Online optimization of nonlinear dynamics for diffraction limited storage rings (DLSR)

Presentation at 4th Diffraction Limited Storage Ring (DLSR) Workshop (Argonne, 2014)

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Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Motivation
  - Nonlinear dynamics challenges in DLSR
- Accelerator optimization with automatic tuning
  - Considerations
  - The robust conjugate direction search (RCDS) method
  - Simulation and experiments
- Recent experimental nonlinear dynamics optimization at SPEAR3
  - Experimental setup
  - Experimental results with significant improvement to SPEAR3 dynamic aperture.
- Summary

DLSR is big step forward

- High-gradient quadrupoles allowed compact MBA lattice to reach diffraction limited emittance
  - B_1 : 20~25 T/m → 43 T/m (MAX-IV) → ~85 T/m (new generation)
- Scaling laws of lattice property with quadrupole gradient, energy and circumference
  - A linear lattice cell can be scaled with phase advance fixed by keeping $\sqrt{K_1}L = \text{const}$, with $K_1 = \frac{B_1}{E}ec$, and L cell length.

Scaling of properties:

Lattice functions: $\beta \propto L,\ D \propto \frac{L^2}{\rho},\ D' \propto \frac{L}{\rho},\ \mathcal{H} \propto \frac{L^3}{\rho^2}$

Emittance: $\epsilon \propto \gamma^2 \frac{L^3}{\rho^3}$

Applying $NL = C$ and assuming $\frac{C}{2\pi\rho} = \text{const}$ and $\sqrt{\frac{B_1}{E}}L = \text{const}$ we get

$$\boldsymbol{\epsilon = F\frac{E^{3.5}}{B_1^{1.5}C^3}}$$

F form factor

Comparison of rings

	energy [GeV]	circumference [m]	emittance [nm]	gradient B1 T/m	**Form factor**
SPEAR3	3	234	9.8	22	**0.28**
ALS	1.9	196.8	2	22	**0.17**
APS	7	1104	2.5	19	**0.31**
Diamond	3	561.6	2.7	20?	**0.91**
NSLS-II	3	780	0.55	20	**0.50**
TPS	3	518.4	1.7	18	**0.39**
SSRF	3.4	432	3.9	21	**0.42**
Soleil	2.75	354.1	3.74	21	**0.46**
ALBA	3	266	4.5	23	**0.20**
SIRIUS	3	518	0.28	40	**0.21**
MAX-IV	3	528	0.24	43	**0.21**
spring8-II	6	1435.95	0.067	56	**0.16**
ESRF upgrade	6	844.4	0.15	85	**0.13**
APS-U	6	1104	0.06	85?	**0.12**
ALS 9BA	2	200	0.1	100	**0.071**
SLS upgrade	2.4	288	0.073	85?	**0.064**
SPEAR3 MBA	3	234	0.5	85	**0.11**

Gradient of existing rings are 110% of maximum gradient in lattice.

DLSR are very nonlinear

- Scaling of sextupole strength needed to correct chromaticity

For each cell

$$\Delta\xi \propto \beta D[K_2\Delta L] \propto \frac{L^3}{\rho}[K_2\Delta L], \quad \rightarrow \quad [K_2\Delta L] \propto \Delta\xi\frac{\rho}{L^3} \propto \Delta\xi\frac{B_1^{1.5}}{E^{1.5}}C$$

- Tune shifts with amplitude

This depends on lattice design, we assume

$$\frac{\Delta\nu}{\Delta J} \propto N[K_2\Delta L]^2 \propto \Delta\xi^2\frac{B_1^{3.5}}{E^{3.5}}C^3$$

- Dynamic aperture scaling (only as a rough estimate)

DA may be limited by amplitude-dependent tune shift $\max(\Delta\nu) \sim 0.1 - 0.2$, so

$$J_{DA} = \frac{A^2}{\beta} \propto \frac{E^{3.5}}{B_1^{3.5}C^3}$$

Or

$$J_{DA} \propto \frac{\epsilon}{B_1^2} \quad \text{and} \quad A \propto \frac{\epsilon^{0.5}}{B_1^{1.25}}E^{0.25}$$

Scaling of MAX-IV DA (15 mm@$\beta_x = 9$ m) to APS-U ($\beta_x = 3$ m) would give $A = 2.2$ mm.

Nonlinear dynamics are susceptible to errors

- There are many strong quadrupoles and sextupoles in the ring – sources of optics errors.

$$< \Delta\psi >_{rms} = \frac{1}{2} < \frac{\Delta\beta}{\beta} >_{rms} = \frac{\sqrt{N}\bar{\beta} < \Delta K l >_{rms}}{2\sqrt{2}\sin 2\pi\nu}$$

N number of error sources, $\bar{\beta}$ average beta function.

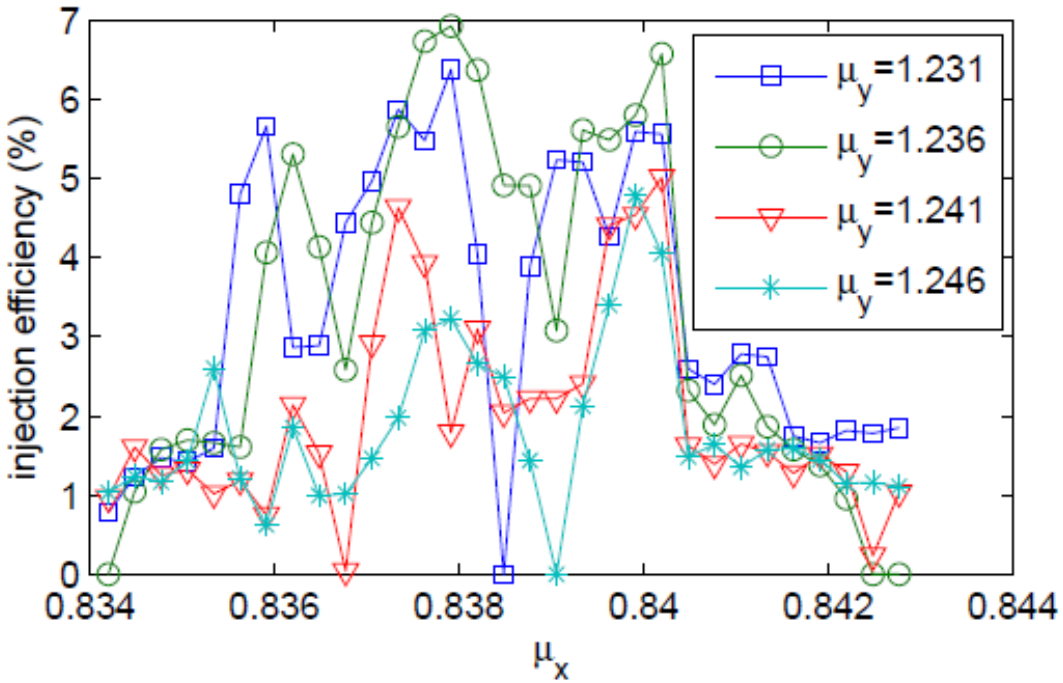
- Optics errors cause changes to nonlinear dynamics.
  - Betatron phases between sextupoles are critical. Example (a RDT formula by C-X. Wang):

$$h_{22000} = \sum \frac{i}{64} \bar{b}_{3i} \bar{b}_{3j} \beta_{xi}^{3/2} \beta_{xj}^{3/2} \left[e^{i\,3(\psi_{xi} - \psi_{xj})} + 3 e^{i(\psi_{xi} - \psi_{xj})} \right]$$

- Although optics correction (with LOCO or turn-by-turn BPM data) can largely eliminate the initial optics errors, the remaining errors can still have a big impact to DA/MA for a large ring.

An example of the impact of phase advances

Experiments for SPEAR3 emittance reduction study



With the tunes ([15.32, 6.18]) fixed, injection efficiency (for the 6 nm lattice of SPEAR3) varies with phase advance per standard cell (14 standard cells, 4 matching cells).

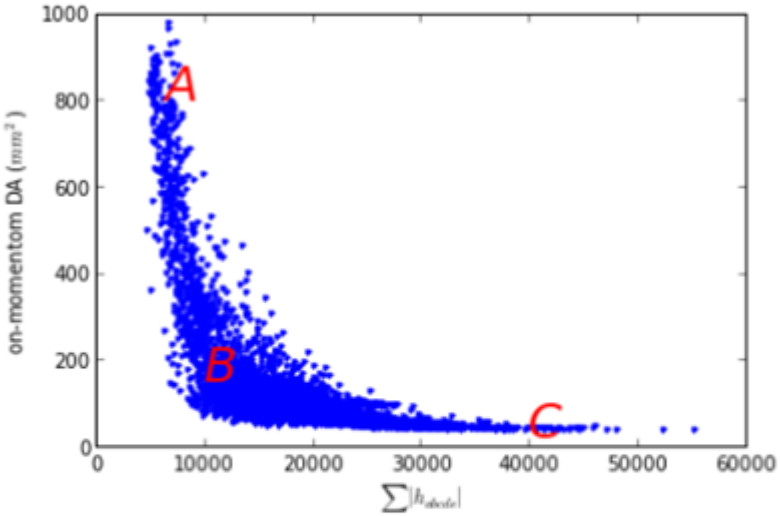
Small betatron phase advance changes can have big impact on DA.

