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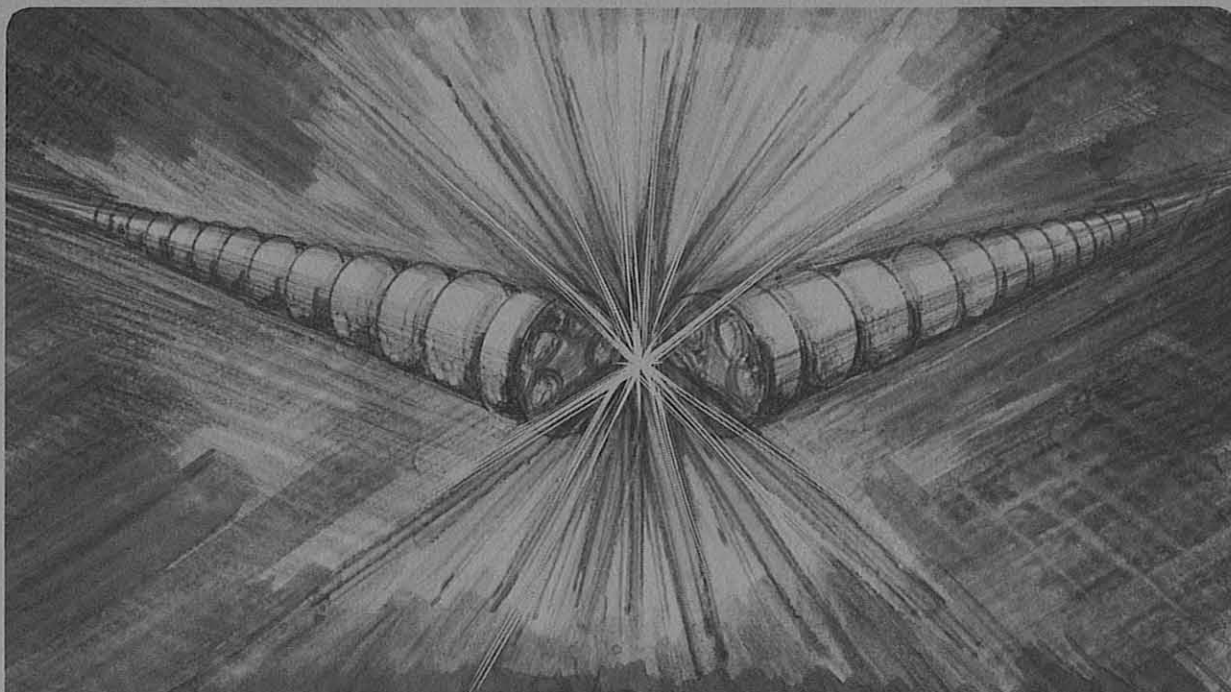
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Abstract

The lattice of the Advanced Light Source (ALS) 1-1.9 GeV electron storage ring was reexamined, introducing an additional family of focusing quadrupoles and looking for a working point with larger dynamic aperture. In the first part of this study, the ideal lattice was investigated to confirm the anticipated behavior, and indeed conditions with increased dynamic aperture were found. In the second part, realistic magnet errors and an undulator in one of the straight sections were taken into account. Under these conditions the dynamic aperture could not be significantly improved over the nominal configuration. Further studies included investigation of the Touschek momentum acceptance of the lattice. In this case too, no net benefit was obtained from the additional quadrupoles.

Introduction

The nominal ALS lattice,¹ designed to produce an emittance of 3.4×10^{-9} m-rad, exhibits a potentially high sensitivity to alignment and magnetic field errors. In this study we examine if more relaxed lattices producing higher emittances would be advantageous (a), for the commissioning phase where there will not be any insertion devices but where the machine behavior has not been well characterized, and (b), as a fall back position for operation (while still keeping the emittance below the specified value of 10×10^{-9} m-rad).

This task was undertaken in three steps: At first, after introducing a new family of focusing quadrupoles, QF2, it was investigated how the lattice functions (beta functions, dispersion, and emittance) changed with the excitation of the new quadrupoles. With this knowledge, some calculations of the dynamic aperture were performed for two different horizontal tune values, using the simulation code TRACY.²

Secondly, an entire field of horizontal and vertical tune values was examined, again using TRACY, resulting in closely spaced, two-dimensional sets of horizontal and vertical dynamic aperture values over the tune ranges covered, for several excitations of the QF2 magnets. These first two steps did not include any errors. Finally, a possible connection with the realistic, error-dominated, lattice was looked for using the GEMINI package,³ now including the undulator U5.0 and assuming the presence of standard alignment and magnetic field errors. Because earlier studies⁴ had shown the sensitivity of the momentum acceptance to errors and nonlinearities we concentrated on investigating the momentum acceptance, which strongly influences the Touschek lifetime.

