ALS-N – A CANDIDATE FOR A NEXT-GENERATION SYNCHROTRON LIGHT-SOURCE

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1 INTRODUCTION

Judging from the experiments currently being pursued at the ALS, there is already a compelling case to be made for considering a future synchrotron radiation source that has a higher beam brightness than the third-generation facilities. For example, a large, and growing fraction of the ALS scientific program is based on soft x-ray microscopy experiments in materials science. Currently these experiments use high-brightness undulator radiation, on beam lines that are already oversubscribed. Dedicated beam lines from bend magnet sources would be useful for these techniques if the source brightness could be pushed to $\approx 2 \cdot 10^{16}$ $\mathrm{photons/(s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%b.w.)}$, i.e., a factor of 20-100 higher (depending on wavelength), than currently available at the ALS. Another growing class of experiments uses microfocused beams for microanalysis, microdiffraction, microEXAFS, microXPS, and microNEXAFS. These are classic brightness experiments, but even at the high ALS brightnesses, require long exposure times. Finally there is a requirement to get to ≈ 2 keV in the fundamental peak of the undulator spectrum, to access most transition-metal L-edges, and the rare-earth M-edges. This could be achieved with a machine energy of 2.5-3.0 GeV. An alternative strategy is to go to smaller gaps with a shorter period undulator – which is compatible with lower emittance beams [1].

With this incentive we have begun studies of a storage-ring based source of soft x-rays. We are concentrating on machines with an energy of 2-2.5 GeV, and a circumference of $\approx$ 350-400 m, with the ultimate goal of building such a machine on the site of the Bevatron at LBNL. We will address the following questions in this paper: can a lattice be generated with these constraints, plus have a natural emittance of ≈ 0.5 nm-rad, and have sufficient dynamic aperture; can the emittance be maintained under the influence of intrabeam scattering (IBS); what is the Touschek lifetime?

Other considerations are beam stability and cost. Part of our thinking is to build an inexpensive machine. To this end we are borrowing an idea from the FNAL recycler ring [2] to use permanent magnets for most of the lattice. With the small aperture anticipated for the ring (around 20 mm horizontal x 10 mm vertical full widths), such magnets could be relatively small and inexpensive. Further, the magnets would be of light weight, therefore have a relatively inexpensive mounting system, and have no low-frequency vibrational modes. Another advantage is that the magnets have no power requirements (maybe a little for trims), and therefore do not require cooling water. Cooling water and air temperature variations have been the source of many motion problems in the ALS [3].

* This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy, under Contract No. DE-AC03-76F00098

2 LATTICE DESIGN

The primary goal for the lattice design of ALS-N is to reach an horizontal emittance of $\epsilon_x \approx 0.5$ nm-rad at 2 GeV while the ring fits on the Bevatron site at the Berkeley. This restricts the circumference to $\approx$ 350-400 m. For optimal use of the more or less rectangular site, a racetrack-shaped ring is considered. It consists of two $\approx 120^o$ arcs, and dispersion-free straight sections which are separated by weak bending magnets.

2.1 Theoretical minimum emittance

The horizontal equilibrium emittance is given by

$$\epsilon_x \approx \frac{\gamma^2}{J_x \rho} < H >_{dipole} \tag{1}$$

where J_x is the horizontal damping partition number, ρ is the bending radius of the dipole, and $< H >$ is the function

$$H = \frac{1}{\beta_x}(\eta_x^2 + (\alpha_x \eta_x + \beta_x \eta_x')^2) \tag{2}$$

averaged over the dipole. $\beta_x, \alpha_x, \eta_x, \eta_x'$ are the usual optical functions and their derivatives. It has been shown [4] that the theoretical minimum emittance is reached if the horizontal beta- and dispersion-functions reach their minimum in the center of the bending magnets, with the following values:

$$\beta_{x,min} = \frac{1}{2\sqrt{15}} L \qquad\qquad \eta_{x,min} = \frac{L^2}{24\rho^2} \tag{3}$$

The horizontal emittance is then:

$$\epsilon_{x,min} \approx \frac{\gamma^2}{J_x \rho} \frac{1}{12\sqrt{15}} \rho \theta^3 \tag{4}$$

where θ is the bending angle of the dipole; $\epsilon_{x,min}$ then depends solely on the bending angle and the damping partition number.

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Since the dispersion-function has a minimum in the middle of the bending magnet, lattices built with this strategy do not provide dispersion-free straight sections as the Chasman-Green lattices do. The dispersion-induced emittance in the middle of a straight section ($\alpha = \eta' = 0$) is given by

$$\epsilon_\eta = \frac{(\eta_x \delta)^2}{\beta_x} \quad , \tag{5}$$

where δ is the relative energy spread. Thus the gain in horizontal emittance is partly compensated by an enlargement of the beam size due to dispersion.

