BUNCH LENGTH MEASUREMENTS USING CORRELATION THEORY IN INCOHERENT OPTICAL TRANSITION RADIATION

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Abstract

As Free Electron Lasers create ultra-short bunch lengths, the longitudinal diagnostic for such femto-second bunches becomes more difficult. We suggest a bunch length method using the spectral analysis of Optical Transition Radiation (OTR) in the visible frequency domain.

The frequency content of OTR is measured by inserting an aluminium coated silicon wafer into the electron beam. The OTR light is collected with mirror optics into an optical fibre, which is coupled to a spectrometer (316 THz to 1500 THz). The resolution of the spectrometer allows us to measure bunch lengths lower than 100 fs rms.

The bunch length was varied from 100 fs down to a few fs. The spectral content of OTR showed an increase of the correlation between neighbouring frequencies as bunch length was reduced.

INTRODUCTION

Conventional diagnostic methods of bunch length measurements in Free Electron Lasers (FELs) have difficulties in measuring electron bunches in the femtosecond range. As FELs are developed, the temporal resolution of the user experiment depends on the electron bunch length. The FEL design is for femtosecond X-ray pulses thus the electron bunch length must be in the same order of magnitude. In order to characterise these electron bunches, diagnostics need to be developed to measure such femto-second bunches.

The bunch length may be diagnosed by measuring the spectral response of Optical Transition Radiation (OTR). OTR is generated as the high energy electron beam experiences a dielectric discontinuity between vacuum and metal. The backward emitted OTR light is then coupled into the spectrometer. If bunch length information is stored in the spectra, the correlation between frequencies will increase.

In this paper we show that the correlation of OTR spectra depends on bunch length. The spectra show fluctuations which increase in width as bunch length decreases. The analysis of these frequencies is done by first order correlation theory. The width of the correlation from neighbouring frequencies increases with reduced bunch length.

Similar studies have been performed using two different methods. Firstly, bunch length studies using spectral correlation have been performed using undulator radiation [1, 2, 3], all of which use correlation theory to analyse the data. Lutman *et al.* used bunch lengths below 100 fs, 1.5 keV photons. Bunch lengths in the ps range have been analysed by the other cited authors, but in contrast use 'visible' light from undulator radiation. Secondly, ps long bunch lengths have been measured using fluctuations in the 'visible' spectrum domain [4, 5]. Statistical methods were used such that bunch length could be correlated to fluctuations in a narrow bandwidth. We make use of both experimental methods, namely radiation in the visible domain, sub 100 fs bunch length and correlation theory to measure bunch length.

We begin by describing the accelerator setup and outlining the experimental conditions. Secondly, results are presented which strongly indicate a dependence of fluctuation versus bunch length. Finally, the conclusions and outlook complete this paper.

EXPERIMENTAL

All experiments presented in this paper were performed at the SwissFEL Injector Test Facility (SITF) [6]. The SITF was built as a test bed for the future SwissFEL. Fig. 1 shows the layout of the SITF.

The gun laser is a Titanium-Sapphire laser. The pulse length is 10 ps FWHM. The momentum after the gun is 7.1 MeV/c with a bunch charge of 200 pC.

Four accelerating structures are employed to bring the electron momentum up to 200 MeV/c. A magnetic chicane is used for bunch compression. Accelerator structures A3 and A4 in Fig. 1 introduce a momentum chirp. The dispersive section, i.e. magnetic chicane, employs the momentum spread to longitudinal position matrix element to reduce bunch length.

The X-band compensates second order effects in the longitudinal phase space, i.e. linearises the longitudinal phase space. The X-band decelerates the bunch, which is compensated by A3 and A4 in Fig. 1. The X-band phase is set on-crest with a π phase shift.

In the FODO section the transverse and longitudinal phase space are analysed. The transverse deflecting structure employs the angular to spatial transfer matrix element to analyse the longitudinal profile. Point Grey Flea cameras C2 and C3 are used to view the temporal profile and the longitudinal phase space respectively.

