Incorporation of a 5 T Superconducting Wiggler in an MLI Synchrotron Light Source

Dan Y. Wang and F.C. Younger
Maxwell Laboratories, Inc., Brobeck Division
4905 Central Avenue
Richmond, California 94804

H. Wiedemann
Stanford Synchrotron Radiation Laboratory

Abstract

The MLI Model 1.2-400 synchrotron light source employs a Chasman-Green lattice with room temperature dipoles producing synchrotron radiation with a critical wavelength of 9.5 Å at 1.2 GeV. To perform angiography studies and micromachining research, the radiation spectrum must be shifted towards shorted wavelength. In this paper it is shown that a 5 pole, 5 T wiggler can be incorporated into the lattice in one of the 3.2 meter long straight sections to obtain a critical wavelength of 2 Å at 1.4 GeV without jeopardizing beam stability.

I. Introduction

The MLI Model 1.2-400 Synchrotron Light Source was optimized for x-ray lithography research. With a view towards other applications, the ring magnets were designed such that they are capable of operation up to 1.4 GeV. Moreover, there are free 3-meter straight sections. Therefore it is of interest to consider incorporating a 5 pole, 5 T superconducting wiggler in one of these straights. With a beam energy of 1.4 GeV, the critical wavelength becomes 2 Å, and the resultant radiation is suitable for micromechanics research as well as for angiography studies.

A 5 pole, 5 T wiggler introduces a significant perturbation to the beam dynamics of the storage ring. In terms of linear optics, wiggler fields add to the vertical focusing, causing a potentially unacceptably large vertical tune shift. In terms of non-linear optics, the higher order fields of the wiggler serve to reduce the dynamic aperture and thus limit the beam lifetime. Both these effects are discussed in section IV. It will be shown that tune compensation can be achieved, and that after including the combined effects of wiggler non-linearities, ring magnet non-linearities and orbit distortions, the dynamic aperture is roughly the same size as the physical aperture.

II. Wiggler Magnetic Fields

The characteristics of the 5 tesla superconducting wiggler for use in the MLI storage ring are shown in table 1. This wiggler is based on a cold iron core and Nb-Ti superconductor. The design uses three full-field poles and two half-field poles to give the field profile shown in figure 1. This profile resulted from a 2D calculation. The field profile is symmetrical and has a zero field integral, so the exit angle equals the entrance angle. The second integral is also zero to give zero net deflection of an on-axis on-angle electron. The calculated path for the on axis beam is shown in figure 2. As can be seen, the displacement at the center of the wiggler is 11.5 mm, and the peak displacement is 17.2 mm.

The wiggler has five coils per half, arranged in the conventional manner. Zero-field clamps at each end limit the extent of the fringe fields. The iron core provides strength and stiffness in addition to providing a highly saturated flux path. All of the cold portions of the wiggler are cooled by liquid helium and are supported in a cryostat with suitable insulation and current leads. A persistent current switch is not included because the magnetic

Table 1. Key Parameters

Maximum field strength	5 tesla
Number of poles	3 full strength, 2 half strength
Pole axial spacing	180 mm
Magnetic gap	70 mm
Rated coil current at 5 tesla	250 amperes
Superconductor	NbTi : Cu :: 1 : 1.8
Size	1.7 × 0.85 mm
Number of turns: large coil	2400
Number of turns, small coil	800
Total photon power at 400 mA	7.8 kW
Peak power per unit length	24.8 W/mm
Heat load to liquid helium	5 W

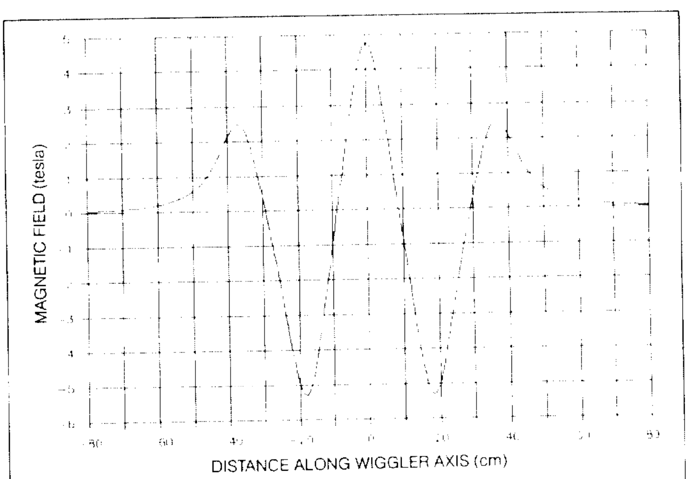

Figure 1. Magnetic field, 5 T wiggler.

