PERFORMANCE REQUIREMENTS AND METRICS FOR FUTURE X-RAY SOURCES*

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Abstract

The future directions of x-ray science and the photon beam properties required to pursue them were recently evaluated by a joint LBNL–SLAC study group [1]. As identified by this group, essential x-ray capabilities for light sources in the future (but not necessarily from any single source) include: 1) x-ray pulses with Fourier-transform-limit time structure from the picosecond to attosecond regime, synchronized with conventional lasers, and with control of longitudinal pulse shape, amplitude and phase; 2) full transverse coherence; 3) high average flux and brightness for some applications, and high peak flux and brightness for others; and 4) energy tunability in soft and hard x-ray regimes, and polarization control. Metrics characterizing source properties include not only average and peak spectral brightness but also the photons per pulse (both incoherent and coherent) and repetition rate as a function of pulse length, and the proximity to transform-limited dimensions in six dimensional phase space. We compare the projected performance of various advanced x-ray source types, with respect to these metrics and discuss their advantages and disadvantages.

ACCELERATOR-BASED SOURCES

The major options for x-ray light sources in the 10–20 year time frame, based on the essential new scientific capabilities identified in [1], include storage rings, energy-recovery linacs (ERLs) and free-electron lasers (FELs), based on projections from the present state of the art. A combination of these types of sources is projected to be required to meet all of the needs. While undulators are the primary source of photons for all sources described here, their performance characteristics are strongly linked to the accelerator technology used, and our discussion is in terms of accelerator type accordingly.

GRAPHICAL REPRESENTATION OF SOURCE CAPABILITIES

Brightness

X-ray source brightness is defined as photon density in 6-dimensional phase space, with phase space dimensions defined by horizontal and vertical beam size and divergence, time and fractional bandwidth of energy (or frequency). The usual units for brightness are photons/s/mm^2/mrad^2/0.1% bandwidth. Average and peak brightness of various source types are compared in Figure 1. In this and in all figures here, the envelopes shown are representative but not fully inclusive of all sources that exist or are envisioned. The high average brightness from the linac- and ERL-based FELs, all of which have low repetition rate compared to ring- and ERL-based spontaneous sources (see Fig. 2), is not usable by a large class of experiments due to the associated very high peak brightness, which can excite extreme states or cause damage in samples. Brightness of the seeded FEL sources is increased by their intrinsically narrow bandwidth, which can approach the transform limit, and can be several orders smaller than incoherent sources (see Fig. 4). The CW soft x-ray FEL envelopes represent spectra for beam from a fixed linac configuration; hard x-ray FEL envelopes represent estimates for a variety of source configurations. ERL-based, single-pass FELs may achieve peak brightness comparable to the CW and pulsed linac FELs, and average brightness comparable to the CW linac FELs indicated. Future-technology ERL performance assumes a 25-m undulator in high-flux mode (31 pm-rad, 100 mA); 3.5–8-m undulators are assumed for large-circumference "ultimate" ring performance. Peak brightness from advanced 3rd generation ring sources having long undulators (~20 m) and operating with a large current per bunch (>~3 mA/bunch) in a small number of bunches approaches that shown for "ultimate" rings having shorter undulators and much less current per bunch. The peak brightness from long undulators on "ultimate" rings would be greater than shown if they too were operated with greater current per bunch.

Pulsed FELs are presently in construction. CW-linac FELs and ERLs require future technology; notional designs indicated are for a 100-kHz bunch rate CW soft x-ray FEL and a 1.3-GHz bunch rate hard x-ray ERL. The range shown for FEL performance reflects SASE and seeded modes of operation and ability to tune performance over a wide range. The peak brightness for FELs is several orders of magnitude greater than incoherent sources, resulting in high average brightness even at low repetition rate. The average brightness from pulsed linac FELs can be increased by operating with a large number of closely-spaced bunches within the RF pulse of the linac, resulting in a "burst-mode" time structure—in this notional design 4000 bunches spaced by 200 ns repeating at 10 Hz.

