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On the Path to the Next Generation of Light Sources*

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Abstract

At the Fourth Generation Light Source Workshop in January 1996, storage-ring-based FELs and linac-based FELs were considered for VUV/soft x-ray and hard x-ray ($\lambda \sim 1 \text{ \AA}$) photon production, respectively. The general requirements of a diffraction-limited source—bunch lengths less than 1 ps (100 fs in case of the linac-based source), coherence, and a brightness several orders of magnitude brighter than third-generation sources—were among the features discussed. Examples of progress in demonstrations, measurements, or calculations that support research towards these areas are cited. These range from the 50-fs bunch length measurement at low current in a linac to few- μ rad divergence measurements on a 7-GeV storage ring. The possible extension of transition radiation beam characterization techniques to nonintercepting diffraction radiation is briefly addressed as well.

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1. Introduction

The next generation of light sources can be considered as included as the main topics of the Fourth Generation Light Source Workshop held in January 1996 in Grenoble, France [1]. At this workshop, storage-ring-based FELs and linac-based FELs were considered for VUV/soft x-ray and hard x-ray ($\lambda \sim 1 \text{ \AA}$) photon production, respectively. The general requirements of a diffraction-limited source, bunch lengths less than 1 ps (100 fs in the case of the linac-based sources), coherence, and a significantly higher brilliance than third-generation synchrotron radiation sources were among the features discussed. Progress towards such sources will depend critically on the ability to generate and to measure key beam parameters.

Recently, several demonstrations, measurements, and calculations have been reported that may be considered as on the path to the next generation. A few examples selected from the areas of beam position, beam profiles, beam divergence, and beam bunch length are illustrative. Demonstrations in generating and measuring ultrashort bunches on a linac in the 50- to 100-fs regime, albeit at very low charge and at the several-ps regime on storage rings, have been reported [1-3]. Vertical couplings of less than 10% on the third-generation storage ring beams have resulted in $25 \times 10^{-12} \text{ m rad}$ emittance at ESRF [4] and the direct measurement of 5- μrad divergence at APS [5]. A proposed "diagnostics undulator" should allow even lower measurements to the 1- μrad regime (a fourth-generation target). Transverse position and profile measurements using a thin, intercepting optical transition radiation (OTR) foil have been performed successfully on 3.25-GeV electrons at Jefferson Lab (formerly CEBAF) [6], and a nonintercepting extension may be possible using diffraction radiation (DR) [7]. Bunch lengthening measurements versus single-bunch current have indicated peak currents of about 300 A with no significant energy spread increases in a 7-GeV ring [8]. Such a result should have relevance to considerations of gain in

storage-ring-based FELs. Since the last FEL conference, three workshops have been held that have collected in their presentations and proceedings many of the results: (1) Micro Bunches Workshop [9], (2) Fourth Generation Light Sources, and (3) 1996 Beam Instrumentation Workshop. Space limitations will preclude full discussion of the results, but their relevance to the development path should become clearer following the discussion.

2. Background on Relevant Parameters

Almost all discussions on the next generation of light sources include the need for low-emittance, ultrashort, bright beams. Both low transverse emittance and low longitudinal emittance are needed. There are probably different wavelength regimes where linac-based FELs and storage-ring-based FELs would focus in the future [1].

2.1. Linac-based FELs

One of the more intriguing aspects of the Grenoble Workshop was the evident interest by the hard x-ray research community in the linac-based FEL using self-amplified spontaneous emission (SASE) techniques to generate a brilliant photon beam at 1 Å. In order to generate such photon beams, it is calculated that one needs a transverse emittance of $\sigma_{x,y} \sim 1-2 \pi \text{ mm mrad}$ (normalized, rms), at tens of GeV, with a bunch length of 100 fs (σ) and peak currents of 1-5 kA. The energy spread would need to be about 0.01%. These very high quality, ultrabright beams would be injected into a wiggler of 10-20 gain lengths (implying 30- to 50-m wiggler length) to reach saturated FEL outputs. An additional challenge involves the ability to keep the particle beam and photon beam aligned and in overlap during a gain length. This may result in approximately a 1- μm positioning capability being required.

