

# BUNCH SHAPE DIAGNOSTICS USING FEMTOSLICING\*

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## Abstract

Laser-induced energy modulation of relativistic electron bunches as needed for the BESSY femtosecond (fs) x-ray source is accompanied by the emission of fs THz pulses [1]. The total THz intensity probes the square of the longitudinal particle density within a slice of 30-50 fs length (fwhm). The bunch shape can be directly monitored while sweeping the time delay between laser and bunch clock. The method is demonstrated for bunch lengths between 2.1 and 30 ps (rms) in different operation modes of BESSY II.

## INTRODUCTION

Femtosing [2] was experimentally demonstrated at the Advanced Light Source (ALS) in Berkeley [3] with radiation from a bend magnet. A first facility to produce 100 fs undulator radiation with linear and circular polarization up to 1400 eV was constructed in 2004 at BESSY in Berlin and is now in routine operation for pump-probe experiments on magnetic materials. The layout of the novel fs soft-x-ray source is illustrated by Fig. 1. Pulses from a Ti:sapphire laser system (wavelength 780 nm, pulse duration 30-50 fs (fwhm), pulse energy  $E=2.7$  mJ at 1 kHz repetition rate [4] copropagate with electron bunches in an undulator (U139, the "modulator"), a planar undulator with a period length of 139 mm and 10 periods).

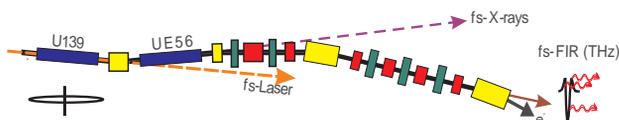


Figure 1: Footprint of the BESSY femtoslicing facility. After laser-induced modulation of the electron beam energy in the modulator (U139), fs x-rays are emitted by the radiator (UE56) after angular short-pulse separation by the intermediate bend magnet (yellow). The interaction is probed by coherent THz pulses at a bending magnet (yellow, the "THz radiator") following the UE56.

Laser-induced energy modulation in the modulator causes a longitudinal density modulation emitting coherent THz pulses from the THz-radiator (bending magnet, see Fig. 1). Coherent THz signals of that kind have been observed at the ALS [6], at BESSY [5] and recently also at the SLS [7]. The total THz intensity measured at BESSY

probes the square of the longitudinal particle density within a slice of 30-50 fs length (fwhm) as given by the laser pulse length. The bunch shape is probed while sweeping the time delay between laser and bunch clock. The present paper describes how this novel bunch shape detector is used in different operation modes of the storage ring.

## PRINCIPLE

If the energy modulation is established and optimized with respect to all other phase space parameters [8], a longitudinal detuning only changes the number of electrons  $N$  involved in the slice. A coherent THz signal probed after the interaction would show up a spectral power  $P \cong N^2 f p$ , where the form factor  $f$  is the square of the fourier transform of the longitudinal density modulation at the THz radiator and  $p$  the incoherent power emitted by a single electron.

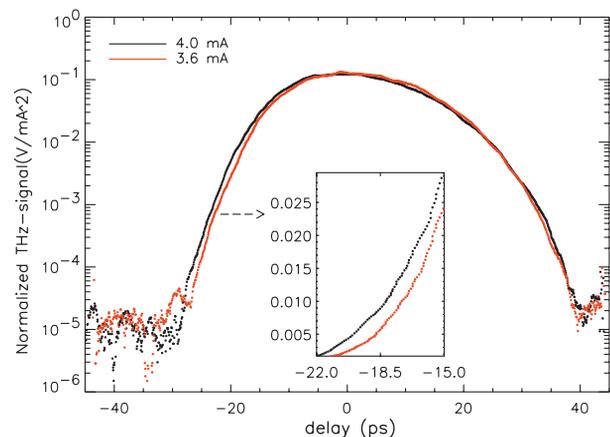


Figure 2: THz signal from an InSb detector, normalized to the square of the bunch current, as function of delay between a 2.1 mJ laser pulse and a single bunch taken at different bunch currents. The inset shows a magnification of the head region of the bunch.

