Automatic tuning for machine control

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Outline

- Motivation and general considerations of online optimization.
- The robust conjugate direction search (RCDS) method.
  - Algorithm
  - Simulation
- Examples of RCDS application.
  - Coupling correction.
  - Kicker bump matching.
  - Dynamic aperture optimization.
- Stochastic algorithms for online optimization
  - MOPSO vs. MOGA

The general need of online optimization

Machine performance tuning is a multi-variable (usually nonlinear) optimization problem. Often times online optimization is needed (for accelerators and beyond) .

- Lack of diagnostics (that monitor the sub-systems)
  - Injection steering and transport line optics.
- Target values of monitors not established (or drifting)
  - Initial commissioning.
- Lack of deterministic procedure to go to target values.
  - Nonlinear beam dynamics in storage rings (may also meet the other two conditions).
- Manual tuning works only for small scale problems (a few, <=4 knobs?) and is slow. Automated tuning is needed.
  - Early automated experimental optimization of accelerators: L. Emery et al, PAC'03.

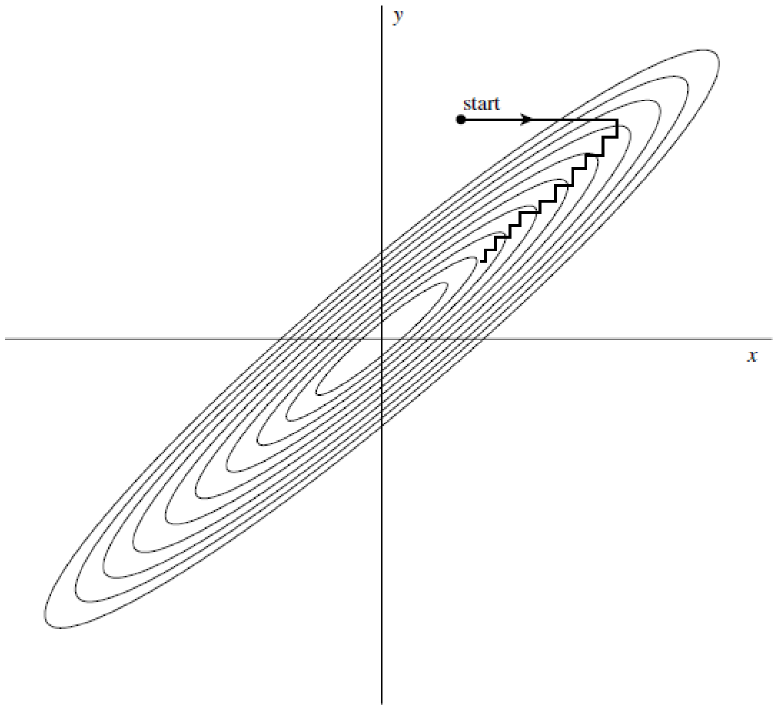
Algorithms for online optimization

- Requirements
  - High efficiency – get to the optimum fast
    - Online evaluation of the objective is usually slow.
    - Machine study time is usually limited (and expensive).
    - Efficiency may be measured by the number of function evaluations.
  - Robustness – surviving noise, outliers and machine failures
  - (Live status reporting during optimization.)
- Candidates:
  - Gradient based method are not considered because of noise.
  - Iterative 1D scan (that automates manual tuning procedure)
  - Powell's conjugate direction method
  - Nelder-Mead (downhill) simplex method
  - MOGA?
  - MOPSO
  - Robust conjugate direction method (RCDS*) – A combination of conjugate direction method and a new noise resistant line optimizer.

*X. Huang, et al, Nucl. Instr. Methods, A 726 (2013) 77-83.

The RCDS algorithm for noisy function optimization

- Powell's conjugate direction method



Powell's method* has two components:
1. A procedure to update the direction set to make it a conjugate set.
2. A line optimizer that looks for the minimum along each direction.

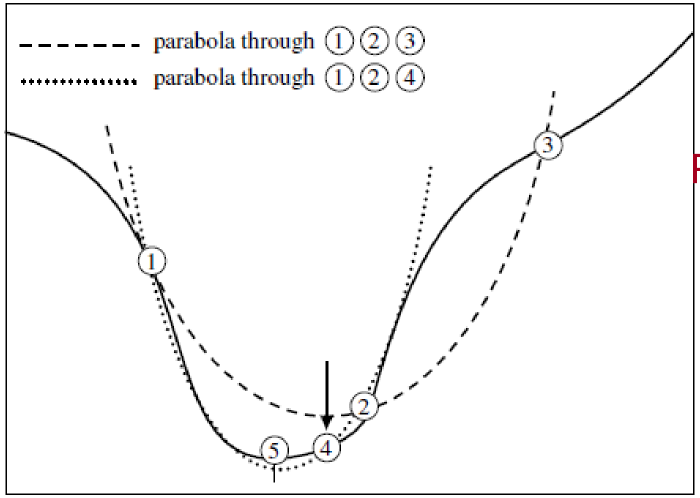
Directions **u**, **v** are conjugate if:
$\mathbf{u} \cdot \mathbf{H} \cdot \mathbf{v} = 0$ where the Hessian matrix is defined

$$H_{ij} = \frac{\partial^2 f}{\partial x_i \partial x_j}$$

Iterative parameter scan can be very inefficient.

*W.H. Press, at al, Numerical Recipes
*M.J.D. Powell, Computer Journal 7 (2) 1965 155

The robust line optimizer



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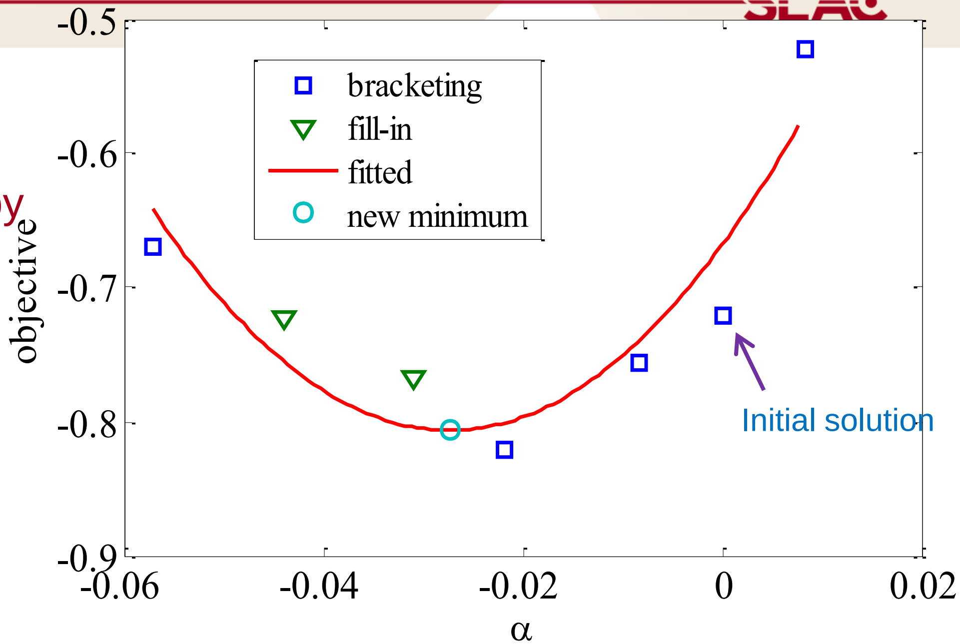


Inverse parabolic interpolation (figure from Numeric.Recipe.)

Step 1: bracketing the minimum with noise considered.
Step 2: Fill in empty space in the bracket with solutions and perform quadratic fitting. Remove any outlier and fit again. Find the minimum from the fitted curve.

Global sampling within the bracket helps reducing the noise effect.

