PROPOSED COHERENT DIFFRACTION RADIATION MEASUREMENTS OF BUNCH LENGTH AT ASTA

A.H. Lumpkin[#], J. Ruan, and R. Thurman-Keup

Fermi National Accelerator Laboratory*, Batavia, IL 60510, USA

Abstract

The feasibility of using the autocorrelation of coherent diffraction radiation (CDR) as a non-intercepting diagnostics technique for bunch length and indirectly rf phase measurements is evaluated and proposed for the Advanced Superconducting Test Accelerator (ASTA) facility under construction at Fermilab. Previous experiments on an rf thermionic cathode gun beam at 50 MeV provide a proof-of-principle reference for the ASTA injector. The ASTA injector is based on an L-band rf photocathode (PC) gun with UV pulse drive laser, two L-band superconducting accelerator structures, a chicane bunch compressor, and an electron spectrometer. The injector energy of 40-50 MeV is expected. The 3-MHz micropulse repetition rate with micropulse charges up to to 3.2 nC and 1-ps bunch lengths should generate sufficient CDR signal for standard pyroelectric detectors to be used. The CDR signals will also be evaluated as a bunch compression signal for beam-based feedback for rf phase. The technique would also be applicable at high energy in straight transport lines after the cryomodules.

INTRODUCTION

The high-power electron beams for the Advanced Superconducting Test Accelerator (ASTA) facility involve up to 3000 micropulses with up to 3.2 nC per micropulse in a 1-ms macropulse [1]. With beam energies projected from 45 to 800 MeV the need for non-intercepting diagnostics for beam size, position, energy, and bunch length is clear. In this Note, we address non-intercepting (NI) diagnostics of the bunch length and inferred rf phase by using coherent diffraction radiation (CDR) techniques [2,3]. Previous evaluations of incoherent optical synchrotron radiation indicated that the source strength for visible photons is quite weak for a single micropulse at 40 MeV from the chicane dipoles, but synchroscan streak techniques to determine the bunch length after the chicane should be viable by synchronous summing of the long pulse train's micropulses [4]. This would be complemented by optical transition radiation (OTR) and coherent transition radiation (CTR) measurements of the tune-up beam with an intercepting metal screen after the chicane. It is proposed that at this station, the metal screen would also have an insertion position where a 4-5 mm tall slit/aperture is centered on the beam position to provide a non-intercepting source of CDR from the surrounding metal surface. The autocorrelation of the far infrared (FIR) CDR would then be processed for the bunch-length information, and the potential for rf phase feedback for the injector cavities would also be possible based on the signal intensity monitored by the FIR detector, either Golay cell or pyroelectric detector. An early measurement of CDR from a screen with a circular aperture was actually an intercepting configuration because the beam subsequently struck a 45-degree metal mirror to redirect the CDR (and CTR) to the FIR detector [2]. The first non-intercepting proof-of-principle demonstration was done with an rf thermionic cathode gun beam at 50 MeV with an integrated charge of only 4 nC using a slit geometry [3]. This means that potentially one would only need a few micropulses of the ASTA injector beam at the full 3.2 nC per micropulse for 1ps rms bunch length to obtain reasonable signal levels with a Golay cell, and the full pulse train could be integrated to obtain information on even longer bunch lengths where FIR generated per pC is lower in the detector-response regime.

EXPERIMENTAL ASPECTS

The ASTA linac with photocathode (PC) rf gun, two booster L-band SCRF accelerators (CC1 and CC2), and beamline is schematically shown in Fig. 1 with beam parameters given in Table 1. The L-band accelerating sections will provide 40- to 50-MeV beams before the chicane, and an additional acceleration capability up to a total of 800 MeV will eventually be installed in the form of three cryomodules with eight 9-cell cavities with average gradient of 31 MV/m after the chicane. It is proposed that a multi-purpose station should be located after the chicane for incoherent OTR, CTR, and CDR generation and studies. As schematically indicated in Fig. 1, the OTR will be transported to a Hamamatsu C5680 synchroscan streak camera (transferred from A0PI) [5], and the CTR and CDR will be transported to the Martin-

Table 1: Summary of Electron Beam Properties at ASTA

Parameter	Units	Values
Bunch charge	pC	20-3200
Emittance, norm	mm mrad	1-3
Bunch length, rms	ps	3-1
Micropulse umber		1-3000

