LOW ALPHA MODE FOR SPEAR3 *

Xiaobiao Huang, James Safranek, Jeff Corbett, Yuri Nosochkov, Jim Sebek, Andrei Terebilo,
SLAC, Menlo Park, CA 94025, USA

Abstract

In the interest of obtaining shorter bunch length for shorter X-ray pulses, we have developed a low-alpha operational mode for SPEAR3. In this mode the momentum compaction factor is reduced by a factor of 21 or more from the usual achromat mode by introducing negative dispersion at the straight sections. We successfully stored 100 mA with the normal fill pattern at a lifetime of 30 hrs. The bunch length was measured to be 6.9 ps, compared to 17 ps in the normal mode.

In this paper we report our studies on the lattice design and calibration, orbit stability, higher order alpha measurement, lifetime measurement and its dependence on the sextupoles, injection efficiency, longitudinal stability and bunch lengths.

INTRODUCTION

The pioneering work of low-alpha mode operation of an electron storage ring to produce stable coherent synchrotron radiation (CSR) at BESSY [2] has stimulated much interest in the synchrotron light source community. The bunch length shrinks as the momentum compaction factor (alpha) is reduced. In addition to producing CSR in Tera-Hertz range for user experiments, shorter bunch length is also preferred by some users for time-resolved experiments.

At SSRL, we started developing the low-alpha mode for SPEAR3 in the 2006 run. We successfully tested lattices with various reduction factors of alpha and measured the corresponding bunch length. A lattice with a factor of 21 reduction in alpha was chosen for future operation at regular total current (100 mA). Lattices with smaller alpha may also be used for lower current operation to produce shorter X-ray pulses or for CSR generation. Various operation aspects are discussed.

THE MACHINE OPTICS

SPEAR3 is a third generation electron storage ring. It consists of 18 double-bend achromat cells with a 2-fold periodicity on a 234 m circumference. In the normal achromat lattice the straight sections have zero dispersion with a corresponding alpha of 1.18×10^{-3} and the horizontal emittance is 18 nm. To reduce alpha one needs to create negative dispersion in the straight sections by adjusting the quadrupole magnet strengths. At SPEAR3 we need -21 cm dispersion at the straight sections to get a factor of 20 or more reduction in alpha. The horizontal emittance for the low alpha lattices is increased to 42 nm due to larger dispersion in bending magnets. Including the existing insertion devices, the emitttance is calculated to be 35 nm. For stable operation in low alpha mode, one has to reduce the second order momentum compaction factor, α_2, to retain a sizable rf-bucket [3]. This can be achieved by adjusting the sextupole strengths. SPEAR3 has only two families of sextupoles (SF and SD) for chromaticity correction in both transverse planes. Therefore we have only two controls for three free parameters. Since SF sextupoles are more efficient in α_2 control, we gave up the horizontal chromaticity and allowed it to settle on a negative value.

To initially implement the low alpha lattice, we first filled to the normal lattice and then ramped to the low alpha lattice by linearly scaling the quadrupole magnet currents. At this point we used LOCO [4] to calibrate the linear lattice. Unlike the normal lattice, there was difficulty to make LOCO converge to the design lattice through iterations because the LOCO solution tend to have a large degeneracy term. This was overcome by introducing constrained fitting to the LOCO algorithm in which we now add a term to the merit function to minimize the total changes of the quadrupoles in each iteration. The lattice was then calibrated to the same level as the normal lattice, with beta beating below 1% and linear coupling below 0.1%. After the lattice was established, we always directly fill to this lattice. We have developed two calibrated lattices, with a factor of 21 and 59 reduction of alpha, respectively. For smaller alpha values, we simply change the QFC quadrupoles according to an experimentally determined linear $\alpha_1 \sim I_{\rm QFC}$ relation.

