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RING ENERGY SELECTION AND EXTRA LONG STRAIGHT SECTIONS FOR THE ADVANCED PHOTON SOURCE

A Report and Recommendations by the National Task Group

National Task Group:

G. Brown	Stanford Synchrotron Radiation Laboratory
Y. Cho	Argonne National Laboratory
J. Hastings	National Synchrotron Light Source
S. Krinsky	National Synchrotron Light Source
D. Moncton	Exxon
G. K. Shenoy (Chairman)	Argonne National Laboratory
P. J. Viccaro	Argonne National Laboratory

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NTIS price codes
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April 1987

This report has been approved by the Advanced Photon Source Users Organization Executive Committee, Chicago, Illinois, February 25, 1987.

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I. EXECUTIVE SUMMARY

A National Task Group was formed to address the question of ring energy selection for the Advanced Photon Source (APS) and its effect on undulator tunability, and to evaluate the viability and merit of including long straight sections in the ring design. As part of this charge, criteria have been developed for undulator tunability ranges during the initial and mature operational phases of the facility. The recommended ranges for a single undulator are 7 to 14 keV for the initial phase and 4.7 to 14 keV for the mature or final operational phase of the APS. This device should also provide appreciable 20 keV radiation in the third harmonic. A second undulator, supplying 20 keV radiation in the first harmonic with limited tunability, is recommended for those cases where the flux at this energy from the tunable device is not sufficient.

These criteria were then translated to the ring energy necessary to achieve the recommended tunability for a given minimum stay-clear aperture required for operation of the ring.* The minimum ring energy that satisfies the tunability criteria for the expected machine aperture is approximately 7 GeV. In addition, it is recommended that the fixed-aperture vacuum chambers originally proposed for the insertion devices on the APS be maintained.

With regard to the addition of long straight sections to the APS, the National Task Group concluded that the inclusion of a limited number would be useful for future scientific development. The maximum desirable length was established to be 12 meters and the minimum length, 8 meters. The number and exact length will be dictated by the additional cost of these sections and their effect on the overall performance of the ring.

II. BACKGROUND AND CHARGES

The conceptual design for the Advanced Photon Source (APS) [1] satisfies the original user specification [2] of obtaining 20 keV radiation from the first harmonic of an undulator. This design was governed by the storage ring energy of 6 GeV and the minimum magnet gap of 10 mm. However, as additional capabilities of undulator sources were investigated, it became evident that at 6 GeV, the energy tunability of radiation from undulators is rather limited for first harmonic energies above 10 keV. As a result, as many as five undulators would be needed at every straight section of the ring to span the photon energy interval of 5 to 20 keV. Each of the five undulators would cover a small energy range.

The range of tunability of an undulator can be increased by increasing the energy of the storage ring; only one or two undulators would then be required at any straight section to cover a 5-to-20-keV interval [3,4]. An increase in the storage ring energy entails increased construction costs for the storage ring and the facility. However, it also decreases the total cost of the undulators because fewer of them are needed.

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*This aperture is directly related to the minimum magnet gap achievable for the insertion device.

The above issues were reiterated by the DOE Review Committee chaired by L. E. Temple, Jr., which reviewed the Argonne proposal for the APS. In response, Dr. K. L. Kliewer asked Dr. G. K. Shenoy to form a National Task Group to develop criteria for the radiation tunability of the APS (see Appendix). These criteria could then be used by the accelerator designers at Argonne to define the operating energy of the ring. An excessively high energy requirement for storage ring operation would mean increased operating costs (the power required varies roughly as the square of the ring energy) and might limit the operational period available to the users. The Group also addressed the question of long straight sections on the APS storage ring. This report is an outcome of the National Task Group meetings held in Chicago and Brookhaven and of numerous conversations with other members of the user community. The report gives recommended criteria for the performance of the machine.

III. DETAILED ANALYSIS

1. Undulator Tunability Criteria

In arriving at the tunability criteria for the undulators on the APS, the National Task Group has incorporated the information on user requirements presented in a large number of documents and articles, and, in particular, the Scientific Case Workshop Report [5]. The criteria also reflect optimum utilization of the facility during its initial and mature stages of operation. The distinction between the two stages is related primarily to the apertures of the injected and stored beam required to obtain useful beam lifetimes. During the initial stage, large apertures (~ 12 mm) may be necessary for operation of the ring. During the mature stage of operation, smaller apertures (~ 8 mm) would be possible. Both apertures set lower limits on the closed-gap value of the undulators in the straight sections, which in turn is one of the major factors that determine the tunability range of the undulator.

Under these conditions, during the initial stage, undulators should provide the following:

- First harmonic radiation from a single device tunable over the energy range from 7 to 14 keV.
- Third harmonic radiation of the above device spanning the interval from 21 to 42 keV. Second harmonic radiation in the range of 14 to 28 keV is a possible source in this region. Whenever the flux or brightness of the second or third harmonic is not adequate, a second device with limited first harmonic tunability in the range near 20 keV could be included in the beamline to meet the user requirements.

During the mature stage of operation, undulators should provide the following:

- First harmonic radiation from a single device tunable over the energy range from 4.7 to 14 keV.

