BUNCH LENGTH MEASUREMENTS WITH LASER/SR CROSS-CORRELATION*

T. Miller[1], J. Corbett[2], J. Wittenberg[1], D. Daranciang[1], J. Goodfellow[1], A. S. Fisher[2], X. Huang[2], W. Mok[2], J. Safranek[2], H. Wen[1] and A. Lindenberg[1]
[1]PULSE Institute, SLAC National Accelerator Laboratory and Stanford University
[2]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park

Abstract

By operating SPEAR3 in low-α mode the storage ring can generate synchrotron radiation pulses of order 1ps. Applications include pump-probe x-ray science and the production of THz radiation in the CSR regime. Measurements of the bunch length are difficult, however, because the light intensity is low and streak cameras typically provide resolution of only a few ps. Tests are now underway to resolve the short bunch length using cross-correlation between a 60-fs Ti:Sapphire laser and the visible SR beam in a BBO crystal. In this paper we report on the experimental setup, preliminary measurements and prospects for further improvement.

INTRODUCTION

In the past 10 years the use of electro-optic crystals (EO) has made its way into a variety of accelerator systems. For timing applications, field-induced birefringence is used to synchronize accelerator components [1] and to correlate pump lasers with an x-ray probe for materials science applications [2]. Similarly, the THz Coulomb field of a linac bunch can be used to temporally resolve the longitudinal charge profile on a single-shot basis [3].

In a storage ring, the bunch length is typically measured with a streak camera (SC) down to a few ps. At shorter bunch lengths, a far-IR interferometer can be used to infer the bunch form factor, or coherent synchrotron radiation (CSR) can be used to spectrally encode the pulse length on a stretched laser beam in EO crystals [4].

Alternatively, as demonstrated by Zolotorev [5], the visible SR component can be mixed with a short laser pulse in a BBO crystal to generate second-harmonic or sum-frequency radiation. The output of a photodiode sensor is proportional to the number of photons in a 'slice' of the SR pulse.

Since SPEAR3 does not have an IR beam port, we are investigating the laser/SR cross-correlation method to measure short bunches in the low-momentum-compaction mode (low-α). For scientific applications, the low-α configuration has the potential for efficient, high-repetition-rate detection techniques using a large fraction of the synchrotron bunches for high photon throughput. In this paper we report on a cross-correlation experiment to measure the nominal 21 ps bunch length, and with α reduced by a factor of 20 to yield σ_t~5ps rms.

LOW-α OPTICS IN SPEAR3

SPEAR3 is a 3GeV, 234m storage ring with nominal emittance ε_x=10nm-rad. In low-α mode [6], the accelerator can produce short bunches with beam intensity limited by the vacuum chamber and CSR impedance. The resulting x-ray pulses have application to pump/probe studies or as a staging ground for high-power femtosecond experiments at the LCLS.

By reducing α, however, the bunch length quickly becomes less than the streak camera resolution limit of ~2.4ps rms and therefore difficult to characterize [7]. An empirical scaling law fit to SPEAR3 data†

$$\left(\frac{\sigma}{\sigma_o}\right)^4 = \left(\frac{f_s}{f_{s,o}}\right)^4 + \left(\frac{I}{I_o}\right)^n \qquad (1)$$

predicts that with a modest reduction to α_o/50 the low-current bunch length is 2.5ps rms, near the SC resolution limit [8]. In this configuration the bursting current threshold is about I_b=30μA or 23pC, the peak current is 3.7A, and within a 60-fs slice at the center of the pulse the total charge is only 0.6pC.

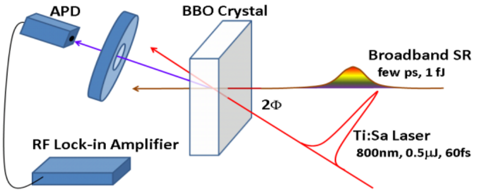

Figure 1: Cross correlation and detection, 2 Φ =20°.

CROSS-CORRELATION GEOMETRY

Similar to streak camera measurements, broadband SR extending from UV into the infrared is initially extracted from a bending magnet and collimated to a 5mm diameter beam on an optical bench. The SR beam is then bandpass-filtered around 800nm and focused to a 50-μm spot in the BBO.