We also scaled the sextupoles to the design values initially and then experimentally determined the optimal working point by scanning the SF sextupoles to obtain the best lifetime. The range in which we can change SF without losing all beam is greater than $\pm$10 A, surprisingly large, which was found to be due to a positive third order alpha ($\alpha_3 \approx 0.05$). Fig. 1 shows the lifetime at 100 mA for the SF scan.

We have measured and confirmed the linear alpha with synchrotron frequency measurements by a spectrum analyzer and the turn-by-turn BPMs. Another method we used was to make a small change to the rf frequency and measure the change of close orbit Δx. The momentum deviation is determined by $\delta = \langle \Delta x D\rangle / \langle D^2\rangle$, where D is dispersion from the design model and $\langle \bullet \rangle$ denotes averaging over all BPMs. The linear alpha is then given by $\alpha_1 = -\frac{\Delta f_{\rm rf}}{f_{\rm rf}\delta}$. In principle, this method can be extended to measure the second order alpha and dispersion simultaneously. But we found the complication of the BPM nonlinearities (due to the geometry of the vacuum pipe) made it not useful. We measured the second order alpha by changing the rf fre-

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quency and measuring the synchrotron tune. Then we use [1]

$$\nu_s = \sqrt{\frac{heV_{\rm rf}\cos\phi_s}{2\pi E}} \left(\alpha_1^2 - 4\alpha_2\frac{\Delta f_{\rm rf}}{f_{\rm rf}}\right)^{1/4}, \qquad (1)$$

to fit ν_s^4 vs. $\Delta f_{\rm rf}$ to a linear model to obtain both α_1 and α_2. This measurement was repeated at different values of SF current, through which we obtained the dependence of α_2 on SF sextupoles. A plot of α_2 vs. SF is shown in Fig. 2. The measured α_2 vs. SF current slope agreed with model calculation well. According to Eq. (27) of Ref. [3], $|\alpha_2| < 1000\alpha_1^{3/2}$ is the condition for SPEAR3 to be in the rf-bucket regime. This corresponds to only a small range of SF change, 108.5 ± 1.5 A in Fig. 1. The longitudinal motion must be in the alpha-bucket regime outside of this range. The transition from rf-bucket to alpha-bucket does not seem to cause obvious beam loss. As α_2 grows, the alpha-bucket shrinks, which eventually reduces beam lifetime.

OTHER OPERATIONAL ISSUES

Under the low-alpha mode, the beam orbit is considerably noisier than the normal lattice. Orbit variations up to 0.1 mm were typically observed. Further analysis showed that the orbit variations come mostly from momentum variations (on the order of 0.2×10^{-3}). Slow orbit feedback

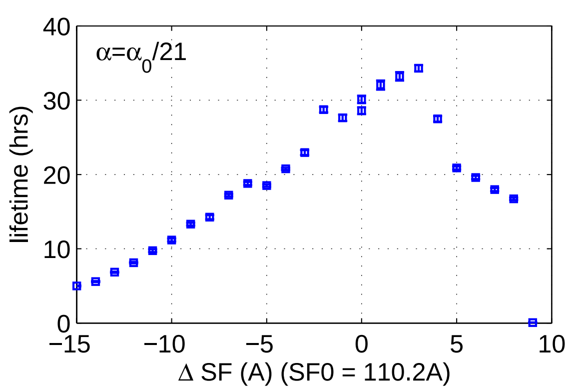

Figure 1: The lifetime for a fill at 100 mA in 280 bunches with respect to different SF setting.

