Linac-Beam Characterizations at 600 MeV Using Optical Transition Radiation Diagnostics*

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Abstract. Selected optical diagnostics stations were upgraded in anticipation of low-emittance, bright electron beams from a thermionic rf gun or a photoelectric rf gun on the Advanced Photon Source (APS) injector linac. The upgrades include the installation of optical transition radiation (OTR) screens, transport lines, and cameras for use in transverse beam size measurements and longitudinal profile measurements. Using beam from the standard thermionic gun, tests were done at 50 MeV and 400 to 650 MeV. Data were obtained on the limiting spatial (σ ~ 200 µm) and temporal resolutions (300 ms) of the Chromox ($A1_2O_3$: Cr) screen (250 µm thick) in comparison to the OTR screens. Both charge-coupled device (CCD) and charge-injection device (CID) video cameras were used, as well as a Hamamatsu C5680 synchroscan streak camera operating at a vertical deflection rate of 119.0 MHz (the 24th subharmonic of the S-band 2856 MHz frequency). Beam transverse sizes as small as σ_x = 60 µm for a 600 MeV beam and micropulse bunch lengths of σ_τ < 3 ps have been recorded for macropulse-averaged behavior with charges of about 2 to 3 nC per macropulse. These techniques are applicable to linac-driven, fourth-generation light source R&D experiments, including the APS's SASE FEL experiment.

INTRODUCTION

An increased interest in diffraction-limited light sources for the next-generation sources and the implementation of prototype or scaling experiments has been evident since the Fourth Generation Light Source Workshop, held in Grenoble in January 1996 (1). At the Advanced Photon Source (APS), a research and development effort had been underway for several years to use the injector linacs with a low-emittance electron beam source (2-4). More specifically, an rf thermionic gun would be used for injection into the 100 to 650 MeV linac subsystem based on the existing 200 MeV electron linac and 450 MeV positron linac. The low, normalized emittance beams ($\varepsilon_n \approx 5\ \pi$ mm mrad)

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require an upgrade to the existing Chromox viewing screens for characterization of beam transverse size and bunch length. We are in the process of testing optical transition radiation (OTR) screens at selected positions in the beamline to provide sub-100 μm spatial resolution and sub-ps response times (5, 6). In order to compensate for the reduced brightness of this conversion mechanism, both gated, intensified cameras and streak cameras are being used to measure the beam properties. Initial tests with beam at 550 to 650 MeV (but generated by a conventional thermionic gun) have been done with a charge-injection device (CID) camera, a charge-coupled device (CCD) camera, and a streak camera. Additionally, the feasibility of using coherent transition radiation (CTR) and diffraction radiation (DR) based techniques will be evaluated. The diagnostics will be used to characterize, optimize, and monitor the bright beams needed to support self-amplified spontaneous emission (SASE) scaling experiments at $\lambda \sim$ 120 nm and a beam energy of 400 MeV as described separately (7).

EXPERIMENTAL BACKGROUND

Linac

The APS facility's injector system uses a 250 MeV S-band electron linac and an in-line S-band 450 MeV positron linac. The electron gun is a conventional thermionic gun in standard operations. For the alternate configuration, an rf thermionic gun, designed to generate low-emittance beams (<5 π mm mrad) and configured with an α-magnet, injects beam just after the first linac accelerating section (4). Then both in-line linacs can be phased to produce 100–650 MeV electron beams when the positron converter target is retracted.

The rf-gun's predicted, normalized emittance is about an order of magnitude lower than that of the conventional gun. Consequently, much smaller beam spot sizes are produced ($\sigma_{x,y} \approx 100$ μm). The standard intercepting screens are based on Chromox of 0.25 mm thickness, with a 300 ms decay time (8). Previous experiences on the Los Alamos linac-driven free-electron laser (FEL) with a low-emittance photoelectric injector (PEI) support the applicability of optical transition radiation screens in this case (9). A summary of projected beam properties is given in Table 1.

TABLE 1. APS Linac Beam Properties in the Low-Emittance Mode (rf Gun)

Parameter	Specified Value
rf frequency (MHz)	2856
Beam energy (MeV)	100–650
Micropulse charge (pC)	350
Micropulse duration (ps)	3–5 (FWHM)
Macropulse length (ns)	30
Macropulse repetition rate (Hz)	1–20
Normalized emittance (π mm mrad)	~5 (1 σ)

However, initial tests of a Ti foil used as an OTR screen, the transport of the OTR out of the tunnel, and the CCD camera and streak camera setup have been done with a "surrogate" beam from the conventional gun. These were done at a beam energy of 650 MeV, 2–5 nC in the macropulse, and 25–30 pC in each of 80 micropulses.