Ideal Lattice

The aim of the first part of this study was to see if a larger dynamic aperture of the ideal lattice could be achieved by allowing the natural emittance to grow from its nominal value of 3.4×10^{-9} m-rad. In order to change the standard lattice optics, another pair of focusing quadrupoles, each with 0.2 m effective length, was introduced into the lattice, see Fig. 1. As described in Ref. [5], excitation of these quadrupoles causes an increase of dispersion in the center bend magnet and a decrease of phase advance across the achromat; to keep the overall tunes fixed the horizontal and vertical β -functions in the straight section must be reduced. The higher dispersion leads to a substantial emittance increase, up to 12.3×10^{-9} m-rad, see Fig. 2. In the beginning, the horizontal and vertical tunes were kept at their standard values, $\nu_x = 14.277$ and $\nu_y = 8.169$.

When the QF2 magnets are excited, we find that the sextupole excitations (adjusted to keep the chromaticity equal to zero) do not decrease monotonically but, after passing pronounced minima, take on

even higher values than without the QF2 quadrupoles. This behavior can be explained by the fact that at the highest QF2 excitation, the QF1 strength is zero; in other words, the QF1 family of magnets has been replaced by the QF2 family, at a less convenient location in the lattice. In consequence, any possible benefits created by the QF2 family are likely to occur below about $k_{QF2} = 3 \text{ m}^{-2}$.

Dynamic apertures are in all cases evaluated at the symmetry points of the long straight sections. For calculations at standard tune, the value $k_{QF2} = 2.0 \text{ m}^{-2}$, at the minimum of the focusing sextupole excitation (and nearly the minimum of the defocusing sextupole excitation), was chosen. The three main lattice functions for this condition are shown in Fig. 1. The increase in emittance at $k_{QF2} = 2.0 \text{ m}^{-2}$ was accompanied by a considerable loss in aperture, see Fig. 3, and this holds even when the large decrease in the horizontal β function is taken into account, judging normalized coordinates rather than absolute ones. Without being able to identify the real cause for this unexpected behavior of the ALS storage ring lattice, we further investigated a different working point by reducing the horizontal tune, symmetrically around the closest integer value, to 13.723. Now the minimum excitation of the focusing as well as the defocusing sextupoles is found at $k_{QF2} = 2.4 \text{ m}^{-2}$.

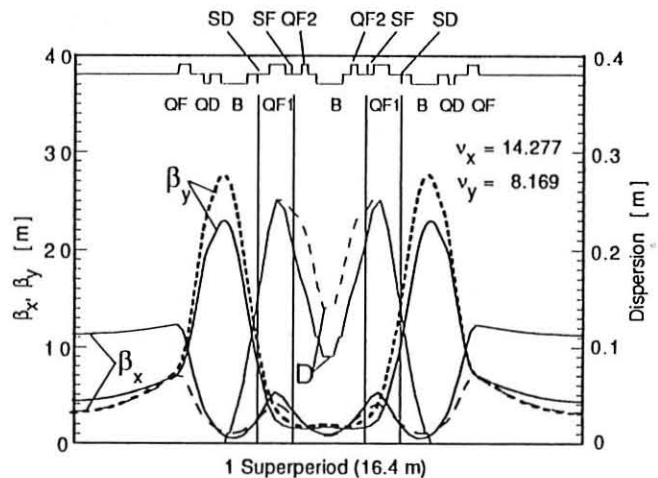


Figure 1. ALS storage ring lattice functions with standard tune, as functions of the position in one superperiod. The position of the sextupoles is emphasized by long vertical lines. The additional quadrupoles, QF2, are placed between the central bending magnet and the focusing sextupoles. Solid curves: $k_{QF2}=0$ (standard); dashed curves: $k_{QF2}=2.0 \text{ m}^{-2}$.

