Beam-Based Optimization of Storage Ring Nonlinear Beam Dynamics

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Outline

- Motivation
  - Storage ring nonlinear beam dynamics challenge
  - Beam based correction vs. beam based optimization
- Online optimization algorithms
  - RCDS and PSO
- SPEAR3 dynamic aperture optimization
- ESRF beam lifetime optimization
- Summary

Bridging design and reality for accelerators

- Accelerators are built by design. But in reality errors always exist.
- For complex systems such as a storage ring, small errors add up to significant deviations from design
  - Alignment errors, magnetic field errors, insertion devices, fringe fields, etc.
- Three layers of errors
  - Orbit distortions – dipole errors
  - Linear optics errors, linear coupling – quadrupole and skew quadrupole errors
  - Nonlinear dynamics errors
    - Errors in nonlinear magnetic fields (mainly sextupoles)
    - Linear optics errors aggravate the difficulty as they ruin the cancellation schemes.
- How to realize (or exceed) the design nonlinear beam dynamics performance?
  - Beam based correction
  - **Beam based optimization** ← Topic of this talk

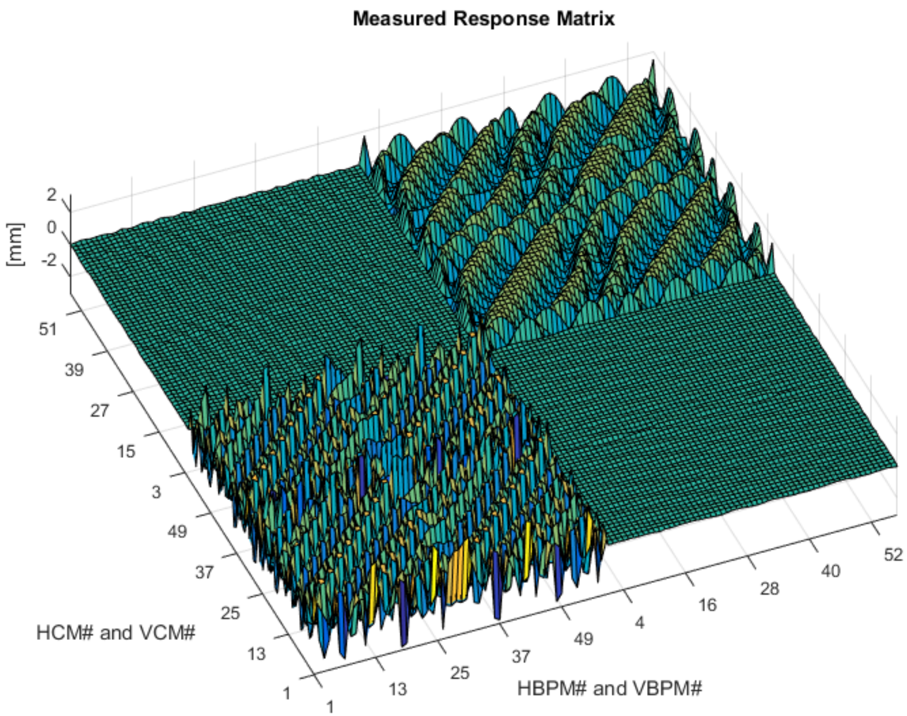
Beam based correction (BBC) vs. Beam based optimization (BBO)

- Beam based correction – measure the differences between design model and actual machine and apply deterministic correction.
  - Needs diagnostics
  - Needs correction target
  - Needs deterministic method (such as response matrix)
- Beam based optimization – use beam measurements to probe the objective function over the parameter space and optimize.
  - No model is needed.
  - Only need to evaluate the objection function – the performance measure

For more discussion of BBC and BBO, see X. Huang talk at NAPAC'16

Linear optics correction – an example of BBC

- Orbit response matrix (ORM) is commonly used on light sources for optics and coupling correction (LOCO).



Response matrix

$$R_{ij} = \frac{\Delta x_i}{\theta_j} = \frac{\sqrt{\beta_i \beta_j}}{2\sin\pi\nu}\cos(|\psi_i - \psi_j| - \pi\nu)$$

To find sources of optics errors, fit quadrupoles in the model

$$f(\Delta\boldsymbol{K}) = \chi^2 = \sum_{i,j} \frac{\left(R_{ij}^{meas} - R_{ij}^{model}(\Delta\boldsymbol{K})\right)^2)}{\sigma_i^2}$$

Apply changes to quadrupoles using fitting results $\Delta\mathbf{K}$ to correct optics.

Three ingredients: Diagnostics – ORM samples optics
Correction target – optics from ideal model (represented by model ORM)
Deterministic procedure – fitting to find quadrupole errors.

Nonlinear resonances

- Nonlinear magnetic fields can drive all sorts of resonances

All deviations from the ideal linear motion can be cast into perturbation terms (for on-energy particles)

$$H_1 = \sum_{jklm\geq 0} \sum_{p} h_{jklm}^{(p)} J_x^{\frac{j+k}{2}} J_y^{\frac{l+m}{2}} e^{i[(j-k)\phi_x+(l-m)\phi_y+p\theta]}$$

Coefficients $h_{jklm}^{(p)}$ are related to magnetic field error distribution and linear optics (beta functions and phase advances).

Terms with $j = k$ and $l = m$ cause tune shifts with amplitude
Other terms drive resonances $(j-k)\nu_x + (l-m)\nu_y + p = 0$

For off-energy particles, yet more tune shifts and resonances conditions to consider.

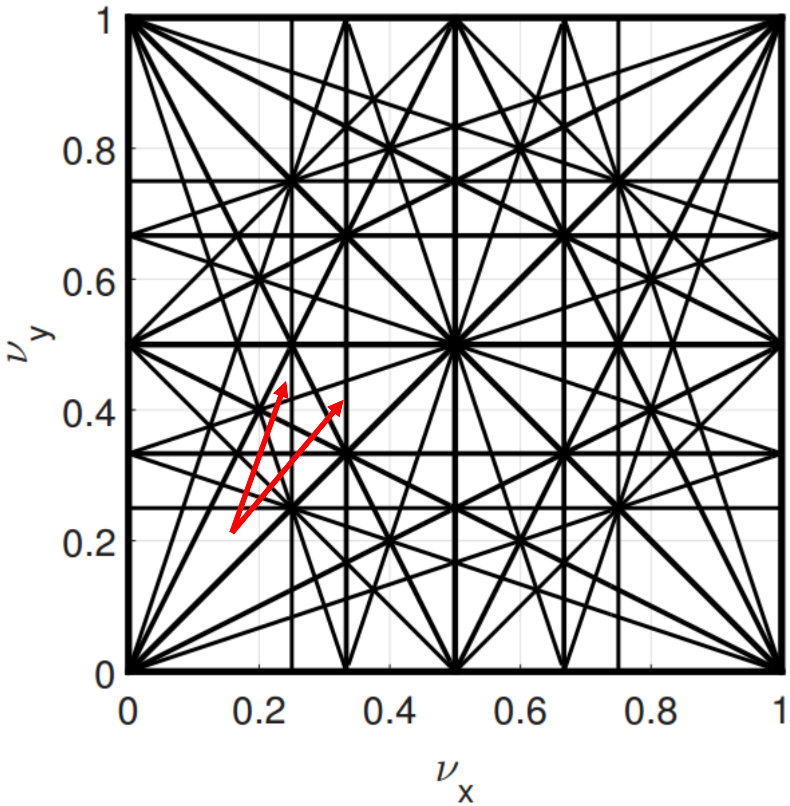
Some of the resonances will limit the dynamic aperture, if they are strong enough, and if beam motion satisfies the resonance conditions.

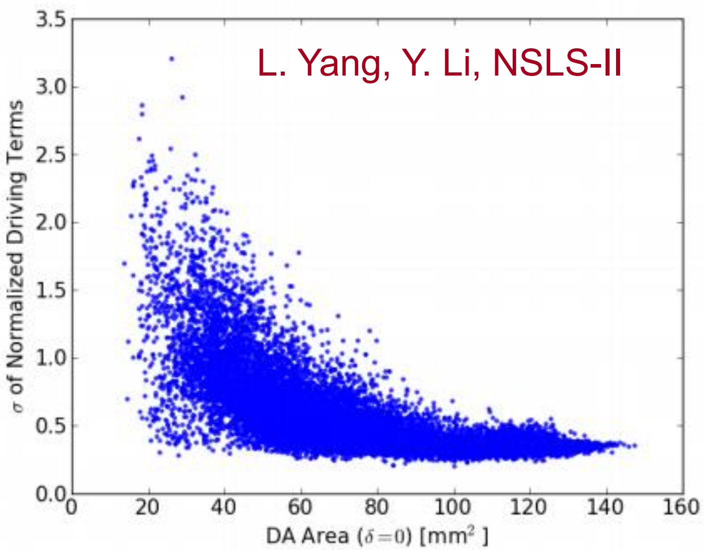
It seems, we can target these resonances by weakening their stopband, or steering the tune footprint of beam away from them, to improve dynamic aperture.

