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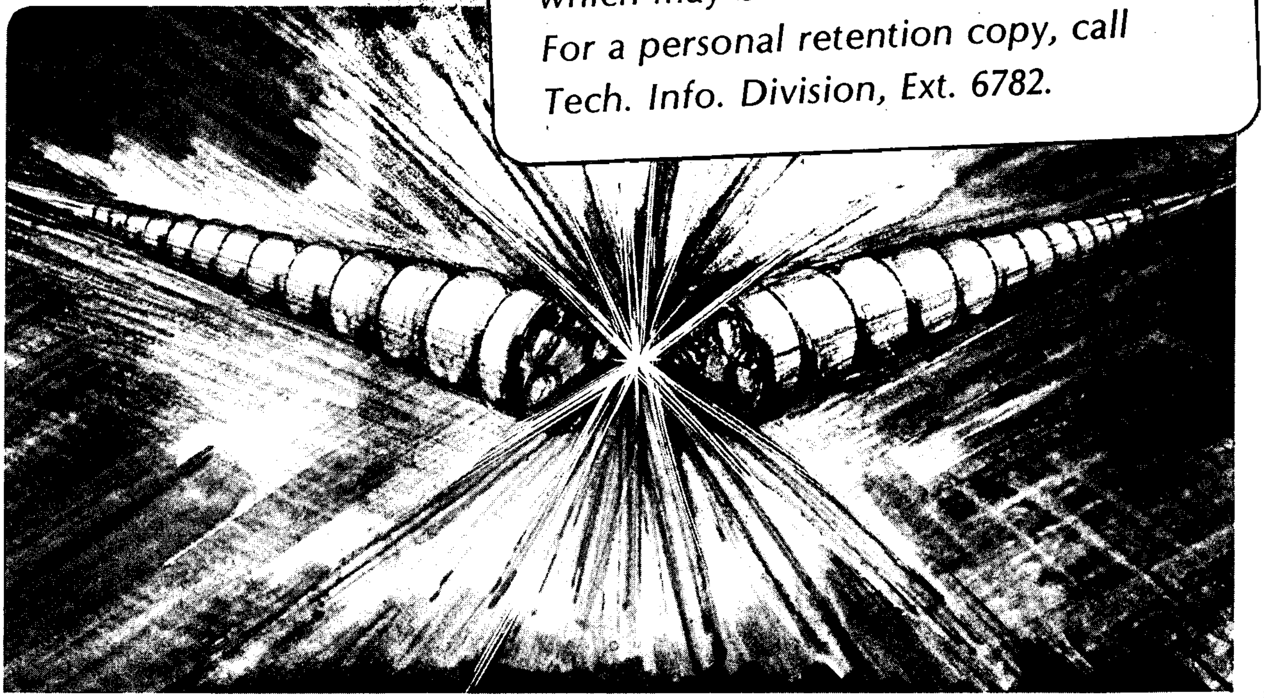

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ABSTRACT

Magnetic structures in modern storage rings provide an assured route to fundamentally new opportunities for extending coherent radiation experiments to the vacuum ultraviolet and soft x-ray spectral regions. Coherent power levels of order 10 milliwatts are anticipated, in a fully spatially coherent beam, with a longitudinal coherence length of order 1 μm. In addition to broad tuneability and polarization control, the radiation would occur in 20 psec pulses, at 500 MHz repetition rate.

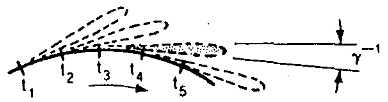
I. INTRODUCTION

Undulators in modern storage rings are capable of generating substantial coherent power in the heretofore inaccessible spectral region extending from photon energies of a few eV to several thousand eV. In addition to providing an **assured route** to coherent techniques in the important soft x-ray and vacuum ultraviolet spectral regions (collectively referred to here as the XUV), the radiation is also **broadly tuneable**. The latter feature is a significant advantage with respect to potential x-ray lasers that might become available in the next decade or so, in that it permits imaging and spectroscopic probe studies to be conducted around the important atomic and molecular resonances so prominent in that region. The purpose of this paper is to give an introductory review of the coherence characteristics of undulator radiation.

