

TIME-RESOLVED IMAGING FOR THE APS LINAC BEAMS*

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 SEP 22 1999
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Abstract

The particle-beam imaging diagnostics for the Advanced Photon Source (APS) injector linac have been enhanced by the installation of optical transition radiation (OTR) screens and the use of Ce-doped YAG crystals as beam profile monitors. Both converters have improved spatial resolution and time responses compared to the standard Chromox ($\text{Al}_2\text{O}_3:\text{Cr}$) screens used elsewhere in the linac. These enhancements allow us to address the smaller beam sizes ($< 100 \mu\text{m}$) and the critical micropulse bunch length of higher brightness gun sources. For the linac macropulse of 30-ns duration composed of 86 micropulses at S-band frequency intervals, only the OTR mechanism is prompt enough to separate individual micropulses and to allow streak camera measurements of the micropulse averaged bunch length. Tests have been performed at 400 to 625 MeV using the gated DC thermionic gun source. Beam sizes less than $\sigma_x=30 \mu\text{m}$ have been observed with a micropulse bunch length of $\sigma_t=2-3 \text{ ps}$ using OTR. First results on the lower-emittance rf thermionic gun are briefly discussed.

1 INTRODUCTION

The imaging of particle beams on linacs via intercepting screens and video cameras is a well-established practice. However, the time-resolving of individual micropulses in an rf linac macropulse and the measuring of micropulse bunch length requires a radiation conversion mechanism that is prompt compared to the time scale of interest [1]. In the case of the Advanced Photon Source (APS) injector linac, the addition of a lower emittance gun and the critical need for high peak currents in the developing self-amplified spontaneous emission (SASE) free-electron laser (FEL) application have motivated our enhancement of these diagnostics [2]. Optical transition radiation (OTR) screens and Ce-doped YAG crystals have been installed in selected places in the beamline. Both converters have improved spatial resolution and time responses compared to the standard Chromox ($\text{Al}_2\text{O}_3:\text{Cr}$) screens used elsewhere in the linac. Of the three converters only the OTR screens provide the

response required to separate the S-band micropulses and to allow streak camera measurements of the micropulse averaged bunch length and longitudinal profile. At low currents the YAG:Ce provides good spatial resolution like OTR, but we report an apparent "size-blurring" effect for the YAG:Ce converter as current is increased that may limit its usefulness. Many tests have been performed at 400 to 625 MeV using the gated DC thermionic gun source to commission the diagnostics, and the first results with the rf thermionic gun were obtained in the summer of 1998.

2 EXPERIMENTAL BACKGROUND

The APS facility's injector system uses a 250-MeV S-band electron linac and an in-line 450-MeV S-band positron linac. The primary electron gun is a conventional gated DC thermionic gun. For one alternate configuration an rf thermionic gun, designed to generate low-emittance beams ($< 5 \pi \text{ mm mrad}$) and configured with an α magnet, injects beam just after the first linac accelerating section [3,4]. Then both in-line linacs can be phased to produce 100- to 650-MeV electron beams when the positron converter target is retracted.

The rf gun's predicted, normalized emittance at higher peak current is lower than that expected of the DC gun, and correspondingly smaller beam spot sizes ($< 100 \mu\text{m}$) should result. In an early test we used a Ti OTR foil to cover half of a standard intercepting screen based on Chromox of 0.25 mm thickness (rotated 45° to the beam). The 45° angle also directed the OTR light out the same 90° port as the Chromox radiation. Previous experiences on the Los Alamos linac-driven FEL with a low-emittance photoelectric injector (PEI) showed the OTR screens could be used for profiling small beams [5]. This assembly allowed us to steer the e-beam from one converter to the other to compare observed beam spot sizes for spatial resolution tests and assess response time. Because the Chromox decay was so slow, we used a Spiricon video digitizer that could digitize and save images to disk at a 15-Hz rate. This proved more than adequate to track the Chromox decay time.

