CONF-851255--2

CONF-851255--2

DE86 014607

SPECTRAL CHARACTERISTICS AND POWER DISTRIBUTION FROM INSERTION DEVICES ON A 6 TO 7 GeV STORAGE RING*

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June 1986

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Presented at the Workshop on Insertion Devices for a 6 GeV Synchrotron Source, Argonne, IL, December 11, 1985.

*This work supported by the U.S. Department of Energy, BES-Materials Sciences, under Contract W-31-109-ENG-38.

WORKSHOP ON INSERTION DEVICES FOR A 6 GeV SYNCHROTRON SOURCE

Argonne National Laboratory
December 11, 1985

SPECTRAL CHARACTERISTICS AND POWER DISTRIBUTION FROM INSERTION DEVICES ON A 6 TO 7 GeV STORAGE RING

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INTRODUCTION:

The electromagnetic radiation from insertion devices (IDs) can be used as a very versatile probe in scientific and technological research which is far superior to that based on a BM source. Two different types of IDs--undulators and wigglers--have been developed to satisfy the requirement of various investigations. These requirements include the need for radiation with specific polarization characteristics, a few micron-sized source, extremely narrow opening angle of the radiation (low divergence), tunability of the energy from soft to hard, and a matching of the radiation characteristics with those of the x-ray optical elements for maximum utilization of the potential of such sources. All these can be provided by a proper match between the characteristics of the positron beam in the storage ring and the ID characteristics. Unlike the IDs presently retrofitted on existing storage rings, the IDs on a 6 to 7 GeV storage ring should be optimized in every aspect of their performance to form an integral part of the design and to meet the specific needs of the research programs that are planned and proposed for this storage ring.

UNDULATOR AND WIGGLER SOURCES

In Table I we list the important parameters of a model lattice considered for the 6-GeV storage-ring.[1] It uses 64 BMs in the storage ring to keep the positrons in a nearly circular orbit. We can extract SR from 32 of these

Table 1

SUMMARY OF MODEL 6-GeV STORAGE RING PARAMETERS

Beam energy	6 GeV
Beam current	> 100 mA
Beam lifetime	> 10 hr
Number of bunches	1-40
Bunch duration	10-100 ps
Horizontal emittance	< 7×10^{-9} m rad
Circumference	≈ 800 m
Number of straight sections	32
Straight se^tion length	6 m standard
Machine radiation	8 mm gap
Output radiation	Bending magnets Wigglers Undulators
Fundamental undulator energy (8 mm)	20 keV

BMs. There are 32 straight sections between the BMs in which one can introduce the IDs. The positrons traveling along the length of such an ID experience transverse motion due to periodic magnetic fields that alter in their polarity. The spectral distribution from this motion of the positrons can be continuous and wide, in which case the ID is called a "wiggler." On the other hand, the emitted radiation can have spectrally narrow and discrete peaks, in which case the ID is called an "undulator." The distinction between wigglers and undulators is determined quantitatively by the value of the so-called deflection parameter K. If the motion of the positron in a transverse ID is approximately sinusoidal, then K is given by

$$K = 0.934\ B_o\ \lambda_o \tag{1}$$

where B_o is the peak magnetic field in tesla and λ_o is the spatial period of the magnetic structure in centimeters. When $K > 10$, the device is called a wiggler and each of the magnetic poles of the wiggler acts as an independent radiation source similar to a BM. The number of poles (or magnetic periods) in such a "multipole wiggler" determines the degree to which the photon intensity (or total flux) will be enhanced. One can also alter the energy of the photons from such a device by proper choice of B_o. The photon critical energy, E_c, for the 6 GeV ring is given by

$$E_c\ (\mathrm{keV}) = 23.95\ B_o. \tag{2}$$

There are situations when one merely wants to increase the photon energy without increasing the total radiated power from a wiggler. This is accomplished by designing a wiggler made up of a single magnetic period with a large magnetic field B_o. Such a wiggler is usually referred to as an "energy-shifter." On the other hand, there are situations where one would prefer to have a high-flux wiggler with a low value of E_c. This is of special interest in applications where higher photon harmonics are detrimental to the success of the investigation. This so-called "high-brightness wiggler" can be designed by incorporating multipole periods with low B_o.

For cases with $K < 1$, the radiation from various poles of an undulator shows constructive interference effects, which produce a spectrum consisting of one or several (harmonic) peaks. Because of the compression of radiated energy into these narrow peaks, one can realize very large photon fluxes in an energy range of choice from undulators.

Instead of a transverse motion of positrons in the ID, one can have helical motion. The characteristics of radiation emitted by such a helical ID are somewhat different from that emitted by a transverse device. The helical devices, however, perturb the storage ring beam in a major way. Hence we shall limit our discussion primarily to transverse IDs.

The positron source size is determined by the emittance of the lattice and the amplitude of Betatron-functions in various straight sections. These are given in Table 2 for some typical situations. There are some important observations that are specific to he 6-GeV lattice: (1) The effective size of the source is fairly independent of photon energies larger than about 1 keV. (2) In the same energy range, the apparent source size and divergence due to radiation are smaller than the same quantities for the positron beam. Consequently, the positron beam size and beam divergence mainly govern the spectral characteristics of the radiation from the various sources on the 6 GeV storage ring.

Table 2

Betatron Functions, Positron Beam Size, and Positron Beam Divergence In Different Parts of a Model 6 GeV Storage Ring

	Bending Magnet	Undulator	Wiggler
β_x(m)	0.92	22.5	1.37
β_y (m)	24.4	13.15	1.24
σ_x (μm)	82	405	100
σ_y (μm)	133	98	30
σ'_x (μrad)	89	18	73
σ'_y (μrad)	5	7	24

Undulators can provide a very bright, quasi-monochromatic photon beam. In the lattice considered here, there are a large number of straight sections for such undulators. Out of 32 straight sections, as many as 28 will be available for the IDs after 4 are used for the accelerator components. The low emittance of the present lattice and large betatron functions in the undulator straight sections provide a low-divergence photon beam of high brilliance. The photon energy of the nth harmonic at an observation angle θ (in radians) relative to the undulator axis is given by

$$E_n = \frac{949\ E_R^2 n}{\lambda_o(1 + K^2/2 + 2\theta^2)}\ , \tag{3}$$

where E_n is in eV, E_R is in GeV, and λ_o is in cm. On axis ($\theta = 0$),

$$E_n = \frac{949\ E_R^2 n}{\lambda_o(1 + K^2/2)}\ ;\ n = 1,3,5,\ldots\ldots, \tag{4}$$

and only the odd harmonics are present. However, one will observe the even harmonics of radiation even along the axis if either (a) the pinhole along the axis has a finite size or (b) the positron beam has a finite size and divergence.

The minimum period of an undulator magnetic structure can be about 1.6 cm with present-day magnet technology. Thus, from Eq. (4), the highest first-harmonic energy that one can realize from an undulator on the 6 GeV storage ring will be about 20 keV. The analogous value for the NSLS is about 3 keV. Thus, the 6 GeV source is unique in providing undulator radiation in the hard x-ray range.

The average spectral brilliance or the flux from an undulator can be calculated to various degress of precision. These procedures are described in more detail in Ref. 2 where many spectral distributions are presented for the undulators with different period.

Figure 1 shows energy spectra for a typical 6 GeV undulator with a first-harmonic peak energy of ~11 keV. These calculations which take into account the finite size and the divergence of the positron beam, were made for undulators made of hybrid $SmCO_5$ (REC) magnets and with the undulator parameters given in Table 3.

From Table 3 and Fig. 1, the following observations are made:

1. On-axis angle-integrated brilliance increases with increasing value of K, as expected from a simple undulator theory.
2. Small values of K suppress the higher harmonics.
3. There is a fairly large contribution to the second-harmonic brilliance even when the radiation is collected along the undulator axis, because of the finite size of the positron beam.
4. The energy of the radiation peaks exhibits broadening and, as will be discussed below, this broadening is influenced by the non-zero-emittance beam of 6 GeV positrons.
5. This particular undulator can be tuned so that the first-harmonic energy can be varied between approximately 11 keV and 14 keV by varying the undulator gap between 1.2 cm and 2.0 cm, respectively. There is concurrent variation in the second- and third-harmonic energies and this fact can be exploited in many experiments needing third-harmonic energy tunability.
6. The second- and third-harmonic radiation in most cases has higher brilliance than the BM brilliance.