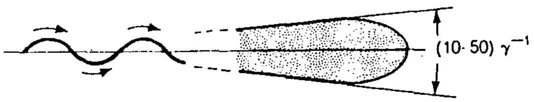
II. MODERN SYNCHROTRON RADIATION SOURCES

An extremely relativistic electron experiencing bending motion produces a narrow cone of synchrotron radiation[1] directed along its instantaneous direction. The angular width of the radiation cone, γ^{-1}, is typically several hundred microradians, where γ is the ratio of total electron energy to its rest energy.

Historically, the primary source of synchrotron radiation in storage rings has been at the bending magnets, as illustrated at the top of Figure 1. However, bending magnet radiation is incoherent, and spread across a wide horizontal fan. A more efficient manner of producing and collecting synchrotron radiation involves utilization of periodic magnet structures, in particular permanent magnet which permits combination of high field strengths with short periods.[2] This general scheme is illustrated in Figures 1 and 2. These many period, N, magnetic structures produce an N-fold increase in radiated flux and offer options for spectrally shifting to higher photon energies with a strong field "wiggler", or coherent intensification on axis with a moderate field "undulator". The parameter determining this option is the deflection parameter K = .934 x magnetic field strength in Tesla x period length in cm. K is the ratio of the maximum electron deflection angle to the natural radiation angle γ^{-1}. For $K \gg 1$, the wiggler case, the electron experiences large magnetic deflections, thus producing more flux at higher photon energies, and radiating into a proportionately larger radiation cone. Although incoherent in nature, wigglers are currently the most powerful source of laboratory x-rays.[3]

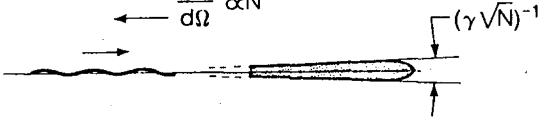


Bending Magnet — A "Sweeping Searchlight"



Wiggler — Incoherent Superposition

$$\frac{dP}{d\Omega} \propto N$$



Undulator—Coherent Interference

$$\frac{dP}{d\Omega} \propto N^2$$

$$\Omega \propto \frac{1}{N}$$

$$P \propto N$$

N = number of magnetic periods (~100)

$$\gamma^{-1} = \frac{m_0c^2}{E_e} = \frac{0.511}{E_e(\text{GeV})} \text{ mrad}$$

Figure 1. Synchrotron radiation sources include (a) historically significant bending magnets, with relativistically narrowed radiation patterns, (b) multiperiod strong field wigglers, and (c) many period coherent undulators.

Undulators are fundamentally different. As structures for which $K \lesssim 1$, the radiated fields associated with various magnetic periods all fall within the primary radiation cone of the individual relativistic electrons. Consequently, interference effects occur between radiation from the various periods. This results, for instance, in N-fold field additions on axis, or N^2 increases of power density (intensity) on axis. To the present synchrotron radiation community this would be described as greater source "brightness". More significantly, undulators have introduced substantial coherent radiation opportunities to important regions of the spectrum.

