Online dynamic aperture optimization at CESR

Suntao Wang

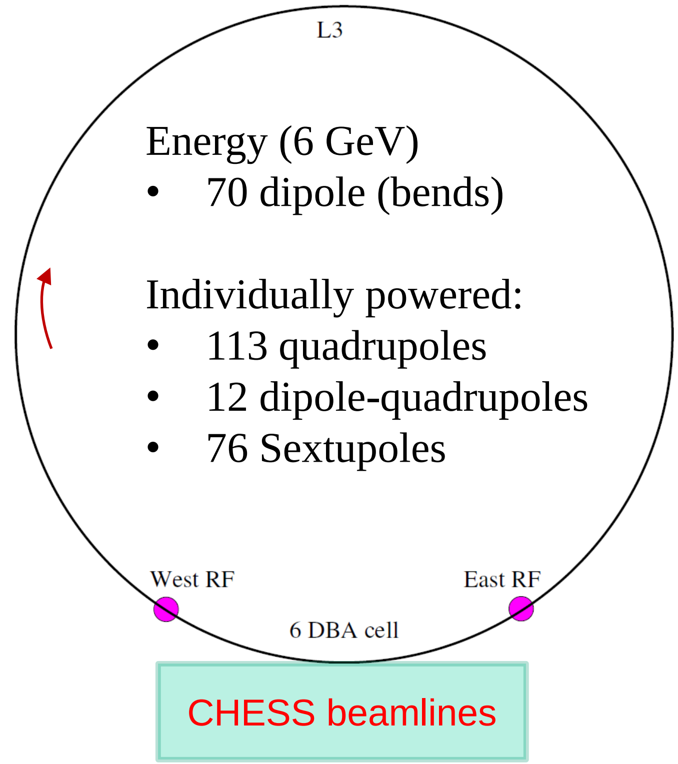
CLASSE, Ithaca, New York, USA

Overview

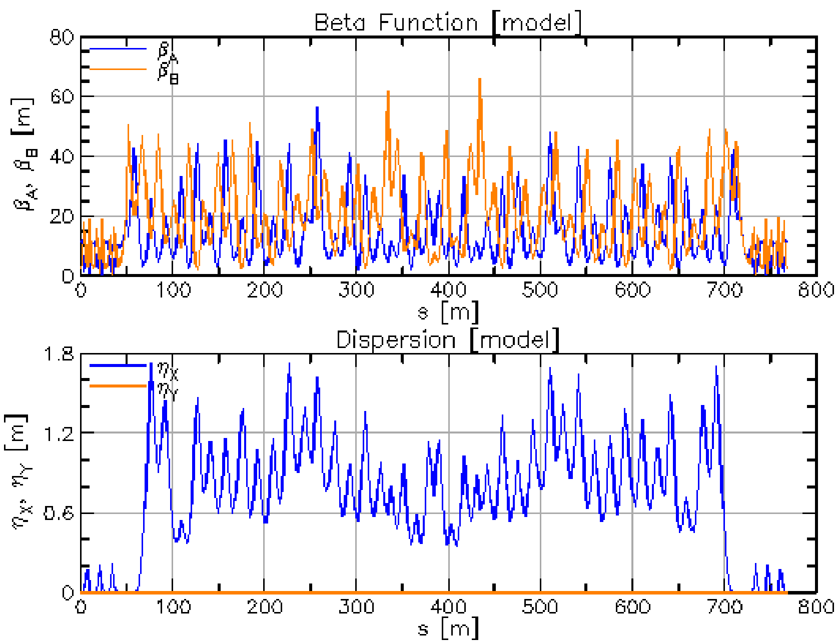
- Introduction
  - CESR lattice and modeling
  - Offline optimization and online tuning
- Online optimization
  - Methods
- Simulation for CHESS-U lattice
  - DA knobs
  - Results
- Simulation for TRIBs lattice
  - TRIBs lattice
  - DA knobs
  - Results
- Summary

Cornell Electron Storage Ring

- Storage ring lattice (optics)
  - Lattice components: dipole, quadrupole, sextupole
- CESR lattice design
  - Linear optics (quadrupoles)
    - Emittance, injection, radiation protection (undulator), feedback
  - Nonlinear optics (sextupoles)
    - Chromaticity, dynamic aperture and momentum aperture



Optics design software: Bmadz, Tao, etc.



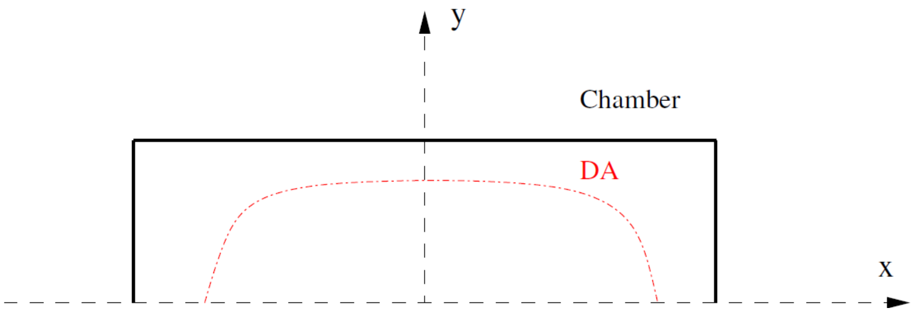
CHESS-U lattice

```
                         A-Mode              |            B-Mode
                  Model          Design      |     Model          Design
            Q   16.555737      16.555737         12.635648      12.635648   ! Tune
        Chrom    0.975029       0.975029          0.971751       0.971751   ! dQ/(dE/E)
       J_damp    1.246733       1.246733          0.911991       0.911991   ! Damping Partition #
    Emittance  2.69776E-08    2.69776E-08       3.28066E-14    3.28066E-14  ! Unnormalized
Emit (photon vert opening angle ignored)        0.00000E+00    0.00000E+00
   Alpha_damp  2.19517E-04    2.19517E-04       1.60578E-04    1.60578E-04  ! Damping per turn
 Damping_time  1.16767E-02    1.16767E-02       1.59626E-02    1.59626E-02  ! Sec
```

Offline DA optimization

Variable: all sextupoles

- Chromaticity (dQ/dE) compensation $\chi_{x,y} \sim 1$
- Improve Dynamic Aperture and Momentum Aperture



Particles outside DA will be lost even if it is still inside physical aperture.

Larger DA and MA yield better injection and better life time.

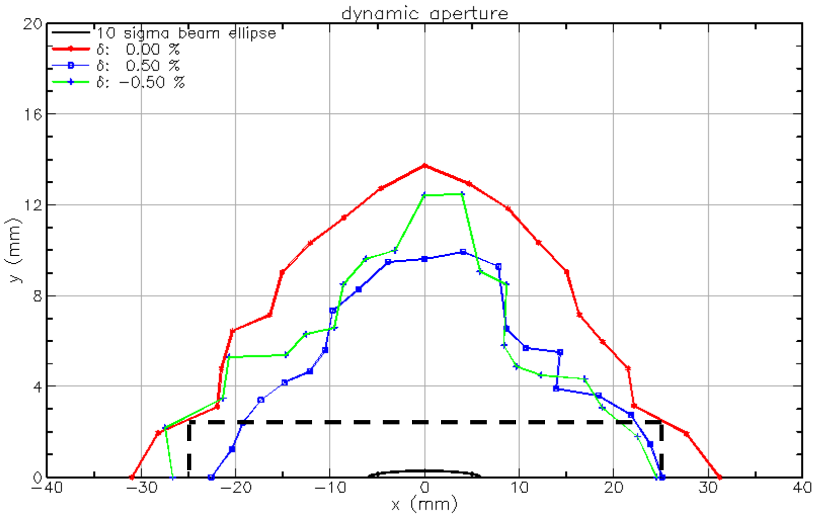
Goal: maximize DA to exceed physical aperture and MA to exceed RF bucket.