2.2. Storage-Ring-Based FELs

It still appears that storage-ring-based FELs using an oscillator configuration may play a useful role in the 200-nm to 20-nm wavelength regime where there are very few competitive laser sources. However, in the context of a coherent, 1-Å source with 100-fs bunch length, the general feeling of the Grenoble Workshop was that storage ring options are quite unlikely. The thrust for storage rings for a diffraction-limited source in the VUV is real (ESRF running at 2 GeV). For the hard x-ray case, the general requirement on the emittance, $\epsilon \leq \lambda/4\pi$, implies an emittance of about 0.01 nm-rad, or 10 pm-rad. Roughly speaking, for a beta function of $\beta = 10$ m, an rms beam size of 10 μm and a divergence of 1 μrad would be targets for research. A bunch length ≤ 1 ps with reasonable charge would also be a goal. The simultaneous achievement of these parameters is limited by the effects of intrabeam scattering, but a brilliance of about 10^{23} ph sec^{-1} mm^{-2} , per 0.1% BW would be a solid objective. Full use of these beams would probably require demonstration of beam stabilities of ≤ 1 μm . As a point of reference, the third-generation synchrotron radiation sources typically have a natural emittance of about 8 nm rad with 10% vertical coupling and with 50- to 100-ps bunch lengths as a baseline design. So it is of interest to explore separately low vertical coupling and generation of short bunches, and then try to combine the features.

2.3. Comments on Transition Radiation and Diffraction Radiation Techniques

An interesting extension of transition radiation measurements of beam position, profile, and divergence into a nonintercepting optical method involves the use of diffraction radiation (DR), which is generated as a charged particle beam passes through an aperture in a metal foil. Figure 1 shows a schematic of this effect where the backward DR would be emitted into a direction around

the angle of specular reflection. Unlike OTR, much of this radiation is emitted into the far-infrared since the threshold wavelength is approximately given by $\lambda/2\pi \approx a/\gamma$, where a is the aperture radius and γ the Lorentz factor. Table 1 shows a short summary of possible beam energies, the threshold wavelengths, and relevant laboratory accelerators. For the 5-mm-radius aperture, the threshold wavelength varies from 250 μm to 0.25 μm for this extended range of γ 's. The table is adapted from reference 7. This potential is even more likely for bunch length measurements using coherent diffraction radiation. Shibata et al. have reported measurements in the 300-fs regime [10], and W. Barry has calculated its use in an autocorrelation technique [11].

3. Examples of Relevant Measurements "On the Path"

In this section, several examples will be selected from relatively recent results in laboratories around the world that have relevance to these new sources. Most of these are related to low emittance (transverse or longitudinal).

3.1. Beam Position

This subsection only addresses the nominal results on submicron resolution beam position monitors (BPMs). For the linac application, it appears that some adaptation of a cavity-based BPM such as developed at SLAC for s-band pulse trains is appropriate [12]. The development of a device or technique compact enough for use in the very long wiggler vacuum chamber of an x-ray SASE experiment is an area of need. For storage rings, the APS storage ring rf BPM in a small-gapped chamber (8-mm) provides a resolution of about 0.1 μm in a 1-Hz bandwidth with 1 mA average beam current. As an example, for a 2-mA single bunch circulating at 271 kHz, a resolution of 0.5 μm at 100 Hz BW is expected [13].

3.2. Transverse Beam Profile

The ability to measure the transverse beam profile is needed. Although not performed on a normal linac transport line, the recent report of a beam profile measurement at 3.25 GeV using a thin, optical transition radiation (OTR) foil is relevant [6]. The observed spot size was consistent with normal diffraction-limited resolution concepts showing that properly utilizing OTR's angular distribution pattern can result in adequate resolution at higher γ . These data support the discussion provided by Rule and Fiorito [14] on resolution at high γ for OTR techniques applied to beams of 1-100 μm radii.

