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A New Approach to High-Current Operation of the Advanced Photon Source

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Contents

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Abstract

It is shown that the operation of the Advanced Photon Source (APS) storage ring at 6 GeV will 1) deliver higher brilliance at x-ray energies used by a majority of users due to natural reduction in electron beam emittance at lower storage ring energy, and 2) lower the total power produced by insertion devices thus permitting stored currents up to 300 mA with minimal changes in accelerator or beamline hardware. While higher brilliance x-ray beams can be realized from the APS undulators by only increasing the stored current for the present modes of operation, this however leads to serious high heat load concerns. This report includes detailed analyses of radiation brilliance, undulator tunability, power, power density, and total and coherent flux as a function of x-ray energy from various harmonics of undulator-A, for operation at 6.0, 6.5 and 7.0 GeV with 100, 140, 200 and 300 mA currents. A discussion of a smaller period (2.7 cm) undulator's spectral performance is also presented. It is shown that the APS can be immediately operated at 6 GeV with 200-300 mA current to benefit user science in the x-ray energy range below 35 keV. This may not require any hardware change either in the storage ring or the beamlines, making this switch without any interruptions to user research programs. Finally, the suggested 6 GeV operation with 300 mA should be considered a temporary step towards higher brilliance operation. A need for re-optimization of the APS technical operations, defined by storage-ring energy, current, undulator period, and power, are also addressed in this report.

1. Introduction

It is of continued interest to the user community to increase the brilliance of beams from undulator-A at the Advanced Photon Source (APS), so long as the increased brilliance does not jeopardize the performance of the beamline optics due to higher heat loads from the x-ray beam. A broad set of improvements of the APS accelerator and undulator operational parameters has been discussed [1], which would enhance the brilliance of x-ray beam from undulator-A (3.3 cm period, 77 periods). They included lowering the emittance, increasing the current, decreasing the ratio of vertical to horizontal coupling, and increasing the undulator length. Recent simulations show that the emittance may be reducible to 70 pm-rad, which is an improvement by a factor of 50 over current operations [2]. However, these reductions in the emittance would require a change in storage ring configuration leading to key modifications or complete replacement of the storage ring hardware. Alternatively, the undulator length or the stored current can be increased to realize higher brilliance. However, any scenario involving 7 GeV operation with stored currents above about 140 mA with a single undulator-A is considered beyond the heat load handling capability of accelerator hardware and beamline hardware (such as front-end components, shutters and windows) [3]. Also presently installed beamline optics would not perform well above this stored current with closed undulator gaps. Hence, any of the suggested improvements to achieve 7 GeV operation with higher stored current (e.g., 200-300 mA) would require considerable R&D over many years, major capital investment in new hardware, and a well-planned implementation that would not disrupt ongoing user scientific research.

In this report, a new approach is presented in which the total performance of the APS facility is evaluated with the storage ring operating at energies lower than 7 GeV, with the main intent to lower the emittance, along with undulator beam power and power density. The electron emittance is proportional to square of electron energy making brilliance *inversely* proportional to the fourth power of storage ring energy. The total power of radiation from an undulator at any given gap is *directly* proportional to the square of the storage ring energy, and the power density is proportional to its fourth power. All these facts bode well for the idea of lowering the storage ring energy to enhance brilliance and reduce heat loads. Indeed, lowering the electron energy would have a major influence on the spectral properties of the undulator radiation, primarily on the tunability range, the extent of overlap of the harmonic envelopes, and the higher energy spectrum.

The approach of lowering the storage ring energy is contrary to the major effort in 1987 that decided the optimal energy of the APS storage ring operation to be 7 GeV, primarily reflecting the desire from the user community to broaden the energy tunability to achieve overlap of energy harmonic envelopes [4]. This, in turn, allowed a single undulator (undulator-A with a 3.3 cm period) to support broad science and technology research. However, it should be recognized that, over the past 15 years, significant progress has been made both in radiation source design and storage ring operations. For example, improved undulator technology, small aperture insertion-device vacuum chambers, and top-off mode have increased the flexibility of APS operation. Indeed, it is time to revisit the optimization of the APS operational parameters and hardware and its capabilities to meet the needs of the current and future user communities. While this broad subject will not be addressed in this report, it is the intent here to point out that an operational scenario at lower storage ring energies will deliver brilliance increases well above those with operation at 7 GeV.

The proposed lower energy operation, perhaps for a defined duration, with no major additional costs either to the APS or to the user community, should boost APS performance immediately. This will give time for a more in-depth optimization to fix the future operational point (undulator period, energy and current) for the APS, which will be the subject of a future report. This will also lead to a strategy for R&D and upgrades in the future.

In an operational scenario included in this report, the electron energy of 6 GeV resembles that of European Synchrotron Radiation Facility (ESRF) operation. But we hasten to point out two differences: 1) The smaller bend-radius of electrons in the APS will permit one to achieve a lower horizontal emittance compared to ESRF, with a potential for higher brilliance numbers; 2) The front ends on APS beamlines are designed and operated to handle higher powers (at 7 GeV) than those at ESRF.

2. Alternative Operational Parameters

We will consider the operation of the APS at 6.0 and 6.5 GeV with no change in the length of the magnetic period or the length of undulators. For simplicity of comparison, the analysis is done with the assumption that the parameters of machine operation (such as β functions, dispersion, etc.) are unchanged on lowering the energy, and that the lowered emittance is only governed by a decrease in the stored electron energy. This may be a conservative assumption, and it is expected that smaller electron phase space dimensions may be achievable with further machine-physics R&D.

Assuming that the contribution to the x-ray beam phase space size is only governed by the electron properties, the values of the beam size and divergence are given by:

$$\sigma_{x,y} = [\,\varepsilon_{x,y}\beta_{x,y} + \eta_{x,y}^{2}\,(\Delta E/E)^{2}\,]^{1/2}$$

$$\sigma'_{x,y} = [\,\varepsilon_{x,y}/\beta_{x,y} + \eta'^{\,2}_{x,y}\,(\Delta E/E)^{2}\,]^{1/2}.$$

Here, all standard notations have been used [5]. In an ideal lattice, the insertion device straight sections will be “dispersion-free regions,” where $\eta_{x,y} = \eta'_{x,y} = 0$.

The horizontal emittance in a storage ring with a bend angle θ is proportional to $\gamma^2\theta^3$, where γ is given by $E = \gamma mc^2$, and E is the energy of stored electrons. In order to keep θ unchanged when E is changed, the bend magnet field will have to be altered. In Table 1, the values of parameters used in the analysis of the problem are given.

Table 1. Values of parameters for storage ring operation.

Parameter	APS (7.0)	APS (6.5)	APS (6.0)
Energy (GeV)	7.0	6.5	6.0
Current (mA)	100/ 140/ 200/ 300	200/ 300	200/ 300
BM Field (T)	0.599	0.556	0.513
BM ε_c (keV)	19.52	15.62	12.28
ε_x (nm.rad)	3.0	2.6	2.2
y/x Coupling (%)	1.0	1.0	1.0
ε_y (nm.rad)	0.03	0.026	0.022
β_ (m in undulator section)	14.5	14.5	14.5
β_y (m in undulator section)	3.8	3.8	3.8
η_x (m)/ η_y (m)	0.124/0.001	0.124/0.001	0.124/0.001
η'_x (rad)/ η'_y (rad)	0.00/0.00	0.00/0.00	0.00/0.00
$\Delta E/E$ (10^{-3})	0.95	0.95	0.95
σ_x (μ)	239.5	227.1	213.9
σ_x'(μrad)	14.4	13.4	12.3
σ_y (μ)	10.9	10.0	9.2
σ_y'(μrad)	2.8	2.6	2.4

Next we present parameters of undulator-A used in this analysis. The deflection parameter K_y is given in terms of undulator period λ_u(cm) and the effective peak magnetic field, B_{eff}(T) by $K_y = 0.934\ \lambda_u\ B_{eff}$. In Table 2, the values of gap, B_{eff} , K_y, and approximate first-harmonic x-ray energies are given. The numbers given are typical for an undulator-A (3.3 cm period) currently installed in the straight sections of the APS.

Table 2. Approximate values of first-harmonic x-ray energies (in keV) from a 3.3-cm-period undulator-A as a function of undulator gap at various storage-ring energies.

Parameter			APS (7.0 GeV)	APS (6.5 GeV)	APS (6.0 GeV)
Gap (mm)	B_{eff}(T)	K_y			
8.0	1.14	3.51	2.00	1.75	1.45
9.0	1.03	3.17	2.35	2.05	1.73
10.5	0.88	2.71	3.00	2.60	2.25
11.5	0.79	2.44	3.51	3.05	2.65
13.5	0.65	1.99	4.75	4.05	3.50
15.5	0.53	1.63	6.00	5.25	4.45
18.5	0.39	1.21	8.00	7.00	6.00
24.5	0.22	0.68	11.30	9.80	8.30
30.0	0.13	0.40	13.00	11.20	9.50
35.0	0.09	0.27	13.50	11.65	9.85
Open	0	0	14.11	12.16	10.36

3. Undulator Tunability, Brilliance, Power, and Power Densities

The values of beam brilliance, power, and power density at different x-ray energies delivered by undulator-A are obtained using XOP 2.0 [6] for various operational parameter sets shown in Table 1. The results, given in Tables 3-5 and Figs. 1–8, are discussed below.

It is clear from Table 3 that higher brilliance can be realized up to 30 keV from the present APS if the operational energies are decreased and higher currents are stored. The increase in brilliance in the lower x-ray energy range is more than just the factor of three expected from the increased current to 300 mA. The lower phase space volume of the beam at lower storage ring energies adds to the increase. For example, the brilliance realized between 5 and 10 keV from 6 GeV operation at 300 mA results in a gain in brilliance by a factor of 3 to 4. On the other hand, if one is limited to only the fifth harmonic in this operational scenario, a lower brilliance will result in a high x–ray energy range, above about 30 keV. The advantage of operating the APS at lower storage ring energies is to decrease the power and power densities compared to similar operation at 7 GeV, as can be seen from Tables 4 and 5. The lower energy operation at [6 GeV, 300 mA] would not require major changes to the present APS hardware or beamline optics.

Table 3. Values of brilliance (in units of 10^{20} ph/s/0.1%BW/mrad^2/mm^2) of x-ray beams produced by a 3.3-cm-period undulator with 70 periods at various x-ray energies for various operational scenarios.

