ELECTRON STORAGE RING FOR X-RAY LITHOGRAPHY

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Abstract

This paper presents a conceptual design by Brobeck Corporation for an electron storage ring and its associated subsystems, dedicated to the needs of an X-ray lithography program as outlined at a workshop held at Brookhaven National Laboratory.[1] The necessary beam energy, magnetic field, and beam current were calculated from the X-ray spectrum and intensity specified at the workshop. The facility described in this paper is designed to meet the requirements of a commercial X-ray lithography program based on synchrotron radiation with a critical wavelength of 9.3 Å. The radiation for the lithography program emanates from special high-field (2 T) bending magnets that are embedded in an otherwise conventional 1 GeV storage ring. The radiation power density is about 250 mW/mrad for a circulating electron beam current of 100 mA. The storage ring systems have been designed for a beam current of 400 mA. Electrons are injected into the storage ring from an injection system comprising a 350 MeV, 5 Hz booster synchrotron and a 10 MeV linac.

Introduction

This is a first-cut conceptual design for an electron storage ring and its associated subsystems, to serve as a basis for cost estimates and to get a feel for what such a machine might look like. In designing the various systems, special emphasis has been placed on conservative or well-proven designs, with reliability being put at a premium. The major storage ring parameters are summarized in table 1, and a preliminary layout is shown in figure 1.

TABLE 1. MAJOR STORAGE RING PARAMETERS

Circumference (m)	36.0
Injection energy (GeV)	0.350
Maximum energy (GeV)	1.0
Current (mA)	400
Orbit period (ns)	120.0
Betatron tunes: radial	2.28
vertical	1.39
Momentum compaction factor	0.237
RF harmonic, 500 MHz	60
Damping times, 1 GeV: radial (ms)	7.06
vertical (ms)	7.18
energy (ms)	3.62
Natural emittance, 1.0 GeV (mm·mrad)	0.41