Different methods

- Minimize the determinant of 1-Turn matrix
- Resonant Driving Terms (RDT) optimization
- Direct DA optimization
- Genetic Algorithm
- Square Matrix method
- …

Simulation to check the DA and MA:

Tracking, Frequency map analysis, Injection, …



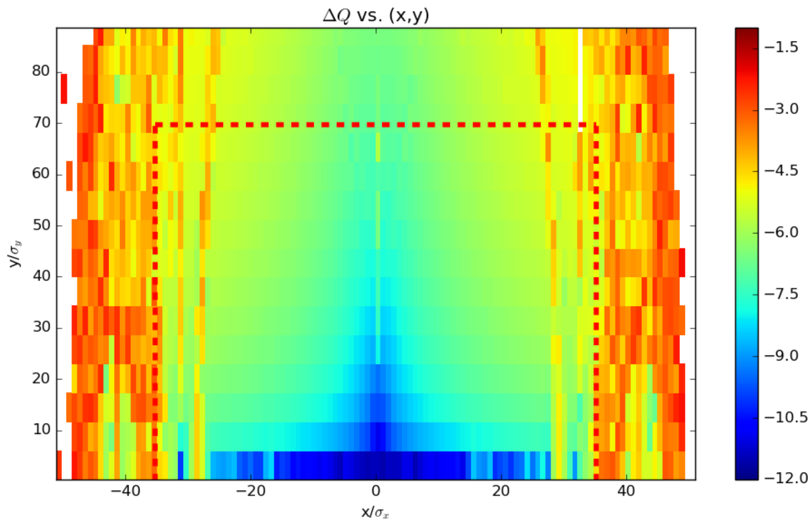
DA and MA

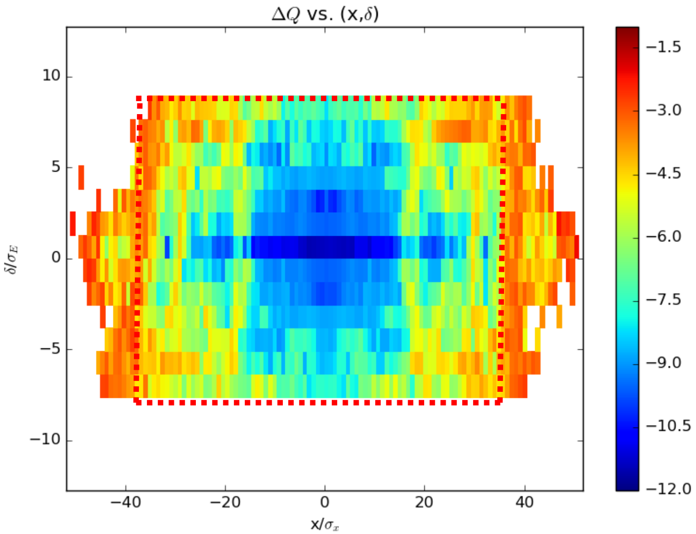
Frequency map analysis (FMA)

Track particle at initial offsets (x, y) or (x, δ) for 2000 turns
Calculate the diffusion constant *D*

$$D = \log_{10}\sqrt{(Q_{y2}-Q_{y1})^2+(Q_{x2}-Q_{x1})^2}$$

First 1000 turns (Q_{x1}, Q_{y1})
Second 1000 turns (Q_{x2}, Q_{y2})





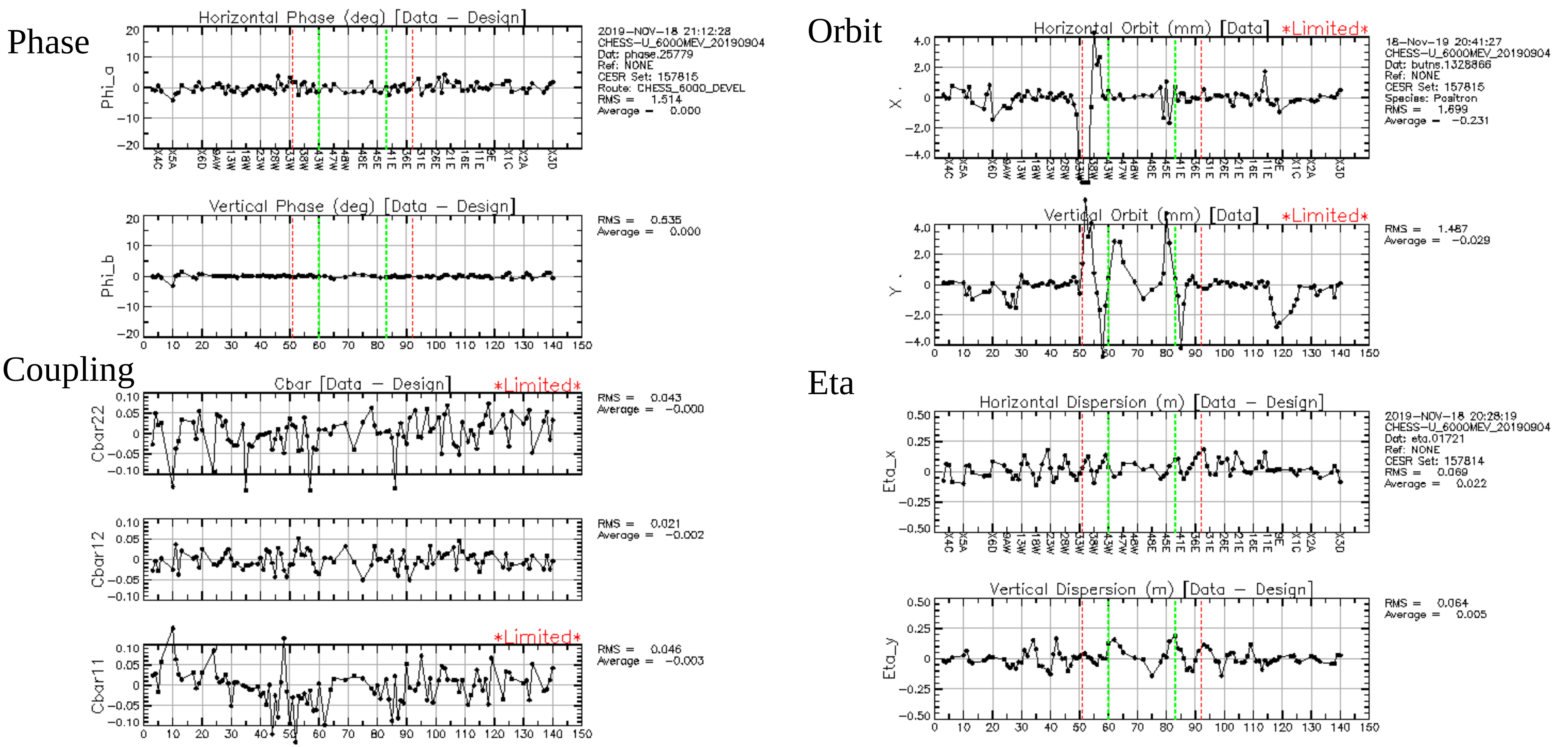
DA exceeds the physical aperture (red dashed line)
MA exceeds the RF bucket (8.1σ_E at 6MV)

Higher order multipoles from bends, quadrupoles, sextupoles, and DQs as well as field integrals of CCUs are not included.

CESR online tuning

- Optics correction
  - Linear optics correction (orbit, phase, coupling, dispersion)
  - Sextupoles loaded as design, chromaticity measured and corrected.

Beam-based optics correction using CESRV



- Other tuning: injection, x-ray positions, etc – adjust magnets (knobs) iteratively (manual or auto)

Online optimization methods

- Traditional method
  - Tuning iteratively (cycle through all variables manually or automatically)
- Robust conjugate direction search (RCDS) [1]
  - Powell's algorithm to minimize the objective and update the conjugate search direction
  - Robust line scan to find the minimum on each direction
  - Multi-variables but one objective (could expand to multi-objective)
  - Develop a conjugate direction set which cannot be modeled
  - Successfully demonstrated in several light sources (SPEAR3, ESRF, NSLS2, …)
- Dimension-reduction and genetic algorithm [2]
  - Reduce number of variables and create conjugate knobs
  - Demonstrated in the low emittance tuning (minimize vertical emittance) at CESR
- Machine-learning algorithm [3] and other algorithms

- Online DA optimization at CESR
  - Create conjugate DA knobs
  - Tune with RCDS method

1. X. Huang, J. Corbett, J. Safranek, J. Wu, Nucl. Instr. Methods, A, 726 (2013) 77-83
2. W.F. Bergan, I.V. Bazarov, C.J.R. Duncan, D.B. Liarte, D.L. Rubin, J.P. Sethna, Phys. Rev. Accel. Beams, 22 (2019) 054601
3. A. Hanuka, X. Huang, J. Shtalenkova, D. Kenneday, A. Edelen, Z. Zhang, V.R. Lalchand, D. Ratner, J. Duris, Phys. Rev. Accel. Beams, 24 (2021) 072802

DA knobs in CHESSU lattice

Goals:
1. Create knobs (combination of sextupoles) to adjust DA
2. Keep two chromaticities unchanged when dialing the knobs

