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A.A. Garren, D.B. Cline, M.A. Green, D.E. Johnson,
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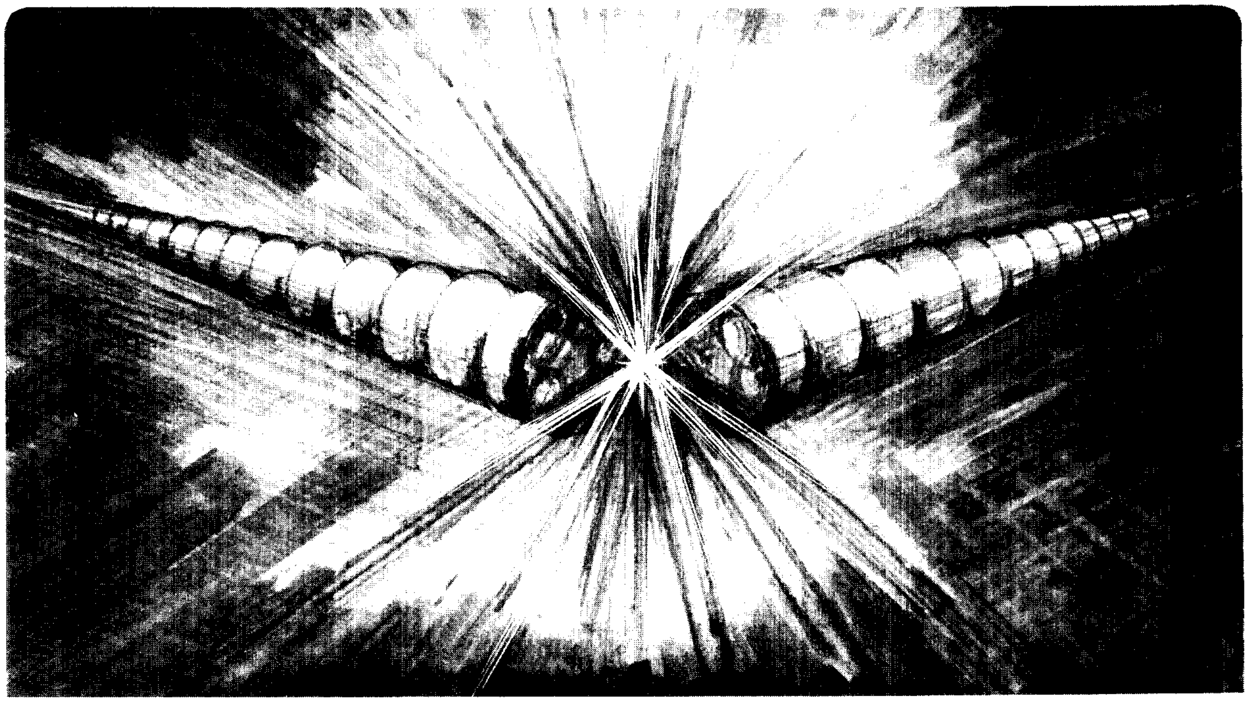

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A.A. Garren,[a,b,c] D.B. Cline,[a,b] M.A. Green,[c] D.E. Johnson,[a] J.J. Kolonko,[a,b]
E.M. Leung,[d] D.D. Madura,[d] and L.C. Schachinger[a]

[a]Particle Beam Lasers, Inc., Northridge, CA 91324
[b]UCLA Center for Advanced Accelerators, Los Angeles, CA 90095
[c]Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory,
University of California, Berkeley, CA 94720
[d]Martin Marietta Technologies, Inc., Rancho Bernardo, CA 92125

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A 1.5 GeV Compact Light Source with Superconducting Bending Magnets*

A A. Garren[a,b,c], D. B. Cline[a,b], M. A. Green[c], D. E. Johnson[a], J J. Kolonko[a,b],
E. M. Leung[d], D. D. Madura[d] and L. C. Schachinger[a]

a. Particle Beam Lasers, Inc., Northridge CA 91324
b. UCLA Center for Advanced Accelerators, Los Angeles CA 90095
c. Lawrence Berkeley Laboratory, Berkeley CA 94720
d. Martin Marietta Technologies Inc., Rancho Bernardo CA 92125

Abstract —This paper describes the design of a compact electron synchrotron light source for producing X-rays for medical imaging, protein crystallography, nano-machining and other uses up to 35 keV. The source will provide synchrotron light from six 6.9 tesla superconducting 60° bending magnet stations. In addition the ring, contains conventional quadrupoles and sextupoles. The light source has a circumference of 26 meters, which permits it to be located in a variety of industrial and medical facilities.