Table 3

Parameters of the 6 GeV Undulator for Which the Undulator Energy Spectra of Fig. 4 Were Calculated

	Case A	Case B
Magnetic Gap, G (cm)	1.2	2.0
Undulator Period, λ_o(cm)	2.4	2.4
Peak Field on Axis, B_o (T)	0.34	0.11
Peak K on Axis	0.76	0.25
Number of Periods, N	208	208
Undulator Length, L (m)	5.0	5.0
1st-Harmonic Energy (keV)	10.987	13.813
1st-Harmonic Peak Brilliance[a] (10^{16})	265.0	40.20
2nd-Harmonic Peak Brilliance[a] (10^{16})	17.3	0.45
3rd-Harmonic Peak Brilliance[a] (10^{16})	24.6	0.07

[a]On-axis brilliance in ph/sec/0.2%BW/mrad^2/mm^2.

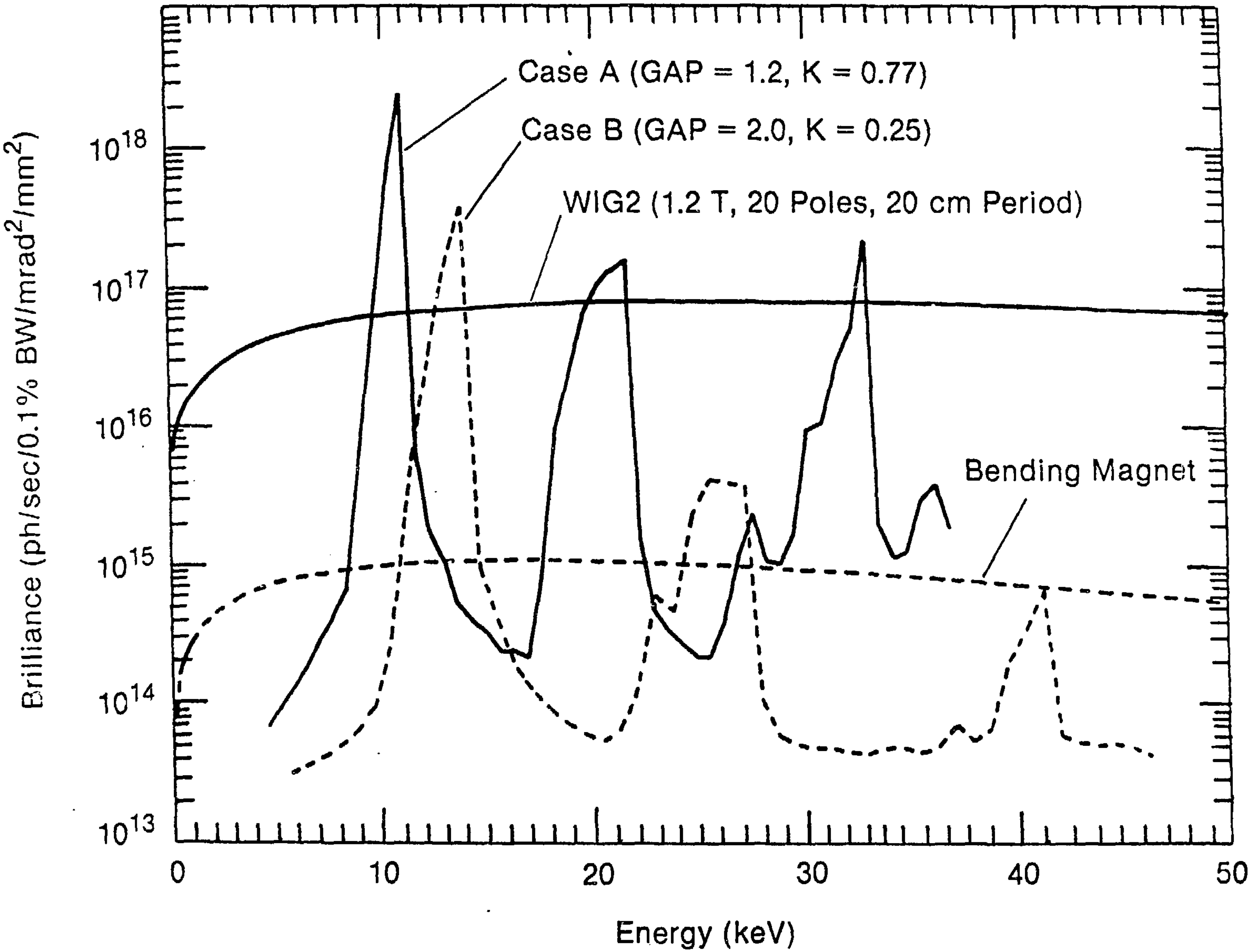


Fig. 1 Brilliance from an undulator (assuming two different magnetic gaps), compared with that from a wiggler and a BM source on a 6 GeV (100 mA) synchrotron

For the various types of wiggler-devices mentioned, the major prerequisite that they have a K value larger than about 10, which will result in a continuous and wide energy spectrum from them. This is achieved by having either large B_o and/or large λ_o. In principle, a multipole wiggler can supply the same number of photons per second in the same bandwidth as an undulator with an identical number of periods in the first harmonic. However, the opening angle of radiation and the effective source size for a wiggler are considerably larger than those of an undulator. Thus the spectral brilliance (or brightness) of a wiggler is lower than that of an undulator.

In Fig. 1, the central brilliance is plotted as a function of photon energy for a wiggler ("WIG2") defined by the following parameters: B_o = 1.2 T, λ_o = 20 cm, N = 10, and K = 22. The brilliance is also compared with that of the undulator discussed above, and with BM radiation. This wiggler source, with a critical energy of 28.7 keV, will be adequate for a large number of experiments requiring photon energies up to about 100 keV. It is important to recognize that for most conceivable applications of the 6 to 7 GeV source, there will be no need to use wigglers based on complex superconducting-magnet technology, of the type presently being designed and built for the NSLS.

It is useful to compare the performance of 6 GeV wigglers with those operating or planned on other storage rings. In Figs. 2 we present the dependence of brilliance for various wigglers as a function of photon energy using the parameters given in Table 4.

Table 4

Parameters of Various Tranverse Wiggler Sources

	6 GeV WIG2	6 GeV WIG3	CHESS	SSRL VI	NSLS X-17
E_R(GeV)	6.0	6.0	5.5	3.0	2.5
I (mA)	100	100	40	100	500
ρ(m)	16.7	28.6	13.2	8.4	1.4
B_o(T)	1.2	0.7	1.39	1.2	6.0
σ_x(mm)	0.1	0.1	1.9	2.5	0.3
σ_y(mm)	0.03	0.03	1.2	0.15	0.02
E_c(keV)	28.7	16.8	27.9	7.16	24.9
Number of Poles	20	30	6	54	6
Period (cm)	20	10	35	7.25	17.8
K	22	7	45	8	99
L (m)	2.0	1.5	1.05	1.96	0.53
Total Power (kW)	6.5	1.7	1.6	1.6	37.9
Peak Power (kW/mrad^2)	16.7	14.6	1.6	2.8	3.8

