Argonne NATIONAL LABORATORY

Symmetry in storage rings - a wider look

Vadim Sajaev

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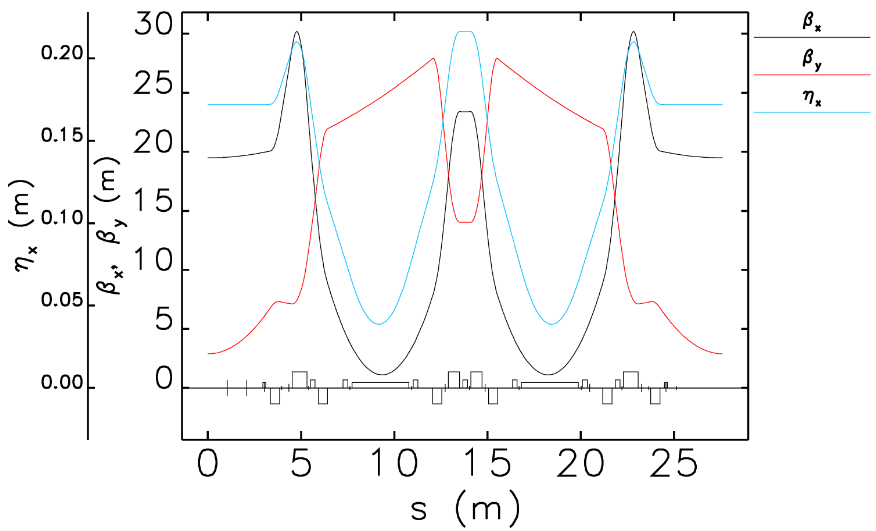
Layout

- General discussion on benefits of symmetry
- Application to 8RLSS lattice
- Application to sextupole failure correction
- Example when breaking symmetry gives better results

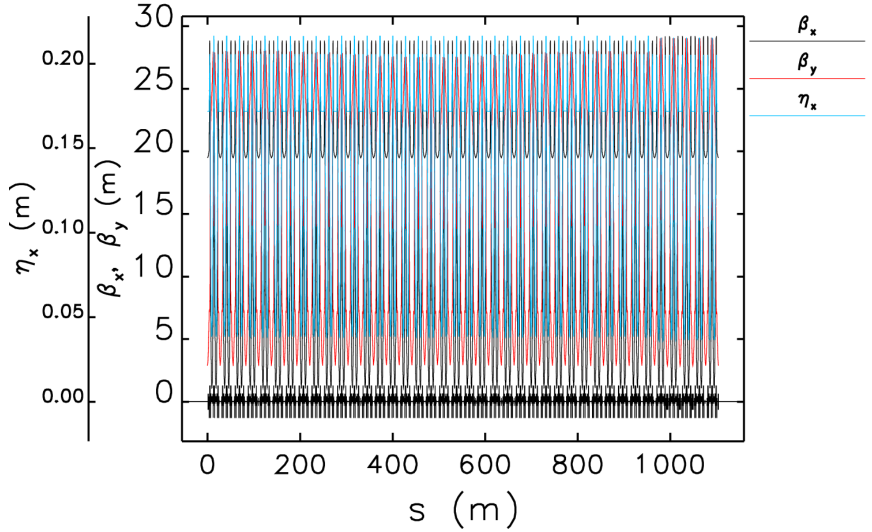
What is symmetry in storage rings?

- Symmetric storage rings consist of many repeating cells: APS consists of 40 identical cells

APS: one sector lattice



APS: full lattice (40 sectors)



- In addition, cells themselves have reflective symmetry

Why are repeating cells good?

- In ideal machine, particle traveling through the accelerator lattice sees repeating cells, it has no way of knowing that 40 cells make up storage ring
- Therefore, the only betatron tune that exists for that particle is betatron tune per cell ν_c
  - For example, for APS ν_{xc}=0.905 and ν_{yc}=0.482
  - All resonances that can be driven by the lattice magnets exist:
    - $\nu_{xc}=1$, $3\nu_{xc}=2$, or $\nu_{xc}+2\nu_{yc}=2$
- Physicist in MCR still measures betatron tune per full turn, or ν_x=36.20 and ν_y=19.27
  - One might think that dangerous resonances are nearby like
    - $\nu_x=36$, $3\nu_x=36.33$, or $\nu_y=19$
  - But when those resonances recalculated to one cell, they become:
    - $\nu_{xc}=0.9$, $3\nu_{xc}=0.908$, or $\nu_{yc}=0.475$
  - They are not resonances at all!