The cross-correlation laser is a mode-locked Ti:Sapphire long-cavity oscillator synchronized to the storage ring with a phase-locked loop. For this application, the 93rd harmonic of the laser signal from a photodiode monitoring the output is mixed with the 476.3 MHz storage ring RF, and a piezoelectric mirror adjusts the laser cavity length to minimize the error signal. The overall system jitter is estimated to be 1ps.

The Ti:Sapp laser produces a train of 500nJ, 60-fs pulses at 5.1MHz (four times the SPEAR3 ring frequency). The laser beam is then passed through a

---

* Work sponsored by U.S. Department of Energy Contract DE-AC03-76SF00515, Office of Basic Energy Sciences and SLAC Laboratory Directed Research Development funds (LDRD).
corresponding author: tamiller@stanford.edu

†here, σ_o=16.8ps, $f_{s,o}$=10kHz, I_o=3.8mA and n=1.7

precision delay stage to control arrival time relative the SR beam. Spatial overlap of the laser with the SR beam is achieved with the aid of a CCD camera. Temporal overlap is achieved by directing part of the Ti:Sapp beam along a path co-linear with the SR beam. As illustrated in Fig. 2, when the two Ti:Sapp beams spatially and temporally overlap, the frequency-doubled component bisects the two fundamental beams.

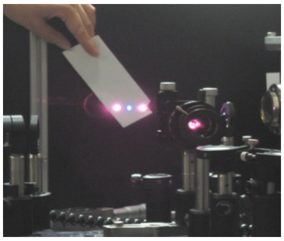
Figure 2: SHG from crossed Ti:Sapp beams.

The cross correlation signal is generated by mixing the SR and laser beams in a BBO crystal. The $\chi^{(2)}$ nonlinearity exhibited by the non-centrosymmetric crystal generates a second order polarization in the crystal at the second harmonic of the input beams. The crystal was cut at the phase matching angle (θ=29.2°) for SHG of the 800nm incident light, and oriented on the optical bench to maximize the laser/SR cross-correlation signal. The non-collinear geometry of the input beams allows the cross correlated beam to be spatially separated from input beams by means of an iris, and an avalanche photodiode (APD) detects the relatively weak mixing signal. A 400nm bandpass filter eliminates 800nm photons but the output signal can be polluted by direct, broadband SR throughput or SHG scatter at 1.28 MHz.

The cross-correlation photon flux is estimated as follows. The 500-nJ Ti:Sapp beam contains ~10^{12} photons/pulse. Based on the measured SR power, the diagnostic beam line collects ~10^7 SR photon/pulse/mA. Of these, ~10^6 photons pass through the 800nm bandpass filter upstream of the BBO crystal. Assuming the low-power BBO efficiency is linear with pump intensity, typical efficiencies for SHG production lead to an anticipated 10^{-3} 400nm photons/pulse from cross correlation at low bunch intensities.

An important ingredient of the SPEAR3 measurements was the use of an RF-lock-in amplifier. The 1.28 MHz repetition rate of the SR pulse provides the 'chop' frequency sensed by the amplifier. The laser delivers 4 short pulses $l(t)$ per turn T_0, for a one-turn signal L:

$$L(t)=\sum_{k=0}^{3} l\left(t+kT_0/4+\tau\right) \tag{2}$$

Here τ is the laser delay, to be scanned through the cross-correlation peak. The SR pulse train, with N_b bunches of different charge q_k, has the form:

$$S(t,\lambda)=\sum_{k=0}^{N_b} q_k s\left(t+kT_0/N_b,\lambda\right) \tag{3}$$

over each turn. Single-bunch mode, with q_k>0 for only the k^{th} bunch, generates a 1.28 MHz SR pulse train. The APD signal after the BBO:

$$\begin{aligned} P(t) &= a_1 L(t) S(t,\lambda_1) \\ &+\int a_2(\lambda) S(t,\lambda)\,d\lambda + a_3 L(t) + a_4 L^2(t) \end{aligned} \tag{4}$$

consists of the desired 400nm cross-correlation component, leakage of direct synchrotron and laser light, plus any frequency-doubled laser light that scatters into the 400nm cross-correlation signal. SHG from the weak SR pulses is negligible.

