Nd-Fe-B Undulator Design for CESR

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Introduction

It is proposed to build a Nd-Fe-B based undulator on CESR ring which would provide pseudomonochromatic tunable radiation in the hard x-ray range from 4 to 15 keV. Such an intense radiation source opens unlimited possibilities for doing exciting science in material science and condensed matter physics.

Here, we present the design goals for such an undulator and discuss the influence of various parameters that govern the properties of radiation from undulators. The analysis of these results leads us to select the specific design parameters of the undulator that will meet the radiation needs of the experimental program.

Undulator Design Goals

The criteria of selecting an undulator is intimately related to the research program that is planned for this proposed insertion device facility at CHESS. But more importantly, this will provide the first evaluation of the characteristics of a small period undulator on a low emittance lattice.

In planning the science, the scientists from Argonne and Cornell have met on many occasions during 1985 and 1986. Briefly, the undulator in a high-β section of CESR will provide low divergence beam when the ring is operated in its low emittance mode. This highly collimated radiation will primarily be used for the investigations in the following areas:

1. Scattering from surfaces.

2. Scattering from collective excitations.

3. Nuclear coherent scattering and the study of time development of coherent radiation.

4. Investigation of high-heat load optics.

The energy of undulator radiation required for these studies is in the range of 4 to 15 keV. Achieving tunability in the first harmonic energy over this range using a single undulator by varying its gap is virtually impossible withn the constraints of operation of the CESR ring from 4.5 to 6.0 GeV. In view of these facts the following design goals were developed:

- The radiation should be tunable by varying the gap of a single undulator and/or the CESR ring energy from 4.5 to 6.0 GeV.
- The energy range of 4-15 keV is to be realized by using the radiation from the first and the third harmonics of the undulator.
- The classical range of x-ray energies (4 to 9 keV) should be accessible in the first harmonic.
- The third harmonic should then provide energy from 9 to 15 keV.
- The K value at 3 to 4 keV range should at least be 1.5, while it should be larger than 0.5 at 9.0 keV.
- The brilliance of the third harmonic in the energy range from 9 to 15 keV should be 10^{16} to 10^{17} at least photons/sec/0.1%BW/mrad^2/mm^2

Optimization of Undulator Parameters

Undulators can provide a very bright, quasi-monochromatic photon beam. For the proposed operation of the undulator, the CESR parameters are given in Table 1.

TABLE 1. Low Emittance Mode of CESR

Ring Energy Variability (GeV)	4.5 to 6.0
Beam Current (mA-projected)	100
Horizontal Emittance - ε_x (m.rad)	5×10^{-8}
Vertical Emittance - ε_y (m.rad)	1×10^{-9}
Maximum Undulator length (m)	2.4
β_x in the straight section (m)	12.0
β_y in the straight section (m)	6.0
Estimated beam lifetime (h)	5-7
Number of bunches	1-7
Orbit Period (nsec)	2560
Bunch duration (psec)	160
Interbunch period (nsec)	2560 to 366

The emittance of the CESR for the undulator based studies has been carefully minimized (1) and the betratron functions have been increased in the straight section to provide a low-divergence photon beam of high brilliance. The photon energy E(p) in keV of the pth harmonic on axis of the undulator is given by

$$E(p) = \frac{0.947\, E_R^{\,2} p}{\lambda(1+K^2/2} \text{ keV} \qquad (1)$$

$$P = 1,3,5.....$$

where E_R is the ring energy in GeV, K is the deflection parameter, and λ is the undulator period. In this single-particle relationship, only the odd harmonics are present along the undulator axis. However, one will observe the even harmonics of radiation even along the undulator axis if either (a) the observation pinhole along the axis has non-zero dimensions or (b) the particle beam in the accelerator has a finite size and divergence.

As a result of the chosen values of the β-functions in Table 1, the volume of the radiation phase space is totally governed by the volume of the particle phase space, the contribution from the radiation field in the hard x-ray range being negligible. In the Table 2, the dimensions of the phase space are given.

TABLE 2. The Size of the Source for 6-GeV CESR

σ_x	770 μm
σ_x'	64 μrad
σ_y	88 μm
σ_y'	13 μrad

It is interesting to note that the phase space volume of the proposed Advanced Photon Source at Argonne is roughly an order of magnitude smaller than that of the low-emittance mode on CESR. The larger the phase space, the more will be the reduction in the photon flux in the first harmonic and larger, the commensurate increase in the flux in the higher (both even and odd) harmonics.

The flux or the brilliance of radiation in the various harmonics of the undulator is a strong function of the deflection parameter K:

$$K = 0.934\ B(T)\lambda(cm) \tag{2}$$

The value of B for the hybrid Nd-Fe-B magnet with vanadium permendur pole-tips is

$$B(T) = 0.95 \times 3.44[\exp(-R(5.08-1.54R)] \tag{3}$$

where

$$R = Gap/\lambda. \tag{4}$$

In Eq. (3), the factor 0.95 represents the "filling factor" to account for losses in the magnetic flux due to packing of the high-permeability material in the undulator assembly. The equation is valid for $0.07<R<0.7$. The important aspect of this equation is the inverse exponential dependence of B on R. Hence, the gap becomes an important factor determining B and, in turn, the value of K, which governs both the energy of the radiation (Eq. (1)) and the photon flux distribution in various harmonics.

In order to visualize the influence of gap and ring energy on the tunability of various period undulators, Figs. 1-8 have been prepared. In Figs. 1-4, we present the variation of first harmonic photon energy for various undulators with different periods as a function of gap. The lower limit on the undulator magnet gap of 1.4 cm is dictated by the minimum aperture required for operation of CESR with long lifetimes. One observes that shorter period devices provide higher energy photons but small tunability ranges. The longer period devices provide larger ranges of tunability, but they cover lower energy ranges.

Figures 5-8 provide the values of K at various photon energies for different undulators operated at various CESR ring energies from 4.5 to 6.0 GeV. It should be emphasized that higher K values are vary desirable for a device to produce ample flux in higher harmonics.

A close scrutiny of the Figs. 1-8, leads us to select a device with a period of either 3.0 cm or 3.2 cm which would satisfy most of the design goals presented earlier. In Table 3, all the pertinent parameters have been presented.

TABLE 3

The characteristics of radiation from 3.0, 3.2, and 3.4 cm period undulators.

	3.0 cm Period	3.2 cm Period	3.4 cm Period	Design Goal
Minimum first harmonic energy (keV) at 1.4 cm gap and ring energy				
a. 4.5 GeV	3.6	3.0	2.5	4.0
b. 6.0 GeV	6.4	5.4	4.1	4.0
Maximum first harmonic energy (keV) at R=0.7 and ring energy				
a. 4.5 GeV	5.4	5.0	4.2	9.0
b. 6.0 GeV	9.8	8.9	7.0	9.0
Value of K at 1.4 cm gap	1.22	1.42	1.7	1.5
Minimum third harmonic energy (keV) at 1.4 cm gap and 4.5 GeV	10.8	9.0	7.5	9.0

It is clear from Table 3 that the device with a period of 3.2 cm to 3.4 cm comes very close to our design goal. In Fig. 9 and 10, we present the energy and brilliance of photons from a 3.2 cm hybrid Nd-Fe-B device in the first and the third harmonic over the gap tunability range (minimum gap = 1.4 cm, maximum gap = 0.7 x period = 2.24 cm) for various ring energies. The brilliance calculations are done using a single-particle theory and hence should be considered approximate. However, they provide a general guideline and show that an acceptable brilliance range is covered by the third harmonic. A more complete calculation of brilliance including the source sizes of Table 2, show an enhancement of the brilliance for the third harmonic relative to the first. Such calculations were done only at a few points since they involve considerable computational cost.

In Fig. 11, we present a complete calculation including the source size for the energy spectrum of 3.2 cm undulator with 75 periods (undulator lengths of 2.4 m) for CESR at 6.0 eV and 100 mA current. The spectrum substantiates most of our discussions presented here with regard to the radiation characteristics. The figure compares the quality of the spectrum on decreasing the emittance. While the brilliance of the first harmonic is gained by emittance reduction, the larger emittance provides more brilliance at higher photon energies. It should be mentioned that the calculation of each of the spectra took approximately 2 hrs of CPU time on a IBM 370/3034.