Why are repeating cells good?

- Only those resonances are excited, that are resonances for one cell
  - $\nu_{xc}=1$ => $\nu_x=40$
  - $3\nu_{xc}=2$ => $3\nu_x=80$
  - $\nu_{xc}+2\nu_{yc}=2$ => $\nu_x+2\nu_y=80$

- Conclusion: the only allowed resonances are
  - $k\times\nu_{xc}+m\times\nu_{yc}=N\times n$, where N is the number of repeating cells

Hamiltonian of nonlinear motion

- Hamiltonian of the nonlinear motion can be expanded into Fourier harmonics of several types that look like this:

$$A_{1m} = \int_0^{2\pi} \beta_x^{3/2} S \cos(\psi_x - (\nu - m)\theta)\, d\theta$$

- It is the integration of repeating terms that leads to their cancellation

- Non only beta functions need to repeat, but sextupoles too
- Having reflective symmetry inside cells helps too
  - When performing resonance harmonic expansion, only cosine terms remain non-zero

Real machine

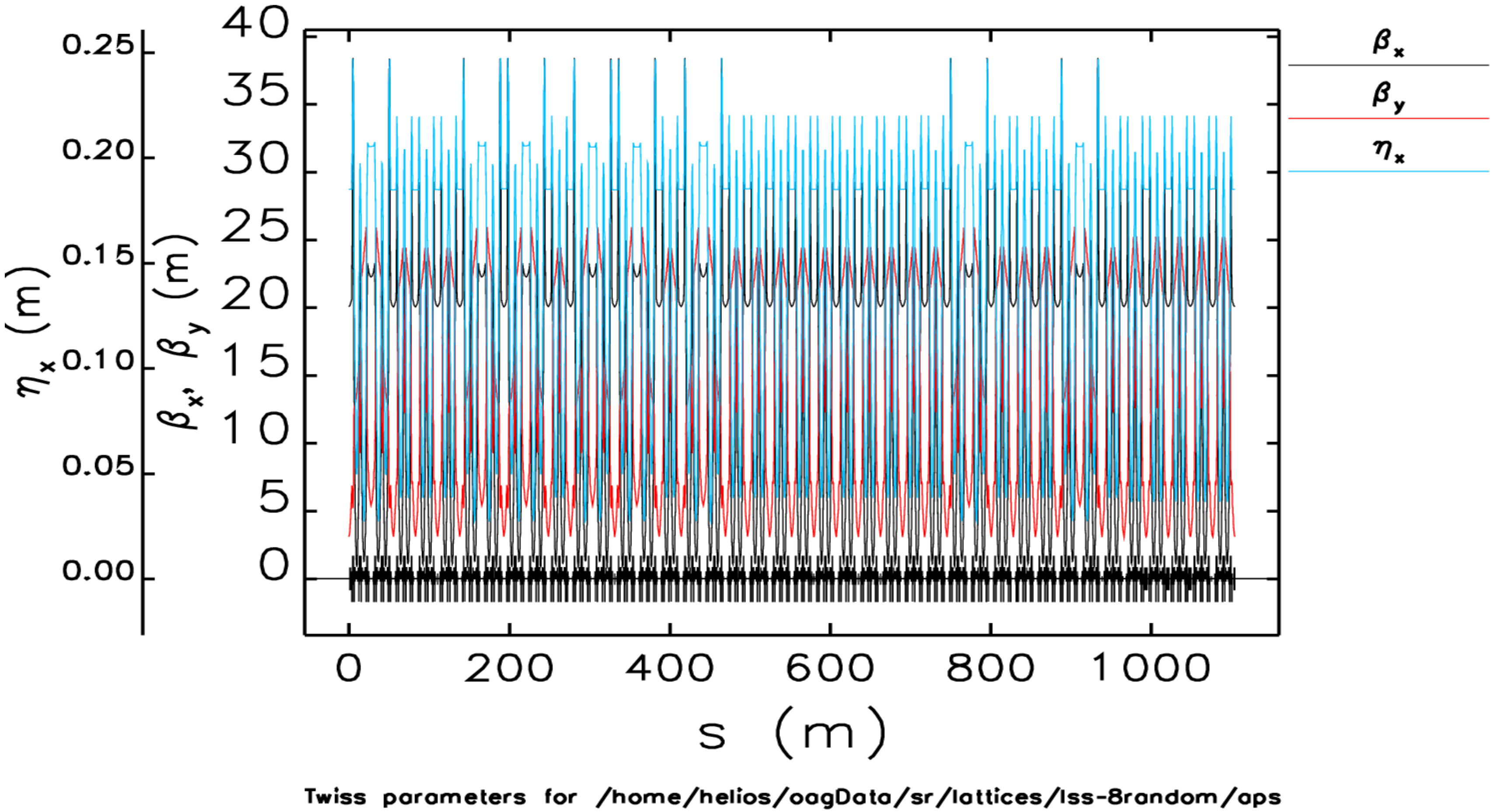
- Real machines have errors that do not repeat, therefore real machines have all resonances
- But those resonances are defined not by strong lattice magnets but by lattice magnet errors
  - Errors are usually of the order of 1% of the magnet strength
  - Can be corrected

