Dynamic Aperture Optimization of storage ring based colliders with Multi-Objective Algorithm

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Many Thanks: J. Qiang(LBNL), K. Oide(KEK), D. Zhou(KEK)

Outline

- Introduction
- Algorithm
- Application
- Summary

Multi-objective genetic algorithm (MOGA)

- Application in storage ring based light source is very popular and successful
  - APS/DLS, ELEGANT, M. Borland, in 48th ICFA Beam Dynamics Workshop on Future Light Sources
  - NSLSII，L. Yang, Y. Li, W. Guo and S. Krinsky, PRST-AB, 14, 054001 （2011）
  - SLS, BMAD, M. Ehrlichman , arXiv: 1603.02459
  - HEPS, Accelerator Toolbox, Y. Jiao and G. Xu,
  - …

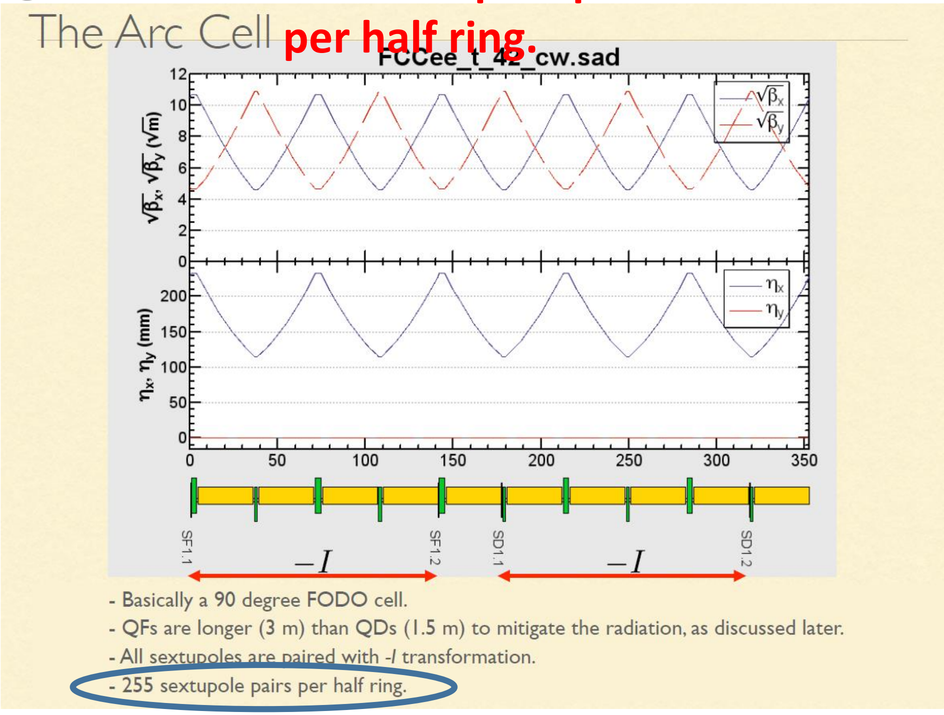
Different Algorithm

- Particle Swarm, SPEAR3, X. Huang, J. Safranek, NIMA 757, 48, 2014
- Differential Evolution, J. Qiang *et al.,* IPAC' 13
- Downhill Simplex, SuperKEKB, FCC, K. Oide *et al.*
- …….

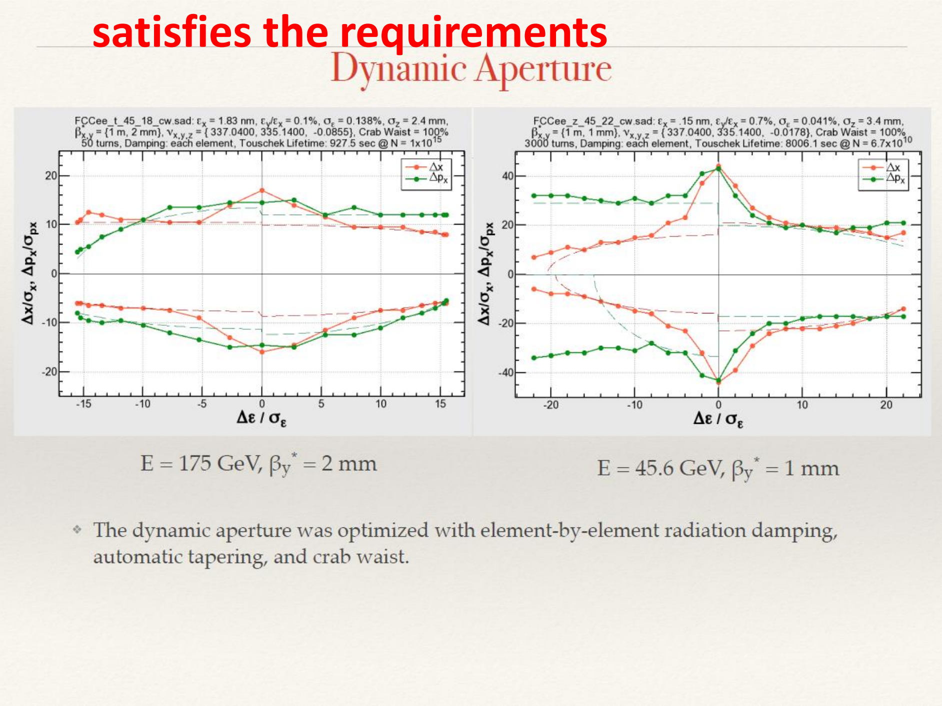
Excitation

- K. Oide, "A design of beam optics for FCC-ee", Sep. 2015 @IHEP

255 sextupole pairs per half ring.



Resulting dynamic aperture alomost satisfies the requirements



Why we did the job?

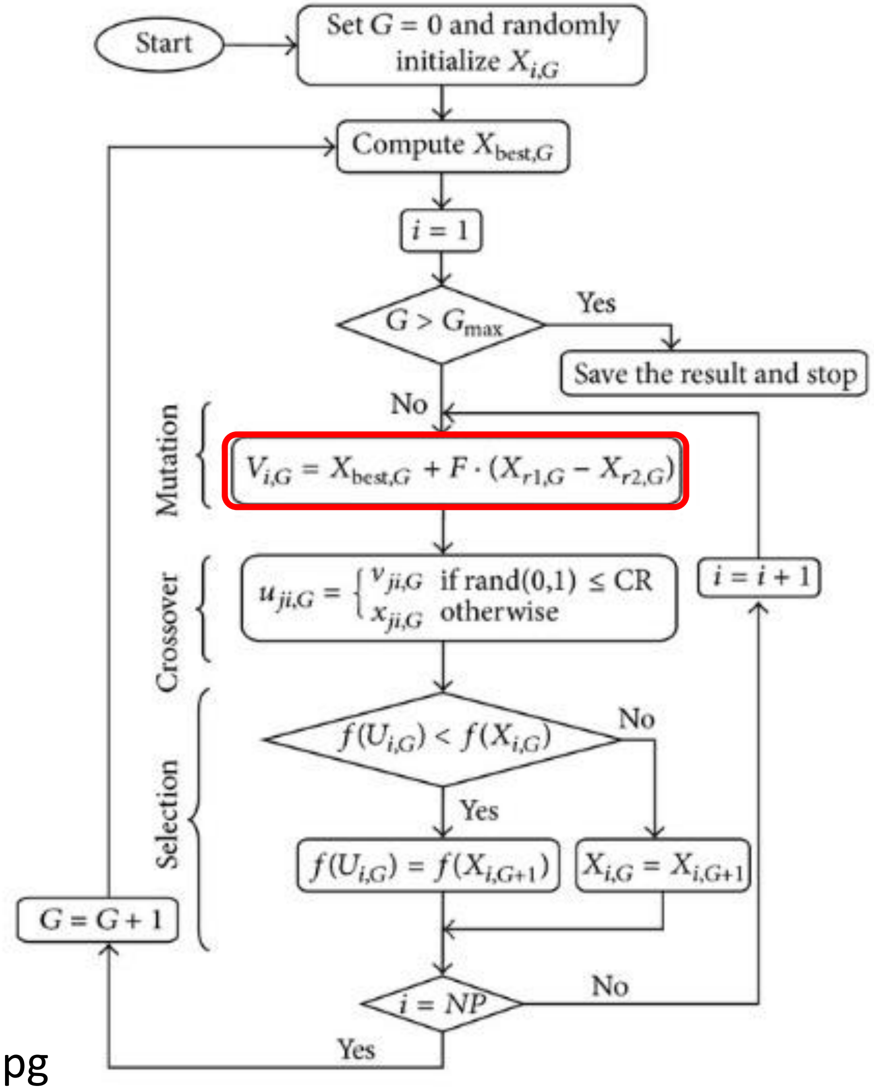
- We need to optimize the DA of CEPC
- We want to try the direct DA optimization in collider, just as the community has done in light source
- Different optimization algorithm is worth to be tried
- SAD(http://acc-physics.kek.jp/sad/) is used for the DA determination. It is a parallel code, but the scalability is not very good. A MPI-based parallel code to call SAD will be much more efficient.

Differential Evolution Algorithm (single objective)

- The “DE community” has been growing since the early DE years of 1994 – 1996
- DE is a very simple population based, stochastic function minimizer which is very powerful at the same time.
- There are a few strategies, we choose ‘rand-to-best’. Attempts a balance between robustness and fast convergence.

$$v(i,j) = \begin{cases} x(i,j) + F \times [x(b,j) - x(i,j)] + F \times [x(r1,j) - x(r2,j)], & If\ rand(j) < CR \\ x(i,j), & Otherwise \end{cases}$$

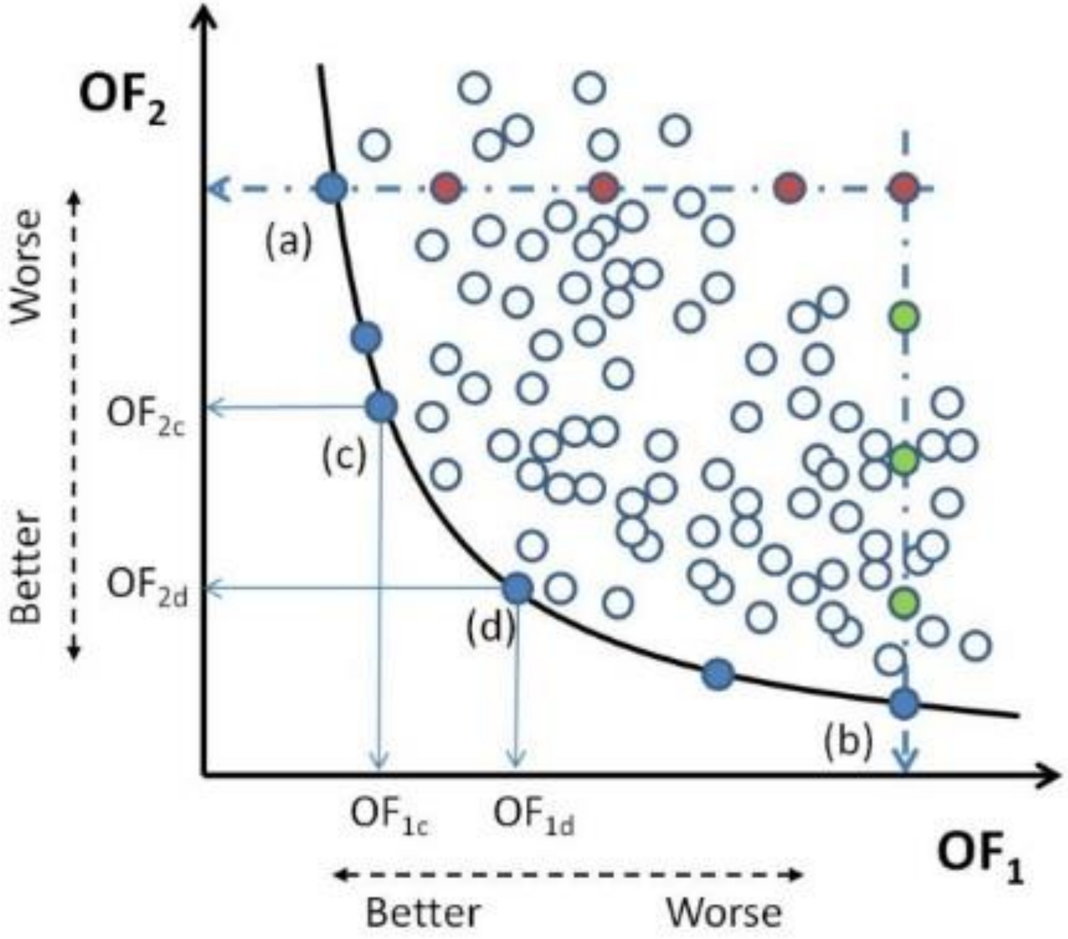
- Different problems often require different settings for NP, F and CR



http://www.hindawi.com/journals/ijap/2013/713680.fig.003.jpg

Multi-objective Optimization

- Most problems in nature have several (possibly conflicting) objectives to be satisfied.
- Many of these problems are frequently treated as single-objective optimization problems by transforming all but one objective into constraints.
- The term ***optimize*** means finding such a solution which would give the values of all the objective functions acceptable to the decision maker.



