FERMILAB-CONF-08-109-AD

OBSERVATIONS OF ENHANCED OTR SIGNALS FROM A COMPRESSED ELECTRON BEAM*

A.H. Lumpkin, Fermilab, Batavia, IL U.S.A. 60510
N.S. Sereno, M. Borland, Y. Li, K. Nemeth, and S. Pasky,
Argonne National Laboratory, Argonne, IL U.S.A. 60439

Abstract

The Advanced Photon Source (APS) injector complex includes an option for photocathode (PC) gun beam injection into the 450-MeV S-band linac. At the 150-MeV point, a 4-dipole chicane was used to compress the micropulse bunch length from a few ps to sub 0.5 ps (FWHM). Noticeable enhancements of the optical transition radiation (OTR) signal sampled after the APS chicane were then observed as has been reported in LCLS injector commissioning. A FIR CTR detector and interferometer were used to monitor the bunch compression process and correlate the appearance of localized spikes of OTR signal (5 to 10 times brighter than adjacent areas) within the beam image footprint. We have done spectral dependency measurements at 375 MeV with a series of band pass filters centered in 50-nm increments from 400 to 700 nm and observed a broadband enhancement in these spikes. Discussions of the possible mechanisms will be presented.

INTRODUCTION

During the commissioning of the LCLS injector in 2007, unexpected enhancements of the signals in the visible light optical transition radiation (OTR) monitors occurred after compression in a chicane bunch compressor [1]. These signals were attributed to a microbunching effect of some kind and the generation of coherent OTR (COTR). Since the Advanced Photon Source (APS) injector complex includes a flexible chicane bunch compressor that is similar to that at LCLS, we have an option to use an rf photocathode (PC) gun, and we had experience with SASE-induced microbunching [2], a series of experiments was performed to explore the phenomena. We initially performed studies on OTR measured at three screens located after the bunch compressor. We used focus-at-the-object or near-field imaging optics and established that there were clear enhancements of the OTR signals at maximum bunch compression. The compression was also monitored with a FIR CTR monitor and interferometer. The shortest bunches generally generate the strongest FIR signals, and the appearance of the enhanced OTR was strongly correlated with the maximum FIR signal, although there appeared to be a slight phase shift between the two maxima. We also accelerated the compressed beam to the end of the linac and evaluated the enhancements at 375 MeV. The localized spikes in the beam distribution were still visible at this energy. At this latter station we have the light transported outside of the tunnel to a small optics lab that allowed us to perform additional spectral dependency measurements. Moreover, the use of a thermionic cathode gun pulse train with only 40 pC per micropulse did not show the OTR enhancements when the bunch length was compressed comparably to that of the PC gun beam. Discussions of the possible mechanisms will be presented for the APS case which is similar, but not identical to that of LCLS.

----

*Work supported by U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Contract No. DE-AC02-06CH11357.

EXPERIMENTAL BACKGROUND

The tests were performed at the APS facility which includes an injector complex with two rf thermionic cathode (TC) guns for injecting an S-band linac that typically accelerates the beam to 325 MeV, the particle accumulator ring (PAR), the booster synchrotron that ramps the energy from 0.325 to 7 GeV in 220 ms, a booster-to-storage-ring transport line (BTS), and the 7-GeV storage ring (SR). In addition, there is an rf photocathode (PC) gun that can also be used to inject into the linac as shown schematically in Fig. 1. An extensive diagnostics suite is available in the chicane and after the chicane area as also shown in Fig. 1. The tests were performed in the linac at the three imaging stations (indicated by a flag symbol) after the chicane bunch compressor and at the end of the linac where another beam imaging station is located. A FIR coherent transition radiation (CTR) detector (Golay cell) and Michelson interferometer [3] are located between the three-screen emittance stations. A vertical bend dipole and diagnostics screens in this short beamline allow the monitoring of tranverse x-beam size and energy following compression.

The CTR converter is an Al-coated mirror with an 18 mm diameter clear aperture on a zerodur substrate, and it is mounted with its surface normal at 45 degrees to the beam direction on a pneumatic actuator assembly. A synthetic quartz lens at the port of the cross collimates the beam into the interferometer box. A remotely controlled translation stage steps the position of one arm of the interferometer for the autocorrelation tests. An EPICS interface allows the acquisition of the autocorrelation data. The YAG:Ce and OTR were directed by turning mirrors and relay optics to a Pulnix CCD camera located 0.5 m from the source. These Chicane stations also have options for low- and high-resolution imaging of the beam spot by selecting one of two lens configurations [4].

