CONF-970255--3
ANL/ASD/CP--92683

# Beam diagnostics challenges for future FELs*



Alex H. Lumpkin

Argonne National Laboratory, Advanced Photon Source, Argonne, IL 60439

## ABSTRACT

Designs are being developed to produce diffraction-limited sources based on storage-ring free-electron lasers (FELs) for the VUV and soft x-ray regime and linac-driven FELs in the few Å regime. The requirements on the beam quality in transverse emittance (rms, normalized) of 1-2 $\pi$ mm mrad, bunch length (1 ps to 100 fs), and peak current (1 to 5 kA) result in new demands on the diagnostics. The diagnostics challenges include spatial resolution (1-10 $\mu$m), temporal resolution (<100 fs), and single-pulse position measurements (~1 $\mu$m). Examples of recent submicropulse (slice) work are cited as well as concepts based on spontaneous emission radiation (SER). The nonintercepting aspects of some of these diagnostics should also be applicable to high-power FELs.

**Keywords:** FELs, beam diagnostics, SER

## 1. INTRODUCTION

The growing interest in diffraction-limited light sources at short wavelengths involves a concomitant interest in the development of future free-electron lasers (FELs) and the diagnostics to characterize them. At the Fourth-Generation Light Source Workshop held in January 1996 in Grenoble,[1] storage-ring-based FELs were considered for VUV and soft x-ray production and linac-based FELs using self-amplified spontaneous emission (SASE) were considered for hard x-rays (~1 Å). The most extreme case of 1-Å wavelength demands a transverse particle beam emittance, $\varepsilon \leq \lambda/4\pi$ of about 0.01 nm rad or 10 pm rad. Assuming a beta function, $\beta = 10$ m, the rms beam size of 10 $\mu$m and a divergence of 1 $\mu$rad are implied. Additionally, the bunch length in the SASE case is required to be in the 100-fs ($\sigma$) regime.

These criteria present challenges for diagnostics in spatial resolution, divergence or angular resolution, temporal resolution, and in tracking the beam through the long magnetic structures. Progress has been made and a set of examples on the path to the next generation were discussed at the Rome FEL'96 conference by this author.[2] In this paper a complementary set of examples and developments will be discussed. They include recent published work on obtaining information from slices of a micropulse by slit-sampling[3] or laser probes[4] and a recent example of a streak camera used on spontaneous emission radiation at a wavelength shorter than the present FEL record (240 nm). The nonintercepting nature of some of these techniques make them directly applicable to high power particle beams as well.

## 2. BACKGROUND ON RELEVANT PARAMETERS/CHALLENGES

Almost all discussions on the next generation of light sources include the need for low-emittance, ultrashort, bright beams.[5] Both low transverse emittance and low longitudinal emittance are needed. As mentioned in the introduction, a diffraction-limited source at 1 Å implies a 10 pm rad particle beam, and the SASE gain requires an ultra-short bunch (100 fs) and a peak current of 1-5 kA.





*Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

## DISCLAIMER

### 2.1 Spatial (profile and position)

In order to evaluate such a low-emittance beam with a projected transverse size of 10 μm(σ), one needs few-micron resolution in the detection system. Comparable resolution would effectively have to provide sub-microradian angular resolution since we must measure 1-μrad divergences. Demonstrations in this regime were discussed.[2] Additionally, beam particle position and photon beams in the long wiggler must be kept in overlap during a gain length. This is probably at the 1–μm level. Challenges are added by the requests to take time slices of the transverse information or to be heavily constrained in access within the wiggler vacuum chamber.