Kung et al., J. ACM 22, 4 (Oct. 1975), 469-476

Giuseppe Narzisi, “Multi-Objective Optimization”, 2008

MODE:

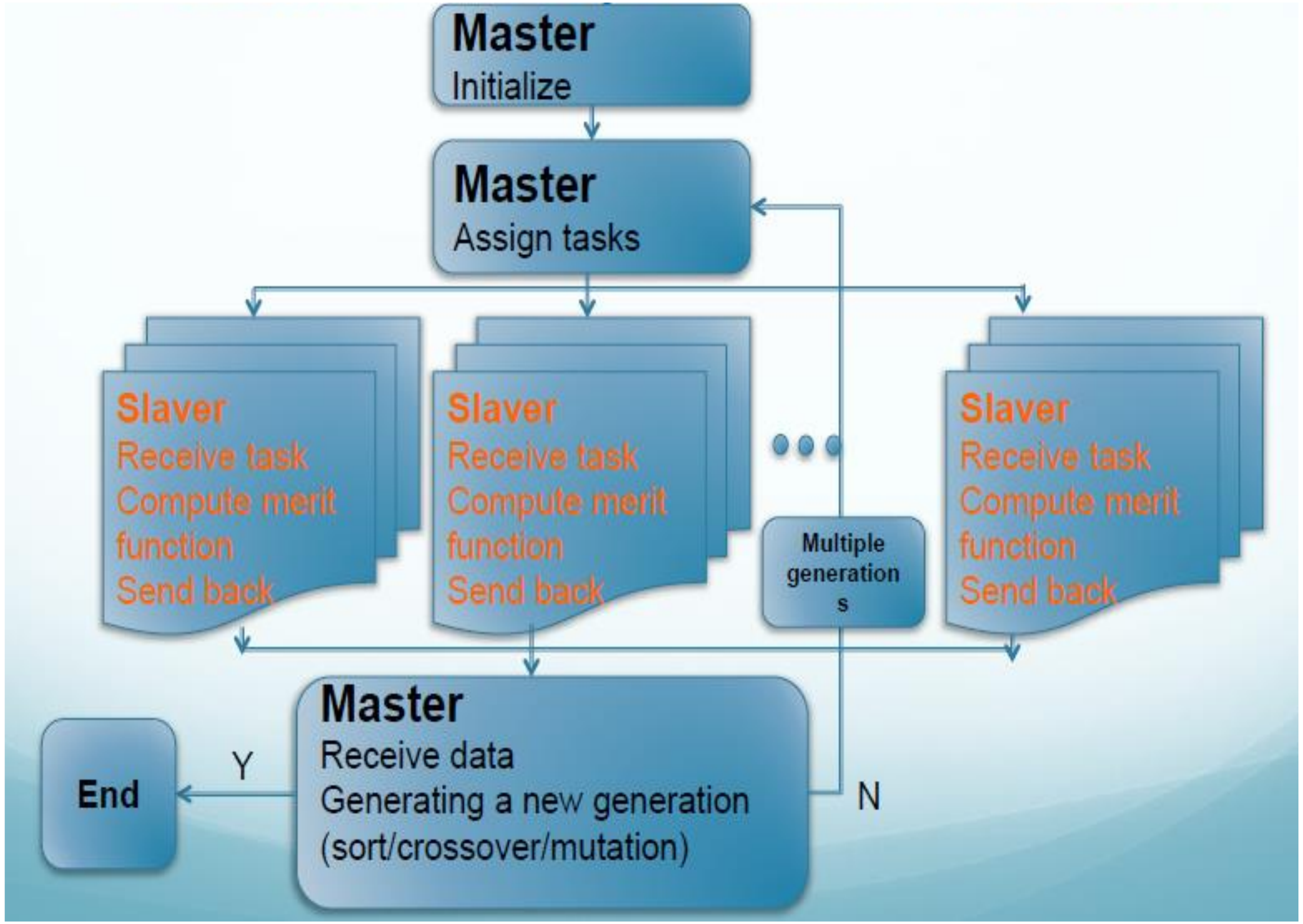
Multi-**O**bjective optimization by **D**ifferential **E**volution

The parallel algorithm is referencing to J. Qiang(IPAC'13)

1. Initialize the population of parameter vectors
2. Generate the offspring population using the above differential evolution algorithm
3. Find the non-dominated population, which are treated as the best solutions in DE to generate offspring
4. Sorting all the population, select the best NP solution as the parents
5. Return to step 2, if stopping condition not met

MODE: Scalable Enough at 1000-nodes farm?

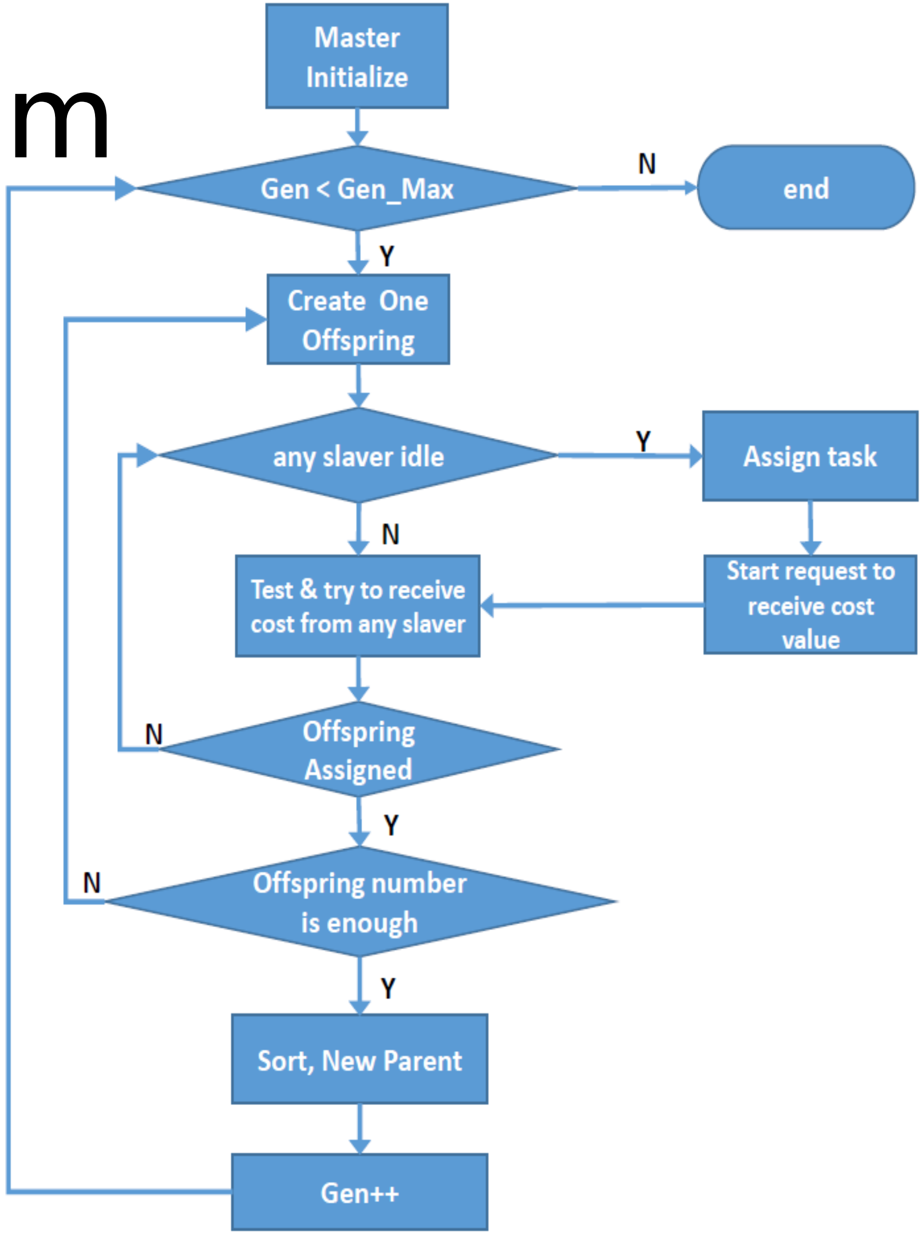
Courtesy of Yongjun Li(BNL)



New Parallel Paradigm

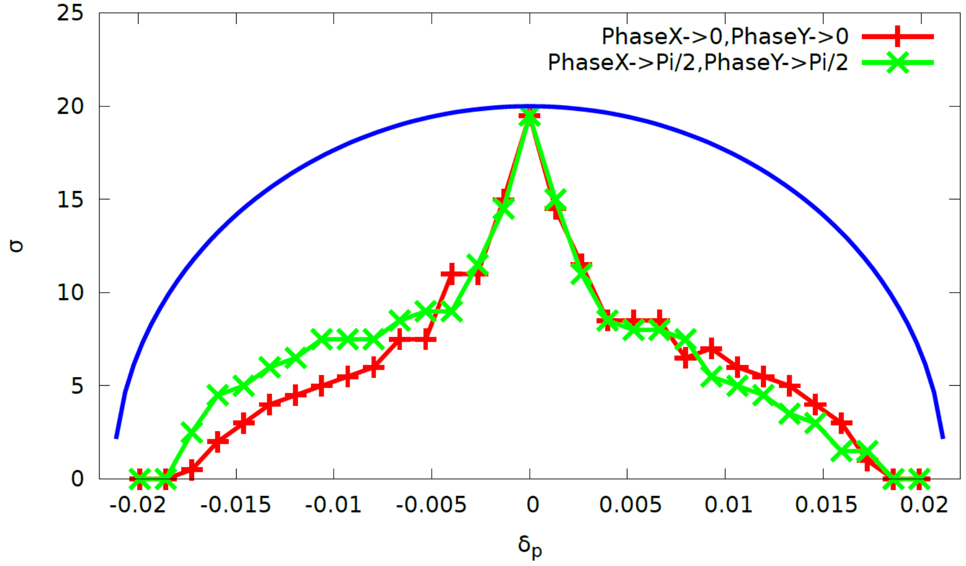
High Parallel + High Scalability

- Even the time taken by different task is different
- Even some node is very busy



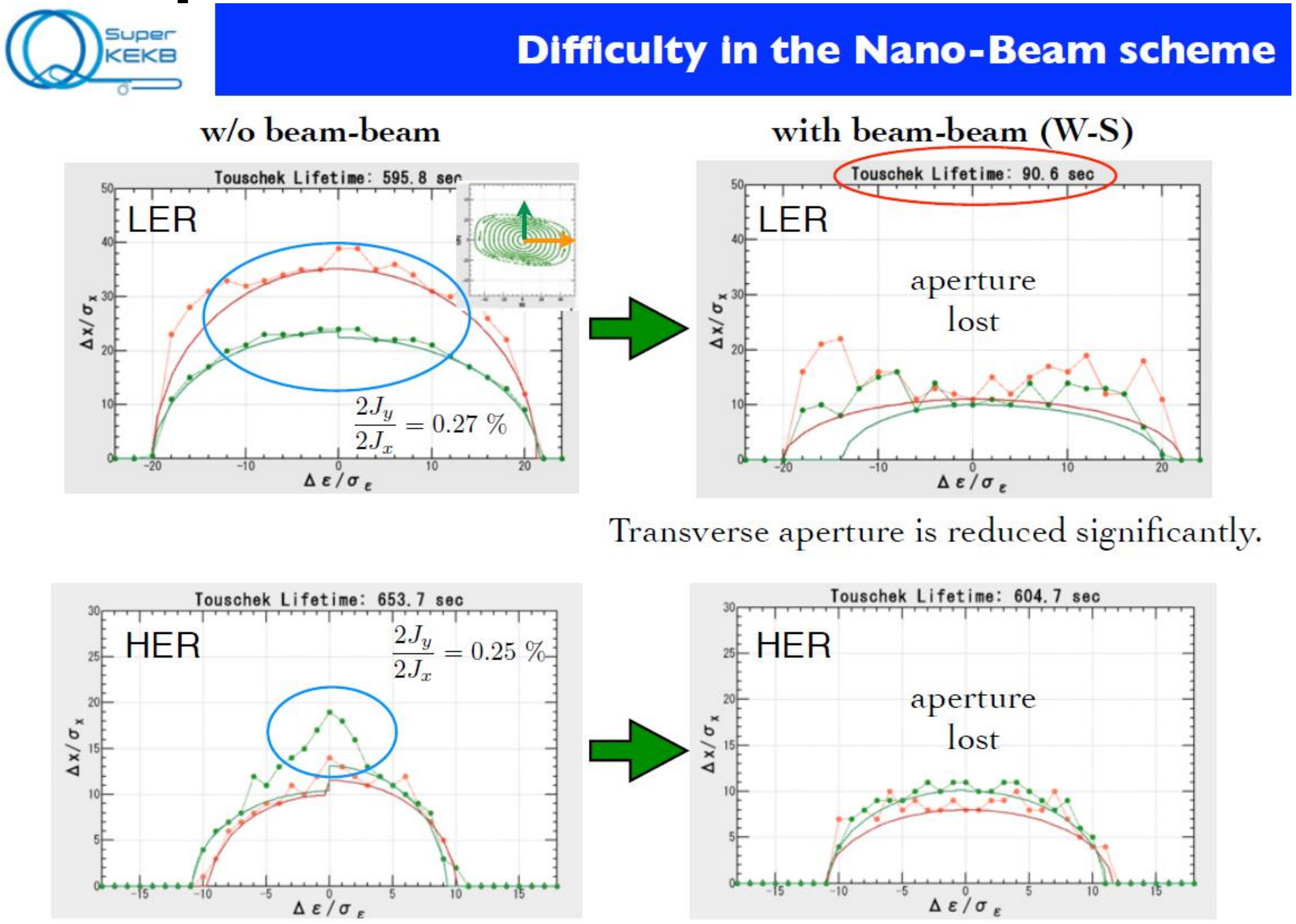
Definition of Objective Cost Value

- DA Boundary:
  - $\frac{x^2}{20^2} + \frac{z^2}{16^2} = 1$ (example)
  - z for energy deviation in unit of σ_p
  - x for transverse amplitude in unit of σ
  - transverse coupling: designed value
- The difference between the DA boundary and real DA is defined the objective cost value
- Less cost value is better