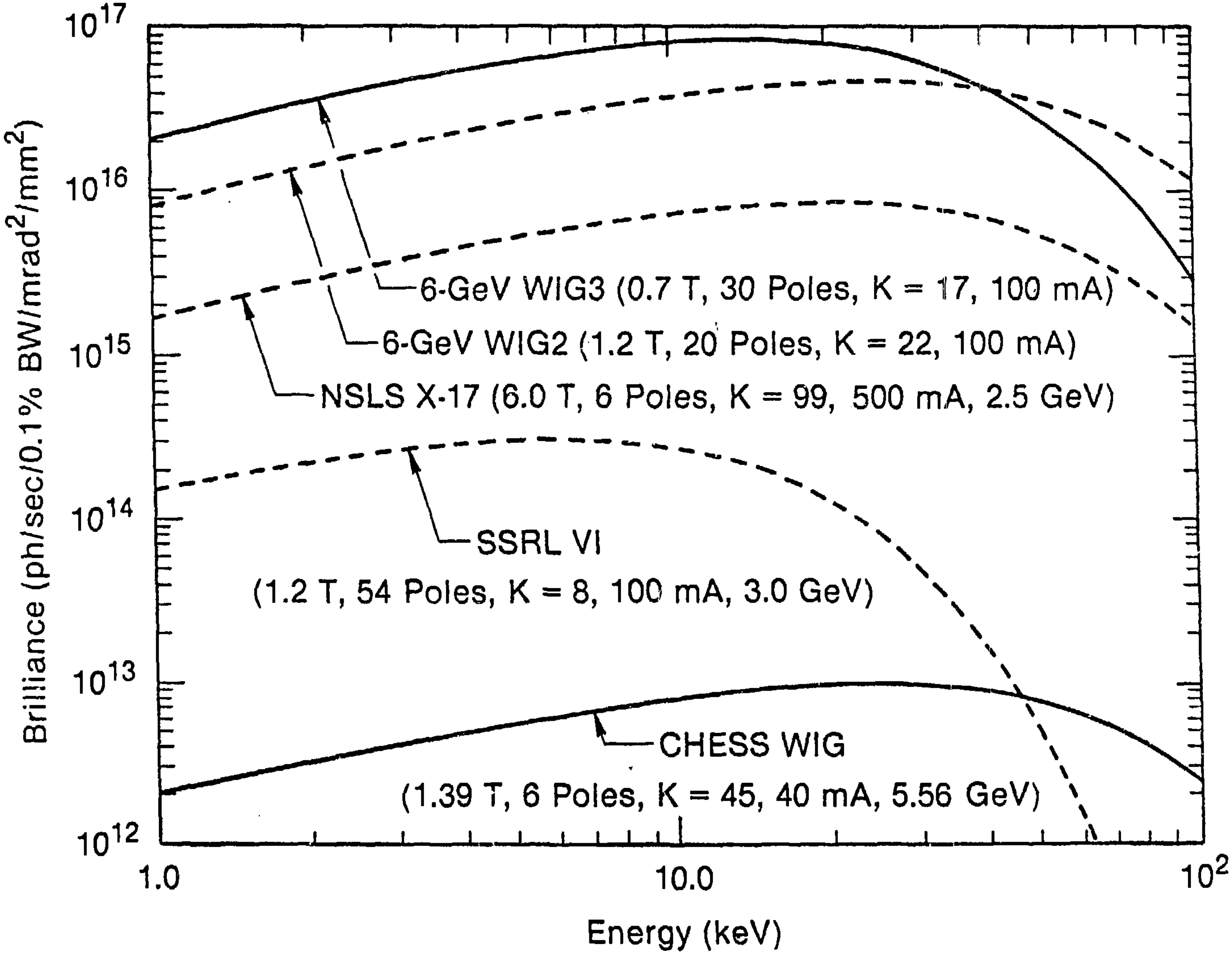


Fig. 2 Brilliance from wigglers on a 6 GeV (100 mA) storage ring, compared with those from wigglers on other synchrotron sources

Energy Spread in Undulator Peaks

For an undulator with N periods, the natural bandwidth of the emitted radiation for an ideally parallel positron beam is given by

$$\Delta_1 = \frac{\Delta E_n}{E_n} = \frac{1}{nN} \ , \tag{5}$$

where n is the radiation harmonic. Thus, for a typical undulator with 200 periods, this bandwidth is 0.5% for the first harmonic. In the case of a 6 GeV ring with non-zero emittance, there are other sources of energy spread.

The contribution to the intrinsic bandwidth from the angular spread of the positron beam is

$$\Delta_2^i = (\sigma_i' \ \gamma)^2/(1 + K^2/2) \ , \ i=x,y. \tag{6}$$

For an undulator straight section in the present lattice, we have (from Table 2) $\sigma_x' = 18$ μrad and $\sigma_y' = 7$ μrad. For a typical value of K = 0.3, the energy spreads along the x and y directions are 4.3% and 0.6%, respectively. Since the broadening effects along the two directions are not equal, the energy spread will be a convolution of these effects. The width at half maximum will be closer to the bandwidth in the y direction, and the distribution will have wings with spread closer to the bandwidth along the x direction.

The size of the positron beam also contributes to the energy spread. This can be estimated for a typical beamline length of D meters from the expression

$$\Delta_3^i = (\sigma_i/D)^2 \gamma^2, \ i=x,y. \tag{7}$$

For our lattice with $\sigma_x = 405$ μm and $\sigma_y = 98$ μm, the bandwidths along the x and y directions will be 0.9% and 0.05%, respectively. This spread is small compared to that produced by the beam divergence.

All the above sources of intrinsic broadening of the energy peak add to produce a halfwidth of about 2%.

An additional extrinsic source of peak broadening is due to the acceptance angle, θ_o. The acceptance angle in an ideal situation can be set equal to σ_x', and this produces a bandwidth of $\gamma^2\theta_o^2$. For the proposed lattice, $\sigma_x' = 18$ μrad, which gives a broadening of 4.5%. This is the dominant contribution to the broadening of the peaks in Fig. 1.

Insertion Device Magnets and Gap

The permanent-magnet technology for IDs is advancing very rapidly and many new undulator magnet design concepts are currently being developed. We foresee the following types of magnet designs being considered for room-temperature transverse IDs:

Type 1: Hybrid magnet devices based on REC or Nd-Fe-B with the field-defining poles made of iron or vanadium permendur.

Type 2: Electromagnetic devices with or without active permanent-magnet materials.

For the hybrid magnets based on permanent-magnet blocks and vanadium permendur pole-tips, the dependence of the peak magnetic field B_o on the magnet gap G (in cm) and undulator period λ_o (in cm) is given by the semi-empirical relation

$$B_o(T) = 0.95a \exp\left[-G/\lambda_o(b - cG/\lambda_o)\right] \qquad (8)$$

In Eq. (8) the factor 0.95 represents the "filling factor" to account for losses in the field due to poor packing of the high-permeability material in the undulator assembly. The equation is generally true for $0.07 < G/\lambda_o < 0.7$. The values of the constants a, b, and c are given in Table 4 for REC and Nd-Fe-B hybrid magnets.

Table 5

Constants Used in Eq. (8), and Values of Remnant Field, for Hybrid Magnets Based on REC or Nd-Fe-B

	$SmCo_5$ (REC)	Nd-Fe-B
a	3.33	3.44
b	5.47	5.08
c	1.8	1.54
Remnant Field, B_r (T)	0.9	1.1

The important aspect of Eq. (8) is the inverse exponential dependence of B_o on the gap-period ratio, G/λ_o. Hence, as indicated earlier, the gap becomes an important factor determining B_o and, in turn, the value of K, which determines the character of the radiation emitted by an ID. In Section 4.2, we showed that in order to obtain 20 keV first-harmonic radiation from an undulator, λ_o

has to be ~1.6 cm. For such short-period devices, to maintain G/λ_o less than 0.7, it is necessary to work with small gaps (0.9 cm). Reducing gaps to such small values is central to the detailed design of an ID.

In choosing between Nd-Fe-B, REC and electromagnets, the following points of comparison are important. (1) Nd-Fe-B can be mechanically worked more easily than REC. (2) The cost of Nd-Fe-B is lower than that of the high-grade REC that is needed for a successful undulator design. (3) For long-period (>20 cm) undulators and wiggler, electromagnets are best suited and least expensive.

With regard to undulator design, we should point out the following:

1. The gap cannot be reduced below a certain minimum value, since there will be a definite aperture size needed for the positron beam injection. If the undulator is inserted in the vacuum ring, the minimum gap can be about 0.8 cm. However, this makes the undulator design complex and reduces the flexibility of storage ring operation. On the other hand, if the poles of the ID magnets are located outside the vacuum jacket of the straight section, the minimum gap will have to be about 1.0 to 1.2 cm, to include the vacuum chamber wall thickness.

2. There are constraints on the K values that will permit the ID to work as an undulator. For K > 3, the positron deflection becomes appreciable and higher-order harmonics become prevalent in the energy spectrum. The utility of higher harmonics (n > 3) is often limited in 6-GeV undulator applications. The value of K cannot be infinitesimally small either. Any value of K smaller than 0.2 drastically reduces the photons from the device.

For the 6 GeV storage ring, we have calculated the first-harmonic energy E vs G/λ_o for hybrid REC undulators with various values of λ_o. The plots are shown in Fig. 3. The variation of K vs G/λ_o for various values of λ_o is shown in Fig. 4. The boundaries of these figures are determined by the constraints discussed above, viz., $G > 0.8$ cm, $0.07 < G/\lambda_o < 0.7$, and $K > 0.2$. These diagrams can be used to define the 6 GeV hybrid REC undulator parameters required to deliver various first- and higher-harmonic energies.