Other sources of errors – the accelerator model

- Accelerator model makes simplifying assumptions
  - Hard edge model of magnets works great, but something is still missing.
  - Nonlinear effects of dipole fringe is usually left out in nonlinear dynamics study.
  - Fringe field effects of quadrupoles.
  - Effects of cross talk between neighboring magnets.
  - Other effects …
- Hence a perfectly implemented design (no alignment and field errors) still may not achieve the desired nonlinear dynamics behavior
  - This has not been a problem for existing rings. But we don't know for DLSR – much more nonlinear, many more error sources.
- Improving the model at the design phase helps, but may not completely eliminate the uncertainty.
  - What random error seed the machine will get?

Calibration of storage ring nonlinear dynamics

- DLSR nonlinear dynamics may need calibration to deliver the desired performance(DA/MA).
- Potential calibration methods:
  - Fit nonlinear tune shifts (chro
    - R. Bartolini et al, PRSTAB 14,
  - Fit nonlinear RDT –
    - R. Bartolini et al PRSTAB 11,
    - A. Franchi, report at LER 201
- Difficulty with these methods
  - Nonlinear dynamics behavior RDT or tune shifts – more so



Correlation of NDT and DA
Yang and Li, PRST-AB
Figure from Y. Li's talk at LER 2014, Frascati, Italy

Despite amazing RDT measurement results, RDT correction was not effective at ESRF

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ESRF correction of resonance driving terms & lifetime A Light for Science

sextupole correctors (12 at the ESRF SR) may be used to retrieve the ideal RDTs:

hypothesis: the more "matched" the RDTs, the larger the dynamic aperture, and (hopefully) the longer the lifetime

filling pattern P= 6.03 GeV/c	E_y E_x=4nm	lifetime correctors OFF	lifetime manual correction	lifetime RDT correction
multibunch (1 mA/bunch) low chroma	7 pm	16.2 h	24.2 h	22.4 h
16 bunch (~6 mA/bunch) large chroma	5 pm	2.5 h	3.2 h	2.0 h

(Slide of A. Franchi's talk at LER 2014, Frascati, Italy)

European Synchrotron Radiation Facility Andrea Franchi Resonance Driving Terms 57

X. Huang, 11/19/2014, at DLSR workshop 2014 (Argonne)

An alternative approach: online optimization

- We can directly optimize injection efficiency and lifetime in experiments with nonlinear dynamics knobs.
- Potential knobs
  - Sextupole (and/or octupole) strengths
  - Selected combination of quadrupoles for phase adjustment.
- This is a logical step forward
  - Harmonic sextupoles are used in storage rings and their strength may differ from design values.
  - In simulation we have already been using DA/lifetime as optimization objectives (pioneered by M. Borland at APS), bypassing indirect nonlinear dynamics measures such as tune diffusion, RDTs.

Question is: how to efficiently optimize ring performance with beam-based measurements?

The general need of online optimization

There are many places (for accelerators and beyond) that need online optimization.

- 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?). Automated tuning is needed.
  - Early automated experimental optimization of accelerators: L. Emery et al, PAC'03.

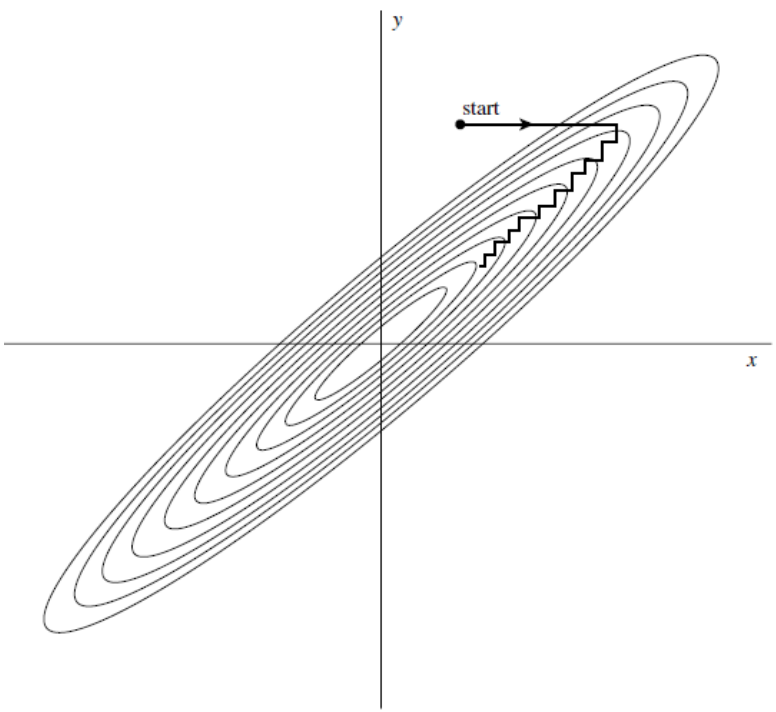
Algorithms for online optimization

- 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, J. Corbett, J. Safranek, J. Wu, "An algorithm for online optimization of accelerators", 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

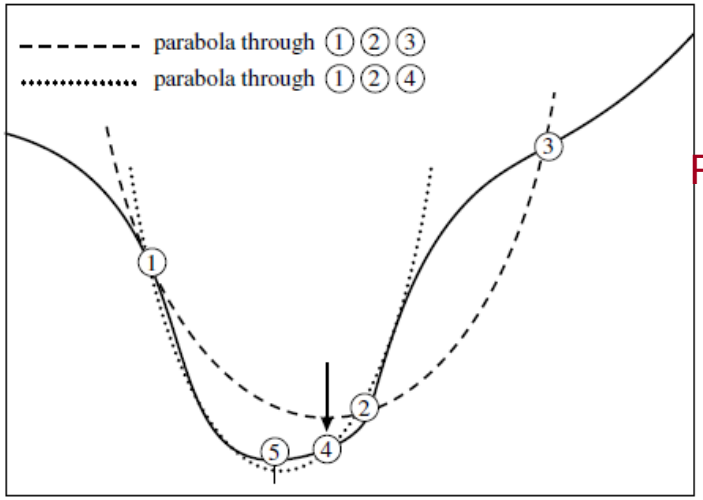
$$H_{ij} = \frac{\partial^2 f}{\partial x_i \partial x_j}$$

Iterative parameter scan can be very inefficient.

*W.H. Press, at al, Numerical Recipes

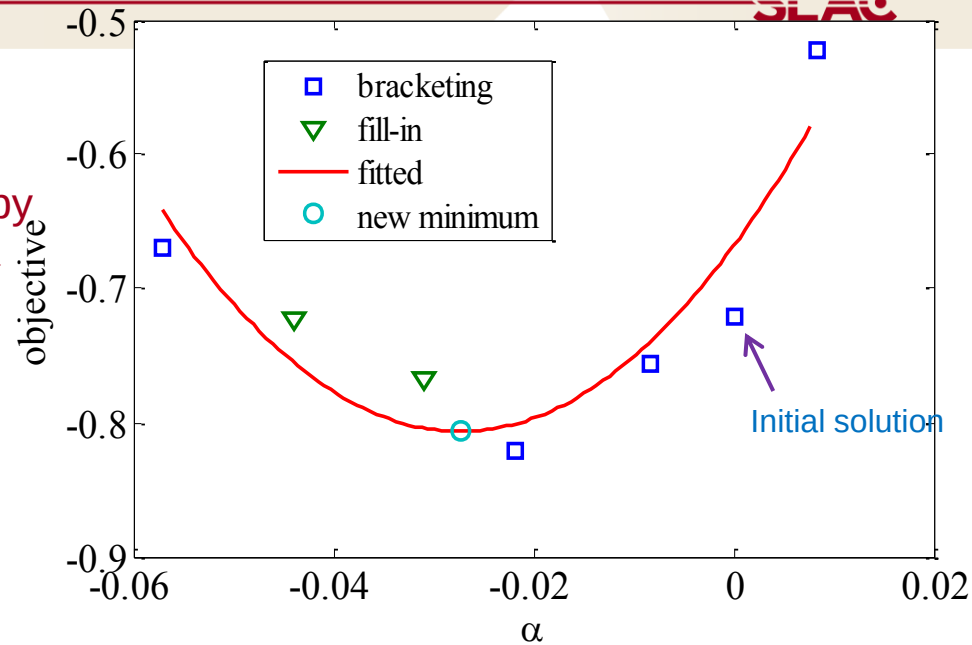
*M.J.D. Powell, Computer Journal 7 (2) 1965 155

The robust line optimizer



Inverse parabolic interpolation (figure from Numeric.Recipe.)

Replaced by →



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.

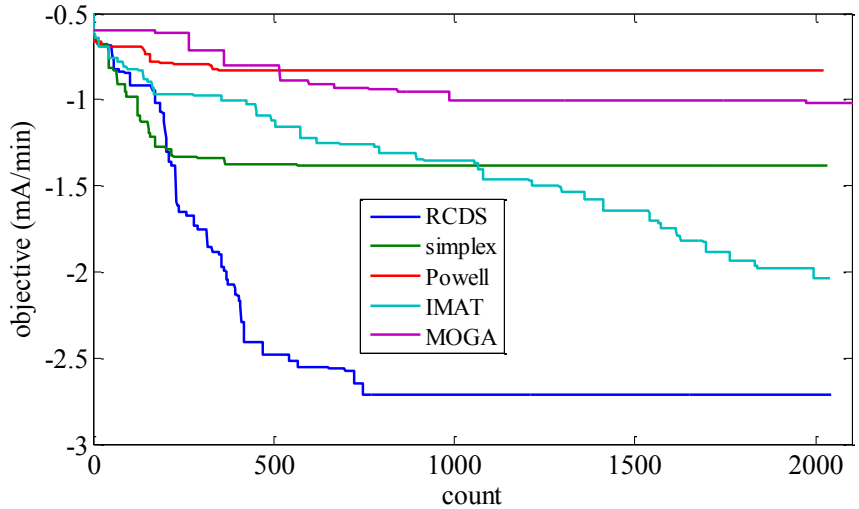
RCDS is Powell's conjugate method* + the new robust line optimizer.

