Proceedings of the Brookhaven Conference on Advances
in Soft X-ray Science and Technology, Upton, NY
October 17-20, 1983

BNJ-33874

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CONF-8310172--9

BNL--33874

DE84 002859

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Storage ring design for X-ray lithography*

A. van Steenberg* and W. Grobman**

Abstract

The design of an electron storage ring for Industrial X-ray Lithography is examined and a parameter optimization carried out based on a model lithography system in use at the National Synchrotron Light Source at Brookhaven National Laboratory. In this optimization the potential use of superconducting or permanent magnet wigglers is considered. The basic parameters and geometry of a number of "t(exposure) = 5 sec., λ (operating) = 8.26 Å" devices are presented.

Introduction

Synchrotron radiation soft X-ray lithography is one of the approaches presently being pursued towards the objective of developing the technology for future VLSI production with line width definition of submicron magnitude and adequate throughput of the resist-wafers for industrial production purposes. Initial work¹⁻² on radiation source and technique optimization led to a basic approach of coupling the synchrotron radiation source to an exposure chamber in which resist-wafers are exposed. For reasons of high throughput and necessity of cooling the mask-resist combination to avoid distortion, exposure of the wafers must take place in a helium gas environment rather than the ultra high vacuum environment of the storage ring. This requires then the separation of the synchrotron radiation source and sample environment by means of, typically, a beryllium window, which attenuates the soft part of the radiation spectrum. Since the vertical opening angle of the radiation is of small magnitude ($\sigma' = 1/\gamma$), a stationary convex or oscillating grazing incidence mirror may be used for full area exposure of the resist-wafer unit. This attenuates the hard part of the radiation spectrum. As a result, the synchrotron radiation power incident on the mask-wafer is typically centered in the 1000-2000 eV photon energy region. A lithography exposure system based on this arrangement has been developed by the IBM group³ at the National Synchrotron Light Source VUV storage ring at Brookhaven National Laboratory. The basic elements of this synchrotron radiation lithography system are illustrated in Fig. 1. Based on this system as a realistic model lithographic exposure system, parameters have been developed of radiation power spectral throughput, as shown in Fig. 2, and resist wafer-exposure time as a function of elementary storage ring parameters, as shown in Fig. 3. The basic conclusions to be drawn from these studies are the optimum operating wavelength region, and from this, derive guidance as to the optimum combination of storage ring energy and guide field parameters, since $\lambda_c = 186.4/(BE^2)$. Typically, for a fixed power spectrum maximum at $\lambda_p = 10$ Å (or, $\lambda_c = 23.8$ Å) $BE^2 = 7.83$ and $B^3\rho^2 = 8.7 \cdot 10^3$ where ρ is the guide field magnetic bend radius. These relationships only permit a limited optimization of the storage ring system as a source for soft X-ray lithography, since they do not focus on the possible trade-off between storage ring energy and beam current; the latter are critical parameters either from a storage ring capital cost point of view (rf system costs, etc.) or from a beam parameters point of view (high beam current value, need for high injection energy, beam instabilities, etc.). Therefore, before defining the parameters of a number of optimum storage rings for purposes of X-ray lithography, some basic parameters will be reexamined and the parameter optimization carried further, based on the IBM lithographic system model.

Figure 1. Basic elements of the synchrotron radiation lithography system.

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***Research carried out under the auspice of the U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

EDAB

Figure 2. Power distribution in beamline at five positions, and resist absorbed power distribution.

Figure 3. Resist exposure time versus energy.

Exposure Scaling Factor

The X-ray energy absorbed per volume of resist per second is obtained by the procedure of modeling the transmission of the photon energy-dependent spectral output of the storage ring as this output traverses the lithographic system. In this process, three main factors determine the final utilization of the photon in resist exposure under the clear areas of the mask: a) reflection from optical surfaces and transmission through absorbing films; b) the geometrical factor which maps the angular width of the beam onto the full mask area; and c) the absorptivity of the resist versus photon energy, which determines the fraction of the incident flux absorbed in the resist. The exposure time of the resist² is given here in simplified form as follows:

$$E_{\text{resist}} = t_{\text{exp}} \theta \left[\int \frac{dP}{d(h\nu)} \right] \cdot d(h\nu) I T_{\text{MW}} \epsilon$$

where E_{resist} is the energy density (J/cm^3) absorbed in the resist, $t(\text{exp})$ in seconds, θ the geometrical factor (mrad/cm^2), I the beam current (A.), T_{MW} the "transmission" factor of mirror and in line absorbers, ϵ the resist "response" (cm^{-1}) and, as given in Appendix I,

