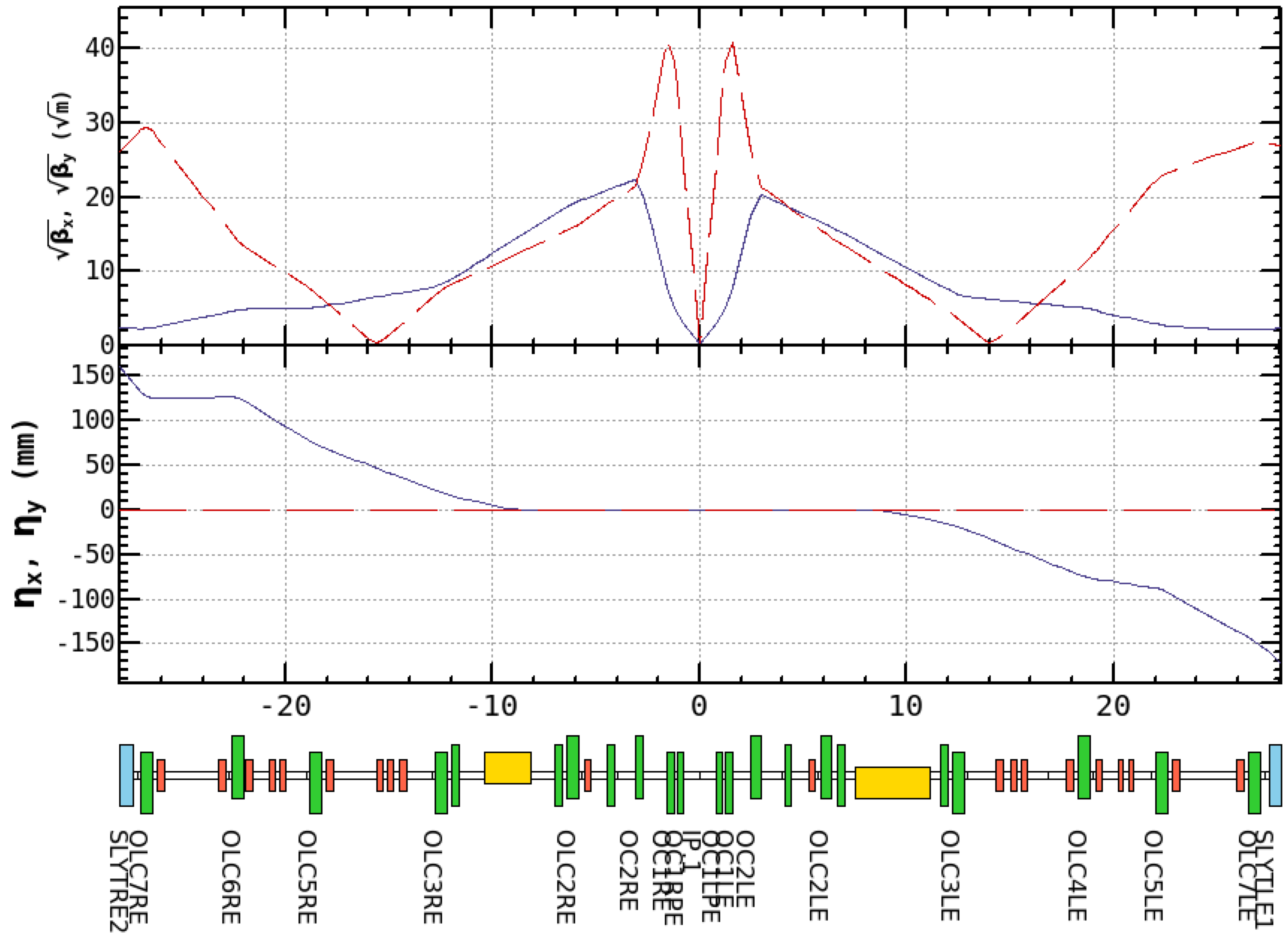
QC2 QC1 QC1 QC2

QC1 and QC2 are hard edge.

Simple IR Model in HER

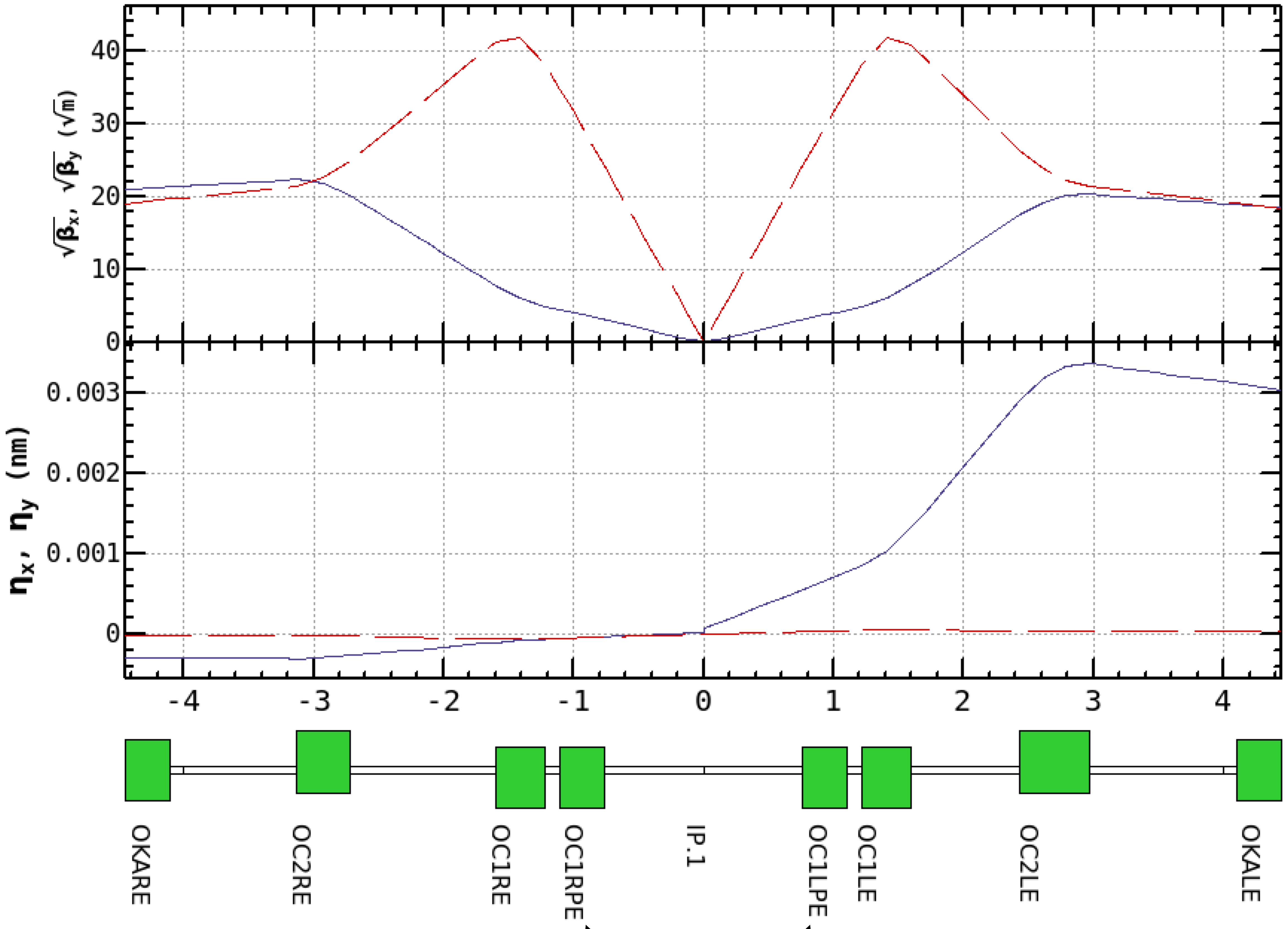
No solenoid, no higher order multipole fields, no X-Y couplings, no offset of magnets

$$\beta_x^* = 60mm \qquad \beta_y^* = 1mm$$



SLY1
(crab sextupole)

SLY1
(crab sextupole)



QC2 QC1 QC1 QC2

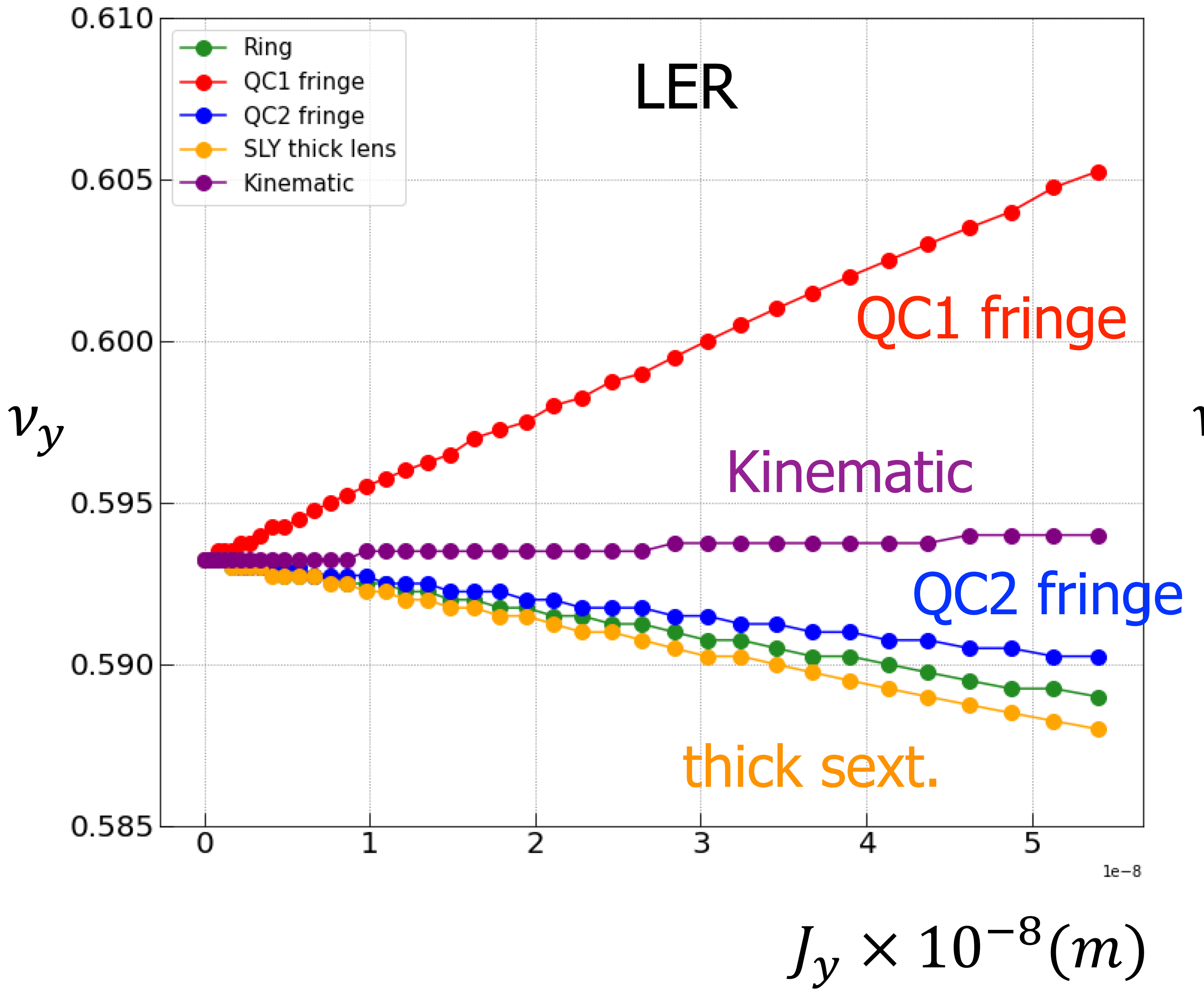
leakage field
from LER

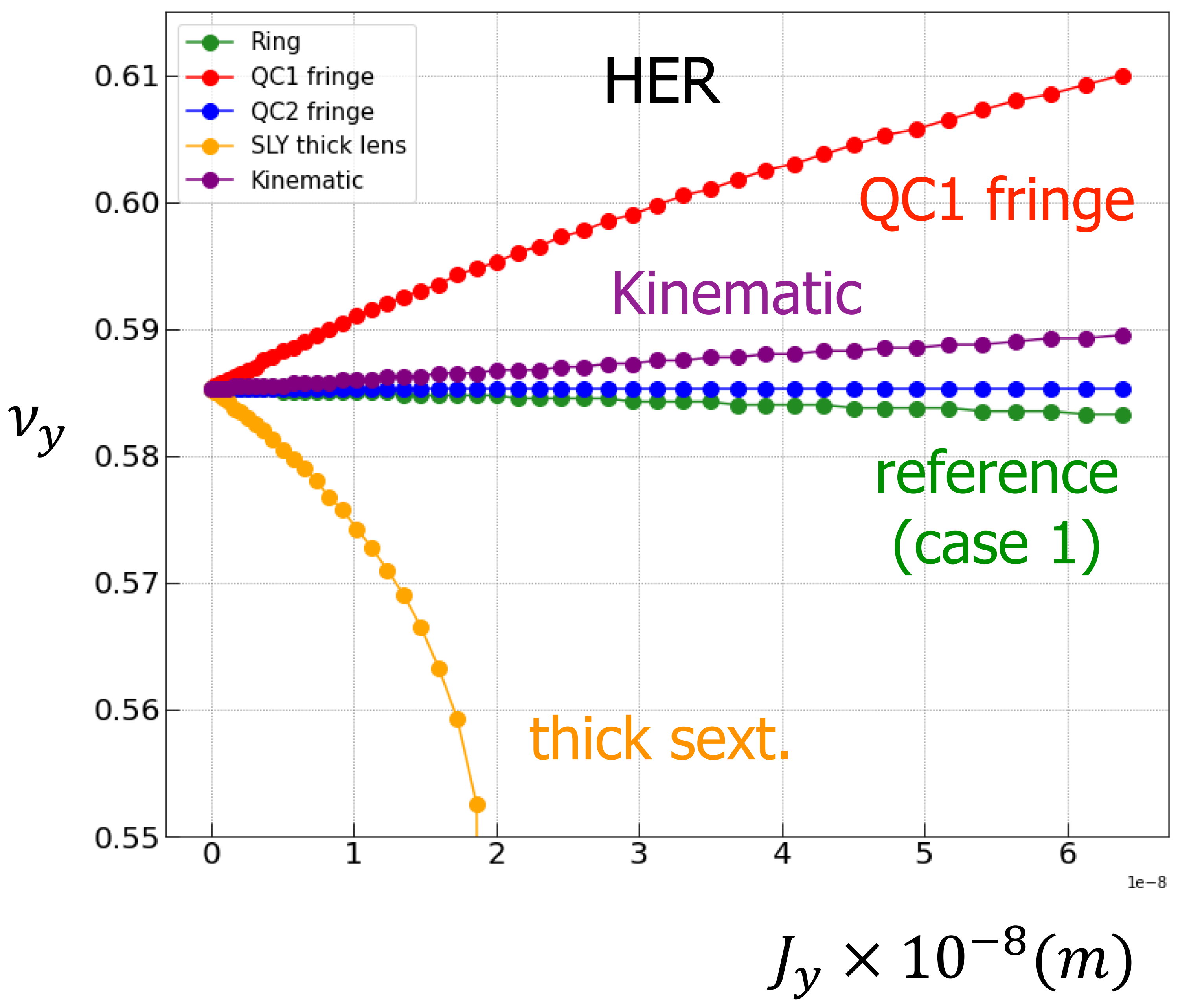
QC1 and QC2 are hard edge.

Estimation of Amplitude Detuning

Simple IR model

Tracking simulation





upper: tracking / lower: analytic

a_{yy}	LER	HER
Beta at IP	80 mm / 1 mm	60 mm / 1 mm
crab waist	80%	40%
Kinematic trem	0.91 x 10^5	1.05 x 10^5
	1.12 x 10^5	1.68 x 10^5
QC1 fringe	3.01 x 10^5	5.80 x 10^5
	3.01 x 10^5	6.47 x 10^5
QC2 fringe	0.12 x 10^5	0.30 x 10^5
	0.14 x 10^5	0.25 x 10^5
SLY thick lens (crab waist)	-0.17 x 10^5	-7.24 x 10^5
	-0.24 x 10^5	-9.44 x 10^5

The largest detuning of a_{yy} is QC1 fringe in the LER.
The thick sextupoles compensate the detuning of QC1 fringe and kinematic term in the HER.

The tracking simulation is consistent with analytic calculation.