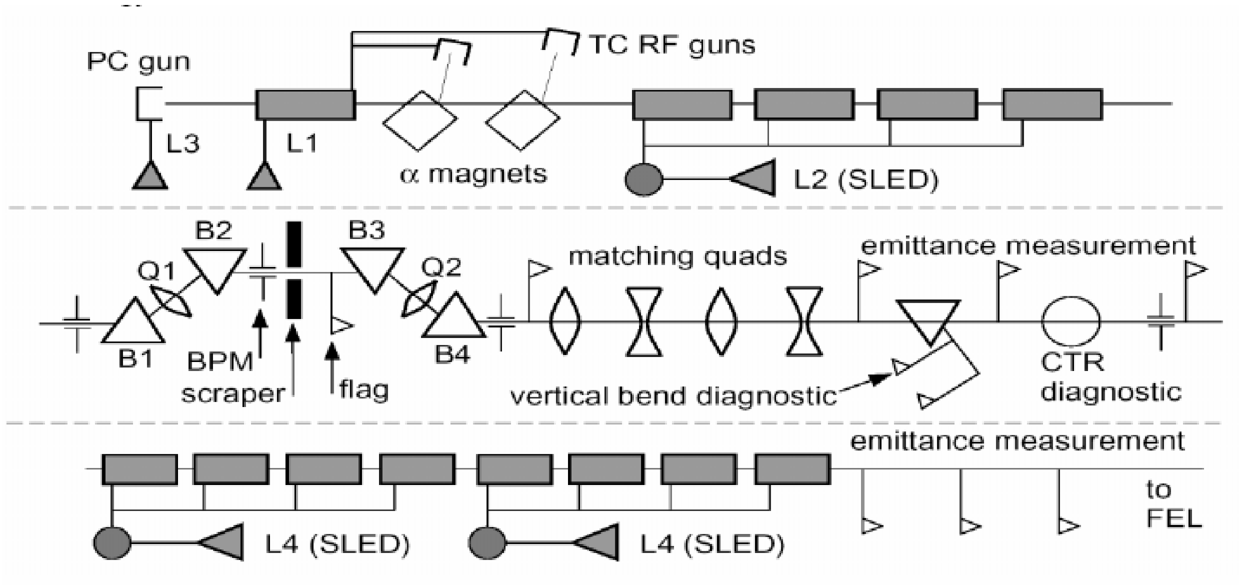

Figure 1: A schematic of the APS linac test area showing the PC gun, the two TC rf guns, the accelerator structures, the chicane, and the diagnostics suite. This includes rf BPMs, beam profile screens (flags), FIR CTR diagnostic, and the vertical bend diagnostic line.

The near-field, low-resolution magnification resulted in calibration factors of 48.8 μm per pixel in x and 38.9 μm per pixel in y. The OTR signal strength with a 400 pC micropulse was too low to use the high-resolution mode. The signal intensity was adjusted with a remotely-controlled iris (with no absolute position readback) in the path to the camera. The OTR and YAG:Ce images were recorded with a Datacube MV200 video digitizer for both online and offline image analyses, and a video switcher was use to select the camera signal for digitizing.

At the end of the linac, the imaging station included the optical transport of the visible light out of the tunnel to a small, accessible optics lab where the CCD camera was located. This allowed the access for exploring the spectral dependency of the enhanced OTR. A set of bandpass filters with center wavelengths in 50-nm increments from 400 to 700 nm and 40-nm band width as well as a 500-nm shortpass filter and 500-nm long pass filter were used in the tests. The beam energy was 375 MeV at this station.

Data were also recorded from the electron spectrometer at the end of the linac, but this focal plane converter screen was made of Chromox.

