Application of Differential Evolution Algorithm in Future Circular Colliders

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Outline

- Introduction
- Differential Evolution Algorithm
- Application in CEPC & SuperKEKB
- 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, in this proceeding
  - …

Different Algorithm

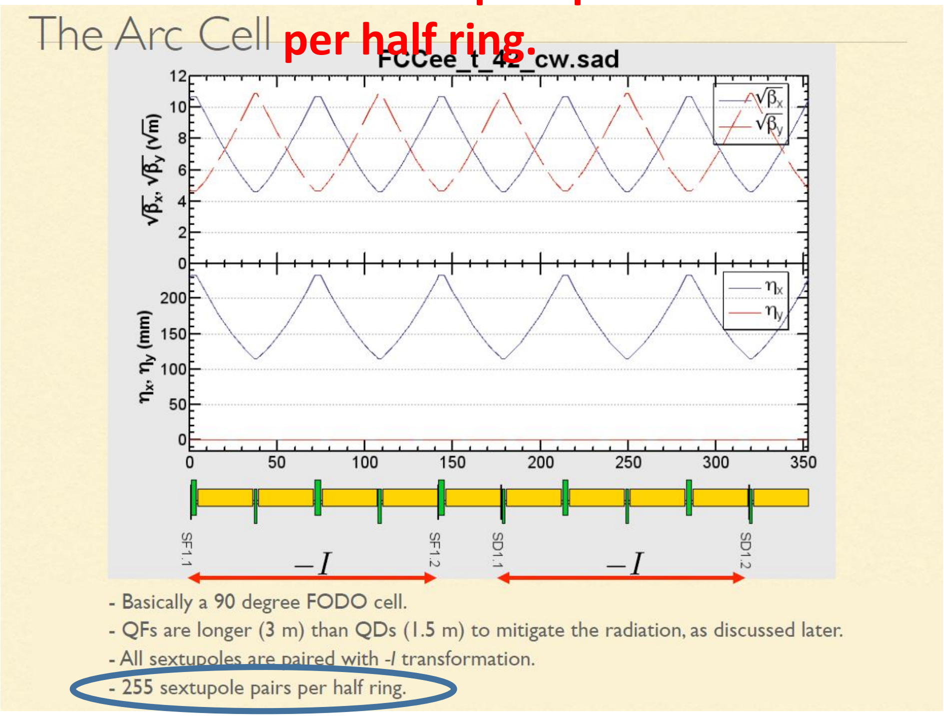
- Particle Swarm, SPEAR3, X. Huang, J. Safranek, Nucl. Instr. Meth. In Phys. Research A. 757, 48, 2014
- Differential Evolution, J. Qiang *et al.,* IPAC'13
- Downhill Simplex, SuperKEKB, FCC, K. Oide *et al.*
- …….

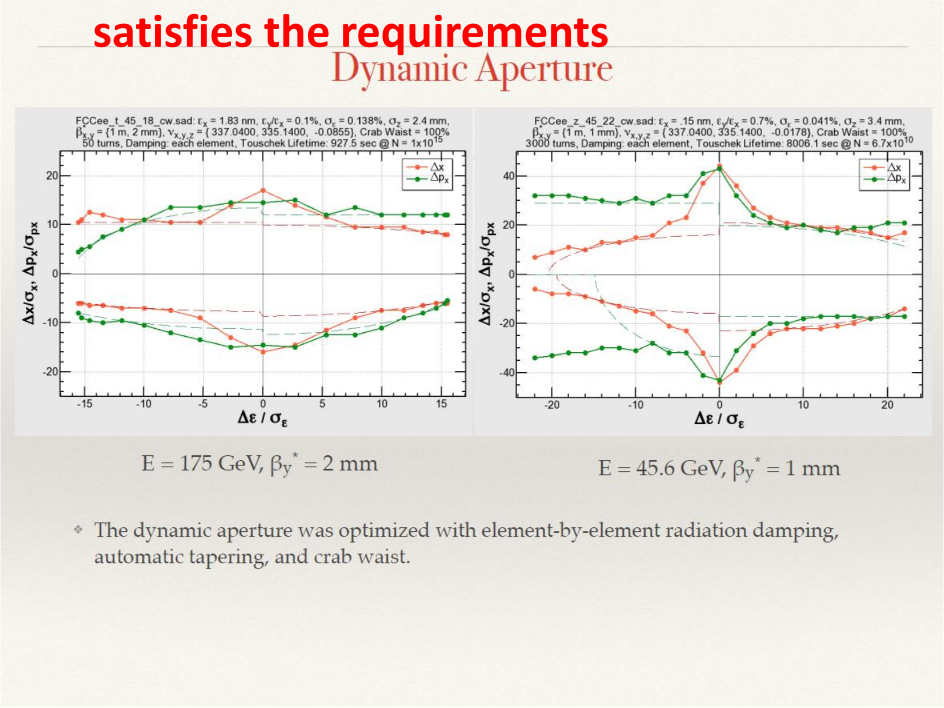
Excitation

- 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?

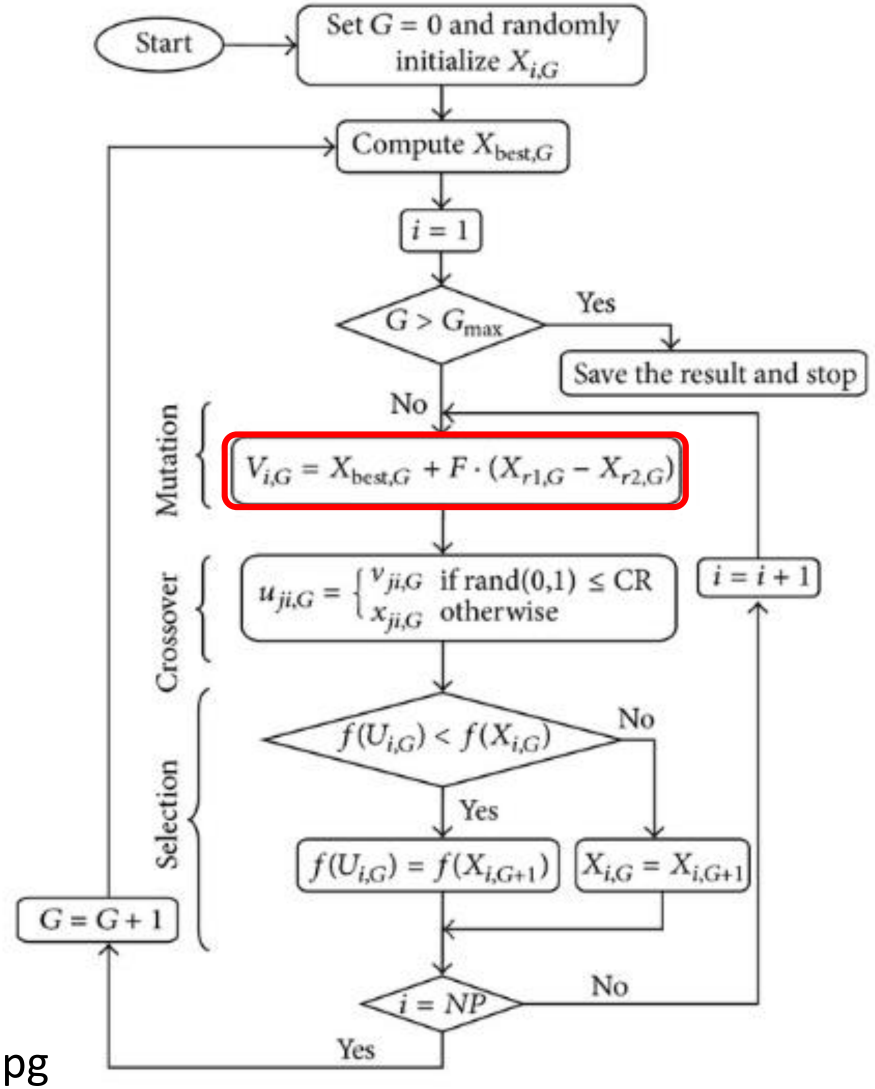
- We need to optimize the DA of CEPC
- We want to try the direct DA optimization in collider, just as the community has done in light source
- Different optimization algorithm is worth to be used
- SAD(http://acc-physics.kek.jp/sad/) is used for the DA determination. It is a parallel code, but the scalability 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.

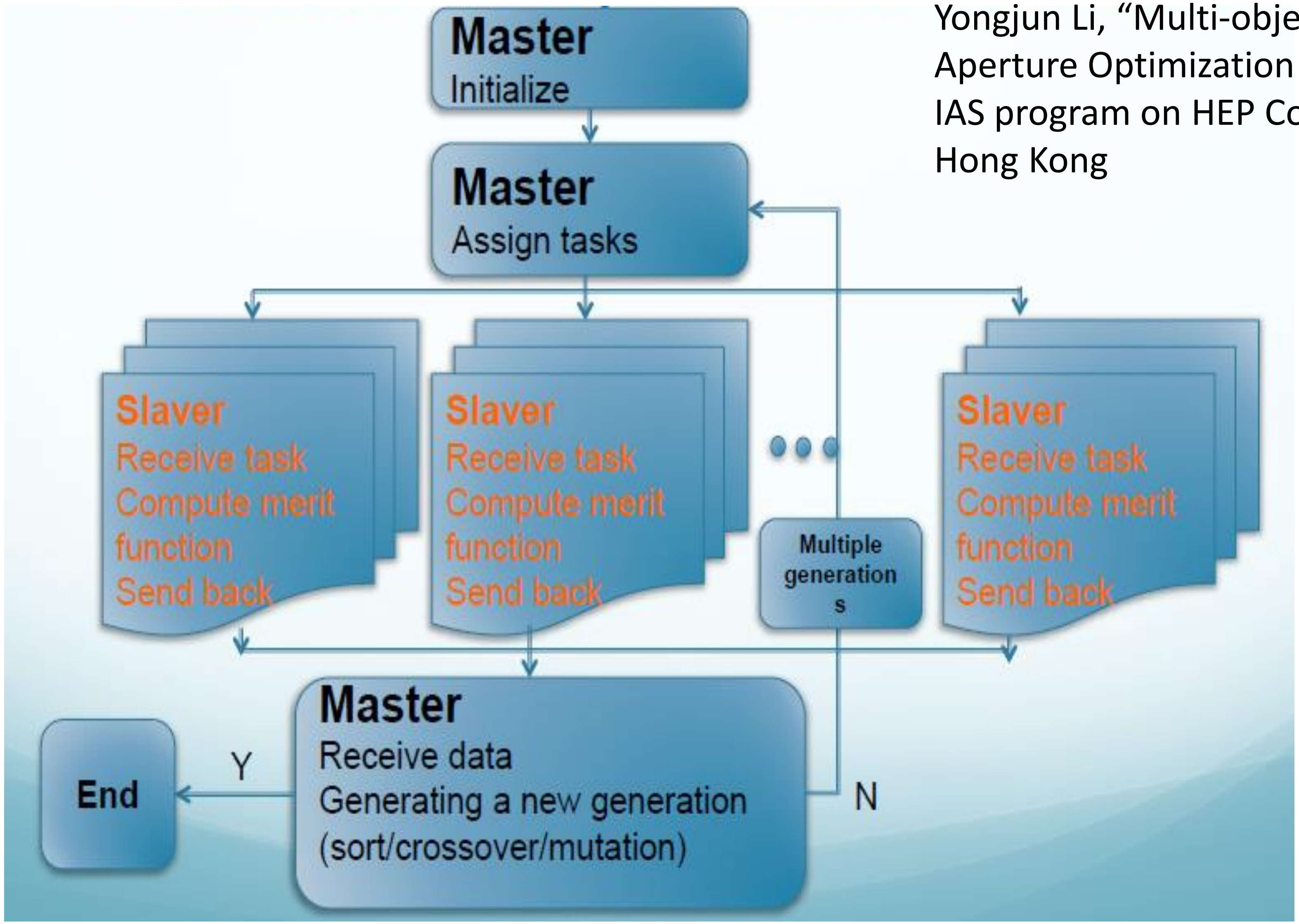
$$\mathrm{v(i,j)} = \begin{cases} x(i,j) + F \times [x(b,j) - x(i,j)] + F \times [x(r1,j) - x(r2,j)], & If\ rand(j) < CR \\ x(i,j), & Otherwise \end{cases}$$