### 2.2 Temporal (duration and profile)

For a storage ring, bunch lengths appear to be limited to about 1 ps (σ) due to intrabeam scattering for any meaningful amount of charge. This regime is readily addressed by current, commercially available streak camera technology for measuring both beam duration and longitudinal profile. For the linac beams projected for SASE at 1 Å, a final 100-fs (σ) length is specified, but most injectors will start with a photoinjector at a few ps bunch length and in their first compression may reach 600 fs — still in streak camera range. The final compression stage results in about a 100-fs (σ) bunch length. Measurements of the profiles and time slices <u>within</u> this micropulse are challenges to be met. The duration issue at this point is addressable using the coherent transition radiation (CTR)-based technique although it is expected that a nonintercepting coherent diffraction radiation (CDR) measurement will be applicable at high energies. Demonstrations to date with CTR have been with 50 MeV to a few hundred MeV beam energies.[6,7]

### 2.3 Charge

Most of the scenarios described for linac FELs[5] discuss the goal for generating a 1-nC pulse from the photoinjectors with the 1-2 π mm mrad normalized emittance. Space charge forces may yet win this battle, and one may actually deal with less than 1 nC in a micropulse to achieve this emittance objective. This beam intensity is on the margin of operations with an optical transition radiation (OTR) screen, optical synchrotron radiation (OSR), or SER as conversion mechanisms to image the beam in one shot with high enough magnification to obtain good spatial resolution in the system. If one then asks for slices in time or space the signal only goes down in the sample. In prototype devices, we may have less than 1 nC as well. There is a challenge in these simultaneous constraints. If we could believe in very good stability shot-to-shot, then signal averaging can be used. In this area the use of coherent aspects of radiation from the particle moves the detection problem to the far infrared regime. Image intensifier and Peltier-cooled or cryo-cooled detection also will probably be used more and more to address the low signals.

The final aspect of the challenge is to have a full set of diagnostics available to apply to verify the preservation of beam quality in the compression stages and the tracking of trajectories in the long SASE magnetic structures (with all the constraints on fielding a diagnostic in the small-gap vacuum chamber).

## 3. EXAMPLES OF RECENT DEVELOPMENTS

In this section, several examples will be selected from relatively recent results that have potential relevance to assessing the beam in prototype or future facilities. They illustrate an assessment of sub-micropulse phenomena or new results using spontaneous emission radiation.

### 3.1 Submicropulse measurements

The first example involves the recent work by X. Qiu et al.[3] in evaluating the slice emittance of a 10-ps electron bunch to demonstrate emittance compensation. In their experiments they used the second linac section, a dipole, and slit to form a filter that only passes a short time slice (~1.1 ps) of the beam pulse downstream of the slit (see Fig. 1). They then used a quadrupole magnet field scan with a profile monitor with 100-μm spatial resolution to track the vertical beam size. Next they "measured" the slice emittance ellipse alignments as a function of the solenoid lens setting which was used as the emittance compensation technique.[8] They were able to reduce the emittance growth due to linear components of space charge forces. Figure 2 shows examples of the vertical beam size measurement versus quadrupole field strength for three time slices in the micropulses.

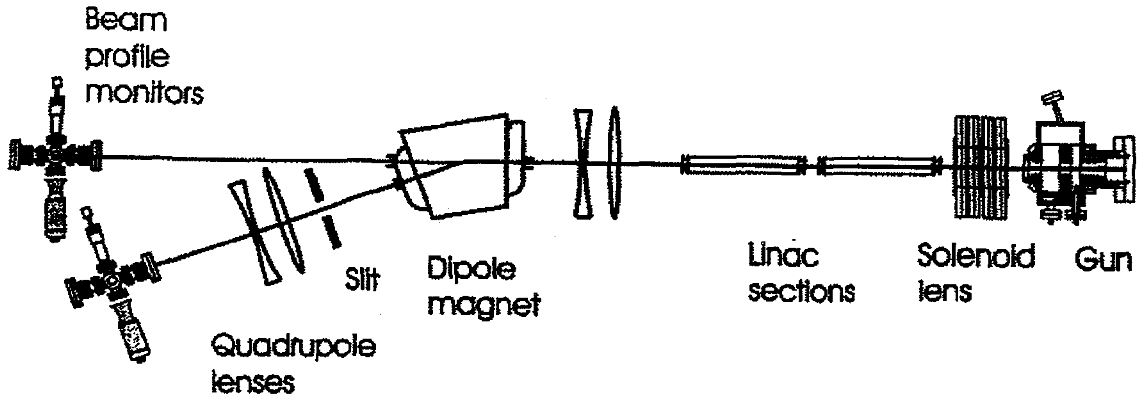


Fig. 1. Schematic of the BNL Accelerator Test Facility (ATF) photoinjector linac and components relevant to slice measurements. The slits after the dipole magnet select the time slice of the micropulse. The beam profile monitor downstream of the quadrupole lenses is used to track the beam size. (Courtesy of X. Wang.[3])