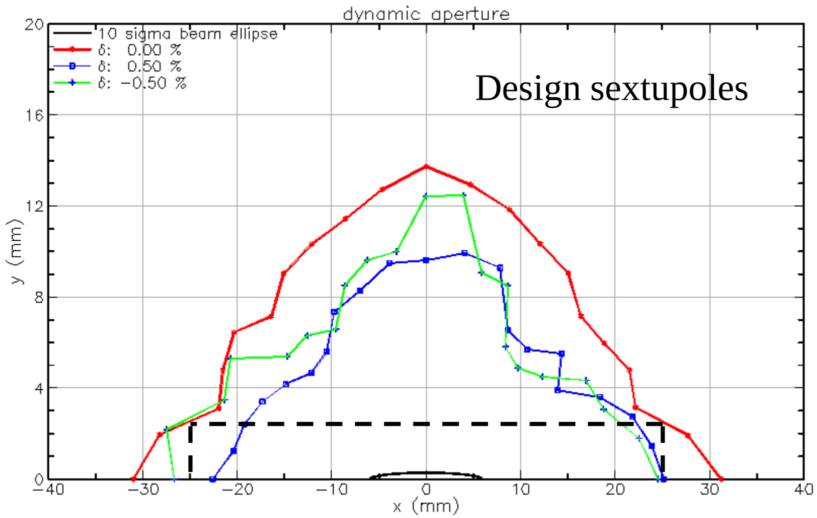
Variables:
In CESR, total 76 sextupoles can be changed.
Keep injection intact (large H bump at injection point) - ignore 9 sextupoles (29W-37W)
Available 67 sextupoles to vary

Steps:
- Make a direct DA Hessian matrix from CHESSU lattice: H (67x67)
- Make a Jacobian matrix for 2 SRDT terms (h11001, h00111) from 67 sextupoles: J (67x2)
- Find the null-space vectors of 2 SRDT terms in the Jacobian matrix: Q (67x65)
- Create a modified Hessian matrix based on these null-space vectors: $\hat{H}=Q^T H Q$ (65x65)
- Find the eigenvectors $\hat{E}$ of $\hat{H}$ and create the knobs $E=Q\hat{E}$ (67x65)
- Total 65 knobs to vary

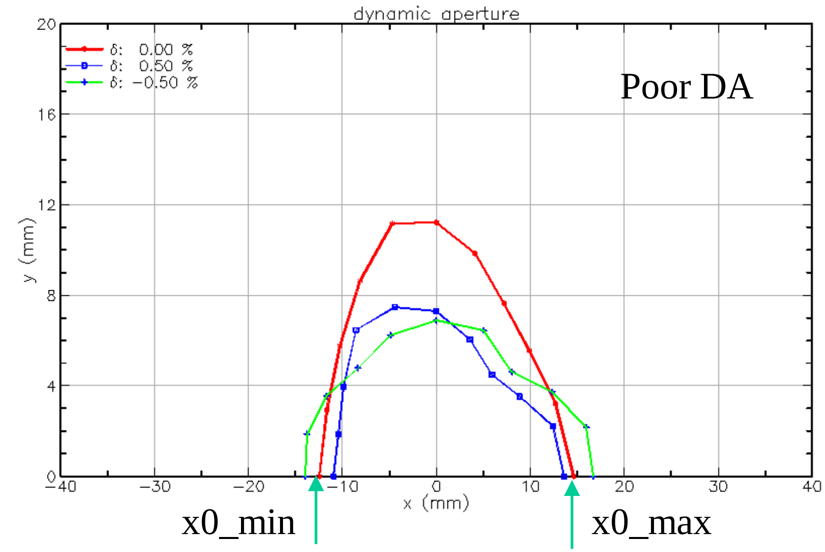
Will Bergan, Ph D thesis 2020

Simulation

Start with a small DA lattice created with random knob values: [1, 1, 0, 1, 0, 1, -1, 1]



8 knobs with random values



Evaluate the DA with tracking:

Track for 2000 turns at 11 angles within [0, π]
On energy case only δ=0

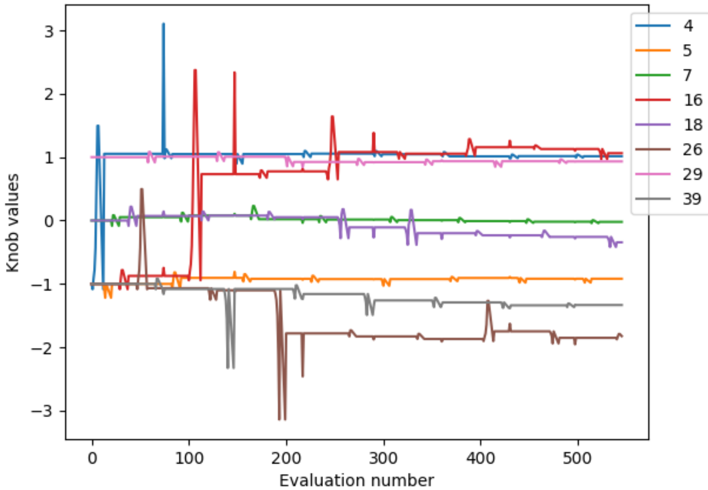
Objective
1) Obj = abs(x0_max) + abs(x0_min)
2) Obj = Area within the DA curve

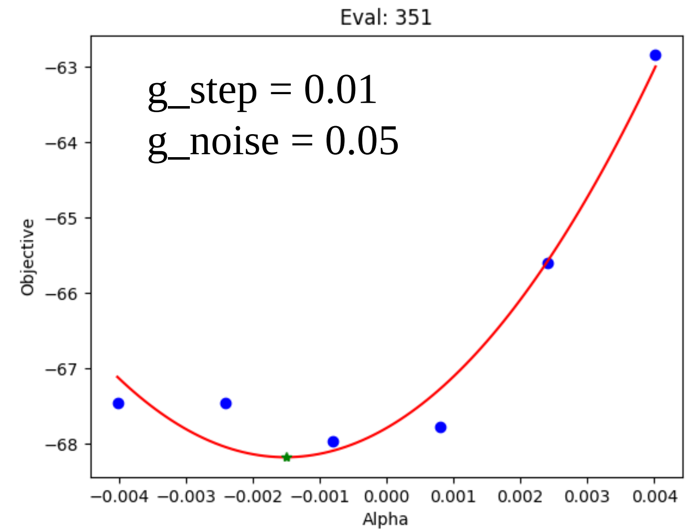
Variables
8 knob out of 65 knobs are used for optimization

Knob limit [-5, 5]

CHESSU results

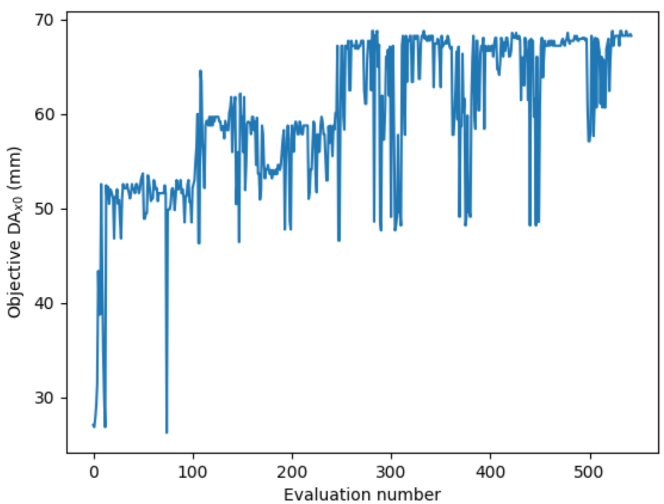
Method 1: Obj = abs(x0_max) + abs(x0_min)

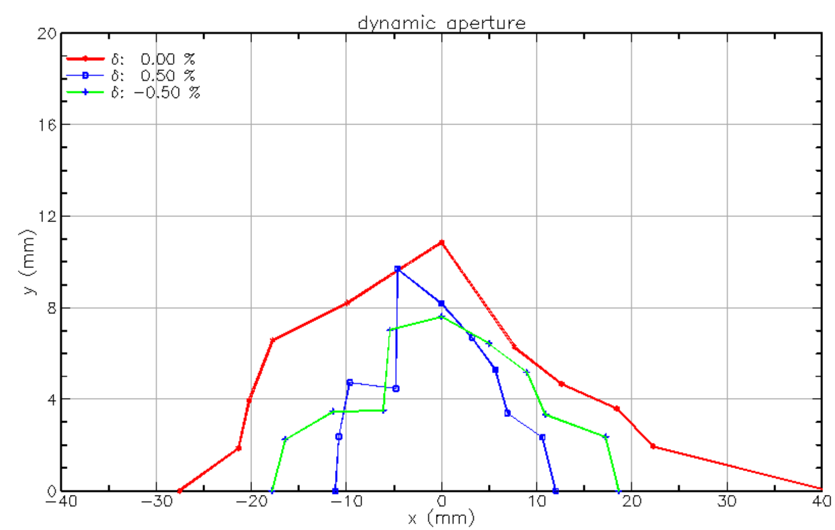




Knobs: [-1.01, 0.92, 0.02, -1.06, 0.32, 1.85, -0.93, 1.33]