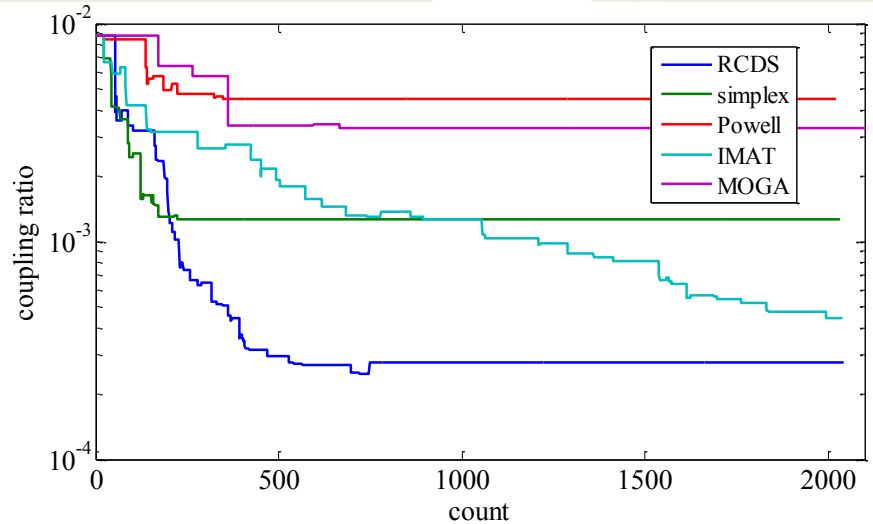
*however, since the online run time is usually short, it is important to provide good an initial conjugate direction set which may be calculated with a model.

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,

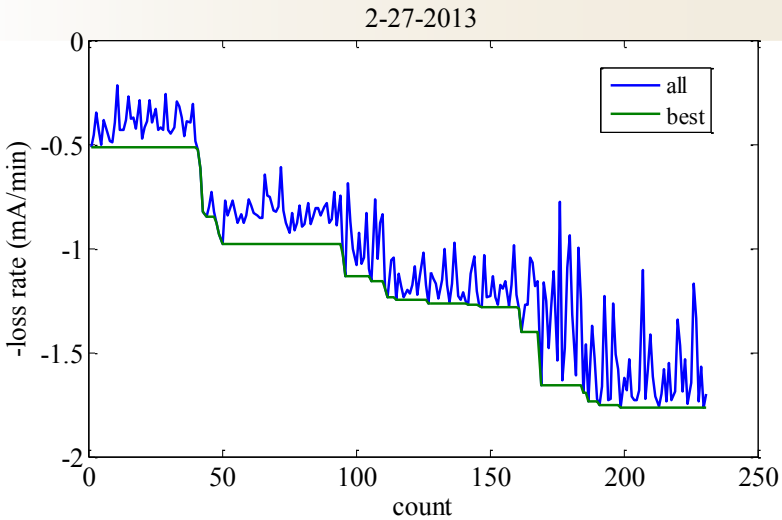
(1) The line optimizer is robust against noise.

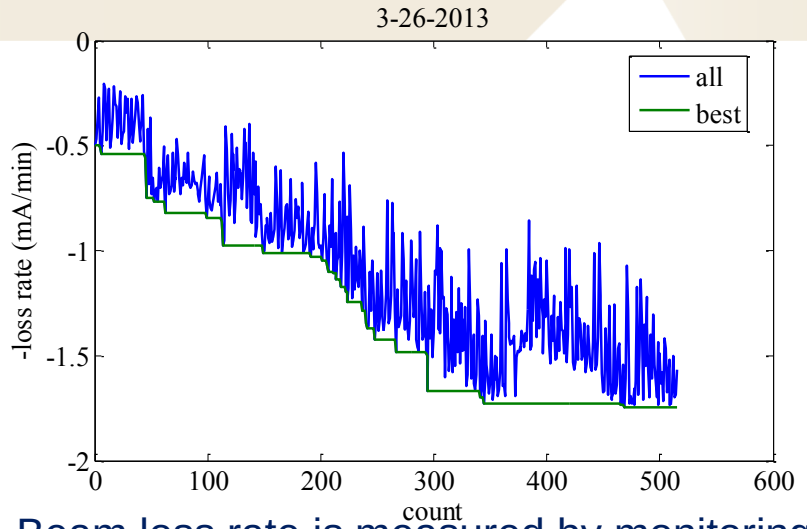
(2) Searching with a conjugate direction set is much more efficient.

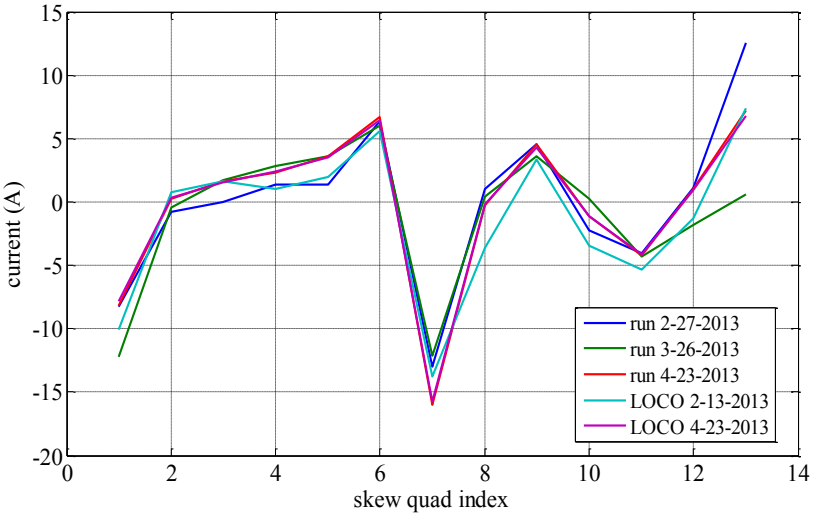
(3) Original Powell's method, downhill simplex and MOGA are not effective for noisy problems.

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.

Coupling correction with loss rate







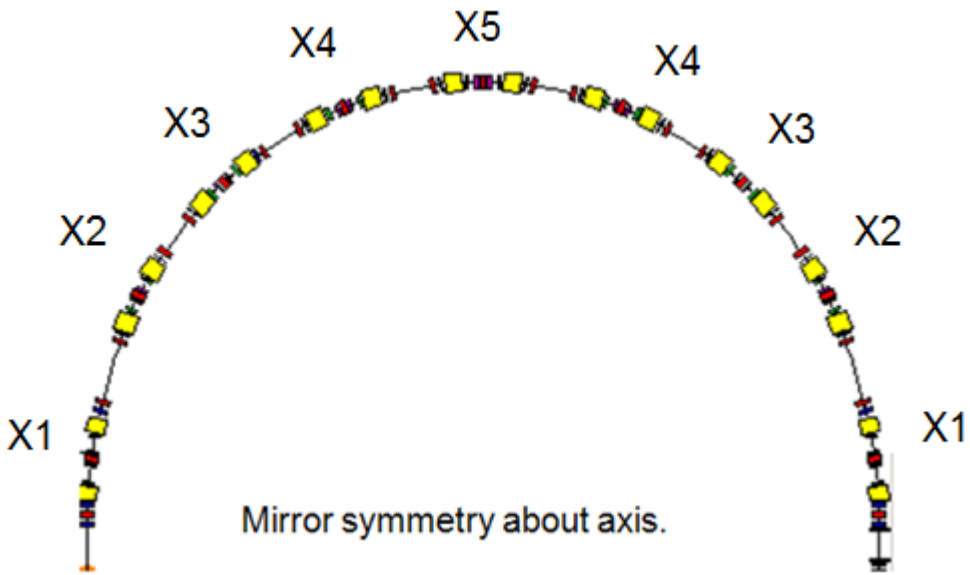
Beam loss rate is measured by monitoring the beam current change on 6-second interval (no fitting). Noise sigma 0.04 mA/min.
Data were taken at 500 mA with 5-min top-off.

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.