Optimization of Undulator Geometry

In a hybrid configuration, the magnetic field strength and distribution depend on the geometry of the pole-tips, and field quality is much less dependent on the magnetic and geometric quality of permanent magnet material Nd-Fe-B. The present exercise was to obtain a preliminary optimization of geometries of the magnetic structure. In this procedure, various geometrical parameters of the structure were iteratively optimized through a two-dimensional field computation in the yz plane. The resulting parameters are presented in Table 4. Three-dimensional effects were then estimated in order to obtain a pole and permanent magnet width which gives the required field homogeneity.

Table 4

Optimized Parameters for the Nd-Fe-B Undulator

Undulator period (cm)	3.2
Magnet gap (cm) (variable)	1.4 - 2.2
Undulator length (m)	2.4
Vanadium permandur pole tip:	
Width (mm)	48
Height (mm)	35
Thickness (mm)	6
Nd-Fe-B magnet:	
Width (mm)	64
Height (mm)	42
Thickness (mm)	10
Pole-tip overhang (mm)	0.8 to 1.0
B_o(T), on axis	4.9 to 2.1

Figure 12 shows the optimized two-dimensional magnetic flux lines of a 1/4 period of the 3.2 cm-undulator at its minimum gap of 1.4 cm. The shapes of the vanadium permendur pole-tip and the Nd-Fe-B permanet magnet shown in the insert in Fig. 12 were optimized to have sinusoidal field variation along the undulator, to avoid flux saturation at the corners of the pole tip, and to avoid demagnetization of the permanent magnet. This optimization reduces the peak field only 2% from the expected value of 0.5 T.

The field variation along a 1/4 period of the undulator at its minimum gap of 1.4 cm is shown in Fig. 13. For the gap of 1.4 ~ 2.2 cm, the field increase at $y = 0 \pm 1$ mm from the value at the midplane is 2%.

The widths of the pole-tips and the permanent magnet blocks were determined from harmonic analysis. The pole width of 48 mm is wide enough to consider the undulator field configuration as a two-dimensional model. The Nd-Fe-B blocks are then 64 mm. If an additional tolerance in the horizontal direction is desired, the pole width could be increased, for example, from 48 mm to 54 mm and at the same time, Nd-Fe-B magnet width would increase from 64 mm to 70 mm.

Reducing the pole overhang from 1.0 mm to 0.5 mm, for example, increases the peak field by 1.4%. Increasing the thickness of the permanent magnet by 2 mm and at the same time reducing that of the pole by 2mm increases the peak field by 2.5%. From the above exercise, the following dimensional tolerances can be specified as:

Thickness tolerance	±0.05 mm (±2 mil)
Height tolerance	±0.25 mm (±10 mil)
Width tolerance	±0.25 mm (±10 mil)

Conclusions:

A detailed study of the influence of the undulator parameters on spectral characteristics have been discussed in context of designing a device for CESR lattice. It appears that an undulator with a period between 3-2 cm and 3.4 cm will provide the needed radiation to perform various proposed scientific tasks. The present study is adequate to begin an engineering design of a hybrid device of Nd-Fe-B with a period of 3.2 cm. At the same time, a mock up of a few periods of this device should be carried out to test the validity of modeling procedures for such a device through magnetic measurements.

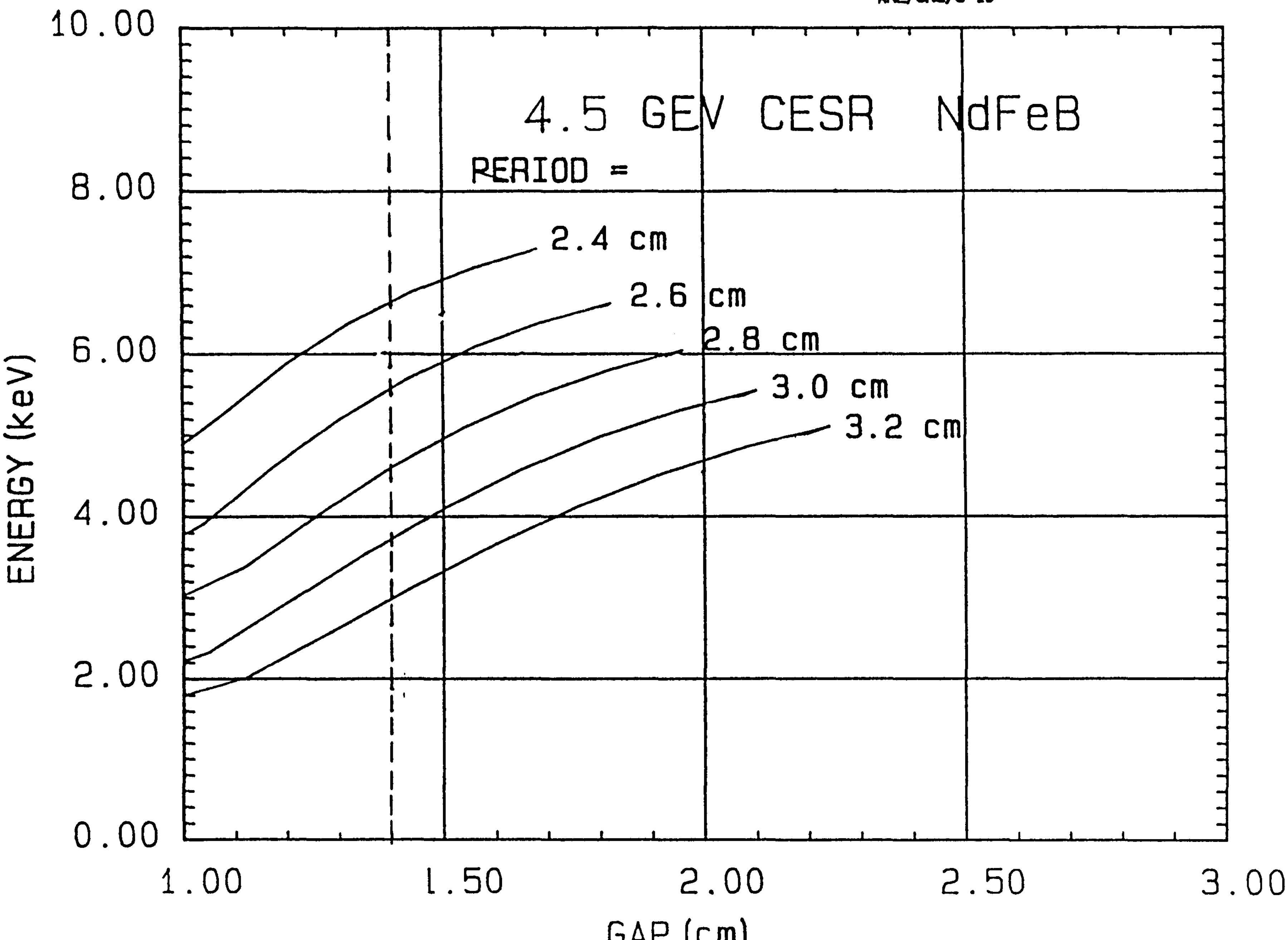
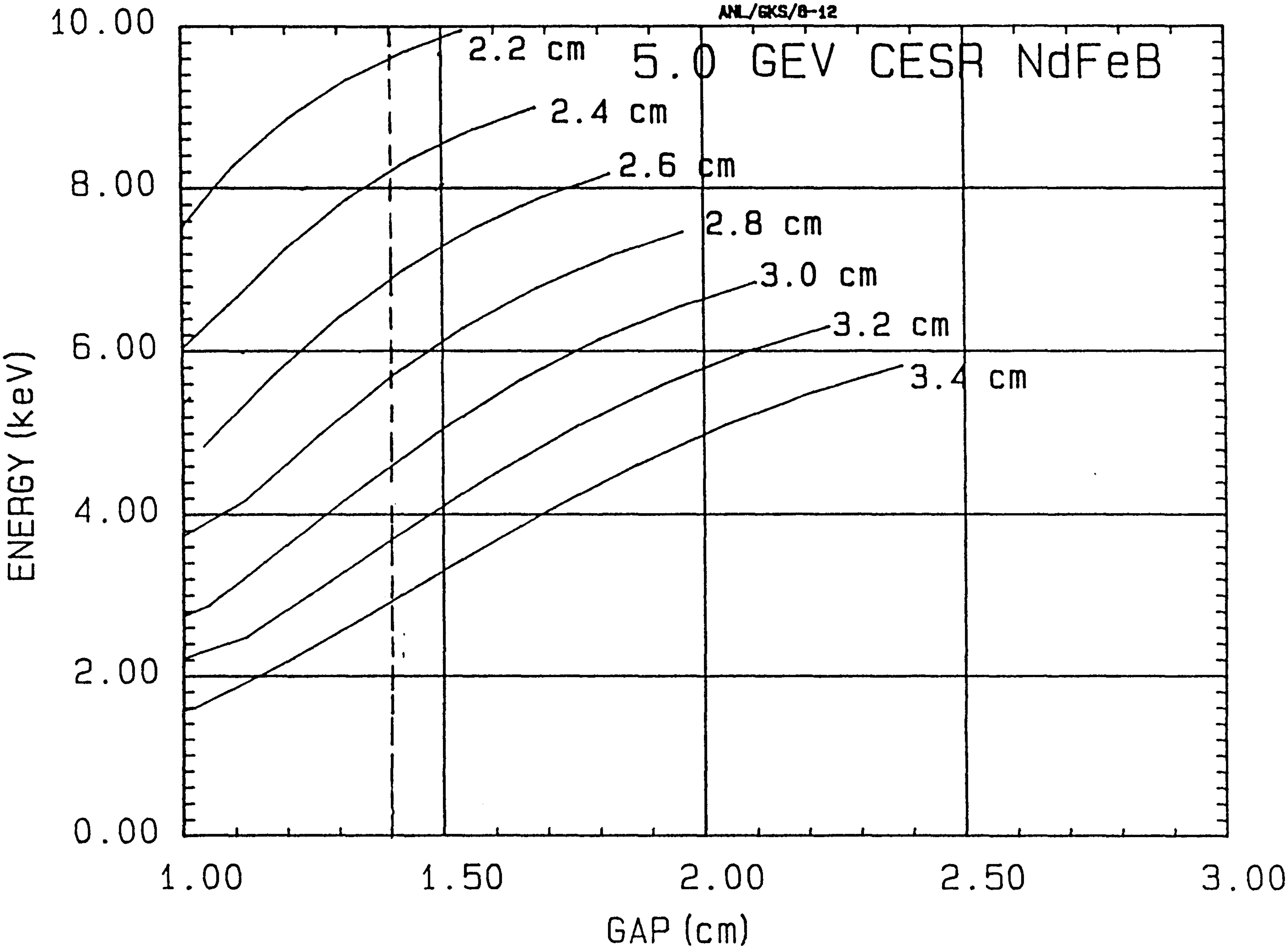