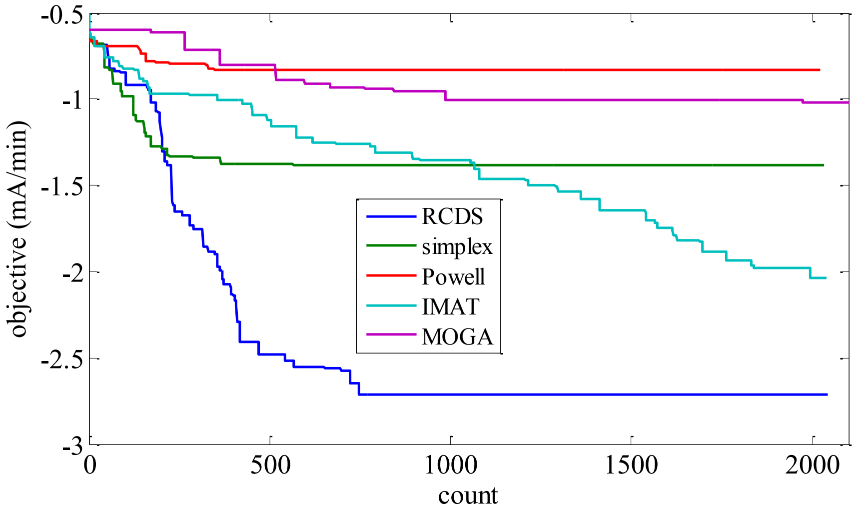
RCDS is Powell's conjugate method* + the new robust line optimizer.

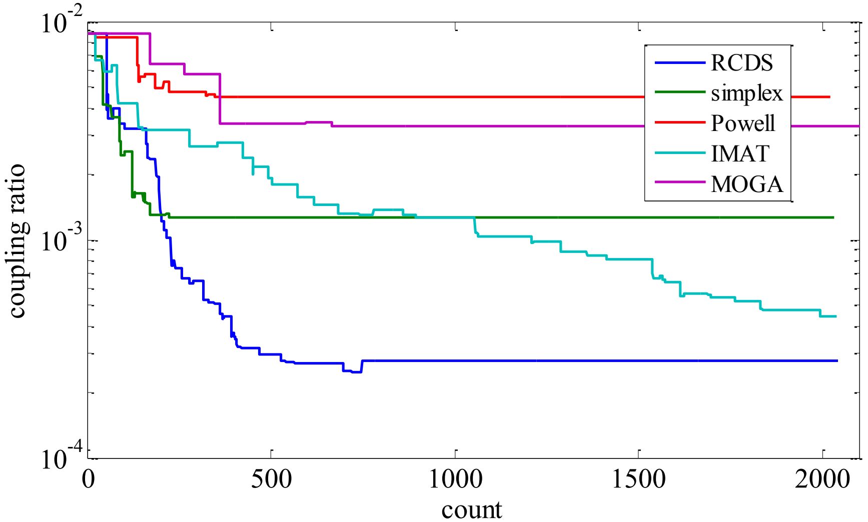
*however, since the online run time is usually short, it is important to provide good an initial conjugate direction set which may be calculated with a model.

Simulation – SPEAR3 storage ring coupling correction

- Using calculated beam loss rate as the objective function.
- Noise is generated in the objective function by adding random noise to beam current values (used for loss rate calculation).
- There are 13 coupling correction skew quads in SPEAR3.
- Initial conjugate direction set is from SVD of the Jacobian matrix of orbit response matrix w.r.t. skew quads
- With
  - 500 mA beam current with 1% random variation. On top of that a DCCT noise with sigma = 0.003 mA. The beam loss rate noise evaluated from 6-s duration is 0.06 mA/min.
  - 40 hour gas lifetime; 10 hour Touschek lifetime with 0.2% coupling.
  - The coupling ratio with all 13 skew quads off is 0.9% (with simulated error), corresponding to a loss rate of 0.6 mA/min.

Comparison of algorithms in simulation: coupling correction





The IMAT method uses the same RCDS line optimizer, but keep the direction set of unit vectors (not conjugate).

Clearly,

(1) The line optimizer is robust against noise.

(2) Searching with a conjugate direction set is much more efficient.

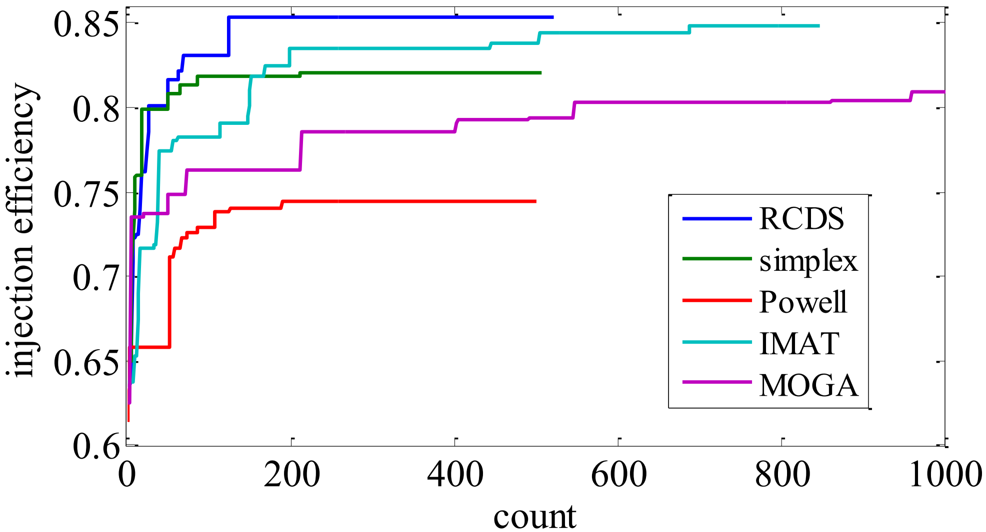
(3) Original Powell's method, downhill simplex and MOGA are not effective for noisy problems.

Note that the direction set has been updated only about 8 times after 500 evaluations (out of 13 directions). So the high efficiency of RCDS is mostly from the original direction set.

Simulation: injection into SPEAR3

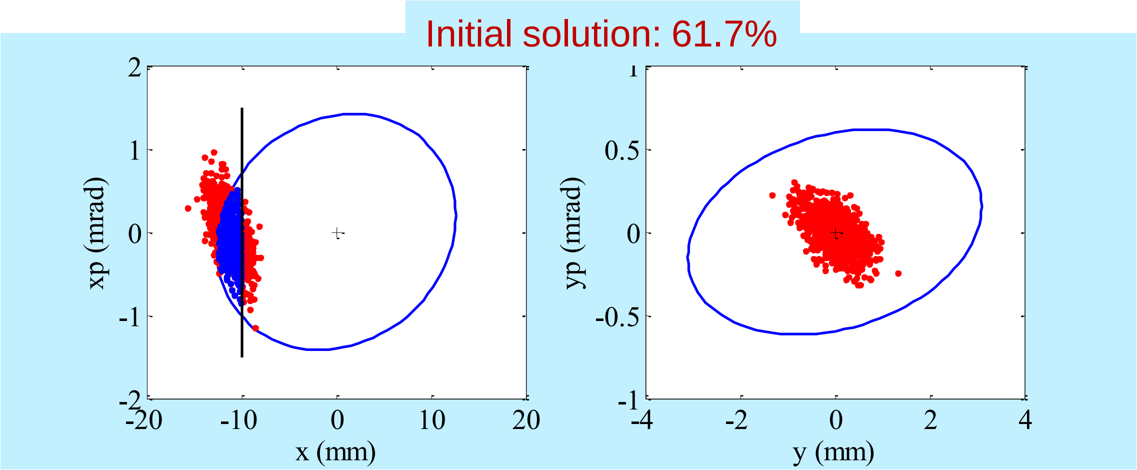
BTS transport line optics matching:

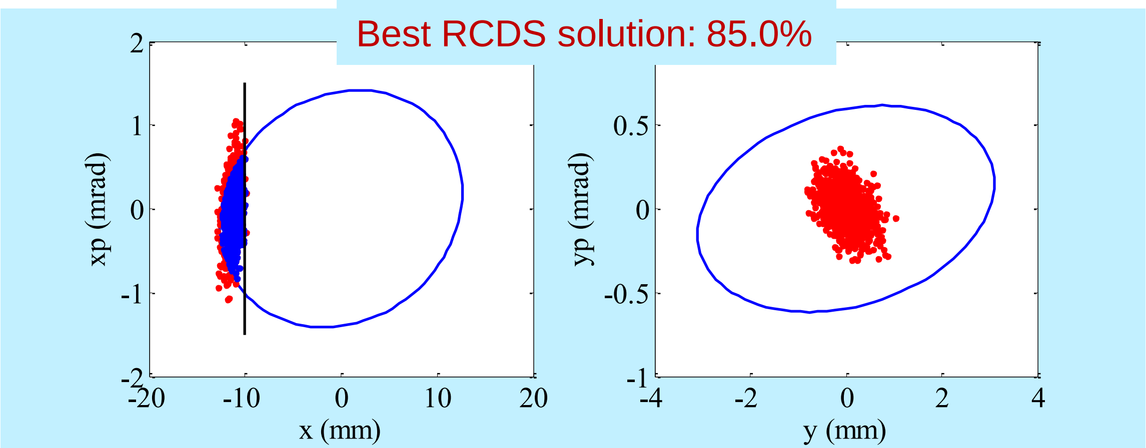
Varying 6 quads in BTS for optics matching between transport line and storage ring.
Noise is generated from the finiteness of the number of particles.
With 1000 particles in a distribution, the noise sigma of injection efficiency is 1.6%.
Initial conjugate direction set is from SVD of beam moments (elements of the σ-matrix) w.r.t. quads.
Dynamic aperture of the ring is intentionally shrunk to 12.5 mm in the simulation.



Performance similar to the coupling study is observed.

Solutions for injection optimization

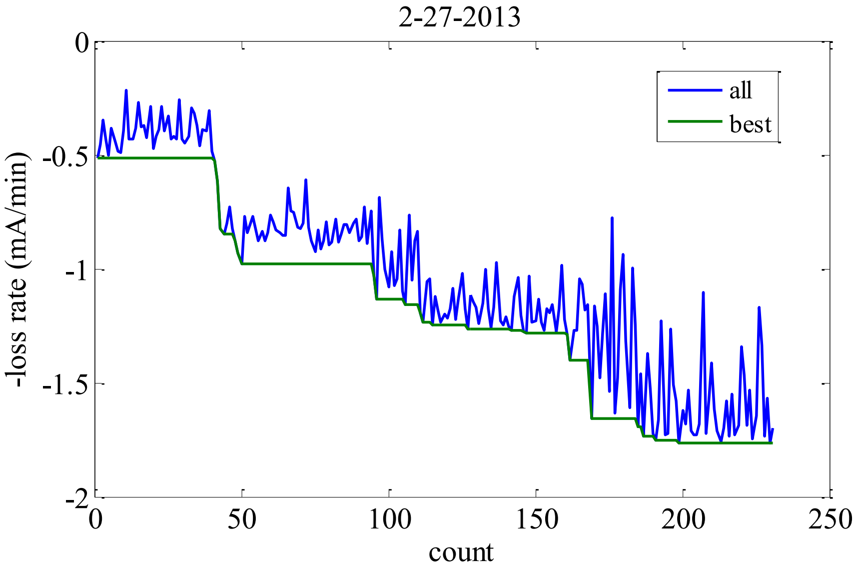


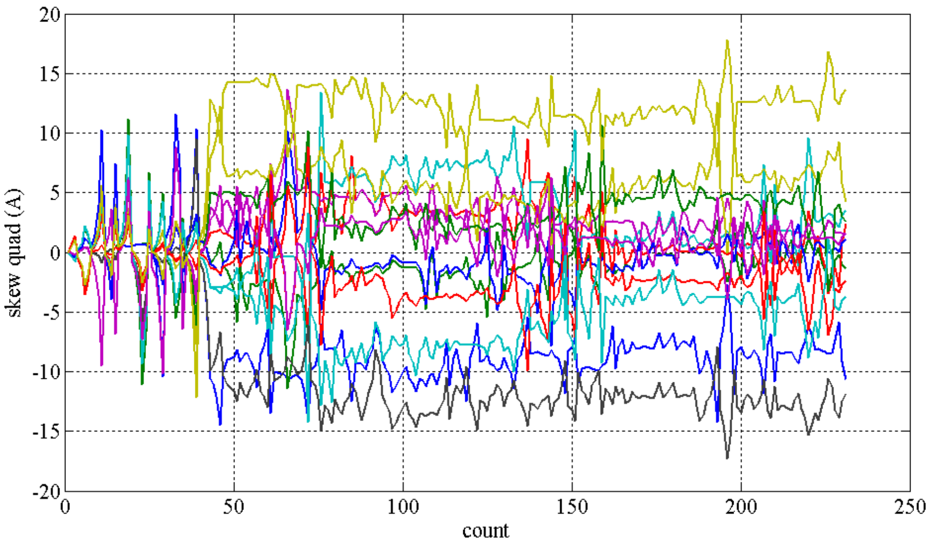


Application of RCDS in experiments

- Application to SPEAR3
  - Coupling correction
    - w/ loss rate
    - w/ vertical beam size
  - Kicker bump matching
  - Injected beam steering
  - Transport line optics matching
  - Gun-to-Linac steering and optics
  - Dynamic aperture (injection efficiency)
- Application elsewhere
  - LCLS undulator taper profile (J. Wu, et al)
  - BEPC-II luminosity (H. Ji, Y. Jiao, et al)
  - ALS injection (C. Sun)

Coupling correction w/ loss rate





Beam loss rate is measured by monitoring the beam current change on 6-second interval (no fitting). Noise sigma 0.04 mA/min.
Data were taken at 500 mA with 5-min top-off.

Initially setting all 13 skew quads off. Loss rate at about 0.4 mA/min.
Final loss rate at about 1.75 mA/min.
At 500 mA, the best solution had a lifetime of 4.6 hrs. This was better than the LOCO correction (5.2 hrs)

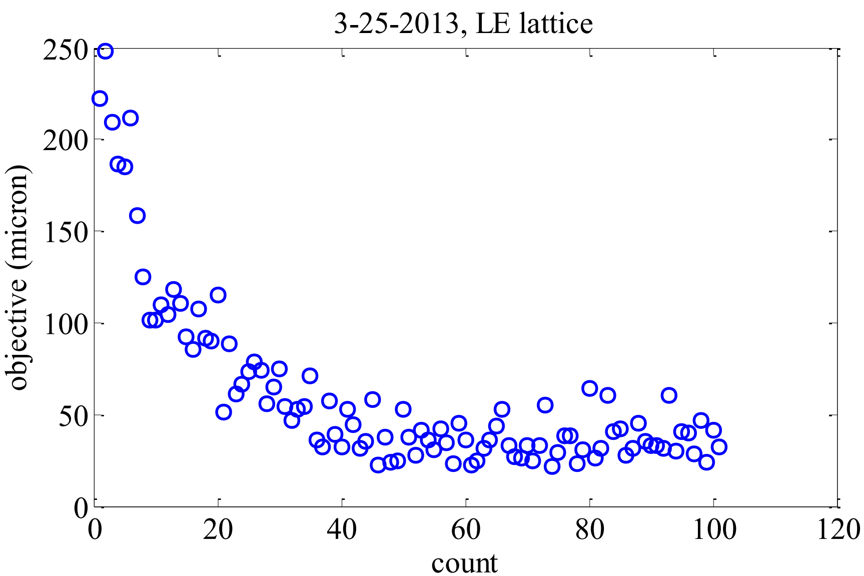
On a later shift (5/6/2013), with 6-s DCCT data **fit** for loss rate, loss rate reached >2.0 mA/min at 500 mA and lifetime was 4.2 hrs.

