Parallel tracking-based optimization of dynamic aperture and lifetime with application to the APS upgrade

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The Problem

- Low emittance is vital for storage ring light sources
  - ➔ Strong focusing
  - ➔ Strong chromatic aberrations and small dispersion
  - ➔ Strong chromaticity correction sextupoles
  - ➔ Geometric aberrations
  - ➔ More sextupoles...
- The designer needs to adjust working point and sextupoles to obtain
  - Adequate single-bunch threshold (via positive chromaticity)
  - Adequate local momentum aperture (LMA) for good lifetime
  - Adequate dynamic aperture (DA) for good injection efficiency
- We've developed a successful "direct" genetic optimization method
  - "Direct" means "based on tracking"
- This method evolved gradually from several less successful methods[1,2]

[1]M. Borland *et al*., Proc. PAC09, TH6PFP062.
[2]M. Borland *et al*., Proc. ICAP09, to be published.

Introduction

- We'll show applications of this method to APS
  - Operations lattices
  - Upgrade lattices and mock-ups
- Has also been applied to DLS and NSLS-II
- Important components
  - Fully-scriptable lattice tuning and simulation of DA and LMA
  - Robust measure of DA and LMA
  - Computation of lifetime from LMA
  - Genetic optimization algorithm
- Need adequate computing resources
  - Typically use at least 100 cores (Nehelem processors)
  - Have used up to 38,000 (IBM BlueGene)

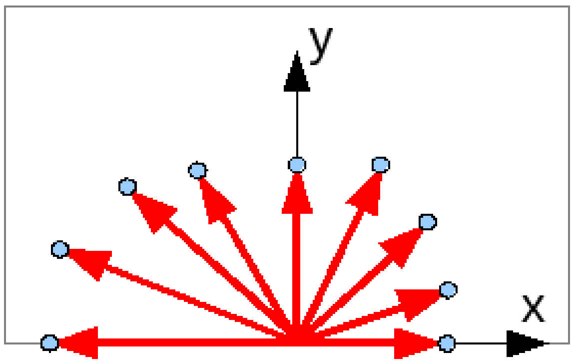
Genetic Optimizer in a Nutshell

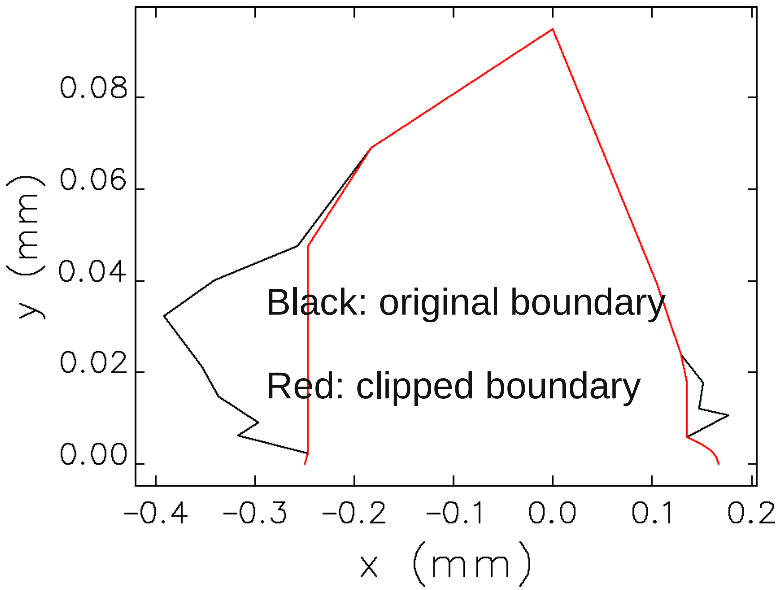
1. Create N (e.g., 40~1000) randomized configurations
   - Typically "small" perturbations from a reasonable starting point
2. Submit N jobs to a cluster to evaluate configurations
   - On ordinary clusters, each job uses one core (**elegant**[1])
   - On IBM BlueGene, each job uses many cores (**Pelegant**[2])
3. Wait until at least M (e.g., 4~6) configurations are completed
4. If the best configuration is adequate, stop
5. Select the best M or rank-1 configurations as "Parents"
6. Randomly blend the attributes of the Parents to make new configurations
   - Make as many as needed to maintain N jobs
7. Submit the new jobs
8. Wait for at least one job to complete
9. Return to step 4

[1]M. Borland, APS LS-287, September 2000.
[2]Y. Wang *et al.*, Proc. ICAP09, to be published.

DA Computation

- **elegant** supports several DA search methods
  - We used a line search from the origin
- Typical parameters
  - 400 turns with 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



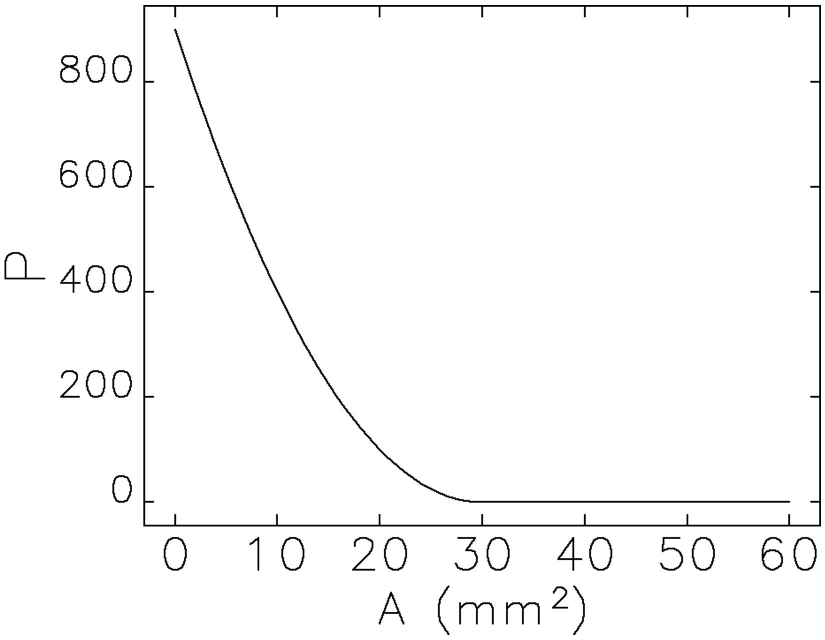


DA (Contribution to) Penalty Function

- In single-objective mode:
  - 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
  - For APS, typically $A_d = 30\ mm^2$ (-13mm < x < 7mm and |y|<1.5mm)
  - Typical value for ΔA is 1 mm^2
- For multi-objective mode
  - Penalty function is -A