4.5 GEV CESR NdFeB
PERIOD =
2.4 cm
2.6 cm
2.8 cm
3.0 cm
3.2 cm
ENERGY (keV)
10.00
8.00
6.00
4.00
2.00
0.00
1.00
1.50
2.00
2.50
3.00
GAP (cm)

Fig. 1



ANL/GKS/8-12
5.0 GEV CESR NdFeB
2.2 cm
2.4 cm
2.6 cm
2.8 cm
3.0 cm
3.2 cm
3.4 cm
ENERGY (keV)
10.00
8.00
6.00
4.00
2.00
0.00
1.00
1.50
2.00
2.50
3.00
GAP (cm)

Fig. 2

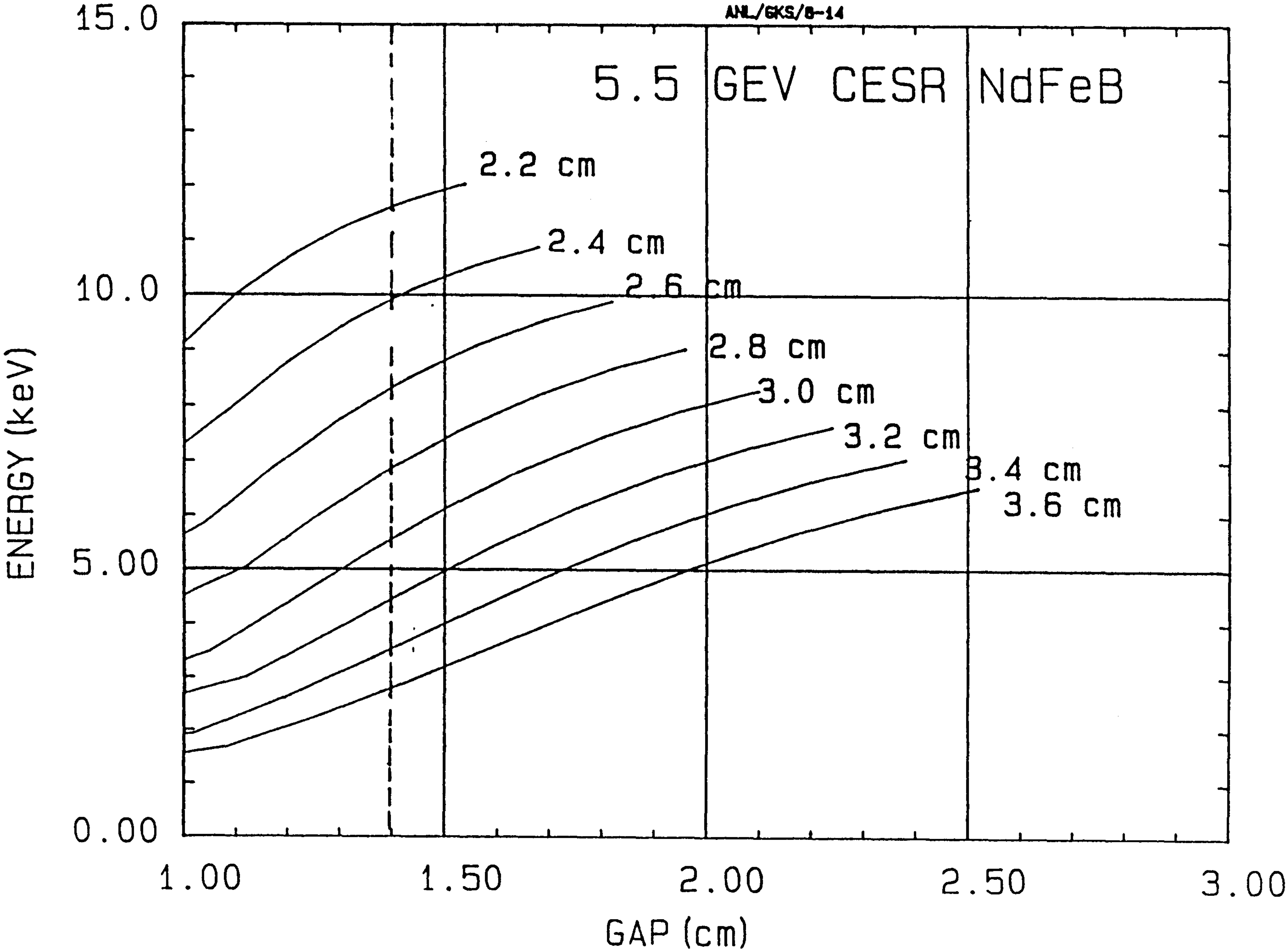

ANL/GKS/8-14
5.5 GEV CESR NdFeB
2.2 cm
2.4 cm
2.6 cm
2.8 cm
3.0 cm
3.2 cm
3.4 cm
3.6 cm
15.0
10.0
5.00
0.00
ENERGY (keV)
1.00
1.50
2.00
2.50
3.00
GAP (cm)