Such plots are also easily generated for the hybrid Nd-Fe-B undulators. For λ_o = 1.6 cm, the gap required to produce a 20 keV first-harmonic energy with this undulator is about 1.2 cm, versus 1.0 cm for an optimized hybrid REC configuration.

We can also observe from Fig. 3 that the tunability of energy differs for undulators with different periods. It is very limited for the short-period undulators on a 6-GeV storage ring.

Undulator Tunability from Gap Variation on a 6-GeV Lattice

In Fig. 1, we showed the range of tunability that could be achieved for one of the undulators by varying the undulator gap. Table 6 shows the energy-tuning capability, based on gap variation, for a typical set of hybrid undulators designed for the 6 GeV storage ring. This set of 5 m long undulators covers the first-harmonic-energy range from 3.0 to 20 keV (see Table 5).

There are numerous questions regarding the undulator energy tuning achieved through gap variation. The design should include beam monitoring and feedback systems, which will reduce the interaction between IDs to a minimum. Hence, it should be possible to vary the gap at one undulator without perturbing the photon beam delivered by other sources on the ring. This might mean a gap variation at only one device at a time. The task of varying the gap will hence be handled by the storage-ring operations group. The frequency of gap variation at any device will depend on the operating

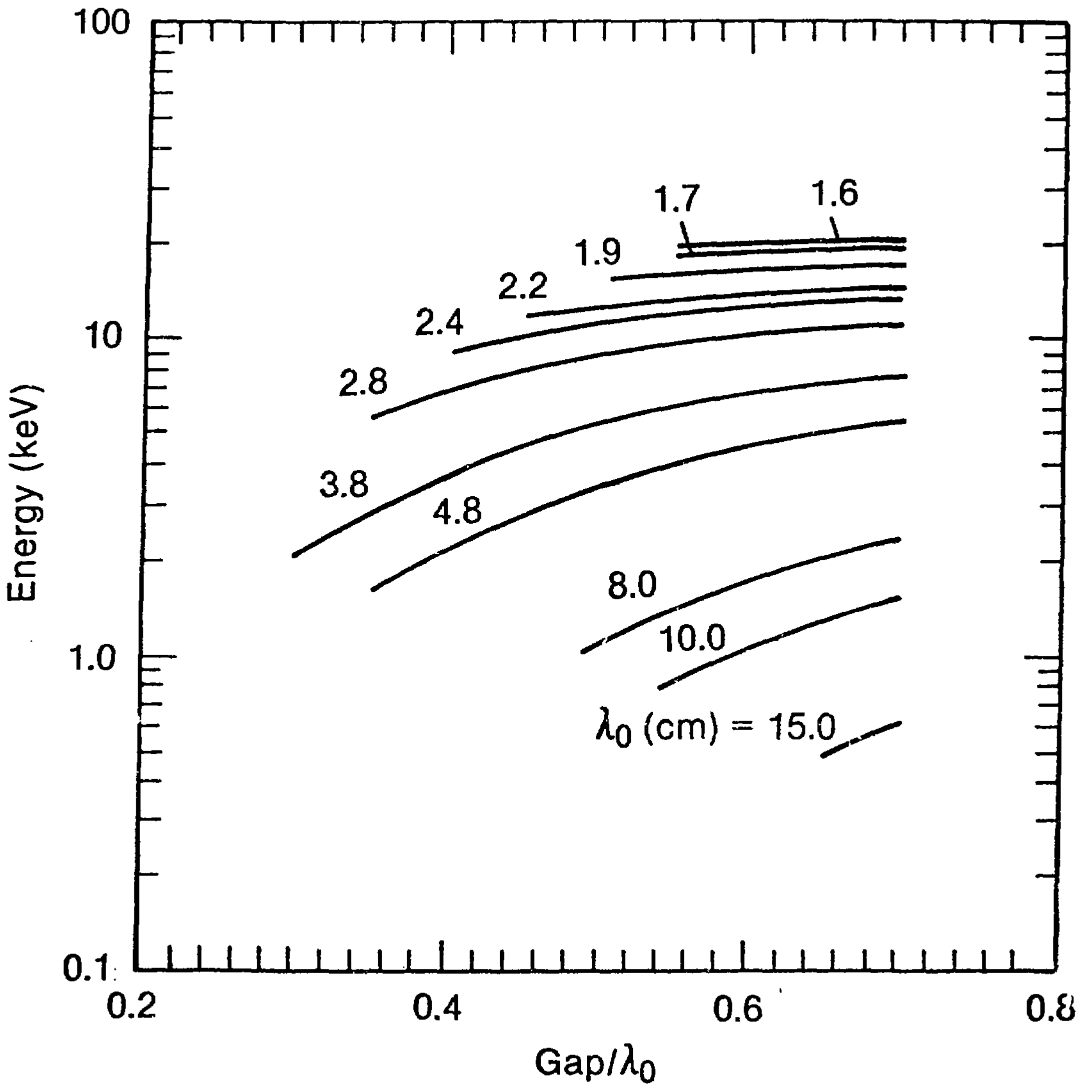


Fig. 3 Energy of radiation as a function of G/λ_o for a set of hybrid undulators with different periods

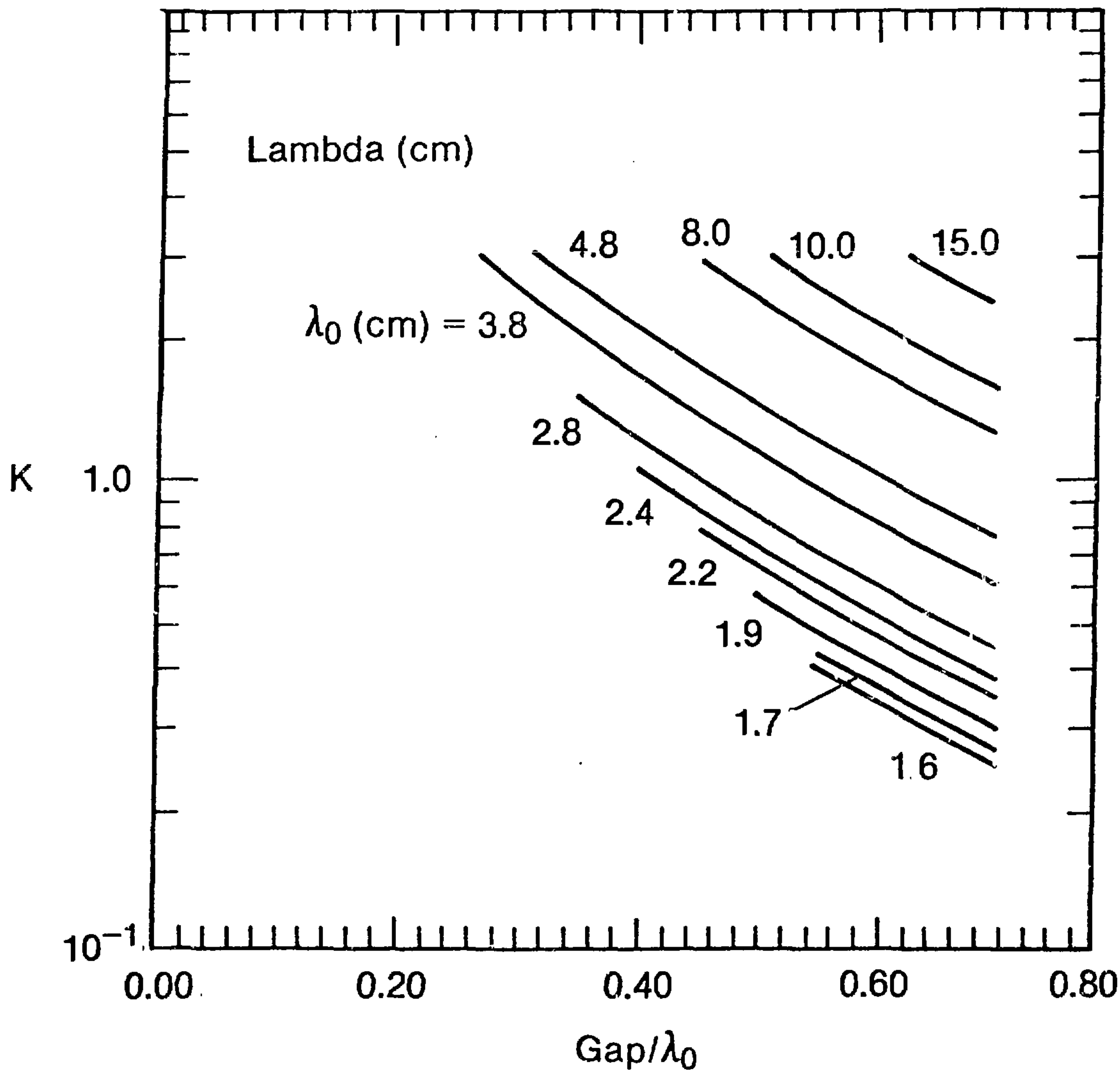


Fig. 4 Deflection parameters K as a function of G/λ_o for a set of hybrid REC undulators with different periods

