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PHOTON ENERGY TUNABILITY OF ADVANCED PHOTON SOURCE UNDULATORS*

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ABSTRACT

At a fixed storage ring energy, the energy of the harmonics of an undulator can be shifted or "tuned" by changing the magnet gap of the device. The possible photon energy interval spanned in this way depends on the undulator period, minimum closed gap, minimum acceptable photon intensity and storage ring energy. The minimum magnet gap depends directly on the stay clear particle beam aperture required for storage ring operation. The tunability of undulators planned for the Advanced Photon Source with first harmonic photon energies in the range of 5 to 20 keV are discussed. The results of an analysis used to optimize the APS ring energy is presented and tunability contours and intensity parameters are presented for two typical classes of devices.

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I. INTRODUCTION

The relationship between the energy tunability of an undulator and the storage ring energy, E_R has been investigated previously [1,2,3] for the specific case of the Advanced Photon Source (APS) to be built at Argonne. As was shown, both the tunability as well as the fundamental undulator photon energy are determined by the period, λ, of the device, the magnetic gap, G, and E_R. The minimum ring energy necessary to provide a given tunability interval around a particular photon energy of the undulator can be uniquely specified given the minimum acceptable photon flux and minimum achievable magnet gap. The latter parameter in turn, depends on the particle beam aperture required for operation of the storage ring.

For a majority of the undulators on the APS, the photon energies will span the energy range of approximately 5 to 20 keV. The obvious requirement is to achieve this energy span on a given beam line with as few undulators possible. As has been discussed, the tunability of a single device increases with increasing ring energy. Obviously, there exists a minimum E_R below which the tunability criteria are not satisfied. An unambiguous determination of this minimum E_R is essential if a realistic choice of the storage ring energy is to be made.

For the case of the APS, the ring energy will be (7+10%) GeV [4]. This value is based on an analysis similar to the one described above. The undulator tunability characteristics used were (1) the availability of first harmonic photon energies in the interval of approximately 4.7 to 14 keV from a single device, and (2) the availability of 20 keV first harmonic radiation from a second device with limited tunability [3]. Both criteria are satisfied at the proposed APS ring energy and expected storage ring aperture.

In the following, we present a brief summary of the optimization procedure used in the analysis and discuss the photon energies and intensity characteristics of two types of undulators planned for the APS.

II. ANALYSIS

The energy in keV of the i^{th} harmonic of an undulator for an observation point along the midplane axis of the device is given by: [5,6]

$$E_{Pi} = \frac{0.949 \, E_R^2 i}{\lambda(1 + K^2/2)} \tag{1}$$

Where E_{Pi} is photon energy in keV, E_R is the ring energy in GeV, λ is the undulator period in cm and i is the harmonic number. We will consider only the first harmonic $i = 1$ and $E_{Pi} = E_P$. The deflection parameter K is given in terms of the undulator period (in cm) and the peak magnetic field B_o (in Tesla) by

$$K = 0.934 \, \lambda B_o \tag{2}$$

K is related to the maximum deflection angles (slope) of the particles trajectory through the undulator and is closely seated to the photon intensity the device delivers at the harmonics. For hybrid magnets based on permanent magnet blocks and permendur pole tips, B_o is given by [7]

$$B_o = 0.95 \, a \exp(-G/\lambda(b-cG/\lambda)) \tag{3}$$

where G is the magnet gap of the undulator in cm.

In Eq. 4, the factor 0.95 represents the "filling factor" which approximates the packing factor of high-permeability blocks in the undulator assembly. The constants a, b and c depend on the magnetic material and are given in Table 1 for two permanent magnet candidate materials, $SmCo_5$/permendur and Nd-Fe-B permendur.

TABLE 1

Constants used in Eq. 3 for Hybrid Magnetic based on REC or Nd-Fe-B

	REC/Hybrid	Nd-Fe-B
a (T)	3.33	3.44
b	5.47	5.08
c	1.8	1.54

Equation 3 for the peak field is valid in the interval $0.07 < G/\lambda < 0.7$. Although the upper limit for G/λ does not define the maximum operational gap of the device, for small period devices ($\lambda<3$), the K-values and, hence, photon intensities are small. Therefore, the operational limits of a given device are usually near the upper gap to period ratio.