Fig. 3

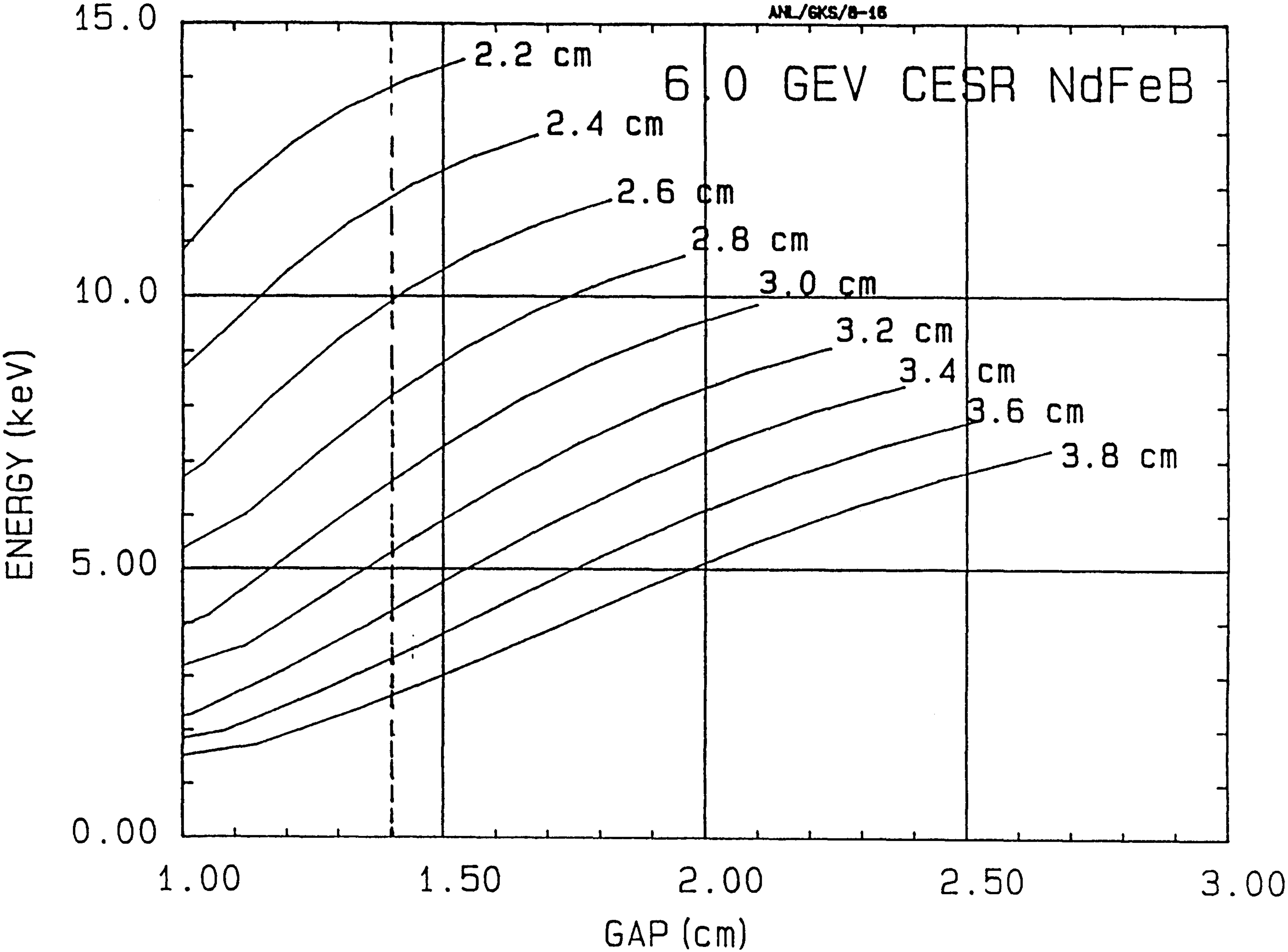
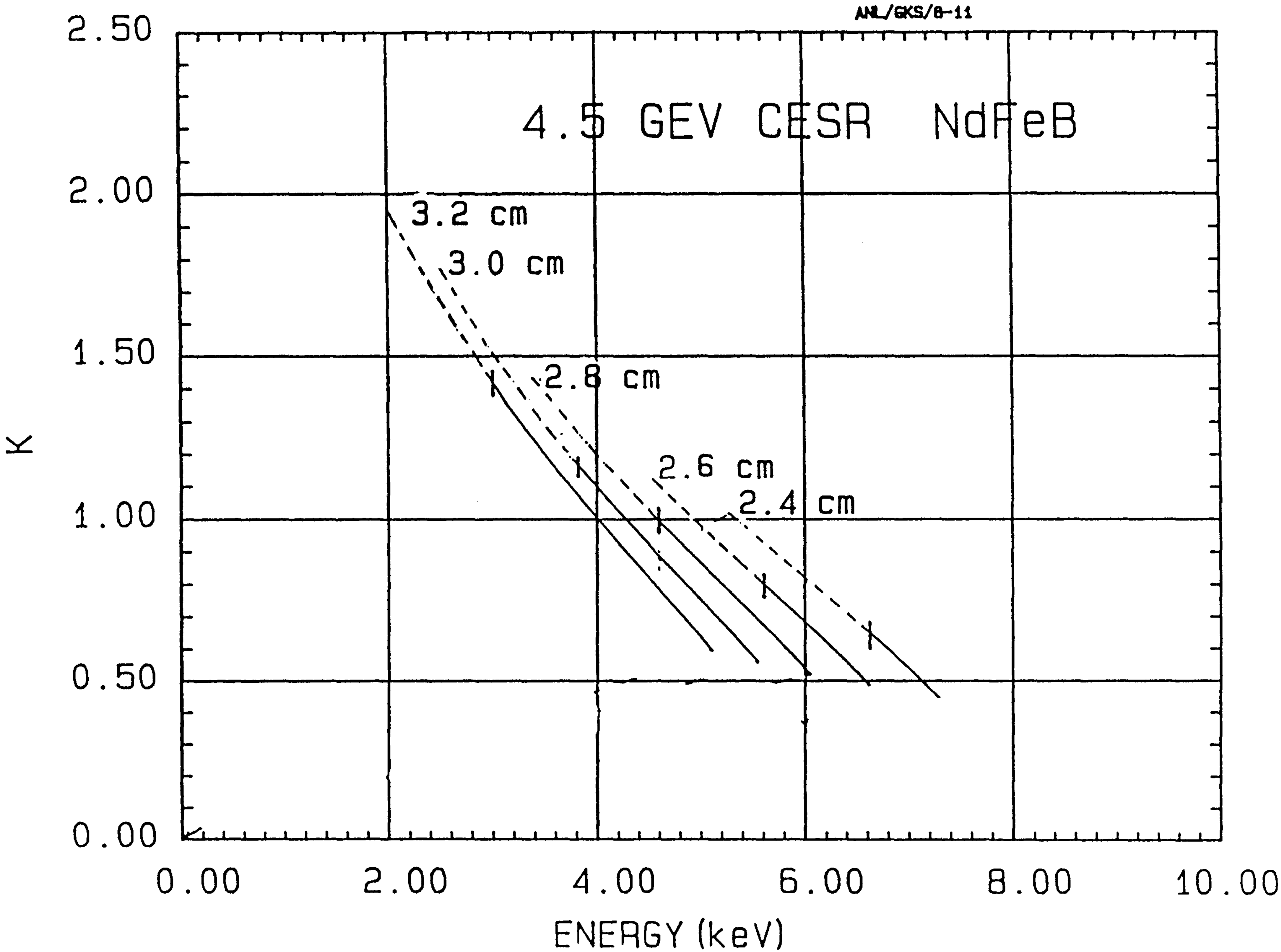
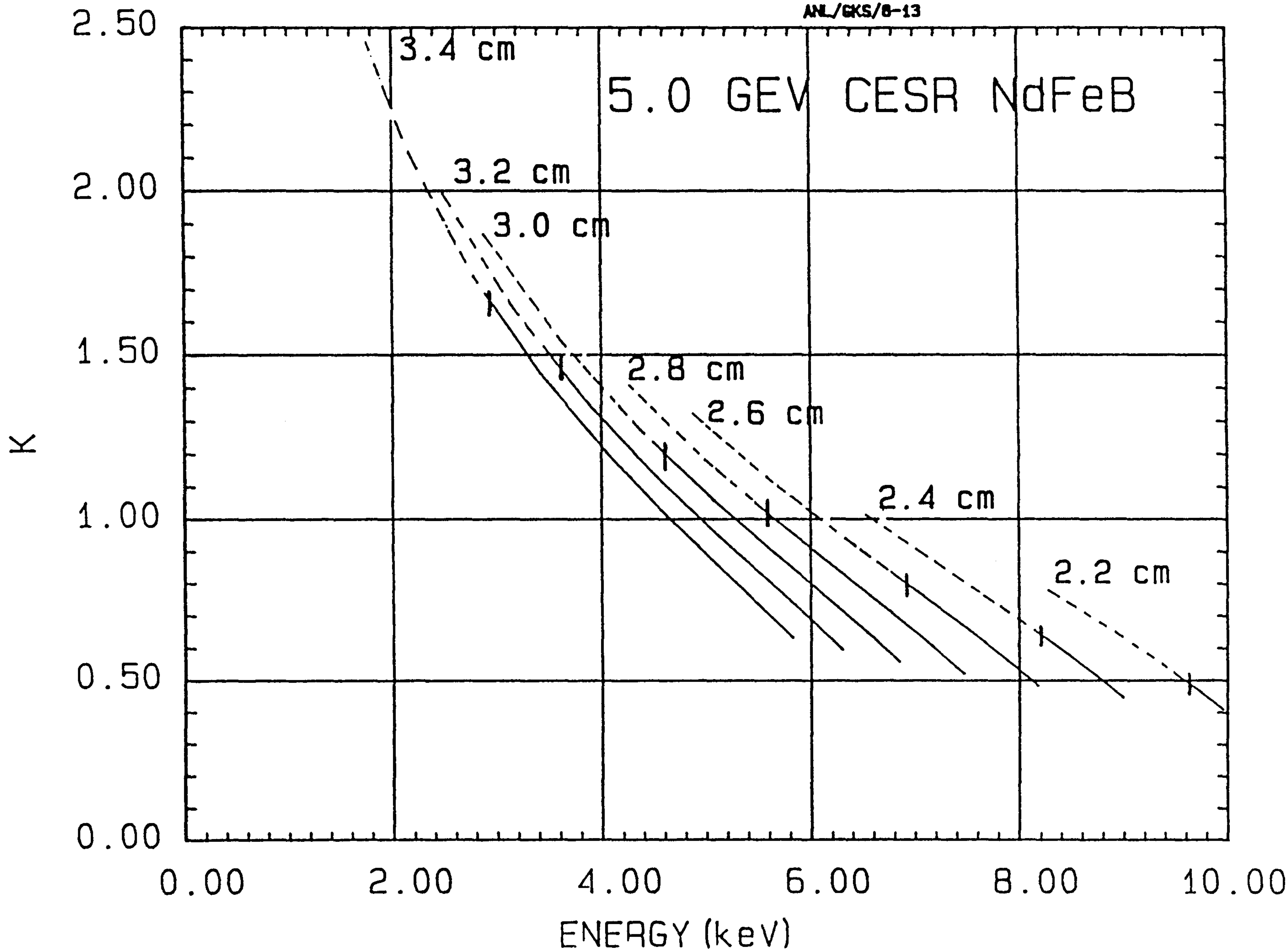

