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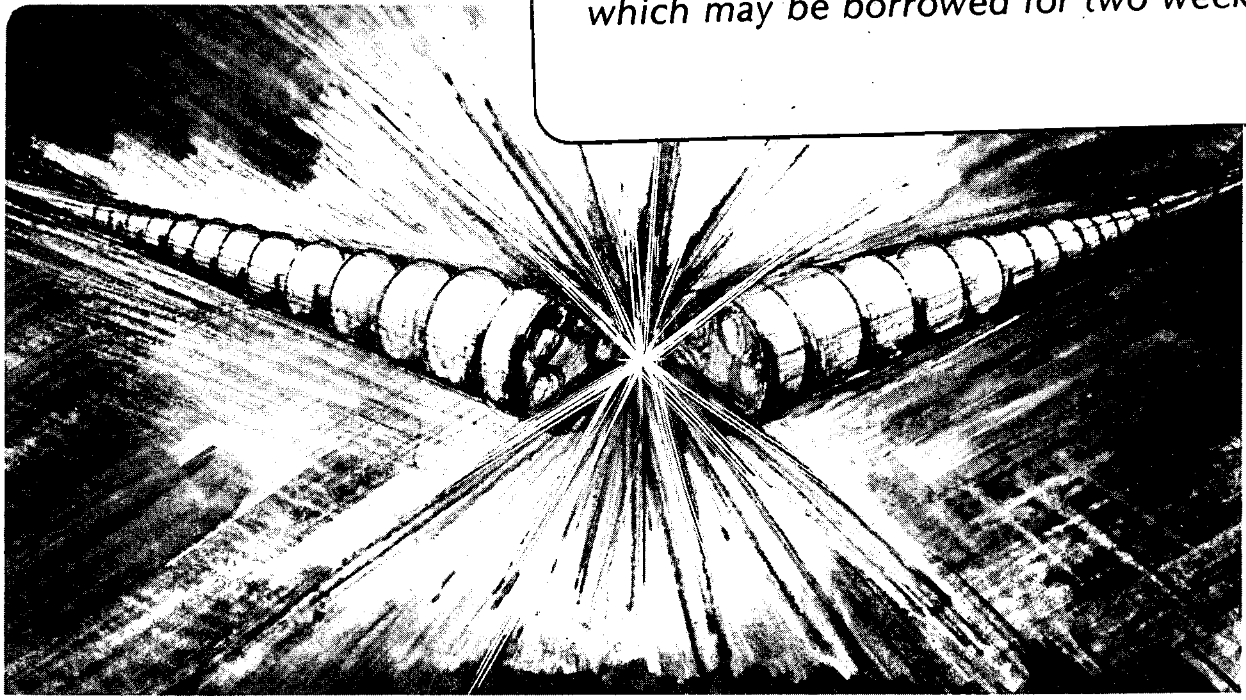

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Partial Coherence and Spectral Brightness at X-ray Wavelengths

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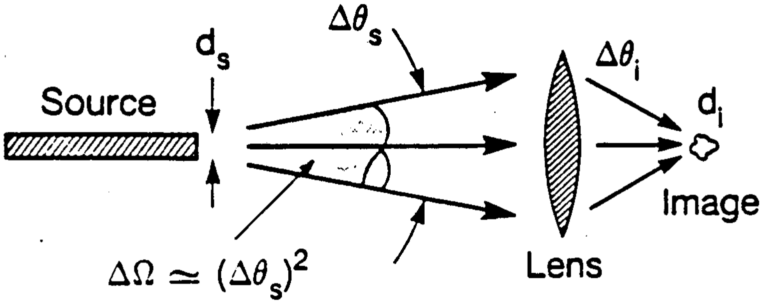
Microscopic examination of physical and biological systems requires short wavelength radiation which can be focused to very small dimensions. Indeed it is possible in the limit to both "see" and "write" features approaching the radiation wavelenghth λ, and furthermore to identify particular chemical elements through their characteristic electronic transitions. Sources of radiation which can deliver a substantial flux of photons to very small dimensions are said to be of high brightness. Sources of high brightness radiate a large photon flux (photons/second), from a small area · solid angle product ($\Delta A \cdot \Delta \Omega$). If, in addition, the photons are emitted within a spectrally narrow region, $\Delta\lambda$, the radiation is said to be of high spectral brightness. The focusability of such radiation is, however, set by additional attributes of spatial coherence and, of course, by available optics [1]. The emphasis in this paper is on radiation which is not only of high spectral brightness, but which has additional attributes which permit it to be focused to dimensions approaching that set by its finite wavelength, λ. With a near perfect lens [1] such radiation could be focused to dimensions approaching the Rayleigh limit, 1.2 Fλ, where F is the lens F number. Spatially coherent radiation, capable of being focused to wavelength limited dimensions, is often referred to as "diffraction limited". Figure 1 illustrates the concept of source brightness and focusability.



