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Intermediate Energy Storage Rings (2.5-4.0 GeV)

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Introduction

The pioneering third generation light sources fell into two distinctly different groups: low energy machines (E<2 GeV) intended primarily for vacuum ultraviolet and soft x-ray science and high energy machines (6-8 GeV) designed for hard x-ray science. The high energy machines featured undulators operating in the 5-25 keV range on the fundamental and lowest harmonics where undulator brightness approached theoretical predictions. As undulator technology matured, however, magnetic pole field shimming proved a viable means to correct undulator fields such that now nearly theoretical brightness is obtained at higher harmonics[1]. This development, coupled with recent work on small gap undulators[2], demonstrated that undulator sources on intermediate energy rings (2.5-4.0 GeV) could serve many of the demands of high brightness x-ray research. Moreover, wiggler and bend magnet sources on these rings provide cost effective sources for x-ray applications that do not require nor fully utilize the brightness of undulator beams. These factors, coupled with regional needs and lower construction and operations costs, have led to the recent growth in high current, 2.5-4.0 GeV rings with third generation light source properties such as low emittance and numerous insertion device (ID) straight sections.

This article provides a survey of existing and proposed light sources operating in the intermediate energy range and outlines motivations for constructing future machines in this energy range. The Intermediate Light Source (ILS), a strawman 3.3GeV/500mA light source design, is used to illustrate typical photon beam properties available from a third generation, intermediate energy light source. The photon beam properties are compared with those obtained from a typical third generation, 6-8 GeV storage ring. Technical issues associated with the construction of high current storage rings and technological innovations that can be used to enhance accelerator and photon beam performance are discussed.

Survey of Intermediate Energy Light Sources

The class of 'intermediate energy light sources' can be defined as storage rings with beam energy in the 2.5-4.0 GeV range. At present, as illustrated in Table 1, about a dozen sources are proposed, under construction or operate in this energy range. The first few intermediate energy sources were first and second generation predecessors to the large third generation high energy machines (6-8 GeV). Since construction of these high energy machines, a motivation for construction of intermediate energy machines is the lower construction and operational cost coupled with excellent photon beam performance. The reduced cost permits the resource flexibility to distribute hard x-ray sources regionally.

Table 1. Survey of Existing and Proposed 2.5-4.0 GeV Intermediate Energy Light Sources. Ring status is denoted by O (operational), C (under construction), or P (proposed). Several of the proposed rings are expected to start construction shortly.

storage ring	location	E	I	ε_x	lattice	straights	circum.
		(GeV)	(Amp)	(nm-rad)			(m)
SPEAR2[3] (O)	Stanford	3.0	0.1	160	FODO	18	234
NSLS x-ray[4] (O)	Brookhaven	2.8	0.35	50	DBA	8	165
Photon Factory[5] (O)	Tsukuba	2.5	0.5	30	FODO	6	187
Siberia-2[6] (O)	Moscow	2.5	0.3	79	DBA	6	125
ROSY[7] (P)	Saxony	3.0	0.25	26	QBA	16	148
NC Star[8] (P)	Raleigh	3.0	0.4	29	FODO	8	147
LSB[9] (P)	Barcelona	2.5	0.25	8.5	TBA	12	252
SOLEIL[10] (P)	Orsay	2.5	0.5	3.1	DBA	16	336
ANKA[11] (C)	Karlsruhe	2.5	0.4	39	DBA	8	110
CLS[12] (C)	Saskatoon	2.9	0.5	20	DBA	12	170
SPEAR3[13] (C)	Stanford	3.0	0.5	18	DBA	18	234
DIAMOND[14] (P)	England	3.0	0.3	8	DBA	20	400
SSRF[15] (P)	Shanghai	3.5	0.3	12	DBA	20	384
Boomerang[16] (P)	Australia	3.0	0.3	16	DBA	12	164
ILS	demonstration	3.3	0.5	10	DBA	22	307

In recent years, proposals for new third generation sources in the intermediate energy range have demonstrated a trend toward slightly higher beam energy to produce harder spectra with improved beam stability and longer beam lifetime. The last entry in Table 1, the ILS, provides an example of a 3.3 GeV machine operating at 500 mA. In the following sections, we outline the ILS machine design and compare ILS photon beam properties with those of a representative third generation, high energy light source. For a wide range of research applications, the photon beam characteristics available from the ILS are found to be comparable with those of a high energy, third generation storage ring.