ANL/GKS/8-16
6.0 GEV CESR NdFeB
2.2 cm
2.4 cm
2.6 cm
2.8 cm
3.0 cm
3.2 cm
3.4 cm
3.6 cm
3.8 cm
15.0
10.0
5.00
0.00
ENERGY (keV)
1.00
1.50
2.00
2.50
3.00
GAP (cm)

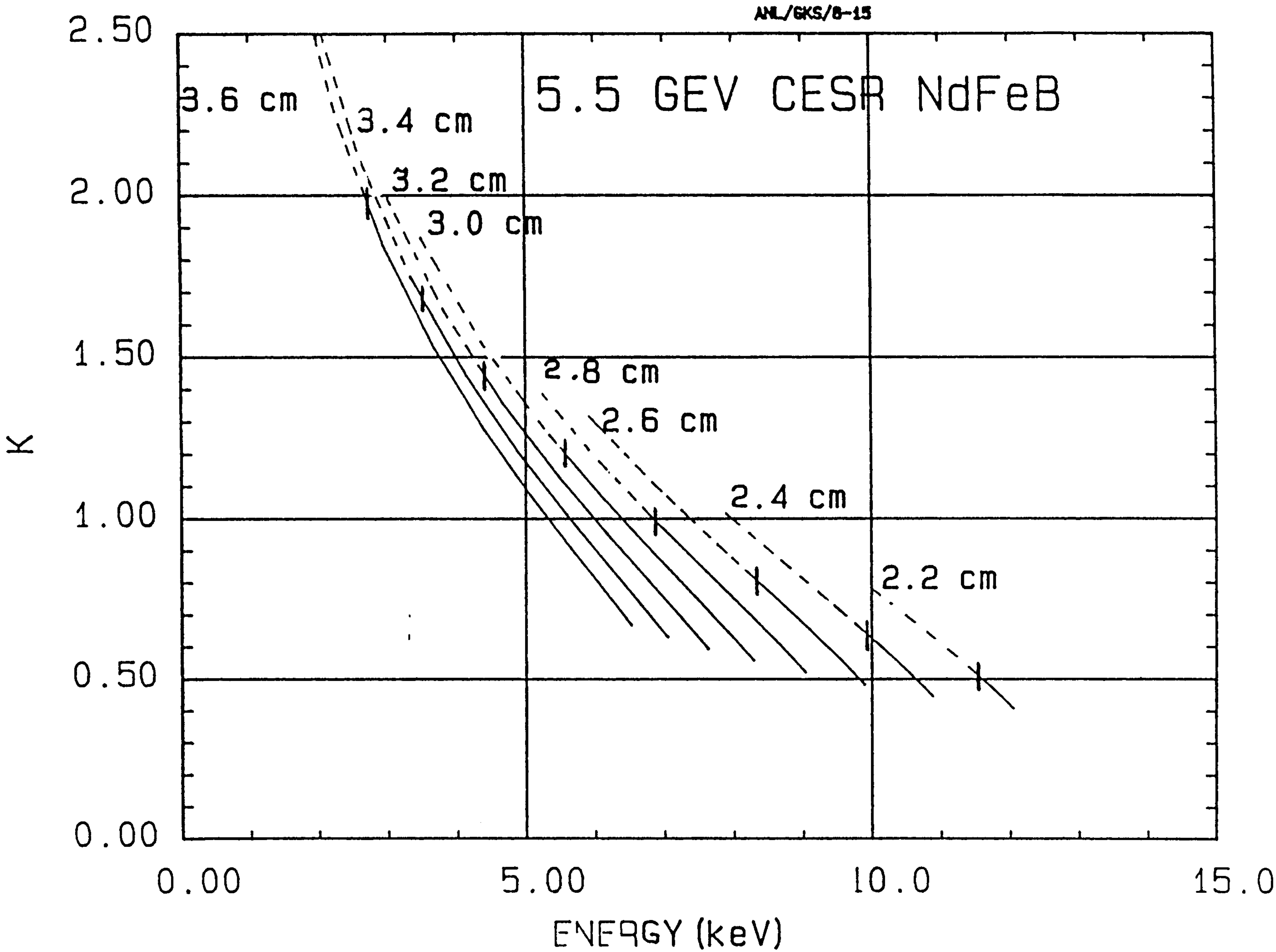
Fig. 4


ANL/GKS/8-11
4.5 GEV CESR NdFeB
3.2 cm
3.0 cm
2.8 cm
2.6 cm
2.4 cm
K
2.50
2.00
1.50
1.00
0.50
0.00
0.00
2.00
4.00
6.00
8.00
10.00
ENERGY (keV)
Fig. 5



ANL/GKS/8-13
5.0 GEV CESR NdFeB
3.4 cm
3.2 cm
3.0 cm
2.8 cm
2.6 cm
2.4 cm
2.2 cm
K
2.50
2.00
1.50
1.00
0.50
0.00
0.00
2.00
4.00
6.00
8.00
10.00
ENERGY (keV)

Fig. 6



ANL/GKS/8-15
5.5 GEV CESR NdFeB
3.6 cm
3.4 cm
3.2 cm
3.0 cm
2.8 cm
2.6 cm
2.4 cm
2.2 cm
2.50
2.00
1.50
1.00
0.50
0.00
K
0.00
5.00
10.0
15.0
ENERGY (keV)

