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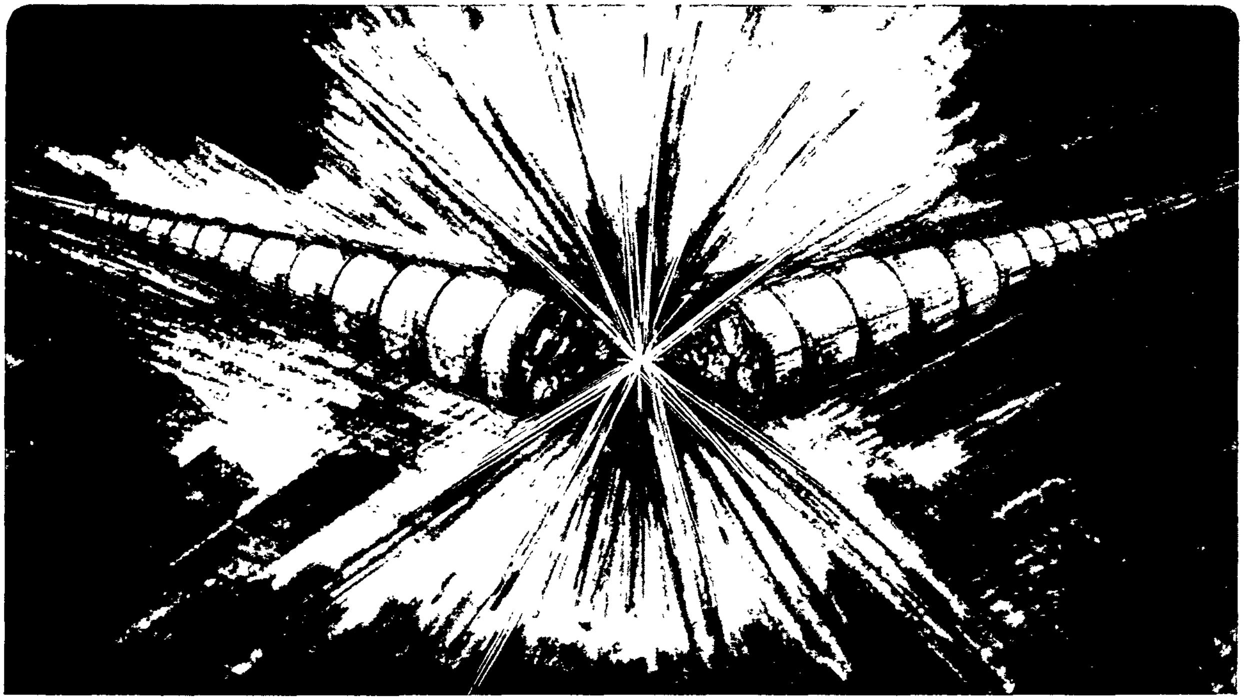

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Optimization of Superconducting Bending Magnets for a 1.0 to 1.5 GeV Compact Light Source*

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***Abstract*---Compact light sources are being proposed for protein crystallography, medical imaging, nano-machining and other areas of study that require intense sources of x rays at energies up to 35 keV[1]. In order for a synchrotron light source to be attractive, its capital cost must be kept low. The proposed compact light source has superconducting bending elements to bend the stored beam and produce the x rays. Additional focusing for the machine is provided by conventional quadrupoles. An important part of the cost optimization of a compact light source is the cost of the bending magnets. In the case of a machine with superconducting bending elements, the bending magnet system can represent close to half of the storage ring cost. The compact light source storage rings studied here have a range of stored electron energies from 1.0 to 1.5 GeV. For a number of reasons, it is desirable to keep the storage ring circumference below 30 meters. Cost optimization parameters include: 1) the number of superconducting bending elements in the ring, and 2) the central induction of the dipole. A machine design that features two superconducting dipoles in a single cryostat vacuum vessel is also discussed**

I. BACKGROUND

The type of electron storage that is discussed in this report will be designed primarily as a light source for industrial and medical applications[1]. As a result, the storage ring should be inexpensive to build and it should produce intense x rays with energies up to 35 keV. For compactness, the energy of the storage ring is limited to a maximum energy of 1.5 GeV. The lattices described here are optimized for low emittance, low cost, and minimum circumference.

