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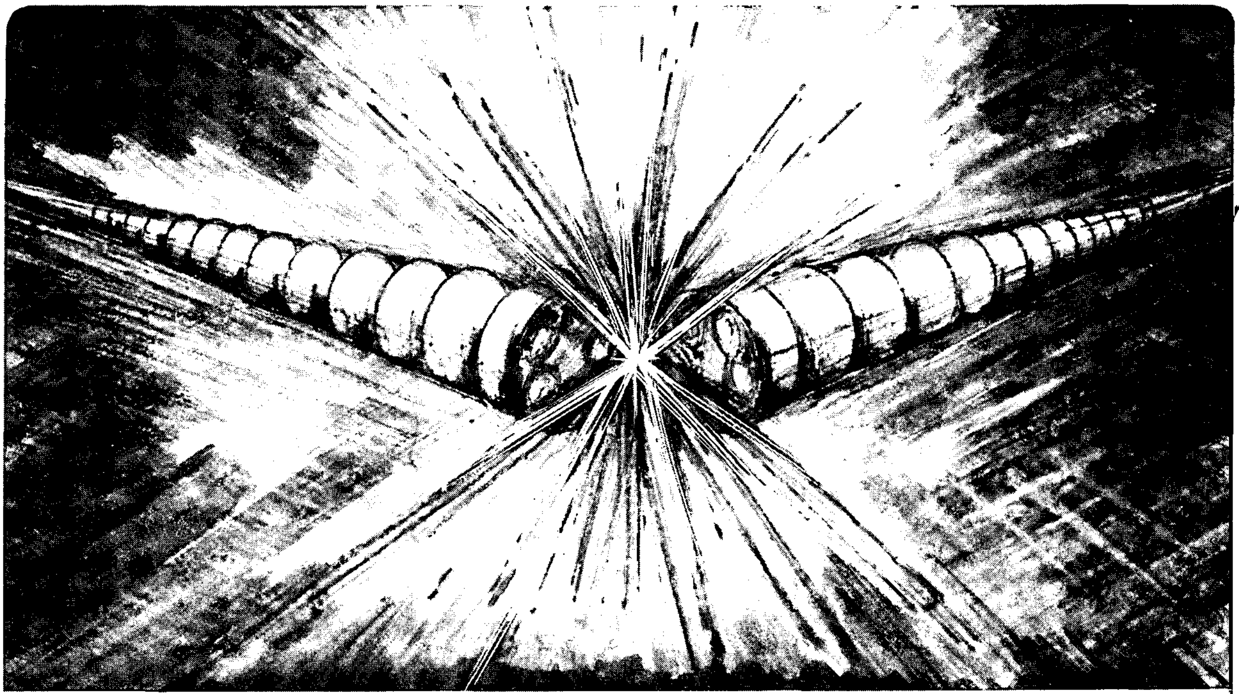

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Ideas for Future Synchrotron Light Sources[1]

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Abstract

Synchrotron light sources have advanced in the past two-to-three decades through three "generations", from irritating parasitic sources on high-energy physics accelerators to dedicated electron and positron storage rings of unprecedented low emittance, utilizing undulator and wiggler magnets. The evolution through these three generations followed a predictable, science-driven, course towards brighter beams of VUV- and x-radiation. The requirements of future light sources is not so clear. The limit on low emittance has certainly not been reached, and diffraction-limited sources at shorter wavelengths would be the natural progression from previous generations. However, scientists are now looking at other radiation characteristics that might better serve their needs, for example, more coherent power, fast switching polarization, ultra-short (sub-picosecond) time structure, and synchronized beams for pump-probe experiments. This paper discusses some current ideas that might drive the fourth-generation synchrotron light source.