- Third harmonic radiation of the above device spanning 14 to 42 keV. Whenever the flux or brightness of the third harmonic is not adequate, a second device with full first harmonic tunability from 14 to 20 keV could be included to meet the user requirements.

It is the view of the National Task Group that the above set of criteria should cover almost all of the projected user demands on the APS as it develops to its full potential and specified operating goals.

2. Relationship of the Tunability Criteria to the Storage Ring Energy and Undulator Gap

Here we briefly describe the dependence of the photon energy tunability range on the energy of the storage ring and the minimum undulator gap. A detailed analysis is presented in Ref. 8.

The energy in keV of the p-th harmonic of an undulator for an observation point along the axis of the device is given by

$$E_p = \frac{0.949\ E_R^2 p}{\lambda(1 + K^2/2)} , \tag{1}$$

where E_p is photon energy in keV, E_R is the ring energy in GeV, λ is the undulator period in cm, and p is the harmonic number. The deflection parameter K is given in terms of the undulator period (in cm) and the peak magnetic field B_o (in Tesla) by

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

For hybrid magnets based on permanent-magnet blocks and vanadium permendur pole tips, B_o is given by [6]

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

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

In Eq. (3), the value 0.95 represents the "filling factor," which takes into account 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 candidate permanent-magnet materials, $SmCo_5$/permendur (REC-hybrid) and Nd-Fe-B.

Equation 3 for the peak field is valid in the interval $0.07 < G/\lambda < 0.7$. Although the upper limit for the ratio $R=G/\lambda$ does not define the maximum operational gap of the device, we have taken this as the maximum gap in our calculations because the K values encountered for $G > 0.7\lambda$ are small and hence the intensities of the photon beam are too small. We have taken the ratio $R = G/\lambda = 0.7$ to define a conservative limit on the maximum value of the gap.

If the same maximum open gap condition of R=0.7 is used for both magnet materials, the Nd-Fe-B undulator will have a slightly higher K-value than the REC-hybrid undulator, and consequently a higher intensity. The tunability and ring energy properties are almost identical [7].

TABLE 1

Constants Used in Eq. (3) for Hybrid Magnets 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

A gain in tunability for the Nd-Fe-B device over the $SmCo_5$ one is achieved if the gain in K (i.e., intensity) is sacrificed for a larger open gap maximum. This is reflected in smaller ring energies resulting from a larger maximum gap (see Section IV).

From Eqs. (1-3), it follows that any three of the four parameters λ, E_p, G, and gap uniquely determine the fourth. For example, a given undulator period, ring energy, and desired photon energy specify the required gap. In Fig. 1, the gap values needed to obtain photon energies of 14, 7, and 4.7 keV with undulators of several different periods are plotted against the ring energy. The upper bounds on the gap for 14 keV (Fig. 1a) and 7 keV (Fig. 1b) are determined by the condition R=0.7. If a minimum-gap line is drawn in each figure, then only those devices which fall above this line can provide the indicated first harmonic photon energy at any given ring energy. For example, an undulator with a period of 3.7 cm will require gaps of 2.6 and 1.5 cm to provide 14 and 7 keV, respectively, at 8 GeV.

Various aspects of the tunability analysis have been presented in detail in Ref. 8. Here we discuss the constant-photon-energy curves shown in Fig. 2. At any ring energy, a first harmonic photon energy of 14 keV is constrained to occur at the open gap limit R=0.7. This condition uniquely determines the open gap and period of the device for that ring energy. The gap values necessary for the device to produce 7 and 4.7 keV photon energies can then be obtained. These are shown for REC-hybrid undulators in Fig. 2 as a function of ring energy for three photon energies. The "optimum" period of the device for each ring energy, determined at 14 keV and $R = G/\lambda = 0.7$, is shown at the top of the figure.

The intersection of any constant-gap line and one of the constant-photon-energy curves (7 or 4.7 keV in this case) of Fig. 2 corresponds to the minimum ring energy necessary to achieve tunability between the maximum first harmonic photon energy and the selected lower photon energy. Thus, for a minimum gap of 1.5 cm, for example, the minimum ring energy necessary to provide tunability between 14 and 7 keV is approximately 8 GeV for the REC-hybrid undulator.

Another way of presenting the tunability analysis involves plotting the minimum photon energy achievable for a specified minimum gap as a function of ring energy. This approach is shown in Fig. 3 for a REC-hybrid device with