Fig. 7

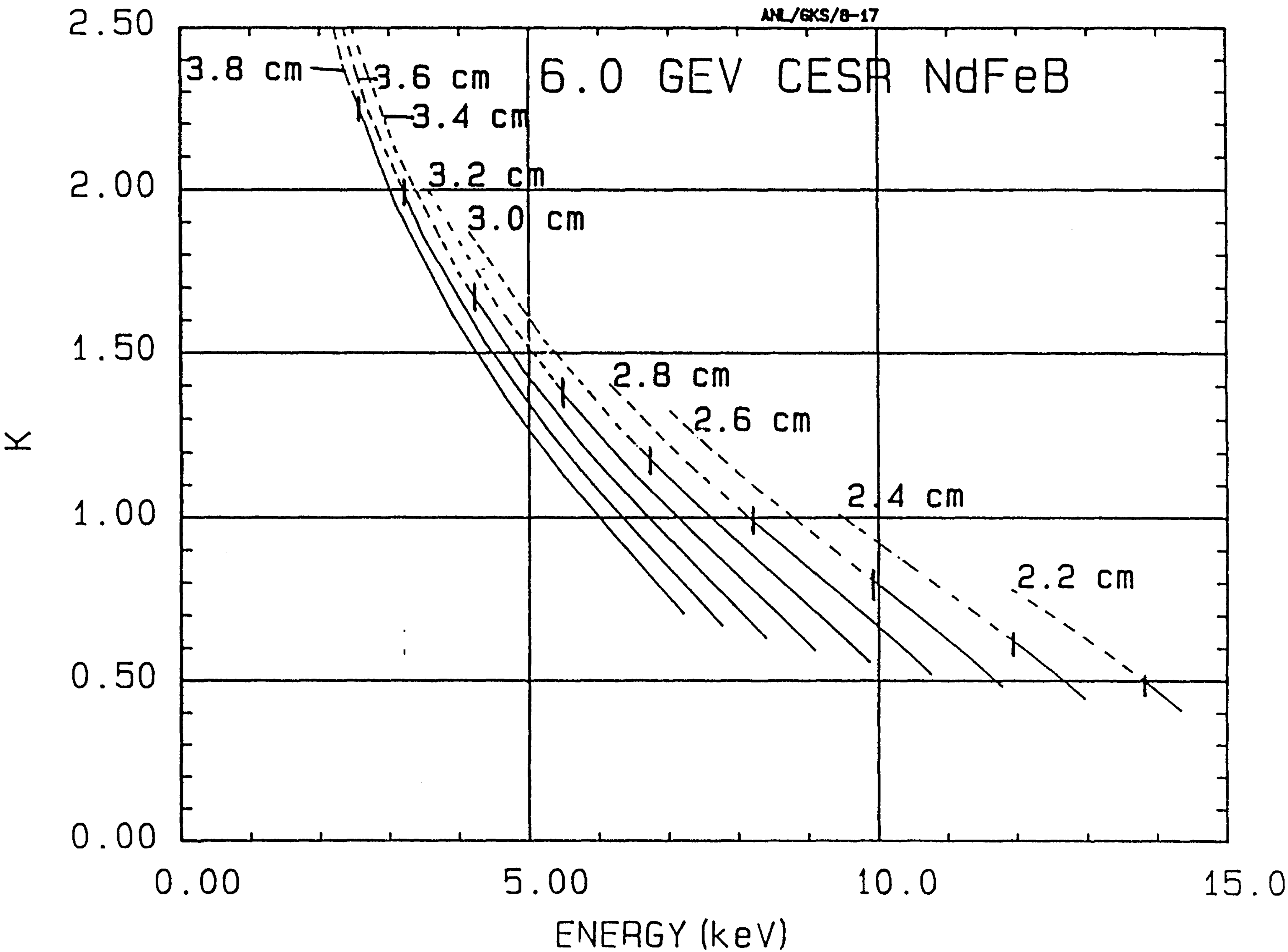

ANL/GKS/8-17
6.0 GEV CESR NdFeB
3.8 cm
3.6 cm
3.4 cm
3.2 cm
3.0 cm
2.8 cm
2.6 cm
2.4 cm
2.2 cm
2.50
2.00
1.50
1.00
0.50
0.00
K
0.00
5.00
10.0
15.0
ENERGY (keV)

