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UNDULATORS ON A 6-GeV RING

GENERAL CONSIDERATIONS

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Summary

It is argued that the power delivered may not be a serious limitation for the use of radiation from a conventional undulator on a 6-GeV storage ring. A conservative approach in deciding the undulator parameters is discussed. Parameters for a spectrum of undulators to cover the photon energy range from 1 to 20 keV are presented in tabular form.

Introduction

In designing undulators on a 6-GeV storage ring the primary consideration will be the power that such devices will deliver. The beam line design should be capable of handling large powers that such undulators will deliver. Specifically, in a beam line in the front end we have masks (fixed and movable) followed by various optical components. Many thermal designs are now being developed to improve on the capability of various components to handle a greater heat load than ever been possible before. For example, designs for rotating optics and liquid metal cooled optics are actively pursued in the MST division.

A conservative approach to power handling problems is to go by our experience on devices operating on existing storage rings. The 54-pole wiggler on SPEAR is perhaps the world's hottest device operating today. The fixed and movable masks located at 6.5m from the source on this Beam Line VI at SSRL are designed to handle 200W/sq. mm. These components are only water cooled with an efficient cooling design. The heat load handling can be improved by many factors with newer approaches. These considerations are most important in deciding the design of various undulators on a 6-Gev storage ring.

The other important aspects in an undulator design are related to the capability of permanent magnets and to the minimum permissible undulator gap. There are many limitations in meeting all the user demands on the spectral range and brilliance or flux, as the case may be, due to these two undulator parameters. Our approach again will be conservative depending on already existing technology and methodology.

Finally, in this report on general considerations, we will present a spectrum of undulators that will cover most of the presently conceived user demands from 1 keV to 21 keV at a 6-GeV storage ring.

Undulator Power

Let us assume the length of the undulator to be L meters and that it has N periods each of length λ_o cms. Then the total power radiated by the undulator on a storage ring with electrons of energy E and current I is given by

$$W(\text{watts}) = 7.25\ E^2\ (\text{GeV}^2)\ I(\text{Amp})\ N\ K^2/\lambda_o \tag{1}$$

where $K = 0.934\ B_o\ \lambda_o$. ($B_o$ peak field in Tesla). One can also express

$$W(\text{watts}) = 634\ E^2\ (\text{GeV}^2)\ B_o^{\,2}\ (T^2)\ I(\text{Amp})\ L(m) \tag{2}$$

A typical value of B_o is 0.3T which for L=5m, I=0.1A, E=6GeV yields a total radiated power of 1027 watts.

For a point source, this radiation will be emitted in a solid angle of about γ^{-2} (provided K<1.0 which is usually true), and hence the effective area irradiated at a distance of D meters away from the source is given by

$$A(\text{sq.mm}) = 1.0E6\ D^2\ (m^2)/\gamma^2. \qquad (3)$$

If we consider the case with all values of K,

$$A(\text{sq.mm}) = 0.26\ D^2\ (m^2)\ (1. + 5.25\ K^2)^{1/2}/E^2\ (\text{GeV}^2) \qquad (4)$$

The power density (Watts/sq.mm) at a distance D from the source is given by W/A. In the 6-GeV storage ring it is most likely that the first beam line component (masks) are at a distance of more than 30m. Within the point source approximation this leads to A = 9.3 sq. mm and a power density of 110 watts/sq. mm. This number is indeed less than that currently handled at the 54-pole wiggler beam line.

The finite size of the source will reduce this density further by a factor of about 2. In addition, many high resolution experiments will demand 100m long beam lines. At 100m, the power density in the above example will be under 10 watts/sq. mm. and the effective illuminated area is only 104 sq. mm.

Undulator Magnets and Gap

The above discussion points to a very important fact that the power density is primarily governed by the length of the undulator L, and the peak magnetic field B_o. If we keep their values around or under those used in the above example, viz. L = 5 m and B = 0.3 T, there should be no serious difficulties of power handling by the beam line components.