0-7803-0135-8/91$03.00 ©IEEE

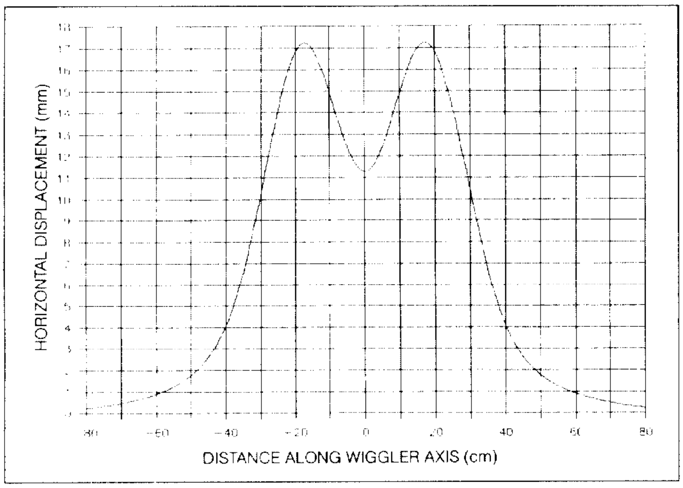

Figure 2. Beam displacement through 5 T wiggler.

field must be reduced during injection. The cycling of the magnetic field is inconsistent with the use of a persistent current switch.

For the purposes of the beam dynamics calculation, a pure sinusoidal field distribution was assumed. In addition, it is assumed that the field is completely uniform in the midplane of the wiggler. The fields can be written approximately as:

$$B_y = B(m) \sin (k_p(z-(m-1)A_p/2)) (1+\{(k_py)^2/2!+ (k_py)^4/4! \})$$
$$B_z = B(m) \cos (k_p(z-(m-1)A_p/2)) (k_py + \{(k_py)^3/3!\}) \quad (1)$$

where B(m) is given by

m	1	2	3	4	5
B(m)	$B_0/2$	$-B_0$	B_0	$-B_0$	$B_0/2$

The terms outside of braces contribute to linear optics perturbations due to the wiggler. The first term in B_y gives the deflection in the trajectory, while the first term in B_z causes vertical focusing. The terms within braces contribute to non-linear perturbations of the beam dynamics from the wiggler.

III. Tune Compensation

A series of hard-edged rectangular magnets were used to model the additional vertical focusing caused by the wiggler. To define each rectangular pole, two conditions were used: the net deflection angle and the net vertical focusing had to equal that resulting from the sinusoidal field distribution (1). Using the hard-edge model, lattice matching was performed using the program COMFORT with the wiggler inserted in the middle of a straight section. Local compensation was sought whereby only the Q_d's and Q_f's bracketing the straight section containing the wiggler were adjusted. This is preferable to global tune compensation from a synchrotron user viewpoint since the beam conditions in other superperiods are left nominally untouched. Due to the strong effect of the wiggler, local compensation alone led to a vertical tune shift of 0.04 which was deemed too large. To bring the tunes back to the original horizontal/vertical values of 3.264/1.168 (within ±20.004), small global adjustments of quadrupoles in all superperiods were made.

Two quadrants of the lattice functions of the resultant solution are shown in figure 3. With the wiggler included, for the same tune, the quadrupoles bracketing the wiggler are significantly reduced in strength, especially Q_d. The vertical focusing otherwise supplied by Q_d has been replaced by that of the wiggler. From a practical viewpoint, the reduction in quadrupole strengths is advantageous since no new quadrupoles are required. The small change in quadrupole strengths in non-wiggler quadrants changes the beam sizes by no more than 2.5%.