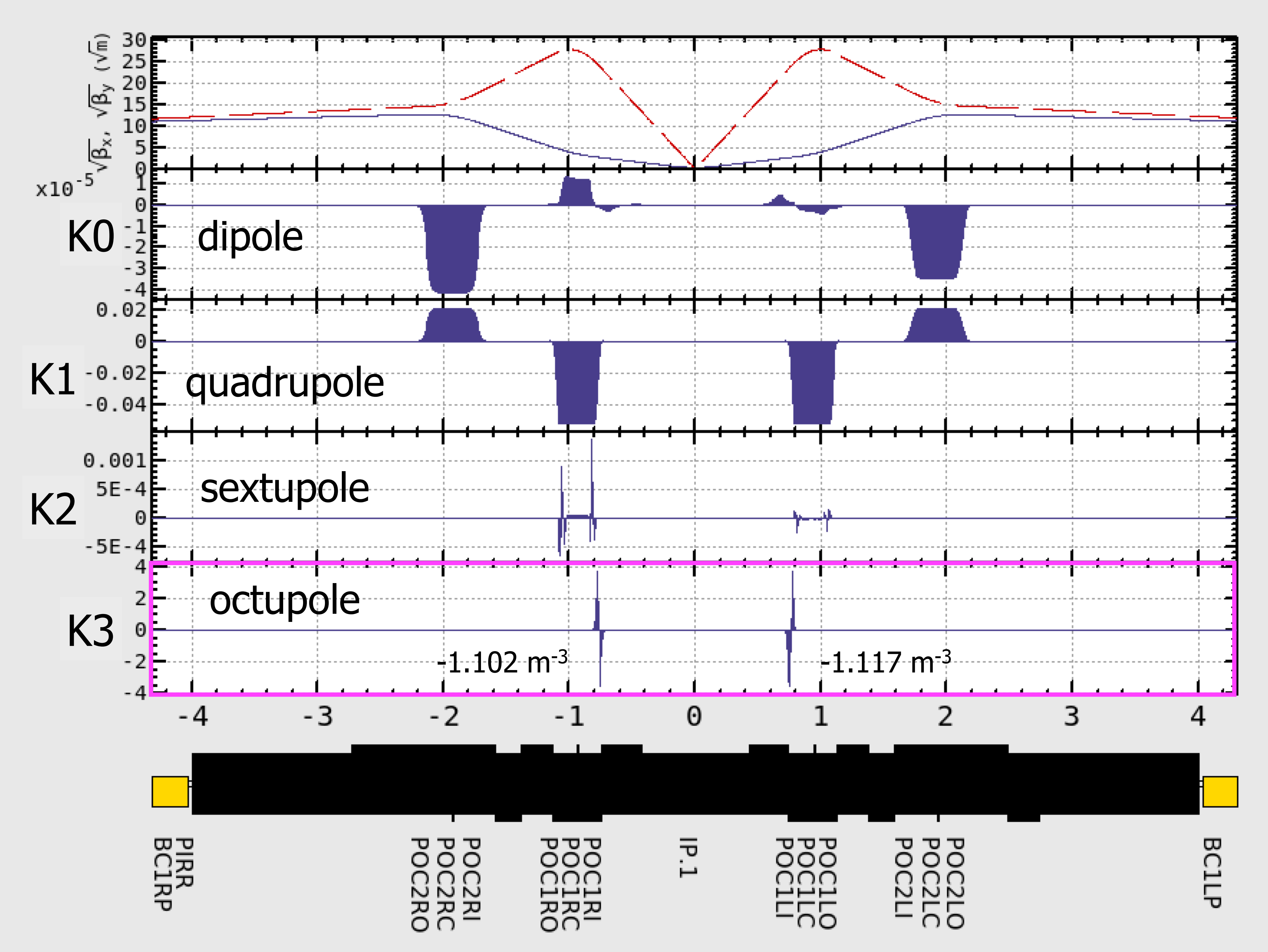
Higher-Order Multipole Magnetic Field

SuperKEKB: $\beta_y^* = 1mm$

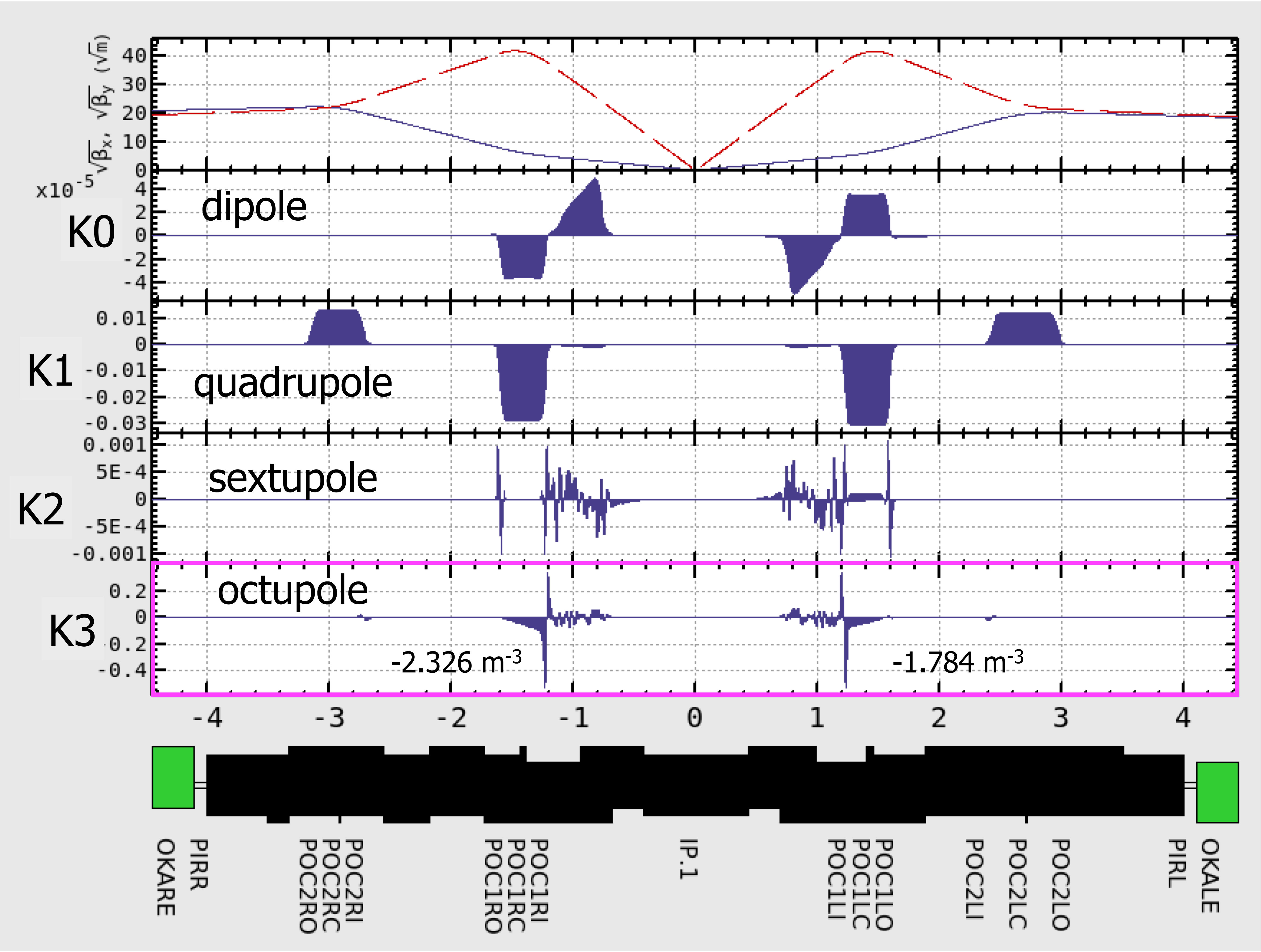
Realistic model calculation in the IR

The slice of 1 cm for ±4m region from IP

LER



HER



sextupole: K2 = 6.36x10^{-4} (m^{-2})

octupole: K3 = -2.22 (m^{-3})

sextupole: K2 = 3.32x10^{-3} (m^{-2})

octupole: K3 = -4.11 (m^{-3})

Octupole	a_{xx}	a_{xy}	a_{yy}
LER	53	-295	1186
HER	-128	10315	-256676

Different sign between IR in LER and HER

Multi-Particles Tracking in LER (CW 80%)

$\beta_y^* = 1mm$

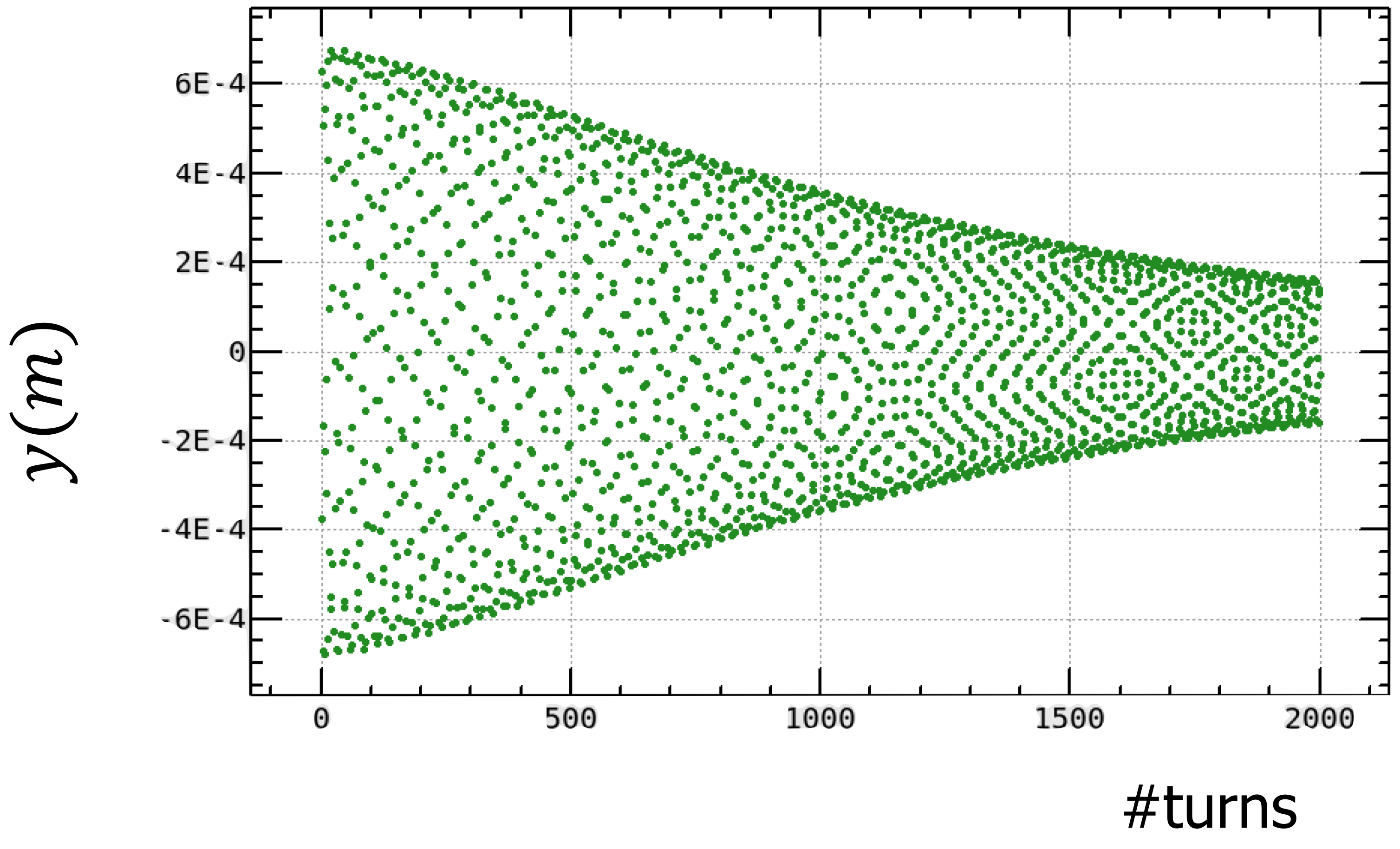
$\theta_y = 10\mu rad$ $\sqrt{2J_y} = 8.22 \times 10^{-5}\sqrt{m}$

$\theta_y = 20\mu rad$ $\sqrt{2J_y} = 1.64 \times 10^{-4}\sqrt{m}$

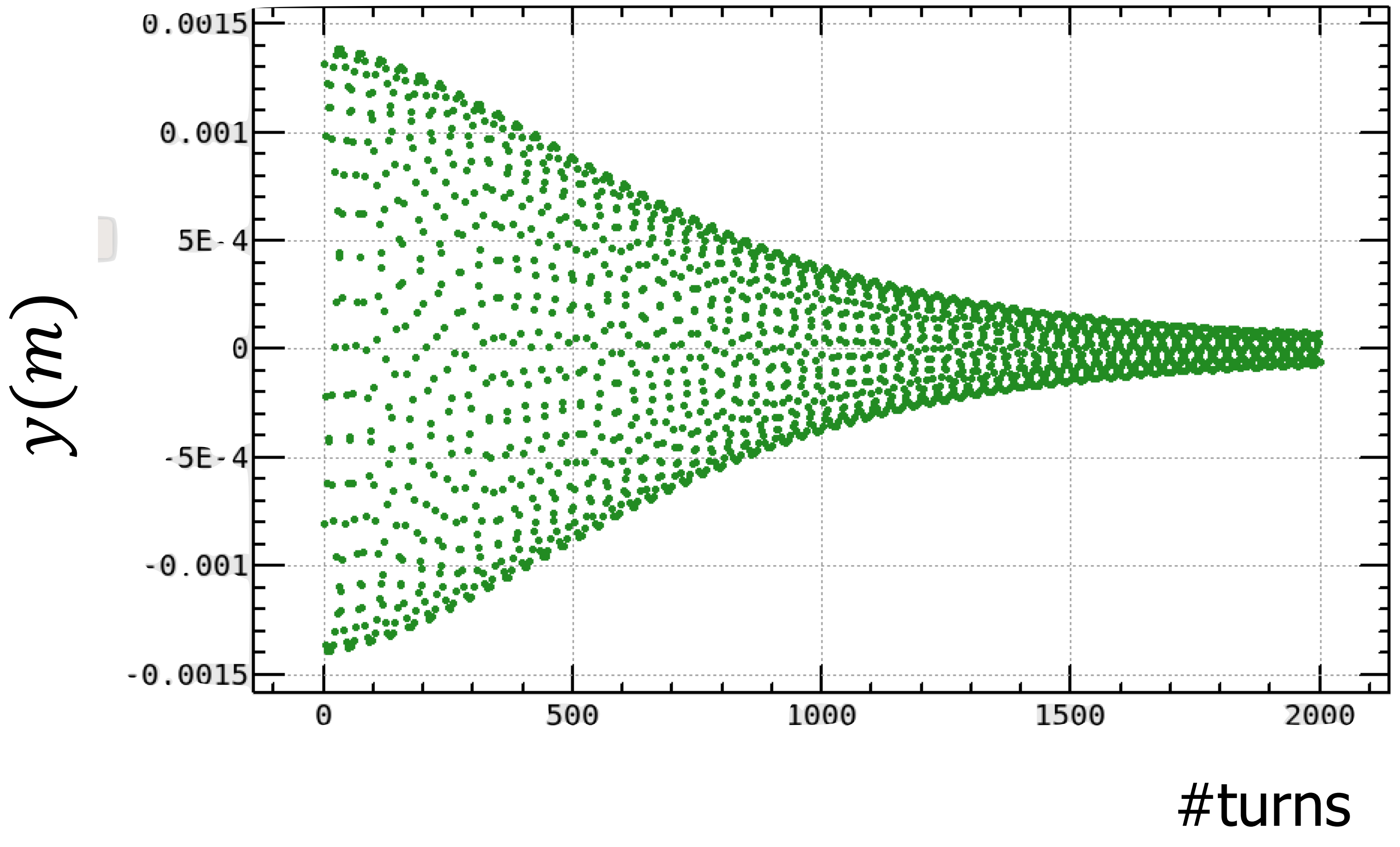
$\theta_y = 30\mu rad$ $\sqrt{2J_y} = 2.47 \times 10^{-4}\sqrt{m}$