$$\frac{dP}{d(h\nu)} = \frac{1.96 \cdot 10^4 \cdot E^7}{(h\nu)^2 \rho^2} G_3(y) \left[\frac{W_{\text{all } \nu}}{eV \cdot \text{mrad} \cdot A} \right]$$

with $\rho[\text{m}]$, $h\nu[\text{eV}]$, $E[\text{GeV}]$; and $G_3(y)$ the Tomboulion-Hartman function with $y = (\lambda_c/\lambda) = (h\nu/h\nu_c)$, numerically given in Fig. 4. Assuming the use of the model lithography line, as indicated above, the mean operating photon energy is fixed here at $h\nu(\text{operating}) = 1500 \text{ eV}$ (or, $\lambda(\text{operating}) = 8.265 \text{ \AA}$). Further, for simplicity, taking into account the transmitted power distribution, as shown in Fig. 2, and approximating this by a "square box" distribution:

$$\int \frac{dP}{d(h\nu)} d(h\nu) = \left[\frac{dP}{d(h\nu)} \right]_{h\nu = 1500 \text{ eV}} \cdot 10^3$$

This permits then the definition of a scaling factor Φ , for equal exposure time devices, as:

$$\Phi = [E_{\text{resist}} / (t_{\text{exp}} \cdot T_{\text{MW}} \cdot \epsilon \cdot 10^3)] = \theta \cdot \left[\frac{dP}{d(h\nu)} \right]_{h\nu = 1500} \cdot I$$

where $\Phi \equiv$ target power flux density per eV in units $\text{W}/\text{cm}^2 \cdot \text{eV}$.

Using relevant parameters for the storage ring ($E = 900 \text{ MeV}$, $\rho = 1.67 \text{ m}$; $B = 18 \text{ kG}$; $\lambda_c = 12.8 \text{ \AA}$; $G_3(y) = 1.08$; $I = 0.41 \text{ A}$) and lithographic system ($\theta = 25/36 \text{ mrad}/\text{cm}^2$; $T_{\text{MW}} = 0.3$; $\epsilon = 360 \text{ cm}^{-1}$, $(h\nu) = 10^3 \text{ eV}$; resist sensitivity = $250 \text{ J}/\text{cm}^2$) one finds that for an exposure time of $t(\text{exp}) = 5 \text{ sec}$, the required power flux density per eV, centered at a photon energy of 1500 eV is given by:

$$\Phi_r [t(\text{exp}) = 5 \text{ sec}; h\nu(\text{oper}) = 1500 \text{ eV}] = 4.63 \cdot 10^{-4} \text{ J}/\text{cm}^2 \cdot \text{eV} \cdot \text{sec}$$

Using $\rho = 33.4 (E/B)$, the expression for Φ can be written as:

$$\Phi(h\nu = 1500 \text{ eV}) = 7.8 \cdot 10^{-6} \theta B^2 E^5 G_3(y) I N F(\alpha)$$

for either a regular magnetic arc source ($\theta = \theta_{\text{arc}}$; $N = F(\alpha) = 1$) or a wiggler source ($\theta = \theta_W$, $N = N_W$, $F(\alpha) \leq 1$).

Using now $\Phi = \Phi_r [t(\text{exp}) = 5 \text{ sec}]$ and adopting specific values for B , an optimum combination of storage ring, or storage ring - wiggler, parameters can be determined by maintaining $\theta E^5 G_3(y) I N F(\alpha)$ constant. This requires knowledge of $G_3(y)$ as a function of energy. With a fixed mean operating wavelength, $\lambda(\text{oper}) = 8.26 \text{ \AA}$, and for specific field values, this can be readily arrived at. It is shown graphically in Fig. 5.

Figure 4. Tombouliau-Hartman Function $G_3(y)$ [$y = (\lambda_c/\lambda) = (c/\epsilon \lambda)$]

Figure 5. $G_3(\lambda_c/\lambda_{\text{oper}})$ versus E
 $\lambda_{\text{oper}} = 8.26 \text{ \AA}$.