INITIAL CTR AND OTR RESULTS

The experiments were initiated by transporting the PC gun beam accelerated to 150 MeV to the chicane area. The rf phase of the L2 accelerator structure located before the chicane was used to establish the appropriate conditions for compression in the chicane. The degree of compression was tracked with the Golay cell signals as shown in Fig. 2. A very strong variation of the FIR signal with L2 phase is observed. There is almost no signal seen when uncompressed and 300 units seen at the peak compression. The autocorrelation scan was then done and showed a profile width of ~65 um (FWHM) as seen in Fig. 3. Two separate scans are displayed in the plot. This would mean a roundtrip time of 130 µm, or about 430 fs (FWHM). The initial PC gun bunch length was 3 to 4 ps (FWHM) as determined by the drive laser pulse.

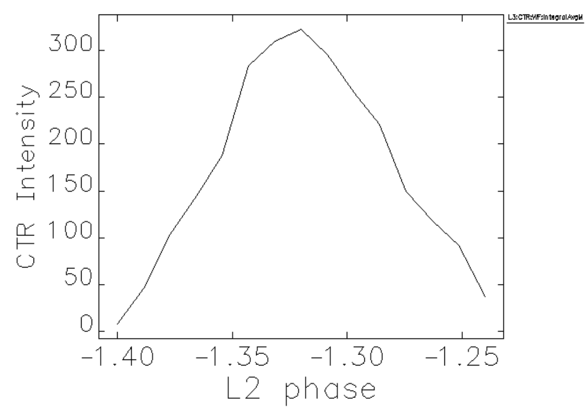

Figure 2: FIR CTR signal from the Golay cell variation with the upstream L2 phase setting (reading in V).

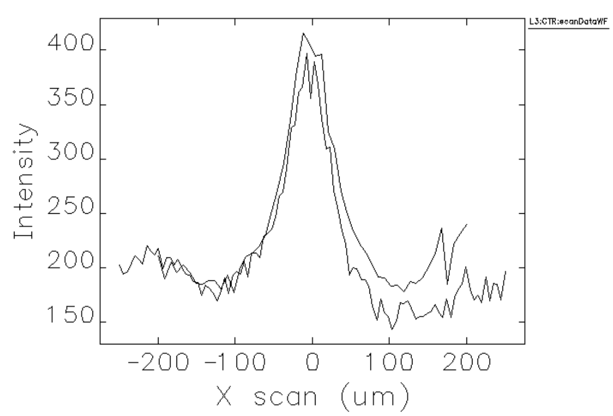

Figure 3: FIR CTR autocorrelation performed after the chicane near maximum compression setup for the PC gun. The two scan profile widths are about 65 µm (FWHM).

Having determined we had good compression from the Golay-cell data, we then sampled the beam images at the three screens after the chicane in the emittance measurement area. The samples shown are from FS5, the third screen of the set. At the point of minimum compression the OTR image is weak, but visibly tilted in x-y space. No sharp features are seen as shown in Fig. 4. The profile is sampled a little off center of this image, but it is representative of its flatness and low intensity of 15-25 counts. In contrast, the image taken near full compression as indicated by the FIR CTR signal has significantly enhanced localized spikes of about 250 µm extent as shown in Fig. 5. The pseudo-color intensity scale at the right of the image shows that the red areas are high intensity. The profile at the right shows the peak intensity of 180 counts, almost 10 times the adjacent intensities in the beam-image footprint. We do not see the ring-like structure in the enhancement reported at LCLS, but we also don't have a harmonic cavity for linearizing longitudinal phase space before the chicane as LCLS has. On this particular run, we noted that there seemed to be a preferred location in the beam image to be enhanced. The enhanced vertical band in Fig. 5 is the same area that shows less enhancement with less compression.

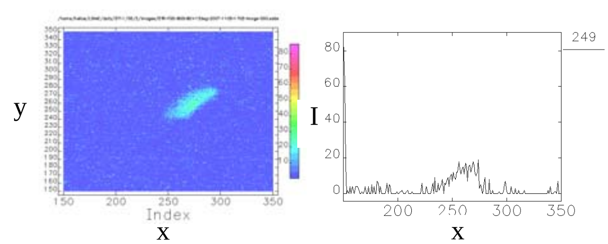

Figure 4: OTR beam image (left) and horizontal profile (right) sampled through distribution after BC with L2 phase = 12 degrees, close to minimum compression.