The pre-amplified photodiode signal P is then sent to a lock-in amplifier (Stanford Research Systems SR844) clocked to detect the SR pulse train at f_0=1.28 MHz. P is internally processed in two channels, X and Y, which multiply P by cosine or sine respectively at f_0 and then low-pass filter between 100ms and 1s:

$$X(t)=\langle P(t)\cos(2\pi f_o t)\rangle,\quad Y(t)=\langle P(t)\sin(2\pi f_o t)\rangle \tag{5}$$

The output is read as R (magnitude) and θ (phase).

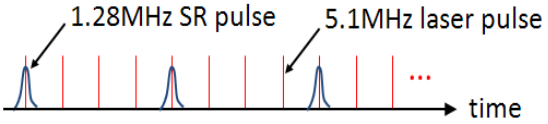

Figure 3: Pulse Train Diagram, 1.28MHz SR and 5.1MHz laser pulses make a 1.28MHz signal. Only the 1.28MHz component is detected by the lock-in.

As indicated in Fig. 3, at 5.1 MHz the Ti:Sapp laser is a harmonic of the1.28 MHz SR bunch train, so the L and L^2 terms of Eq. 4 do not contribute to the output of the lock-in amplifier. The rejection of the 5.1 MHz laser background is the principal advantage of the lock-in over photon counting for the SHG configuration. The other two terms in Eq. 4 involve S through cross-correlation and leakage of the broadband background SR component. Note that the time averages in Eq. 5 are fill-pattern dependent. For instance, the maximum 1.28 MHz cross-correlation signal is obtained by synchronously aligning two electron bunches with two consecutive 5.1 MHz laser pulses while leaving the remaining buckets empty.

EXPERIMENTAL RESULTS

Starting with measurements in the low-emittance lattice (low-ε), representative cross-correlation scans are plotted in Fig. 4. The outer, blue scan was taken at I_b=14.2mA single-bunch current and the inner, red curve at I_b=0.96mA. Gaussian fits to bunch length yield 31ps and 21.8 ps rms, respectively. Comparison with streak camera data in [9] shows good agreement, including the appearance of distortion from the pure Gaussian shape due to resistive impedance in the vacuum chamber.

After switching the lattice to low-α mode, Fig. 5 compares the same 0.96mA low-ε bunch with a 1.5mA low-α bunch. In this case the bunch length is reduced from 21.8 ps to 8.66 ps rms, a result which according to Eq. 1 is about 1-2 ps less than anticipated. The difference may be due to the fact that the 1.5 mA bunch is just below the CSR bursting threshold for this value of α. At these bunch lengths the 60-fs laser pulse is two orders of magnitude shorter than the SR pulse, and the lock-in amplifier's filter time was set to 300ms.

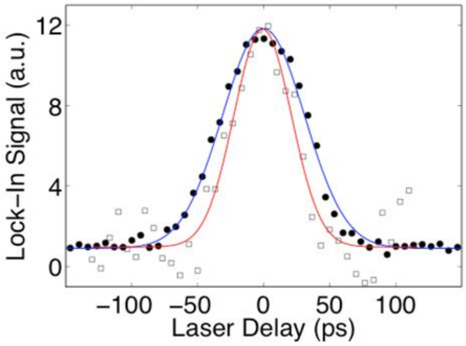

Figure 4: Low-emittance scans with I_b=14.2 mA (blue, 31 ps) and I_b=0.96mA (red, 21.8 ps).

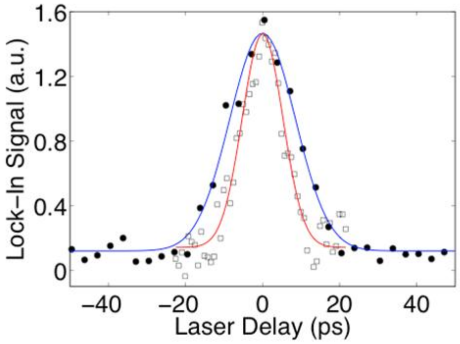

Figure 6: Low-α scans with I_b=1.5mA (blue, 8.66 ps) and I_b=86μA (red, 5.94 ps).