Local Momentum Aperture

- Touschek scattering is the primary determinant of beam lifetime in 3rd generation light source rings
  - Occurs when electron-electron scattering gives 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 (LMA)
  - Algorithm is essentially that of M. Belgrounne (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 LMA at the exit of various sextupoles on either side of the dipoles for the first 6~12 sectors of the ring

LMA (Contribution to) Penalty Function

- In single-objective mode
  - LMA 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.
  - For APS, δ_{des}=2.35% (rf bucket half-height)
  - $\Delta\delta$ is typically 0.01%
- Approach for multi-objective mode
  - Compute the Touschek lifetime τ using **touschekLifetime**[1]
    - *Reads **elegant**'s LMA and Twiss parameter output*
  - Use $-\tau$ as the penalty function
  - Has yielded better results for APS upgrade

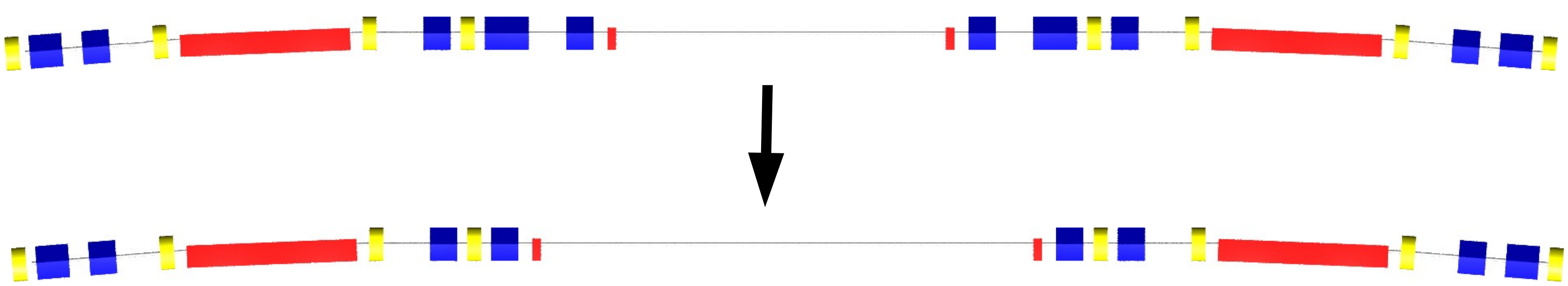
[1]A. Xiao and M. Borland, Proc. PAC07, 3453-3455 (2007).