Lattice optimization for APS-U[1]

- Previous version of APS-U lattice assumed 8 Long Straight Section insertions (LSS)
- Each LSS insertion means changes to beta functions in 2 cells – or symmetry breaking
- LSS were placed in “convenient” locations that we simply called random – 8RLSS
- At first, such symmetry breaking was considered unworkable
- We decided to adjust sextupoles around LSS insertions in attempt to recover symmetry
- We used multi-objective genetic optimization
  - Direct optimization based on tracking results
  - Objectives: dynamic acceptance and lifetime
    - Dynamic acceptance is dynamic aperture with physical apertures taken into account
    - Lifetime is computed based on Local Momentum Acceptance calculation[2]

[1]M. Borland et al., LS-319
[2]A. Xiao, M. Borland, PAC03

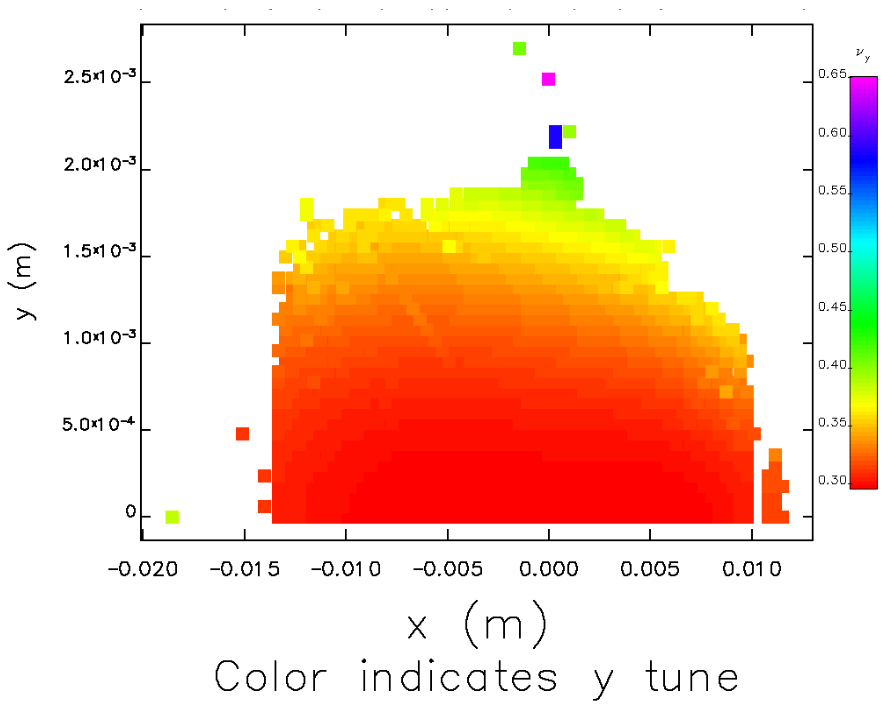
8RLSS lattice functions



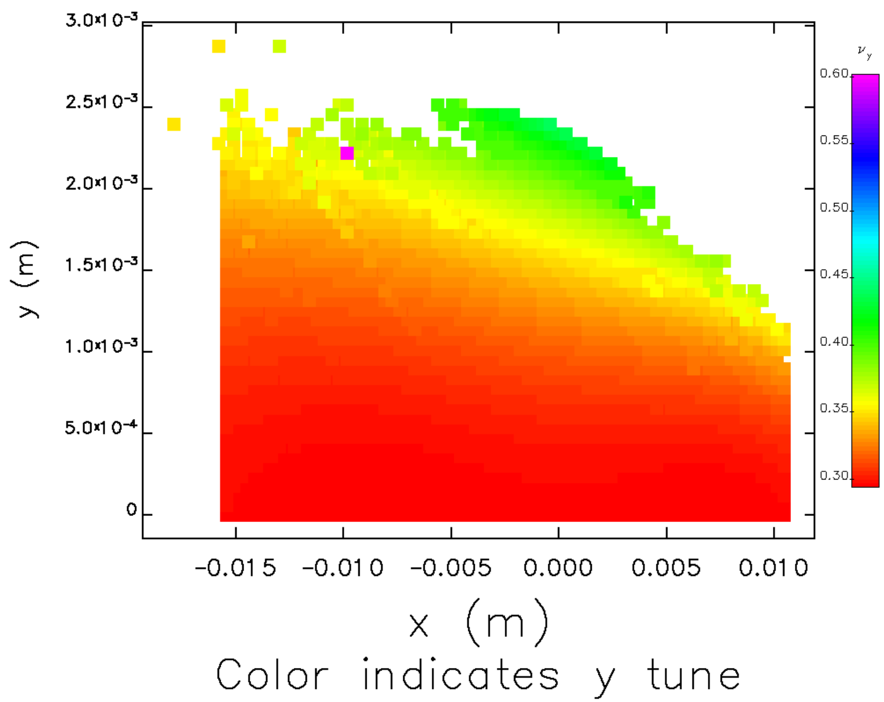
APS-U lattice optimization results

- We were able to develop APS-U lattice with 8 LSS insertions that has lifetime and injection efficiency as good as the present APS lattice

8RLSS with symmetric sextupoles

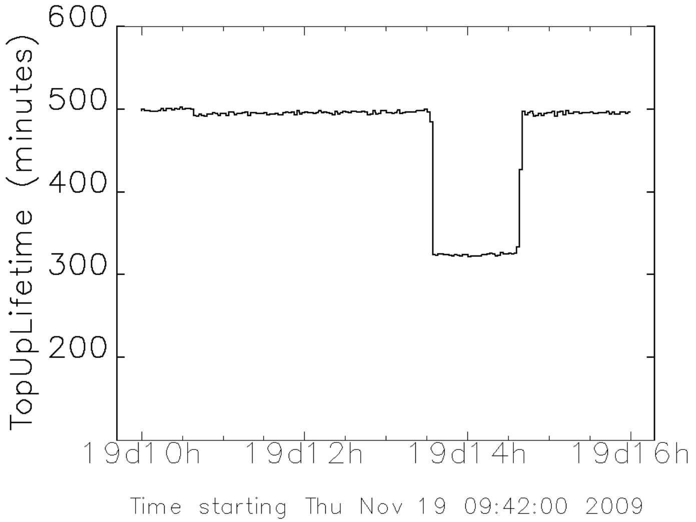


8RLSS with optimized sextupoles



Sextupole failure

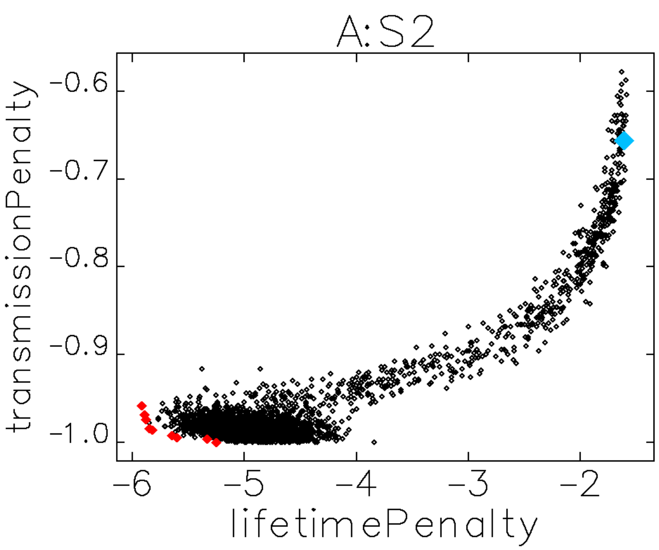
- Recently, we had an incident when a sextupole power supply tripped during user top-up operation
  - Lifetime and injection efficiency dropped