Taking into account motion of the delay stage and equipment settle times each data point requires about 3 sec to acquire. The total time to measure a single scan through a ±40 ps pulse interval is of order 1 minute. After approximately thirty minutes of experimentation, the location of the fitted centroid varies by less than 500fs about the nominal time-zero.

The shortest, low-current bunch recorded to date is σ=5.94 ps rms at 86uA in low-α optics (Fig. 6). Substituting these values into Eq. 1, the estimated momentum compaction factor is $\alpha=\alpha_o/8.4$, larger than the anticipated value of $\alpha_o/21$ which would yield σ=4.25 ps rms. Sources of error could be the inherent noise level (1.28 MHz lock-in signal 100μV in several mV background) or jitter in the timing system. At 5 ps bunch lengthes the nominal 1-2 ps synchrotron oscillation amplitude begins to contribute to the error. In this case the bunch current is 20% below the bursting threshold.

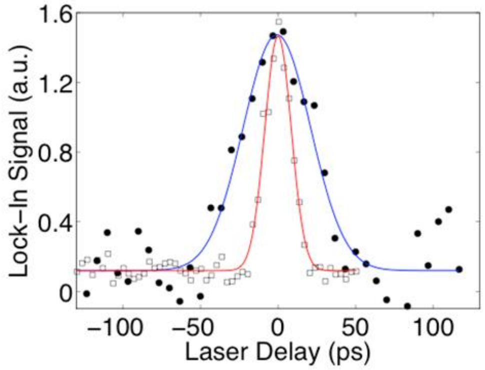

Figure 5: Comparison of scans with I_b=0.96 mA in low-emittance optics (blue, 21.8 ps) and I_b=1.5 mA in low-α optics (red, 8.66 ps).

SUMMARY AND FUTURE PLANS

The double-bend achromat configuration of SPEAR3 affords a unique opportunity to produce short-pulse, high-repetition rate x-ray beams in low-α mode. Streak camera measurements are viable down to ~2.4 ps rms. Without access to FIR or THz radiation, shorter bunch lengths require a multi-turn laser/SR cross-correlation measurement. Although the count rate is low, preliminary results are promising and will be pursued with lock-in and single-photon detection. By modulating the Ti:Sapp pulse arrival time we plan to compensate for synchrotron oscillations at low current that modulate the SR pulse arrival time.

Future measurements will include tests with sum-frequency and Type-II crystals. With the Type-II crystals the input beams do not self-generate harmonics, and the mixing product from the orthogonal E-field components appear at a unique frequency.

To assist the pump/probe materials science program, tests will be made to detect timing jitter at the SR beam line and transmit bunch arrival time to pump lasers located at x-ray beam lines around SPEAR3.

REFERENCES

[1] S.Schultz, et al, 'An Optical Cross-Correlation Scheme to Synchronize Distributed Laser Systems at FLASH', EPAC08, Genoa, Italy (2008).

[2] A.L.Cavalieri, *et al*, 'Clocking Femtosecond X Rays' Phys. Rev. Lett. 94, 114801 (2005).

[3] B.Steffen, 'Electro-optic Methods for Longitudinal Bunch Diagnostics at FLASH', PhD Dissertation, (2007).

[4] F.Müller, *et al*, 'Electro-optic Sampling of Coherent SR for Picosecond Bunches with few-pC Charge', BIW10, in press.

[5] M.Zolotorev, *et al*, 'Development of a Longitudinal Density Monitor for Storage Rings', PAC03, Portland, Oregon, (2003).

[6] X.Huang, *et al.*, 'Low-Alpha Mode for SPEAR3', PAC07, Albuquerque, NM, (2007).

[7] W.Cheng, A.S.Fisher and J. Corbett, 'Streak Camera Measurements in PEP-II and Variable Optics in SPEAR3', BIW08, Lake Tahoe, CA (2008).

[8] J.Corbett, *et al*, 'Short Bunch Measurements in SPEAR3', PAC09, Vancouver, Canada (2009).

[9] J.Corbett, *et al*, 'Bunch Length and Impedance Measurements at SPEAR3', EPAC08, Genoa, Italy, 2008.