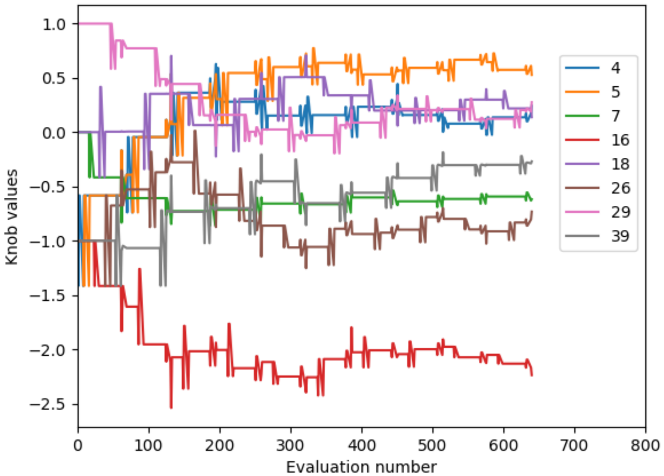
On-energy DA increases but not the off-energy DAs





CHESSU results

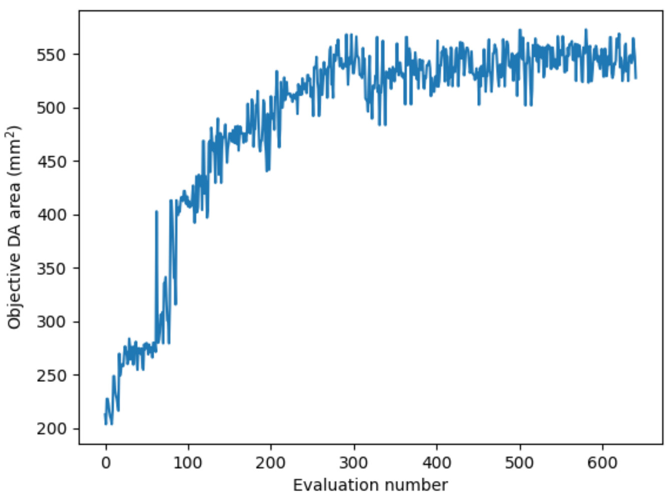
Method 2: Obj = area within the DA curve

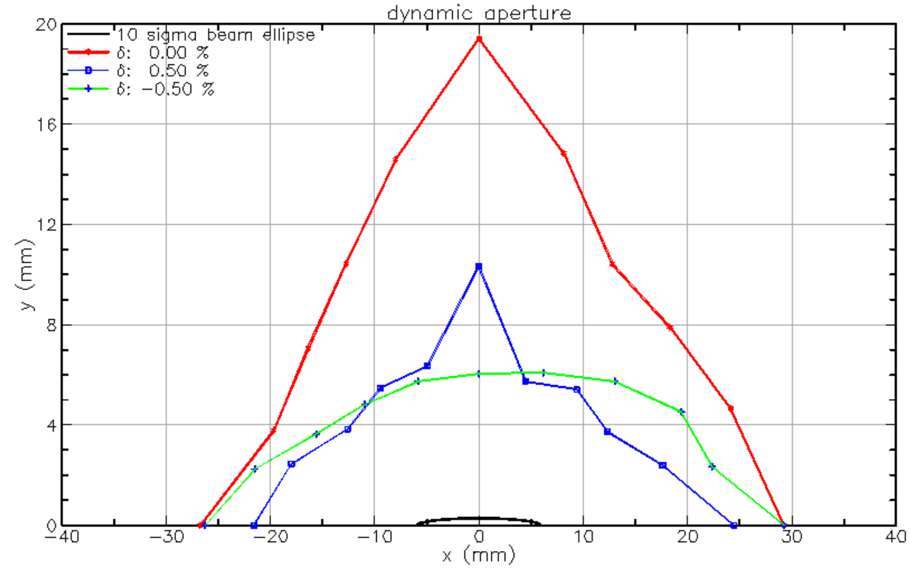


Opt parameters: g_step = 0.05, g_noise = 0.0

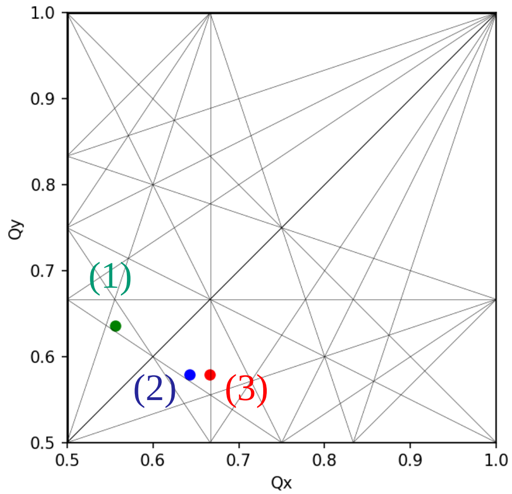
Knobs: [-0.16, 0.59, 0.64, 2.00, -0.21, 0.78, -0.20, 0.30]

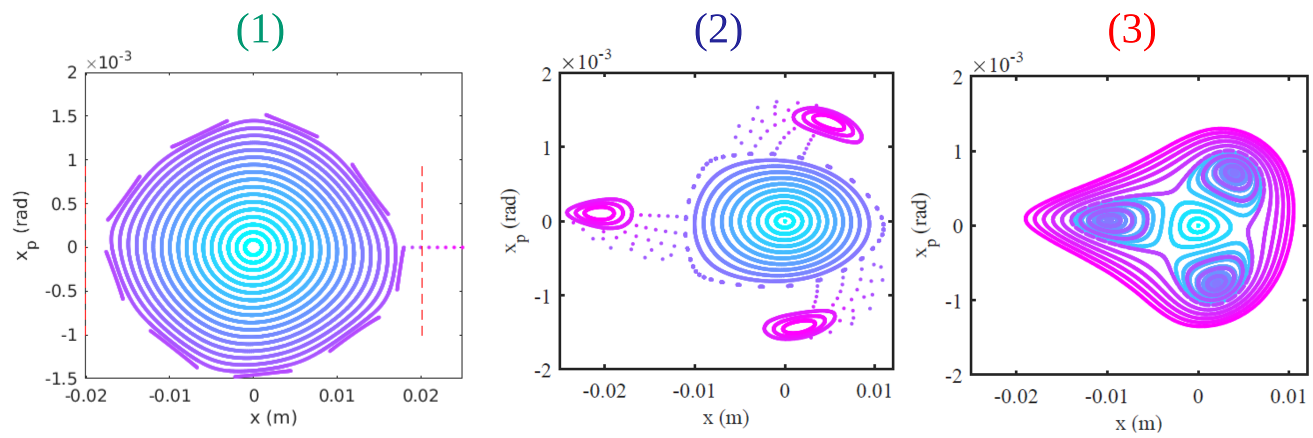
Both on-energy and off-energy DAs increases





TRIBs lattice





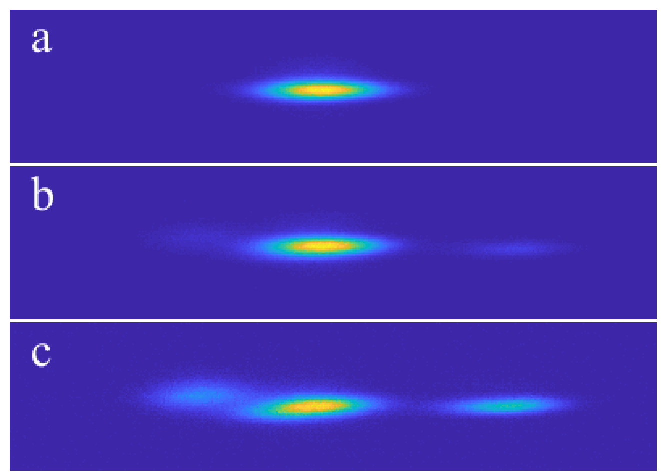
Transverse Resonance Island Buckets (TRIBs)

