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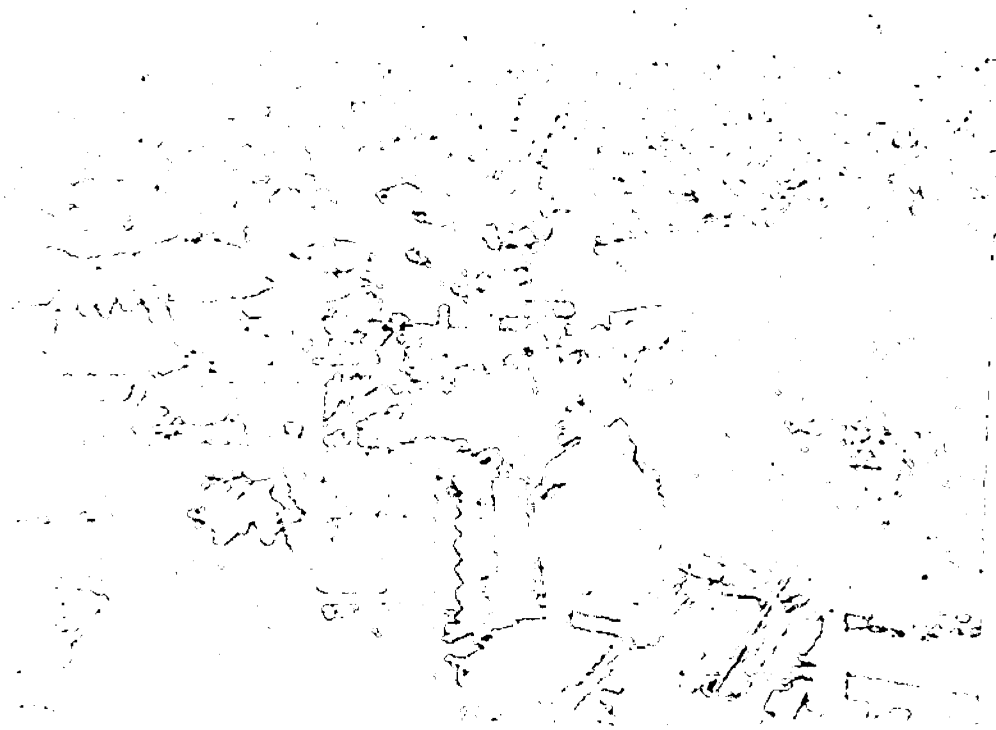

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Critical Review of High Gain X-Ray FEL Experiments*

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1. Introduction

There is a renewed interest at the present time to develop x-ray free electron lasers (FELs). The interest is driven by the scientific opportunities with coherent x-rays glimpsed at the third generation light sources [1]. With the recent development in linac technology in producing high-energy, high-brightness electron beams, it is now possible to design intense coherent x-ray source for wavelengths as short as one Angstrom based on the self-amplified spontaneous emission (SASE) principle [2,3]. Major linac laboratories such as SLAC and DESY are therefore actively pursuing detailed design studies for the x-ray SASE facilities [4,5]. The x-rays from these facilities will provide a peak brightness more than a ten order of magnitude higher than that of the current synchrotron radiation sources.

Short wavelength coherent radiation could also be generated with harmonic generation techniques in linacs [6] or storage rings [7]. However, these schemes are not expected to be effective for 1 Å wavelengths, either because of the limitation in the electron beam phase space density in the case of the storage rings, or the absence of coherent input in the case of the linac based scheme. This review will therefore concentrate on the linac based SASE scheme.

The general scheme of a linac based SASE generation is illustrated in Fig.1. The critical components of the SASE are: an electron source consisting of an RF photocathode gun with the emittance corrector producing high brightness electron beam; the beam bunching and acceleration; and a long undulator in which the radiation develops from initially incoherent radiation to intense, coherent radiation. We discuss the critical experimental issues in these components in sections 2, 3 and 4, respectively, highlighting some relevant recent experiments. Section 5 is devoted to issues related to the SASE experiment which are distinct from the usual free electron lasers. In section 6, we give a brief survey of the world-wide SASE experiments. Section 7 contains a summary and outlook.

There have been several reviews on the SASE FELs. In particular, a detailed discussion of the status as of 1994 can be found in a series of papers presented at the 1994 FEL conference [8-13].