I. BACKGROUND

The machine presented here is designed primarily as a light source for industrial and medical applications. Modified versions of the design may have other applications as a damping ring or collider.

The ring is designed to produce X rays with energies up to 35 keV. To make the ring compact, its energy is limited to 1.5 GeV. This beam energy allows use of conventional quadrupoles and sextupoles without greatly increasing the ring circumference. In order to get useful quantities of X rays at 35 keV or above, the bending dipole should have a central induction above 6 T. For the machine described, with a bending induction of 6.9 T and beam energy of 1.5 GeV, the critical synchrotron-radiation energy is 10.3 keV. The lattice has been designed to optimize dynamic aperture, emittance, cost, and ring size, while providing adequate space for the rf and injection systems.

II. THE COMPACT STORAGE RING LATTICE

The racetrack-shaped ring has a hybrid magnet structure, consisting of superconducting dipoles and conventional quadrupoles and sextupoles. The two arcs are identical and each is symmetric about its center. The straight sections have the same length but different structure. Each is symmetric about its center, so the ring is reflection-symmetric about the line joining the center points. Figure 1 shows the ring layout.

Each arc consists of six 30° dipoles, four quadrupoles and six sextupoles. The dipoles are grouped into three pairs, each of which shares a single cryostat. Conceptually, the arc is built up from three cells, where the outer two cells are truncated beyond the two dipoles. Referring to Figure 1, the center cell consists of the magnet sequence (SFH QF SD B B SD QF SFH), the first cell is (B B SD QF SFH) and the last cell is (SFH QF SD B B). Here SFH is a half focusing chromaticity sextupole, QF a focusing quadrupole, SD a defocusing chromaticity sextupole, and B is a dipole.

The rectangular dipole has a field of 6.9 T and zero gradient. Vertical focusing comes from its edges. The cell has horizontal and vertical phase advances of 120° and 90° respectively; these values are obtained by adjusting the strength of QF and the distance between QF and B. The horizontal phase advance of three cells is 360°, so the arc is an achromat and the dispersion is zero in the straight sections (see Figure 2). The vertical phase advance is chosen to make the arc as short and the emittance as low as possible.

The straight section at the top of Figure 1 has a 1.6 meter drift in the center for injection. The straight section at the bottom of Figure 1 has seven quadrupoles, between which the rf modules would be located. Both straight sections are adjusted so that the periodic beta functions in the arc are brought to waists at the straight section centers. Consequently the emittance depends on the arc design only, not on the straight sections or the tunes. Table I presents the basic parameters for the Lattice.

The bottom straight section produces 3π horizontal and vertical phase differences between the centers of the two arcs. Thus, each magnet in one arc is paired with one in the other so as to partially cancell their nonlinear effects. The top straight section quadrupoles are adjusted to make the tunes favorable with respect to resonances, minimization of beam size and chromaticity and the provision of useful drift spaces.

Figure 2 shows the lattice and orbit functions of the ring, running clockwise from the center of the top straight section.

The following variations have been investigated:

1) The arc was composed of either three 60° dipoles or six 30° dipoles.
2) Values of the cell vertical phase advance of 120°, 90°, and 60° were compared.
3) The number and location of the defocusing chromaticity SD sextupoles have been varied.
4) Different ring tune values were compared.