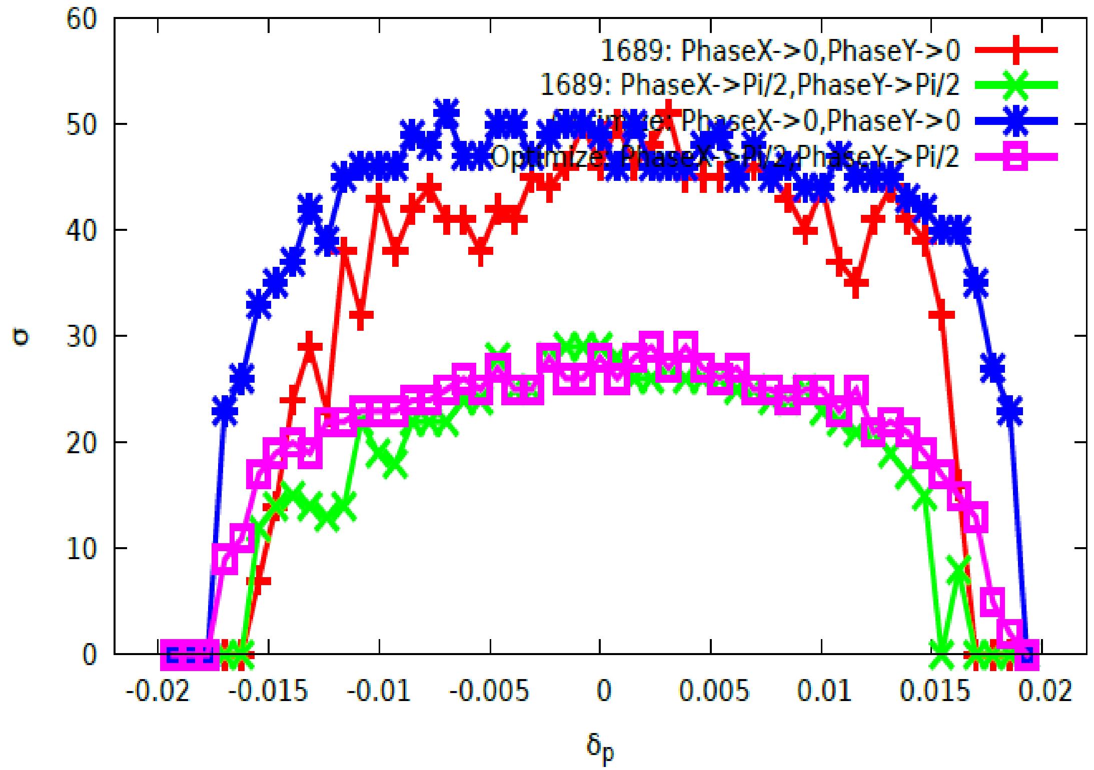
SuperKEKB: dynamic aperture is a serious issue

Y. Ohnishi, “Optics Issues”, 18th KEKB Review, March 3-5, 2014



DA Optimization of LER (SuperKEKB)

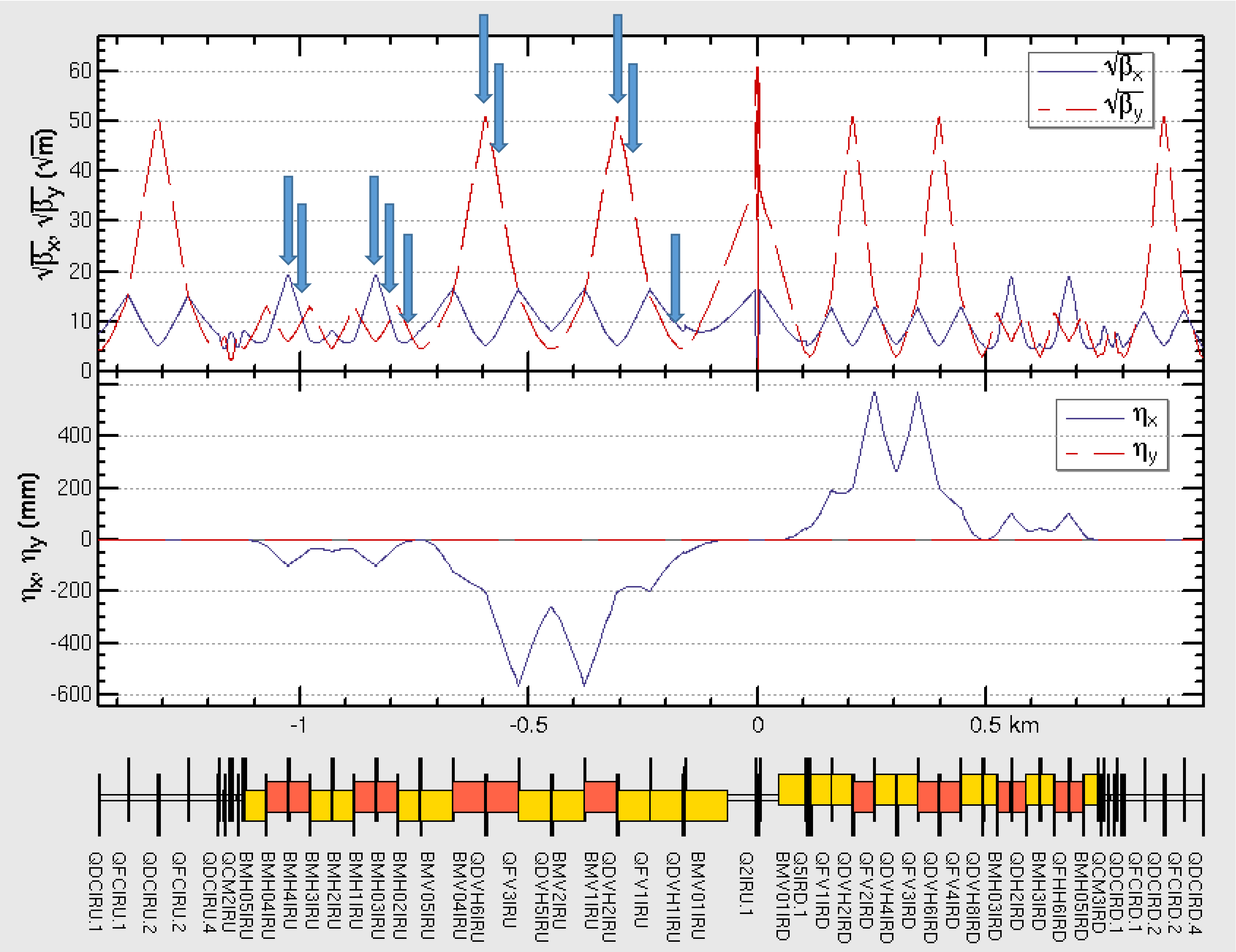
- Objectives:
  - $\nu_x \in (0.53, 0.66), \nu_y \in (0.55, 0.66)$, for $\delta_p \in (-0.019, 0.019)$
  - $\frac{x^2}{50^2} + \frac{z^2}{26^2} = 1$, for z=Range[-24,24,3], $\epsilon_{x,0} = 1.89$ nmrad, $\delta_{p,0}$=7.7e-4
- Variables: 68
  - 2 Octupoles
  - 54 sextupole pairs
  - 12 skew sextupole pairs



CEPC DA Optimization Knobs

50 knobs in total

- IR sextupoles: (10)
- Arc Sextupole (32)
- Phase advance (8)



IR knobs

- Main Chromaticity Sextupoles (2)
- Neighbor weaker sextupole to correct finite length effect (2)

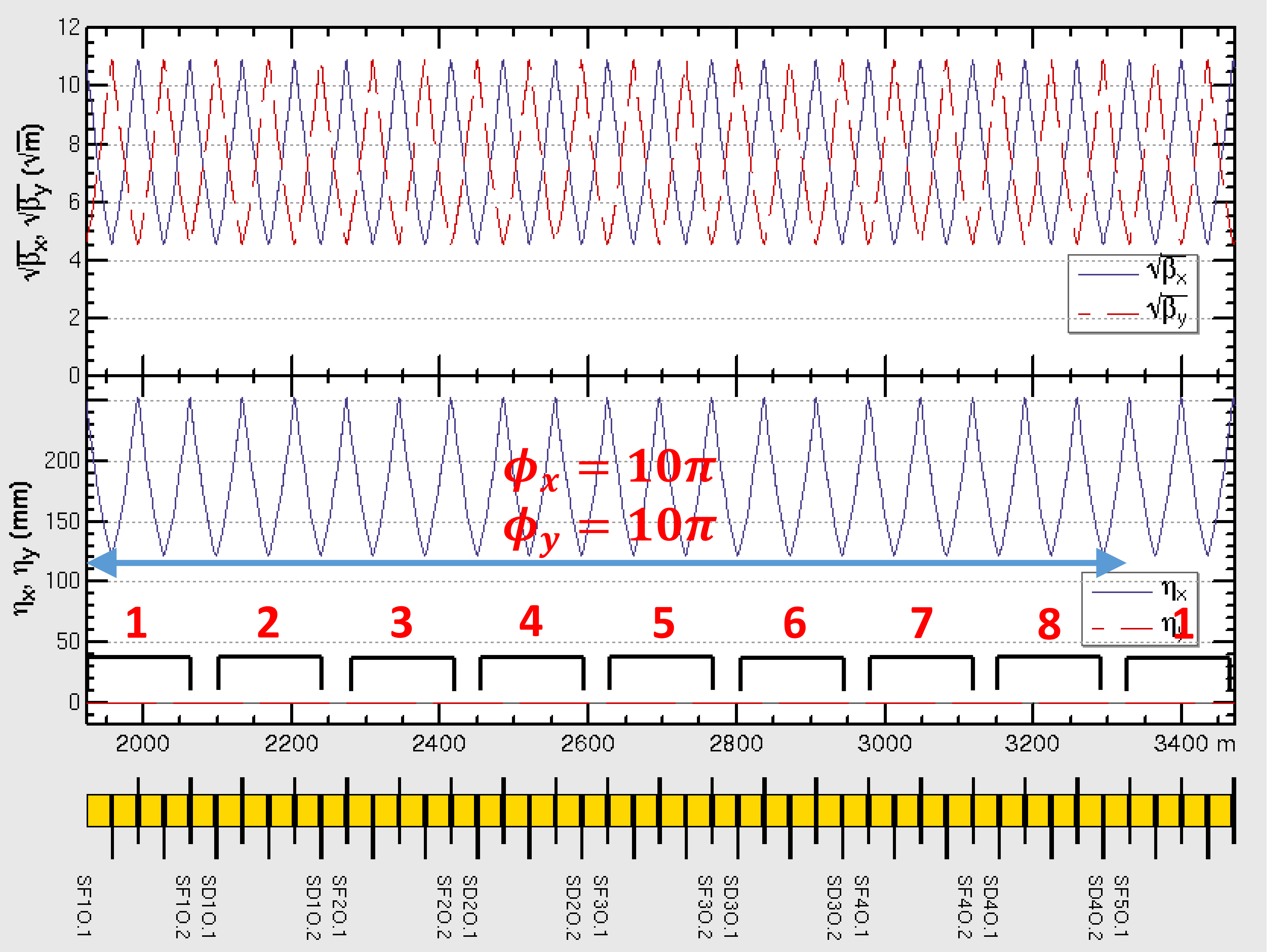
A. Bogomyagkov, ArXiv:0909.4872

- Sextupole to correct higher order chromaticity in vertical direction (1)

  Y. Cai, PRAB.19.111006

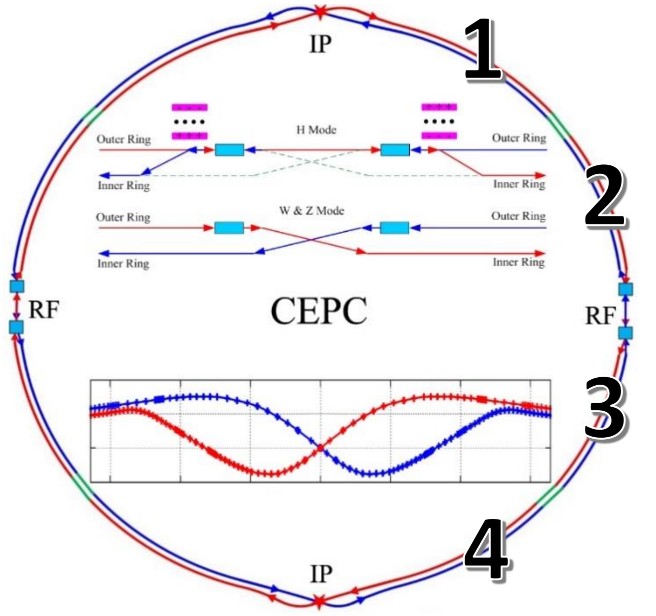
Different strength between Upstream and Downstream of IP.
10 knobs in IR.

Arc sextupole



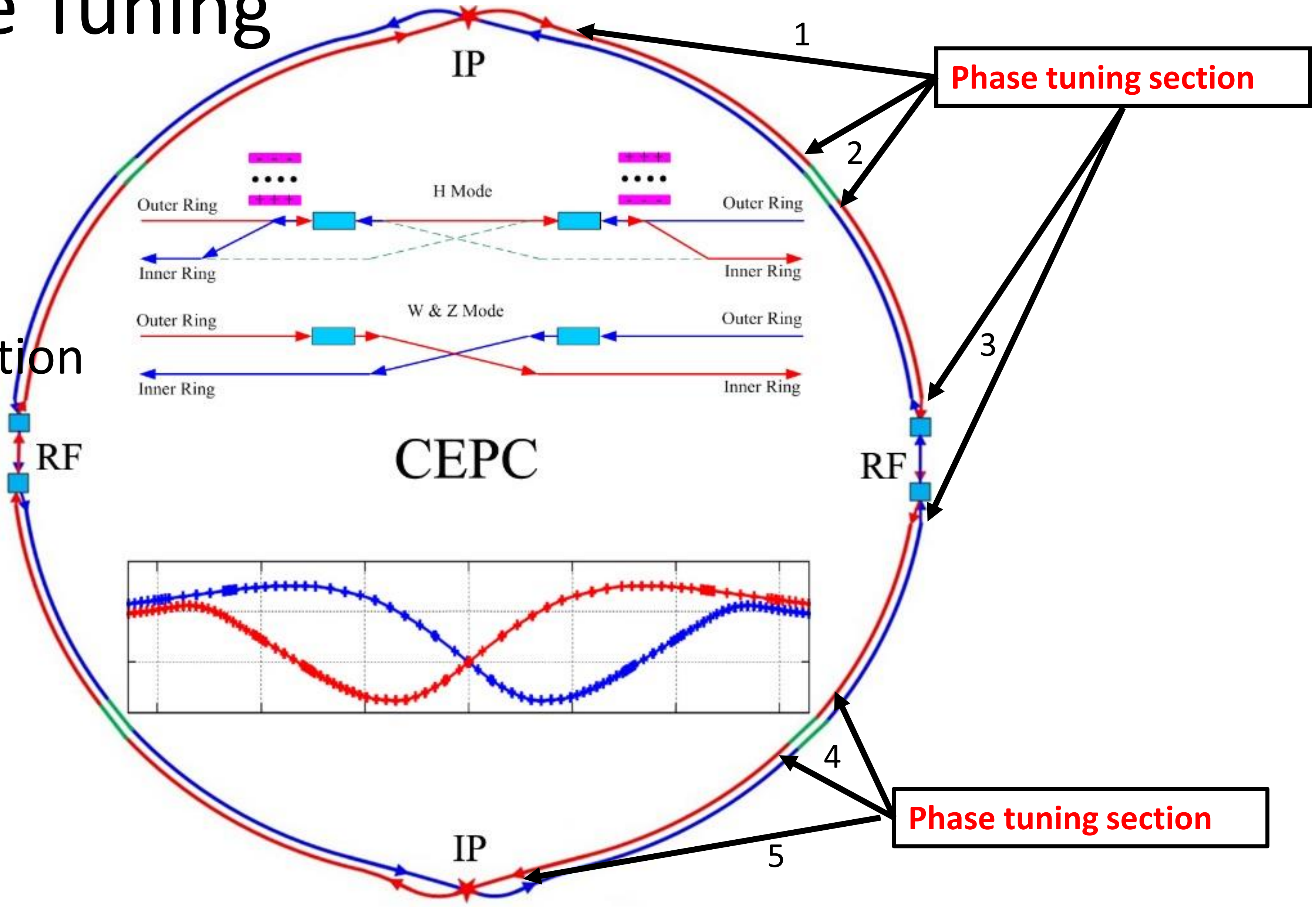
- 90/90 FODO
- Non-interleave sextupole scheme
- 4 SF + 4 SD sextupole configurations in one arc section
- 7 sub-period in in one arc section，
- 4 arc section in half ring