2. RF Photocathode Gun Development

All of the current SASE projects take advantage of the low emittance that can be realized with the RF photocathode gun [14]. For SASE at x-ray wavelengths, it is important that the already low emittance from an RF photocathode be further reduced by an emittance compensation scheme[15]. The emittance from such a gun is mainly due to the space charge effect, causing the beam to expand with a rate varying along the length of the bunch--stronger at the beam center and weaker at the ends. In the phase space picture, the emittance ellipses at different longitudinal positions "rotate" with different speeds, causing an increase in the overall emittance over the small "slice" emittance. If the beam expansion is reversed by means of a focusing element, the emittance ellipses can be realigned with respect to each other, analogous to the spin echo phenomena. Recently the variation of the emittance ellipse as a function of the slice position and their realignment through a focusing element were directly observed experimentally [16]. The experiment is important, not only as a confirmation of the compensation scheme but also as an example of refined beam diagnostics exploring the details of the phase space distribution. These types of diagnostic techniques should be further refined and improved, since an understanding of the electron beam distribution, in as much detail as possible, would be the first step toward achieving an x-ray SASE.

One of the most advanced RF photocathode guns is being developed by the so-called Gun-III collaboration involving SLAC, BNL and UCLA [17]. Using an RF cavity design minimizing the multipole components, a transversely flat laser profile, and an emittance correction scheme, the design value of the normalized rms emittance (ε_n) is less than 1 mm-mrad, sufficient for a 1 Å SASE. Further improvement may be possible by shaping the longitudinal laser pulse profile, removing beam tails, etc. The first gun of the collaboration is currently being characterized at the Accelerator Test Facility (ATF) at BNL. A second gun will be installed this October in the Gun Test Facility at SLAC.

The ultimate performance limit of an RF photocathode gun may not known yet. For example, a gun producing ε_n=1 mm-mrad with a bunch charge larger than 2nC may be feasible [18]. With such a beam, assuming that it could be bunched and accelerated to the specification, the FEL gain could significantly increased, thus leading to a significant saving in the undulator cost.

3. Electron Bunching and Acceleration

Although the electron beam from an RF photocathode is already bunched to a few picoseconds, it needs to be further bunched to increase the peak current to the level of a few kA for an x-ray SASE. It is important that the space charge and wakefield effects of the high current beam do not spoil the low emittance in the bunching process. Also, the coupling of the timing jitter to the intensity jitter could be a serious issue and should be evaluated carefully [9,10]. Recently two new effects have been identified as potentially troublesome, those due to the centrifugal space charge force [19] and the coherent synchrotron radiation [20]. The Thomas Jefferson Accelerator Facility (TJNAF, formerly CEBAF), BNL, and several other laboratories are planning experiments to study these effects in detail.

The emittance could be diluted also in the course of the acceleration process in linacs, either from the single particle effects such as the focusing mismatch, the dispersive and the chromatic effects, and from the collective wakefield effects, etc. Many of these dilutions can be corrected, as in the case of the RF photocathode gun, because they are manifestations of correlations between different degrees of freedoms[10]. These are extensively studied with numerical modeling in connection with the linear collider design efforts. Experimentally, it was shown that the increase in the normalized vertical emittance in the SLAC linac, which is about 1.5 mm-mrad at the beginning, can be controlled to less than 50 % through the 3 km-long linac accelerating the beam to 50 GeV [21]. This is about the level of the control required for the x-ray FEL.

4. Undulator Issues

Currently, most of the undulators in the synchrotron light sources are of the planar Halbach design [22] in either the pure permanent magnet or hybrid configurations. An undulator with a stronger field with a shorter period than possible with these designs would reduce the gain length significantly. The super conducting helical undulator concept based on bifilar coil is attractive in this sense [23] and should be further investigated to demonstrate the mechanical stability, error control, etc., by constructing prototypes. Even if one chooses to employ the standard planar design, the last few gain lengths may need to be replaced by a helical undulator because of the user demand on circular polarization.

