MINI-BETA LATTICE FOR THE FEMTO-SECOND X-RAY SOURCE AT THE ALS*

Y. Wu, H. Nishimura, D. S. Robin, A. A. Zholents
LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA
E. Forest
High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0810, Japan

Abstract

After generating the first femto-second X-ray pulses at the Advanced Light Source (ALS), it becomes critical to improve the flux of this femto-second source for user experiments. A narrow-gap in-vacuum undulator has been proposed to be installed in one of the ALS straight sections. To realize the optimal performance of this undulator, a straight section lattice with a mini vertical beta function has been designed. Separation of electrons has been achieved by generating a sizable vertical dispersion via a local dispersion bump and a closed orbit bump. Particle tracking study shows that the modified ALS lattice for the femto-second x-ray source has an adequate dynamic aperture.

1 INTRODUCTION

A source of femto-second x-ray pulses had been recently commissioned at the Advanced Light Source (ALS) [1]. This source utilizes the technique where an ultra-short laser pulse is used to modulate the energy of electrons within a 100-femtosecond slice of the stored 30-picosecond electron bunch. The energy-modulated electrons are spatially separated from the main electron bunch by horizontal dispersion and are used to generate 300-femtosecond synchrotron radiation pulses at a dipole magnet. At present we are considering using an undulator rather than a bend magnet as a high flux source of femto-second x-rays. Lattice modifications have been studied to optimize the performance of this new source.

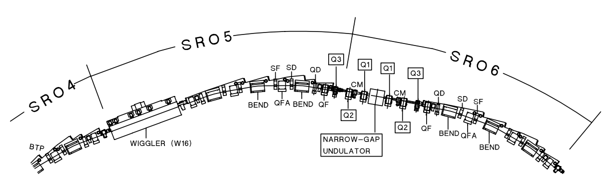

Figure 1: The layout of the ALS sector 5 and sector 6 with the wiggler magnet and the narrow-gap in-vacuum undulator. Three pairs of extra quadrupoles (Q1, Q2, Q3) are required to reduce the vertical beta function and preserve the beam dynamics.

The optimal performance of the ring with the narrow-gap undulator can be achieved by providing a small vertical beta function at the center of the undulator. A small vertical beta function provides a better match between the electron beam and x-ray beam in the undulator and helps preserve the available vertical physical aperture of the ring. In addition, a sizeable transverse η-function at the undulator or in the neighboring wiggler is necessary to separate the energy modulated electrons from the beam core.

An effective dispersion function describing the off-energy trajectory at the center of the undulator is,

$$(\eta_2)_{\rm eff} = \eta_2 - (\sqrt{\frac{\beta_2}{\beta_1}} \cos\Delta\phi\ \eta_1 + \sqrt{\beta_2\beta_1}\sin\Delta\phi\ \eta_1'), \tag{1}$$

where $\alpha_1 = \alpha_2 = 0$ at centers of the wiggler and undulator, η_1 and η_1' are dispersion functions at the center of the wiggler, η_2 is the dispersion function at the center of the undulator, and $\Delta\phi$ is the phase advance between the two centers. For a given amplitude of the relative energy modulation of electrons, $\Delta E/E_0$, the transverse separation of modulated electrons from the beam core is,

$$\frac{\Delta z}{\sigma_z} = \frac{\frac{\Delta E}{E_0}(\eta_2)_{\rm eff}}{\sqrt{\epsilon_z\beta_z + \sigma_E^2\eta_2^2}}, \tag{2}$$

where $z = x, y$ stands for one of the transverse planes, σ_z is the beam size, ϵ_z, β_z are the beam emittance and beta function, σ_E is the energy spread of the beam. It is apparent that a much smaller vertical emittance would allow the use of a smaller vertical dispersion to achieve the same relative separation. Let us point out that for a given $(\eta_2)_{\rm eff}$, the dispersion generated at the wiggler has advantage over that in the undulator. Because the dispersion function will contribute to the transverse beam size.