(1) CHESS-U lattice (16.556, 12.636)
- Small amplitude-dependent tune shift (ADTS)
- Cross strong coupling resonant line (x - y)

(2) TRIBs lattice (16.643, 12.579)
- Optimize quadrupoles and sextupoles
- Desired ADTS and resonant term at 3rd order line

(3) Near the third-order resonant line at 2/3 (0.6667)
- Three stable fixed points (TRIBs) form
- 2nd stable closed orbit (3-turn)

Observed at vBSM when adjusting tune from 258 kHz to 259.4 kHz



$Q_x = 0.6613$ (258.0 kHz)

$Q_x = 0.6631$ (258.7 kHz)

$Q_x = 0.6648$ (259.4 kHz)

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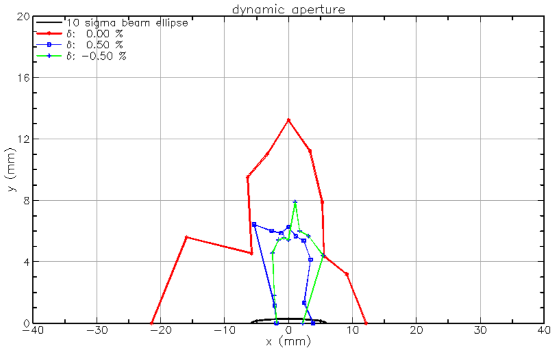
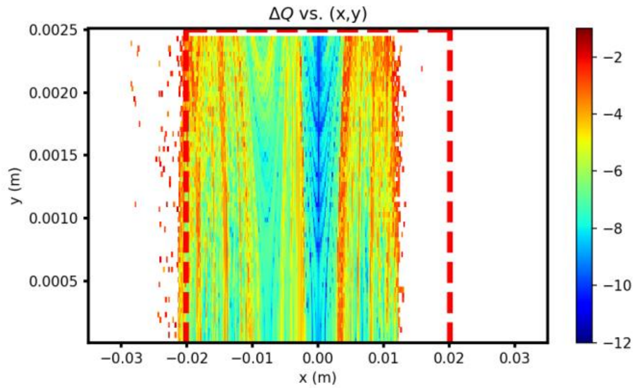
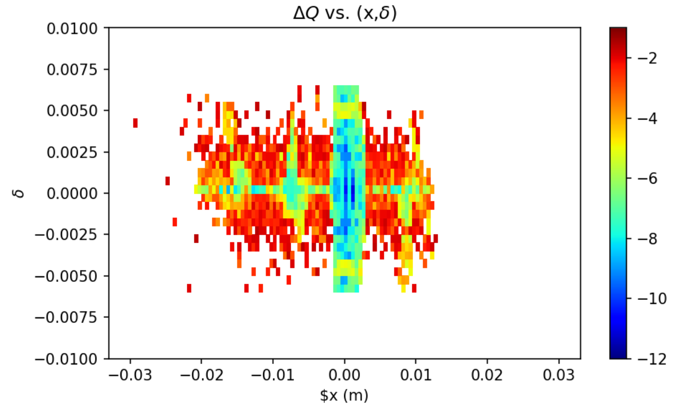
DA knobs

TRIBs are observed at CESR but beam life time is not great as the off-energy DAs show

Need to improve DA especially MA







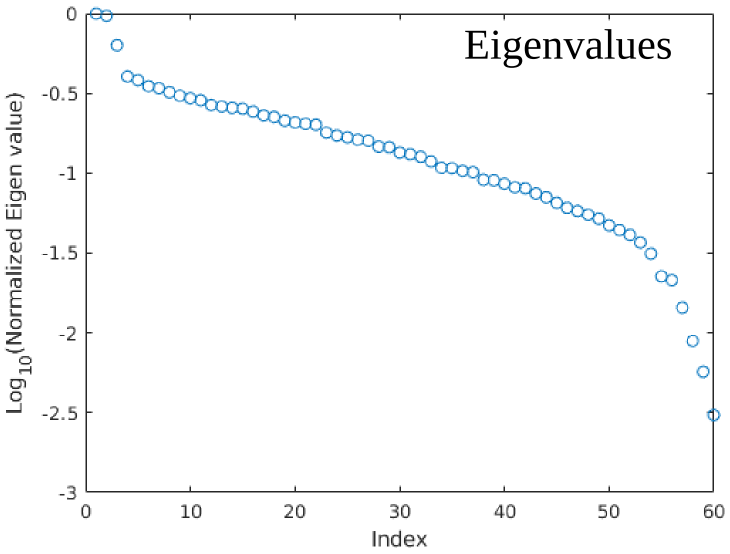
Similar procedures to create DA knobs

Additional constraints: ADTS and 3-rd order terms

- Chromaticities: h11001, h00111
- ADTS: h22000r, h11110r, h00220r
- 3rd-order resonant term: h30000r, h30000i

Create 60 knobs

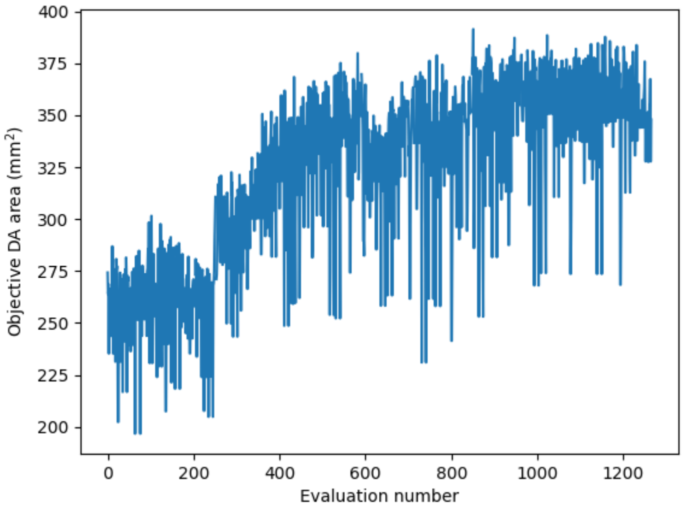
In the simulation, only first 8 knobs are used