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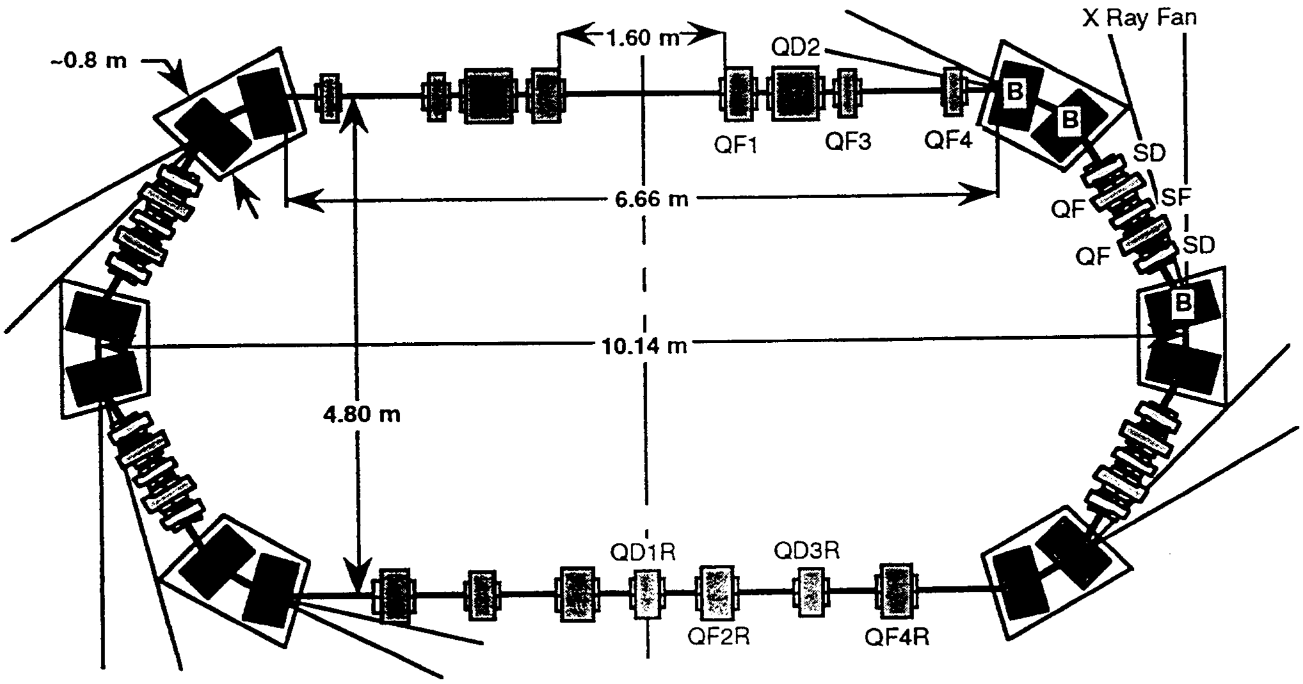

Fig. 1. A Compact Storage Ring with Superconducting Dipoles and Conventional Focusing Elements

Table I Lattice Parameters for the Compact Light Source

Maximum Stored Beam Energy (Gev)	1.50
Projected Injection Beam Energy (Gev)	0.10
Projected Beam Current (mA)	~20.
Circumference (m)	26.0
Bend Radius (m)	0.7257
Dipole Bend Angle (deg)	30.
Integrated Dipole Induction* (T m)	2.6197
Dipole Central Induction (T)	6.894
Dipole Magnetic Length along the Bend (m)	0.380
Critical Energy (keV)	10.3
Horizontal Natural Emittance* (μm)	2.34
Vertical Coupled Emittance* (μm)	1.17
Vertical Operating Emittance*(μm)	0.0234
Horizontal Tune	3.17
Vertical Tune	2.57
Horizontal Chromaticity	-2.22
Vertical Chromaticity	-5.24
Maximum Horizontal Beta Function (m)	3.09
Maximum Vertical Beta Function (m)	6.66
Maximum Dispersion (m)	1.29
Energy Loss per Turn* (MeV/turn)	0.617
RF Voltage (MV)	2.5
RF Frequency (MHz)	499.
Energy Spread (parts in 1000)	1.52
Bunch Length rms* (mm)	30.
Horizontal Damping Time* (ms)	0.412
Vertical Damping Time* (ms)	0.422
Energy Damping Time* (ms)	0.213
Quantum Lifetime (s)	$2.2\ 10^8$

* at the maximum design beam energy

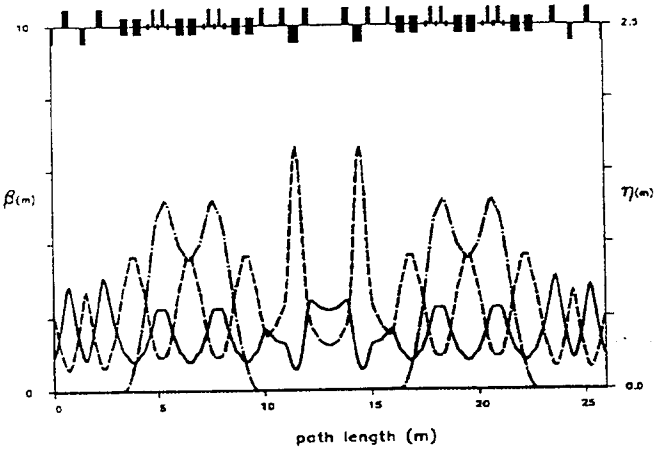

Fig. 2 Orbit Functions of the Compact Storage Ring. The solid, dashed, and dot-dashed curves show βx, βy, and η