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



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

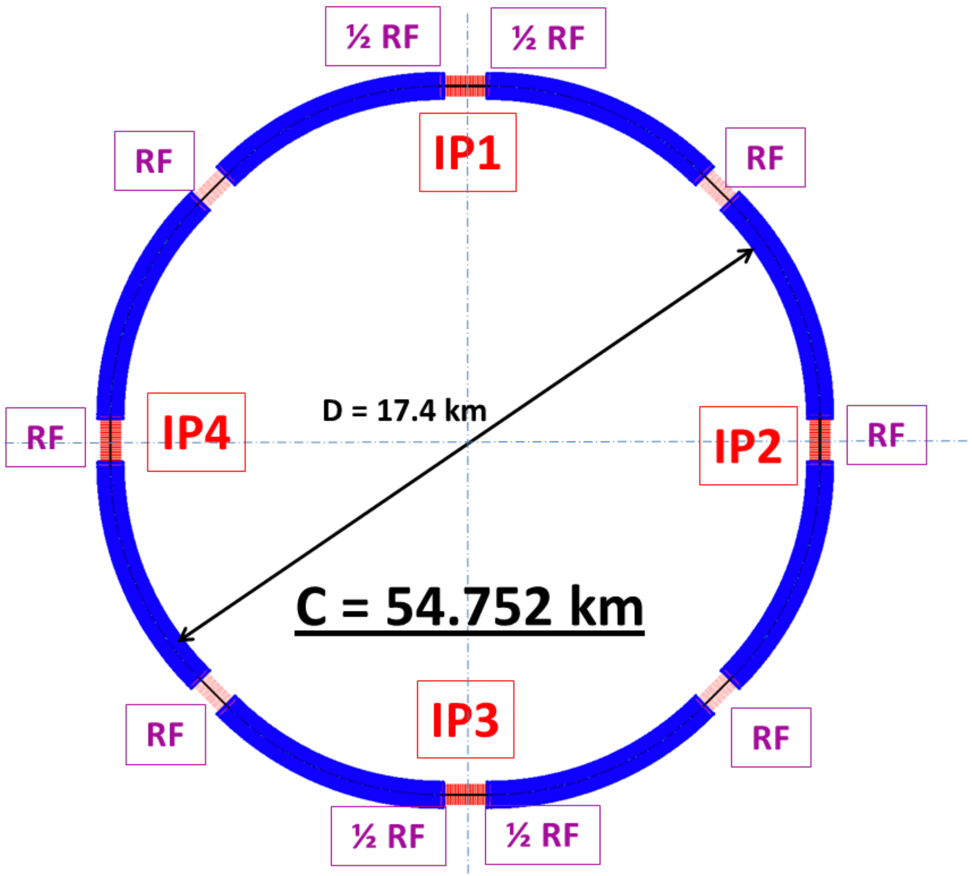
Parallel Computation



Yongjun Li, "Multi-objective Dynamic Aperture Optimization for NSLS-II Ring", IAS program on HEP Conference 2016, Hong Kong

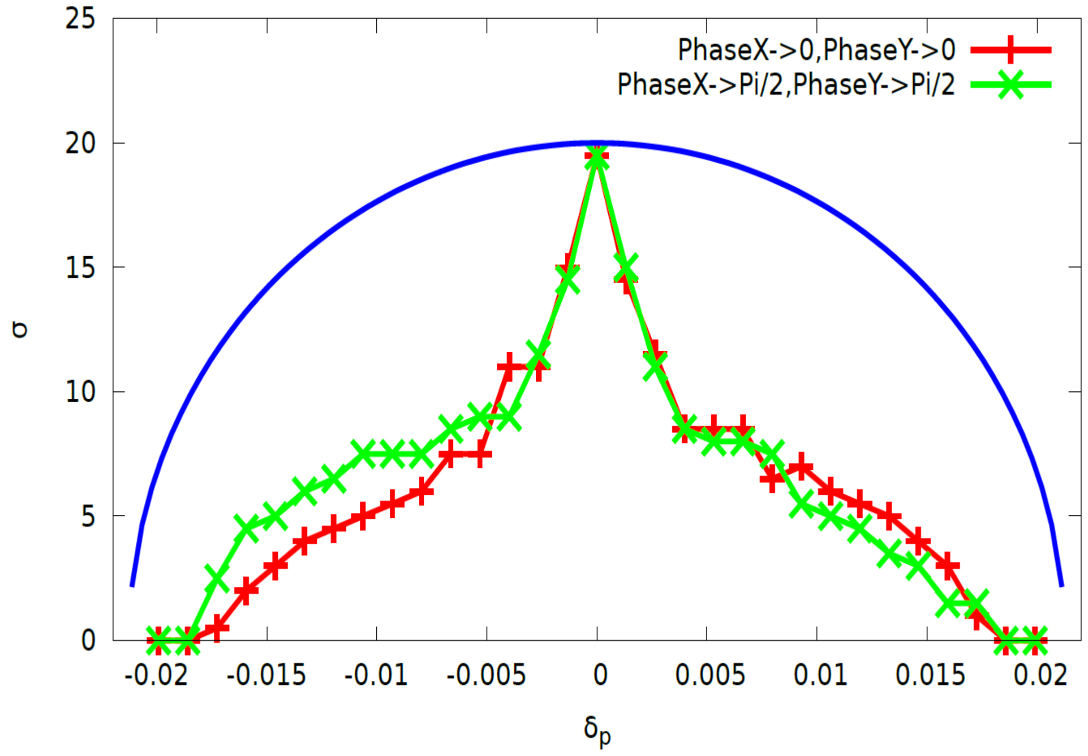
CEPC (PreCDR)

- Beam energy: 120GeV
- Circumference: 54 km
- SR power: 51.7 MW/beam
- 8*arcs, 2*Ips
- Luminosity: 2e34/IP
- Emittance X/Y: 6.12/0.018 nmrad
- β_x^*/β_y^*=0.8m/1.2mm
- FODO cell: 47.2m, 60/60 degrees
- Damping time: 78/78/39 turns
- Dynamic Aperture: $20\sigma_x \times 40\sigma_y \times 0.02$



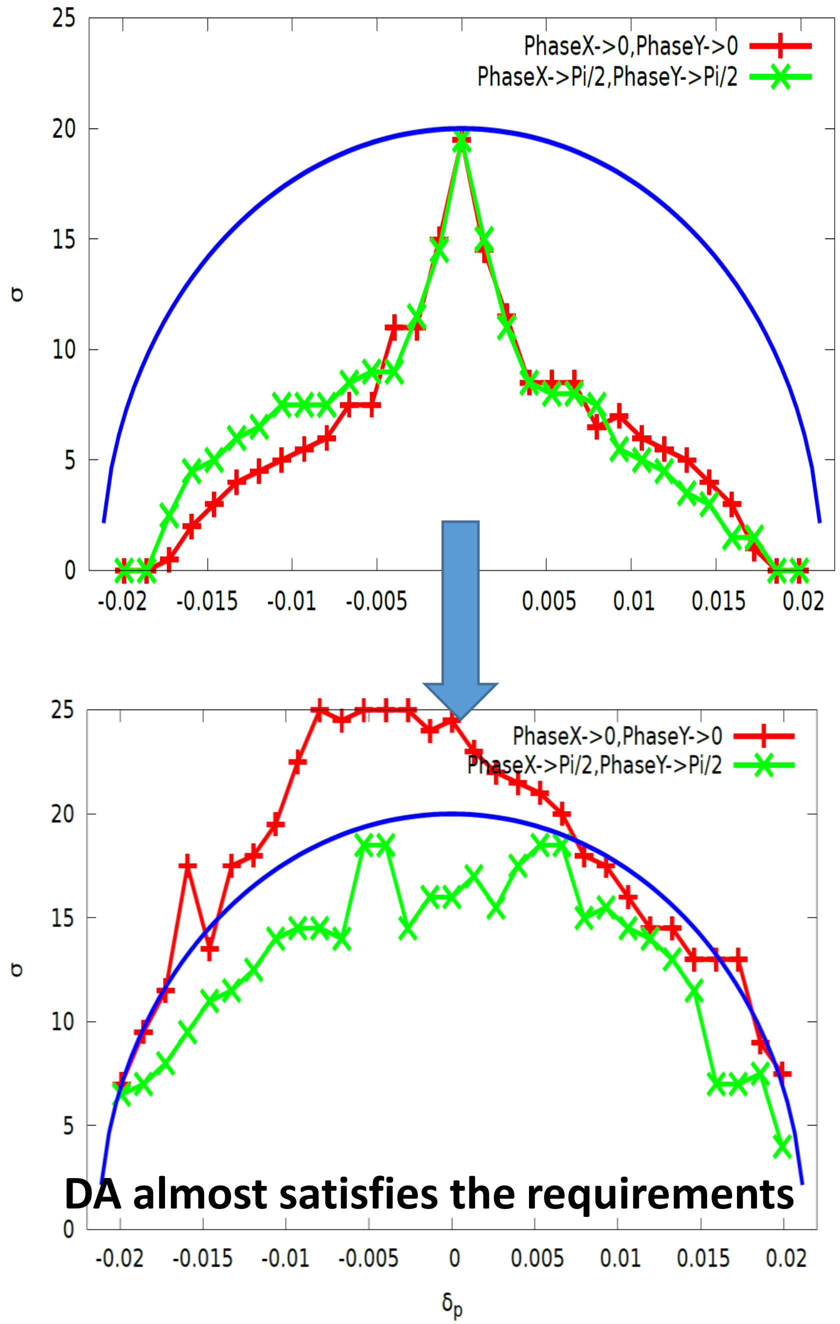
Case of CEPC

- Before optimization:
  One SF/SD family in arc
- Initial IR optimization
  (by Y. Wang, Mar 2015)
- β_x^*/β_y^*=0.8m/3mm
- Without pretzel scheme
- No solenoid and compensation