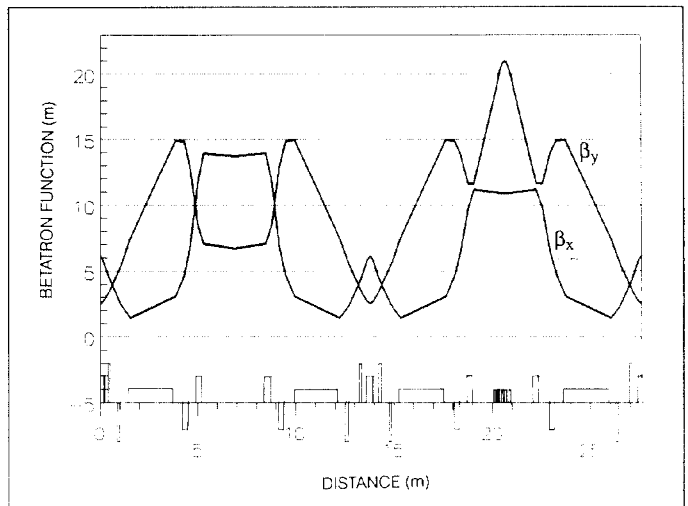

Figure 3. Betatron functions for quadrants without and with 5 T wiggler.

IV. Dynamic Aperture

All calculations of dynamic aperture were performed using an extended version of PATPET. The wiggler was represented as a series of rectangular magnets as described in section III for the purposes of modeling its beam deflection and focusing behavior. The effect of the non-linear fields which are shown within braces in equation (1) was modeled as concentrated kicks on the beam found by integration of the momentum changes caused by these fields along the first order beam path, over which the betatron phase advance is only a couple of degrees in either plane.

To obtain the most realistic estimate of the dynamic aperture (DA) in the presence of the wiggler, other effects which have an impact on the DA were included in this study: the higher order multipoles of the magnets (the strengths of which were found by measurement) and orbit distortions caused either by misalignment or magnet strength errors (the magnitudes of which were based on survey/alignment and power supply tolerances). The magnitudes of these terms are summarized as follows:

Multipole errors: All multipole strengths are defined as the magnetic multipole field at a radius of 1 cm relative to the field of associated main magnet at this radius.

Dipole: main magnet strength = 3.69249 T-m

order	6	8	10
strength	-1.18×10^{-4}	4.76×10^{-6}	-7.39×10^{-6}

Quadrupole: main magnet strength = 3.68 T/m-m (Q_a)

order	6	10	12
strength	4.82×10^{-4}	2.00×10^{-5}	-2.95×10^{-5}

Misalignment/strength errors: all quantities quoted are rms values of Gaussian distributions with a 2σ cutoff.

	x	y	ANGLE	STRENGTH
Quadrupoles, Sextupoles	0.3 mm	0.3 mm	0.05 deg	0.1%
Monitors	1 mm	1 mm	0.5 deg	NA
Dipole	NA	NA	0.1 deg	0.1%

Figure 4 shows the DA computed in units of beam sigma for a variety of circumstances. The baseline reference (curve I) is the DA for a ring with a bare lattice, a single "linear" wiggler insertion and sextupole correction to obtain a chromaticity of +1 in both planes. As seen, when the non-linear fields of the wiggler are included (curve II), the DA is reduced mostly in the vertical, as expected. The net reduction is about 30%. Adding the non-linear terms of the ring magnets (curve III) reduces the DA by another 60%. A further comparable reduction in DA is caused by misalignment and strength errors, as seen from curve IV. For curve IV, even though orbit errors were generally allowed throughout the ring, the orbit error at the wiggler was kept to no more than 0.5 mm. From this study it may be concluded that while wiggler non-linearities do have a significant negative impact on the DA, it is not the dominant one for the lattice studied.