An Intermediate Energy Light Source (ILS)

To illustrate the properties of a third generation light source in the intermediate energy range, we examined a relatively conventional 3.3 GeV storage ring with 307 meter circumference and 500 mA stored current. Since the ILS was created expressly as a demonstration for this article, its design has not been as extensively studied as the other rings listed in Table 1. The storage ring has 22 cells with 4.8 m straight sections with 3.5

m available for insertion devices. Of the 22 straights, five are employed for injection and RF leaving 17 available for insertion devices. Figure 1 illustrates the classic double bend achromat (DBA) cell structure of the ILS. Table 2 summarizes the machine parameters. Similar to many storage rings now in operation, the lattice exploits vertical focusing in the dipole magnets and finite (but small) dispersion in the straight sections to reduce horizontal emittance (ε_x=9.9 nm-rad). The bare lattice electron beam dimensions are σ_x~0.30mm by σ_y~0.022 mm in the straight sections; however, with the addition of high power wigglers, radiation damping reduces the horizontal emittance and the associated beam dimensions.

The intent of the ILS lattice is to demonstrate the photon beam properties attainable by a high current, third generation storage ring in the intermediate energy range. To meet specific machine performance goals and user needs, a more sophisticated design might incorporate features such as alternating high and low beta straight sections (see Table 4 below).

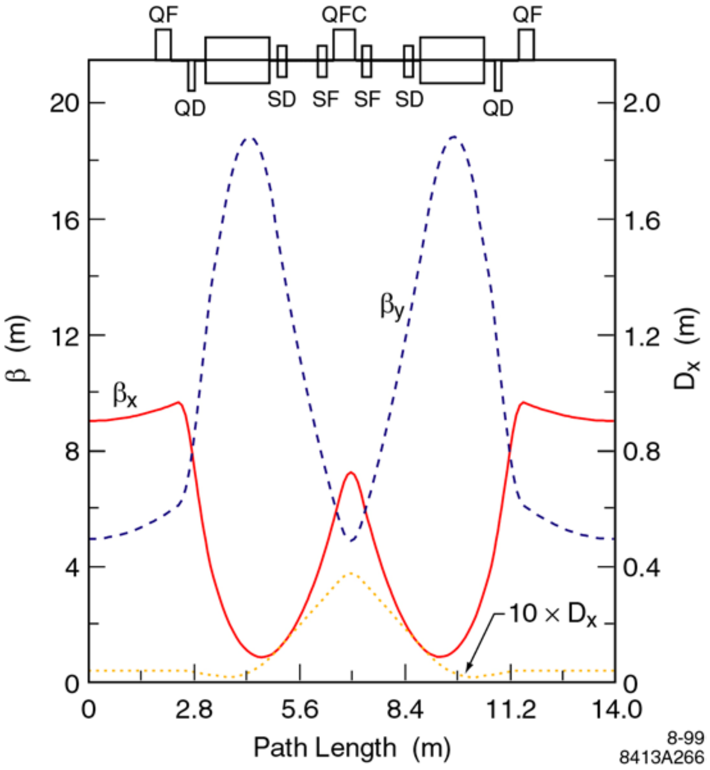

Figure 1. Unit cell for the ILS storage ring.

Table 2. ILS machine parameters.

Parameter	Value	Units
Energy	3.3	GeV
Current	500	mA
Emittance	9.9	nm-rad
Energy Spread	0.1	%
β_x / β_y -straight	9.0 / 4.9	m/rad
Q_x/Q_y	17.18 / 6.28	
Ring Circumference	307	m
Number Cells	22	
Straight Section Length	4.8	m
RF frequency	476	MHz
RF voltage	5	MV
Beam Lifetime	>20	hr

Dynamic aperture simulations with alignment errors, field errors and 3% energy oscillations included indicate the ILS has an aperture of approximately ±20 mm in the horizontal plane. The intra-beam scattering lifetime (Touschek effect) scales as [17]

$$\tau_T \sim \gamma^2 \sigma_x \sigma_y \sigma_z (\delta p/p)^3 / N_b$$

where $\sigma_{x,y,z}$ are the rms beam sizes, N_b is the number of particles per bunch, γ is the beam energy and $\delta p/p$ is the momentum acceptance of the storage ring. Since for a given ring $\sigma_{x,y}$ scales linearly with γ, the Touschek lifetime scales strongly with γ, yielding longer lifetimes for higher ring energies. Owing to the cubic dependence of Touschek lifetime on $\delta p/p$, one of the main objectives of any light source design is to achieve large momentum acceptance through careful adjustment of sextupole magnets. The performance of the vacuum system is also critical since 1-2 nTorr pressures are required for long gas scattering lifetimes. Including beam scattering from neutral gas, the lifetime of an intermediate energy light source like the ILS should exceed 20 hours with 500mA stored current.