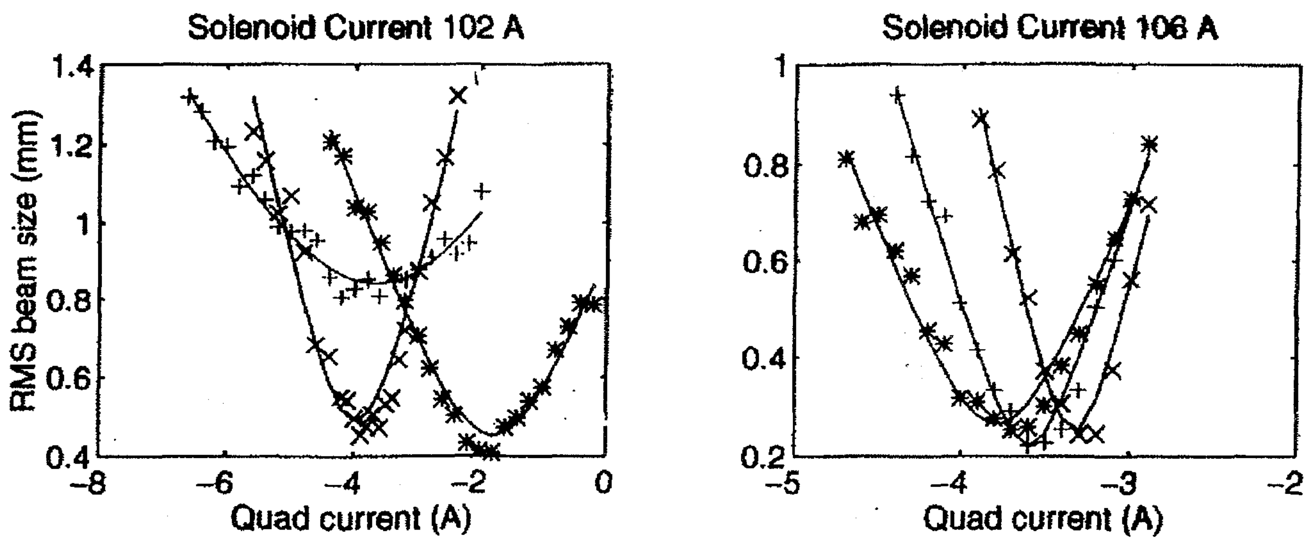


Fig. 2. Examples of vertical beam size versus quadrupole field strength for three different times within the micropulse and for two cases of the solenoid current. The deduced ellipses are more aligned for the 106-A case. (Courtesy of X. Wang.[3])

The second example involves the extension of laser probes for particle beams to the 100-fs regime,[4] as shown in a schematic in Fig. 3. Here Leemans et al. were able to use 90° Thomson scattering of a tightly focused $Ti{:}Al_2O_3$ laser beam off a 50-MeV electron beam to scan or map out both the transverse charge profile and the longitudinal profile. Micropulses having about 1.3 nC of charge with a 10-15 ps rms bunch length were studied. The scattered photons with energies up to 30 keV were analyzed and imaged using a phosphor screen and a 16-bit CCD camera. In Fig. 4 a comparison of the spatial profiles from the OTR image and the Thomson x-rays is shown. Agreement in size at the half width, half maximum intensity was obtained. The camera's sensitivity was a critical part of the experiment since about $5 \times 10^4$ x-rays were produced in the collection angle. They also reported e-beam divergence information through measurement of spatial and spectral characteristics of the scattered x-ray beam. They report spatial resolution of the imaging system of about 14 μm and horizontal slice emittance (unnormalized) of about $0.25 \pm 0.03$ mm mrad or about 25 mm mrad (normalized).