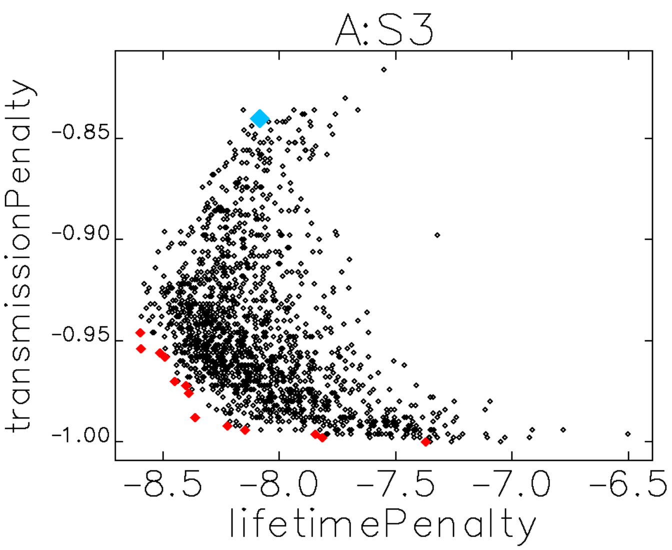


- Power supply was later reset
- It can happen again, and if the power supply would no reset, we would need to operate with lower lifetime until next intervention

Sextupole failure correction

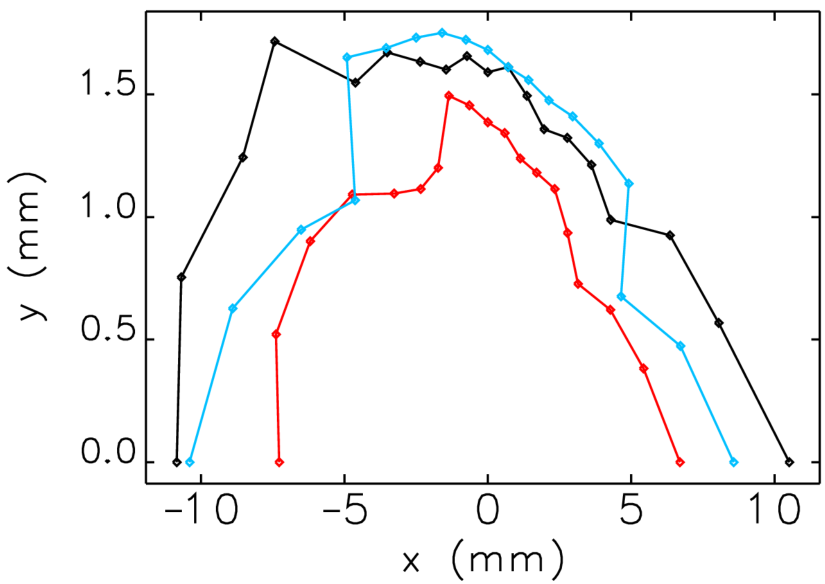
- We used sophisticated optimization to find such settings for nearby sextupoles that partially recover symmetry and lifetime and injection efficiency
- This optimization was developed initially for APS-U lattice development
  - Multi-objective optimization that uses injection efficiency and lifetime