In addition, we subsequently installed a Ce-doped YAG single crystal of 0.5 mm thickness (obtained from Startec) normal to the beam direction with a polished metal mirror at 45° to the beam just behind it. A separate actuator was used to insert the OTR screen (Molybdenum mirror from

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

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Melles Griot) so that its surface was at 45° to the beam. The light was transported out of the linac tunnel to an optics table via two 150-mm-diameter achromat lenses. The Chromox, OTR, or YAG:Ce light could be viewed by a Vicon charge-coupled device (CCD) camera; a charge-injection device (CID) camera; a Stanford Computer Optics Quik-05 gated, intensified camera; and/or a Hamamatsu C5680 dual-sweep streak camera. The synchroscan unit was phase-locked to 119.0 MHz, the 24th subharmonic of the 2856-MHz linac frequency. A low jitter countdown circuit has been built using Motorola ECLIN PS logic to generate the 24th subharmonic with sub-ps jitter [6].

3 EXPERIMENTAL RESULTS

3.1 Radiation Converter Comparison

As mentioned in the previous section, comparisons were made for Chromox versus OTR and YAG:Ce crystals versus OTR in the past year. In the first series, the beam was initially steered into the high efficiency Chromox. The electron beam optics were then adjusted to give the "best focus" on the OTR screen. The size was recorded, and then the beam was steered back to the Chromox. For beam sizes in the 150- μm regime as measured by OTR, we observed a larger size in the Chromox. We then estimated the Chromox-limiting resolution by subtracting the OTR image size from the total observed Chromox image size in quadrature. This resulted in a limiting value of $\sigma_{\text{res}} \sim 200 \mu\text{m}$ as reported previously [7].

The response time of the Chromox was determined by triggering a single macropulse from the DC gun at 1 Hz and recording the succession of video images on the Spiricon hard disk. The digital images were then analyzed and intensities plotted as a function of elapsed time from the trigger. The 30-ns-long macropulse was like a delta-function in time compared to the Chromox decay time. In Fig. 1 this decay of image intensity is shown, and the 1/e value was determined as 300 ms. Using the OTR screen, only one frame had an image since OTR is indeed prompt versus video rates. The Chromox decay time is even long compared to macropulse separations of 30 ms at the 30-Hz rate.

In the YAG:Ce and OTR comparison, the tests were performed in a similar manner. Over the course of brief tests at 100-mA average beam current (about 3 nC in a macropulse), we repeatedly observed a larger beam size with YAG:Ce than with OTR. In the June 12, 1998 experiments we first established our beam size comparisons at low currents of 30 and 60 mA. We used an elongated vertical focus (aspect ratio H/V of 1/10) because this seemed to result in the smallest sizes we could make: 70 μm (FWHM) or 30 μm (σ). This value is close to the calculated resolution of the transport line. The neutral density filter difference of

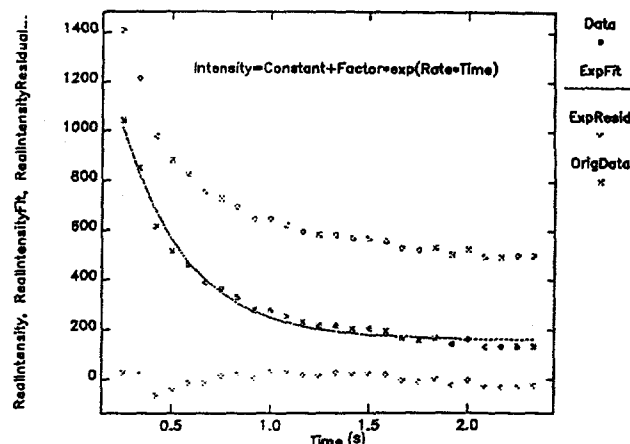


Figure 1: "X" Data with background subtracted are fitted to an exponential. The 1/e time is about 300 ms.

2.0 was used at this reference point, and the camera position in Z was adjusted to compensate for the YAG surface and OTR mirror surface location difference. These low-current data basically normalize and validate the screen comparison in terms of calibration factors, source strength compensation, camera saturation, and bremsstrahlung effects in the YAG:Ce. As shown in Fig. 2, at 100 mA and higher the YAG:Ce images are observed to be increasingly larger with current than the OTR images. There is a slight increase in the OTR image with current. The threshold for this "size-blurring" effect for this particular crystal/mirror and these conditions is 1.1 to 1.6 $\text{pC}/\mu\text{m}^2$ using the FWHM size. If the one-sigma beam sizes are estimated using a Gaussian shape assumption, the threshold is $(2.35)^2$ times smaller or 0.2 to 0.3 $\text{pC}/\mu\text{m}^2$.