Importance of Lattice Errors

- DA and LMA 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

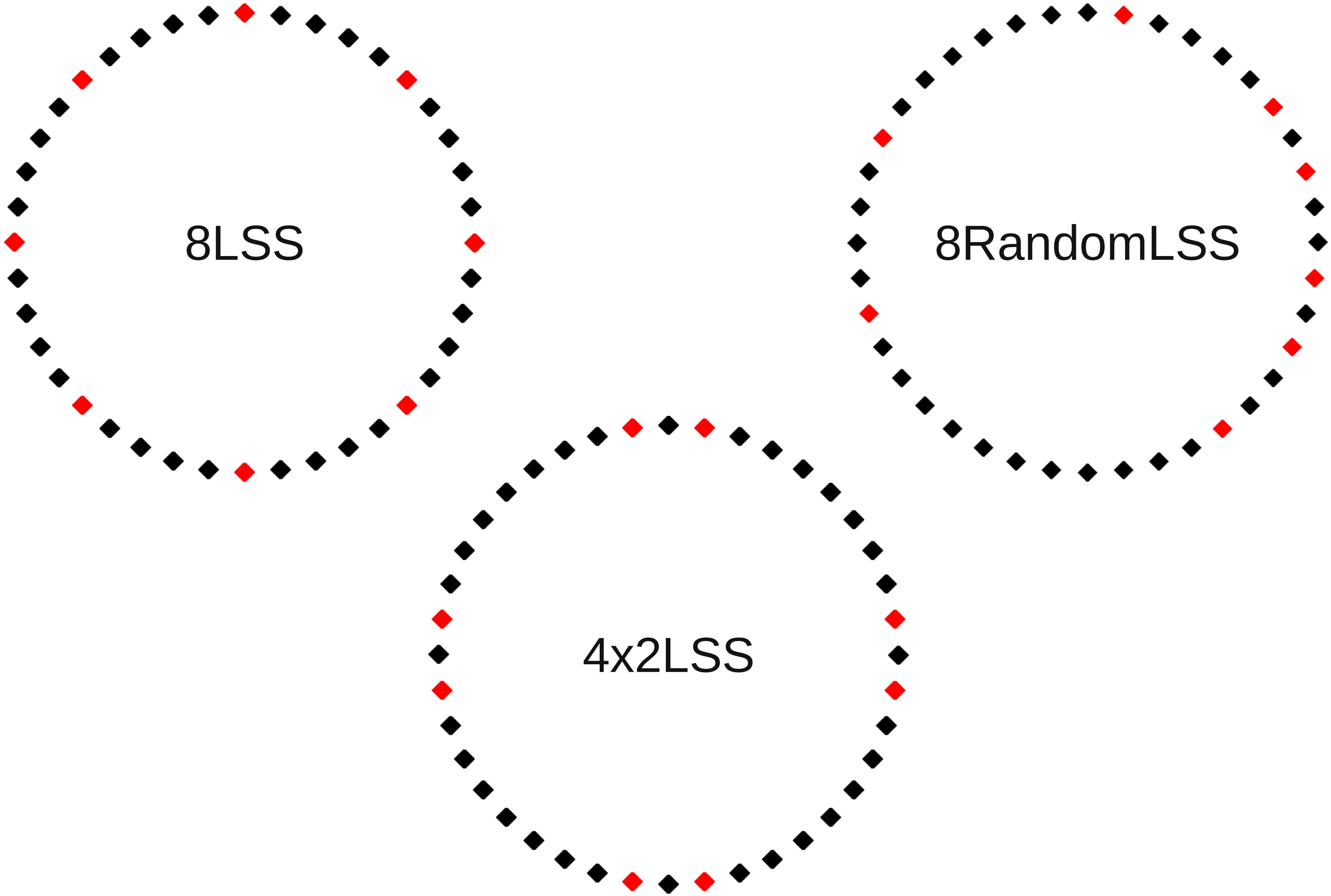
Applications to APS Upgrade

- 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)
- Upgrade likely to include long straight sections (LSS)



- Can only afford 8 LSS

A Few LSS Options for APS

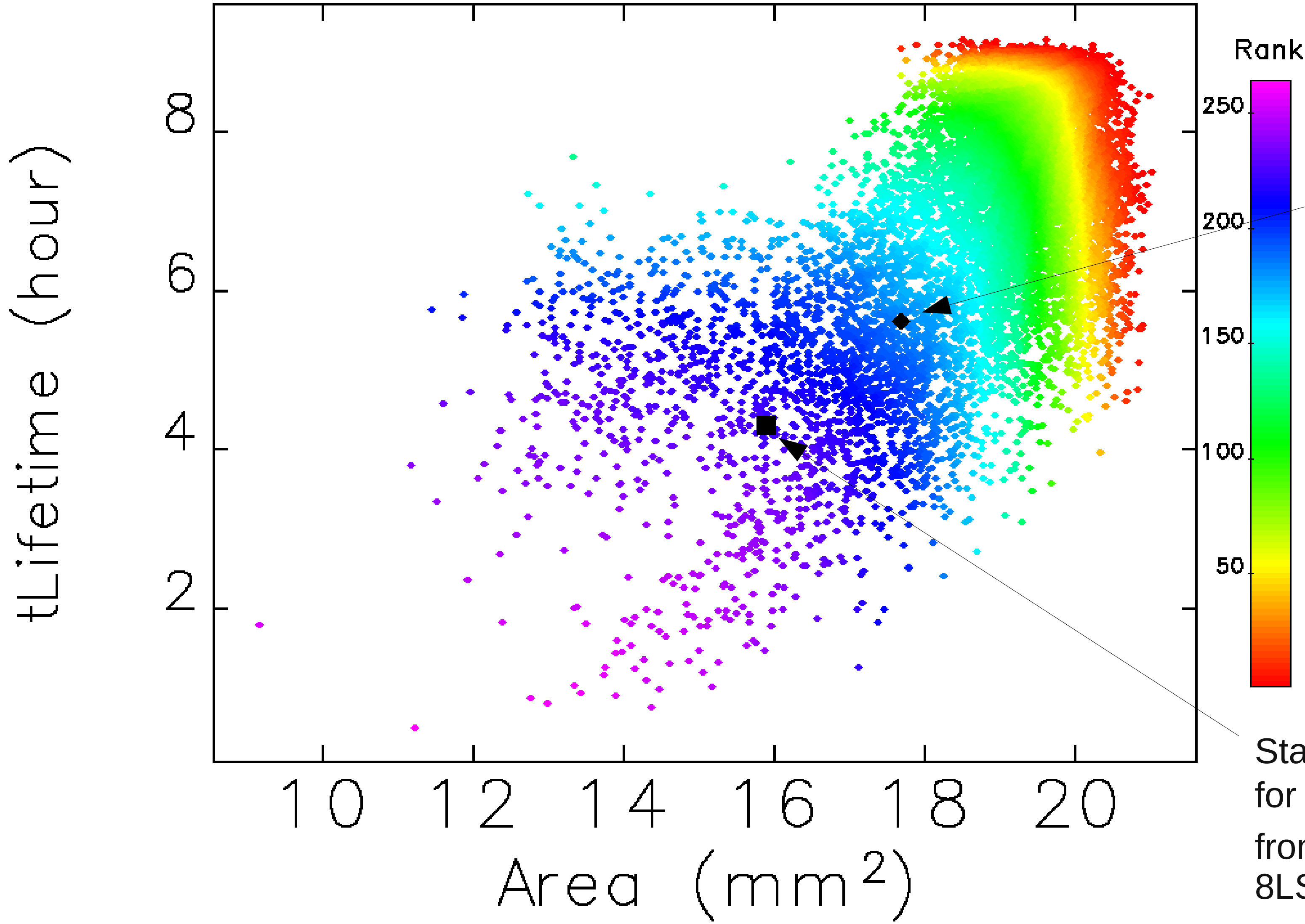


8-Random LSS (8RLSS) Optimization

- We learned previously[1] that breaking the reflection symmetry of the sextupoles about the LSS was essential
- For 8RLSS, we use 26 sextupole knobs
  - SSS-to-LSS sector has 7
  - LSS-to-SSS sector has 7
  - Ordinary Decker distorted sector has 7
    - *Two used for chromaticity*
  - Ordinary non-Decker distorted sector has 7
- The other knobs are the tunes
- For each trial configuration
  - Match three types of sectors with tune and emittance contraints
    - *Ordinary Decker-distorted and non-Decker-distorted sectors*
    - *Short-to-long transition sectors*
  - Correct chromaticity
  - Track to obtain DA and LMA