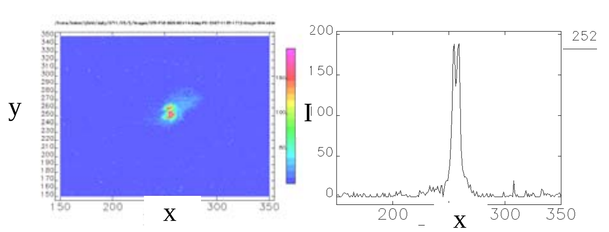

Figure 5: OTR beam image (left) and horizontal profile (right) through spike in distribution after BC with L2 phase = 14.9 degrees, close to maximum compression.

An additional indication of the effect is shown in Fig. 6, where the peak intensities from the vertical profiles taken though the images at each phase setting show the rapid increase in the enhanced OTR signal in just a few degrees of L2 phase change. The order of magnitude enhancement is clearly seen in this plot. A similar plot for horizontal profiles was done, and this showed a slight shift of the intensity peak compared to the CTR data by 0.4 degrees in L2 phase. Integrated areas of the ten images at each phase setting do not show this degree of enhancement, but

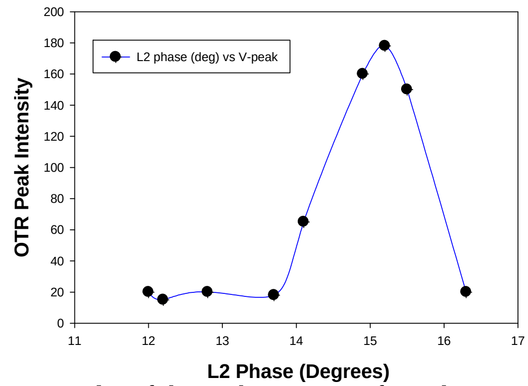

Figure 6: Plot of the peak intensities from the OTR image vertical profiles taken near the enhanced regime coordinates as a function of L2 phase in degrees.

about a 1.6-2 times larger counts integral at peak compression was seen with larger fluctuations in the compressed conditions as shown in Fig. 7 (top). The peak intensities on average increase by 3-4 as shown in the lower plot of Fig. 7. This fact is consistent with the premise that the charge transport intensity is not the cause of the effect nor CSR- induced clumping of electrons, but rather a coherent enhancement of some kind is involved.

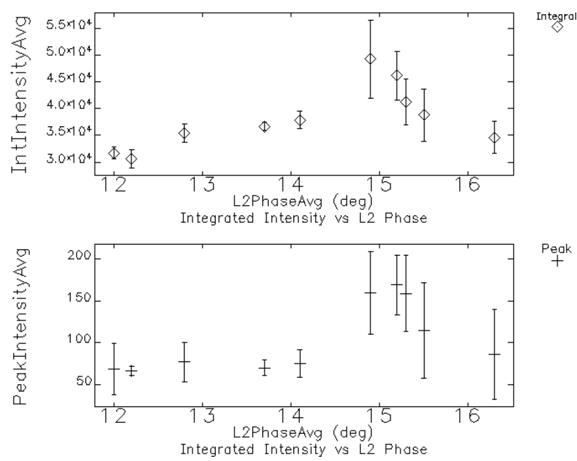

Figure 7: Plot of the OTR image integrals (top) and OTR peak intensities (bottom) using automated post processing versus L2 phase (degrees). The enhancements occur near the FIR CTR signal maximum.

In order to assess the spectral dependency of the OTR enhancements, we accelerated the beam to 375 MeV and again imaged the beam spot with OTR at a downstream station. As described previously, this station included transport of the signal outside of the tunnel to a small optics lab. First, we still see enhanced localized spikes when we have compressed the beam as shown in Fig. 8. We also confirmed that these spikes were present at even a compression level of ½ the CTR signal, although their intensity varied more from shot to shot. In Fig. 9 we show the post-processed image intensity integrals (top) and the peak intensities (bottom) versus the L2 phase set point at this location. In this case enhancements of the OTR signals when at maximum compression are about 3-6 times the normal intensity. The strong fluctuations of these enhanced areas are again suggestive of a coherent process, perhaps seeded by noise. (We also recall that previously our self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiments indicated preferred hot spots in the spatial distribution of the compressed beam.)