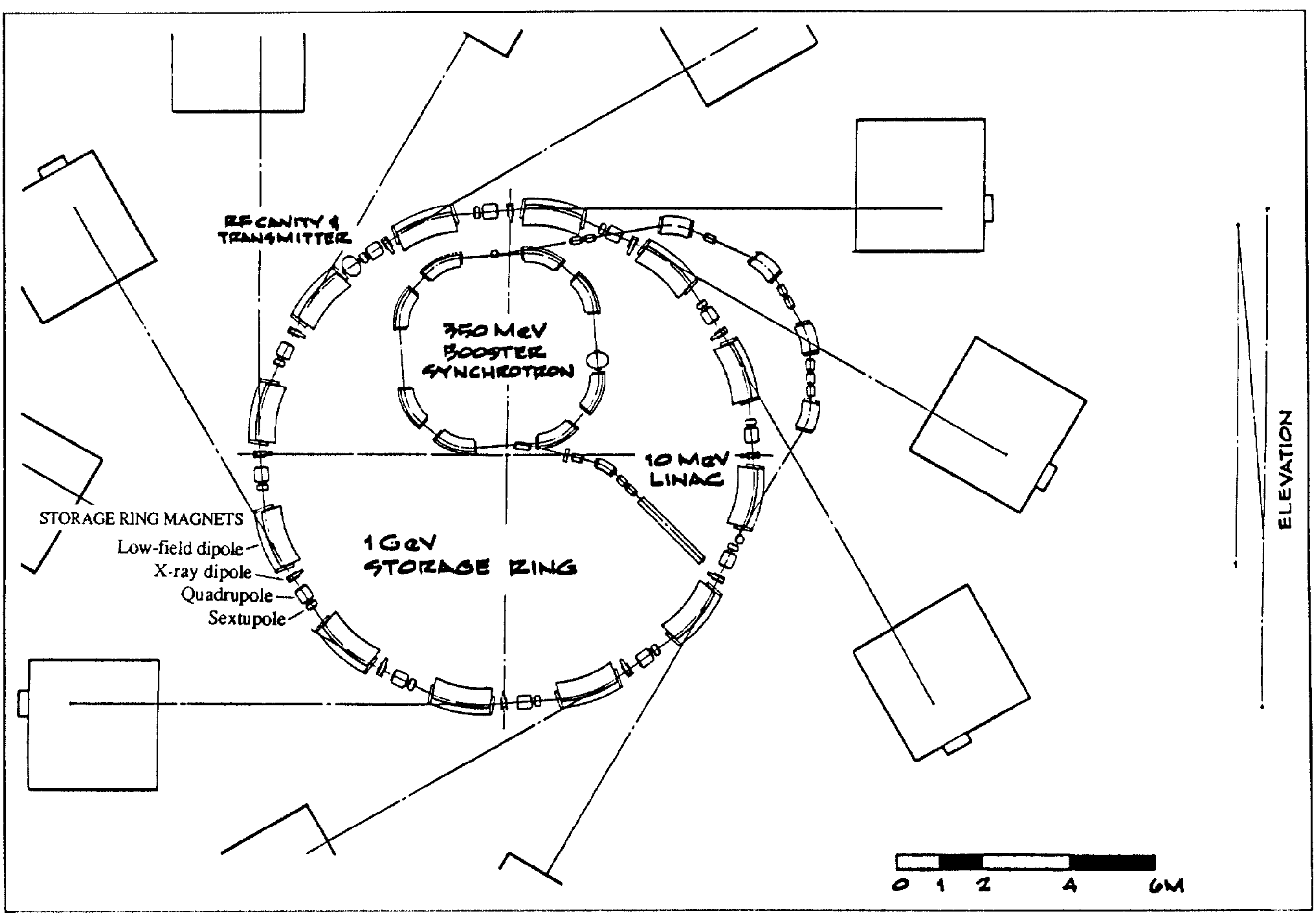

FIGURE 1. ELECTRON STORAGE RING FOR X-RAY LITHOGRAPHY - - SCHEMATIC LAYOUT

Electron Beam Characteristics

The critical wavelength of radiation λ_c [Å] emitted by an electron, energy E [GeV], bent by a magnetic field B [T], is given by:

$$\lambda_c = 18.6/(B \times E^2)$$

Thus, to achieve λ_c = 10.0 Å with superconducting magnets (at B = 5.0 T) would require E = 0.61 GeV and rho = 0.407 m. To achieve the same λ_c with conventional iron-dominated magnets (at B = 2.0 T) would require E = 0.96 GeV and rho = 1.600 m.

Since the bending radius, rho, of conventional magnets is four times greater than that of superconducting magnets, the circumference of the resulting conventional machine is obviously going to be larger -- but not by a factor of four, as the machine will need straight sections for injection elements, etc.

Being cognizant of the premium placed on reliability (for which superconducting systems are not renowned), we have based our system on conventional magnets.

Setting a beam energy of 1.0 GeV and a peak field of 2.0 T gives λ_c = 9.3 Å, which is in line with user requirements.

A good estimate of the power in the synchrotron radiation in the spectral range useful for X-ray lithography (6-12 Å) can be obtained from the "Universal Curve" of Suller[2], which gives the photon flux in terms of the number of photons at a given wavelength, in a 0.1% bandwidth, in a radial opening angle of 1 mrad, per mA of beam current, per GeV of beam energy. Integrating from 6-12 Å gives an intensity of 1.2x10e+13 photons/s/mrad/mA, which reduces to 2.5 mW/mrad/mA. Because the lithography program requires powers >250 mW/mrad, the storage ring must operate at electron beam currents >100 mA.

Storage Ring Magnet Lattice

A separated function FODO lattice has been chosen in which the unit cell contains two long, low-field bending magnets, two special short high-field magnets (from which the the X-rays are extracted), and two quadrupole magnets (one focusing radially, and the other vertically). Six such cells make up the full machine.

The lattice quadrupoles are powered to give the highest radial betatron tune (and thereby the smallest electron beam emittance) consistent with beam stability (μ_x = 3.0) and a favorable injection tune (for which $\Delta\mu_x$ = 0.25 is required).