Source Parameters

Considering the use of the magnetic arc source, two cases are of interest here, i.e., a room temperature storage ring with $B_{\text{arc}} = 18 \text{ kG}$, or, a superconducting storage ring with $B_{\text{arc}} = 50 \text{ kG}$, as has been adopted for the "Klein Erna" concept.⁵ Using a 36 mrad acceptance angle for the external beam line, or a geometrical factor $\theta_{\text{arc}} = 1 \text{ mrad}/\text{cm}^2$ (mask-wafer exposure area 36 cm^2), it follows numerically that, for a room temperature storage ring, $I = f(E)$, for $t(\text{exp}) = 5 \text{ sec}$, is given by

$$I = 395.7 \frac{\Phi_r}{E^5 G_3(y_{18})}$$

and, similarly, for the superconducting ring ($B = 50 \text{ kG}$),

$$I = 51.3 \frac{\Phi_r}{E^5 G_3(y_{50})}$$

The photon flux density emerging from the storage ring can be enhanced greatly by making use of an electron orbit "wiggler," a sequence of alternating field direction dipoles terminated by half field value end poles. Development of these devices has progressed dramatically in recent years and both devices with superconducting excitation coils ($B = 60$ kG, typically), for flux enhancement in the shorter wavelength region, and permanent magnet wigglers, for specific flux enhancement, in addition to standard electromagnetic devices have been developed. A wiggler may be characterized by its deflection parameter, K , given by, $K = 9.34 B_W \lambda_W$ (kG, m) where B_W is the maximum wiggler field and λ_W is the wiggler period length. The effective radiation opening angle from the wiggler is given by $2\theta_{1/2}(\text{eff.}) = 1.2 (K/\gamma)$, as is further detailed in Appendix II, where the elementary wiggler relationships are given. Taking into account now a limit on the external beam line acceptance (i.e. 36 mrad), it is necessary to distinguish two regimes: θ_W (geom factor) ≤ 1 , or $2\theta_{1/2}(\text{eff.}) \leq 36$ mrad; and, $\theta_W > 1$. Two wiggler units with the following parameters are considered here:

SUM*

A superconducting wiggler, length $L = 1.2$ m; number of poles at $B = \hat{B}$, $N_W = 7$; $\hat{B} = 50$ kG; $\lambda_W = 0.2$ m; $K = 93.4$; vacuum gap, $g = 2$ cm. This could be a structure similar to the NLS 60 kG wiggler design⁶ or similar to the unit produced by Brown, Roveri Cie.⁷

RTW

A room temperature, permanent magnet (REC) - Vanadium Permendur hybrid wiggler, based on the "Halbach" design,⁸ length $L = 1.2$ m; number of poles at $B = \hat{B}$; $N_W = 20$; $\hat{B} = 12$ kG; $\lambda_W = 0.1$ m; $K = 11.2$; vacuum gap, $g = 1.8$ cm.

Taking these parameters into account, the two regimes, as indicated, can be further delineated by using

$$\theta_W = \frac{2 \theta_{1/2}(\text{eff.})}{36} = \frac{1.2 (K/\gamma)}{36} = \frac{1.7 \cdot 10^{-2} K}{E} \text{ [mrad/cm}^2 \text{]}$$

with E [GeV], such that for the "SUM regime," with $K = 93.4$; $\theta_W \leq 1$ for $E \geq 1.6$ GeV and for the "RTW regime," with $K = 11.2$; $\theta_W \geq 1$ for $E \leq 0.19$ GeV. Numerically then, the following relationships apply:

$$\text{"SUM," } E \leq 1.6 \text{ GeV, } \theta_W \geq 1$$

$$I = 7.32 \frac{\Phi_R}{E^5 G_3(\gamma_{50})} \cdot \theta_W F(\alpha)$$

As given in Appendix II, $F(\alpha) = (2/\pi)(\alpha + 1/2 \sin 2\alpha)$ which for small values of α can be written as $F(\alpha) = (4/\pi)\alpha$, with $\alpha = \theta_{1/2}(\text{ext.})/(K/\gamma)$. Consequently the product $\theta_W F(\alpha)$ can be written as $\theta_W F(\alpha) = 0.6(4/\pi)$ which is found to be valid (see Fig. 6) to within 6% within the electron beam energy region of interest here, i.e., $0.3 \leq E \leq 1.6$ [GeV]. Therefore:

$$I = 9.6 \frac{\Phi_R}{E^5 G_3(\gamma_{50})}$$

$$\text{"RTW," } E \geq 0.19 \text{ GeV, } \theta \leq 1$$

$$I = 62.70 \frac{\Phi_R}{E^5 G_3(\gamma_{12})} \cdot \theta_W$$

or, with $\theta_W = 1.7 \cdot 10^{-2} (K/E)$, it follows that

$$I = 329.3 \frac{\Phi_R}{E^4 G_3(\gamma_{12})}$$

Evaluating now the functions $E^N G_3(\gamma_B)$, the relationship I versus E can be arrived at for the various cases considered here. This is graphically shown in Fig. 7. The following observations may be drawn from these results:

*The use of a "matched" superconducting wiggler, whereby the effective opening angle of its radiation equals the acceptance of the lithography line has been considered. This is further detailed in Appendix IV.

