BUNCH LENGTH MONITORING AT THE A0 PHOTOINJECTOR USING A QUASI-OPTICAL SCHOTTKY DETECTOR*

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Abstract

Noninvasive bunch duration monitoring has a crucial importance for modern accelerators intended for short wavelength FEL's, colliders and in some beam dynamics experiments. Monitoring of the bunch compression in the Emittance Exchange Experiment at the A0 Photoinjector was done using a parametric presentation of the bunch duration via Coherent Synchrotron Radiation (CSR) emitted in a dipole magnet and measured with a wide-band quasi-optical Schottky Barrier Detector (SBD). The monitoring resulted in a mapping of the quadrupole parameters allowing a determination of the region of highest compression of the bunch in the sub-picosecond range. The obtained data were compared with those measured using the streak camera. A description of the technique and the results of simulations and measurements are presented and discussed in this report.

INTRODUCTION

A parametric presentation of the bunch duration via measurements of the CSR signal amplitude has been used in the Transverse to Longitudinal Emittance Exchange Experiment at the A0 Photoinjector. Monitoring of the bunch length using the CSR signal with a relatively narrow-band Schottky detector first was proposed and described in [1].

We employed the wide-band quasi-optical SBD sensitive to radiation polarized in the plane of the detector traveling-wave antenna, [2]. Evaluating the detector sensitivity in the wavelength domain and convolving the computed CSR spectra with the characteristic detector response we have expressed the bunch duration in parametric form as a function of the CSR signal amplitude. Unlike the parametric presentation of the bunch length via the CSR angular distribution, [3], this method provides single shot measurements, that are acceptable for a large number of measurements, e.g. for mapping of the beam optical system settings. The obtained results in the sub-picosecond to picosecond range were compared with direct measurements employing a streak camera and were used for mapping of the beamline quadrupole settings to obtain the highest compression of the bunch. The parametric presentation results and comparison with the direct measurements of the bunch duration obtained with the streak camera are presented and discussed in this paper.

PARAMETRIC PRESENTATION OF THE BUNCH DURATION VIA THE CSR ENERGY SPECTRA

The Synchrotron Radiation (SR) energy emitted by a single electron moving in a circular orbit having radius ρ per unit frequency interval and per unit of solid angle for photons polarized in plane of bend is, [4]:

$$\frac{d^2 I}{d\omega \cdot d\Omega} = I(\omega,\theta) = \frac{e^2}{3\pi^2 c}\left(\frac{\omega\rho}{c}\right)^2 \left(\theta^2 + \gamma^{-2}\right)^2 \cdot K_{2/3}^2(\xi), \quad (1)$$

Here: $\xi(\theta,\omega) = \frac{\omega\rho}{3c}\left(\theta^2 + \gamma^{-2}\right)^{3/2}$ and $K_{2/3}(\xi)$ is the modified Bessel function. Assuming a Gaussian or quasi-Gaussian longitudinal distribution of the charge and a transversely infinitely small bunch, one can evaluate the CSR spectral energy, $I_{CSR}(\omega,\theta)$ via the bunch form-factor, F(ω), where $F(\omega) = \left(N \cdot \exp\left(-\omega^2/2\sigma_\omega^2\right)\right)^2$, σ_ω is taken in the angular frequency domain and N is the number of electrons in the bunch, [5]. That gives the following expression for spectral energy of the coherent radiation in latitudinal angle $\pm\theta_d$ for N electrons in the bunch moving in the circular orbit:

$$I_{CSR}(\omega) \cong 2\pi \int_{-\theta_d}^{\theta_d} F(\omega) \cdot I(\omega,\theta) \cos\theta \cdot d\theta, \quad (2)$$

Convolving the spectral energy of the CSR with the detector response one gets the spectral distribution of the detected CSR, $I_{CSRd}(\omega)$. Integration of the convolved spectral energy, $I_{CSRd}(\omega)$, over all frequencies gets the total CSR detected energy, $W_{CSRd} = \int_\omega I_{CSRd}(\omega) d\omega$ vs. the parameter σ_t; the bunch duration σ_t is taken in the time domain. The inverse function, $\sigma_t(W_{CSRd})$, is the parametric presentation of the bunch duration versus the CSR detected energy.

We have evaluated the detector characteristic response which demonstrates a drop for wavelengths ≤ 0.337 mm and a flat part for wavelengths ~ up to 1 mm, [2]. This was confirmed by tests of the SBD in a wide band using calibrated radiation from a terahertz FEL in the sub-millimeter wavelength range, radiation generated by

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klystrons in the mm wavelength range, and a Gunn diode at the wavelength of 3 cm. The klystron generators and the Gunn diode transmitter were loaded by horn antennas with directivities of ≈ 17 dB. The results are shown in the SBD response characteristic, Figure 1.