Finally, the lattice must contain sextupole magnets. These are used to set the "chromaticity" of the machine, defined by:

$$\xi_{x,y} = d\mu_{x,y}/(dp/p),$$

at zero, or slightly positive. This is necessary to reduce the tune spread of the injected beam, to improve the capture efficiency, and, more importantly, to combat an effect known as the "head-tail" instability, which would limit the achievable current to a few milliamperes.

Storage Ring Magnets

All magnets in the storage ring, with the exception of the special short X-ray magnets and injection elements, will be built from 1.5 mm thick laminations of decarburized, annealed, low-carbon steel sheet (Armco special magnet steel). The field-defining contours of the laminations are computer optimized to yield the required field quality, and are punched to a precision of ± 13 µm.

Since the lengths and strengths of the magnets are defined by lattice considerations, the major parameter left to be specified is the aperture.

In the radial plane, the vacuum aperture of the storage ring must accommodate large-amplitude betatron oscillators (in order to cope with elastic scattering of residual gas molecules), large energy excursions (to give a large quantum lifetime), and closed-orbit distortions caused by misalignment of the lattice elements. It is beyond the scope of this paper to detail these effects. However, rules of thumb can be used to define the aperture:

a. Needed for betatron oscillations: $\pm 15\ \sigma_x$

   At maximum (12.0 m) in the F-quad, 15 σ_x = 33 mm

b. Needed for quantum lifetime: $\pm 10\ \sigma_\varepsilon$

   At D-max (2.2 m) in the F-quad, 10 σ_ε = 11 mm

c. For closed-orbit distortion: Xc.o. = 5 mm

Thus, (a) and (b) are added in quadrature with (c) to obtain a total radial aperture in the quadrupoles of 40.0 mm. Since it is customary to build quadrupole magnets with four-fold symmetry, vertical vacuum aperture of the quads is also defined.

In the vertical plane, there is no energy dispersion, and the maximum vertical beam emittance is 0.5 x radial emittance, corresponding to the case of "full coupling." Then, the aperture required in the bending magnets for vertical betatron oscillations is:

$$33 \text{ mm} \times \sqrt{0.5} \times \sqrt{\beta \text{ mag}/\beta \text{ max}} = 17.3 \text{ mm}$$

In this plane, the closed orbit is usually smaller than the radial plane. Thus, ± 20.0 mm was chosen for the vertical vacuum aperture in the bending magnets.

The inscribed aperture in the sextupoles is chosen to be the same as in the quadrupoles, i.e., 40.0 mm.

In order to define the magnet apertures, a vacuum chamber is added on with a thickness of ± 2 mm and a clearance of ± 1 mm, to arrive at:

dipole magnet gap	46.0 mm*
quadrupole inscribed radius	43.0 mm†
sextupole inscribed radius	43.0 mm

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* The magnet gap is slightly smaller than the Lawrence Berkeley Laboratory (LBL) Light Source magnets (50.0 mm)[3], but the pole width is larger in order to accommodate a bigger good field region in the radial plane.

†If an elliptical vacuum chamber is used in the quadrupoles, this could be reduced to about 32.0 mm.

The function of the high-field bending magnets is to produce a 10 mrad fan of X-rays. At 2.0 T, the magnetic length of such a magnet is only 17 mm, which is a fraction of the required gap (i.e., the magnet is all ends!). For the purposes of this paper, the X-ray magnets have been given a 2.5° bend, which translates to a magnetic length of 75.0 mm, with a nominal field of 1.94 T.

Injection and Accumulation

Accumulation of electrons in the storage ring is by the well-proven technique of stacking in radial phase space, injection taking place from the outside of the machine. Prior to injection, the storage ring closed orbit is deflected close to the edge of a septum magnet. The three kicker magnets are powered individually, and are capable of producing a deflection of 40 mm at the position of the septum magnet. A pulse of electrons is then ejected from the booster synchrotron and transported through the injection septum magnet into the storage ring. The kicker magnets are then turned off in a time corresponding to about three orbits of the storage ring to prevent the new beam from colliding with the septum. This newly injected beam then undergoes coherent motion about the closed orbit that is rapidly damped by the process known as synchrotron radiation damping. The radial betatron damping time at 350 MeV is 165 ms. This process is repeated at the cycle rate of the booster synchrotron (5 Hz) until the desired current is reached.