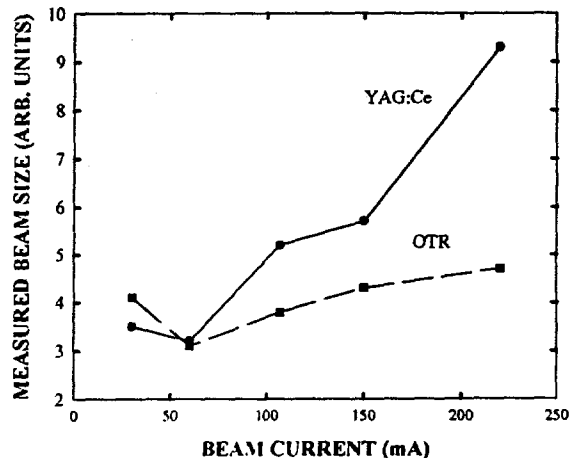


Figure 2: Comparison of observed beam image sizes using OTR (dashed line) and the YAG:Ce converter screens. Noticeable YAG:Ce (solid line) image size growth is observed beginning at $\leq 100\text{mA}$ and with spot size of about $40 \times 400 \mu\text{m}^2$ ($\sigma_x \times \sigma_y$).

Simplistically speaking, there may be a saturation-like phenomenon in the peak-intensity regime that results in the half-maximum intensity points growing relative to the peak. How the very large number of Ce-related impurity levels could be exhausted is unclear. Alternatively, mechanisms involving radiation trapping or photoionization may be involved [8]. The very small beam spots from a PEI that involve several hundred pC could easily approach this threshold observed in these 625-MeV tests. These charges and beam energies are higher than used in the single micropulse experiments previously [9]. Further tests and a search for alternative explanations are planned.

The reported response time for this YAG:Ce is 80 ns (FWHM) [9] so it averages the micropulses in a 30-ns macropulse. A measure of this was shown by comparing the micropulse bunch length seen with OTR to the YAG:Ce result. The OTR result was 4 ps (FWHM) while the YAG:Ce decay filled the 150-ps field of view and completely obscured the micropulse structure and a fortiori, the bunch length. The OTR result is very similar to that obtained previously by an rf phasing technique [10].

Table 1 summarizes these comparisons of the radiation converter spatial resolution, temporal response, and conversion efficiency. The limiting resolution number for APS-installed screens of Chromox and YAG:Ce are given and the OTR number estimated. The OTR response time is only an estimate, but this surface phenomena should be in the regime of the skin depth for visible light in a metal [11].

Table 1: Comparison of the Chromox, YAG:Ce, and OTR Converter Screens for Particle Beam Imaging at 600 MeV at APS

Screen	Spatial Resolution σ (μm)	Temporal Response	Intensity Arb. Units
Chromox (0.25 mm)	200	300 ns	1
YAG (0.5 mm)	<30 low current <100 200 mA	80 ns	1
OTR	<10	~ 10 fs	$\sim 2 \times 10^{-3}$

3.2 RF-Gun Accelerated Beam

On August 12, 1998 our first images of the rf-gun beam at 400 MeV were obtained at this station at the end of the linac. Both OTR and YAG:Ce images were obtained with the YAG:Ce size again being larger than the OTR size for ~ 160 -mA average current and an approximate 130×130

μm^2 spot size. A preliminary synchroscan streak image gave a $\sigma_t = 3$ to 6 ps result even though no optimization of the rf gun had yet been done.

4 SUMMARY

In summary, the time scales for time-resolved imaging on the APS linac have been significantly enhanced. The targeted beam spot sizes of 100 μm (σ) can be addressed by YAG:Ce at low current (areal charge density) and OTR at higher currents. Micropulse bunch lengths at the ps-regime can also be addressed now. Optimization of the accelerated rf gun beam will be facilitated by these enhanced techniques.

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