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Low Alpha Experiments at the ALS¹

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Abstract.

We present a modified, low alpha lattice for the Advanced Light Source where the quadrupole field strengths have been detuned to allow the momentum compaction factor to be varied smoothly from positive to negative values. With this low alpha lattice we decrease the momentum compaction factor by a factor of 5 to 0.0003 over normal operation resulting in a measured bunch length reduction of 2. We also measure the size the second order momentum compaction factor as well as store beam in a negative momentum compaction lattice. Streak camera measurements at positive and negative momentum compaction operation show longitudinal beam profile distributions that are in agreement with simulations by Fang et al (8).

INTRODUCTION

At the Advanced Light Source there is interest in decreasing the bunch length and increasing the peak current of electron bunches. Very short bunches (less than 1 ps) promise coherent infrared radiation as well as better time resolution. High peak currents promise larger radiation power. Recent experimental work at UVSOR (1-3) and Super-ACO (3-5) have demonstrated that it is possible to decrease the bunch length in a storage ring by reducing the momentum compaction factor. In these experiments the momentum compaction factors were reduced by two orders of magnitude giving a reduction in bunch length of 10. In addition, results at Super-ACO have demonstrated that at negative values of the momentum compaction factor, there is less bunch lengthening than at positive values of the momentum compaction factor (3). Therefore it is possible to store larger peak currents at negative than at positive momentum compaction.

An experimental program to reduce the momentum compaction is underway at the Advanced Light Source (ALS). At this time we have succeeded in reducing the bunch length by a factor of two from that of normal operation. We have also stored beam in a negative momentum compaction configuration. In this paper we report on the current status of these experiments.

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LATTICE

The lattice of the ALS is built up of 12 triple bend achromat (TBA) cells. The layout of a typical cell can be seen in figure 1. There is one bend family, B, Three quadrupole families, QF, QD, and QFA, and two sextupole families, SF and SD.

FIG. 1. Top-down view of a typical sector (1/12 of the ring).

The Twiss parameters for the lattice in its usual operation mode can be seen in figure 2 (a). For the usual operation mode the lattice is designed such that there is zero dispersion, η , in the straight sections to the outside of the outer bends and positive dispersion elsewhere.

FIG. 2. Lattice functions for an ALS cell. a: normal ALS sector (top). b: modified sector (bottom).

Because the dispersion is positive in the bends, higher energy particles have a longer total orbital path length than lower energy particles. This is because higher energy particles travel radially outward of lower energy particles in the bends. The momentum compaction factor, α , is a measure of the path length difference, ΔL , of an off and on-energy particle relative to the energy difference, ΔE , of an off and

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on-energy particle and is expressed as:

$$\frac{\Delta L}{L_o} = \alpha \frac{\Delta E}{E_o}, \quad (1)$$

where L_o and E_o are the total path length and energy of the ideal particle respectively. To first order in $\Delta E/E_o$, the path length difference is given by the first order momentum compaction factor, α_1 and is given as (6):

$$\alpha_1 = \int_0^{L_o} \frac{\eta}{\rho} ds, \quad (2)$$

where ρ is the radius of curvature of the bends and η is the dispersion in the bends. Because the dispersion in the bends is positive (figure 2 (a)), α_1 is positive.

For our experiment the initial aim was to find a new lattice configuration that α_1 could be smoothly tuned from positive to negative values. We also imposed the constraint that we would only be allowed to vary the quadrupole field gradients — k_{QF} , k_{QD} and k_{QFA} . In other words, we did not want to make physical changes to the lattice. With these aims and constraints we arrived at the lattice seen in figure 2 (b). In this modified or low alpha lattice the dispersion is positive in the straight sections and the outer bends and negative in the middle bend. So higher energy particles travel radially outward in the outside bends but radially inward in the middle bend. Therefore the higher energy particles “cut the corner” in the middle of the straight section and reduce their total path length. If the dispersion function is made more negative in the middle bend, the higher energy particles will “cut the corner” more, and the momentum compaction will be reduced further — and can even become negative.

In table 1 a comparison is made between the parameters for normal operation lattice and the low alpha lattice. It is clear from table 1 that the properties of the lattices are very different. In particular for the low alpha lattice, the emittance is 10 times larger, and the horizontal tunes and chromaticities are lower.

In the low alpha lattice, the QF quadrupoles are located in a region of maximum dispersion, $\eta = 0.7$ m (figure 2 (b)). Since the change in α_1 , resulting from a change in integrated quadrupole field Δk_l , is proportional to the square of the dispersion at the location of the quadrupole,

$$\Delta \alpha_1 \propto \Delta k_l \eta^2, \quad (3)$$

changing the QF's field is a very effective method of changing α_1 . In figure 3 we plot calculated α_1 against QF excitation current, ΔI_{QF} (7).