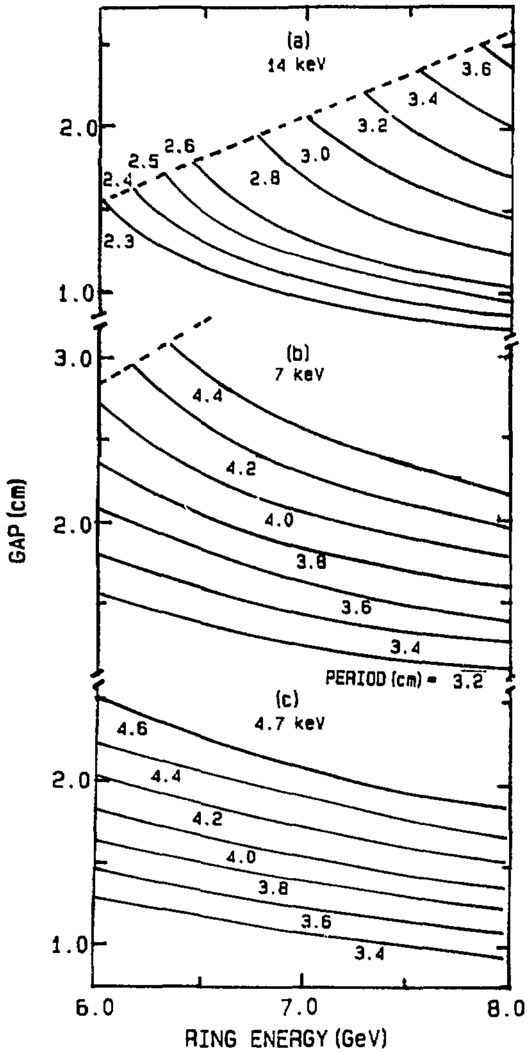

Fig. 1

Gap required by undulators with various periods, λ (shown on curves), to obtain photon energies of (a) 14, (b) 7, and (c) 4.7 keV, as a function of ring energy. The upper bound on gap, G, is given by G/λ = 0.7.

four different minimum gap values. It is apparent from Fig. 3 that the minimum ring energy needed to achieve a given tunability interval is a steep function of the minimum magnet gap. For example, if the closed gap is 1.1 cm rather than 1.0 cm, the minimum ring energy necessary for a photon energy of 4.7 keV increases from 7.4 to 7.7 GeV. This emphasizes the necessity of precisely defining the closed-gap tolerances.

The other aspect of this analysis has to do with the photon flux or brilliance, which is closely related to the K value. At the maximum photon energy, the K-value is lowest and is determined by the maximum gap condition of G/λ = 0.7 for each ring energy. At lower photon energies (i.e., at smaller gaps), the K-value depends on the actual gap and ring energy. The resulting K-values for a 14 keV undulator operating at 7 and 4.7 keV in the closed-gap mode are shown as a function of ring energy in Fig. 4. This plot shows that the open-gap K-value at 14 keV is less than 0.5 for ring energies less than about 7.5 GeV. At a ring energy of 7.5 GeV, for the closed-gap energies of 7 and 4.7 keV, the K-values are approximately 1.5 and 2, respectively. This means that the third harmonic of the device operating between 4.7 and 7 keV has a high intensity which may be adequate for many experiments needing 14 to 20 keV radiation. In addition, second harmonic radiation will have an appreciable flux on-axis and could in principle be used in a variety of

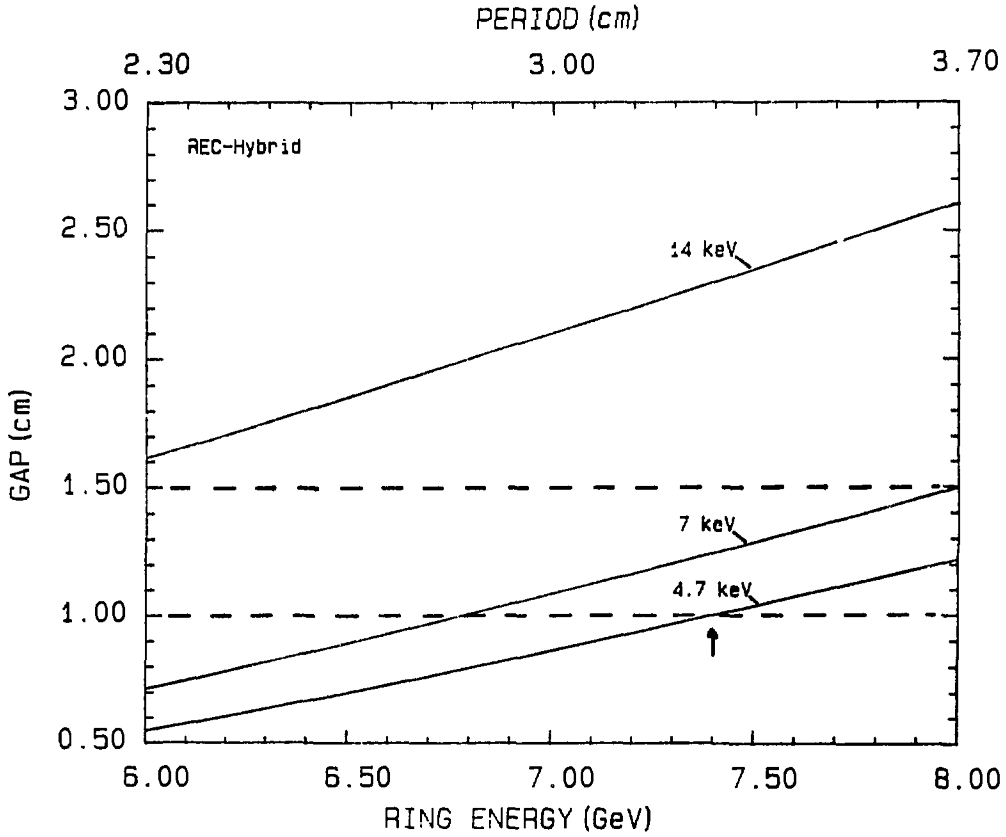

Fig. 2 Constant-photon-energy plots of the gap values needed by a 14 keV undulator to obtain photon energies of 14, 7, and 4.7 keV, as a function of ring energy. The period λ of the device is the maximum one permitted by the maximum gap condition, $G/\lambda = 0.7$.

situations. As a result, in many cases, a separate 20 keV undulator may not be necessary to cover the range from 14 to 20 keV.

