Application of Direct Methods of Optimizing Storage Ring Dynamic and Momentum Apertures

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The Problem

- Low emittance is vital for storage ring light sources
  - High horizontal phase advance
  - Strong focusing
  - Strong chromatic aberrations and small dispersion
  - Strong chromaticity correction sextupoles
  - Geometric aberrations
  - More sextupoles...
- The designer needs to adjust sextupoles to obtain
  - Adequate momentum aperture (MA) for good lifetime
  - Adequate dynamic aperture (DA) for good injection efficiency
- We've developed a successful "direct" optimization method
  - "Direct" means "based on tracking"
- This method evolved gradually from several less successful methods[1]

[1]M. Borland *et al*., Proc. PAC09, TH6PFP062.

Introduction

We'll show applications of this method to two rings

- APS: an existing 7 GeV ring, facing a significant upgrade
- NSLS-II: an ultralow emittance ring under construction[1,2]

Important components

- Adequate computational resources
- Fully-scriptable lattice tuning and simulation of DA and MA
- Robust measures of DA and MA
- Genetic optimization algorithm

[1] S. Kramer and J. Bengtsson, Proc. PAC05, 3378-3380 (2005).
[2] W. Guo *et al.*, Proc. PAC09, TU5RFP008.

Genetic Optimizer in a Nutshell

Create N (e.g., 40~80) randomized configurations

- Typically "small" perturbations from a reasonable starting point

Submit N jobs to a cluster to evaluate configurations

Wait until at least M (e.g., 4~6) configurations are completed

If the best configuration is adequate, stop

Select the best P configurations as "Parents"

Randomly blend the attributes of the Parents to make new configurations

- Make as many as needed to maintain N jobs

Submit the new jobs

Wait for at least one job to complete

Return to step 4

Values for N, M, P are selected from experience. N (number of simultaneous jobs) obvisouly also depends on resources

More Details

- We implemented this algorithm in the **geneticOptimizer** script[1]
  - Written in Tcl
  - Assumes a DQS- or PBS-like batch system
  - Script has a multi-objective mode, i.e. Keep penalty function terms separate, so that the "final solution" is a set of solutions on an optimal front.
- User must provide
  - Configuration file giving variables, initial values, ranges, and randomness levels
  - A script to run the simulation
    - Script accepts the values of the variables on the commandline using tag/value syntax
  - A script to return the penalty value (to stdout)
- Success depends on a good penalty function
  - In our case, we need good measures of DA and MA
  - One could use proxies, like tune footprint or tune shifts
    - Hard to beat something derived from tracking to obtain DA and MA

[1]M. Borland, H. Shang, unpublished program (available on request).

Code Issues

- The ring code must provide 100% scriptable lattice matching and analysis
  - Automated input preparation
  - Automated post-processing
  - GUI-free
- **elegant** is well suited to this task
  - Command file templates
    - Macro substitution from commandline allows changing parameters without editing files
    - Rootname-based input and output file naming allows many simulations at once without confusion
  - Use of SDDS files
    - Provides robust, easy data transfer between stages of a simulation
    - SDDS Toolkit provides automatic data analysis and collation
  - Everything is open source
    - No licensing issues on arbitrary number of nodes
  - Supplies appropriate, robust measures of DA and MA

DA Computation

elegant supports several DA search methods

- For this work, we used a line search from the origin

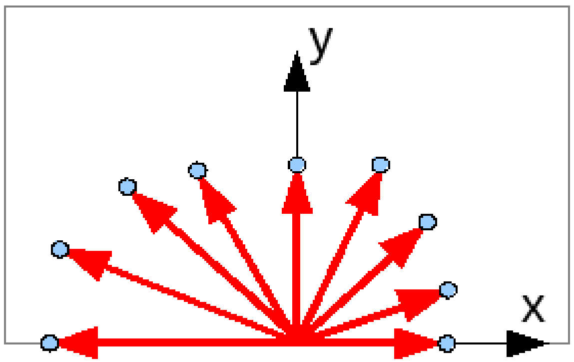
Typical parameters

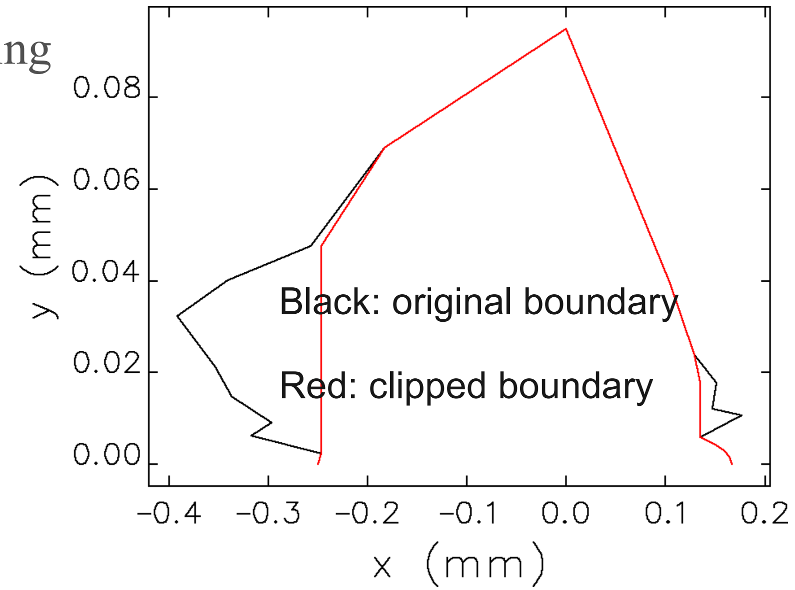
- 400 turns with radiation damping and physical apertures
- 21 lines
- 30 steps along each line
- Subdivide interval once (1/10 step)

After finding the DA boundary, we apply a clipping algorithm

- Eliminates features that do not contribute usefully to the DA
- We then compute the area A inside the clipped boundary

We restrict the vertical extent of the search to prevent optimizing vertical DA at expense of horizontal





DA Contribution to Penalty Function

DA contribution to the penalty function is computed as

$$P(A) = \begin{cases} (A - A_d)^2/\Delta A^2 & A < A_d \\ 0 & A \geq A_d \end{cases}$$