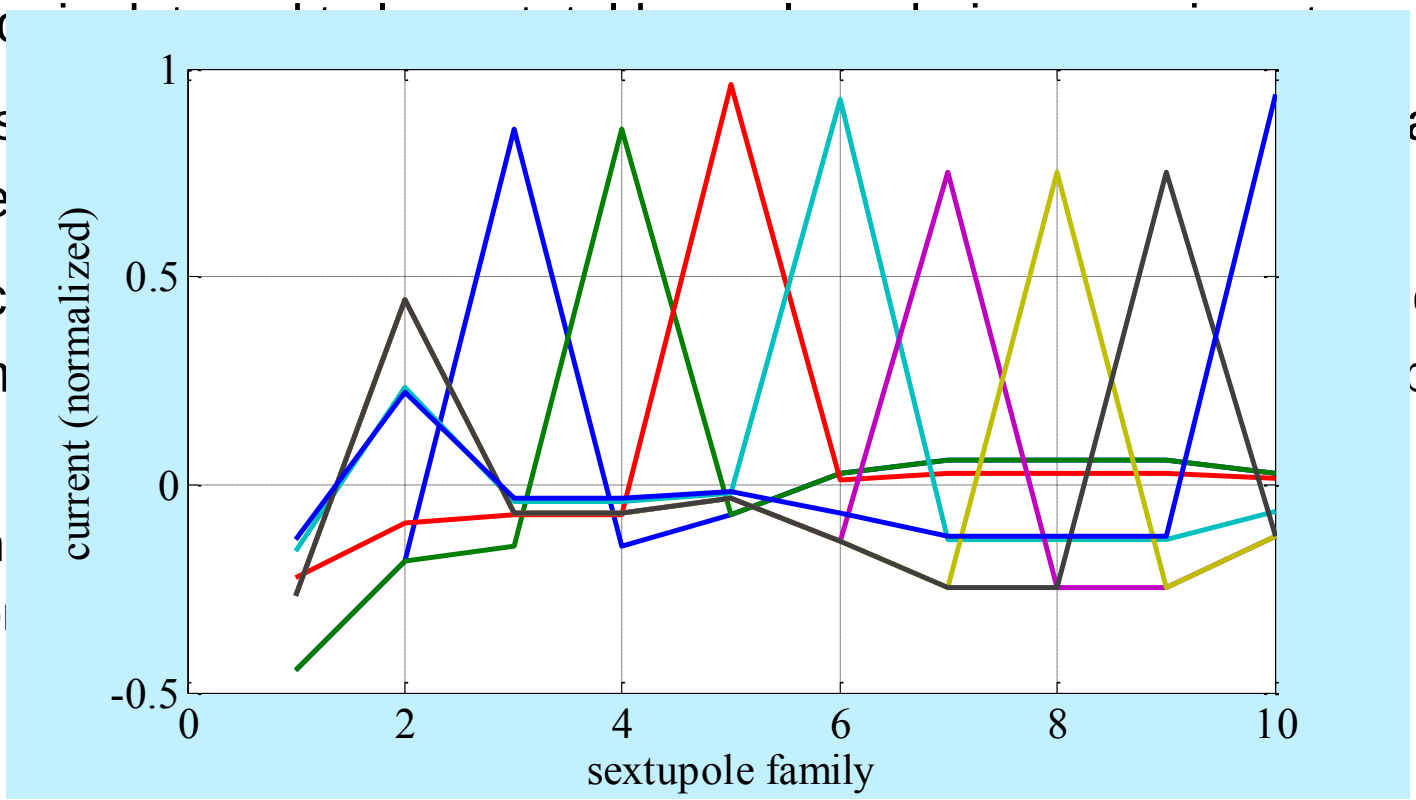
SPEAR3 nonlinear dynamics optimization

- SPEAR3 sextupole power supplies are upgraded in 2014 summer shutdown
  - There are now 10 independently powered sextupole groups
  - Simulation showed an optimized sextupole setting can improve DA/MA for emittance reduction lattices.
  - During 2014 fall startup, we did experimental optimization of injection efficiency for the operation lattice (next few slides).

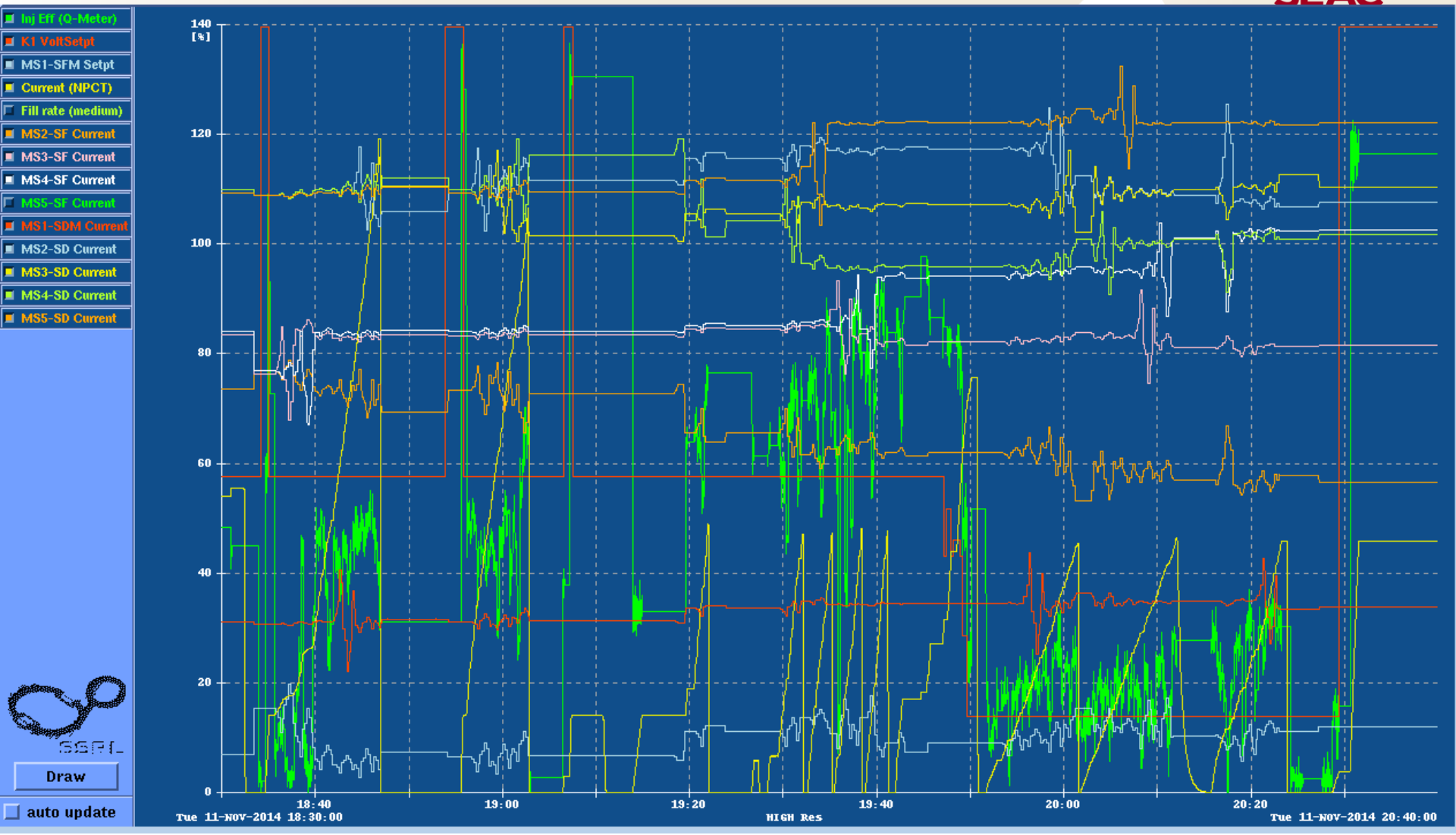


Experimental setup

- Normal operation lattice has good injection. We reduced the kicker bump by 34% (~7.5 mm) to have a low injection efficiency starting point.
- Injecto
- Knobs ameter space
- Objec over 10 secon period.
- Initial
  - Sin matrix (so

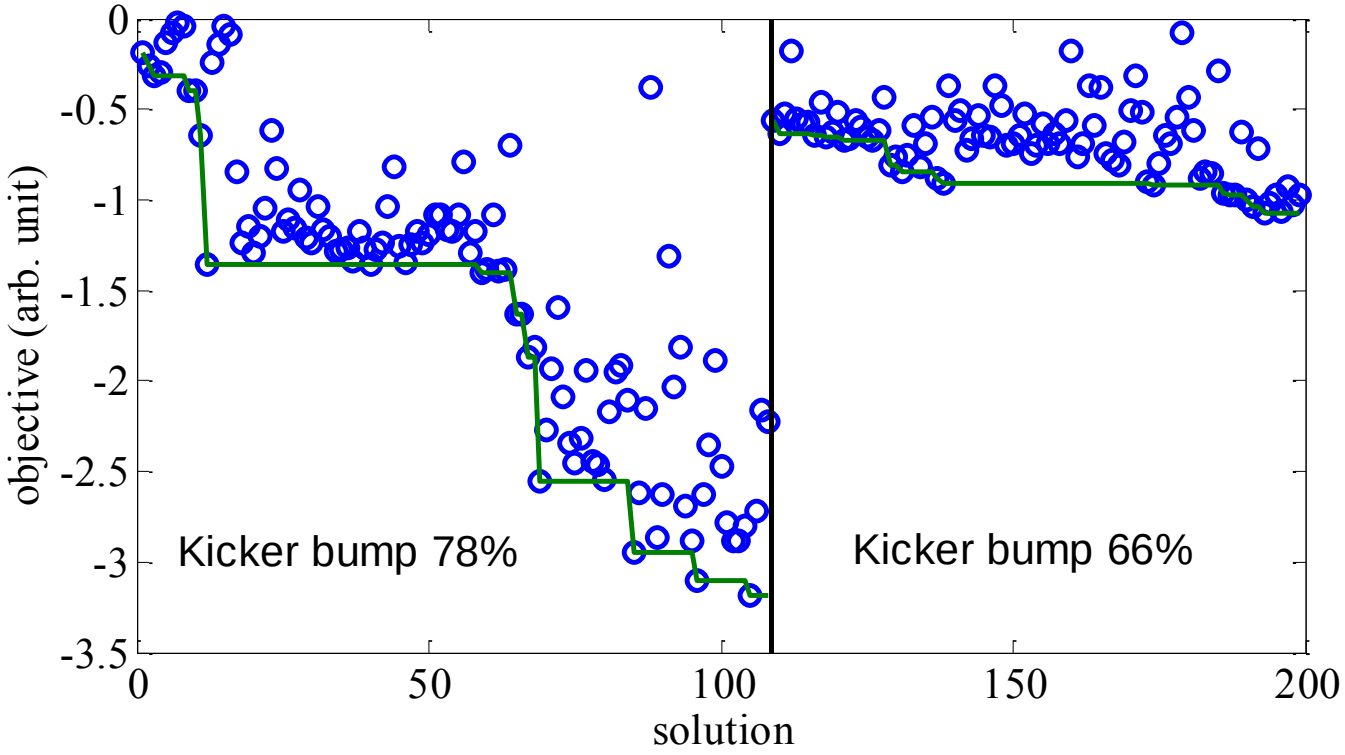


Optimization (Nov 11, 2014)