Another issue that was addressed was the feasibility of obtaining 20 keV radiation in the first harmonic of a device in the initial and final phases of operation. Constant-photon-energy plots of gap versus ring energy for a 20 keV undulator are shown in Fig. 5 for devices capable of delivering radiation at a maximum energy of 20 keV. These curves show that at a 1.5 cm gap, for example, the minimum ring energy necessary to produce 20 keV photons in the first harmonic is approximately 7 GeV. At a minimum gap of 1.0 cm, the lowest photon energy achievable at 7 GeV is approximately 16.5 keV, as seen from Fig. 6. At higher ring energies, the tunability interval increases.

In Fig. 7, the K-values for several first harmonic photon energies are shown as a function of ring energy. At the maximum gap limit and 20 keV, the K-values are less than 0.5 for ring energies up to 8 GeV and hence the third harmonic intensity from these devices will be small. Again, in many cases, the 14 keV device operating over the full tunable range may provide sufficient flux at these energies to make the 20 keV device unnecessary.

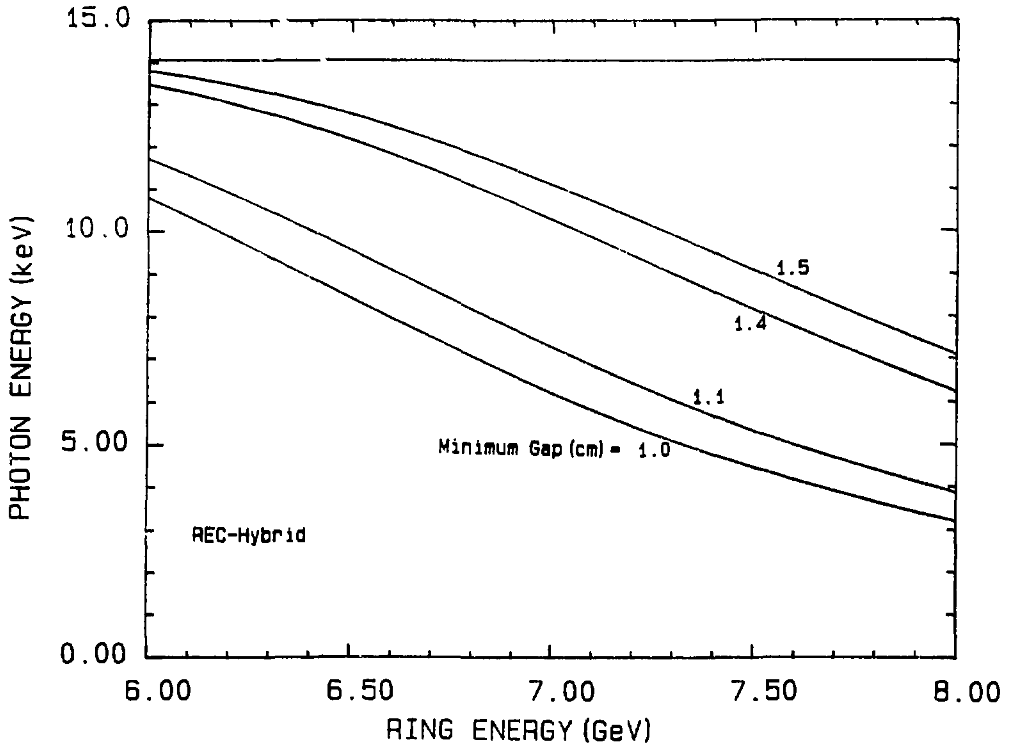

Fig. 3 Photon energies achievable for the 14 keV undulator of Fig. 2 at the minimum gaps shown, as a function of ring energy.

3. Length of Straight Sections

In the Argonne Conceptual Design Report [1], all 28 straight sections have lengths of 6 m. The insertion devices on these straight sections are considered adequate to carry out the proposed scientific research. However, it has been suggested that it would be of interest to include some longer straight sections in order to provide additional flexibility. For example, it would be possible to perform experiments involving two insertion devices in tandem at the longer sections.

It was concluded that the maximum required length for the straight section is 12 m, which is double the length of the proposed straight section for a single insertion device. A lower limit on the length is 8 m, which would be sufficient to accommodate two shorter devices. The final length chosen for the facility should be dictated primarily by the cost and overall ring performance criteria. The number of such longer straight sections should be determined by the symmetry requirements of the lattice. The betatron function can be intermediate between the proposed high (undulator) and low (wiggler) values and again should be fixed for the best overall ring performance.