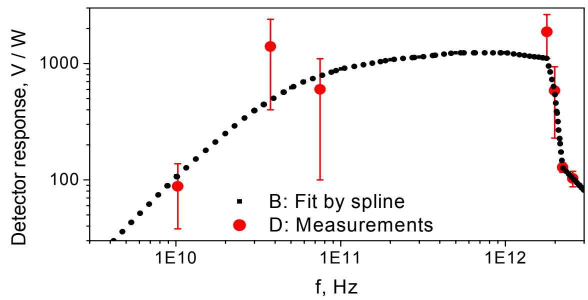

Figure 1: Quasi-optical SBD evaluated and measured response.

The drop of the SBD sensitivity for the wavelength ~ 1 mm or longer is caused by diffraction on the detector lens aperture (40 mm diameter Teflon lens used to focus radiation onto the antenna system). An absorption decrease in the lens for longer wavelengths partially compensates this drop.

Note that the SBD input optic which was initially designed for quasi-parallel far infrared beams limits the detector entrance angular acceptance by an angle of ~ 20 mrad with a decrease in sensitivity of ~ 3 dB on the boundary, [2]. So, for noticeably divergent beams the SBD sensitivity can be underestimated by few dB, while for the FEL quasi-parallel beam the measured detector response is quite correct.

The computed CSR spectra convolved with the characteristic detector response for various value of σ_t are shown in Figure 2 by dotted lines.

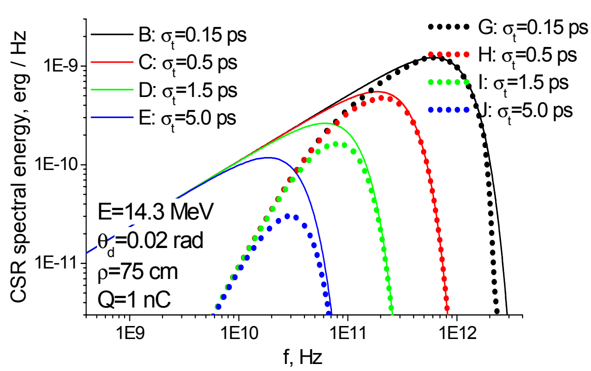

Figure 2: Computed CSR spectral energy vs. σ_t for 1 nC bunch emitted in the A0 Photoinjector dipole magnet (solid lines), and convolved with the SBD response characteristic (dotted lines).

The solid lines in the same colors show the computed CSR spectral energy corresponding to a flat characteristic detector response.

Computed plots of the inverse functions expressing the bunch duration via the CSR detected energy for different detector responses are shown in Figure 3.

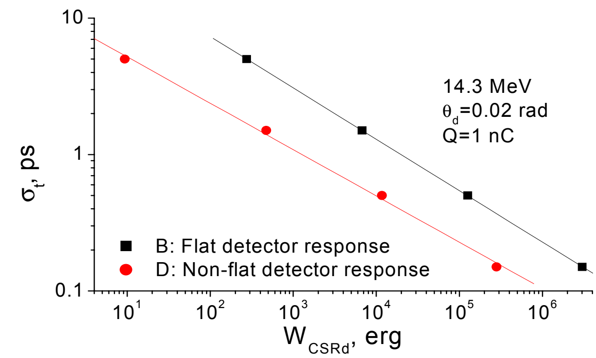

Figure 3: The bunch duration σ_t as a function of the CSR energy detected in a latitudinal angle of ±20 mrad.

Approximation shows that the function of the CSR detected energy, $\sigma_t(W_{CSRd})$, in the considered energy range can be expressed by following functions:

$$\sigma_t[ps] \approx 10^{1.06} \cdot W_{CSRd}^{-0.34}[erg], \tag{3}$$

and $\sigma_t[ps] \approx 10^{1.62} \cdot W_{CSRd}^{-0.38}[erg]$, for the cases with non-flat and flat response characteristics, respectively.

MATCHING OF THE QUASI-OPTICAL SBD CHARACTERISTICS TO THE BUNCH DURATION MONITORING

To get a parametric presentation of the bunch duration, via the SBD signal we have assumed that the SBD signal amplitude is proportional to the Schottky diode current at a constant amplifier input impedance. The SBD I-V characteristic has been computed using a system including the Shockley equation for the Schottky diode and an equation for the SBD amplifier impedance and following from the Kirchhoff's current law. Figure 4 presents the SBD I-V characteristic which is a square-law in the neighborhood of the point of inflection.

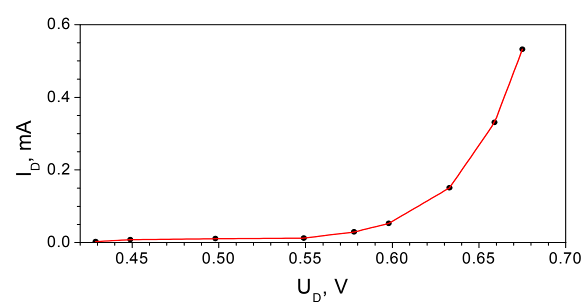

Figure 4: The SBD I-V characteristic.

The plot was computed for an amplifier gain of 100 at the amplifier input impedance of 150 Ohm.