Another important issue is the need for an external focusing in addition to the natural focusing. The conventional wisdom is that, with a pure permanent magnet, the external quadrupoles can simply be superimposed on the main undulator field, allowing a variable strength focusing scheme. However, this statement needs to be carefully checked in view of the fact that the field errors should not exceed a few tenths of a percent and that the relative permeability of the permanent magnet is slightly different from unity. With a hybrid design, the extra focusing can be realized either by canting the poles, introducing additional permanent magnets off axis [24], or by interrupting the undulator at certain intervals and placing quadrupoles there. With the first two methods, the focusing strength cannot be varied. With the undulator interruptions, the gain could be reduced [25]. There is also an optimized three dimensional design, combining the canting and wedging of the poles, for a desired peak field and focusing strength [26]. These new concepts of undulator construction need to be tested with prototyping and further analysis.

The development of the precision permanent magnets in connection with the synchrotron radiation source has been remarkable. With various correction techniques, the radiation phase errors in these devices can be controlled to within a degree. However, an additional figure of merit for a long SASE undulator is the rms displacement of the electron trajectory [27]. The required level of the steering tolerance in the presence of the magnet errors and the external focusing is very stringent [28], but within the current state-of-the-art.

5. Experimental issues in SASE Physics

The physics of the high gain FEL amplifier in the linear regime is rather well understood. Given an analytically simple electron beam distribution (rectangular, Gaussian,...), the growth rate can be predicted accurately [29]. Summarizing these results by a simple interpolating formula [30] has been very useful in quickly optimizing the FEL design parameters. However, there are other aspects of the high-gain FEL physics in addition to the power growth. Thus, measuring both the real and imaginary parts of the gain and comparing with theory, as was done in the mm wavelengths [31], will not only enhance the confidence in the analysis, as well as the confidence that these parameters are experimentally under control. In addition, it would also be interesting to observe the higher order transverse modes predicted by the theory [32].

The performance of x-ray SASE will be sensitive to the details of the electron beam phase space distribution, the focusing property, and the undulator imperfections, etc. Thus it is very important to continue to improve the simulation capability, taking into account these effects. The available codes are reviewed in Ref. [12], and a few more codes have been written since then [33,34].

The evolution of an SASE FEL from noise was first observed at mm wavelengths at LLNL [35]. The measurement was preliminary but indicated an effective input noise larger than that estimated from the theory [36]. A recent experiment at 47 microns may also have detected an input noise larger than the theoretical prediction [37]. It is likely that the discrepancy can be explained by the presence of some density modulation in the initial electron beam. Thus, it would be highly desirable to develop electron beam diagnostics providing information on density modulation or fluctuation in electron beam distribution at the FEL wavelength scale. Recently a French group directly observed electron density modulation in a FEL amplifier at 8 mm by analyzing the beam-induced transition radiation with a streak camera [38]. The experiment is interesting as the first direct evidence of the FEL induced micro-bunching. Extension of this experiment to the SASE regime to obtain the auto-correlation of the electron distribution would yield important information on the randomly distributed coherent modulations.

For a wavelength shorter than a few mm, a direct observation of the beam modulation with a streak camera would be difficult. The coherence enhancement of the various radiation phenomena, such as transition radiation, Cerenkov radiation, Smith-Purcell radiation and diffraction radiation, could be exploited for this purpose [39,40].

6. Some Proposed Projects

Figure 2 gives a partial list of the planned SASE experiments with the projected timeline. In addition to those listed in the figure, other laboratories, including Duke University, KEK, LBNL, JNAF, Boeing, etc., are also engaged either in the integrated FEL experiments or in the critical R&D items such as the buncher test, beam diagnostics, undulator magnets, etc. Together, these experiments explore various aspects of the SASE FEL physics at various strategic wavelengths from a few microns to a few Angstrom.

A variety of linacs are used; the stand-alone types with energy of a few tens of MeV (two hundred MeV in the case of the Source Development Laboratory [SDL] at BNL), the light source injectors and their upgrades with energy up to about one GeV, and the linacs for the high energy physics with energies larger than 10 GeV. There have been also discussions to coordinate these activities [41]. While these discussions have not so far resulted in a coherent program for the SASE R&D, they nevertheless led to several fruitful collaborations in key areas, such as the Gun III collaboration mentioned above, and exchanges of undulators such as the transfer of the Palladin undulator from LLNL to Duke University, and the loaning of the NISUS undulator to Brookhaven.

Anticipating the success of these experiments, SLAC and DESY are currently carrying out detailed design reports for their x-ray SASE facilities.