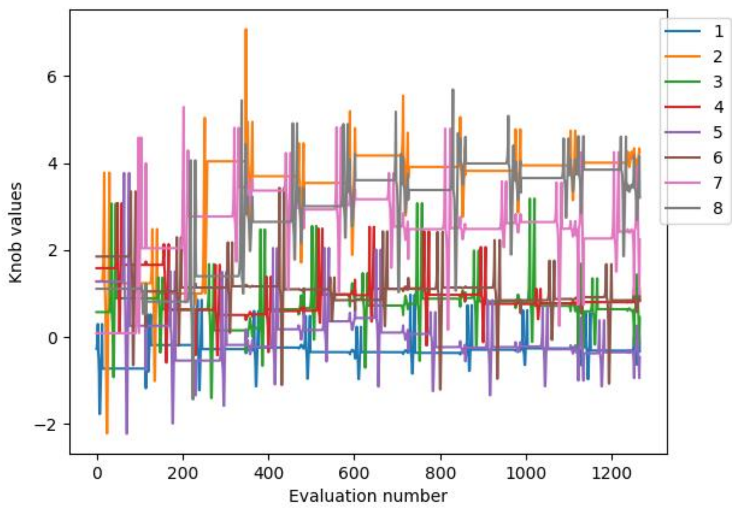


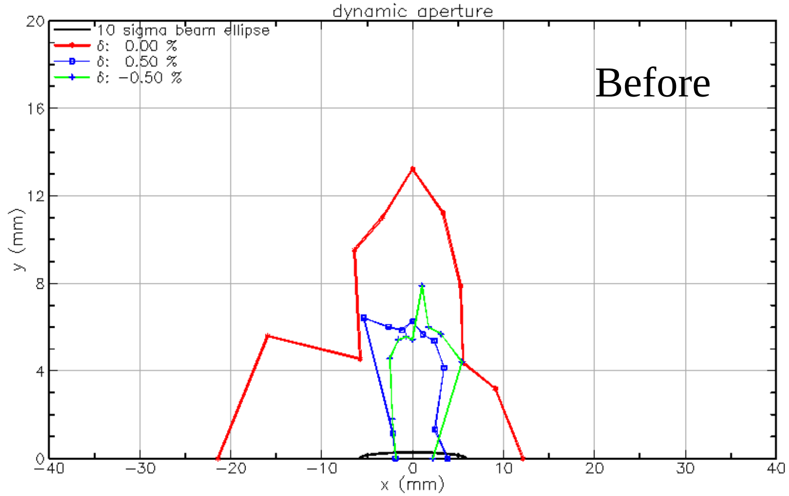
Simulation results - approach 1

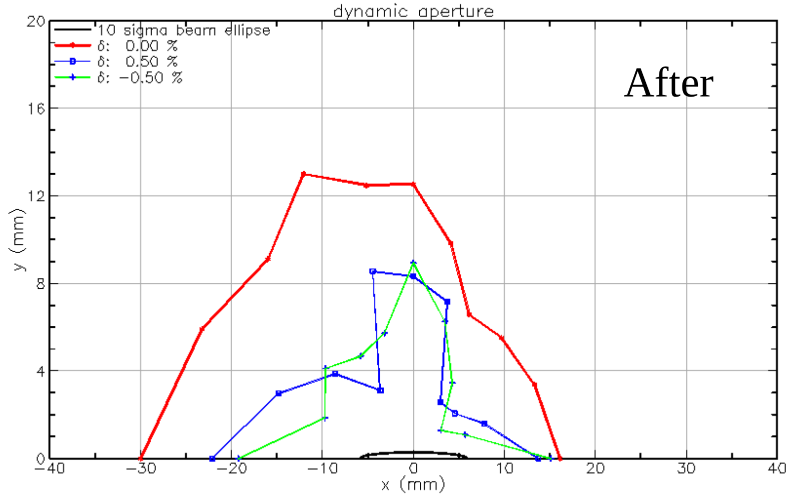
Approach 1: on-energy DA area as objective

g_step = 0.01, g_noise = 10, knob limit: [-10, 10]







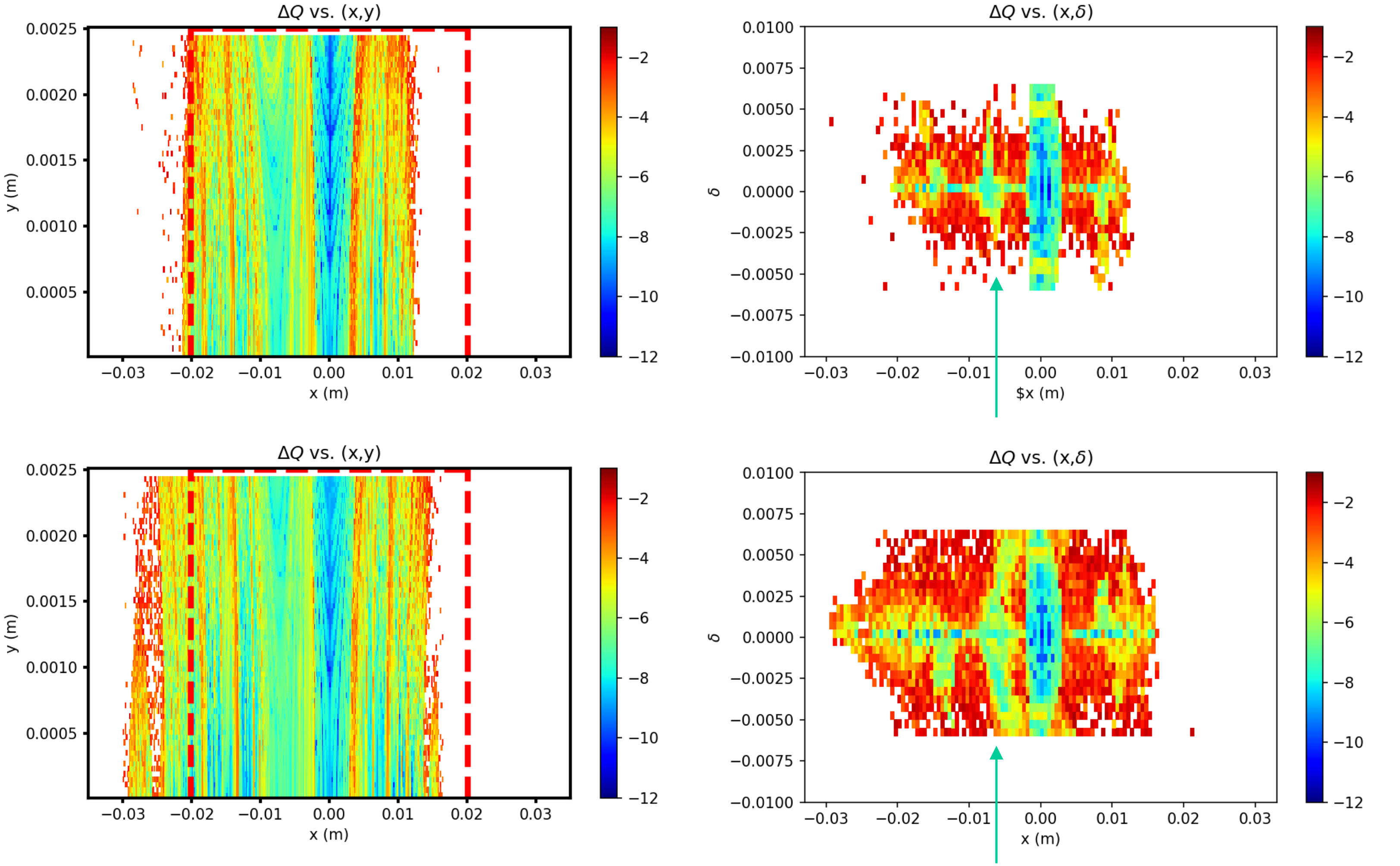


Q_x=259.0 kHz, RF on for DA calculation

Approach 1 DA and MA

DA | MA

Before / After



Both DA and MA are significantly improved.

The stable region of TRIBs is enlarged.

Simulation results - approach 1

Verify 7 RDT terms while adjusting knobs — After (Model) / Before (Design)

```
                                                                                                  |  Useit
                                   Ref_Ele   Start_Ele   Ele                  Meas           Model           Design | Opt  Plot
     1  normal.h.110001.a <target>                                    0.0000000E+00   1.4346788E-01   1.4682064E-01    T     F
     2  normal.h.001101.a <target>                                    0.0000000E+00   2.9061492E-01   2.9204696E-01    T     F
     3  normal.h.300000.r <target>                                    0.0000000E+00  -1.3502905E+00  -1.3589464E+00    T     F
     4  normal.h.300000.i <target>                                    0.0000000E+00  -5.9987741E-01  -5.8174760E-01    T     F
     5  normal.h.300000.a <target>                                    0.0000000E+00   1.4775444E+00   1.4782306E+00    T     F
     6  srdt.h30000.r <target>                                        0.0000000E+00  -1.2107309E+00  -1.2139426E+00    T     F
     7  srdt.h30000.i <target>                                        0.0000000E+00   5.4457370E-01   5.3880564E-01    T     F
     8  srdt.h30000.a <target>                                        0.0000000E+00   1.3275654E+00   1.3281446E+00    T     F
                                   Ref_Ele   Start_Ele   Ele                  Meas           Model           Design | Opt  Plot
                                                                                                                     |  Useit

Tao> show data ptc.adts
Data name: ptc.adts

                                                                                                                     |  Useit
                                   Ref_Ele   Start_Ele   Ele                  Meas           Model           Design | Opt  Plot
     1  normal.h.220000.r <target>                                    0.0000000E+00  -1.3175294E+03  -1.5238668E+03    T     F
     2  normal.h.111100.r <target>                                    0.0000000E+00   1.6977209E+03   1.8507190E+03    T     F
     3  normal.h.002200.r <target>                                    0.0000000E+00  -4.0844371E+02  -5.2835912E+02    T     F
     4  srdt.h22000.r <target>                                        0.0000000E+00  -1.2747606E+03  -1.4611581E+03    T     F
     5  srdt.h11110.r <target>                                        0.0000000E+00   1.7354312E+03   1.8825673E+03    T     F
     6  srdt.h00220.r <target>                                        0.0000000E+00  -3.4483988E+02  -4.6605218E+02    T     F
```

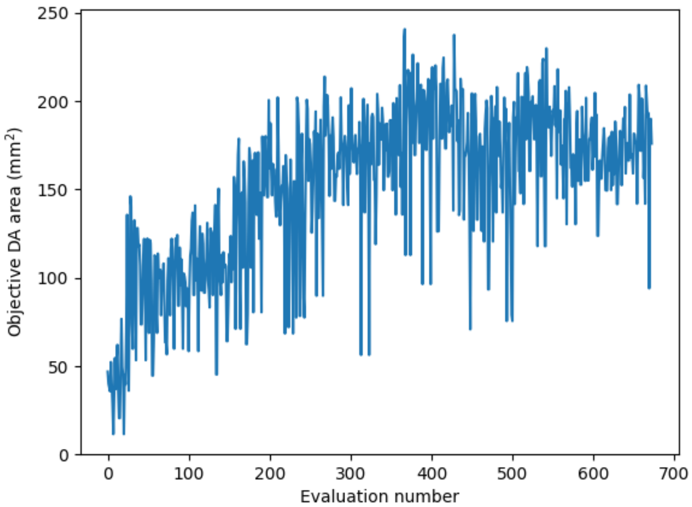
Very small effect on chromaticities and h300000 terms after optimization