$G(G_{\text{eOM}}, \text{FACTOR}) = 36 \text{ MRAD}/36 \text{ CH}^2$;
 $K_W = 93.4$; $(Q_W, \text{EFF}) = 0.6 Q_W, \text{TOT}$

Figure 6. Fractional radiation power acceptance versus energy for a 50 kG superconducting wiggler.

$T(\text{expos}) = 5 \text{ sec}$; $I(\text{oper}) = 8.26 \text{ A}$
 $\kappa(G_{\text{eOM}}, \text{FACTOR}) = 36 \text{ MRAD}/36 \text{ CH}^2$
 $[SUN(50)] = 7 \text{ POLE, } 50 \text{ kG WIGGLER}$
 $[RTW(122)] = 20 \text{ POLE, } 12 \text{ kG WIGGLER}$

Figure 7. Storage ring current versus beam energy

- For the model lithography beam line considered here, operating at $\lambda(\text{oper}) = 8.26 \text{ \AA}$, a mask-resist exposure time of 5 seconds requires, for a "conventional" storage ring ($B = 18 \text{ kG}$) a beam current of 200 mA, at a beam energy of 1 GeV. Alternatively, a maximum beam current of 550 mA should be specified for a beam energy of 0.8 GeV.
- Taking into account the reduction of potential number of radiation ports around the storage ring, the adoption of room temperature REC - VP hybrid wigglers offer no advantage in reducing these parameters (E, I) significantly in magnitude (i.e., for the same exposure time and beam energy of 1 GeV the beam current maximum value could be reduced to 130 mA), unless a storage ring design were to be adopted with very long straights to accommodate room temperature wigglers $\geq 5 \text{ m}$ in length.
- The "Klein Erna" superconducting ring concept permits a significant reduction in maximum beam energy, nevertheless, at its design specification of $E = 0.43 \text{ GeV}$, a beam current of 1000 mA is required to satisfy the 5 seconds exposure time requirement for the adopted lithography beam line model.
- Multipole superconducting wigglers offer a real advantage in reducing the required beam energy and/or beam current values, i.e., for a $E = 0.6 \text{ GeV}$ maximum energy storage ring, with 7 poles (effective) superconducting wigglers, a maximum current of 50 mA would satisfy the 5 second exposure time requirement. Similarly, in this case, a beam current of only 20 mA is required for a maximum beam energy of 0.8 GeV. It should be noted that superconducting wigglers are now available commercially for modest cost. Their practicability in a non-laboratory environment may be judged by the fact that, with standard excitation supply connections, only a single Helium refill per week is anticipated.⁷

Storage ring parameters

A number of considerations enter into the optimum choice of beam current, beam energy values for a lithography source. A few of these are: absence of beam instabilities, long beam lifetime, reliable operation at design current, and, certainly, minimum cost of the overall system. In this connection a few observations are relevant.

With regard to beam instabilities, without entering into the broad (and well documented) field of single bunch and multiple bunch, longitudinal and transverse instabilities in an electron storage ring, a few instabilities are dominant and explicit threshold relationships have been developed for these. For example, the head-tail beam instability, whereby the head of a circulating beam bunch affects the tail of the same bunch via a beam-wall interaction induced wakefield. A simple growth rate expression, which follows from the general theory of bunched beam instabilities,¹⁰ is given by $(1/\tau) < Z_1 I_c / (h \Delta E_0)$

where ζ is the ring chromaticity, $(\Delta v/v)/(\Delta p/p)$, Z_1 the transverse impedance, I_0 circulating beam current, h number of beam bunches, α a ring momentum compaction factor, $(\Delta C/C)/(\Delta p/p)$, and σ_b the bunch length. If the growth rate is fast compared with the synchrotron radiation damping time, beam instability, resulting in beam loss, occurs. Although in general, this instability can be controlled by means of chromaticity corrections,* it is evident that high energy operation with low beam current is favored. Further, the "bunched beam microwave" instability for which the current threshold value can be written as¹¹: $I_p < \alpha E (\Delta E/E)^2 / (e Z_{11})$, similarly indicating a direct proportionality of stable current threshold to beam energy.

In general, it can be stated, that in order to achieve high beam current in a storage ring its injection energy should be commensurately high. The maximum beam current achievable for a specific beam injection energy value is partly based on specific theoretical treatment of possible beam instabilities which could occur in a particular storage ring design, also, partly, on accumulated experience of operating parameters for a variety of small storage rings.