Equations 1, 2, and 3 form a set of coupled equation which determine the photon energy of a given harmonic as a function of gap, device period and ring energy. At a given ring energy E_R, the undulator period and gap, determine the on-axis 1st harmonic energy, E_p. Decreasing the gap increases B_o and hence the value of K resulting in a lower photon energy.

In summary, the largest photon energy occurs at the largest gap for a given undulator period and has both the <u>smallest</u> K and intensity. The energy may be shifted down from this maximum by decreasing the gap. The K-value and therefore photon intensity increase with decreasing gap. The tunability from the maximum to minimum photon energy is limited by the maximum gap determined by the minimum acceptable intensity from the fundamental of the undulator and the minimum gap determined by the ring aperture. In addition, the tunability interval depends on the storage ring energy.

At any given E_R, the maximum desired photon energy, E_U and minimum deflection parameter, K_U, at the open gap (G_U) position determine the required device period, $\lambda(E_R)$ at each ring energy. This value of λ is the maximum one at E_R capable of producing E_U and is also the one with the largest tunability range consistent with E_U and K_U because it has the smallest closed-gap to λ-ratio. Once this period is determined for E_U, then the gap at each E_R required to produce any E_P smaller than E_U can be determined. In particular, the minimum gap, G_L, then determines the minimum possible first harmonic photon energy, E_L. The interval E_U-E_L is the tunability interval at a given E_R. The maximum interval possible within the constraints on K_U is that provided by the period determined above.

Once a particular photon energy interval is chosen, e.g., 4.7 to 14 keV first harmonic tunability, then it is clear that within the constraints on K_U and the closed gap G_L, there is a minimum ring energy at which this tunability can be achieved. As mentioned, this minimum E_R is important in deciding the optimum ring energy.

Within this analysis, there is an equivalent way of analyzing the tunability vs. ring energy questions which involves solutions to Eq. 1 with the constraints imposed by the tunability criteria. For example, E_L be the minimum photon energy at the closed gap position G_L of the undulator. Let $E_L = fE_U$ where $f < 1$; then the expressions for the fundamental on-axis energies of the undulator result in the equation

$$f(1 + \frac{K_L^2}{2}) = (1 + \frac{K_U^2}{2}). \tag{4}$$

The value of K_U is either a minimum acceptable K-value or that determined by a maximum gap/λ value. In either case, if the minimum gap value is specified, then Eq. 4 determines a unique undulator period which is independent of the photon energy and the ring energy. This is the smallest period for which E_L will be achieved at G_L. It also yields the largest K-value at E_L. This minimum undulator period also corresponds to the minimum ring-energy at which the tunability range $E_U - E_L$ will be achieved. At higher ring-energies, the same photon energy interval can be spanned with devices with periods larger than the minimum λ given by Eq. 4.

For example, consider the case of a $SmCo_5$-Hybrid undulator maximum $G_U/\lambda = 0.7$. Then we have $K_U = 0.1551\lambda$. Suppose the minimum gap is $G_L = 1.5$ cm, and the desired E_L/E_U corresponds to $f = 0.5$. Then the solution of Eq. 4 is $\lambda = 3.73$ cm. If a 14 to 7 keV tunability is required from this device, then a minimum ring energy of $E_R = 8.01$ GeV is required. Following this procedure, in Table 2 has been constructed for several tunability ranges from the value maximum of $G_U/\lambda = 0.7$ to the minimum gap G_L.

TABLE 2

Values of minimum ring-energies E_R period λ and K-values for the various tunability intervals and minimum gap values, G_L for undulators. The largest gap considered, G_U, was determined by the maximum gap to period ratio of 0.7. The values for Nd-Fe-B devices are given in parenthesis below those for a $SmCo_5$-Hybrid one.