X-ray Energy (keV)	Harmonic	7 GeV				6.5 GeV		6.0 GeV	
		100 mA	140 mA	200 mA	300 mA	200 mA	300 mA	200 mA	300 mA
2.0	1	0.20	0.28	0.40	0.60	0.46	0.69	0.53	0.80
4.0	1	0.33	0.46	0.66	0.99	0.77	1.14	0.90	1.34
6.0	1	0.39	0.55	0.78	1.17	0.89	1.33	0.96	1.45
8.0	1	0.39	0.55	0.78	1.17	0.81	1.20	0.71	1.06
10.0	1	0.33	0.47	0.66	0.99	0.60[a]	0.91[a]	0.69[a]	1.04[a]
12.0	3	0.27	0.38	0.55	0.82	0.60	0.91	0.65	0.98
14.0	3	0.26	0.37	0.53	0.79	0.56	0.85	0.57	0.84
15.0	3	0.25	0.36	0.52	0.77	0.54	0.81	0.51	0.78
20.0	3	0.20	0.28	0.40	0.61	0.35	0.53	0.25	0.40
30.0	5	0.10	0.14	0.20	0.30	0.17	0.25	0.09	0.13
40.0	5	0.04	0.06	0.08	0.11	0.04	0.06	0.01	0.01
50.0	5	0.007	0.010	0.014	0.020	0.002	0.003	-	-

a Using the 3rd harmonic.

Table 4. Values of total power (in kW) from x-ray beams produced by a 3.3-cm-period undulator with 70 periods at various x-ray energies or undulator gaps for various operational scenarios.

X-ray Energy (keV)	Harmonic	7 GeV				6.5 GeV		6.0 GeV	
		100 mA	140 mA	200 mA	300 mA	200 mA	300 mA	200 mA	300 mA
2.0	1	8.80	13.0	17.7	26.5	13.5	20.0	9.2	13.8
4.0	1	3.77	5.30	7.54	11.30	5.34	8.00	3.40	5.20
6.0	1	1.33	2.80	4.00	6.00	2.67	4.00	1.53	2.30
8.0	1	1.15	1.55	2.30	3.45	1.37	2.05	0.63	0.95
10.0	1	0.57	0.80	1.14	1.71	6.60[a]	9.90[a]	4.60[a]	6.90[a]
12.0	3	3.77	5.30	7.54	11.30	5.27	7.90	3.47	5.20
14.0	3	3.0	4.20	6.00	9.00	4.00	6.00	2.60	3.90
15.0	3	2.73	3.90	5.47	8.20	3.67	5.50	2.33	3.50
20.0	3	1.60	2.20	3.20	4.80	2.07	3.10	1.20	1.80
30.0	5	2.00	2.80	4.00	6.00	2.67	4.00	1.53	2.30
40.0	5	1.17	1.60	2.33	3.50	1.34	2.00	0.53	0.80
50.0	5	0.57	0.80	1.14	1.71	0.55	0.82	0.10	0.15

a Using the 3rd harmonic.

Table 5. Values of peak power density (in kW/mrad^2) from x-ray beams produced by a 3.3-cm-period undulator with 70 periods at various x-ray energies or undulator gaps for various operational scenarios.

X-ray Energy (keV)	Harmonic	7 GeV				6.5 GeV		6.0 GeV	
		100 mA	140 mA	200 mA	300 mA	200 mA	300 mA	200 mA	300 mA
2.0	1	201	285	400	600	280	410	180	270
4.0	1	130	182	260	390	170	255	109	163
6.0	1	93	130	186	280	120	180	73	110
8.0	1	69	97	138	208	83	125	43	65
10.0	1	48	67	96	145	200[a]	300[a]	127[a]	190[a]
12.0	3	128	179	256	385	173	260	110	165
14.0	3	115	161	330	345	150	225	96	144
15.0	3	110	154	220	330	143	214	89	133
20.0	3	84	118	168	250	108	162	63	95
30.0	5	90	126	180	270	120	180	69	103
40.0	5	70	98	140	210	83	125	45	67
50.0	5	48	67	96	145	50	75	10	15

a Using the 3rd harmonic.

4. Comparison of Radiation Characteristics Resulting from Operation with 7 GeV (100 mA), 7 GeV (140 mA), and 6 GeV (300 mA)

The comparison is performed to obtain a quantitative appreciation for the suggested operational mode of [6 GeV, 300 mA] over the present operational mode [7 GeV, 100 mA]. Also a comparison is made with [7GeV, 140 mA] operation, since it has been demonstrated that all the hardware on the accelerator, beamline front ends, and beamline optics can generally handle powers from undulator-A at 7 GeV and 140 mA. In Fig. 1, the beam brilliance at various x-ray energies is shown for 7 GeV operation with 100 mA and 140 mA and for 6 GeV operation at 300 mA. Clearly by proper choice of harmonics, one realizes more than three times higher brilliance with [6 GeV, 300 mA] operation in the lower x-ray energy range than would be expected from the increase in stored current. The additional increase is from the reduced phase space volume of the beam when the operational energy is reduced to 6 GeV. We define the brilliance enhancement factor as the ratio of brilliance at any given x-ray energy delivered by undulator-A for two operations of the APS determined by the values of storage ring energy and stored current. In Fig. 2, the brilliance enhancement factor is plotted for two sets of operations: [6 GeV, 300 mA]/[7 GeV, 100 mA] and [6 GeV, 300 mA/7 GeV, 140 mA].

It is equally important to compare such ratios for total power and power density at the x-ray energies for various harmonics resulting at various undulator gaps. These comparisons are shown in Figs. 3 and 4.

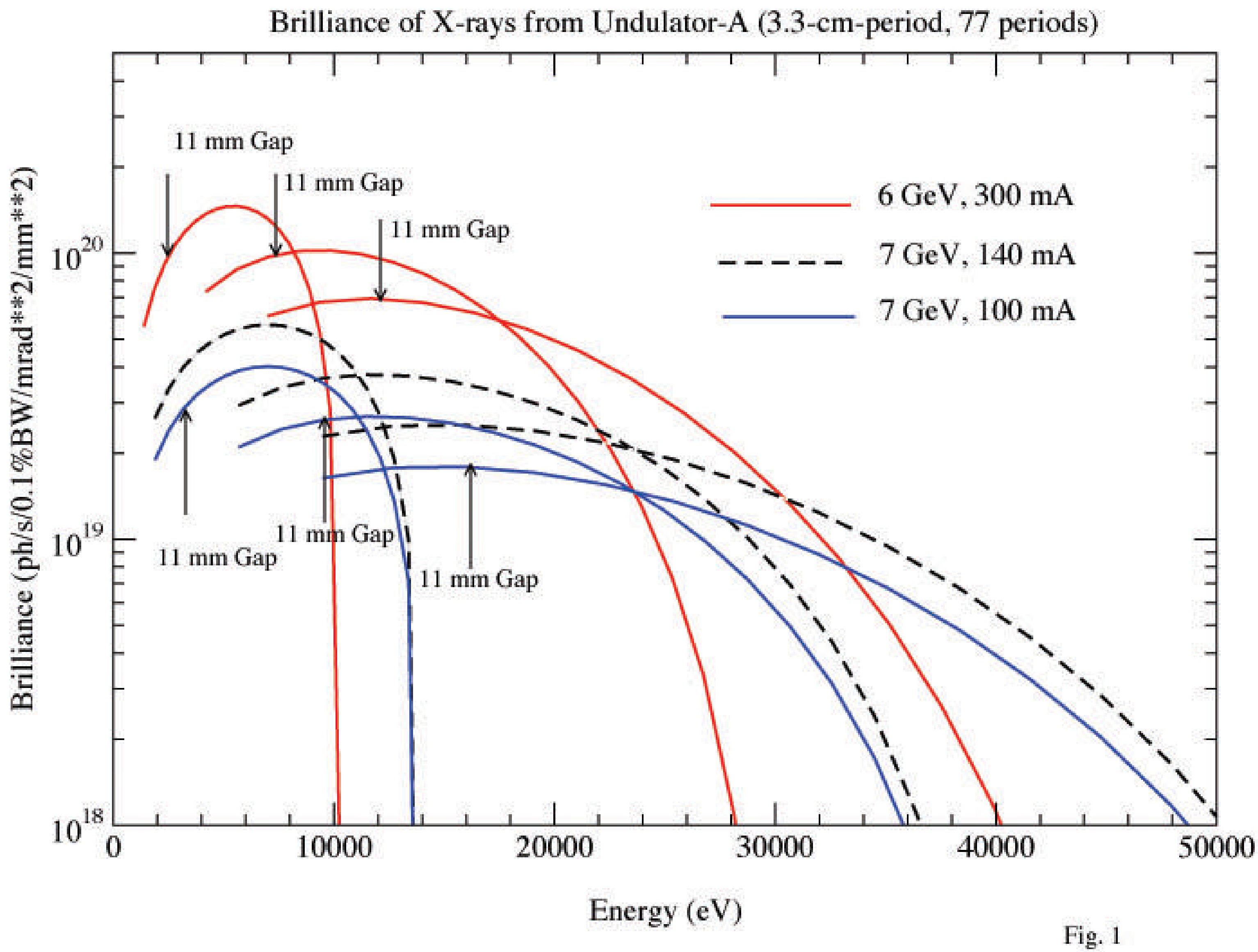

Fig. 1. Tunability envelopes for undulator-A with 3.3-cm-period (77 periods) operated at various storage ring energies and currents shown in the legend. The assumed values of the electron beam properties are given in Table 1.