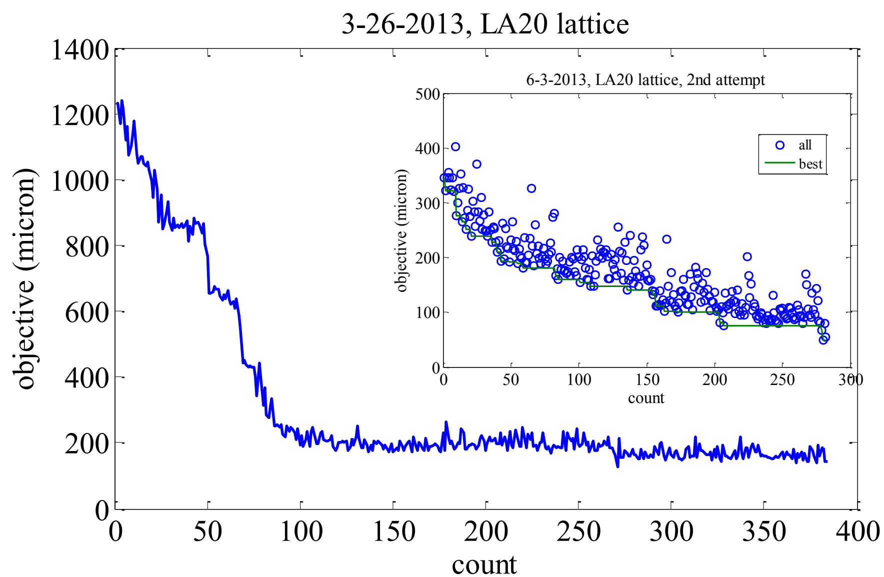
Kicker bump matching

SPEAR3 has three injection kickers (horizontal) located in three neighboring straight sections. The transient residual oscillation of the stored beam after injection needs to be minimized.

Parameters: Adjusting pulse amplitude, pulse width and timing delay of K1 and K3 (with K2 fixed) and two skew quads for vertical plane, 8 parameters total.

Objective: sum of rms(x) and rms(y) of turn-by-turn orbit (for 30~300 turns).



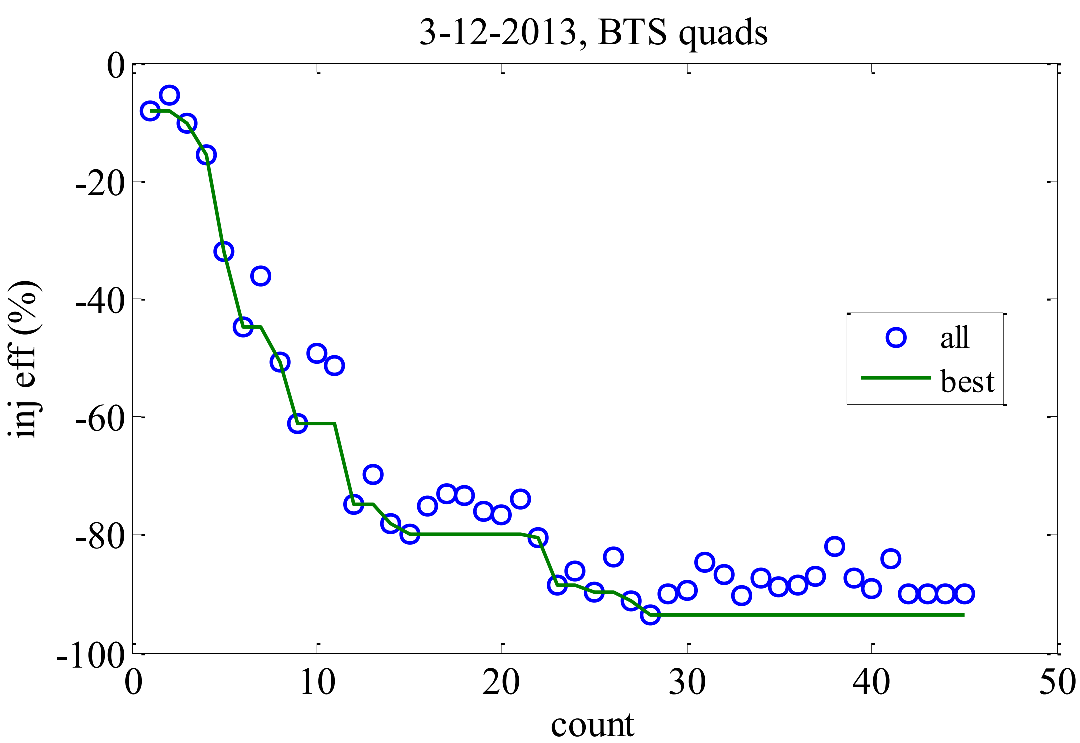


First time of getting kicker bump for low alpha lattice matched.

BTS optics

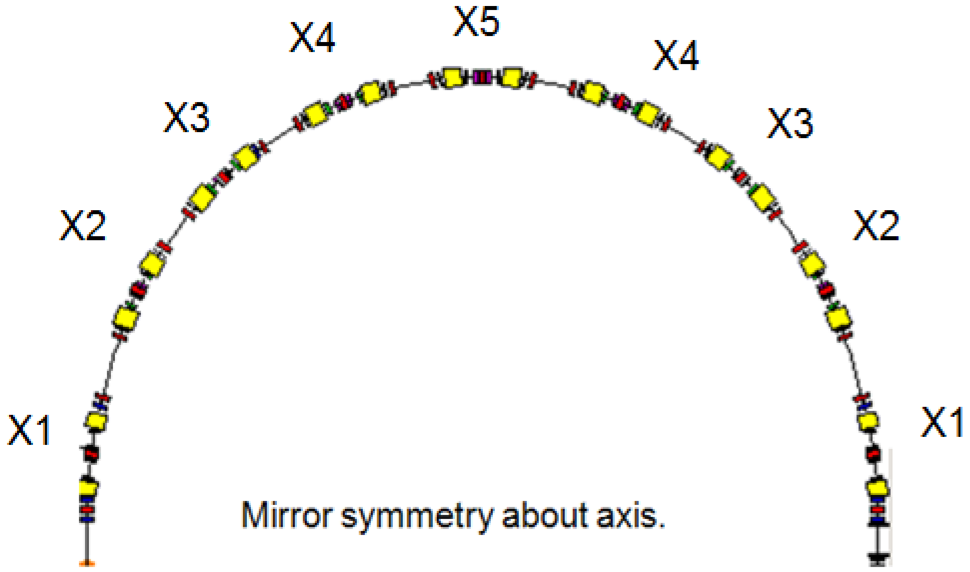
For injection optics matching, ideally we need to decouple the steering effect of quadrupole changes (when beam trajectory is off-center). But we haven't done that yet.
To test the algorithm, we changed the 9 BTS quads setpoints randomly to mess up injection and use the code to bring injection back.

Knobs: 9 BTS quads.
Objective: injection efficiency.