In the storage ring arena, recent x-ray synchrotron radiation measurements using an x-ray pinhole at ESRF have observed beam sizes consistent with a vertical emittance of about 25 pm rad with a resolution projected to 5 pm rad [4]. Low vertical coupling and reduced natural emittance can give vertical emittance very close to, or at, the diffraction limit in a third-generation source.

3.3. Transverse Beam Divergence

A key aspect of the emittance measurement issue involves the ability to measure directly beam divergence. The low normalized emittance results in challenges to measurement techniques at higher γ . OTR interferometric (OTRI) techniques have been used in the past for $\gamma \leq 220$. Extensions to $\gamma > 1000$ require adjustments. An example of calculations for the low-divergence beam at 650 MeV is given in Fig. 2. Here the formation length $\gamma^2\lambda$ is close to a meter, and the calculation was done for an interfoil spacing of 125 cm and a nominal λ of 650 nm. The various curves show the reduction in fringe visibility with increasing beam divergence from 20 μrad to 100 μrad . Additionally, Fig. 3 shows an alternate use of the fringe patterns' two innermost lobes for a coarse

(1%) energy measurement. The curves are for energies in 5-MeV increments from 620 to 680 MeV.

In the storage ring, direct monitoring of the undulator radiation angular distribution pattern can be directly related to the particle beam divergence if this undulator radiation cone angle is comparable to or smaller than that of the particle beam. At ALS, a reported use of off-axis and red-shifted radiation has been used to enhance sensitivity to particle beam values ($\sim 30 \mu\text{rad}$) [15]. This technique is graphically displayed in the results from an APS experiment with the 7-GeV beam and a 3.3-cm period undulator [5]. Figure 4 shows the experimental schematic. The energy selection is done with a cryogenically cooled crystal (Si(111)), and the radiation is converted by a CdWO_4 crystal to visible light. A charged-coupled device (CCD) camera records the two-dimensional image projected on the crystal located about 30 m from the insertion device (ID) source. Figure 5 shows a very clear measurement of the two-lobed angular distribution pattern with the data points given as squares. The other two curves are for divergence values $\pm 10\%$ from the $5.3\text{-}\mu\text{rad}$ value. In Fig. 6 the technique is projected into a "diagnostics undulator" application at APS with $\lambda = 1.8 \text{ cm}$, $N = 198$ periods, and an undulator radiation cone of about $1.2 \mu\text{rad}$ on axis. If the off-axis technique is applied, measurements at the desired $1\text{-}\mu\text{rad}$ level seem feasible.

3.4. Bunch Length (Duration) and Profile

For the linac side, a significant step has been taken in handling the projected 100-fs microbunches. Papers in the Micro Bunches Workshop have directly addressed the advent of coherent transition radiation Michelson interferometric, auto correlation measurements. Lihn et al. reported a 50-fs bunch generated and measured from an rf gun at low charge [2]. The technique will continue to be applicable as long as an intercepting foil can be used with the beam.

W. Barry has proposed an extension of the interferometric technique to coherent DR which would then become a nonintercepting device, if wakefields do not become an issue. This extension might also be applied to storage ring beams [11]. First-bunch length measurements with coherent diffraction radiation (CDR) (without using the interferometer) were done by Shibata et al. on a 150-MeV linac beam [10]. About 300-fs resolution was reported for those conditions. A temporal resolution limit can be estimated by $\chi_e \approx \frac{2\pi a}{\gamma}$, where a is the aperture radius [11]. It should be noted that longitudinal profile measurements are not yet done unambiguously.

Meanwhile, it is noted that an 80-fs (σ) resolution streak camera has been developed by a commercial company and tested on a 40-fs (σ) laser pulse [16]. It has also been used on a linac beam and a microbunch of 770 fs (FWHM) was measured [17]. This measurement does have profile information with it, although the incoming photon flux must be matched to the tube's dynamic range very carefully.