But which resonances to target, and how?

- Nonlinear resonances are complicated – all terms are intertwined.

When you change nonlinear field distribution, everything (tune shift and resonance driving terms) changes. Usually no simple path for improvement.





Reduction of driving terms does not guarantee better dynamic aperture.

In storage ring design practice, direct optimization of tracking results (dynamic aperture and momentum aperture) has become the main-stream.

Difficulties with nonlinear dynamics BBC

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- The complicated relationship between nonlinear dynamics performance (DA and MA) and the measurables (tune shifts and resonance driving terms, or RDTs) make it very hard to do BBC on nonlinear dynamics.
- Furthermore, it is difficult to accurately measure RDTs because nonlinear resonance signals on turn-by-turn data can be very weak.
- Lack of knobs to control higher order RDTs
  - Storage rings usually does not have octupoles or higher multipoles.
  - Space in a storage ring is precious.

Nonlinear dynamics BBC work

- Great progress have been made for beam based correction of nonlinear beam dynamics
  - Fit nonlinear tune shifts (chromatic and geometric)
    - R. Bartolini et al, PRSTAB 14, 054003 (2011)
  - Fit nonlinear RDTs –
    - R. Bartolini et al PRSTAB 11, 104002 (2008)
    - A. Franchi, et al PRSTAB 17, 074001 (2014).
    - J. Bengtsson, R. Bartolini, et al PRSTAB 18, 074002 (2015).

There was report that lifetime after RDT correction got worse (A. Franchi talk at LER2014, Frascati)

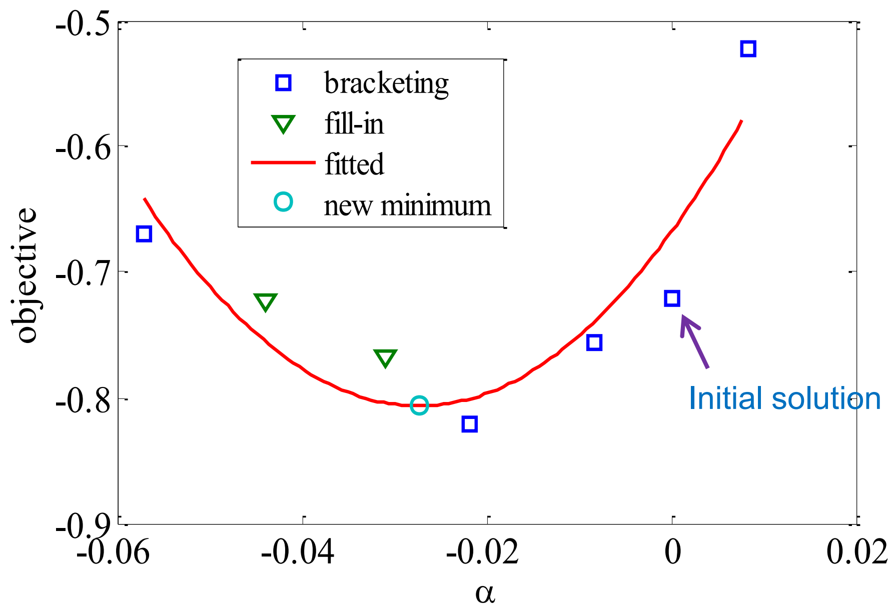
Despite the progress, further improvement is needed before nonlinear dynamics BBC becomes a reliable, common tool like LOCO.

Development of beam based optimization at SPEAR3

- We saw the challenge of realizing model optimized sextupole solution (using MOGA) for the SPEAR3 emittance reduction project.
- Inspired during a trip to SSRF (Shanghai) where I witnessed colleagues (S. Tian, et al) turning 6 harmonic sextupole knobs *randomly* to establish injection.
  - Tried Simplex to optimize injection on that shift (May 2012).
  - MOGA would be too time consuming.
- Explored possible online algorithms
  - Simplex, Powell, 1D/2D scans, MOGA, etc.
  - Developed our own online optimization algorithm – the robust conjugate direction search (RCDS) method (2013).
  - Later also found PSO is efficient as a stochastic online optimization (2014).

The RCDS online optimization algorithm

- The RCDS was designed to deal with noise – which is a big challenge for online optimization.
  - The main component is the robust 1D optimizer



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

See X. Huang talk at NAPAC'16.

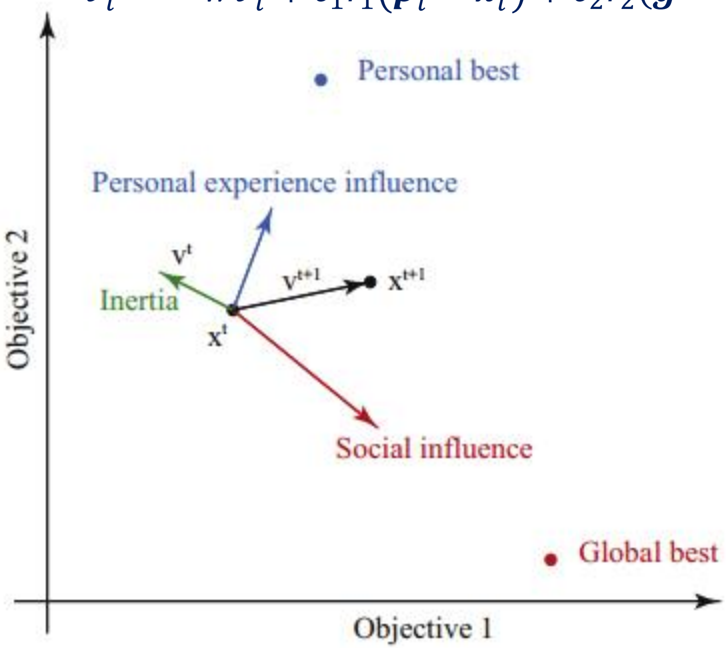
Searching along conjugate directions improves efficiency, but is not required, or always available.

The particle swarm optimization (PSO) algorithm

- The PSO algorithm is a stochastic algorithm that search the parameter space by creating new solutions along “trajectories of particles”.

Updating particle population in an iteration

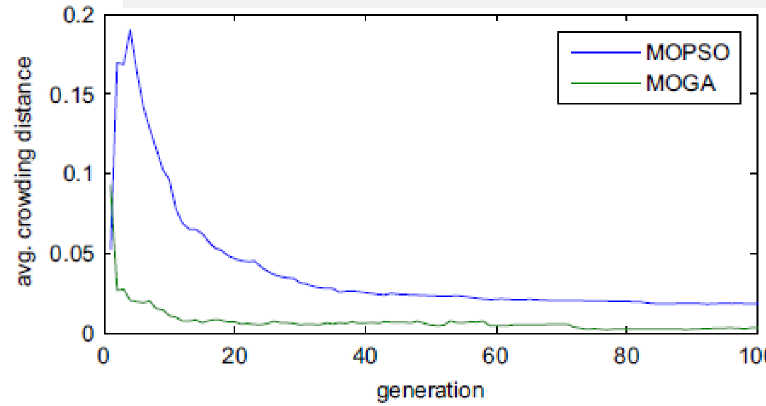
$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \boldsymbol{v}_i^{t+1}$$
$$\boldsymbol{v}_i^{t+1} = w\boldsymbol{v}_i^t + c_1 r_1(\boldsymbol{p}_i^t - \boldsymbol{x}_i^t) + c_2 r_2(\boldsymbol{g}^t - \boldsymbol{x}_i^t)$$



X. Pang, L.J. Rybarcyk, NIMA 741 (2014)

In our application of PSO to nonlinear beam dynamics optimization (model), we found PSO converges much faster than MOGA, due to higher diversity in new solutions.