For the REC based hybrid magnets, we will use the following equation to describe the peak field dependence on the magnet gap G (cms) and undulator period λ_o (cms),

$$B_o\ (T) = 3.33\ \exp[-G/\lambda_o\ (5.47\ -1.8\ G/\lambda_o)] \qquad (5)$$

Since B is governed by the ratio G/λ_o, increase in the gap will demand an increase in λ_o to keep B a constant. Also we note that $G/\lambda_o = 0.5$ gives $B_o = 0.33T$, which is nearly the value of the field used in the discussion of the last section.

The energies of photons from an undulator peak around

$$E_i(ev) = \frac{949\ E^2\ (GeV^2)\ i}{\lambda_o(cm)\ (1 + K^2/2)} \qquad (6)$$

where

$$K = 0.934\ B_o\ (T)\ \lambda_o\ (cm) \qquad (7)$$

and i is the harmonic.

From Eqs.(6) and (7), we observe that one can realize any photon peak energy from an undulator by selection of G and λ_o. However, there are two major limitations:

1. The gap cannot be reduced below a certain minimum since there will be a definite sized aperture needed for the electron beam. This minimum will also be governed by the details of the length of the straight section, the vacuum requirements and procedures to obtain them, etc. If the undulator is inserted in the ring vacuum, then the minimum gap can be about 0.8 cm. On the otherhand, if the poles of the undulator are located outside 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. The value of K (hence of B_o) cannot be made infinitesimaly small in order to increase the photon peak energy. Value of K much smaller than 0.2 drastically reduces the flux from the device to be of any real value to the user. On the other hand, large values of K (>2.0), destroys the psuedo-monochromatic character of the radiation delivered by such a device.

Within the above limitations on the choice of G and λ_o, we present in Fig. 1 a set of undulators with various parameters to cover the photon energy range from 1 to 21 keV using the machine parameters shown in Table 1. The Tables II contain details of the calculations on each of the undulators. Higher energy radiation can be obtained through the use of higher harmonics.

Conclusions

This report presents a conservative approach to the selection of parameters of various undulators which will deliver the photon spectrum of interest to the users of the 6-GeV storage ring. Figure 1 is a complete summary of this report. It is safe to consider that such devices can be built and that they will function to the satisfaction of the users. However, with improvements on machine design, vacuum design, and magnet materials, not only the discussed goals can be easily achieved, but even more efficient undulatator designs will be possible. For example, the new magnet material NEOMAX available from Sumitomo Corporation produces 30% higher fields than the REC magnets and should be considered in future undulator designs.

If and when more power can be handled by the beam line components, the undulator lengths can be increased by designing them as modular blocks of say 1 or 2 meters lengths.

Table I. Machine Parameters Used in these Calculations

Energy (GeV)	6.00
Current (A)	0.1
Hor Emittance	7.0×10^{-9}
Coupling (ek^2)	0.1
B_x (m)	29.5
B_y (m)	7.3
Undulator Length (m)	5.0

TABLE II

Undulator # 1

Photon Energy (eV) (1st-Harmonic)	21000.0	20000.0	19000.0
Undulator Period (cm)	1.60	1.60	1.60
Undulator Gap (cm)	1.329	0.946	0.808
Peak Field (T)	0.123	0.246	0.333
K	0.183	0.368	0.498
Undulator Length (m)	5.0	5.0	5.0
Number of Periods	312	312	312
Total Power (watts)	171.1	689.5	1262.3
Power Density (watts/sq.mm.)	8.7	29.2	46.1
Flux (PH/sec/0.1 c/o BW)	0.145E+15	0.544E+15	0.923E+15
On Axis Brilliance ($Ph/sec/0.1BW/mrad^2/mm^2$)	0.829E+18	0.309E+19	0.522E+19
Horizontal Source size (mm)	0.4333	0.4333	0.4333
Vertical Source size (mm)	0.0684	0.0684	0.0684
Horizontal Divergence (mrad)	0.0151	0.0151	0.0151
Vertical Divergence (mrad)	0.0099	0.0100	0.0100