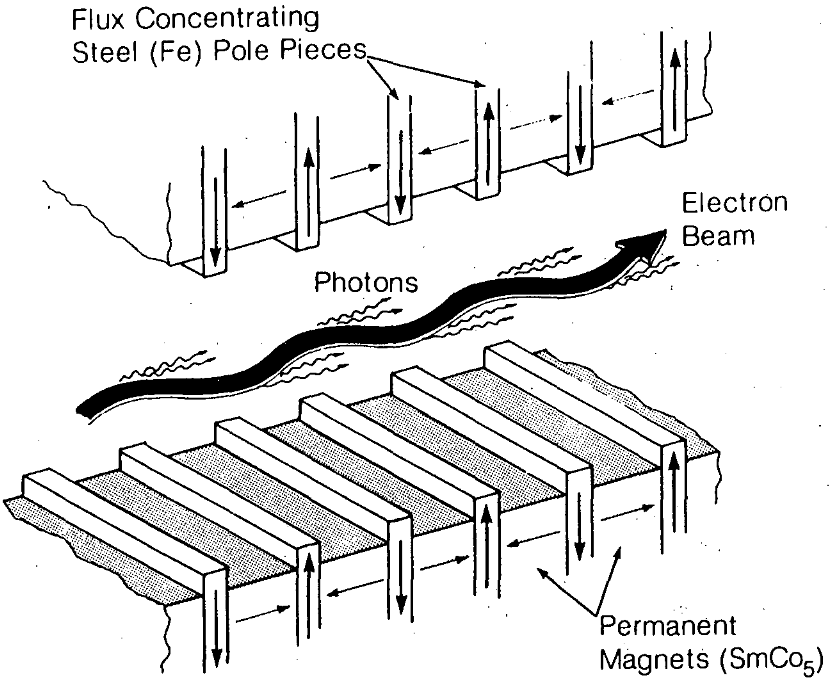


Figure 2. Many period magnetic insertion devices generate an N-fold increase of radiated power. Wigglers are strong field structures, driving electron trajectories of large angle, leading to an incoherent superposition of fields. Undulators employ electron deflections within the nominal radiation cone, such that the coherent superposition of fields dominate - leading to on axis field intensification, radiation cone narrowing, and substantial coherence properties in modern low-emittance storage rings.

III COHERENT UNDULATOR RADIATION

The spectral characteristics of undulator radiation can be understood by considering the radiation seen by an observer fixed in the laboratory frame, looking directly at the relativistic electron as it passes through the magnetic structure. Electromagnetic waves, emitted as the electron passes successive periods of the structure, will arrive at the fixed observer at times seperated by $\Delta t = \lambda_u (1-\beta_z)/c$, where λ_u is the magnetic period length, c is the velocity of light in vacuum, and $c\beta_z$ is the electron's average velocity in the z-direction. In the extreme relativistic case $\beta_z = 1 - (1 + K^2/2)/2\gamma^2$, from which it follows that the radiated fields are relativistically contracted from the undulator period λ_u to an electromagnetic wavelength

$$\lambda_x = c\,\Delta t = \frac{\lambda_u(1 + K^2/2)}{2\gamma^2} \qquad (2)$$

and its harmonics, λ_x/n. Since is large (~1,000), undulator periods of order 1 cm are contracted to soft x-ray wavelengths of order 100 Å, with shorter wavelength harmonics. Changing the magnet gap changes the peak field B_o, providing easily tuned radiation (through variations in K).

In order to realize the full benefits of a coherent undulator it is necessary that the full electron beam be sufficiently constrained in phase space that these interference effects are not washed out. That is to say, the full electron beam must be constrained to an area . solid angle product comparable to a diffraction limited source at the desired wavelength. When this condition is achieved, radiation from the entire electron beam-magnetic structure interaction will be capable of participation in collective interference, e.g., the entire radiated flux will be spatially coherent within a certain coherence length.[4]

The technological breakthrough permitting this extension of coherent radiation techniques to the XUV has been provided by the accelerator design community, which can now construct a storage ring whose electron beam is characterized by a space . angle phase space "emittance" comparable to that of a diffraction limited radiation source of 100Å wavelength. Quantitatively, the resulting radiation will be spatially coherent if the phase space of the electron beam, described by the horizontal and vertical emittances ε_x and ε_y, are equal to or less than the diffraction limited radiation phase space defined by $d(2\theta) = 2.4\lambda_x$, where λ_x is the wavelength. When this condition prevails, that is when

$$\varepsilon_x\,\varepsilon_y \leqq (2.4\lambda_x)^2, \qquad (3)$$

the resulting radiation will be fully spatially coherent. The spatial radiation pattern of an undulator designed for Berkeley's proposed ALS synchrotron radiation facility[5] ("Advanced Light Source") is shown in Figure 3.

Undulator radiation is both spatially and longitudinally coherent, displaying spectral peaks* of width $\lambda_x/\Delta\lambda_x \sim N$ as illustrated in figure 4. The coherence length, for

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* As pointed out by B. Kincaid of Bell Laboratories, the higher harmonics, as in his 20th harmonic optical klystron, are threatened by period to period random variations in magnetic field strength. However, present fabrication tolerances provide sufficient fidelity to assure performance of the fundamental and low order harmonics of interest in this paper.