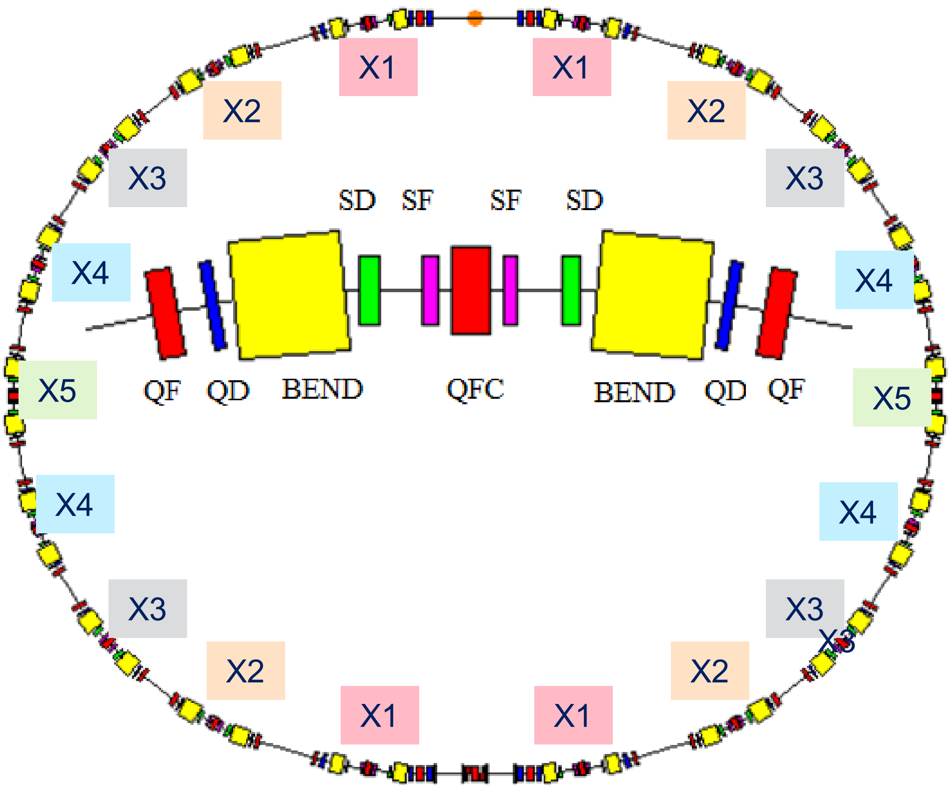
X. Huang, J. Safranek, NIMA 757 (2014)



Diversity in new solutions.

The SPEAR3 nonlinear dynamics optimization setup

- SPEAR3 added 6 sextupole power supplies in 2014.
  - There are a total of 10 sextupole knobs.

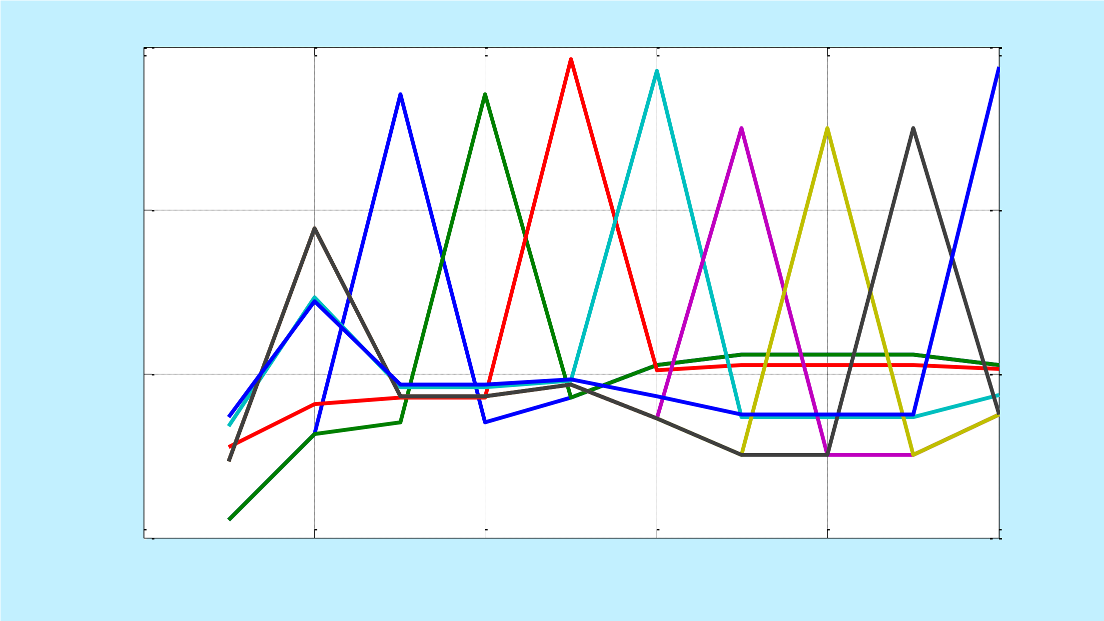


Parameter	value
Energy	3 GeV
Circumference	234 m
Emittance (ϵ_x)	10 nm
Tunes (ν_x, ν_y)	14.106, 6.177

All sextupoles are in dispersive region.

Combined sextupole knobs

- Sextupole optimization should not change chromaticities.
- Combined knobs not changing chromaticities were made using the chromaticity response matrix



$$\begin{pmatrix} C_x \\ C_y \end{pmatrix} = \mathbf{R}_{2\text{x}10} \begin{pmatrix} S_1 \\ S_1 \\ \vdots \end{pmatrix}$$

Singular value decomposition of the response matrix

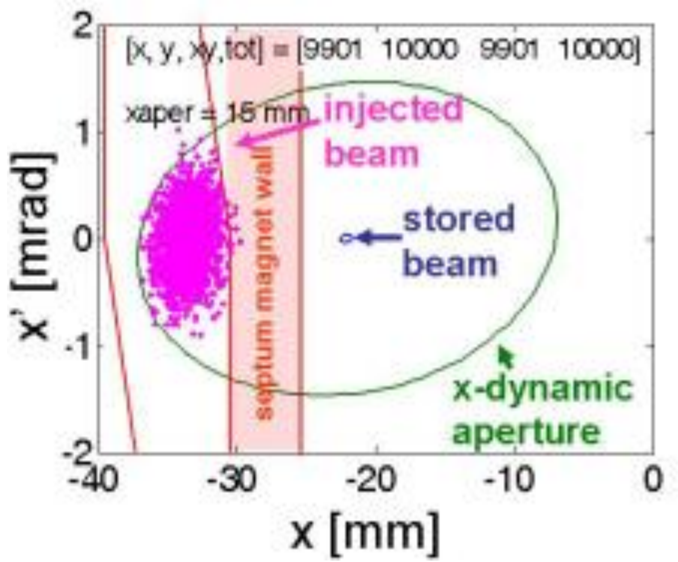
$$\mathbf{R} = \mathbf{USV}^T$$

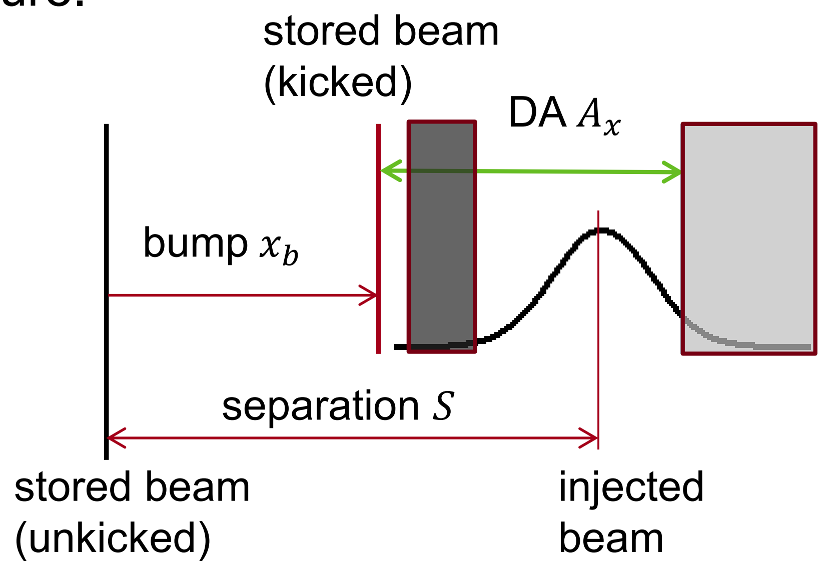
With $\mathbf{S} = (s_1, s_2, 0,0, \cdots)^T$
The $\mathbf{V}_i$, $i = 3,4,\cdots,10$ vectors are the combined knobs transparent to chromaticities.