Quantity	Symbol	Normal-Alpha Lattice	Low-Alpha Lattice
Horizontal Tune	ν_x	14.28 *	10.26
Vertical Tune	ν_y	8.18	8.15
Natural Horizontal Chromaticity	ν_x'	-25	-11
Natural Vertical Chromaticity	ν_y'	-28	-28
Horizontal Emittance	ϵ_x	4 nm-rad	40 nm-rad
Dispersion at SF	η_{SF}	0.211 m	-0.111 m
Dispersion at SD	η_{SD}	0.124	-0.014
Momentum Compaction	α_1	0.0016	0.0003

TABLE 1. Parameters for the normal and low alpha lattices.

FIG. 3. Calculated value of α_1 versus QF excitation current.

EXPERIMENT

In July and August of 1995 we performed four experiments where we studied the properties of this new lattice. In all of the experiments, the sextupoles were turned off. The first two experiments were dedicated to characterizing the low alpha lattice at larger values of α_1 . In the last two experiments we proceeded to reduce and even make α_1 negative by adjusting the QF magnets.

Characterizing the Low Alpha Lattice

In the first experiment beam was successfully injected into the new lattice. Because of the large (negative) values of the chromaticity, it was very difficult to measure the tunes with a spectrum analyzer. Instead we used the 96 beam position monitors (BPMs) which are able to measure the beam orbit every turn. A bunch was then injected off-axis and its orbit location was recorded over a number of consecutive turns. From this data the integer and noninteger tunes were extracted. The tunes were measured to be $\nu_x = 10.25$ and $\nu_y = 8.45$. The resolution of the tune measurement was ± 0.05 .

Measurement of α_1

Synchrotron Tune. We were able to observe self-excited synchrotron frequency side bands about the revolution harmonic frequency. This was an indication of some instability in the beam. As a result we were able to measure the the synchrotron tune, ν_s , without having to excite longitudinal oscillations.

The first order momentum compaction factor, α_1 , is proportional to the square of the synchrotron tune, ν_s^2 ,

$$\alpha_1 = \frac{2\pi E_o}{ehV_o \cos(\phi)} \nu_s^2, \quad (4)$$

where V_o , h and ϕ_o are the peak voltage, the harmonic number and the synchronous phase of the RF cavity. Therefore by measuring ν_s it is possible to determine α_1 .

The peak RF cavity voltage, V_o , was adjusted to 350 kV. Then we measured ν_s^2 as we increased the QF excitation current, I_{QF} . The results are plotted in figure 4.

FIG. 4. Measured values of the ν_s^2 versus QF excitation current.

The plot is linear as expected from equations 3 and 4. From equation 4 it is possible to determine the values of α_1 as a function of I_{QF} . The results are plotted in figure 5. A comparison between figures 3 and 5 shows good agreement between the model and the machine.

FIG. 5. The momentum compaction as a function of QF excitation current.

Horizontal Beam Displacement. A second method of measuring α_1 is to measure the horizontal beam displacement as a function of RF frequency. By measuring the horizontal beam displacement, Δx_{BPM} , at a beam position monitor (BPM) resulting from a change in the RF frequency, Δf_{RF} , it is possible to measure the ratio, $-\eta/\alpha_1$,

$$\alpha_1 = -\frac{\eta_{BPM}}{f_{RF}} \frac{1}{\Delta x_{BPM}/\Delta f_{RF}}, \quad (5)$$

where η_{BPM} is the horizontal dispersion at the BPM. In figure 6 we plot $\Delta x/\Delta f_{RF}$ versus BPM number for two setting of I_{QF} . The shape of the curves looks like a mirror image of the dispersion function as viewed in figure 2 (b). From equation 5 we know that $\Delta x/\Delta f_{RF}$ is proportional to $-\eta/\alpha_1$ so if α_1 is positive then $\Delta x/\Delta f_{RF}$ will be the mirror image of η . Therefore from the shape of the plot we know that α_1 is positive.

FIG. 6. Horizontal beam displacement as a function of a change in RF frequency at each beam position monitor.

In order to determine the magnitude of α_1 from equation 5 it is necessary to assume some value for the dispersion at the BPMs. From our model of the machine we computed the dispersion in the outer straight section BPMs, BPM1 and BPM8 in figure 1, to be 0.7 m. Then from equation 5 we determined that $\alpha_1 = 0.001$ (solid line in figure 6) and $\alpha_1 = 0.0003$ (dashed line figure 6).

Measurement of the Bunch Length

At low currents the bunch length, σ_b , is:

$$\sigma_b = \frac{\alpha_1 R_o \sigma_e}{\nu_s E_o}, \quad (6)$$

where R_o is the ring's average radius of curvature and σ_e/E_o is the relative energy spread of the bunch. Since ν_s is proportional to the square root of α_1 (equation 4), σ_b is proportional to the square root of α_1 .

The peak RF voltage, V_o , was adjusted to 1 MV. Using a streak camera with 500 femtosecond resolution we measured σ_b as a function of ν_s . The results are plotted in figure 7. In the normal lattice configuration the bunch length is 16 ps and ν_s is 0.0075. From equations 4 and 6 we expect σ_b to decrease linearly with ν_s (solid line in figure 7). With the low alpha lattice, ν_s was adjusted between 0.0033 and 0.0068. However at values of ν_s below 0.004 we were not able to store more than 0.2 mA of current in a single bunch and as a result we were not able to measure σ_b . The smallest value of ν_s at that we were able to measure σ_b was 0.0046. At this value of ν_s , σ_b was 8.1 ps.

