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Symmetric Long Straight Section Lattices for 2, 4, and 8 Sectors

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1 Introduction

Long straight sections [1] (LSS) are anticipated to be one of the significant changes to the accelerator as part of the APS Renewal. Previously [2], we developed a lattice with eight LSS that, while workable, would have presented some operational challenges. In the present note, we show improved results for 8LSS, along with new solutions for 4LSS and 2LSS. As before, these lattices are developed by removing the Q2 quadrupoles and moving the Q1 back into its place, permitting a 7.7-m-long insertion device (as judged by the increase in face-to-face distance for the innermost powered quadrupoles). Further increases in length (perhaps 10%) might be possible by removing corrector magnets, but at present we have not considered this in detail.

2 Optimization Methods

The linear optics are very similar to what was used previously. We made some changes to make the lattice functions more regular and to ensure that the phase advance per sector was as close to constant as possible. The nonlinear optimization was performed using the method described in [2]. In addition to optimizing sextupoles, we also allowed the tune to vary. As before, we targeted chromaticities of 6 in both planes.

In the course of the work, an error was made that lead to a useful discovery: it is possible to obtain significantly better results by removing the constraint that the sextupoles in the LSS sectors have reflection symmetry about the center of the long straight. That is, the 14 sextupoles on either side of the long straight are allowed to vary independently. The lattices still have translational symmetry, with the period equal to the distance between the long straights. This significantly increases the number of variables in the optimization, but for the genetic optimization technique it doesn't really matter.

3 Evaluation of Lattices

To ensure robustness, we evaluated each lattice using 50 random error ensembles. Quadrupole and sextupole strength errors were Gaussian distributed with an amplitude of 0.02%, while quadrupole and sextupole tilt errors were Gaussian distributed with an amplitude of 0.5 mrad. We know from experience that these values give beta function and horizontal dispersion beating of about 1% rms and vertical emittances of 30 pm or more. These correspond roughly to operational conditions after lattice correction.

In the course of evaluating an early version of the 4LSS lattice, we found that the dynamic aperture for many seeds was very small. We determined that there was a significant negative correlation between the dynamic aperture and the coupling integral [3], which measures the strength of the driving term for linear coupling. In many cases, we found the emittance ratio was unrealistically large. We further determined that removing quadrupole tilt errors resulted in much larger dynamic apertures. In addition, using frequency map analysis we observed that the dynamic aperture was limited by the $2\nu_x - \nu_y$ resonance, which would not be driven in a machine without x-y coupling. Hence, we concluded that we needed to employ coupling correction in the simulations.

The coupling correction was performed in a fashion that emulates the methods used in actual APS operations [4]:

1. The vertical dispersion was corrected using the inverse of the skew strength response matrix. The matrix was inverted using `sddspseudoinverse`, with the largest 9 singular values retained.
2. The beam size at S35BM was minimized using two 17^{th}-harmonic knobs: the cosine-phase of the A skew quads and the sine-phase of the B skew quads.
3. The beam size at S35BM was minimized using two 17^{th}-harmonic knobs: the sine-phase of the A skew quads and the cosine-phase of the B skew quads.
4. Zeroth harmonic was added to the skew quads to obtain a vertical projected emittance at S35BM of 50 pm (corresponding to the measured value as of this writing).

After applying coupling correction, we evaluated the dynamic aperture, momentum aperture, and coupled beam moments again. The momentum aperture and coupled beam moments data were used to compute the lifetime for each ensemble, as follows:

1. Compute the effective Twiss parameters for each plane from the moments. For example, $\eta_x = \sigma_{16}/\sigma_{66}$ and $\beta_x = \sigma^2_{x,\beta}/\epsilon_{x,\beta}$.
2. Compute the average (over all elements) betatron emittance in both planes.
3. Run `touschekLifetime` [5] with these Twiss parameters and emittances, plus the corresponding momentum aperture file, to obtain the lifetime for a 15-nC bunch with 32-ps rms duration (corresponding to 24-bunch mode [6]).

As input to the lifetime predictions, we evaluated the momentum aperture at the exit of the sextupoles in each ensemble. We did this with an rf voltage of 12 MV, giving an rf acceptance of about $\pm 3.5\%$. This means that the momentum aperture is determined not by the rf voltage, but by the transverse dynamics. This may of course give an artificially high lifetime. However, we can reduce the effective rf voltage before computing the Touschek lifetime by imposing a limiting value of the momentum acceptance corresponding to a lower rf voltage. This avoids having to run the momentum aperture computations again for each rf voltage. A voltage of 9.5 MV, the limiting value in operations today, gives an rf acceptance of $\pm 2.6\%$. In practice, we found little difference, because the momentum aperture is rarely above 2.4% anywhere in the lattice. To be conservative, we imposed a limit of $\pm 2.35\%$, corresponding to 9 MV. We also added the Touschek lifetime reciprocally with a gas scattering lifetime of 150 hours [7] to make direct comparisons with measured lifetime easier.