E_P(keV)	E_L(keV)	G_L(cm)	G_U(cm)	λ(cm)	K_U	K_L	E_R(GeV)
14	14	1.5	-	2.143	0.33 (2.143)	- (0.40)	5.78 (5.84)
14	7	1.5	2.61 (2.50)	3.730 (3.574)	0.57 (0.66)	1.63 (1.70)	8.01 (8.01)
14	7	1.4	2.49 (2.38)	3.559 (3.407)	0.55 (0.63)	1.62 1.67	7.78 (7.76)
14	7	1.3	2.37 (2.27)	3.386 (3.239)	0.53 (0.60)	1.60 1.65	7.54 (7.51)
14	8	1.5	2.48 (2.38)	3.541 (3.393)	0.55 (0.63)	1.42 (1.48)	7.75 (7.74)
14	9	1.5	2.35 (2.26)	3.363 (3.223)	0.52 (0.60)	1.24 (1.29)	7.51 (7.49)
14	4.7	1.0	2.31 (2.21)	3.297 (3.152)	0.51 (0.58)	2.19 (2.24)	7.42 7.38
20	20	1.5	- -	2.143 (2.143)	0.33 (0.40)	- -	6.90 (6.98)
20	14	1.0	1.70 (1.63)	2.434 (2.323)	0.38 (0.43)	1.03 (1.06)	7.41 (7.31)

As is evident from Table 2, the Nd-Fe-B-Hybrid undulator results in a larger K-values compared to those for $SmCo_5$-Hybrid, but does not significantly alter the minimum ring energy necessary to achieve the desired tunability range at the maximum gap condition if $G_U/\lambda = 0.7$. Hence, a Nd-Fe-B device will always have a higher photon flux than the equivalent $SmCo_5$ one, as expected from previous analyses.

However, if the gain in peak field achieved with Nd-Fe-B is offset by larger open gap ratio then for the same initial K_U and period for both devices, the Nd-Fe-B undulator will have a larger tunability interval than the corresponding $SmCo_5$ one. This reflects directly in the minimum ring energy necessary to achieve a given tunability interval. The maximum gap to period ratio for the case for equal peak field is $G_U/\lambda = 0.76$ for Nd-Fe-B.

A final aspect of this analysis which is pertinent to the radiation characteristics of APS undulators is the total possible photon energy spans of devices with a certain fundamental photon energy. That is, a first harmonic of say 20 keV is achievable by any undulator whose period falls within certain limits for a given ring energy. However, each device will this radiation at this energy at a value of the magnet gap which depends on the period of the device. Each device has, therefore, a unique tunability interval which <u>includes</u> 20 keV. The actual tunable range depends, as usual, on the open and closed gap constraints. For a given ring energy, the contours of a first harmonic photon energy versus undulator period have maximum and minimum values determined by the open magnet gap K-values and minimum closed gap. All possible photon energies which <u>include</u> 20 keV are determined in this way.

The result for 20 keV are shown in Fig. 1 for specific ring energies ranging from 8 to 6 GeV and Nd-Fe-B-Hybrid undulators. The area bounded by each contour is a measure of the tunability at that ring energy. The radiation of the devices represented in the figure include 20 keV photons from the first harmonic in this example. As is evident, tunability at this photon energy range is severely restricted at 6 GeV.

The K-value and hence photon intensity is not the same for each device at 20 keV. As shown in Fig. 2, the K-value is largest at the largest period devices capable of delivering 20 keV.

The contours are shown in Fig. 3 for Nd-Fe-B Hybrid undulators with first harmonic radiation which includes 14 keV. The tunability of the devices becomes significant at 7 GeV and above. In addition, the K-value at 14 keV shown in Fig. 4 for the ring energies indicated imply significant intensity in the second and third harmonics of these undulator. This means that the effective tunability interval is two to three times larger than that implied by considering the fundamental only.

3. CONCLUSIONS

These preceding results indicate that for the APS at a ring energy of (7 + 10%) GeV large tunability intervals in the range of approximately 5 to 14 keV can be expected for devices with periods above 3 cm. In addition, the K-values larger than 1 can be expected at the lower photon energies. This implies that significant third (and second) harmonic radiation should be achievable which effective will extend the first harmonic tunability range to nearly three times the maximum first harmonic photon energy. We conclude from these results that the intensity contained in the second and third harmonic should be small and the total tunability of these undulators will be determined by the first harmonic radiation only.