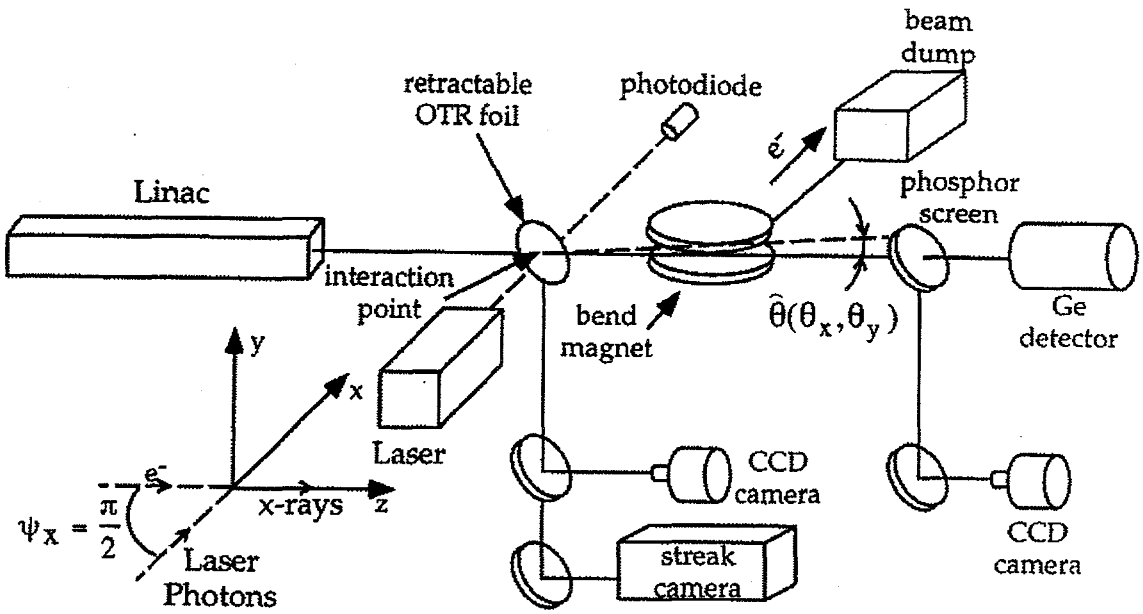


Fig. 3. Schematic of the LBNL laser-probe experiment using 90° Thomson scattered photons with energies up to 30 keV. The electron beam energy was 50 MeV. The Ti:$Al_2O_3$ laser and the 16-bit CCDs are critical to the experiment. (Courtesy of W. Leemans.[4])

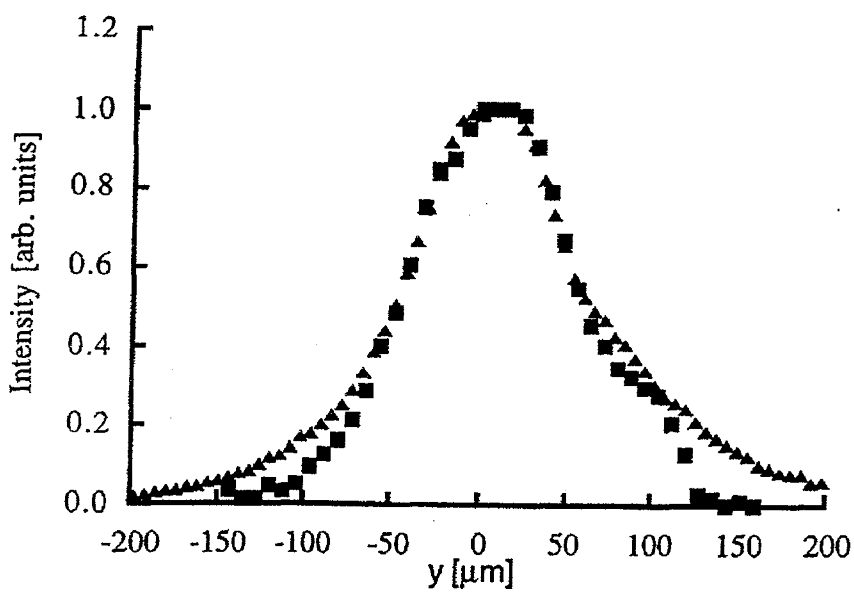


Fig. 4. Comparison of the beam transverse profiles using the OTR screen and 16-bit CCD camera (triangles) versus the x-ray yield versus vertical laser position as detected at the phosphor screen located 80 cm downstream of the interaction point (squares). (Courtesy of W. Leemans.[4])