4 8LSS Lattice

Figure 1 shows the lattice functions for the 8LSS lattice, while Table 1 list 5 various values of interest. The effective emittance for the non-LSS straights is 3.36 nm, a 6.7% increase from the symmetric lattice. Figure 2 shows the sextupole strengths. One can clearly see the asymmetric tuning around the LSS.

We evaluated this lattice for 50 random ensembles. For each ensemble, we computed the rms fractional deviation of the lattice functions. The averages over all ensembles are 1.5% for β_x, 0.8% for β_y, and 1.7% for η_x. These are similar to what would be expected after lattice correction [8].

Figure 3 shows the dynamic aperture results, which are quite good. Coupling correction makes a small increase in the dynamic aperture.

Figure 4 shows various quantities plotted against the total lifetime for the case with coupling correction. The mean predicted lifetime is 9.8 hours, with a standard deviation of 0.6 hours. For comparison, the lifetime in top-up mode at 100 mA is presently just over 7 hours, so the predictions here may be optimistic. On the other hand, in experiments [9] with a mock-up 8LSS lattice we obtained a lifetime that was about 1 hour longer than the normal lattice.

Table 1: Parameters of the 8LSS Lattice

Betatron Tunes		
Horizontal	36.135	
Vertical	19.281	
Lattice functions		
Maximum β_x	37.278	m
Maximum β_y	25.739	m
Maximum η_x	0.254	m
Average β_x	13.733	m
Average β_y	14.500	m
Average η_x	0.157	m
Radiation-integral-related quantities at 7 GeV		
Natural emittance	2.638	nm
Energy spread	0.096	%
Effective emittance	3.358	nm
Horizontal damping time	9.626	ms
Vertical damping time	9.631	ms
Longitudinal damping time	4.817	ms
Energy loss per turn	5.353	MeV
Miscellaneous parameters		
Momentum compaction	2.814×10^{-4}	
Damping partition J_x	1.001	
Damping partition J_y	1.000	
Damping partition J_δ	1.999	

5 4LSS Lattice

Figure 5 shows the lattice functions for the 4LSS lattice, while Table 2 lists various values of interest. The effective emittance for the non-LSS straights is 3.27 nm, a 3.8% increase from the symmetric lattice. Figure 6 shows the sextupole strengths. One can clearly see the asymmetric tuning around the LSS.

We evaluated this lattice for 50 random ensembles. For each ensemble, we computed the rms fractional deviation of the lattice functions. The averages over all ensembles are 1.1% for β_x, 0.8% for β_y, and 1.1% for η_x. These are similar to what would be expected after lattice correction [8].

Figure 7 shows the dynamic aperture results, which are quite good. Coupling correction makes a small but worthwhile increase in the dynamic aperture.

Figure 8 shows various quantities plotted against the total lifetime for the case with coupling correction. The mean predicted lifetime is 9.6 hours, with a standard deviation of 0.8 hours. For comparison, the lifetime in top-up mode at 100 mA is presently just over 7 hours, so the predictions here may be optimistic. On the other hand, in experiments [9] with a mock-up 8LSS lattice we obtained a lifetime that was about 1 hour longer than the normal lattice.

6 2LSS Lattice

Figure 9 shows the lattice functions for the 4LSS lattice, while Table 3 list various values of interest. The effective emittance for the non-LSS straights is 3.23 nm, a 2.5% increase from the symmetric lattice. Figure 10 shows the sextupole strengths. One can clearly see the asymmetric tuning around the LSS.

We evaluated this lattice for 50 random ensembles. For each ensemble, we computed the rms fractional deviation of the lattice functions. The averages over all ensembles are 1.4% for β_x, 0.9%

Table 2: Parameters of the 4LSS Lattice

Betatron Tunes		
Horizontal	36.218	
Vertical	19.296	
Lattice functions		
Maximum β_x	36.997	m
Maximum β_y	25.623	m
Maximum η_x	0.259	m
Average β_x	13.783	m
Average β_y	14.688	m
Average η_x	0.158	m
Radiation-integral-related quantities at 7 GeV		
Natural emittance	2.530	nm
Energy spread	0.096	%
Effective emittance	3.271	nm
Horizontal damping time	9.626	ms
Vertical damping time	9.631	ms
Longitudinal damping time	4.817	ms
Energy loss per turn	5.353	MeV
Miscellaneous parameters		
Momentum compaction	2.808×10^{-4}	
Damping partition J_x	1.001	
Damping partition J_y	1.000	
Damping partition J_δ	1.999	

for β_y, and 1.5% for η_x.