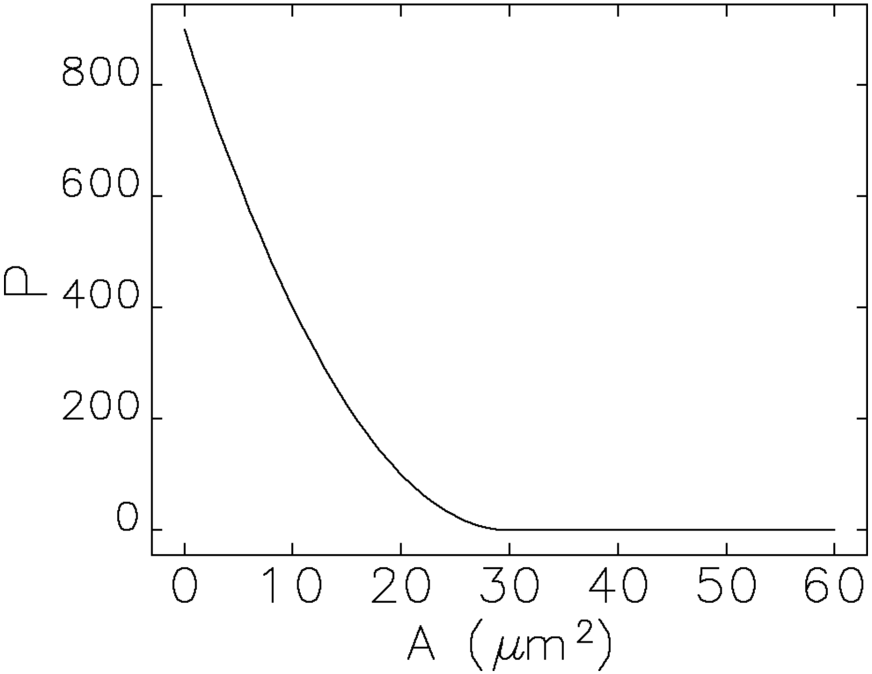
where A is the area, A_d is the desired area, and ΔA is a weighting factor

Typical choices for A_d

APS: 30 μm^2
(-13mm < x < 7mm and |y|<1.5mm)

NSLS-II: 50~100 μm^2

Typical value for ΔA is 1 μm^2



Momentum Aperture

Touschek scattering is the primary determinant of beam lifetime in 3rd generation light source rings

- Occurs when intra-beam scattering gives a large momentum offset
- Strongly affected by the local momentum aperture in the ring

elegant allows determining positive and negative apertures at the exit of user-selected elements

- The algorithm is essentially that of M. Belgroune (PAC03, 896-898)

Details of implementation

- Use tracking (typ. 400 turns) with rf cavities, radiation damping, and physical apertures
- Starting at zero, gradually increase the momentum kick at selected element and track for each value
- When loss occurs, step back and resume with, e.g., 1/10 step size
- Repeat in other direction

We typically compute MA at the exit of various sextupoles on either side of the dipoles for the first 6~12 sectors of the ring

MA Contribution to Penalty Function

MA contribution to the penalty function is

$$P(\delta_{min}) = \begin{cases} (\delta_{min} - \delta_{des})^2/\Delta\delta^2 & \delta_{min} < \delta_{des} \\ 0 & \delta_{min} \geq \delta_{des} \end{cases}$$

where δ_{min} is the minimum of $|\delta_{lim}|$ over all elements, δ_{des} is the desired value, and $\Delta\delta$ is a weighting factor.

Typical values

APS: δ_{des}=2.35% (rf bucket half-height)

NSLS-II: δ_{des}=3.0%

$\Delta\delta$ is typically 0.01%

An alternative:

Compute the Touschek lifetime using **touschekLifetime**[1], which reads **elegant**'s MA and Twiss parameter output

[1]A. Xiao and M. Borland, Proc. PAC07, 3453-3455 (2007).

Importance of Lattice Errors

DA and MA are strongly affected by lattice errors, e.g.,

- Magnet strength errors
- Orbit in sextupoles
- If we don't include errors in the optimization, we'll get useless results

Effective methods exist for correction

- Typically ~1% rms lattice function beats are achieved
- Typically ~1% coupling is achieved

To avoid simulating correction, use errors that approximate lattice errors at *post-correction* levels, e.g.,

- 0.02% quadrupole and sextupole strength errors
- 0.5 mrad quadrupole and sextupole roll

Use a single error ensemble during optimization

- This is not 100% fool-proof
- Evaluate many ensembles as post-optimization check
- Surprises are rare

Applications to APS "Renewal”

APS is a 7 GeV storage ring light source

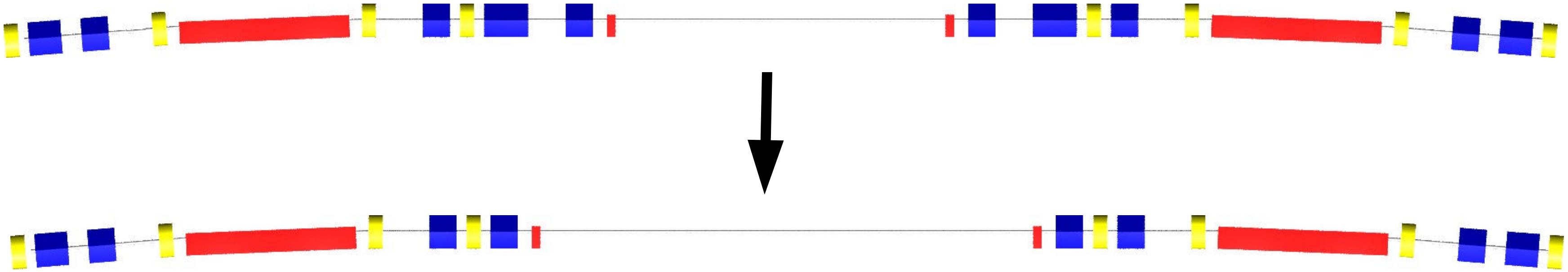
- In operation since 1996
- Low emittance lattice (3,1nm effective emittance)
- Top-up mode ~80% of the time

Usually run with high single-bunch charge (15 to 60 nC)

- Requires chromaticity of 6 to 11 to stabilize beam
- Integer tunes are 36 (x) and 19 (y)