For the storage ring arena, a number of measurements of bunch length vs. single-bunch current have been reported in the Grenoble Workshop in January 1996. Measurements made at SUPER-ACO, ALS, ESRF, and APS are among the results. These four labs now each have a dual-sweep streak camera, so further information should be forthcoming. An example of the APS storage ring bunch length measurements of 40 ps (σ) is given in Fig. 7. As an example of an instability that could dramatically impact brightness, a vertical, head-tail instability was induced and observed in APS as shown in Fig. 8. In Fig. 9, measurements are plotted vs. single-bunch current out to the 12-mA level (43 nC) in March 1996 data. This corresponds to a peak current of 300 A in the single bunch. Recently, 18 mA in a single bunch were obtained that corresponded to almost 400-A peak current. With the nominal 0.6-ps resolution on the fastest scale for a streak

camera with dual-sweep capability, the storage ring bunch length measurement problem is also well in hand.

Space limitations preclude discussion of the use of laser probes, Smith-Purcell radiation, rf phasing, etc. for additional characterizing of parameters.

4. Summary

In summary, several key demonstrations of parameters and their measurements which would support research on the path to the next generation of light sources have been discussed. Key aspects on beam divergence for both linac beams in the 50- μ rad regime and a storage ring target of 1 μ rad seem in hand. In the ultrashort bunch length area (~ 100 fs), demonstrations of the use of coherent transition radiation with the potential extension to coherent diffraction radiation have been noted. Additionally, a 80-fs resolution, visible streak camera tube has been noted and is a potentially viable alternative. For storage rings it appears that work in the approximate 1-ps regime is ably supported by existing single-sweep and dual-sweep streak camera technology. Challenges still remain in submicropulse sampling and high-resolution BPMs in a long wiggler (30 m) and bringing the full complement of parameters together into the linac-based source or the storage-ring-based source.

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References

1. Proceedings of the Workshop on Fourth Generation Light Sources, J. LaClare (Ed.), Grenoble, France, Jan. 22-25, 1996.
2. H. C. Lihn et al., Phys. Rev. E, 53, No. 6, June 1996.
3. A. Jackson et al., in reference 1.
4. P. Ellaume, C. Fortgang, C. Penel, and E. Tarazona, J. Synchrotron Rad., 2, pp. 209-214, (1995).
5. R. Dejus et al., (Argonne National Laboratory) private communication, April 1996.
6. P. Piot et al., "High Current CW Beam Profile Monitor Using Transition Radiation at CEBAF," Proceedings of the 1996 Beam Instrumentation Workshop, Argonne, IL, May 6-9, 1996, to be published.
7. D.W. Rule, R.B. Fiorito, and W.D. Kimura, "Noninterceptive Beam Diagnostics Based on Diffraction Radiation," Ibid.
8. A.H. Lumpkin, B.X. Yang, and Y-C. Chae, "Observations of Bunch Lengthening Effects in the APS 7-GeV Storage Ring," these proceedings.
9. Proceedings of the Micro Bunches Workshop, Upton, NY, Sept. 1995, Ed. E.B. Blum, M. Dienes, J.B. Murphy, AIP Conference Proceedings 367, (1996).
10. Y. Shibata et al., Phys. Rev. E, 52, 6787, (1995).
11. W. Barry, "Measurement of Sub-Picosecond Bunch Profiles Using Coherent Transition Radiation," Proceedings of the 1996 Beam Instrumentation Workshop, Argonne, IL, May 6-9, 1996, to be published.
12. S. Smith, (Stanford Linear Accelerator Center), private communication, May 1996.