position of bunch

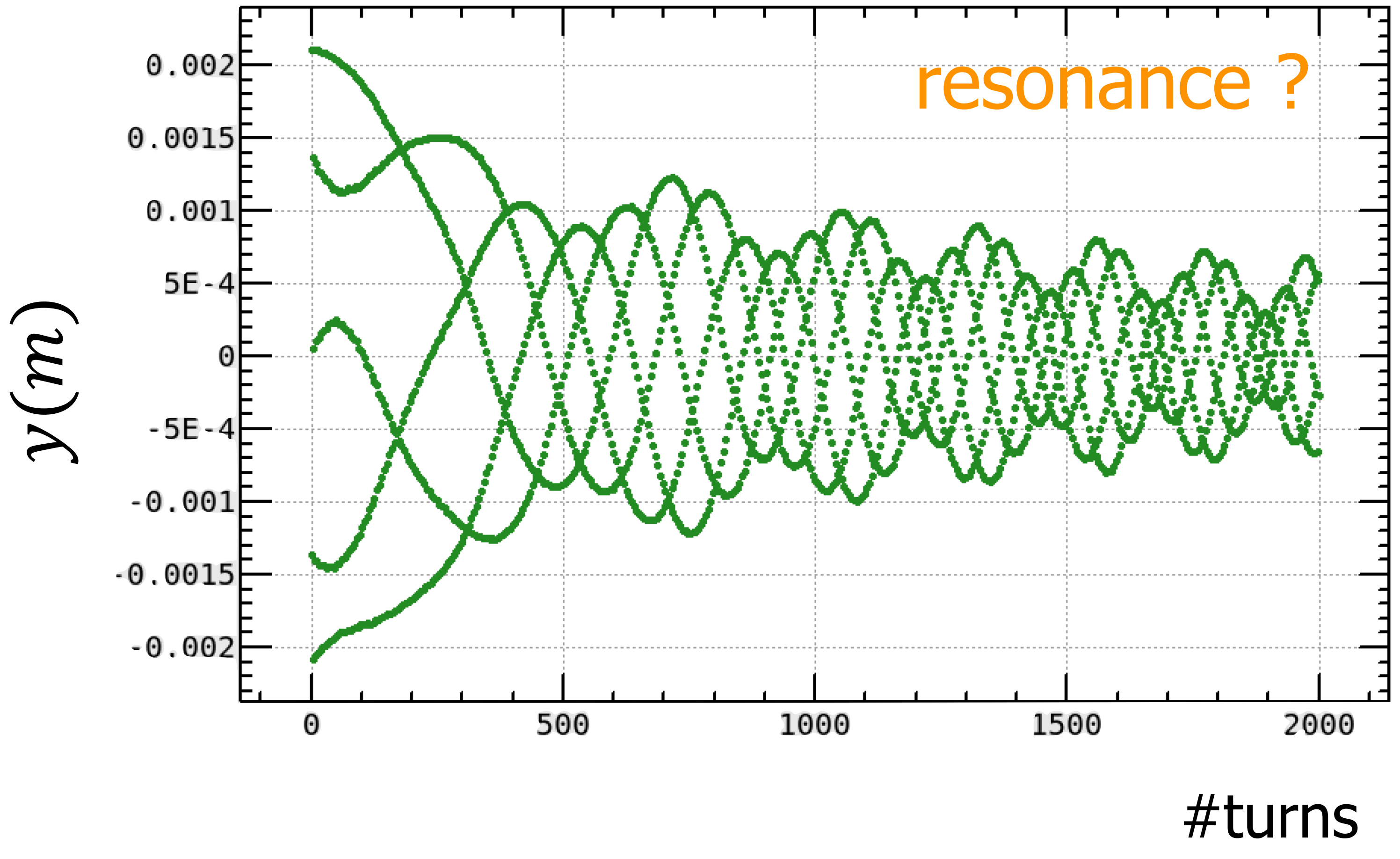
$\nu_y = 0.5925$

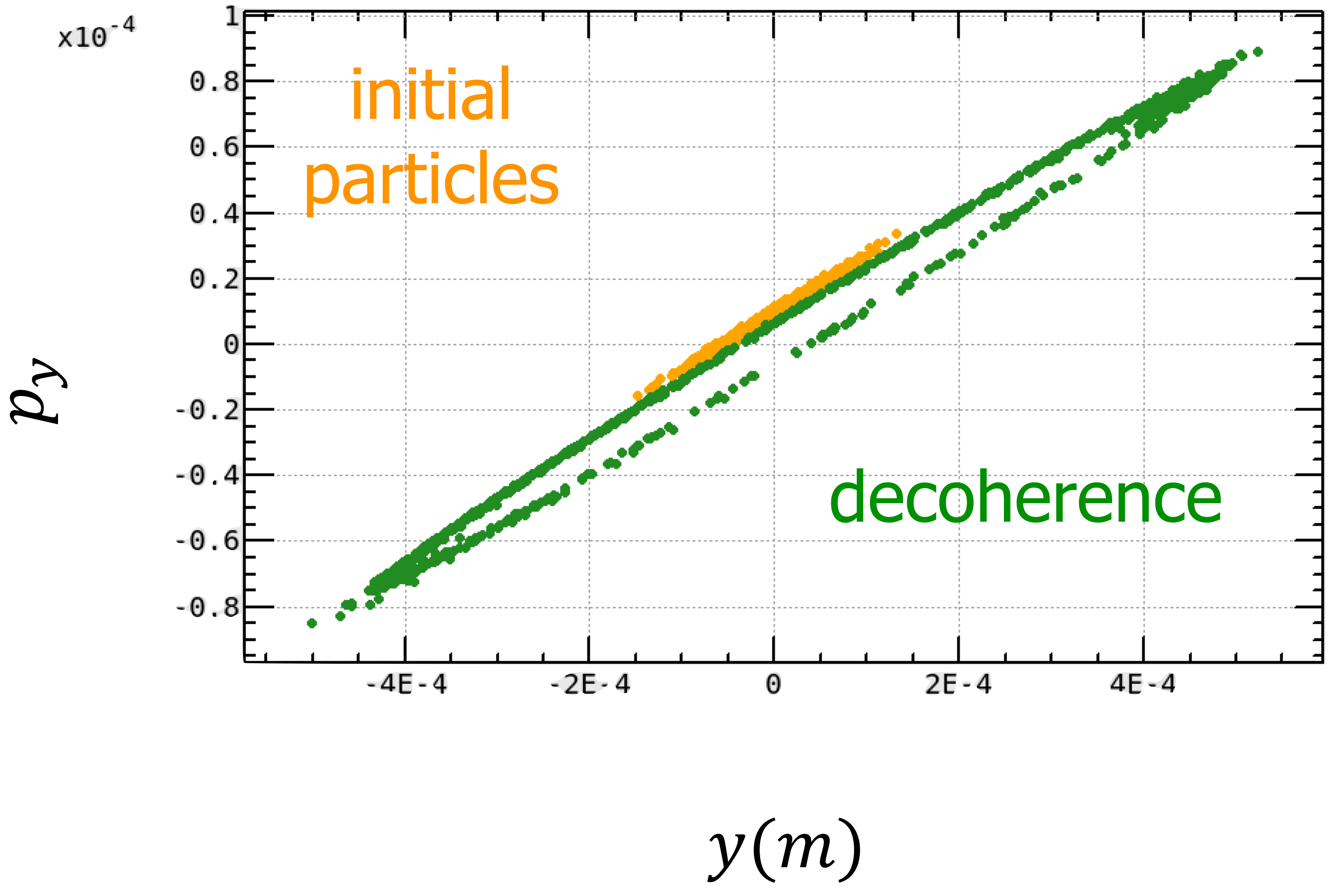


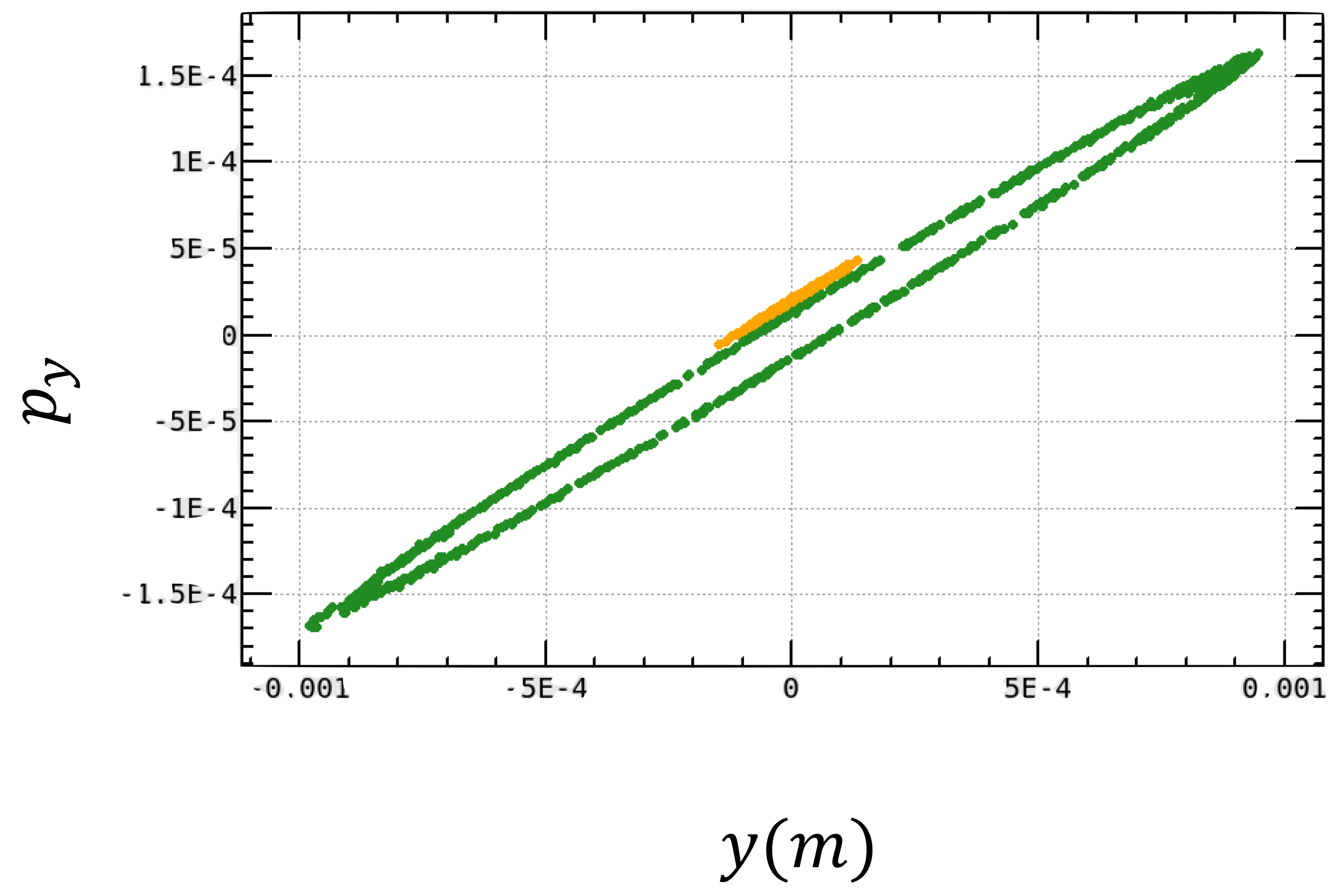
$\nu_y = 0.595$

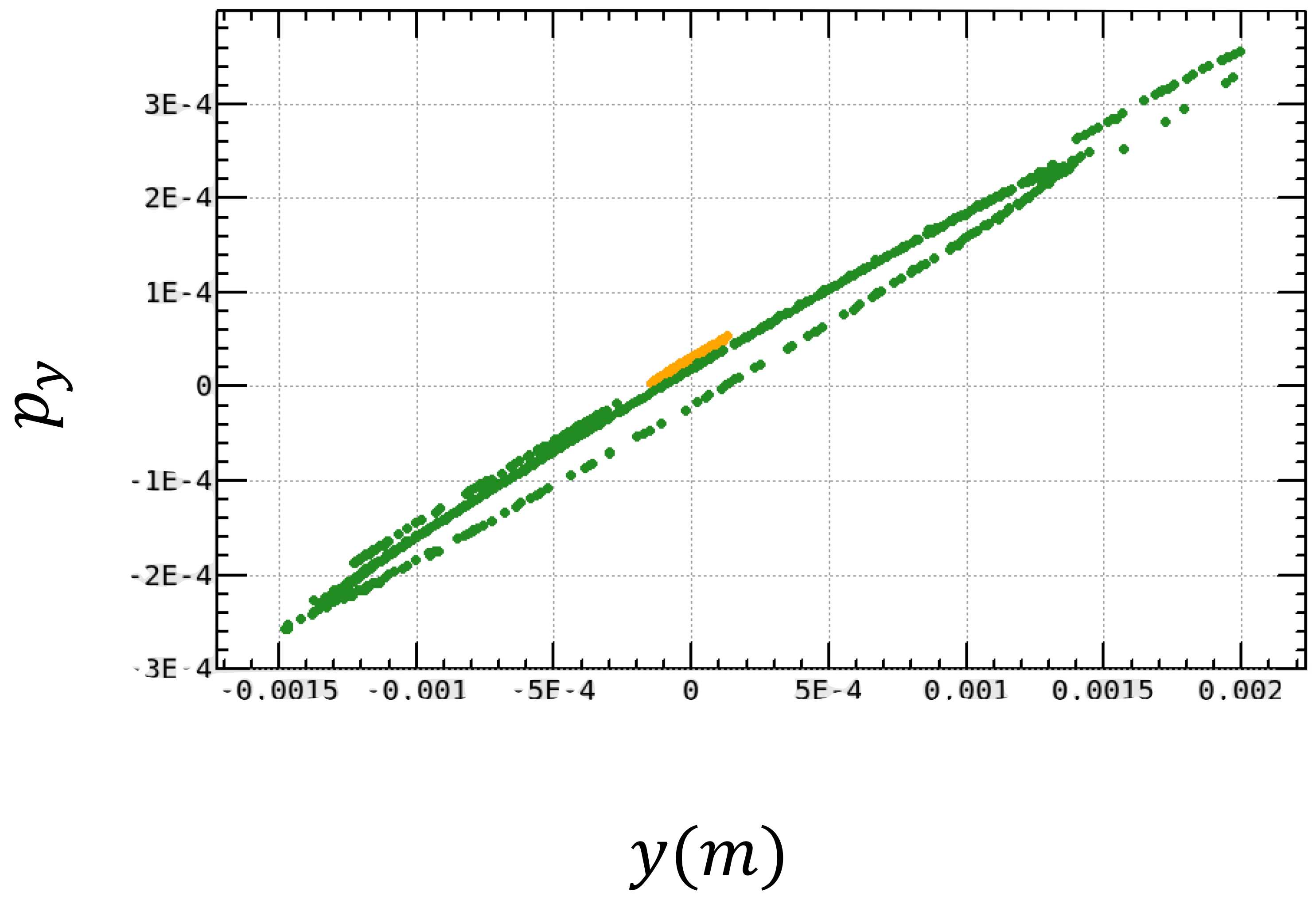


$\nu_y = 0.599$









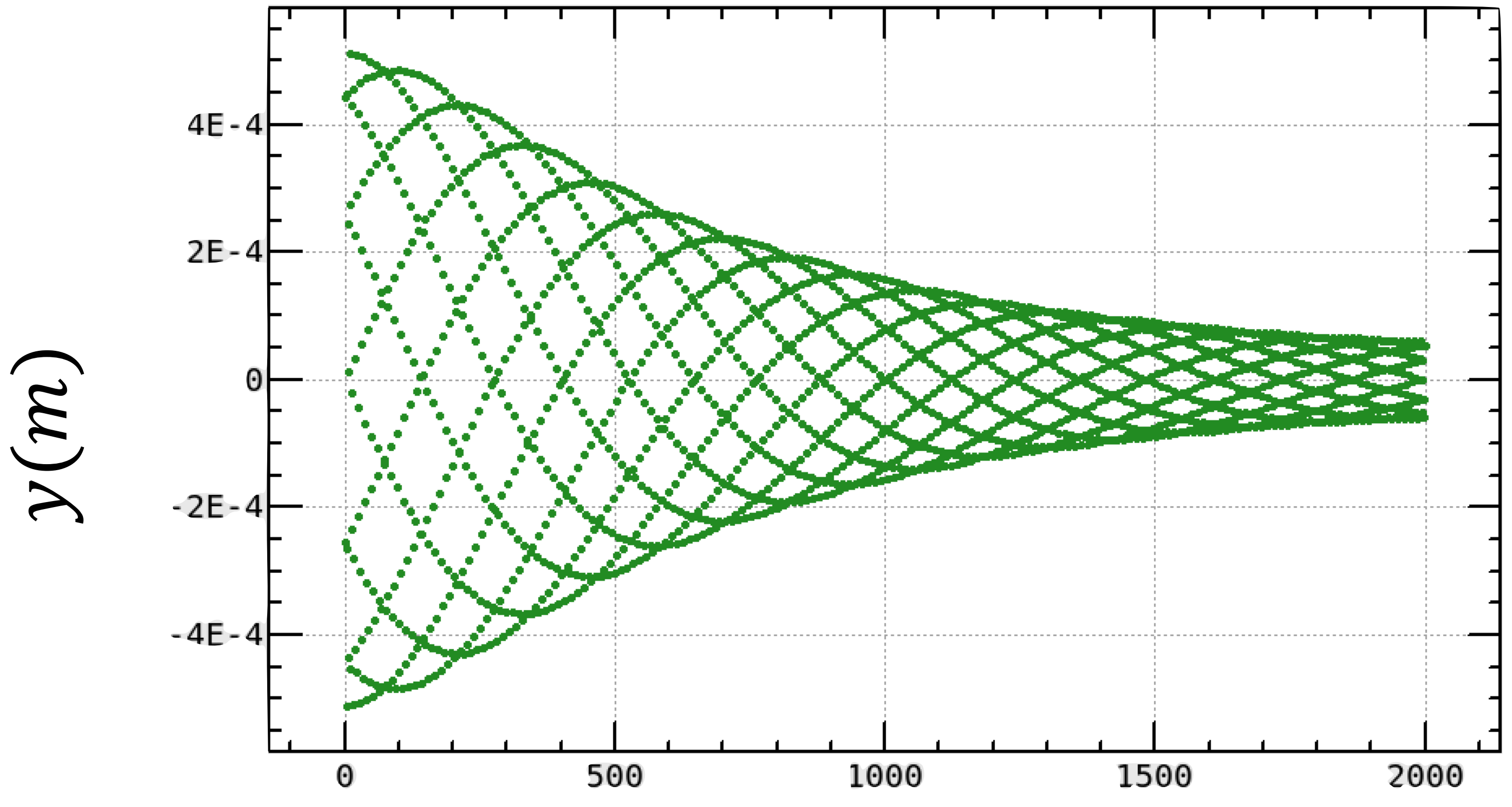
Multi-Particles Tracking in HER (CW 40 %)