Fig. 8

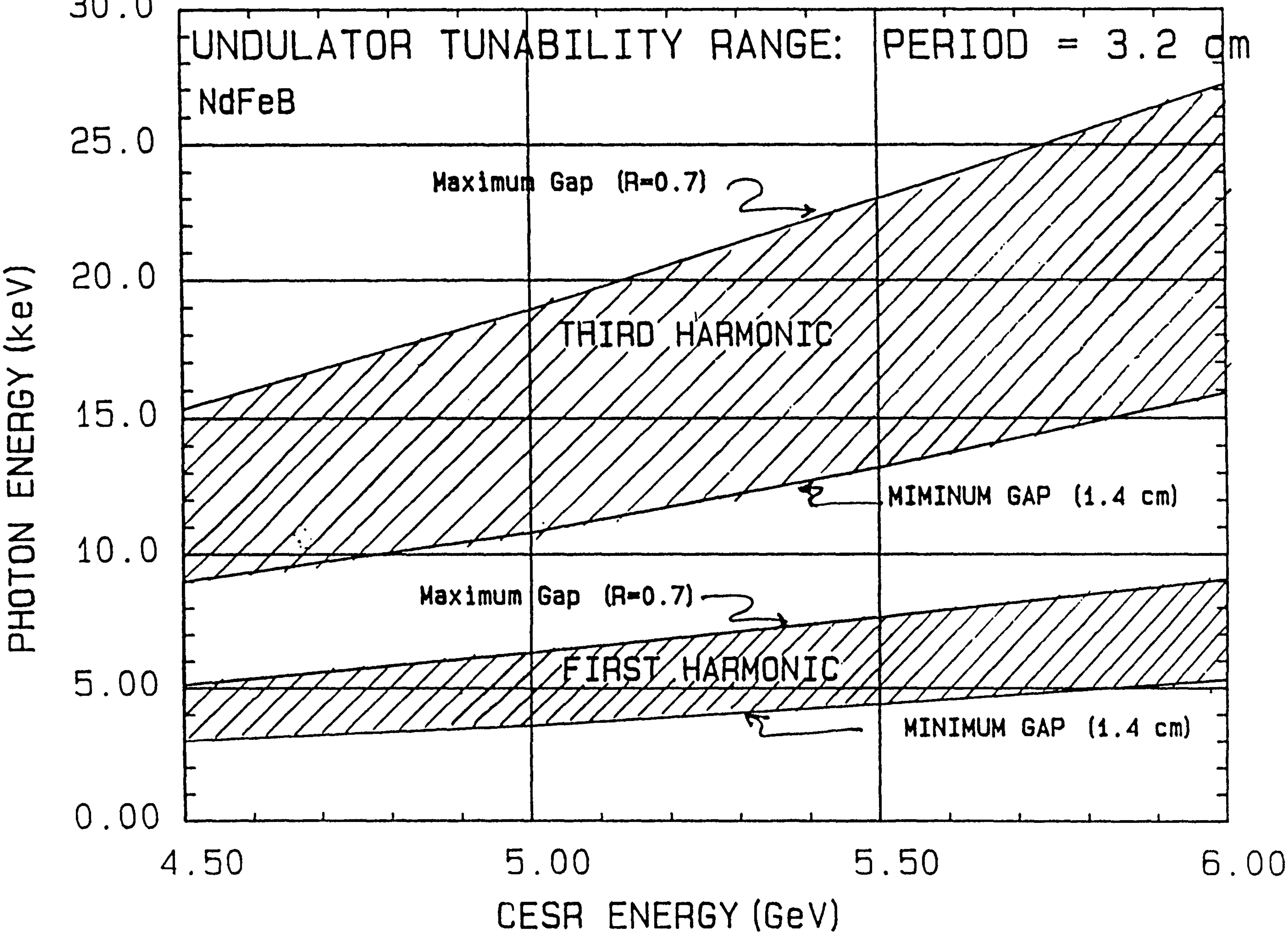
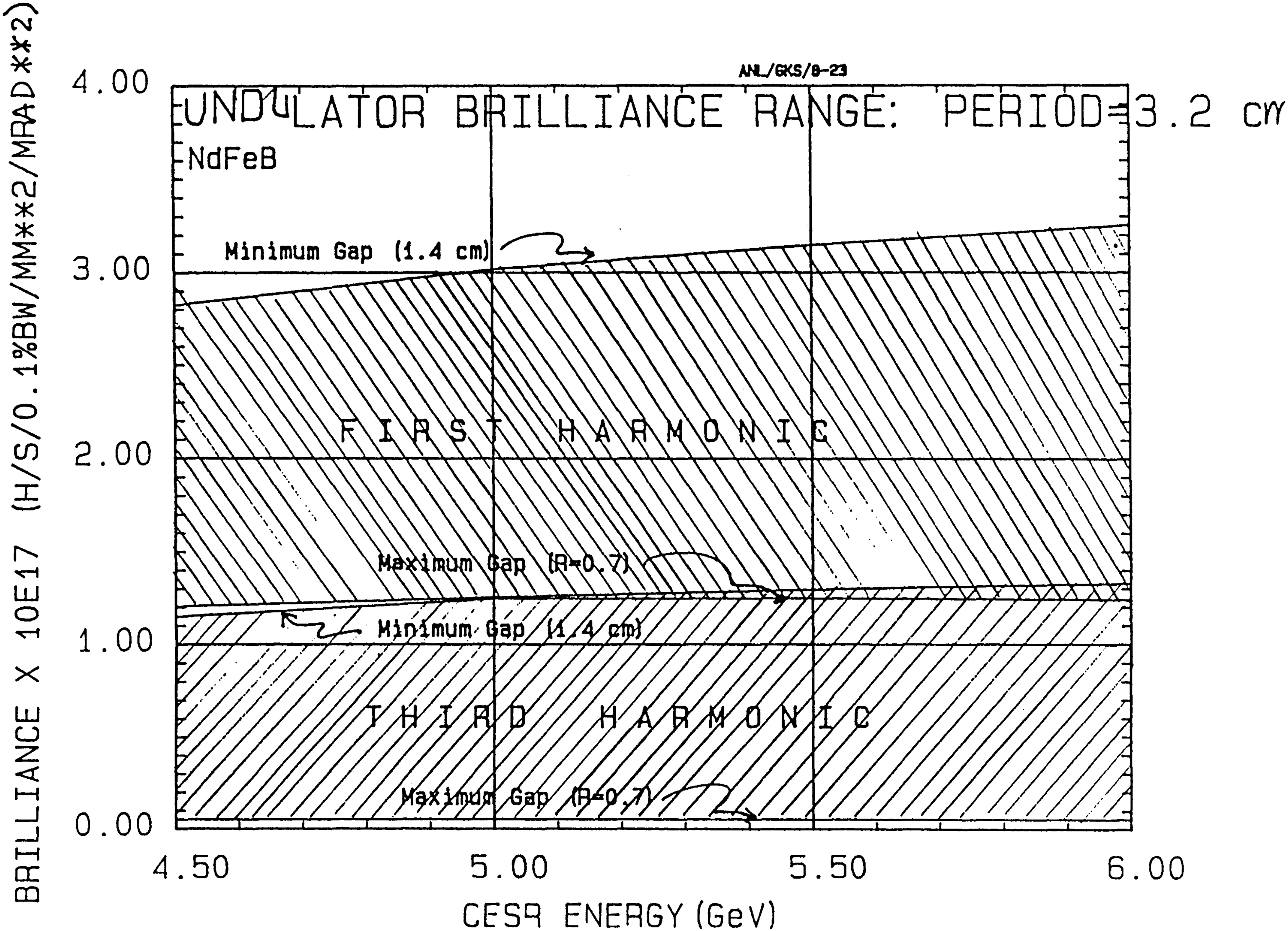
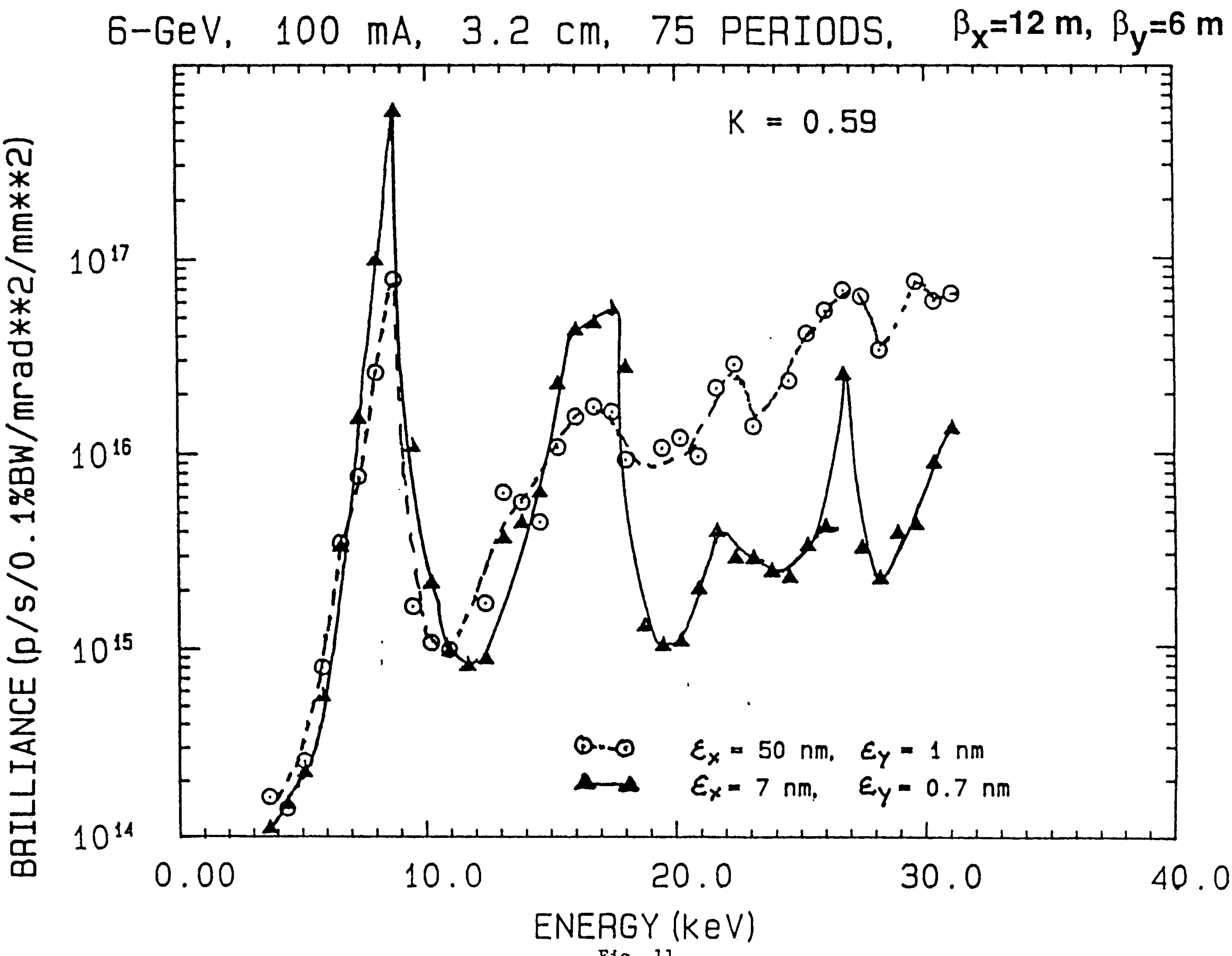

UNDULATOR TUNABILITY RANGE: PERIOD = 3.2 cm
NdFeB
Maximum Gap (R=0.7)
THIRD HARMONIC
MIMINUM GAP (1.4 cm)
Maximum Gap (R=0.7)
FIRST HARMONIC
MINIMUM GAP (1.4 cm)
PHOTON ENERGY (keV)
30.0
25.0
20.0
15.0
10.0
5.00
0.00
4.50
5.00
5.50
6.00
CESR ENERGY (GeV)

Fig. 9



ANL/GKS/8-23
UNDULATOR BRILLIANCE RANGE: PERIOD=3.2 cm
NdFeB
Minimum Gap (1.4 cm)
FIRST HARMONIC
Maximum Gap (R=0.7)
Minimum Gap (1.4 cm)
THIRD HARMONIC
Maximum Gap (R=0.7)
BRILLIANCE X 10E17 (H/S/0.1%BW/MM**2/MRAD**2)
4.00
3.00
2.00
1.00
0.00
4.50
5.00
5.50
6.00
CESR ENERGY (GeV)