We have 8 sextupole knobs.

Injection and dynamic aperture

- Capture of the injected beam requires kicking the stored beam toward the septum and an adequate dynamic aperture.



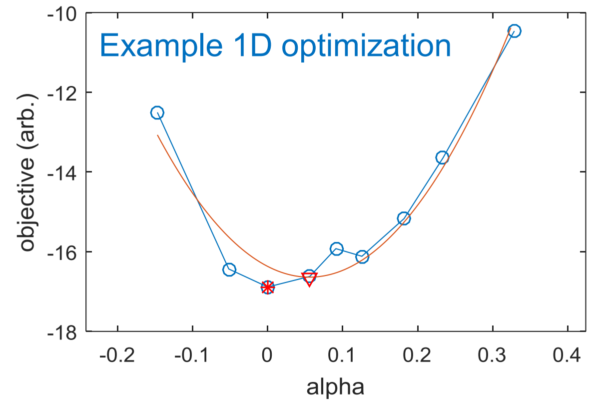


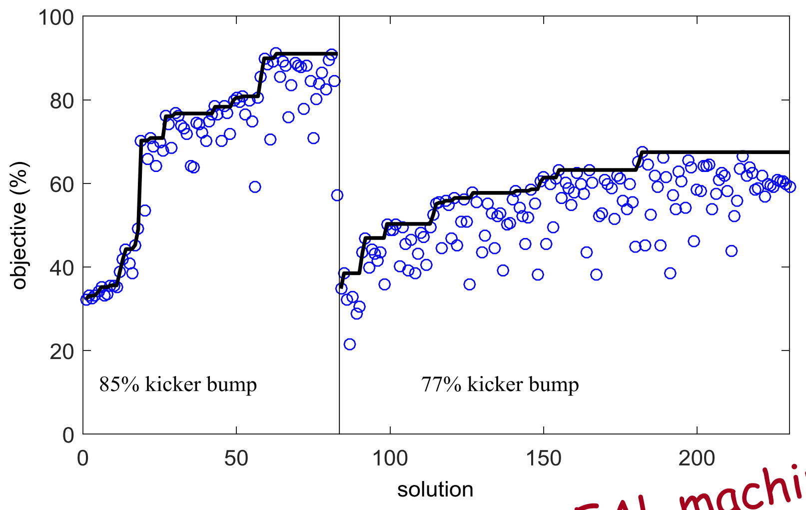
Reducing the kicker bump effectively increases the required dynamic aperture.

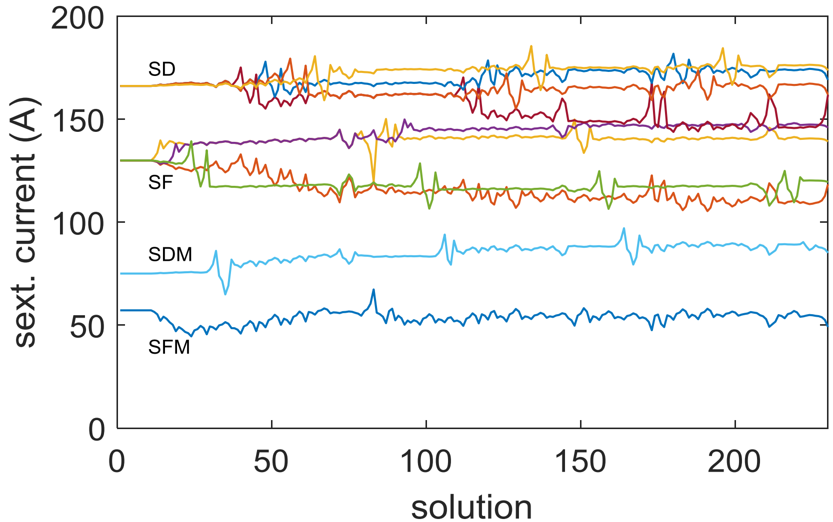
- The objective function is injection efficiency – evaluated as captured beam charge divided by average Booster beam intensity over 10 seconds.
  - Noise sigma $\sigma \sim 3\%$ (mostly from Booster intensity fluctuation).

Optimization w/ RCDS

- Started from flat sextupole pattern (old nominal).
- Reduced kicker bump to 85% first, injection efficiency came back quickly.
- Kicker bump reduced to 77% for second run.
- Took about 55 min total.





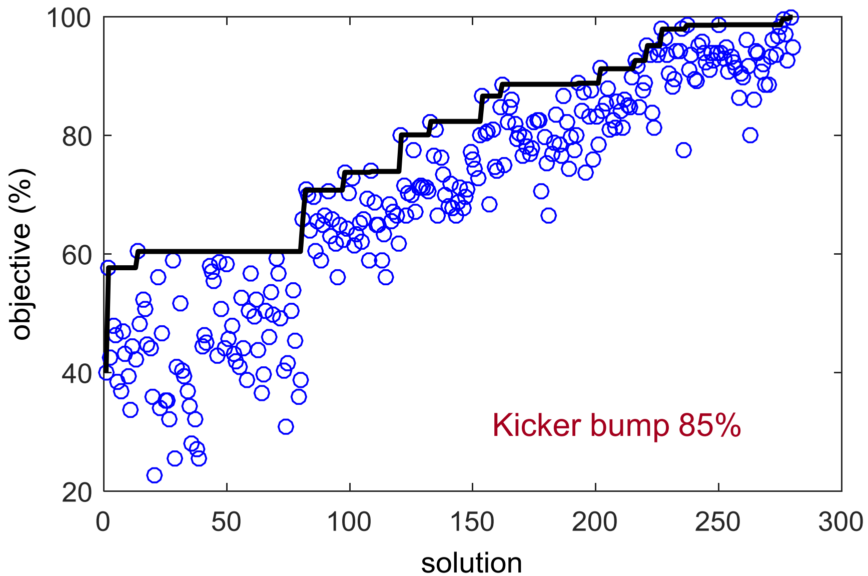


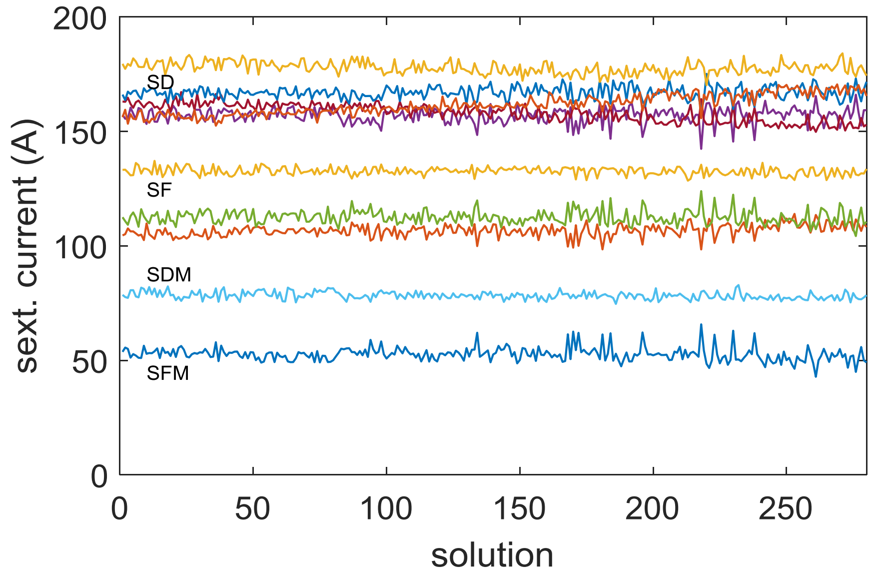
Optimization on the REAL machine!

First 10 points are at nominal for noise sigma evaluation.

