A Design of a Compact Superconducting X-Ray Source

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ABSTRACT
We describe a compact light source that follows from an early design of the UCLA 0 Factory. This source uses novel superconducting magnets and can provide several amps of current, making it suitable for x-ray lithography uses. The key feature of the source is the high beam current and flexibility of the machine lattice with the potential for short electron bunches to increase the longitudinal source brightness. We show how the light source can be scaled to 3 GeV to provide hard x-rays and still be kept compact.

1. INTRODUCTION

Several first generation compact light sources are presently being constructed around the world.1 We believe it is time to start the design and construction of a second generation compact source based on recent developments in superconducting magnet technology and beam dynamics in storage rings. It is essential that such a second generation source be more flexible as well as more stable than the first generation. Our design follows a careful study of a compact electron storage ring for a high luminosity 0 factory. Based on this study we believe it is now possible to design and construct a superior compact x-ray light source for commercial applications.

This paper explores a nearly conventional compact synchrotron light source. The greatest novel feature of this light source is the strong superconducting bend magnets. This allows the ring to be compact and to deliver high energy synchrotron x-rays. However these strong bend magnets have a great impact on the linear lattice of the storage ring. The sextupole magnets for chromatic correction of the lattice are also
dealt with carefully, attempting to get cancellation of their nonlinear effect on the beam. These factors and the small size of the ring (18 meters) make the design of the linear lattice nontrivial.

The following paper discusses and summarizes our results for the lattice of a 700 MeV electron storage ring for use as a synchrotron light source. In the following, the properties of the bend magnets are summarized, the linear lattice design and rationale are given, the dynamic aperture is calculated, and the characteristics of the synchrotron light is discussed. In addition, we briefly contemplate the first design of a compact multi GeV light source for hard x-rays for various applications including micro-machining and medical applications.

2. THE φ FACTORY

The present design of the light source is based on the design of the UCLA φ Factory. In the φ Factory, 510 MeV electrons collide with 510 MeV positrons for the study of detailed properties of the φ meson and fundamental questions of quantum mechanics. The earlier Phase I design uses six strong, superconducting bend magnets and has a small circumference. Because of possible difficulty reaching the high end of the design luminosity, later efforts shifted to the study of a larger circumference quasi-isochronous storage ring. However, the small circumference and strong bends in the Phase I lattice led some of us to redesign it as a compact synchrotron light source. It is this design that is discussed here.

3. THE LIGHT SOURCE LATTICE

The ring has a racetrack shape, shown schematically in Fig. 1. It has reflection symmetry about a vertical line through the center of the figure. It consists of two arcs and two straight sections: the straights have equal lengths but different beam optics. The magnet layout and orbit functions are shown in Fig. 2. The origin is in the center of the insertion-device region. Quadrupoles are represented by rectangles shown above or below the axis, according to whether they are horizontally focusing or defocusing, respectively. Dipoles are shown as rectangles centered on the axis.

Each arc consists of three cells, with the following cell structure:

\[
QF \ D \ B \ D \ QF,
\]

where \(QF\) is half of an F-quadrupole, \(D\) is a drift space, and \(B\) is a rectangular dipole. The cell closest to the insertion straight in each arc is missing its first two elements.
Fig. 1: Schematic layout of the light source. The bend magnets are shown as large boxes at each angle in the central orbit. The quadrupoles are shown as thinner rectangles and the sextupoles as lines terminated with arrows or inverted arrows.

Fig. 2: Lattice parameters for the light source. The insertion device region is in the center of the straight section shown at the ends of the figure; the injection system is in the straight section shown in the center of the figure.
The phase advance of a cell is $\mu = 120^\circ$, horizontally and vertically, which is achieved by fitting the length of the drift and the strength of the quadrupole. Consequently, the phase advance of an arc is $360^\circ$, which causes the dispersion to have zero value in each of the straight sections. The large $\mu$-value gives a relatively small emittance to the ring. Each arc contains two F-sextupoles combined with the F-quadrupoles and two D-sextupoles in the drift spaces adjacent to the center dipole.

