Development of a Coherent Transition Radiation-Based Bunch Length Monitor with
Application to the APS rf Thermionic Gun Beam Optimization*

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Abstract

We report further development of an EPICS-compatible bunch length monitor based on the autocorrelation of coherent transition radiation (CTR). In this case the monitor was used to optimize the beam from the S-band thermionic rf gun on the Advanced Photon Source (APS) linac. Bunch lengths of 400 to 500 fs (FWHM) were measured in the core of the beam, which corresponded to about 100-A peak current in each microphone. The dependence of the CTR signal on the square of the beam charge for the beam core was demonstrated. We also report the first use of the beam accelerated to 217 MeV for successful visible wavelength SASE FEL experiments.

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

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1. Introduction

An interest in generating beams of sufficient brightness to support self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiments continues to drive the development of beam characterization techniques at the Advanced Photon Source (APS). In this case we have developed an EPICS-compatible version of a bunch length monitor based on the autocorrelation of coherent transition radiation (CTR) [1]. We have taken advantage of the technique to observe sub-0.5-ps micropulse structure in a beam from a thermionic rf gun, and have developed procedures for optimization of the gun's performance by appropriate adjustments of gun current, the rf power to the gun cavity, the α -magnet current, and a scraper installed on the low energy particle trajectory as guided by the CTR signal strength [2]. The processing of the data was done using a series of application scripts developed over the past year [3]. The bunch profile was calculated using a fast Fourier transform (FFT) of the autocorrelation followed by an application of the minimal phase approximation of Lai and Sievers [4]. Bunch lengths of the core of the beam corresponded to peak currents of ~ 100 A in each micropulse of the S-band macropulse. The dependence of the CTR signal on the square of the beam charge for the beam core was demonstrated. Although the charge per pulse was lower than initially simulated several years ago [5], the peak current and the beam emittance implied sufficient brightness to support SASE FEL gain experiments. We also report the first successful use of the beam accelerated to 217 MeV for such visible wavelength gain experiments.

2. Experimental Background

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The APS thermionic rf gun has been described previously as well as its use as the source of electrons for injection into the main storage ring [6]. In this case the gun was operated at a higher gradient in order to increase the charge per micropulse, and hence peak current. For a target of 100 A, the 40-50 pC micropulse charge available implied a bunch length of less than 0.5 ps would be needed. In order to address this regime, we have implemented a far infrared (FIR) Michelson interferometer at the 40-MeV station in the linac. Table 1 lists the basic beam parameters at this location, and Fig. 1 shows a schematic of the experiment. The initial measurements were done with a 40-ns-long macropulse, but subsequently we were able to operate with only the 8-ns macropulse.

2.1 Coherent Transition Radiation Monitor

The bunch length monitor is based on the autocorrelation of FIR CTR generated as the charged-particle beam strikes the metal mirror oriented at 45° to the beam direction. This particular interferometer has a novel, compact design using an Inconel-coated beam splitter [1]. It was constructed at the University of Georgia under an ANL contract. A Golay cell, model OAD-7 from QMC Ltd., is used as the FIR detector. Its entrance window transmits well from 20 μm to 1 mm. The moveable arm of the interferometer and the data acquisition are handled via EPICS.

Complementary bunch length measurement information is available at the end of the linac using either an optical transition radiation (OTR) conversion mechanism and a C5680 Hamamatsu streak camera or the rf zero-phasing technique combined with the electron spectrometer. The approximate temporal resolutions of these two systems are 1.5 ps (FWHM) and 0.6 ps (FWHM), respectively. These two techniques can provide supplementary asymmetry information.

2.2. Recent CTR System Development

In the earliest configurations of the CTR system we had used a digitizing oscilloscope to process the Golay cell signal. In the last year we have added a transimpedance amplifier, modified the APS-built gated integrator module, and added a Hewlett-Packard waveform digitizer. The latter item has allowed us the ability to evaluate still the analog waveforms and to archive them.

The EPICS scripts have been augmented to allow tracking of CTR signal during the α -magnet current, low-energy scraper, or interferometer scans. The rf BPM sum signals just before the intercepting CTR screen location are also monitored during these scans for normalization data if needed. The scripts track the 6-Hz pulse rate.

The data analysis/processing tools have been particularly enhanced. Scripts compatible with the APS self-describing data set (SDDS) format [7] have been written. These scripts apply the FFT routine to the autocorrelation data which gives the square of the bunch spectrum. Using the method of Lai and Sievers [4] involving the minimal phase approximation, the phase spectrum is reconstructed from the amplitude spectrum by computing a principal value integral. Once the phase spectrum is obtained, an inverse FFT is performed to derive the microbunch profile.