While the ILS is representative of third generation, intermediate energy light sources, intermediate energy storage rings also enter into discussions of fourth generation light sources. The companion article by Hofmann and Rivkin[18], for instance, discusses a 4.0 GeV fourth generation light source with 2.2 km circumference and $\varepsilon_x \sim 0.1$ nm-rad emittance.

Source Performance: Figures of Merit

Before examining the photon beam properties of the ILS, we digress to consider source performance figures of merit. Unfortunately, no one metric can adequately characterize performance given the diverse range of scientific applications. One common figure of merit is photon flux, or the number of photons per unit band width produced by the source. Flux is the appropriate merit function for applications where little beam collimation is required and the sample transverse size is sufficiently large so as to intercept the entire photon beam. For a typical focused beam this translates into several mm^2 of sample area and several tens of mm^2 of sample area for an unfocused beam. Many x-ray absorption spectroscopy (XAS) applications, for example, fall into this category.

Brightness, or flux per unit source phase space, is another common figure of merit. High brightness is required for experiments that involve samples or optics with very small phase space acceptance or techniques that exploit beam coherence. Examples of such experiments include micro-focus applications (microscopy, micro-probe, micro-XAS, etc.), diffraction from high perfection small crystals and speckle measurements. In fact, the production of high brightness beams at hard x-ray energies was the major motivating factor behind the development of 6-8 GeV undulator sources and brightness limited experiments have benefited enormously from these sources.

While flux and brightness are the most widely quoted metrics, many synchrotron experiments do not fall neatly into flux or brightness limited measurements. Specifically, a large class of experiments requires modest beam collimation and focused spot size. For such experiments, most synchrotron sources are sufficiently bright in the vertical dimension that vertical beam properties do not meaningfully distinguish source capabilities. Instead, horizontal brightness, the one dimensional analog of brightness as defined above, provides a more meaningful measure of source capability than either flux or brightness. Many scattering and diffraction experiments (including most macromolecular crystallography) fall into this category. Horizontal brightness, therefore, is an appropriate merit function to compare bend and wiggler source capabilities for experiments that do not require the extreme beam collimation of an undulator.

Another useful figure of merit for experiments requiring only modest collimation is flux density or intensity. Flux density (flux per unit source area) is a measure of the number of photons ideal 1:1 optics can image onto a unit sample area. Note that one must exercise care in applying this merit function since the vertical beam dimensions of some sources are smaller than can be faithfully imaged with state-of-the-art x-ray optics. In such cases, flux density may provide a misleading basis for source comparison.

Perhaps the best alternative merit function maps the source phase space into the sample acceptance phase space. Assuming appropriate optics are used in the transformation from source to sample phase space, this sample-based approach provides the flexibility to accurately relate the demands of a given experiment to the source properties. Consider, for the sake of concreteness, macromolecular crystallography. A typical sample with 0.1-0.3 mm transverse dimensions and a 3 mrad (0.2°) or larger mosaic spread has approximately an $(0.5\ \text{mm-mrad})^2$ acceptance phase space. Since the sample acceptance significantly exceeds the 0.05 mm-mrad x 0.001 mm-mrad source phase space of typical third generation hard x-ray undulators, the flux from the entire central cone of the undulator radiation can be imaged onto the sample. In contrast with undulators, a typical wiggler on a low emittance ring over-fills the horizontal phase space acceptance while under filling the vertical acceptance. Integrating the wiggler source phase space over the sample acceptance phase space yields the flux onto the sample. As shown below, the accepted wiggler flux is often quite comparable with the undulator flux despite the orders of magnitude difference in source brightness. This surprising result underscores the importance of selecting the appropriate figure of merit for the science in question.