In the absence of loss inducing beam instabilities, beam loss will still occur as a result of beam-rest gas interaction. At relatively low beam energy, the total cross section for scattering is dominated by the elastic scattering on rest gas nuclei for which the cross section is inversely proportional with E^2 . The beam lifetime is then given by $(1/\tau) = \sigma c n$ where σ is the scattering cross section, n is the density of the residual gas, or $n = C_p P_{vac}$, and c is the velocity of light. Recent experience with synchrotron radiation sources has shown that the storage ring pressure may be written as, $P = P_0 + dI$, where d is a desorption coefficient and I is the beam current. Consequently,

$$(1/\tau) \propto (P_0 + dI)/E^2.$$

Specifically using NSLS VUV experience, numerically leads to

$$\tau \propto E^2 / (0.86 + 11 I), \quad I[A].$$

Clearly, for good beam lifetime it is preferable to operate at high beam energy and low beam current. It is worthwhile to note that if the beam intensity is not to vary more than 10%, a beam lifetime of 9.5 hours is required, if the time spacing of the storage ring recharge cycle is to be no less than 1 hour, $[t_d = \tau \ln(I/I_0)]$.

The beam lifetime may be further affected as a result of intrabunch Coulomb scattering. The lifetime associated with this process, the so called Touschek effect is given in its simplest form by

$$\tau_{Tou} \propto h v_{rf} v_{bunch} E^2 / I$$

Further examination, also taking into account the multiple Touschek effect, suggest that for the storage ring parameters under consideration here the beam lifetime could be significantly reduced in the energy region between 100 MeV and 500 MeV.

In the light of some of the above considerations, it is not only desirable to operate at relatively high beam energies, but also to inject beam at the highest beam energy commensurate with reasonable cost of the injection system.

Taking into account the foregoing and the above results of the parameter optimization for a 5 second exposure time lithography source, the basic parameters and conceptual design has been worked out for four simple storage rings, two of which rely on the use of superconducting wigglers and two of which are of a more conventional nature. The basic parameters are summarized in Table 1, the lattice structure of two of these devices with structure functions are given in Figs. 8 through 11, and a more detailed list of their parameters is given in Tables 2 and 3 in Appendix 3.

*The chromaticity correction in a "pure" weak focussing structure is difficult, because of lack of adequate β function modulation and free straights to locate correcting sextupole magnets.

Table 1. Principal parameters for a Lithography Source with T(expos) = 5 sec; $\lambda(\text{oper}) = 8.26 \text{ \AA}$ and Optics Acceptance of 36 mrad

		LISO 0.6, 50, 50	LISO 0.8, 50, 20	LISO 1.0, 18, 200
Energy	(GeV)	0.6	0.8	1.0
Source:		SUW	SUW	ARC
Field	(kG)	50	50	18
Current	(mA)	50	20	200
λ_c	(\AA)	10.4	5.8	10.4
Injector	(MeV)	20	10	100
(Microtron)	(MA)	20	20	10
Injection		multi-turn	single turn	multi-turn multicycling
Lattice Structure		hybrid SF-WF C=22m, $N_g=4$	SF structure C=20m, $N_g=6$	hybrid SF-WF C=26m, $N_g=6$
				WF structure C=18m, $N_g=3$
Ports		3 SUW * $\theta(\text{eff})=96\text{mrad}$	5 SUW * $\theta(\text{eff})=72\text{mrad}$	12

*Electron beam fast orbit manipulation may permit 2 ports per SUW.

LITHOGRAPHY SOURCE: T exp = 5 sec, $\lambda(\text{oper}) = 8.265 \text{ \AA}$
 SUPERCONDUCTING WIGGLERS (S)
 $E = 0.8 \text{ GeV}$, $I = 20 \text{ mA}$, $B(\text{source}) = 50 \text{ kG}$
 $C = 25.4 \text{ m}$ INJECTOR: MICROTRON, 10 MeV , 20 mA

Figure 8. LISO (0.8; 50, 20)

Figure 9. Structure Functions

LITHOGRAPHY SOURCE: $T_{EXP} = 5 \text{ SEC.}$, $X_{OPEN} = 3.26 \text{ Å}$
 $E = 1.0 \text{ GeV}$, $I = 200 \text{ nA}$, $B(\text{SOURCE}) = 10 \text{ nT}$
 WIGGLER FOCUSSED STRUCTURE, DIPOLE ARC SOURCES (12)
 $C = 18 \text{ m}$; Injector: Microtron 100 MeV, 10 nA

Figure 10. LISO (1.0; 18; 200; "W")

Figure 11. Structure Functions

No conclusion has been reached at this stage as to a final set of parameters for an optimum lithography source. Approximate cost estimate and further comparisons are being made. In general, the conventional structures require high beam current and suffer from the lack of an adequate energy cost-effective injector, but have the advantages of a greater number of ports per storage ring; whereas, the rings with superconducting wiggler sources require significantly lower current, have adequate injection energy injectors, but are more limited in the total number of ports per ring.