Figure 11 shows the dynamic aperture results, which are quite good. Coupling correction makes a small increase in the dynamic aperture.

Figure 12 shows various quantities plotted against the total lifetime for the case with coupling correction. The mean predicted lifetime is 10.0 hours, with a standard deviation of 0.6 hours. For comparison, the lifetime in top-up mode at 100 mA is presently just over 7 hours, so the predictions here may be optimistic. On the other hand, in experiments [9] with a mock-up 8LSS lattice we obtained a lifetime that was about 1 hour longer than the normal lattice.

7 Further Work

In this section we list some additional investigations that are needed, or that may be of interest:

- In the present work, we left the H1 in its present location, though clearly it wouldn't stay there in an actual LSS configuration. This will make a small difference in the matching when it is moved.
- We should repeat our tests [2] of the impact of asymmetric distribution of LSS, to confirm that it is not workable.
- We need to test gradual implementation strategies. The most likely one is a combination of real LSS with mocked-up LSS in opposing positions, to provide a nearly symmetric configuration.

Table 3: Parameters of the 2LSS Lattice

Betatron Tunes		
Horizontal	36.152	
Vertical	19.326	
Lattice functions		
Maximum β_x	37.002	m
Maximum β_y	25.854	m
Maximum η_x	0.255	m
Average β_x	13.627	m
Average β_y	15.009	m
Average η_x	0.156	m
Radiation-integral-related quantities at 7 GeV		
Natural emittance	2.510	nm
Energy spread	0.096	%
Effective emittance	3.231	nm
Horizontal damping time	9.626	ms
Vertical damping time	9.631	ms
Longitudinal damping time	4.817	ms
Energy loss per turn	5.353	MeV
Miscellaneous parameters		
Momentum compaction	2.823×10^{-4}	
Damping partition J_x	1.001	
Damping partition J_y	1.000	
Damping partition J_δ	1.999	

8 Conclusion

Lattices for 2, 4, and 8 long straight sections were developed by removing the Q1 magnets around straight sections and decreasing the length of the Q2 magnets from 0.8 m to 0.5 m. This allowed us to increase the maximum insertion device length from 4.8 m to 7.7 m. We performed optimization of tunes and sextupole strengths for the lattices, resulting in very good dynamic aperture and lifetime predictions. Lifetime predictions included a realistic correction of vertical dispersion and x-y coupling.

9 Acknowledgement

The author thanks L. Emery for discussion of the coupling correction methods used in APS operations.

10 Revision Notes

- Revision 1: Revised 8LSS lifetime predictions and graphs. Previously, the 2.35% momentum aperture limit was not in place for 8LSS. Added values for mean and standard deviation of predicted lifetime.
- Revision 2: Revised lifetime estimates to use 150 hours instead of 60 hours for the gas scattering lifetime. Thanks to Louis Emery for pointing out this error.

References

[1] Study of Long Straight Section for IXS-CAT.

[2] M. Borland. Private communication, 2009.

[3] H. Wiedemann. Equilibrium beam emittances. In Alexander Wu Chao and Maury Tigner, editors, *Handbook of Accelerator Physics and Engineering*, page 211. World Scientific, 1999. Section 3.1.4.4.

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[6] B. Yang M. Borland, V. Sajaev. Storage ring studies log, 2008/07/22/3, 2008.

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[9] A. Xiao M. Borland, V. Sajaev. Storage ring studies log, 2009/02/10/3, 2009.