The dynamic aperture calculations for $\nu_x = 13.723$ and $k_{QF2} = 2.4 \text{ m}^{-2}$, see Fig. 3, show only a minor improvement over the former conditions $\nu_x = 14.277$ and $k_{QF2} = 2.0 \text{ m}^{-2}$, and the aperture is definitely smaller than the one obtained with standard tune and the QF2 quadrupoles left out.

Another simulation was performed at $\nu_x = 13.723$ with $k_{QF2} = 1.4 \text{ m}^{-2}$. Now β_x in the long straight section is high again, and the dispersion in the central part is lower, as compared to the case $k_{QF2} = 2.4 \text{ m}^{-2}$. But even here the absolute dynamic aperture is practically equally large, compared to the standard case, being somewhat narrower in the horizontal and somewhat higher in the vertical direction.

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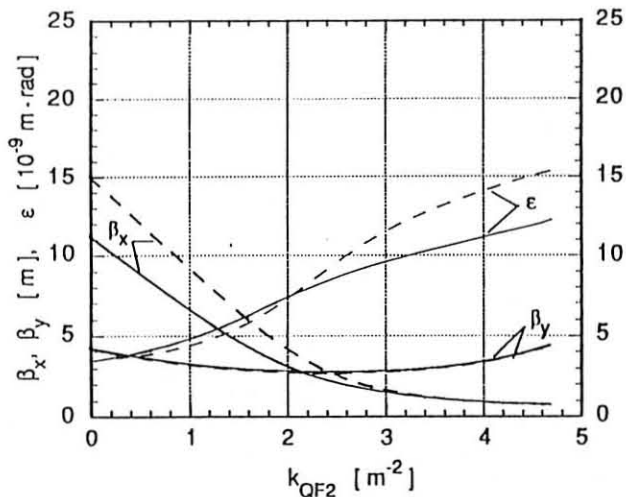


Figure 2. Variations of the main lattice parameters at the symmetry point with excitation of the quadrupoles QF2, for standard tune (solid curves) and reduced tune (dashed curves).

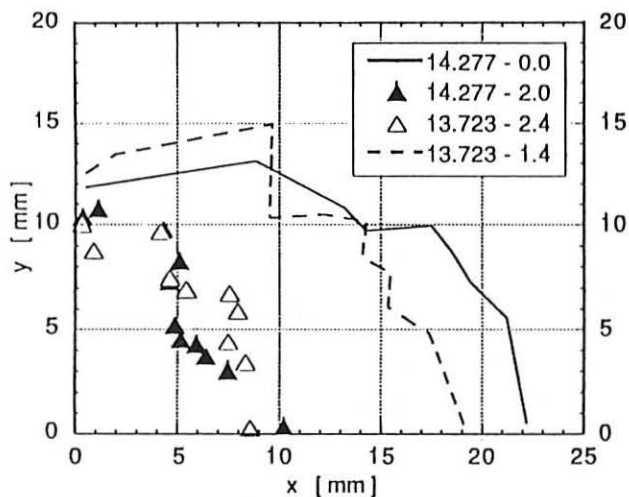


Figure 3. Absolute dynamic apertures of the ideal lattice at the symmetry point in a straight section, for two horizontal tunes and k_{QF2} [m^{-2}] values as marked in the legend. Full symbols or solid line, standard tune; open symbols or broken line, reduced tune. The vertical tune is $\nu_y=8.169$.

Dynamic Aperture Scans for the Ideal Lattice with QF2

To gain more insight into the behavior of the ideal lattice, we looked for a strength of QF2 which leads to a bigger and more stable dynamic aperture over a finite neighborhood in tune space ($13.6 \leq \nu_x \leq 14.4$ horizontally and $7.6 \leq \nu_y \leq 8.4$ vertically). The results of this part of the study were obtained as contour plots of constant dynamic aperture values in tune space. These plots help choosing a working point in tune space by showing the variation of aperture values with tune shifts around the working point. Ideally, one would look for a wide plateau with highest values for horizontal and vertical dynamic apertures, see Fig. 4. We selected $k_{QF2} = 1.0 m^{-2}$ for further investigation; at this value of k_{QF2} , we explored the standard

condition ($\nu_x = 14.277 / \nu_y = 8.169$) as well as the neighborhood of ($\nu_x = 13.75 / \nu_y = 8.21$). A summary of the results is presented in the next section.