On the basis of storage ring source and injector parameters alone the LISO 0.8; 50; 20 structure is favored over the alternate structures. Its low beam current promotes long beam lifetime (on the basis of the scaling relation for lifetime given above, the expected lifetime for this unit would be a factor of ≈ 2 higher than either the 0.6 GeV option or the 1.0 GeV device) in addition to which the somewhat reduced opening angle of the radiation from the source simplifies the superconducting wiggler construction.

Conclusion

The results presented here demonstrate the possibility of specifying a storage ring synchrotron radiation source for purposes of industrial lithography which would permit short exposure times of the mask-resist wafers and permit high overall throughput, while using relatively low beam current values in the storage ring, commensurate with the low energy beam injection employed and favorable in terms of beam instabilities and beam lifetime.

References

1. Spiller, E., Eastman, D., Feder, R., Grobman, W., Gudat, W., and Topalian, J., *J. Applied Phys.*, 47 S450 (1976).
2. Grobman, W., "Synchrotron Radiation X-ray Lithography," Handbook on Synchrotron Radiation, E.E. Koch, et. al., Editors, North Holland, Amsterdam (1983).
3. Silverman, J., Haelbach, R., Grobman, W., Warlaymont, J., "X-ray Lithography Exposures Using Synchrotron Radiation," *Proc. of the SPIE, Santa Clara, CA, Vol. 393* (1983).
4. Green, G.K., "Spectra and Optics of Synchrotron Radiation," BNL 50522, April 1976.
5. Jahnke, A., Nolden, F., Trinks, U., "Klein Erna," Interner Bericht, Technical Note, University of Munchen, (1981).
6. H. Hsieh, S. Krinsky, A. Luccio, and A. van Steenberg, *IEEE Trans. Nucl. Sci.* NS28, 3292 (1981).
7. Dustmann, H., Brown, Boveri, & CIE, personal communication.
8. Halbach, K., Chin, J., Hoyer, E., Winick, R., Cronin, R., Young, J., Zambre, Y., *IEEE Trans. Nucl. Sci.* NS28, 3136 (1981).
9. Krinsky, S., Brookhaven National Laboratory, personal communication.
10. Sacherer, F., "Theory of Transverse Beam Instability," *Proc. 9th Conf. on High Energy Accelerators*, Stanford, CA, (1974).
11. Boussard, D., CERN, LAB II/RT/INT/75-2, (1975).
12. J. Blewett, R. Chasman, "Fields and Orbits in Flat Wigglers," Wiggler Workshop, SSRP Report 77/05, p. II-24, 1977.

Appendix I: power spectrum

The synchrotron radiation power radiated per mrad opening angle, per A, per mA of circulating current, integrated over the full vertical opening angle ψ , is given by⁴:

$$\frac{dP}{d\lambda} = 1.438 \cdot 10^{-23} \frac{\gamma^7}{\rho^2} G_3(y) \quad \left[\frac{W, \text{ all } \psi}{A, \text{ mrad, A}} \right]$$

with $y = (\lambda_c/\lambda) = (h\nu/h\nu_c)$. Note: $\rho[m]$. Using

$$\frac{dP}{d(h\nu)} = \frac{dP}{d\lambda} \cdot \frac{hc}{(h\nu)^2} \quad \text{with} \quad hc = 12398 \text{ eV}\cdot\text{\AA} \quad \text{it follows}$$

$$\frac{dP}{d(h\nu)} = \frac{1.96 \cdot 10^4 E^7 G_3(h\nu/h\nu_c)}{(h\nu)^2 \rho^2} \quad \left[\frac{W, \text{ all } \psi}{\text{eV, mrad, A}} \right]$$

For $\lambda \neq \lambda_c$, the power density decreases rapidly towards shorter wavelengths as

$$\frac{dP}{d(h\nu)} \propto \frac{1}{(h\nu)^{1/2}} \exp -(h\nu)/(h\nu_c) \quad \text{for } \lambda \ll \lambda_c$$

and, towards longer wavelengths as

$$\frac{dP}{d(h\nu)} \propto (h\nu/h\nu_c)^n; \text{ with } n \approx 2; \quad \text{for } \lambda \gg \lambda_c$$

It is evident from the numerical data given in Fig. 4 that only those values of λ for which (λ_c/λ) given by $1 < (\lambda_c/\lambda) < 5$ are of possible interest in the lithography source parameter optimization process.