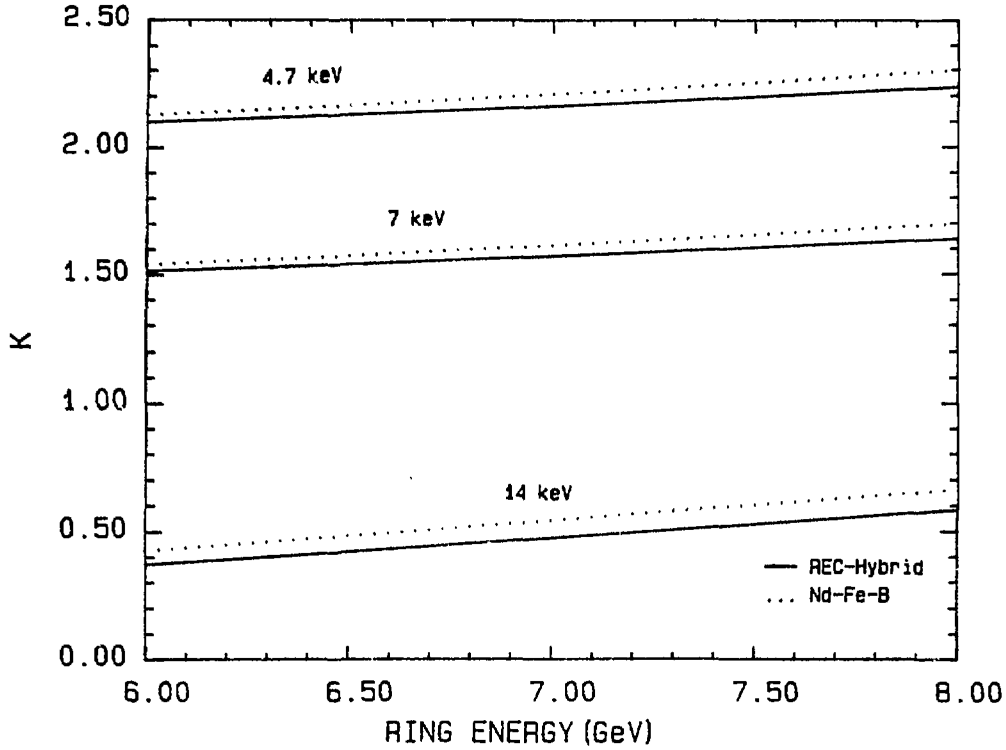

Fig. 4 K-values for 14 keV REC-hybrid and Nd-Fe-B undulators at photon energies of 14, 7, and 4.7 keV, as a function of ring energy. The corresponding gaps are given in Fig. 2.

IV. CONCLUSIONS AND RECOMMENDATIONS

It is clear from the above analysis that the criteria set forth in section II of this report can be met by a proper choice of ring energy and minimum gap. Both these parameters are determined by the storage ring lattice and the details of the design.

If the minimum gap is limited in a straight section by the injection apertures, then in principle, smaller magnet gaps can be achieved by designing either a variable-gap undulator in the ring vacuum or a variable-aperture vacuum chamber for the straight section. Both these concepts have been used in the past. However, the vacuum chamber design is complex and expensive and would greatly complicate the process of changing devices. The added complexity and reduced flexibility would reduce the useful operational periods of the machine. Therefore, it is the present view of the National Task Group that the concept of a rigid vacuum chamber with the insertion device external to it, as presented in the Conceptual Design Report [1], provides the best operational strategy. Consequently, every effort should be made to reduce the machine apertures required for injection and operation.

In summary, the Task Group recommends that as part of the storage ring design effort, both the energy of the ring and the minimum achievable machine