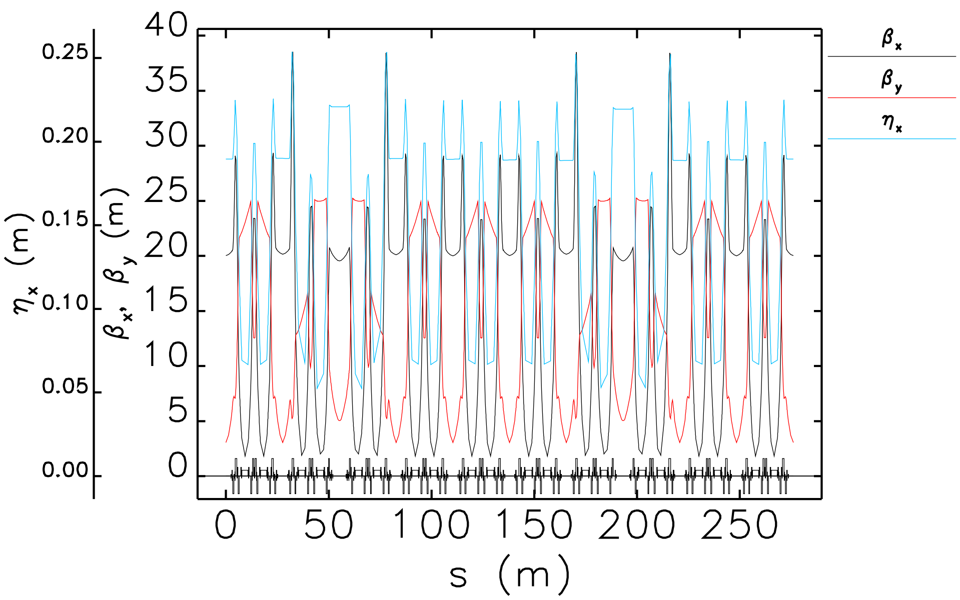

Figure 1: Optics for 8LSS lattice, showing 10 sectors including two LSS.

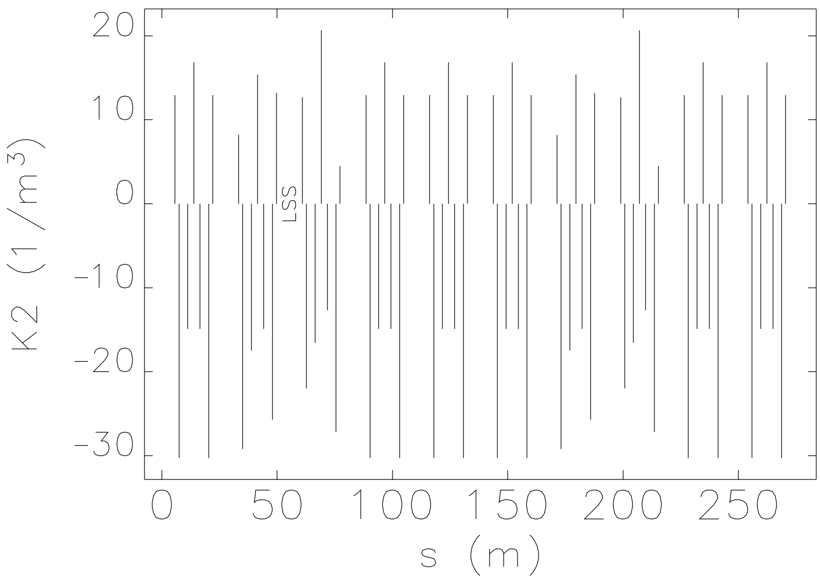

Figure 2: Sextupole strengths for the 8LSS lattice.

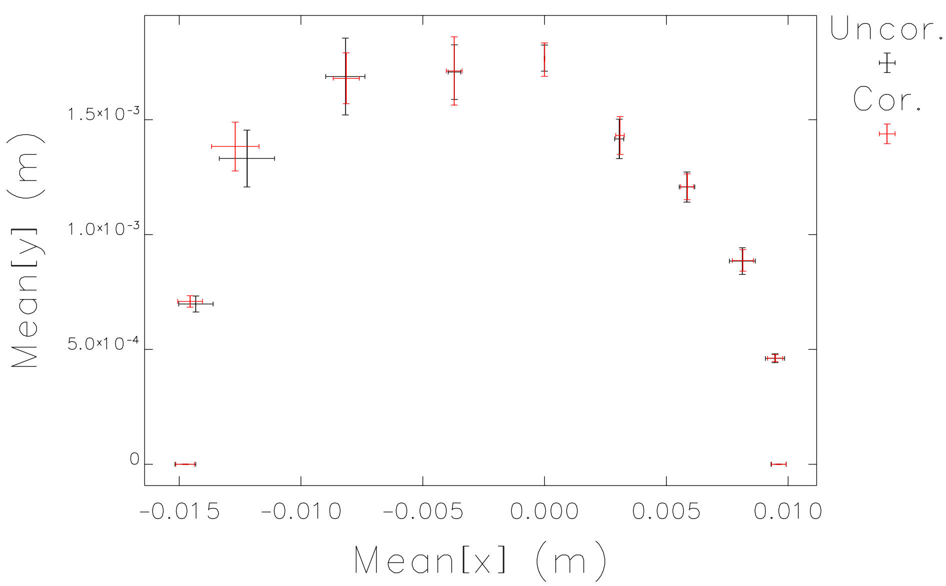

Figure 3: Dynamic aperture for the 8LSS lattice, with and without coupling correction.

