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DESIGN CONSIDERATIONS FOR AN ULTRALOW EMITTANCE STORAGE RING FOR THE CANADIAN LIGHT SOURCE

L.O. Dallin, Canadian Light Source, Saskatoon, Canada

Abstract

Demands from light source scientists for more brilliant xray beams have resulted in the emergence of 4th generation storage rings. These demands include photon beams that are highly focussed and beams with high transverse coherence. Both these requirements are achieved with ultralow electron beam emittance. The practical development of the multi-bend achromat (MBA) concept by MAX IV [1] has spurred many synchrotron light sources around the world to develop similar machines. For existing facilities two options are available: upgrading existing machines or building a new structure. The Canadian Light Source (CLS) has explored both options and has determined a new storage ring is required. Several design options for a 3.0 GeV ring have been developed. Best results are achieved when the tune advances, through MBA unit cells, are integers. A shown by tracking this reduces the geometric effects of sextupoles. As a result lattices where no geometric sextupoles are required have been achieved while producing ultralow emittances.

INTRODUCTION

The CLS presently operates a 2.9 GeV storage ring [2] that has been in use since 2004. This ring has an electron emittance of 18 nm-rad. While this has been adequate many experiments to date the demand is steadily growing for a much more brilliant source. This is required in order to produce xray beams that can be focussed to sizes orders of magnitude smaller than is presently available. For such beams the stored electron beam emittance, ε, should be as small as possible. Of course, there are diminishing returns going to emittances much below the photon emittance, ε_{ph}, produced by the insertion devices (IDs). This so-called "diffraction limit" is given by ε_{ph} [pm] ≈ 100 / E_{ph} [keV] where E_{ph} is the photon energy.

As well, there is a desire for a high degree of transverse coherence [3]. This also requires a low emittance electron beam as shown in Fig. 1. To optimize the transverse coherence the electron β-functions should be matched to the photon β-function given by $\beta_{ph} = L/\pi$ where L is the ID length. For small coupling an electron emittance of 100 pm will produce a transverse coherence of 50% for 1 keV photons.

Consequently the CLS has been investigating lattice options for a 3 GeV storage ring with electron emittance less than 100 pm – an ultralow emittance lattice. An MBA with sufficient dynamic aperture (DA) for off-axis injection is desired. Attempts to fit a low emittance lattice into the existing CLS tunnel [4] have been discontinued.

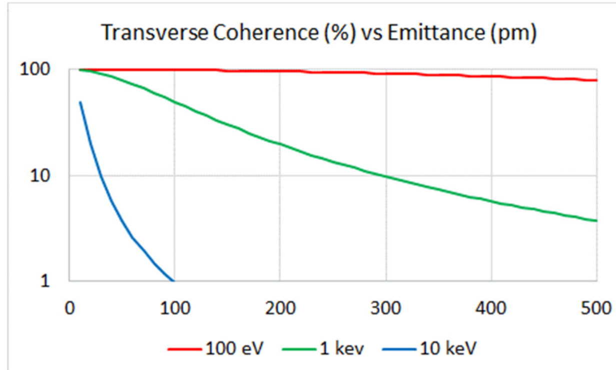

Figure 1: Transverse coherence vs electron emittance for three photon energies. (The electron and photon phase spaces are assumed to be matched. The vertical coupling is 1 %.)

MBA UNIT CELLS

A generic unit cell is shown in Fig. 2. Horizontal focussing is supplied by the quadrupole magnets and vertical focussing by the gradient bend magnet. Two families of sextupoles are used to adjust the horizontal and vertical chromaticities. Beam optics calculations were done with OPA [5]. To achieve an ultralow emittance a horizontal tune advance of about 0.4 is near optimum.

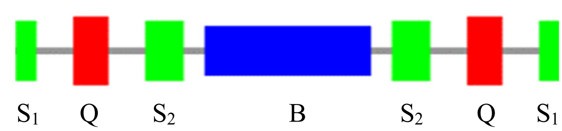

Figure 2: Generic unit cell for the MBA lattice. S: sextupole; Q: quadrupole; B: (gradient) bend magnet.