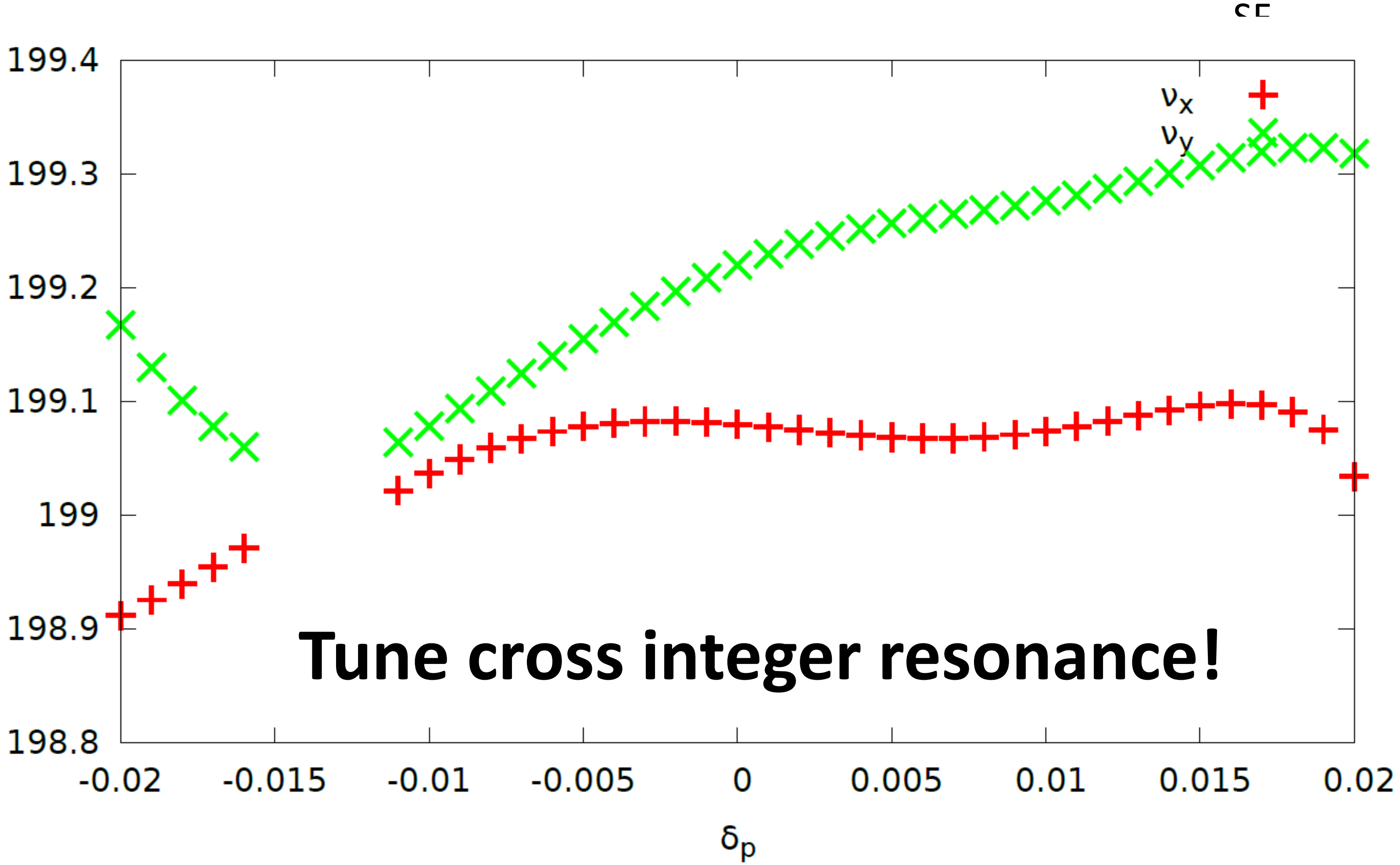


CEPC: Dynamic Aperture Optimization

- DA Objective: $\frac{x^2}{20^2} + \frac{z^2}{16^2} = 1$
  - z for energy deviation in unit of σ_p
  - x for transverse amplitude in unit of σ
- Variables: 240 sextupole familiy in arc
  - Sextupoles interleaved with $-I$ map is one pair
- Options:
  - DAPWIDTH=15
  - Turns = 100
  - Synchrotron oscillation on

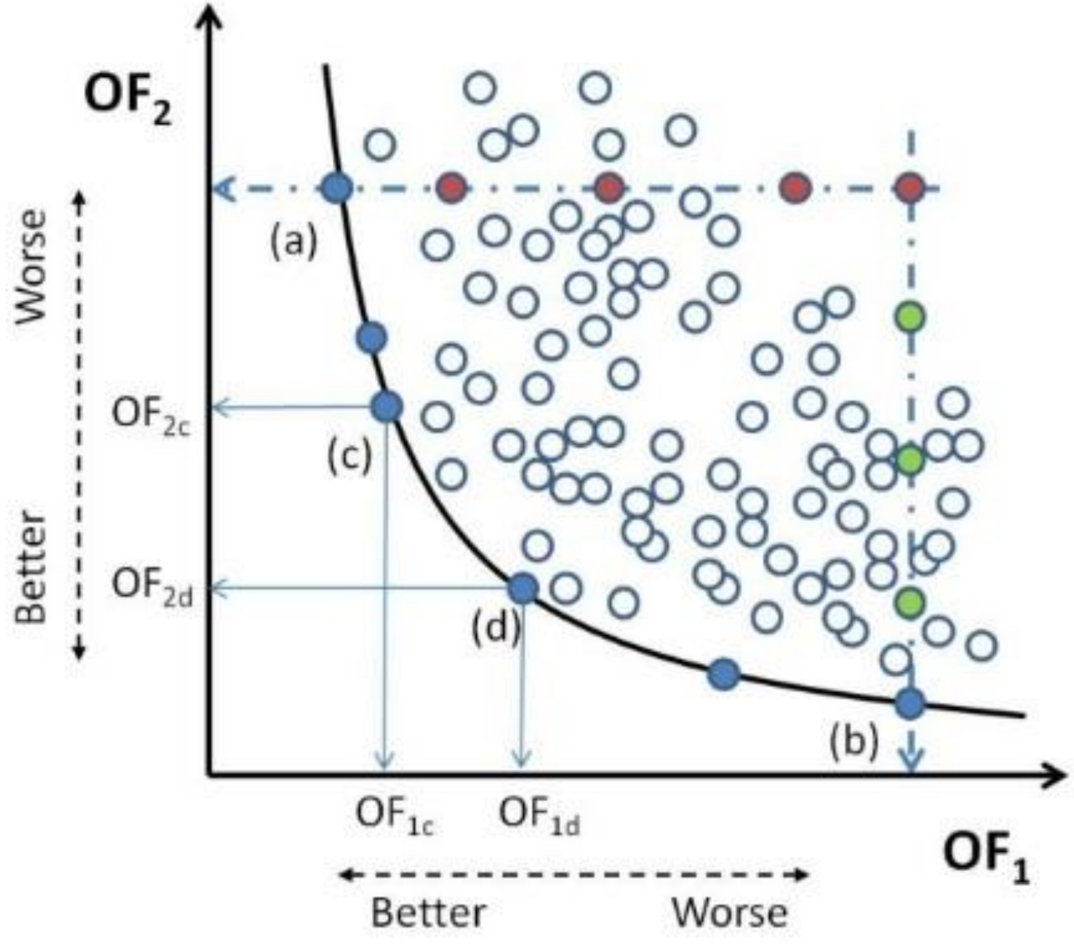


CEPC: Dynamic Aperture Optimization (2)



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

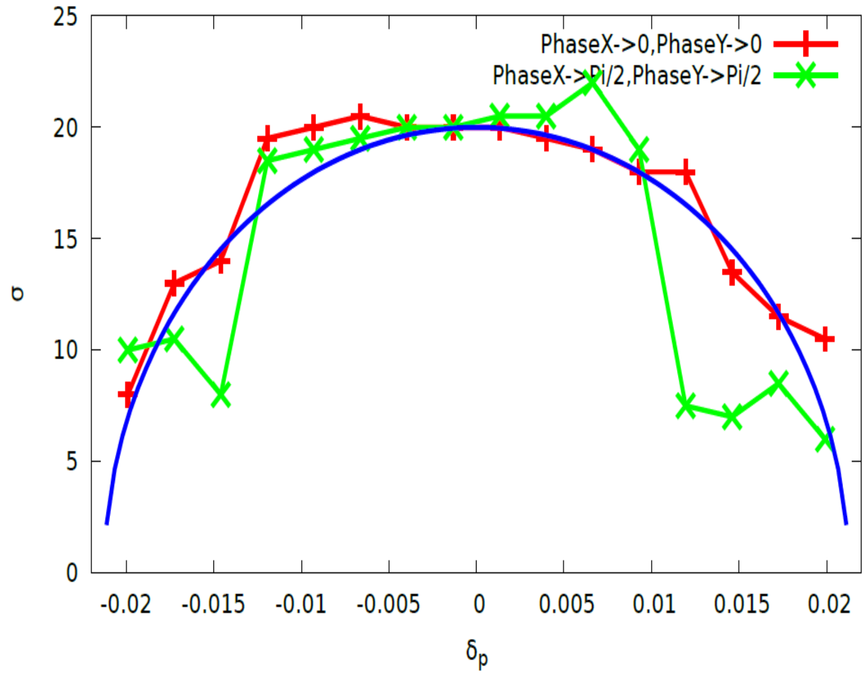
MODE:
Multi-Objective optimization by Differential Evolution