### 3.2 Spontaneous emission radiation (SER) diagnostic

It is a well-established technique to use the SER from the FEL wiggler to characterize properties of the particle beam that passes through it. This is somewhat facilitated if the wavelengths are compatible with electro-optic devices such as streak cameras. By combining a streak camera readout of a polychromator, time-resolved spectra are possible. A comprehensive set of measurements was reported within the Boeing/LANL visible FEL experiments of the late 1980s.[9] In this case the fundamental wavelength was about 650 nm although the second harmonic on-axis SER was also detected at 325 nm and longer wavelengths for larger off-axis angles. Bunch length and profile, position, and beam energy were readily determined from the SER measurements.

Quite recently in a collaborative effort between Duke and APS, the first dual-sweep streak camera images were taken of the output radiation of the Duke optical klystron version 4 (OK-4) installed on the 1-GeV storage ring. As shown schematically in Fig. 5, the SER was picked off by a retractable mirror positioned upstream of the cavity mirror. Mirrors and beam splitters were also used to bring the cavity's outcoupled radiation to the APS streak camera. Key parameters are listed in Table 1 (see Ref. 10). As shown in Fig. 6, the single bunch could be imaged turn-by-turn and the bunch length, 120 ps (FWHM) directly measured. These data are at $\lambda = 450$ nm and a beam energy of 270 MeV. We then adjusted the OK-4 to generate 220 nm SER (already shorter than the 240-nm FEL lasing record). Additionally, we actually were able to assess the ring orbit length versus the resonator round trip time using 195-nm radiation transmitted through the cavity mirrors as shown in Fig. 7. The second pass in the resonator arrives 100 ps later (lower in image). Having determined the beam peak current (FEL gain) for various charge and rf voltage conditions and having verified the rf frequency for synchronism, we were ready to enter lasing experiments. These first occurred within a few weeks and details will be reported by Litvinenko et al. elsewhere in these proceedings.[11] One other observation of the lasing at 388 nm involved laser pulses with bunch lengths as short as 3-4 ps ($\sigma$) under some conditions. These types of measurements are scalable to the soft x-ray regime with 1 ps ($\sigma$) resolution and to 100 fs in the UV regime.