Beam Characterizations

A general description of the proposed techniques for beam characterization is given in Reference 2. A subset of those, based on optical techniques, now in the installation and testing stage, are presented here.

Transverse Characterizations

The transverse beam sizes and profiles are key to evaluating the beam emittance and its preservation throughout the accelerator and transport lines. At the 50 MeV station, two additional OTR screens are being installed. Although their axial spacing is less than 1 meter, beam quality will be initially checked at this point using the two-screen-beam-size-measurement technique, as well as the beam-size-versus-quadrupole-field-strength scan technique.

Another key station is at the end of the linac in the transport line, nominally the 650 MeV station. At this point, an optical transport line has been installed to bring the OTR light to an optical table outside of the linac tunnel. This table will provide an experimental base for measurements with a streak camera and a gated, intensified charge-coupled device (ICCD) camera (Stanford Computer Optics, Quik-05A). With the microchannel plate (MCP)-based shutter, samples 5 ns wide from the beam macropulse are possible. The gain factor of the MCP also allows for imaging of defocused spots during a quadrupole field scan for an emittance measurement. The tests of these cameras have already been done on the APS positron accumulator ring (PAR) and the booster synchrotron using synchrotron radiation from ~1 nC charge passing through a dipole.

The PAR bypass transport line provides a unique opportunity with its 10 m drift space to perform a three-screen emittance measurement. As described in Reference 7, the center screen is 4.8 m from the two end screens. Relay optics will bring the images to a lead-shielded ICCD camera. A fourth screen may be used for OTR interferometer experiments in conjunction with the center screen.

Longitudinal Characterizations

Because longitudinal beam brightness is related to evaluations of SASE gain, the measurement of bunch duration and profile are also critical in this program. At the 50 MeV station, one of the OTR screens and one part of the beamline cross will be configured to send the far-infrared (FIR) coherent transition radiation, generated by the few-ps or mm-long bunches, to a FIR Michelson interferometer. An optical autocorrelation technique will be evaluated as a bunch duration diagnostic (10).

The baseline technique will use a Hamamatsu C5680 dual-sweep streak camera viewing the incoherent OTR signal from the 650 MeV station. The transport of OTR to the optics table outside the tunnel has facilitated these experiments. The most useful vertical sweep plug-in has been a synchroscan unit phase-locked to 119.0 MHz, the 24th subharmonic of the 2856 MHz linac frequency. Low jitter of the synchronous sum of beam bunches is advantageous in dealing with the very low charge in a single micropulse. Because the S-band micropulse spacing is much smaller than the 119.0 MHz period, the sequence of micropulses will best be displayed using the dual-sweep technique *if* light levels are sufficient. This particular 119.0 MHz unit has been successfully phase-locked to an rf source at the Duke Storage Ring FEL facility, which is injected by an S-band linac (11). At the APS, a low-jitter countdown circuit has been built using Motorola ECLIN PS logic to generate the 24th subharmonics. It has been tested with a 0.7 ps (rms) jitter pulse generator, and the total jitter was observed to be 1.1 ps. Band-pass filters on the output result in a clean 119.0 MHz sine wave to be used with the synchroscan unit (12). The initial results are given in the next section.

RESULTS

An initial test of OTR source strength has been done using 1–3 nC of beam in a macropulse from the conventional gun, at energies of 580 and 650 MeV, with an in-tunnel camera (13). Since the Ti foil was placed over only half of the Chromox screen at this station, the e-beam could be steered and focused on the Chromox first and then steered onto the OTR foil.

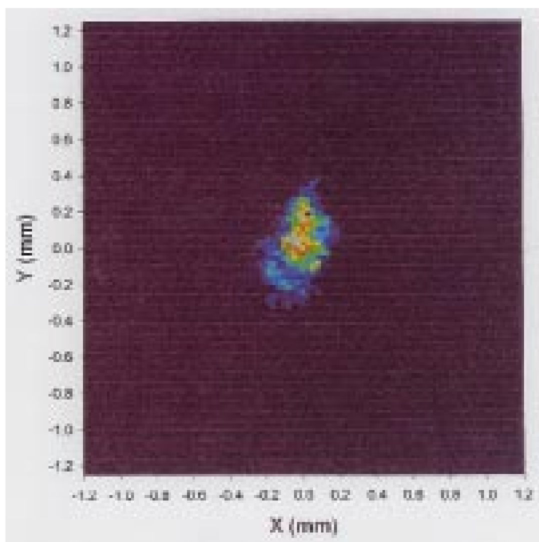

FIGURE 1. One of the first OTR images of APS linac beam at 650 MeV and ~3 nC in a macropulse from the *conventional* thermionic gun. A four-frame average was used to improve the statistics.