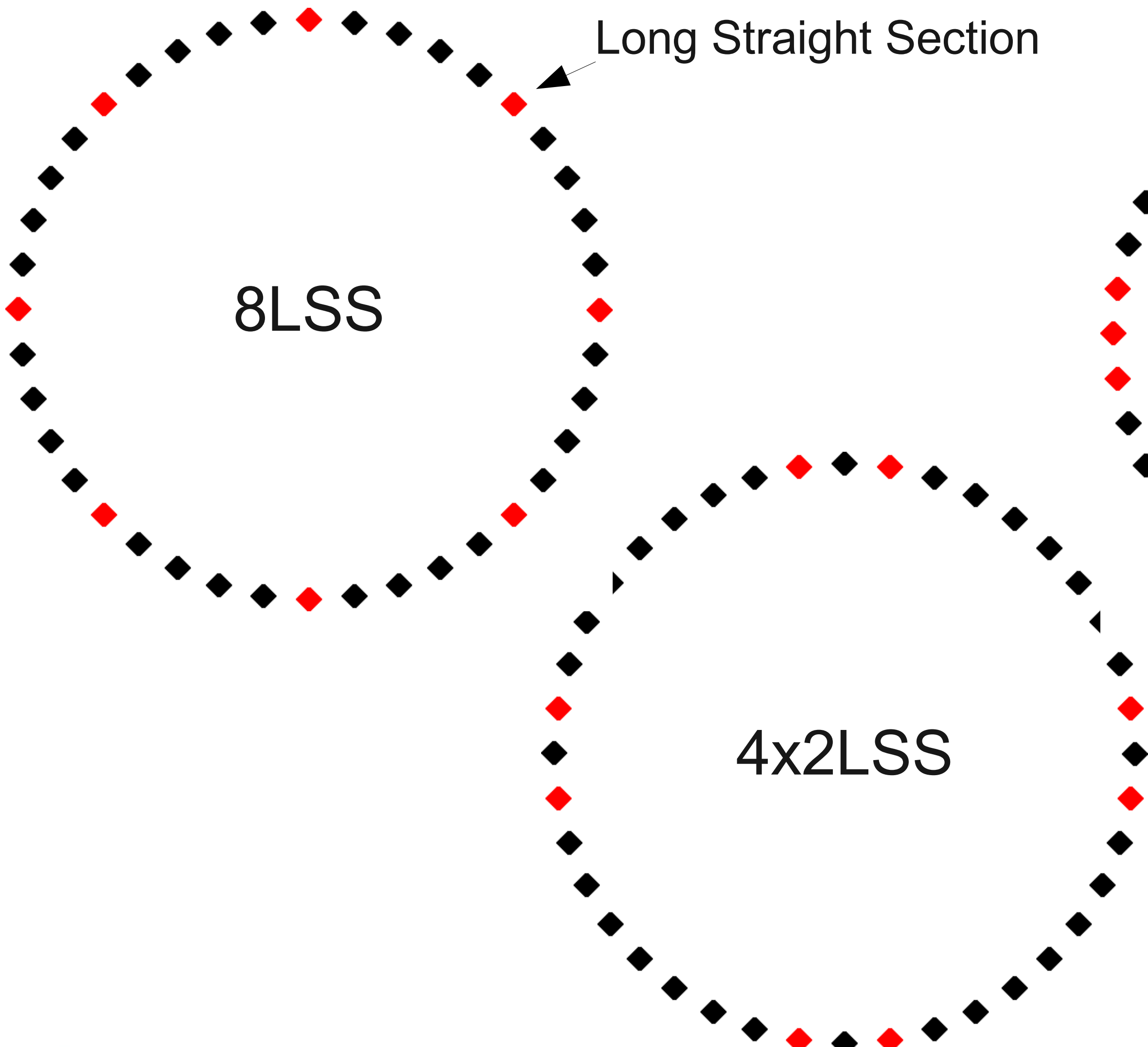
Significant upgrades anticipated as part of “Renewal” project

- Likely to include long straight sections (LSS)



Lots of options for how to place LSS in our 40 sector ring

LSS Options for APS



Latest: 8x(S,L,S,L,S) plus short-pulse-xray plus reduced horizontal beam-size

4x2LSS Optimization

When optimizing 8LSS, reflection asymmetric sextupole powering essential[1]

- Verified experimentally

For 4x2LSS, there are potentially 21 sextupole knobs

- 7 each for long ➔ short and short ➔ long sectors
- 7 for the standard sector
  - We use three of these for chromaticity
  - We assume symmetry for the remaining four knobs
- Results in 16 independent sextupole knobs

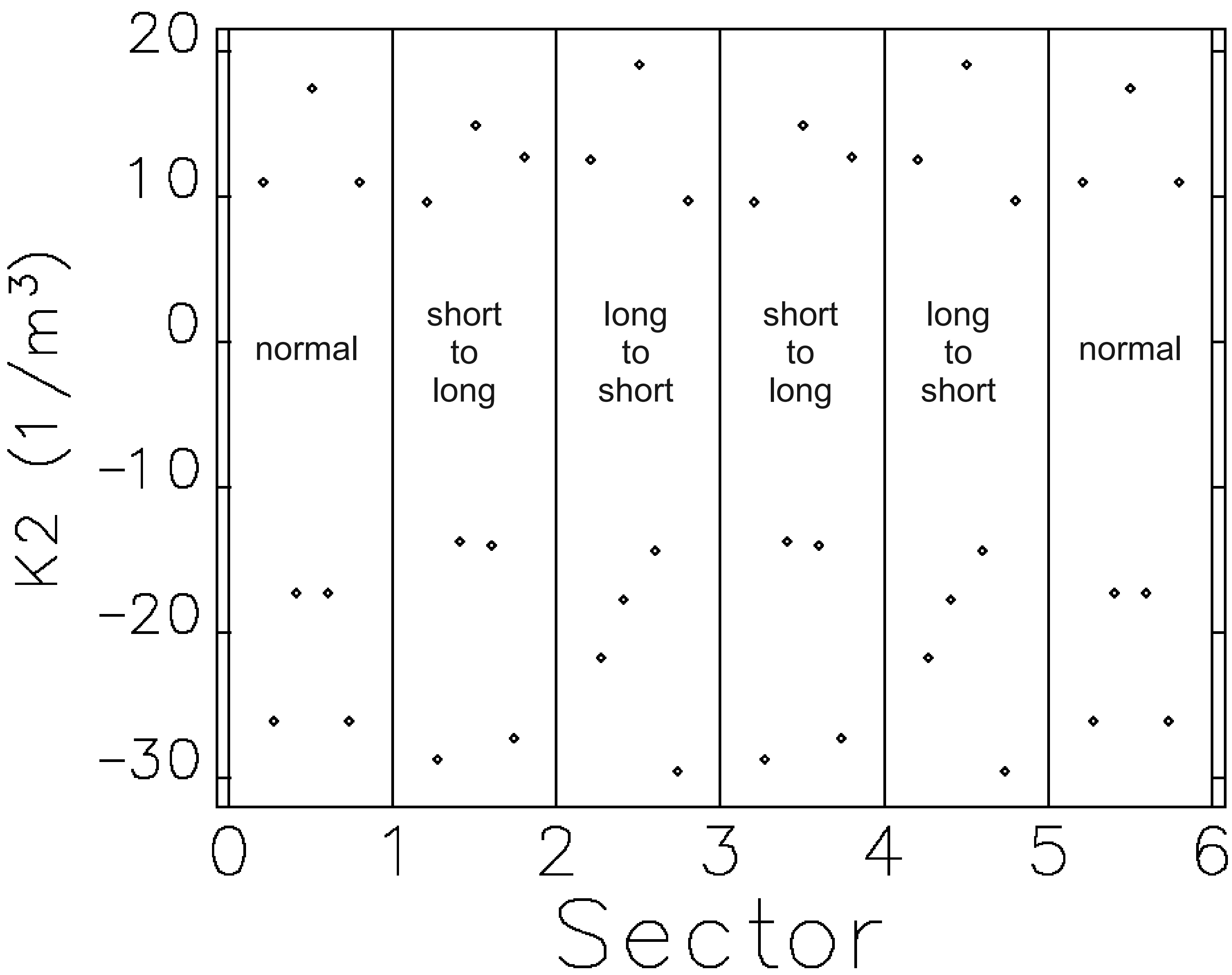
The only other knobs are the tunes

For each randomized configuration

- Match three types of sectors with tune and emittance constraints
  - Ordinary Decker-distorted and non-Decker-distorted sectors
  - Short-to-long transition sectors
- Correct chromaticity
- Track to obtain DA and MA