1. INTRODUCTION

Through the first three generations of synchrotron light sources, scientists have focused progressively more attention on tailoring source characteristics to a particular set of user requirements. In particular, the development of third-generation sources has led to storage rings within two distinct energy bands, to service two complementary regions of the electromagnetic spectrum [1]. We believe that this trend will continue, and that the next generation of light sources will be even more application-specific. These views were strengthened by presentations and conversations at the Workshop on Fourth-Generation Light Sources, held at the Stanford Linear Accelerator Center (SLAC) in February 1992. Much of the content of this paper is distilled from material either presented or developed at that workshop.

The goal of fourth-generation sources will be to provide diffraction-limited radiation, maybe in very short pulses (down to fractions of a picosecond), in the wavelength range of interest. Already free-electron lasers (FELs) have demonstrated performance to wavelengths down to 240 nm with an energy resolution, $\Delta\lambda/\lambda$, of 4×10^{-6} [2]. Third-generation storage rings are promising particle beam emittances that will give diffraction-limited radiation down to around 1 nm, and extremely high brightness radiation below 0.1 Å, as demonstrated on the PEP storage ring at SLAC [3]. Beyond this current state-of-the-art, proposals are already on paper to drive FELs to yet lower wavelengths (as small as 20 nm at DELTA, Dortmund [4]), and storage ring natural emittances down to 10^{-11} m.

Very short pulses of radiation (sub-picosecond) will probably remain the realm of linac-driven FELs, where the short electron bunches can be derived from laser-driven photo-cathodes. However, short bunches (around 1.0 ps) can be realized in isochronous rings, or in more conventional rings with localized pulsed bunch compression systems.

Finally, whatever the nature of the particle accelerator, it will almost certainly utilize undulators to produce radiation. One of the conclusions of the workshop was that the tolerances required for next-generation sources are already being met by the plane-polarizing undulators being constructed for third-generation facilities. However, ideas for more exotic devices for circularly polarizing and fast switching, are still being developed in many laboratories around the world.

In this paper, then, we summarize the limits to which we feel the various technologies applicable to next-generation facilities can be pushed.

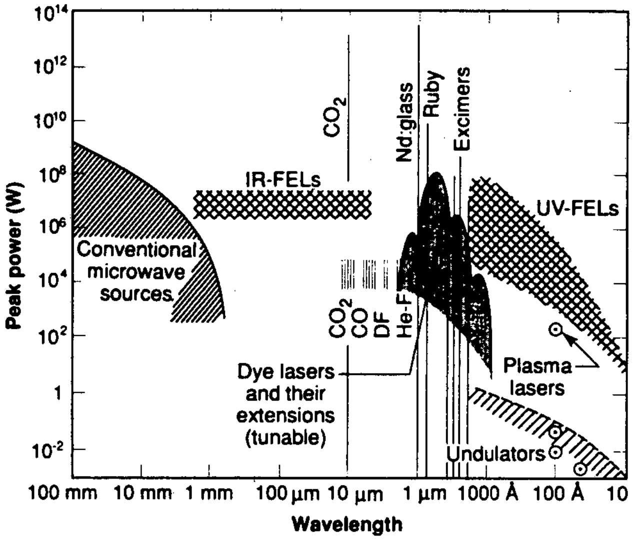

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Figure 1
Peak power of various radiation sources.

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2. LINAC- AND RING-DRIVEN FELS

The recent conceptual and technical advances in linac-driven FEL devices make them very promising candidates for next-generation radiation sources. In addition to the now well established configurations based on FEL oscillators and self-amplified spontaneous emission (SASE), novel ideas based on subharmonically seeded SASE and master oscillator power amplifiers (MOPAs) are being studied. Furthermore, ideas to "condition" the electron beam characteristics in order to enhance the gain are being developed [5]. With these techniques, and the development of very-high-brightness electron sources, it is anticipated that linac-based FEL sources will *eventually* produce intense, bright and coherent radiation down to wavelengths of a few angstrom. Figure 1, taken from reference 6, indicates the peak powers that can be expected from such sources.

In order to establish an initial condition to compare different FEL configurations, the workshop established specific (and realistic) characteristics for the electron source, given in table 1.

