NONINTERCEPTING DIAGNOSTICS FOR TRANSVERSE BEAM PARAMETERS: FROM RINGS TO ERLs*

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ABSTRACT

The characterization of particle-beam parameters in accelerators and transport lines is important to the experiment’s success. The development of nonintercepting (NI) diagnostics is of growing interest in the community due to top-up operations for storage rings such as the Advanced Photon Source (APS), as well as the rapidly developing energy recovering linacs (ERLs). In both areas beam position and beam quality are relevant, and the ability to measure these in an NI manner is critical. Beam transverse size and divergence are more of a challenge, and examples of the minimally intercepting or nonintercepting measurements based on optical transition radiation (OTR), optical synchrotron radiation (OSR), x-ray synchrotron radiation (XSR), optical diffraction radiation (ODR), and undulator radiation
(UR) will be presented as space permits. These are relevant to the various ERL parameter spaces and operating modes.

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**Keywords:** nonintercepting diagnostics, beam size, synchrotron radiation, transition radiation, diffraction radiation

1. INTRODUCTION

The emerging energy recovering linacs (ERLs) for infrared free-electron lasers (IR FELs) and proposals for x-ray sources present a number of challenges for diagnostics of high-average-power bright beams. Some of these issues have been addressed in the large synchrotron radiation facility at the Advanced Photon Source (APS) where the top-up mode of operation for the 7-GeV storage ring requires beam injections every two minutes. The ability to monitor the trajectory and beam quality while transporting charge through three accelerators and transport lines in the injector complex is critical to top-up efficiency. Our nonintercepting (NI) techniques include the nominal rf beam position monitors (BPMs) and the synchrotron radiation monitor using the dipole sources in the rings or bends. Generally, the rf BPMs address position only, but the need for beam quality (transverse size, divergence, and emittance) is as important.

Conversion of beam information to optical signals allows visualization of the beams, and some of the mechanisms are nonintercepting. At the APS we have explored the minimally intercepting or nonintercepting measurements based on optical transition radiation (OTR), optical synchrotron radiation (OSR), x-ray synchrotron radiation (XSR), optical diffraction radiation (ODR), and undulator radiation (UR). Examples of these will be presented as space permits. Once the information is in the optical field (and XSR can be converted to visible light with a YAG:Ce scintillator), imaging technology is directly applicable to the signals. I will address the relevance to the various ERL parameter spaces and operating modes in the subsequent sections.

2. EXPERIMENTAL BACKGROUND

Our fundamental objectives are to have minimally intercepting diagnostics (at low power) and NI diagnostics (at high power) for beam position and profile in the ERLs. This will be addressed in the context of the APS diagnostics that have been developed throughout
the facility. Figure 1 shows a schematic of the APS with the rf thermionic gun (or rf photocathode (PC) gun), the S-band linear accelerator, the particle accumulator ring (PAR), the injector synchrotron (IS), and the 7-GeV storage ring (SR) whose average current of 100 mA is comparable to proposed light sources driven by ERLs [1].

The rf BPMs are well established using striplines or buttons as pickups with cavities under development. In the APS the beam position is routinely monitored with striplines or buttons during top-up operations. Top-up operations involve injection of one pulse every two minutes into the storage ring with about 2.5 to 3.0 nC per shot from the synchrotron. A universal BPM topology is currently being applied to the APS injector applications [2]. This is summarized in Table 1 for the linac, linac to PAR, and booster to SR. In Table 1 the number of BPMs, frequency, aperture, stripline sensitivity, and approximate normalized position are given. With noise levels at the mV regime, resolutions of 15 µm are achieved on a single pulse for the PC gun beam with charge 0.1 to 2 nC. A log-ratio system with subtraction in software addresses the injector needs. The system block diagram is shown in Fig. 2 with the receiver, data acquisition, and digital I/O indicated [2].

As presented in the Introduction, our strategy for measuring beam size and profile is based on conversion of the particle beam information to optical radiation. One can then take advantage of imaging technology, including video digitizers and image processing programs. The conversion mechanisms include: 1) OTR, which is generated when a charged-particle beam transits the interface of two media with different dielectric constants (e.g., vacuum to metal); 2) ODR, which is generated when a charged-particle beam passes near the interface of two media with different dielectric constants; 3) OSR and XSR, which are generated when a charged-particle beam transits the magnetic field of a dipole magnet (bend and edge); and 4) UR, which is generated as the electron beam transits the periodic array of magnets. The latter has special properties in wavelength bandwidth, harmonics, and intensity.
As an example, in the case of OTR, thin metal foils may be used to minimize beam scattering and Bremsstrahlung production, so we identify this as a minimally intercepting technique. The OTR images can provide information on transverse position, transverse profile, divergence and beam trajectory angle, emittance, intensity (no saturation), energy, and bunch length (with fs response time). There are coherence factors for wavelengths longer than the bunch length. The longitudinal phase-space aspects are discussed elsewhere in these Workshop proceedings [3]. The transverse aspects basically apply to ODR, OSR, and XSR as well, although the beam needs to pass by a metal plane or through an aperture or transit a dipole field, respectively. The OTR and OSR photon yields are comparable in the APS applications for 1-nC charge in a single pass and for wavelengths integrated from 400 to 700 nm. A summary is provided in Table 2. The photon yield ranges from 3.1 to 10.6 times $10^7$ as calculated with the various angle integrations [4].