For FELs and sub-10 pm·rad emittance ERLs, the flux is spatially coherent; some FELs may have a high degree of temporal coherence. The potential brightness range of a seeded hard x-ray FEL is represented by an x-ray FEL cavity oscillator (XFELO) in Figure 1, in this case based on a 1-MHz pulse repetition rate with low-charge (< ~50 pC) picosecond electron bunches provided by a CW linac,

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multipass recirculating linac, or an ERL, and an x-ray optical cavity tuning system using four crystals movable in position and angle. Other types of seeded hard x-ray FELs using pulsed linacs or high energy CW linacs could have comparable performance to the XFELO. The depicted upper energy limits for linac-based FELs are not absolute; they may be extended with higher-energy linacs. The lower energy bound for all sources extends to the sub-eV (THz) range.

Pulse Structure

The temporal characteristics of the different sources depicted in Fig. 1 are illustrated in Figure 2. Future FEL performance may encompass a wide range including the envelopes shown, dependent on details of design. The number of photons per pulse for FELs is dependent on wavelength and electron-beam energy.

Transform Limits

The quality of a photon source may be characterized by two limits, comparing to a perfectly coherent source. The "diffraction-limited" emittance ε_{ph} of a photon beam expresses the fundamental coupling of transverse source size and angular divergence in the space-momentum domain and defines complete spatial coherence. For a Gaussian beam, $\varepsilon_{ph} = \lambda/4\pi$. For spontaneous radiation generated from magnets in an electron accelerator, the photon beam emittance for a given wavelength is a function of source magnet properties (i.e. undulator or dipole magnet parameters) and of the electron beam emittance. In effect, the radiated photon emittance at a given wavelength is a convolution of the diffraction limited photon emittance and the electron emittance.

As the electron emittance in one transverse plane approaches the diffraction limit for a given wavelength, the degree of spatial coherence, or coherence fraction, of the radiated photons in that plane increases, reaching the order of 50% from undulators when the electron emittance reaches the diffraction limit, subject to the matching of the electron beam emittance ellipse to the diffraction-limited photon beam ellipse.

The coherent fraction increases towards 100% as the electron emittance is reduced below the diffraction limit. In contrast, the amplified radiation from FEL sources is 100% transversely coherent and diffraction-limited in both planes when the emittance of the round electron driving beam is close to or, for sufficiently long undulators, even greater than the diffraction limit, by virtue of "gain guiding", where only a single diffraction-limited radiation mode is amplified to saturation in the FEL process. In Fig. 3 we have plotted the electron beam emittance versus photon energy for the different undulator-based sources of Figures 1 and 2.

Just as the "diffraction limit" characterizes complete spatial coherence, the "Fourier transform limit" defines complete temporal coherence. It expresses the fundamental coupling between energy resolution and time resolution, and is described by the product of time duration and energy width of the x-ray pulse, and for a