$\beta_y^* = 1mm$

position of bunch

$\theta_y = 10\mu rad \quad \sqrt{2J_y} = 7.15 \times 10^{-5}\sqrt{m}$

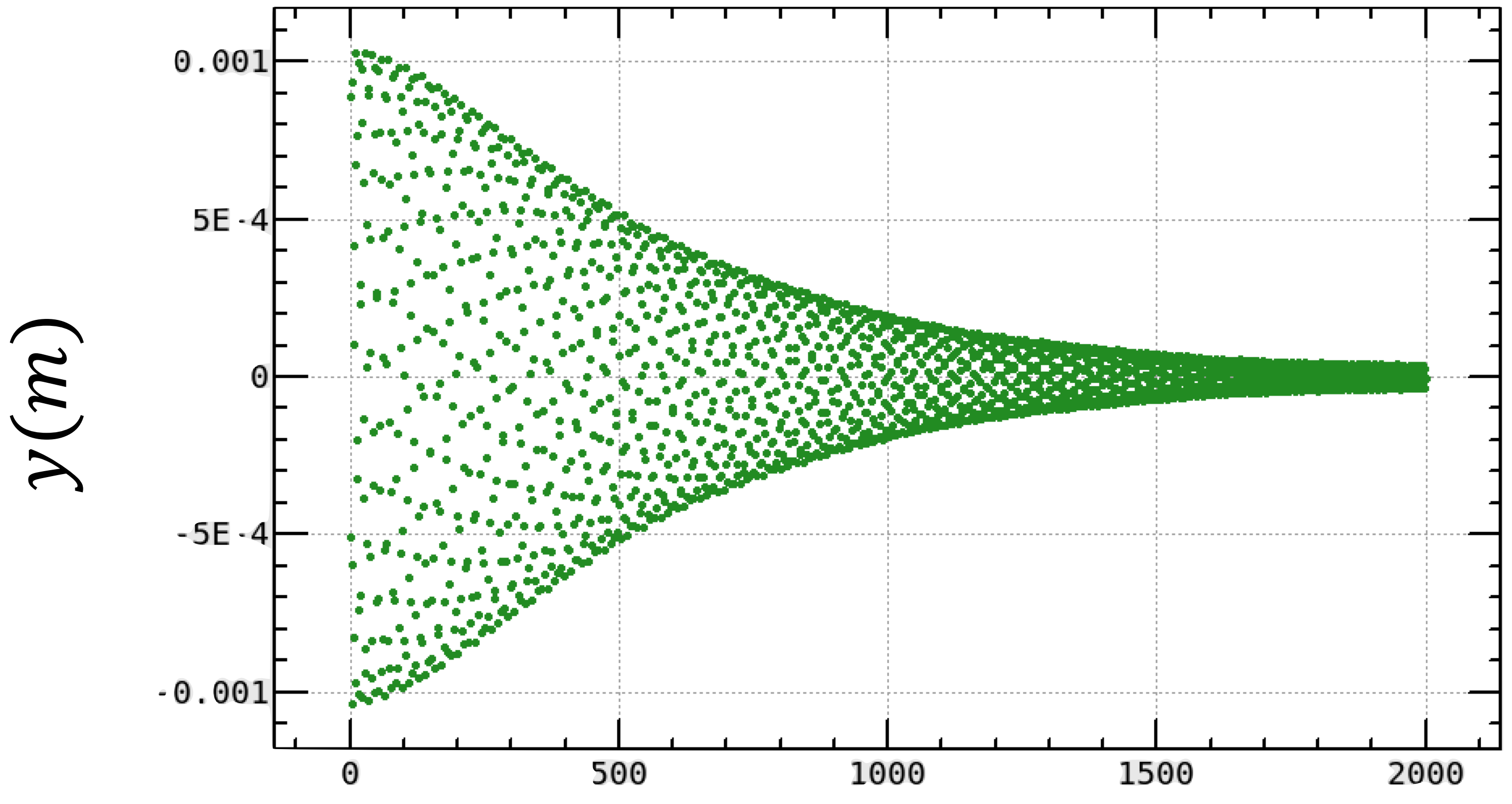
$\nu_y = 0.583$



#turns

$\theta_y = 20\mu rad \quad \sqrt{2J_y} = 1.43 \times 10^{-4}\sqrt{m}$

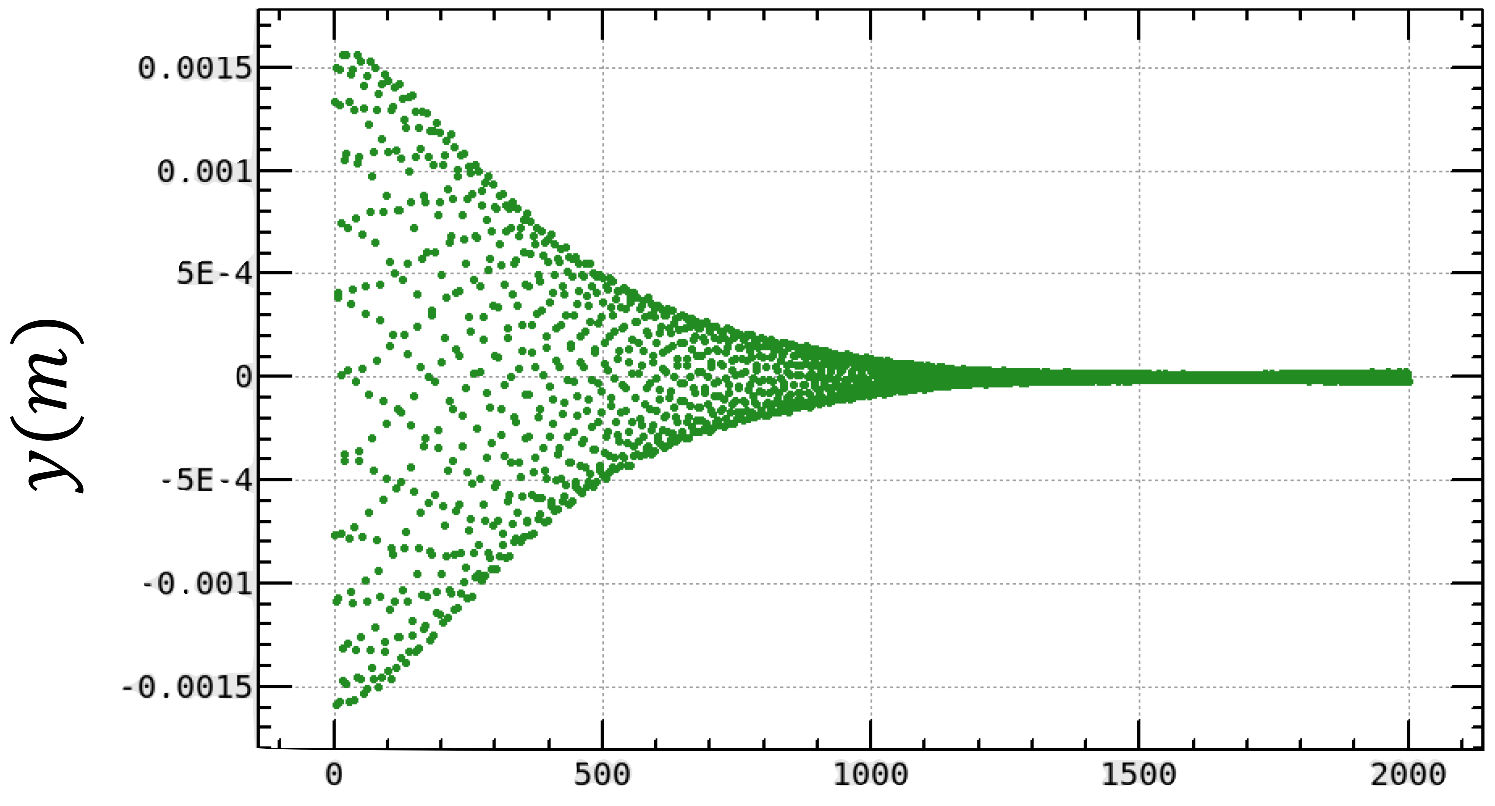
$\nu_y = 0.5815$



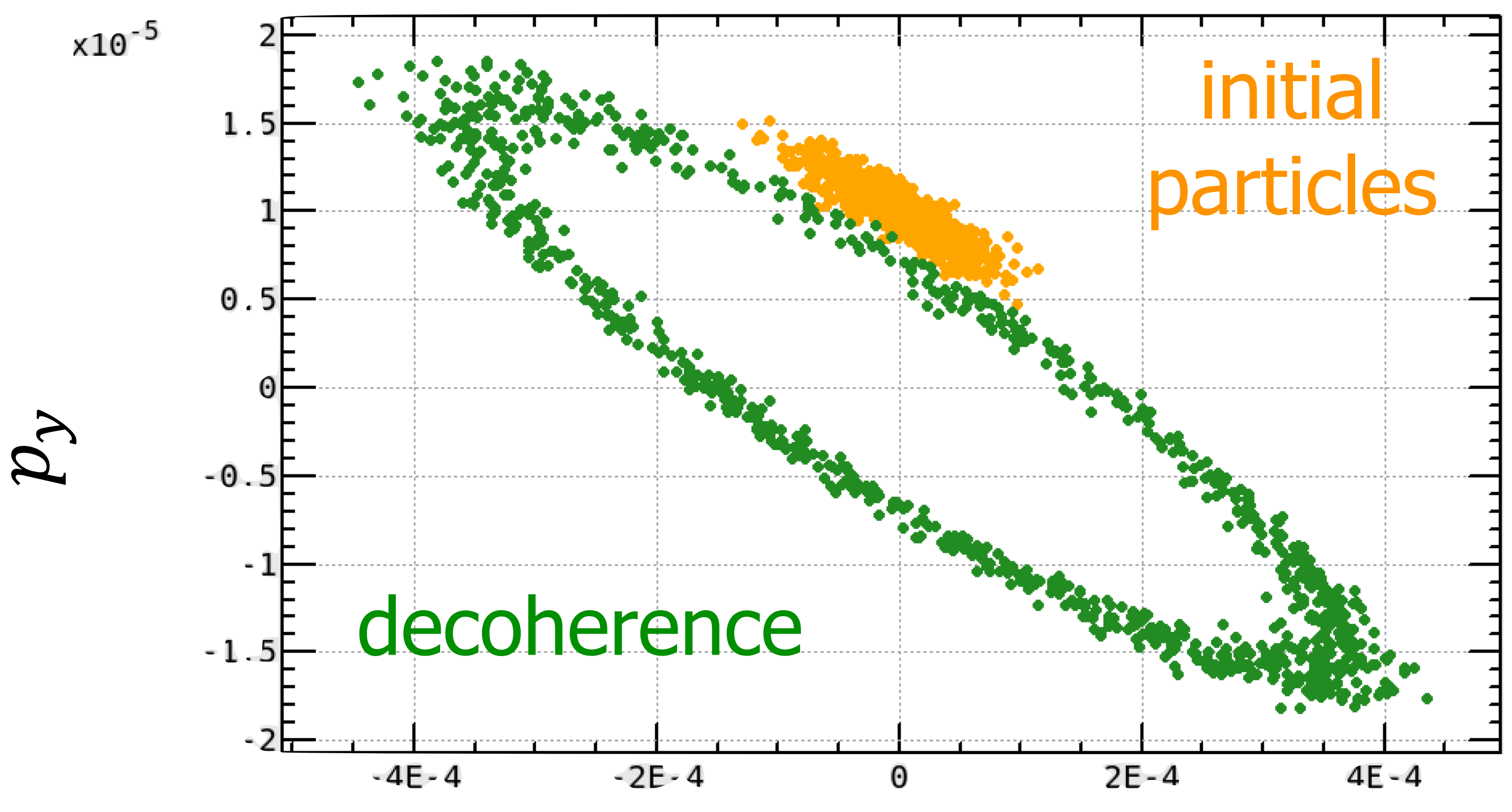
#turns

$\theta_y = 30\mu rad \quad \sqrt{2J_y} = 2.14 \times 10^{-4}\sqrt{m}$

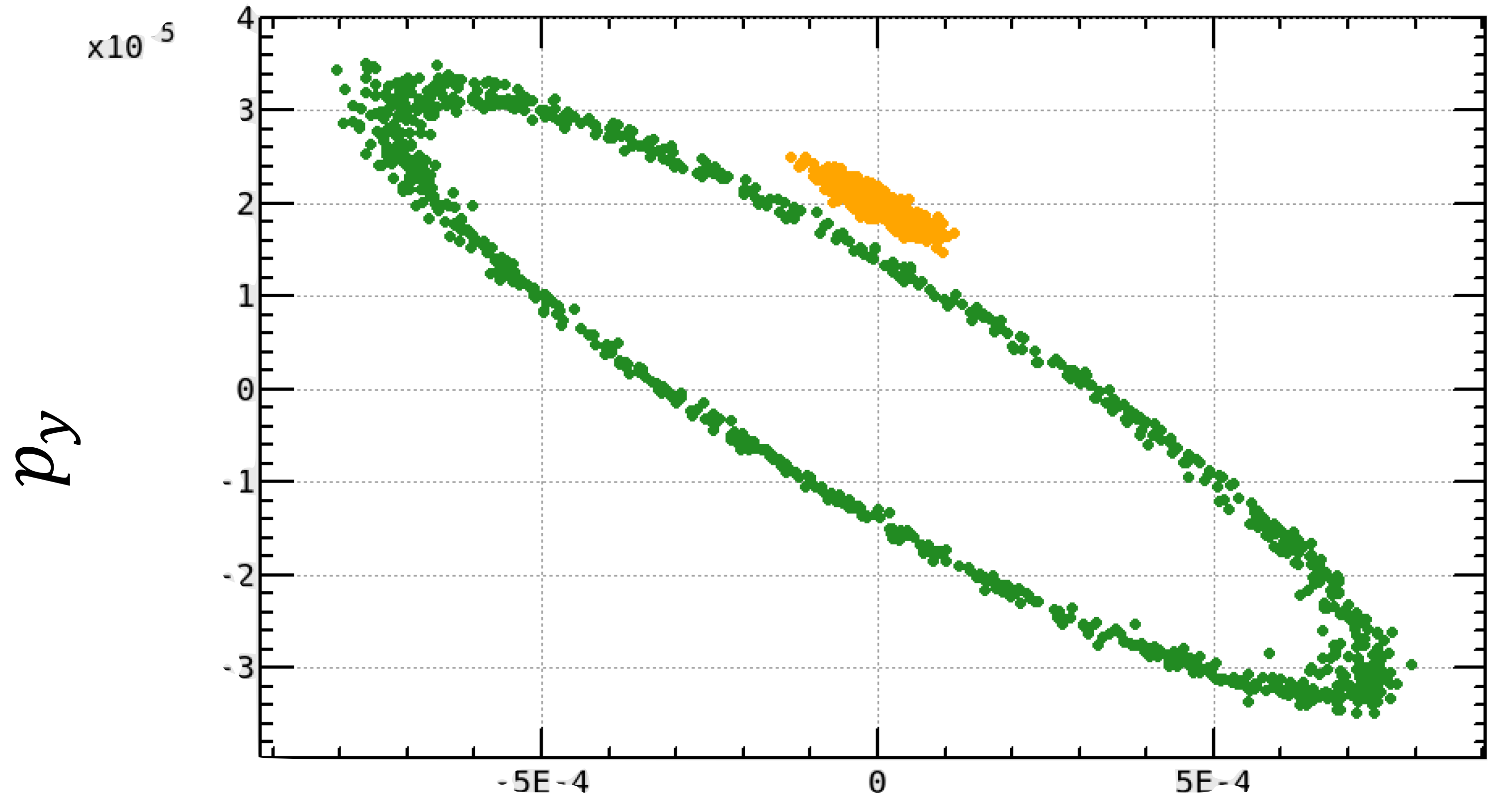
$\nu_y = 0.578$



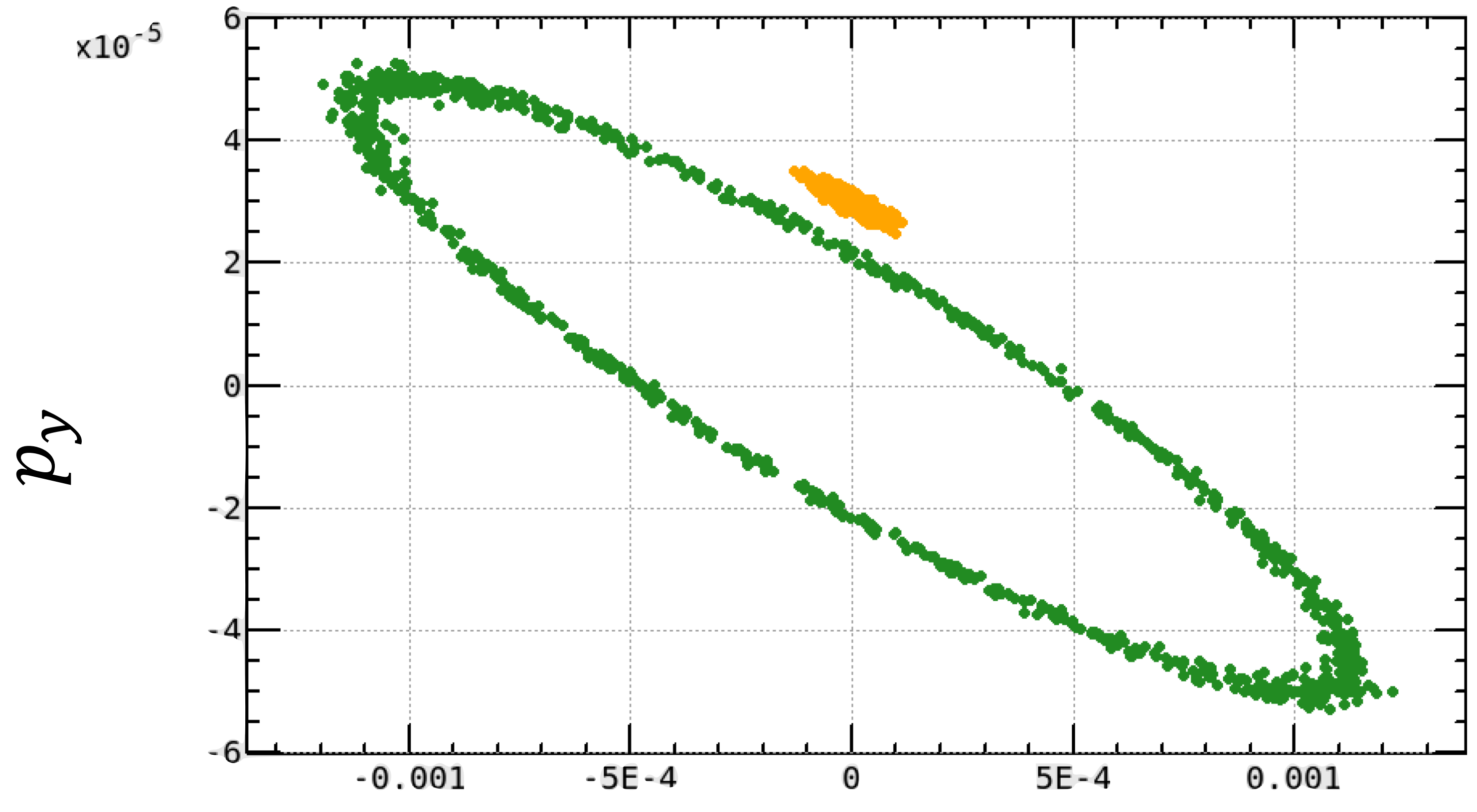
#turns



$y(m)$



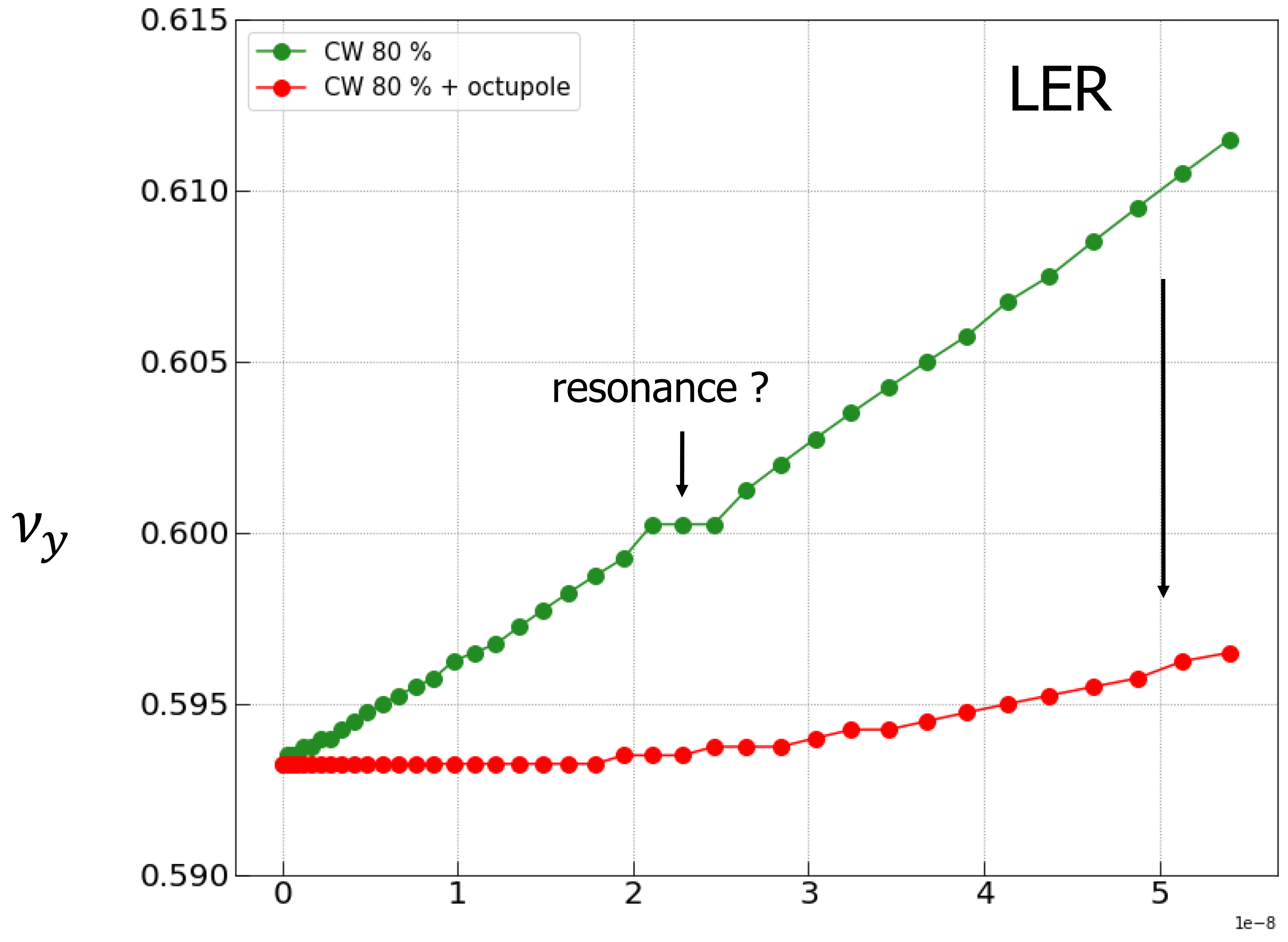
$y(m)$



$y(m)$

Realistic IR Model

$\beta_y^* = 1mm$ CW : 80 %



uncorrected

corrected

$J_y \times 10^{-8}(m)$

Correction of detuning:

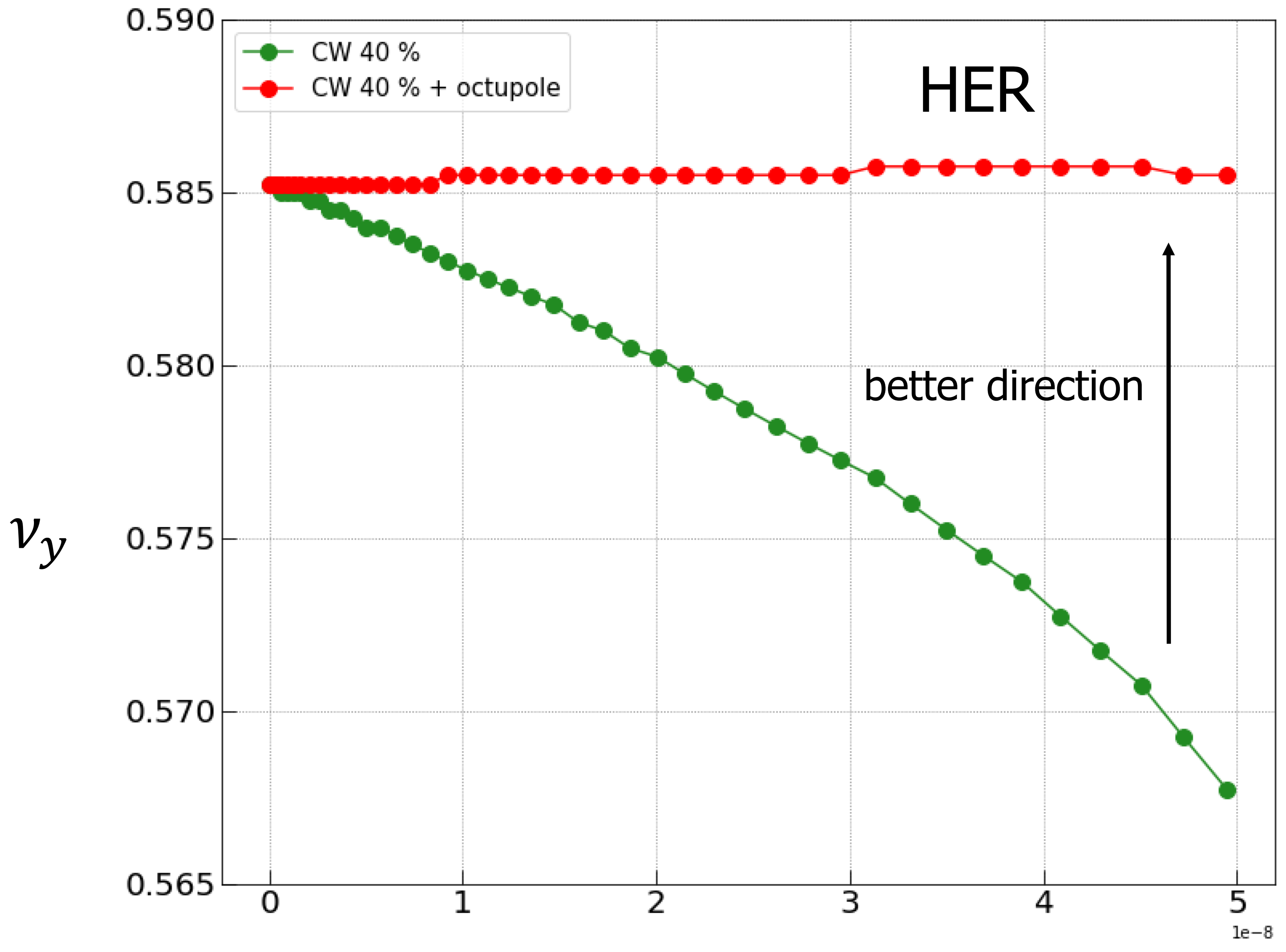
QC1LP: K3 = -12.5 (m^{-3})

QC1RP: K3 = -12.5 (m^{-3})

octupole corrector coil

The detuning of LER comes from QC1 fringe.