Fig. 10


6-GeV, 100 mA, 3.2 cm, 75 PERIODS, β_x=12 m, β_y=6 m
K = 0.59
BRILLIANCE (p/s/0.1%BW/mrad**2/mm**2)
10^{17}
10^{16}
10^{15}
10^{14}
0.00
10.0
20.0
30.0
40.0
ENERGY (keV)
ε_x = 50 nm, ε_y = 1 nm
ε_x = 7 nm, ε_y = 0.7 nm
Fig. 11

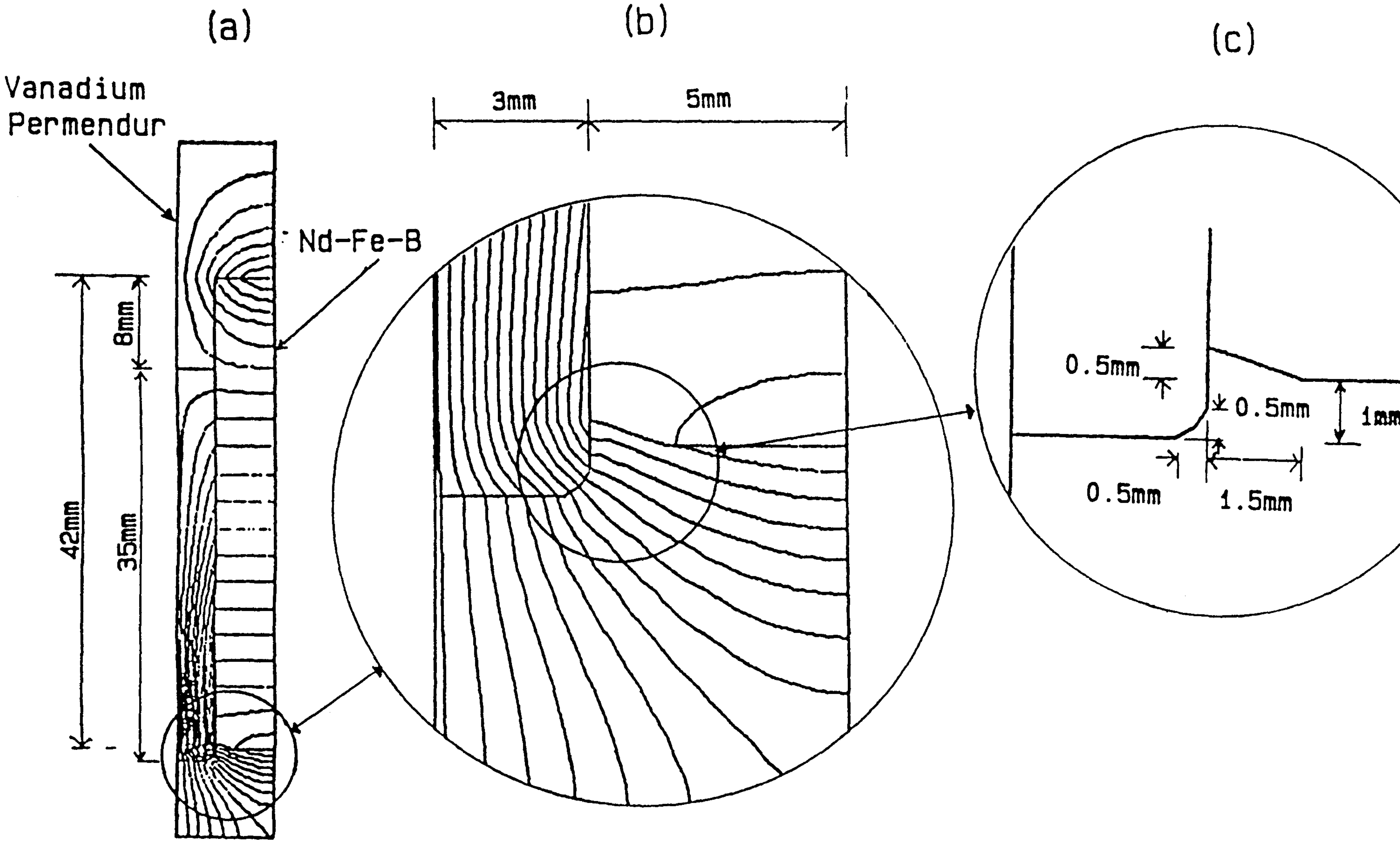

(a)
(b)
(c)
Vanadium
Permendur
Nd-Fe-B
8mm
42mm
35mm
3mm
5mm
0.5mm
0.5mm
1mm
0.5mm
1.5mm

Fig. 12

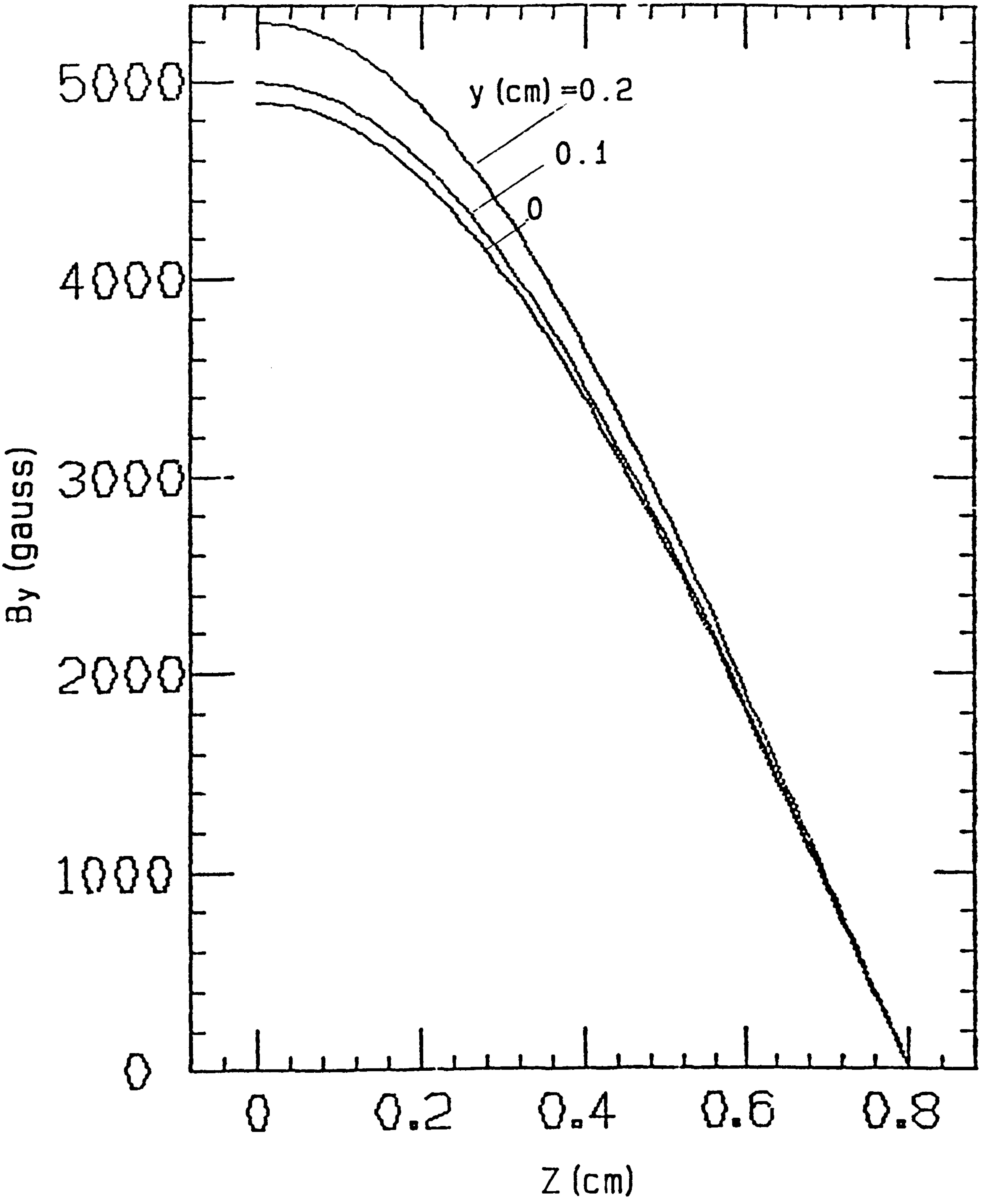


Fig. 13