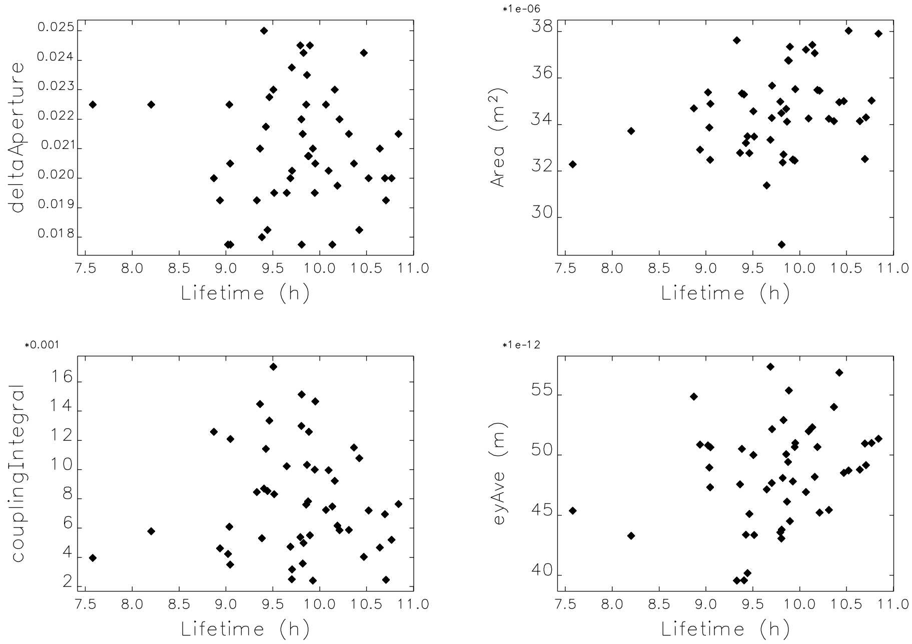

Figure 4: Total lifetime in 24-bunch mode for the 8LSS lattice, correlated with various other quantities. The quantity `deltaAperture` is the minimum absolute value of the momentum aperture from tracking.

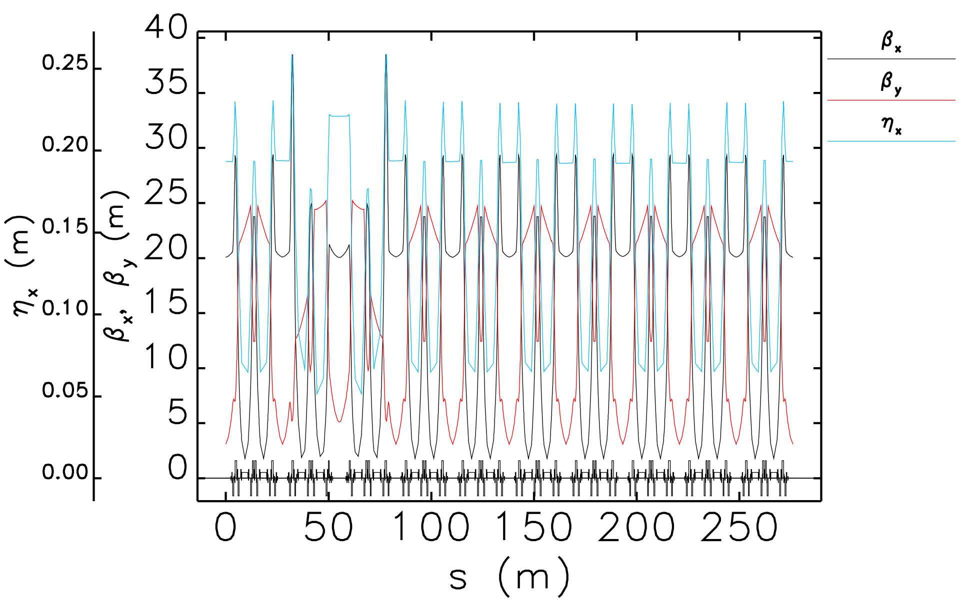

Figure 5: Optics for 4LSS lattice, showing 10 sectors including one LSS.