Table 1
Electron Source Characteristics

Characteristic	**Parameters**
Normalized emittance	1.5×10^{-6} m
Charge	1.0 nC per bunch
Electron bunch length	1.0 ps (after compression)
Relative energy spread	5×10^{-4} FWHM

2.1 *FEL Oscillators*

Oscillator performance in the future will be paced by the development of reflectors with sufficiently high reflectivity at high power loadings. Starting with predicted reflection efficiencies table 2 was developed as initial design characteristics for oscillator based systems:

Table 2
Oscillator Parameters

λ (Å)	R (%)	E (MeV)	N_W	P_{peak} (MW)
600	80	120	100	100
120	60	270	200	50
40	35	465	300	25
4	90	1470	250	25

It is interesting to note that the concept of an "application-specific source", through wavelength, and therefore required beam energy, is already embedded in table 2. The question of tunability of the FEL oscillator system at the shorter wavelengths remains a difficult problem.

2.2 *Sub-Harmonically Seeded, Single-Pass FELs*

This system uses multiple undulator magnets, separated by dispersion sections to amplify sub-harmonic radiation starting from a longer wavelength conventional laser. The scheme (as presented by Li-Hua Yu at the Workshop) is described schematically in figure 2. It uses an electron bunch that is several times longer than the seed laser pulse and dispersive sections to enable use of fresh parts of the electron bunch at each stage. The tunability of this system is limited by the tunability of the seed laser. In the example with the characteristics described in figure 2, the peak power output is calculated to be 400 MW at 40 Å in a relative bandwidth of 10^{-4}.

2.3 *Self-Amplified Spontaneous Emission*

Examples of what might be achieved through self-amplified spontaneous emission (SASE) were calculated during the workshop. The initial beam properties described above were used, together with undulators with gaps down to 4 mm, tapered where appropriate to give maximum efficiency. Other assumptions are given in table 3.

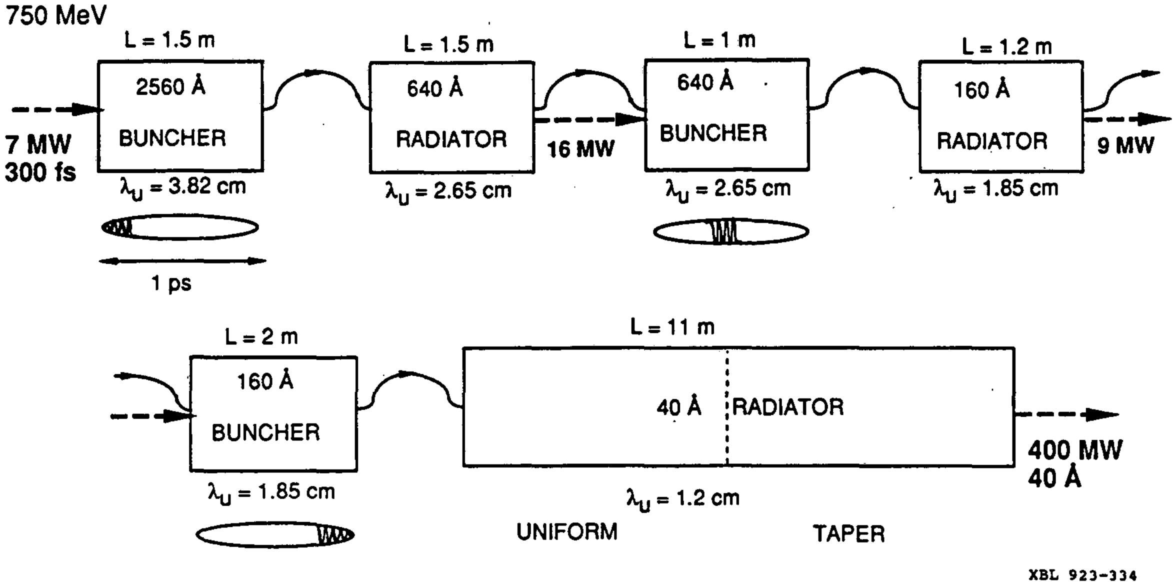

Figure 2
Sub-harmonically seeded single-pass FEL.