Table 5

Tunability of Typical 5 m Long Hybrid REC Undulators for the 6 GeV Storage Ring

Undulator	Undulator Period, λ_o (cm)	Gap, G (cm)		First-Harmonic Energy, E (keV)		Peak Deflection Parameter, K		First-Harmonic Brilliance, BR[a]		Number of Periods, N
		G_1	G_2	E_1	E_2	K_1	K_2	B_1	B_2	
1	1.6	0.92	0.78	20.0	19.0	0.37	0.50	1.2	2.1	312
2	1.7	1.22	0.82	19.5	17.5	0.25	0.54	0.5	2.3	294
3	1.9	1.44	0.90	17.5	15.0	0.25	0.63	0.5	2.5	263
4	2.2	1.72	1.06	15.0	12.5	0.27	0.70	0.5	2.5	227
5	2.4	2.03	1.16	14.0	11.0	0.25	0.77	0.4	2.4	208
6	2.8	2.56	1.39	12.0	9.0	0.25	0.85	0.3	2.4	178
7	3.8	3.47	1.80	8.5	5.0	0.34	1.26	0.4	2.5	131
8	4.8	4.33	2.22	6.3	3.0	0.44	1.66	0.5	2.2	104

[a] On-axis value, in ph/sec/0.1%BW/mrad^2/mm^2.

experience gained at the ring. In the worst-case scenario, the gap variation might have to be carried out prior to a new injection of positrons into the ring.

In both the first- and third-harmonic cases, the tunability of the undulators varies between 5% and 50% of the photon peak energies. If a larger variation of photon energy is desired at a given beam port, then the experimenter should use either the radiation in the higher harmonic range at the cost of peak brilliance (depending on the K value of the device) or a set of undulators with different first-harmonic energies, assembled at a single straight section on a translation stage. Switching of undulators on a translation stage will have to be done less frequently than a gap variation.

Procedures will have to be established to accomplish either the gap variation or the device switching at a straight section through the use of software locks at various levels of sophistication, as needed. This will ensure successful and smooth operation of the storage ring without interaction between various experiments.

In summary, undulator energy tuning, by means of either a gap variation or device switching, is desirable at a 6 GeV storage ring; with a properly structured procedure, this can be accomplished by the storage-ring operations group after implementation of the essential diagnostics and monitoring that are included in the present design.

Undulator Tunability on a 7-GeV Lattice

The undulator on the 6 GeV storage ring deliver first harmonic radiation with energies ranging from 1 to 20 keV. There are, however, certain aspects of their performance that are restrictive. We make the following observations in comparing the ID performances on a 6- and 7-GeV lattice.

- Maintaining the peak brilliance within a factor of three, the first harmonic energy can be tuned on a 6-GeV storage ring only to a very limited extent by varying the gap of undulators that deliver radiation with energy greater than 15 keV. Hence, if one needs first harmonic energy ranging from 10 to 20 keV for an experiment on a beam line, one has to provide as many as five undulators on a movable stage to cover the desired energy range. Such an operation is cumbersome and costly.

- The brilliance of undulators is roughly a quadratic function in the deflection parameter, K. For the REC or Nd-Fe-B hybrid 6-GeV undulators, which are designed to deliver high photon energy radiation in the first harmonic, the value of K is rather small. For example, the highest value of K for the 20-keV undulator is 0.35 with the REC hybrid configuration.

- The above two restrictions can be overcome by operating the storage ring at a higher energy, such as 7 GeV. To demonstrate this, we have show in Figs. 5 and 6 the variation of the photon energy and K value as a function of the ratio of the gap to the undulator period. Since the first harmonic energy is proportional to the square of the three in the 20-keV range for 7-GeV operation compared with a 6-GeV operation. As a result, the first harmonic between 10 and 20 keV can be easily obtained by using only two undulators mounted on a movable stage. From Fig. 6, it is observed that the K values are also higher. This means higher brilliance from a 7-GeV undulator, provided the emittance is the same for the two storage rings.

- For energies lower than 15 keV, one will need only one undulator to cover the range from 2 to 15 keV. This will reduce device costs dramatically.

- The minimum gap requirement to obtain 20 keV will be at least 12 mm on a 7-GeV lattice (than 9 mm on a 6-GeV lattice).

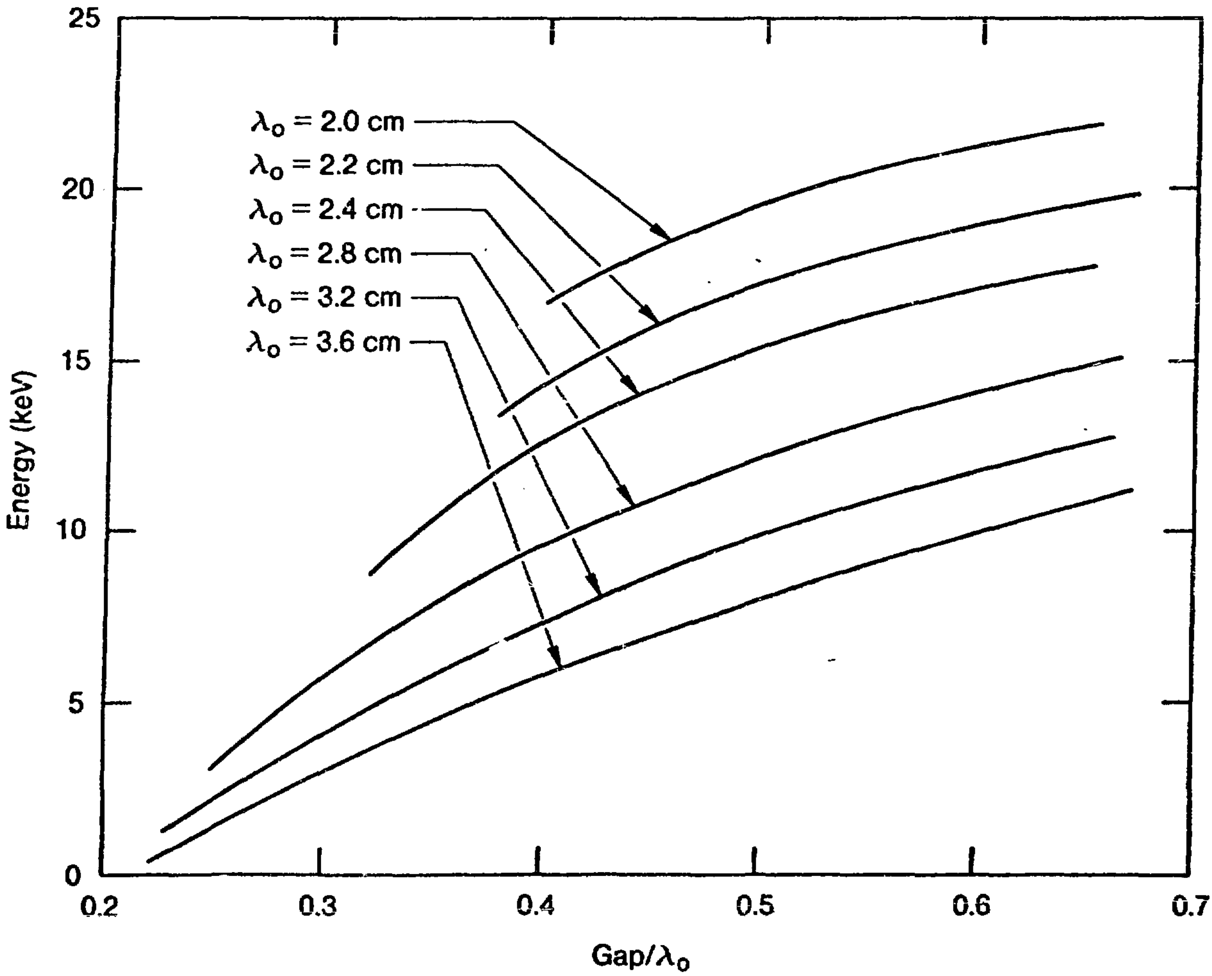


Fig. 5 Energy of radiation from a set of hybrid REC undulators with different periods on a 7-GeV storage ring as a function of the ratio of the magnet gap and undulator period (G/λ_o).

