SHORT ELECTRON BEAM BUNCH CHARACTERIZATION THROUGH MEASUREMENT OF TERAHERTZ RADIATION

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Abstract

This paper presents measurements of sub-picosecond relativistic electron beam bunch lengths derived from an analysis of the spectra of the coherent terahertz pulses using Kramers-Kronig transformation. The results are compared with autocorrelation from a scanning polarization autocorrelator that measures the coherent optical transition radiation. The limitations of the different methods to beam characterization are discussed.

INTRODUCTION

Very high-power THz radiation has been successfully generated at Jefferson Lab[1]. The powerful short pulse THz source provides unprecedented opportunities for applications such as THz imaging and material studies. These THz pulses also carry important characteristic information about the electron bunch length which is very important to FEL and accelerator physics studies.

A measurement of the radiation spectrum will give the form factor and the electron density distribution through a Fourier Transform[2-4]. However, this always provides a symmetric distribution. By introducing a mini-phase under certain conditions, the lost phase information can be recovered and the bunch distribution asymmetry may be revealed[6]. This method requires a Kramers-Kronig transformation (KKT) analysis to calculate the mini-phase followed by an inverse Fourier transform, resulting in the expected longitudinal electron density distribution. Different from Coherent Transitional Radiation (CTR), the Coherent Synchrotron Radiation (CSR) is generated by the electrons through bending magnets and therefore requires no foils. There is no interruption to the running beam while the measurement is going on. We will use the CSR that is conveniently available form our FEL facility for the beam bunch measurement. Discussions and comparisons with other measurement methods will also be addressed.

SETUP AND MEASUREMENT

Fig.1 is an overall sketch of the Jefferson Lab 10KW upgrade FEL facility. Electrons coming from the gun are accelerated by linac and then compressed into very short bunches before traveling to the optical cavity. Synchrotron radiation is generated in several locations where the magnets bend the beam orbit. For the experiments, the primary instrument used in is a Nicolet FT-IR spectrometer. Fig.2 shows the optical layout of the experimental setup with a simplified spectrometer schematic. The THz pulses from relativistic electrons exit a diamond window through a vacuum beam port near the bending magnet that directs the 89Mev electron beam into the optical cavity and wiggler. Several silver mirrors are used to bring the THz beam into the spectrometer bench. To minimize the water absorption by THz pulses, the whole optical beam path is purged with nitrogen.

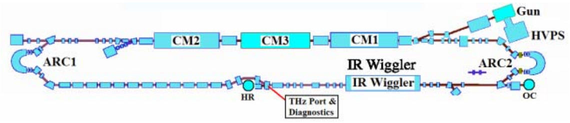


Fig.1. Layout of FEL facility and THz beam port. GUN is the photo-cathode electron source. HPVS, high-voltage power supply. CM, Linac Cryo-Module. HR, high-reflector. OC, output coupler.

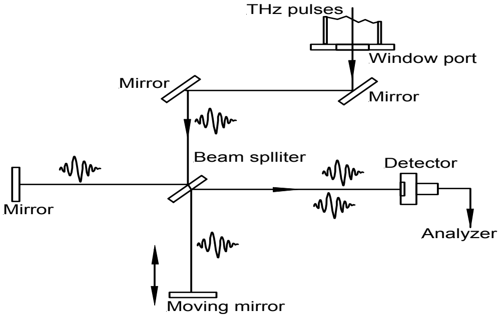
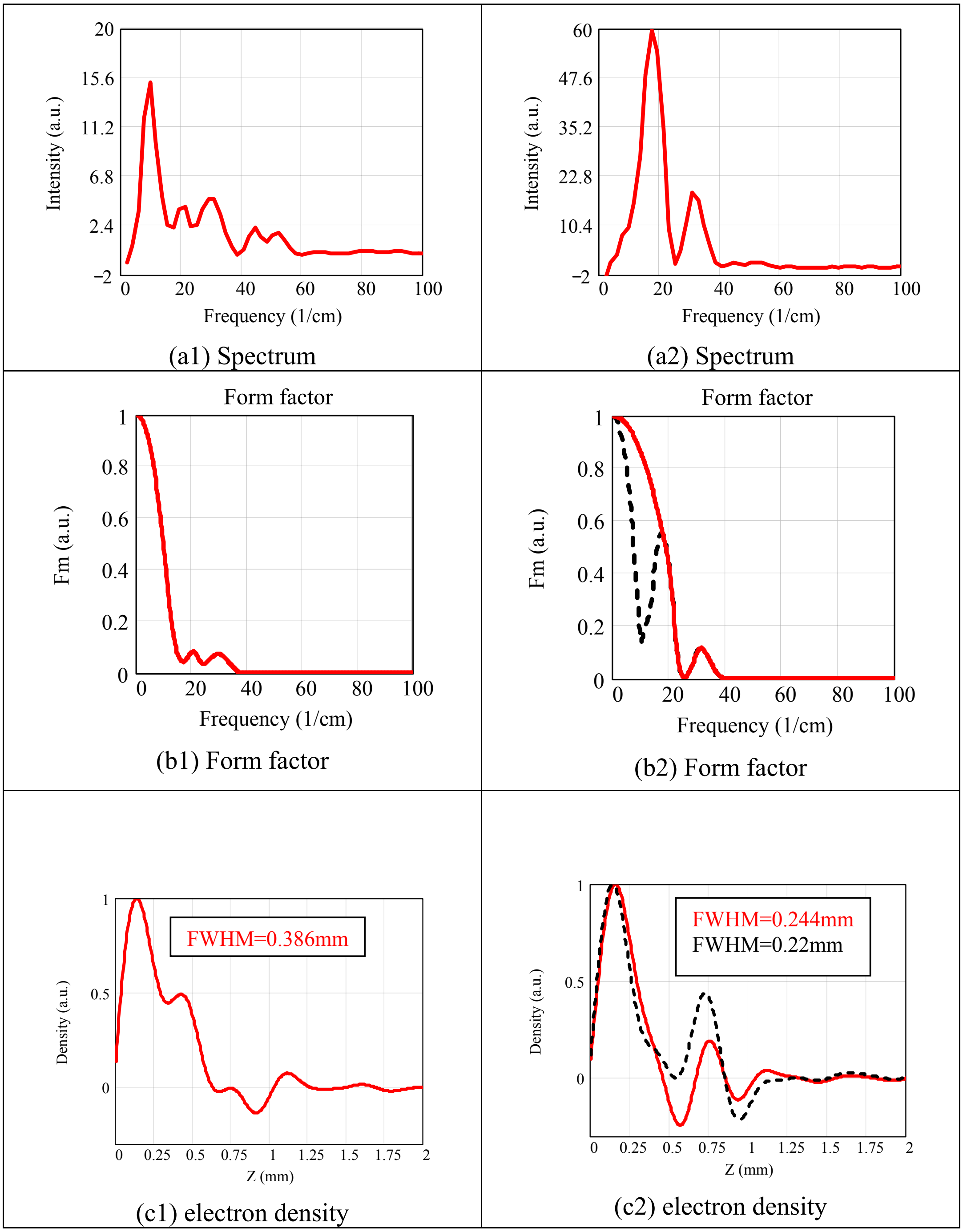