A Point Grey Flea camera and an OceanOptics QE65000 spectrometer are installed at position C1. OTR light is coupled into an optical fibre using aluminium coated off-axis parabolic mirrors. Mirrors are used to avoid chromaticity effects because of the wide spectral band range. The spectral range of the spectrometer is 316 THz to 1500 THz (950 nm - 200 nm). The resolution of the spectrometer is 1.1 THz FWHM in the infrared (316 THz) and 25 THz FWHM

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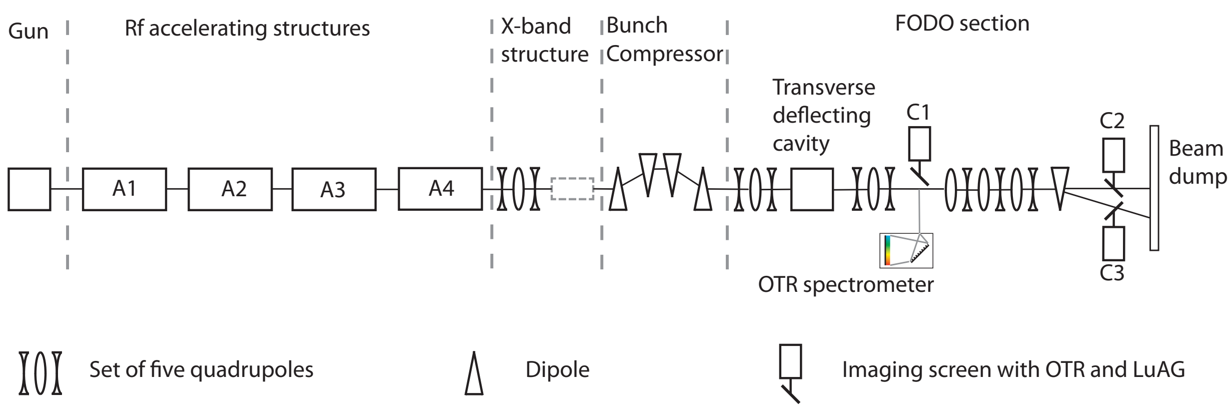

Figure 1: Schematic overview of the SITF

in the ultra-violet (1500THz).

RESULTS

From OTR theory we know that the single particle electric field response of OTR is unity in the frequency domain. The low and high frequency cutoffs are determined by the screen size and the plasma frequency respectively. The spectral power of OTR may be described as [7, 8]:

$$\frac{dI}{d\omega} = |e(\omega)|^2[N + N(N-1)|f(\omega)|^2] \qquad (1)$$

In which $e(\omega)$ is the radiated electric field of a single particle, N the number of particles and $f(\omega)$ is the Fourier transform of the temporal profile, i.e. form factor. If the bunch length is long, the form factor becomes zero and hence the above equation reduces to:

$$\frac{dI}{d\omega} = |e(\omega)|^2 N \qquad (2)$$

In which the radiated intensity is linear proportional to the charge as shown in Fig. 2.

Single shot OTR spectra are shown in Fig. 3. Towards higher compressions we observe a gain in spectral intensity at the lower frequencies. The gain is a coherence effect, possibly from space charge and/or synchrotron radiation. Superimposed on the gain we observe fluctuations, which broaden as the bunch length is reduced. Moreover we see that the fluctuations' period is constant along frequency.

Because fluctuations are variant under repetition, statistics need to be built up. The first-order correlation function is defined as [9]:

$$C = \frac{\langle I_{\omega_i}(t) I_{\omega_j}(t)\rangle - \langle I_{\omega_i}(t)\rangle\langle I_{\omega_j}(t)\rangle}{\sqrt{\langle (I_{\omega_i}(t) - \langle I_{\omega_i}(t)\rangle)^2\rangle\langle (I_{\omega_j}(t) - \langle I_{\omega_j}(t)\rangle)^2\rangle}} \qquad (3)$$

Where $I_{\omega_i}(t)$ and $I_{\omega_j}(t)$ denotes the temporal evolution of the intensity at frequencies ω_i and ω_j.