TABLE II

Undulator #2

Photon Energy (eV) (1st-Harmonic)	19500.0	17500.0
Undulator Period (cm)	1.70	1.70
Undulator Gap (cm)	1.258	0.844
Peak Field (T)	0.156	0.343
K	0.247	0.545
Undulator Length (m)	5.0	5.0
Number of Periods	294	294
Total Power (watts)	276.2	1339.9
Power Density (watts/sq.mm.)	13.3	46.4
Flux (PH/sec/0.1 c/o BW)	0.244E+15	0.101E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.138E+19	0.565E+19
Horizontal Source size (mm)	0.4333	0.4333
Vertical Source size (mm)	0.0684	0.0684
Horizontal Divergence (mrad)	0.0151	0.0152
Vertical Divergence (mrad)	0.0100	0.0101

TABLE II

Undulator #3

Photon Energy (eV) (1st-Harmonic)	18500.0	16500.0
Undulator Period (cm)	1.80	1.80
Undulator Gap (cm)	1.425	0.919
Peak Field (T)	0.135	0.326
K	0.228	0.548
Undulator Length (m)	5.0	5.0
Number of Periods	277	277
Total Power (watts)	209.0	1210.8
Power Density (watts/sq.mm.)	10.3	41.8
Flux (PH/sec/0.1 c/o BW)	0.197E+15	0.962E+15
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.111E+19	0.536E+19
Horizontal Source size (mm)	0.4333	0.4333
Vertical Source size (mm)	0.0684	0.0684
Horizontal Divergence (mrad)	0.0151	0.0152
Vertical Divergence (mrad)	0.0100	0.0101

TABLE II

Undulator # 4

Photon Energy (eV) (1st-Harmonic)	17500.0	15000.0
Undulator Period (cm)	1.90	1.90
Undulator Gap (cm)	1.522	0.926
Peak Field (T)	0.132	0.355
K	0.234	0.630
Undulator Length (m)	5.0	5.0
Number of Periods	263	263
Total Power (watts)	198.7	1436.9
Power Density (watts/sq.mm.)	9.7	45.3
Flux (PH/sec/0.1 c/o BW)	0.197E+15	0.113E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.111E+19	0.625E+19
Horizontal Source size (mm)	0.4333	0.4333
Vertical Source size (mm)	0.0684	0.0685
Horizontal Divergence (mrad)	0.0152	0.0152
Vertical Divergence (mrad)	0.0101	0.0102

TABLE II

Undulator # 5

Photon Energy (eV) (1st-Harmonic)	16500.0	14000.0
Undulator Period (cm)	2.00	2.00
Undulator Gap (cm)	1.547	0.975
Peak Field (T)	0.142	0.355
K	0.266	0.664
Undulator Length (m)	5.0	5.0
Number of Periods	250	250
Total Power (watts)	230.2	1436.4
Power Density (watts/sq.mm.)	10.9	43.7
Flux (PH/sec/0.1 c/o BW)	0.238E+15	0.116E+16
On Axis Brilliance ($Ph/sec/0.1BW/mrad^2/mm^2$)	0.132E+19	0.635E+19
Horizontal Source size (mm)	0.4333	0.4333
Vertical Source size (mm)	0.0684	0.0685
Horizontal Divergence (mrad)	0.0152	0.0153
Vertical Divergence (mrad)	0.0101	0.0102

TABLE II

Undulator # 6

Photon Energy (eV) (1st-Harmonic)	15000.0	12500.0
Undulator Period (cm)	2.20	2.20
Undulator Gap (cm)	1.781	1.100
Peak Field (T)	0.129	0.339
K	0.266	0.696
Undulator Length (m)	5.0	5.0
Number of Periods	227	227
Total Power (watts)	190.2	1306.8
Power Density (watts/sq.mm.)	9.0	38.4
Flux (PH/sec/0.1 c/o BW)	0.216E+15	0.113E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.119E+19	0.610E+19
Horizontal Source size (mm)	0.4333	0.4333
Vertical Source size (mm)	0.0685	0.0685
Horizontal Divergence (mrad)	0.0152	0.0153
Vertical Divergence (mrad)	0.0102	0.0103