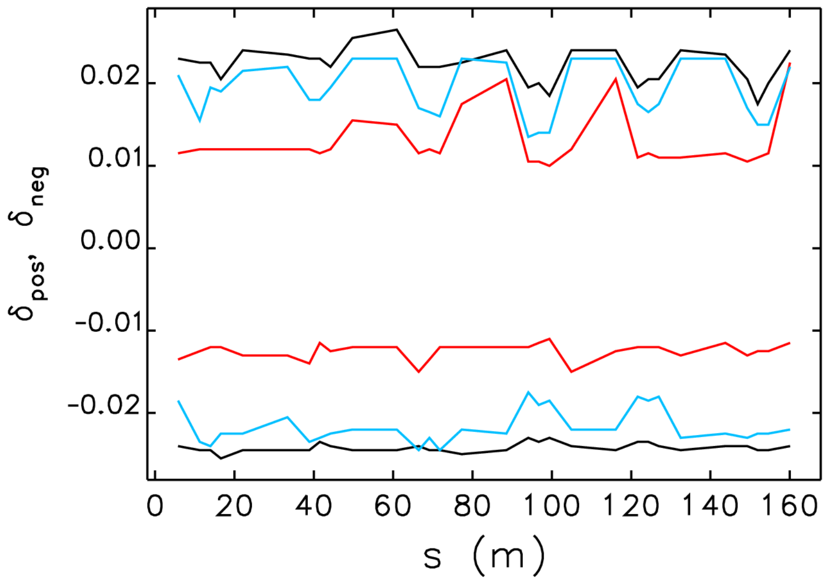


Optimization results

DA for A:S4



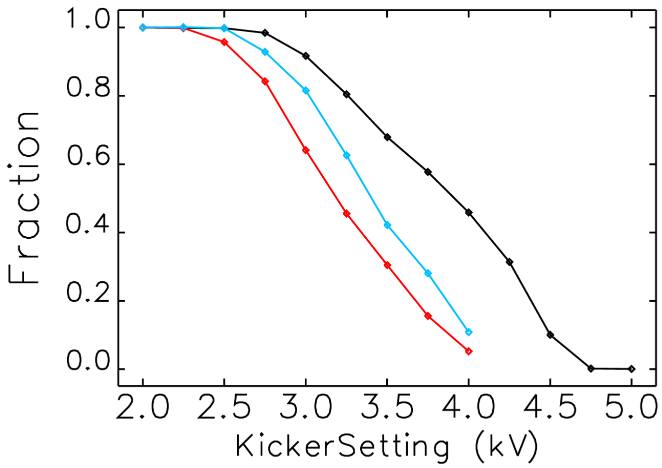
LMA for A:S2



Black – initial lattice
Red – after failure
Blue after correction

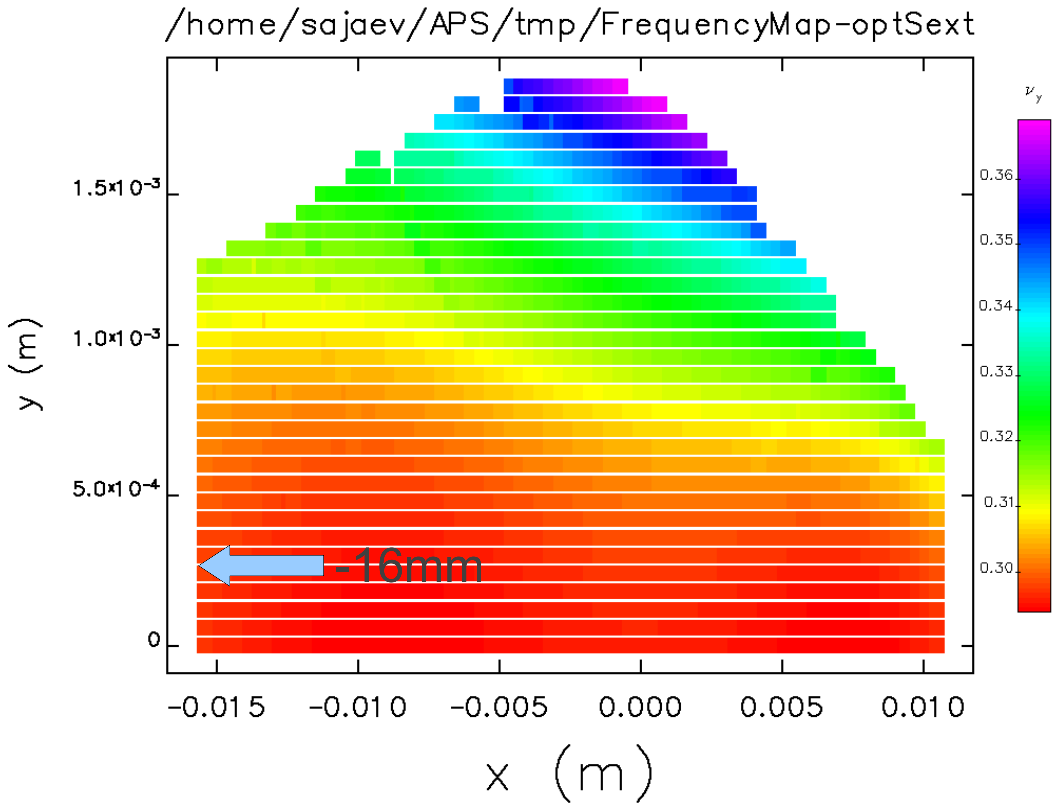
Experimental tests of sextupole failure correction

Sextupole	State	Lifetime (min)	Injection (%)
A:S4	Initial lattice	440	85
	After failure	230	60
	After correction	330	75
A:S2	Initial lattice	550	80
	After failure	430	70
	After correction	550	80
B:S2	Initial lattice	540	80
	After failure	390	75
	After correction	440	75



Interesting finding during 8RLSS optimization[1]