Total knobs: 32

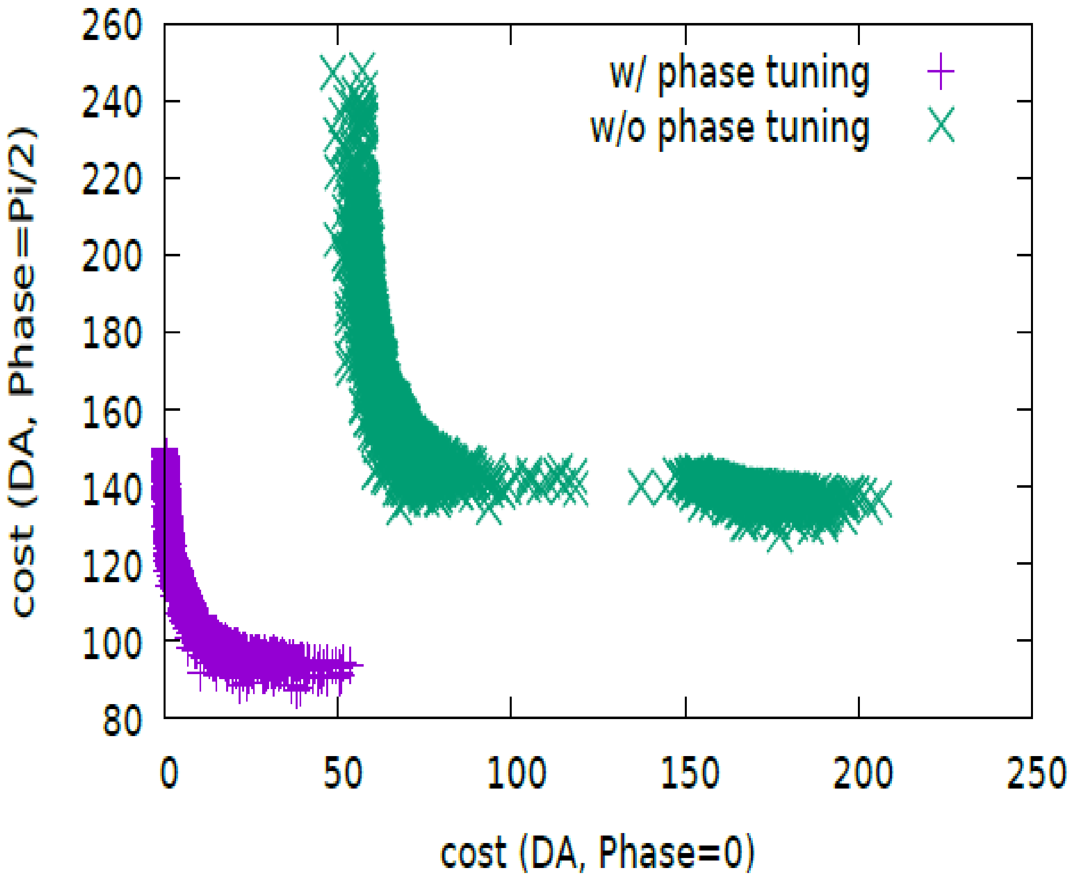


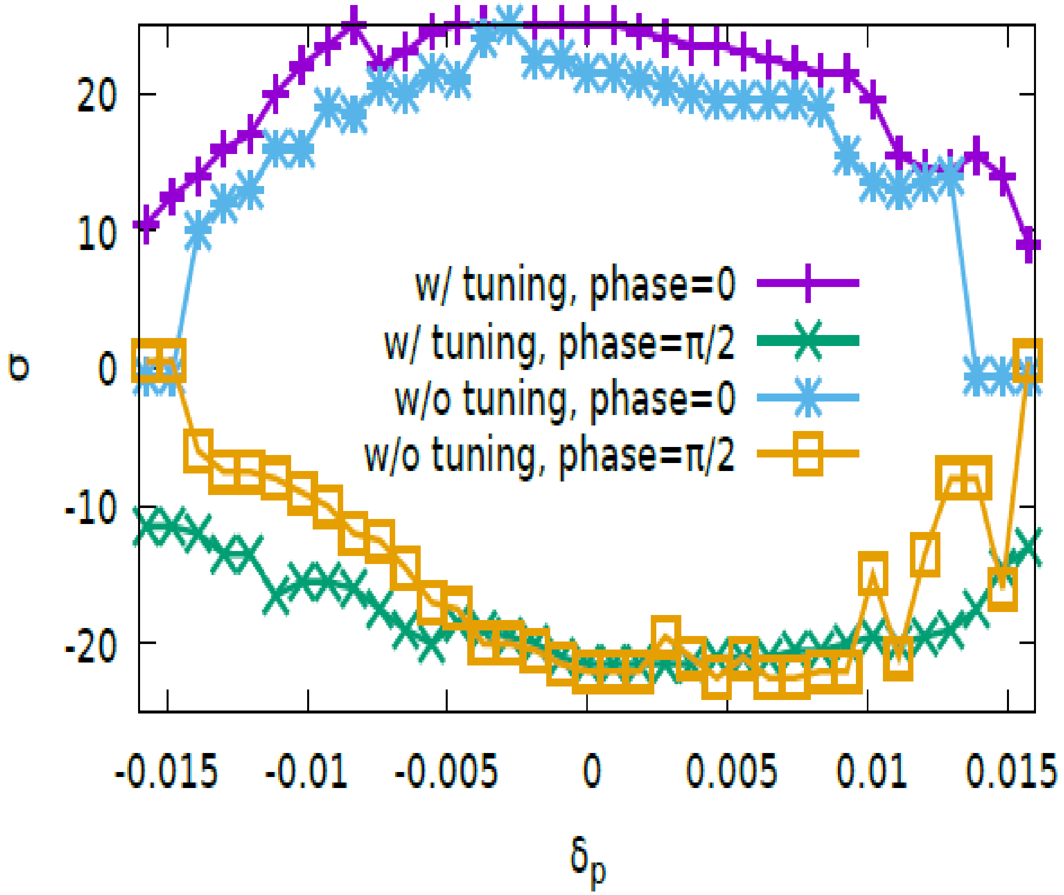
Phase Advance Tuning

- 10 knobs in x/y direction
- Keep tune fixed
- Only 8 free knobs



Contribution from phase advance





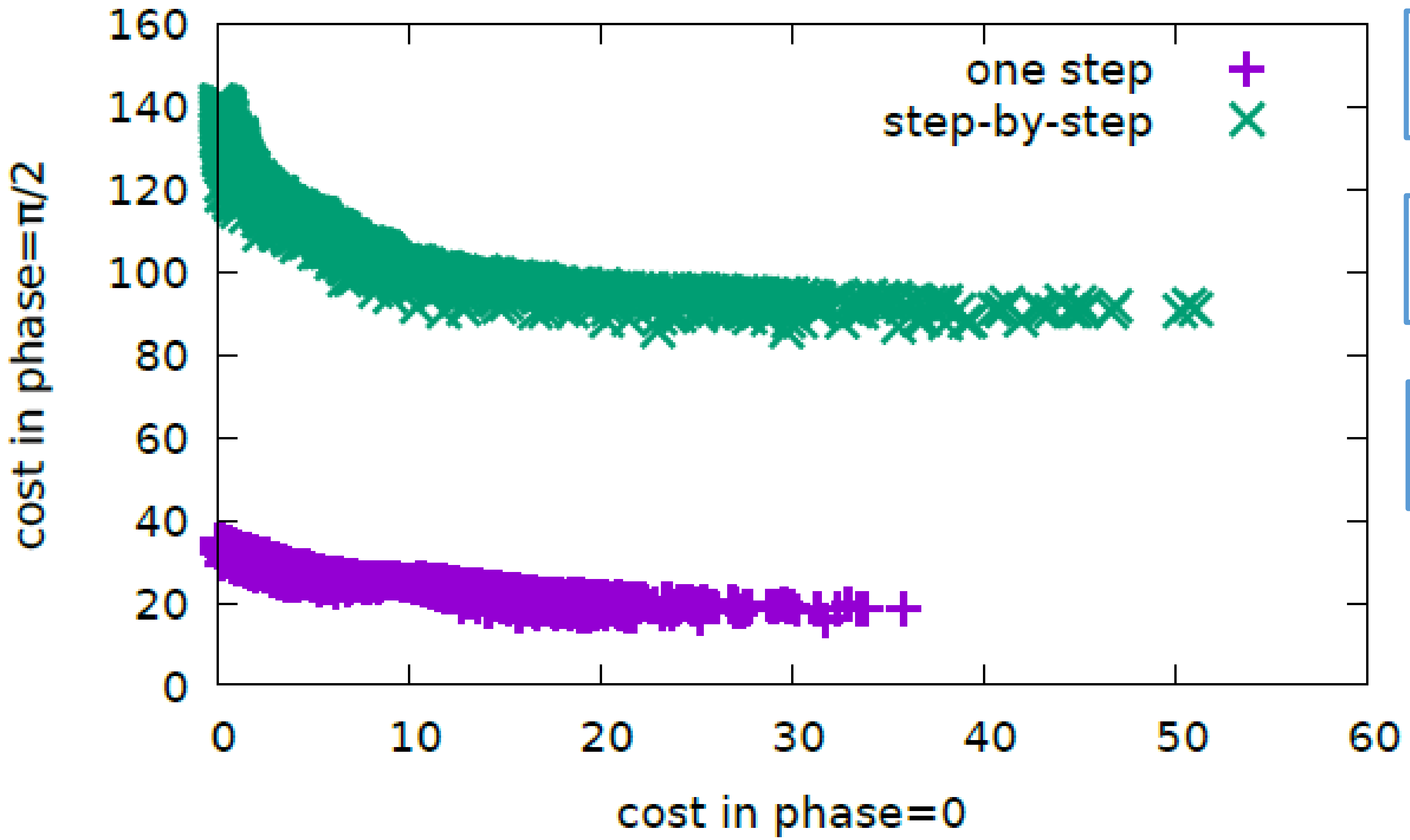
Some Try of Speed-up/Optimization Method

Brute-force dynamic aperture tracking is very time consuming

- More strategy of DE algorithm are randomly selected used
- The objective is first eased, for example only track 50 turns instead of 100 or 200 turns.
- The time consuming cost function is calculated only when the necessary constraints be satisfied. [arXiv: 1603.02459]
- First try to optimize with less variables, then more variables.
- Iteration with non-dominated solution

Optimization in one-step vs multiple steps (32 arc sextupole familiy)

If computing resources are enough, It's better optimize all the variables in one step



STEP-BY-STEP:

4 Arc Sextupoles:
SFO/SDO/SFI/SDI

↓

16 Arc Sextupoles:
4*(SFO/SDO)+4*(SFI/SDI)

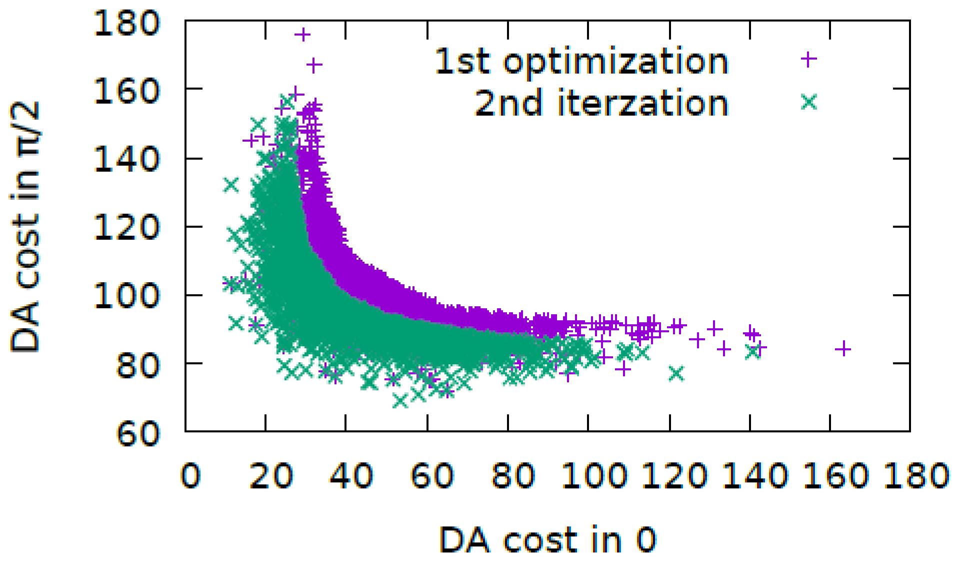
↓

32 Arc Sextupoles:
8*(SFO/SDO)+8*(SFI/SDI)

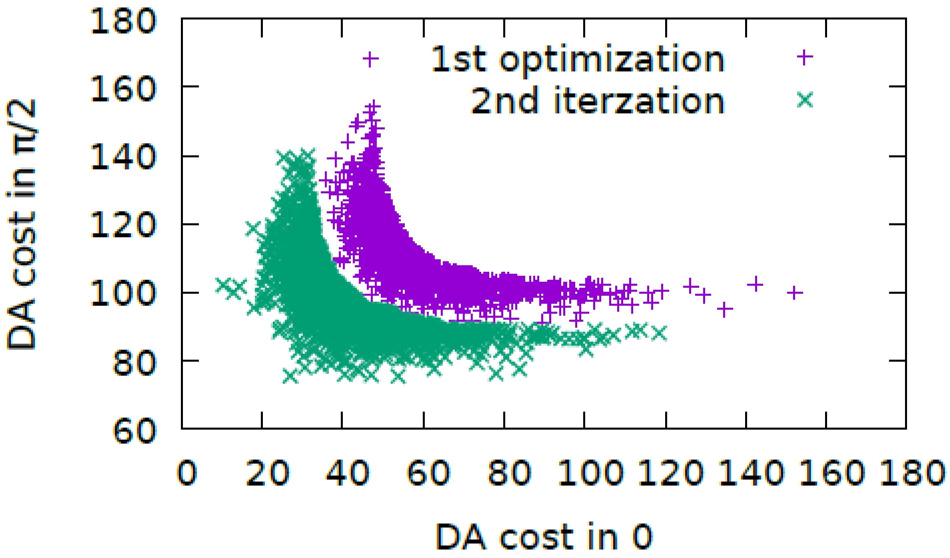
Iteration with Pareto Front Solution

- Non-dominated solution achieved + Other initialized solutions are randomly generated
- No very clear further optimization
- We usually do the iteration if time permits