A good signal-to-noise ratio for the femto-second x-ray radiation can be achieved by providing adequate transverse separation of the energy modulated electrons from the beam core [2]. A separation of 5σ is desirable at the center of the undulator where $\beta_y = 0.5$ m. This can be achieved by a laser induced energy modulation of ~ 9 MeV (readily available in the current system) and an effective vertical dispersion of $(\eta_2)_{\rm eff} \approx 8.5$ mm, assuming a two percent emittance coupling, i.e. $\epsilon_y = 10^{-10}$ m-rad.

The narrow-gap undulator source also means a much reduced vertical physical aperture. A 5 mm undulator gap is nearly a factor of two smaller than the narrowest vacuum chamber (9 mm) that presently exists in the ALS ring. One particular concern is the potentially negative impact on the ring performance due to such a significant aperture reduction, namely the injection efficiency and lifetime. The inclusion of this device should not significantly change the single particle beam dynamics and a minimum of ± 10 mm horizontal dynamic aperture should remain for injection.

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2 SINGLE PARTICLE BEAM DYNAMICS

The ALS ring consists of 12 periodic sectors. The 16-cm period wiggler (W16) is located in straight 5 and the narrow-gap undulator will be located in straight 6 (see Fig. 1). To accommodate the narrow-gap undulator, the vertical β-function in straight 6 needs to be lowered from the present value of 4.0 m to 0.5 m. Therefore, the lattice periodicity breaking is inevitable in the mini-beta lattice. If one is not careful with the design of the mini-beta straight, the strong nonlinearities in the lattice become unbalanced to yield a significant dynamic aperture reduction as observed in our first simple mini-beta lattice design using two extra quadrupole pairs.

On the other hand, it is well known that the on-momentum single particle dynamics is unaffected if a portion of linear lattice is modified in such a way that a multiply of 2π phase advance ($2\,n\,\pi$, $n =$ integer) is added to either transverse plane while keeping this modified portion matched to the rest of the ring. However, it is impractical to implement such a large phase advance change in the extremely short ALS straight. Noticing that the ALS ring employs only the magnets with a mid-plane symmetry (normal dipoles, quadrupoles, and sextupoles) in its baseline lattice, we find that increasing the vertical phase advance by π in the mini-beta lattice will not affecting the on-momentum single particle dynamics.

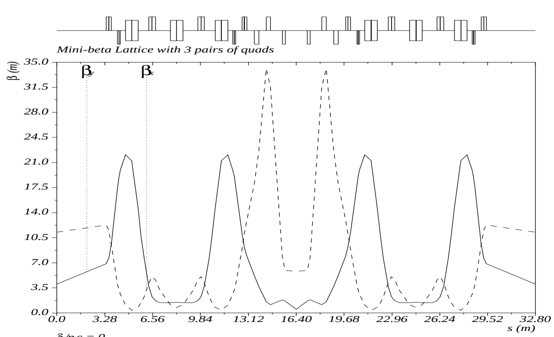

Figure 2: Symmetric mini-beta lattice with modified phase advances: $\Delta\phi_x = 0, \Delta\phi_y = \pi$.

Let us prove this. Suppose that $\mathcal{N} = \exp(:\, g(\vec{z})\, :)$ is the one-turn Lie map for the unmodified ring with the mid-plane symmetry, where $g(\vec{z})$ is the one-turn Lie operator and $\vec{z} = \{x, p_x, y, p_y\}$ is the 4D phase space vector. For a ring consisting of only magnets with the mid-plane symmetry, $g(\vec{z})$ is an even function of y and p_y, which yields,

$$\mathcal{N}(x, p_x, -y, -p_y) = \mathcal{N}(x, p_x, y, p_y). \quad (3)$$

Now we add a matched section to the linear lattice to alter its phase advances with $\Delta\phi_x = 2m\,\pi$ and $\Delta\phi_y = (2n+1)\,\pi$, where $m, n =$ integer. The Lie map for this addition, $\mathcal{R}(\vec{z})$, satisfies:

$$\mathcal{R}\,x = x,\ \mathcal{R}\,p_x = p_x,\ \mathcal{R}\,y = -y,\ \mathcal{R}\,p_y = -p_y, \quad (4)$$

therefore, $\mathcal{R}^{-1}(\vec{z}) = \mathcal{R}(\vec{z})$. Writing the modified one-turn map, $\mathcal{M} = \mathcal{N}\mathcal{R}$, we find for two turns:

$$\mathcal{M}^2 = \mathcal{N}\,\mathcal{R}\,\mathcal{N}\,\mathcal{R} = \mathcal{N}\,\exp(:\mathcal{R}\,g(\vec{z})\,:) = \mathcal{N}^2. \quad (5)$$

Thus it results in exactly the same two-turn 4D map as for the original ring. This proves the theorem.