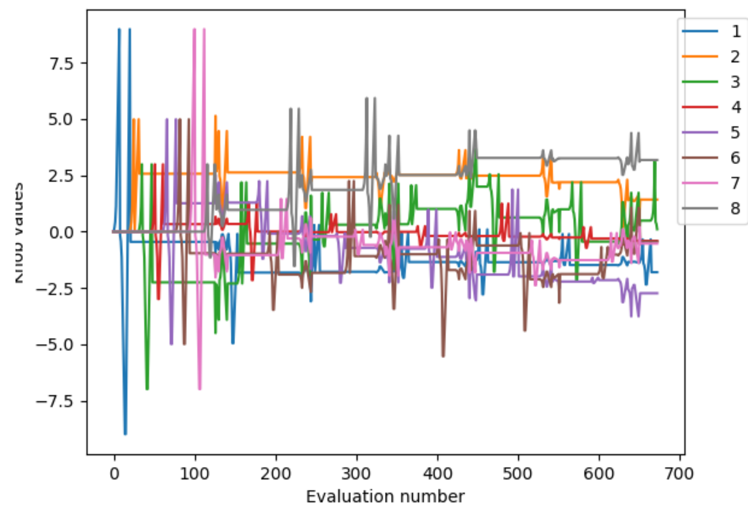
Small changes on ADTS (h22000, h11110, h00220)

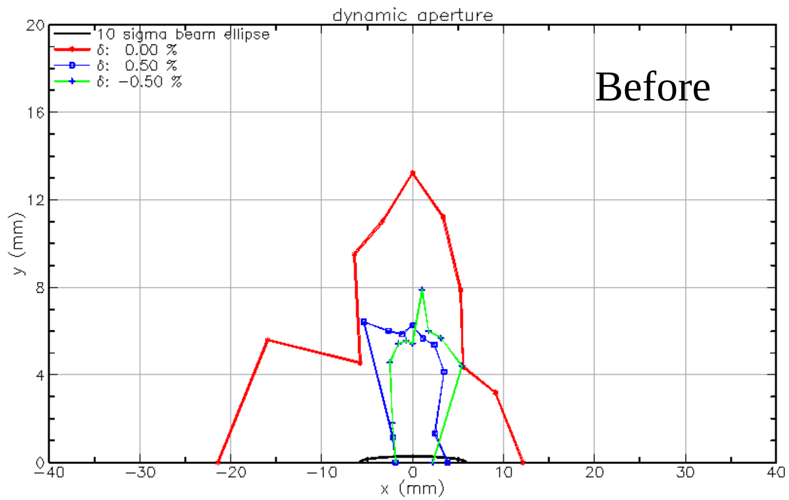
Simulation results - approach 2

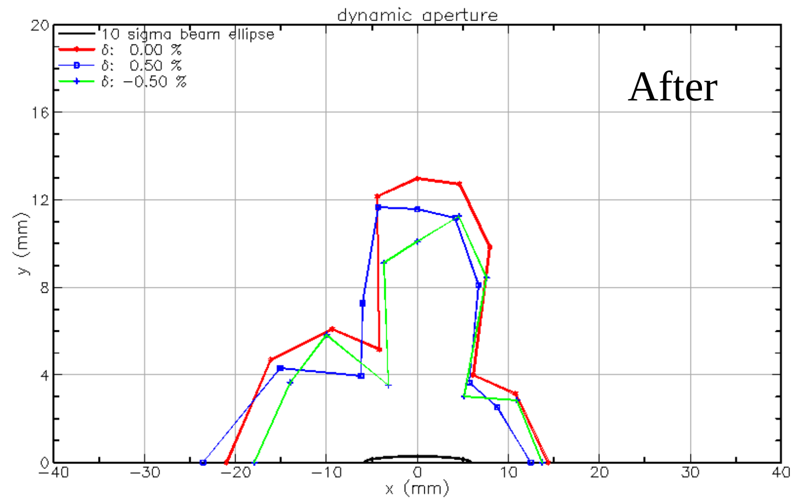
Approach 1: off-energy DA area as objective δ=0.5%

g_step = 0.01, g_noise = 10
Range [-10, 10]







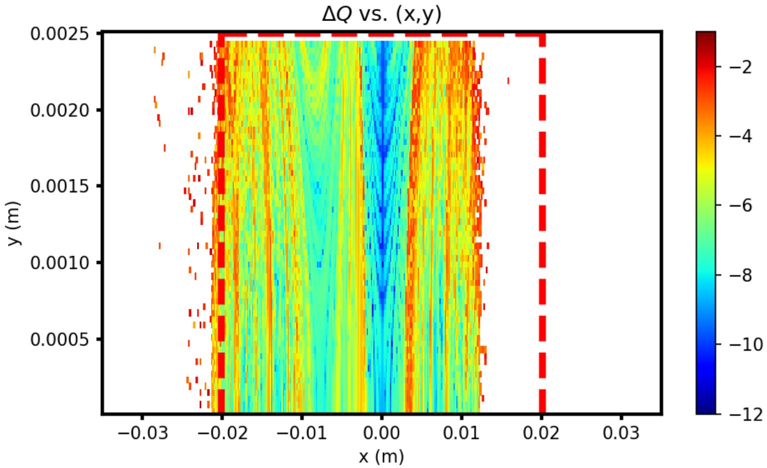


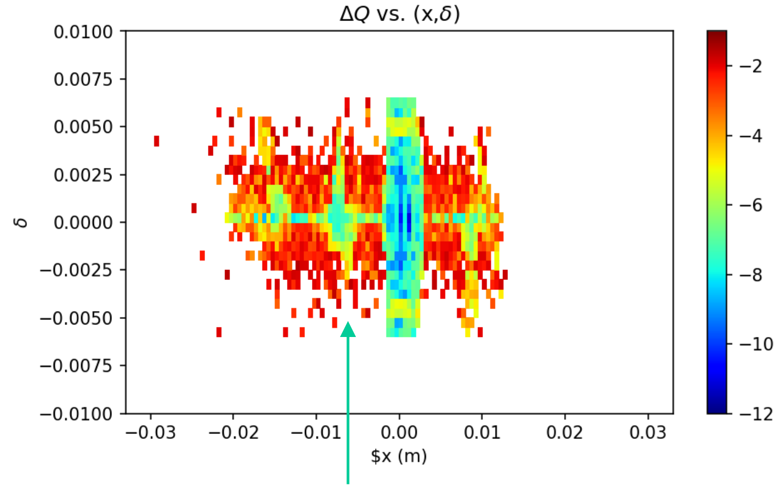
Q_x=259.0 kHz, RF on for DA calculation

Approach 2 DA and MA

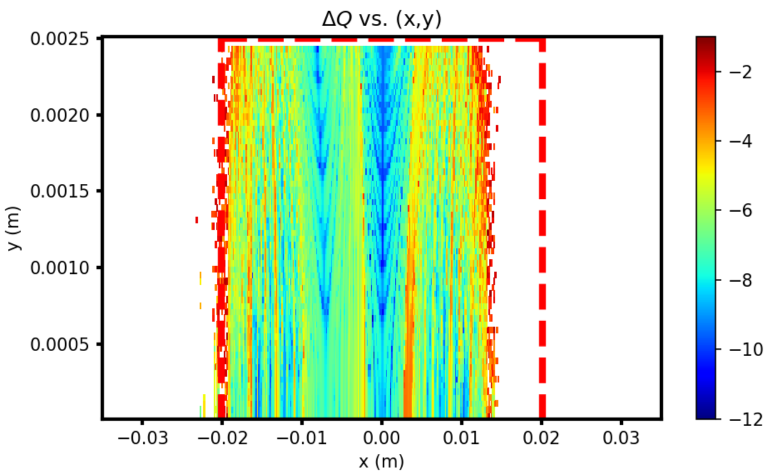
DA | MA

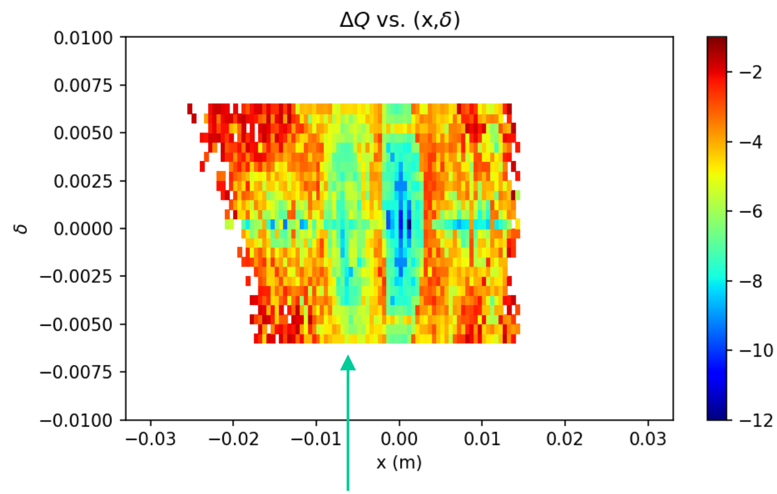
Before





After





MA is significantly improved.