$\beta_y^* = 1mm$ CW : 40 %



corrected

uncorrected

$J_y \times 10^{-8}(m)$

Correction of detuning:

QC1LE: K3 = +4.0 (m^{-3})

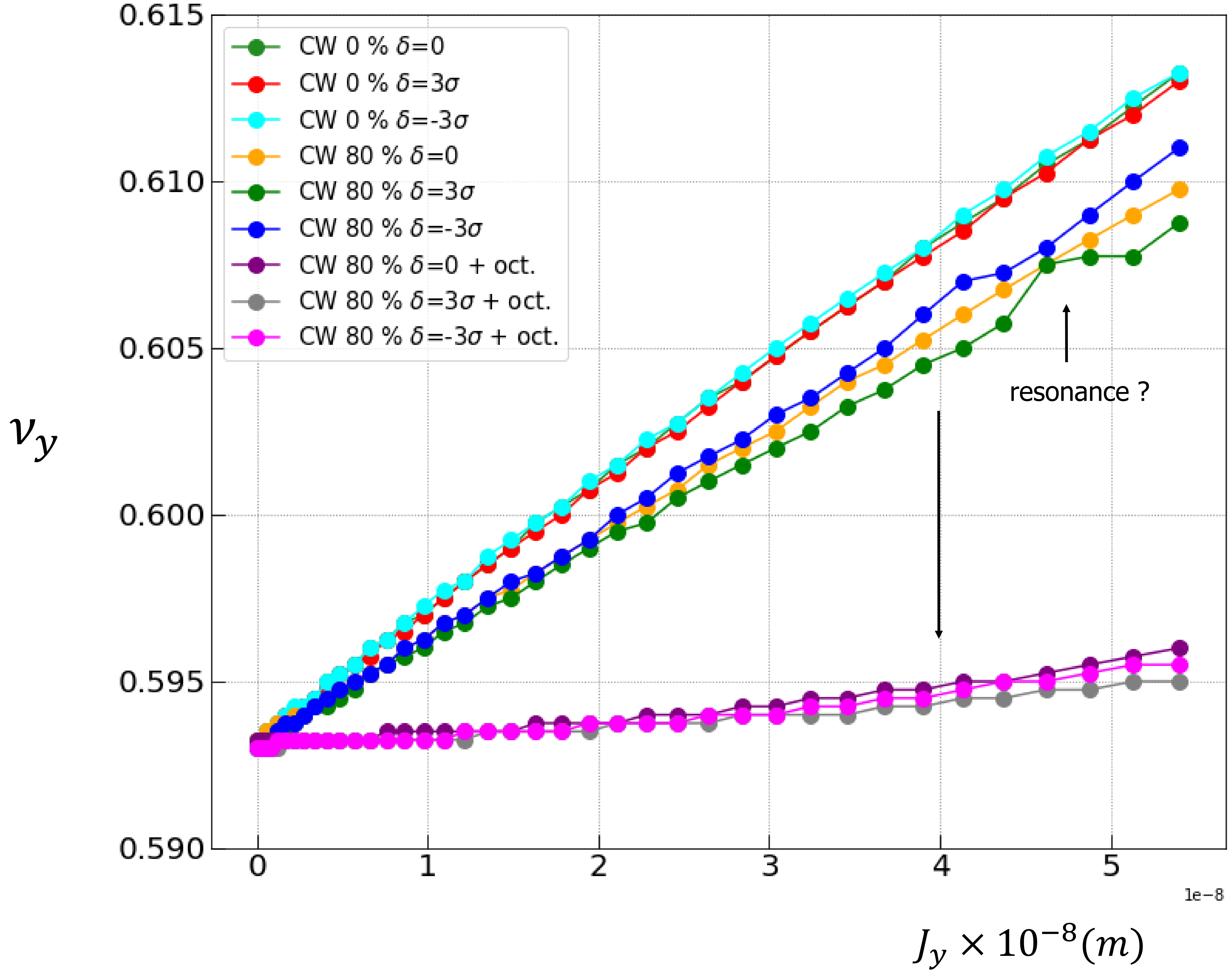
octupole corrector coil

The detuning of HER comes from residual octupole field, QC1 fringe and SLY thickness are almost cancelled each other.

Max. field of octupole corrector is 15 ($1/m^3$) for each QC1 and QC2.

Correction of Amplitude Detuning (Simple IR Model)

$\beta_y^* = 1mm$ LER



CW 0 % The momentum dependence is small.

CW 80 %

The momentum dependence is larger than CW 0 %.

Off-momentum amplitude matching is necessary ?

CW 80 % + correction of detuning with octupoles

nonlinear vs nonlinear

Comparison of Dynamic Aperture (Simple IR Model)

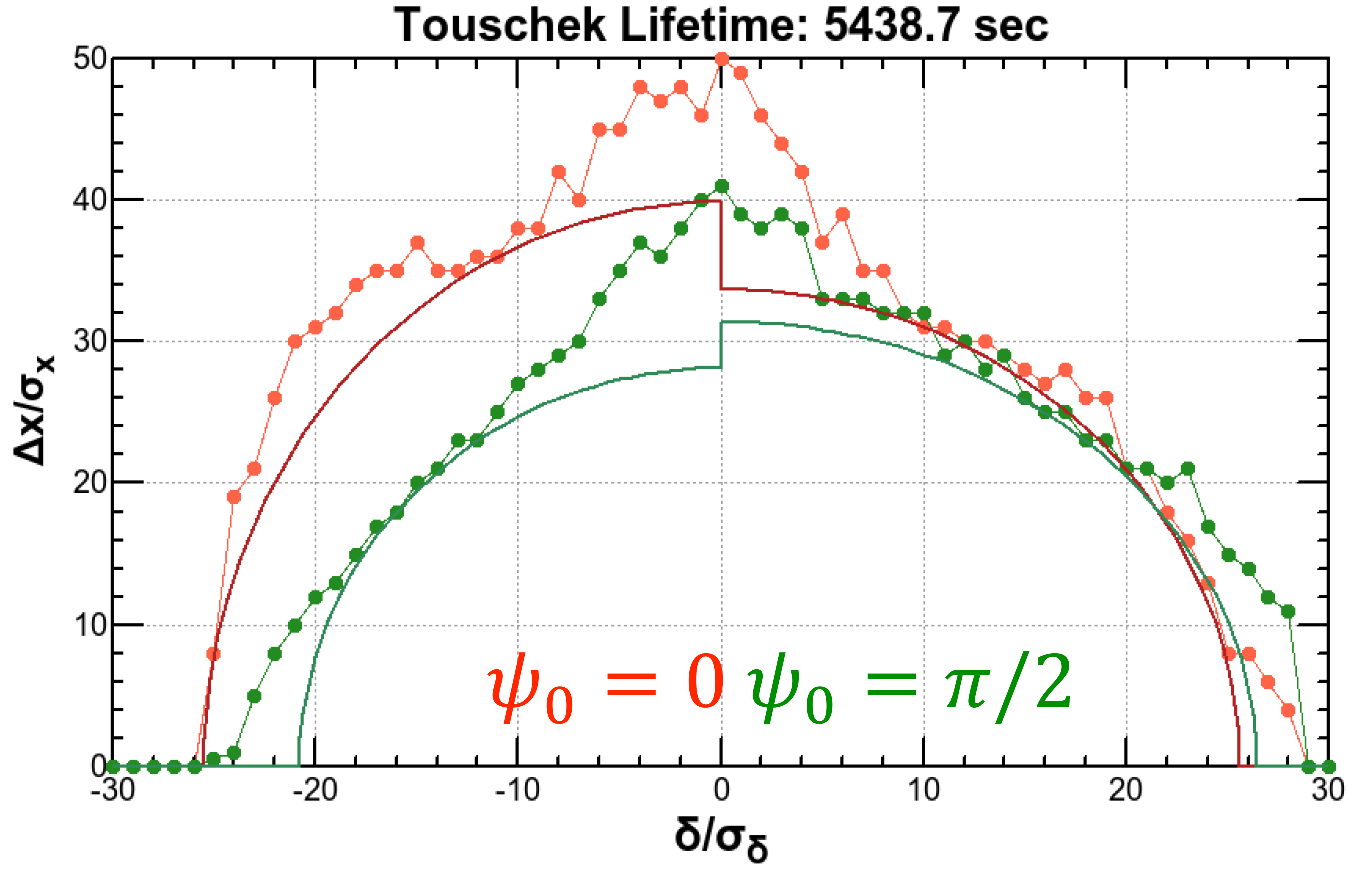
LER $\beta_y^* = 1mm$ 1% coupling, 0.62 mA/bunch for lifetime estimation