Because  $f$  (of the short density modulation) does not depend on  $N$  (as confirmed by THz spectra), probing the coherent THz power reproduces  $(dN/dz)^2$  in the bunch with a resolution limited by the laser pulse length. The square root of the power (THz field strength) directly probes  $dN/dz$ . The high dynamic range of the method is demonstrated by examples depicted in Fig. 2, probing a THz signal with a fast InSb detector (2 GHz oscilloscope, triggered on the laser trigger and gated on one revolution). Because a long bunch does not emit coherent radiation, the signal increases by 4 orders of magnitude when the laser pulse

\* Work supported by the Bundesministerium für Bildung und Forschung and by the Land Berlin

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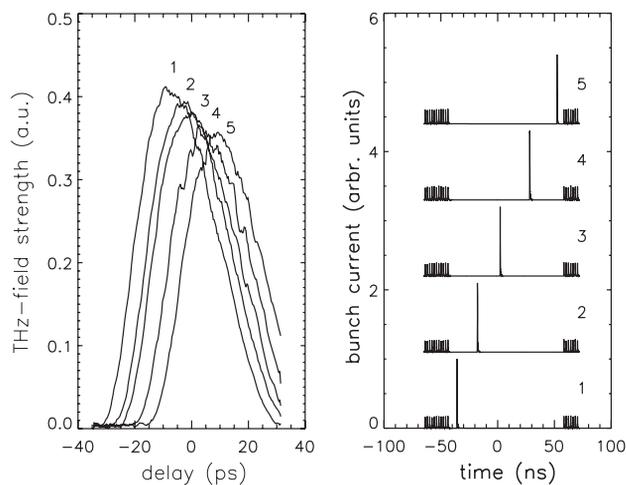


Figure 3: Bunch shapes during femtoslicing for different positions of a sliced bunch of 2 mA within 100 ns gap in a multibunch fill of 250 mA with 0.7 mA/bunch. Increased noise in sweep No. 4 arises from a loss of transverse overlap.

approaches the center of the bunch. Very small shifts in bunch shape of 1 ps can be detected as demonstrated by the inset in Fig.2. Asymmetric bunch shapes and current-dependent changes are expected above 4.3 mA caused by the influence of wake fields [9] and indicated by quasiperiodic CSR bursts. Bunch lengths derived from these type of measurements have confirmed that the square root of the THz power corresponds to streak camera data [10]. For femtoslicing, these changes are of significant relevance, because current-dependent deformations and shifts of the synchronous phase (up to 20 ps) have to be corrected by an active feedback in order to preserve fs x-ray intensities in the beamline.

## EXAMPLES

### Multibunch Effects

Femtoslicing is operated in regular user mode using an extra bunch of 2-10 mA bunch current within a gap of 100 ns and 350 buckets filled, at a beam current of 250 mA. Due to the current-dependent beam loading effects (gained by third-harmonic cavities) [11], bunch shape and synchronous phase depend on the position of the bunch within the gap. As derived from the measurements in Fig. 3, the electron density increases by 15% at small delay between multibunch train and single bunch, increasing fs x-ray intensity. However, the bunch length (mainly due to a steeper slope in the head region) as well as its lifetime decreases by the same value and there is almost no positive effect integrated over a time of 8 hours (injection period).

### Single Bunch Effects

At bunch currents  $\geq 4.3$  mA bursting coherent synchrotron radiation (CSR) from the regular bunch (laser off) is observed using a broad band detection. Hence, at large detuning of the delay, spontaneous bursting appears as noisy background depicted in Fig. 4a, while an asymmetric curve appears as an onset with worse signal-to-noise. At large positive delay (laser follows the bunch) even a "damping" of spontaneous bursting seems to occur. The temporal structure of bursting CSR moving the laser pulse along the bunch is depicted in Fig. 4b. Starting at negative delays (head of bunch), spontaneous bursting appears, being asynchronous to laser- and revolution trigger but at average rates of  $\approx 1$  kHz. Approaching the center of the bunch, the bursting is "locked" to the laser rate at 1 kHz and a stable waveform triggered to the laser appears. Behind the bunch, CSR bursting becomes again asynchronous. At higher currents (above 7 mA), when spontaneous bursting is more chaotic and not resonant to the laser rate, the effect is less pronounced. In general, if bursting CSR is involved, the electron density in the bunch is not directly reproduced from the square root of the THz power and additionally depends on the time resolution of the detection. For bunch shape measurements at high currents, spontaneous and triggered bursting can be discriminated by 10-20  $\text{cm}^{-1}$  high pass filters from the higher-energetic laser-induced THz pulse. Without bursting, all further measurements of delay scans - THz pulses from another radiator after 1/2 turn, from subsequent turns, using bandpass or polarization filters in the THz spectrum or other detectors - indicate that the bunch shape is always reproduced by the square root of the THz power.