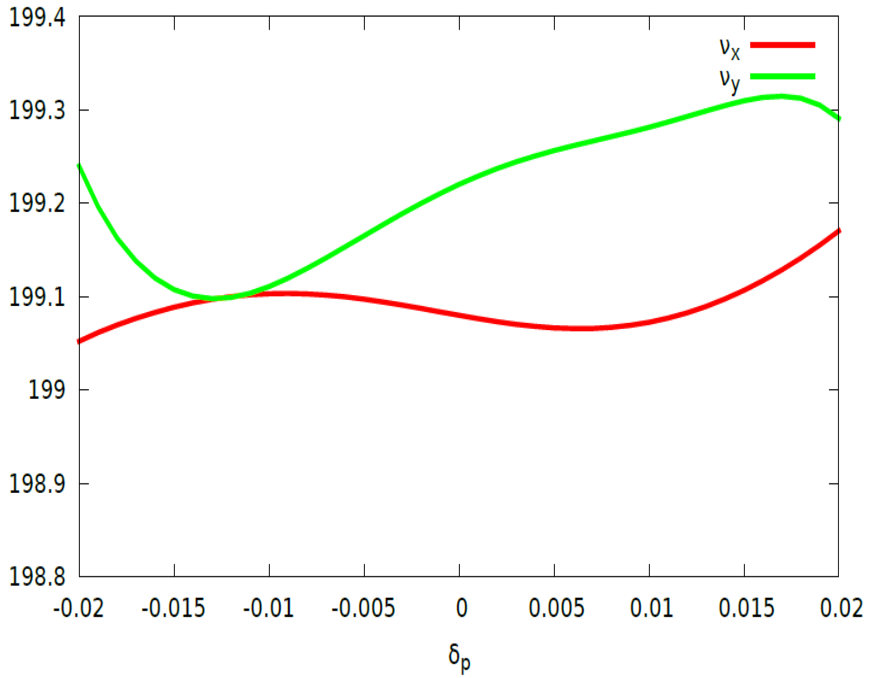
The parallel algorithm is referencing to J. Qiang(IPAC’13)

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

Multi-Objective Optimization of CEPC

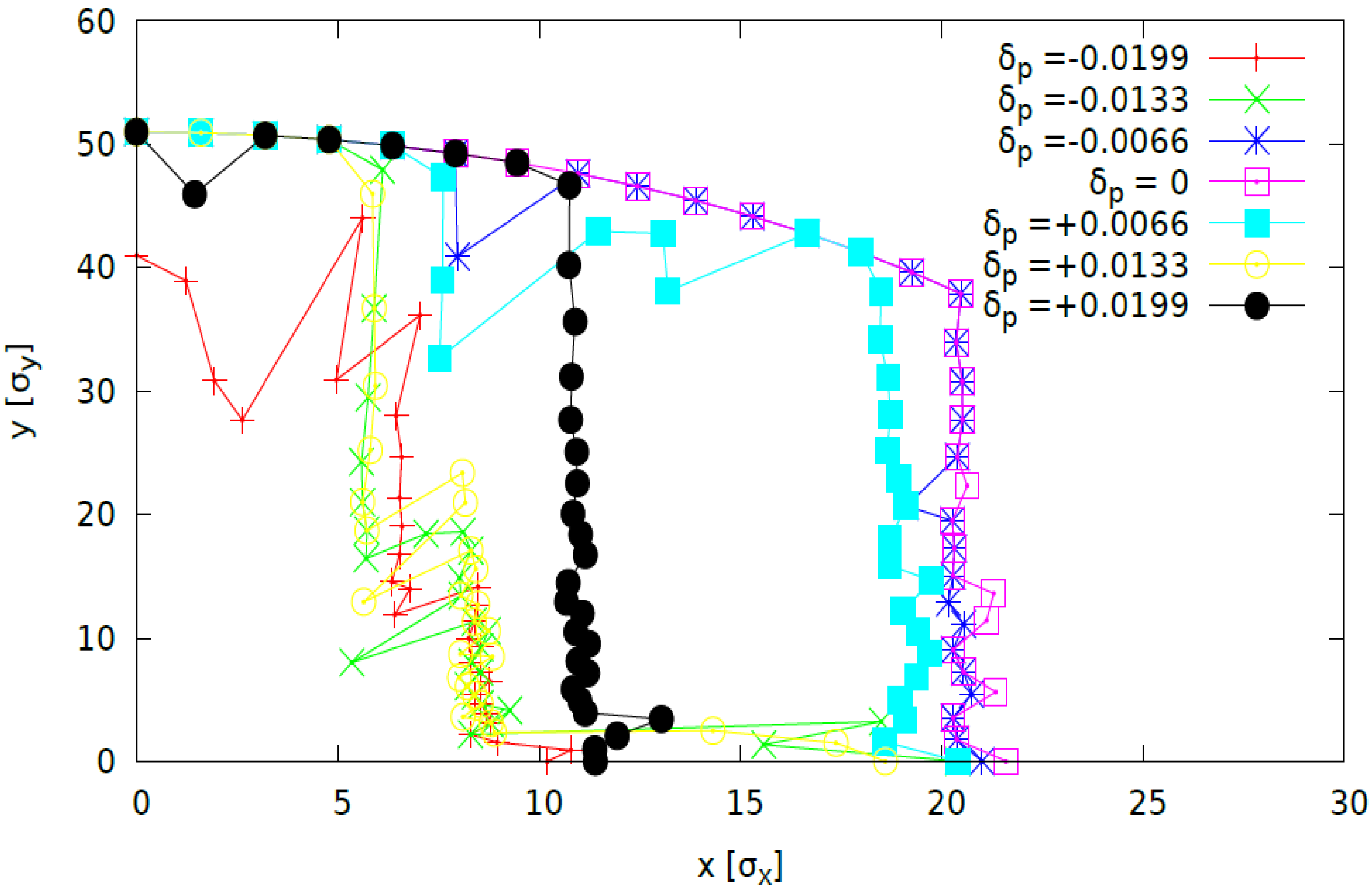
- Objectives:
  - $\nu_x \in (0.05, 0.31), \nu_y \in (0.10, 0.31)$, for $\delta_p \in (-0.02, 0.02)$, with $\nu_{x0} = 0.08, \nu_{y0} = 0.12$
  - $\frac{x^2}{20^2} + \frac{z^2}{16^2} = 1$, for z=Range[-15,15,1]
  - Options: DAPWIDTH=30, turns=200