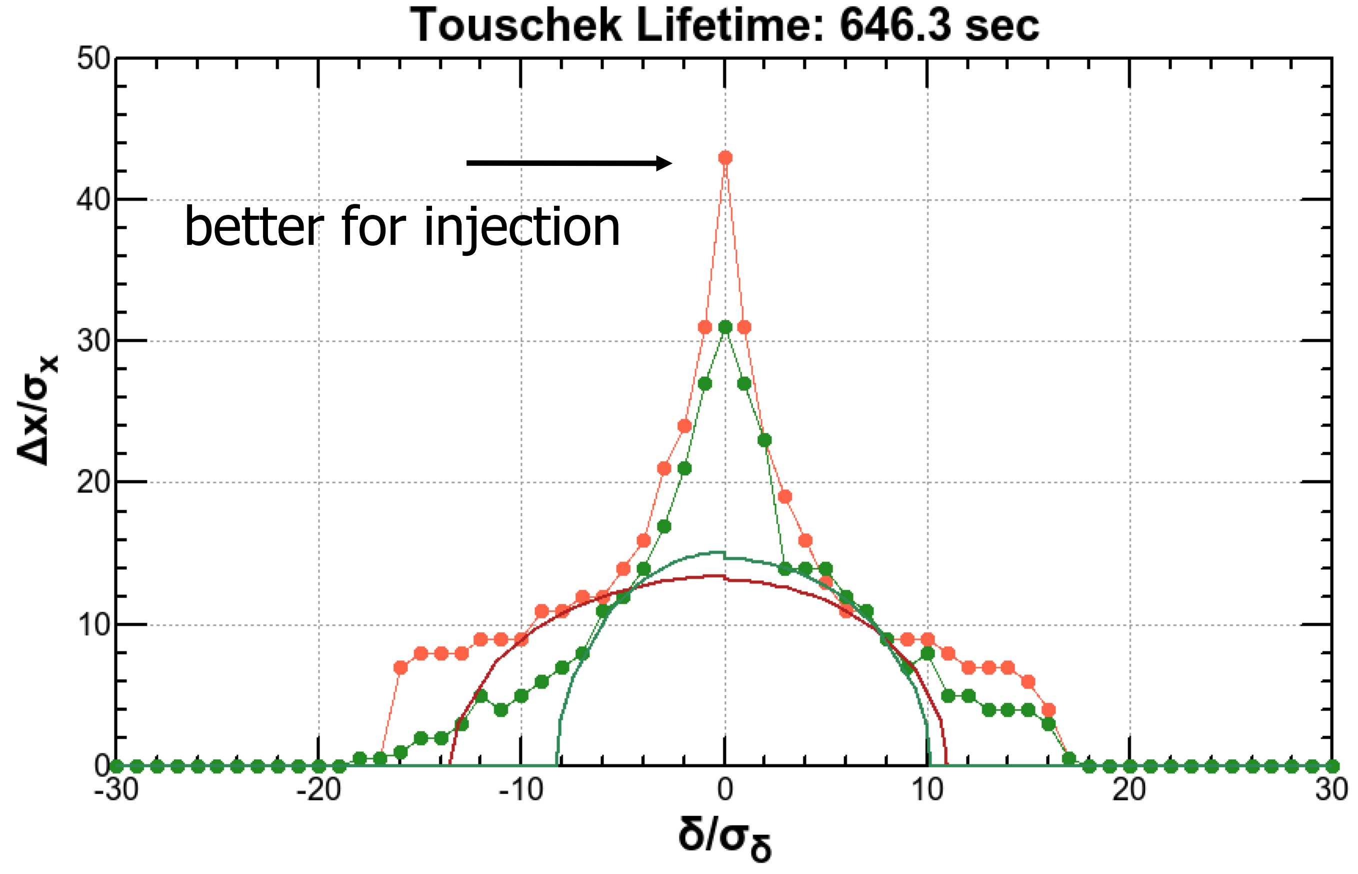
CW 0 %

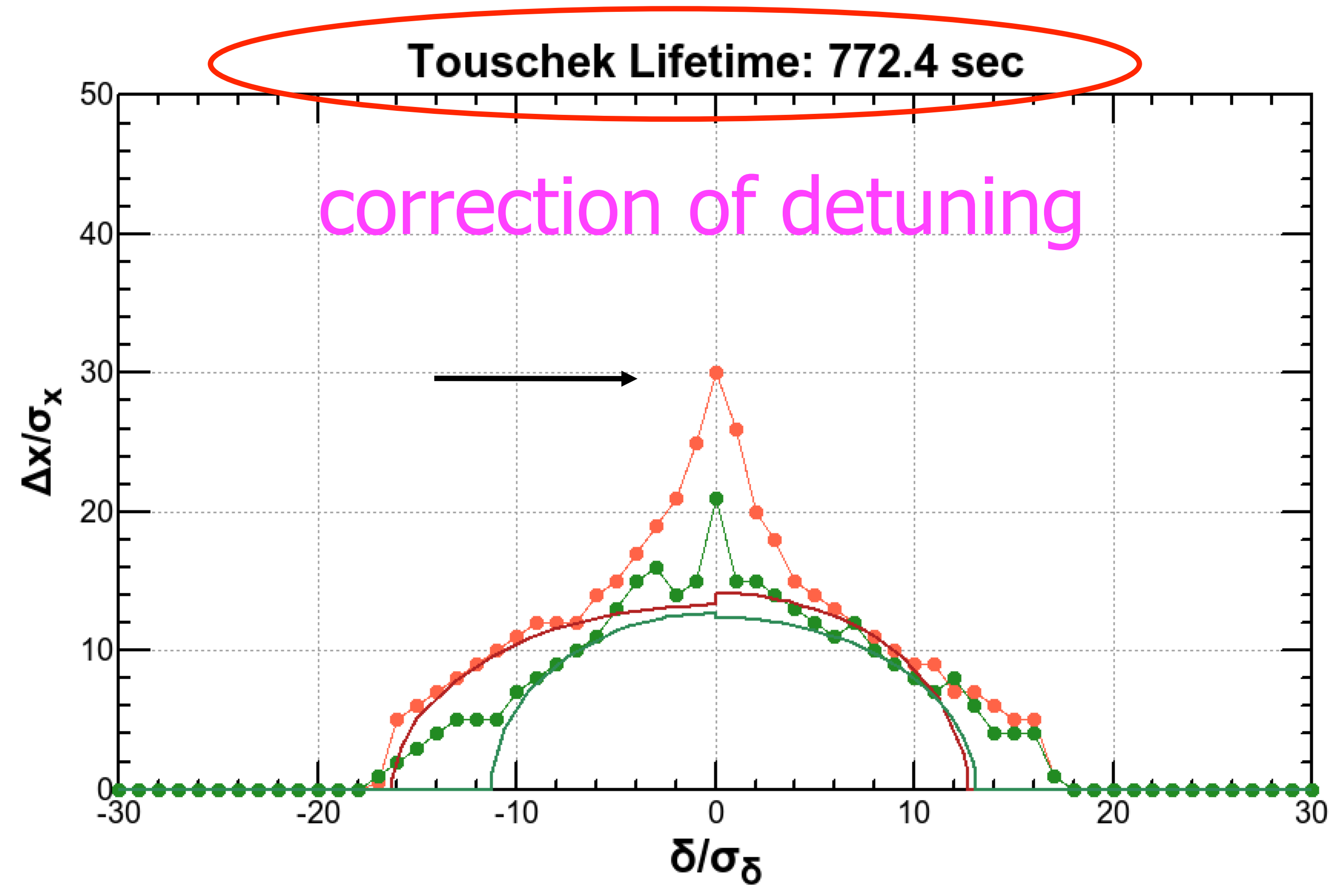
CW 80 %

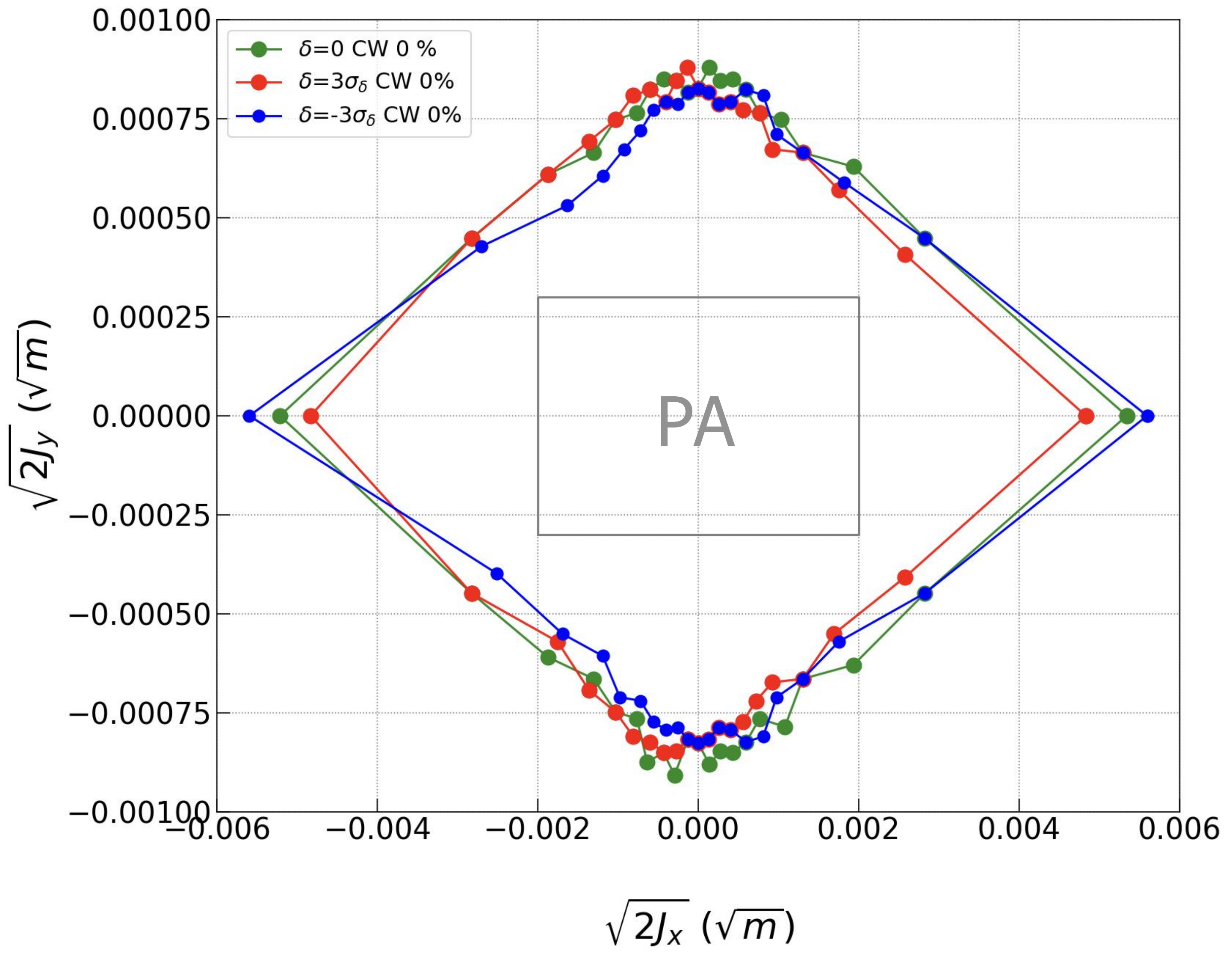
CW 80 %

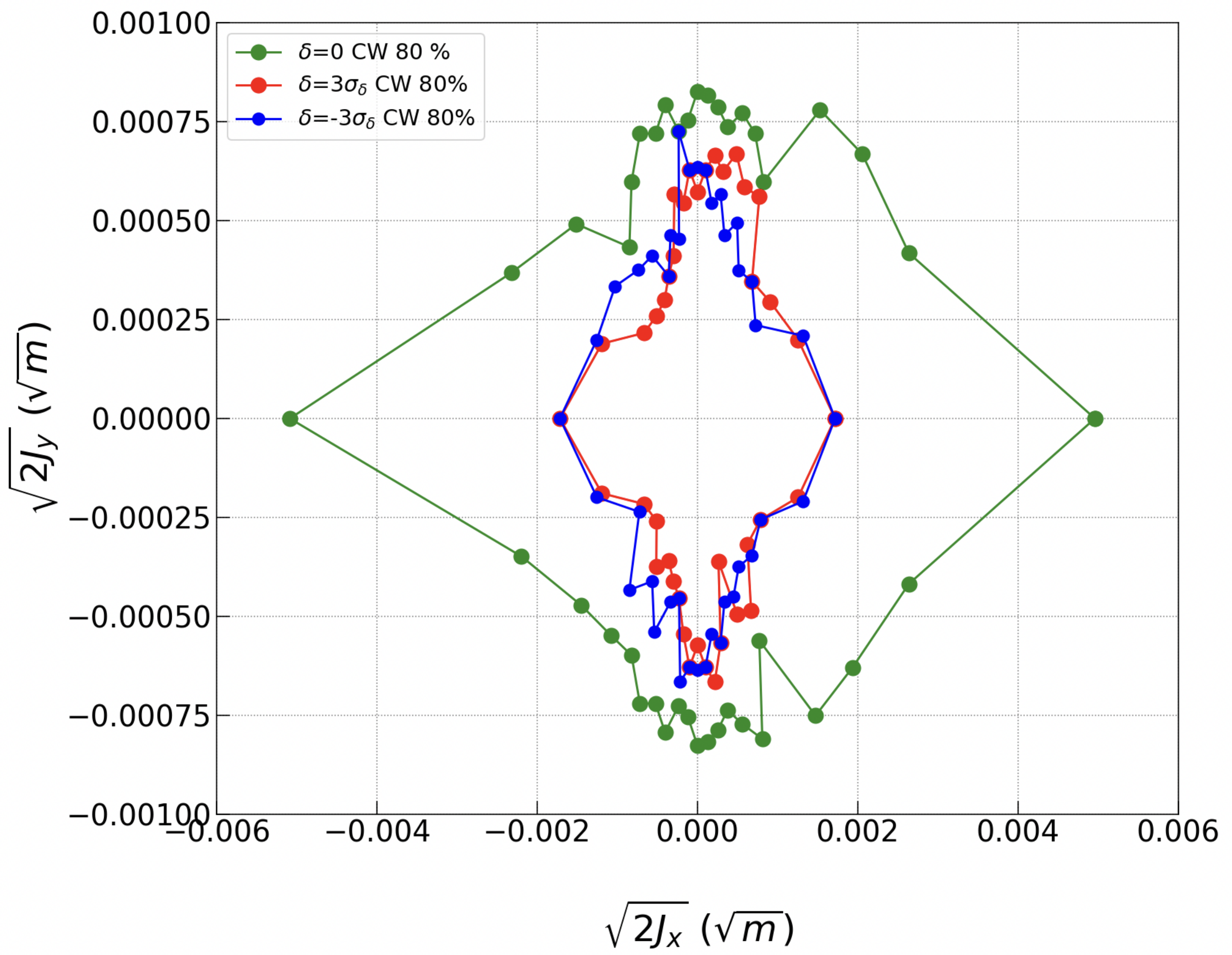
octupole + sextupole re-optimization

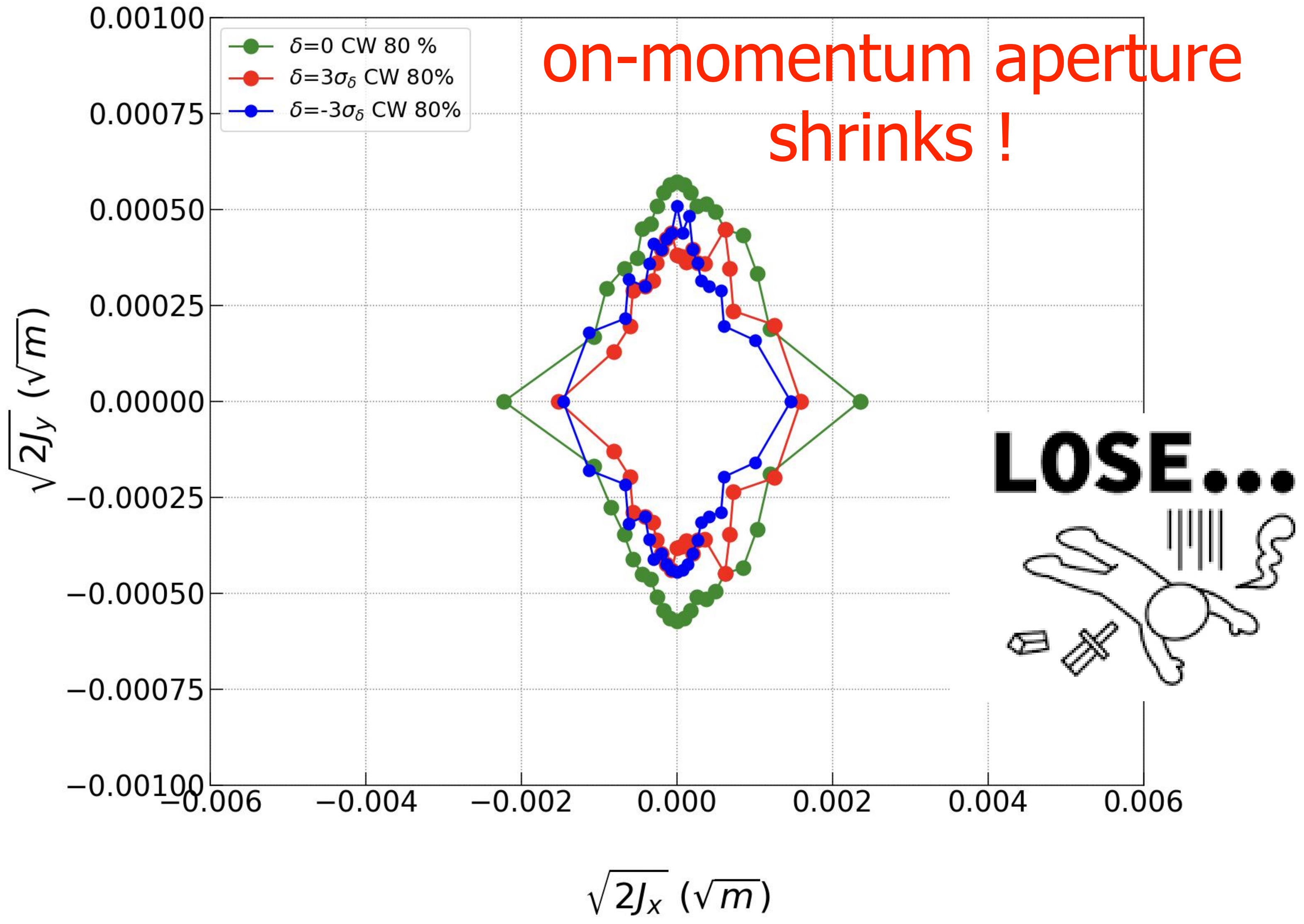








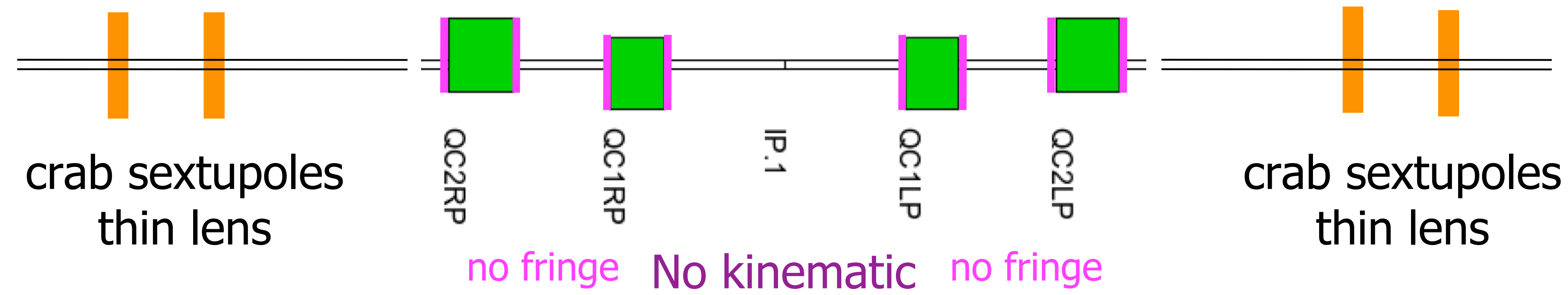




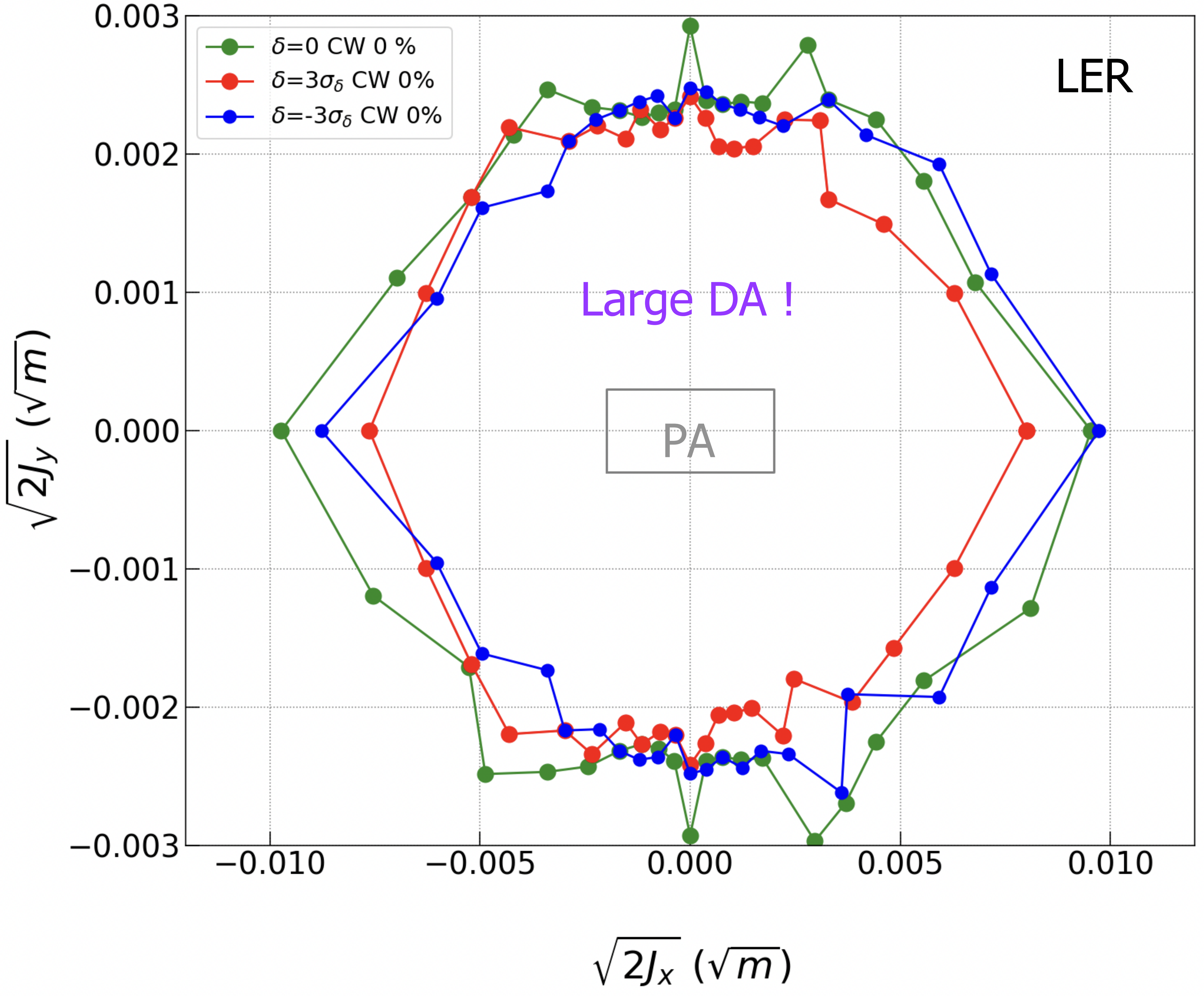
Comparison of Dynamic Aperture (Simple+Linearized IR Model)

Case 1: Kinematic term, QC1 nonlinear fringe, QC2 nonlinear fringe, Crab sextupole thickness are turned OFF in the LER.

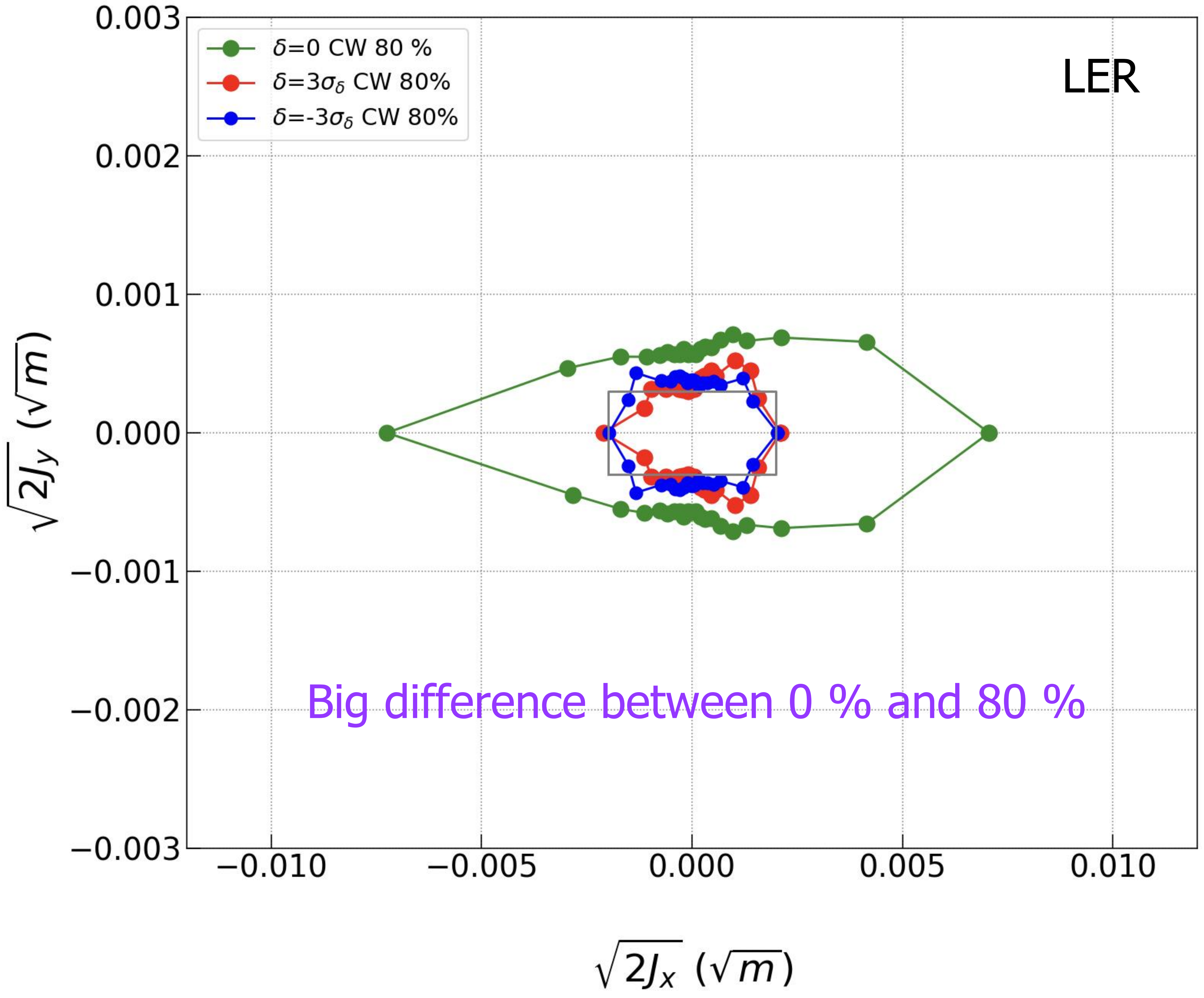
Simple IR model



CW 0 %



CW 80 %



Possible Location of Vertical Kicker

Motivation:

Dynamic and physical aperture is one of the most important issue.
Evaluation of both horizontal and vertical aperture is necessary to optimize sextupole magnets.
Collimator aperture can be calibrated.

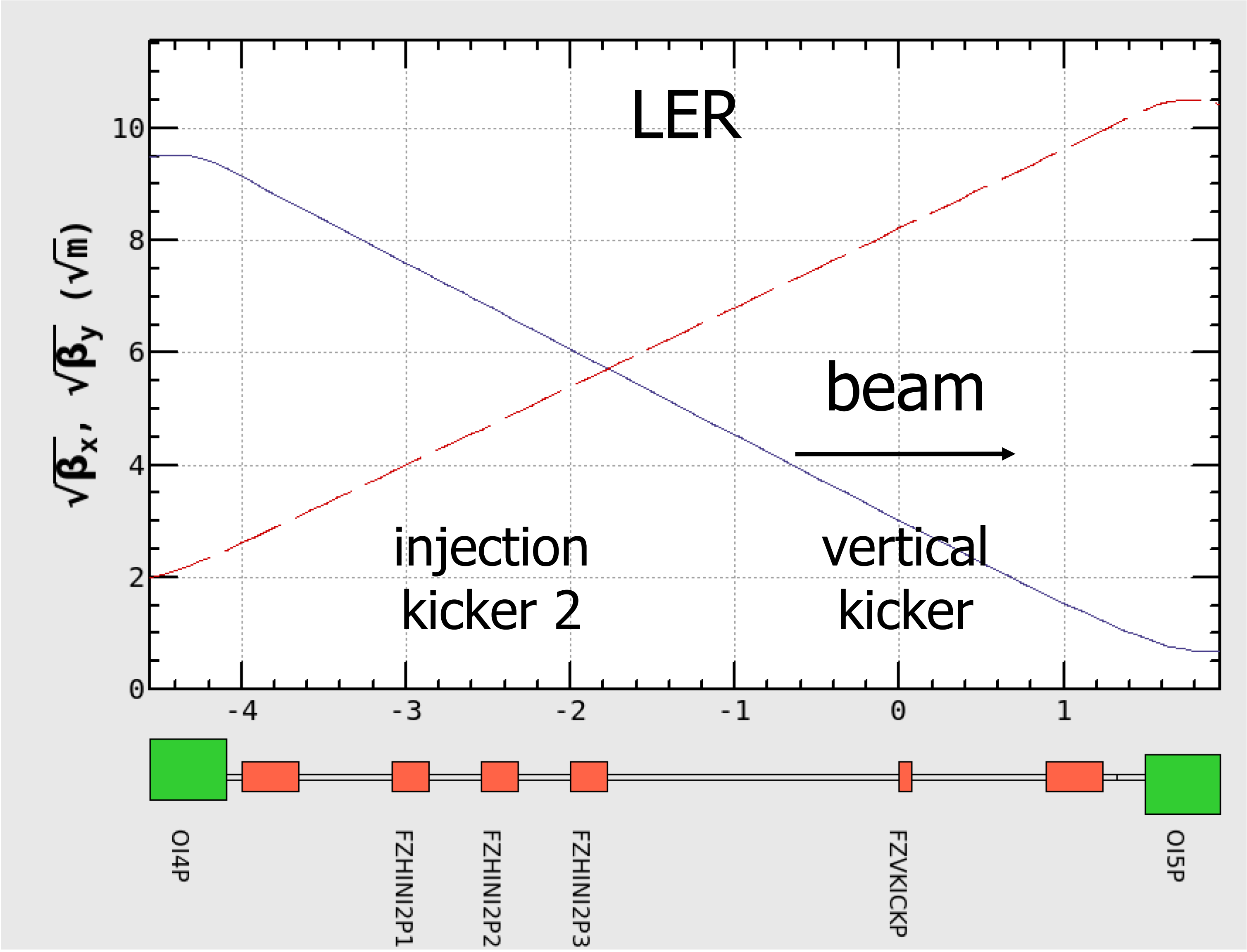
Nonlinear effects should be also evaluated.