Several synchrotron radiation source lattices have been worked out [5] [6] following the theoretical minimum emittance strategy.

2.2 The arc cell

The main contribution to $< H >_{dipole}$ and thus to the emittance of the storage ring comes from the bending magnets in the arcs. A compact low-emittance arc is obtained by placing a combined-function bend-magnet at the position of the defocusing element in a FODO cell. This leads to a minimum of the horizontal beta- and dispersion-functions in the middle of the dipole, which is a requirement for small emittance. Furthermore a combined-function magnet reduces the emittance even more by increasing the horizontal damping partition number J_x.

The phase advance per cell is 90^o horizontally and 60^o vertically, thus allowing for a sextupole scheme with cancelation of the first-order driving-terms after 3 cells. The cell length and dipole strength are chosen to give a compact arc and the desired emittance of $\epsilon_x \approx 0.5$ nm-rad. This is far away from the theoretically minimum achievable value but gives moderate focusing and phase advance per cell. The total cell length is 2.3 m. The dynamic acceptance for this cell is rather large ($A_x \approx A_y \approx 50$ mm-rad for $\delta p/p \pm 3\%$).

2.3 The insertion-device straight sections

The insertion-device sections contain only a small fraction of the bending magnets of the storage-ring. Their contribution to the natural emittance is small and so one does not have to put much emphasis on getting a low-emittance lattice in this part of the ring. On the other hand, the insertion-device straight sections should have zero or very small dispersion to prevent enlargement of the source size due to energy spread in the beam. With equation 5 and the assumptions $\delta \approx 1 \cdot 10^{-3}$, $\beta_{x,straight} \approx 3$ m, the dispersion in the straight should be smaller than ≈ 0.02 m in order not to contribute more than 20% to the overall beam-size. Either a double-bend (DBA) or a triple-bend achromat (TBA) structure, including combined function magnets with weak bending (2.5^o bending angle per magnet), fulfills these requirements. Because of the weak bending in these cells, the dispersion function stays small and thus the sextupoles for the chromatic correction have to be strong. This leads to a very small dynamic acceptance for these cells. Sextupole arrangements to overcome this problem are being investigated.

2.4 The complete ring

The two parts of the storage ring are connected by matching sections. Due to the degeneration of symmetry from several tens down to two, the dynamic acceptance collapses. A more complicated sextupole distribution may overcome this problem. Another solution would be a machine made of identical cells, which however would not fit so well into the existing site. Up to now, a storage ring constructed out of 52 FODO cells and 18 DBA cells gives the best performance. A footprint of the machine on the Bevatron site is shown in figure 1; the main machine parameters are summarized in table 1.

The magnet aperture will be decreased to values of ≈ 10 mm best-field diameter. These small magnets can be built with standard permanent-magnet technology to achieve the fields and gradients given in table 1 [7].

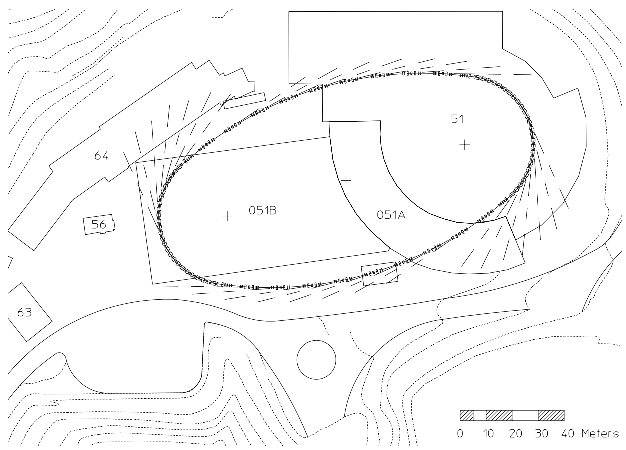

Figure 1: Footprint of ALS-N on the Bevatron site. The straight-section beam lines are 40m long.

Table 1: Main parameters of ALS-N

Energy	2 GeV
Circumference	380 m
Natural emittance	$5.5 \cdot 10^{-10}$ m-rad
Natural energy spread	$8 \cdot 10^{-4}$
Momentum compaction	$6.7 \cdot 10^{-4}$
Tunes x,y	33.18, 23.73
Chromaticities x,y	$-46, -76$
Number of free straights	16, each 5 m long
β_x, β_y in straight	3 m, 3.2 m
β_x, β_y in arc bend	0.8 m, 4 m
Max. current	400 mA
Bending magnet	$l = 1.0$ m, $B_y = 0.585$ T, $\partial B_y/\partial x = 12$ T/m
Strongest Quadrupole	$\int \partial B_y/\partial x = 10$ T
Strongest Sextupole	$\int \partial^2 B_y/\partial x^2 = 160$ T/m

3 BEAM SIZE AND LIFETIME

The electron density of a next-generation light-source will be one order of magnitude higher. The beam lifetime will be short due to Touschek scattering and the beam emittance will grow due to intrabeam scattering. The deleterious high-intensity effects can be considerably mitigated by increasing the bunch-length using well-known techniques such as adding a third harmonic cavity. These high-intensity effects were studied using a modified ZAP code [8]; the results are summarized in table 2.