06 Instrumentation, Controls, Feedback and Operational Aspects
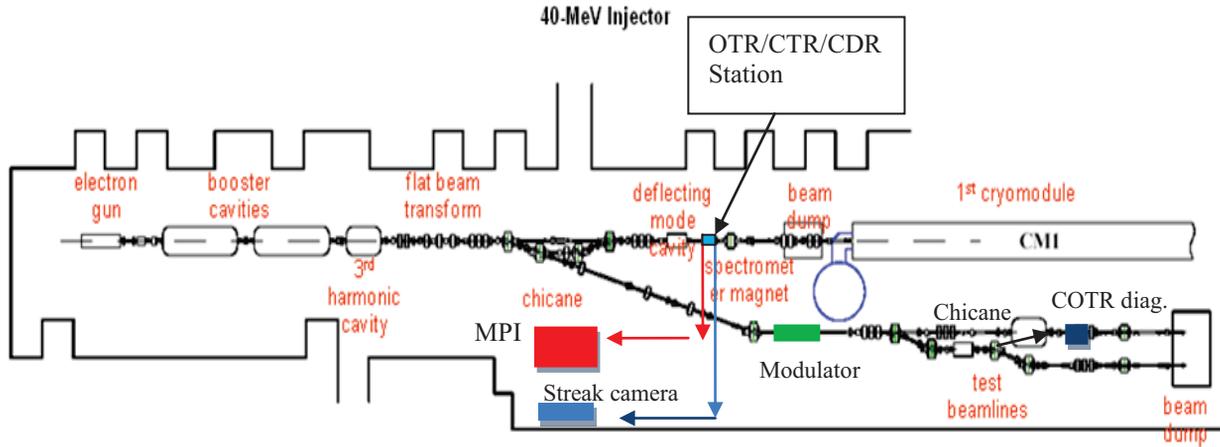
T03 Beam Diagnostics and Instrumentation

Figure 1: Schematic of the injector for the ASTA facility showing PC rf gun, booster accelerators, and beamlines. (courtesy of M. Church). The locations of the streak camera and MPI are also indicated.

Puplett interferometer (MPI) for measuring the auto-correlation of the FIR radiation [6]. A metal screen can be used for the first two mechanisms interceptively, and by centering the 5-mm slit/aperture machined in the screen on the beam axis the CDR will be generated non-interceptively as the beam transits through the aperture. In principle, this latter configuration will work for the full pulse train. Alternatively, a single plane screen with its horizontal edge positioned above or below the beam axis might be used. In this case, a beam abort signal could initiate the withdrawing of the screen away from the beam. The electric field scaling parameter, $\gamma\lambda/2\pi$, where γ is the Lorentz factor and λ is the wavelength, sets the practical scales. For example with FIR 628-µm radiation and $\gamma=100$, this parameter is 10 mm so a 5-mm slit height is reasonable. One prefers a radiating surface of 100 mm, however, this is unlikely to be attained in our beam pipe so some finite screen effects may be involved.

Coherent Radiation Analytics

A brief review [3] of the source of the CTR and CDR is in order. Coherent radiation generated by a bunch of electrons can be expressed as a product of a term representing the radiation process due to a single particle and a term which takes into account how much of the total charge in the bunch radiates together constructively, in phase. Thus the spectral, angular distribution of the radiation can be expressed as,

$$\frac{d^2W}{d\omega d\Omega} = \left| r_{\perp,//} \right|^2 \frac{d^2W_1}{d\omega d\Omega} \Im(\mathbf{k}) \tag{1}$$

where $\dfrac{d^2W_1}{d\omega d\Omega}$ is the spectral angular distribution for

the single particle radiation process, whether transition radiation (TR), synchrotron radiation, or diffraction radiation (DR), for example. In the present case we take it as for DR. $\Im(\mathbf{k})$ is the coherence factor for a bunch of N

electrons, and this term is related to the square of the Fourier transform of the spatial distribution of the bunch:

$$\Im(\mathbf{k}) = N + N\left(N - 1\right)\left|H(\mathbf{k})\right|^2 \tag{2}$$

with the Fourier transform of the charge form factors using a simple Gaussian model being,

$$H(\mathbf{k}) = \frac{\rho(\mathbf{k})}{Q} = g_x(k_x)g_y(k_y)F_z(k_z) \tag{3}$$

and where Q=Ne is the total charge. Note the first term in Eq. (2) yields the incoherent radiation produced by N electrons in the bunch, while the second term gives the coherent production, which is proportional to N^2. The transverse form factors are for $i=x,y$,

$$g_i(k_i) = \frac{1}{\sqrt{2\pi}} e^{-\sigma_i^2 k_i^2 / 2} \tag{4}$$

with the longitudinal form factor for an individual micropulse,

$$F(k_z) = \frac{1}{\sqrt{2\pi}} e^{-\sigma_z^2 k_z^2 / 2} \tag{5}$$

Note that for the coherence factor to be sizable, the beam rms radius and the wavelength of interest λ must be less than 1.4 $\gamma\lambda/2\pi$ for angles of order $1/\gamma$. The wavelengths of interest are determined by the longitudinal part of $\Im(\mathbf{k})$ such that the rms bunch length $\sigma_z < \lambda/2\pi$. The results of the calculations of CDR for several cases of σ_t from 0.2 to 6 ps are summarized in Fig. 2 for a 50-MeV beam with 8 nC of charge transitting the center of a 5-mm tall slit in a metal plane [3]. (This was approximated as two infinite metal strips separated by 5 mm in the model.) Note the form factor results in significant enhancements of radiation at wavelengths about three times longer than the bunch length. For the ASTA case much higher total