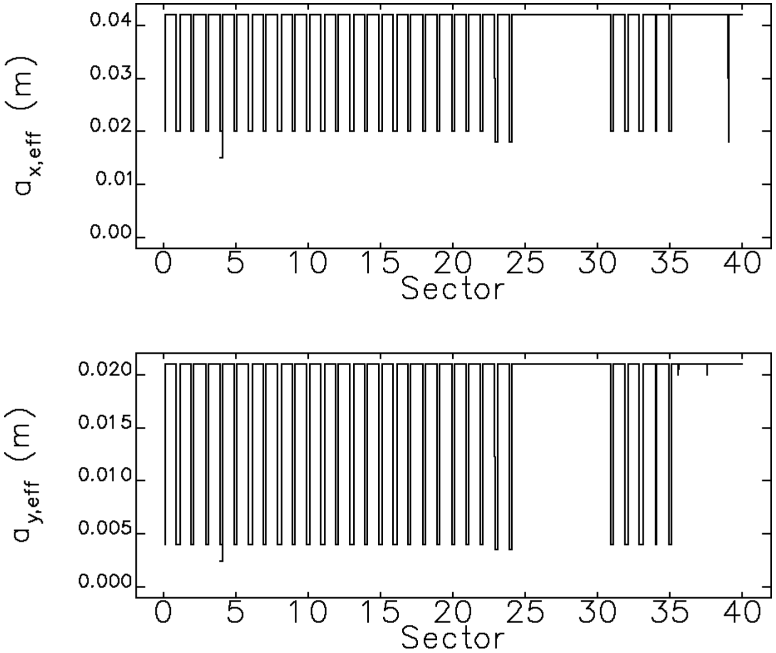
- We found that the dynamic acceptance of the lattice is larger than the physical aperture

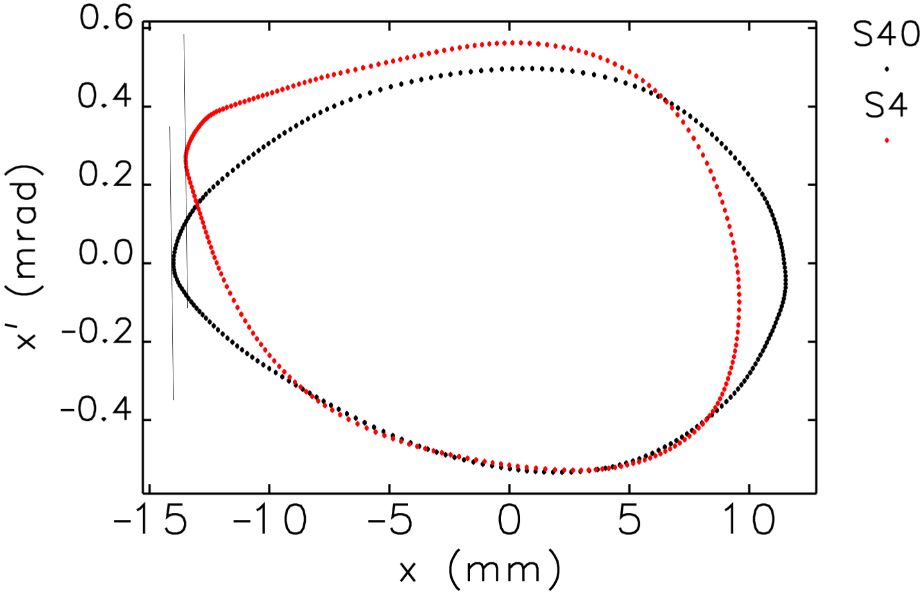


[1]M. Borland

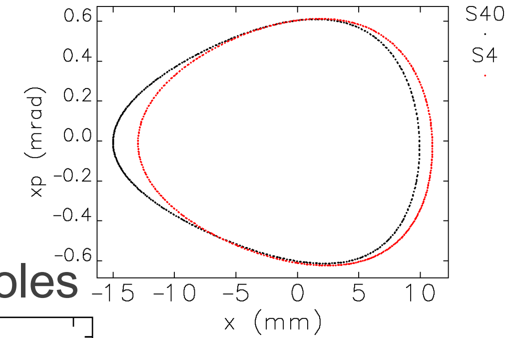
Explanation - physical aperture is not symmetric