Appendix II: wiggler basics

The basic parameters of a wiggler source follow from simple consideration of the electron trajectory in the wiggler magnet. For a sinusoidally varying periodic B field:

$$B_y = B_W \cos(2\pi z/\lambda_W)$$

where B_W is the maximum wiggler field magnitude and λ_W is the wiggler period length, the electron trajectory is described by $x = (\lambda_W/2\pi)(K/\gamma) \cos(2\pi z/\lambda_W)$; $x' = (K/\gamma) \sin(2\pi z/\lambda_W)$ with K , the wiggler "deflection parameter" given by $K = 9.34 B_W \lambda_W$ (kG, m). From this it follows that the maximum opening angle of the radiation, in the plane of the electron orbit wiggle is given by $2\theta_{1/2} = 2 K/\gamma$ where $\gamma = E/m_0 c^2$ and the maximum electron orbit excursion is given by $2a_{1/2} = 2 (\lambda_W/2\pi)(K/\gamma)$.

The total radiation power emitted by the wiggler source follows from consideration of the emitted power per unit arc

$$\frac{dP}{d\phi} = \frac{2}{3} r_e (m_0 c^2) \frac{\gamma^4}{\rho^2} I = 2.65 B_W^3 E^3 I / 2\pi \quad [W, \text{ kG, A, mrad}]$$

the sinusoidal B field variation, integration over a one half period length and multiplication by N_W , the number of wiggler poles. It follows:

$$P_{\text{tot}} = 3.17 N_W \lambda_W E^2 B_W^2 I \quad [W, \text{ m, GeV, kG, A}]$$

This is the total radiation power emitted by the wiggler incorporating also emission from those sections of the wiggler where $B \ll B_W$.

The usual approach is to define that part of the radiation spectrum from the wiggler emitted from regions where $(B/B_W) > 0.8$ as the effective wiggler source, i.e., that part of the radiation spectrum emitted within $2\theta_{1/2} = 2(K/\gamma) \sin(2\pi z/\lambda_W)$, for which $\cos(2\pi z/\lambda_W) = 0.8$. This yields $\sin(2\pi z/\lambda_W) = 0.6$ and

$$2\theta_{1/2}(\text{eff}) = 1.2(K/\gamma).$$

The total radiation power emitted within an opening angle $2\theta_{1/2}$ is given by⁹

$$P_f = 3.17 N_W \lambda_W E^2 B_W^2 I F(\alpha)$$

where, the function $F(\alpha)$ is given by $F(\alpha) = (2/\pi) (\alpha + 1/2 \sin 2\alpha)$ and $\sin \alpha = \theta_{1/2}/(K/\gamma)$. For $\theta_{1/2} = \theta_{1/2}(\text{eff.})$, as given above, it follows $F(\alpha) = 0.71$.

Appendix III. Parameters of two lithography source structure options

Table 2. LISO structure: 0.8, 50, 20
Summary principal parameters

E	(GeV)	0.8	Injector: Microtron	
I	(mA)	20	E	(MeV) 10
B (source)	(kG)	50	I	(mA) 20
B (dipole)	(kG)	16	E _x	(mrad) $4\pi \cdot 10^{-6}$
λ (crit.)	(Å)	5.8	E _y	(mrad) $12\pi \cdot 10^{-6}$
λ (oper)	(Å)	8.26	($\Delta p/p$)	$\pm 5 \cdot 10^{-3}$
t (exp)	(sec)	5	Mode:	single-turn injection
Circ.	(m)	26.4		
N(e ⁻)		$1.1 \cdot 10^{10}$	Magnetic Structure*: ($N_S = 6$)	
h		4	ρ	(m) 1.66
ν (rf)	(MHz)	45.45	Dipoles (6)	(m) 1.74
$\Delta E/\text{turn}$ (arc)	(keV/t)	21.8	Quads (12)	(m) 0.2
$\Delta E/\text{turn}$ (wiggler)	(keV/t)	35.4	Straight	(m) 1.66
V (rf, max)	(kV)	100	Tunes	(ν_x, ν_y) 2.15; 1.20
Rad. Power (arc)	(kW)	0.44	β_x, β_y	(m) 4.6; 7.0
Rad. Power (wiggler)	(kW)	0.71	Aperature	(cm) 5(B); 12(Q)
P (max rf)	(kW)	10	$\tau_x = \tau_z$	(msec) 2.8

Lithography Sources: SUW: 5, 50 kG, 7 poles.

$$k_W = 93.4; \lambda_W = 0.2 \text{ m}; \theta(\text{eff}) = 72 \text{ mrad.}$$

$$\theta(\text{geom. factor}) = 36 \text{ mrad}/36 \text{ cm}^2; p(\text{tot. source})/\text{unit} = 7.1 \text{ W/mA.}$$

*Strong focussing structure, doublet optics.