7. Summary and Outlook

Although extremely weak in the FEL standard, the coherent flux in the x-ray wavelengths in the currently operating "third generation" synchrotron radiation facilities is already producing interesting scientific results. Free electron lasers operating in high energy accelerators, especially the single pass SASE FELs operating in linacs, will enhance the coherence capability by many orders of magnitudes. While an extension of the FEL operation from the current wavelength record of 2400 Å all the way down to less than 1 Å would be a very challenging task, there are reasons to be optimistic in these developments. These are: the advance in the linac technology through the development of RF photocathode gun and the refinement of the beam control technique through the linear collider R&D; the advance in the techniques of handling high brightness, high power x-ray beams in the third generation synchrotron radiation facilities; and the large number of demonstration experiments being planned and underway in various laboratories.

References

[1] J.L. Laclare, Proc. of 10th ICFA Workshop on 4th Generation Light Source, ESRF publication.
[2] R. Bonifacio, C. Pellegrini and L.M. Narducci, Opt. Commun. 50 (1984) 373.
[3] See, for a review, K.-J. Kim and M. Xie, NIM A 331 (1993) 359.
[4] H. Winick, et al., Nucl. Instr. and Meth. A 347 (1994) 199; R. Tatchyn, et al., NIM A375 (1996) 274.
[5] J. Rossbach for the TESLA FEL Study Group, NIM A 375 (1996) 269.
[6] L.-H. Yu, Phys. Rev. A 44 (1991) 5178.
[7] V.N. Litvinenko, "X-Ray Storage Ring FELs: New Concepts and Directions," presented at Int. Workshop on Generation and Application of Coherent X-Rays, Tsukuba, Japan (Feb. 1996).
[8] K.-J. Kim, NIM A 358 (1995) 31.
[9] P.G. O'Shea, NIM A 358 (1995) 36.
[10] T.O. Raubenheimer, NIM A 358 (1995) 40.
[11] R.D. Schlueter, NIM A 358 (1995) 44.
[12] G. Travish, NIM A 358 (1995) 48.
[13] I. Ben-Zvi, NIM A 358 (1995) 52.
[14] R.L. Sheffield, in: Physics of Particle Accelerators, AIP 184, eds. M. Month and M. Dienes (1989) 1500.
[15] B. Carlsten, Nucl. Instr. and Meth. A 285 (1989) 313.
[16] X. Qiu, K. Batchelor, I. Ben-Zvi, and X.-J. Wang, PRL 76 (1996) 3723.
[17] D.T. Palmer, R.H. Miller and H. Winick, Proc. 1995 Part. Accel. Conf., IEEE Catalog No. 95CH35843 (1996) 2432.
[18] R.L. Sheffield, private communications.
[19] B.E. Carlsten and T.O. Raubenheimer, Phys. Rev. E 51 (1995) 1453.
[20] Y.S. Derbenev, J. Rossbach, E.L. Saldin and V.D. Shiltsev, DESY preprint TESLA-FEL 95-05 (1995).
[21] D. Burke, et. al., Proc. of 4th European Part. Accel. Conf., London, England (1994).
[22] K. Halbach, J. Phys. (Paris, France) 44, C1-211 (1983).
[23] S. Caspi and C. Taylor, NIM, A375 (1996), 433.
[24] A.A. Varfolomev, et al., NIM A 358 (1995) 70; T. Cremer and R. Tatchyn, SLAC PUB-95-6886; Yu.M. Nikitina and J. Pflueger, NIM A 375 (1996) 325.
[25] K.-J. Kim, M. Xie and C. Pellegrini, NIM A 375 (1996) 314.
[26] R.D. Schlueter, NIM A 358 (1995) 44.
[27] L.-H. Yu, S. Krinsky, R.L. Gluckstern and J.B.J. van Zeijts, Phy. Rev. A 45 (1992) 1163.
[28] H.-D. Nuhn, E.T. Scharlemann, W.M. Fawley and R. Schlueter, Proc. 1995 Part. Accel. Conf., IEEE Catalog No. 95CH35843 (1996) 231.
[29] L.-H. Yu, S. Krinsky and R.L. Gluckstern, PRL 64 (1990) 3011; Y.H. Chin, K.-J. Kim and M. Xie, Phys. Rev. A 46 (1992) 6662; L.-H. Yu, C.M. Hung, D. Li and S. Krinsky, Phys. Rev., E51 (1995) 813.
[30] Y.H. Chin, K.-J. Kim and M. Xie, Phys. Rev. A 46 (1992) 6662; M. Xie, Proc. 1995 Part. Accel. Conf., IEEE Catalog No. 95CH35843 (1996) 183.
[31] T. J. Orzechowski, E.T. Scharlemann and D.B. Hopkins, Phys. Rev. A 35 1987) 2184.
[32] Y.H. Chin, K.-J. Kim and M. Xie, Phys. Rev. A 46 (1992) 6662; M. Xie, to be published.
[33] H.P. Freund (MEDUSA), Phys. Rev. E52 (1995) 5401.
[34] V.N. Litvinenko (FEL3D), private communications.
[35] T.J. Orzechowski, et al., NIM A 250 (1986) 144.
[36] W.M. Fawley, A.M. Sessler and E.T. Scharlemann, Proc. 1993 Part. Accel. Conf., Washington D.C., USA (1993) 1530.