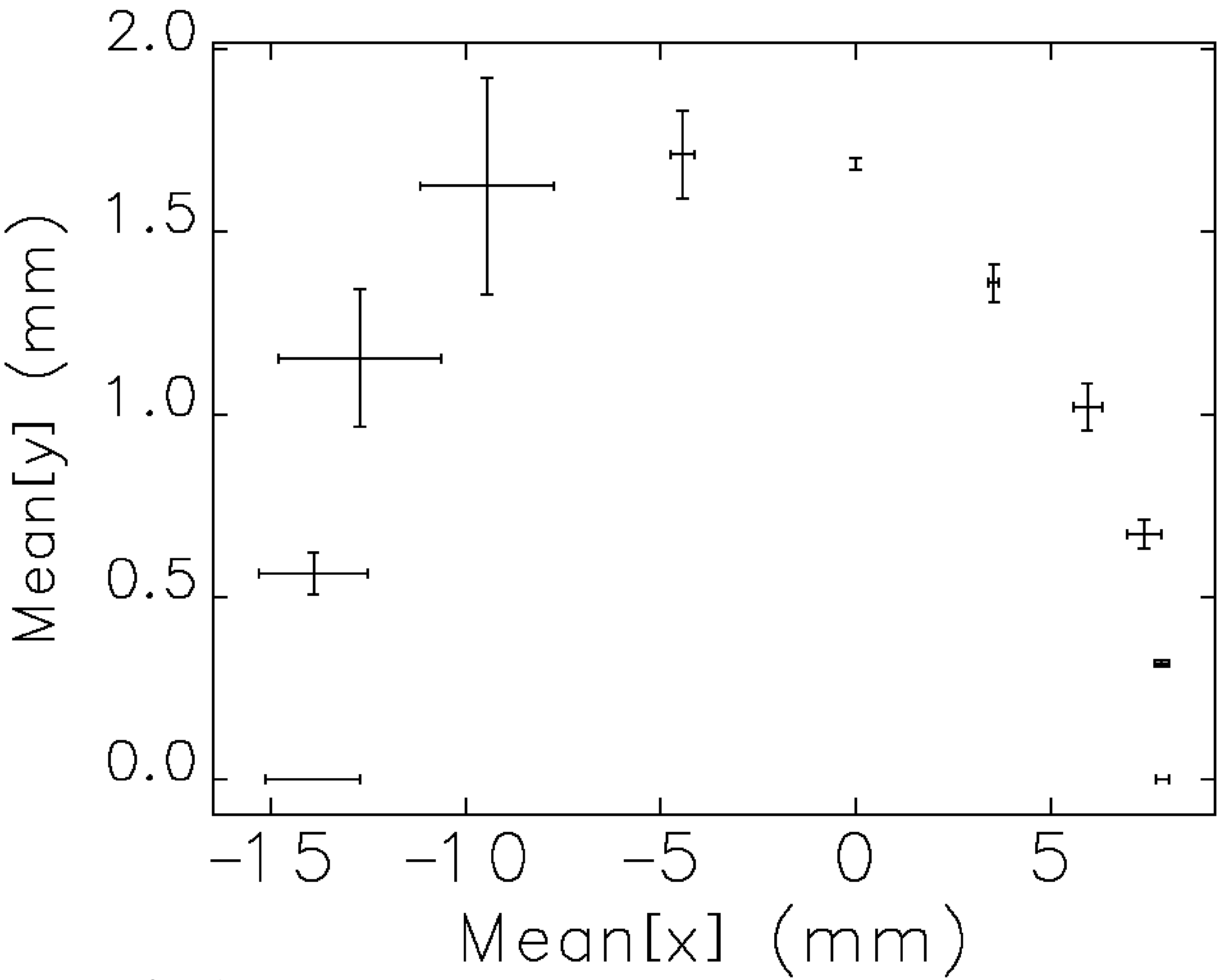
[1]M. Borland *et al.*, Proc. PAC09, TH6PFP062.