From these estimates it is apparent that a brightness of three orders of magnitude over third-generation sources can be achieved, and that again, any particular scheme would be very wavelength-specific.

2.4 Master Oscillator Power Amplifier

The MOPA configuration is a hybrid of the oscillator (which is used to provide "seed" radiation), and an amplifier section. The advantage over other schemes is in its relatively compact size, and that the conventional seed laser and harmonic generation are not required. This scheme is in its infancy and, as yet, no conceptual design has been studied in sufficient detail to judge its practicality.

3. RING-BASED SOURCES

When radiation emittances are dominated by the electron beam characteristics, i.e., at low wavelengths and for radiation from undulators, the radition is diffraction limited down to wavelengths of around 4π x (electron beam emittance). In third-generation machines the natural particle beam emittances are typically 5 nm. Therefore, with vertical-to-horizontal emittance coupling of 3% (regarded as typical), diffraction-limited radiation down to 630Å in the radial plane and 20 Å in the vertical plane is expected.

Table 3
SASE Parameters

λ (Å)	**1000**	**100**	**$40^{(a)}$**	**20**	**10**	**$1^{(b)}$**
E (GeV)	0.325	0.8	10	1.8	3.25	50
$P_{satur.}$ (MW)	450	360	5000	175	0.65	3500
Photon/sec$^{(c)}$	2×10^{18}	2×10^{17}	2×10^{14}	2×10^{16}	3×10^{13}	4×10^{13}
Brightness$^{(c)}$	8×10^{20}	8×10^{21}	6×10^{19}	2×10^{22}	10^{20}	10^{20}
P_{taper} (GW)	30	36	2000			25000
Photon/sec$^{(d)}$	1.5×10^{20}	2×10^{19}	7×10^{17}			2×10^{18}
Brightness$^{(d)}$	6×10^{22}	8×10^{23}	2×10^{23}			10^{27}
L_{gain} (m)	0.24	0.66	5.0	1.8	3.1	14
λ_w (cm)	2.0	1.75	10	1.75	2.0	11
ε_n (mm mrad)	1.5	1.5	2.5	1.5	1.5	1
I_{peak} (kA)	1	1	2	1	1	5
σ_λ/λ (10^{-4})	2.2	2.2	4	2.2	2.2	4
Δt_{pulse} (ps)	1	1	0.16	1	1	0.16
$L_{wiggler}$ (m)	9.6	30	75	30	30	102

(a) This column describes an FEL based on beam performance of the SLAC linac with currently available guns. The FEL requires additional external focussing.

(b) This column describes an FEL based on expected parameters of the SLAC linac with improved electron guns. The FEL requires additional external focussing.

(c) Variables for the saturated power before tapering. The photon rate and brightness are calculated assuming a 10-kHz (average) pulse repetition frequency except for the SLAC linac where 120 Hz was used. Brightness is in photons per second per 0.1% bandwidth per mm^2 mrad^2.

(d) Same as (c), except that the output power out of the tapered wiggler is used.

3.1 Ultra-Low-Emittance Storage Rings

One target of the workshop was to determine if ring technology could be reasonably pushed another order of magnitude in natural emittance (and therefore two orders of magnitude in radiation brightness). Several specific ring designs were discussed that give predicted natural emittances in the 0.01 – 0.1 nm range, thereby meeting this workshop criteria. Concepts for ensuring sufficient dynamic aperture (a few centimeters) in such machines were presented, including specifically designed lattices, properly phased sextupole families, combined-function magnets, modified sextupoles, and the utilization of octupoles. From these considerations it was agreed that the lower-emittance lattices were indeed achievable in practice. However, it was also agreed that the preliminary design of a particular machine would need to include a comprehensive study of the beam dynamics, including the effects of undulators and damping wigglers, reasonable assumptions about construction and alignment tolerances, synchrotron motion, synchrotron damping, and dynamic momentum acceptance.