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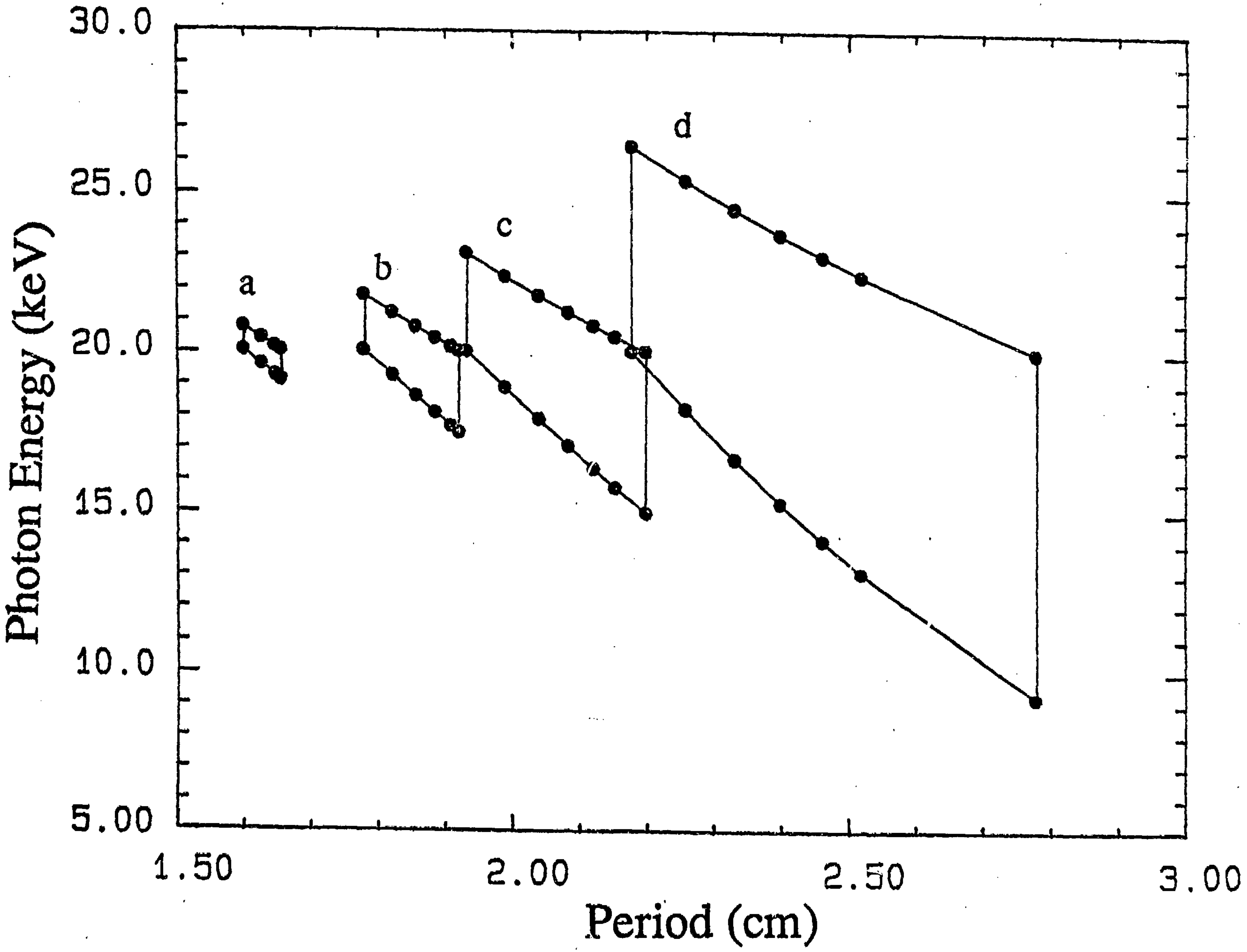
FIGURE CAPTIONS

Fig. 1 A plot of achievable first harmonic photon energies which include 20 keV verses undulator period for the storage ring energies (a) 6 GeV, (b) 6.5 GeV, (c) 7 GeV, and (d) 8 GeV. The lower bound for a given contour is determined by the minimum gap of $G_L = 1$ cm and the upper bound by the maximum ratio $G_U/\lambda = 0.76$.

Fig. 2 A plot of K-values at 20 keV verses undulator period for the ring energies (a) 6 GeV, (b) 6.5 GeV, (c) 7 GeV, (d) 7.5 GeV, and (e) 8 GeV. The dashed line is determined by the minimum gap of $G_L = 1$ cm.