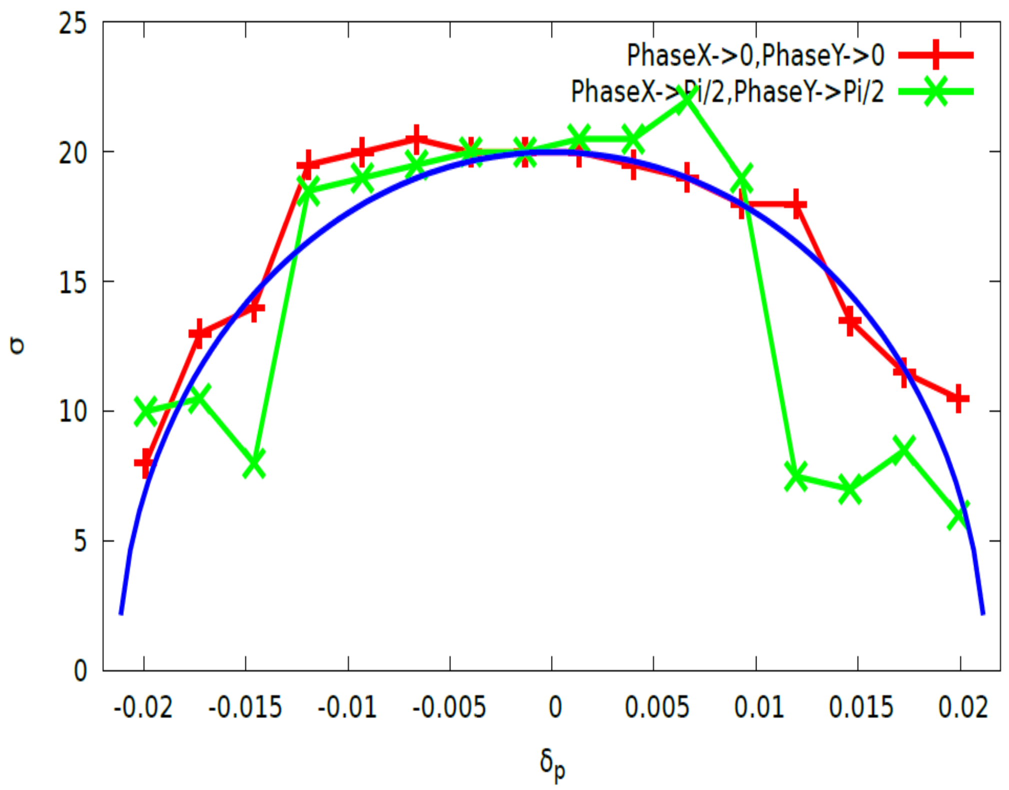
Multi-Objective Optimization of CEPC

The dynamic aperture required in X-Y space not satisfying

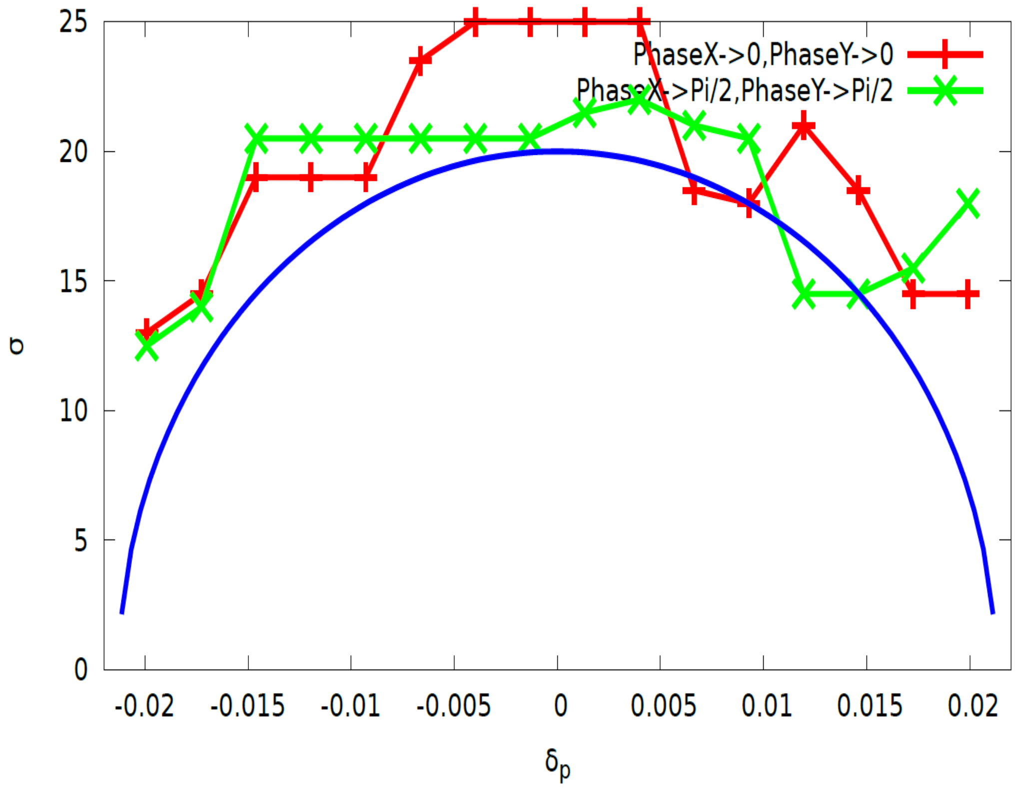


Dynamic Aperture with Damping

Synchrotron oscillation

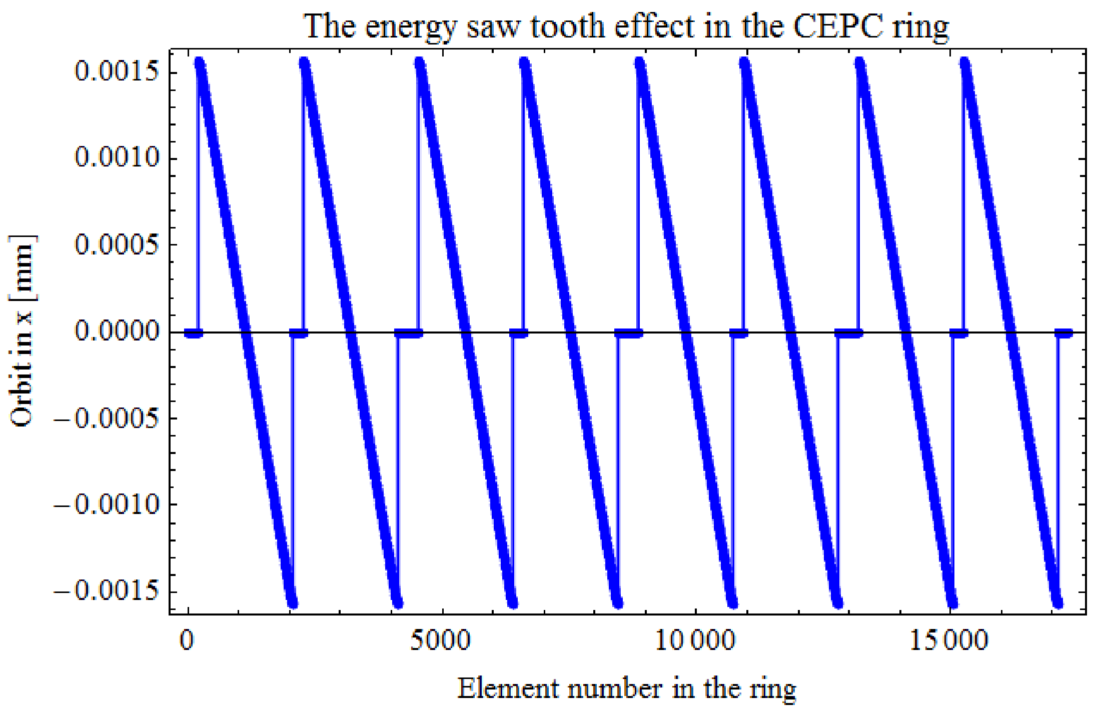


Synchrotron oscillation
Radiation damping

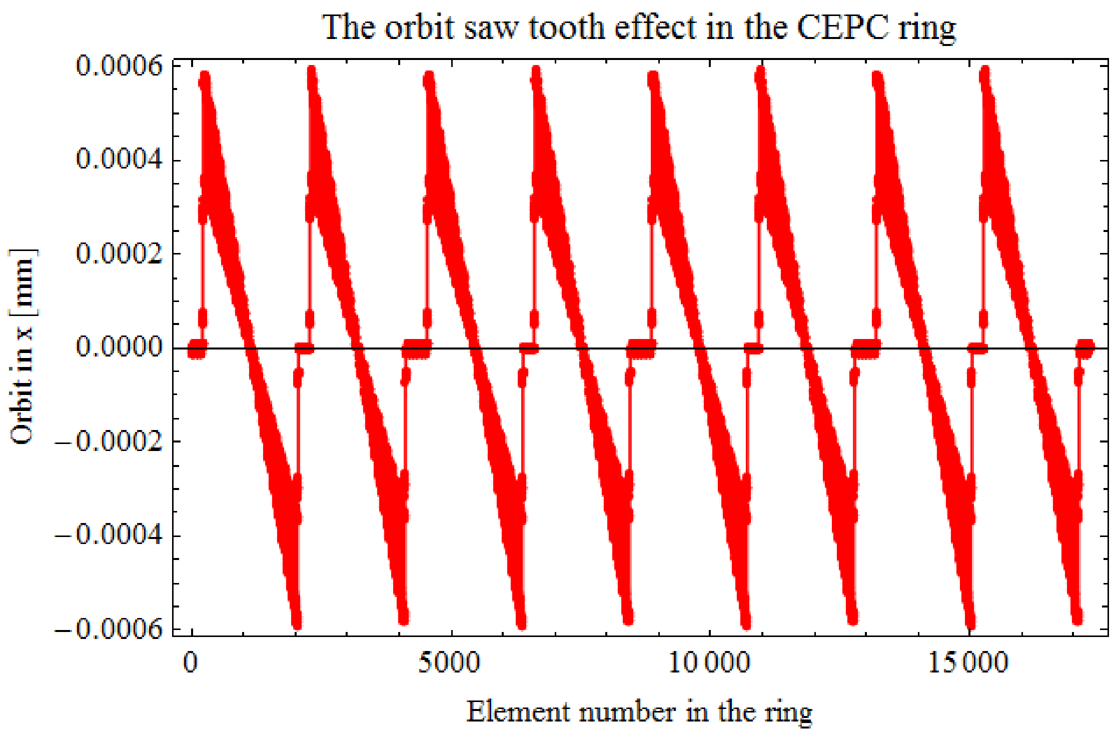


Sawtooth effect without FFS

- Energy sawtooth amplitude 0.15%



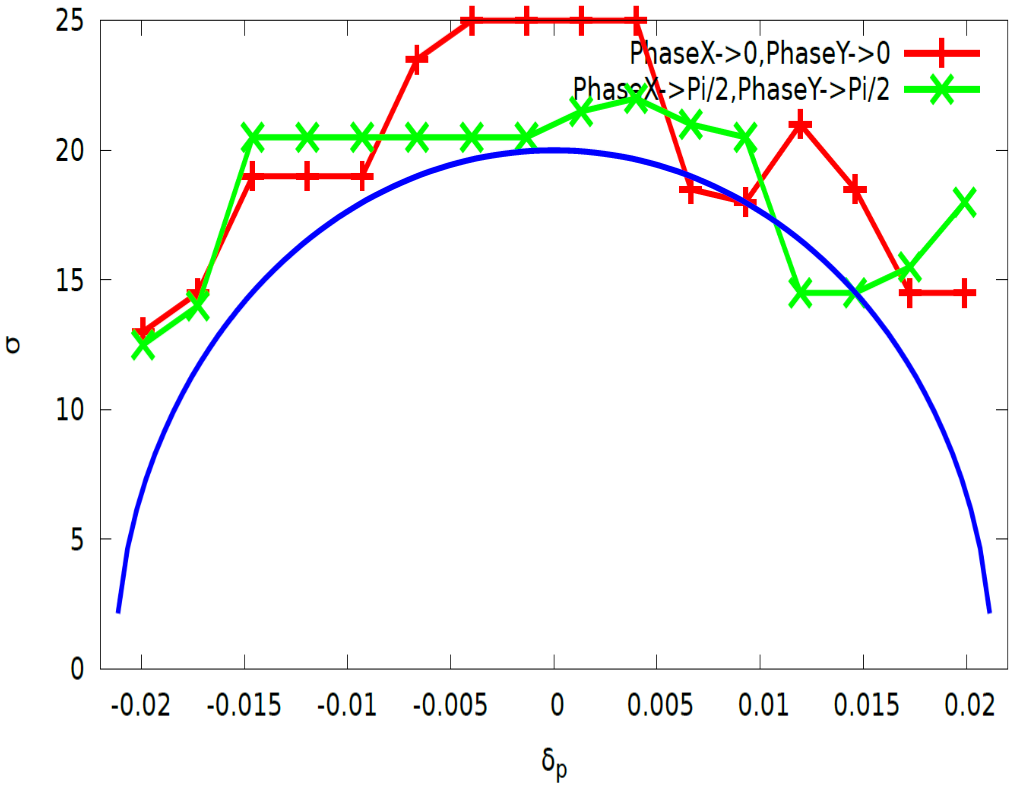