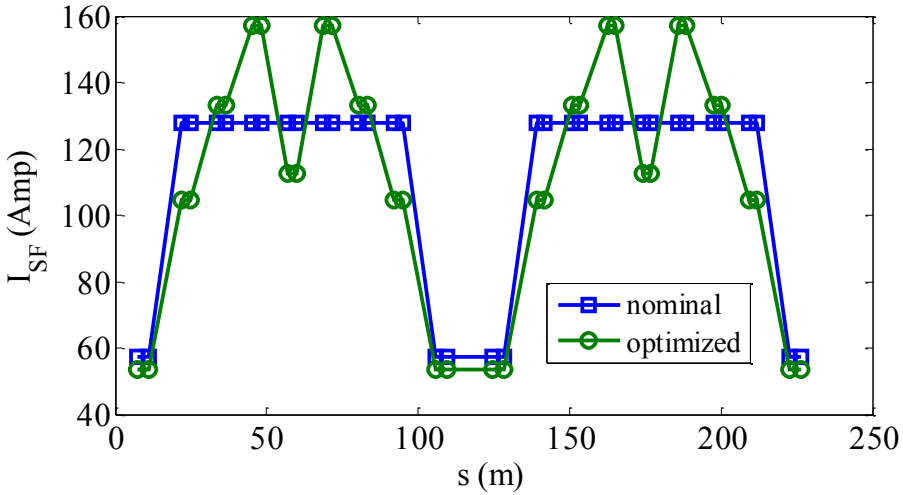
Optimization run was interrupted three times.

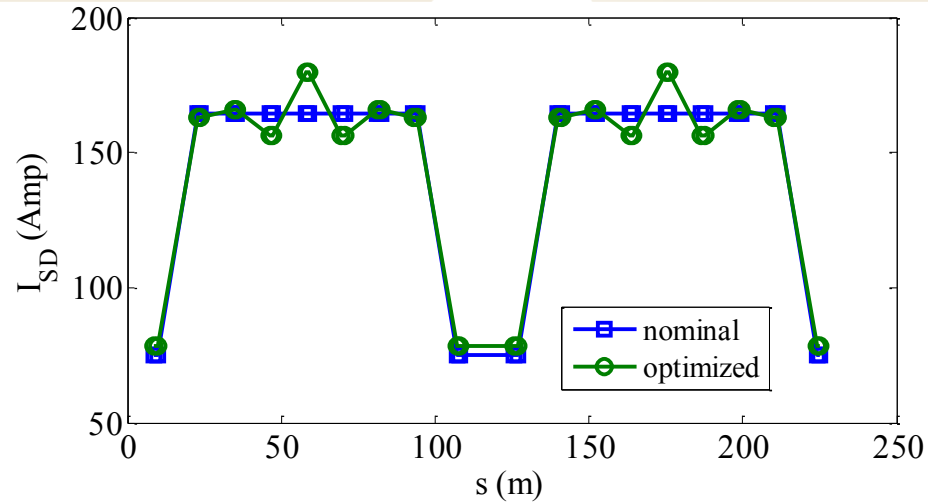
Objective function for all evaluated solutions

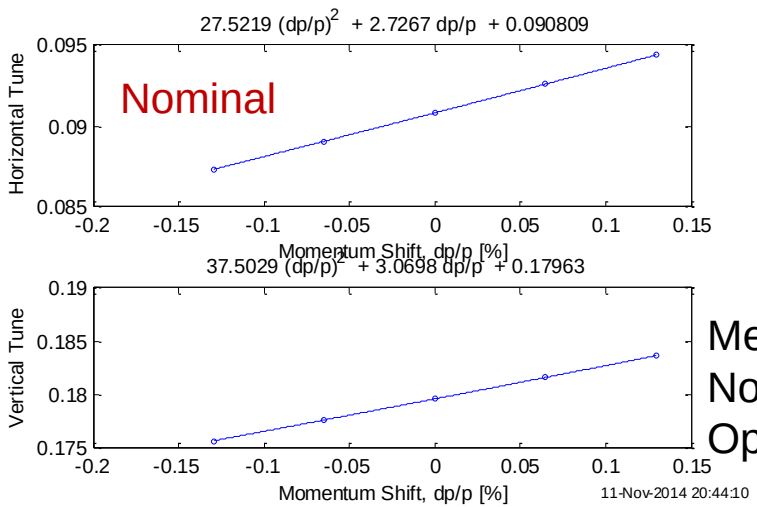


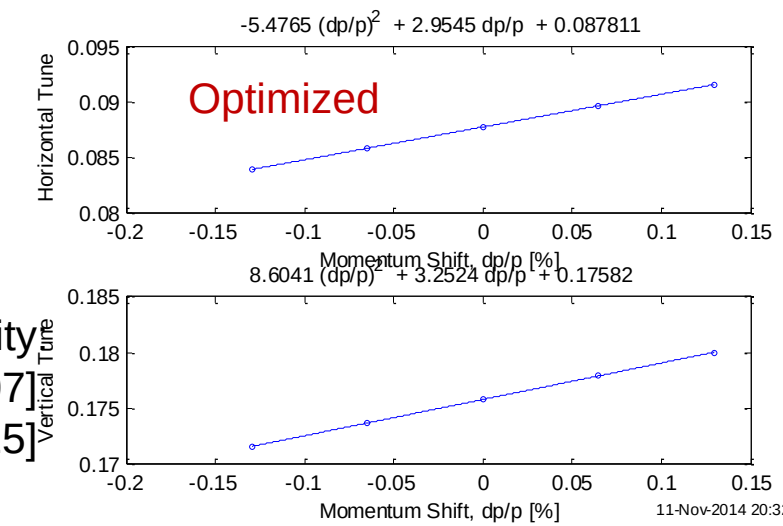
The code RCDS completed a little more than 2 iterations in total.