The stable region of TRIBs is enlarged.

Simulation results - approach 2

Verify 7 RDT terms while adjusting knobs — After — Before

```
                                                                                        |  Useit
                                   Ref_Ele   Start_Ele   Ele           Meas           Model          Design | Opt  Plot
    1  normal.h.110001.a <target>                               0.0000000E+00   1.4533694E-01   1.4682064E-01    T     F
    2  normal.h.001101.a <target>                               0.0000000E+00   2.9151973E-01   2.9204696E-01    T     F
    3  normal.h.300000.r <target>                               0.0000000E+00  -1.3586027E+00  -1.3589464E+00    T     F
    4  normal.h.300000.i <target>                               0.0000000E+00  -5.8873652E-01  -5.8174760E-01    T     F
    5  normal.h.300000.a <target>                               0.0000000E+00   1.4806796E+00   1.4782306E+00    T     F
    6  srdt.h30000.r <target>                                   0.0000000E+00  -1.2137555E+00  -1.2139426E+00    T     F
    7  srdt.h30000.i <target>                                   0.0000000E+00   5.4123096E-01   5.3880564E-01    T     F
    8  srdt.h30000.a <target>                                   0.0000000E+00   1.3289595E+00   1.3281446E+00    T     F
                                   Ref_Ele   Start_Ele   Ele           Meas           Model          Design | Opt  Plot
                                                                                                            |  Useit

Tao> show data ptc.adts
Data name: ptc.adts

                                                                                                            |  Useit
                                   Ref_Ele   Start_Ele   Ele           Meas           Model          Design | Opt  Plot
    1  normal.h.220000.r <target>                               0.0000000E+00  -1.4538650E+03  -1.5238668E+03    T     F
    2  normal.h.111100.r <target>                               0.0000000E+00   1.8138485E+03   1.8507190E+03    T     F
    3  normal.h.002200.r <target>                               0.0000000E+00  -5.6084658E+02  -5.2835912E+02    T     F
    4  srdt.h22000.r <target>                                   0.0000000E+00  -1.4008822E+03  -1.4611581E+03    T     F
    5  srdt.h11110.r <target>                                   0.0000000E+00   1.8429674E+03   1.8825673E+03    T     F
    6  srdt.h00220.r <target>                                   0.0000000E+00  -4.9667353E+02  -4.6605218E+02    T     F
```

Very small effect on chromaticities and h300000 terms after optimization

Small changes on ADTS (h22000, h11110, h00220)

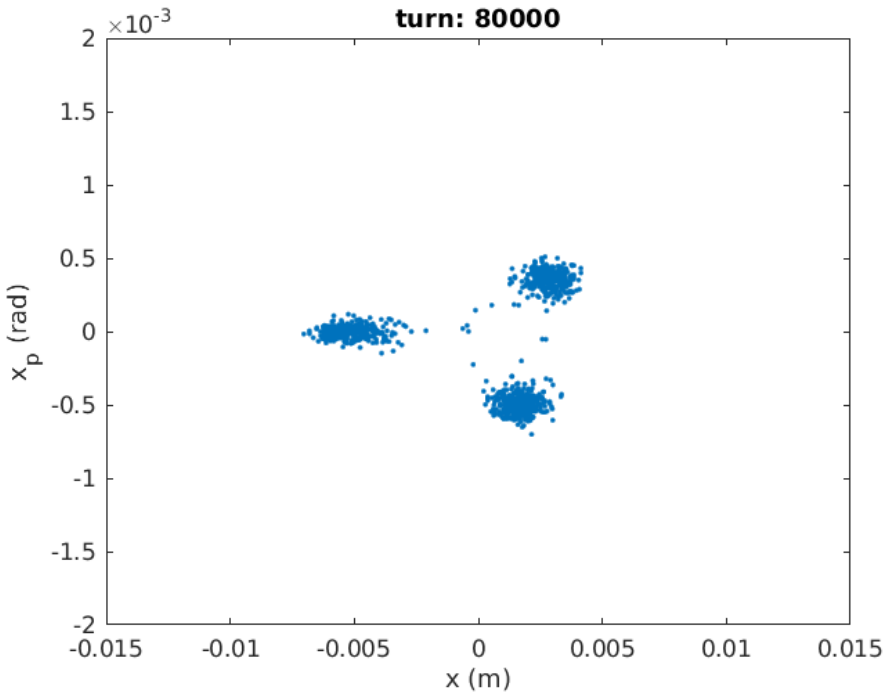
This method could be used to optimize the DA and MA offline as well

Tracking simulation

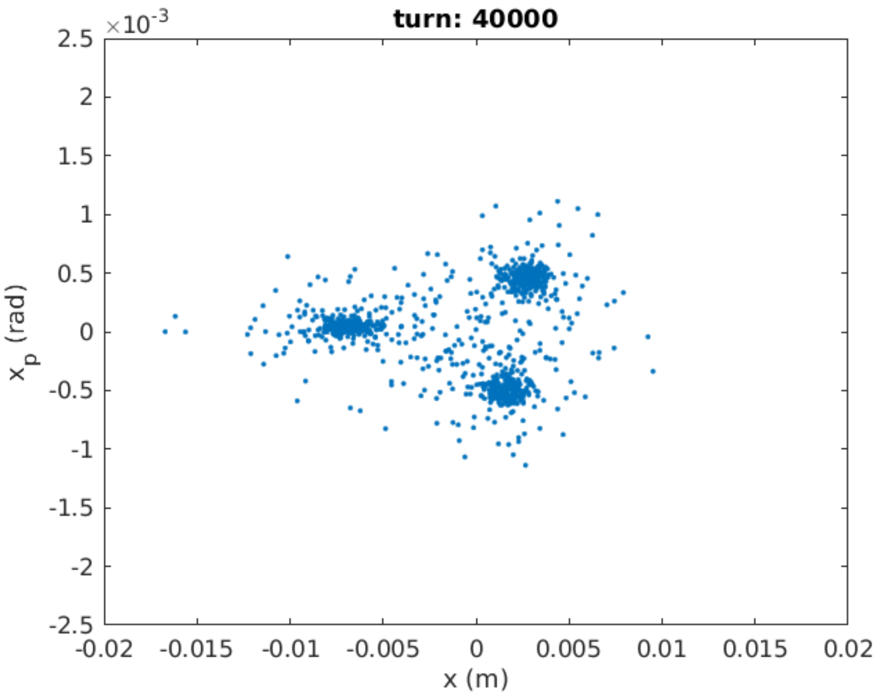
Qx=259.5 kHz, feedback kick amp=1.5 μrad

Track 1000 particles for 4E4 turns (~8$\tau_{x_damping}$)

RCDS optimized



Design sextupoles



With one set of RCDS optimized sextupoles included, the tracking results show no particles lost at different kick amplitudes (0.5 – 5 μrad).

All particles are confined in the island buckets at low kick amplitudes.

Summary and future work

- The algorithm works fine and the objective matters
- The RCDS algorithm can be applied to other applications

- Machine study
  - For online DA tuning
    - Choose the proper objective (lifetime, injection efficiency, etc)
    - Find the noise (take multiple measurements and get STD or RMS)
    - Find the proper step size of knob value
    - Define the limits
    - Create a real function with loading knobs and reading objective
  - For injection transfer rate tuning
    - Read Xetec scope plot and transfer to a number (transfer rate) as objective
    - Define input parameters, range, and noises (transfer line elements)
  - Others
- Improve offline optimization
  - Choose more effective objective
  - Create a merit function with multiple objectives for optimization
  - Check different optimization algorithm