ILS Photon Beam Properties

To demonstrate the photon beam properties of the ILS, we calculated the emission spectra from bend magnet, wiggler (W70) and undulator (U32) sources on this ring. These sources, whose properties are summarized in Table 3, are general purpose sources that do not employ unusually small magnet gaps (the pole gaps are 10 mm and 16 mm for U32 and W70, respectively) or particularly aggressive magnetic technologies (ie., no superconducting or highly saturated pole designs).

Specialized sources optimized for specific applications can improve performance in many cases. For example, small gap undulators in low beta straights enhance brightness at higher photon energies, high field hybrid or superconducting wigglers yield increased critical energy for high energy applications, wigglers located on low beta straights develop greater flux density, and elliptically polarized undulators provide polarization control[19].

To place the ILS performance into context, the ILS sources are benchmarked by sources on a representative third generation, high energy light source, the HLS. The HLS features twice the energy of the ILS, half the emittance of the ILS, the same Twiss functions as the ILS (see Figure 1), and 200mA stored current. A description of the HLS source parameters is listed in Table 3. Examination of this table reveals that the HLS is a high performance composite of the current operating characteristics of the three existing high energy, third generation light sources. While the overwhelming majority of insertion devices installed on these high energy rings are undulators, the performance comparison includes both wiggler (W70) and undulator (U32) sources for completeness. Note, however, the technical challenges associated with the power radiated by high flux wigglers on high energy machines are substantial (see below). These challenges, coupled with the brightness advantages of undulators, have rendered undulators the insertion device of choice on high energy rings except in specialized applications such as those requiring high photon energies.

Table 3: ILS and HLS source characteristics.

parameter	ILS bend	ILS W70	ILS U32	HLS bend	HLS W70	HLS U32
energy (GeV)	3.3	3.3	3.3	6.6	6.6	6.6
current (mA)	500	500	500	200	200	200
emittance_x (nm*rad)	9.9	9.9	9.9	5	5	5
coupling (%)	1.0	1.0	1.0	1.0	1.0	1.0
energy spread (%)	0.1	0.1	0.1	0.1	0.1	0.1
sigma_x (mm)	0.127	0.302	0.302	0.109	0.216	0.216
sigma_x' (mrad)	0.163	0.033	0.033	0.147	0.024	0.024
sigma_y (mm)	0.041	0.022	0.022	0.029	0.016	0.016
sigma_y' (mrad)	0.008	0.0045	0.0045	0.0057	0.0032	0.0032
Bpeak (T)	1.12	1.05	0.78	0.70	1.05	0.78
period (mm)	na	70.0	32.0	na	70.0	32.0
number periods	na	50	109	na	50	109

The spectral flux curves for the sources listed in Table 3 are plotted in Figure 2. Only the fundamental and third harmonic are shown for the HLS U32, while the ILS U32 spectra includes tuning curves for the fundamental and odd harmonics up to n=11, including energy spread effects. For flux limited measurements, high flux wigglers on a machine like the ILS are quite competitive with undulator sources on high energy rings.

The brightness advantages of high energy rings are apparent from the curves of Figure 3. While the ILS U32 source provides high brightness (ie., > 5x10^{18}) below about 7.5keV, the HLS U32 provides higher brightness at these energies and sustains high brightness to much higher photon energies.

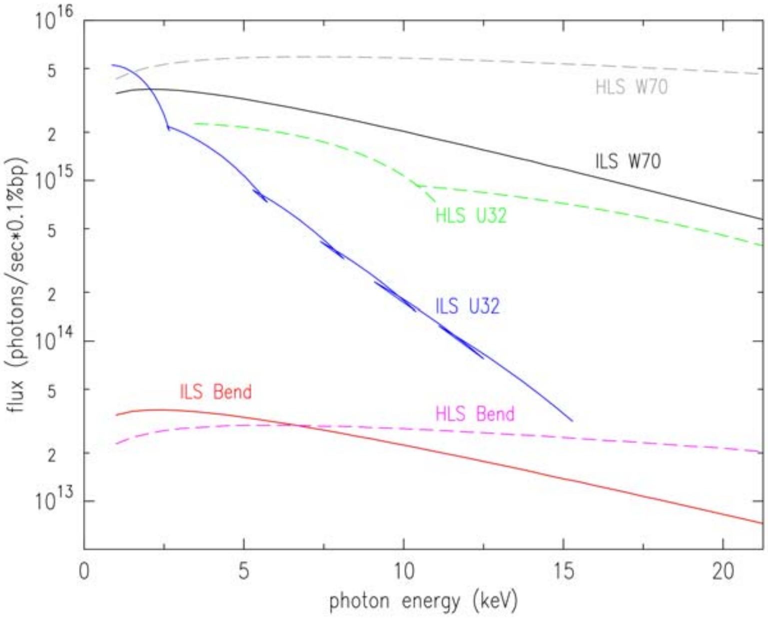

Figure 2: Spectral flux curves for the sources listed in Table 3. The wiggler and bend curves are flux per horizontal mrad while the undulator curves are integrations over the central emission cone.