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

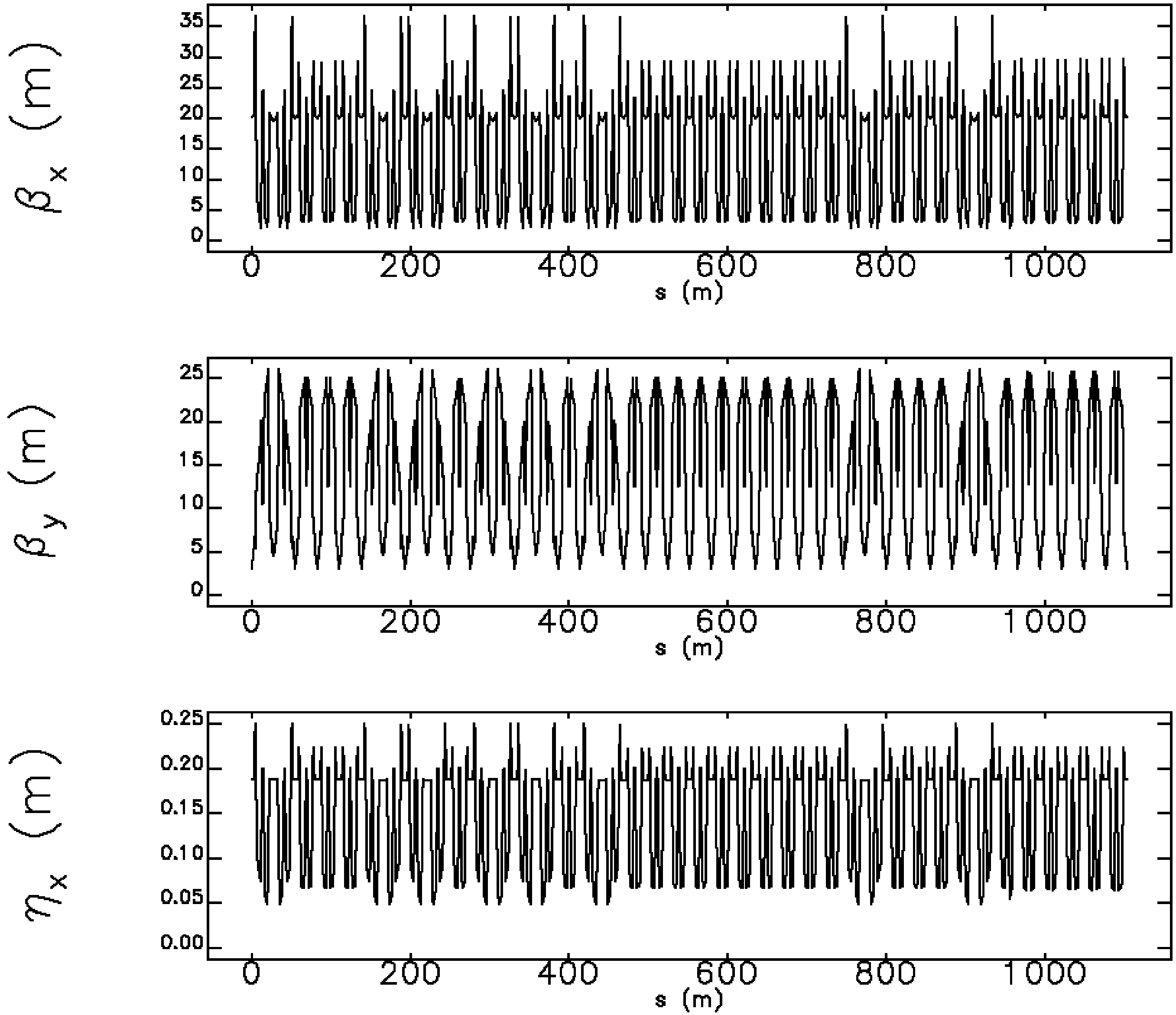
Optimization of 8RLSS for $\xi_x = \xi_y = 7$



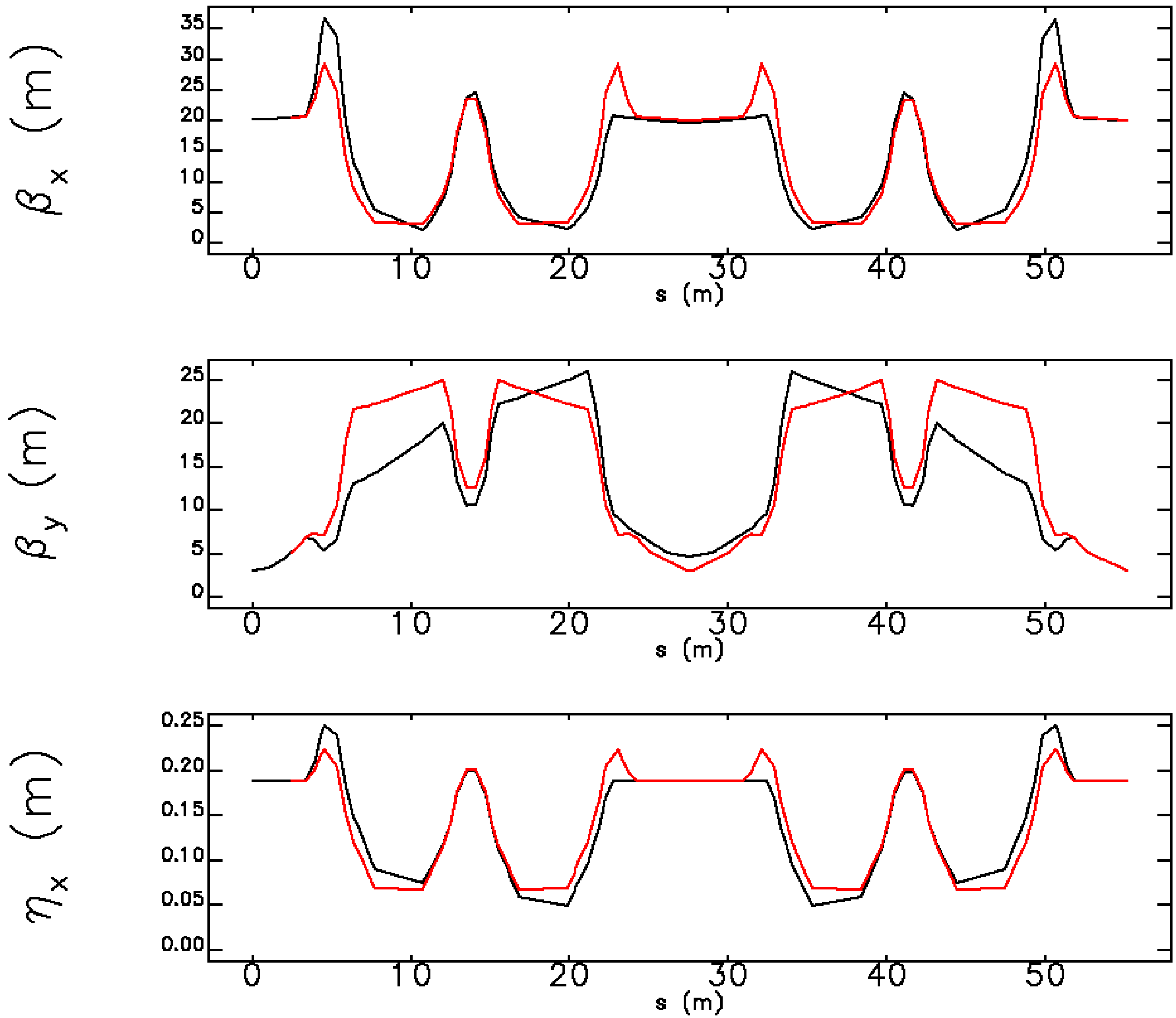
Started here from $\xi_x = \xi_y = 5$ optimization result.