13. Y. Chung, E. Kahana, "Performance of the Beam Position Monitor for the Advanced Photon Source," Proc. 1995 SRI Conference, Rev. Sci. Instrum. 66 (9) 1995.
14. D.W. Rule and R.B. Fiorito, "Imaging Micron-sized Beams with Optical Transition Radiation," Proceedings of the 1990 Accelerator Instrumentation Workshop, Batavia, IL, AIP Conference Proc. No. 229, p. 315 (1991).
15. P. Heimann et al., Rev. Sci. Instrum. 66 (2), February 1995.
16. A. Takahashi et al., "A New Femtosecond Streak Camera," SPIE Proceedings, 2002, pp. 22-30 (1993).
17. M. Uesaka, (Univ. of Tokyo), presentation in Working Group at Micro Bunches Workshop, Sept. 28, 1995, Upton, NY.

Table 1: Comparison of Diffraction Radiation (DR) Parameters for a 5-mm-Radius Aperture at Various Representative Accelerators[†]

E (GeV)	γ	$\lambda^{(1)}$ (μm)	Linac
0.05	10^2	250	BNL/ATF
0.5	10^3	25	ANL/APS, Duke Upgrade, DESY
5.0	10^4	2.5	Jefferson Lab (CEBAF)
50	10^5	0.25	SLAC/LCLS

(1) Threshold DR wavelength for incoherent production.

[†]Adapted from Table 1 of Rule, Fiorito, Kimura [7].

Figure Captions

- Fig. 1. Schematic of the emission of diffraction radiation (DR) as a charged particle beam passes through an aperture of radius a in a metal foil.
- Fig. 2. OTR interference pattern for a 650-MeV beam and interfoil spacing of 125 cm. The fringe visibility is highest when the divergence is lowest as shown by the different curves.
- Fig. 3. OTR interference pattern for an 80- μ rad divergence beam and interfoil spacing of 125 cm. In this case the two innermost lobes are shown to be sensitive to the beam energy with about 1% sensitivity in the 650-MeV regime.
- Fig. 4. Schematic arrangement for the storage ring beam divergence measurement using a cryogenically cooled Si crystal as a monochromator, a CdWO_4 converter screen, and a CCD camera.
- Fig. 5. Measurement of the off-axis, red-shifted third harmonic radiation from undulator A of APS showing the double lobe structure and the match to data (x's) at $5.3 \pm 10\%$ μ rad.
- Fig. 6. Simulation of a divergence measurement capability using a $\lambda = 1.8$ cm, $N = 198$ undulator at APS. Measurement capability in the 1- μ rad regime is targeted.
- Fig. 7. Dual-sweep streak image of a single bunch in the APS storage ring without the vertical, head-tail instability. The fast time axis is vertical and the horizontal time axis covers 10 μ s so these passes around the ring are seen.
- Fig. 8. Dual-sweep streak image of a single bunch in the APS storage ring with the vertical, head-tail instability induced.
- Fig. 9. Variation of bunch length with single-bunch current in the APS storage ring at 7-GeV. The 12-mA average current corresponds to a 300-A peak current.

Diffraction Radiation (with wave vector k) produced by a charged particle with velocity v transiting a distance (b) from the center of a circular aperture (radius a). Aperture is inclined at an angle Ψ with respect to the particle trajectory (z direction). The angle of observation θ is measured with respect to direction of specular reflection.

Fig. 1

OTR Interference Pattern

650 MeV, Foil Spacing 125 cm, Divergence 30-130 μ rad

Fig. 2

OTR Interference Pattern

620-680 MeV, Foil Spacing 125 cm, Divergence 80 μ rad

Fig. 3

Beam Divergence Measurement Setup

Fig. 4

Vertical Beam Profile @ E = 33.36 keV

Vertical
Vertical

Beam Divergence = $5.3 \mu\text{rad} \pm 10\%$
Beam Size = $53 \mu\text{m}$

Fig. 5

Fig. 6

File Image Display Analysis Control Others

72795sr.016 (R3/10us/-40um)

Peak: 561.26ps 32992.0nt
P=0.004 300.509ps

Fig. 7