One obvious consequence of moving to lower emittance is that with a given charge the electron density within the bunch increases, leading to questions about beam lifetime through the Touschek effect. The solutions to this problem are provided by higher electron energy (it was felt that 4 GeV would be the lower energy limit for this type of machine), lower bunch current requirements (which may also alleviate single-bunch instability threshold limits in narrow vacuum chambers), and using continuous top-off injection.

It is also apparent that in order to maintain the photon emittance provided by these sources, the source itself and the experimental aparatus must be extremely stable. A source with a vertical emittance of 0.01 nm at a position where β_v = 1.0 m has a vertical size of about 3 microns. To maintain beam stability to one tenth of this value requires floor stability of around 30 nm (because of floor-girder-magnet-beam amplification). This degree of stability will require particularly special attention to site selection, and girder and magnet mounting systems.

Short pulses from ultra-low-emittance machines were also discussed. It was agreed that the two requirements were mutually incompatible below a bunch length of around 10 ps, mainly because of the lifetime problem. However, with long straight sections or long bypasses, it would be possible to achieve about 1-ps bunches through pulsed rf bunch rotation techniques.

3.2 Quasi-Isochronous Rings

Isochronous rings are accelerators in which the rotation frequency of a particle is independent of its energy. In such rings very short pulses (in the order of a few picoseconds) with correspondingly high peak currents can be established. Such rings are being designed as high-luminosity colliders for high-energy physics experiments, and as drivers for FELs. Preliminary designs for machines of each of these types, utilizing unique lattices with small reverse bends at the high dispersion points, were discussed at the workshop. These are obviously novel sources with much to be learned yet through modeling and a pilot machine. However, the promise as far as the next-generation light source is concerned is in the production of coherent infra-red radiation, and as a driver for yet lower-wavelength FELs.

4. INSERTION DEVICES

Just as we anticipate the accelerators for next-generation sources will be application-specific, we expect that the insertion devices will be equally specialized. Many will be based on the technology currently being developed for the third-generation sources, including:

- many-period undulators with very tight tolerances on magnetic field quality [7];
- devices for circular polarization [8];
- variable-phase devices [9]; and
- undulators operating inside the vacuum chamber to achieve high k values with short periods.

In addition, devices are proposed that are likely to require the special features of next-generation accelerators to provide for their ultimate performance. These devices include:

- microwave undulators [10];
- superconducting small period devices;
- field synthesizers [11]; and
- plasma-based undulators [12].

From many discussions with accelerator designers, the user community, and insertion device experts, it is clear that the design of the insertion device and its effects on particle beam dynamics must be taken into account from the earliest stages of the overall conceptual design. This did not happen on third-generation machines—devices were effectively added on to the machines—and as a result most facilities will not give optimum performance from certain undulators. Moreover, in the case of the lower-energy sources, this oversight will probably result in reduced lifetime performance. Further, the coherent approach to providing a high-quality photon beam to the user must continue past the design of the machine and insertion devices to include the development of beamlines and optical elements. Power loading on existing beamline elements of hundreds of watts per mm^2 is already critical and is likely to increase in some fourth-generation sources. Thus, maintaining high-quality optical characteristics of the beamlines to take adantage of diffraction-limited and coherent sources will provide an additional challenge to the teams designing fourth-generation light sources.

5. SUMMARY

Synchrotron light sources are now well established tools for research into many branches of science, and the latest generation of facilities will provide unprecedented opportunities for the broad scientific community well into the next millennium. Future sources will almost certainly be more application-specific, and we have indicated that accelerator technologies and novel concepts can be developed to meet anticipated user requirements through a very wide range of the electromagnetic spectrum. We look forward to meeting this challenge.

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