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FOR X-RAY LITHOGRAPHY**

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NATIONAL SYNCHROTRON LIGHT SOURCE

**BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.**

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Conventional Magnet Storage Rings For X-Ray Lithography

NSLS Staff

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Abstract

A first pass at the design of a conventional magnet storage ring for x-ray lithography is presented.

Back-Of-The-Envelope Ring Design

A rough estimate of the parameters of a conventional magnet ($B < 2$ Tesla) storage ring to produce bending magnet radiation with a critical wavelength of 10 Å can be obtained from the following formula for the critical wavelength (λ_c), the energy of the ring (E), the circumference of the ring (C) and the white light power emitted by the electron beam (P).

$$\lambda_c (\text{Å}) = \frac{18.6}{B (T) E^2 (GeV)} \quad (1)$$

$$E (GeV) = .3 B (T) \rho (m) \quad (2)$$

$$C = 2\pi\rho + L_{drifts} + L_{quads} + L_{sexts} \quad (3)$$

$$P (w/mrad) = \frac{0.0787 E (GeV) I (ma)}{\lambda_c (\text{Å})} \quad (4)$$

Table 1 displays the implications of choosing a conventional magnet or a superconducting magnet ($B \approx 4.5$ Tesla) to construct the ring. A conventional magnet ring with a critical wavelength of 10 Å will have an energy of 1.1 GeV and just the dipole magnets will account for 14 meters of circumference. Because the energy of the conventional magnet ring is necessarily higher than its superconducting cousin the required current to achieve the desired average power output of $P = 2.5$ watts/mrad will be lower in the $B = 1.6$ T machine. Accounting for the decay of the stored electron beam, the maximum fill current should be on the order of 500 ma.

Table 1

$\lambda_c (\text{Å})$	B (T)	$\rho(m)$	$2\pi\rho(m)$	E (GeV)	$P_{I=100}$
6.	1.6	2.9	18.	1.4	1.8
6.	2.0	2.1	13.	1.2	1.6
6.	4.5	.61	3.9	.83	1.1
10.	1.6	2.2	14.	1.1	.85
10.	2.0	1.6	10.	.96	.76
10.	4.5	.48	3.0	.64	.51

Electron Beam Size and Power Specifications

The x-ray lithographers specified the source requirements in a previous workshop held in March 1986 at Brookhaven National Lab (see BNL 52005). Ideally the electron beam should have a size and angular spread given by,

$$\sigma_{x,y} \leq 1 \text{ mm}, \quad \sigma'_{x,y} \leq 1 \text{ mrad} \quad (5)$$

where σ and σ' are given by,

$$\sigma_x = \sqrt{\epsilon_x \beta_x + \eta^2 \sigma_p^2} \quad \sigma_y = \sqrt{\epsilon_y \beta_y} \quad \epsilon_y = \chi \epsilon_x \quad (6)$$

$$\sigma'_x = \sqrt{\epsilon_x \gamma_x + \eta'^2 \sigma_p^2} \quad \sigma'_y = \sqrt{\epsilon_y \gamma_y} \quad \gamma_i = \frac{1 + \alpha_i^2}{\beta_i} \quad (7)$$

There are two contributions to the beam size; $\sqrt{\epsilon\beta}$ due to the emittance of the beam, and $\eta\sigma_p$ due to the energy spread of the beam (σ_p) and the dispersion (η).

Ignoring η for the moment, and taking $\beta \approx 10$ m, implies that the emittance should satisfy, $\epsilon \approx 10^{-7}$ m rad, a not unrealistic demand. But, the η contribution is not negligible! For a 1.1 GeV storage ring constructed from magnets with a bending radius of $\rho = 2.25$ meters the energy spread, $\sigma_p = \sqrt{\left(\frac{C_q \gamma^2}{\rho J_\epsilon}\right)}$, is on the order of $\sigma_p \approx 1 \times 10^{-3}$. To achieve the 1 mm beam size the dispersion in the magnet must be less than 1 meter.

In a storage ring the length of the electron bunch and the energy spread in the beam are in general proportional. As the current in a given bunch is increased the length of the bunch is similarly increased, due to a phenomena known as anomalous bunch lengthening. The resulting increased energy spread means that to insure that the source specifications are met, the dispersion in the magnet will have to be reduced below the 1 meter value mentioned above. As a margin of safety $\sigma_p \approx 2 \times 10^{-3}$ is a reasonable assumption for the energy spread implying that the dispersion at the source point in the magnet should be about 0.5 meters.