To reduce the geometric effects of the sextupoles the total tune advance, $\Delta\nu_x$, in all the MBA cells should be an integer. For the CLS lattice 7 cells are used with a total tune of 3 or a tune of 3/7 (= 0.429) per cell. The effects of the sextupoles are shown in Fig. 3. An off axis particle (x = 10 mm) is tracked through 7 cells with sextupoles ON, to give zero chromaticity, and sextupoles OFF. Tracking results for a ½ integer tune advance ($\Delta\nu_x = 2.5$) and an integer tune advance ($\Delta\nu_x = 3.0$) are shown. Clearly the integer tune advance ($\Delta\nu_x = 3.0$) is desirable as the geometric effects of the sextupoles cancel after 7 cells.

To maximize the DA there is also some advantage to adjusting the vertical tune advance, $\Delta\nu_y$, through the 7 cells. A tune advance of $\Delta\nu_y = 1.0$ is used. The reworked unit cell with these tune advances is shown in Fig. 4. A bend angle of 2.8125° is used. Including to half angle bends in the matching cells (see below) the total bend of the MBA is 22.5°. A unit cell emittance of 85 pm is achieved.

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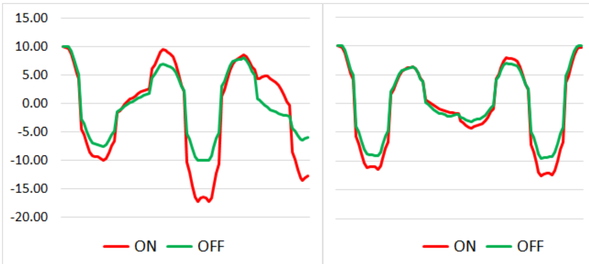

Figure 3: Tracking through 7 cells starting from a horizontal offset of 10 mm with sextupoles ON and OFF. Left: $\Delta\nu_x = 2.5$; Right: $\Delta\nu_x = 3.0$.

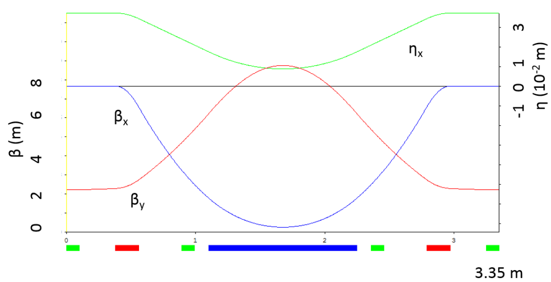

Figure 4: Unit cell with tune advances set to $\Delta\nu_x = 3/7$ and $\Delta\nu_y = 1/7$.

MATCHING CELLS AND THE MBA

The 7 unit cells are the core of the MBA structure. Matching cells are added at each end to provide straight sections for IDs, to adjust the MBA tunes, and to control the dispersion in the straights. In each matching cell a single bend is used to adjust the dispersion. The bend angle is one half that of the bends in the unit cells. Drifts of 5 m are available for IDs and for injection. The full MBA structure is shown in Fig. 5. The emittance is 81 pm for the full MBA structure.

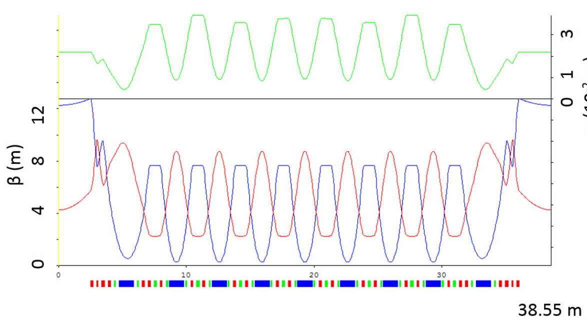

Figure 5: MBA.

In the centre of the long straights the machine functions are $\beta_x = 12.3$ m, $\beta_y = 4.3$ m, and $\eta_x = 0.022$ m (i.e., some dispersion is allowed in the straights). The horizontal β-function in the centre of the straight is kept large for off-axis injection.