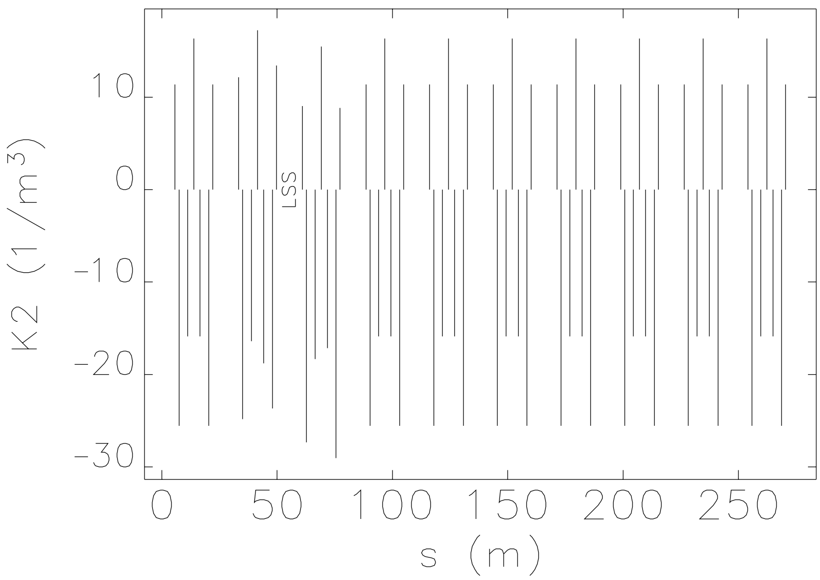

Figure 6: Sextupole strengths for the 4LSS lattice.

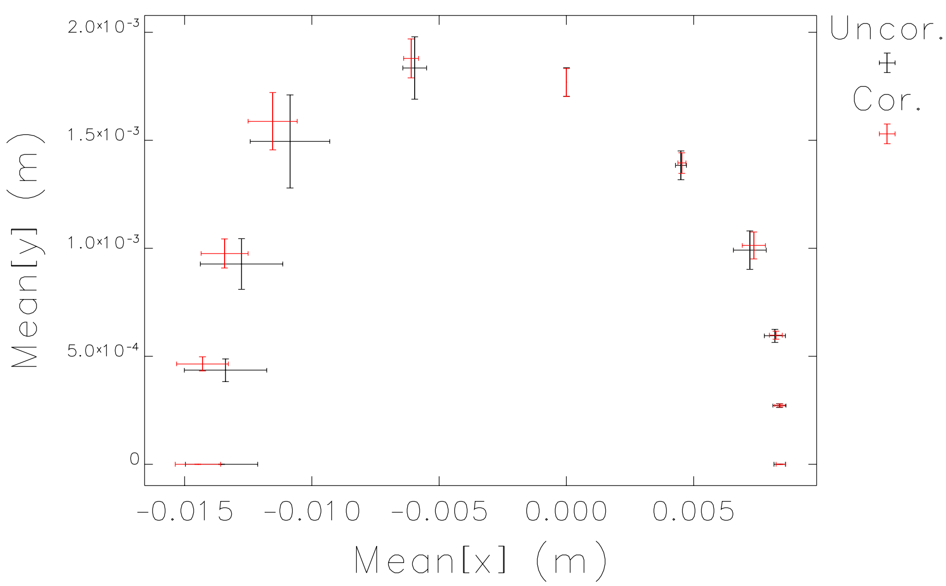

Figure 7: Dynamic aperture for the 4LSS lattice, with and without coupling correction.