$$B = \frac{\text{Power}}{\Delta A \cdot \Delta\Omega}$$

$$SB = \frac{\text{Power}}{\Delta A \cdot \Delta\Omega (\%BW)}$$

Fig. 1. The left side of the illustration shows a source of aperture d_s radiating into a cone of full angle $\Delta\theta_s$. The brightness of a radiation source measures the power, or photon flux, per unit area and per unit solid angle. For small angles $\Delta\Omega = (\Delta\theta_s)^2$. Brightness is an important measure because it is a conserved quantity in a perfect optical system. For a perfect lens the notion that "brightness is conserved" leads us to $d_s \cdot \theta_s = d_i \cdot \Delta\theta_i$. In a real optical system lens and mirror efficiencies, imperfections, and aberrations modify this statement.

If one considers the propogation of such radiation from its source, to and through requisite optics, it is convenient to describe the radiation in terms of field properties along and transverse to the local propogation direction. It is the transverse properties that determine focusability. When the fields are perfectly correlated everywhere along transverse contours, the radiation is said to be of full transverse coherence, equivalent to being "diffraction limited". Phase correlations in the propogation direction are related to longitudinal or "temporal" coherence. Assuming sufficient transverse coherence properties, the ability to form interference patterns ("fringes") in interferometers, or in holographic recordings, is often described in terms of the longitudinal coherence length [2],

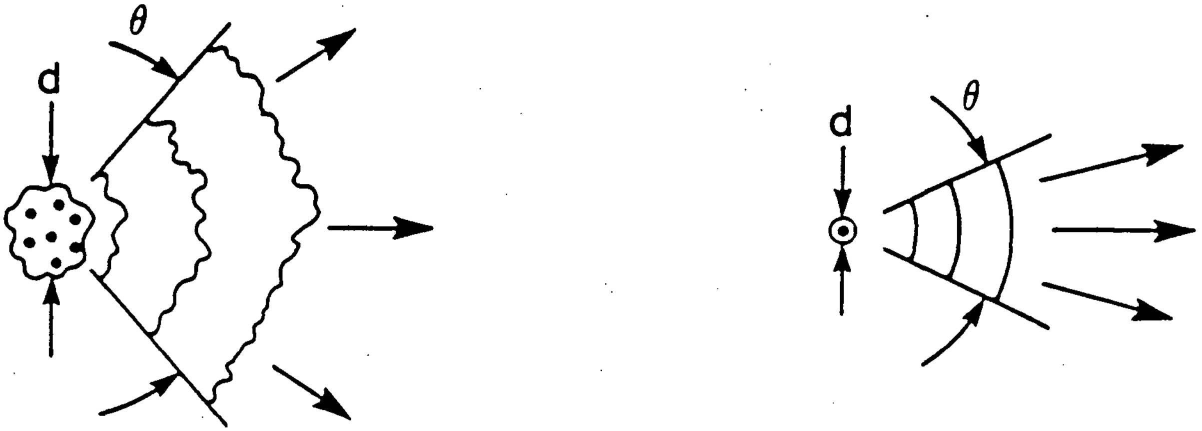
$$\ell = \lambda^2/\Delta\lambda \qquad (1)$$

where $\Delta\lambda$ is the spectral width of the radiation.