For off-axis injection a horizontal DA greater than 5 m is desirable. With the reduction of the geometric effects from the sextupoles a good DA is achieved using only the two families of sextupoles in the unit cells. I.e., no geometric sextupoles are required. The DA and momentum acceptance (MA) for the MBA are shown in Fig. 6.

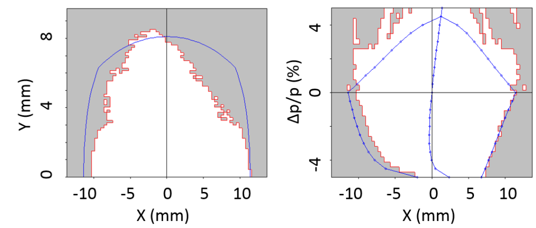

Figure 6: DA (left) and MA (right) for the MBA.

MBA WITH REVERSE BENDS

A substantial decrease in emittance can be achieved by introducing 'reverse bends' in the unit cells. For this purpose the quadrupole magnets are offset to produce a reverse bend of -0.2°. The total bend of the cell is kept the same by increasing the gradient bend to 3.2125°. For the quadrupole BL = 8.60 T. Consequently an offset of -4.1 mm will produce the desired reverse bend.

With the reverse bends the dispersion in the main dipole is reduced by about a factor of two as shown in Fig. 7. The emittance is reduced from 81 to 36 pm. Small increases in the sextupole values are required to adjust the chromaticities to zero. As shown in Fig. 8, the reverse bends cause very little change to the DA and MA.

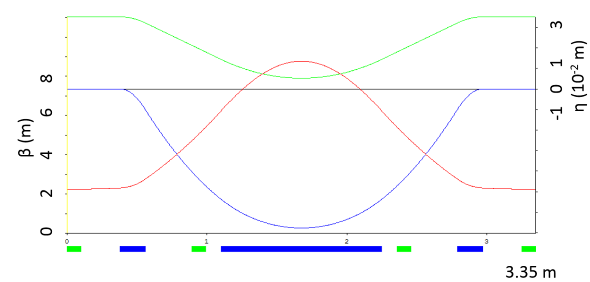

Figure 7: Unit cell with quadrupoles replaced by reverse bends. A reduction of dispersion in the main dipole results.

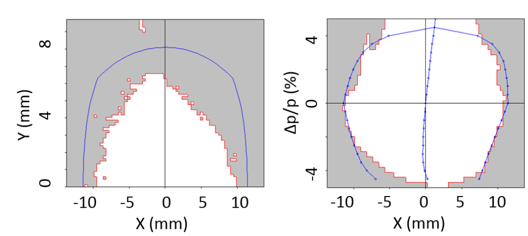

Figure 8: DA and MA for MBA with reverse bends.

DISCUSSION

The ultralow emittance lattice presented here was designed with considerations for off-axis injection. As a result β_x in the long straights is large and is not optimized to produce the largest possible transverse coherence (see Fig. 9). Improvement to the coherence could be achieved by reducing β_x in the straights not used for injection. With 1% coupling there is little to be gained by reducing β_y.

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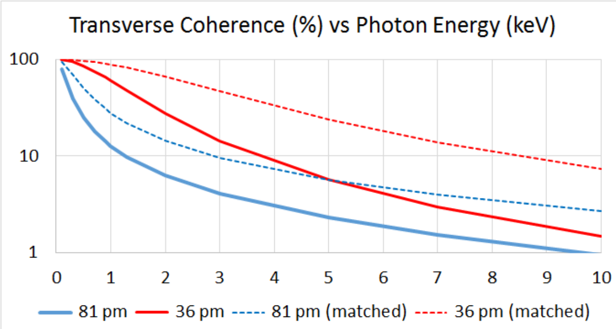

Figure 9: Transverse Coherence for the 81 pm and 36 pm MBAs. ID length is 4 m and vertical coupling is 1 %.

TRACY-3 [6] was used to check the effects of misalignments on the DA. Elements were considered to be placed on girders with rms errors of 25 µm. Girders were assumed to be aligned with rms errors of 100 µm. Best results were achieved when four girders were used. This result is shown in Fig. 10. To begin with TRACY predicts a smaller DA for the bare lattice. Even, so it appears that the design goal of 5 mm DA for injection can be met. The MA with errors is shown in Fig. 11.