At small values of α_1 we observed large bunch size oscillations. In addition we occasionally saw what appeared to be a small satellite bunch orbiting the main bunch (figure 8).

FIG. 7. Measurements of the bunchlength versus synchrotron tune.

We also saw that the bunch length was oscillating by ± 2 ps. In addition we sometimes observed the bunch breaking into two.

FIG. 8. Observations of a bunch satellite at small α_1 with a streak camera. In the two figures the bunch is traveling from right to left. Left: horizontal size versus bunch length. Right: Intensity versus bunch length.

Limits to Further Reduction of α_1

As discussed in the paper by Robin et al (3) the size of the next order momentum compaction factor α_2 can limit stability of motion at small α_1 . For this reason we proceeded to measure α_2 .

If α_2 is nonzero, then a change in f_{RF} will result in a change in ν_s (2):

$$\nu_s = \nu_{s0} \left(1 - 4 \frac{\alpha_2}{\alpha_1^2} \frac{\Delta f_{RF}}{f_{RF}} \right)^{1/4}, \quad (7)$$

where ν_{s0} is the value of the synchrotron tune at $\Delta f_{RF} = 0$. Figure 9 shows the measurement of ν_s versus f_{RF} . From the data and equation 7 we determined α_2 to be 0.03. The energy acceptance in the low α_1 regime is α_1/α_2 (9). Therefore at our smallest measured α_1 value of 0.0003, the energy acceptance is only 1% (figure 10). For this small energy aperture we expect the Touschek effect (10) severely limits the single bunch current. Because the stable longitudinal phase space area is proportional to α_1 , at smaller values of α_1 the stable area is too small to store

beam. At smaller values of α_1 the stable longitudinal phase space shrinks further and prevents us from storing any current.

FIG. 9. Measurement of the second order momentum compaction factor.

FIG. 10. Longitudinal phase space ($\phi = 2\pi h\Delta L/L_o$)

In principle we can reduce α_2 by changing sextupole fields in regions of large dispersion (3). Unfortunately, in the present low alpha lattice, both sextupole families are located in regions of small dispersion (table 1). Therefore we are unable to change α_2 .

NEGATIVE MOMENTUM COMPACTION

Higher peak currents and shorter bunch lengthening have been predicted by Fang et al. (8) and measured by Nadji et al at Super-ACO (5,3) when operating with a negative momentum compaction factor. Based upon the success of these experiments, we have begun to explore negative α_1 operation of the ALS.

In order to adjust I_{QF} to make α_1 negative, we fit the data displayed in figure 4 with a straight line (solid line in figure 4) and then extrapolate to negative α_1 . For a value of $I_{QF} = 71.5$ A, we expected a value of $\alpha_1 = -0.0008$ (square dot in figure 4).

I_{QF} was then adjusted to 71.5 A and the phase of the RF cavity, ϕ_o , was shifted by 180 deg with respect to the injector. The peak RF cavity voltage was set to 1 MV. Under these conditions we were able to store beam current — about 1 mA in a single bunch.

Characterizing the Negative α_1 Lattice

Because we injected and stored beam with the RF phase shifted by 180 deg we had confidence that α_1 was negative. But to definitively check the sign of α_1 we measured the horizontal beam displacement as a function of the RF cavity frequency. The results are plotted as dashed lines in figure 11. We have also plotted as a solid line in figure 11 our measured data for positive α_1 (same as the solid line in figure 6)

As can be seen in figure 11 the dashed line is "flipped" with respect to the solid line. This is expected from equation 5 and it clearly says that α_1 is negative.

FIG. 11. Measured horizontal beam displacement at each BPM as a function of RF cavity frequency. Solid line : $\alpha_1 = 0.001$. Dashed line : $\alpha_1 = -0.0011$.

Streak camera images show that at negative α_1 the beam distribution is leaning backwards in time (figure 12). At positive α_1 distribution is leaning forwards in time. This is consistent with results by Fang et al (8) who have simulated the effects of potential-well distortion. In addition the beam was noticeably more stable at negative α_1 .

FIG. 12. Longitudinal beam distribution based on an average of 17 streak camera images taken with 0.5 mA in a single bunch and $\alpha_1 = -0.0011$.

SUMMARY OF RESULTS

By just changing quadrupole strengths we have detuned the ALS lattice in order to reduce α_1 . At this time we have been able to reduce α_1 by a factor of 5 to 0.0003

and the bunch length by a factor of 2 to 8 ps. However at 8 ps we were only able to store 0.1 mA of current in a single bunch. The size of α_2 was measured to be 0.03 and it was determined to be the limit to further reduction of α_1 . In addition we also stored current in a negative α_1 lattice.

By imaging the beam with a streak camera, we have seen evidence of the on-set of the head-tail instability and satellite bunches in the positive α_1 configuration. We have also observed a shifts in beam tail distributions when operating with a positive and negative α_1 .

In the future we will attempt to correct the α_2 in order to reduce α_1 further. Also we will further investigate negative α_1 operation.

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