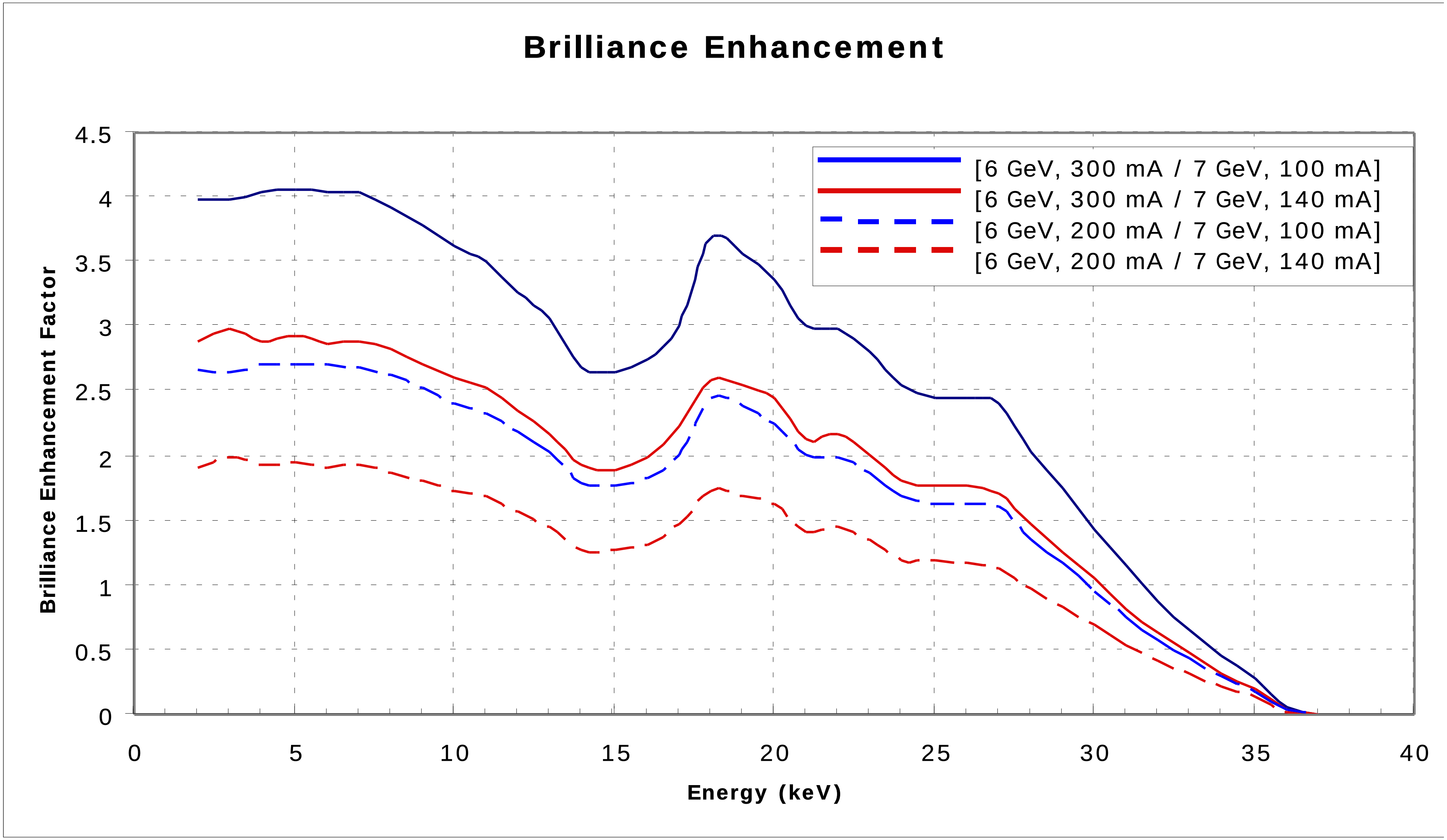

Fig. 2. Brilliance enhancement factor for undulator-A radiation for various storage ring energies and currents, shown in the legend, as a function of x-ray energy. The x-ray range is covered by using 1st, 3rd and 5th harmonic.

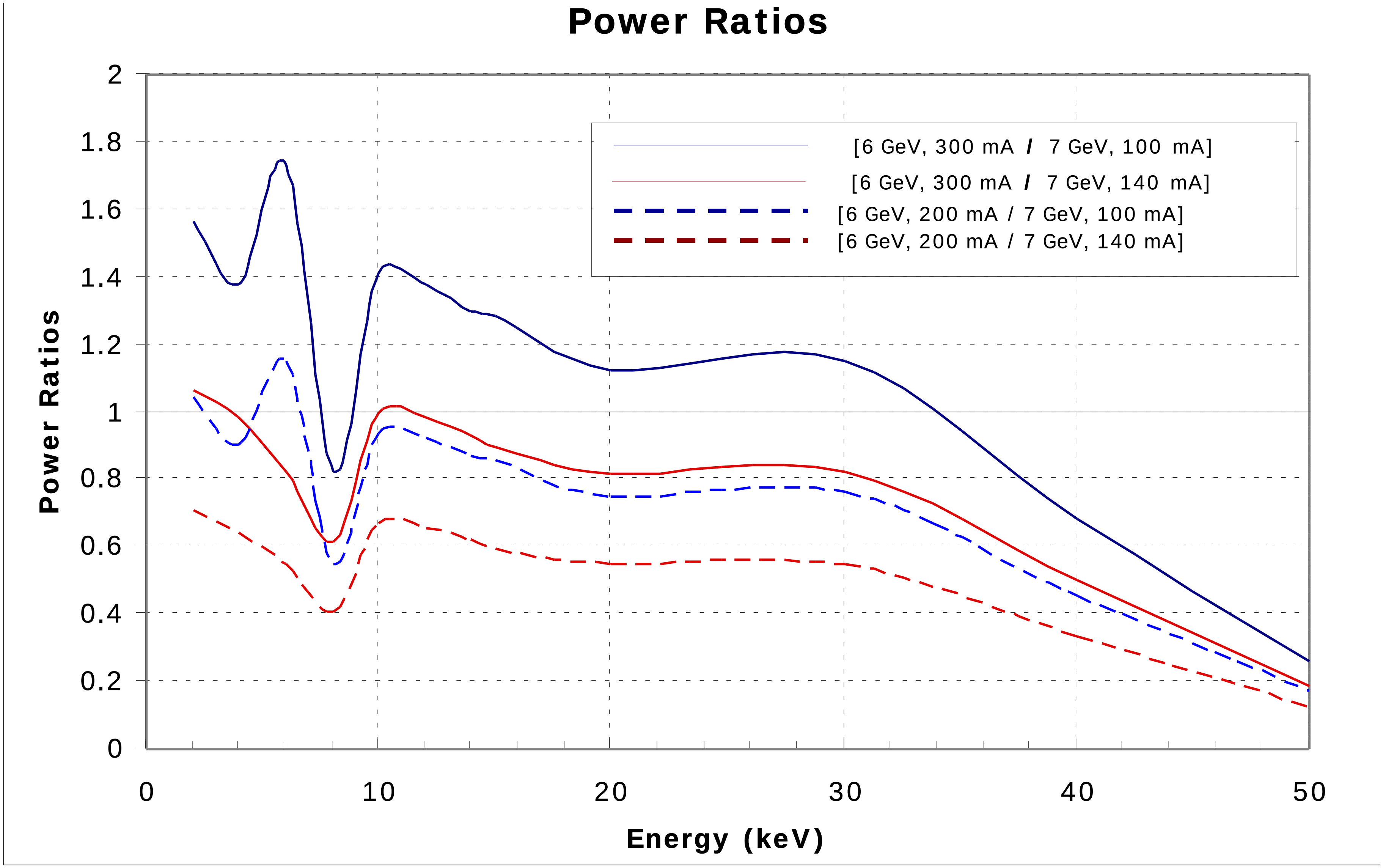

Fig. 3. Ratios of total power delivered by the undulator-A (3.3 cm period, 77 periods) at various gaps as a function of x-ray harmonic energies. The ratio-plots represent operation parameters shown in the legend.

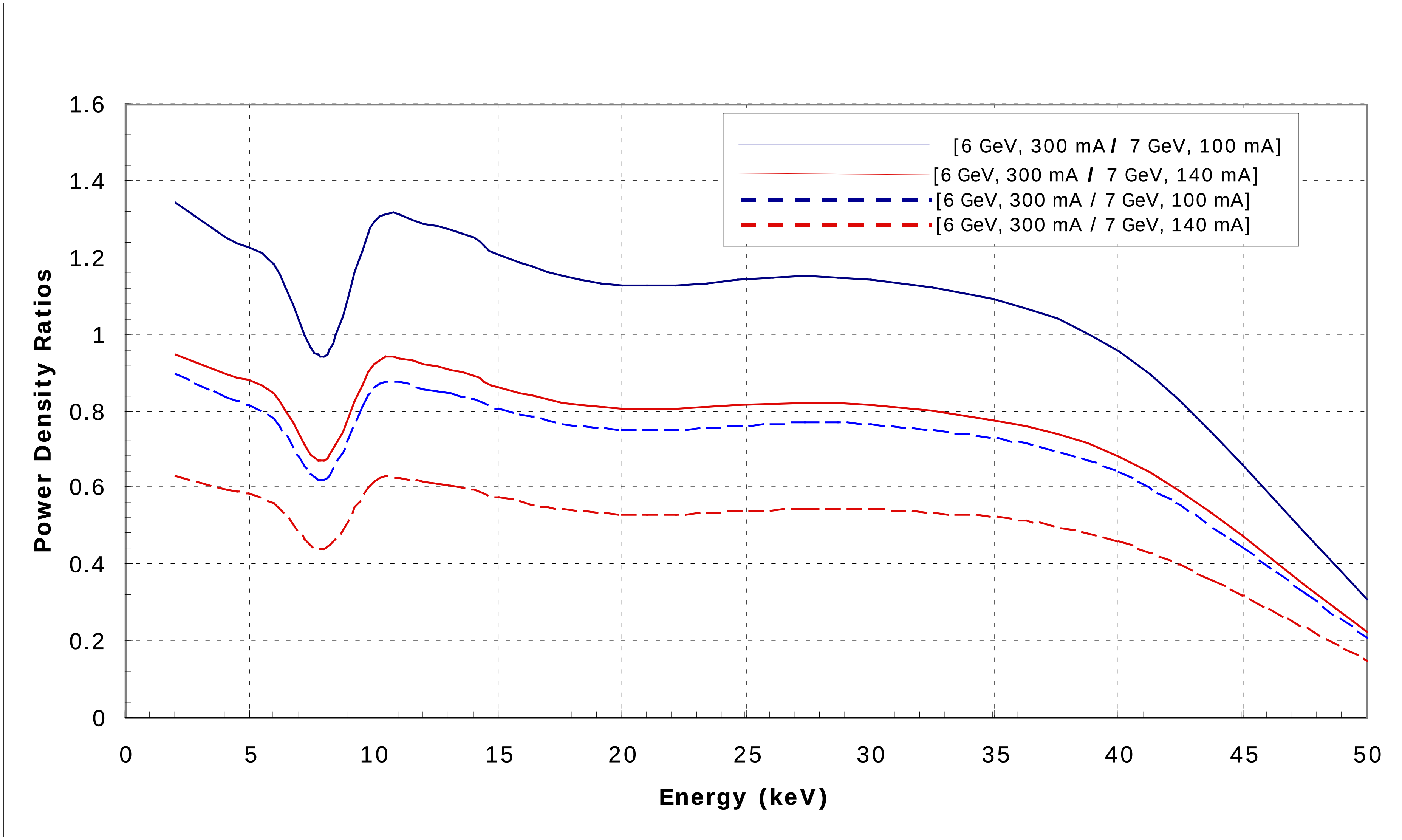

Fig. 4. Ratios of power densities delivered by the undulator-A (3.3 cm period, 77 periods) at various gaps as a function of x-ray harmonic energies. The ratio-plots represent operation parameters shown in the legend.