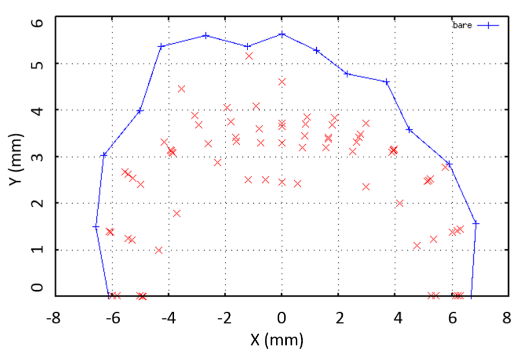

Figure 10: DA with alignment errors.

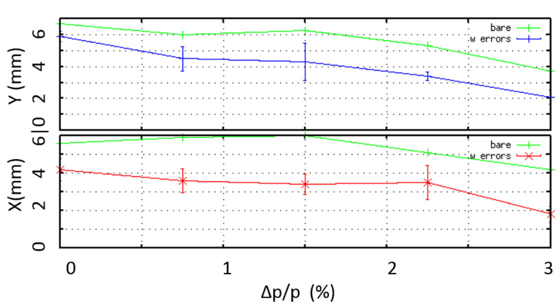

Figure 11: MA with alignment errors.

CONCLUSION

A MBA lattice has been designed with an ultralow emittance and adequate DA for off-axis injection. Improvement to the transverse coherence can be improved reducing the machine functions in the ID straights. Selected machine parameters are listed in Table 1. Values are the same for the reverse bend lattice unless listed different. The longitudinal beam parameters are calculated by OPA using an RF frequency of 500 MHz.

Table 1: Selected Machine Parameters

		Reverse bend
Energy	3.0 GeV	
Circumference	616.8 m	
Periodicity	16	
Tunes		
ν_x	62.2	
ν_y	23.3	
Emittance	**81** pm	**36** pm
Chromaticities		
χ_x	-130	
χ_x	-56	
Momentum Compaction	$0.11e^{-3}$	$0.048e^{-3}$
RF frequency	500 MHz	
RF voltage	3 MV	
Harmonic number	1028	
Energy spread	0.06 %	0.08 %
RMS bunch length	1.56 mm	1.35 mm
Momentum acceptance	6.9 %	10.3 %
Current	300 mA	
Coupling	1 %	
Total lifetime	7.1 hr	16.7 hr

An input file is given in the appendix. It should be noted that no difficult magnets are required.

APPENDIX

Input values for the reverse bend MBA lattice.

```
long: drift,l=2.50;
d1: drift,l=0.28;
d2: drift,l=0.33;
d3: drift,l=0.11;
dm: drift,l=0.28;
qm1: quadrupole,l=0.18,k=1.085912;
qm2: quadrupole,l=0.12,k= -5.174688;
qm3: quadrupole,l=0.24,k=5.045731;
qm4: quadrupole,l=0.18,k= -3.34117;
qm5: quadrupole,l=0.18,k= -0.21080;
qm6: quadrupole,l=0.18,k=3.273964;
gbend: bending,l=1.15,t=3.21250,k= -0.990;
rbend: bending,l=0.18,t= -0.2,k=4.764;
mbend: bending,l=1.15,t=1.40625,k= -0.3486;
s1: sextupole,l=0.10,k=211.512562;
s2: sextupole,l=0.10,k= -327.942371;
/correctors/
c1: sextupole,l=0.10,k=0.0;
c2: sextupole,l=0.10,k=0.0;
c3: sextupole,l=0.10,k=0.0;
cell: s1,d1,rbend,d2,s2,d3,gbend,d3,s2,d2,rbend,d1,s1;
match: long,qm1,dm,qm2,dm,qm3,dm,qm4,dm,c1,dm,
  mbend,dm,c2,dm,qm5,dm,qm6,dm,c3;

mba: match,7*cell,-match;
ring: 16*mba
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