Bx= 0.37m

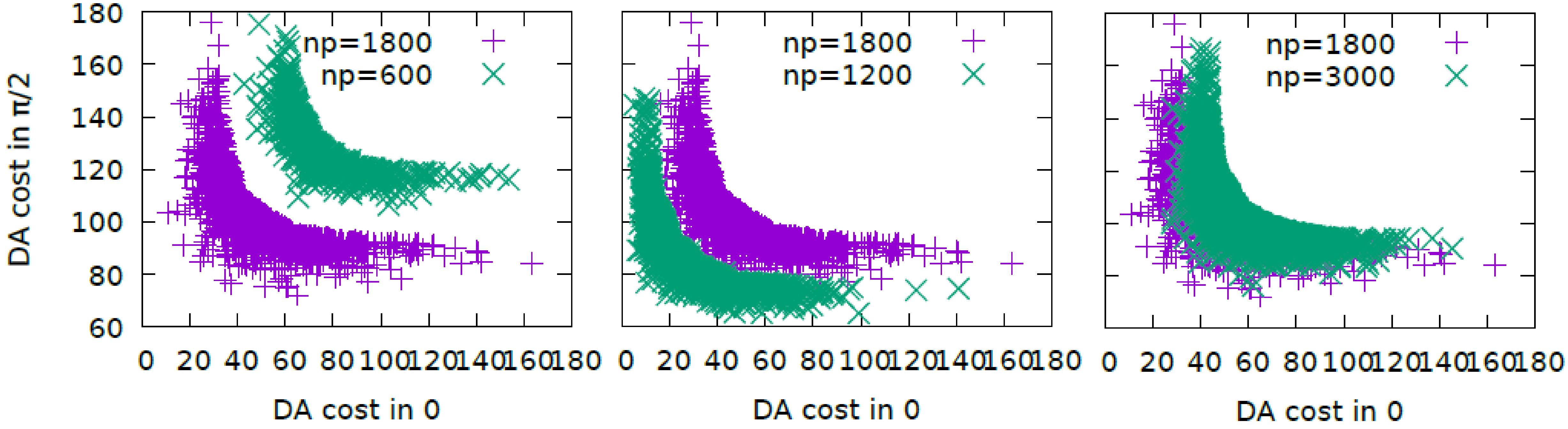


Bx= 0.50m



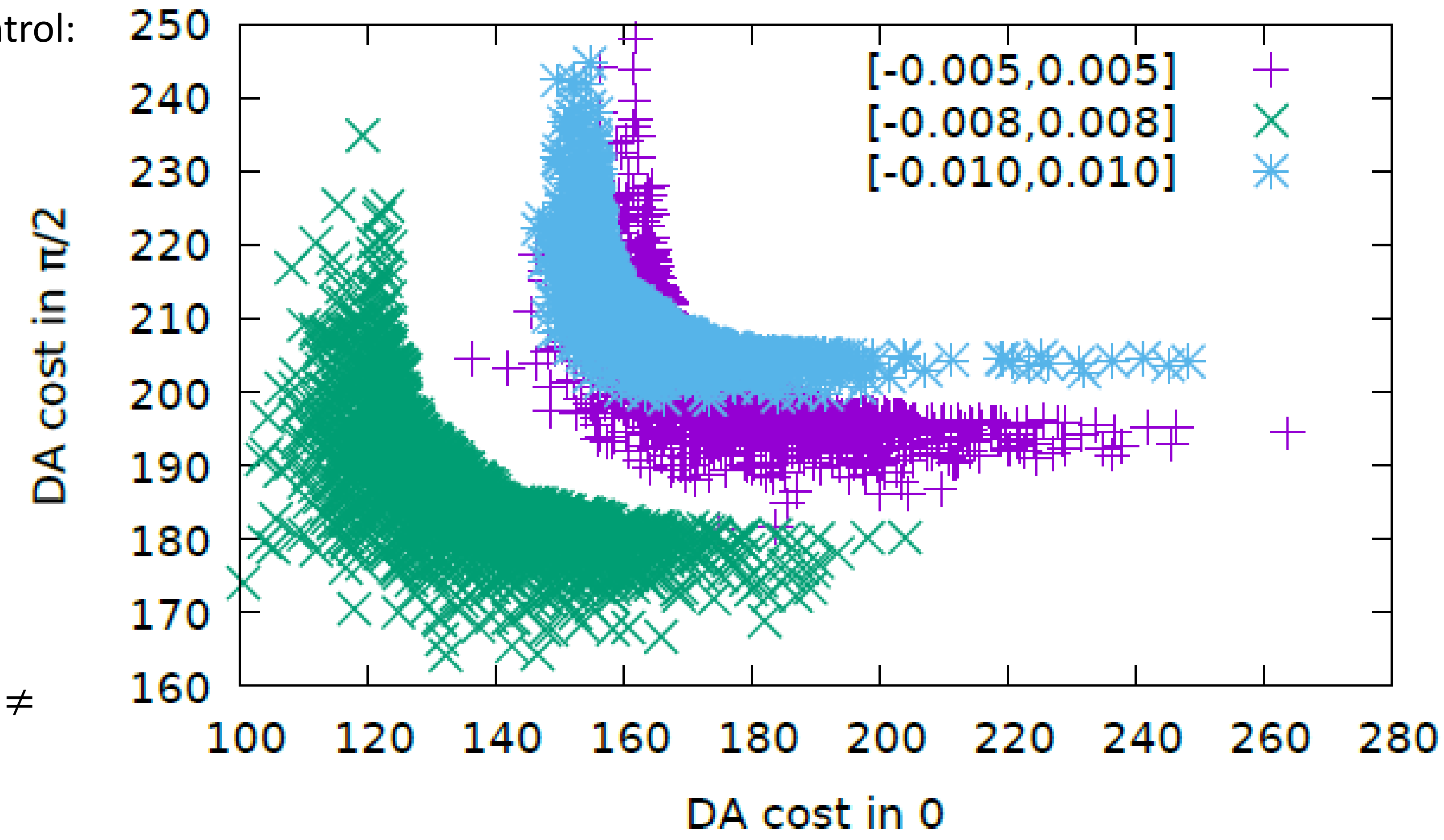
Optimize with different population size

Np=1200~1800 (20-30 times variable number) is good enough



Different Chromaticity Constraint

Half ring tune control:
Qx in (0.52, 0.58)
Qy in (0.58, 0.64)

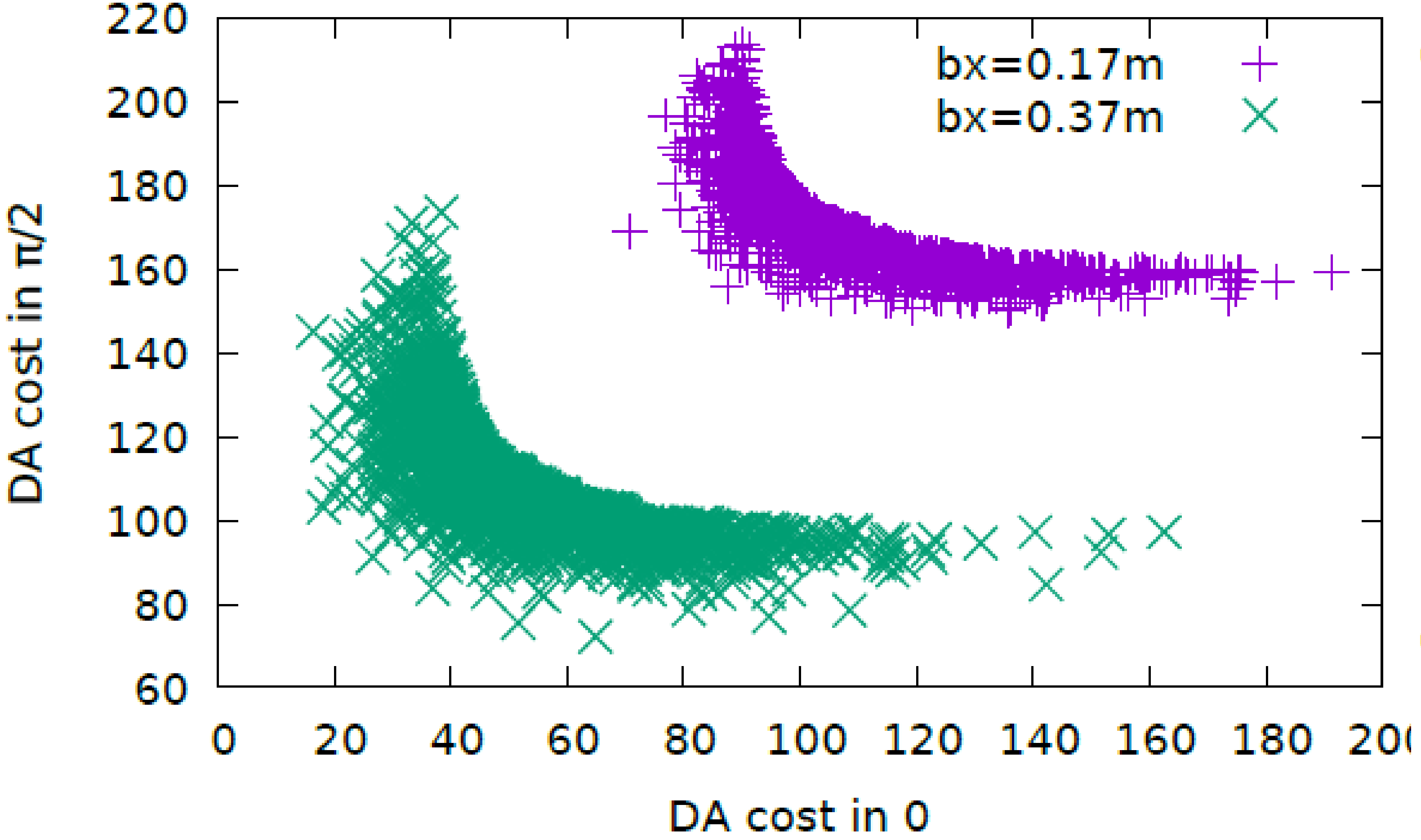


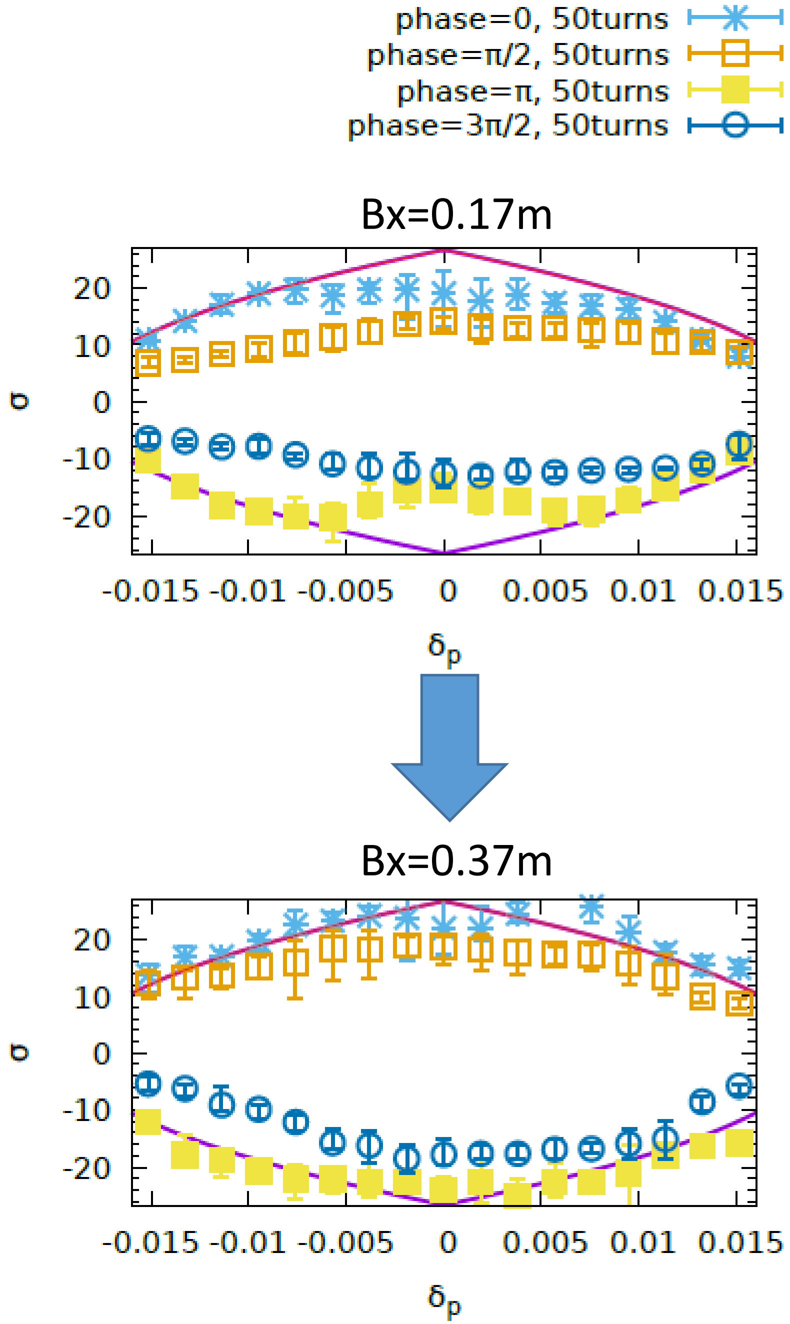
In our normal optimization, we prefer to control the tune in the maximum momentum offset (0.006~0.008)

The final optimum momentum acceptance is about 0.016.