Optimization w/ PSO

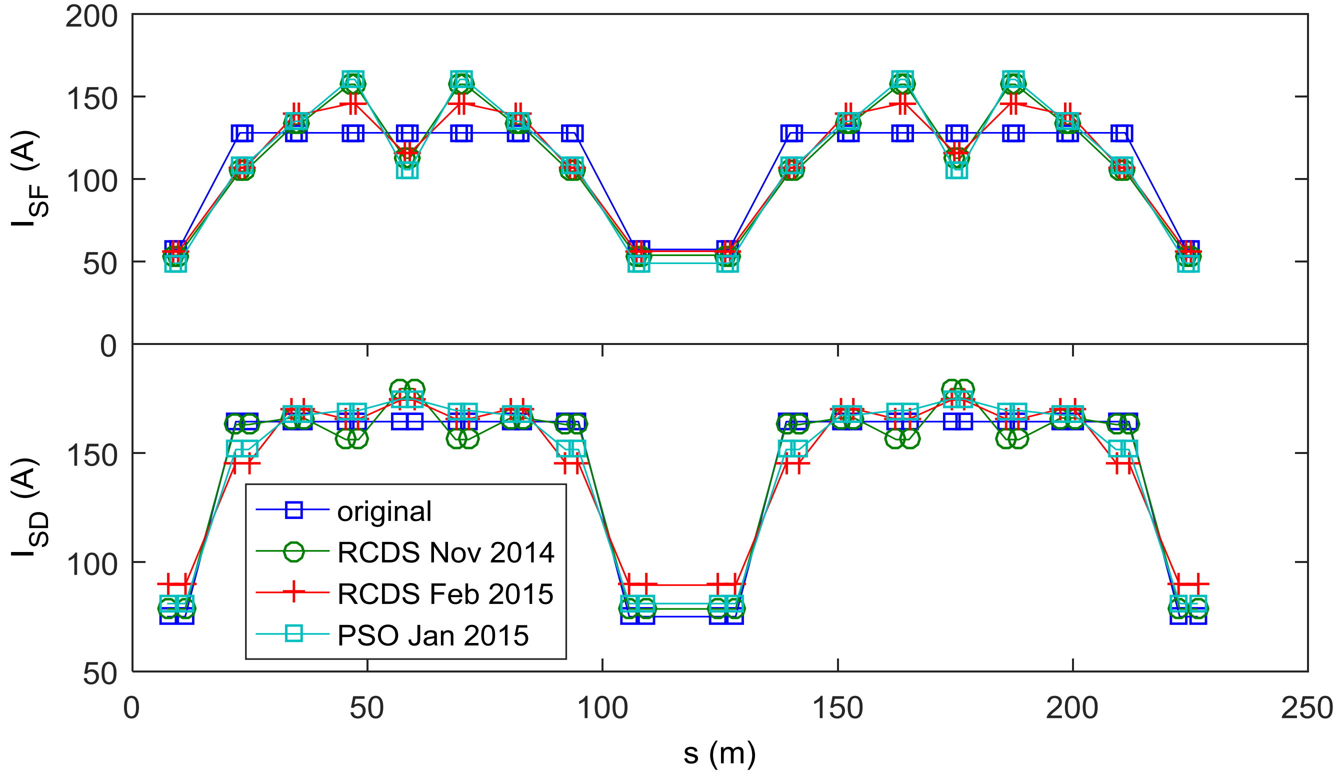
- PSO optimization started from an earlier RCDS solution (Nov 2014), which has increased DA by ~3 mm already.
- Population size = 40. Ran 7 generations.





New sextupole solutions

- The optimized sextupole solutions differ significantly from the original (old nominal) values.

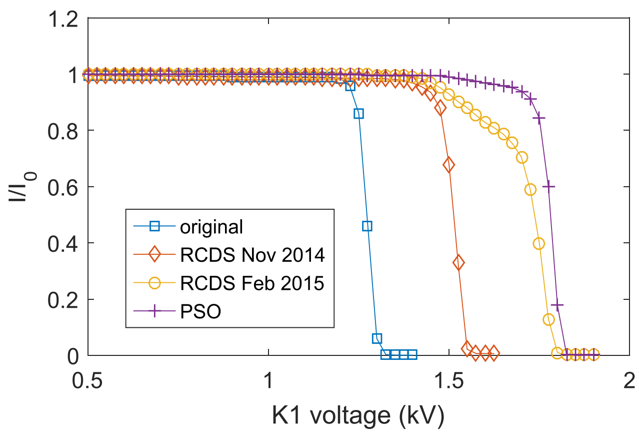


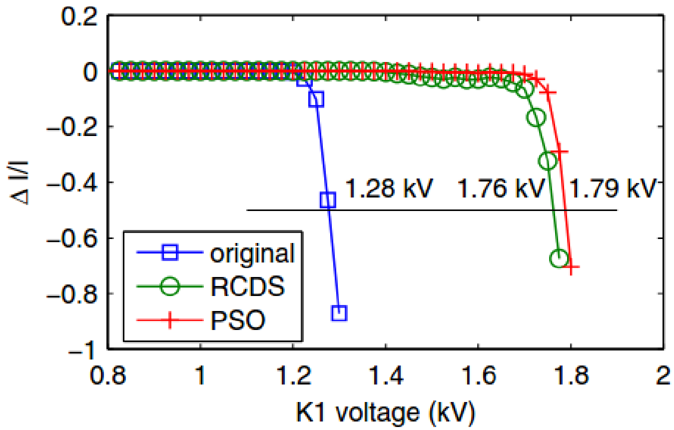
The RCDS and PSO solutions share similarities, but are not identical.

(The PSO optimization started from around the RCDS Nov 2014 solution.)

Dynamic aperture measurements

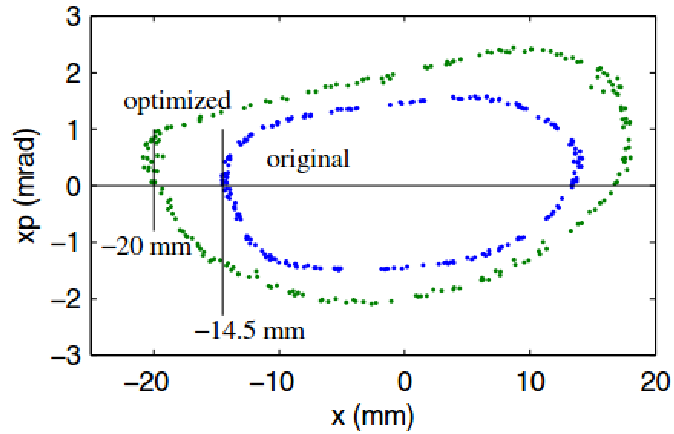
- Dynamic aperture is measured by kicking the stored beam with a kicker until beam is lost.





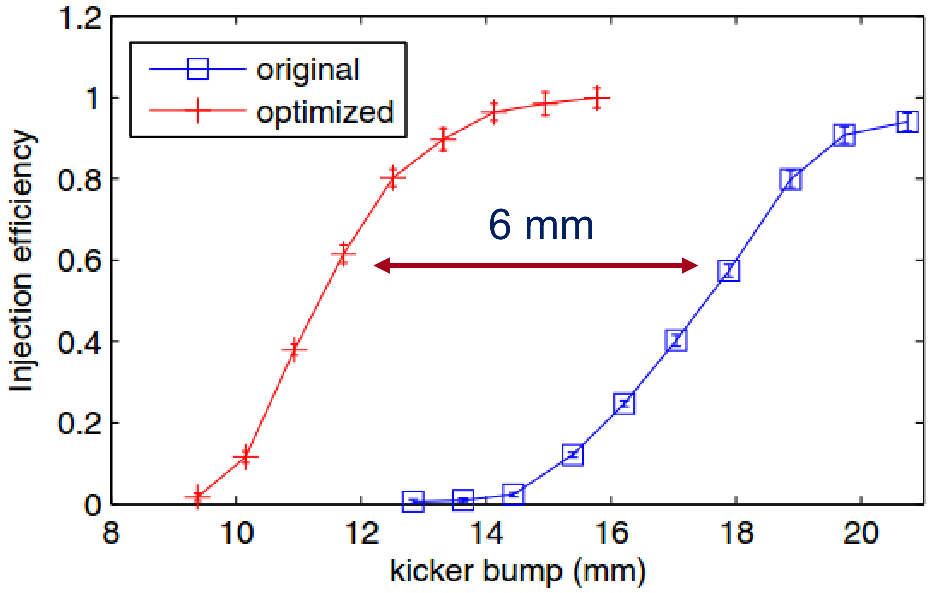
The kicker voltage is converted to kick angle and used in tracking to find out the dynamic aperture.