A particular application of this idea is for the linear lattice modification to gain a π phase advance increase in the vertical plane while keeping the horizontal phase advance unchanged, i.e. $\Delta\phi_x = 0$ and $\Delta\phi_y = \pi$. Such a solution is referred as the π-trick. It is worth pointing out that by adding extra focusing elements, a slight increase in sextupole strengths will be needed in the modified ring to properly compensate the chromaticity. This will have a slight impact on the dynamic aperture.

Applying the π-trick, we designed two mini-beta lattices: one symmetric lattice with three pairs of additional quadrupoles in straight 6 for the case when the wiggler is open (see Fig. 2); the other slightly asymmetric lattice with six independently powered quadrupoles for the case when the wiggler is closed and wiggler compensation is on. We performed particle tracking for both lattices without errors to determine the bare lattice dynamic aperture. The results are compared with the standard ALS lattices. Fig. 3 shows that the on-momentum dynamic apertures of the ALS lattice remains the same after the mini-beta straight is created regardless of whether the wiggler is open or closed. These results illustrate the effectiveness of the π-trick. Note that the wiggler compensation in the unmodified ALS ring breaks the twelve-fold periodicity of the lattice to a certain degree, which has already resulted in a reduced dynamic aperture (comparing Fig. 3.(a) and Fig. 3.(b)).

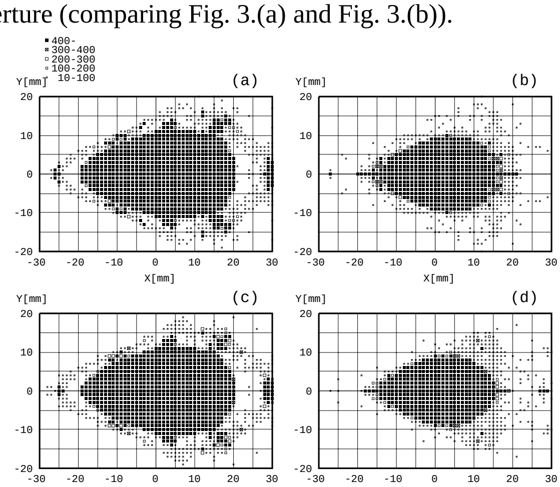

Figure 3: Dynamic apertures at the center of the regular straight ($\beta_x = 11$ m, $\beta_y = 4$ m) for the ALS bare lattice. Particles survived after more than 400 turns of tracking are considered to be stable. (a) ALS lattice with the wiggler open; (b) ALS lattice with the wiggler closed; (c) mini-beta lattice with the wiggler open; (d) mini-beta lattice with the wiggler closed.

3 GENERATION OF VERTICAL ETA

Two methods have been studied to generate the vertical dispersion. The first method creates a vertical η-bump at the wiggler by coupling the horizontal dispersion into the vertical plane. The second method generates a vertical η-wave using a local vertical orbit bump around the undulator.

At the ALS, sextupoles are equipped with the coils producing skew gradient of the magnetic field. A skew quadrupole kicks the horizontal dispersion into the vertical plane in the same way that a corrector magnet steers a closed orbit distortion around the ring. Turning on a skew quadrupole at the location s_0 with the horizontal eta function $\eta_x(s_0)$, a vertical η-function wave will be produced,

$$\eta_y(s) = \frac{K\,\eta_x(s_0)}{2\sin(\pi\nu_y)}\sqrt{\beta_y(s)\beta_y(s_0)}\,\cos(\phi_y(s_0) - \pi\nu_y), \tag{6}$$

where K is the normalized strength of the skew gradient, ϕ_y is the vertical phase advance, and ν_y is the vertical tune. A symmetric local vertical η-bump can be created using two pairs of skew quadrupoles in a part of lattice with mirror symmetry. However, due to the global coupling, some combinations of the skews would result in unacceptably large vertical emittances.