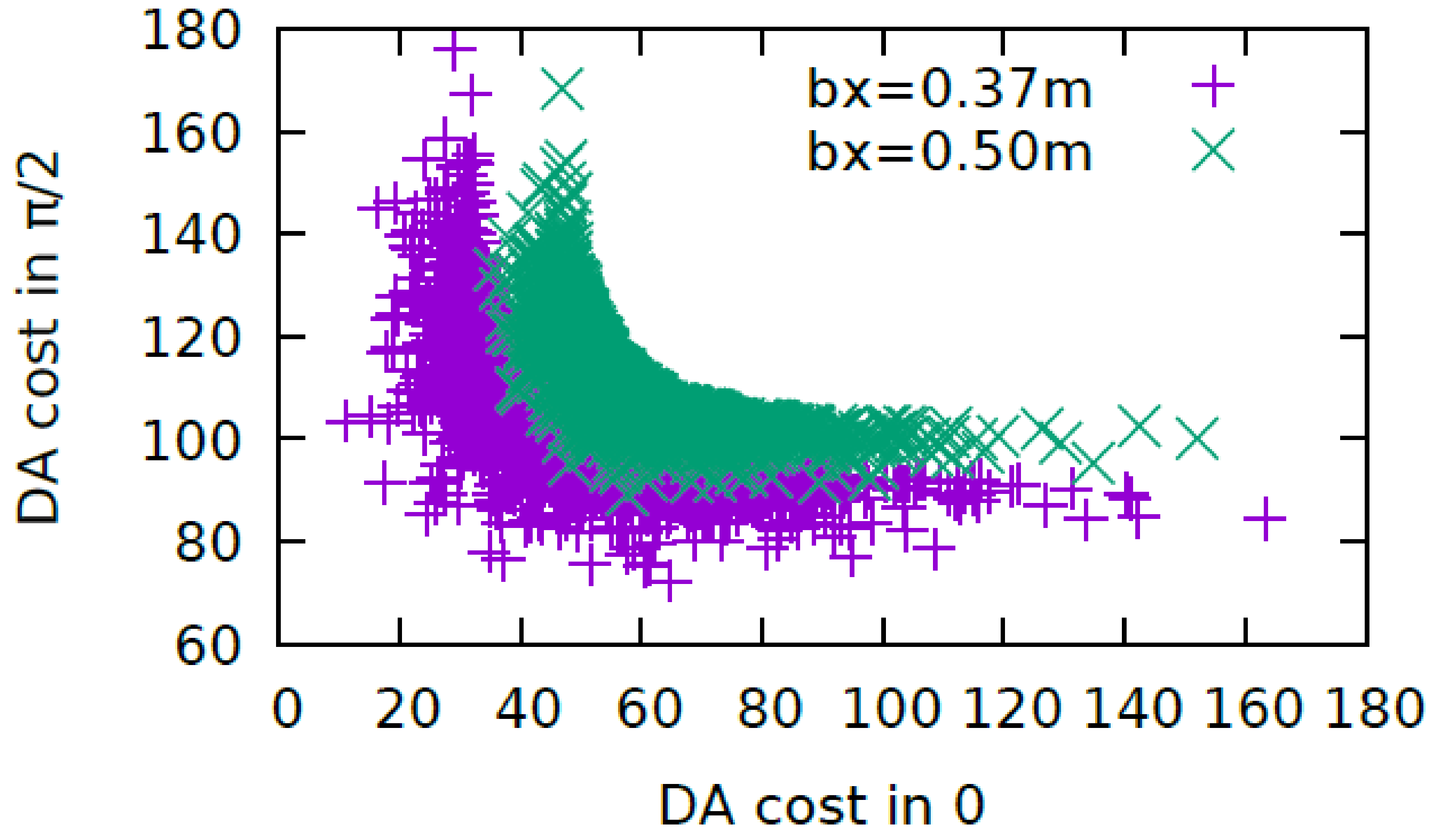
K. Oide (2016):
Less chromaticity ≠ Better dynamic aperture

Contribution of β_x^*

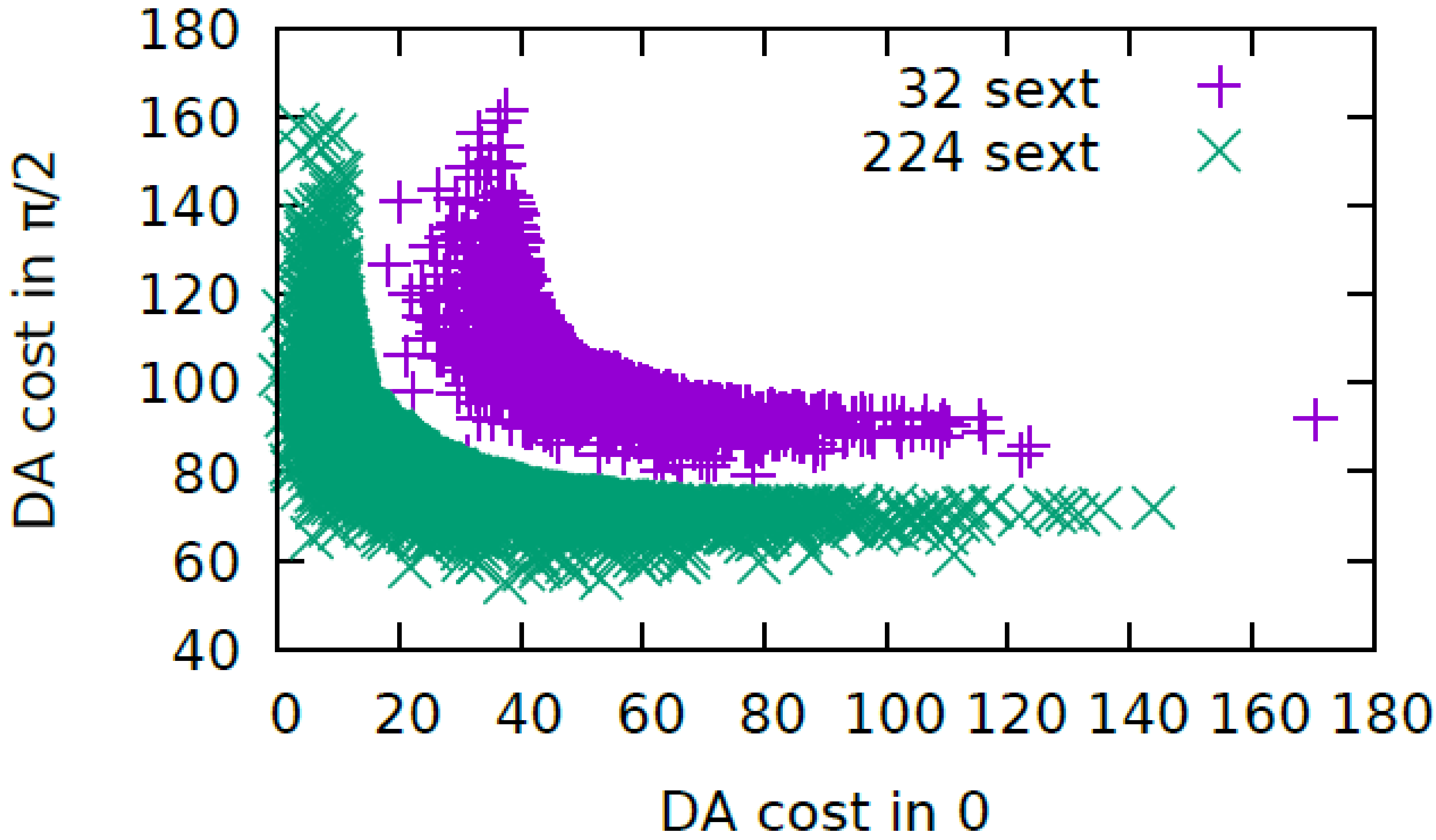




Contribution of β_x^* (2)



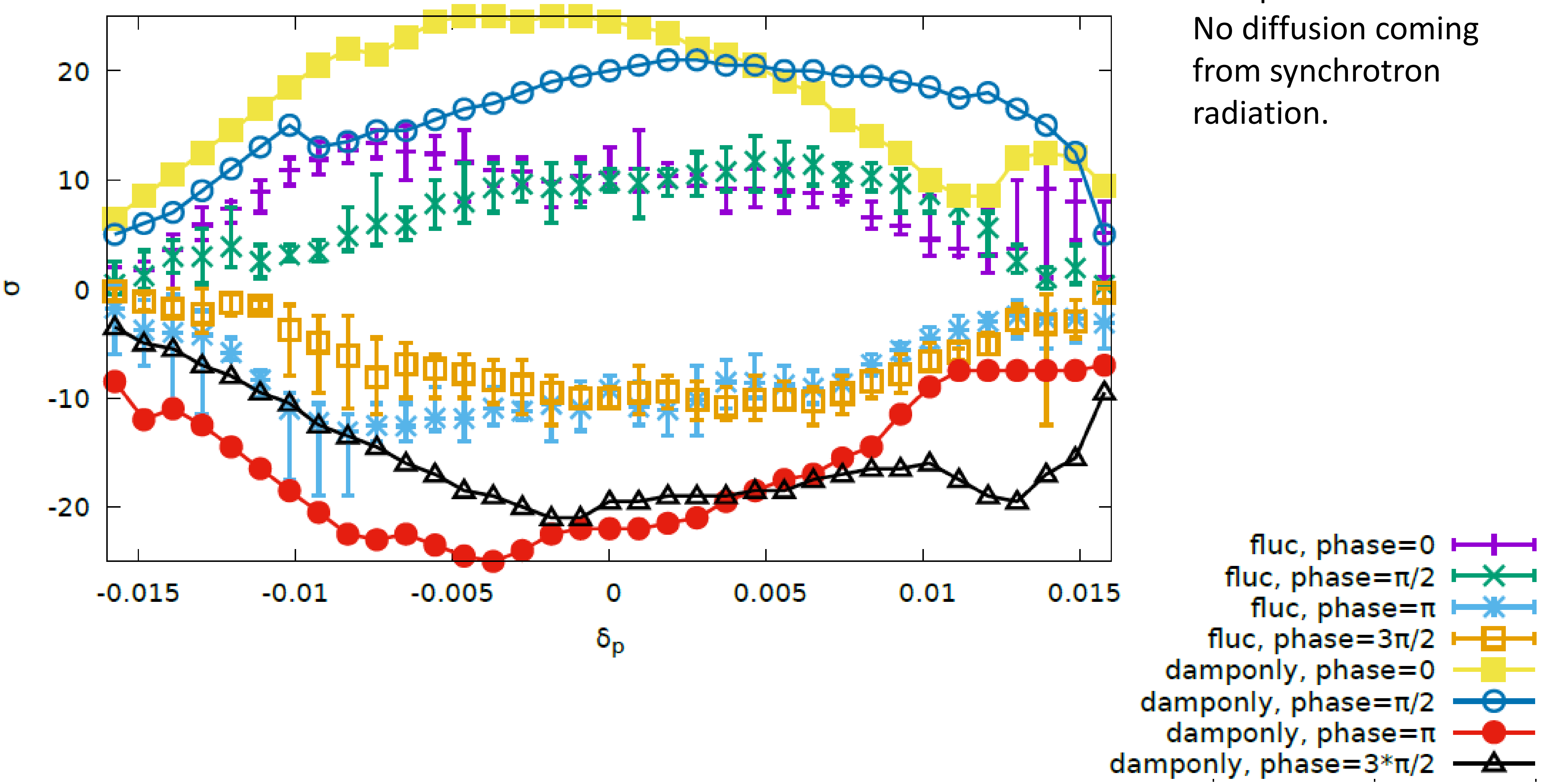
More sextupole configurations



Enlarge the DA about 1-σ on average

Optimize with DAMPONLY model

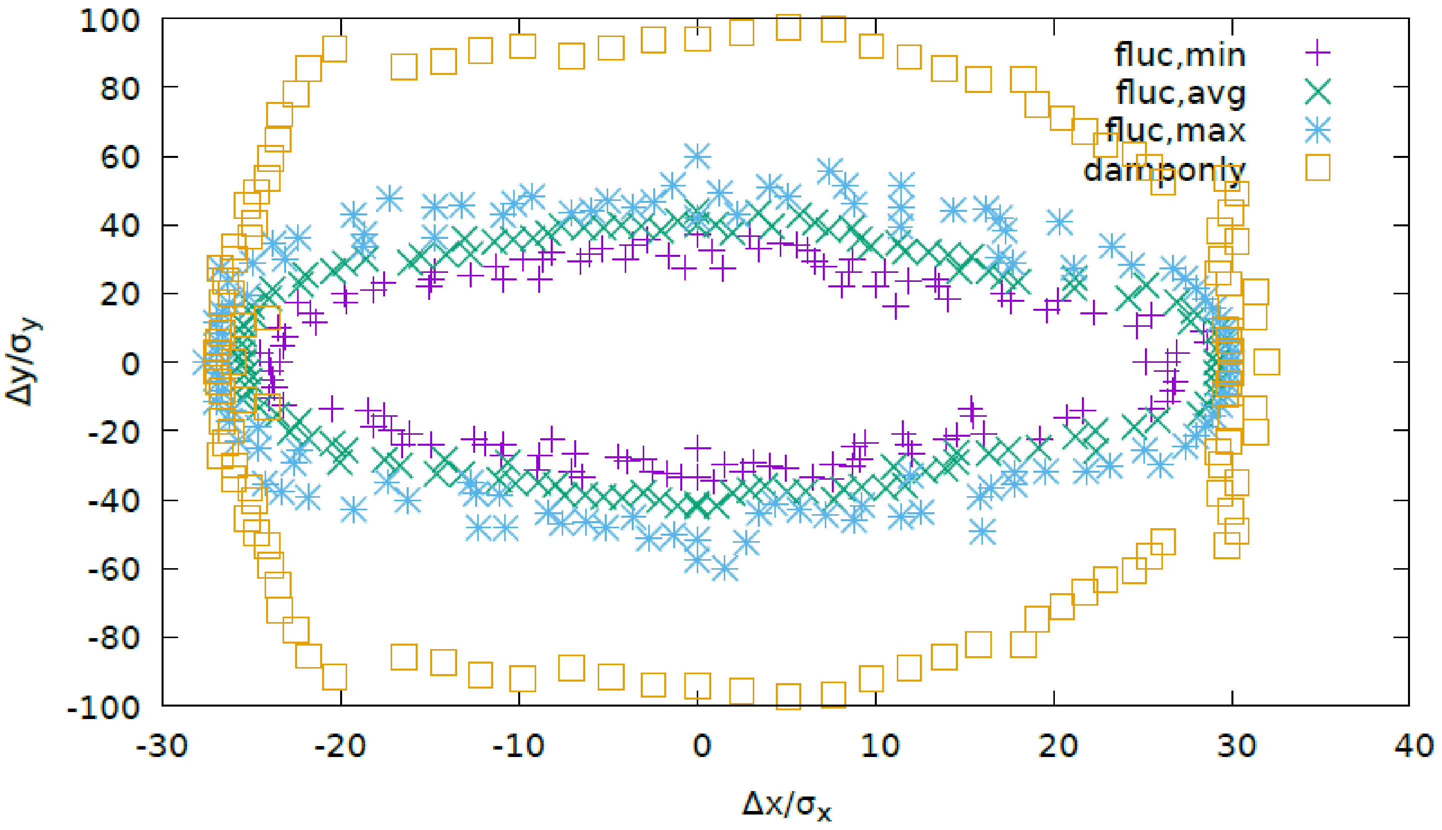
Damp at each element:
No diffusion coming
from synchrotron
radiation.