The following observations are made:

1. The brilliance enhancement ratios are uniformly higher for [6 GeV, 300 mA] operation over the present [7 GeV, 100 mA] operation or for possible [7 GeV, 140 mA] operation.

2. In the 3 to 8 keV range, the highest brilliance gains—by a factor of 4—are made over the current [7 GeV, 100 mA] operation and by a factor of close to 3 over [7 GeV, 140 mA] operation (see Fig. 2).

3. The brilliance enhancement factor reduces below 1 for x-ray energies above 30 keV.

4. In Fig. 1, the harmonic energies for 11 mm gap are shown for both 6 and 7 GeV operation. The overlap of tunability curves between odd energy harmonics from undulator-A is not compromised at 6 GeV. This assures that the present undulator vacuum chamber is adequate for 6 GeV operation.

5. The lowest energy reachable with a 10.5 mm gap will permit access to the sulfur K-edges at 6 GeV operation with undulator-A.

6. The power and power density ratios (Figs. 3 and 4) over the entire x-ray energy range are higher for [6 GeV, 300 mA] operation compared to [7 GeV, 100 mA] operation, as expected. On the other hand, the same ratios are below nearly 1 for [6 GeV, 300 mA] operation in comparison to [7 GeV, 140 mA] operation. This gives full confidence that all the hardware and optics can handle the thermal loads in the [6 GeV, 300 mA] operation.

7. The operation at [6 GeV, 200 mA] generates less power and power density than that at [7 GeV, 100 mA] (see Figs. 3 and 4) while enhancing the brilliance (see Fig. 2).This operational scenario may be ideal to begin early testing of ideas presented in this report.

5. Comparison of Radiation Characteristics Resulting from Operation with 7 GeV (100 mA), 7 GeV (140 mA), and 6.5 GeV (200 and 300 mA)

In Figs. 5-8, the performance of undulator-A when the APS storage ring is operated at 6.5 GeV with 200 mA and with 300 mA of stored current is shown. The results are compared with operation of the APS at [7 GeV, 100 mA] and [7 GeV, 140 mA]. An inspection of Figs. 5-8 identifies that operation with [6.5 GeV, 200 mA] will require no modification of the existing hardware in the accelerator, front ends, or beamlines, including the optics, if the existing undulators-A are used.

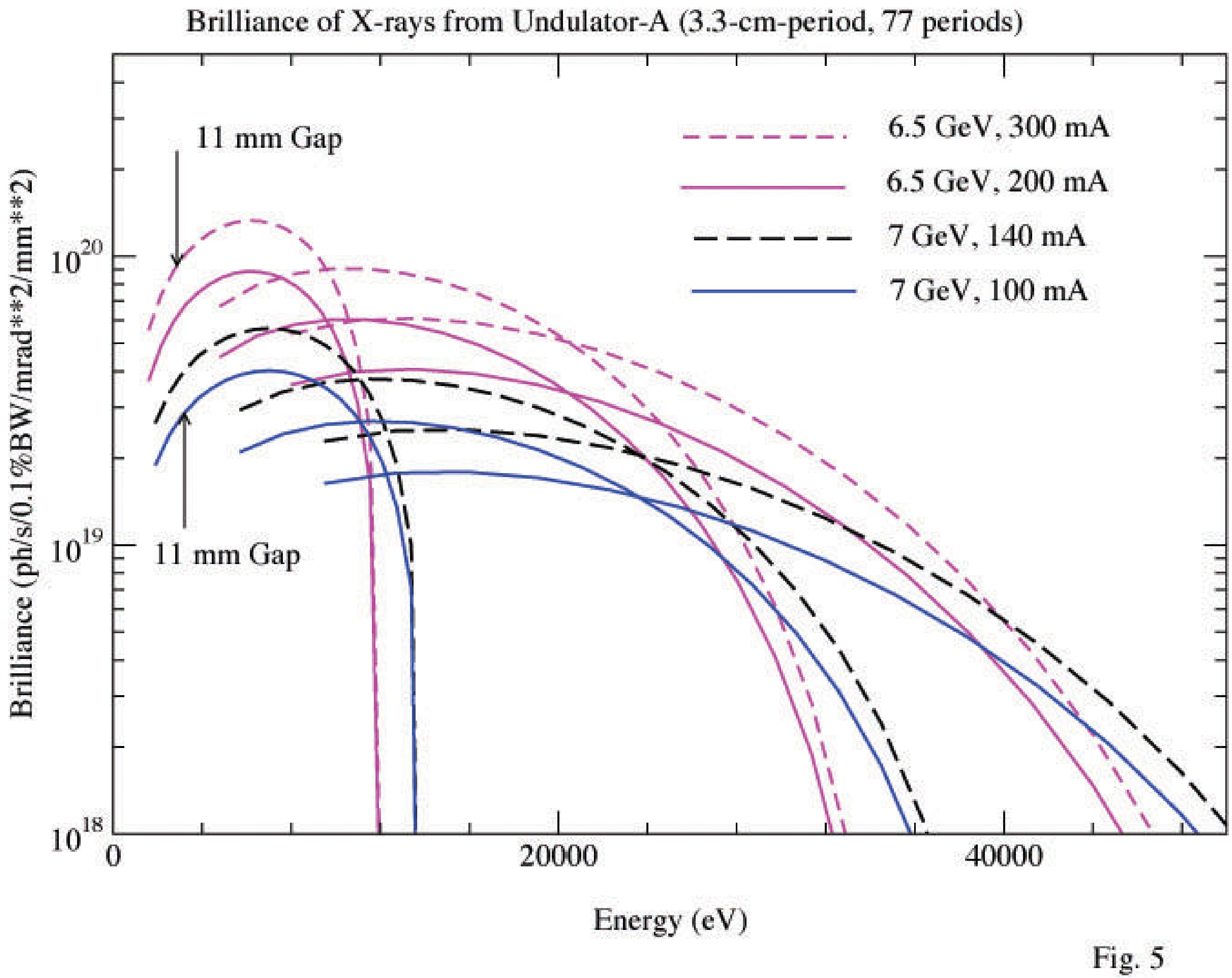

Fig. 5. Tunability envelopes for undulator-A with 3.3-cm-period (77 periods) operated at various storage ring energies and currents shown in the legend. The assumed values of the electron beam properties are given in Table 1.

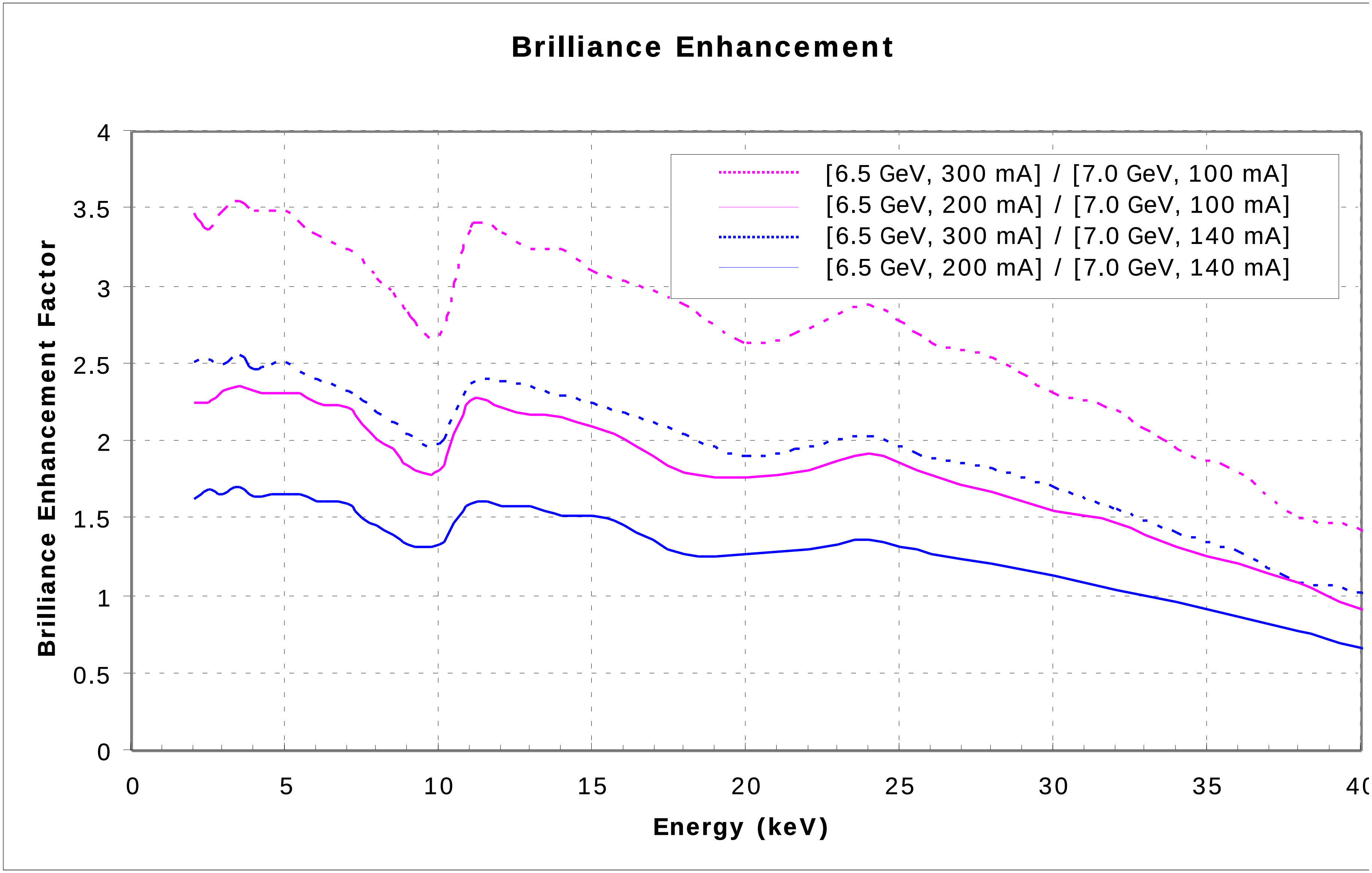

Fig. 6. Brilliance enhancement factor for undulator-A radiation for various storage ring energies and currents, shown in the legend, as a function of x-ray energy. The x-ray range is covered by using 1st, 3rd and 5th harmonic.