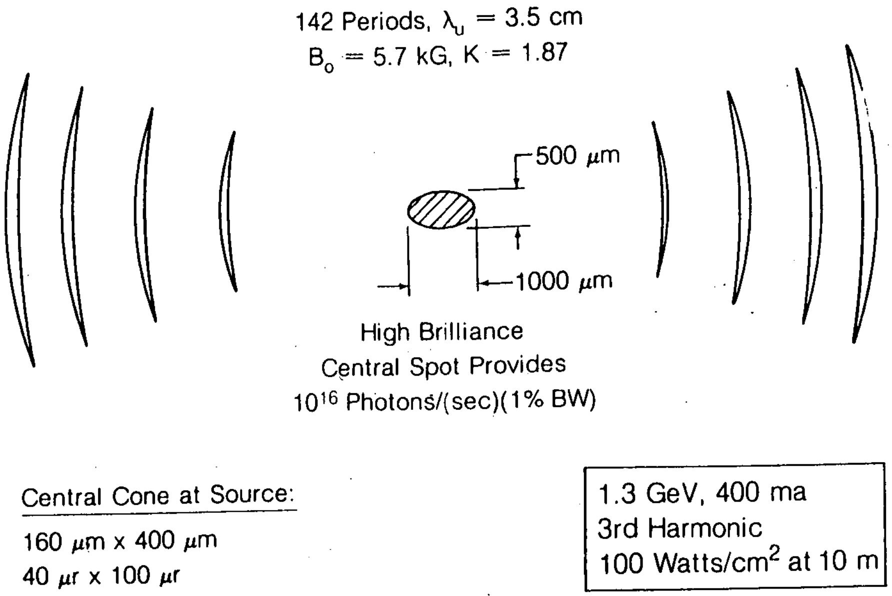


Figure 3. The spatial distribution of undulator radiation, demonstrating coherent interference at 500 eV photon energy. Calculations are for undulator D, of the proposed ALS synchrotron facility at Berkeley (Ref. 5).

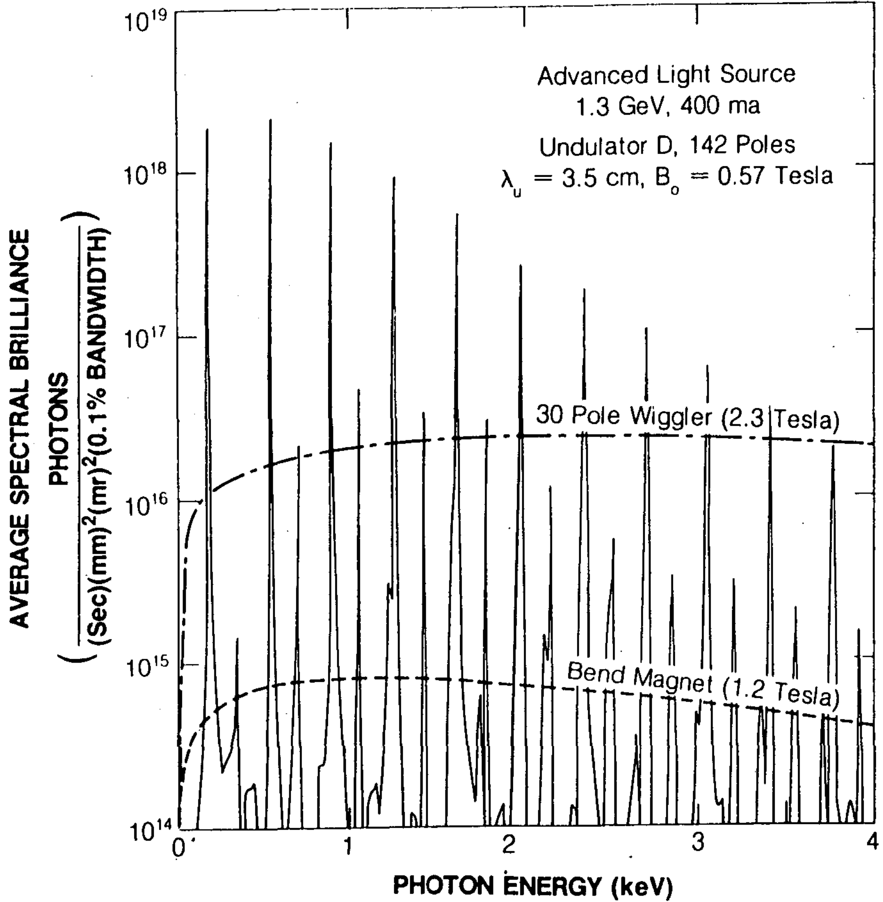


Figure 4. Spectral Characteristics (harmonic structure) of undulator D radiation is compared with that of a wiggler and a bend magnet at the ALS.