Bunch length information is stored in the width of the correlation function. As bunch length reduces the width of the correlation peak is expected to increase. Figure 4 shows the correlation of a pixel at 333 THz to neighbouring frequencies. 1000 Spectra were used for the correlation computation.

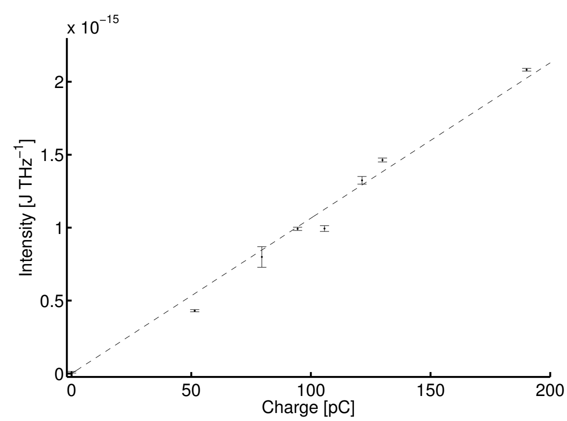

Figure 2: Spectral intensity versus charge at 667 THz of incoherent spectra. The dashed line guides the eye to a linear fit of the data. The errorbars show the standard error. Bunch charge was reduced using scrapers in the bunch compressor.

The correlation plot confirms that in the uncompressed electron bunches no correlation was present. The frequency is exclusively correlated to itself, $C = 1$. As bunch length is reduced the general correlation over all frequencies increases, e.g. the base of the '$<$ 40 fs rms' line goes up to $C = 0.8$. This is due to the 'coherence domain', see Fig. 3, which fluctuates as a whole. Moreover it can be seen that the correlation peak of neighbouring frequencies becomes wider as the bunch length decreases. This is where bunch length information is stored.

CONCLUSIONS AND OUTLOOK

Figures 3 and 4 show a clear indication that the fluctuations depend on bunch length. The fluctuations sit on a coherence effect, possibly from space charge effects.

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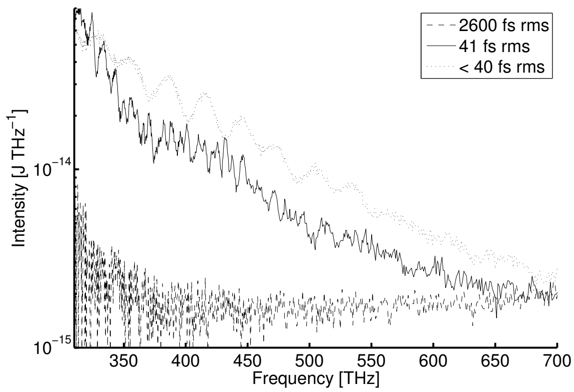

Figure 3: Spectral response, intensity versus frequency, of three different bunch lengths. Single spectrum.

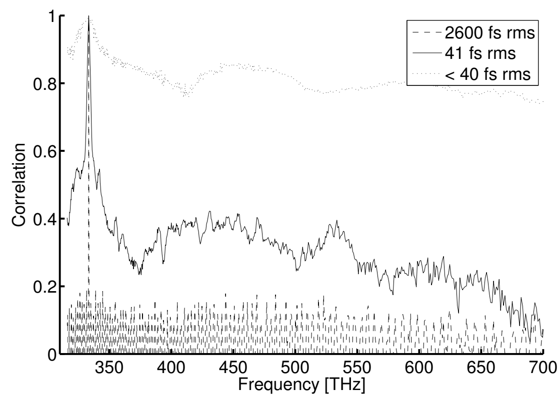

Figure 4: Correlation of a pixel at 333 THz to all neighbouring frequencies of 1000 spectra.

For future experiments the fluctuations observed must be correlated to bunch length. Measuring bunch length is not straight forward because of the limited resolution of the TDC in the SITF. Moreover an increase of emittance in sub 50 fs bunches, due to space charge effects at low momentum (200 MeV/c), creates an additional challenge for TDC measurements.

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