Starting point for $\xi_x = \xi_y = 5$ from symmetric 8LSS sextupoles.

Optimized Linear Optics

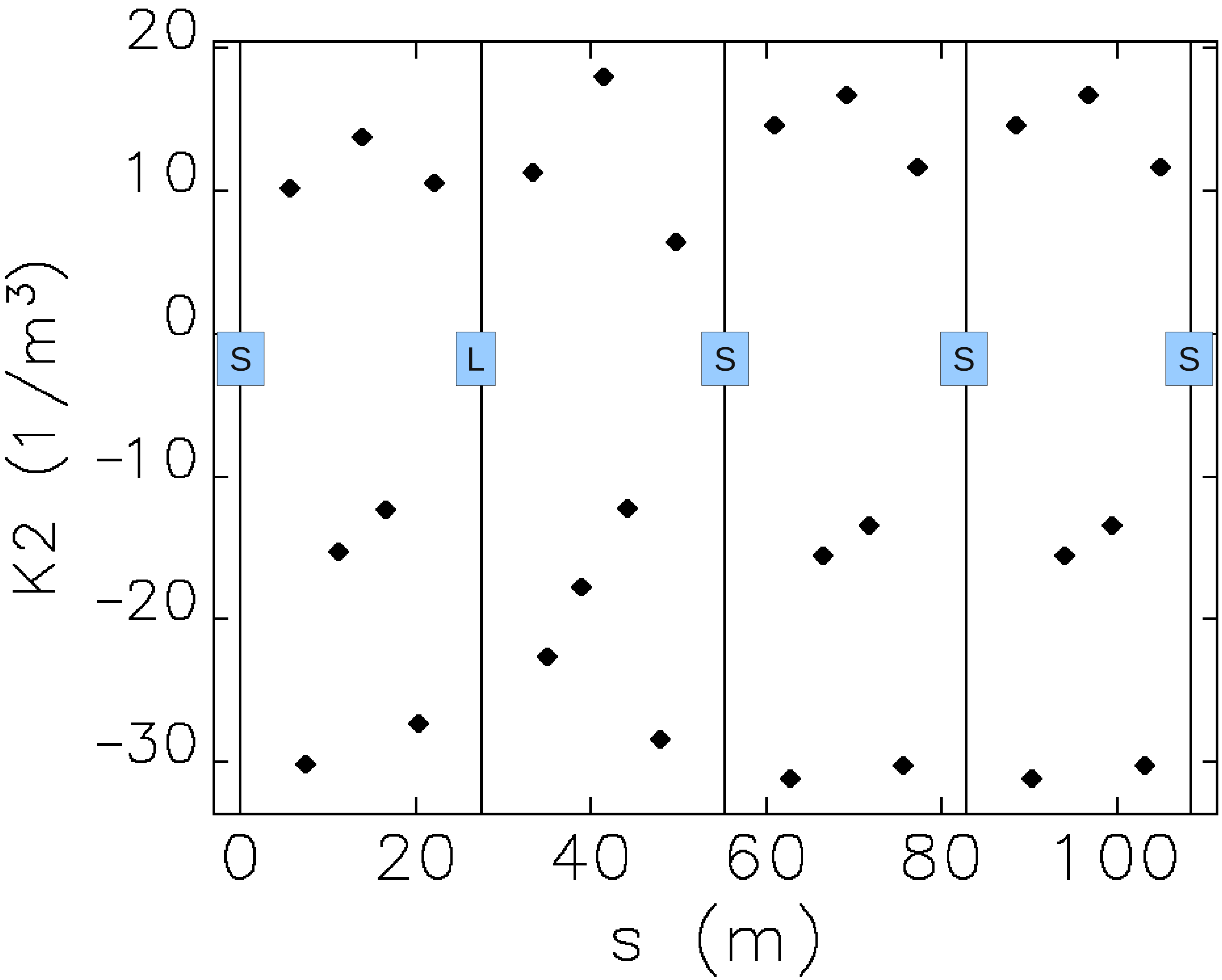


Comparison of Insertion and Normal Optics



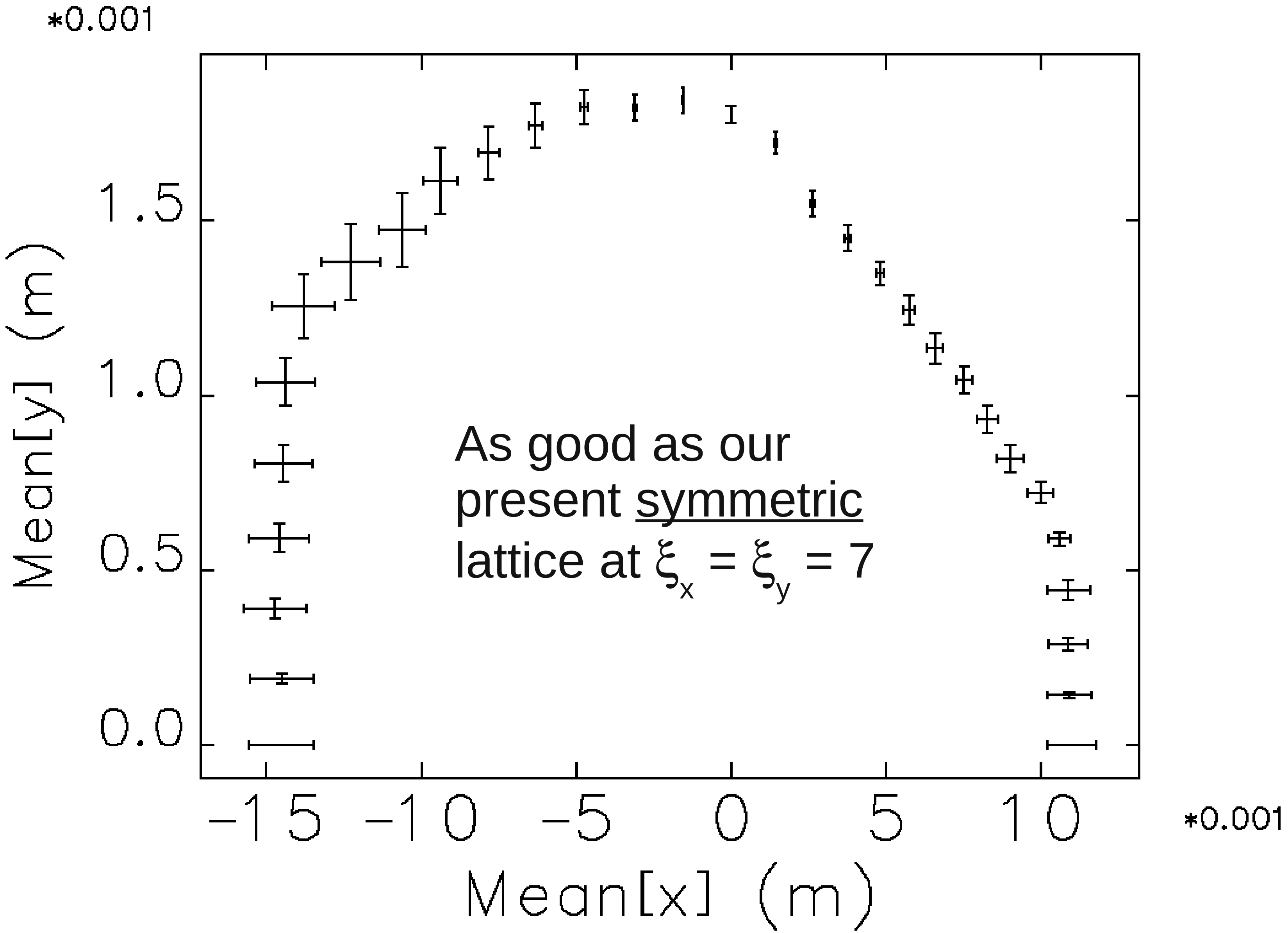
In spite of the asymmetry, we can restore DA/LMA...