interference of mis-matched experimental path lengths, is defined as $l_c = \lambda_x^2/\Delta\lambda_x = N\lambda_x$. For a 100 period undulator radiating at a fundamental of 100Å, this would give a 1 μm coherence length, sufficient for instance for many anticipated soft x-ray microprobe and microholography experiments. Where longer coherence lengths are required, or where greater spectroscopic purity is required, one can introduce monochromators for order of magnitude improvements, with proportionate losses of power. The issues of spatial and longitudinal coherence are summarized in figure 5.

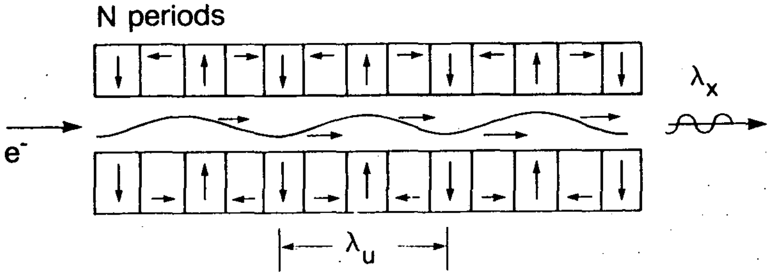
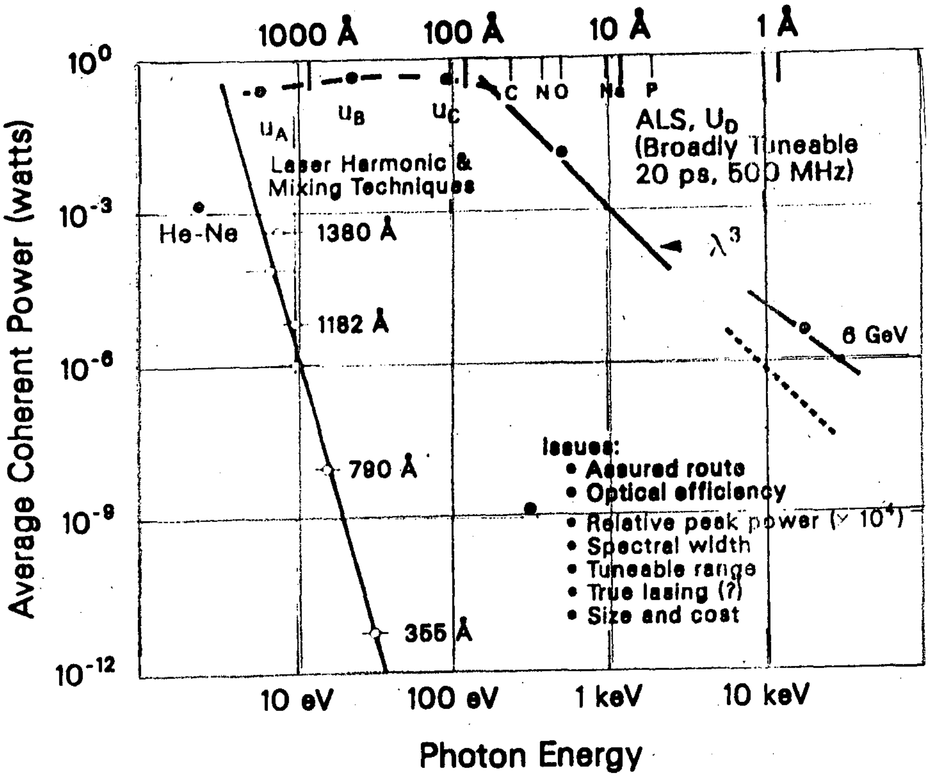


Figure 5. Quasi-coherent soft x-rays are produced in a straight forward manner via the interaction of a well controlled low "emittance" relativistic electron beam and a high fidelity magnetic undulator. Relativistic contraction gives a radiation wavelength $\lambda_x = \lambda_u/2\gamma^2$. Further, the relativistically narrowed cone and small beam size (phase space, $\Delta A \cdot \Delta\Omega$), lead to near diffraction limited (spatially coherent) soft x-rays. The longitudinal "coherence length" is given by $l_c = \lambda_x^2/\Delta\lambda_x = N\lambda_x$.