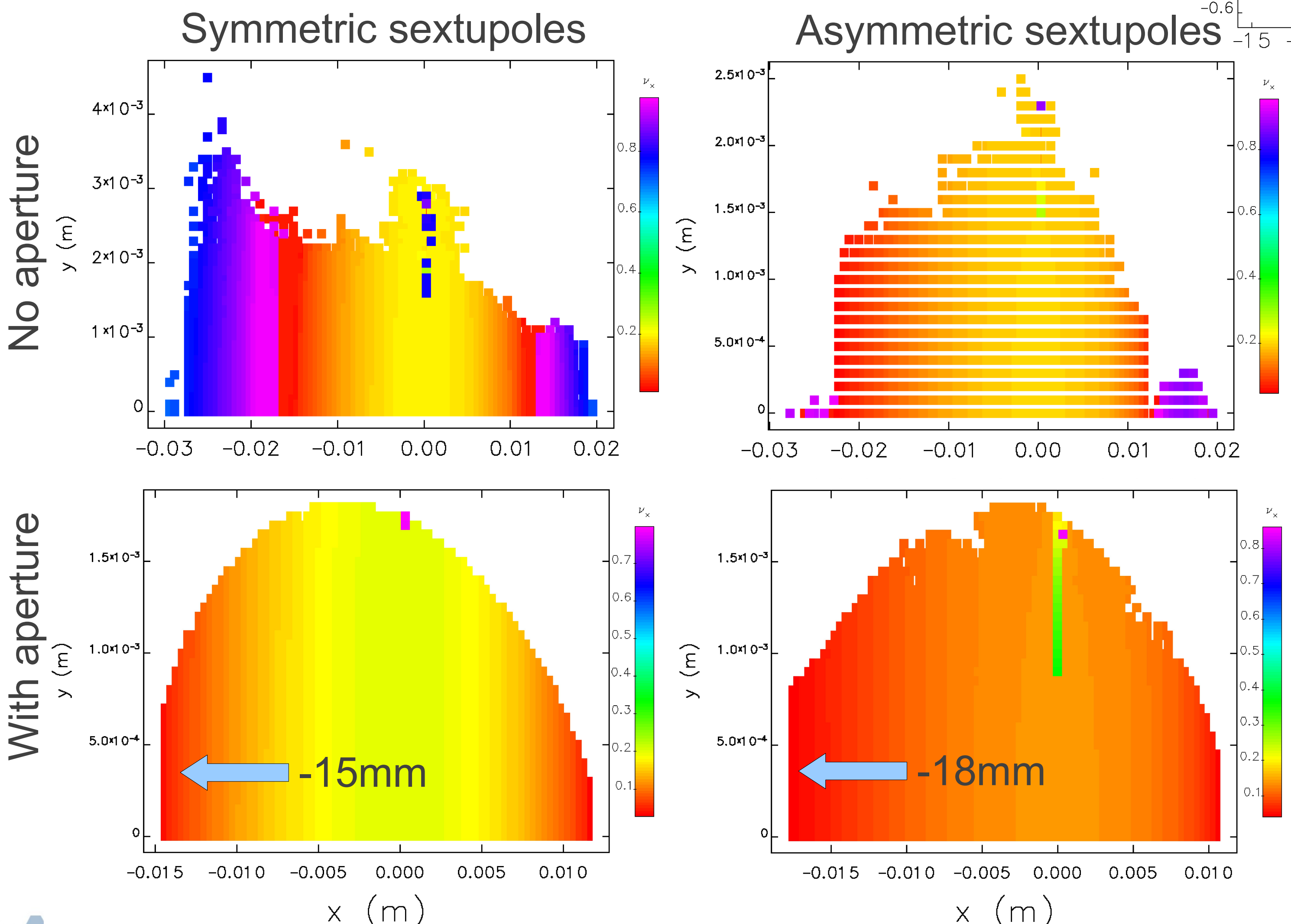
- APS physical aperture does not match lattice symmetry
  - All ID vacuum chambers have -20mm horizontal and ±4mm vertical
  - ID4 has -15mm horizontal and ±2.5mm vertical
- Optimizer changed sextupoles such that phase space at ID4 changed





Application to present APS lattice





Conclusions

- Symmetry in storage rings plays an important role in improving nonlinear beam dynamics

- Symmetry of beta functions together with sextupoles is important, which opens way to create lattices with non-symmetric beta functions where sextupoles are used to recover symmetry
  - Extensive computing power is required

- Imposing non-symmetrical physical aperture limitations can lead to non-symmetrical solutions that