As described by WOLF [2], the only true source of coherent radiation is a point source which oscillates with a purely sinusoidal motion for all time. Thus all physical sources, at best, generate partially coherent radiation, having finite transverse and longitudinal coherence properties. This paper deals with the emergence of partially coherent radiation at x-ray wavelengths--radiation suitable for early experimentation with x-ray microscopy, x-ray microholography, and interferometry. When considering phase uniformity, it is of value to clearly understand the wavelength imposed limitations to transverse coherence. For a Gaussian intensity distribution one finds the far field spatial and angular widths, measured at $1/e^2$ intensity points, to be given by [3]

$$\frac{d_{1/e^2}}{2} \cdot \theta_{HW1/e^2} = \frac{\lambda}{\pi} \qquad (2)$$

which represents a situation of full transverse coherence, where the phase at any point on an appropriate surface transverse to the propogation direction is unambiguously related to the phase at any other point on that transverse surface. With a proper lens, radiation obeying eq. (2) could be focussed to "diffraction limited" dimensions, set only by the finite wavelength λ, and the lens $F^{\#}$, e.g. to a diameter of $1.2\ F\lambda$. When the radiation is not diffraction limited, that is eq. (2) is not met, $d \cdot \theta >> \lambda$, the focussing properties are not as good. As illustrated in Fig. 2, the wavefront is no longer spherical, no longer characterized by a single propogating mode, but rather is multi-mode in nature.



$d \cdot \theta > \lambda$ $\qquad$ $d \cdot \theta \simeq \lambda$

Fig. 2. Diffraction limited radiation is characterized by a size-angle product $d \cdot \theta$ just equal to the wavelength. According to the uncertainty principle radiation characterized by that wavelength and radiation cone (θ), could not be used to infer spatial detail of the source any smaller than d. The resultant phase contours are "wrinkle-free" and excellent for phase-sensitive interference experiments like holography, interferometry, and wavelength limited microscopy. A source characterized by $d \cdot \theta > \lambda$ generates a radiation field characterized by irregular phase contours, is not near the uncertainty or wavelength limit, and in general is not as useful for phase sensitive applications.