Method:

Injection and vertical kickers with TBT BPMs, DCCT (to measure beam loss)

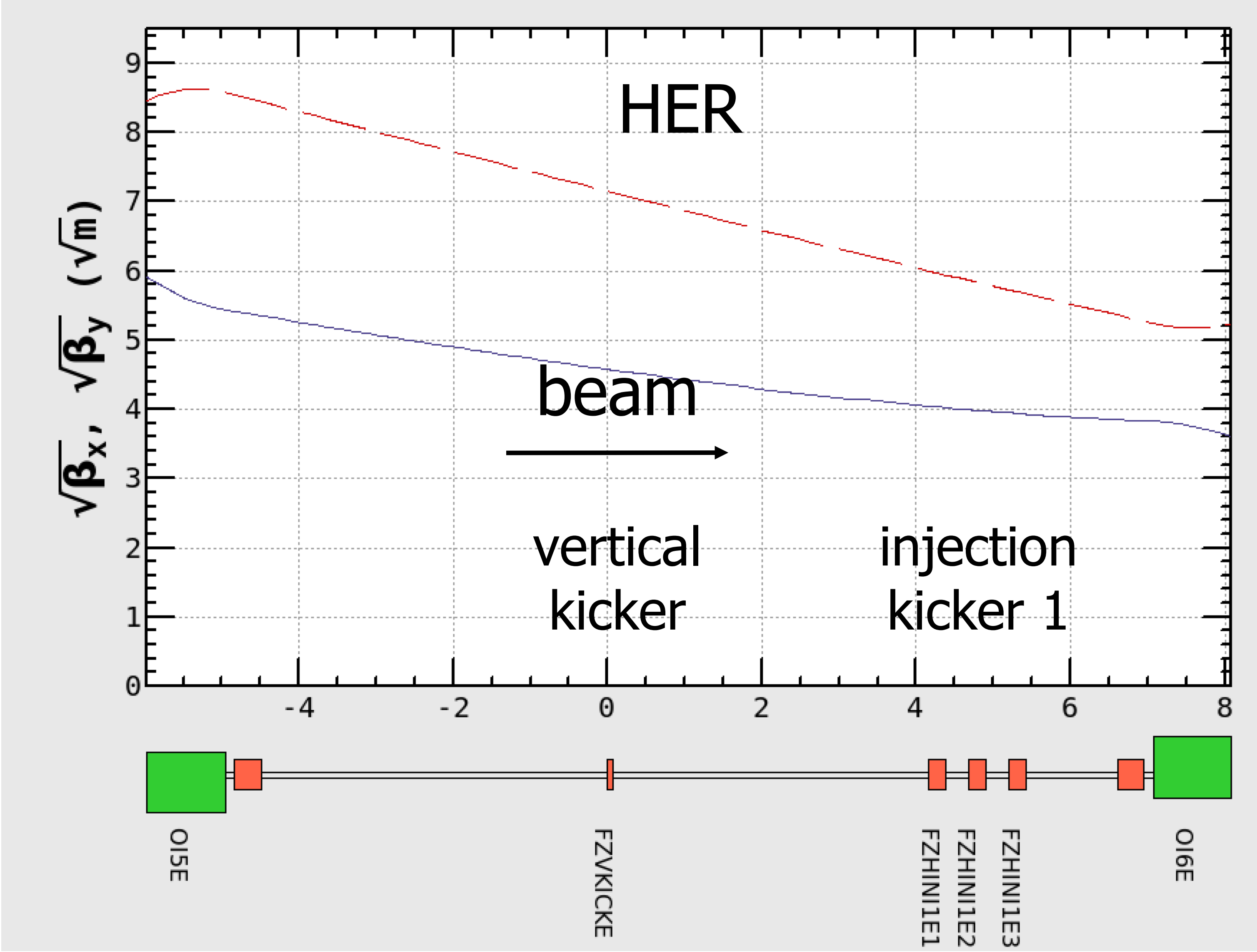
No vertical kicker so far, this is just a plan.
But the ceramic chamber exists.

We also have to prepare power supplies.



$\beta_y = 67.5m$

LER



$\beta_y = 51.1m$

HER

Summary

- Lattice nonlinearity is strong for both rings.
  - Amplitude detuning (vertical) is positive in LER, negative in HER. (Realistic IR Model)
  - QC1 nonlinear fringe is dominant in the LER.
  - Thickness of crab sextupole compensates with QC1 fringe in the HER. Residual octupole field makes negative detuning.
  - TBT BPM data with a vertical and/or horizontal kicker is useful to evaluate nonlinear effects and amplitude detuning.
    - J. Keintzel, the presentation with injection kickers is found in https://kds.kek.jp/event/45852/.
- Amplitude detuning (vertical) can be corrected by octuple correctors in the QC1 and QC2.
  - Dynamic aperture is not improved in the LER even though the vertical detuning is corrected, so far.
- Vertical kicker can be used to survey vertical aperture of the ring. (Dynamic and Physical Aperture)
  - In the horizontal direction, injection kickers (making unbalance of 2 kickers) can be used to measure DA precisely.
  - If both horizontal and vertical kickers can be used simultaneously, DA in the x-y plane can be surveyed.
  - This system is necessary for sextupole optimization to make Touschek lifetime longer. (select better sextupole setting)
  - Off-momentum aperture can be also evaluated with RF frequency shift.

Appendix

COD-BPM Measurement and TBT-BPM Measurement

J. Keintzel, "Turn-by-Turn Optics Measurements in SuperKEKB"
SuperKEKB ITF Optics Tuning Meeting, March 14, 2022

Comparison

Parameter	Closed Orbit Distortion	Turn-by-Turn	
		Injection Kicker	Phase Lock Loop
BPMs in HER	466	68	68
BPMs in LER	444	70	70
Hor. optics measurement	yes	yes	yes
Ver. optics measurement	yes	no	yes
RDTs measurement	no	some	yes
Calibration independent	no	yes	yes
Status for measurements	stable	stable	being explored
Trigger to record data	yes	yes	no
Time for measurement	≈20 mins	≈2 mins	≈2 mins

More TbT BPMs possible? → It depends on budget. The electric circuit is old, so can we get FPGA ?.

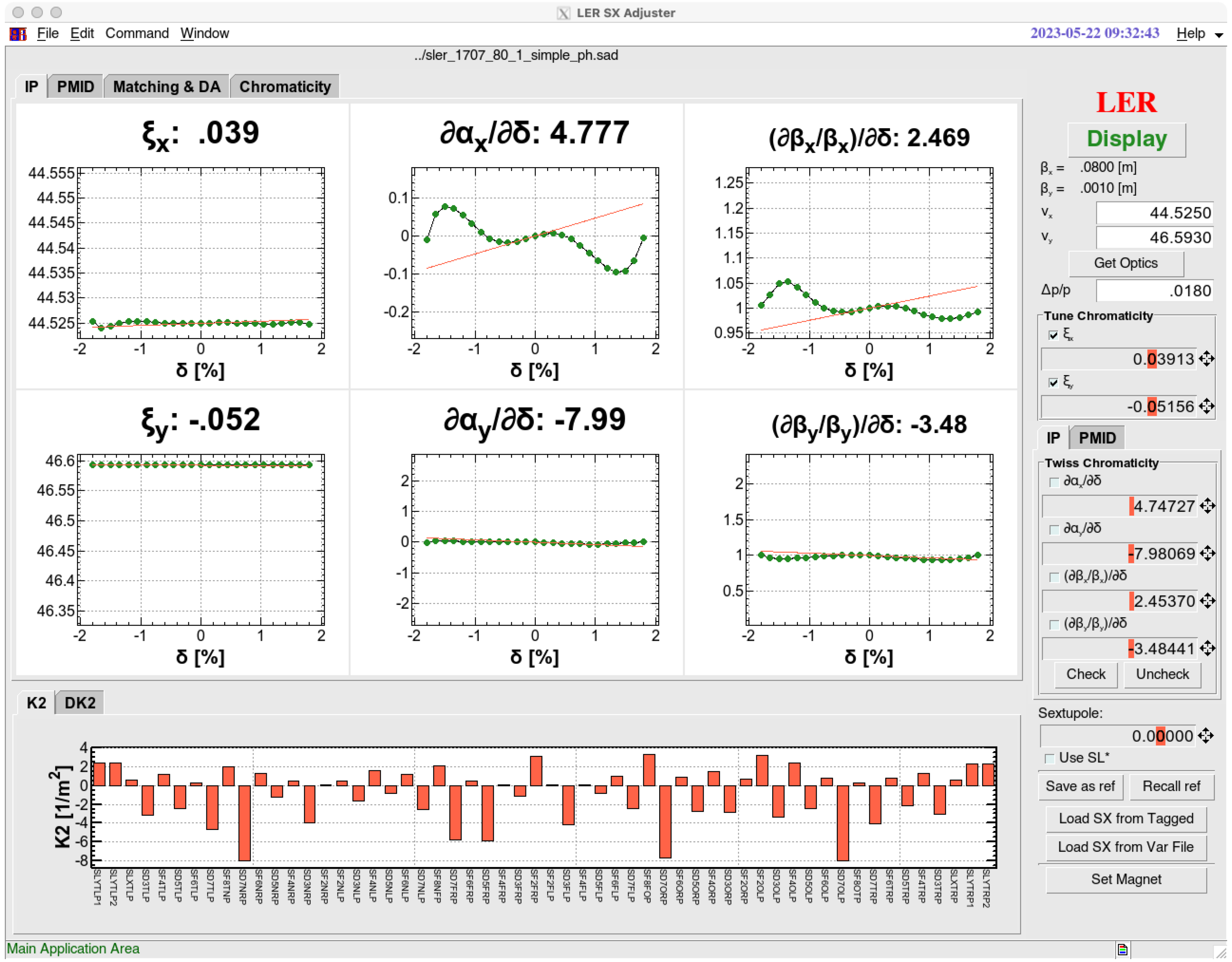
TbT typically faster

The optics correction uses COD based measurements.

Chromaticity in LER (Simple IR Model)

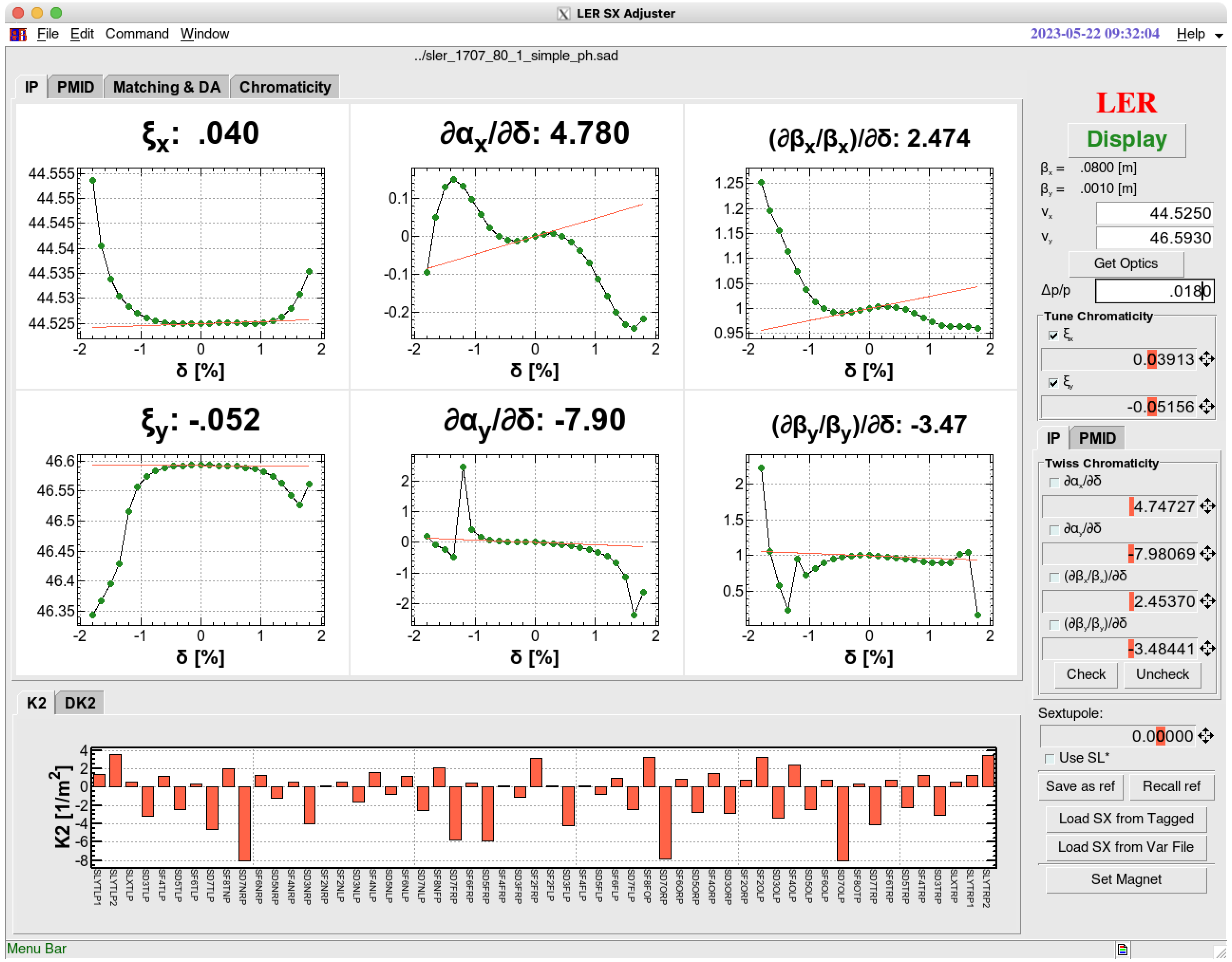
CW 0 %

tune chromaticity | alpha chromaticity | beta chromaticity



CW 80 %

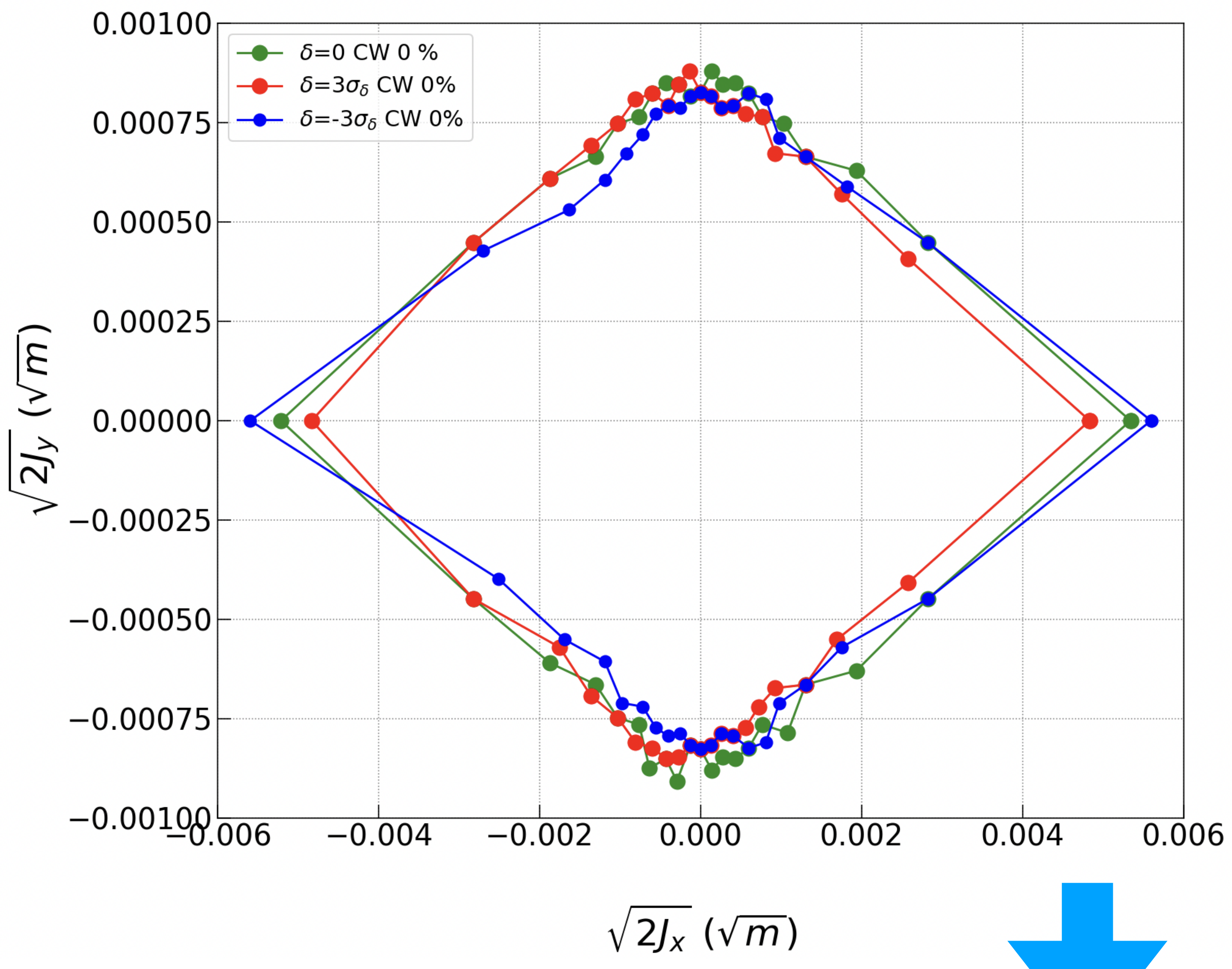
tune chromaticity | alpha chromaticity | beta chromaticity



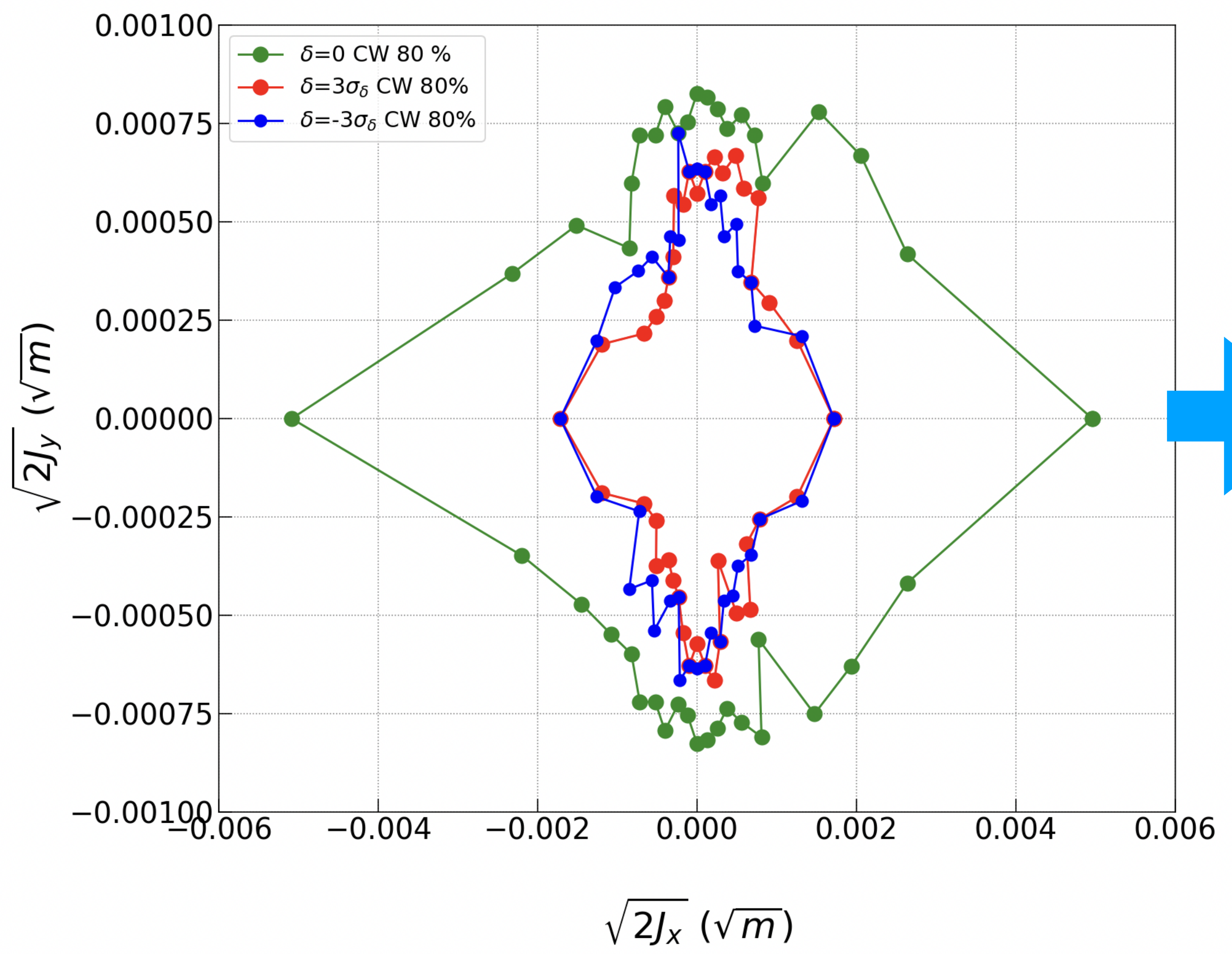
The momentum deviation larger than 1 % is different from CW 0 %.