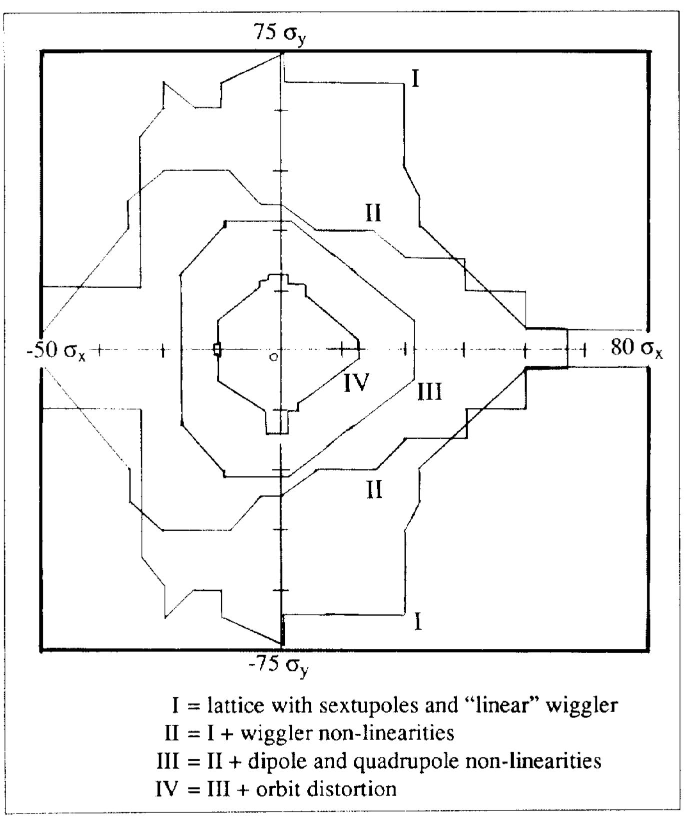

Figure 4. Dynamic aperture reduction from various sources.

Curve IV is a realistic representation of the DA when all non-linearities and orbit distortions are included. A few studies of the DA were made using different starting locations around the ring, effectively changing the sequence of random magnet misalignments. Two examples are shown in figure 5, with starting locations at the midpoint of Q_a and at the wiggler. As expected, the results are comparable in units of sigma, though in absolute space, the values of sigma are quite different (at Q_a, σ_x=1.33 mm, σ_y=0.60 mm; at the wiggler midpoint, σ_x=1.78 mm, σ_y=1.74 mm).

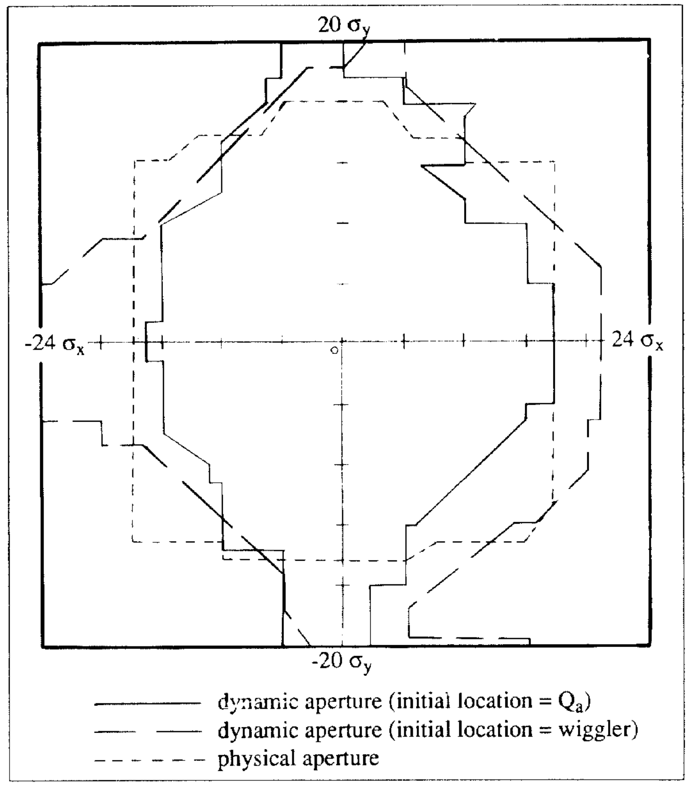

Figure 5. Dynamic aperture with magnet non-linearities, misalignments, and strength errors compared with physical aperture.

The DA can be compared to the physical aperture, which is defined to be the DA for the baseline reference with all real physical limits caused by the vacuum enclosure included. These limits were set at 35 mm × 35 mm for all quadrupoles and sextupoles, and 35 mm × 22 mm for the dipole. The DA with all non-linearities and orbit distortions included is approximately equal to the physical aperture, which is greater than $\pm 10\sigma$ in both planes, thus ensuring adequate quantum lifetime.

V. Conclusion

It has been shown that the MLI 1.2-400 light source operated at 1.4 GeV can accommodate a 5 pole, 5 T wiggler which serves to increase the critical energy of the synchrotron radiation to 6.5 keV. While the wiggler non-linearities do reduce the dynamic aperture by some 30%, the resultant dynamic aperture with all non-linearities and orbit distortions included is still equal to the physical aperture so that beam lifetime is not degraded.