Best optimized solution



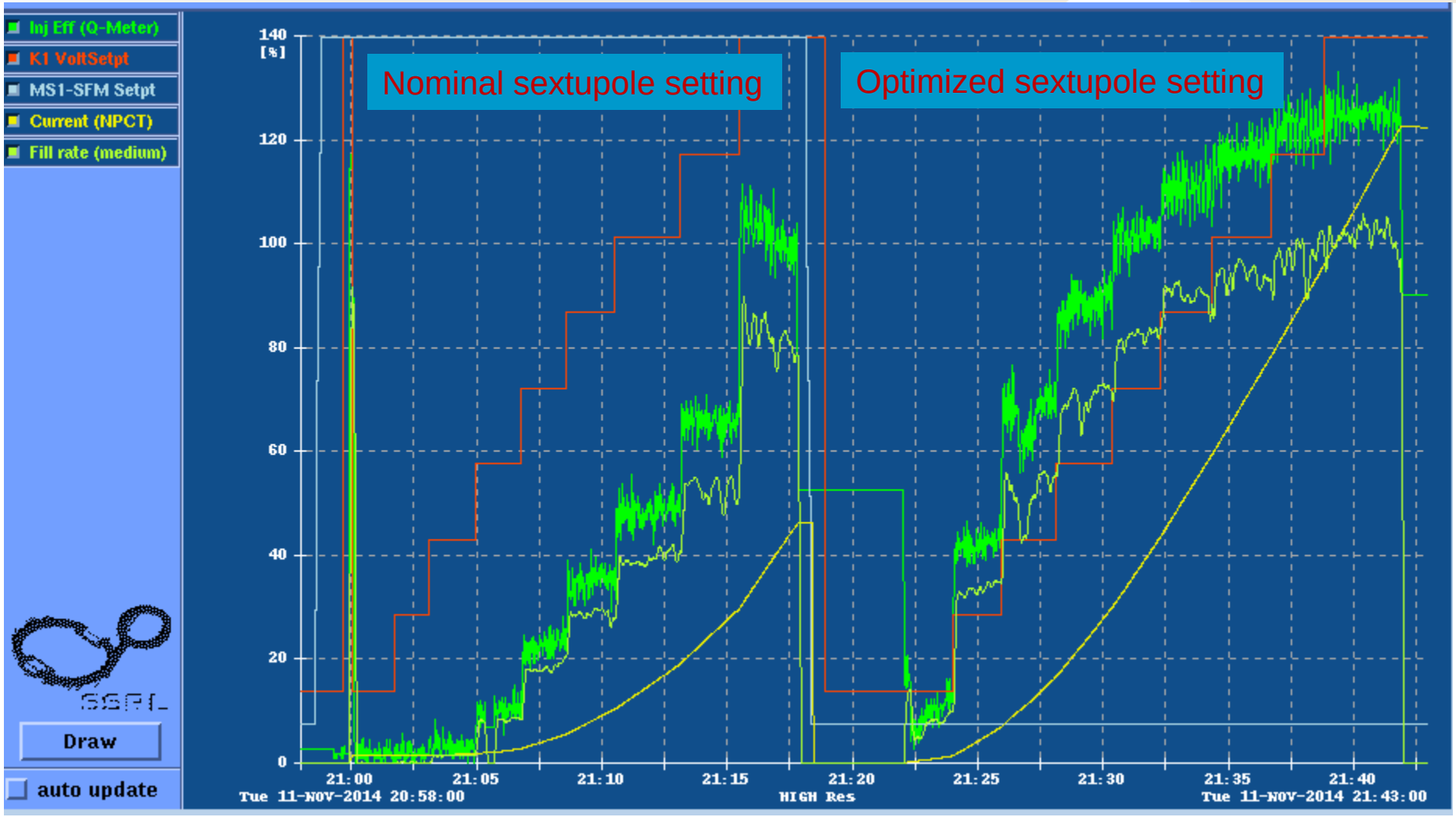






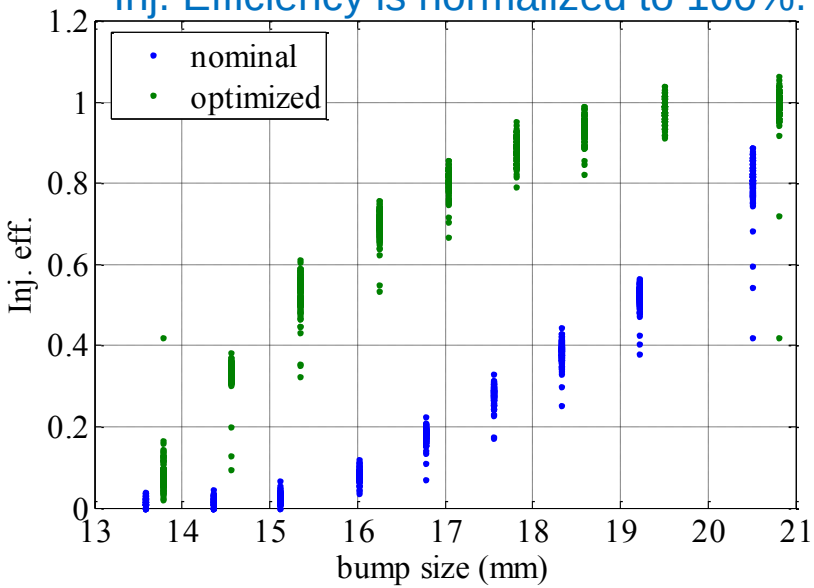
Measured chromaticity
Nominal: [2.73, 3.07]
Optimized: [2.95, 3.25]

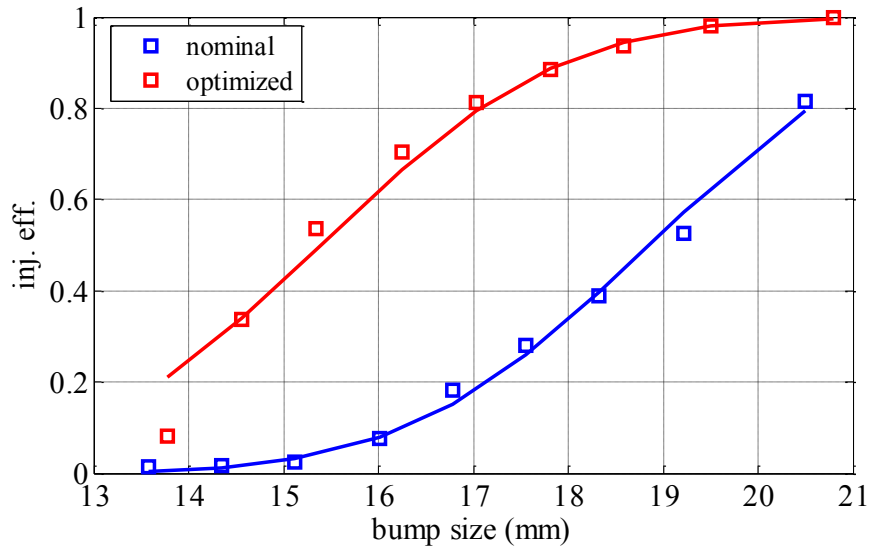
Injection efficiency comparison between nominal and optimized solutions.

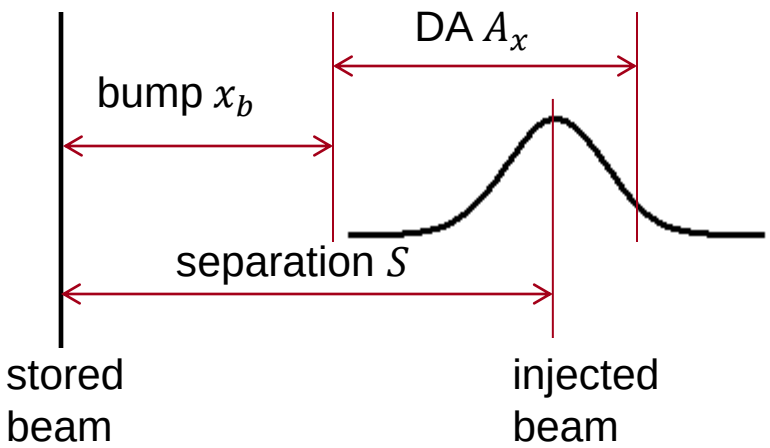


Improvement of dynamic aperture

Inj. Efficiency is normalized to 100%.







Data are fitted to a model:

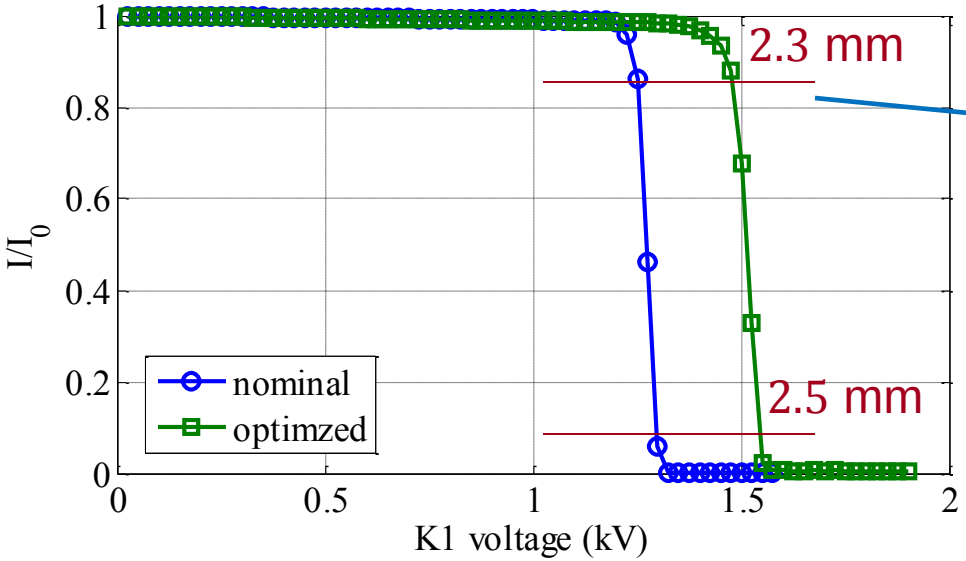
Injected beam size: $p(1) = \sigma_x = 2.0$ mm