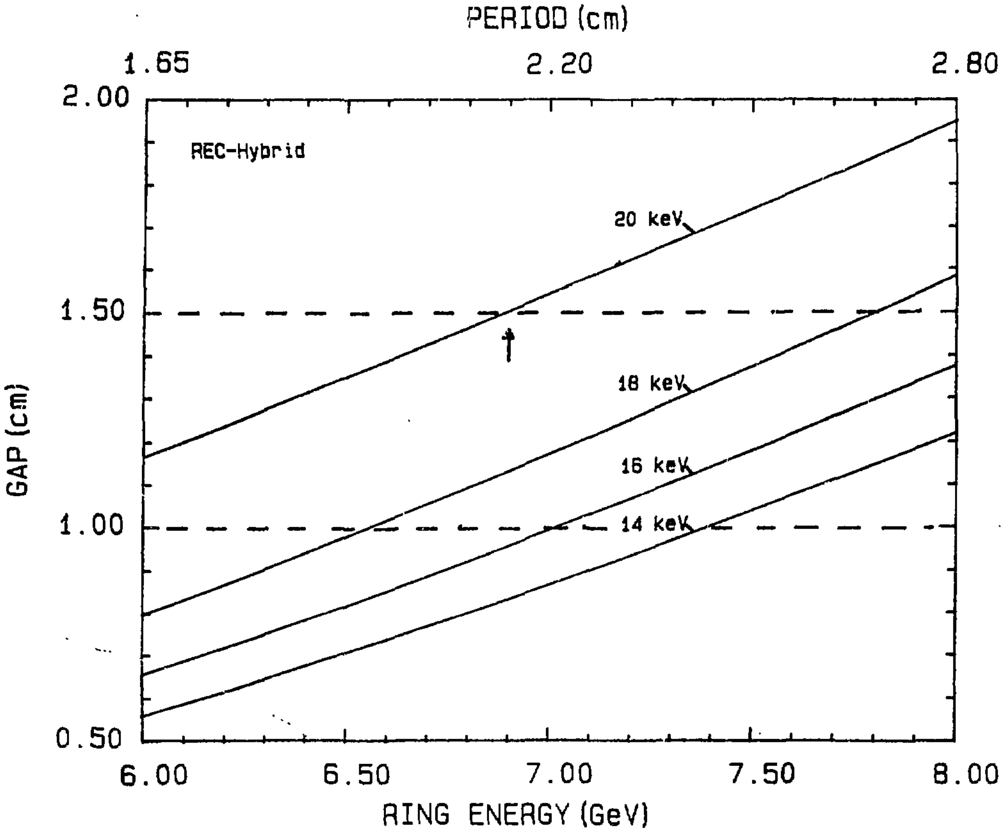

Fig. 5 Constant-photon-energy plots of the gap values needed by a 20 keV undulator to obtain the four photon energies shown, as a function of ring energy. The period λ of the device is that permitted by the maximum gap condition, G/λ = 0.7.

aperture be jointly optimized to satisfy the criteria presented in section II. To guide this design work, we present in Fig. 8 a plot of the storage ring energy required, as a function of the magnet gap, for REC-hybrid and Nd-Fe-B undulators to achieve the first harmonic tunability of 7 to 14 keV deemed desirable during the initial phase of storage ring operation. Both devices provide roughly the same photon intensity. The gap required in the final phase for tunability of 4.7 to 14 keV is presented similarly in Fig. 9. In an actual storage ring, the minimum magnet gap is the sum of the minimum ring aperture and the thickness of the vacuum chamber walls, including toler-ances. Therefore, the minimum gaps in Figs. 8 and 9 directly determine the upper limit for each ring energy necessary to fulfill the criteria listed in section III.1.

We reiterate that the minimum gap values and resulting ring energies are conservative estimates. Devices with a larger open gap-to-period ratio (R) could be considered; these would provide some advantages by reducing ring energy and/or increasing the minimum required gap, at the expense of undulator performance.

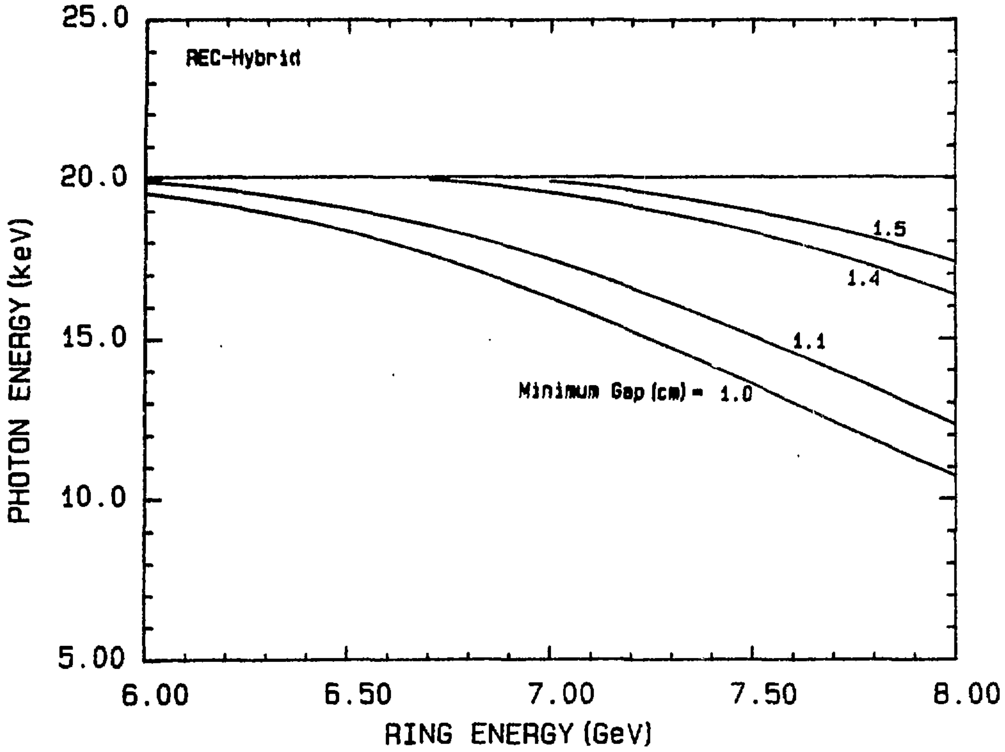

Fig. 6 Photon energies achievable for the 20 keV undulator of Fig. 5 at the minimum gaps shown, as a function of ring energy.