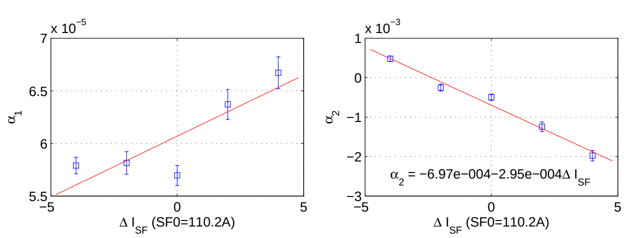

Figure 2: The first (left) and second (right) order alpha α_2 vs. SF. α_1 slightly depends on SF because of residual orbit offsets in sextupoles.

cannot remove the variations because they are at higher frequency. Fast orbit feedback can successfully take out the low-frequency components that are below 30 Hz. An orbit power density plot is shown in Fig. 3. The sources of such momentum variations could be phase errors of the rf cavity originated from the power supply system, or small variations of the magnetic fields. The longitudinal beam stability was derived from turn-by-turn BPM data. A longitudinal phase variation of 0.6 ps rms was measured at 100 mA total current. This is better than the nominal lattice which has 1.2 ps rms phase variation under the same rf setting.

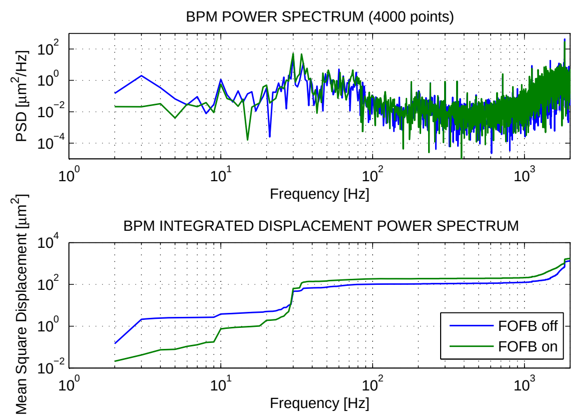

Figure 3: The power density of 4kHz BPM data corresponding to $D_x = 0.5$ m with FOFB on or off. Data taken with 100 mA beam.

Injection to the low-alpha mode is more difficult. The three injection kickers needed to be re-adjusted to weaker strengths, about 75% of that of the normal lattice. Since the allowance for rf frequency error is much smaller ($\sim \alpha$), care has to be taken to assure a proper rf frequency before injection can happen. The rf frequency saved from a previous accelerator physics study period was often found to be improper due to the seasonal and monthly drift. Therefore, the rf frequency of the immediate previous store of beam was usually used as a starting point. As soon as enough beam goes in to allow the BPMs to work, we adjust the rf frequency manually or with orbit feedback. The injection efficiency is also more sensitive to the timing of the injected beam. Typically the injection rate of the low-alpha mode is 10 mA/min, about 50% of the normal mode.

Beam lifetime at 100 mA total current and normal fill pattern (280 bunches) was above 30 hrs after we optimized the sextupole settings. The gas scattering (Coulomb and Bremsstrahlung) lifetime under the same condition was measured for the normal lattice to be about 100 hrs and it should remain roughly the same in the low-alpha mode. So the beam lifetime is dominated by Touschek scattering which is strongly dependent on the linear coupling and the momentum acceptance. We have investigated the momentum acceptance by performing a rf voltage scan in which lifetime was measured while rf gap voltage being reduced. The top plot of Fig. 4 shows the results. The lifetime first went up due to elongated bunch lengths until at $V_{\rm rf} = 1.35$ MV, when the bucket height shrink to below the momentum aperture determined by transverse dynamics. The corresponding momentum aperture, 3.1% was found to agree with our 6D tracking results (bottom plot of Fig. 4). The tracking was performed in the same manner as Ref. [5] using the tracking code AT [6]. The machine lattice used in tracking was determined by LOCO and its linear coupling was 0.04%. The Touschek lifetime for this condition was calculated to be 28 hrs. The measured Touschek lifetime (43 hrs) was longer because of bunch lengthening.