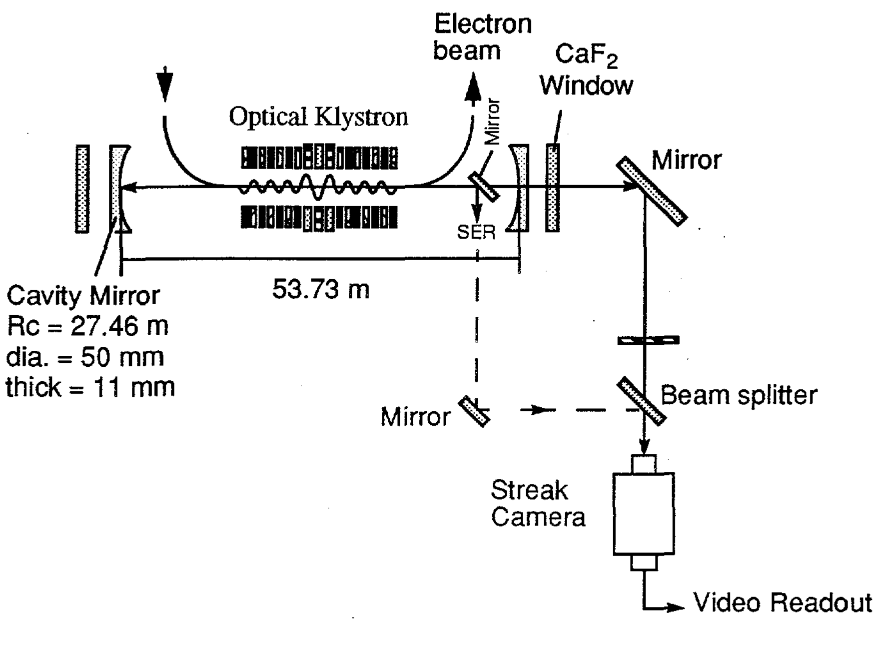


Fig. 5. Schematic of the resonator set-up on the Duke OK-4 storage-ring FEL. A pick-off mirror inserted just upstream of the cavity mirror allows the sampling of the SER. (Courtesy of Y. Wu, Duke FEL.)

Table 1: Summary of parameters of the Duke storage ring and OK-4 (see Ref. 10).

| Parameter | Design Value |
|---|---|
| Storage Ring | |
| Operating energy (GeV) | 0.25-1.0 |
| Ring circumference (m) | 107.46 |
| Revolution freq. (MHz) | 2.789 |
| rf frequency (MHz) | 178.547 |
| Beam current, A | 0.1 |
| Peak current, A | 80-130 |
| Horizontal emittance (m-rad) | $18 \times 10^{-9}$ |
| Vertical emittance, m-rad | $1 \times 10^{-9}$ |
| Bunch length ($\sigma$, ps) | 33 |
| OK-4 Parameter | |
| Undulator length (m) | 3.40 |
| Period (m) | 0.10 |
| Peak magnetic field (kG) | 0.0-5.8 |
| Buncher length (m) | 0.34 |
| Magnetic field (kG) | 0-12 |

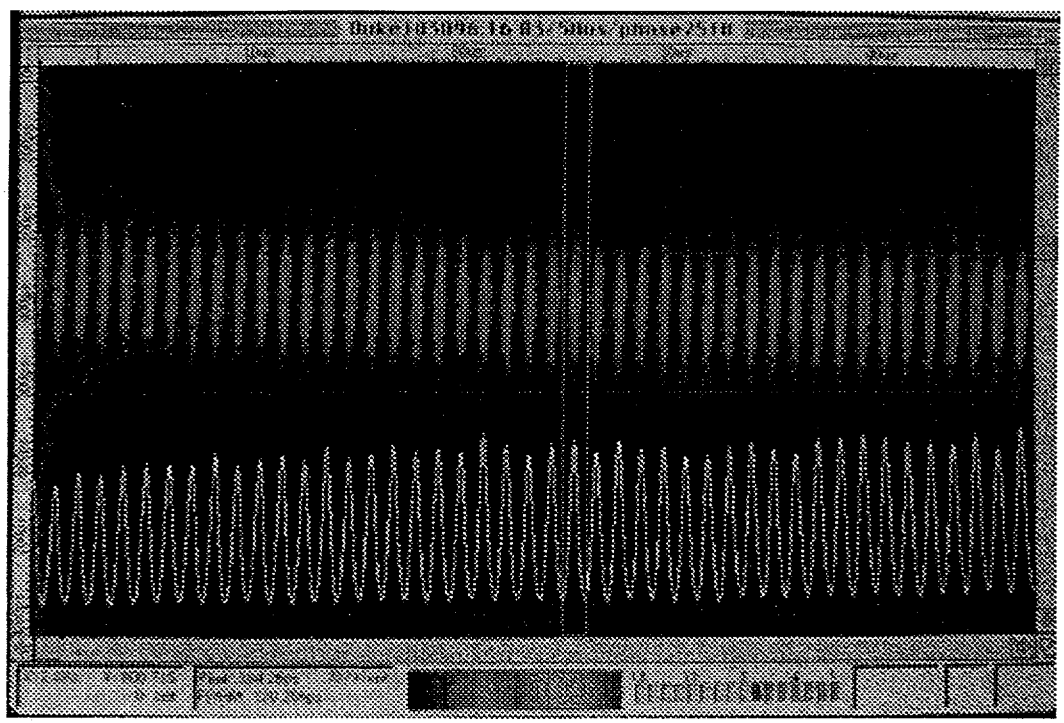

Fig. 6. Dual-sweep streak image of the SER from the OK-4 at $\lambda = 450$ nm and for a beam energy of 270 MeV. The vertical sweep covers 1 ns while the horizontal axis is 50 μs. These are single-bunch data taken turn by turn at the 2.78-MHz revolution frequency. The selected image had a bunch length of 120 ps (FWHM).