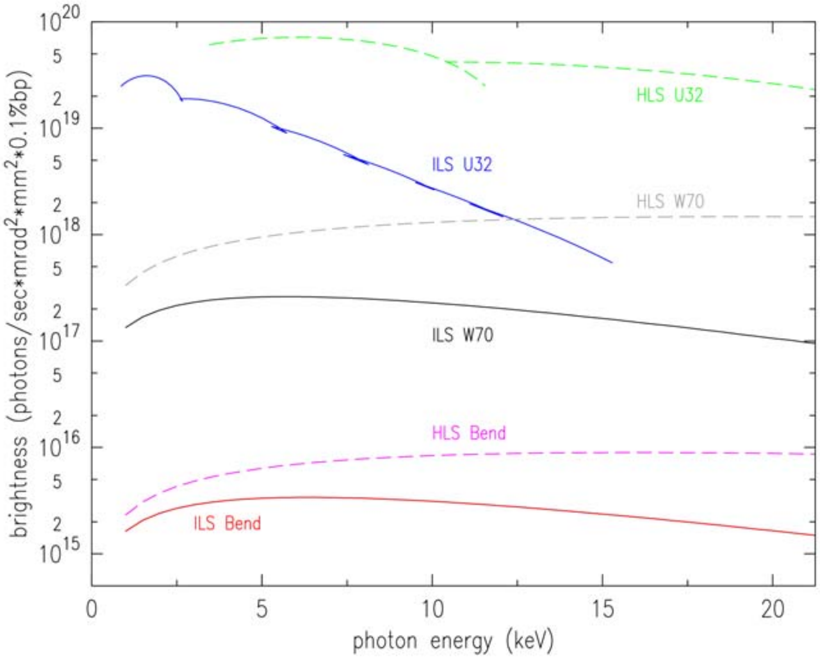

Figure 3: Spectral brightness curves for the sources listed in Table 3.

Next consider the relative source performance for the large class of experiments that require modest beam size and collimation but do not fully utilize the extraordinary collimation provided by undulators. For such measurements neither flux nor brightness is the appropriate merit function. In these cases, the phase space acceptance merit function described above provides a good metric. For example, Figure 4 depicts the flux emitted into the (0.5mm-mrad)^2 sample acceptance phase space of a typical macromolecular crystallography sample. The advantages of high ring energy for undulator spectra at hard x-ray energies is apparent and expected. What is perhaps more surprising is the efficacy of the ILS W70 weak field wiggler source for such experiments. As Figure 4 demonstrates, this wiggler source is sufficiently bright that experiments that do not fully exploit the narrow undulator emission cone are well served by a lower brightness wiggler source on a third generation, intermediate energy ring. This observation applies to appropriately optimized wigglers on high energy rings as well.