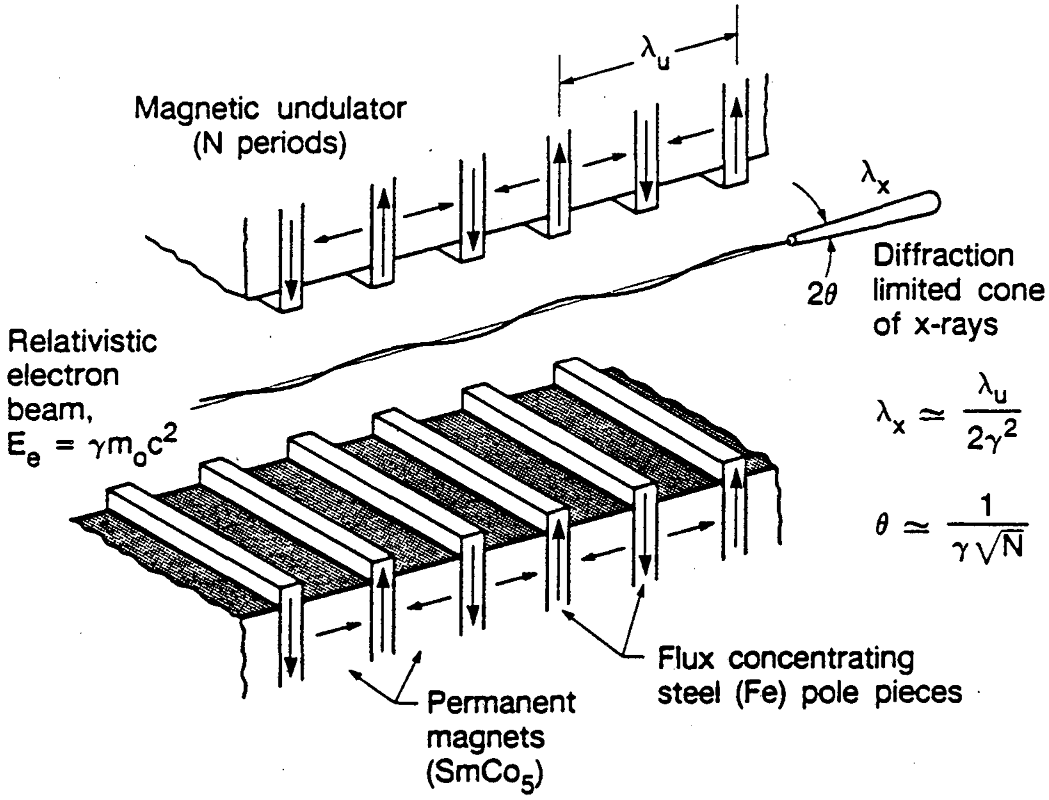


Fig. 3. Undulator radiation is emitted when relativistic electrons traverse a periodic magnet structure. Near diffraction limited radiation results when the electron bunch is contained within a very small phase space, e.g., within a small transverse dimension and within a very narrow angular (trajectory) cone. Modern relativistic storage rings strive to contain the electrons to a phase space volume comparable to that set by diffraction limits at the radiation wavelength, e.g., $(d \cdot \theta)_{e'} \approx (d \cdot \theta)_{x\text{-ray}} \approx \lambda$.

Two particularly interesting sources of partially coherent radiation at short wavelengths, each at the forefront of research on very high brightness radiation, are magnetic undulators on modern electron storage rings, and plasma driven x-ray lasers. Undulators, as illustrated in Fig. 3, are periodic magnet structures traversed by relativistic electrons, typically of energy 1-10 GeV. The radiation from the resultant oscillations is Lorentz and Doppler shifted to very short wavelengths in the ultraviolet and x-ray spectral regions. The radiation cone is greatly narrowed, to units measured in microradians, by these same relativistic effects. If the electrons are maintained within a bunch of small lateral extent and limited random angular motions--that is, within a very small phase spare volume--the resultant radiation can have very good coherence properties. The interesting feature of new storage rings is that the electron beam is contained in an extremely small phase space--or "emittance" as the accelerator community refers to it--allowing the generation of diffraction limited radiation down to soft x-ray wavelengths. For a ring of electron energy $E = \gamma m_0 c^2$, with a periodic magnet structure (undulator) of N periods and periodicity λu, the radiation wavelength is given by

$$\lambda_x = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{3}$$

where K is the magnetic deflection parameter, and where the radiation cone half angle is

$$\theta_{1/2} = \frac{1}{\gamma\sqrt{N}} \tag{4}$$

For a 1.5 GeV machine $\gamma = 3{,}000$, N is of order 100, $K = 0(1)$, and λ_u is typically measured in centimeters. For best performance the storage ring must have an emittance less than or equal to the phase space of diffraction limited radiation at the wavelength generated. Comparing to eq. (2) this requires that the electron beam be contained in a phase-spare such that [4,5,6]

$$\pi \sigma \sigma' < \frac{\lambda}{4} \tag{5}$$

where σ and σ' are the rms measure of electron beam spatial and angular extent, e.g. $\pi \sigma \sigma'$ is the elliptical phase space area. For radiation generated at wavelengths shorter than the phase-space matching condition, eq. (8), the fraction of photon flux or power which is spatially coherent decreases by λ^2, corresponding to the two transvers directions. Another factor λ accrues from decreased coherence length (see eq. 1), so that at decreasingly short wavelengths, coherent power generally declines in proportion to λ^3.

The second major source of very high brightness radiation at short wavelength is that of x-ray lasers. Short wavelength lasers took a giant step in the last three years with the successful plasma driven laser experiments at Lawrence Livermore National Laboratory, [7,8,9] Princeton University, [10,11,12] and more recently, at the Naval Research Laboratory [13]. In these experiments a high power visible (2ω Nd, LLNL) or infrared (CO_2, Princeton) laser is used to form a high temperature, high density plasma of highly ionized atoms. In the Livermore experiments, initially in selenium, the heated atoms collide frequently, stripping off electrons, until a balance is reached between the energy of the colliding ions, and the energy to remove one more electron. Generally an ionization bottleneck can be arranged at some closed shell, as in neon-like selenium, Se^{+24}, where a large fraction (10-30%) of a single ionic configuration is achieved. This is set by choice of the atom (z-dependent ionization energies for the closed shell) and choice of laser intensity, which controls temperature. Collisional pumping of these closed shell ions can then result in lasing as the ion is excited to energy levels for which allowed transitions and decay times result in a population inversion of the proper time scale (matched to the laser-plasma heating and disassembly time) and density to result in observable gain. Multimegawatt outputs in sub-nanosecond pulses have been observed for $3p \rightarrow 3s$ transitions at 206 and 209 Å in Se plasmas. Lesser outputs have been achieved in yttrium at 154 Å, and molybdenum at 131 Å, using the same scheme of collisionally pumping on neon-like ions. More recent results at Livermore [8] have involved nickel-like atoms, such as europium, where lasing has been observed at 71 Å.