The critical energy of the x rays produced by an electron storage ring is proportional to the electron energy squared and the magnetic induction used to bend the electrons. If one uses conventional dipoles to bend the electrons to produce x rays with a given critical energy, the storage ring beam energy must be increased. As a result, the ring circumference and cost must also be increased. To produce high critical energy x rays, the beam should be bent by a high field (above 5 T) dipole. Lower particle beam energies allow one to use conventional quadrupoles and sextupoles without greatly increasing the ring circumference.

II. THE SUPERCONDUCTING BENDING MAGNET

The key to building a compact electron storage ring in the 1.0 to 1.5 GeV energy range is the development of a short superconducting dipole that has field characteristics that are similar to those of short iron-dominated conventional dipoles. Straight superconducting dipoles have been selected for the ring lattice. Since the dipoles are relatively short, an H magnet structure was assumed. While C dipole magnets will allow more x rays to leave the bending magnet, they cost considerably more than an H magnet with the same field.

The design for the dipole is based on a concept proposed by Pavel Vobly at INP Novosibirsk.[2,3]. The dipole design proposed by Vobly will generate a uniform field over a wide range of central induction. 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.

III. THE COMPACT STORAGE RING LATTICE

The proposed ring design has superconducting dipoles and conventional quadrupoles and sextupoles. The shape of the ring is racetrack. The two arcs are identical and each arc is symmetric about its center. The two straight sections joining the arcs have the same length but different structure. Each is symmetric about its center, so the ring has reflection symmetry about the line joining the straight section centers. Each arc cell consists of a dipole, focusing quadrupoles and sextupoles. To simplify the lattice structure and reduce the storage ring circumference, the vertical focusing comes from the edges of the dipoles rather than from quadrupoles.

Rings with six, eight and twelve dipoles were studied. (The bend angle for each dipole is 60 degrees, 45 degrees and 30 degrees respectively.) The horizontal aperture of the dipole (the pole width) is determined by the horizontal width of the beam (a 15 sigma beam), the beam sagita, the x-ray fan allowance (for x rays originating before the middle of the magnet), the material needed to absorb x rays that fail to exit the magnet, and the insulation allowance around the warm storage ring vacuum vessel. The vertical aperture (the gap) is determined by the vertical height of the beam (15 sigma beam) and the insulation allowance in the vertical direction. The cost of the Vobly type dipole magnets is primarily a function the central induction and the pole width.

Figure 1 illustrates possible configurations for storage rings with six, eight, and twelve superconducting bending magnets. The 1.5 GeV storage rings shown in Figure 1 have 6.9 T bending magnets that allow two thirds of the x rays to escape. (The magnets would be physically smaller if only half of the x rays were allowed to escape.) The x-ray critical energy for the rings shown in Fig. 1 is 10.4 keV.