TABLE II

Undulator # 7

Photon Energy (eV) (1st-Harmonic)	14000.0	11000.0
Undulator Period (cm)	2.40	2.40
Undulator Gap (cm)	2.449	1.194
Peak Field (T)	0.082	0.342
K	0.183	0.767
Undulator Length (m)	5.0	5.0
Number of Periods	208	208
Total Power (watts)	76.1	1332.6
Power Density (watts/sq.mm.)	3.9	36.5
Flux (PH/sec/0.1 c/o BW)	0.969E+14	0.119E+16
On Axis Brilliance (Ph/sec/0.1BW/$mrad^2$/mm^2)	0.529E+18	0.627E+19
Horizontal Source size (mm)	0.4333	0.4333
Vertical Source size (mm)	0.0685	0.0686
Horizontal Divergence (mrad)	0.0153	0.0154
Vertical Divergence (mrad)	0.0102	0.0105

TABLE II

Undulator # 8

Photon Energy (eV) (1st-Harmonic)	12000.0	9000.0
Undulator Period (cm)	2.80	2.80
Undulator Gap (cm)	3.122	1.438
Peak Field (T)	0.070	0.323
K	0.183	0.843
Undulator Length (m)	5.0	5.0
Number of Periods	178	178
Total Power (watts)	55.9	1184.2
Power Density (watts/sq.mm.)	2.9	30.1
Flux (PH/sec/0.1 c/o BW)	0.830E+14	0.115E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.444E+18	0.587E+19
Horizontal Source size (mm)	0.4333	0.4334
Vertical Source size (mm)	0.0685	0.0687
Horizontal Divergence (mrad)	0.0154	0.0156
Vertical Divergence (mrad)	0.0104	0.0107

TABLE II

Undulator #9

Photon Energy (eV) (1st-Harmonic)	10500.0	7000.0
Undulator Period (cm)	3.20	3.20
Undulator Gap (cm)	3.906	1.590
Peak Field (T)	0.061	0.343
K	0.183	1.025
Undulator Length (m)	5.0	5.0
Number of Periods	156	156
Total Power (watts)	42.8	1338.6
Power Density (watts/sq.mm.)	2.2	29.0
Flux (PH/sec/0.1 c/o BW)	0.727E+14	0.126E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.381E+18	0.609E+19
Horizontal Source size (mm)	0.4333	0.4334
Vertical Source size (mm)	0.0686	0.0688
Horizontal Divergence (mrad)	0.0155	0.0158
Vertical Divergence (mrad)	0.0105	0.0111

TABLE II

Undulator # 10

Photon Energy (eV) (1st-Harmonic)	8500.0	5000.0
Undulator Period (cm)	3.80	3.80
Undulator Gap (cm)	3.568	1.849
Peak Field (T)	0.096	0.356
K	0.340	1.263
Undulator Length (m)	5.0	5.0
Number of Periods	131	131
Total Power (watts)	104.3	1442.6
Power Density (watts/sq.mm.)	4.6	26.1
Flux (PH/sec/0.1 c/o BW)	0.198E+15	0.128E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.100E+19	0.568E+19
Horizontal Source size (mm)	0.4334	0.4334
Vertical Source size (mm)	0.0687	0.0691
Horizontal Divergence (mrad)	0.0156	0.0163
Vertical Divergence (mrad)	0.0108	0.0117

TABLE II

Undulator # 11

Photon Energy (eV) (1st-Harmonic)	7500.0	4000.0
Undulator Period (cm)	4.40	4.40
Undulator Gap (cm)	5.170	2.218
Peak Field (T)	0.065	0.334
K	0.266	1.372
Undulator Length (m)	5.0	5.0
Number of Periods	113	113
Total Power (watts)	47.6	1268.8
Power Density (watts/sq.mm.)	2.2	21.3
Flux (PH/sec/0.1 c/o BW)	0.108E+15	0.117E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.532E+18	0.486E+19
Horizontal Source size (mm)	0.4334	0.4335
Vertical Source size (mm)	0.0688	0.0693
Horizontal Divergence (mrad)	0.0158	0.0167
Vertical Divergence (mrad)	0.0110	0.0122