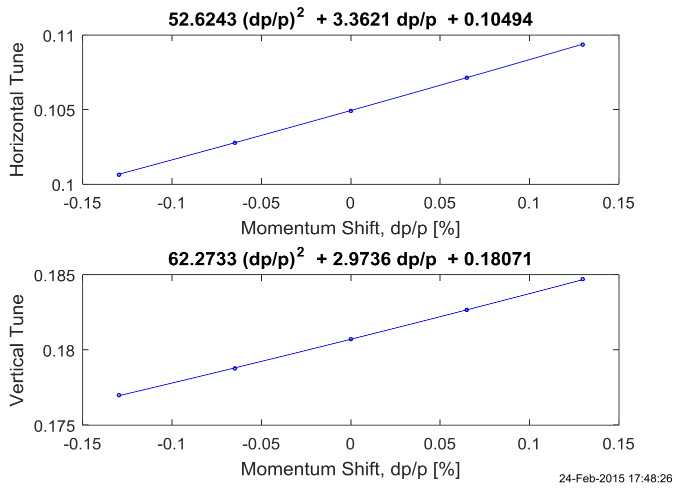
Dynamic aperture was increased from 15 mm (original) to 20 mm.



Injection efficiency vs. kicker bump

- Scan of injection efficiency vs kicker bump gives an indication of the dynamic aperture.
- The kicker bump remain matched after sextupole optimization.
- Chromaticity remain at [+3, +3].

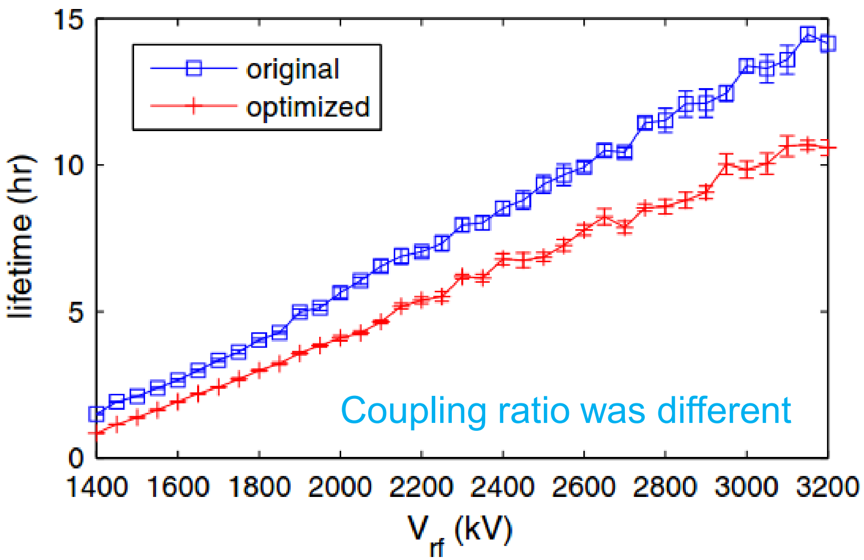




The kicker bump shift is consistent with the DA measurement.

No negative impact to lifetime

- Touschek lifetime of the SPEAR3 10-nm (operation) lattice is mostly determined by RF bucket height, not local momentum aperture from nonlinear dynamics.
- This is not changed with the optimized sextupole solutions.



The (Touschek dominated) lifetime vs. gap voltage shows no sign of "curving back".

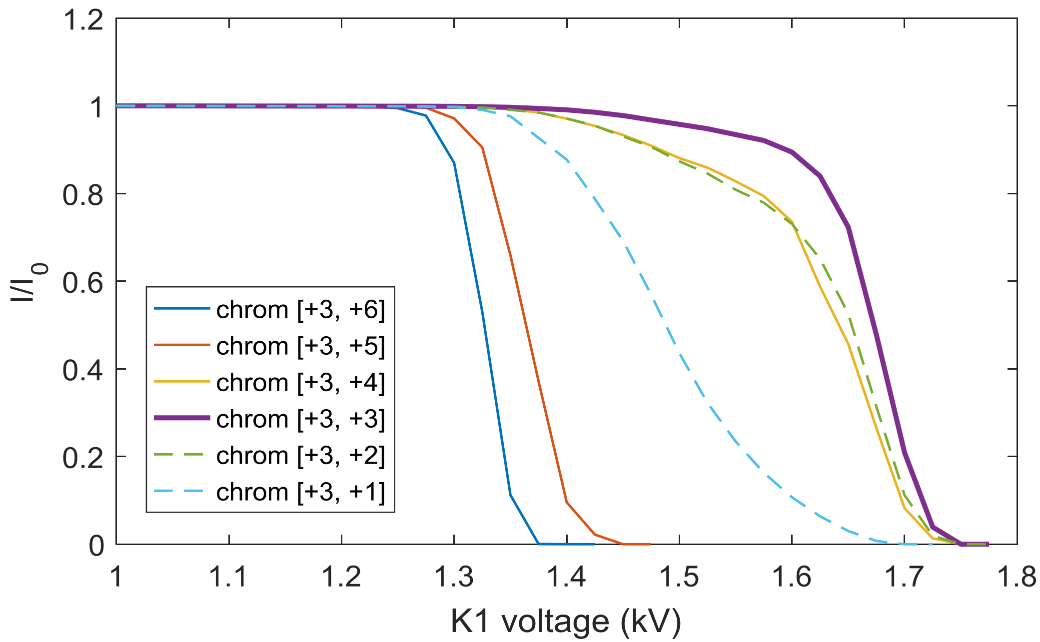
The difference in lifetime in the comparison is due to change of coupling ratio (vertical beam size).

In a later shift, we set equal coupling (w/ LOCO, and confirmed with pin hole camera) and measured equal lifetime.

solution	ϵ_y from LOCO (pm)	Lifetime (@500mA)
Original	8.7	7.66
Optimized	8.8	7.68

Recent work: Dynamic aperture with chromaticity changes

- SPEAR3 nominal chromaticities are set to [+3, +3]. As a new in-vacuum undulator (BL15) has a resonance mode that drives vertical coupled bunch instability, we needed to increase vertical chromaticity.

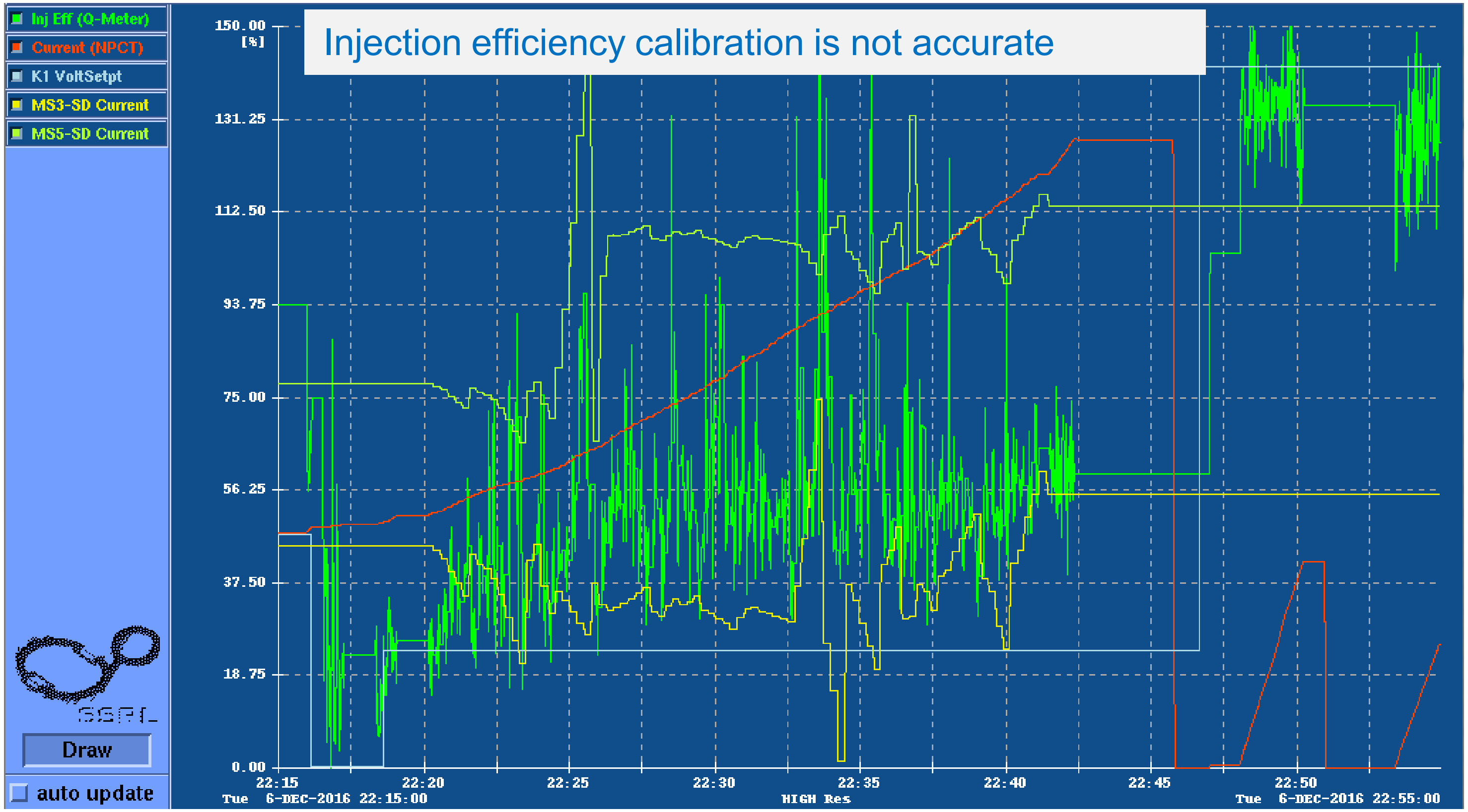


Sextupoles were optimized for chromaticities [+3, +3] w/ RCDS from flat pattern.