8RLSS Sextupole Pattern



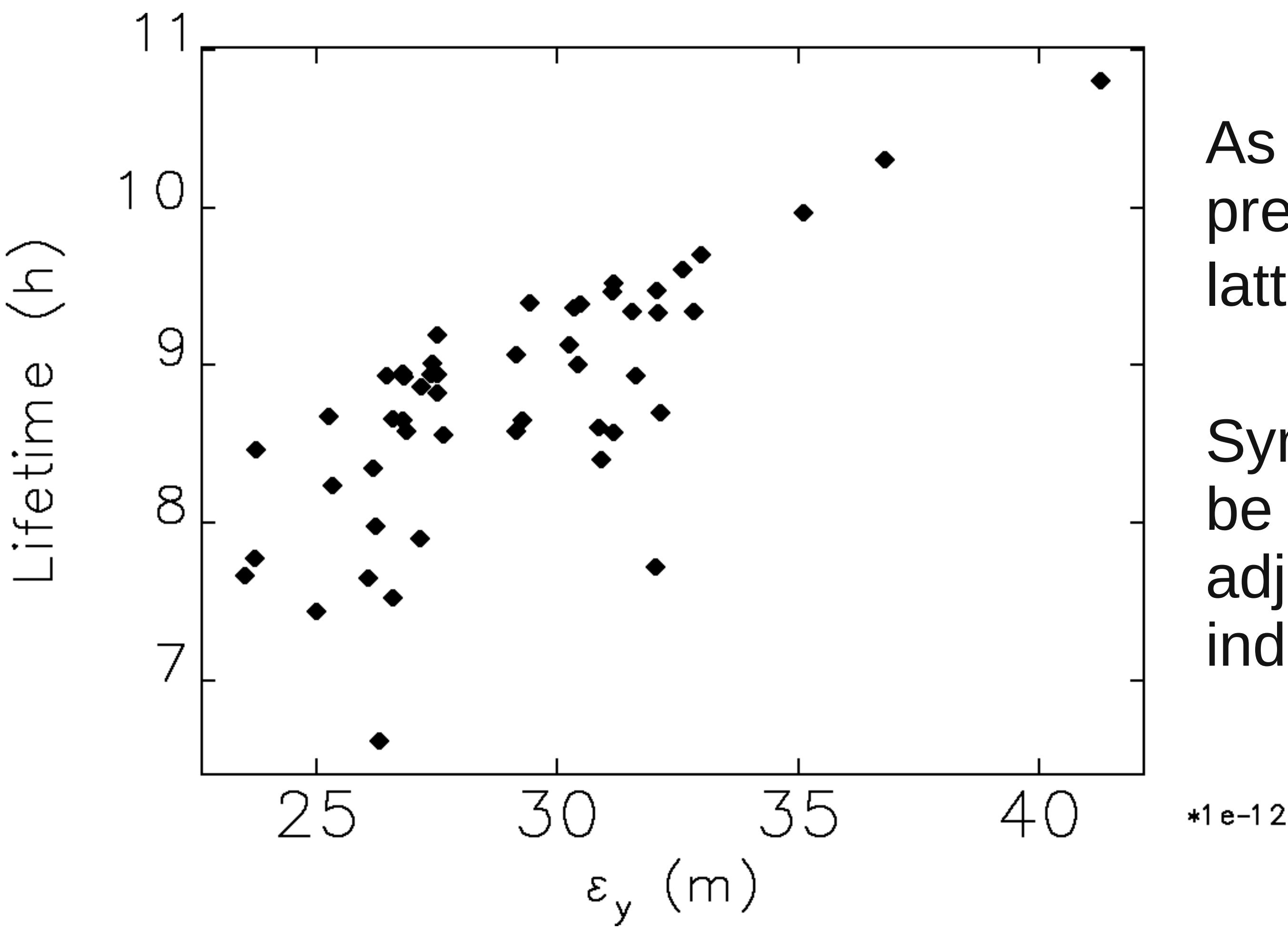
If linear optics is unsymmetric, sextupoles should be also.

8RLSS Dynamic Aperture (50 Ensembles)



As good as our present symmetric lattice at $\xi_x = \xi_y = 7$

8RLSS Lifetime and Vertical Emittance (50 Ensembles)

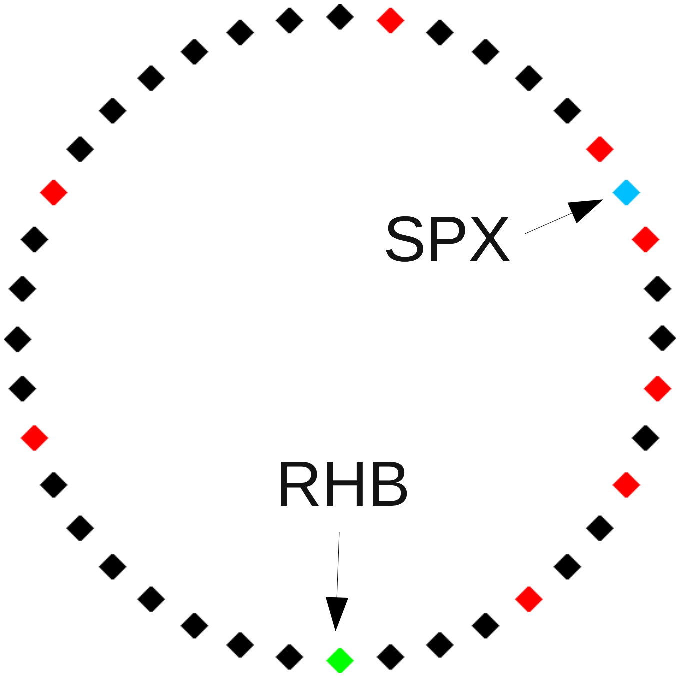


As good as our present <u>symmetric</u> lattice at $\xi_x = \xi_y = 7$

Symmetry seems to be optional if we can adjust sextupoles independently.

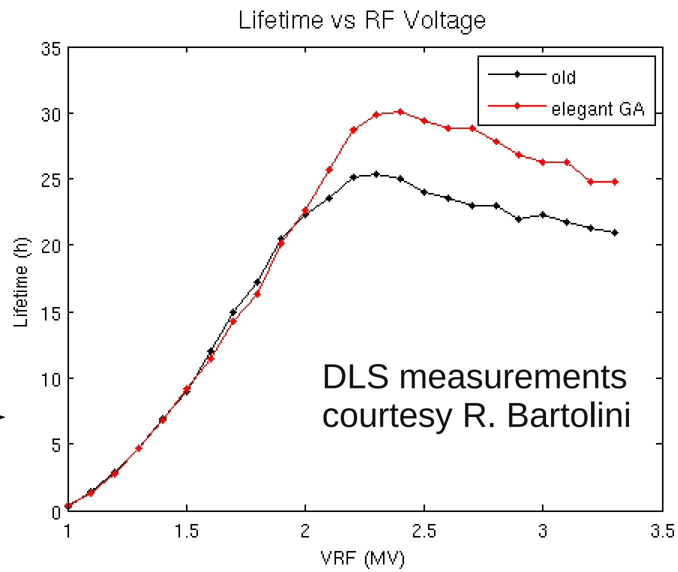
8RLSS+SPX+RHB

- An even more challenging lattice is 8RLSS plus
  - Short Pulse X-ray (SPX) insertion between two LSS sectors
  - Reduced Horizontal Beamsize (RHB) between two ordinary sectors
- This is a challenge just for linear optics
- Mockup 8MLSS+SPX+RHB
  - Excellent up to $\xi_x = \xi_y = 7$ (highest attempted)
  - Helps to have additional independent sextupoles in sectors before and after SPX
- Literal 8RLSS+SPX is harder
  - Seems to result from differences in SPX sector sextupoles
  - So far have good result without RHB for $\xi_x = \xi_y = 7$