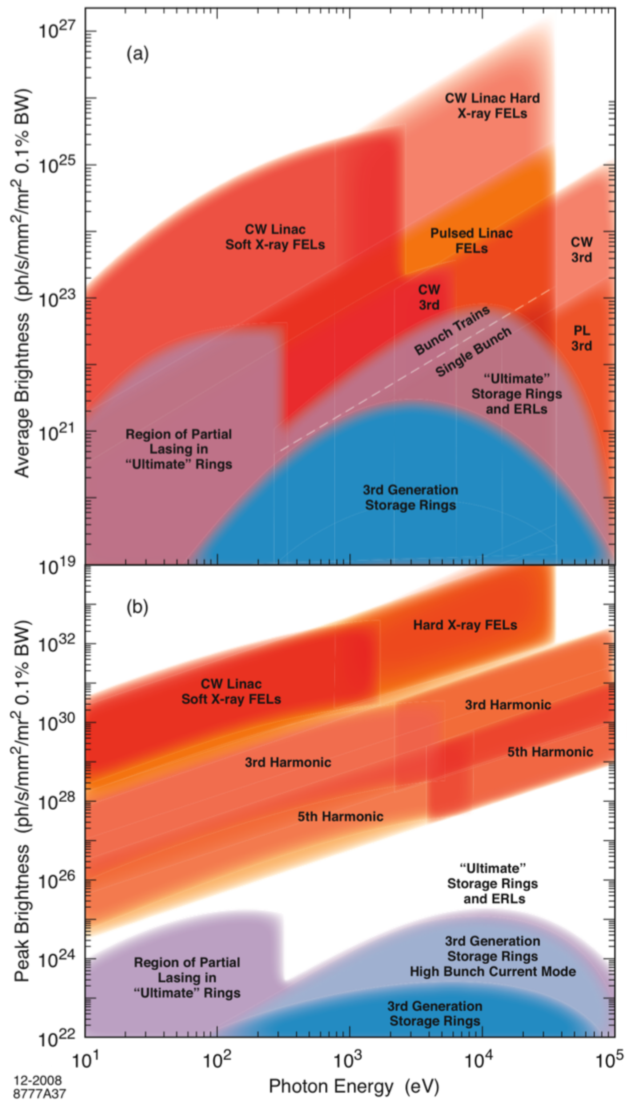

Figure 1: Composite envelopes indicative of the approximate range of average (a) and peak (b) spectral brightness for present and potential future technology source types.

Gaussian pulse intensity is given by $\Delta t \cdot \Delta E = h/4\pi = 0.33 \times 10^{-3}$ [ps (rms) eV (rms)]. In Figure 4, the bandwidth attainable with undulator-based sources is indicated for the notional designs discussed above. Seeded FELs and FEL oscillators with long bunches can approach the transform limit with very narrow bandwidths. For these sources, deviations in the electron phase-space distribution along a bunch are expected to limit the bandwidth to a factor of a few above the transform limit. Narrow bandwidth contributes to increased brightness. The XFELO example in Figure 4 corresponds to a 12-keV photon energy FEL oscillator with narrow bandwidth provided by relatively long electron bunches; other types of seeded hard X-ray FELs could have comparable performance to the oscillator if using similar bunch lengths. SASE FEL envelopes are shown for photon energies of 1 keV and 10 keV. For SASE, the bandwidth is determined by the cooperation length (the distance over which the radiation field moves forward from the electrons in one gain length), not the bunch length. For ultra-short bunches the cooperation length can approach the bunch length, and the (large) bandwidth can be close to the transform limit. For ring and ERL–based sources, undulators radiate the smallest intrinsic fractional bandwidth (given by $\Delta E/E \sim 1/n_u$ where n_u is the number of undulator periods), over a very wide range of photon energies (from a few eV to tens of keV), with bandwidth down to a lower limit imposed by the coherent energy spread in the electron beam (typically $>10^{-3}$ for rings and $>10^{-4}$ for ERLs).

Existing storage-ring spontaneous x-ray sources can produce a maximum photon density that is equal to the