4x2LSS Sextupole Pattern Result for $\xi_x = \xi_y = 6$

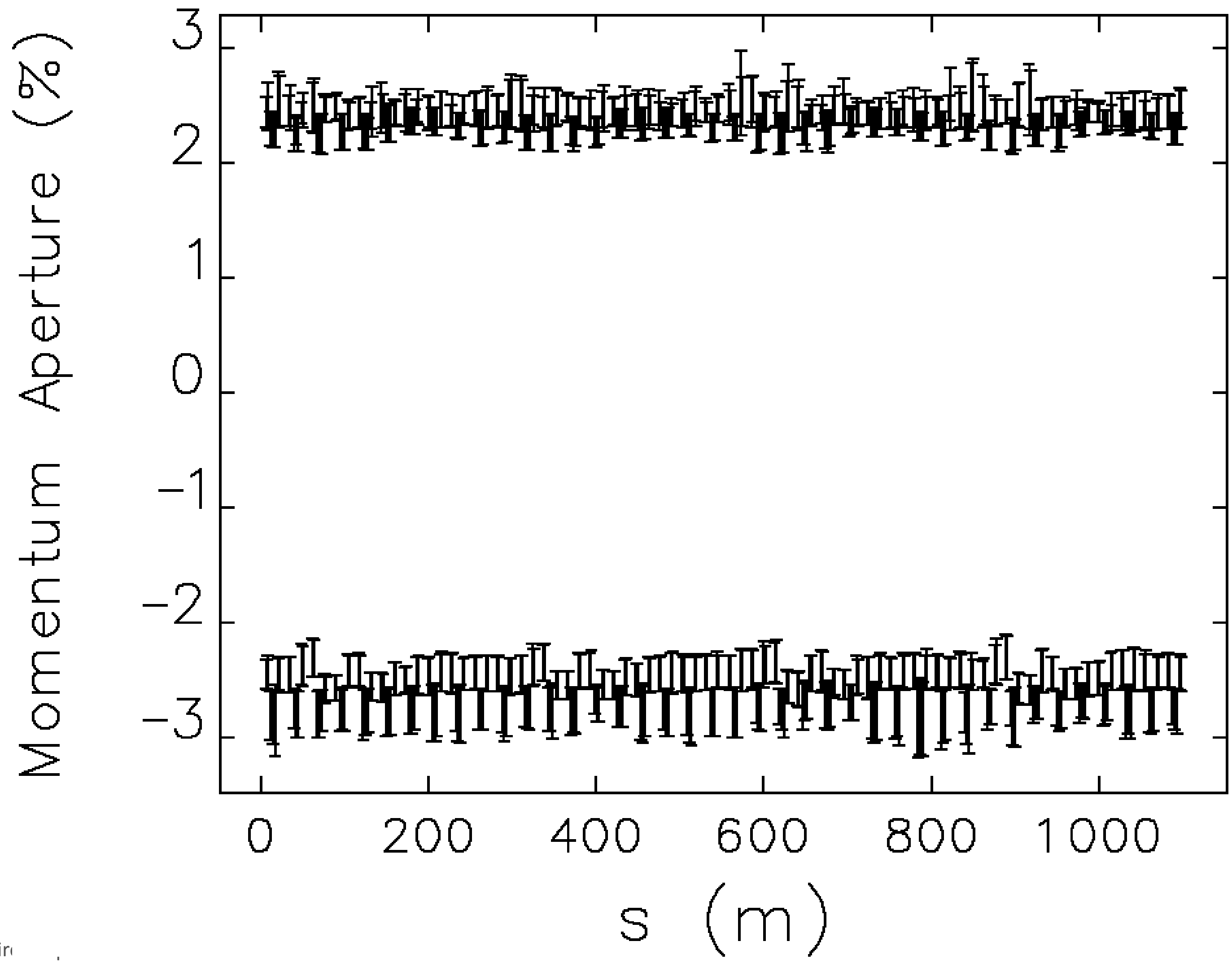


Would probably benefit from removing translational symmetry constraint

4x2LSS Dynamic Aperture (20 Ensembles)



4x2LSS Momentum Aperture (20 Ensembles)



APS Experiments and Operational Experience[1]

- APS has independent power supplies for all quad/sext magnets
  - We can "mock up" an LSS lattice by turning off supplies
  - We did this for 8LSS
    - Optimization rerun to include residual field in quadrupoles at zero current
  - Lifetime 25% better than APS operational lattice, as predicted
  - Same injection efficiency (90~100%)
- We then optimized the APS operations lattices
  - 24-bunch configuration ($\xi_x=\xi_y=6$) – our standard run mode
    - Lifetime improved by 25%
  - Hybrid mode ($\xi_x=\xi_y=11$)
    - Lifetime improved by 10%
  - No reduction in injection efficiency

[1]M. Borland *et al*., Proc. PAC09, TH6PFP062.

NSLS-II Optimization

NSLS-II is under construction

- 3 GeV ring targeting <1nm emittance
- Uses strong damping wigglers and in-vacuum IDs

Considerable prior work[1,2] has been done to optimize design using resonance driving term minimization[3]

Differences in the present work

- Target large chromaticities (up to 5)
- Use more independent sextupole knobs
- Vary tune as integral part of optimization

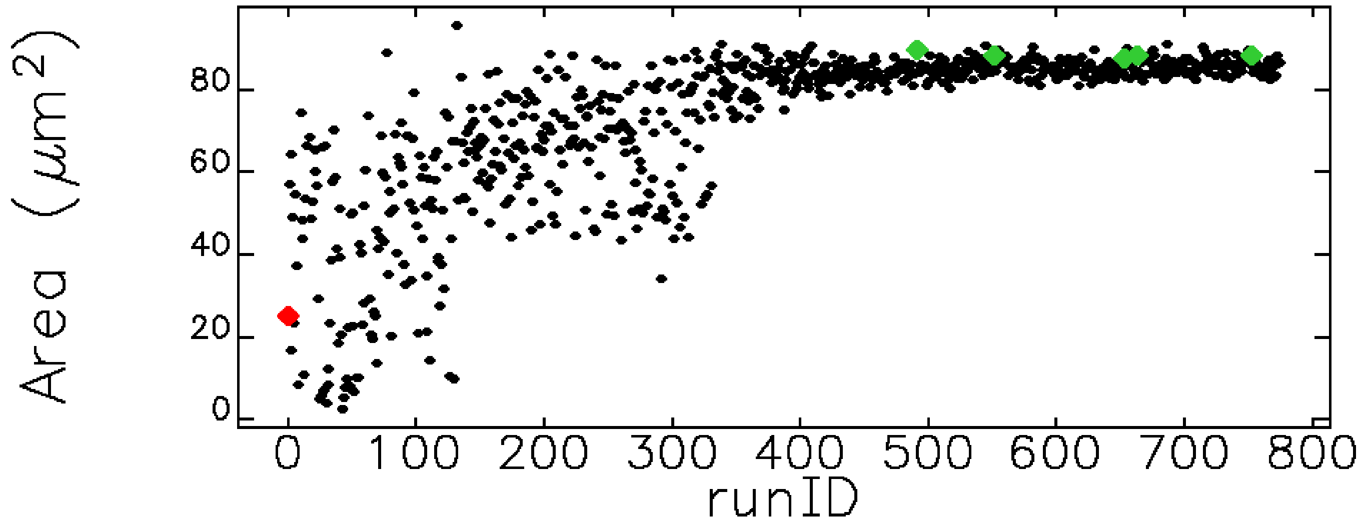
We optimized a lattice with 3 damping wigglers included

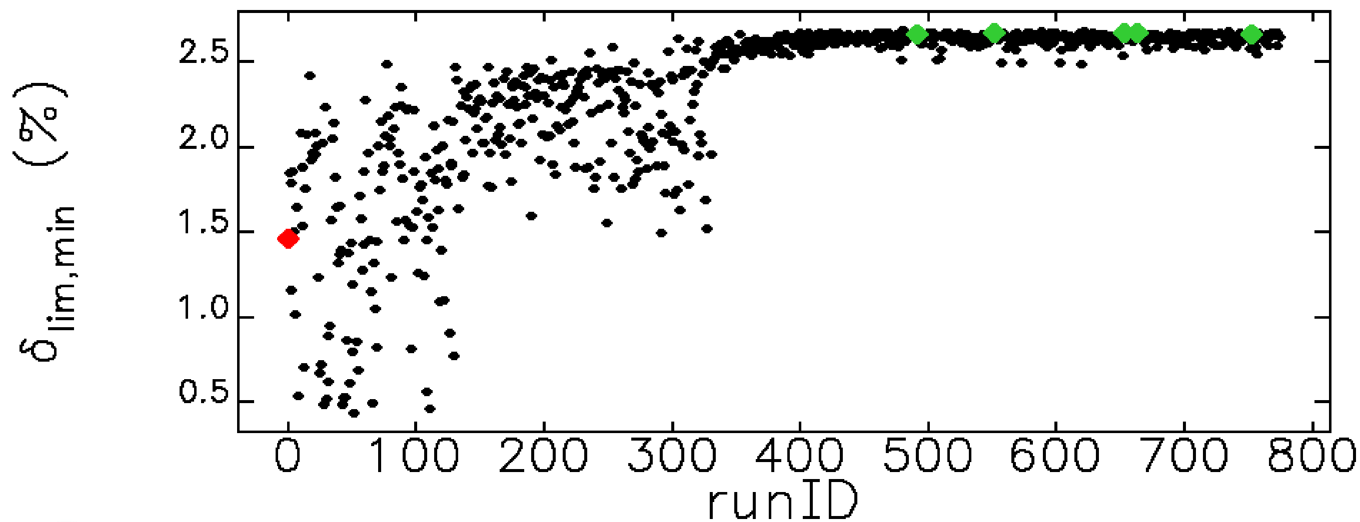
We do not include multipole errors in present work

- Has a considerable impact on DA
- Optimization in progress

[1]S. Kramer and J. Bengtsson, PAC05, 3378-3380.
[2]W.Guo et al., PAC09, TU5RFP008.
[3]J. Bengtsson, SLS Note 9/97 (1997).