The Princeton results [10,11,12] involve CO_2 laser generation of a magnetically confined carbon plasma. In this case the carbon atoms are fully stripped, and then allowed to recombine with electrons as the plasma expands and cools. As the electron cascades down towards the ground state, it too has achieved lasing on a $3 \rightarrow 2$ transition, at 182 Å. Very high peak powers have also been achieved with these recombination lasers. In both recombination and collisionally pumped lasers, plasma heating and expansion lead to relatively large phase-space volumes of the lasing medium, so that the radiation field is far from diffraction limited, e.g. multimode in nature. Very interesting schemes have been proposed to provide mode control, albeit at a concomitant price in output power. One such idea, an offshoot of earlier ideas on "dot spectroscopy" of laser-plasmas, involves imbedding a very thin lasant plasma column within a larger plasma medium [14]. Figure 4 illustrates the concept. Efforts to achieve shorter wavelenghts, moving towards the biologically interesting water window (23 to 44 Å), continue to make progress, but are limited by problems of energetics (ion stripping and excitation), and the avoidance of non-thermal heating processes at higher laser intensities.

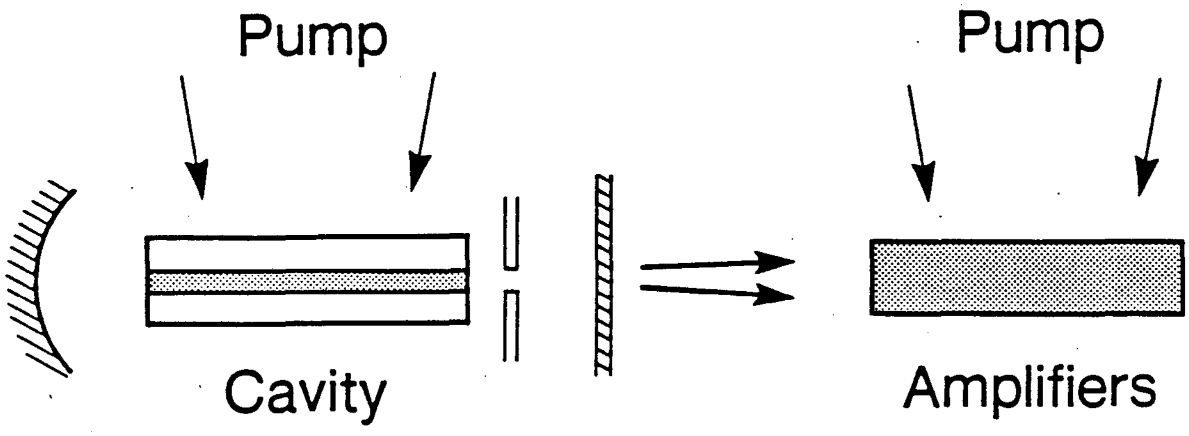


Fig. 4. A scheme for including transverse mode control in a laser-plasma pumped x-ray laser (following reference [14]). The lasant material is contained in a thin filament surrounded by hydrodynamically similar plasma. The pinhole and mirror would limit gain to the lowest order mode. Mirror reflectivities and multi-pass gain duration are areas for future development.

Comparison of the various radiation sources is problematical as each has its own advantages and thus is suitable to differing applications. For instance some applications are critically dependent on exposure time or peak intensity, while others are not. Most applications require a certain minimum number of photons within a specified wavelength range or coherence length. Some are critically dependent on reaching a specified atomic or molecular transition energy--and perhaps tuning through that resonance--while others are not. For phase sensitive applications, which may demand a diffraction limited phase front, and thus coherence is an issue; for other applications simple brightness, spectral brightness (within a specified relative bandwidth), or photon flux may suffice. Thus in Figs. 5, 6, 7 and 8 we present graphs of both peak (single pulse) and average values of spectral brightness and coherent power. Achieved values are shown as solid lines or circular data points. Anticipated performance is shown as dashed lines. Typical repetition rates for storage rings are in the 100 MH_Z range.