[37] D. Bocek, P. Kung, H.-C. Lihn, C. Settakorn and H. Wiedemann, NIM A 375 (1996) 13.
[38] J. Gardelle, J. Labrouche and J.L. Rullier, PRL 76 (1996) 4532.
[39] J. Rosenzweig, G. Travish and A. Tremaine, UCLA preprint.
[40] For a review, see H. Wiedemann, Proc. of Micro Bunches Workshop (1995), AIP Conf. Proc. 367, page 512.
[41] Coordinated Amplifier Research Program, ed. E. Johnson (April 1996).

Figure Captions

Fig. 1. A schematic layout of a SASE generator.
Fig. 2. Planned SASE experiments and their projected timeline.

Here $\overline{B}(\hat{B})$ = average (peak) brightness in units of photons/(S)(mm)^2(mrad)^2(0.1%BW).

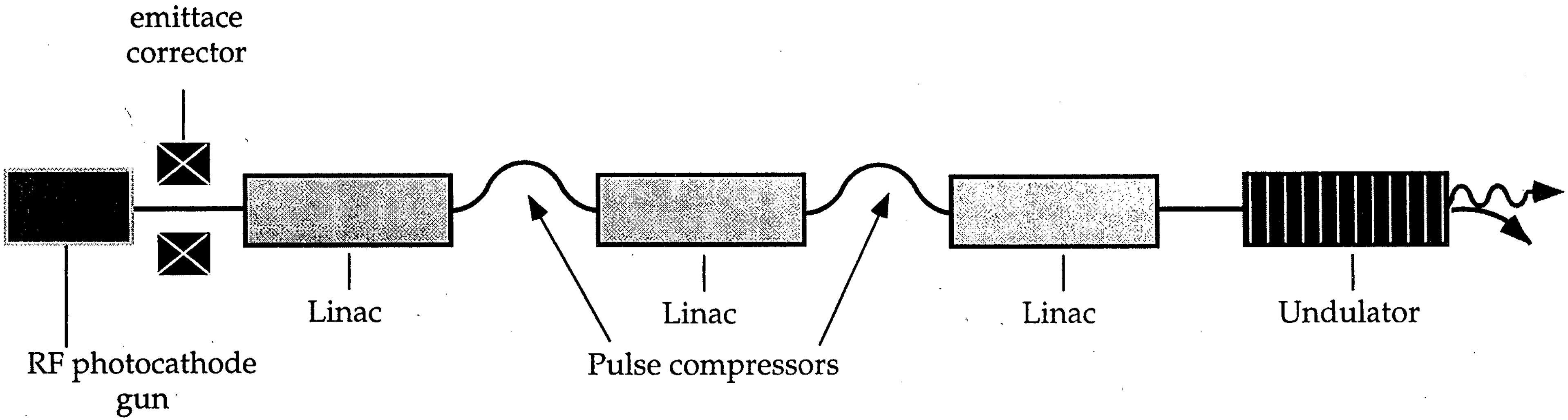
emittace
corrector
Linac
Linac
Linac
Undulator
RF photocathode
gun
Pulse compressors