charges are anticipated, so the signals should be even stronger if a similar geometry be used. These are basically the same wavelengths expected for the CTR measurements in the MPI, and could in principle also be used with the real-time interferometer (RTI) to generate on-line autocorrelations as demonstrated recently at A0PI [7].
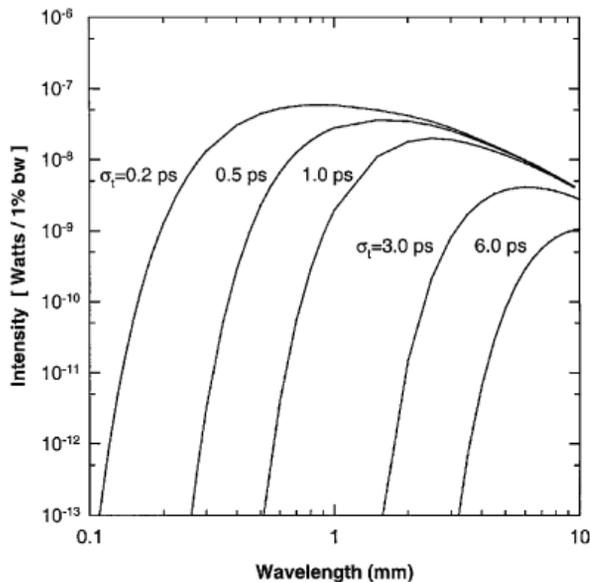

Figure 2: Calculated spectra of CDR for a 50-MeV electron beam passing through a 5-mm slit with 8 nC total charge and bunch lengths σ_t of 0.2, 0.5, 1.0, 3.0, and 6.0 ps [3].

PROPOSED IMPLEMENTATIONS

Low Energy Station (40-50 MeV)

The phase of the CC2 booster cavity can be adjusted to energy chirp the beam entering the chicane to vary bunch-length compression. Maximizing the FIR CTR in a detector after the chicane can be used as the signature of generating the shortest bunch lengths. An alignment laser should be planned to inject at a location after CC2 and through the straight ahead line to the bunch length monitor station and into the streak camera and FIR MPI or RTI. This will facilitate optical alignments of the transport systems to the detectors. Micropulse charges of 20 to 3200 pC will be used typically. The nominal pulse format for high power ILC-like beam is 3.2 nC per micropulse at 3 MHz for 1 ms. This aspect is unique for test facilities in the USA and highly relevant to the next generation of free-electron lasers. The macropulse repetition rate will be 5 Hz.

High-Energy Station (250-800 MeV)

These OTR/CTR/CDR techniques also scale to use at higher energies as will be found after the cryomodule string. The extension of the CDR technique to higher energies should be straight forward as the CDR signal

strengths will be even closer to the CTR signal strengths for a given bunch length and similar effective apertures. This could be used after a proposed second bunch compressor located downstream of the cryomodules. A possible location would be in the straight section afterwards. The streak camera would need to be located in the high energy diagnostics laser lab upstairs, and the MPI would need to be in a locally shielded area. The EOS technique used at A0PI with CTR [8] might be employed with CDR signals to make that also a non-intercepting technique.

SUMMARY

In summary, we have described how a combination of intercepting OTR and CTR techniques and non-intercepting CDR techniques could be implemented after the injector chicane to provide bunch length measurement capability for the 40- to 50-MeV electron beams. The bunch length and deduced phase variation could be used in combination with the beam-arrival monitors in feedback and feed forward systems for rf phase during the macropulse. These OTR/CTR/CDR techniques also scale to use at higher energies found after the cryomodule string. Additionally, such a spectral range with 3000, 1-ps pulses of CDR might be used as a parasitic THz source for some applications.

ACKNOWLEDGMENTS

REFERENCES

[1] S. Nagaitsev, talk presented at ILC-TA Workshop, Fermilab, November 28, 2006.

[2] Y. Shibata et al., Phys. Rev. E **52,** 6787 (1997).

[3] A. H.Lumpkin, N.S. Sereno, and D.W. Rule, NIM A **475**, 470 (2001).

[4] Evaluations presented at NML/Fermilab meetings by A.H. Lumpkin and R. Thurman-Keup (2011).

[5] A. H. Lumpkin, J. Ruan, and T.W. Koeth, "Initial Commissioning of a Dual-Sweep Streak Camera on the A0 Photoinjector", Proceedings of Linac08, JACoW (2008); and A.H. Lumpkin et al., NIMA 2012.05.068.

[6] R. Thurman-Keup, R. Fliller, and G. Kazakevich, "Bunch-length Measurement at the Fermilab A0 Photoinjector Using a Martin-Puplett Interferometer", Proceedings of BIW08, Lake Tahoe,Ca (2008).

[7] J. Thangaraj et al., "Demonstration of a real-time interferometer as a bunch length monitor in a high current electron beam accelerator", Rev. Sci. Instr. **83**, 043302 (2012).

[8] Timothy Maxwell, "Measurement of Sub-picosecond Electron Bunches via Electro-optic Sampling of Coherent Transition Radiation", NIU Dissertation, May 2012.