Figure 1 shows a sample beam image using the new optical transport to bring the OTR outside the tunnel to the optics table. Figure 2 shows the horizontal and vertical profiles with Gaussian fits. Focused spots (~0.5 mm, FWHM) were readily imaged with the CCD camera with about 3 nC in a macropulse. However, normal transport conditions usually have a larger spot size at this location and are seen much more readily with the Chromox screen. This baseline measurement supports the OTR screen choice because the increased beam image size from the Chromox screen implied that it had a 200 μm (σ) resolution limit under these conditions.

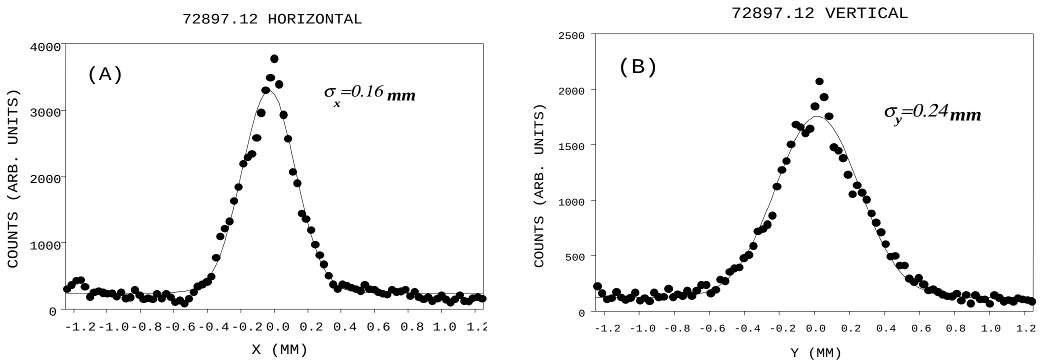

FIGURE 2. The horizontal (a) and vertical (b) spatial profiles for the OTR image in Figure 1. The observed sizes are smaller than those from the Chromox screen with its 200 μm limiting resolution.

We have also performed initial bunch-length measurements using the OTR conversion mechanism and the streak camera operated in synchroscan mode. As noted, the beam was generated by the conventional thermionic gun. Our configuration of rf BPM electronics limited us to 100 mA in a macropulse. This corresponded to only about 25–30 pC in each of 80 micropulses, separated by 350 ps. Although this charge is lower by an order of magnitude than was projected for rf-gun operations, we were able to obtain streak images by using 8- or 16-event averages in the digitizing system. We then performed the synchronous summing of micropulses from the same section in the macropulse.