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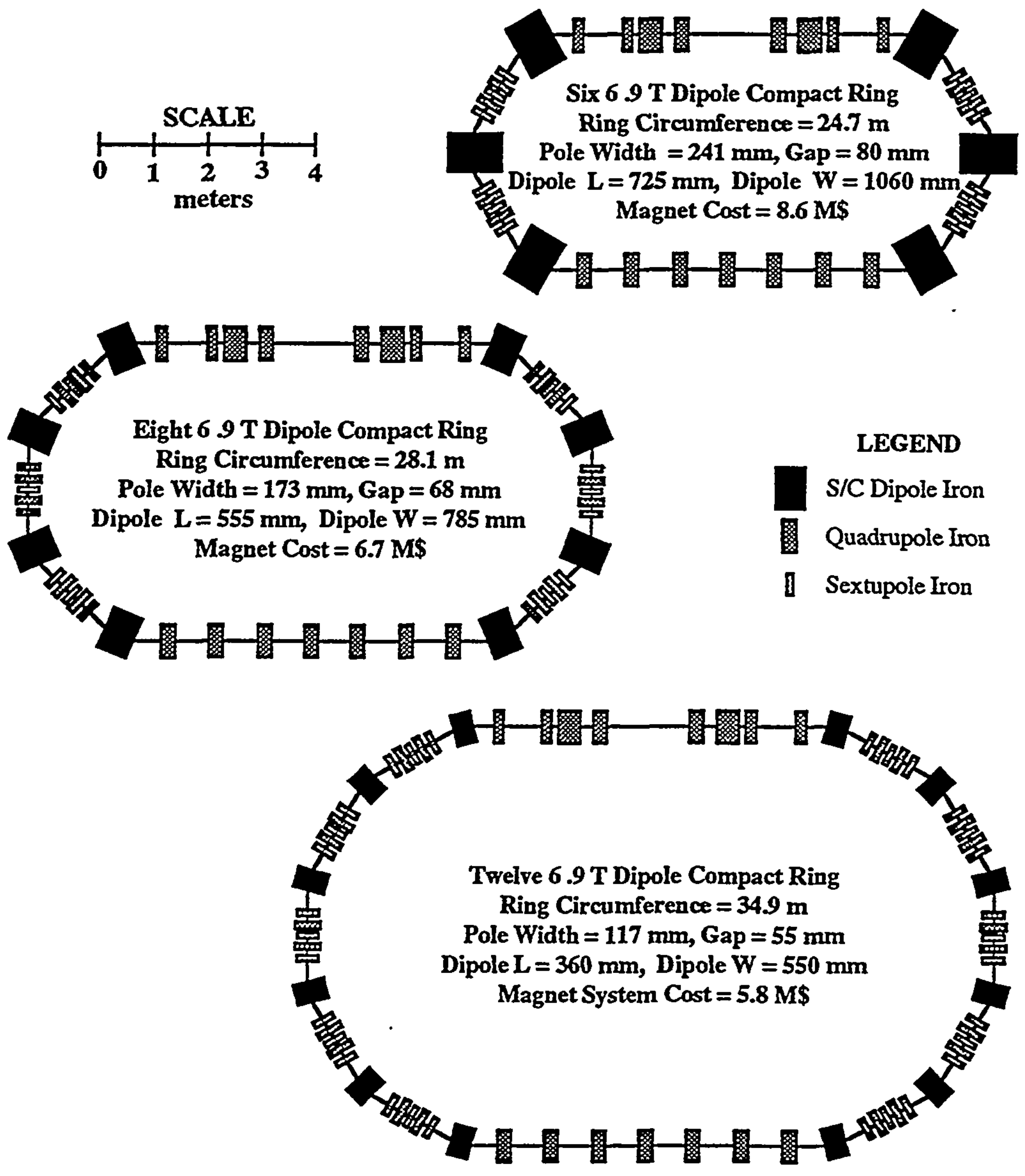

Fig. 1 Various Compact Industrial 1.5 GeV Electron Storage Ring Options for an X Ray Critical Energy of 10.3 keV

IV MAGNET SYSTEM COST OPTIMIZATION

From Fig. 1, one can see that the six dipole storage ring has the smallest circumference. The magnet cost in the six dipole rings is dominated by the large size and mass of the superconducting dipoles. The twelve dipole storage ring has a circumference that is 40 percent larger than the six dipole ring, but the magnet system cost is about 33 percent lower.

A cost optimization study as a function of dipole induction was done for 1.5 GeV rings with six, eight and twelve dipoles. For six dipole 1.5 GeV rings, the optimum dipole induction was between 6 and 7 tesla. For the twelve dipole 1.5 GeV rings, the optimum induction was lower, around 4.5 tesla. It is more meaningful to keep the x-ray critical energy constant as one optimizes for the dipole central induction. Fig. 2 shows the magnet system capital cost as a function of dipole induction for rings with six, eight, and twelve dipoles. Fig. 3 shows the ring circumference as a function of dipole induction for the various rings. In Figs. 2 and 3, the x ray critical energy was kept constant at 6.8 keV. This means that when the dipole induction is 4 tesla, the electron beam energy must be 1.59 GeV. When the dipole induction is 7 tesla the beam energy goes down to 1.20 GeV.

The simple twelve dipole ring shown in Figure 1 has a low magnet system cost. The problem with this ring is its physical size and the extra space that it occupies within an industrial users facility. As a result, a different form of the twelve dipole lattice was studied to keep the lower magnet system cost associated with the twelve dipole ring yet retain the compactness of the six dipole storage ring. A lattice was proposed where two short 30 degree dipoles share a common cryostat. The lattice resembles the six dipole lattice.