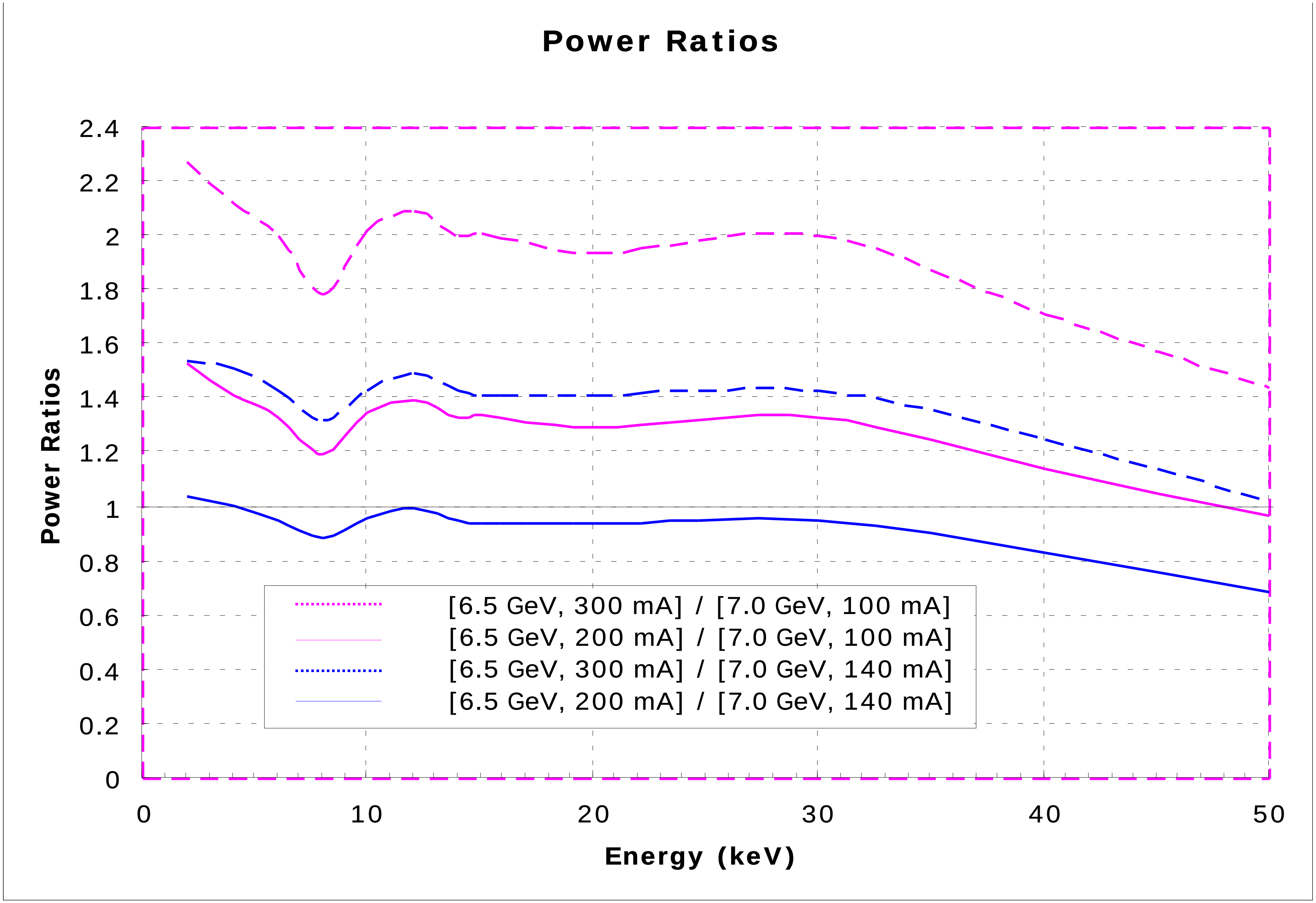

Fig. 7. Ratios of total power delivered by the undulator-A (3.3 cm period, 77 periods) at various gaps as a function of x-ray harmonic energies. The ratio-plots represent operation parameters shown in the legend.

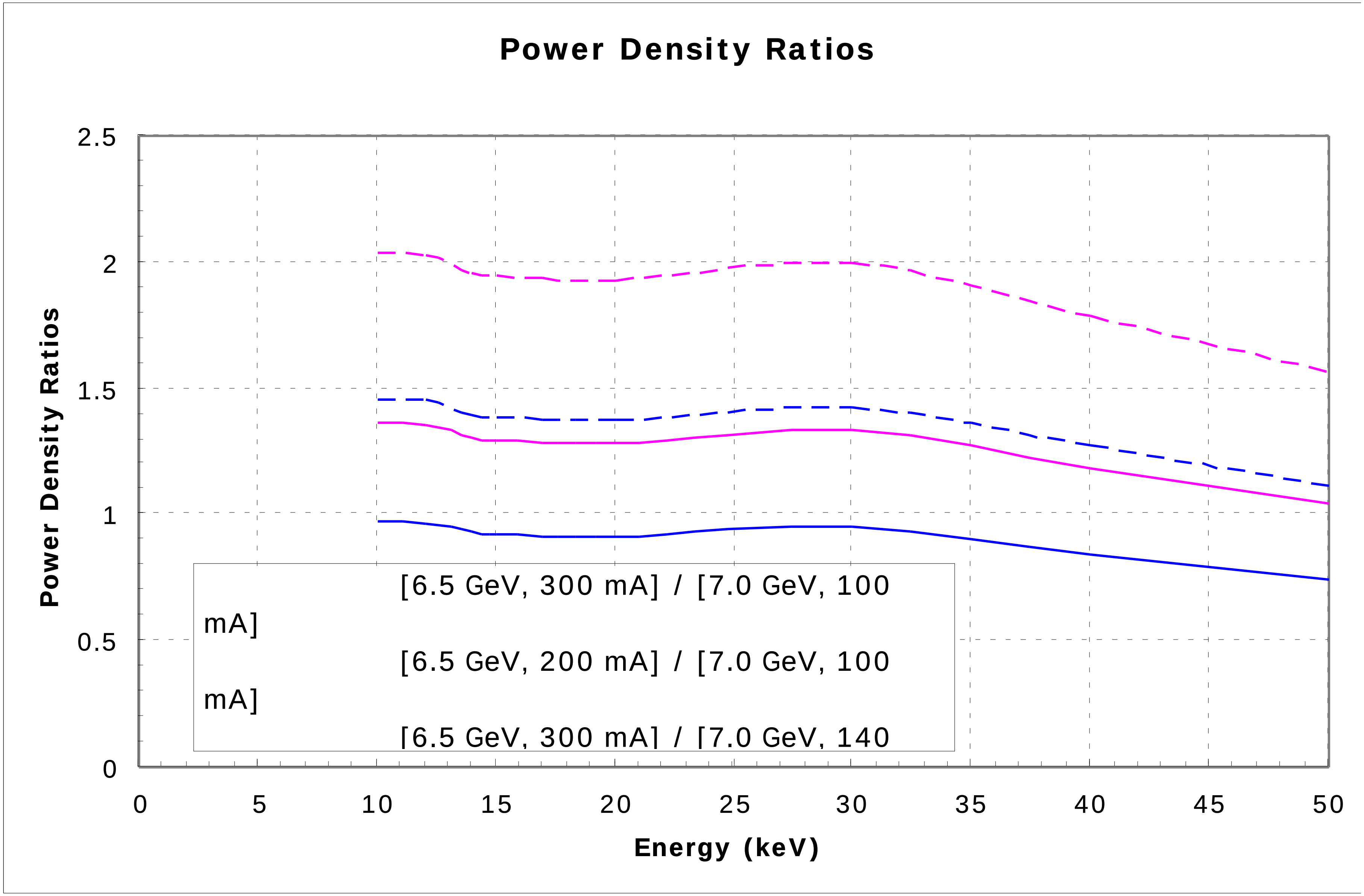

Fig. 8. Ratios of power densities delivered by the undulator-A (3.3 cm period, 77 periods) at various gaps as a function of x-ray harmonic energies. The ratio-plots represent operation parameters shown in the legend.

The following observations are made:

1. The brilliance enhancement ratios are uniformly higher for [6.5 GeV, 200 mA] operation over the present [7 GeV, 100 mA] operation or for possible [7 GeV, 140 mA] operation.

2. The brilliance enhancement factors, [6.5 GeV, 200 mA]/[7 GeV/100 mA], are about 2 in much of the energy range (see Fig. 6).

3. The brilliance enhancement factor reduces below 1 for x-ray energies above 40 keV.

4. The brilliance enhancement factors for [6.5 GeV, 200 mA] operation are inferior to those obtained with the [6.0 GeV, 300 mA] operation. However, not surprisingly, the enhancement will be over a slightly broader spectral range with [6.5 GeV, 200 mA] operation.

5. The power and power density ratios over the entire x-ray energy range are well below 1 for [6.5 GeV, 200 mA] operation in comparison to [7 GeV, 140 mA] operation. This gives full confidence that all the hardware and optics will behave well with [6.5 GeV, 200 mA] operation. Higher current operation at 6.5 GeV is not advisable without further investigations of the engineering performance of all the hardware at 200 mA.

6. Highest Brilliance from [6 GeV, 300 mA] Operation with Undulator-A

There is little doubt that the existing hardware will have to be modified in a major way from accelerator to beamline optics in order to handle the radiation from undulator-A operating with following parameters: [7 GeV, 200 mA], [7 GeV, 300 mA] or [6.5 GeV, 300 mA]. However, it is worthwhile to compare the brilliance from these operational configurations. As can be seen from Fig. 9, the [6 GeV, 300 mA] wins over other operational scenarios at low energies and remains attractive below 30 keV. The brilliance in the first order (and if dispersion is zero) is inversely proportional to the fourth power of storage ring energy, and this is partly reflected in Fig. 9.