TABLE II

Undulator # 12

Photon Energy (eV) (1st-Harmonic)	6500.0	3000.0
Undulator Period (cm)	4.80	4.80
Undulator Gap (cm)	4.472	2.288
Peak Field (T)	0.097	0.370
K	0.436	1.657
Undulator Length (m)	5.0	5.0
Number of Periods	104	104
Total Power (watts)	107.6	1554.8
Power Density (watts/sq.mm.)	4.2	21.9
Flux (PH/sec/0.1 c/o BW)	0.245E+15	0.120E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.117E+19	0.446E+19
Horizontal Source size (mm)	0.4334	0.4335
Vertical Source size (mm)	0.0689	0.0697
Horizontal Divergence (mrad)	0.0159	0.0173
Vertical Divergence (mrad)	0.0112	0.0130

TABLE II

Undulator # 13

Photon Energy (eV) (1st-Harmonic)	3500.0	2000.0
Undulator Period (cm)	6.00	6.00
Undulator Gap (cm)	3.935	2.981
Peak Field (T)	0.200	0.343
K	1.120	1.922
Undulator Length (m)	5.0	5.0
Number of Periods	83	83
Total Power (watts)	454.5	1339.1
Power Density (watts/sq.mm.)	9.1	16.4
Flux (PH/sec/0.1 c/o BW)	0.730E+15	0.102E+16
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.289E+19	0.315E+19
Horizontal Source size (mm)	0.4335	0.4336
Vertical Source size (mm)	0.0695	0.0704
Horizontal Divergence (mrad)	0.0169	0.0184
Vertical Divergence (mrad)	0.0126	0.0145