In addition, it is germane to note that OSR imaging can be used over a wide range of energies. Calculations for 18-40 MeV at 200 mA in a proposed linac-driven FEL of the 1980s indicated the feasibility [5], and the actual measurements with an intensified camera were done at Los Alamos for beam energies of 23-28 MeV and with a charge of 10 $\mu$C in 20 $\mu$s [6]. Several examples at APS have been proposed or implemented: the chicane dipole at 150 MeV (proposed); PAR bends at 325 MeV; IS bends at 325-7000 MeV; SR bends at 7000 MeV and 100 mA; and UR from the 1.8-cm period, 3.4-m-long undulator.

The use of XSR rather than direct OSR imaging is one option for better spatial resolution. We obtain 22-[$\mu$m ($\sigma$)] resolution with a 15-[$\mu$m slit and about 1-to-1 magnification in an x-ray pinhole geometry. In addition, the two-slit optical interferometer technique gives beam size information with better spatial size resolution than direct OSR imaging (which involves diffraction limits). However, the two-slit interferometer fringe modulation analysis involves a Gaussian beam profile assumption.
3. EXPERIMENTAL RESULTS WITH APS ELECTRONS

At APS we have extensive NI OSR and XSR beam diagnostics on one sector of the 7-GeV storage ring [7]. These diagnostics view OSR/XSR from two dipole bends and UR from the dedicated undulator. Example images are shown in Fig. 3 for stable and unstable higher-order mode (HOM) rf conditions in a run at 225 mA. The oscillating pattern signature is clearly seen in Fig. 3b. The on-line video processing system then exhibits the beam profile sizes as shown in Fig. 4. The divergence measurement is done with monochromatic beam. The x-rays are converted to visible light by the YAG:Ce scintillator and imaged. The observed divergences are about $\sigma_x = 16.7 \mu\text{rad}$ and $\sigma_y = 7.3 \mu\text{rad}$. At the fundamental, the nominal operating angle of the UR with zero divergence beam would be 2.5 $\mu\text{rad}$. By using the third harmonic, the system resolution would be even lower.

For top-up we have an interest in the transport line between the IS and SR. In order to evaluate beam quality, we have begun investigating ODR. We note that ODR is emitted when a charged-particle beam passes through a slit as shown in Fig. 5 [8]. The conducting plates are at 45° to the beam direction and backward ODR is emitted at 90° to the beam direction. In our experiments, we started with a single Al metal screen mounted on an actuator arm driven by a stepper motor and viewed by a CCD camera as schematically shown in Fig. 6. The downstream Cherenkov detector is used as a localized loss monitor to evaluate if beam halo particles are hitting the metal blade. Our initial results have been described elsewhere [9,10], but we show the reference OTR image of the 7-GeV electron beam in Fig. 7a. The beam sizes are $\sigma_x = 1375 \pm 25 \mu\text{m}$ and $\sigma_y = 200 \pm 25 \mu\text{m}$. The blade edge is moved vertically with a setability to $\pm 10 \mu\text{m}$ over a range of 27 mm. In Fig. 7b we show the ODR emitted for an impact parameter (distance of beam center to blade edge $d$) of 2 mm. This is a location 10 $\sigma_y$ beyond the beam center. As described elsewhere, we were able to track the
signal peak position and signal peak intensity as a function of blade edge position. A linear behavior of the first parameter and the exponential decay of the second parameter are consistent with the ODR mechanism. We expect this simple near-field optical imaging technique to be directly applicable to our top-up operations in the transport line. It also seems to be directly applicable to ERLs involving GeV beams. Although ODR is weaker than OTR in our experiments with 3 nC, one expects large signals for the 100-mA ERL case.

An additional experiment was done with the blade edge at 0.75 mm (~4 $\sigma_y$) from the beam center, and an upstream dipole field was scanned to change horizontal beam position. In this case the processed horizontal beam centroid was tracked over a range of ±2 mm. The steps were distinguishable to the 50-µm level for this large beam size and limited magnification. We anticipate the technique would attain 10-µm resolution with a smaller inherent beam size and higher optical magnification. The arguments applied to OTR imaging resolution should apply to ODR resolution in the direction parallel to the plane edge [11].

4. APPLICATION TO ERLs

With these results as context, I return to some of the ERL issues for low power and high power. In the commissioning phase with low average power (nA to µA) one could convert e-beam information with the YAG:Ce screen or OTR foils. We note that YAG:Ce screens do exhibit a saturation effect for areal charge densities that exceed 1 nC in a $\sigma_{x,y} = 100$ µm beam size so OTR should be used for the higher areal charge densities [12]. Spatial resolution of 10 µm with appropriate optics and cameras should be obtainable. In addition, the time-resolved imaging techniques with gated, intensified cameras and streak cameras provide access to sub-macropulse effects.