To the extent that the above two criteria for spatial and longitudinal coherence are satisfied, all photons produced by the undulator-electron beam interaction are fully capable of mutual interference. At optimum or longer wavelengths, the coherent volume is set by, and fully includes, the full spatial extent of the electron beam, through a coherence length set by the relativistically contracted length of the undulator. For shorter wavelength radiation shorter than determined by equivalent electron and photon phase spaces, aperturing must be employed to assure full spatial coherence. For the ALS undulator D, designed for 3rd harmonic radiation at 500 eV (24Å), moderate aperturing and monochromatization results in fully coherent soft x-ray radiation at an average power level of 10 milliwatts, with a coherence length of several microns. The radiation will be tuneable over a broad spectral range including the K-edges of such important elements as carbon, oxygen and nitrogen. Further, the radiation will occur in 20 psec pulses at a 500 MHz repetition rate.[6] Similar performance will be available in the VUV utilizing separate undulators specifically designed for that purpose, and placed elsewhere in the ring. The proposed ALS has twelve long straight sections to accomodate different undulators optimized for use in different spectral ranges. The projected ALS capabilities are summarized in Figure 6 for four of its undulators (A, B, C, and D).

For comparative purposes, Figure 6 also shows the results of recent non-linear laser harmonic and mixing experiments.[7] Producing radiation in 10 psec to several nsec bursts, at typically 10 Hz repetition rates, these radiation sources fall off very rapidly in power as they extend to photon energies beyond ten eV, typically as wavelength to an exponent of order the non-linearity involved, e.g., λ^9, etc.



*Full spatial coherence; longitudinal coherence ≥ 1μm

Figure 6. Broadly tuneable coherent radiation will be available - via an assured route - at interesting power levels throughout the VUV and soft x-ray spectral ranges. Laser harmonic and mixing techniques are not competitive in the region beyond 10 eV. Potential XUV lasers may someday provide narrower spectral features and higher peak powers, but will not likely provide broad tuneability, and thus are complimentary to coherent undulator techniques. Undulators may also enjoy additional capabilities as bunching techniques and mirrors (FELs) become available.

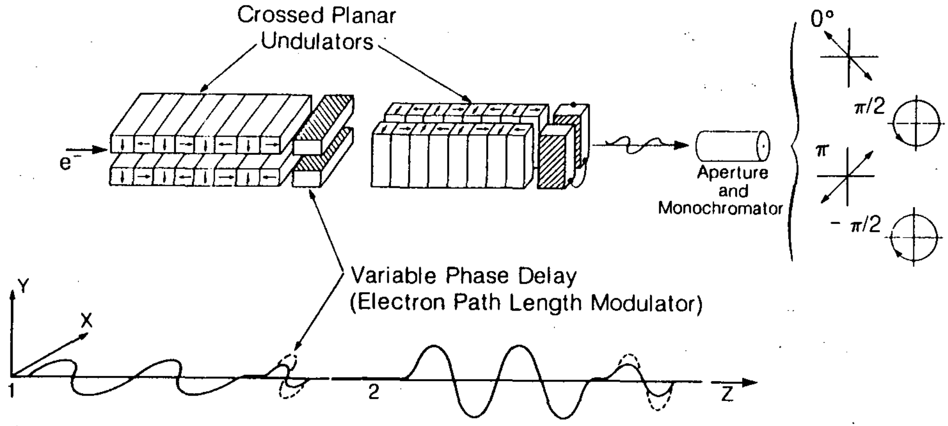
In addition, we note that if available, true lasers would be characterized by narrower spectral content and higher peak power, thus complimenting tuneable coherent undulator radiation capabilities as described here. At the present, however, high reflectivity mirrors do not exist for the XUV, although progress is being made.[8] If such optics did become available, the undulator/storage ring techniques described here could be operated as XUV Free Electron Lasers (FELs), also broadly tuneable, but of greatly increased spectral purity and power. Other proposed schemes for (soft) x-ray lasing are likely to be of high spectral purity, perhaps involve a few discrete spectral lines, but not be broadly tuneable, across absorption features of interest to the experimenter. In addition, such potential lasing schemes would likely be single pass super-radiant schemes, also quasi-coherent in nature. They are also likely to be driven, at least in their early stages, by large pulsed energy facilities, for example, high power lasers originally developed for inertial fusion.