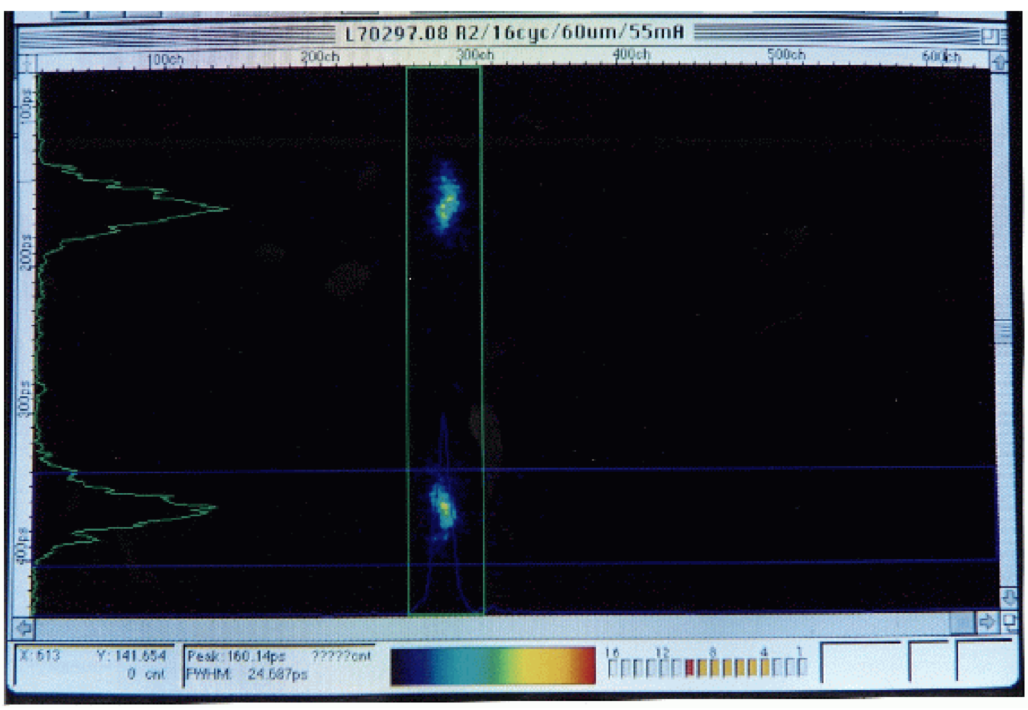

FIGURE 3. Synchroscan streak image summing over several micropulses showing a *y-t* tilt similar to a head-tail wakefield effect. These data were taken without a bandpass filter so the total bunch length was σ = 10 ps or 24 ps (FWHM).

Images on four streak ranges were obtained. Figure 3 shows an example from range #2 (R2) that spans ~480 ps. Due to the S-band repetition frequency of the microbunches, more than one micropulse is displayed with the 119 MHz sweep rate. An intriguing feature of the image is the curvature in *y-t* space displayed. The data are reminiscent of a head-to-tail transverse kick on the submicropulse timescale, perhaps due to transverse beam position offsets while transiting the linac accelerator structures. The displacement of the spatial profile centroid from the early to late part of the micropulse was about 200 μm with the observed bunch length of 10 ps (σ). As the peak current is quite low for this case, further data are needed. A short time later, the e-gun was observed to be arcing, and this resulted in noticeable differences in micropulse arrival time. The data were taken without a bandpass filter, so some temporal dispersion effects are involved.

In Figure 4 the streak camera focus mode profile (a) is shown to give a limiting resolution of about 2.6 ps, while the micropulses bunch length averaged over 4 micropulses for 4 macropulses is about 3.6 ps in Figure 4(b). The 550 × 40 nm bandpass filter was used to reduce the chromatic dispersion effects. These data involved a streak speed three times slower than the fastest range, so 1 ps bunch lengths are addressable.

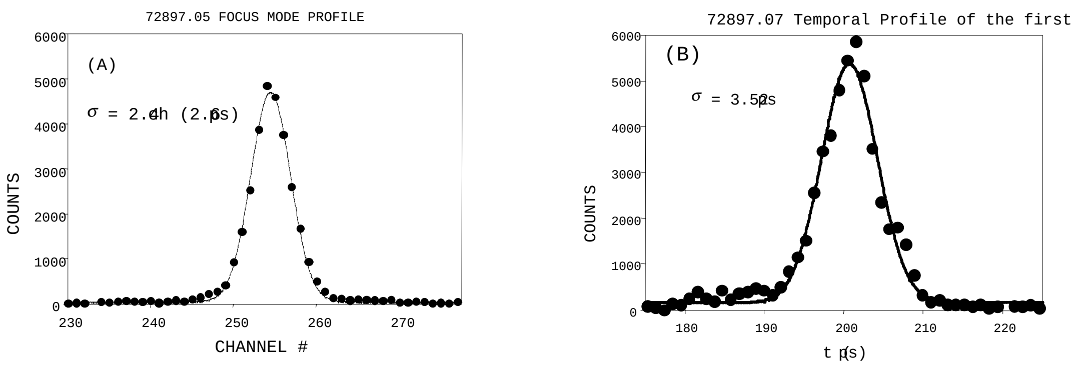

FIGURE 4. Streak camera images taken with a 550 × 40 nm bandpass filter for the focus mode (a) and the R2 streak range (b). The total observed bunch length is about 3.6 ps (σ) from the conventional gun and buncher system.

In the two cases above, an intercepting OTR foil is used. For nonintercepting bunch length measurements, coherent DR is a possible way to extend the Michelson interferometer technique (14, 15). In the streak camera case, a bend in the transport line, a special few-period diagnostics wiggler, or the final prototype wiggler for the SASE experiments are potential nonintercepting sources of optical radiation for a bunch length measurement.

SUMMARY

In summary, the adjustments of optical diagnostic techniques in preparation for low-emittance beams are well underway in the APS linac. Tests of some techniques (e.g., OTR, gated cameras, and the synchroscan (119.0 MHz) streak camera) have already been done with alternative particle beam sources. Further tests will be done with the conventional injector, and the initial tests with rf-gun injected beam are expected in 1998.

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