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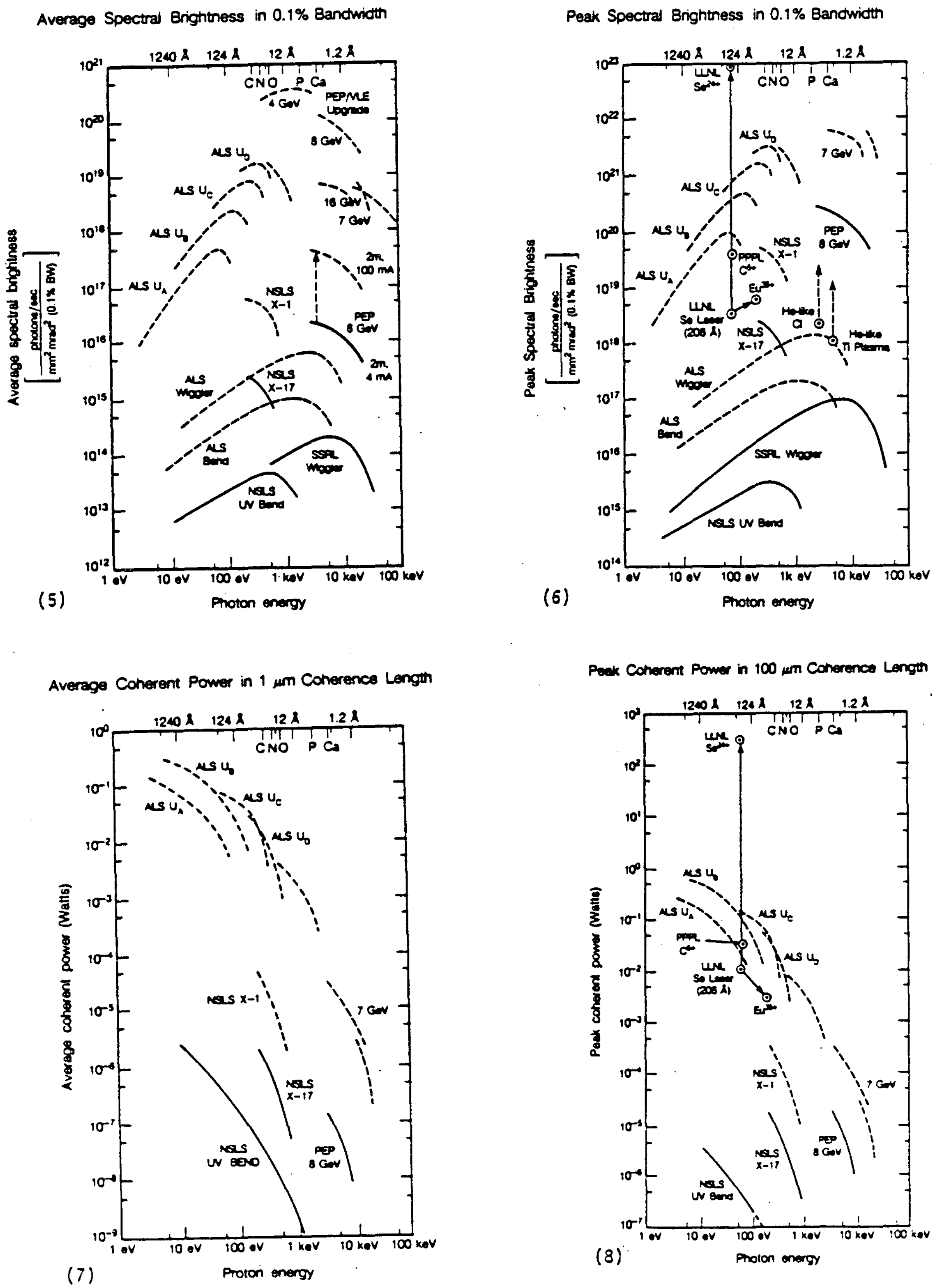

Figs. 5-8. Spectral brightness as a function of photon energy is shown for several sources of short wavelength radiation. Average and peak (single pulse) quantities are shown for both. Shown are various sources of synchrotron radiation lasers and laser heated plasmas. Graphs of average and peak coherent power are shown separately. Coherent power is taken to be diffraction limited and of the longitudinal coherence specified e.g. one micron or 100 microns.

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