TABLE II

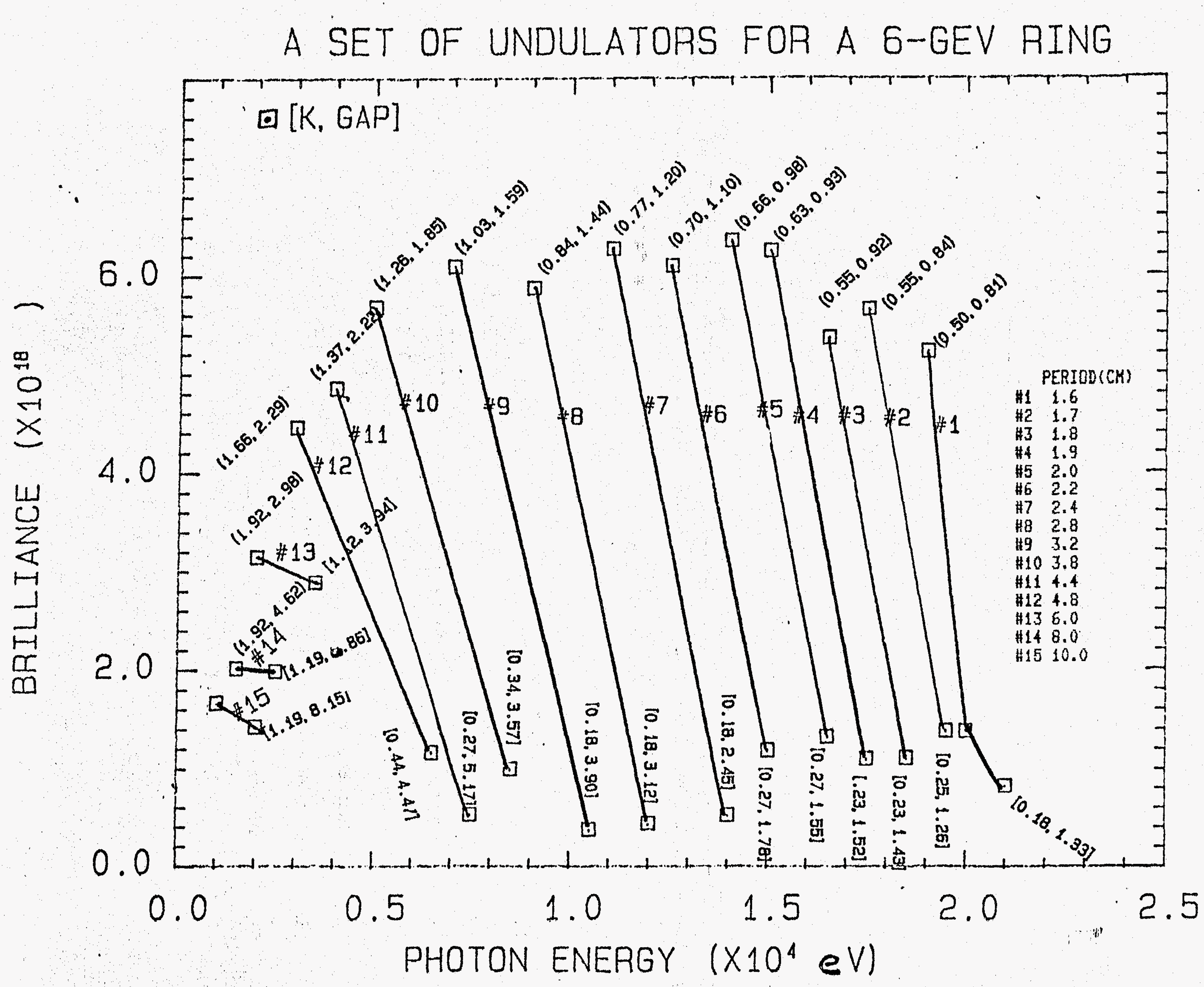
Undulator # 14

Photon Energy (eV) (1st-Harmonic)	2500.0	1500.0
Undulator Period (cm)	8.00	8.00
Undulator Gap (cm)	5.857	4.625
Peak Field (T)	0.159	0.257
K	1.190	1.922
Undulator Length (m)	5.0	5.0
Number of Periods	62	62
Total Power (watts)	288.8	753.2
Power Density (watts/sq.mm.)	5.5	9.2
Flux (PH/sec/0.1 c/o BW)	0.578E+15	0.763E+15
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.199E+19	0.202E+19
Horizontal Source size (mm)	0.4336	0.4338
Vertical Source size (mm)	0.0700	0.0712
Horizontal Divergence (mrad)	0.0177	0.0195
Vertical Divergence (mrad)	0.0137	0.0159

TABLE II

Undulator # 15

Photon Energy (eV) (1st-Harmonic)	2000.0	1000.0
Undulator Period (cm)	10.00	10.00
Undulator Gap (cm)	8.153	6.047
Peak Field (T)	0.127	0.235
K	1.190	2.198
Undulator Length (m)	5.0	5.0
Number of Periods	50	50
Total Power (watts)	184.8	630.7
Power Density (watts/sq.mm.)	3.5	6.8
Flux (PH/sec/0.1 c/o BW)	0.462E+15	0.635E+15
On Axis Brilliance (Ph/sec/0.1BW/mrad^2/mm^2)	0.143E+19	0.130E+19
Horizontal Source size (mm)	0.4336	0.4340
Vertical Source size (mm)	0.0704	0.0726
Horizontal Divergence (mrad)	0.0184	0.0215
Vertical Divergence (mrad)	0.0145	0.0183



A SET OF UNDULATORS FOR A 6-GEV RING
[K, GAP]
PERIOD(CM)
#1 1.6
#2 1.7
#3 1.8
#4 1.9
#5 2.0
#6 2.2
#7 2.4
#8 2.8
#9 3.2
#10 3.8
#11 4.4
#12 4.8
#13 6.0
#14 8.0
#15 10.0
(0.50, 0.81)
[0.18, 1.33]
(0.55, 0.84)
[0.25, 1.26]
(0.55, 0.92)
[0.23, 1.43]
(0.63, 0.93)
[.23, 1.52]
(0.66, 0.98)
[0.27, 1.55]
(0.70, 1.10)
[0.27, 1.78]
(0.77, 1.20)
[0.18, 2.45]
(0.84, 1.44)
[0.18, 3.12]
(1.03, 1.59)
[0.18, 3.90]
(1.26, 1.85)
[0.34, 3.57]
(1.37, 2.22)
[0.27, 5.17]
(1.66, 2.29)
[0.44, 4.47]
(1.92, 2.98)
(1.92, 4.62)
(1.19, 8.15)
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
#11
#12
#13
#14
#15
BRILLIANCE (X10[18])
PHOTON ENERGY (X10[4] eV)
0.0
0.5
1.0
1.5
2.0
2.5
2.0
4.0
6.0