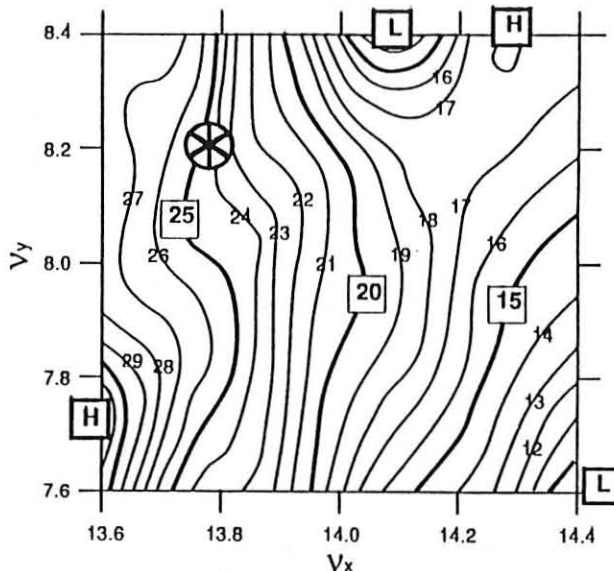


Figure 4. Absolute horizontal dynamic aperture values of the ideal lattice as a function of horizontal and vertical tunes, for $k_{QF2}=1.0 m^{-2}$. The lines connect working points with equal dynamic aperture in steps of 1 mm; peaks are marked by H and valleys by L. The asterisk indicates the overall best working point.

Touschek Scattering Simulations for the Realistic Lattice with Undulator

The Touschek scattering process involves large-angle single Coulomb collisions, which result in momentum being transferred from the transverse planes to the longitudinal one. In nondispersive regions of the lattice, such momentum changes do not excite any betatron oscillations, but in the dispersive region, there can be an appreciable betatron amplitude excited.

In the standard formulation of Touschek scattering⁶ the lifetime is proportional to the bunch volume and to the cube of the momentum acceptance. In the simulations reported here, we explored the stronger one of these effects, calculating how the nonlinearities in the ring affect the momentum acceptance when synchrotron oscillations are being taken into account.

The larger emittance associated with a "relaxed" lattice means that the initial amplitude of the scattered particle will be larger. The dynamic aperture must then increase by a comparable or greater amount to provide a net gain in terms of momentum acceptance. As was made clear in the previous sections, we have not generally found this to be the case for the relaxed lattices studied here.

To perform the simulations, we select a location in the dispersive region and change the momentum (but not the spatial coordinates) of a particle. This off-momentum particle is then tracked to see if it survives. For the results reported here, the momentum deviation was increased in steps until the particle no longer remained stable for 1000 turns. The largest value for $\delta p/p$ determined in this manner is taken as the momentum acceptance, as given in Tables 1 and 2 below.

Fig. 5 shows an absolute dynamic aperture plot for the realistic lattice under conditions judged to be the best from the former scans, $k_{QF2}=1.0 m^{-2}$; $\nu_x=13.75$, and $\nu_y=8.21$. First of all, one notices on Fig. 5 the absence of any improvement of the dynamic aperture with

errors, compared to the standard tune case. However, it should be noted that this does not necessarily correlate with the momentum acceptance. Therefore we went ahead with Touschek simulations as described in the foregoing section; the results are displayed in Table 1 below.

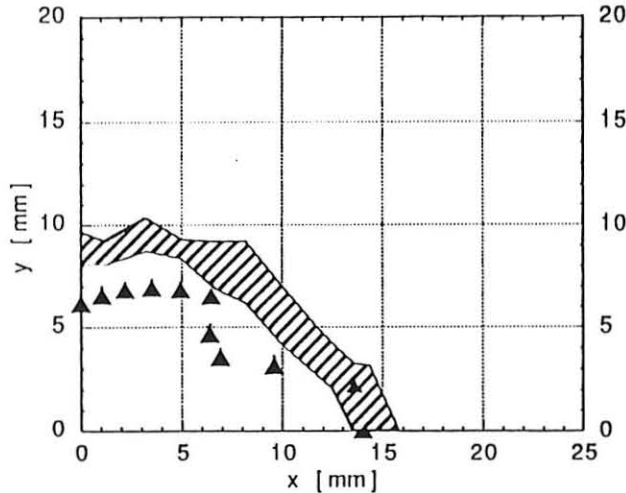


Figure 5. Absolute dynamic apertures of the realistic lattice with undulator U5.0 set to 1.2 T peak field. Full triangles, conditions selected as best for the Touschek scan, with $v_x = 13.75$, $v_y = 8.21$, and $k_{QF2} = 1.0 \text{ m}^{-2}$; one error seed. Hashed area, range of dynamic apertures for standard tunes and without the QF2 family, for different error seeds.