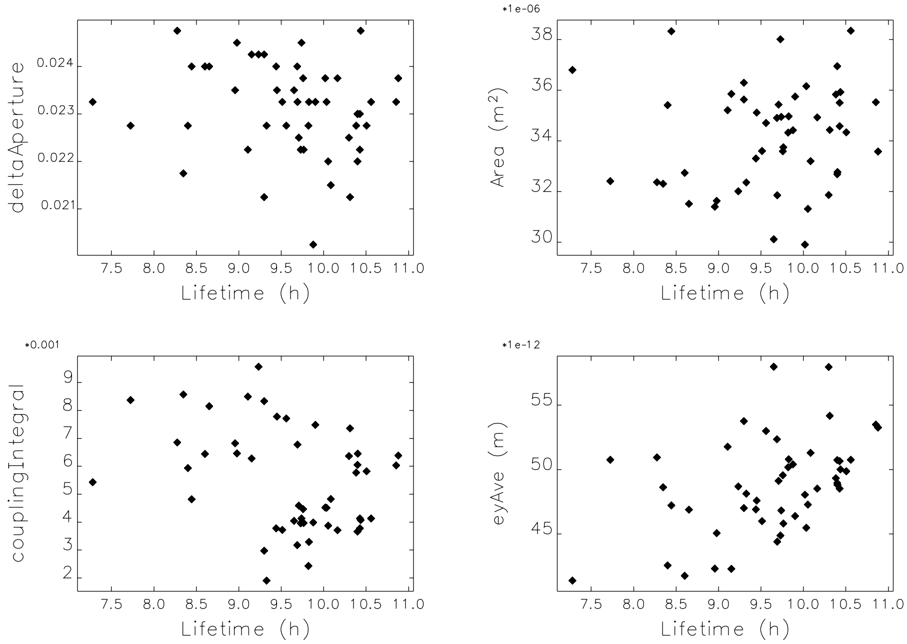

Figure 8: Total lifetime in 24-bunch mode for the 4LSS lattice, correlated with various other quantities. The quantity `deltaAperture` is the minimum absolute value of the momentum aperture from tracking.

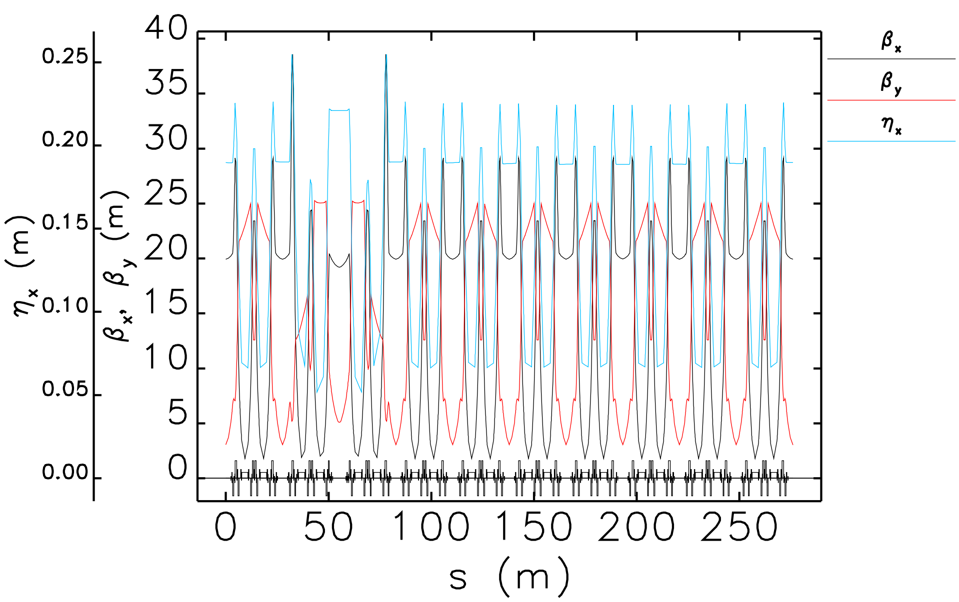

Figure 9: Optics for 2LSS lattice, showing 10 sectors including one LSS.

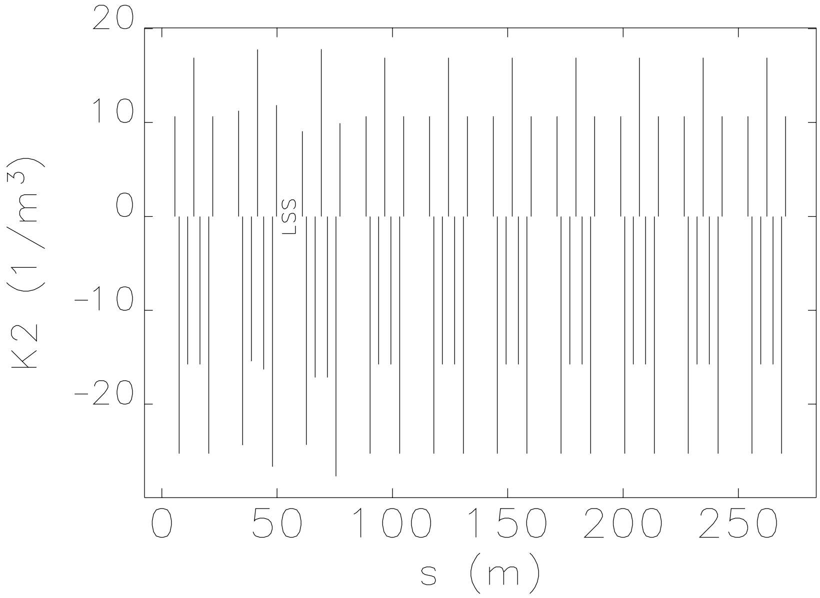

Figure 10: Sextupole strengths for the 2LSS lattice.