Fig. 1

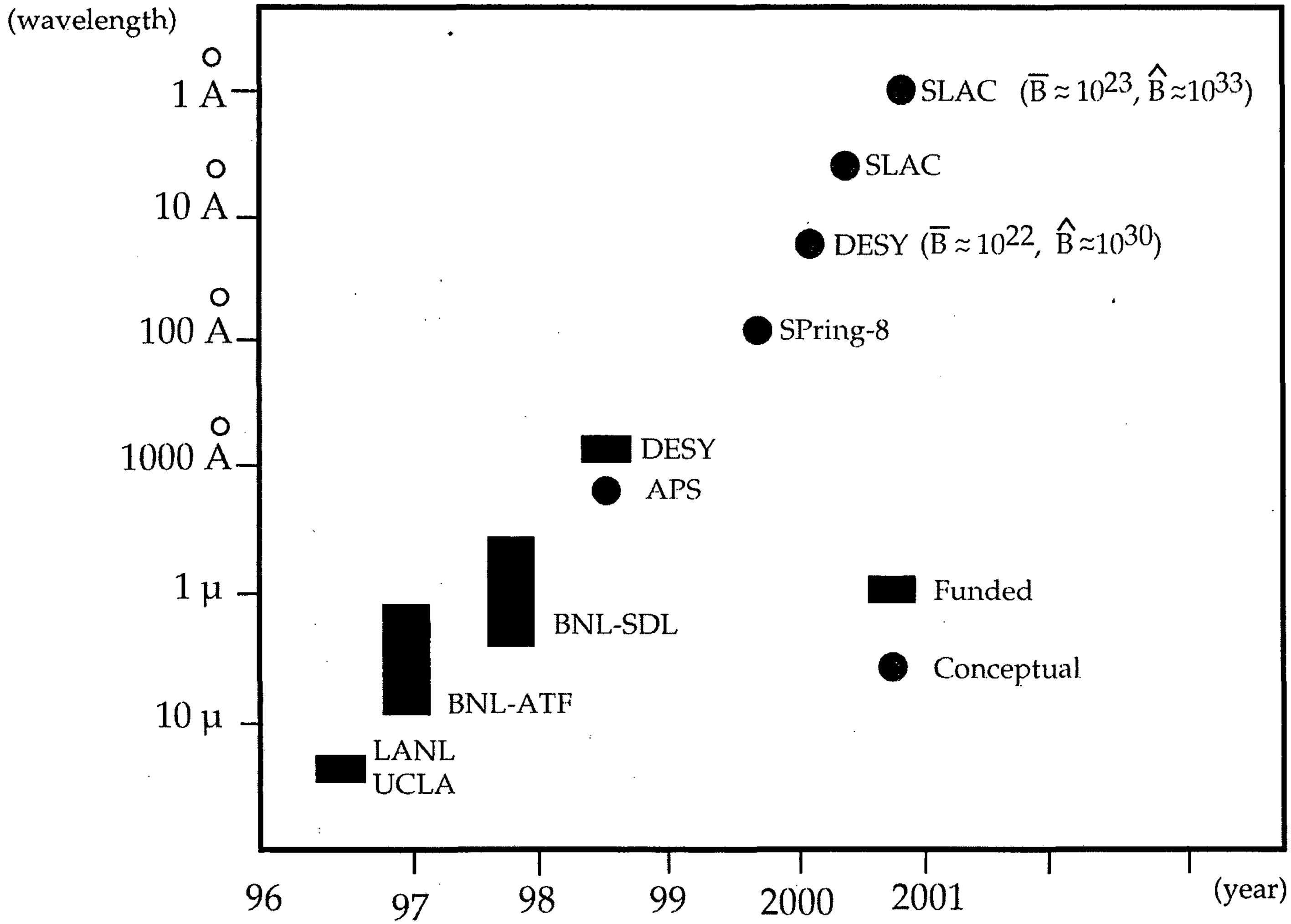
(wavelength)
1 Å
10 Å
100 Å
1000 Å
1 μ
10 μ
SLAC (B̄ ≈ 10^23, B̂ ≈ 10^33)
SLAC
DESY (B̄ ≈ 10^22, B̂ ≈ 10^30)
SPring-8
DESY
APS
BNL-SDL
BNL-ATF
LANL
UCLA
Funded
Conceptual
96
97
98
99
2000
2001
(year)

Fig. 2

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