- Orbit sawtooth amplitude 0.6mm



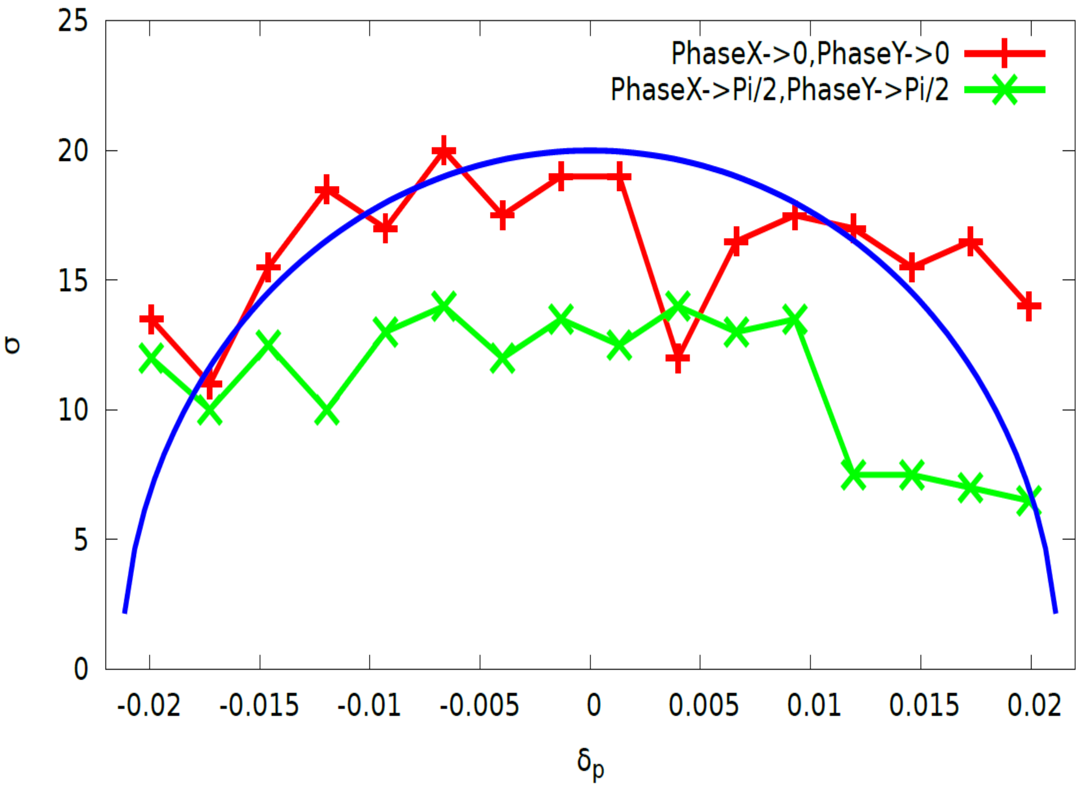
Courtesy of Huiping Geng@IHEP

Dynamic Aperture with Damping & Fluctuation

Synchrotron oscillation
Radiation damping

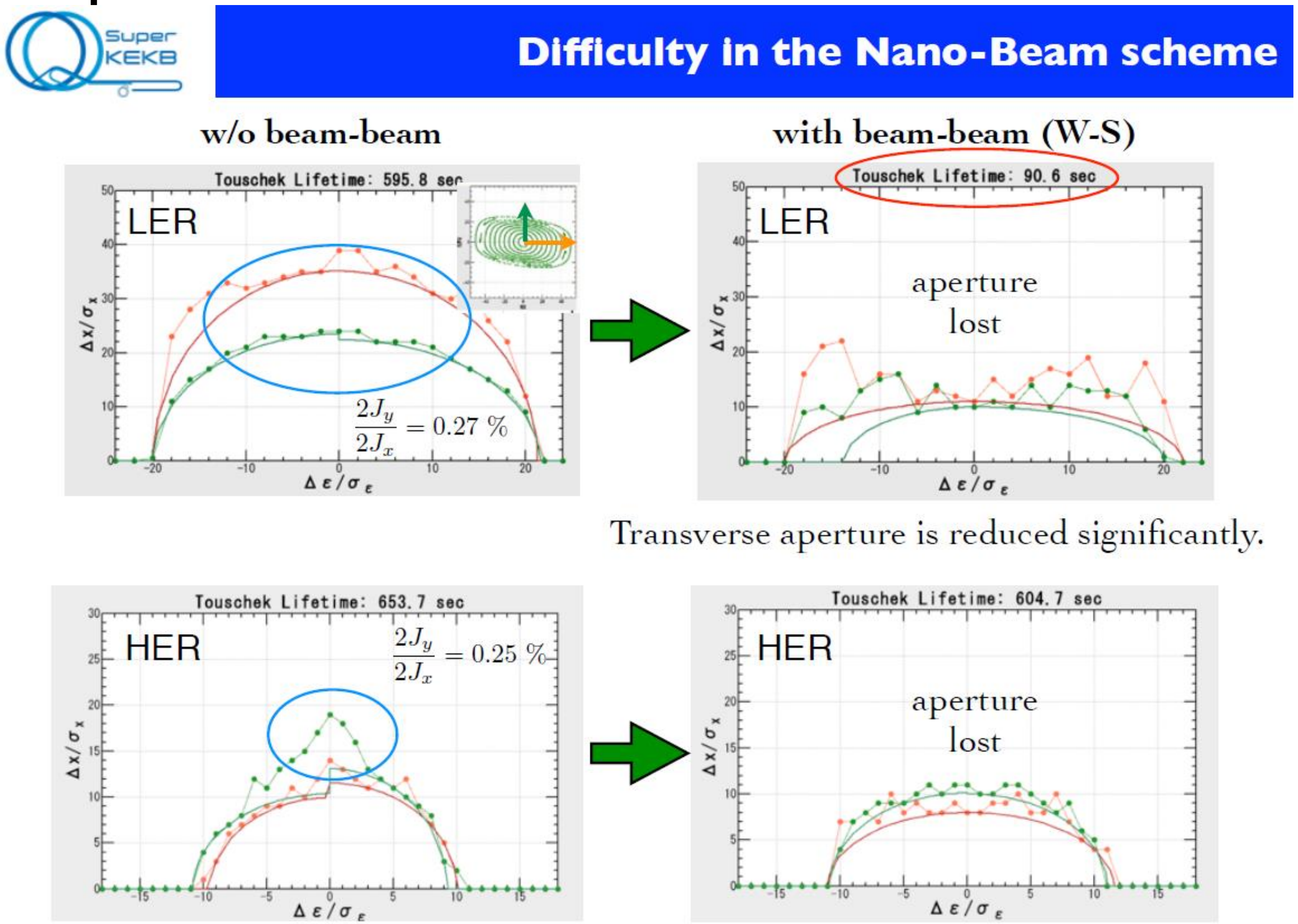


Synchrotron oscillation
Synchrotron Radiation (Fluctuation)



SuperKEKB: dynamic aperture is a serious issue

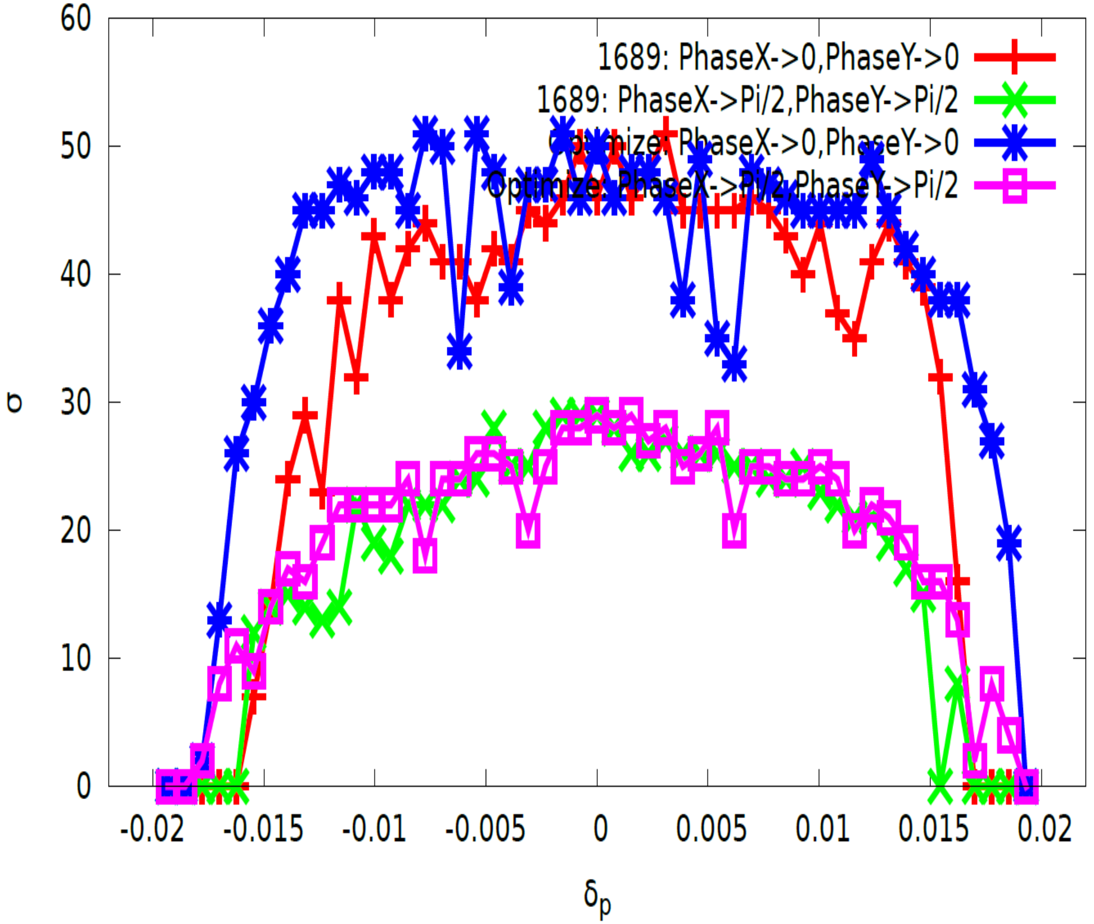
Y. Ohnishi, “Optics Issues”, 18th KEKB Review, March 3-5, 2014