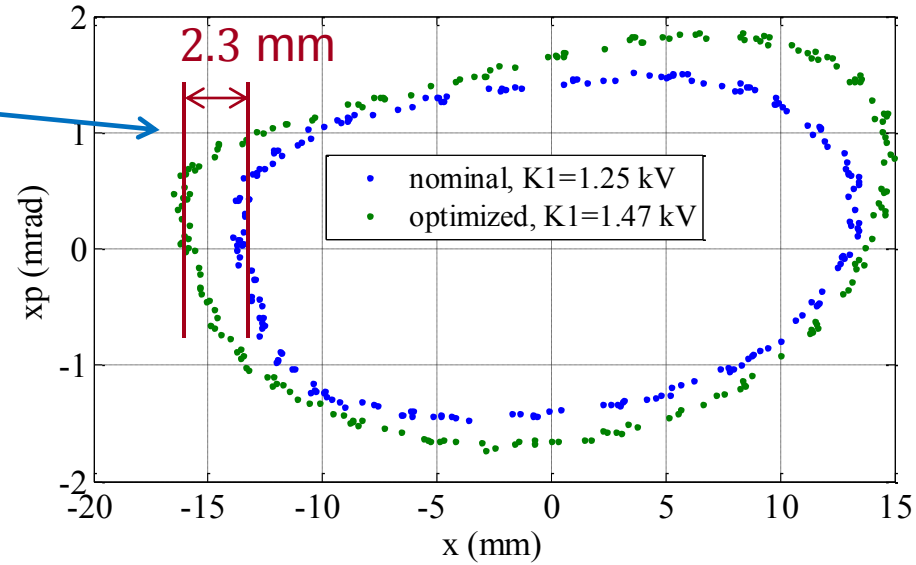
Nominal: $p(2) = S - A_x = 18.8$ mm

Optimized: $p(3) = S - A_x = 15.4$ mm

Dynamic aperture gain by optimization: 3.4 mm

Measurement of dynamic aperture

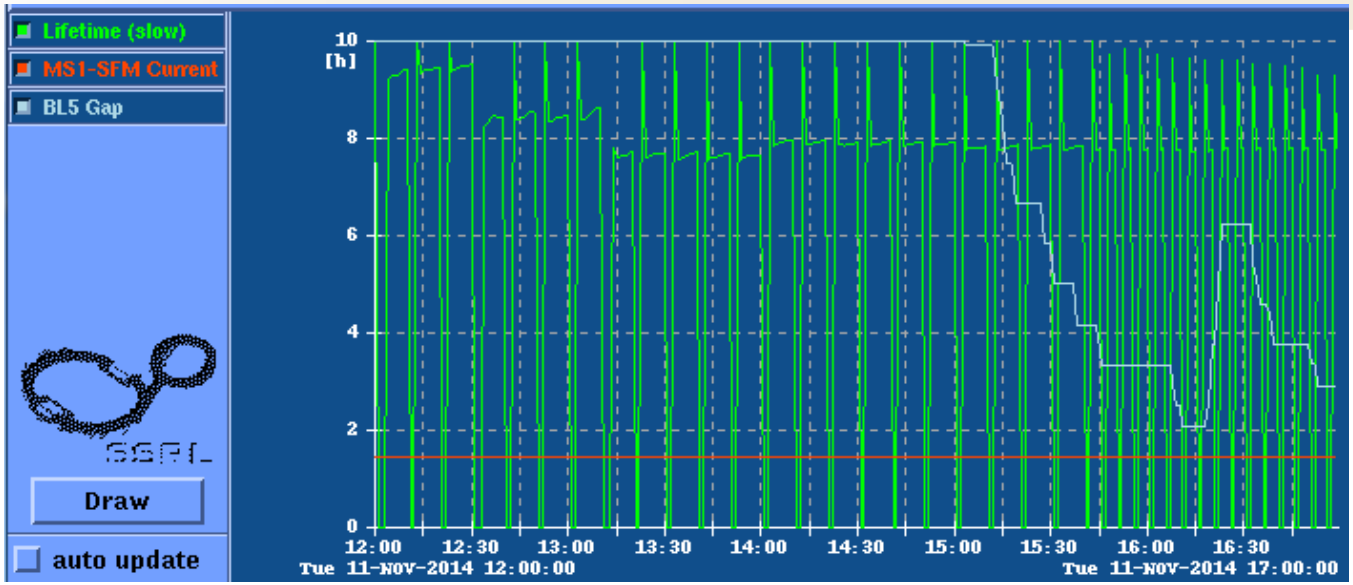




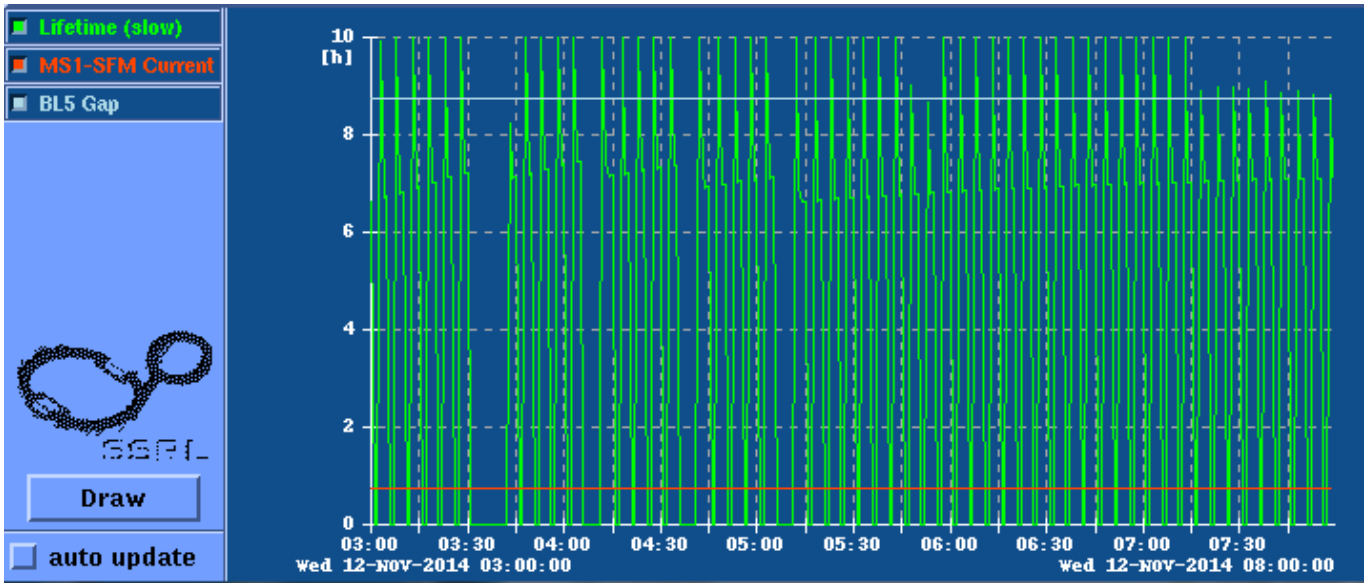
Actual DA = bump limit + 5σ (stored beam)
Nominal: 15.9 mm
Optimized: 18.4 mm.