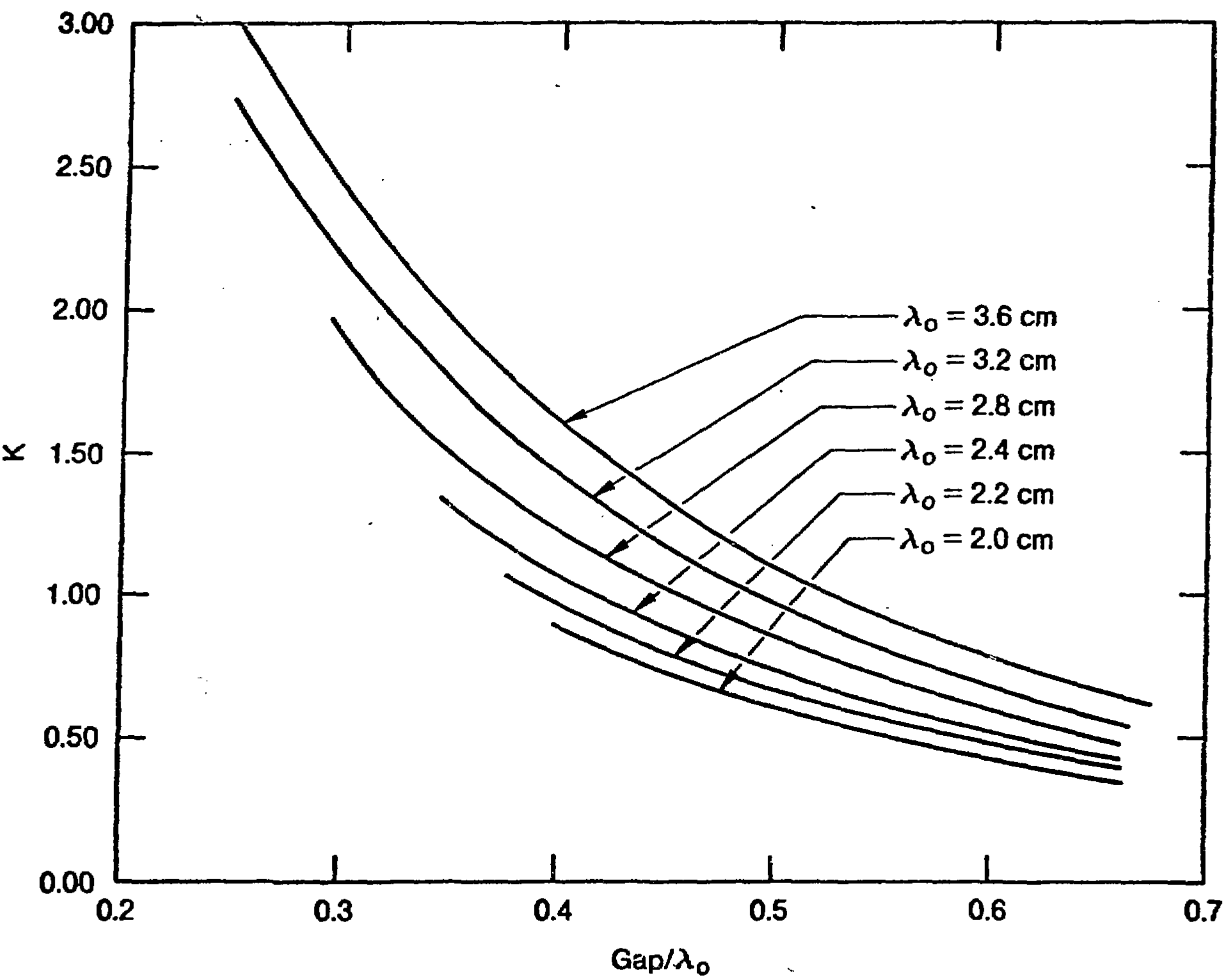


Fig. 6 Variation of the deflection parameter K for a set of hybrid undulators with different periods of 7-GeV storage ring as a function of the ratio of the magnet gap and the undulator period $G(/\lambda_o)$.

- Finally, various tolerances on mechanical and magnetic design on a 7-GeV lattice will be less stringent than on a 6-GeV lattice.

It is clear that to derive the full benefit of 7-GeV operation, one has to design a lattice which will provide the low-emittance positron beam proposed for 6 GeV. For this to be achieved the 7-GeV lattice requires a larger circumference. Under these conditions, a 7-GeV lattice would provide many advantages and flexibilities in the design and operation of the IDs.

Angular Distribution of Power from Various Sources

When one delivers a very brilliant photon beam, one also delivers a large amount of radiated power concentrated in an extremely small solid angle from the low-emittance 6 or 7 GeV storage ring. This power will have to be handled in a beamline by various components such as absorbers, masks, filters, pinholes, windows, and the optical elements (mirrors and monochromator crystals). In this section, we present a quantitative evaluation of the radiated power from the various ID sources and their angular dependences.

The total power (in watts) radiated from an ID of length L (in meters) is given by[3]

$$P = 0.633\ E_R^2\ B_o^2\ I\ L, \tag{9}$$

where B_o is the peak field in the ID. The angular dependence of this power (in W/mrad θ/mrad ψ) is

$$\delta^2 P/\delta\theta\delta\psi = 0.01084\ E_R^4\ B_o I\ N\ G(K)\ f_K(\theta,\psi), \tag{10}$$

where N is the number of periods in the ID and K is the usual deflection parameter. In the above,

$$G(K) = (K^7 + 24K^5/7 + 4K^3 + 16K/7)/(1 + K^2)^{3.5} \qquad (11)$$

and $f_K(\theta,\psi)$ is a complex integral normalized to 1. For $\psi = 0$ and $\theta = 0$, the peak power density (in W/mrad θ/mrad ψ) is obtained from

$$\delta^2 P/\delta\theta\delta\psi\ (\theta=0,\psi=0) = 0.01084\ E_R^{\ 4} B_o I\ N\ G(K). \qquad (12)$$

It is important to note from Eq. (11) that much of the variation in G(K) is for K values smaller than 1.0, with G(K=1.0) = 0.94. As we approach the wiggler regime (K ≥ 10), the value of G(K) approaches 1; G(∞) = 1.0. Hence the variation in the peak power density for a given undulator increases as K approaches 1.0 and then saturates for larger values of K.

The horizontal and vertical sections of the angular power distribution for 6 GeV IDs with various values of K, namely $f_K(\theta,0)$ and $f_K(0,\psi)$, are shown in Figs. 7 and 8, respectively. It should be pointed out that the vertical distribution for K = ∞ is identical with that of a BM. Thus the extent of the vertical distribution of radiation power from any real ID will be smaller than that from a BM. The horizontal power distribution, $f_K(\theta,0)$, approaches that of a wiggler as K increases, with the power cutoff at $\pm K/\gamma$. The extent of horizontal distribution of the power density for a typical undulator is always smaller than that for a wiggler and increases with increasing K.

Let us consider a typical hybrid REC undulator with λ_o = 1.9 cm, for which the first-harmonic energy is ~15 keV. For this undulator, L = 5 m, N = 263, B_o = 0.35 T, λ_o = 0.9 cm, and K = 0.63. From previous equations, it is found that the total power radiated by this device is 1395 W, and the peak power density is 113 kW/mrad^2. Most of the radiated power is distributed in a solid angle of approximately 130 x 130 μrad^2. Next let us consider a wiggler on the 6 GeV ring with B_o = 1.5 T, N = 15, λ_o = 10 cm, and K = 14. The total power from this wiggler is 7.67 kW and the peak power density is 31.6 kW/mrad^2. The horizontal power distribution spreads between ±1.2 mrad.