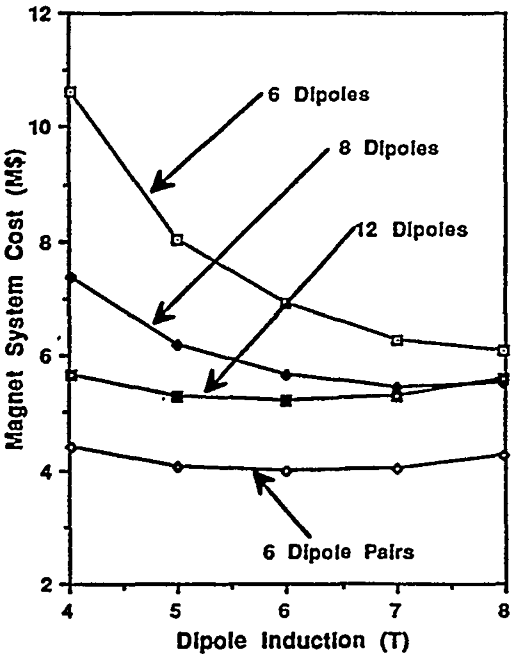

Fig. 2 Magnet System Cost versus Dipole Induction for a Constant X ray Critical Energy of 6.8 keV

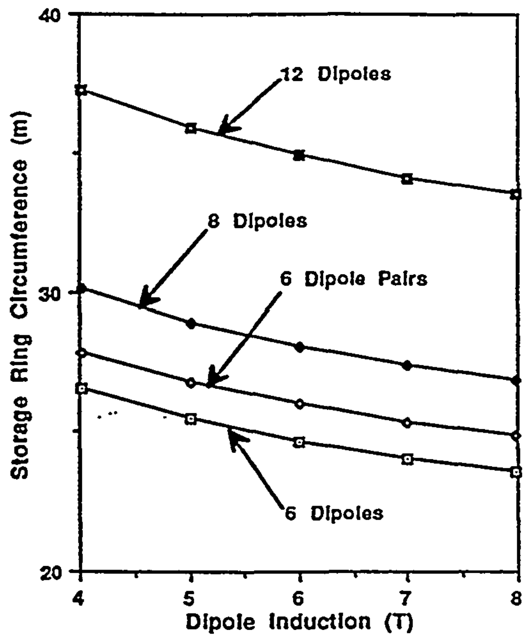

Fig 3. Storage Ring Circumference versus Dipole Induction for a Constant X Ray Critical Energy of 6.8 keV

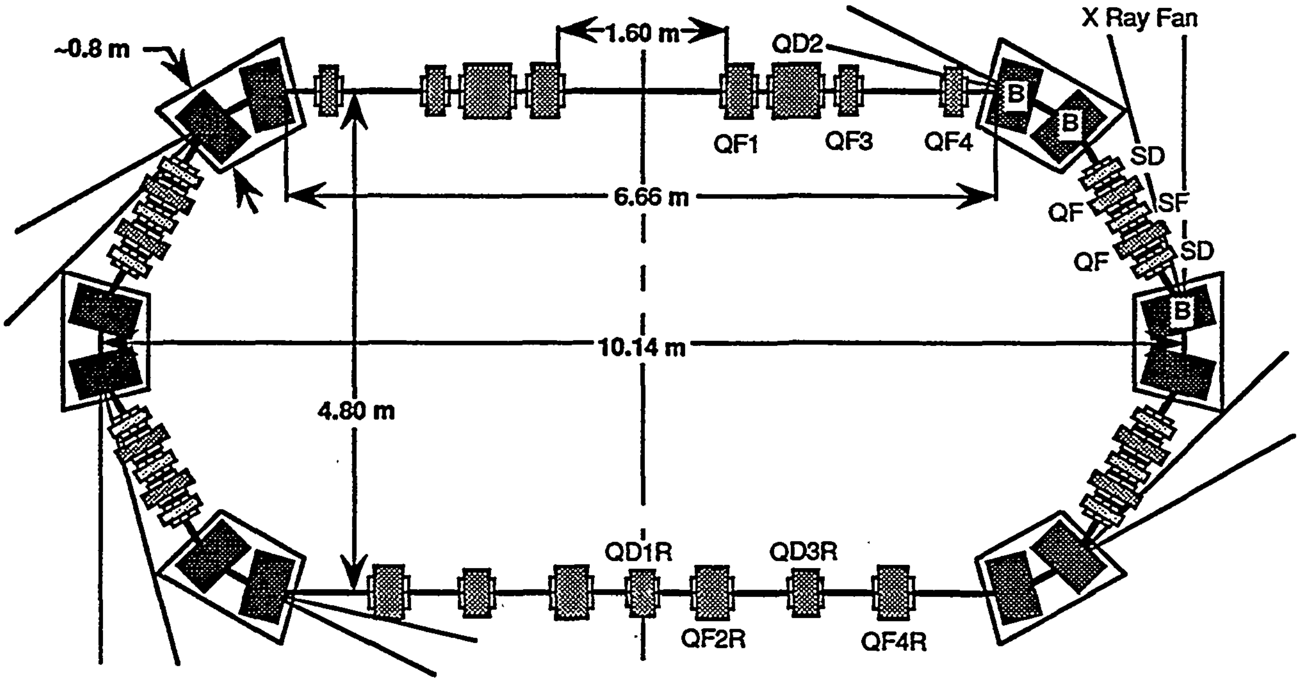

Fig. 4. A 1.5 GeV Compact Storage Ring Lattice with Six Pairs Thirty Degree superconducting Dipoles

