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$^{1,2}$

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$^1$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

![Diagram showing DA Computation](attachment:diagram.png)
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 \( \Delta A \) is a weighting factor

  - For APS, typically \( A_d = 30 \text{ mm}^2 \)
    (-13mm < x < 7mm and |y|<1.5mm)
  - Typical value for \( \Delta A \) 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 $\delta_{min}$ is the minimum of $|\delta_{lim}|$ over all elements, $\delta_{des}$ is the desired value, and $\Delta\delta$ is a weighting factor.
  - For APS, $\delta_{des} = 2.35\%$ (rf bucket half-height)
  - $\Delta\delta$ is typically 0.01%

- Approach for multi-objective mode
  - Compute the Touschek lifetime $\tau$ using `touschekLifetime`
    - *Reads elegant's LMA and Twiss parameter output*
  - Use $-\tau$ as the penalty function
  - Has yielded better results for APS upgrade

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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 (3.1 nm 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

8LSS

8RandomLSS

4x2LSS
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.
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M. Borland, 2/10

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

- Started here from $\xi_x = \xi_y = 5$
- Starting point for $\xi_x = \xi_y = 5$

from symmetric 8LSS sextupoles.
Optimized Linear Optics

\[ \beta_x (m) \]

\[ \beta_y (m) \]

\[ \eta_x (m) \]
In spite of the asymmetry, we can restore DA/LMA...
If linear optics is unsymmetric, sextupoles should be also.
8RLSS Dynamic Aperture (50 Ensembles)

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