Often it is more useful to consider the power distribution on a surface located D meters away from the center of the ID. The normal radiation impinging on a surface can be defined by peak surface power density W_{xy} (in W/mm^2):

$$W_{xy} = [\delta^2 P/\delta\theta\delta\psi \text{ (at } \theta=0,\ \psi=0)]/\ D^2. \tag{13}$$

In the above undulator and wiggler examples, the values of W_{xy} at a distance of D = 20 m from the source are 282 and 79 W/mm^2, respectively. This power falls off rather fast as we move away from the axis of the ID in both the x and y directions. At normal incidence, the power from the undulator exposes an area of roughly 2.6 mm x 2.6 mm at a distance of 20 m. The analogous area for the wiggler is 3 mm x 24 mm.

The above understanding of the angular distribution of radiation from IDs on the 6 GeV storage ring has the following important consequences: Negligible amounts of radiation from the IDs will strike the walls of the vacuum chamber even when the chamber aperture is 8 mm. Thus the photodesorption from the walls of the IDs is not significant. Also, no cooling of the ID walls is necessary. The magnetic structure will not be exposed to the radiation. Hence there will be no radiation degradation of the

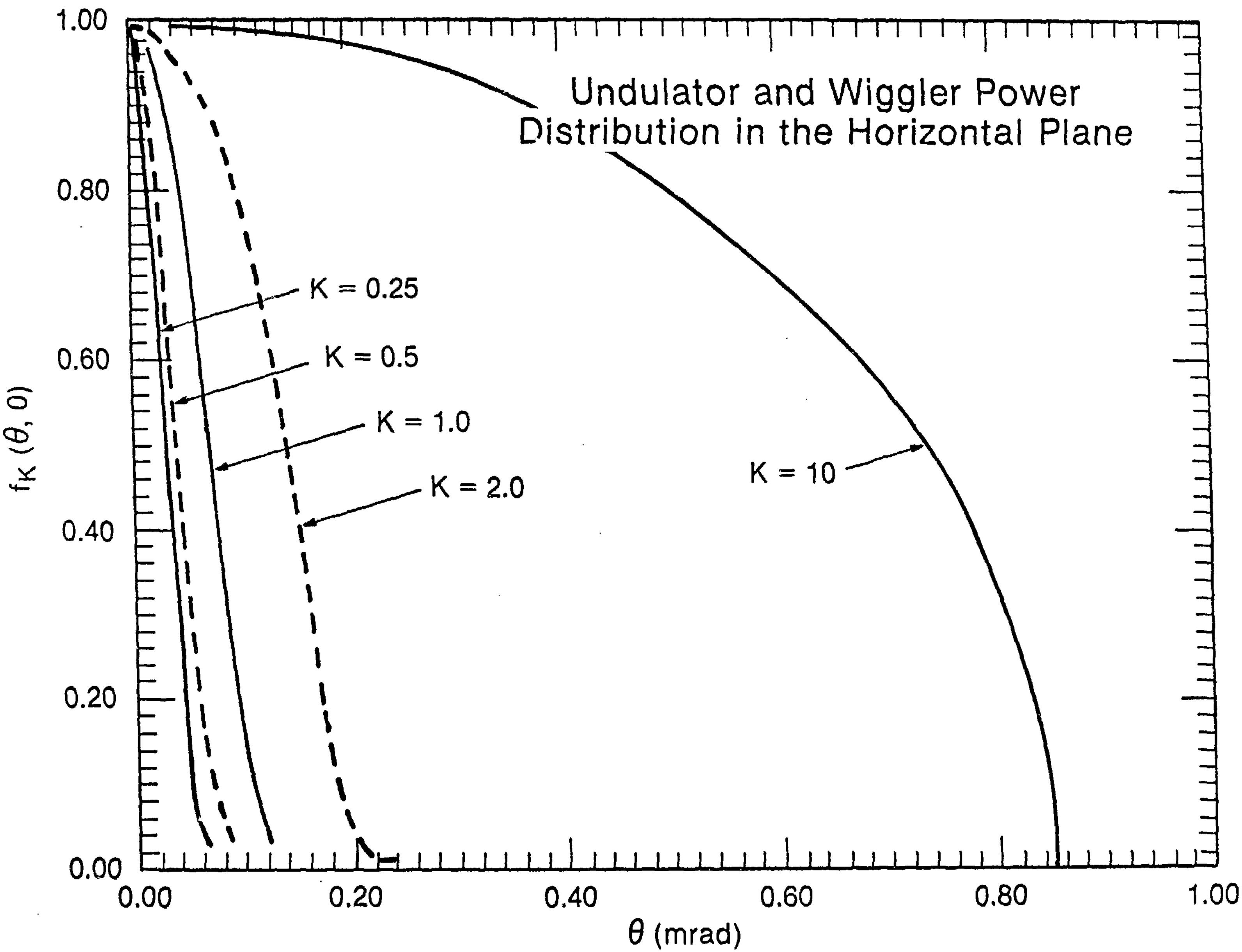


Fig. 7 The horizontal section of the power distribution $f_K(\theta,0)$ for IDs with various K values

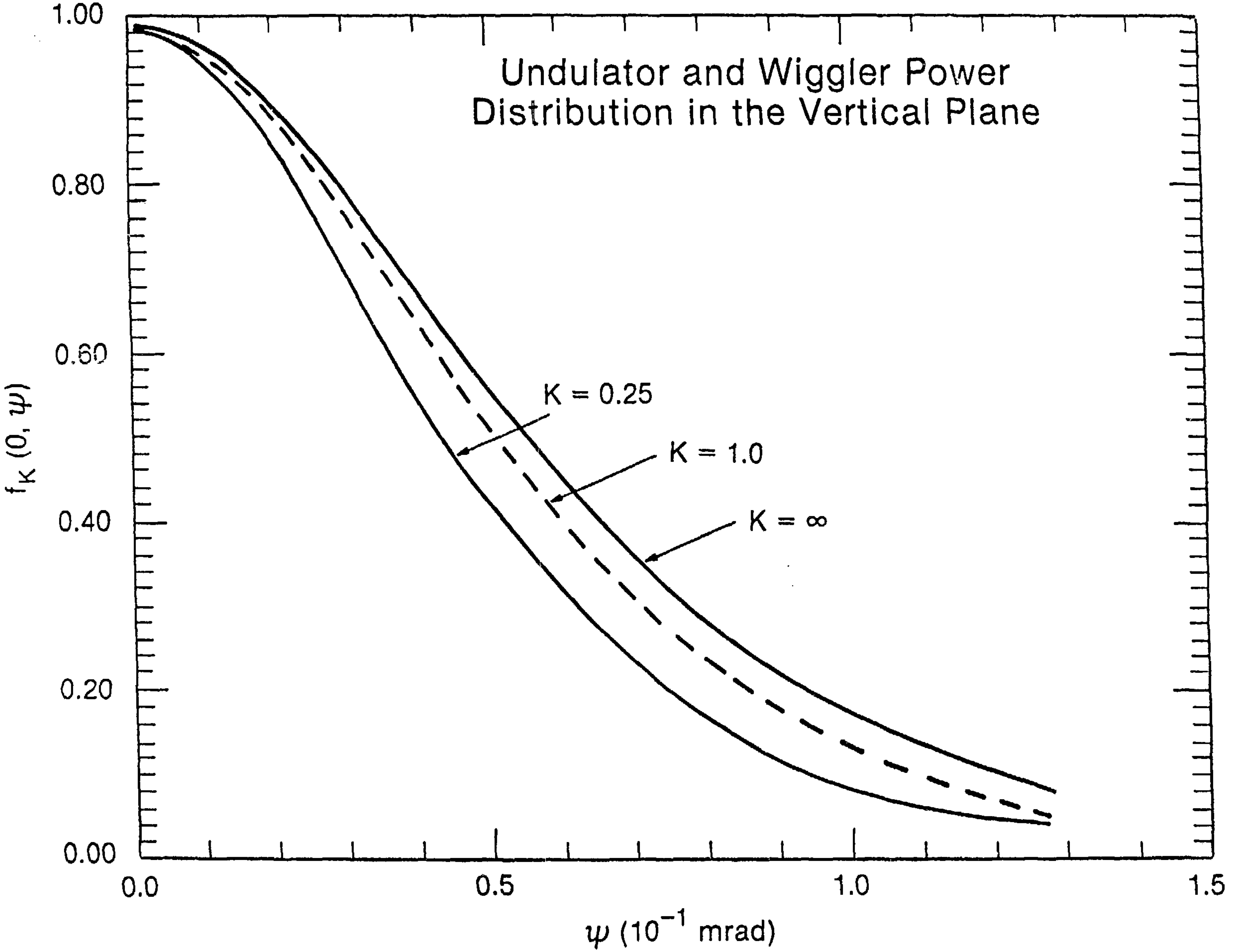


Fig. 8 The vertical section of the power distribution $f_K(0,\Psi)$ for IDs with various K values

magnetic properties that are otherwise anticipated, nor will the magnetic structure be heated by the radiation.