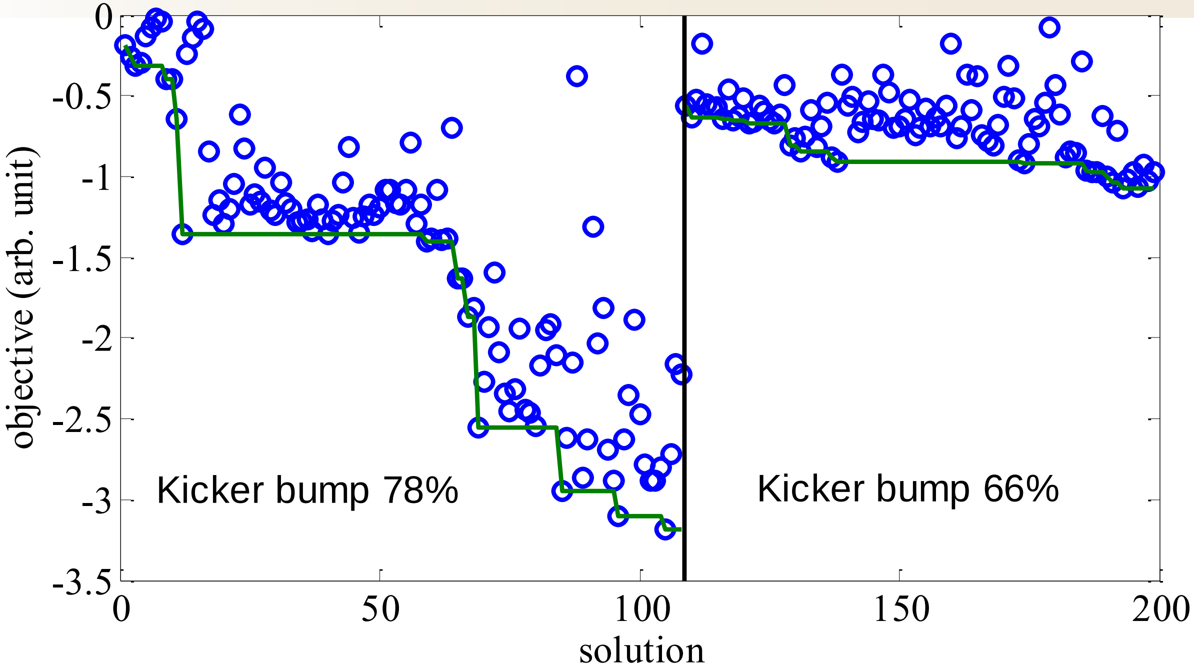
SPEAR3 nonlinear dynamics optimization*

- 10 independently powered sextupole groups
- reduced the kicker bump by 34% to have a low initial injection efficiency
- Injector is detuned to lower total beam loss during experiment.
- Knobs: 8 variables in the subspace of the 10-dim parameter space that keep chromaticities fixed (basis of the null space of the chromaticity response matrix).
- Objective: Injection efficiency calculated as beam current change over 10 seconds normalized by average Booster beam current within the period.

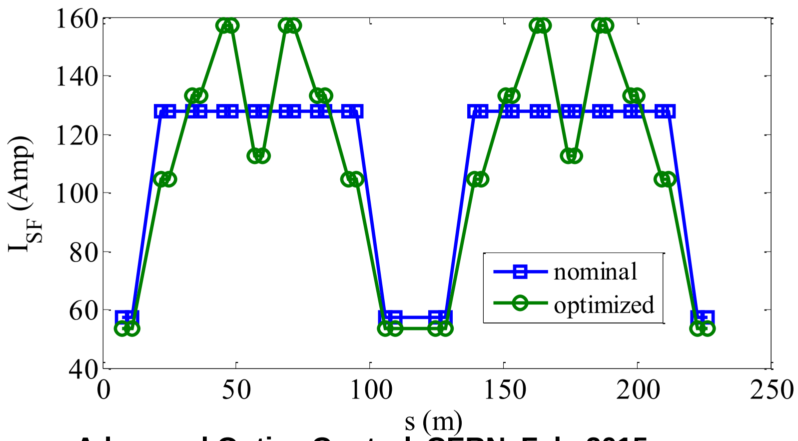


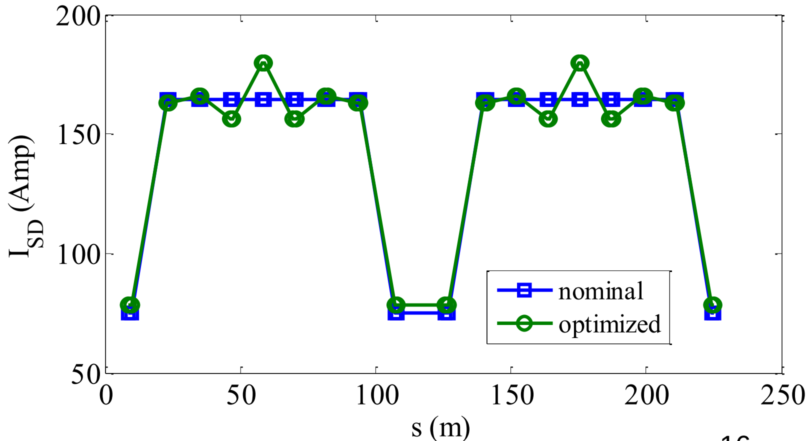
* The SPEAR3 DA optimization study is an ongoing collaboration with James Safranek.