At full compression we checked the spectral dependency of the enhancements by inserting the bandpass filters in front of the CCD camera. Our preliminary results are that the enhancements were seen at all central wavelengths from 400 to 700 nm (in steps of 50 nm), although relatively weaker in the 400 to 500-nm regime than at 550 nm. We subsequently checked the spectral dependence of incoherent OTR from the TC gun beam and saw a similar intensity rolloff in this short wavelength interval which we attribute to the CCD camera response to these different wavelengths. We also saw more enhancement of intensity in the 500-nm longpass filter than in the 550-nm shortpass filter.

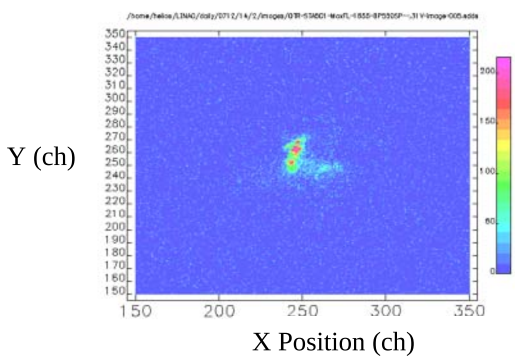

Figure 8: OTR image at 375 MeV showing the enhancements are still present after acceleration beyond the bunch compressor.

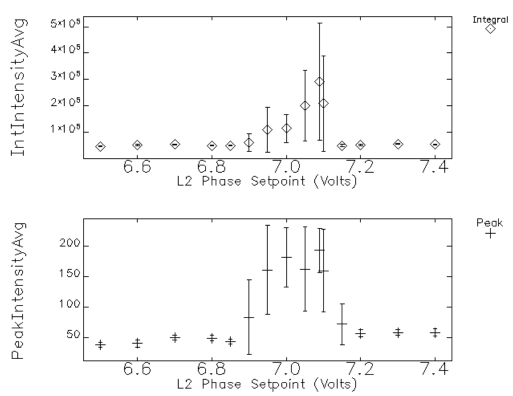

Figure 9: Plot of the OTR image integrals (top) and OTR peak intensities (bottom) at 375 MeV using automated post processing versus L2 phase setpoint (volts). The enhancements occur near the FIR CTR signal maximum.

CTR AND OTR RESULTS WITH TC RF GUN BEAM

In the course of our studies, we decided to test the effect with the TC rf gun beam. In this case we could generate about 40 pC per micropulse in a macropulse of 25 micropulses that contained about 1 nC total. So the integrated OTR signal should be similar to that of the PC gun beam. We also have no drive laser involved. With the combination of compression in the alpha magnet of the TC gun system and the chicane, we were able to generate an autocorrelation profile width of ~62 µm (FWHM) as shown in Fig. 10. This result is very similar to the PC gun result in Fig. 3, so we have again about a sub-0.5 ps FWHM micropulse at a beam energy now of 150 MeV. The main difference at the chicane is there is now 10 times less charge in the micropulse compared to the PC gun beam, and 10 times lower peak current. One would expect a significant reduction in any coherent mechanisms. We observed no localized OTR enhancements at the screen after the chicane, nor at the downstream location at the end of the linac. The integrated intensities were the same to about 10% throughout the L2 phase scan. An image from the latter screen under full compression conditions is shown in Fig. 11. The beam size is larger than that of the PC gun beam due to the larger emittance from the source. We repeated the spectral intensity measurements with the filters and determined the nominal overall response of the system to the OTR spectrum and the CCD sensitivity factors. The intensity vs. wavelength curve is very similar to that of the PC gun beam images with enhancements. Therefore, we have no evidence yet of a specific wavelength enhancement in the visible light regime, such as might be due to longitudinal microbunching. We are planning tests with a UV-IR spectrometer in the near future.

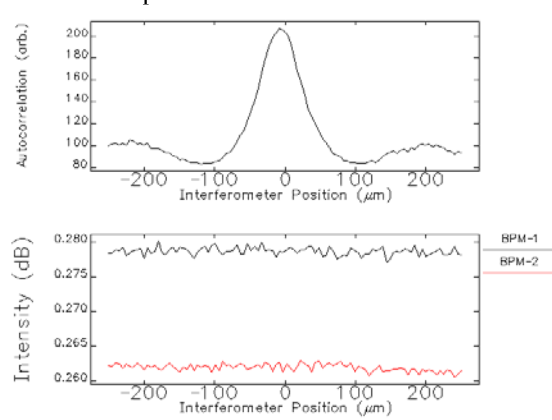

Figure 10: FIR CTR autocorrelation performed after the chicane near maximum compression setup for the TC gun. The scan profile width (top) is about 62 µm (FWHM). The BPM sum signals (bottom) from positions after the chicane were also tracked and show little change during the scan.