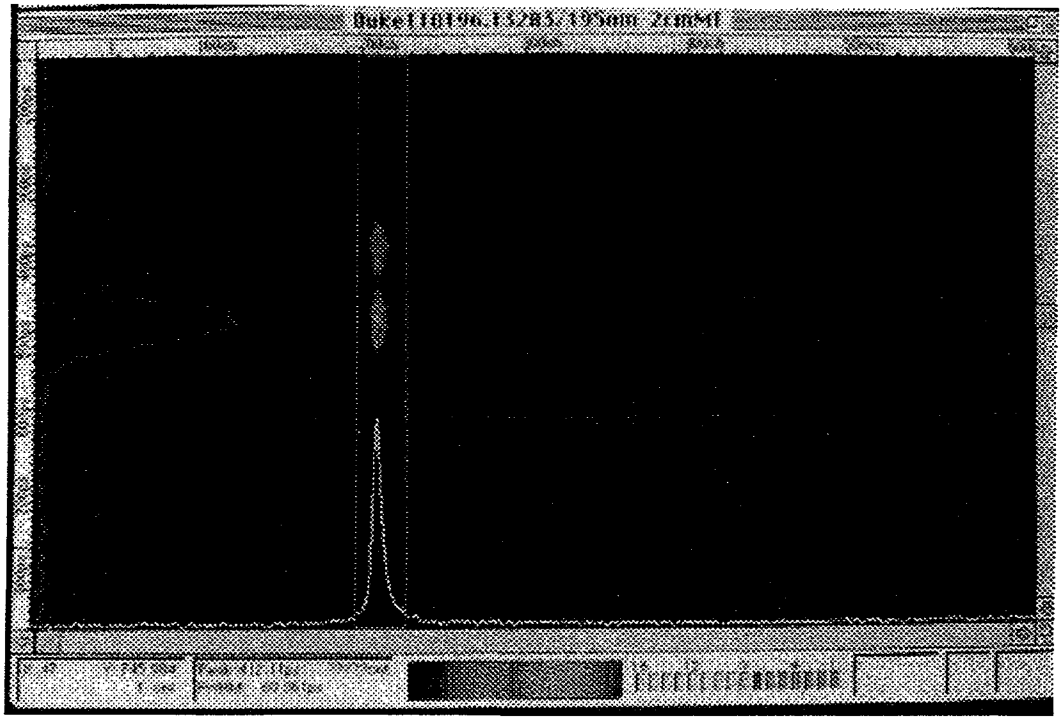

Fig. 7. Synchroscan streak image of the OK-4 output radiation in the deep ultraviolet at λ = 195 nm. This radiation was outcoupled from the resonator cavity itself. The lower (second) vertical image occurs about 100 ps later than the first-pass SER due to the differences between the cavity length and the electron beam orbit length. The bunch length is about 50 ps (FWHM) at this low current of 0.04 mA.

Another aspect of this is the suggestion by J. Ng of the DESY FEL project to use off-axis wiggler radiation to track trajectories within the wiggler using a pinhole imaging technique.[12] The intent appears to be to use off-axis SASE radiation as well.

Very briefly, we expect to use the 1-m prototype SASE wiggler at APS to test application of the SER technique with our rf-gun-generated beams. Milton has described this overall project plans elsewhere in these proceedings[13] and Vinokurov has described the details of the magnetic structure.[14]

We have also just installed a 3.5-m-long, 1.8-cm-period diagnostics undulator in a sector of our 7-GeV storage ring. The low radiation cone of this device is designed to allow measurement of stored beam with few μrad divergence which would occur for low vertical coupling operations at APS. This device's fundamental is at about 0.5 Å for a 7-GeV beam and would allow testing of few bunch detectors.