Objective function for all evaluated solutions

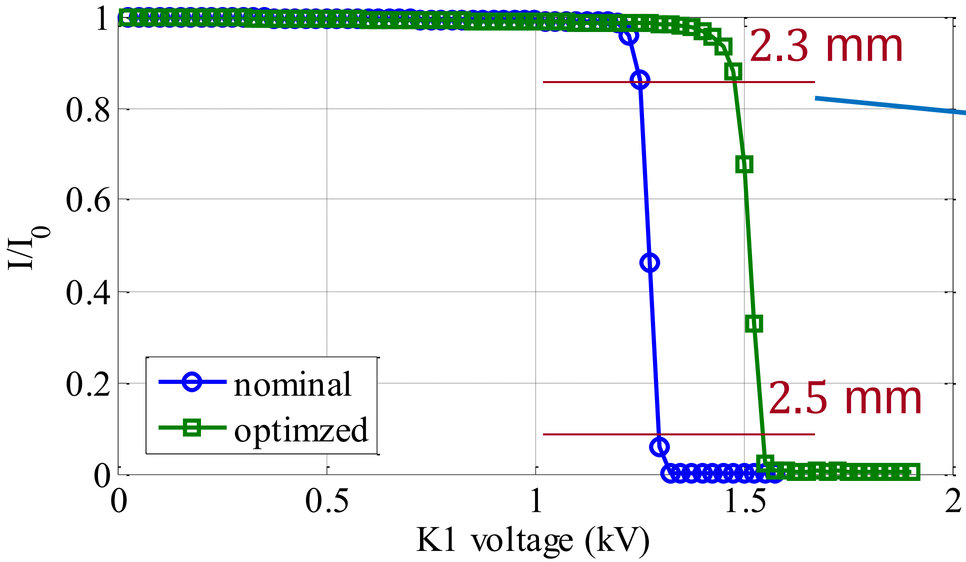


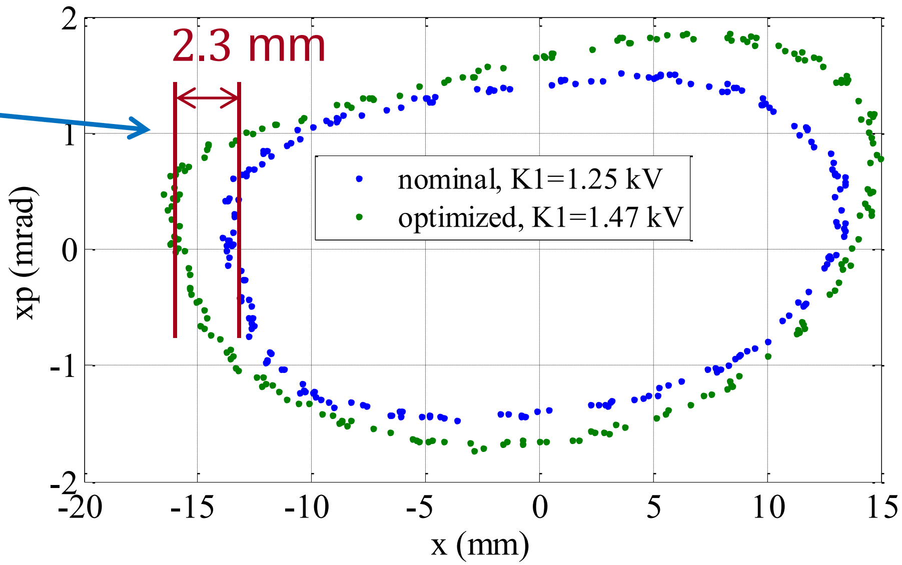
The code RCDS completed a little more than 2 iterations in total.





Measurement of dynamic aperture



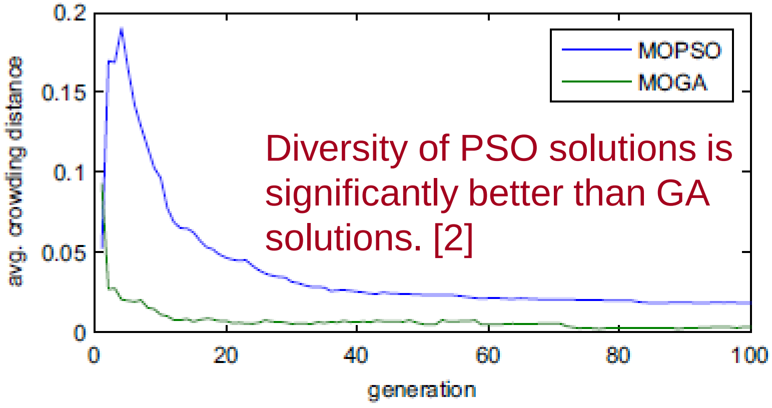


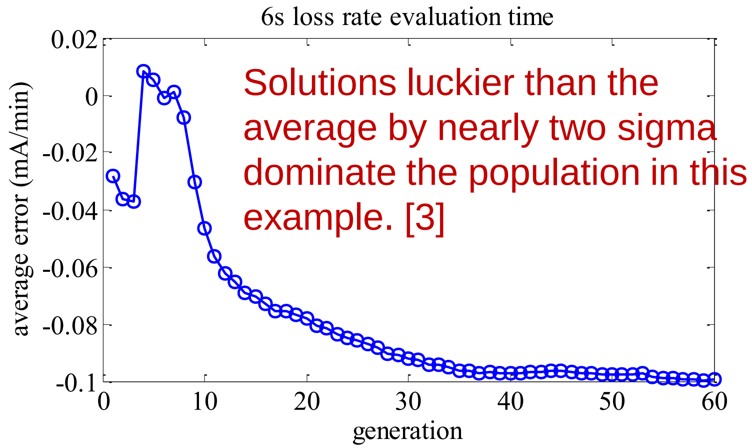
Actual DA = bump limit + 5σ (stored beam)
Nominal: 15.9 mm
Optimized: 18.4 mm.

Phase space at septum exit by tracking with calculated kick.
Difference on the negative side: 2.3 mm.

Stochastic algorithms for online optimization

- Stochastic algorithms give more assurance in finding the global optimum, but are less efficient.
- Particle swarm optimization (PSO) algorithm or genetic algorithms (GA)?
  - There are studies that show particle swarm method is much more efficient than a typical genetic algorithm (NSGA-II)[1-2], due to high diversity of solutions in the former.
  - Results of genetic algorithms are twisted by noise-introduced bias[3].

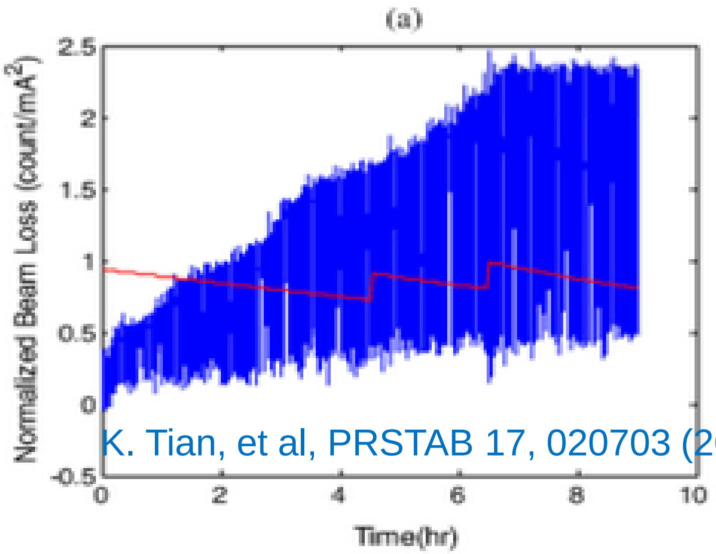




[1] X. Pang, et al, NIMA 741 (2014) 124
[2] X. Huang, et al, NIMA 757 (2014) 48
[3] X. Huang, et al, NIMA 726 (2013) 77-83.

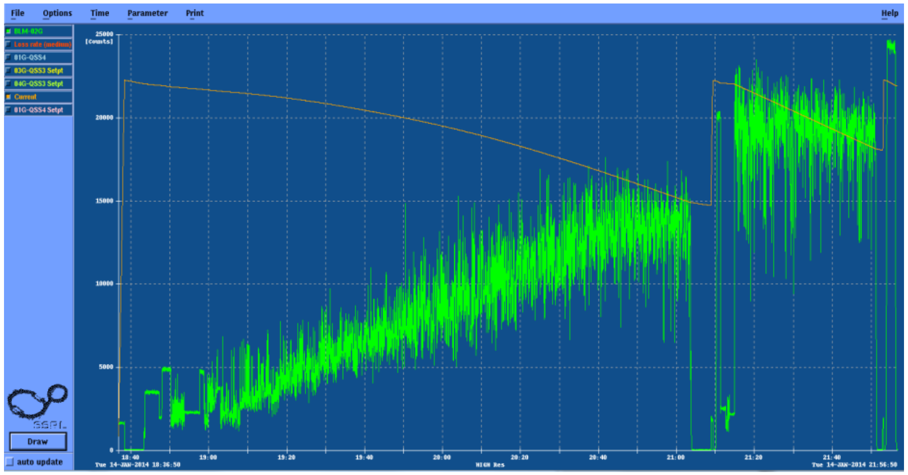
Comparison of GA and PSO performance: an example

SPEAR3 coupling correction with loss monitor data.