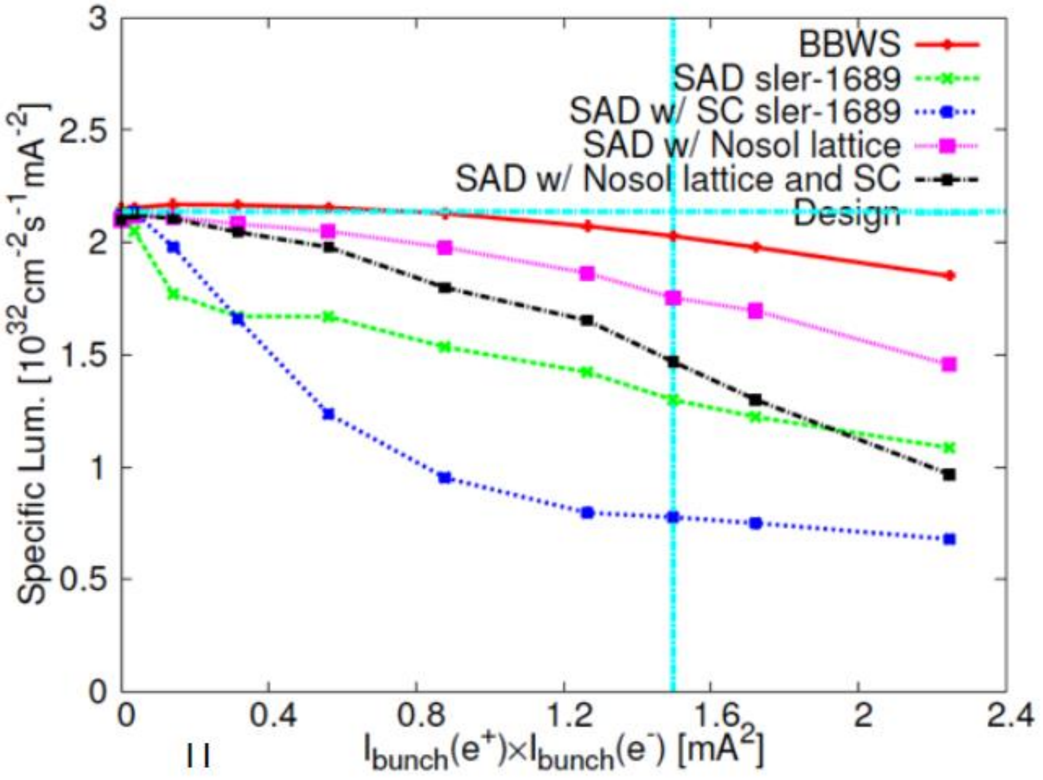
DA Optimization of LER

- 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

Momentum aperture is increased.



LER: beam-beam and lattice nonlinearity



- **Skew-sext resonance reduce the beam-beam performance**

D. Zhou, "Beam Dynamics Issuses in SuperKEKB", The 20th KEKB Accelerator Review Committee, Feb, 2015.

D. Zhou and et al, "Interplay of Beam-Beam Lattice Nonlinearity and Space Charge Effects in the SuperKEKB Collider", IPAC'15

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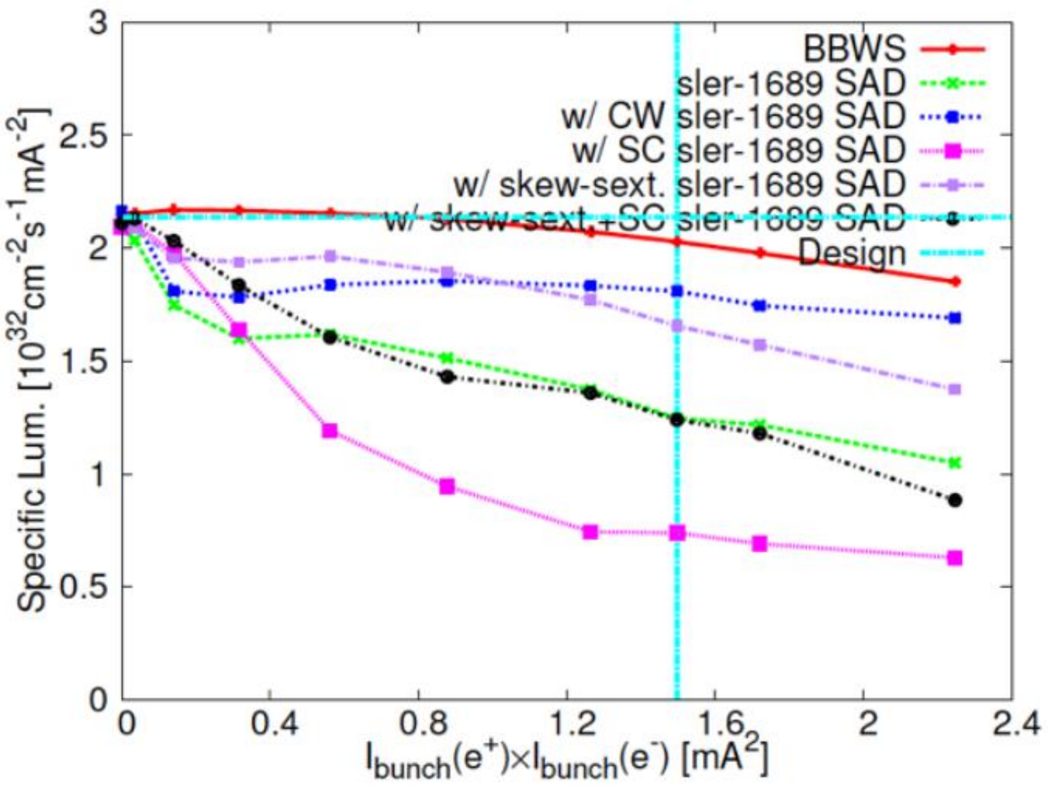

- **Skew-sext resonance reduce the beam-beam performance**
- **Inserting a map of $H = Kx^2y$ into the LER lattice to cancel the nonlinear terms from solenoid and QC***

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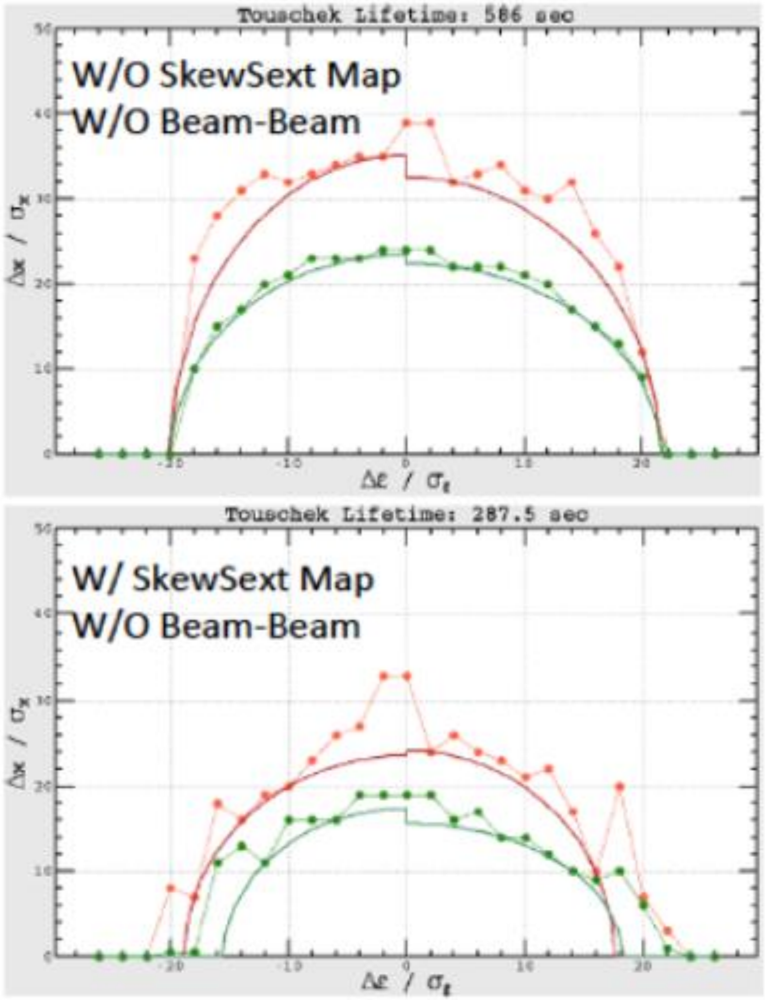
LER: beam-beam and lattice nonlinearity

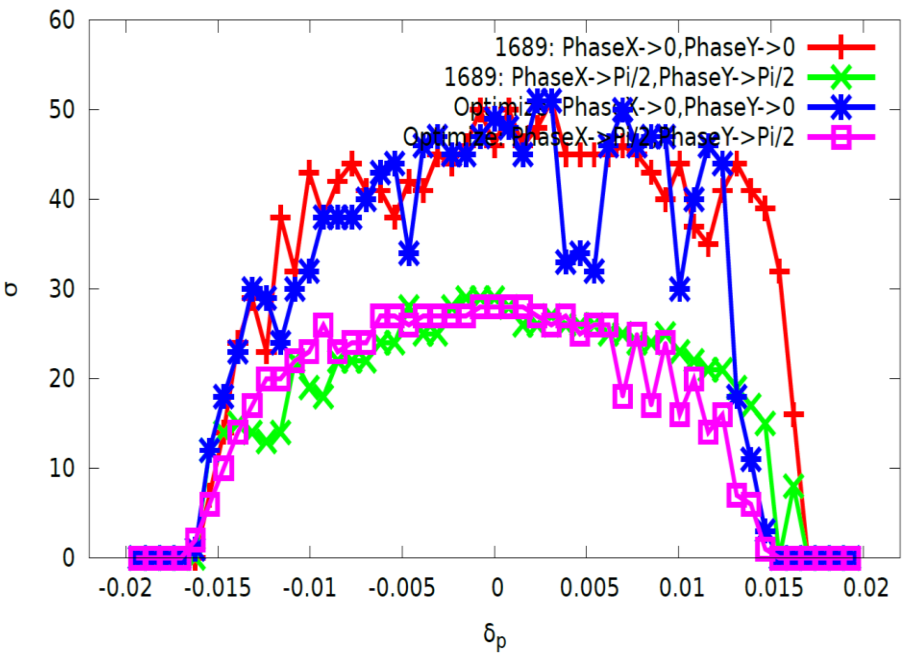


- **Skew-sext resonance reduce the beam-beam performance**
- **Inserting a map of $H = Kx^2y$ into the LER lattice to cancel the nonlinear terms from solenoid and QC***
- **Skew-sext map cause loss in DA and lifetime**