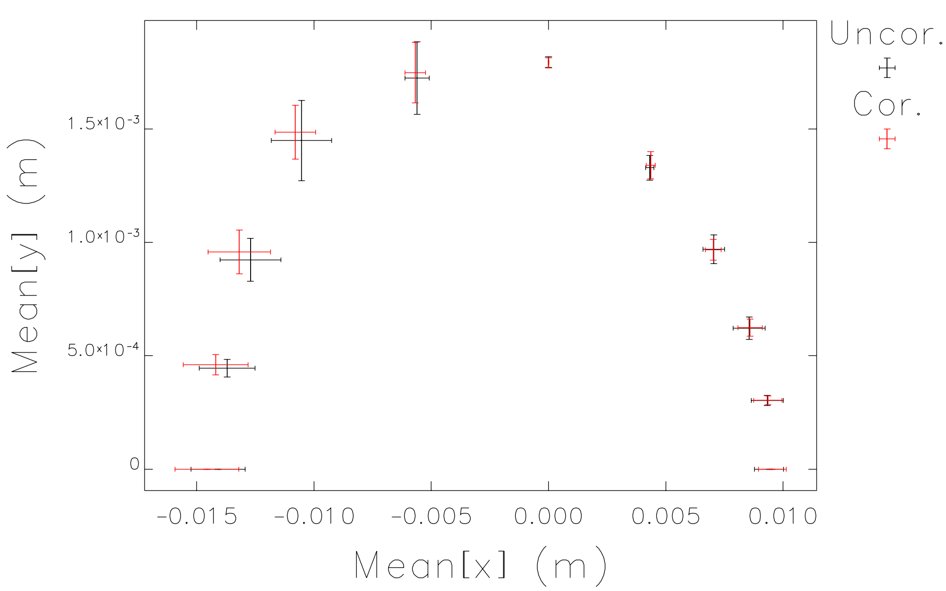

Figure 11: Dynamic aperture for the 2LSS lattice, with and without coupling correction.

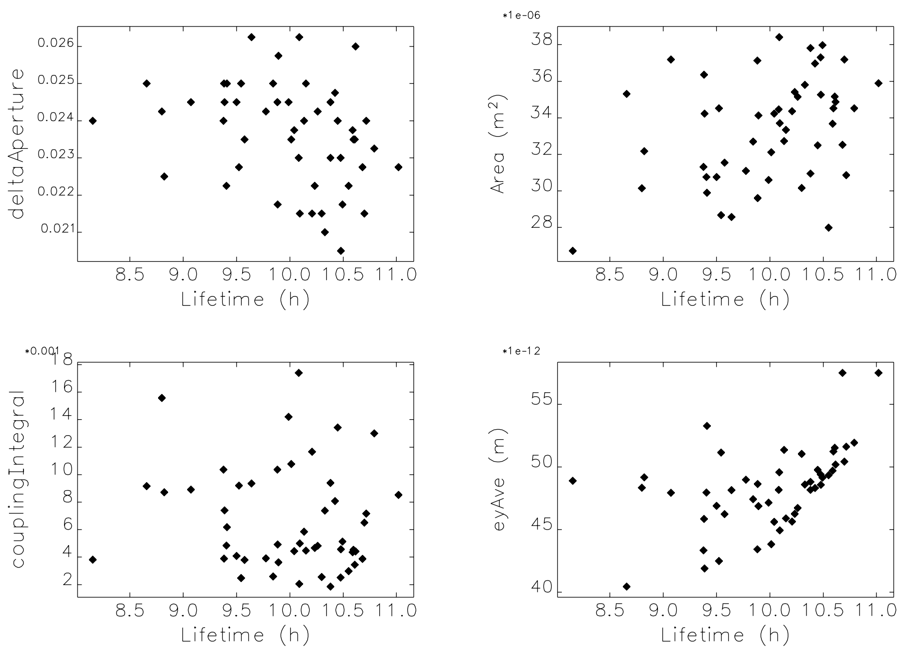

Figure 12: Total lifetime in 24-bunch mode for the 2LSS lattice, correlated with various other quantities. The quantity `deltaAperture` is the minimum absolute value of the momentum aperture from tracking.