Fig. 3 A plot of achievable first harmonic photon energies which include 14 keV verses undulator period for the storage ring energies (a) 6 GeV, (b) 7 GeV, and (c) 7.5 GeV. The lower and upper bounds on each contour are the same as given in Fig. 1.

Fig. 4 A plot of K-values at 14 keV verses undulator period for the ring energies (a) 6 GeV, (b) 6.5 GeV, (c) 7 GeV, and (d) 7.5 GeV. The dashed line as determined by the minimum gap of $G_L = 1$ cm.



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25.0
20.0
15.0
10.0
5.00
Photon Energy (keV)
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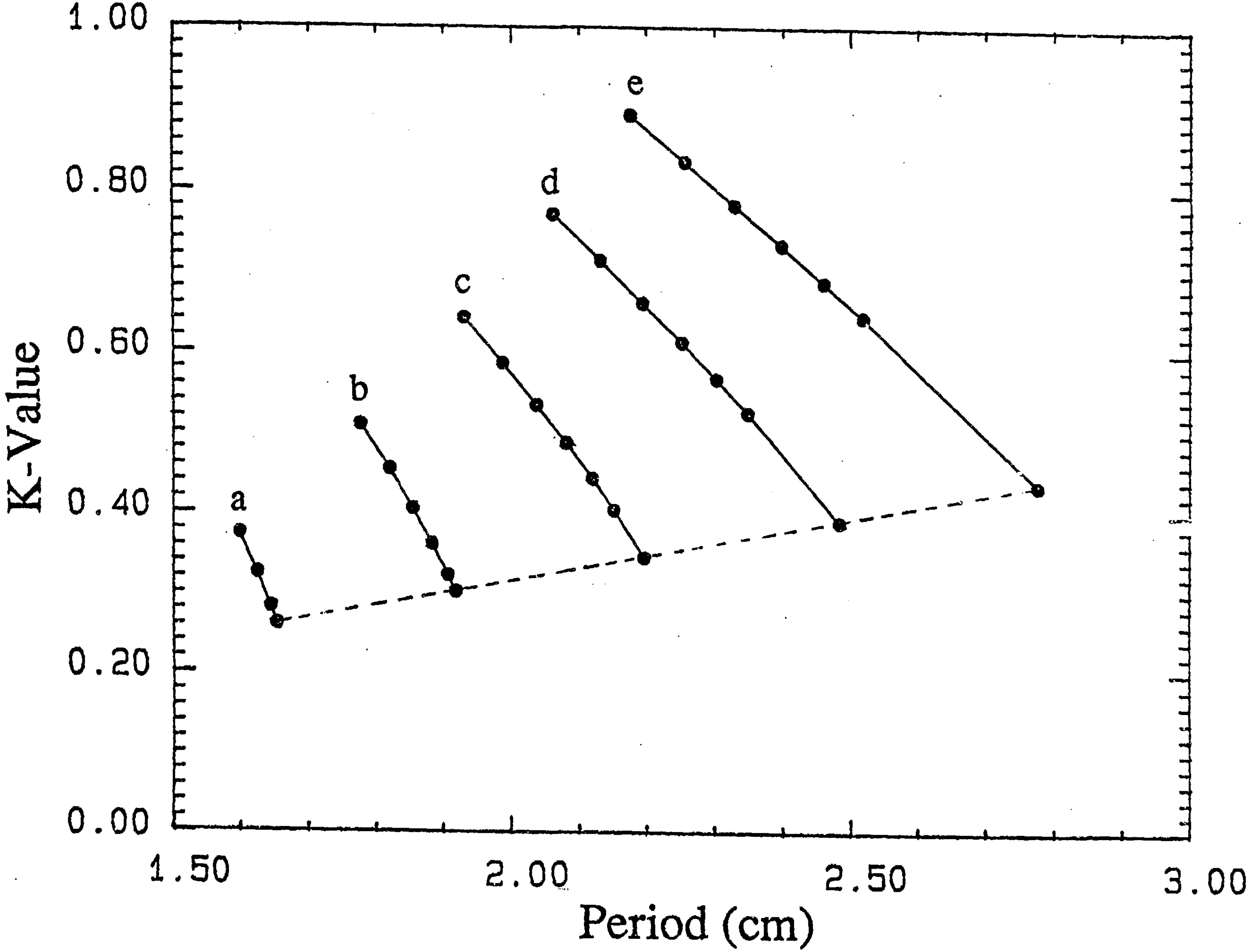
2.00
2.50
3.00
Period (cm)
a