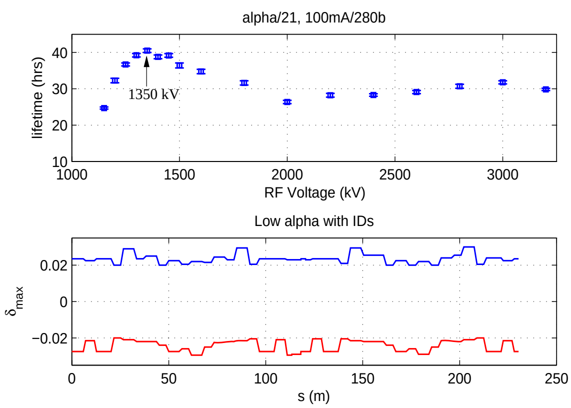

Figure 4: Top: lifetime at 100 mA while rf gap voltage was reduced. Bottom: momentum aperture obtained with AT tracking.

We have measured the bunch length for a variety of low alpha values and intensity levels with a streak camera. The results are reported in a separate paper in this conference [7]. With 100 mA in 280 bunches (0.36 mA/bunch) in the $\alpha_0/21$ mode, the rms bunch length was found to be 6.9 ps, longer than it would be if scaled down with the $\sim 1/\sqrt{\alpha}$ rule. Shorter bunch length was achieved with weaker bunch current and smaller alphas. The shortest bunch length we measured was 2.5 ps rms at $I_b \approx 3.5\ \mu$A when alpha was reduced by a factor of 240. In the low alpha mode, bunch length scales with $\sim 1/\sqrt{\alpha}$ rule only for very low bunch current due to the CSR instability [8]. According to Ref. [8], beam becomes unstable (for $\alpha > 0$) when

$$k\rho < 2\Lambda^{3/2}, \tag{2}$$

where $\Lambda = Nr_0\rho/\sqrt{2\pi}\sigma_z\alpha\gamma\sigma_\delta^2 R$ and $k = 2\pi/\lambda$ is the wave number of the unstable mode, ρ is bending radius, r_0 is the classical electron radius, N is the total number of electrons in a bunch, σ_z is the rms bunch length, γ is electron energy in unit of its rest energy, σ_δ is the rms momentum spread and R is the average ring radius. The long wavelength CSR modes are suppressed by the vacuum pipe when $\lambda > \lambda_{\rm cutoff} = 2b\sqrt{b/\rho}$, where $2b$ is vacuum height [9]. For SPEAR3, $\rho = 8.14$ m and $b = 17$ mm, which makes $\lambda_{\rm cutoff} = 1.55$ m. To fit our data, we found the first unstable mode has $\lambda = 4.5\lambda_{\rm cutoff}$. With this model, the bunch length scales with single bunch current according to the empirical rule $\sigma_{\rm min}[{\rm ps}] = 9.7 I_b[{\rm mA}]^{1/3}$ for SPEAR3. The calculated bunch length threshold and measurements are plotted in Fig. 5. The zero-current limits of bunch length for the two low-alpha modes and the normal operational mode are also shown as horizontal lines.

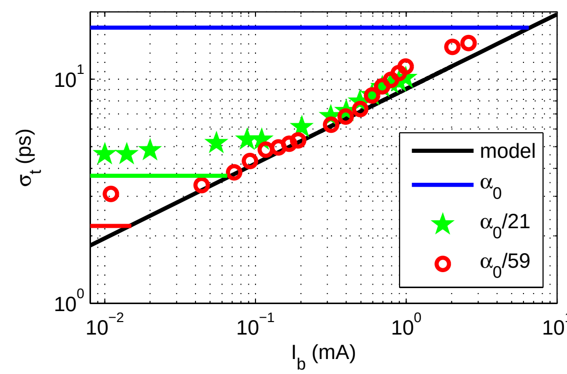

Figure 5: Measured bunch length in the two low alpha modes and the model calculation according to Ref. [8].

The CSR instability imposes a limit on the bunch length we can get by reduction of alpha at certain bunch current. Single bunch current as low as 1 μA is needed to achieve rms bunch length of 1 ps. Presently at this current, the noise level of half of our BPMs is too high for stable orbit control due to interference from the rf system. Work is ongoing to mitigate this problem.

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