Dynamic Aperture in LER (Simple IR Model)

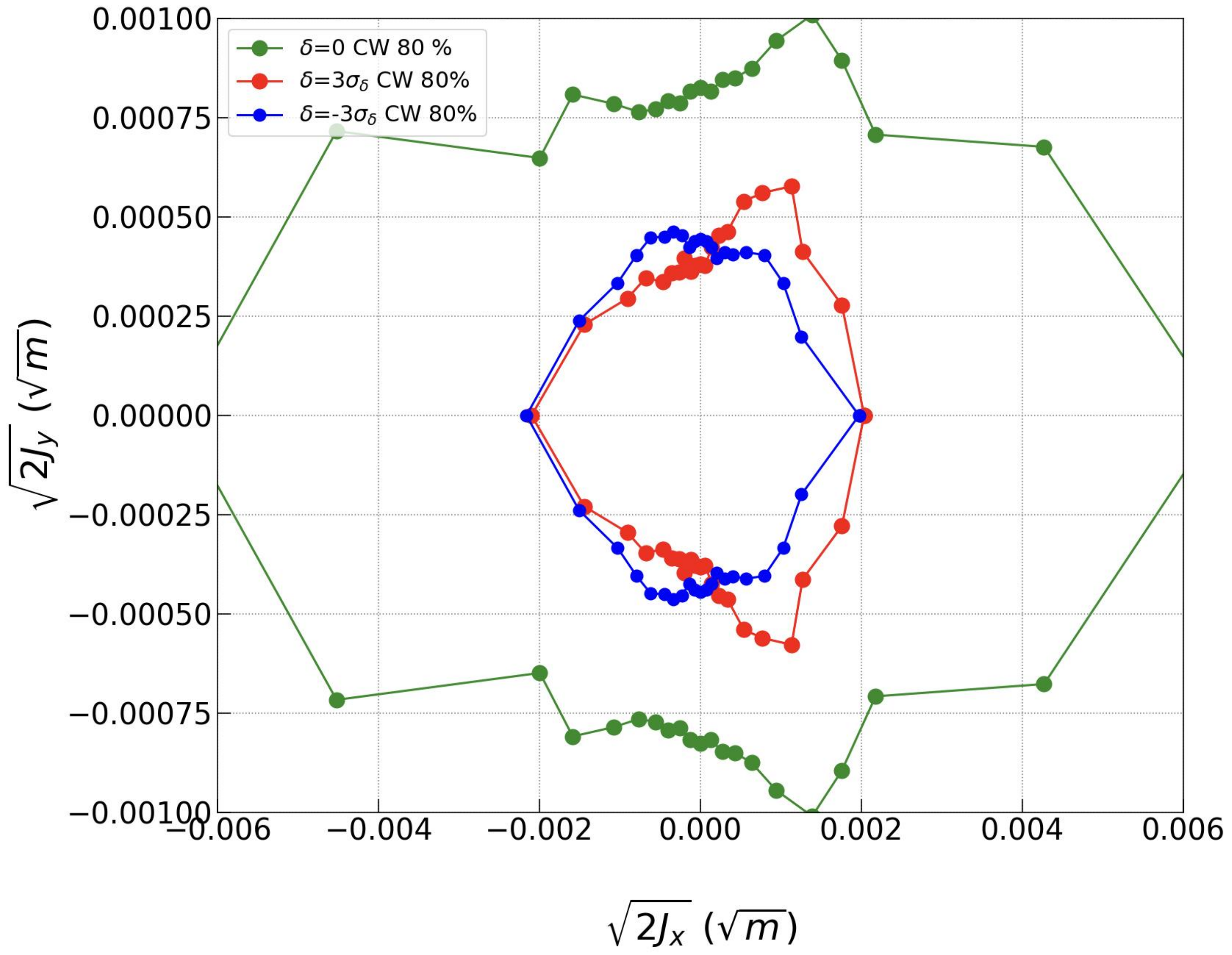
CW : 0 %

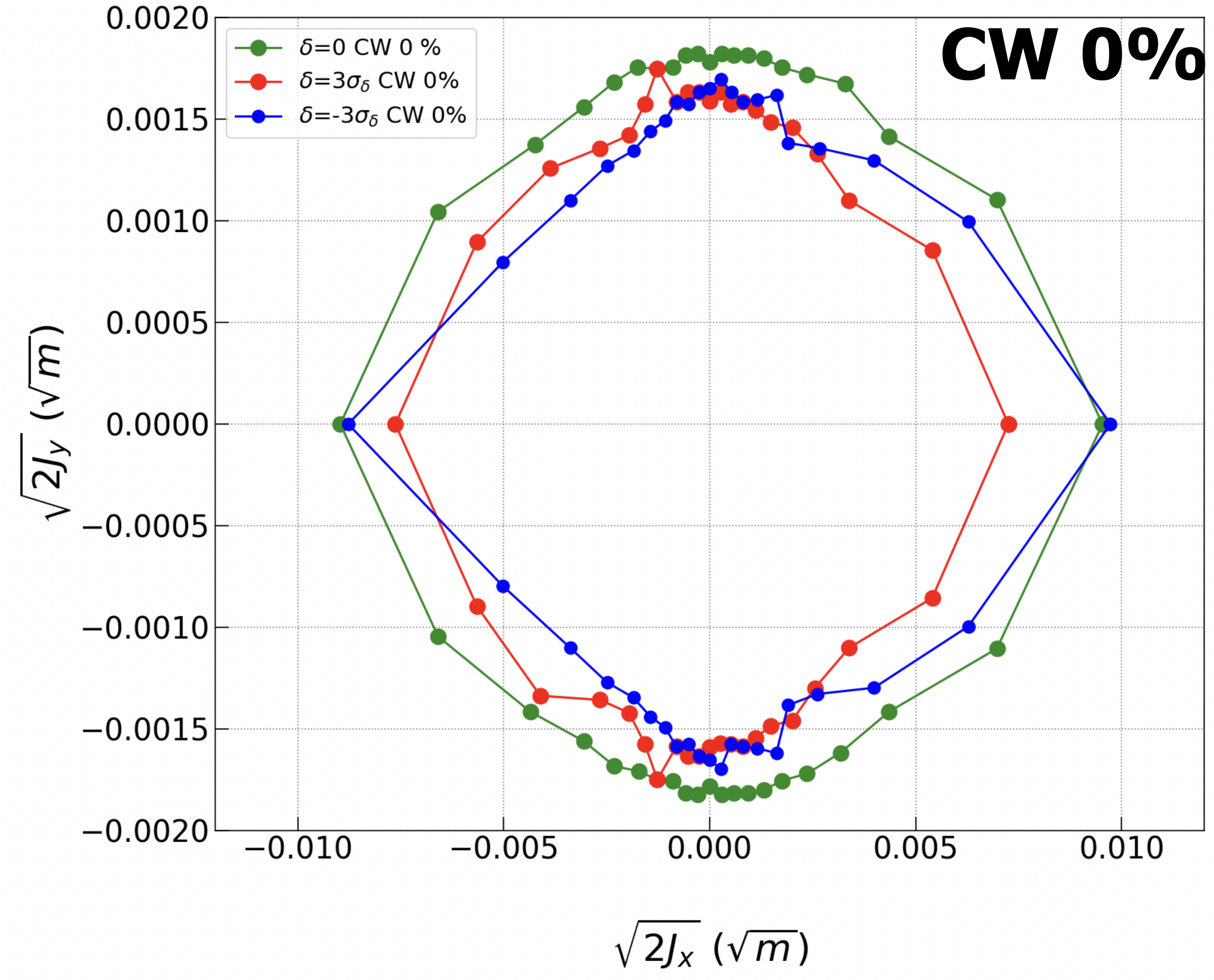


CW : 80 %



CW : 80 % + suppress fringe

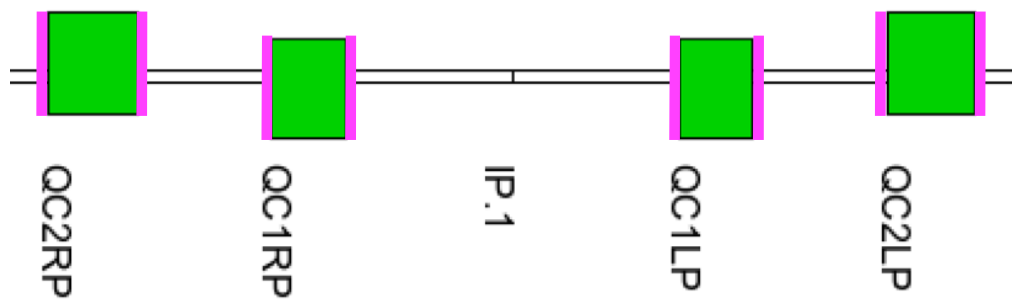




CW 0% + suppress fringe

scale : x2

QC1LP, QC1RP, QC2LP, QC2RP :
artificially, suppress nonlinear Maxwellian fringe



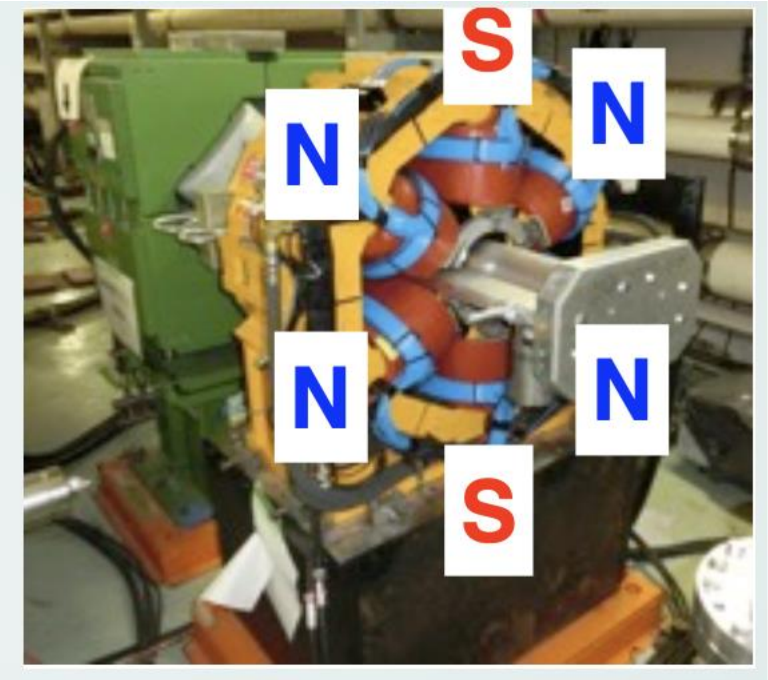
DA for on-momentum particles becomes large, but off-momentum particles is not improved.

Optics Corrections

- The optics correction is performed at a low beam current. Typically, about 50 mA.
- Performance of optics corrections (beta, dispersions, X-Y couplings) for $\beta_y^* = 1mm$:

	LER	HER	unit
$(\Delta\beta_x/\beta_x)_{rms}$	5	5	%
$(\Delta\beta_y/\beta_y)_{rms}$	5	5	%
$(\Delta\eta_x)_{rms}$	10	30	mm
$(\Delta\eta_y)_{rms}$	5	5	mm
$(\Delta y)_{rms}/(\Delta x)_{rms}$	0.016	0.012	
ε_y	25	40	pm
$\varepsilon_y/\varepsilon_x$	0.63	0.87	%

Vertical dispersions and X-Y couplings are corrected by using skew quad-like correctors.



- These results are obtained at low beam currents. The operation beam current is larger than 1 A.
- Beam pipe is deformed due to intense SR heating. BPM with beam pile is connected with a neighbor quadrupole magnet tightly. BPM can push the quadrupole magnet horizontally, horizontal kick is induced.
- Horizontal orbit at the strong sextupole creates large beta-beat.

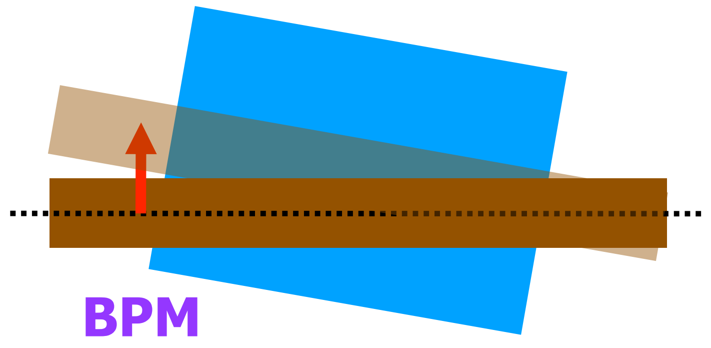
H. Sugimoto et al., TUXAT0103, Proc. of eeFACT'22, Frascati, Italy, 2022

BPMs, Quadrupoles, and Sextupoles

BPM is fixed at quadrupole magnet and displacement monitor measures relative deviation (horizontal and vertical) between the BPM and the sextupole magnet.

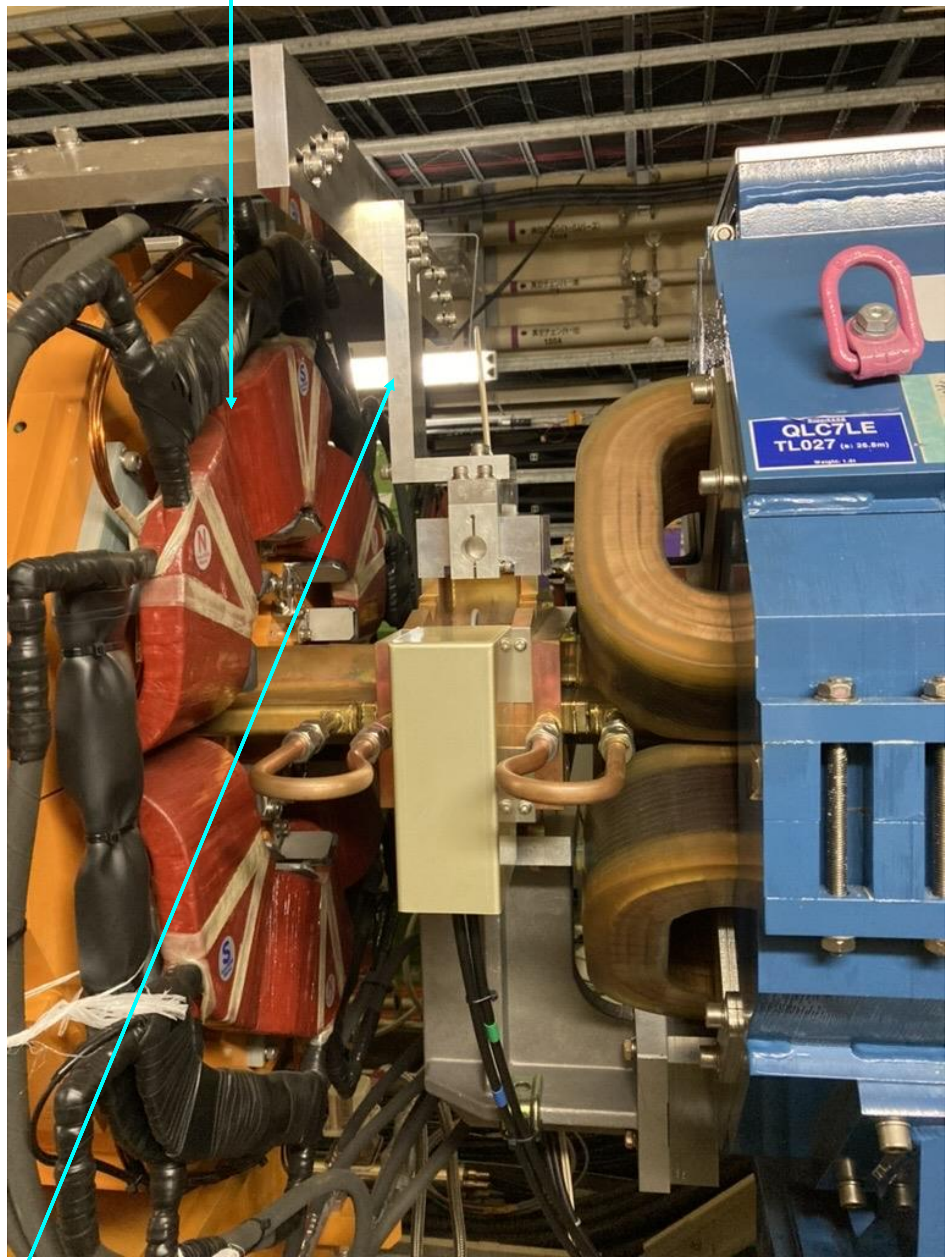
BPM and Quadrupole Magnet

The beam pipe (BPM) is fixed to the quadrupole magnet.



Quad. moves like yaw and horizontal shift if BPM pushes quad.

Crab Sextupole in the HER



Gap sensor measures $(\Delta x, \Delta y)$ between BPM and sextupole. Relation between BPM and quad. does not change. (see left fig.)