The detector antenna emf raises the diode bias voltage thereby increasing the diode current which results in an increase of the SBD output signal. The SBD antenna emf voltage can be presented as a square-law function of the detector output amplitude, Figure 5. Plots in this figure show the computed dependence of the SBD antenna emf on the SBD output voltage, U_{Out}, (right scale) and the measured dependence of the bunch charge on the SBD output voltage (left scale).

For our measurements the SBD operating bias voltage has been adjusted to be in a neighborhood of the point of inflection of the Schottky diode I-V characteristic.

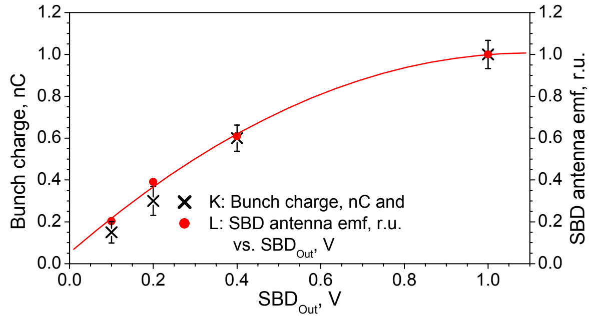

Figure 5: Measured dependence of the bunch charge (left scale) and computed dependence of the SBD antenna emf (right scale) on the detector output signal.

Since the emf of the SBD antenna is proportional to the CSR field the CSR spectral energy should be a square-law function of the antenna emf. This gives following parametric presentation for the σ_t via the SBD output signal, U_{Out}, considering equation (3):

$$\sigma_t(U_{Out}),[ps] \approx A \cdot \left[(U_{Out})^4\right]^{-0.34} = A \cdot U_{Out}^{-1.36},[V]. \quad (4)$$

Here A is a constant. Note that computations show a dependence of the A value on the bunch charge and the integration limit θ_d while the power value in the expression (4) practically does not depend on these parameters, but it noticeably depends on the detector response characteristic, Figure 3.

The constant A has been determined from direct measurements with a streak camera using these as overall scaling and keeping the power dependence of the function $\sigma_t(U_{Out})$.

BUNCH DURATION MONITORING WITH THE SBD

We have used the SBD during the Emittance Exchange Experiment at the A0 Photoinjector for the bunch duration monitoring to find the quadrupole settings providing a position of the bunch ellipse in the phase space corresponding to a minimal longitudinal bunch size. This gives highest longitudinal compression of the bunch. We have detected the CSR polarized in the plane of the bend of the electrons passing through 45^0 bending magnet installed after a deflecting mode cavity at the A0 Photoinjector. Synchrotron radiation passing through a 35 mm diameter crystal quartz window was reflected by a flat mirror to the Teflon lens focusing the radiation onto the detector antenna system. The measurements were done for the electron beam with a bunch charge of 0.25 nC at an energy of 14.3 MeV. An additional channel with a streak camera measuring the duration of an Optical Transition Radiation (OTR) micro-pulse was used for comparison of the SBD monitoring results with direct measurements of the bunch duration; in this case the electron beam passed through the OTR screen, which one can insert after the deflecting mode cavity and just upstream of the bending magnet with the CSR port.

The results obtained with the parametric presentation of the bunch σ_t via the measured SBD output signal in comparison with direct measurements through a streak camera are plotted in Figure 6.

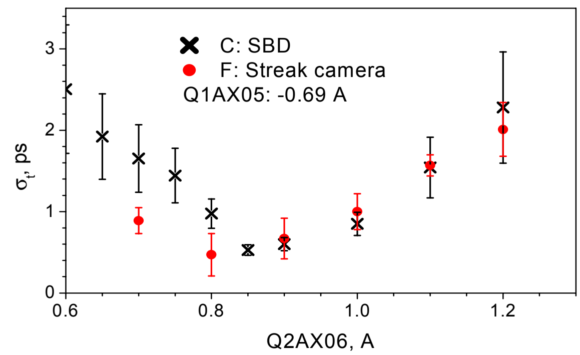

Figure 6: The bunch σ_t obtained with the parametric presentation via the SBD signal and directly measured with a streak camera vs. the quadrupoles settings.

Note that the direct measurements and the measurements with the SBD were not performed at the same time. This can cause a systematic error in some mismatching of the origin of the abscissa axis in Fig. 6 for the two methods of measurements because of a hysteresis in the quadrupole magnets.

The data plotted in Figure 6 demonstrate acceptable agreement for direct measurements of the bunch duration and the parametric presentation via measured the SBD output signal. We note that in the sub-picosecond range the accuracy of this parametric method is higher than the streak camera measurements which become progressively worse for shorter bunches. This makes monitoring of the bunch duration using the parametric presentation via the wide-band SBD signal promising for short bunches.

SUMMARY

A method of parametric presentation of the bunch duration via measurements of the wide-band SBD signal has been proposed, analyzed and realized in the sub-picosecond and picosecond range. The method demonstrates agreement with direct measurements via a streak camera.

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