In the mature phase with high average power, the NI methods should be employable for mA to 100-mA beams. The inherent geometry of ERLs with bends should make OSR
imaging (both direct and 2-slit interferometer) relevant. It is also noted that the high average currents and intensified camera may extend the OSR applicability from GeV beam energies down to 10s of MeV. ODR from metal planes or apertures is a clear candidate for the high energy end of ERL applications as we have described and as shown in the KEK experiments [13]. One should consider a diagnostics undulator in the options for the light source ERL. XSR and UR generally would be converted to visible light by a scintillator. Time-resolved imaging techniques with gated cameras and streak cameras are applicable, of course. One also has to note the potential of scanning wire- and laser-wire-based techniques for these high-current modes.

5. SUMMARY

In summary, I have discussed how e-beam techniques developed on the rings and transport lines of the APS have relevance to a number of ERL diagnostics issues. Transverse position issues are well in hand in general for single-shot and quasi-CW measurements. The inherent architecture of ERLs includes bends in the beamlines, so the opportunity for synchrotron radiation imaging should be exploited. Both OSR and XSR should be considered depending on the beam energy and the resolution needed. A diagnostics undulator in a light source ERL is a good candidate for NI measurements. Recent experiments at KEK, APS, and BNL on ODR show good promise for NI diagnostics. Our recent near-field ODR imaging techniques should be evaluated further. Additional aspects of the transverse diagnostics for ERLs can be found in other papers of these proceedings.

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FIGURE CAPTIONS

Figure 1. A schematic of the APS facility indicating the accelerators and the NI diagnostics options.

Figure 2. A schematic of the APS log-ratio rf BPM electronics.

Figure 3. Example images of beam in the APS SR with 225-mA average current and a) with and b) without the HOM instability.

Figure 4. The online processed profiles for the images in Fig. 3 for a) with and b) without the HOM instability.

Figure 5. Schematic of ODR emitted when a particle beam passes between two metal planes oriented with the normal at 45° to the beam direction (from Fig. 1 of ref. 8).

Figure 6. A schematic of the ODR imaging station in the 7-GeV beamline showing the Cherenkov detector and downstream imaging screen as well.

Figure 7. Images from the 7-GeV beam a) OTR image from Q = 0.4 nC and b) ODR image for Q = 3.3 nC and d = 2.00 mm.
REFERENCES


Figure 1
Figure 2
Figure 3
Figure 4
Figure 5
Figure 7
Table 1. System Applications. (Courtesy of R. Lill)

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of BPMs</th>
<th>Frequency (µHz)</th>
<th>Half Aperture (mm)</th>
<th>Stripline Sensitivity (dB/mm)</th>
<th>Normalized Position (µm/mV)</th>
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<tbody>
<tr>
<td>Linac</td>
<td>15</td>
<td>2856</td>
<td>17</td>
<td>2.0</td>
<td>$13.6 \times V_{out}$</td>
</tr>
<tr>
<td>LEUTL</td>
<td>20</td>
<td>2856</td>
<td>17 and button type</td>
<td>2.0</td>
<td>$13.6 \times V_{out}$</td>
</tr>
<tr>
<td>Linac to PAR</td>
<td>4</td>
<td>2856</td>
<td>17</td>
<td>2.0</td>
<td>$13.6 \times V_{out}$</td>
</tr>
<tr>
<td>Booster to Storage Ring</td>
<td>8</td>
<td>352</td>
<td>25</td>
<td>1.4</td>
<td>$20.0 \times V_{out}$</td>
</tr>
</tbody>
</table>
Table 2. Estimates of Total Visible Photons per 1-nC Charge in a Single Pass ($\lambda = 400$-700 nm) (Reproduced from Ref. 4).

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Beam Energy (GeV)</th>
<th>B – Field (T)</th>
<th>Angular Width</th>
<th>Integrated Flux</th>
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<tbody>
<tr>
<td>Linac OTR</td>
<td>0.20</td>
<td>Thin foil</td>
<td>$2\pi$ solid angle</td>
<td>$10.6 \times 10^7$</td>
</tr>
<tr>
<td>Chicane</td>
<td>0.15</td>
<td>0.6</td>
<td>20 mrad</td>
<td>$4.1 \times 10^7$</td>
</tr>
<tr>
<td>Particle Accumulator Ring</td>
<td>0.375</td>
<td>1.2</td>
<td>10 mrad</td>
<td>$3.1 \times 10^7$</td>
</tr>
<tr>
<td>Injector Synchrotron</td>
<td>7</td>
<td>0.7</td>
<td>8 mrad</td>
<td>$8.4 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(16 mm @ 2 m)</td>
<td></td>
</tr>
<tr>
<td>Storage Ring</td>
<td>7</td>
<td>0.6</td>
<td>3 mrad</td>
<td>$4.4 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(35 mm @ 12 m)</td>
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