200 turns,
10 samples

Fluctuation Effect on the vertical dynamic aperture

Only serious DA loss in vertical direction.



On-Momentum DA with damping at each element and radiation fluctuation at each element.

Effect of Synchrotron Radiation in Quadrupoles

FODO Arc - Horizontal

- K. Oide, PRAB 19.111005
- Maximum momentum deviation
- $\Delta \mathrm{p} = \frac{\alpha_z}{\pi \nu_s J_z} R_Q n^2 \epsilon_x \exp(-\frac{\alpha_z}{4\nu_s})$
- $n \equiv \Delta x / \sigma_x$
- $R_Q = \frac{2\sqrt{2}}{\theta_c^2}\left(\frac{\sqrt{2}+1}{l_{\mathrm{QF}}} + \frac{\sqrt{2}-1}{l_{\mathrm{QD}}}\right)$
- α_Z and J_Z, the synchrotron damping rate and longitudinal damping partition number. $l_{\mathrm{QF,QD}}$ the lengths of the quadrupoles.

IR QD0 – Vertical

- A. Bogomyagkov (BINP), FCC-ee, Z

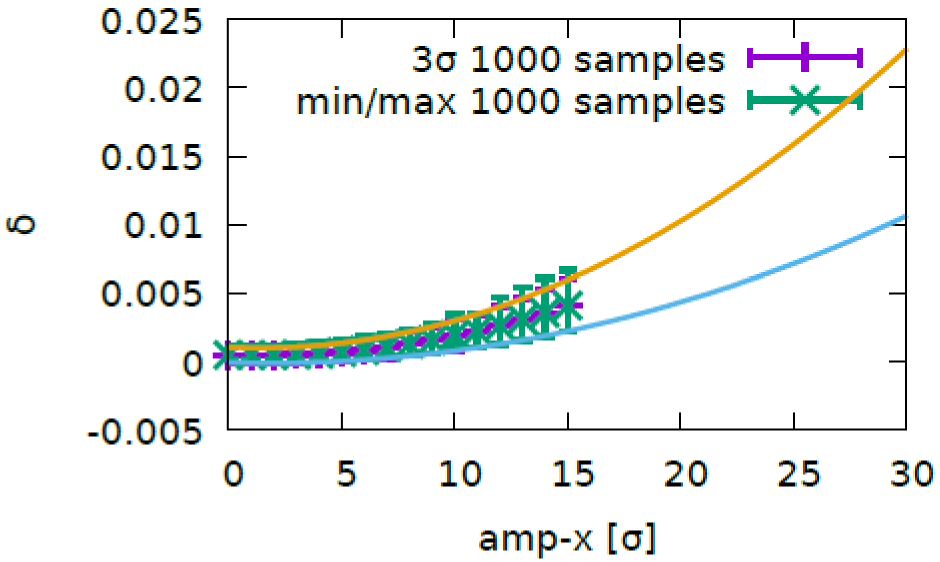
DA limit

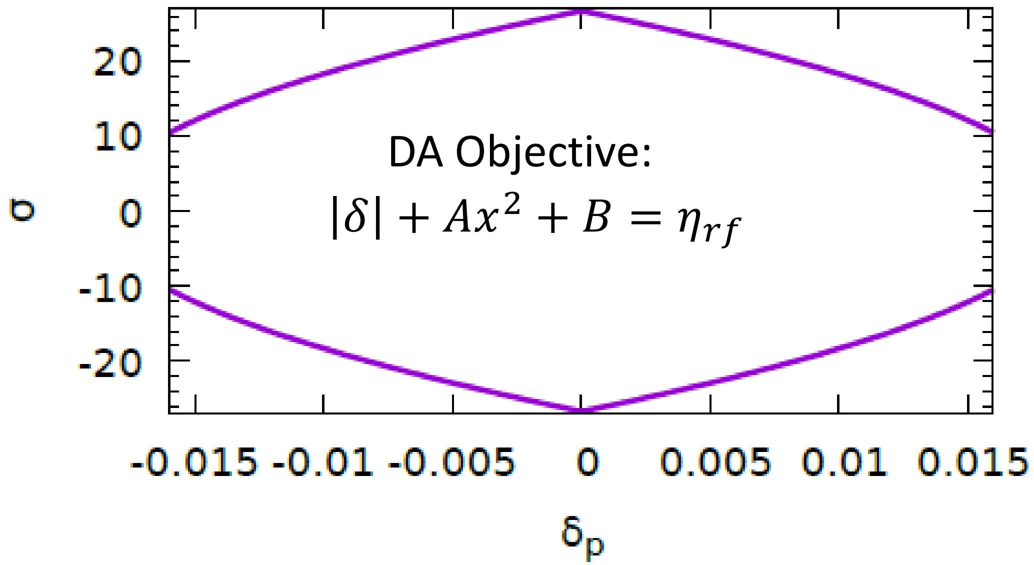
$$J_y' = 0$$

$$J_y = \frac{U_0}{U_q(\sigma_y)} \frac{4\sigma_{q,y}^2 k_y^2}{\cos(2\psi_q)\frac{\{\nu_y\}}{\nu_y}\left\langle \frac{-1+(\beta_y'/2)^2}{\beta_y} \right\rangle} \propto \frac{K_0^2}{K_1^2 L_q}$$

$$J_y \approx 50\sigma_y$$

Momentum deviation versus amplitude

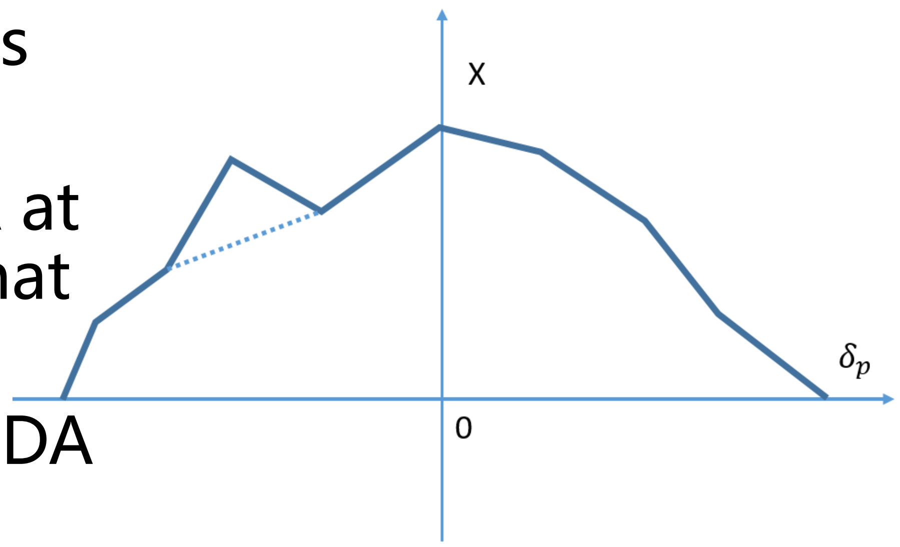




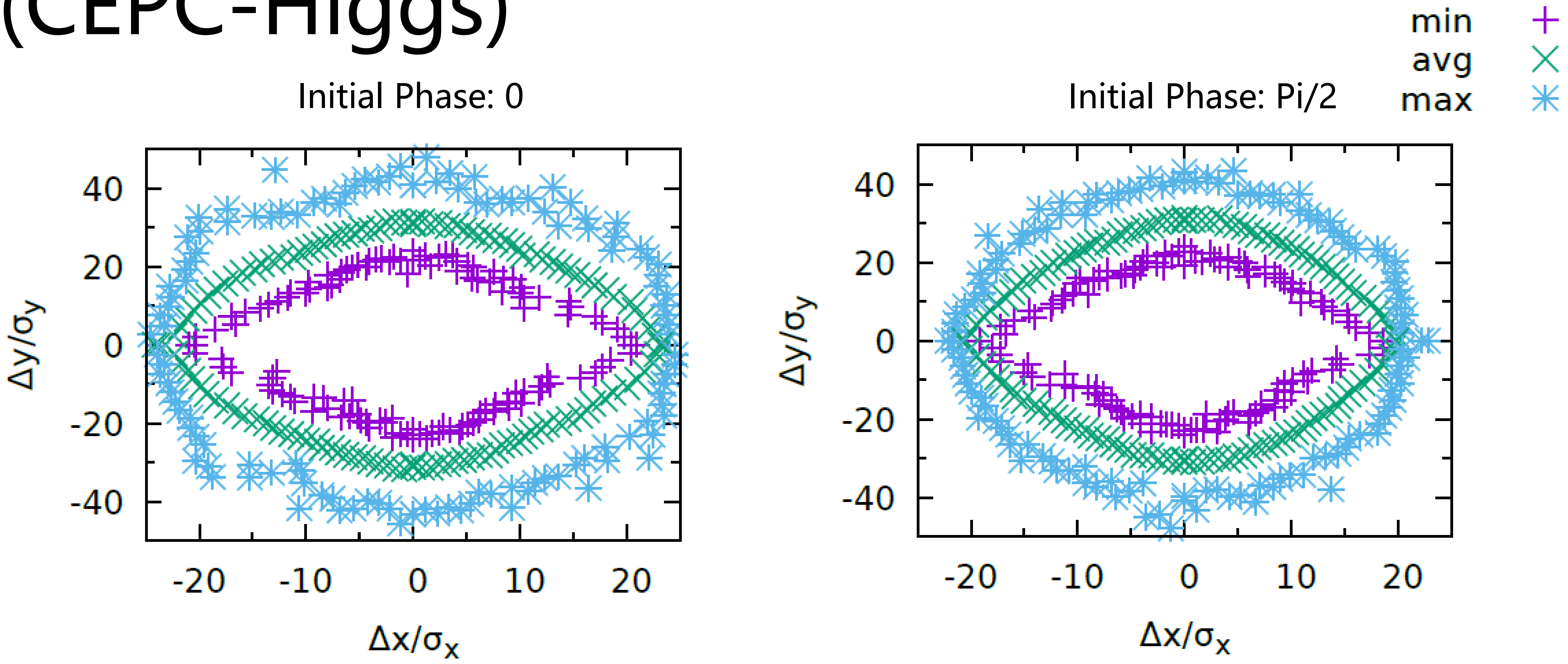
- This could explain why the DA with (FLUC) is flat versus δ
- For example, if we want to achieve $20\sigma@\delta = 0$, the DA should be also about $20\sigma@\delta = 0.01$

Suppress noise of DA result with radiation fluctuation

- DA is tracked with different initial phase: $\left(0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\right)$ for different energy
- 10 more times survey for on-momentum particle is tracked, and the minimum value is treated as the on-momentum DA
- Tracked DA result will be clipped to ensure DA at large momentum deviation will be less than that at small deviation
- Only two objective: min-DA of $(0, \pi)$ and min-DA of $\left(\frac{\pi}{2}, \frac{3\pi}{2}\right)$



On Momentum Dynamic Aperture (CEPC-Higgs)

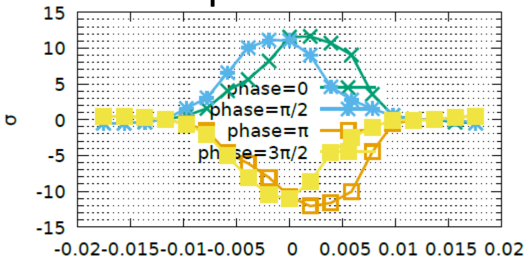


100 samples are tracked. 200 turns are tracked.

Synchrotron motion, synchtron radiation in dipoles, quads and sextupoles, tapering, Maxwellian fringes, kinematical terms, crab waist are included.