The ring shown in Fig. 4 has a circumference of only 26 meters and since the ring has two dipoles in a single cryostat, the total magnet cost is lower than that of the twelve dipole ring shown in Fig. 1. The dipoles shown in Fig. 4 are sized for operation at 1.5 GeV[4]. The ring as a whole would operate with much more margin at 1.3 GeV. Table I shows the parameters of the ring shown in Fig. 4.

The ring shown in Fig. 4 has a projected magnet system cost of about 4.8 million dollars The primary disadvantage of this ring is that the usable x rays come only from the forward dipole in the pair; the x rays that are produced by the rear dipole must be absorbed by the magnet vacuum chamber. It is proposed that the beam vacuum chamber temperature be about 200 K.

TABLE I LATTICE PARAMETERS FOR THE COMPACT 1.5 GeV SYNCHROTRON

Maximum Stored Beam Energy (Gev)	1.50
Projected Injection Beam Energy (Gev)	0.10
Projected Beam Current (mA)	~20.
Ring Circumference (m)	26.0
Bend Radius (m)	0.7257
Dipole Central Induction (T)	6.894
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)	$2.2\mathrm{x}10^{8}$

* at the maximum design beam energy

The straight section at the top of Figure 4 has a 1.6 meter drift in the center for injection, while the straight section at the bottom has seven rather evenly distributed quadrupoles. The rf modules would be located in the drift spaces of the bottom straight section. 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.

A cross-section of the dipole proposed for the lattice shown in Fig. 4 is shown in Fig. 5. The magnet cold gap is 80 mm; the pole width is 130 mm. The warm aperture for the magnet is 60 x 110 mm. The design central induction of the dipole shown in Fig. 5 is 7.2 T. For good field over a wide rang of fields, the shield coils are separately powered from the gap and crossover coils[5]. The field uniformity of the magnet shown in Fig. 5 can be very good provided the magnet is correctly tuned. If a conductor with a low copper to superconductor ratio (like SSC inner conductor) is used, the design current is about 91 percent of critical current along the load line at an operating temperature of 4.4 K.

V. CONCLUSION

A 1.5 GeV compact synchrotron with superconducting bending magnets and conventional quadrupoles and sextupoles can be made with a circumference of only 26 meters. At an energy of 1.3 GeV, the proposed storage ring should perform better because the emittance of the beam is smaller and there is more margin in all of the ring magnets. The proposed ring appears to be suitable for an industrial source of synchrotron light x rays at energies up to 35 keV. In this energy range there are a number of interesting industrial uses for such a ring. It is hoped that the ring with its injection and r.f. systems can be built for about 12 million dollars.

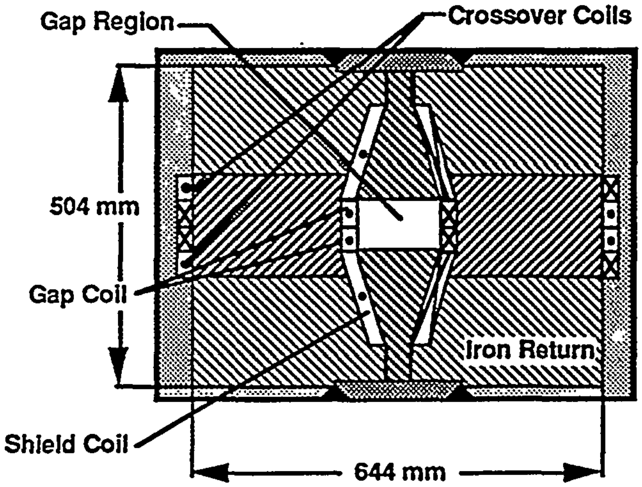

Fig. 5 Cross-section of a 7.2 T Vobly Type Dipole

VI. ACKNOWLEDGMENT

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