Change C_y by shifting all SF/SD and measure DA.

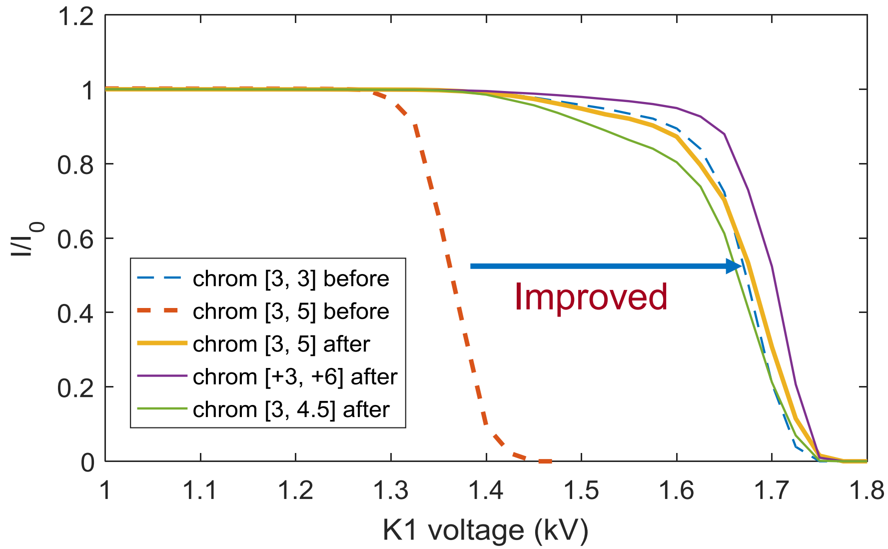
Deviation (even for lower chromaticity) from the optimized solution leads to reduced dynamic aperture.

DA optimization for high chromaticity

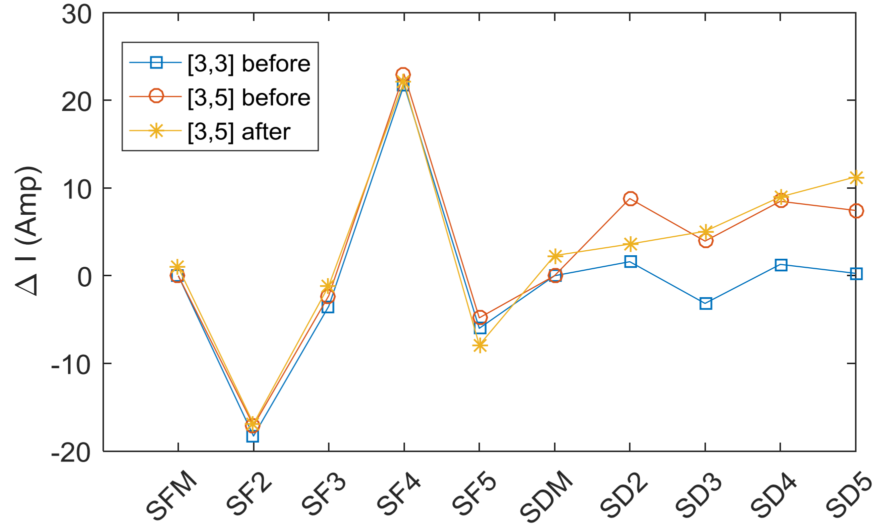


RCDS optimization for one iteration for chromaticties at [+3, +5].

Measured DA for optimized high C_y solution



Before and after optimization for the chrom=[3,5] case.



Sextupole current changes from the flat sextupole case.

After optimization (for chrom=[3, 5]), dynamic aperture at high chromaticity is at the same level as the optimized chrom=[3,3] case.

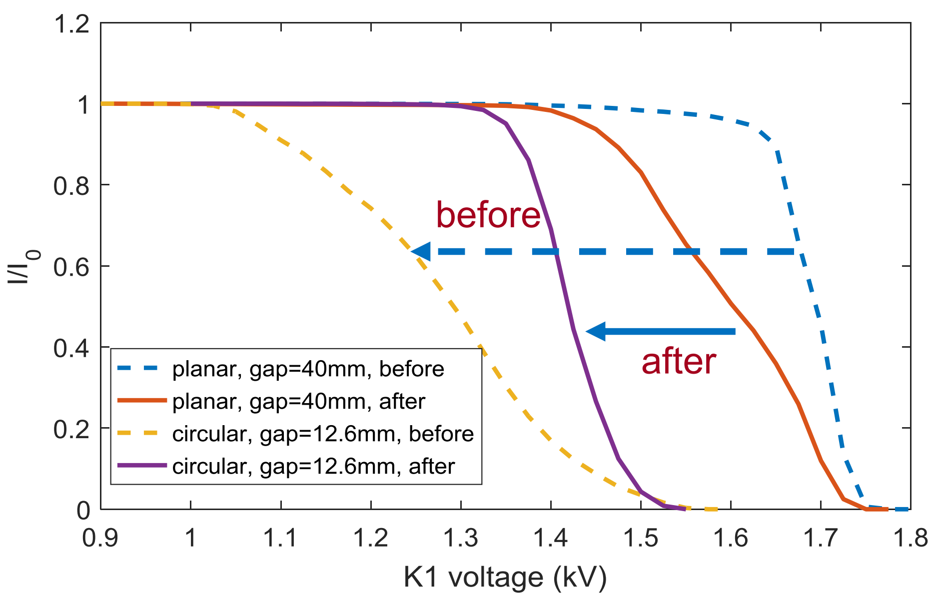
This solution allows us to run high chromaticity to suppress BL15 induced instability before other solutions (e.g. BxB feedback or damper) are implemented.

DA optimization for BL5 EPU at minimum gap

- The SPEAR3 BL5 ID is a strong field, long period ($\lambda = 140$ mm) EPU, which has strong dynamic field integral due to the transverse field roll-off.
  - Previously DA optimization was done with BL5 gap at nominal value (40mm).
  - The recent sextupole solution is sensitive to BL5 perturbation. In operation injection efficiency dropped to 75% when gap closed to 13.4 mm (not yet minimum gap).

We ran RCDS for sextupole optimization with BL5 gap closed to minimum (and at circular phase).

The best solution is less sensitive to BL5.