The first three sets of tunes in Table 1 show a somewhat flat dependence on the tunes in formal agreement with the ideal lattice scan. Unfortunately, the dispersive acceptance is not very high. Indeed, by a slight modification of the original lattice (going from $v_x = 14.277 / v_y = 8.169$ to $v_x = 14.23696 / v_y = 8.22$ at $k_{QF2} = 0$) we can easily bring the dispersive acceptance to 2.5%. The fourth line of Table 1 then shows a dramatic effect never observed in the original lattice. The particle in the dispersion free region is already lost at a very small momentum. Upon investigation, we found that it is due to a so-called "Krein" collision. As the momentum changes the fractional tunes meet on the unit circle. There they undergo a collision and are ejected from the unit circle as the momentum increases. It is a purely linear effect which can only occur in a lattice with errors. The stopband in momentum over which the linear lattice is unstable runs approximately from $\delta p/p = 1.0\%$ to $\delta p/p = 2.0\%$.

The larger acceptance in the dispersive region for this case could be due to a complex nonlinear stabilization of the map since we have a greater transverse component at a given momentum. We did not really check this hypothesis. Notice that the two last sets probably suffer from the same "Krein" malaise.

Table 1. Momentum acceptances in two characteristic regions of the realistic lattice with undulator U5.0, for six cases of (reduced) tune combinations and $k_{QF2} = 1.0 \text{ m}^{-2}$.

| v_x | v_y | dispersion free [%] | dispersive [%] |
|-------|-------|---------------------|----------------|
| 13.75 | 8.19 | 3.70 | 1.60 |
| 13.75 | 8.21 | 4.00 | 1.70 |
| 13.77 | 8.21 | 3.90 | 1.90 |
| 13.80 | 8.23 | 1.20 | 2.10 |
| 13.79 | 8.23 | <2.6 | 2.10 |
| 13.78 | 8.23 | <3.1 | 2.00 |

Looking at the original tunes, we found a situation similar to the $k_{QF2} = 0$ case with the roles of the tunes inverted, see Table 2.

Strangely enough, for the realistic lattice the best tunes are now the original ones. Unfortunately, there is no flat scenery in this quadrant. What appeared to be the best choice for the ideal lattice has to be abandoned when errors and an undulator are added to the scenery.

Table 2. Momentum acceptances in two characteristic regions of the realistic lattice with undulator U5.0, for several cases of tune combinations and $k_{QF2} = 0$ (upper three lines) and $k_{QF2} = 1.0 \text{ m}^{-2}$ (lower five lines).

| v_x | v_y | dispersion free [%] | dispersive [%] |
|----------|---------|---------------------|----------------|
| 14.27696 | 8.17901 | 3.70 | 1.60 |
| 14.23696 | 8.22 | 4.50 | 2.50 |
| 14.29696 | 8.25001 | 5.00 | 2.30 |
| 14.27696 | 8.17901 | 4.10 | 2.40 |
| 14.23696 | 8.22 | 2.60 | 1.20 |
| 14.29696 | 8.25001 | 2.90 | 1.10 |
| 14.27696 | 8.14901 | 3.50 | 2.10 |
| 14.25696 | 8.14901 | 2.80 | 1.80 |

Conclusion

Our study shows that the introduction of a new QF2 family of quadrupoles is rather detrimental, even though studies of the ideal lattice might initially have raised some hopes for improvement.

Although the inclusion of the QF2 family provides a separate knob, the results of the Touschek studies (which involve synchrotron oscillations) are sensitive to the leading order tune shifts which, in turn, are modified by the presence of this new family of quadrupoles.

In practice, the momentum acceptance does not rise to higher peaks and retains its complicated topography in the (v_x/v_y) plane. In the $(13.75 / 8.21)$ regions, new undesirable effects come into play, adding to the complexity of the problem. This seems to be too meager an outcome to justify the inclusion a QF2 family in the ALS lattice. On the other hand, the expected performance of the ring with standard lattice is satisfactory.

Acknowledgments

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