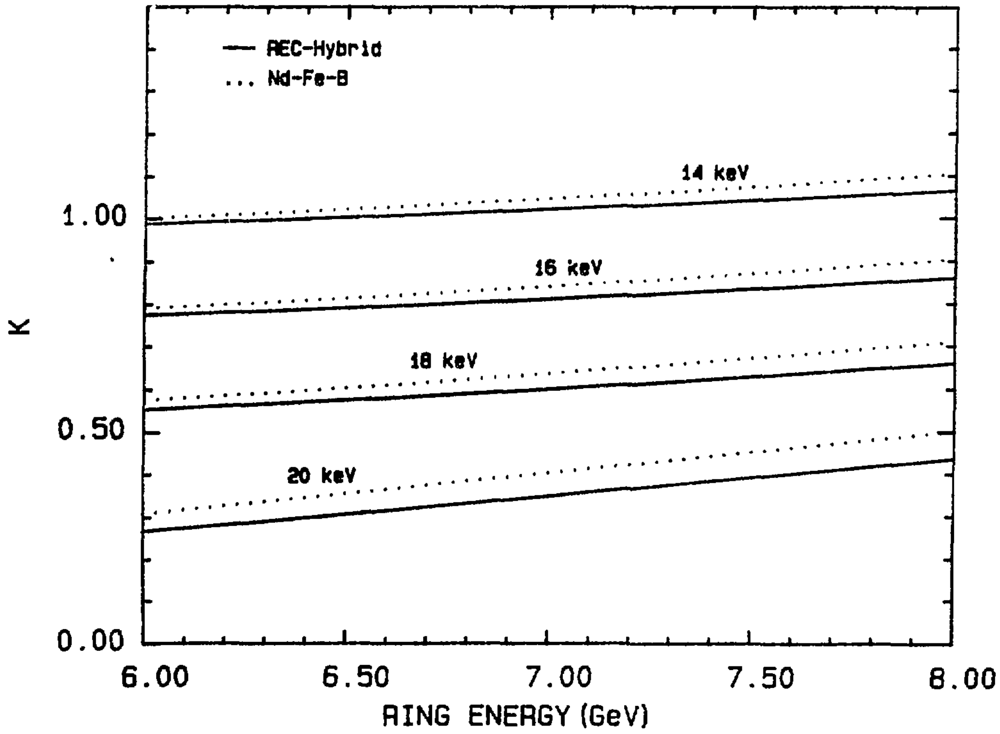

Fig. 7 K-Values for 20 keV REC-hybrid and ND-Fe-B undulators at the constant photon energies shown, as a function of ring energy.

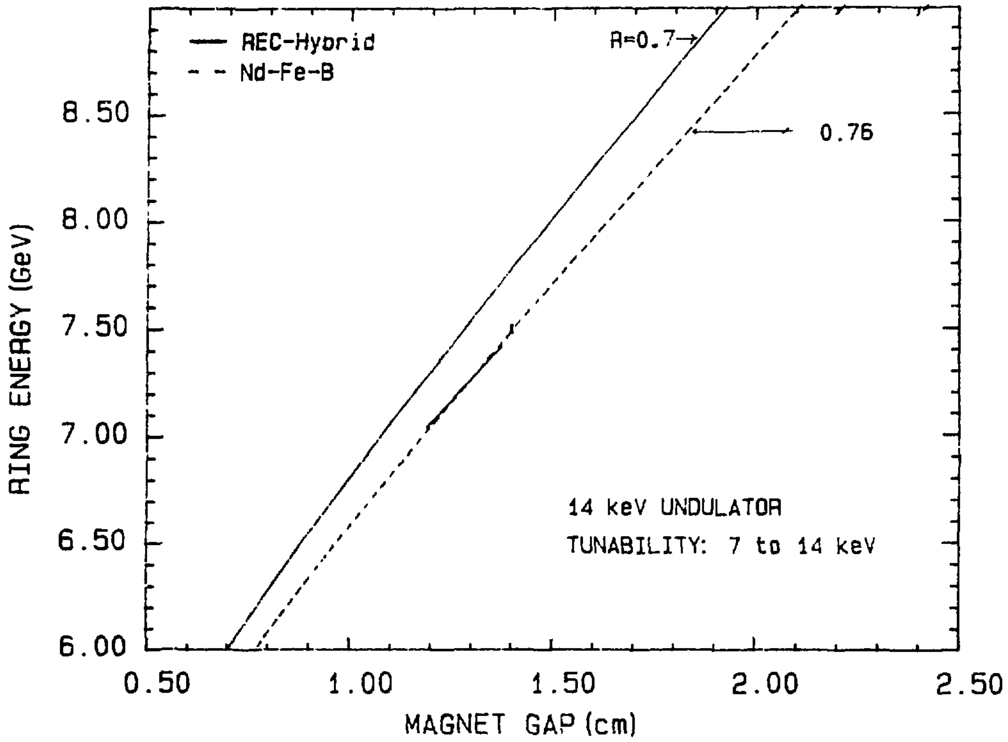

Fig. 8 The ring energy necessary for 14 keV REC-hybrid and Nd-Fe-B undulators to achieve the first harmonic tunability (7 to 14 keV) required in the initial operational phase, as a function of the minimum gap available. Both types of undulators have the same K-value.