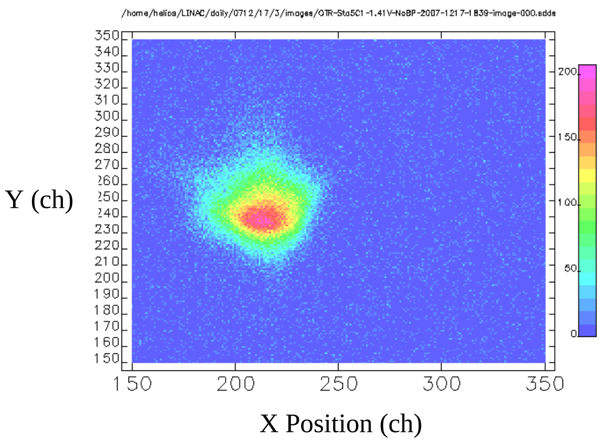

Figure 11: An example OTR image of the TC rf gun beam at the 375-MeV station with maximum compression in the chicane. No localized spatial spikes are evident.

DISCUSSION

We have identified several characteristics of the enhanced OTR signals that may be used to evaluate which mechanism is involved. If we consider electron number constancy, photon number enhancements, and spectral structure observed, we may be able to discriminate among microbunching, a longitudinal spike, and CSR-induced clumping. We initially wondered whether there were microbunching from the drive laser interaction with the low-energy photoelectrons such as found under high laser power conditions [5], but a simple calculation of the laser field strengths showed this effect would not be measurable. Since we accept the transported charge through the chicane is basically constant to 10 % during the phase scan, we cannot explain the large photon number enhancements as only due to CSR-induced clumping of the charge distribution. Finally, our preliminary spectral sampling across the visible light region with 40-nm band widths showed a broadband character like that of incoherent OTR. Our data seem more consistent with coherent enhancements due to longitudinal structure such as a leading-edge spike.

SUMMARY

In summary, we have initiated investigations on enhancement of OTR signals in the visible light regime following bunch compression of our PC rf gun beam at APS. Although the enhancements are not as high as that reported at LCLS, we do see order of magnitude signal increases in localized spatial spikes. At this time the coherent enhancement appears consistent with a fine spike in the longitudinal distribution that develops after bunch compression. The practical effect is that we cannot simply evaluate emittance of the beam for different compressions using the OTR screen images, but we normally use the Yag:Ce screens. We did not see the effects in the TC gun beam when compressed similarly, but this involved only 40 pC per micropulse and a macropulse charge of ~1 nC. The growing interest in these COTR effects is indicated by the time allowed for discussion in the planned high brightness beams workshop at Zeuthen in May 2008 [6].

ACKNOWLEDGEMENTS

The authors acknowledge support from R. Gerig and K.-J. Kim of the Argonne Accelerator Institute and M. Wendt of Fermilab.

REFERENCES

[1] D.H. Dowell et al., "LCLS Injector Commissioning Results", submitted to Proc. of FEL07, Aug. 26-30, 2007, Novosibirsk.
[2] A.H. Lumpkin et al., "First Observation of z-dependent Microbunching using Coherent Transition Radiation," Phys. Rev. Lett., Vol. 86(1), 79, January 1, 2001.
[3] A.H. Lumpkin et al., "Initial measurements of CSR from a Bunch-Compressed Beam at APS." Proc. of FEL05, JACoW/eConf C0508213, 608 (2005).
[4] B.Yang et al., "Design and Upgrade of a Compact Imaging System for the APS Linac Bunch Compressor", BIW2002, AIP Conf. Proc. 648, 393 (2002).
[5] Karoly Nemeth et al., PRL 100, 095002 (2008).
[6] Agenda for Mini Workshop on "Characterization of High Brightness Beams," Zeuthen, May 26-30, 2008.