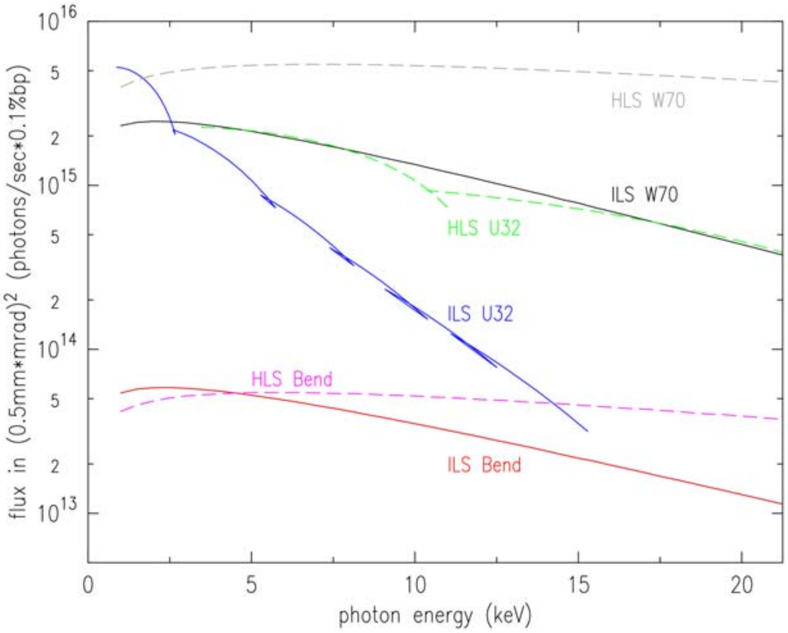

Figure 4: Flux emitted into a (0.5 mm-mrad)^2 sample acceptance phase space.

Technical Challenges and Innovations

Storage Rings

Intermediate energy sources can benefit from recent innovations in lattice design, insertion device technology, vacuum systems and beam control. Some of the more effective innovations are listed in Table 4. Many of these concepts have been employed in new machine designs or incorporated into existing storage rings to produce ever smaller photon beam sizes, higher stored currents, more stable beams and longer beam lifetime.

Table 4. Source Innovations

Innovation	Benefit
harmonic cavities	bunch length control
Mode-Damped Cavities	impedance reduction
Advanced Vacuum Chamber Designs	high current
Top-Up Injection	constant current
Low β_x Straights	high flux density
Long Straights	novel insertion devices
In-Vacuum Undulators	high brightness
Elliptically Polarized Undulators	polarization control
Undulator Pole Shimming	high brightness harmonics
Superconducting Dipoles	high critical energy
High Field Wigglers	high critical energy
Damping Wigglers	emittance control
Laser-aided Bunch ‘Slicing’	short pulse radiation
Low Emittance Optics	emittance reduction
Harmonic Sextupoles	dynamic aperture control
Finite Dispersion Lattices	emittance reduction
Fast Feedback Systems	bunch stability
Advanced Diagnostics	machine development

As light sources store higher beam currents, one of the main technical challenges is radiation power loading. For the 9.7 m bending radius dipole in the 500 mA, 3.3 GeV storage ring outlined above, the total radiated power from the dipoles alone is ~534 kW or 85 W/mrad. This power load is best managed with discrete photon beam absorbers in an ante-chamber vacuum system configuration. Insertion device power densities are considerably higher and can melt components in milliseconds so the chamber must be protected with orbit interlocks and/or aggressive cooling.

Chamber cooling also helps to reduce slow creep of magnets, chambers and beam position monitors (BPMs). To help stabilize the electron beam, recent advances in chamber fabrication have produced high precision stainless steel chamber sections with innovative photon beam absorbers (eg., SLS, ANKA) and very stable BPMs. Another approach uses a copper vacuum chamber with low conductivity inserts under the fast orbit correction magnets to allow fast field penetration (SPEAR3). Independent of chamber design, high current storage rings in the intermediate energy range require aggressive use of photon stops, masking and vacuum pumps (up to 500 l/s per meter) to maintain 1-2 nTorr gas pressures at full current.

Critical operational challenges include holding the photon beam position stable to about 10% of the source size and divergence for a periods of many hours to days and obtaining long beam lifetime. Accurate beam stability requires low impedance chamber design, support structures insensitive to ground vibration, insensitivity to radiation power load, carefully regulated power supplies and stable tunnel temperature. Common stabilization measures include tunnel air conditioning (stability better than 1°C*),* use of low impedance (mode-damped) cavities, closed loop orbit feedback (>0-100 Hz) and multi-bunch feedback systems. Feed-forward techniques can be used to track BPM slow drifts. Feedback systems operating directly on photon beam line components have also come into practice.

Achieving long beam lifetime requires large acceptance in both the longitudinal (rf) and transverse (magnet) directions. Given a 3.3 GeV electron beam, for example, electrons loose about 1,100 keV/turn from dipole radiation and up to 500 keV/turn from insertion devices. To replenish the lost energy would require six 476 MHz PEP-II style cavities[20] (~0.8 MV gap voltage per cell). Such a mode-damped cavity design reduces wide-band feedback requirements. With 4.8 MV gap voltage, the beam lifetime is primarily limited by dynamic aperture of the magnet lattice. To enhance dynamic aperture, many light sources use ‘harmonic’ (as opposed to chromatic) sextupole magnets, often arranged in complicated patterns around the storage ring.