K. Tian, et al, PRSTAB 17, 020703 (2014)

GA (NSGA-II)



PSO

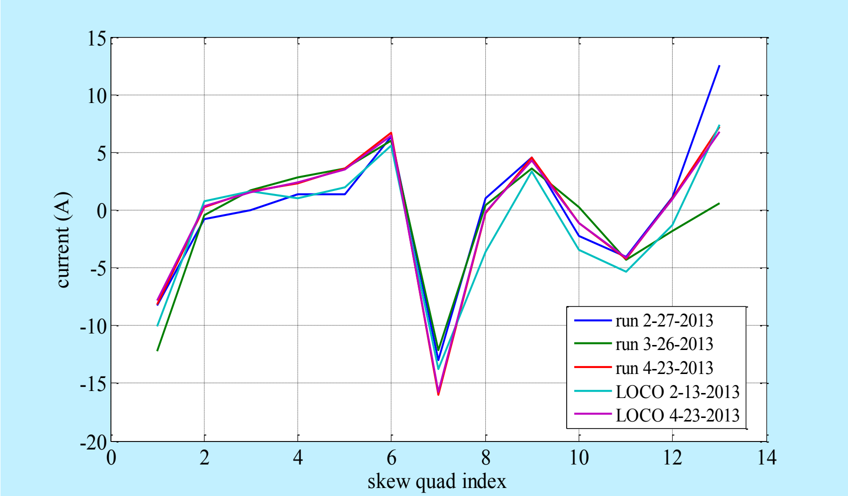
Note: (1) loss monitor data noise is considerably lower than DCCT loss over 6 seconds (as was used for RCDS test). With the latter GA may not work (see backup slide).
(2) To reach the same level of coupling, GA requires ~**20000** evaluations, PSO ~**3000** evaluations, RCDS ~**300** evaluations.

Summary

- There is a need of online optimization algorithm in the era of computerized control. Biggest challenge to conventional algorithms is noise in function evaluation.
- The RCDS method is demonstrated to be robust against noise and efficient when conjugate direction set is supplied.
- The RCDS method has been successfully applied to many accelerator optimization problems.
- When stochastic algorithms are desired, the particle swarm method (PSO) is preferred.

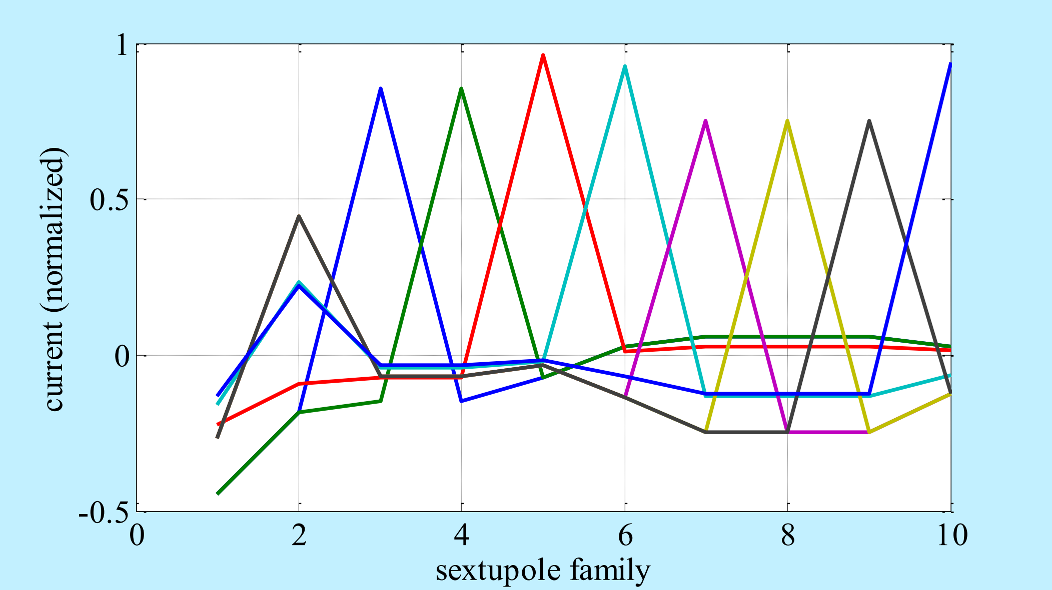
Matlab code of RCDS is available from X. Huang

Backup plots

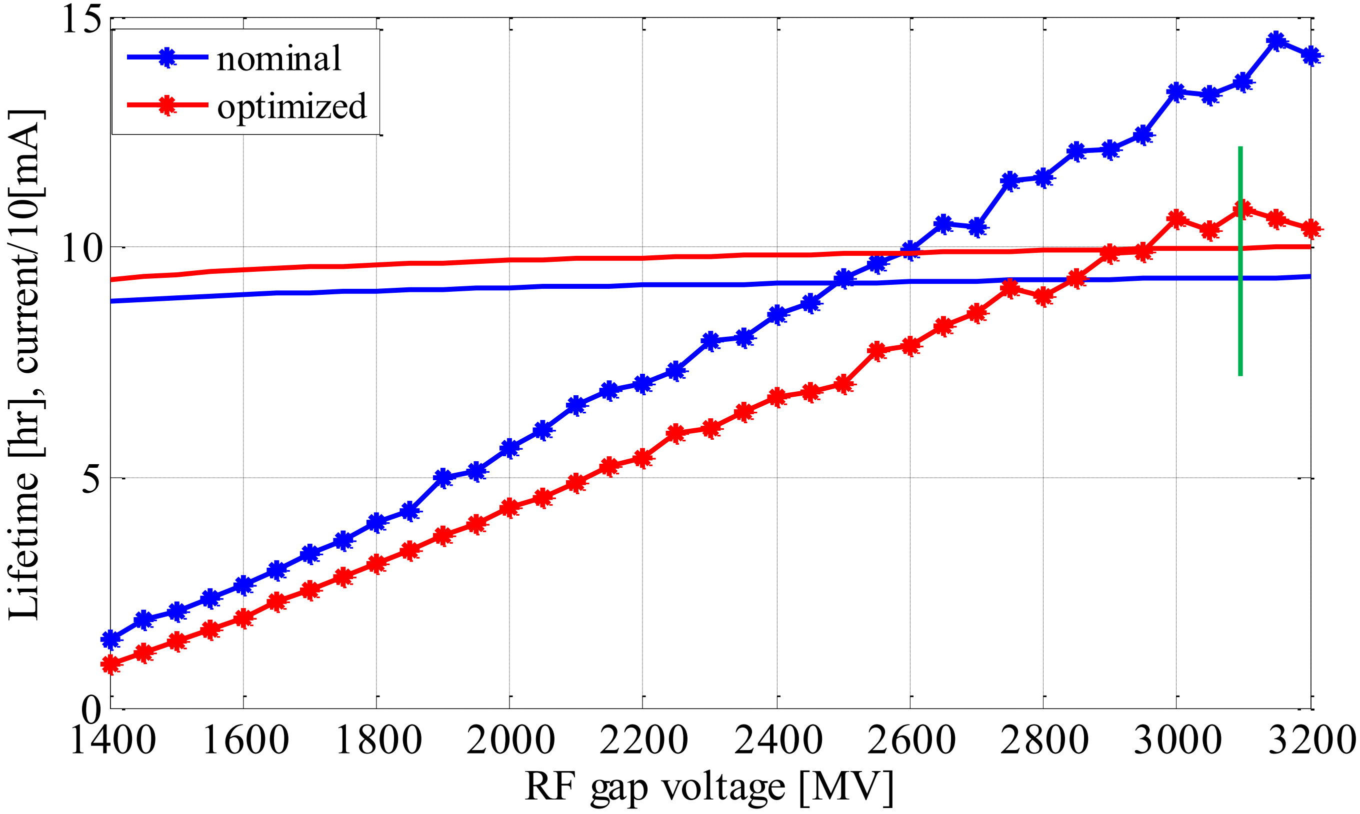


Skew quad solutions found by RCDS are similar to that of LOCO.

Basis of the null space of the chromaticity response matrix, which are used as independent knobs in DA optimization.