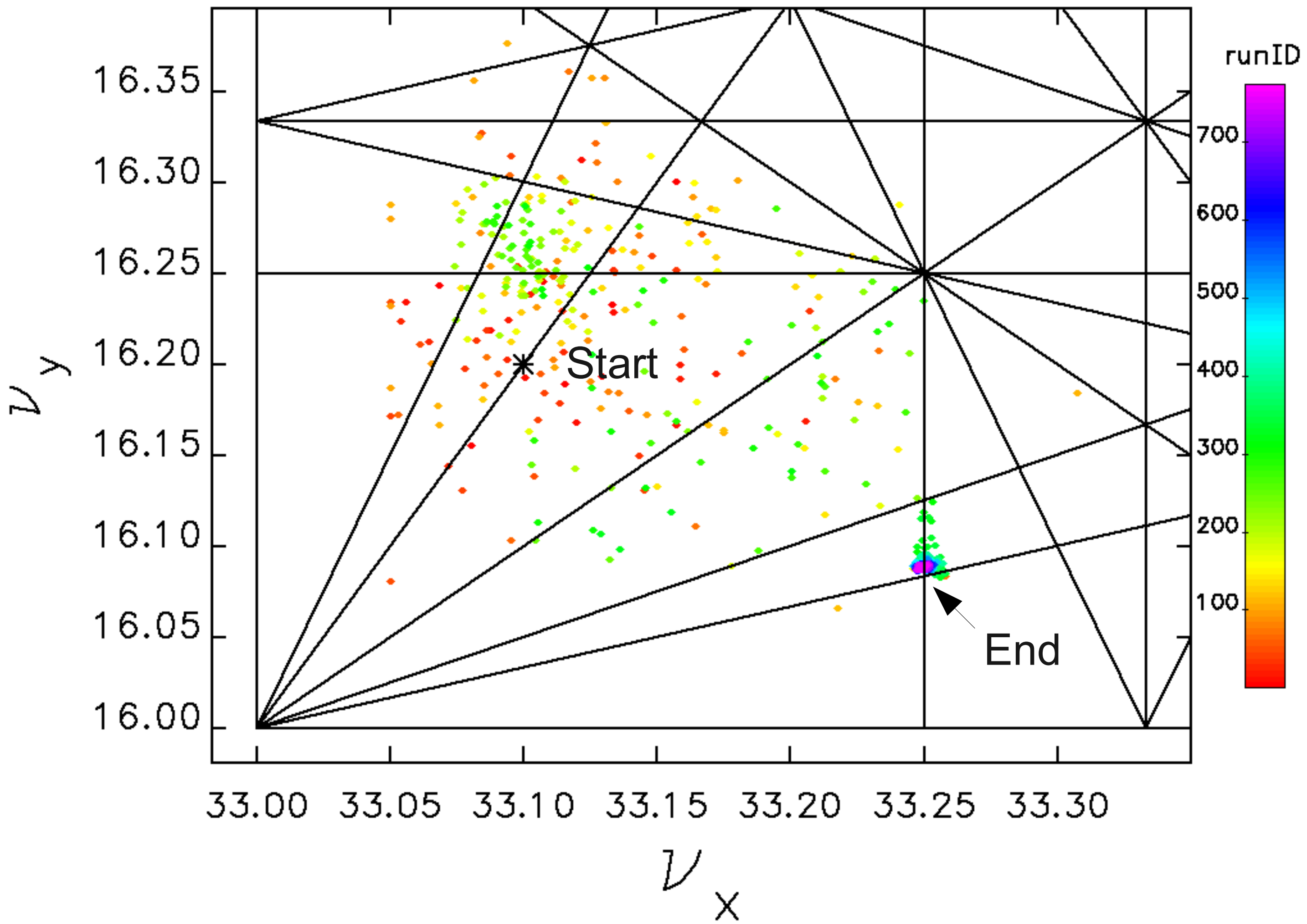
NSLS-II Optimization for $\xi_x = \xi_y = 2$