b
c
d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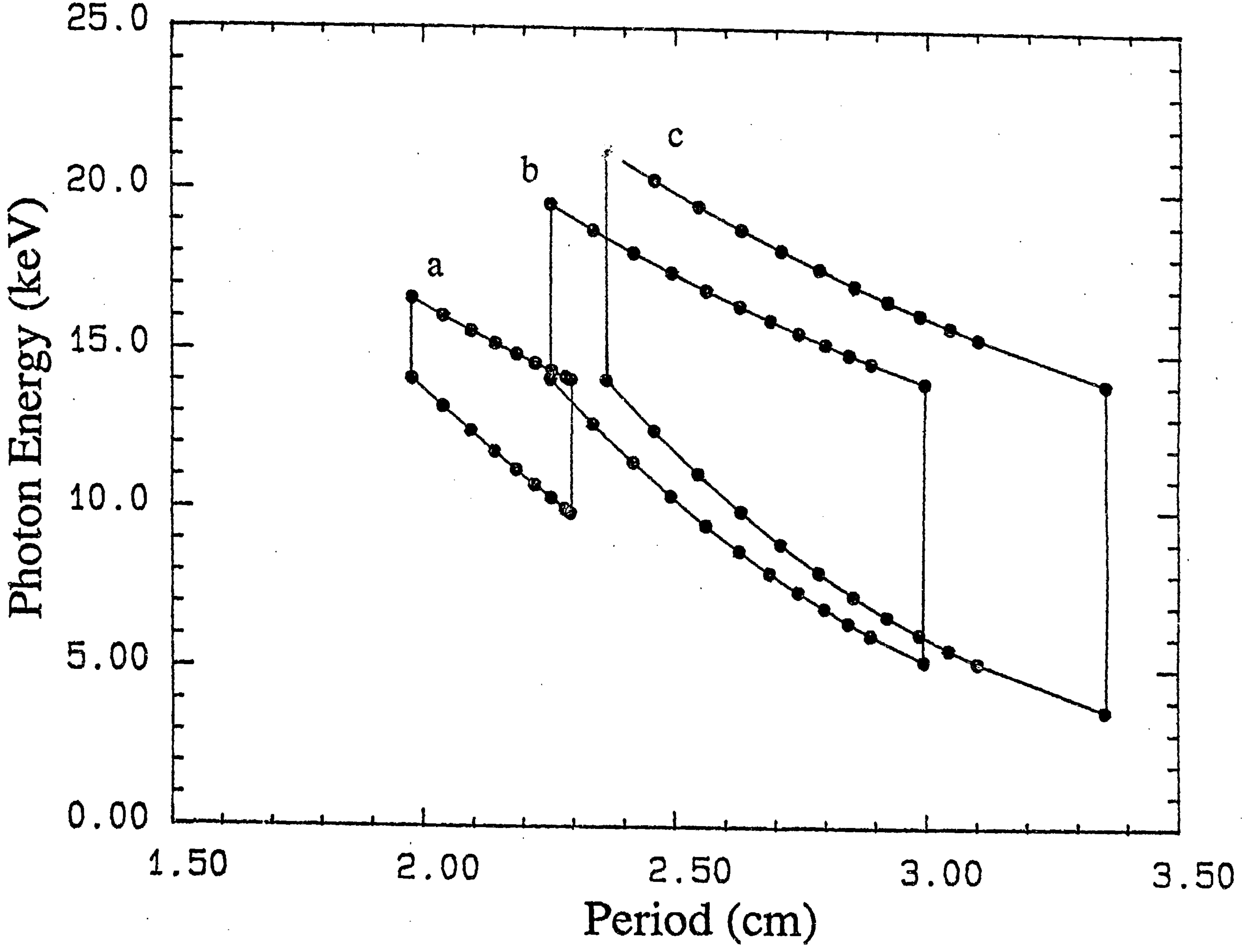
3.00
Period (cm)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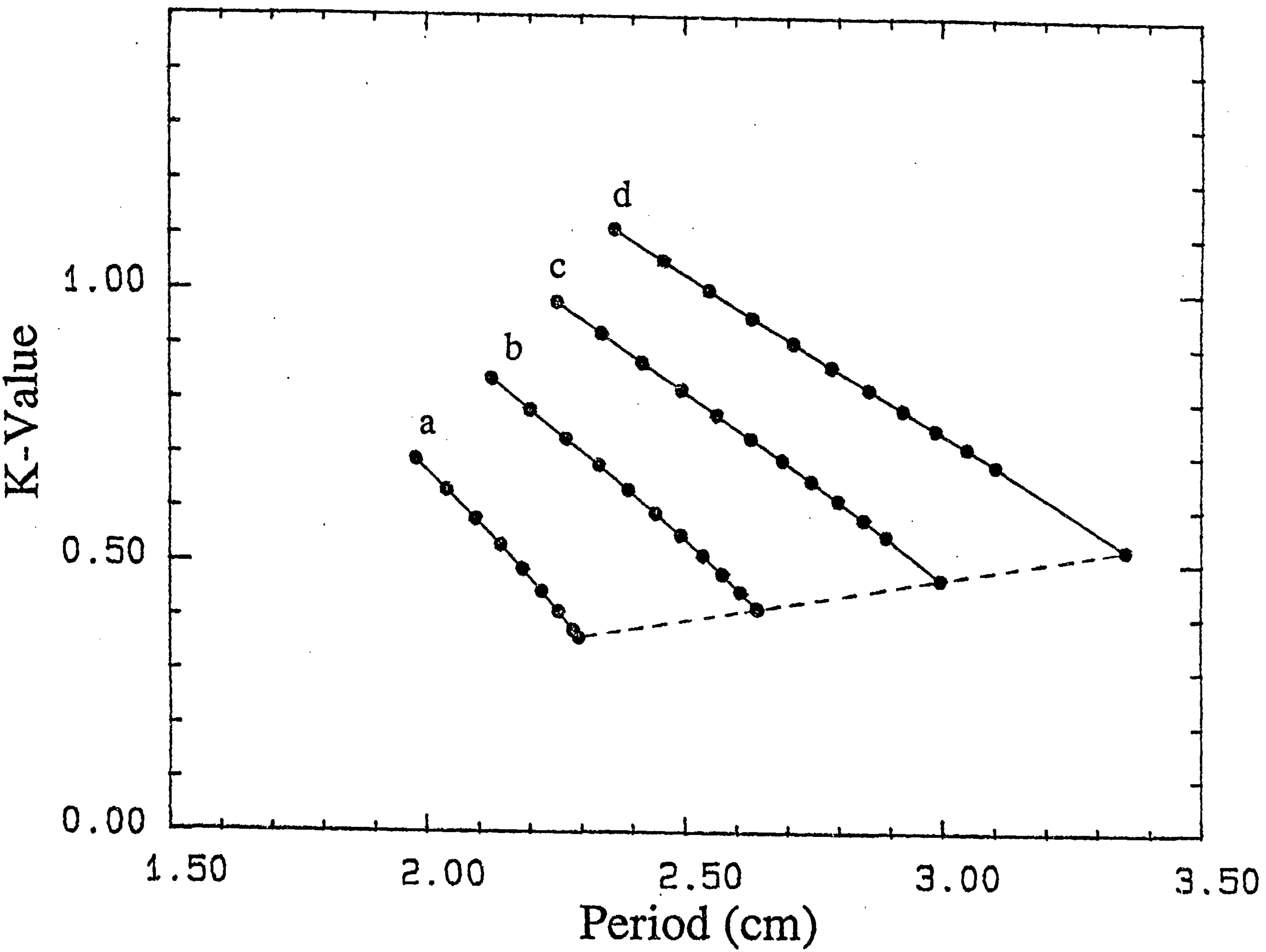
3.00
3.50
Period (cm)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0.50
0.00
1.50
2.00
2.50
3.00
3.50
Period (cm)
a
b
c
d