Table I. Typical parameters for a soft x-ray undulator.

• **Electron Beam Energy**	**1 GeV** ($\gamma = \frac{E}{m_oc^2} = 2{,}000$)
• **Beam Current**	**0.4 amps**
• **Magnetic Wavelength (λ_u)**	**3 cm**
• **Magnetic Periods (N)**	**100**
• **Photon Wavelength (λ_x)**	$\frac{\lambda_u}{2\gamma^2}$ **= 25Å (500 eV)** **(Broadly tuneable 100eV to few keV)**
• **Bandwidth** ($\frac{\lambda_x}{\Delta\lambda_x}$)	**N = 100**
• **Angular Width (2θ)**	$\frac{1}{\gamma\sqrt{N}} \sim 50\ \mu$**rad**
• **Polarization**	**Linear, circular, . . .**
• **Radiated Power**	**1 watt cw in 20 psec bursts**
• **Coherent Power**	**10 milliwatt at 500 eV, tuneable (spatially coherent,** $\ell_c = \frac{\lambda^2}{\Delta\lambda} \sim$ **few microns)**

IV. POLARIZATION CONTROL

In addition to the space-time characteristics of electromagnetic radiation, there is also polarization. In this section we describe a method[9] which utilizes a sequential pair of crossed undulators to obtain complete polarization control. The idea is illustrated in Figure 7. Each undulator produces radiation on axis of linear polarization. By properly overlapping the two cross-polarized wave trains it is possible to produce linear or circular polarization, depending on their relative phases. Phase variation in this scheme is controlled by an electron path modulator between the two linear undulators - effectively using modulated electron transit time to the second undulator as a means of varying phase between the two wave trains - each of which is driven by the electron beam. In order to maintain well defined polarization and phase control it is again necessary that the electron beam emittance be small. Variable polarization control is expected to play an important role in future experiments, such as in probes of bio-chemical structures in which image contrast or differential scattering signals are provided by polarization sensitive scattering from structures in which the diameter or helical pitch may be of sizes comparable to the probing VUV or soft x-ray wavelength.



Mechanical Modulation at 1 Hz
Magnetic Modulation at 10 kHz

Figure 7. Variably polarized radiation can be generated by using crossed undulators in low emittance storage rings.

Table II summarizes parameters which characterize variable polarization capabilities that could be provided at two potential sites, Brookhaven's present VUV ring, and Berkeley's proposed ALS.

Table II Two potential sources of variable polarization radiation are described.

Ring	VUV (NSLS)	ALS
E_e	750 MeV	1.3 GeV
σ_θ	9×10^{-2} m.r.	2×10^{-2} m.r.
N	5	30
λ_u	10 cm	4 cm
λ_1 (ϵ_1)	470 Å (26 eV)	47 Å (260 eV)
$\Delta\lambda/\lambda$	4%	0.14%
P	86%	84%
Flux at Sample (1% Optical Eff)	$\sim 10^{12}$ Photons/sec	$\sim 10^{12}$ Photons/sec

V. CONCLUSION

Coherent VUV and soft x-ray radiation is predictably available with modern low emittance storage rings and permanent magnet undulators. While covering a wide spectral region, with broadly tuneable radiation, these facilities will provide pulses typically of 20 psec duration, at a 500 MHz repetition rate. In Table II, we have summarized typical parameters for a soft x-ray undulator. In addition to providing an assured route to the earliest coherent XUV radiation experiments, these multi-user facilities will eventually be upgradable to Free Electron Lasers as high reflectivity mirrors become available, thus assuring the facilities of long and prosperous lifetimes.

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