The lower straight section in Fig. 1 is the site for the injection and RF systems. It consists of two $\mu = 90^\circ$ FODO cells without bends, so it has a phase advance of $180^\circ$ and a $-1$ transfer matrix. Hence the $\beta$-functions remain matched from one arc to the next, and each of the four sextupoles in the left-hand arc has a $3 \times 180^\circ$ phase difference from the corresponding sextupole in the right-hand arc. This arrangement greatly enhances the single-particle stability of the ring.

The upper straight section in Fig. 1 is called the Insertion Region, since wiggler or undulator insertion devices could be installed there. In each half, symmetrically placed
about the center. are four quadrupoles. These quadrupoles are adjusted to transport the \( \beta \)-functions from periodic values in the arc cells to a waist at the straight-section center, and in addition to give the ring the desired fractional tunes. These fractional tunes were carefully chosen to maximize the dynamic aperture.

The compactness of the ring is due to reducing the number of superconducting magnets and other elements to the minimum number needed to achieve the design requirements.

The linear lattice was designed using the S . NCH program. The main parameters of the ring lattice are shown in Table 1.

4. THE DYNAMIC APERTURE

The dynamic aperture was studied using variants of KRACKPOT, a tracking code useful for small storage rings. This program does not expand the square root of the momentum, thus giving more accurate calculations of the nonlinearity. Using KRACKPOT and SYNCH we found that the dynamic aperture of the ideal machine was robust; see Fig. 3.

Particles were tracked around the ring for a number of turns in order to study the dynamical stability of particles circulating in the ring. The tracking simulator was a simplectic integrator which represented the magnet with thin lenses and drifts. The cavity is represented as a thin lens cavity. The integrator was derived from the full six dimensional Hamiltonian for a particle in an isomagnetic (piecewise constant) guide field. The Hamiltonian is given by

\[
H = -\frac{eA_z(x, y)}{c} - (1 + \frac{x}{\rho})(\frac{E^2}{c^2} - m^2c^2 - p_x^2 - p_y^2)^{1/2}
\]

where \( A_z(x, y) \) is the component of the vector potential along the longitudinal direction of motion, \( \rho \) is the local radius of curvature and \( p_x \) and \( p_y \) are the \( x \) and \( y \) components of the momentum.

It is necessary to use the full isomagnetic Hamiltonian because this ring has a small bending radius of 0.425 meters in the dipoles. Also the particles' transverse momentum can be a significant fraction of its total momentum because of the low energy and strong focusing properties of the lattice. Though this problem is not as significant in the light source design as the collider design where the particles are focused very strongly down to the interaction point to make high luminosity.

The tracking results presented were done for an 'ideal lattice' where no magnetic or position errors were introduced. Particles were tracked without synchrotron oscillations...
Coupled: \[ \sigma_{x_c} = 0.545 \text{ mm} \]
\[ \sigma_{y_c} = 0.380 \text{ mm} \]
Uncoupled: \[ \sigma_{z_0} = 0.771 \text{ mm} \]

**Fig. 3:** Dynamic aperture for the ideal storage ring, i.e. no errors. The aperture is about \( \pm 39\sigma_{z_0} \) in the \( x \) direction and \( \pm 33\sigma_{y_c} \) in the \( y \) direction.

for 400 turns. Particles were launched with initial values of \( x \) and \( y \) and with zero \( p_x \) and \( p_y \). The results can be seen in Fig. 3.
These tracking studies are encouraging but preliminary, and in order to do a more thorough job one must track particles with synchrotron oscillations, errors and synchrotron radiation.9

5. NOVEL SUPERCONDUCTING MAGNET

The key to the success of any compact light source is the design and construction of the appropriate superconducting magnet. Several projects have failed (COSY, XLS) due to a failure to produce an adequate magnet. The φ Factory project has developed a magnet design with LBL, industrial partners and other laboratories that we believe will work adequately.2,10 Fig. 4 shows a schematic of this magnet and Table 2 gives some parameters. The figure is shown with two synchrotron light exit ports for radiation from particle bunches going in either direction.

![Diagram of Superconducting Magnet](image)

Fig. 4: Section 1 plan view of the superconducting dipole. Note the large synchrotron light exit ports on either end.