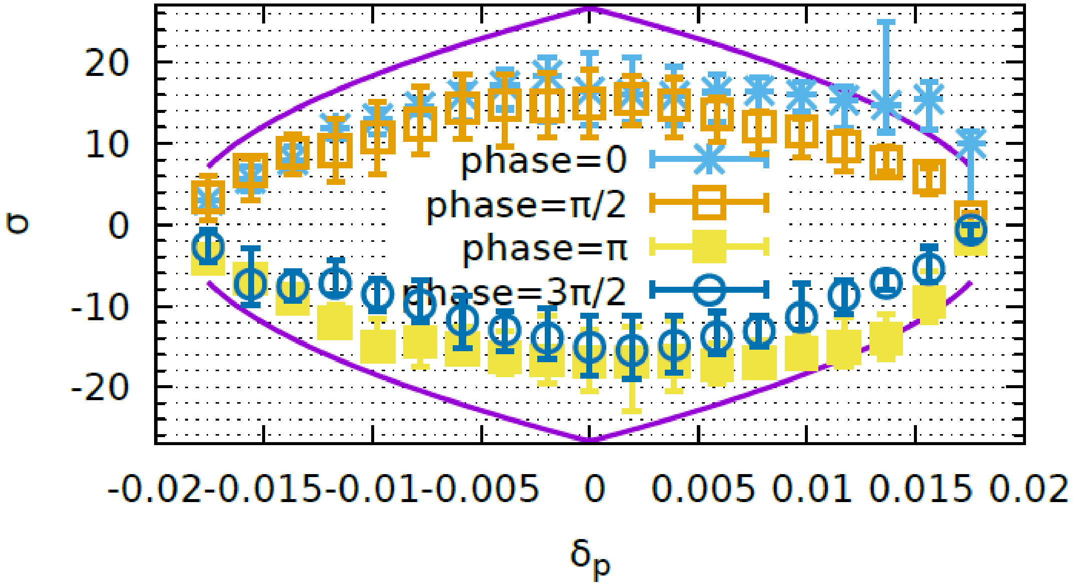
Off momentum Dynamic Aperture

W/O Optimization

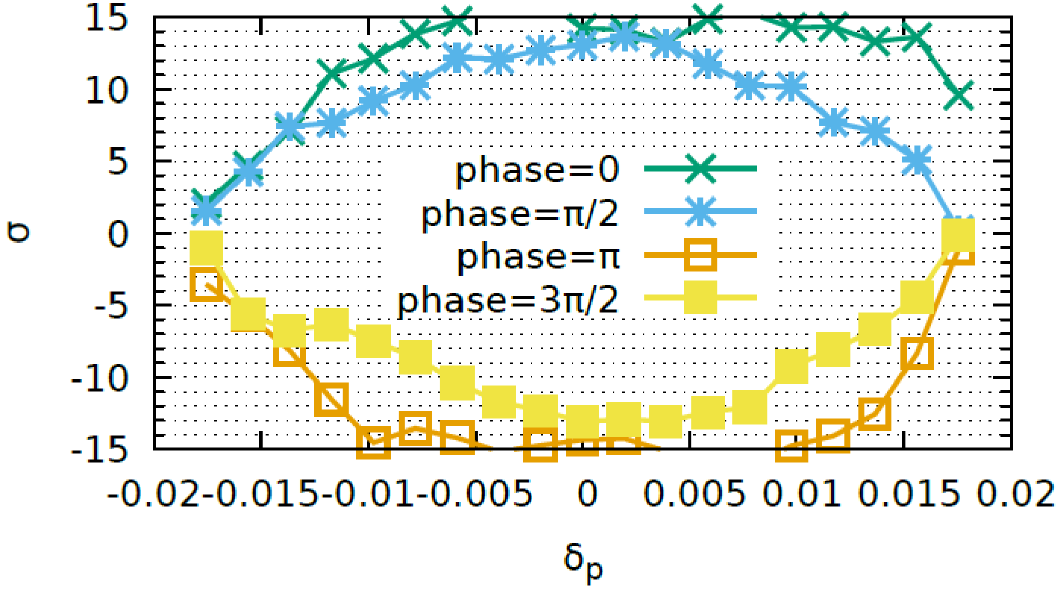


Momentum Acceptance: 0.017

Error bar means min and max

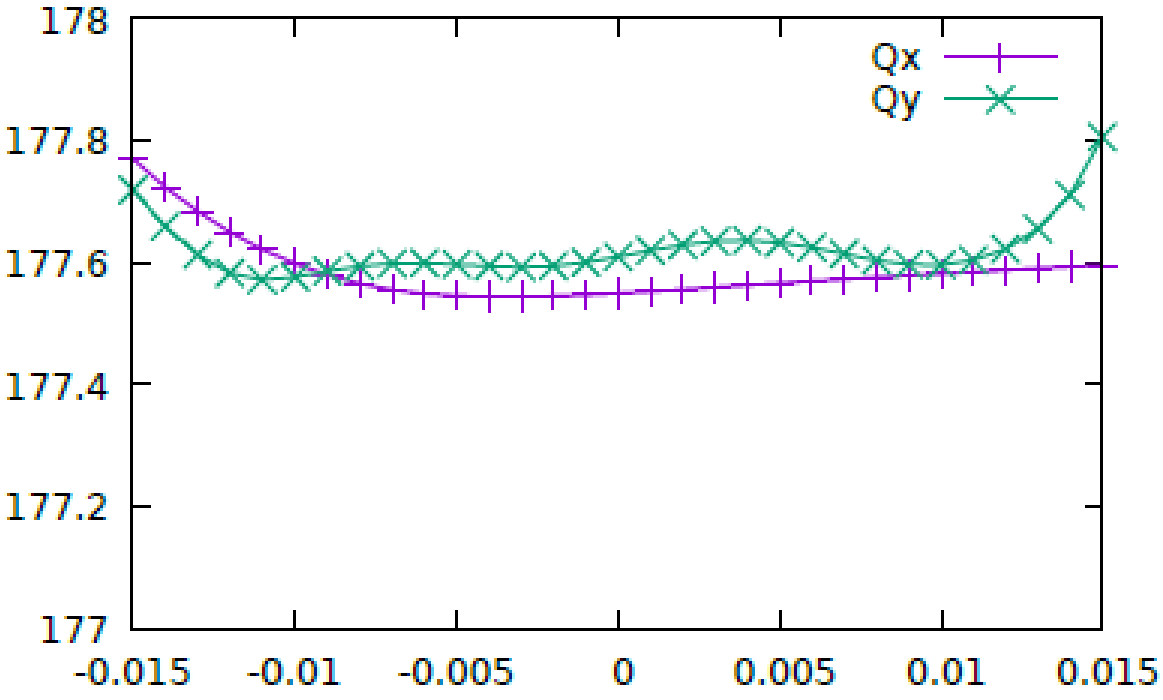


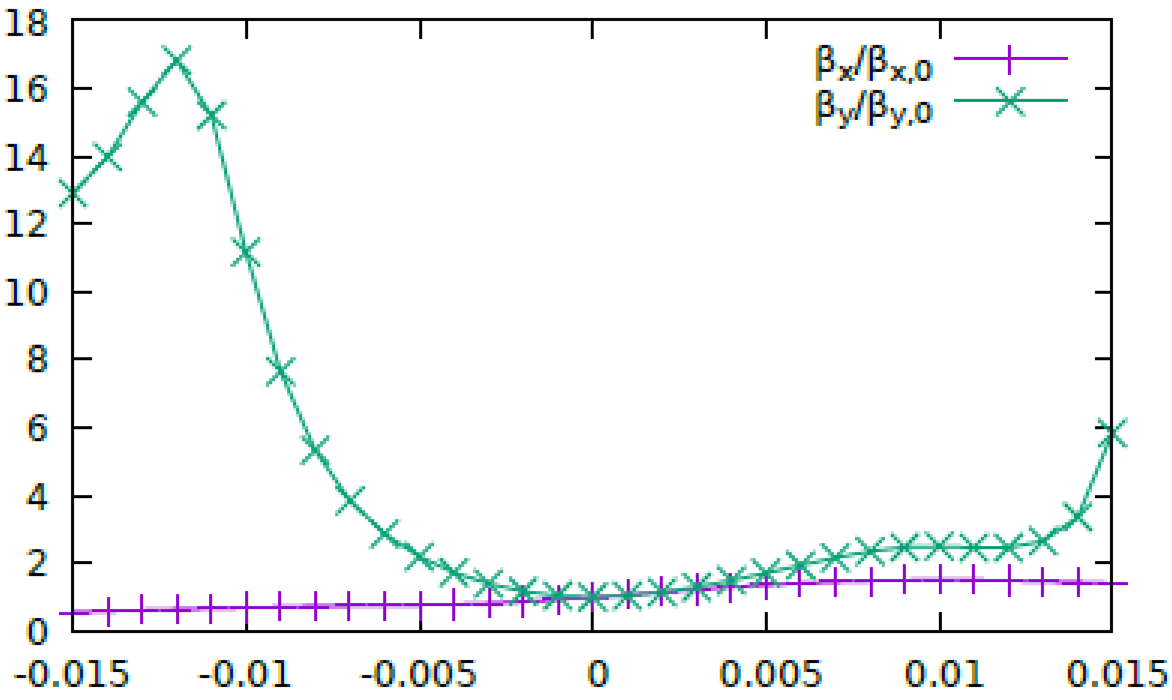
90% survival



100 samples. Radiation fluctuation is included. 0.3% emittance coupling. 200 turns are tracked.

Chromaticity





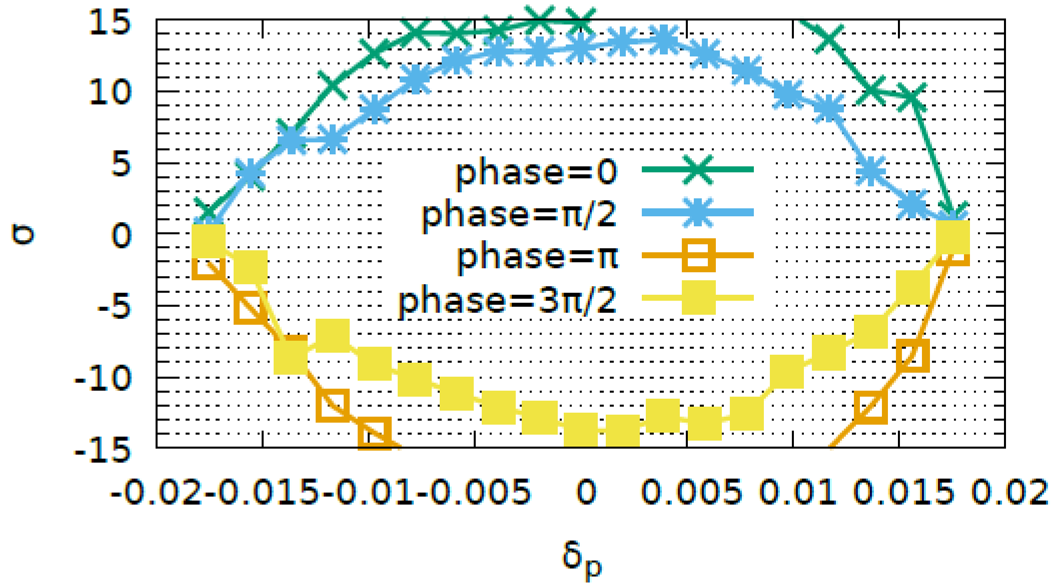
Crab Waist

$$K_2 = \frac{(-1)^m}{2\theta}\sqrt{\frac{\beta_{x,IP}}{\beta_{x,S}}}\frac{1}{\beta_{y,S}\beta_{y,IP}}$$

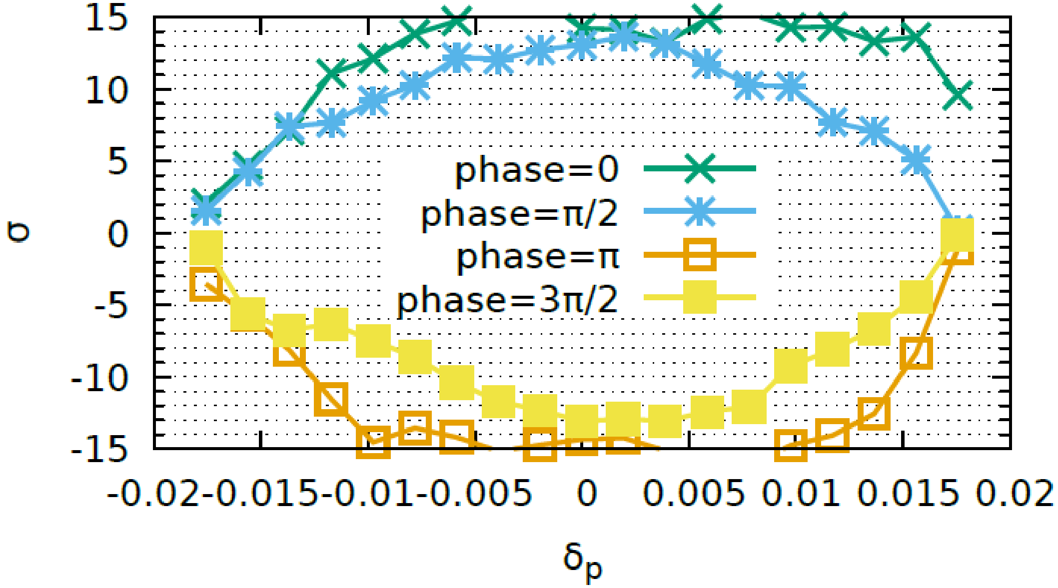
IP Downstream: K2 = 0.69 m^{-2}

IP Upstream: K2 =-0.69 m^{-2}

- 90% survival



CW=0



CW=1.0

Summary

- Mode is developed for CEPC DA optimization
- The normal procedure of optimization is established
- All effects (exception: beam-beam, error, solenoid) is included in the dynamic aperture survey
- DA achieved: $20\sigma_x$*$20\sigma_y$, 1.7% momentum acceptance

- backup

CEPC Parameters

	Higgs	*W*	*Z*
Number of IPs	2		
Energy (GeV)	120	80	45.5
Circumference (km)	100		
SR loss/turn (GeV)	1.68	0.33	0.035
Half crossing angle (mrad)	16.5		
Piwinski angle	2.75	4.39	10.8
N_e/bunch (10^{10})	12.9	3.6	1.6
Bunch number	286	5220	10900
Beam current (mA)	17.7	90.3	83.8
SR power /beam (MW)	30	30	2.9
Bending radius (km)	10.9		
Momentum compaction (10^{-5})	1.14		
β_{IP} x/y (m)	0.36/0.002		
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076
ξ_x/ξ_y/IP	0.024/0.094	0.009/0.055	0.005/0.0165
RF Phase (degree)	128	134.4	138.6
V_{RF} (GV)	2.14	0.465	0.053
f_{RF} (MHz) (harmonic)	650		
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.48	3.7	5.18
HOM power/cavity (kw)	0.46 (2cell)	0.32(2cell)	0.11(2cell)
Energy spread (%)	0.098	0.066	0.037
Energy acceptance requirement (%)	1.21		
Energy acceptance by RF (%)	2.06	1.48	0.75
Photon number due to beamstrahlung	0.25	0.11	0.08
Lifetime due to beamstrahlung (hour)	1.0		
F (hour glass)	0.93	0.96	0.986
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.0	4.1	1.0