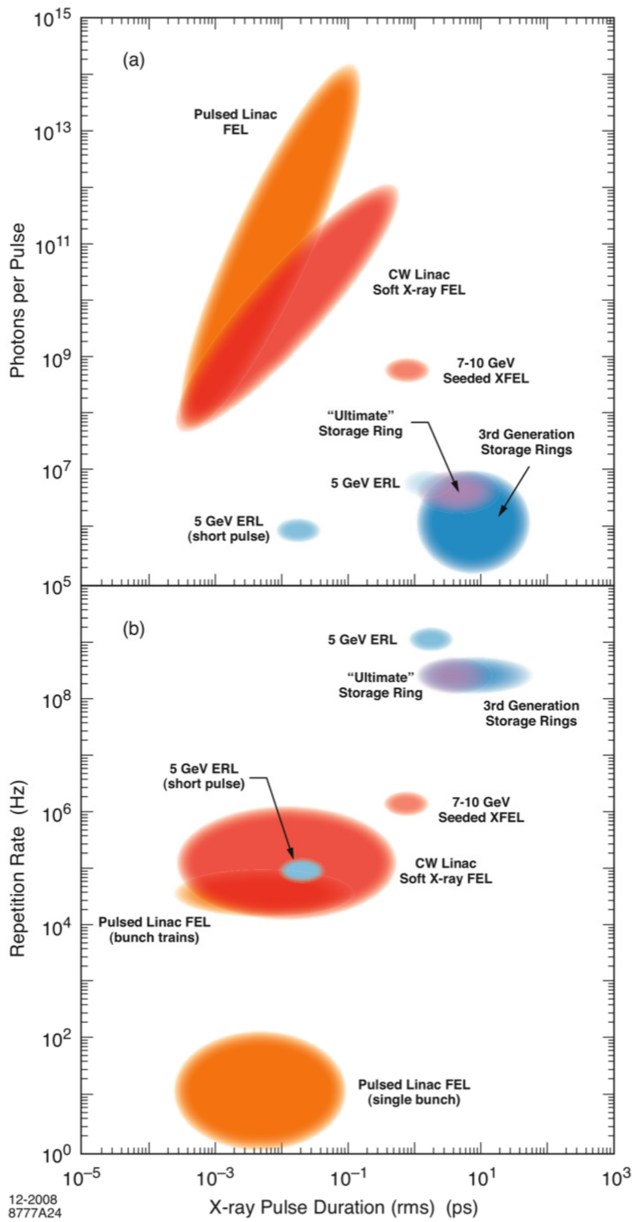

Figure 2: Envelopes indicative of the approximate performance ranges of present and future technology source types illustrating the trade-offs between peak and average performance parameters.

value of the fine-structure constant, or about 0.01 photons per "coherence volume", a unit of phase space whose 6 dimensions satisfy transform limits (sometimes referred to as the degeneracy parameter). ERLs produce photons from a smaller phase-space volume, and may have degeneracy of ~100; FEL sources, through the coherent amplification process, produce highly degenerate x-ray pulses (10^7 or more photons per coherence volume, with further orders of magnitude increased degeneracy obtainable from seeded and oscillator FELs).

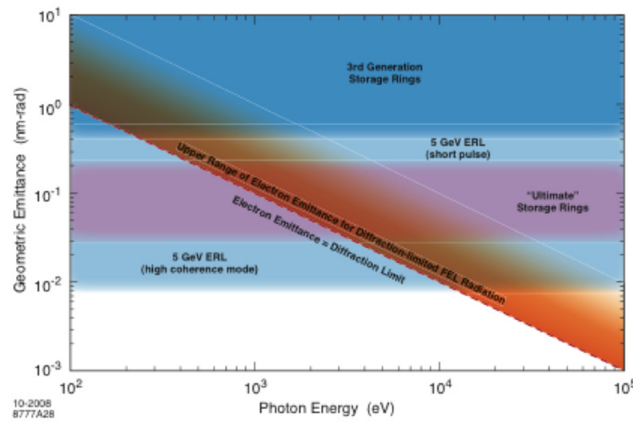

Figure 3: Envelopes indicative of the approximate emittance ranges of present and future sources.

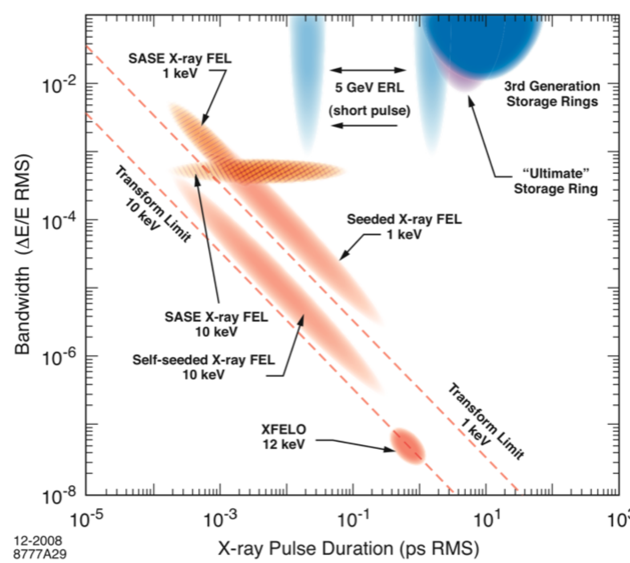

Figure 4: Envelopes illustrating fractional bandwidth capabilities of undulator-based sources in present and future x-ray facilities. Dashed lines indicate the transform limit for 1 keV and 10 keV photon energies. Photon energies are indicated for specific examples used to illustrate coherent sources.

REFERENCES

[1] R. Falcone, J. Stohr et al., "Scientific Needs for Future X-Ray Sources in the U.S. - A White Paper", SLAC-R-910, LBNL-1090E, October 2008.