The magnet is short, superconducting and rectangular in field shape. The length and strength of the magnet keeps the storage ring small and compact. The strong
field also results in powerful synchrotron radiation. Radiation off the dipoles would be the principal source of x-rays. However, the lattice described below does provide a 1.6 m straight section for an insertion device such as a wiggler or an undulator. A key milestone in the project is to construct this superconducting dipole and test its properties at LBL to see if they adequately match the requirement. The rectangular shape, as compared to a sector bend magnet, allows more of the synchrotron light to exit the magnet. This will help the vacuum and cooling problem due to synchrotron radiation on the beam pipe.

### Table 2: Superconducting Magnet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Field (T)</td>
<td>5.5</td>
</tr>
<tr>
<td>Bending Angle, for 700 MeV electron (deg)</td>
<td>60</td>
</tr>
<tr>
<td>Length along arc of central orbit (cm)</td>
<td>44.5</td>
</tr>
<tr>
<td>Bending Radius (cm)</td>
<td>42.5</td>
</tr>
<tr>
<td>Horizontal Gap (cm)</td>
<td>16.8</td>
</tr>
<tr>
<td>Vertical Gap (cm)</td>
<td>7.2</td>
</tr>
<tr>
<td>Cold Mass Magnet (kg)</td>
<td>1000</td>
</tr>
<tr>
<td>Superconducting (mm²)</td>
<td>$2 \times 4$</td>
</tr>
<tr>
<td>NbTi Cable (mm²)</td>
<td>$8 \times \phi 0.85$</td>
</tr>
<tr>
<td>Short Sample Current, at 5T (kAmp)</td>
<td>$&gt; 4.0$</td>
</tr>
</tbody>
</table>

Details of the synchrotron radiation are discussed below. One subsequent problem is maintaining a high vacuum in this high radiation environment. Fig. 5 shows a vacuum design\textsuperscript{11} that meets the φ Factory requirements. It is currently being tested by a LLNL group.

6. CHARACTERISTICS OF THE SYNCHROTRON LIGHT

The radiation from the storage ring comes from either the six superconducting bend magnets or an insertion device in the straight section. In Table 3 the characteristics of the radiation from the bend magnets are given. The average synchrotron radiation power is about 50 kW. The average power per bend is simply this divided by six, and the power per mrad is this divided by $2\pi$ radians of the beam orbit.
Schematic of differentially pumped chamber

Fig. 5: Vacuum system design for the UCLA φ Factory.
Table 3: Synchrotron Radiation from Bends

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy (MeV)</td>
<td>700</td>
</tr>
<tr>
<td>Critical Photon Energy, $\hbar \omega_c^{SR} = \frac{3}{2} \frac{\hbar c \gamma^3}{\mu}$ (keV)</td>
<td>1.8</td>
</tr>
<tr>
<td>Critical Wavelength (Å)</td>
<td>6.9</td>
</tr>
<tr>
<td>Beam Current (Amp)</td>
<td>1</td>
</tr>
<tr>
<td>Beam Population</td>
<td>$3.8 \times 10^{11}$</td>
</tr>
<tr>
<td>$U_0$, energy loss/particle (kev/turn)</td>
<td>50</td>
</tr>
<tr>
<td>Average SR Power/Bend (kW)</td>
<td>8.3</td>
</tr>
<tr>
<td>Average SR Power around ring (W/mR)</td>
<td>8.0</td>
</tr>
</tbody>
</table>

The synchrotron power spectrum produced by the light source is shown in Fig. 6. The critical energy given in Table 3 is that energy with half of the integrated power above it and half below it. The integral of the power spectrum over the energy gives the value 8.0 W/mR, as given in Table 3.

Fig. 6: Power spectrum for synchrotron radiation coming off the 5.5 T dipole magnets.
8. CONSTRUCTION OF THE PROTOTYPE COMPONENTS

As stated before, the key to the development of this superconducting x-ray source is to construct and test some of the components. This is especially necessary for the novel superconducting bend magnet. Construction of such a device will also illuminate problems with short, very high field superconducting bend magnets (multipole terms, edge effects). This will advance the state of the art for compact light sources as well as allow us to understand the overall scaling principles for higher energy machines.