Coupling between the vertical and longitudinal motion is an important factor. For smaller coupling the vertical beam size shrinks and the intrabeam scattering rate increases, which in turn increases the horizontal and longitudinal beam sizes. Higher RF voltage decreases the bunch length and increases the intrabeam scattering rate which in turn increases the transverse beam size. The microwave instability tends to increase the energy spread and the bunch length. Since the threshold for the microwave instability only depends on the peak current, adding a third-harmonic cavity greatly increases the threshold current I_{MWI}. Table 2 gives lifetime and emittance with and without a third-harmonic cavity and with different values for the initial emittance-coupling $\kappa = \epsilon_y/\epsilon_x$. The energy acceptance was assumed to be 3 %, given by the RF-bucket height.

Table 2: Lifetime and emittance of ALS-N at low and maximum current with and without a third-harmonic cavity.

Current [mA]	ϵ_x [nm-rad]	κ %	τ [h]	σ_L [mm]	$\frac{\Delta E}{E}$ %	I_{MWI} [mA]
≈ 0	0.55	3		5.2	0.8	6.4
400	1.05	3	2.9	7.0	1.1	6.4
400[a]	0.8	3	6.4	19.5	0.97	260
400[b]	0.95	1	4.4	19.5	1.0	260

[a] third-harmonic cavity
[b] third-harmonic cavity

4 BRIGHTNESS

The brightness expected from insertion devices and bend magnets is plotted in figures 2 and 3 in comparison to the ALS. The values are calculated up to the 7th harmonic for undulators with 5 cm (U5) and 2 cm (U2) period length and a peak field of 1 T. The storage-ring current is 400 mA, and the coupling ϵ_y/ϵ_x is assumed to be 1%. The dipole radiation is calculated for a normal lattice-dipole and a special high-field dipole ($B = 5$ T) at a location with small beta-functions.

5 SUMMARY

We have begun an investigation of a next-generation light-source, and shown that a factor of 10-100 increase in photon brightness from undulators can be achieved in the soft x-ray energy range. Both the electron emittance and bunch length suffer significantly from the effects of IBS at a beam current of 400 mA. Though this caps the achievable beam brightness, there is a favorable increase in Touschek lifetime. The brightness from bend magnets is also increased, to the level that it starts to become interesting for soft x-ray microscopy. With specially tailored optics at the bend magnet sources, the photon brightness could be increased by another order of magnitude.

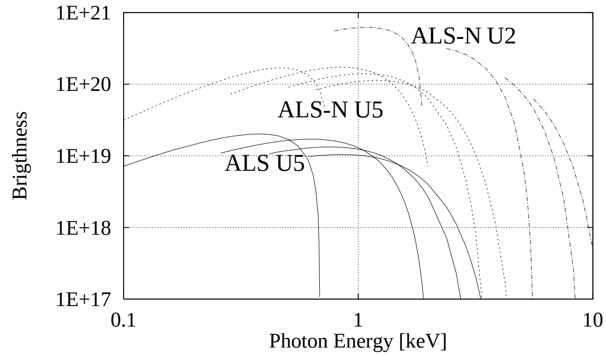

Figure 2: Brightness [$\frac{\mathrm{photons}}{(\mathrm{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\% b.w.})}$] from insertion devices at the present ALS and the ALS-N.

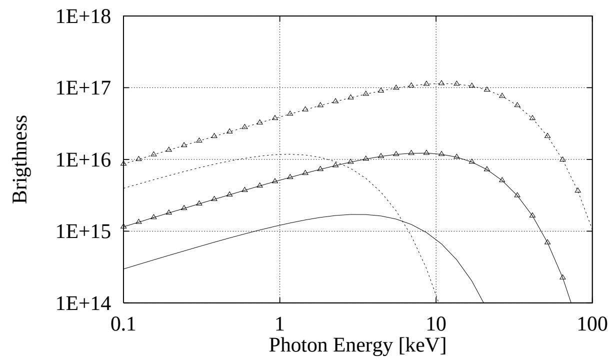

Figure 3: Brightness [$\frac{\mathrm{photons}}{(\mathrm{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\% b.w.})}$] from lattice bend magnets and high-field bend magnets (triangles) at the present ALS (solid lines) and the ALS-N (dashed lines).

6 REFERENCES

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