7. **Performance of Shorter and Longer Period Undulators at 6 GeV and 300 mA**

The undulator in sector 3 of the APS has a period of 2.7 cm. A brief discussion of the performance of this device is presented here. In Fig. 10, the brilliance envelopes for various harmonics are compared for two APS operations with this device: [7 GeV, 100 mA] and [6 GeV, 300 mA]. The tunability curves are nearly optimal for this device operating at 6 GeV. The power and power density numbers increase at smallest gaps. The values at gaps requiring to reach 5 keV in the first harmonic or 15 keV in the third harmonic with [6 GeV, 300 mA] operation are nearly twice compared to those from [7 GeV, 100 mA] operation and are twice those for [7 GeV, 140 mA] operation with 3.3 cm

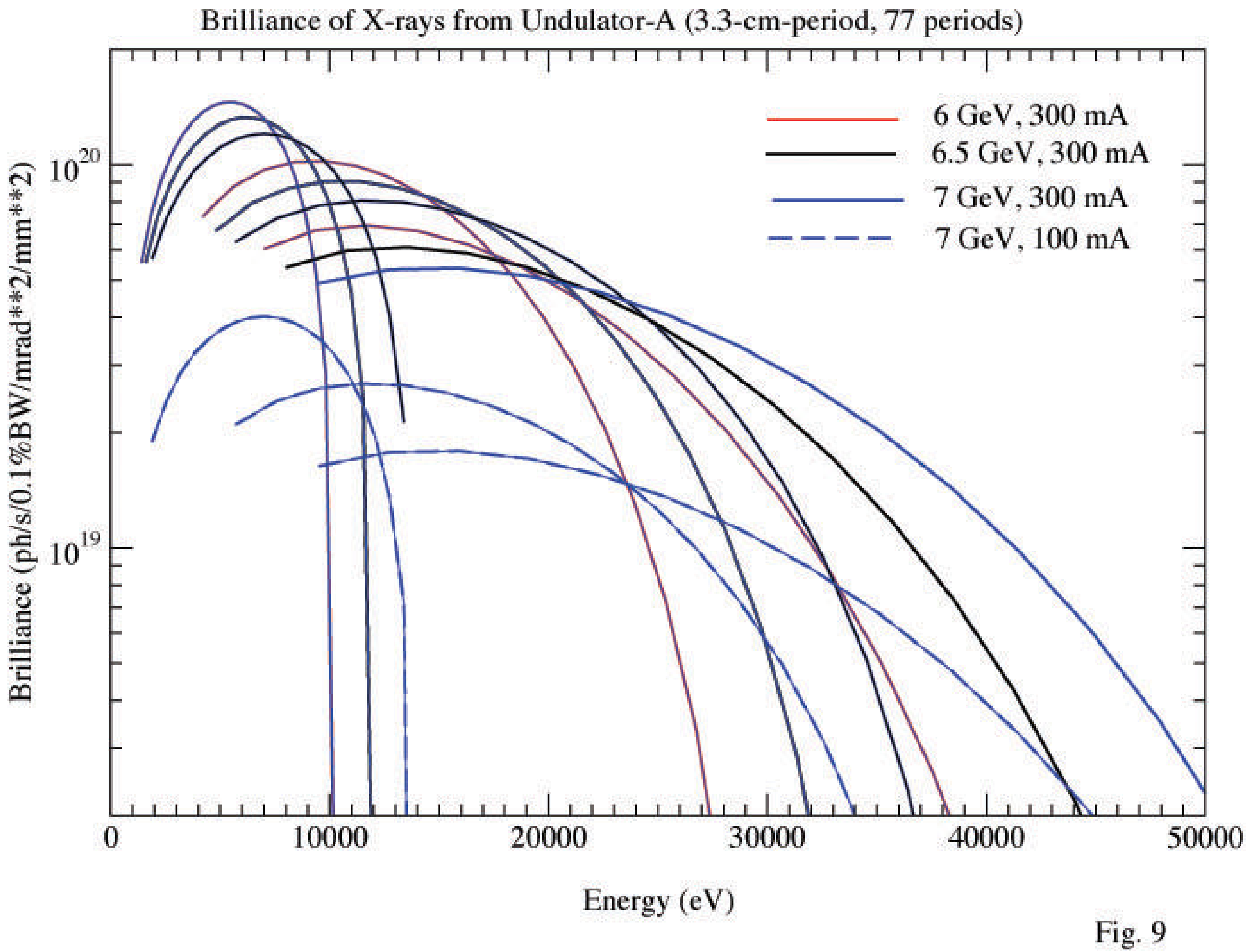

Fig. 9. Comparison of tunability envelopes for undulator-A with 3.3-cm-period (77 periods) operated at various storage ring energies and 300 mA current as shown in the legend. The assumed values of the electron beam properties are given in Table 1.

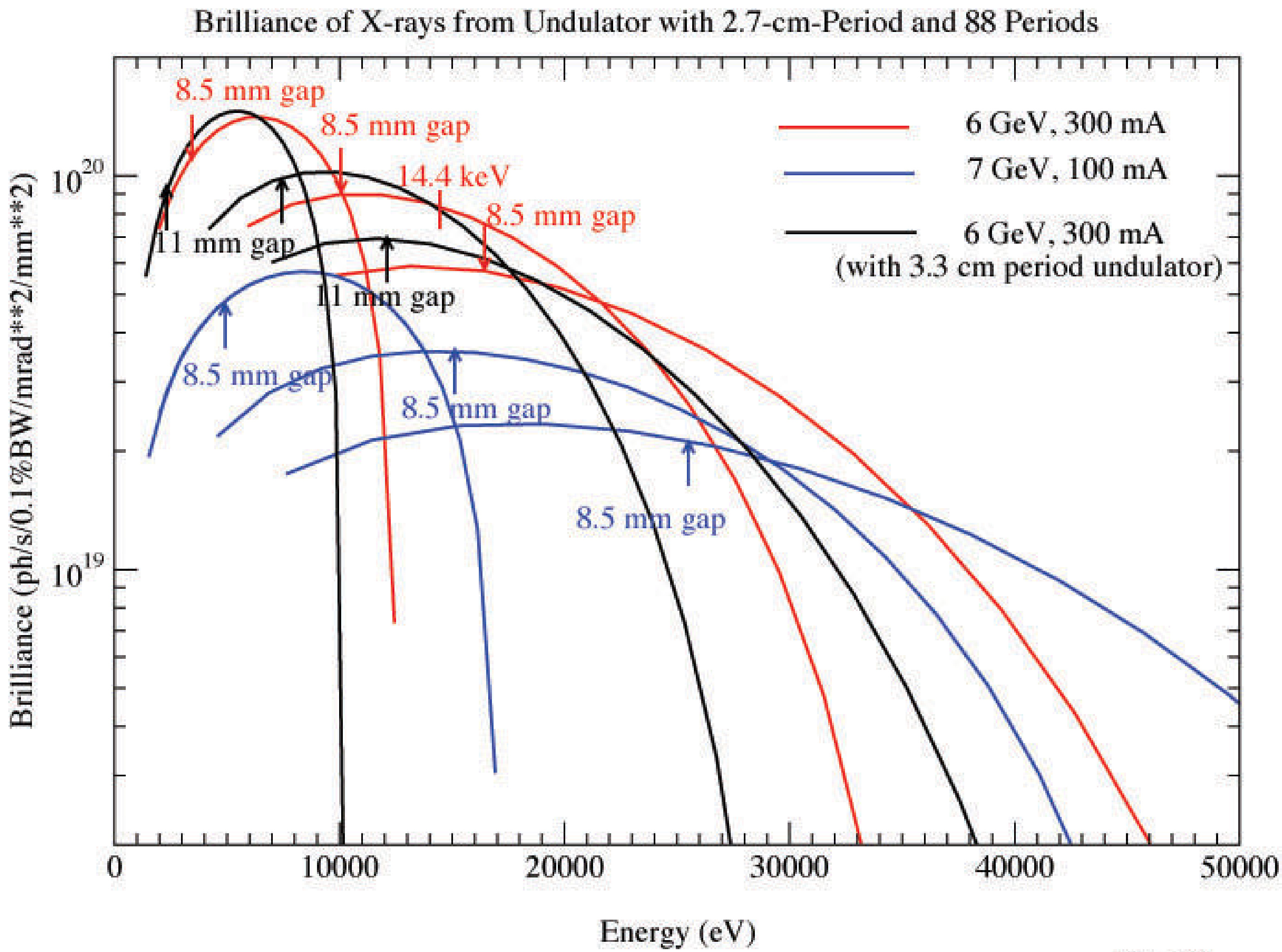

Fig. 10

Fig. 10. Comparison of tunability envelopes for undulator with 2.7-cm-period (88 periods) with those of undulator-A with 3.3-cm-period (77 periods) operated at various storage ring energies and 300 mA current as shown in the legend. The assumed values of the electron beam properties are given in Table 1.

Table 6. Total power delivered by undulators for various gap settings under various operational scenarios. The harmonic used to reach the energy is shown in the parenthesis.

Approximate X-ray Energy (keV)	Total Power (kW)		
	[6 GeV, 300 mA] 2.7-cm-period undulator	[7 GeV, 100 mA] 2.7-cm-period undulator	7 GeV, 140 mA] 3.3-cm-period undulator
5.0	7.8 (1)	2.2 (1)	4.0 (1)
10.0	1.3 (1)	1.2 (1)	0.7 (1)
14.0	8.1 (3)	2.3 (3)	4.0 (3)
20.0	4.4 (3)	1.7 (3)	2.3 (3)

period undulator (see Table 6). In order to take full advantage for this situation at small gaps, some power mitigation would be necessary.

On the other hand, a 3.3-cm-period undulator and a 2.7-cm-period undulator both operating at 6 GeV and 300 mA current have similar brilliance performance up to about 14 keV (see Fig. 10). At the same time, the 3.3-cm-period device delivers less power than the 2.7-cm-period device over the same energy range. It is suggested that a 3.3-cm-period undulator operating at [6 GeV, 300 mA] will out perform two 2.7-cm-period undulators operating at [7 GeV, 100 mA] both in brilliance and over a spectral range up to 20 keV—and without any heat load penalty. A second device with a shorter period (≈ 2.0-2.4 cm) would serve well to deliver higher brilliance above 20 keV. Such devices will use the smaller gap capabilities possible at the APS. The combination of two undulators would be a good choice to enhance much of the needs of sector 3 science.

The longer period undulator in sector 2 with a 5.5 cm period and the CPU in sector 4 are designed and presently operated with the intent of performing research using x-rays with energy of 500 eV and above. The spectral range for these devices when operated at 6 GeV will extend to lower energies. For example, both these devices will deliver about 350 eV x-rays to capture the absorption edges of nitrogen and oxygen. This will be a bonus to increased brilliance at [6 GeV, 300 mA] operation.