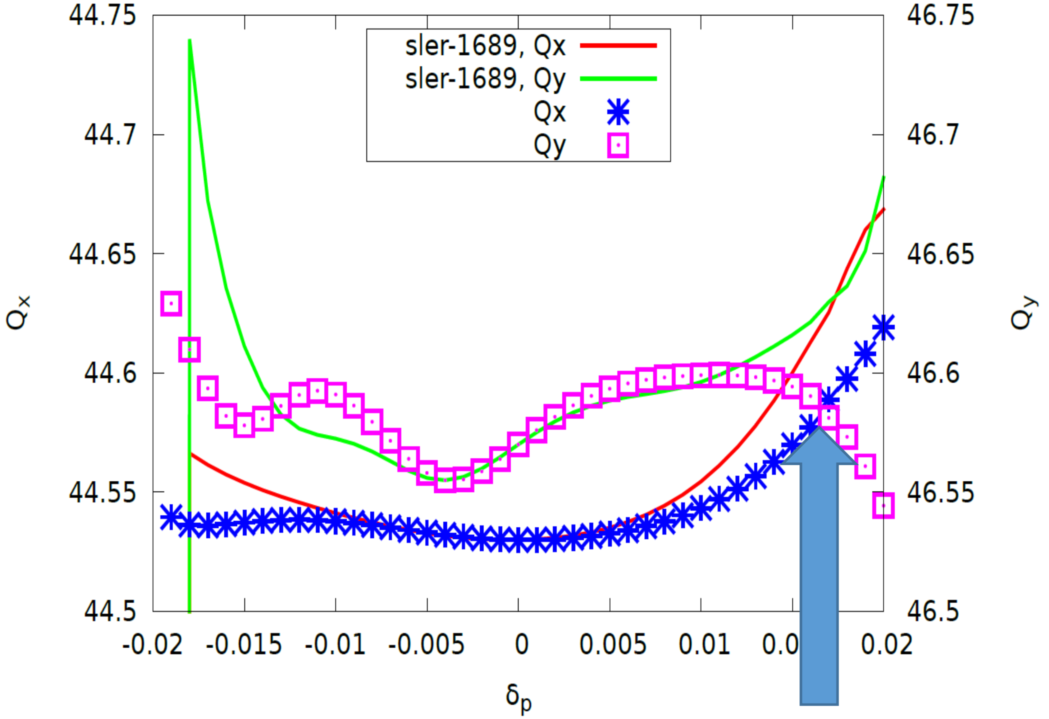
D. Zhou, “Beam Dynamics Issuses in SuperKEKB”, The 20th KEKB Accelerator Review Committee, Feb, 2015.
D. Zhou and et al, “Interplay of Beam-Beam Lattice Nonlinearity and Space Charge Effects in the SuperKEKB Collider”, IPAC’15

Optimization of LER

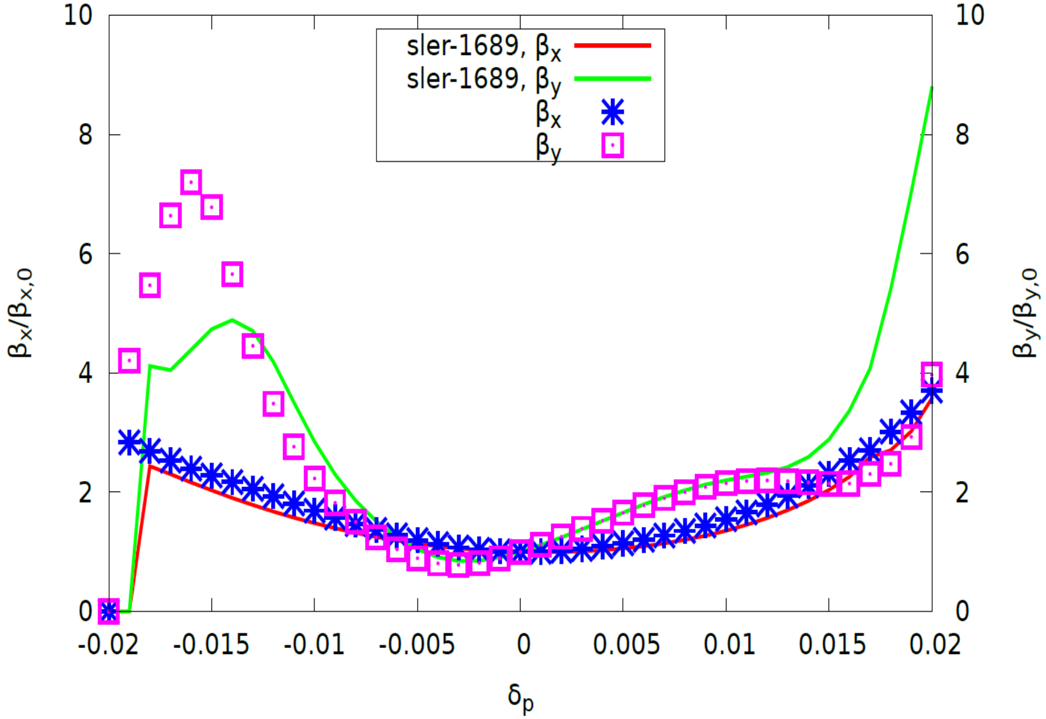
- Objectives:
  - $\nu_x \in (0.53, 0.66), \nu_y \in (0.55, 0.66)$,
  - $\frac{x^2}{50^2} + \frac{z^2}{26^2} = 1$, for z=Range[-24,24,4],
  - **Suppression of skew sextupole resonance**:
    - $\frac{\langle y \rangle}{\sigma_y}$ for a particle with initial coordinate $(5\sigma_x$,0,0,0,0,0)
    - $\frac{|y - \langle y \rangle|}{\sigma_y}$ for a particle with initial coordinate $(5\sigma_x$,0,0,0,0,0)
- Variables: 80
  - 2 Octupoles
  - 54 sextupole pairs
  - 24 skew sextupole(symmetry of skew sextupole pair is broken)



Optimization of LER (2)

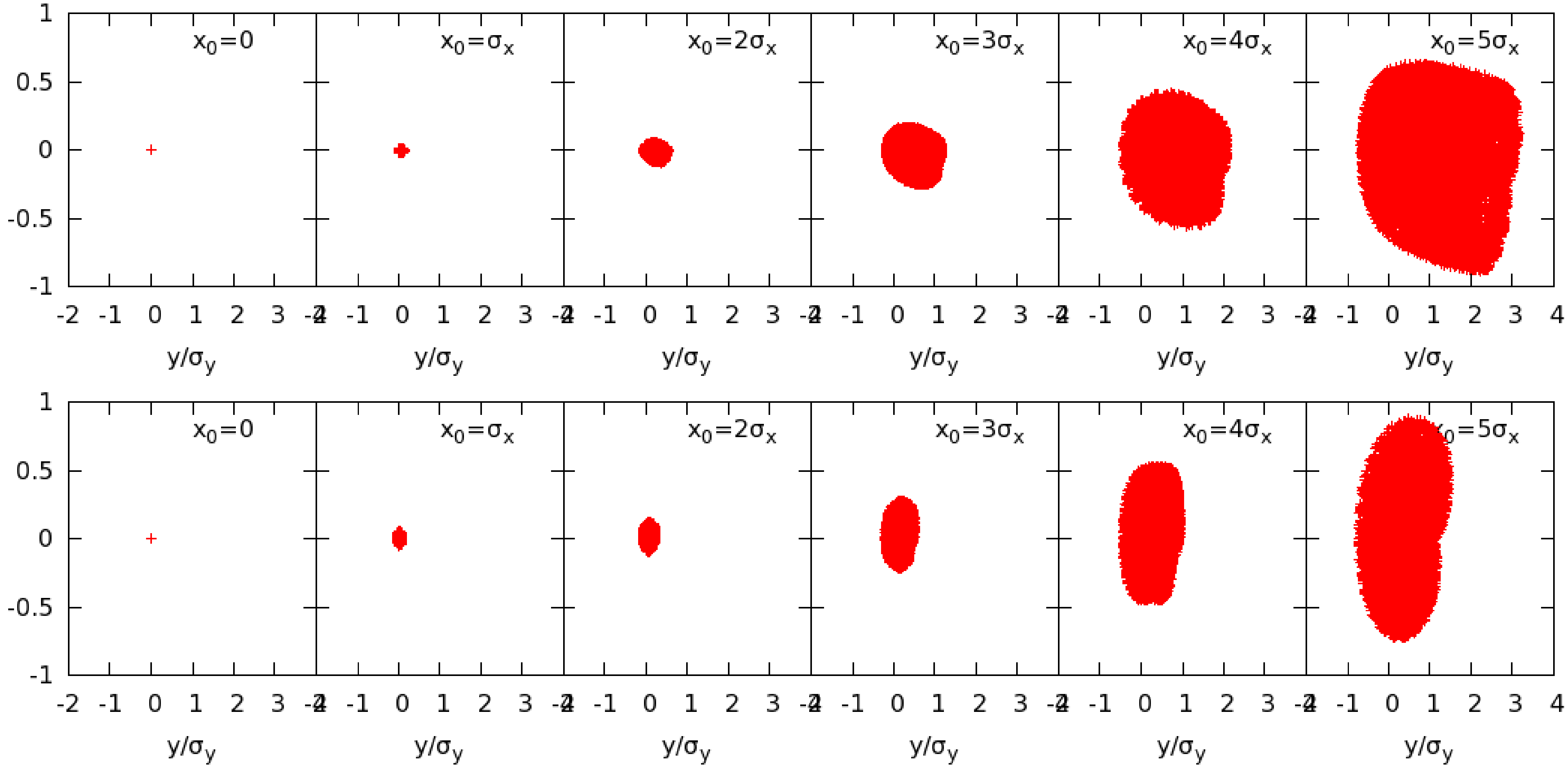


Difference resonance



Optimization of LER (3)

Suppression of skew sextupole resonance



Speed-up Method

- Brute-force dynamic aperture tracking is very time consuming
- The objective is first eased, for example only track 100 turns instead of 1000 turns.
- Some constraints must be satisfied and may be much faster. Referencing to Ehrilichman's work[arXiv: 1603.02459], the multi-objectives are classified into two kinds. The time consuming cost function be calculated only when the necessary constraints (or objective) be satisfied.

Summary

- The multi-objective optimization has been used in light source machine (not only storage ring based) for a few years.
- We did a few multi-objective optimization for future colliders. It shows it could help us.
- The MODE is just a tool, no physics. Physics exist in the definition of objective function. We should continue to find smart objective functions to save time.