Eight skew quadrupoles in the neighboring arc sections are available for generating the vertical η-bump around the wiggler. A total of six different symmetric four-skew quadrupole bump combinations have been studied in their effectiveness in generating the vertical η-bump and in their contributions to the emittance coupling. However, the skew gradient in the ALS sextupoles are presently limited to a maximum value of $K = 0.0237$ at 1.9 GeV. By limiting the vertical emittance coupling to 1%, an optimal combination of the vertical η-bumps was found to create a $\eta_y = 17$ mm at the center of the wiggler, which corresponding to an effective $(\eta_y)_{\text{eff}} = 6.5$ mm at the center of the narrow-gap undulator. The dynamic aperture of this lattice is reduced slightly due to the further periodicity breaking by coupling. Nevertheless, the remaining dynamic aperture is still adequate for injection and good beam lifetime.

An even larger vertical η-bump can be realized if the skew windings in sextupole magnets can be powered at higher values. In addition, individual skew quadrupoles can be located at optimized locations to facilitate the generation of the η-bump while controlling the emittance coupling.

Eta-function can also be generated by the closed-orbit. A closed orbit bump can be utilized to control the eta function at the certain locations in the ring. In fact, the present vertical closed-orbit in the ALS produces a measured ± 2 mm vertical η-function distributed around the ring, which could account for some undesirable η'_y at the center of the narrow-gap undulator. To correct and control this unwanted η'_y in the undulator, a localized vertical orbit bump around the undulator can be used. In addition it can enhance the vertical separation of the energy modulated electrons. For example, we designed a lattice with a 0.4 mm vertical orbit bump at the undulator, yielding an effective $\eta_y = 3.6$ mm at the same location. Since the orbit bump is mostly located in the linear lattice, nonlinearity of the lattice is almost unperturbed. Particle tracking confirms that the dynamic aperture is unchanged with this local orbit bump.

4 MINI-BETA LATTICE WITH η-BUMPS

By combining the two different methods to generate the vertical η-function, we assembled a complete mini-beta lattice to produce an effective η_y about 10 mm at the center of the narrow-gap undulator (see Fig. 4.(a)). Particle tracking indicated that this lattice has an adequate dynamic aperture (see Fig. 4.(b)).

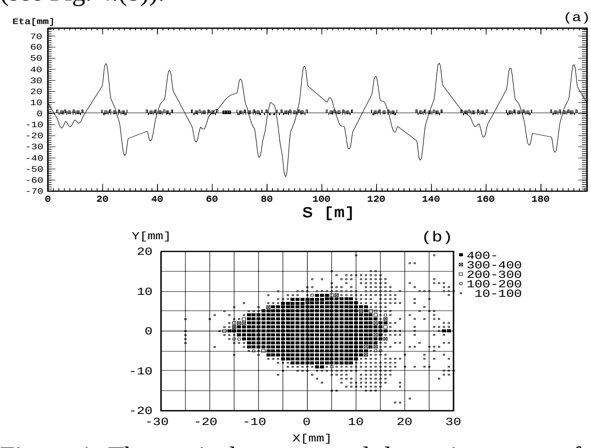

Figure 4: The vertical η-wave and dynamic aperture for a lattice with $(\eta_y)_{\text{eff}} = 10$ mm. (a) η-function generated by both the η-bump and vertical local orbit; (b) dynamic aperture for the lattice.

5 CONCLUSION

A mini-beta lattice ($\beta_y = 0.5$ m) has been designed to accommodate the narrow-gap undulator for the future femtosecond x-ray source at the ALS. We have developed a novel technique to restore the single particle nonlinear dynamics of the mini-beta lattice by increasing the vertical betatron phase advance by π while keeping the horizontal phase advance unchanged. We have investigated two different methods to generate the vertical η-function by coupling and by a local vertical orbit bump. A complete lattice solution with an effective $\eta_y = 10$ mm at the center of the narrow-gap undulator has been found with adequate dynamic aperture for electron beam injection and lifetime.

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