8. Total Flux through a Pin Hole and Coherent Flux

While brilliance is important for most experiments, many experiments require high total flux. In this section we discuss the impact on the flux of operating the APS in the [6 GeV, 300 mA] configuration. In Fig. 11, the flux through a pinhole of size d_x = 2.5 mm and d_y = 1.0 mm placed at 30 m from the source point is shown for this operation. The flux numbers are compared with those resulting from the current operation [7 GeV, 100 mA]. The curve shows an overlap of first three odd harmonics to cover the energy range shown. Note that, while the gain is made over the energy range up to 40 keV, it does not reflect the increase in the stored current by a factor of 3 at all the x-ray energies. The highest gain of 3 is realized at the lowest energies and gradually falls to 1.9 at 20 keV.

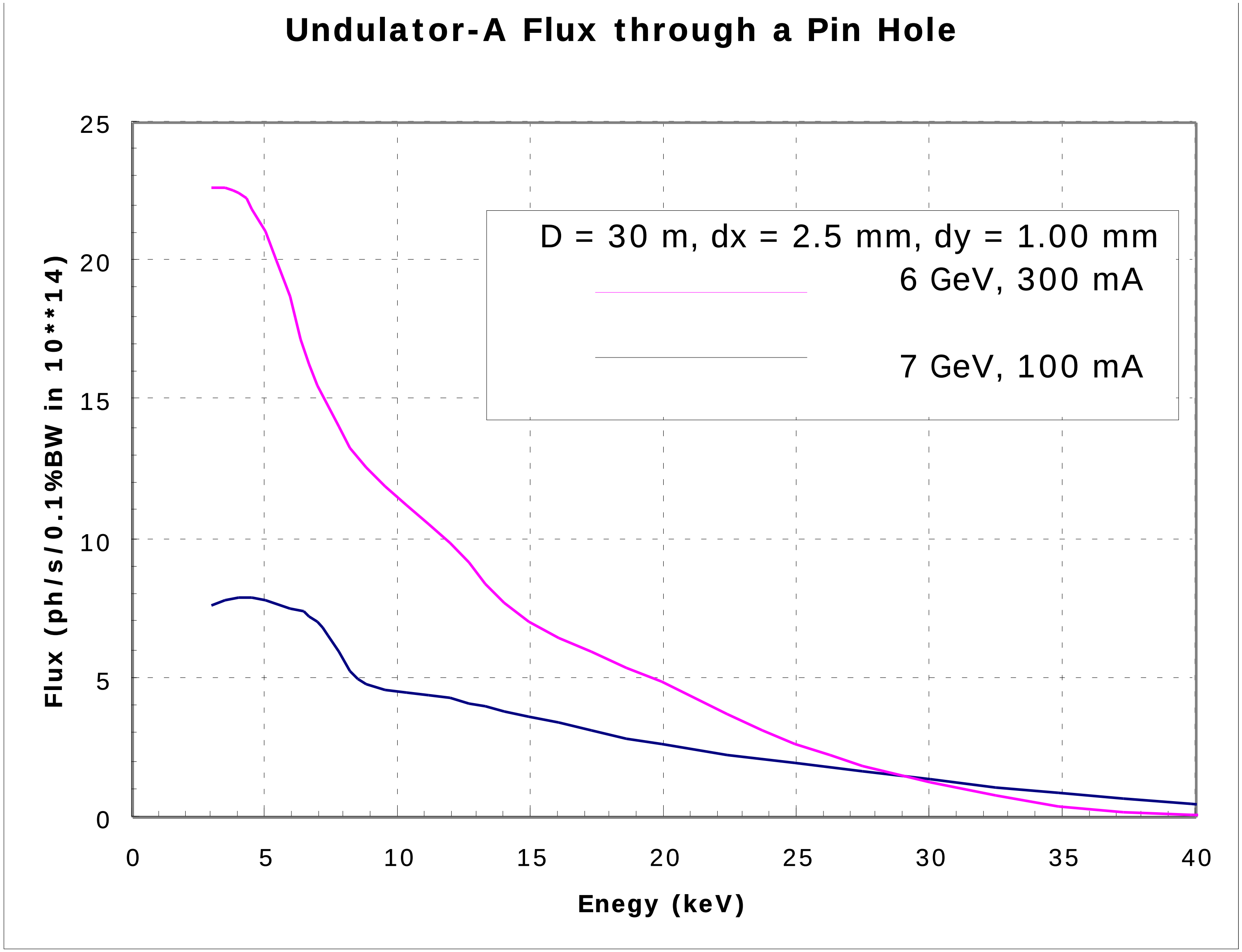

Fig. 11. Comparison of flux through a from undulator-A with 3.3-cm-period (77 periods) operated at various storage ring energies and currents as shown in the legend. The assumed values of the electron beam properties are given in Table 1.

There is no gain made beyond 27 keV. None of these results are surprising since the period of undulator-A is not optimized for 6 GeV operation.

Many experiments at the APS also depend on the coherent flux. The coherent flux F_c is given by:

$$F_c\ (\text{ph/s/0.1\%BW}) = 10^{-8}\ \{\lambda(\text{Å})/2\}^2\ B,$$

where B is the brilliance in usual units. In Fig. 12, the values of F_c for [6 GeV, 300 mA] operation are compared with those from [7 GeV, 100 mA] operation. The F_c from the [6 GeV, 300 mA] operation is uniformly higher by a factor of 4 to 2.5 between 4 and 25 keV. This will help in many coherence-based experiments.

9. Bending Magnet Source

The bending magnet performance with [6 GeV, 300 mA] operation will be enhanced in the lower energy part of the spectrum in comparison to [7 GeV, 100 mA] operation, with the corresponding critical energies being 12.3 keV and 19.5 keV, respectively. User research involving radiation below 40 keV will greatly benefit. In Fig. 13, the bending magnet flux is plotted as a function of photon energy.

10. Pros and Cons

Most of the above sections have emphasized the pros that favor the lowering of the storage ring operational energy, perhaps to 6 GeV, and suggested a trial operation with 200 mA, the final goal being 300 mA current. It would also be important to address the cons, some of which are not dependent on the operational energy of the storage ring.

1. No gains will be made in either brilliance or flux above about 30-35 keV with [6 GeV, 300 mA] operation compared to [7 GeV, 100/140 mA] operation using undulator-A, if one is limited to the fifth harmonic. The users requiring x-rays with higher energies will be required to use higher harmonics. Alternatively, devices with smaller periods can be tailored to meet the needs of high-energy x-ray experiments, as discussed in Section 7. The lower energy operation will also affect the elliptical multipole wiggler and bending magnet source users performing high-energy x-ray experiments.

2. It is assumed that undulators deliver higher harmonics without any loss in brilliance from phase errors. In practice the third harmonic delivers about 80% of the intensity. It should be recognized that, at 6 GeV operation, the user might use the third and fifth harmonics more often than before, and it is prudent to recognize the reduction factor while inspecting the brilliance curves, although net gains made will be larger than these losses.

3. Any increase in stored current, independent of operational energy, will require increase in the number of filled bunches, the current limit of current/bunch

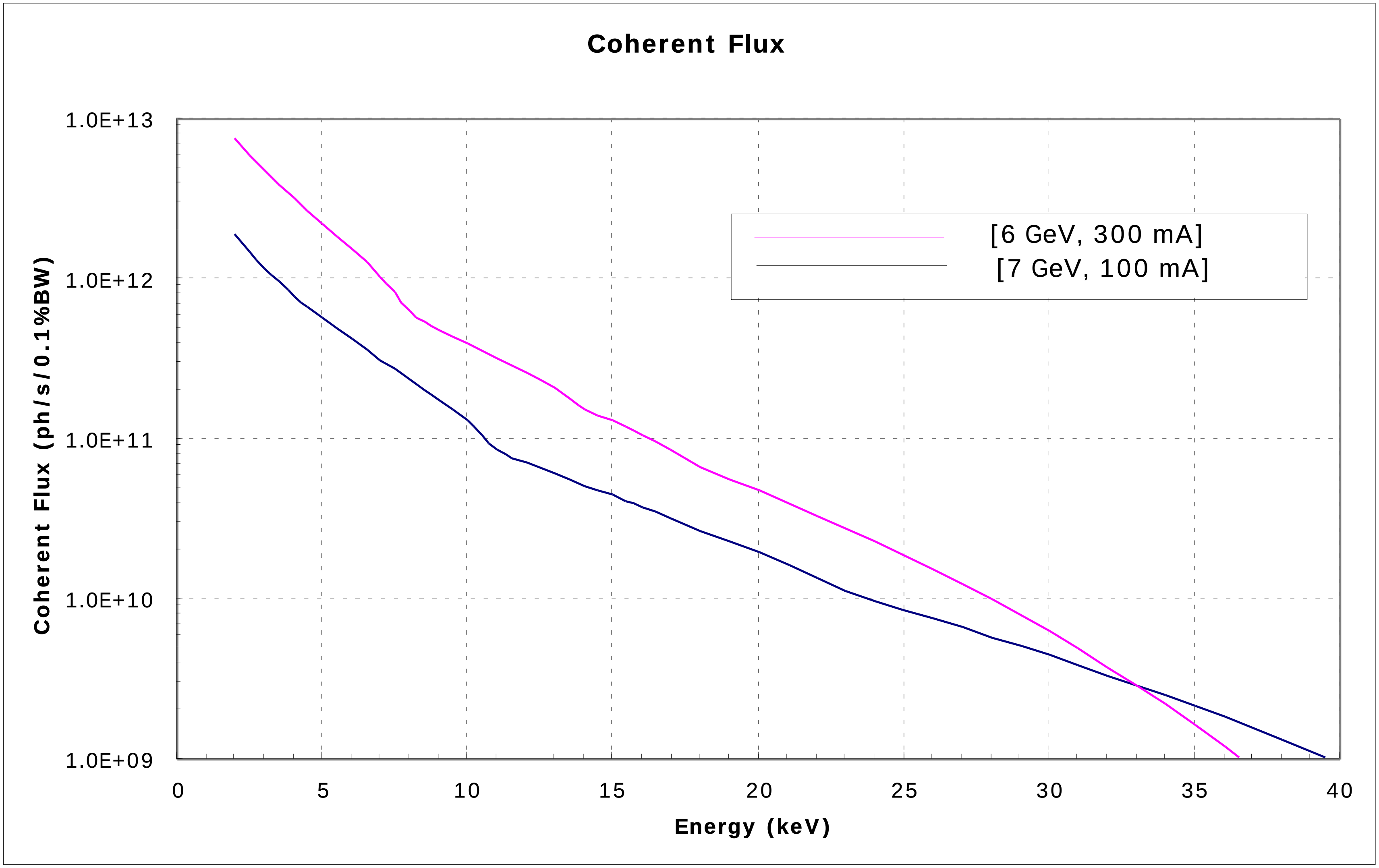

Fig. 12. Comparison of raw coherent flux from undulator-A with 3.3-cm-period (77 periods) operated at various storage ring energies and currents as shown in the legend. The assumed values of the electron beam properties are given in Table 1.