First Pass At A Lattice

As a first pass at a lattice to meet the lithographer's specifications a 4-fold symmetric, gradient FODO cell lattice using $B = 1.6$ Tesla C-magnets was considered. The details of the ring are given in tables 2-4. A scale drawing of the ring which is 30 meters in circumference is given in figure 1. Figure 2 is a scaled drawing including an 8 meter beam line and a model of the lithography end station.

An RF frequency of 21 MHz, implying the harmonic number is 2, was chosen to provide a long bunch to ease injection and maximize the Touschek lifetime. It was envisioned that the ring would be operated in one bunch mode to eliminate the deleterious effects of trapped ions and coupled bunch instabilities. The possibility of two bunch operation is not ruled out should it be deemed desirable from the point of view of increasing the Touschek lifetime. For comparison table 5 lists several RF frequencies along with the RF voltage to achieve an RF acceptance of $\pm 1.5\%$. An estimate of the axial length of the cavity is also given. Depending on the injection energy either the RF cavity or the injection hardware will determine the length of the longest drift space in the ring.

Table 5

h	f_{RF} (MHz)	V (kV)	L (m)
1	10.081	95	1.5
2	20.162	124	1.5
3	30.244	152	1.25
4	40.325	180	1
5	50.407	207	1
20	201.627	602	.6
50	504.069	1385	.6

The betatron functions, β_x and β_y , and the dispersion function, η_x , are plotted in figure 3. As it stands the ring is a "one knob" device, all of the quadrupoles are horizontally focusing, the defocusing quadrupole is incorporated into the dipole magnet by shaping the pole face.

To correct the chromaticity focusing sextupoles are located close to the quadrupoles and to achieve good decoupling between the two planes a defocusing sextupole would be cut into the pole face of the dipole magnet. A few additional defocusing sextupoles are included to provide for fine tuning. At this stage the placement of the sextupoles has not been optimized. It has been suggested that for a ring with this modest magnitude of negative chromaticity that the betatron tune spread may be tolerable and the head-tail instability could be tamed with a

feedback system thus eliminating the sextupoles. This last point of course requires further study.

A plot of the beam size versus azimuth for half of a superperiod is given in figures 4. The emittance coupling, $\chi = \epsilon_y / \epsilon_x$, was taken to be unity and the energy spread was taken to be .2 % to account for anomalous bunch lengthening.

Conventional Magnet Storage Ring
For X-Ray Lithography

4 FOLD · 8 MAGNET RING

BETAX (dashed)
 BETAZ (dot dashed)
 ETA*10 (dotted)
 LATTICE ELEMENTS (solid)

FULL COUPLING SIGMA E= .2%

SIGMAX (MM) (dot dashed)
SIGMAY (MM) (dotted)
LATTICE ELEMENTS (solid)

Table 2 Main Ring Parameters

Energy	1080 MeV
Circumference	29.74 m
Critical Wavelength	10 Å
Lattice Structure	Combined Function
Number of Superperiods	4
Long Straights (4)	1.5 m
Horizontal Betatron Tune, ν_x	3.14
Vertical Betatron Tune, ν_y	1.18
Maximum Dispersion, $\eta_{\max}$	.73 m
Uncorrected Chromaticity, ξ_x, ξ_y	-3.8, -3.2
Momentum Compaction, α	.068
Damped Emittance, ϵ	4.79×10^{-8} m-rad

Table 3 Magnet Complement

Type	Combined Function Dipole
Number of Magnets	8
Magnetic Field Strength	1.6 T
Bending Radius	2.25 m
Bend Angle	45°
Length	1.77 m
Field Index, n	2.95
Full Gap Height	60 mm

Type	Quadrupole
Number of Magnets	8,4
Maximum Gradient	20. T/m
Pole Tip Field	.6 T
Magnetic Length	15, 30 cm
Inscribed Aperture Radius	30 mm

Type	Sextupole
Number of Magnets	8
Maximum $\partial^2 B / \partial x^2$	150 T/m ²
Pole Tip Field	.068 T
Magnetic Length	15 cm
Inscribed Aperture Radius	30 mm

Table4 RF Related Parameters

Energy Loss Per Turn, U_o	53.4 KeV
Revolution Period, T_o	99.2 ns
Damping Partition Numbers, J_x , J_y , J_ϵ	1.7, 1., 1.3
Damping Times, τ_x , τ_y , τ_ϵ	2.3, 4., 3.1 ms
RF Frequency, f_{RF}	20.16332 MHz
Peak RF Voltage, V_{RF}	124.5 KV
Synchronous Phase, ϕ_s	154.6
Synchrotron Frequency, f_s	15.1 KHz
RF Energy Acceptance, ϵ_{RF}	1.5 %
Natural Energy Spread, σ_p	.077 %
Low Current Bunch Length, σ_l	16.4 cm