Beam Lines

From a beam line perspective, the main challenges presented by high current, third generation light sources in the intermediate energy range are power handling and production of insertion devices with state-of-the-art field quality. Since a companion article addresses insertion device technology[19], we restrict our focus to power concerns. Table 5 lists the peak power emitted from the ILS and HLS sources discussed above assuming the operating conditions listed in Table 3.

Table 5. Calculated peak power for ILS and HLS sources.

source	P(W/mrad^2)	P(W/mrad)	P_{total}(W)
ILS bend	360	85	na
ILS W70	33500	7920	13300
ILS U32	54250	na	7340
HLS bend	1350	167	na
HLS W70	216000	21000	21000
HLS U32	350000	na	11750

Inspection of Table 5 indicates that the power densities obtained from ILS sources are modest in comparison to the HLS ID power densities. (Power density scales as ring energy to the fourth power, thus an HLS ID develops 16 times the power density of an ILS ID if all other factors are held equal.) Consequently, *power density* proves less of a design challenge on an ILS class ring than on a high energy ring. The *total power* intercepted by ILS optical components, while less than the HLS W70, is substantial. Thus, the challenge presented to a beam line optics designer on a ring such as the ILS centers on efficient heat transfer for large total power loads but relatively modest power densities.

Similar to beam line designs on high energy rings, power filtering plays an important role on intermediate energy rings. High pass carbon filters and low pass mirror filters with variable energy cutoff minimize the power incident on the monochromator. Monochromators on ILS undulator beam lines could easily adapt technology pioneered at the 6-8 GeV machines. However, many of the monochromator designs that have proven effective coping with highly collimated undulator beams, prove less effective on broader fan wiggler beams. For example, both diamond and inclined crystal monochromator technology are impractical for use with the 20-40 mm wide beams obtained at the monochromator for a typical wiggler beam line optical configuration. Liquid nitrogen monochromator cooling technology can be adapted to high power wiggler applications with some further development of heat exchangers to accommodate the multi-kW power loading of a high power wiggler. Alternatively, intensively water cooled crystals prove effective for monochromator applications where the applied power strikes the crystal over a large area with power densities up to several W/mm^2. Even higher power densities can be managed for smaller beam footprints. Such crystals typically employ micro-channel or pinpost heat exchanger geometries machined directly into the Si diffracting crystal which in turn is bonded to a Si manifold. Further development of low strain, radiation robust Si crystal bonding technology is required to optimize this approach to monochromator crystal cooling.

Cost Estimate

A central argument for constructing third generation, intermediate energy, hard x-ray light sources is the high performance obtained for the investment. By keeping the storage ring circumference relatively small and the beam energy modest, cost savings are realized for conventional components (vacuum chamber, magnets, building size, shielding), the rf system, and power consumption. Table 6 provides a rough direct cost estimate (including salaries but not overhead) for the 307 m, 3.3 GeV ILS machine based on recent experience with the SPEAR3 light source project at Stanford University. Of course, cost, contingency, and overhead are site dependent. Note that the total cost includes a rough cost estimate for an initial complement of 12 ID beam lines of the 17 ID and 20 bend beam lines that can be accommodated on the ILS. The beam line cost estimate stems from recent experience building 3.0GeV/500mA ID beam lines at Stanford University and includes an out of vacuum insertion device and $1M detector.

Table 6. Rough direct cost estimate for the prototype ILS outlined in Table 2 ($M).

System	Cost ($M)
Magnets & Supports	15
Vacuum	15
Power Supplies	7
RF	6
Instrumentation & Control	8
Injector	30
Ring/Booster Shielding (4000m^3)	4
Building (18,000m^2) & Utilities	50
Accelerator Complex Total	135
Beamlines (12 ID @ $7M ea)	84
Ring & Beam Line Total	219

Conclusions

Third generation, high current, intermediate energy storage rings provide excellent source performance for a broad range of hard x-ray research including brightness limited measurements with energies less than approximately 7.5keV. Experiments and techniques requiring modest beam collimation and focused spot size are particularly well suited to wiggler sources on such rings. Owing to the lower ring energy and smaller ring circumference, the construction and operations costs of intermediate energy rings renders such rings attractive regional sources for those hard x-ray applications that do not require the high brightness of undulators on 6-8 GeV rings.

Acknowledgements

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