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

Lifetime at 500 mA

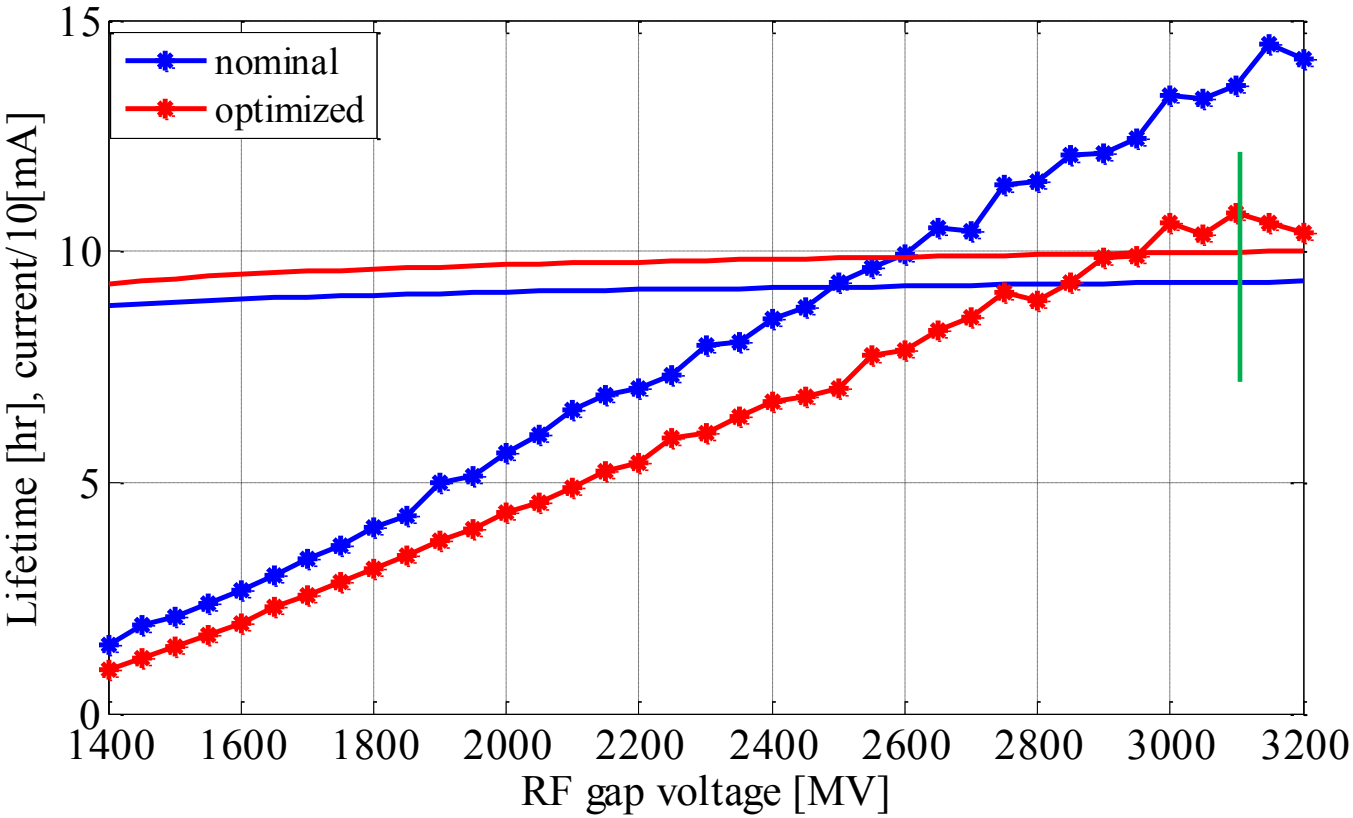


Nominal: 7.8 hrs



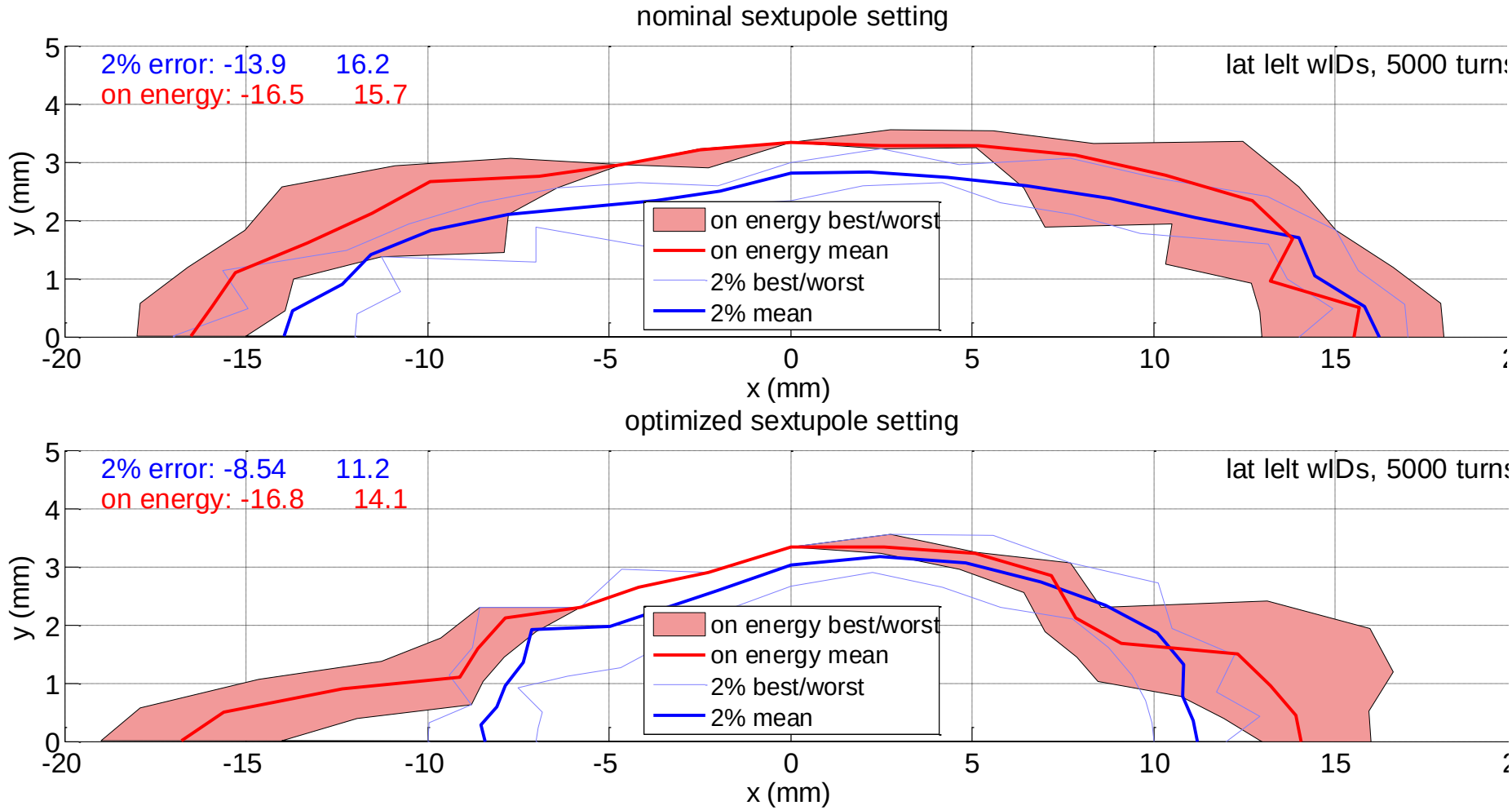
optimized: 6.8 hrs

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.

Discussion

- How to optimize injection efficiency and lifetime together?
  - Iteration: first optimize injection, then lifetime, then injection again.

- How to combine sextupole magnets to make efficient combination knobs?
  - One option: singular value pattern of the Jacobian of Collins's distortion function* w.r.t. to sextupoles.

- How to improve agreement between model and real machine?

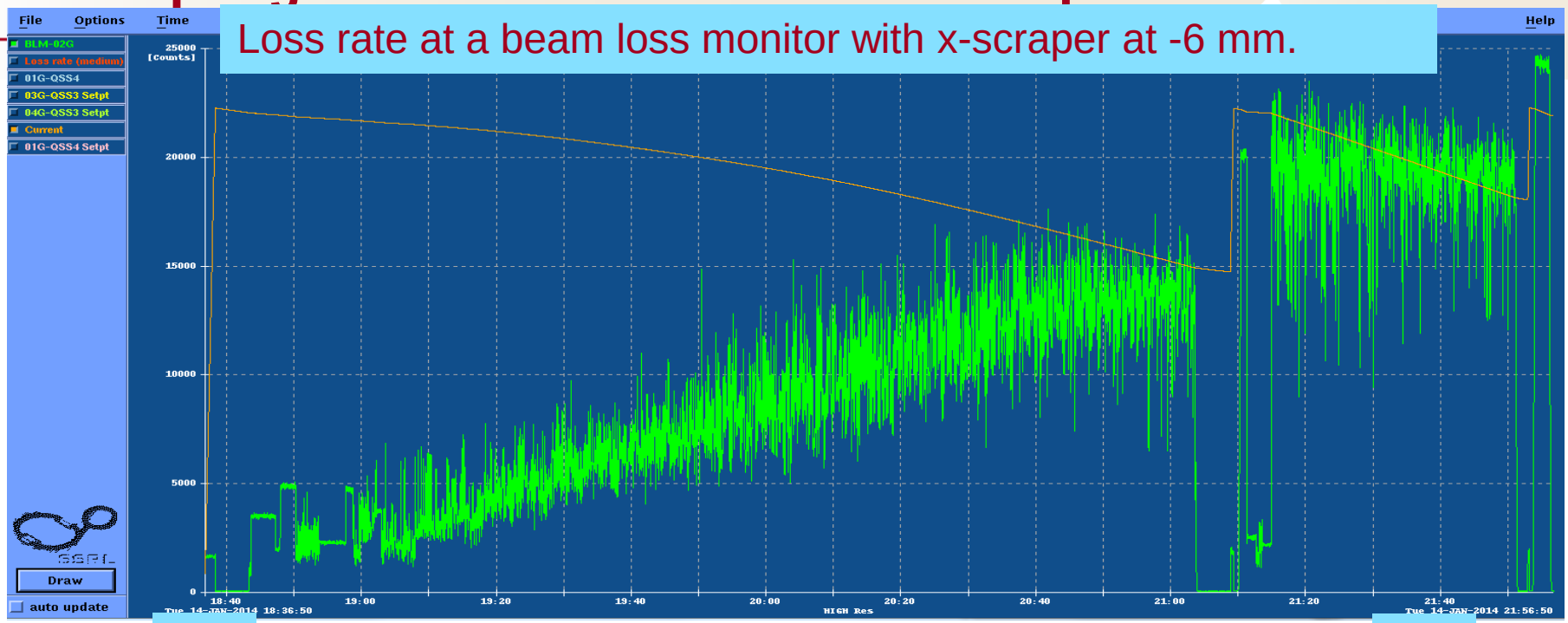
*Thanks to Gode Wustefeld for exposing us to the distortion function concept.

Summary

- DLSR beam dynamics is very nonlinear. Implementing the design lattice to achieve the desired nonlinear dynamics performance is critical to the success of DLSR projects.
- Online optimization may be an effective way to bridge the design model and the real machine.
- Online optimization of injection efficiency for SPEAR3 with the RCDS method has led to a lattice with significantly larger dynamic aperture and workable momentum aperture.
  - This solution is unexpected by our model.
- Further work is needed to efficiently combine the sextupole variables and to optimize both DA and MA.

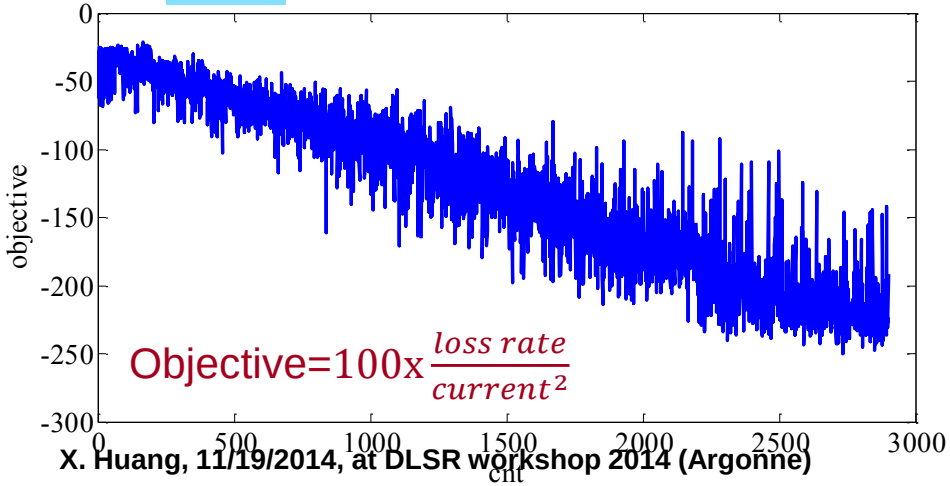
Coupling correction with MOPSO – experiment

Loss rate at a beam loss monitor with x-scraper at -6 mm.



18:40

21:40



After optimization, for the best solution, at 500 mA, the lifetime is 3.78 hrs.
LOCO data showed that coupling ratio is 0.029%, lowest on SPEAR3.

The experiment took less than 3000 evaluations.

Experiment was done with K. Tian.

X. Huang, 11/19/2014, at DLSR workshop 2014 (Argonne)