The kicker magnets must be switched in a very fast time. Here we have chosen to power the magnet with a half sinewave pulse with a duration of six ring revolutions, i.e., 720 ns. The field is produced by a series of conductors placed around the beam.

Radio Frequency (RF) System

The purpose of the RF system is to provide sufficient accelerating voltage to make up beam energy losses to synchrotron radiation, and to provide for sufficient beam quantum lifetime and Touscheck lifetime. At 1.0 GeV, the energy lost to synchrotron radiation amounts to 33.5 keV per turn. In order to provide good quantum lifetime, a voltage of greater than 7 times the energy loss is required. An "overvoltage" of 10 is considered to be conservative. In order to produce this voltage, a 500 MHz system using a harmonic number of 60 is proposed. The principal reasons for this choice are that this voltage can be generated by a single 500 MHz cavity, and the cavity will readily fit into the small amount of straight section available in this compact structure. The cavity utilizes loop coupling and a tuning plunger. The measured shunt impedance (transit time corrected) of similar cavities is 7.2 MΩ. For the purposes of calculating the power requirements for this application, a conservative figure of 6.0 MΩ is taken.

In order to sustain the beam in orbit, the RF system must provide 33.5 kV to the circulating current of 400 mA, i.e., 13.4 kW. For system stability, the total power supplied to the cavity needs to be up to 2.5 times this figure, depending on the coupling and tune state of the cavity. To make up for other possible losses (higher order modes in the cavity, waveguide losses, etc.), it is intended to install a total RF power capability of 40 kW.

Injector Synchrotron

Injection into the storage ring must be made at an energy that is sufficiently high to provide a rapid damping time of the newly injected beam. Since injection rates of about 4 Hz or above are operationally desirable (it is difficult to optimize systems below this frequency), the damping time should be less than 250 ms, which corresponds to a minimum storage ring energy of 305 MeV. An injection energy of 350 MeV has been chosen, where the damping time is 165 ms, and an injection rate of 5 Hz. The most economical way to provide an electron beam at this energy is with a small electron synchrotron. The booster has a combined function FODO lattice, with a superperiodicity of 4, and a circumference of 15 m.

As in the storage ring, injection is via a septum magnet into radial phase-space. The current required in the booster to fill the storage ring to 400 mA in 100 booster pulses averages about 20 mA, which is typical of synchrotrons of this size.

The emittance of the booster beam is determined by adiabatic damping of the injected beam emittance since the effects from the emission of synchrotron radiation are negligible. Thus, the emittance at 350 MeV is 35 times smaller than the beam emittance at 10 MeV.

Acceleration is provided by a 500 MHz RF system using a harmonic number of 25. The choice of the same frequency as the main ring permits phase locking of the two systems, and bucket-to-bucket transfer for efficient transmission of beam between the two rings, even though the two rings operate at different harmonic numbers.

Ejection of beam is achieved in a single turn through the use of a single fast kicker magnet and a thin septum magnet. The thin septum is almost identical in design to the injection septum in the main ring.

Linac and Linac Gun

The linear accelerator is an S-band machine operating at 3 GHz. There are some advantages in choosing a frequency which is a harmonic of the circular accelerators' RF frequency of 499.654 MHz.

In order to achieve 400 mA in the storage ring, with a 20 s filling time at 5 Hz and a 5% transmission efficiency between the gun and the booster, the electron pulse from the linac must have a peak current of ≈0.4 A. A linac pulse of 150 ns duration is proposed.

References

[1] *Proceedings of a Workshop on a Compact Storage Ring for X-ray Lithography.* Brookhaven National Laboratory, March 1986.

[2] *Design Study for a Dedicated Source of Synchrotron Radiation.* Daresbury Laboratory, UK, DL/SRF/R2, 1975.

[3] *1-2 GeV Synchrotron Radiation Source: Conceptual Design Report.* LBL Pub-5127, June 1986.