Experiments and Operational Experience

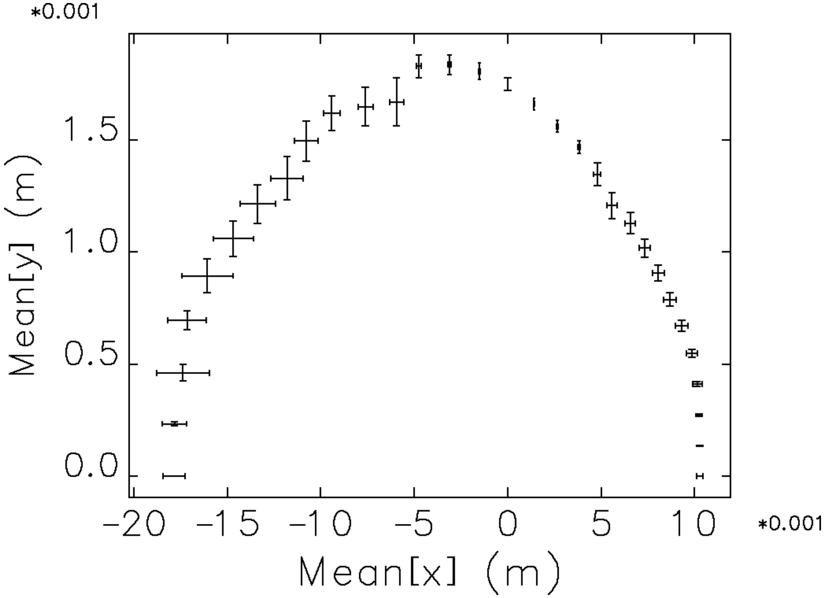
- 8LSS symmetric mockup lattice[1]
  - Lifetime 25% better than APS operational lattice, as predicted
  - Same injection efficiency (90~100%)
- Optimized the APS operations lattices[1]
  - 24-bunch configuration ($\xi_x = \xi_y = 6$)
    - *Lifetime improved by 25%*
  - Hybrid mode ($\xi_x = \xi_y = 11$)
    - *Lifetime improved by 10%*
  - No reduction in injection efficiency
- In all cases, tunes had to be changed from optimizer-recommended values
  - Reason isn't understood
- Also performed an optimization of DLS
  - Lifetime improved by 20%

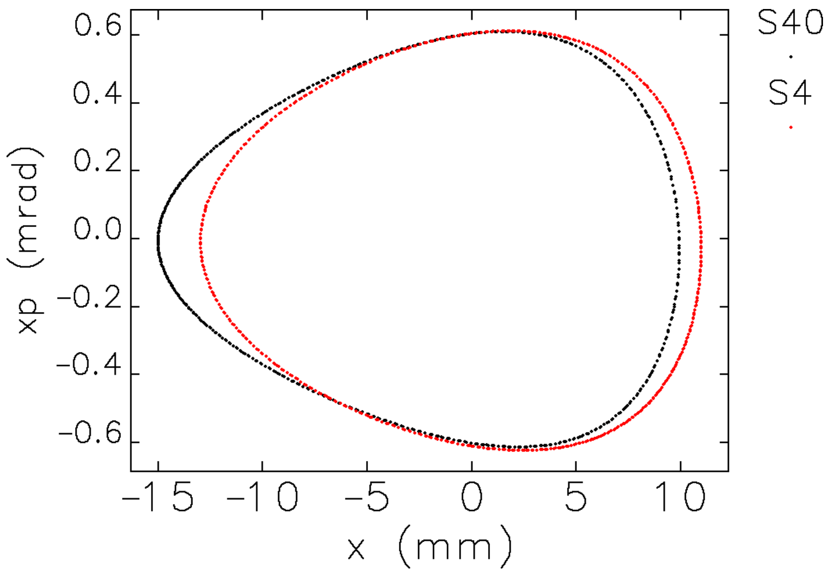


[1]M. Borland *et al*., Proc. PAC09, TH6PFP062.

New $\xi_x = \xi_y = 7$ Configuration for Operations (Sym, No LSS)

- Ring acceptance limit: 15mm (H) by 2.5 mm (V) chamber at sector 4 ID
  – In some 8RLSS simulations, DA at sector 40 beyond acceptance!
    - *Results from distortion of the phase space through 4 ID*
  – Adjusting 28 sextupoles before and after 4 ID allows making deliberate use of this phenomenon
  – DA increased from ~14mm to ~18mm at injection point
  – Lifetime is same as before
  – Tests of this and a new $\xi_x = \xi_y = 11$ configuration planned soon





Plans for Further Work

- More benchmarking
  - We are planning to use a two-kicker method to make a more direct measurement of dynamic aperture
  - We have a series of operations-related and upgrade mockup lattices in-development
- Understand tune discrepancies
  - May be due to large orbits in sextupoles, which drives a skew sextupole resonance[1]
  - If so, another motivation to end APS practice of performing large steering corrections for beamlines
- Presently keep the same sextupole strengths in all sectors with identical linear optics
  - This isn't necessarily best: they have different neighboring optics
- We have sextupoles inside our kicker bump
  - Should be optimized separately for amplitude-dependent bump closure

[1]V. Sajaev, private communication.

Conclusions

- Light source ring designers must simultaneously tune for
  - Large DA to get good injection efficiency
  - Large LMA to get good Touschek lifetime
  - Modern rings typically have ~10 independent sextupoles per cell
- A successful tracking-based optimization method has been developed
  - Well suited to adjusting large number of sextupoles
  - Directly optimizes the quantities we care about
  - Well suited to cases with large linear chromaticity
- Experimental tests validate the method
  - Significant improvements to APS operations
  - Improved DLS lifetime by 20%
  - Symmetric mockup of 8LSS lattice
- Recent results awaiting experimental confirmation
  - Tuning of non-symmetric lattices
  - Distort phase space to enlarge the effective physical acceptance

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- APS computing clusters:

  R. Soliday

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  Argonne Leadership Computing Facility