Table 3. LISO structure: 1.0, 18, 200, "W"
Summary principal parameters

E	(GeV)	1.0	Injector: Microtron	
I	(mA)	200	E	(MeV) 100
B (source)	(kG)	18	I	(mA) 10
B (dipole)	(kG)	18	E _x	(mrad) $\pi \cdot 10^{-6}$
λ (crit.)	(Å)	10.4	E _y	(mrad) $3\pi \cdot 10^{-6}$
λ (oper)	(Å)	8.26	($\Delta p/p$)	$\pm 5 \cdot 10^{-3}$
t (exp)	(sec)	5	Mode:	multi-turn multicycling injection
Circ.	(m)	18		
N(e ⁻)		$7.5 \cdot 10^{10}$	Magnetic Structure*: ($N_S = 3$)	
h		4	ρ	(m) 1.85
ν (rf)	(MHz)	66.6	Dipoles (6)	(m) 1.93
$\Delta E/\text{turn}$	(keV/t)	45.4	Quads (3)	(m) 0.3
V (rf, max)	(kV)	100	Straight	(m) 1.07
Rad. Power (arc)	(kW)	9.1	Tunes	(ν_x, ν_y) 1.2; 1.2
P (max rf)	(kW)	20	β_x, β_y	(m) 2.5; 3.0
			Aperature	(cm) 3(b); 8(Q)
			$\tau_x = \tau_z$	(msec) 2.6

Lithography Sources: ARC sources, 12 ports.

$$\theta(\text{geom. factor}) = 36 \text{ mrad}/36 \text{ cm}^2.$$

*Weak focussing structure, dipole N = 0.5.

Added QD's for minor tune control and β function modulation.

Appendix IV. Matched superconducting wiggler

It is of interest to consider the optimization of the superconducting wiggler such that its effective opening angle of radiation matches the horizontal angle acceptance of the external optical system, i.e., its acceptance angle of 36 mrad, or matches the lithographic system geometrical factor of $\theta_W = 1$ mrad/cm². As given above: $\theta_W = 1.7 \cdot 10^{-2} (K_W/E)$ which, for $\theta_W = 1$ or, a "matched" wiggler leads to:

$$E = 1.7 \cdot 10^{-2} K_W = 0.159 \lambda_W B_W.$$

The maximum on axis field for a superconducting wiggler is given by¹²:

$$B_W = (1.6/2\pi/2) J_0 \lambda_W [\exp - (\pi g/\lambda_W)]$$

Using the Brown, Boeri & Co. wiggler⁷ parameters for normalization one finds,

$$B_W = 350 \lambda_W [\exp - (\lambda_g/\lambda_W)] \quad [m, kG]$$

which, over the region of interest $0.20 \leq \lambda_W \leq 0.08$ and for $g = 2$ cm, to a good approximation, can be written as:

$$B_W = 322.5 \lambda_W - 13.8 \quad [m, kG]$$

Consequently, it follows that

$$E = 51.28 \lambda_W^2 - 2.19 \lambda_W$$

valid, for the range of λ_W values as given. Therefore, for a "matched" superconducting wiggler the parameters B_W and λ_W (and K , λ_c) can be given explicitly as a function of E , the electron beam energy. This is shown in Fig. 12. For a fixed total wiggler length, the reduction of wiggler field and, thereby, wiggler period length permits an increase in the number of wiggler poles per superconducting unit. This has been taken into account in a comparison of target power flux density per unit beam current for a maximum field wiggler or a "matched" wiggler, for a number of relevant beam energies. The results are summarized in Table 4. From this it can be concluded that the use of a maximum field wiggler, rather than a "matched" wiggler is optimum, in the beam energy region of relevance here, notwithstanding, that the radiation power accepted by the external photon line may be as low as 28% (e.g., 0.6 GeV case) of the total radiation power emitted from the superconducting wiggler.

RADIATION EFFECTIVE OPENING ANGLE MATCHED TO EXTERNAL BEAM ACCEPTANCE (36 mrad)

Figure 12. "Matched SUW"

Table 4. Target power flux density per unit current [W/cm^2 mA]

E (GeV)	50 kG, $\lambda = 0.2$ m wiggler	"matched" wiggler	
1	0.046	0.036	(B = 39 kG, $\lambda = 0.165$ m)
0.8	0.022	0.0165	(B = 34.5 kG, $\lambda = 0.150$ m)
0.6	0.0089	0.0047	(B = 29.0 kG, $\lambda = 0.132$ m)