In a 7-GeV lattice, the peak power loads will be nearly double and the angular spreads will be slightly smaller compared to those from a 6-GeV lattice.

Polarization of Radiation from Various Sources

In many experiments, the polarization characteristics of the radiation are of paramount importance, and synchrotron sources provide many possibilities for obtaining radiation of the desired polarization.

The radiation from BM sources is linearly polarized in the orbital (xz) plane. The critical energy radiation (19.13 keV) from the model lattice is 99.92% linearly polarized. With increasing ψ, the perpendicular polarization gradually increases at the cost of polarization parallel to the xz plane. These two components of polarization are phase correlated, and hence one can obtain elliptically polarized radiation as ψ increases. The polarizations above and below the xz plane are opposite in helicity. The ellipticity of the radiation at any given angle also depends on the energy of the radiation.

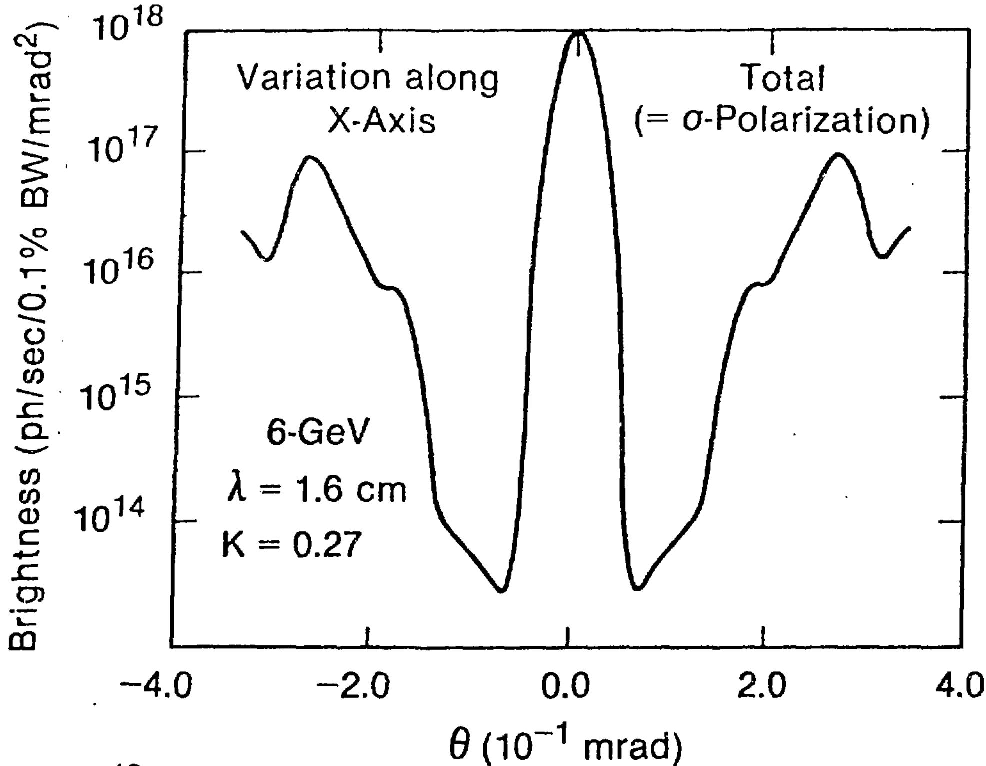
On passing through a transverse multipole wiggler, the positron beam experiences bending forces in two opposite directions. Hence, the radiation is linearly polarized only in the orbital plane (xz). Away from this plane, polarizations of opposite helicity from successive poles add to destroy the net polarization, except for a residual linear component. This should be contrasted with the situation for a BM or a single-period energy-shifter wiggler.

In some situations, linear polarization in the yz plane rather than in the xz plane is desired. This can be accomplished by designing a multipole wiggler with the positron trajectory in the yz plane (and the field along the xz plane). For a 6 or 7 GeV storage ring, such a wiggler can be designed by using permanent magnets.

A helical wiggler can deliver radiation with circular polarization along the axis of the device. However, such a device will produce strong coupling between the horizontal and the vertical motion, with a resultant increase in vertical beam size.

The nature of polarization emitted by a transverse undulator is dependent on the observation angle. The inclusion of the positron beam divergence smears the polarization content of the radiation, but for the low emittance lattice, it is not destroyed. Along the x axis one has linear polarization (σ-component), whereas along the y-axis the σ- and π-components appear at various observation angles (see Fig. 9). Our calculations suggest the possibility of selecting a wide variety of ellipticities of polarization by choosing an appropriate observation angle for a given photon energy.

There are two distinct types of undulators which can in principle deliver on-axis radiation with arbitrary polarized radiation. The first one is a helical undulator which delivers circular polarization along the axis. The second device, is called a "crossed-undulator." These devices will need considerable developmental work before it is constructed for the 6 or 7 GeV storage ring and are discussed in detail by Kwang-Je Kim in this report.



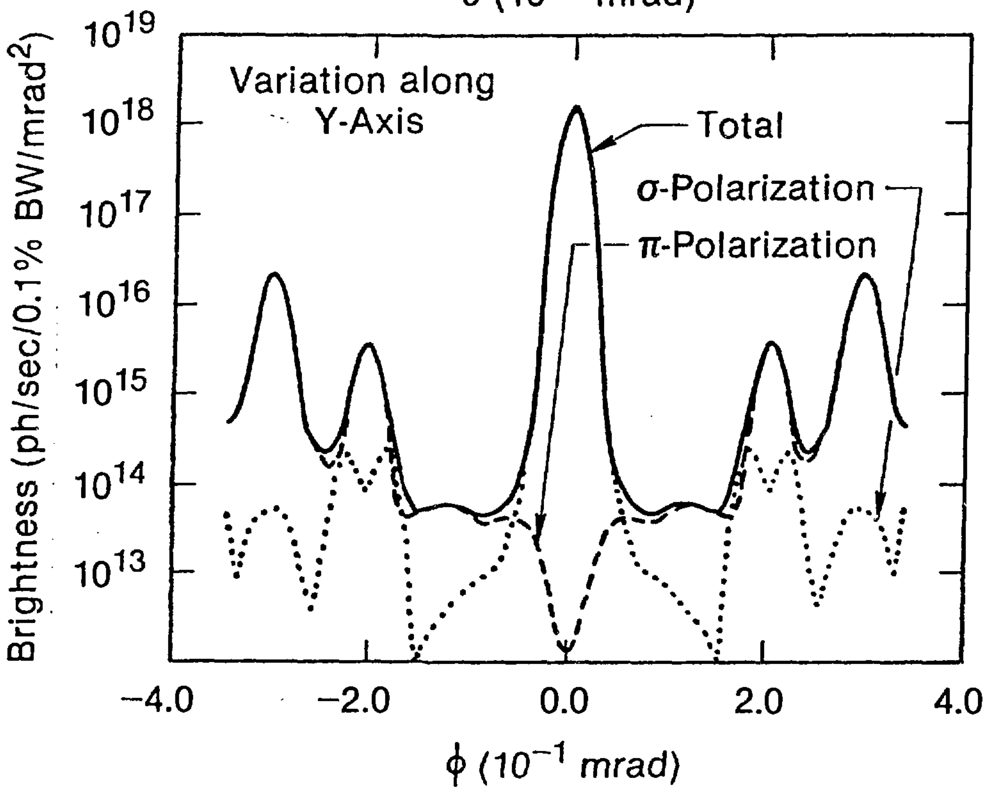


Fig. 9 Angular distribution of 20 keV radiation from a 6 GeV (100 mA) undulator along the x- and y-axes. The σ- and π-polarization components along the y-axis are shown. These calculations include the source size.

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