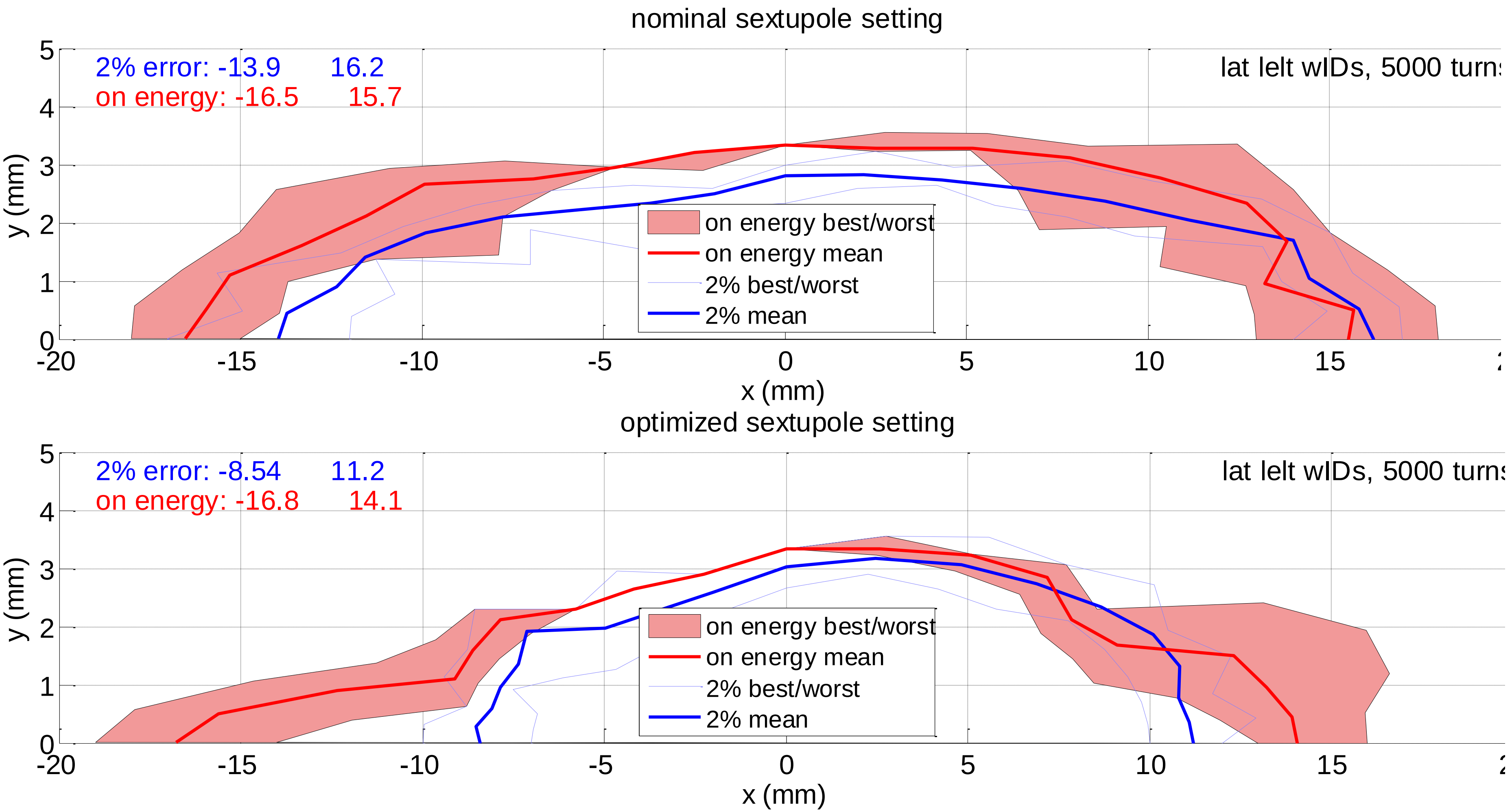


Momentum aperture measurement



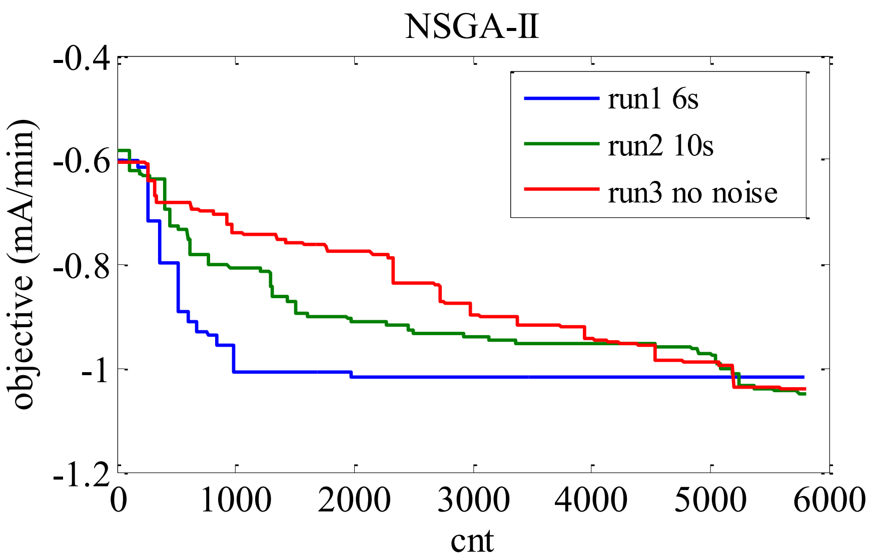
Lifetime vs. RF gap voltage (100 mA in 80 bunches,Touschek lifetime dominated) The optimized sextupole setting may have a smaller minimum MA, corresponding to 3100 kV (bucket height 2.55%). SPEAR is operated at 2850 kV for 500 mA.

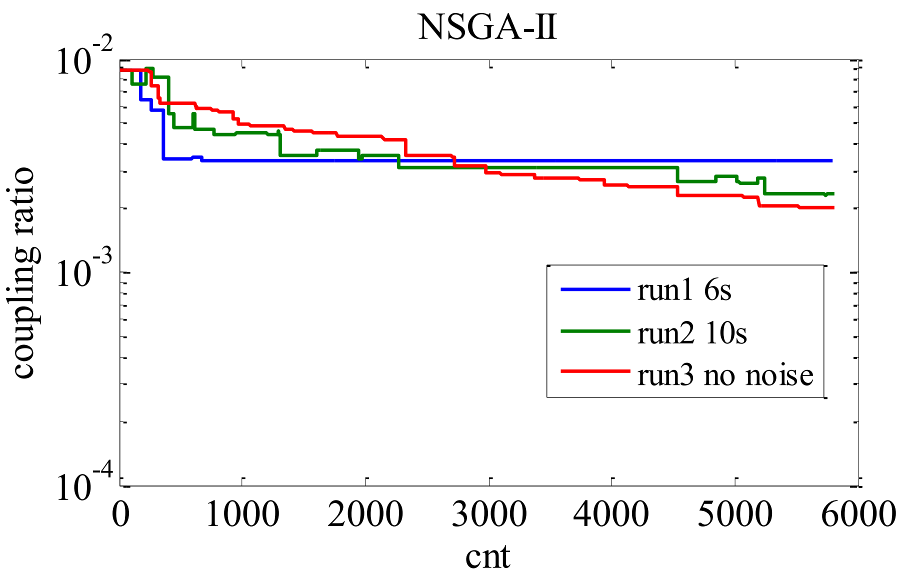
Comparison of DA by tracking simulation



Chromaticities are [3, 3], with 20 seeds of linear and multipole errors, 1% beta beating, 0.2% coupling. With radiation damping. With effects of IDs.

GA with noise in objective function





Objective function (beam loss) for the 6-second case is noisier.
(1) The objective function may appear to be better (before cnt=5000), the actual coupling is not.
(2) With larger noise in data, GA (NSGA-II) fails to make further improvement.

X. Huang, et al, NIMA 726 (2013) 77-83.