### 3.3 High-power beam application

As a complementary thought and for the purposes of this conference, we note that any of the nonintercepting techniques described above should be potential diagnostics for high-power particle beams. Photons emitted by charged-particle beams themselves as they pass through apertures (diffraction radiation or coherent diffraction radiation), through bends or accelerating fields (optical, x-ray, or coherent synchrotron radiation, SER, FELs), or near gratings (Smith-Purcell radiation) may be used to characterize the beam. As an example, OSR has been used at beam energies as low as 25 MeV for a high-charge macropulse.[15] It is reasonable that laser probe techniques are applicable such as described by Shintake[16] or Leemans.[4] Obviously, rf pickups are already a standard, nonintercepting beam position monitor in the accelerator field.

## 4. SUMMARY

In summary, I have tried to address some of the diagnostics challenges related to expected future FELs. Submicropulse or slice evaluations of low-energy (50 MeV) beams have been done recently. Some aspects may scale to evaluating beam after bunch compression stages. Nonintercepting techniques based on laser probes or on the emitted radiation using a variety of mechanisms have significant potential. It is clear that appropriate diagnostics must be in place in any new prototype facility or final facility if these new FELs are to be optimized.

## ACKNOWLEDGEMENTS

The author acknowledges discussions with X. Wang (BNL) and W. Leemans (LBNL) on their work and permitting use of their figures. He also acknowledges B. Yang (APS) and V. Litvinenko and his team for their collaborations on the OK-4 SR FEL tests.

## REFERENCES

1. *Proceedings of the Workshop on Fourth Generation Light Sources*, J. L. LaClare (Ed.), Grenoble, France, Jan. 22-25, 1996.
2. A. Lumpkin, "On the Path to the Next Generation of Light Sources," *Proc. of the 18th International Free Electron Laser Conference*, Rome, Italy, Aug. 26-30, 1996, *Nucl. Instrum. Methods* (in press).
3. X. Qiu, K. Batchelor, I. Ben Zvi, and X-J. Wang, *Phys. Rev. Lett.* **76**, (20), p. 3723, 1996.
4. W. P. Leemans et al., *Phys. Rev. Lett.* **77**, (20), p. 4182, 1996.
5. K-J. Kim, "Critical Review of the High Gain X-ray FEL Experiments," *Proc. of the 18th International FEL Conference*, Rome Italy, Aug. 26-30, 1996, *Nucl. Instrum. Method* (in press).
6. P. Kung et al., *Phys. Rev. Lett.* **73**, p. 967, 1994, and H. Lihn, *Proc. of BIW'96*, Argonne, IL, May 6-9, 1996, AIP (in press).
7. Y. Shibata et al., *Phys. Rev. E* **52**, p. 6787, 1995.
8. B. E. Carlsten, *Nucl. Instrum. Methods A* **285**, p. 313, 1989.
9. A. H. Lumpkin, *Nucl. Instrum. Methods A* **296**, p. 134, 1990.
10. V. Litvinenko et al., *Nucl. Instrum. Methods A* **375**, p. 46, 1996.
11. V. Litvinenko et al., "First Visible/UV Lasing with the Duke OK-4 Storage Ring FEL," these proceedings.
12. J. Ng, "A Beam Trajectory Monitor Using Spontaneous Undulator Radiation at TTF-FEL," TESLA-FEL 96-16.
13. S. Milton, "APS Low-energy Undulator Test Line," these proceedings.
14. N. Vinokurov, "Design Considerations of the Magnetic System for the Prototype of the X-ray FEL," these proceedings.
15. A. H. Lumpkin and M. D. Wilke, "Comments on Advanced, Time-resolved Imaging Techniques for Free-Electron Laser Experiments," *Nucl. Instrum. Methods A* **331**, p. 781, 1993.
16. T. Shintake, "Beam Profile Monitors for Very Small Transverse and Longitudinal Dimensions Using Laser Interferometric and Heterodyne Techniques," *Proc. of BIW'96*, Argonne, IL, May 6-9, 1996, AIP (in press).