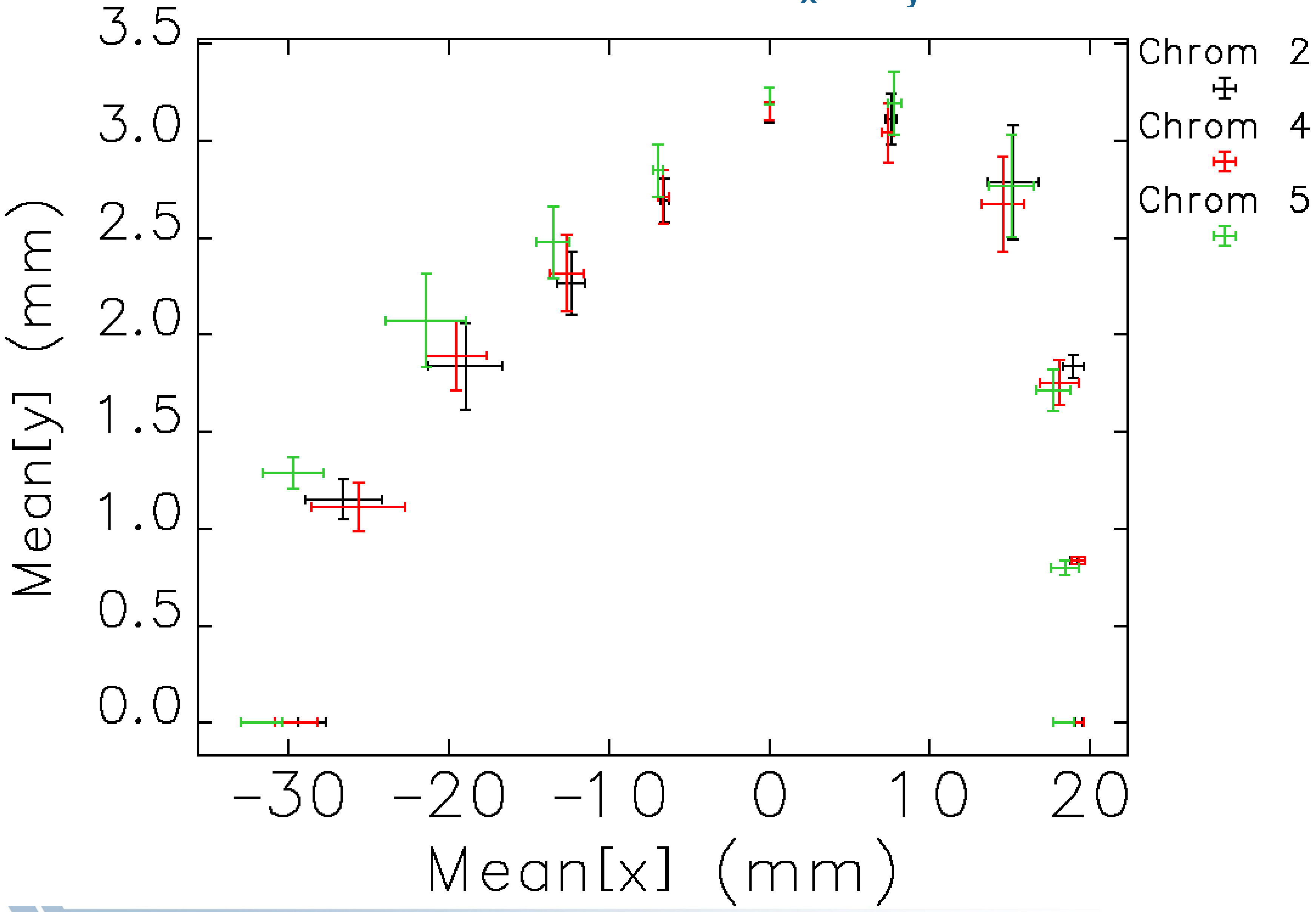


N.B.: Starting conditions *not* optimized for these values of chromaticity

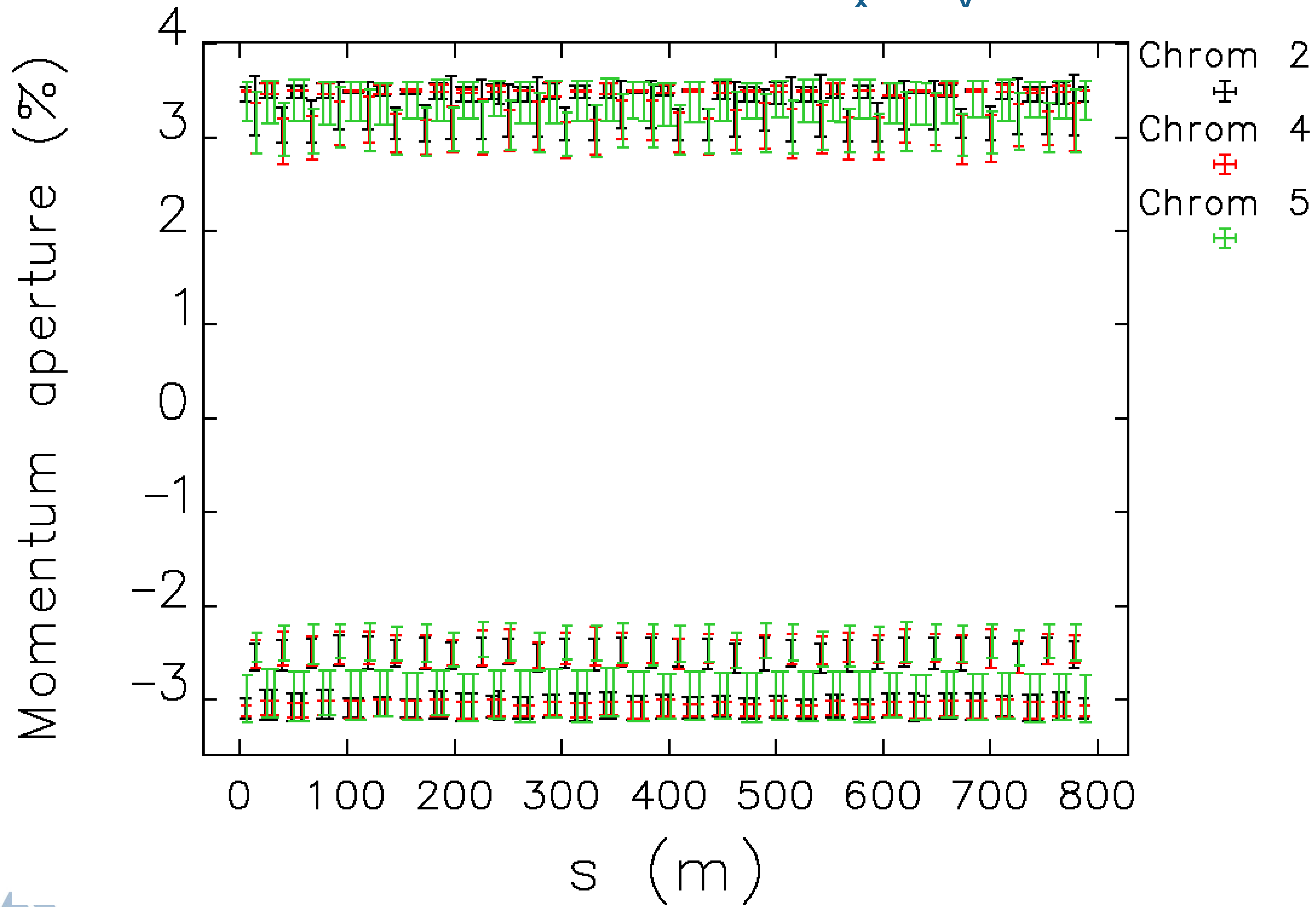
NSLS-II Optimization for $\xi_x = \xi_y = 2$



NSLS-II Dynamic Apertures for $\xi_x = \xi_y = 2, 4, 5$



NSLS-II Momentum Apertures for $\xi_x = \xi_y = 2, 4, 5$



Future Developments

This method is very successful, but can be improved

Version 22.1 of elegant has parallelized DA and MA[1]