Regarding the inclusion of long straight sections in this facility, the Task Group recommends the following: Although there is no demand for long straight sections at present, a few should be considered in the lattice design for future development. The length of these long sections should be at least 8 m, but need not exceed 12 m. In making a final decision about the number and length of such long straight sections, the major considerations should be the overall ring performance and cost. Implementation should in no way degrade the performance of the remaining insertion devices.

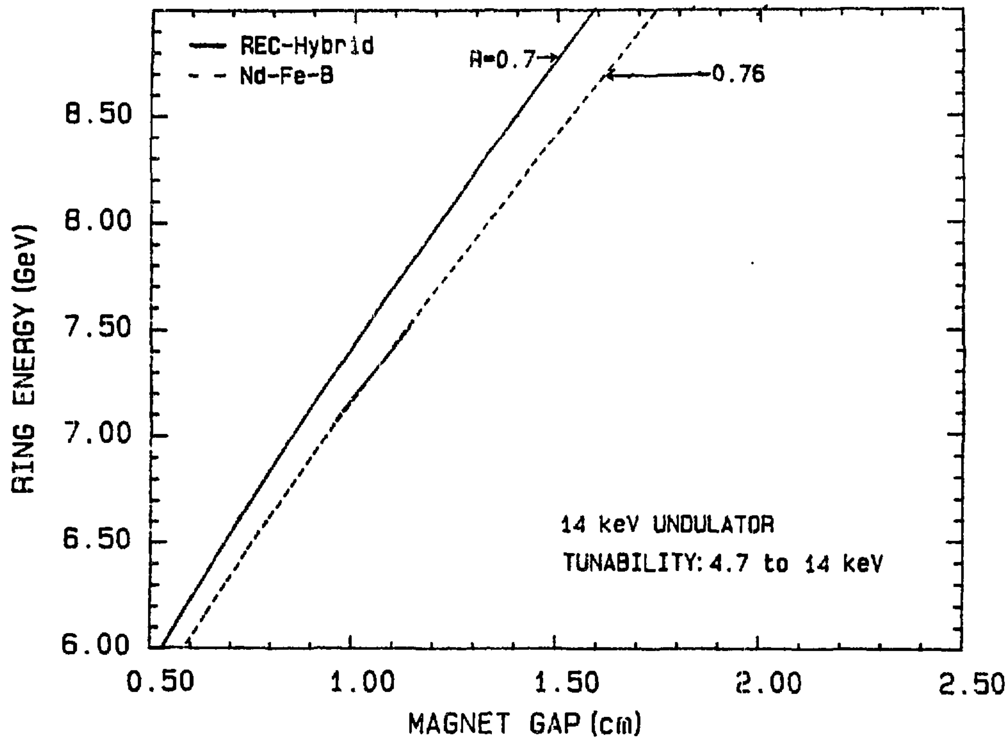

Fig. 9 The ring energy necessary for 14 keV REC-hybrid and Nd-Fe-B undulators to achieve the first harmonic tunability (4.7 to 14 keV) required in the mature operational phase, as a function of the minimum gap available. Both types of undulators have the same K-value.

References

1. "6 GeV Synchrotron X-Ray Source Conceptual Design Report," Argonne National Laboratory Report ANL-86-8 (February 1986).

2. "Synchrotron Radiation Source - Research and Development," DOE Program Review, Ames Laboratory, Ames, Iowa, October 1984.

3. G. K. Shenoy and P. J. Viccaro, "An Overview of the Characteristics of the 6-GeV Synchrotron Radiation: A Preliminary Guide for Users," Argonne National Laboratory Report ANL-85-69 (October 1985).

4. G. K. Shenoy and P. J. Viccaro, in Proc. Workshop on Insertion Devices for a 6 GeV Synchrotron Source, Argonne National Laboratory, Argonne, Illinois, December 11, 1985, in press.

5. Report of the Workshop on the Scientific Case of a 6-GeV Synchrotron Source, Argonne, Illinois, December 9-11, 1985 (USDOE, Washington, DC).

6. K. Halbach, J. Appl. Phys. 57, 3605 (1985) and references cited therein.

7. P. J. Viccaro and G. K. Shenoy, "Undulator Tunability and Ring Energy," Argonne Light Source Note LS-73 (September 1986).

APPENDIX

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue, Argonne, Illinois 60439

1 April 1986

Dr. Peter Eisenberger
Exxon Research & Engineering Co.
Route East, Clinton Township
Annandale, New Jersey 08801

Dear Peter:

Final decisions are needed concerning the energy of the synchrotron source and the need for two (four?) 12-m (18-m or ?) straight sections. These are questions that can only be answered with user input. Accordingly, I would like to proceed as follows. I have asked Gopal Shenoy to head up a small task force to obtain definitive answers to these questions. I would like to ask you as Chairman of the Advanced Photon Source Steering Committee to recommend several participants in this effort. A quick response would be appreciated as we would like to have a task force meeting in April if possible. Please feel free to respond directly to Gopal to expedite the process.

Yours sincerely,

K. L. Kliewer
Associate Laboratory Director
for Physical Research

KLK:jj
cc: G. K. Shenoy
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