Injection efficiency before and after new solution

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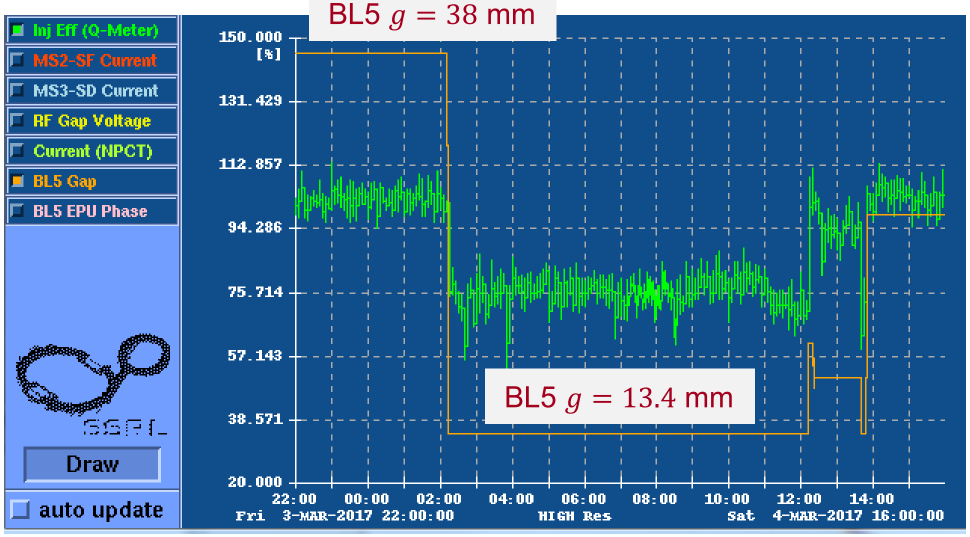
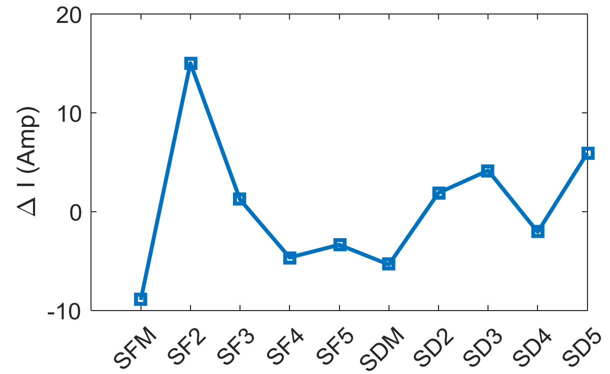
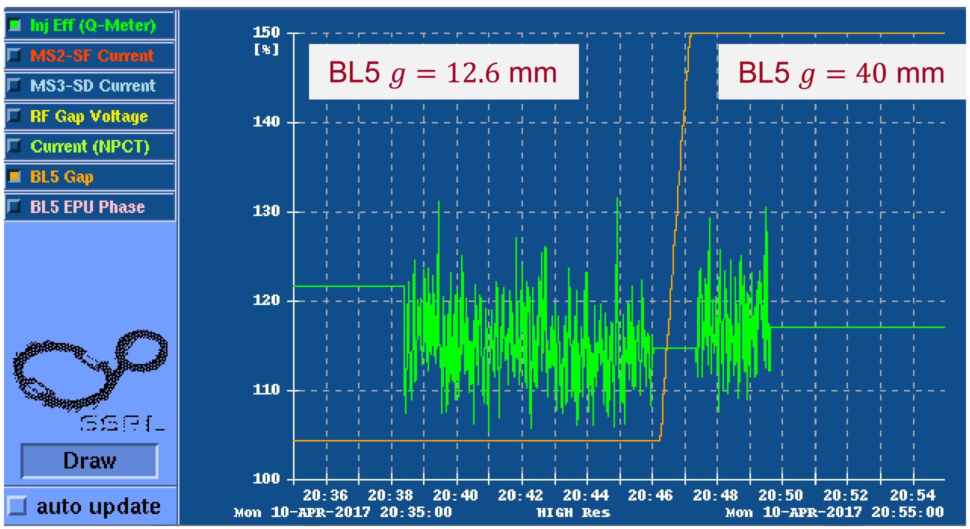


Before optimization, injection efficiency is susceptible to BL5 gap changes.



Changes of sextupole setpoints



After optimization, injection efficiency is not impacted by BL5 gap changes.

The new sextupole solution is more suitable for operation.

Touschek lifetime optimization at ESRF

- Touschek lifetime is another important nonlinear beam dynamics requirement for storage rings.
- At ESRF, Simone Liuzzo et al have successfully applied RCDS to optimize Touschek lifetime

RCDS OPTIMIZATIONS FOR THE ESRF STORAGE RING

S. M. Liuzzo, N. Carmignani, L. Farvacque, B. Nash,
T. Perron, P. Raimondi, R. Versteegen, S. M. White, ESRF, Grenoble, France

(see proceedings of IPAC 2016)

ESRF lifetime optimization:

Objective function: $$\tau_0 = \tau \frac{I}{I_0} \frac{BL(I_0)}{BL(I)} \frac{\sigma_{y,0}}{\sigma_y}$$

Lifetime is normalized by vertical beam size (measured) and bunch length (calculated).

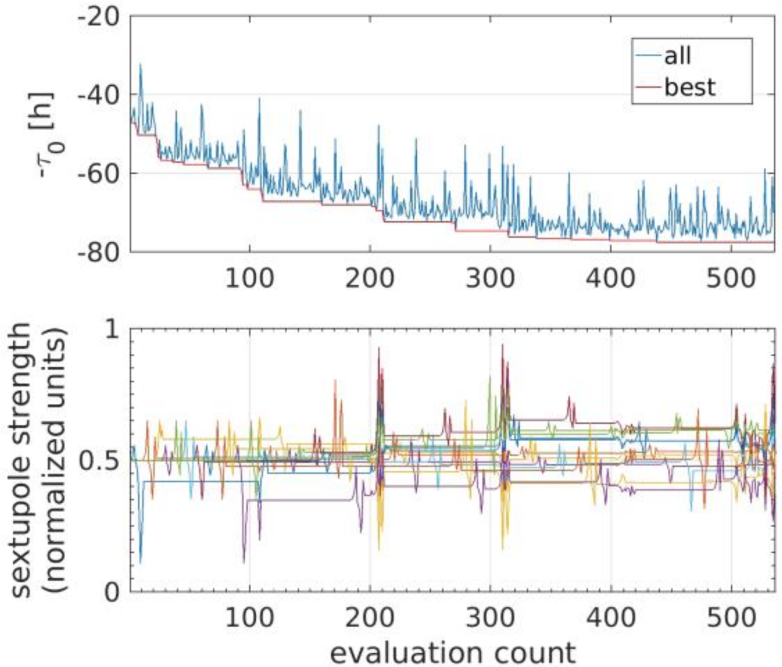
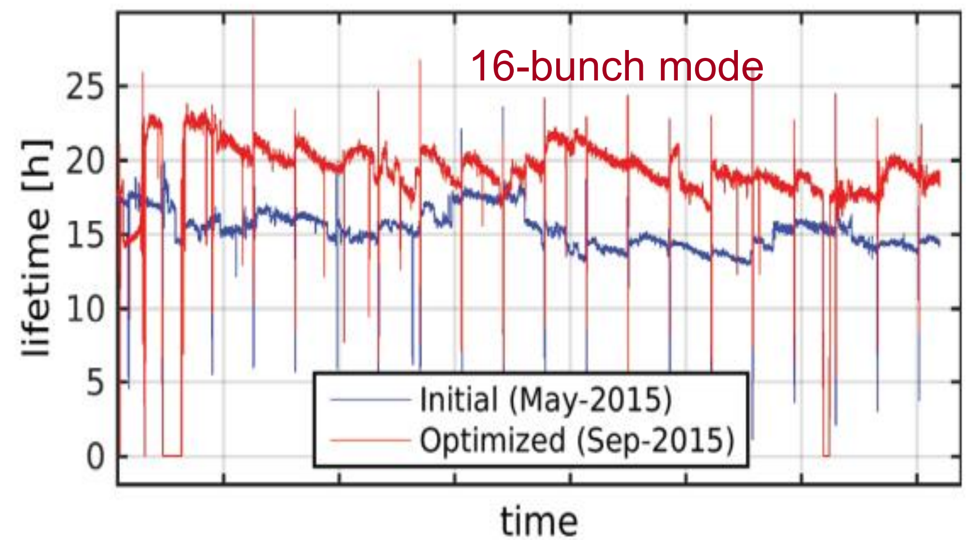


Figure 2: Optimization of lifetime using 12 sextupole correctors in 7/8+1 mode.



Multiple benefits: increased lifetime;
using one lattice for both high and low bunch current modes; higher single bunch current, etc.

S. Liuzzo, et al IPAC 2016)

Summary

- Correction of storage ring nonlinear beam dynamics poses a big challenge, especially for future diffraction limited storage rings (which are much more nonlinear).
- We have proposed and demonstrated that online optimization is an effective and efficient approach to achieve high nonlinear beam dynamics performance.
- At SPEAR3, the online optimization methods have become a useful tool.

You are welcome to contact us to obtain optimization codes (RCDS available in Matlab and Python, PSO in Matlab) and try it out. It is super-easy!

Acknowledgements

- Thanks to S. M. Liuzzo et al (ESRF) for demonstrating beam lifetime optimization on ESRF and allowing us to share their results here.