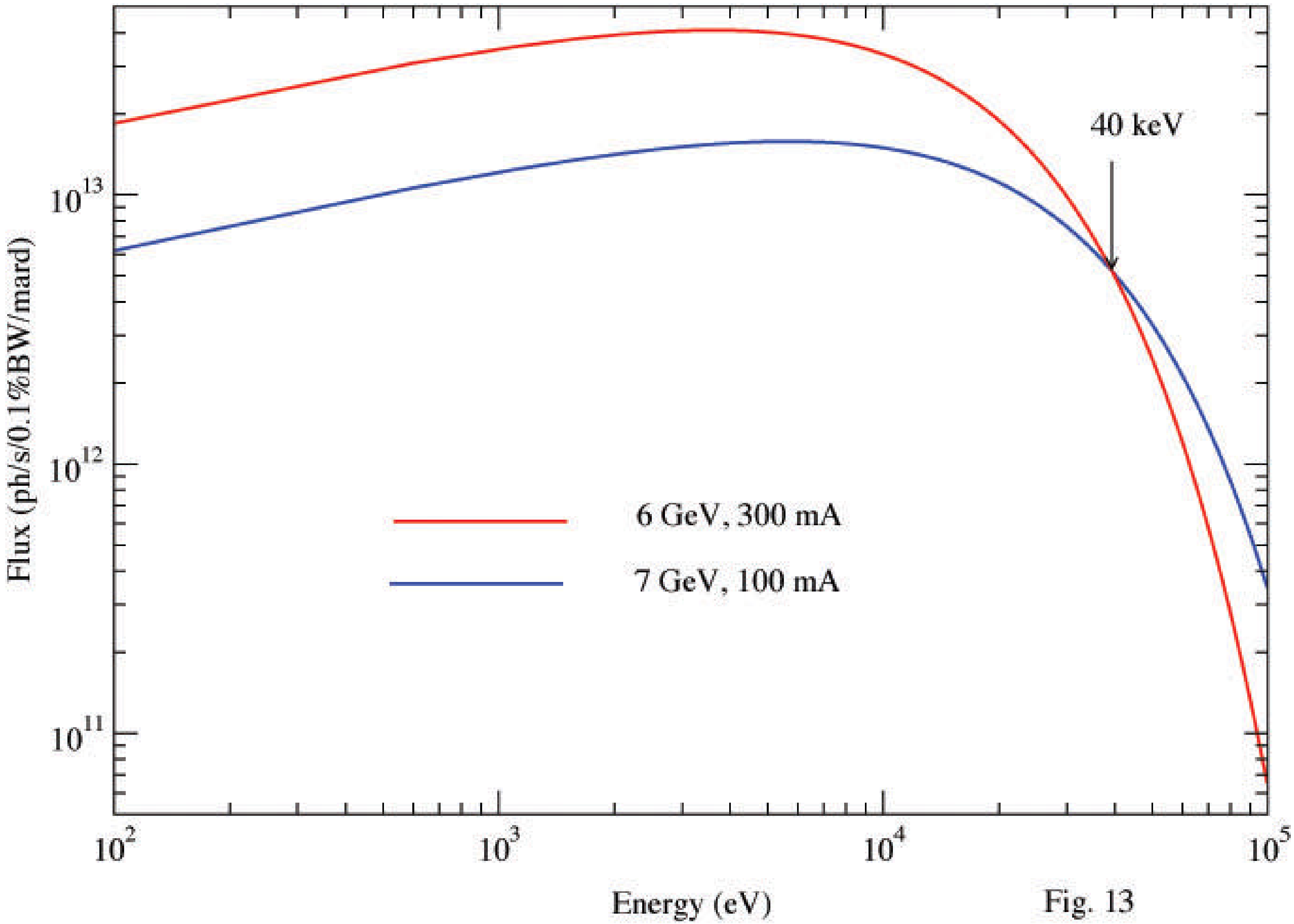

Fig. 13. Comparison of energy distribution of flux from bending magnet sources operated at various storage ring energies and currents as shown in the legend.

4. being 5 mA at 7 GeV. The current/bunch, being a function of storage ring energy, will be smaller than 5 mA in a 6 GeV lattice. To load 300 mA, about 60-100 bunches are required. This provides a bunch-to-bunch separation of about 30-60 ns, if the lattice is filled uniformly with singlets. This would affect timing experiments, a growing area of scientific research. Presently many users employ a bunch-to-bunch separation of about 120-150 ns. Higher current operations will force the users needing similar bunch-to-bunch separation to use different fill-patterns such as (3x30), where 3 neighboring buckets (triplets) are filled 30 times around the lattice to realize approximately 120 ns separation between triplets.

   If bunch length is increased from its current value of about 50 ps to accept larger bunch currents, the above limitation on the bunch-to-bunch separation can be overcome. This will require further studies with higher harmonic rf systems [7].

5. Higher stored currents, again independent of operational energy, might lead to single-bunch instabilities, which must be investigated. The users have enjoyed excellent x-ray beam stability performance with [7 GeV, 100 mA] operation and will expect the same even at higher currents.

6. For a 6 GeV operation, the gap vs. x-ray energy table will be different, although scaling from the 7 GeV table is very straightforward. The users will have to get used to the changed table. If the 6 GeV and 7 GeV operations might be included in a single operation-period to satisfy different user needs, the change in the look-up table should be made transparent to the users. This would involve some advance work on transparent energy switching methodology.

7. In addition to resetting of all the power supplies to magnets in all accelerator systems (e.g., lowering the bending magnet field from its current value of 0.6 T to 0.513 T), the bending field used for lattice distortion (Decker distortion) and that between canted undulators (sector 4) will have to be readjusted. These are only some of the configurational changes associated with switching from 7 to 6 GeV.

All the safety requirements (defined by SAD) for 7 GeV operation should very well satisfy 6 GeV operation.

11. Conclusions

The new approach of enhancing the brilliance of x-ray beams from undulator-A involving operation of the storage ring at lower energy and higher currents can be implemented without any major hardware changes. The [6 GeV, 200 mA] operation seems ideal to begin higher brilliance studies of the accelerator performance, as well as beamline performance. But the suggested goal is [6 GeV, 300 mA]. While the new approach will satisfy a majority of the users, their input would be essential. Many of the accelerator studies, some indicated in section 10, can be started now with [6 GeV, 200/300 mA] operating points. In the calculation of x-ray brilliance at 6 GeV, a horizontal emittance of 2.2 nm.rad (scaled from 7 GeV) was assumed, along with dispersion (η_x (m), η_y (m), etc.) in the straight section measured with the current lattice (Table 1). The brilliance numbers can be further enhanced if the dispersion terms are reduced, since they contribute to the beam phase space volume (section 2). Assuming that the proposed approach is acceptable to the user community, accelerator and beamline specialists, and the APS management, an appropriate short-term implementation plan can be developed. This should include a detailed performance evaluation of the accelerator subsystems, the beamline front-end components, and the first optics in each of the beamlines prior to development of an implementation plan. A pleasant aspect of the proposed approach is that the user programs will be least interrupted, since the hardware changes are likely to be minimal. Also this will give more time to plan a long-term strategy of total optimization of the operational parameters.

It has been emphasized in this report that undulator-A (with a 3.3 cm period) is not the optimal device for operation at 6 GeV (or for that matter, even at 7 GeV). The full advantage of undulator technology, smaller apertures of undulator vacuum chambers, and top-up capabilities have not been fully exploited until now. As was demonstrated in section 7, lowering the period to 2.7 cm improves the x-ray beam spectral characteristics and the tenability, which benefits from the smaller aperture undulator vacuum chamber—but not without some penalty on higher heat loads on the front-end components and the optics, which will have to be mitigated. The suggested operation at 6 GeV should be viewed as a temporary step towards higher brilliance. An ideal value of operational point to obtain highest brilliance is a complex function of energy, current, undulator period, total power and power density. We speculate that the operational point is in the range [6-7 GeV, 300 mA, 2.0 - 3.0 cm undulator period]. There will be more than one value of undulator period with preset gap ranges for each device to meet the diverse scientific goals of APS users. This optimization will be reported in the future.

While user science benefits from the implementation of the suggested approach, following short-term R&D items should be considered. This will include realizing dispersion-free straight sections to enhance brilliance, increasing the current per bunch, if necessary through bunch lengthening, and assuring that beam instabilities can be handled at 300 mA. Long-term R&D priorities would include, but are not limited to, accelerator physics, higher harmonic rf systems, short-period undulators including those based on superconducting technology, and most importantly high heat load engineering.

If brilliance is the only performance measure, it is interesting to ask the best performance of the 6 GeV APS with other facilities. Also, “the ultimate storage-ring-based light source (USRLS)” has recently been proposed, which involves a storage ring with a 2000 meter circumference and 0.8 nm.rad emittance [8]. In Table 7, a comparison is made of the brilliance performance of various facilities at 1Å wavelength. In this table, the possible future APS operation parameters are included, such as 350 mA current and 5-m-long undulator with a 2.7 cm period. The APS will deliver a brilliance of 6 x 10^{20} in standard units.

Table 7. Values of various storage ring parameters and brilliance of 1Å x-ray beam.*

Properties	ESRF	APS	SPring-8	APS**	USRLS
Energy (GeV)	6	7	8	6	7
Horizontal Emittance (nm-rad)	3.9	3.0	6.0	2.2	0.8
Ring Circumference (m)	844	1104	1429	1104	2000
Current (mA)	200	100	100	350	500
Undulator Period (cm)	3.4	3.3	3.2	2.7	3.3
Undulator Length (m)	5.0	2.4	25.0	5.0	7.0
Minimum Undulator Gap (mm)	11.0	11.0	11.0	8.5	6.0
Brilliance (ph/s/0.1%BW/mrad^2/mm^2)	2.9 x 10^{20}	2.2 x 10^{19}	6.7 x 10^{20}	6.0 x 10^{20}	3.7 x 10^{22}

* Most values are from reference [8].
** Proposed configuration with enhancements shown in the table.
*** Power values are for the undulator gap producing 1A wavelength x-rays.

Finally we would like to remark that the APS is referred to as "the 6-7 GeV Synchrotron Radiation Source" for good reasons!

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