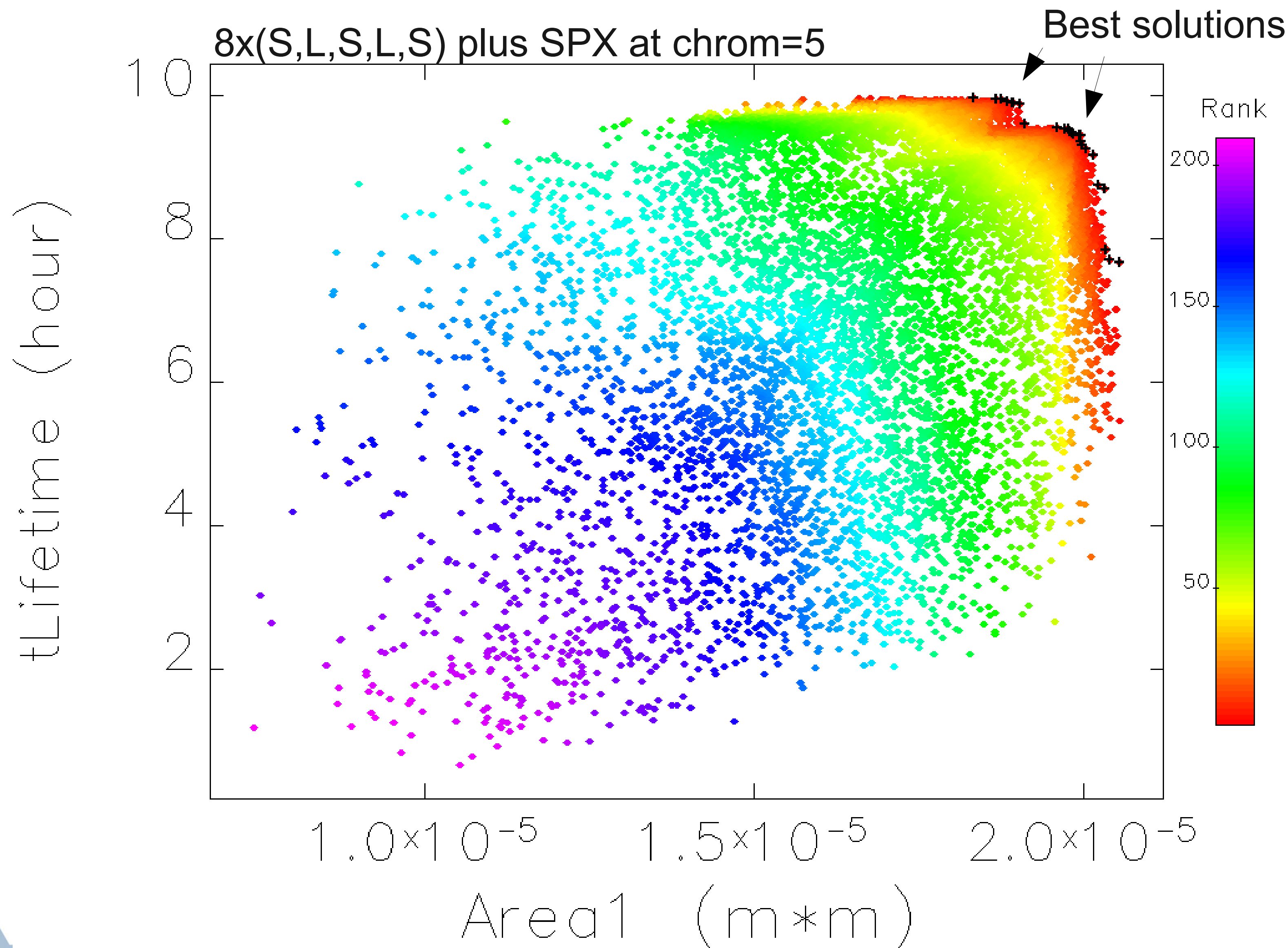
- Can run each job on many cores
  - Promises results in hours instead of weeks
  - Optimize over many possible integer tune choices
  - Optimize with several ensembles of errors, for greater robustness

Should try other optimizers and variants

- Scheduled annealing in genetic optimizer
- Multi-objective genetic optimizer[2]
- Parallel simplex[3]

[1]Y. Wang *et al.*, these proceedings.
[2]K. Deb *et al.*, IEEE Trans. Evol. Comput. 6, 182 (2002).
[3]H. Shang and M. Borland, PAC05, 4230-4232 (2005).

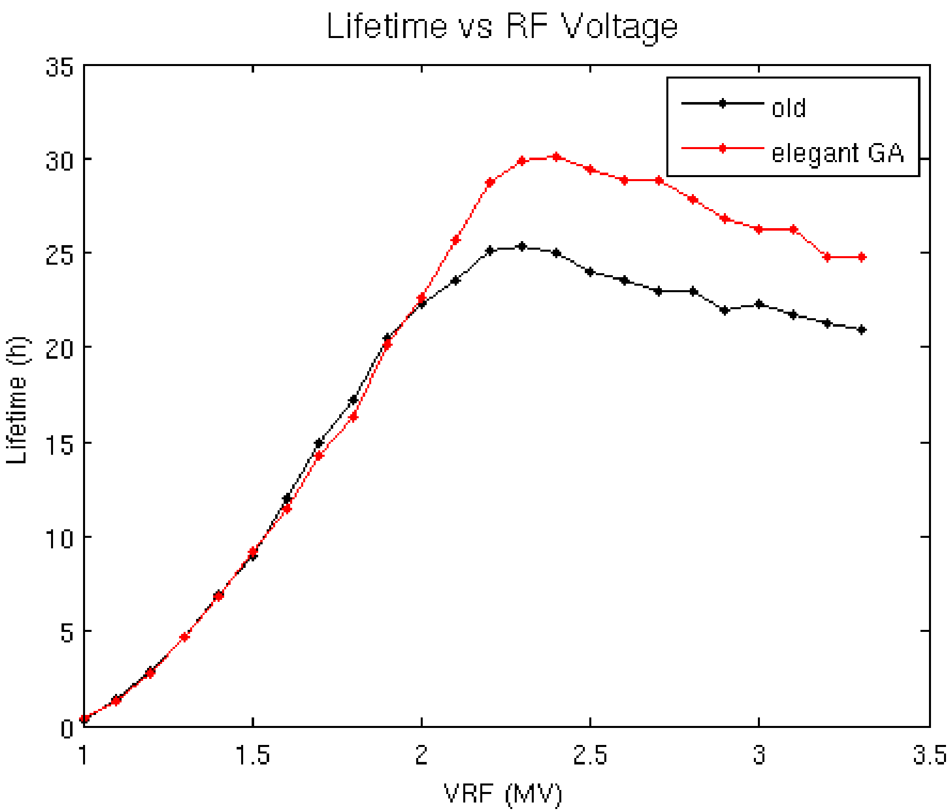
Recent Application with Multi-Objective GA



Future Developments

- Increase realism
  - Optimize accumulation efficiency instead of DA
    - May obtain lop-sided DA with big aperture for off-axis injected beam
  - Optimize Touschek lifetime instead of minimum MA
  - Incorporate lattice and coupling correction
- Benchmarking
  - Method has successfully improved APS operations, but more quantitative comparison would be valuable
  - J. Bengtsson suggests an experimental test with an existing lower-energy ring
    - This was done with DLS sextupoles using our method with a 20% improvement in lifetime achieved (Bartolini, Dec 16th)

Diamond Sextupole Optimization Result



Courtesy R. Bartolini

Conclusions

Light source ring designers must simultaneous tune for

- Large DA to get good injection efficiency
- Large MA to get good Touschek lifetime

Modern rings typically have ~10 independent sextupoles per cell

- The most common method of optimization uses minimization of first- and second-order resonance driving terms
- Tracking is done as a check
- Iteration required

A successful tracking-based method has been developed

- Directly optimizes the quantities we care about
- Well suited to cases with large linear chromaticity
- Solutions seen to be very robust

Has been applied to APS and NSLS-II

- Significant improvements to APS operations
- Promising results for NSLS-II design optimization

Many ideas to improve the method further