3. Thermionic rf Gun Beam Optimization

A sequence of steps has been developed to optimize the rf gun for brighter beams using the high gradient for the gun cavity. We start with a scan of the α -magnet current to find the minimum bunch length. The power to the gun and the cathode heater current are adjusted to produce 1 to 2 nC in a train of 23-25 S-band bunches. The beam is focused at the 40-MeV station on a YAG:Ce scintillating crystal, and then the CTR converter screen

is switched into the beamline. During the scan, the rf gun phase must be adjusted linearly to compensate for path length changes in the α -magnet. Figure 2 shows a sample α -magnet scan with a CTR signal peak at 175 A. The curve represents the digitized output of the Golay detector.

Once the minimum bunch length has been found, an α -magnet scraper scan is performed. Simulations suggest that the microbunch has a low-emittance, high-energy core beam and a high-emittance, low-energy tail. The scraper scan is used to optimize removal of the low-energy tail. Figure 3 shows a scraper scan where the CTR signal is plotted versus scraper position. The edge of the core beam is at ~ 9.5 cm. As shown in Fig. 4, the CTR signal (plotted vs. the nearby rf BPM sum signal) exhibits the expected quadratic dependence on the number of particles in the beam [8,9].

After determining the desired scraper position, the FIR interferometer was employed to measure the autocorrelation of the digitized CTR signal. Typically 151 or 201 steps are done with a scan step of $7.5 \mu\text{m}$ and a 10-shot average per point. Figure 5 shows the result for ~ 1 nC in 23 S-band micropulses. Note that the width of the peak in microns is doubled for the optical path differences. It is approximately $120 \mu\text{m}$ (FWHM). After the correction is applied at low frequencies, the bunch profile is broadened and the dips on either side of the autocorrelation are flattened (since the autocorrelation should be positive). In Fig. 6 the derived bunch profile from the corrected autocorrelation spectrum is shown. There is a high-current peak greater than 100 A and a lower-current shoulder with an overall width of ~ 400 fs. The streak camera data and the zero phasing technique used in other runs of the gun are consistent with a spike on the leading edge of the bunch.

4. SASE FEL Test

The core beam was accelerated to 217 MeV, the charge measured in a Faraday Cup, the energy spread measured in the spectrometer, and the emittance measured using the three-screen technique. The values were found to be $Q = 1$ nC, $\sigma_\epsilon \sim 0.1\%$, and $\epsilon_n \sim 12 \pi$ mm mrad, respectively. The beam was transported to the low-energy undulator test line (LEUTL) hall and through the five 2.4-m undulators. Diagnostics stations after each undulator [10] were used to measure the growth of the 537-nm fundamental intensity. An exponential growth behavior was measured with a SASE gain length of $L_g \sim 1.3$ m as shown in Fig. 7 [2]. These are the first (to our knowledge) such measurements using a thermionic rf gun beam. Although the bunch length is comparable to the slippage length, the gain length is in agreement with expectations based on Xie's parameterization of SASE gain [11].

5. Summary

In summary, a CTR-based monitor has been developed into an on-line technique for optimizing the thermionic rf gun beam's bunch length at the sub-0.5-ps and 100-A peak current regime. This optimized beam core was further characterized and had sufficient brightness to support visible light SASE FEL experiments. The studies with this beam will continue, but a recently installed chicane bunch compressor in the APS linac will allow the relocated CTR monitor to be applied to the PC gun beam as well.

6. Acknowledgements

The authors acknowledge the support of S. V. Milton, K.-J. Kim, and J. N. Galayda of APS. They also thank Geoff Krafft of Jefferson Lab for discussions on their CTR system.

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Figure Captions

- Fig. 1 A schematic of the APS SASE FEL experiment showing the electron gun, accelerator, CTR diagnostics station, and the undulators with their diagnostics.
- Fig. 2 A plot of the variation of CTR signal versus α -magnet current.
- Fig. 3 A plot of the CTR signal versus scraper arm position in the α -magnet.
- Fig. 4 A plot of the CTR signal versus the rf BPM sum signal. The solid line is a quadratic fit to the data showing the CTR's dependence on the square of the number of particles in the beam core.
- Fig. 5 An autocorrelation of the FIR CTR using the Michelson interferometer.
- Fig. 6 The derived longitudinal bunch profile for the autocorrelation after a correction is applied at low frequencies.
- Fig. 7 The intensity of visible undulator radiation (diamonds) versus the undulator length. The exponential growth behavior is clearly seen with a gain length $L_g \sim 1.3$ m.

Fig. 1

Fig. 2

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