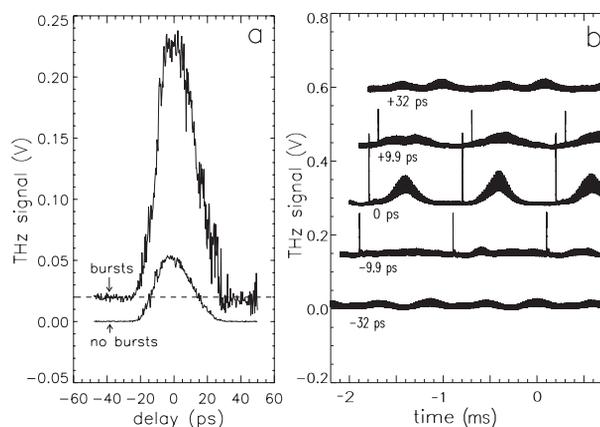


Figure 4: THz signals vs. delay in the regular user optics (a) for bunch currents above- (4.5 mA) and below (2 mA) the burst threshold. Time traces of raw THz signals from an InSb detector on an oscilloscope are shown in (b) over 3 ms for different laser-bunch delays. The waveforms are horizontally and vertically stacked for better presentation.

## Shorter Bunches

By principle, femtoslicing needs a synchronization between laser and bunch with an accuracy much lower than the regular current dependent bunch length of 12-30 ps (rms). As illustrated by the upper curve in Fig.5, longitudinal deviations of 6 ps from the center of the bunch already lead to 14% loss in the number of energy-modulated electrons. Hence, 14% less fs x-ray photons are detected in the beamline. The same curve suggests that stabilizing the number of electrons involved in the slice (number of fs x-ray photons) to a 1% level would require at least 1 ps stability of the timing. The other way around, typical low frequency fluctuations observed in the THz signal of 5% (2.5% in the square root, mainly given by transverse overlap fluctuations between laser and bunch) allows a timing stabilization of 3 ps for the case of laser and regular bunch.

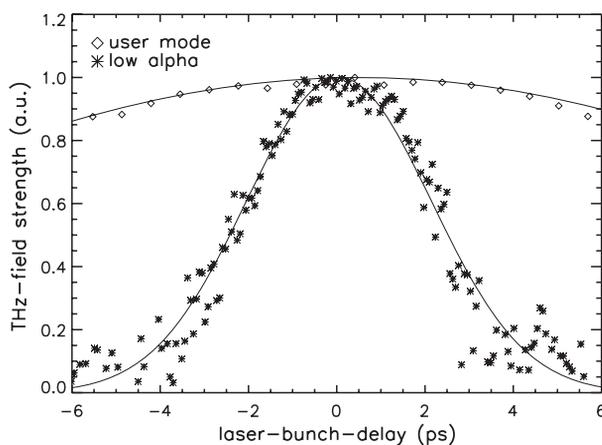


Figure 5: Comparison of bunch shapes in the regular user mode (0.7 mA/bunch) and in the "low alpha" user mode (0.014 mA/bunch).

In order to test resolution limits, laser energy modulation was also performed in the "low alpha" user mode [9] on a compressed bunch (out of 350) in Fig. 5. Here, the momentum compaction factor of the storage ring as well as the bunch current are reduced in order to shorten the bunches by a factor of 6. Even though the bunch current was only 0.014 mA (5 mA total multibunch current), a coherent THz signal can be still detected. The number of electrons  $N$  involved scales with the bunch length ration. Despite the bunch current is a factor of 50 lower, but the observed bunch in low alpha is a factor of 6 shorter,  $N$  is only 8 times smaller (THz power 16 times, well within dynamic range). The corresponding bunch shape indicates an rms bunch length of 2.1 ps (rms) using a Gaussian fit. The noise indicates a residual longitudinal stability of 1 ps which is given by the accuracy of the electronic synchronization (300 fs [4]) and the jitter of the bunch.

## SUMMARY AND OUTLOOK

The temporal overlap of a fs laser and a relativistic electron bunch can be established and controlled detecting coherent THz pulses after the bunch has passed sufficient dispersion. Timing for femtoslicing on bunches of 12-30 ps (rms) is routinely stabilized with  $\approx 3$  ps accuracy. The square root of the THz power is proportional to the number of electrons within a slice of 30-50 fs given by the laser pulse shape. Bunch shapes can be measured regardless of the location of the THz radiator within the ring and whether the pulse is taken from the first or subsequent turns. Bunches down to 2.1 ps rms were successfully probed. The time resolution is at least 1 ps and most likely limited by the rf-stability. CSR from instabilities as well as steady state CSR (if the bunch is short enough) decrease the signal-to-background ratio but can be controlled by spectral filters. Detecting coherent signals from density modulations downstream of the laser-electron interaction is relevant for timing diagnostics at laser-seeded free electron lasers.

## ACKNOWLEDGMENTS

We are indebted to all our colleagues for their invaluable support: H. Bäcker, J. Bahrtdt, H. Dürr, V. Dürr, W. Eberhardt, W. Frentrup, A. Gaupp, E. Jaeschke, P. Kuske, D. Krämer, R. Müller, W. Peatman, N. Pontius, M. Scheer, C. Stamm, F. Senf, G. Wüstefeld as well as P. Beaud and G. Ingold (SLS) for valuable discussions.

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