The comparison of lattice alternatives for the ring, which included engineering and tracking studies, have led to the following conclusions:

1) The split-magnet configuration (six dipoles per arc) is far preferable to the unsplit one.in cost and field quality.
2) The best sextupole configuration is the one that has four SDs per arc.
3) The best vertical cell phase advance is 90^{o}: this value leads to the shortest feasible arc and the lowest emittance.
4) The best working point is at $\nu_x = 3.17$, $\nu_y = 2.57$.

Particles were tracked for 1,024 turns around the ring. Multipole errors were included in the dipoles consistent with the assumption of dipole field uniformity of 1 part in 10000 over a radial dimension of 28mm. The dynamic aperture was at least 25 sigma in both planes, considerably larger than the 15 sigma physical aperture of the magnets. This aperture should be more than large enough for beam lifetime.

III THE SUPERCONDUCTING DIPOLE

Fig. 3 shows a cross-section of the dipole. The design for the dipole is based on a concept proposed by Pavel Vobly at INP Novosibirsk.[2,3]. The dipole shown in Fig. 3 will generate a uniform field over a wide range of central inductions, provided that the current density in the shield coil system is correctly chosen with respect to the current density in the gap and crossover coil system. The shield coil current can be set so that the sextupole and decapole field components are zero, and the 14 pole component is very small. The excitation function can be modified by changing the height and slope of the shield coil.

The dipole has saturated iron in the poles. The shield coils keep the magnetic flux in the pole until it can be returned by an unsaturated iron return yoke. As a result, the field fall off at the end of the dipole is similar to that of conventional low field copper iron dipoles. Since the compact ring dipoles are only 376 mm long, the fall-off of the magnetic field at the end is important.

If one bases the coil design shown in Figure 3 on superconducting cable made from SSC inner conductor, the dipole will operate at about 87% of its critical current along the load line (based on a conductor packing fraction of 0.7 and an operating temperature of 4.4K). The SSC conductor can be cabled into conductor of almost any desired current for this application.

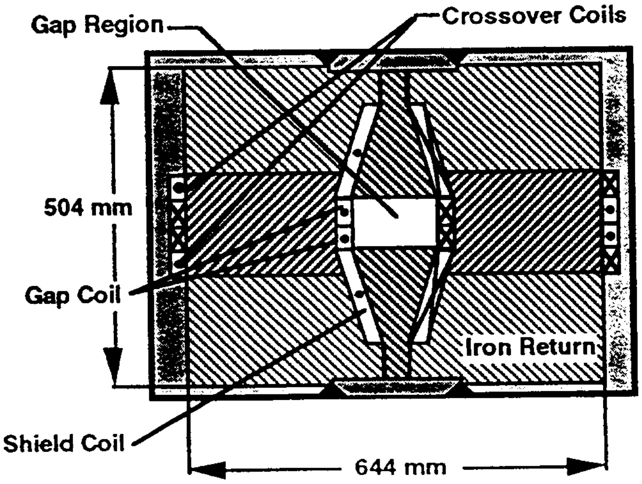

Fig. 3 Cross-section of a 6.9 T Vobly Type Dipole

IV. CONCLUSION

A 1.5 GeV compact synchrotron with superconducting bending magnets and conventional focusing elements can be made with a circumference of 26 meters. At 1.2 GeV, the proposed storage ring should perform even better. The ring appears to be suitable for industrial production of X rays at energies up to 35 keV. In this energy range there are a number of interesting potential uses for such a ring, which, it is expected, can be built for less than 12 million dollars.

The key to building a compact electron storage ring in the 1.2 to 1.5 GeV energy range is the development of a short superconducting dipole with field characteristics similar to that of conventional room temperature iron dominated dipoles. It appears that a Vobly type dipole is an attractive design for a compact X ray source.

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