9. SCALING TO HIGHER ENERGY

For some applications of synchrotron radiation the desired x-ray energy is around 50 keV. For this reason it is interesting to try to scale the ring discussed in this paper in an attempt to describe a compact ring which can deliver hard radiation. Both the 0.7 GeV ring and the 0.51 GeV Phase I φ Factory are good, small rings to use as baseline designs when scaling.

The critical energy of the synchrotron light scales as \( \varepsilon_c \sim E^2 B \), where \( E \) is the particle energy and \( B \) is the field in the bend magnets. When scaling, liberal use is made of the relation \( eCB = E/\rho \) to write relations in terms of the energy and magnetic field. To increase the critical energy, it is obvious that increasing the energy is the best strategy. However, increasing both the energy and the magnetic field will increase the radiation incident on the vacuum chamber walls and worsen the quality of the vacuum. W. Barletta discussed vacuum issues at length in Ref. 2 for the UCLA φ Factory. It appears that using his ante-chamber design we do no worse than the Phase I design for energies below 3 GeV and magnetic fields below about 13 T (for nominal beam currents of 1 amp); so vacuum consideration seems not to limit the design/scaling.

Another consideration in scaling electron rings is the equilibrium emittance, \( \varepsilon_T \sim EB \). So, by increasing the energy and the magnetic field the emittance may be drastically increased. To keep the magnet apertures small and the beam brightness high, the beam emittance should not be increased much. It is well known that small emittance rings favor more bends of weaker fields. Assuming there are \( N_B \) bends of length \( L_B \) then the relation for the total bending to be \( 2\pi \) radians leads to \( N_B L_B B/E \sim constant \). The emittance becomes \( \varepsilon_T \sim E^2/(N_B L_B B) \). That is, for a constant or decreasing emittance, advantageous for keeping the aperture small in the magnets, one would want weaker magnetic field and longer bends. For this reason, the scaling strategy here will be to use the same superconducting magnets as in the 0.7 GeV ring but use more of them.
For a 2.8 GeV ring with 5.5 T magnetic field in the bends, the critical energy of the radiation is 29 keV. The equilibrium emittance increases by a factor of 4, or a factor of 2 increase in the spot size and aperture of the quadrupoles. This could be problematic, however in the 0.7 GeV ring described above the quadrupole pole tip fields are not close to saturation of the metal—typically they are running at less than 1 T pole tip field.

The lattice scaling is not so clear because of the problem scaling the quadrupole strength to keep the same focusing as in the 0.7 GeV ring. Doubling the length of the dipole bends the beam 30° per dipole. The quadrupoles will also have to be doubled in length to give the desired strong focusing considering the aperture increase and the doubling of the pole tip field. This new cell should be tunable for a $\mu = 60^\circ$ betatron phase advance in each plane, though there might be some problem since edge effects at the bends were relied on to give some of the focusing in the 0.7 GeV ring. If this can be done, then 6 cells, each double the length of the old cells, will occupy each arc of the ring. The arcs quadruple in length compared to the lower energy ring; it is expected that the circumference will scale with the energy. It might be possible to have shorter straights than 4 times the length in the 0.7 GeV straights, but in general the circumference will be 72 m give or take 10 m.

This scaling was an attempt to estimate how compact one might make a synchrotron light source for producing hard x-rays. Many assumptions were made to do this. One of which is that you do not want to increase the bend field very much beyond 5.5 T. If you consider very strong superconducting magnets then, as mentioned above, you might decrease the circumference but strong focusing in the lattice becomes problematic. A more complete design effort like that done for the Phase I $\phi$ Factory and the 0.7 GeV ring is needed.

10. CONCLUSIONS

This is a viable design for a small synchrotron light source. The key features being the superconducting bend magnets and the cancellation of the sextupole nonlinearities in the lattice. There is room in the lattice for an insertion device. Not only would this machine be interesting and useful in its own right, but it would lead to better understanding of short, high field superconducting magnets in accelerators.

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6. E. Forest, unpublished computer codes.


11. W. Barletta in Ref. 2.