Fig.2. Schematic of the optical setup for THz spectral measurement.

RESULTS AND DISCUSSIONS

Typical spectra taken from the spectrometer are shown in Fig. 3. We used a DTGS detector with a polyethylene window. The efficiency of the detector has a spectral roll-off on the low frequency side. This can clearly be seen in the spectrum. Another major factor contributing to the low frequency cut-off is the limited diamond window aperture that restricts the diffracted beam from reaching the optical bench. Appropriate spectral fitting in the low and high frequency region is used to help reconstruct the whole spectrum and has turned out to be very effective.

Before extraction of the form factor, the spectrum was corrected by the $\omega^{2/3}$ frequency dependence of the single electron emittance. We assume that the form factor should be parabolic at low frequencies, and use $f(\omega) = 1 - a\omega^2$ as a good approximation. At



(a1) Spectrum

(a2) Spectrum

(b1) Form factor

(b2) Form factor

(c1) electron density

(c2) electron density

Fig.3. Two sets of measurement and analysis with different beam settings. (a) Typical THz radiation spectrum, (b) Form factor extracted from the THz spectrum, (c) Retrieved longitudinal electron density distribution. The FWHM width is 0.386mm (about 1.29ps in time duration) for in (c1) and 0.244mm (about 0.81ps) for (c2). The bunch is much shorter for the latter. The dashed curves in (b2) and (c2) are explained in text.

high frequency we use $f(\omega) = b\omega^{-4}$ (a and b are constants, depending on and decided by each specific spectral distribution). With these asymptotic attachments to each respective side, a reconstructed form factor can be obtained. Applying the KKT to the new form factor, we were able to retrieve the longitudinal electron density distribution or the beam bunch shape. Fig.3 presents the calculated results based on two groups of measured THz spectra. The electron beam energy is 89MeV. Both profiles show clear asymmetry. The asymptotic attachment on both ends has only limited influence on the overall shape of the distribution, especially within small distances from the point where z=0[6]. Fortunately this is the region where the bunch shape and length is decided. More precise measurements at lower frequencies will lead to better determinations of the shapes of longer bunches. The negative values in the density distribution are non-physical and were partly due to the low frequency attachment. With the low frequency attachment pushed farther to the left, as shown in the dashed curves in Fig.3, the negative values in calculated density distribution are apparently reduced. The overall shape of the density distribution basically remains unchanged while a small reduction on the width can be seen.

The data in the right column of Fig.3 shows an apparently shorter bunch than that in the left. The observed higher FEL output power can also be an indication of this shorter bunch. So it is possible to get a fairly good idea about how the beam setting is by just looking at the THz spectrum while tuning the electron beams. We also did calculations on the CSR based on the experimental electron beam parameters and assuming a Gaussian beam. The spectra at different bunch lengths are shown in Fig.4. The low frequency fall-off is due to diffraction. The two sets of spectra are the same as those in Fig.3. Each of them falls into the expected bunch length range. When compared with the purely theoretical calculations, the lack of the low frequency experimental data is once again clearly evident. It can be imagined that better estimates on the bunch could be made by comparing predicted with measured data that included more low frequencies. One aspect worth mentioning is that the shorter bunch tends to push the spectrum to higher frequencies.

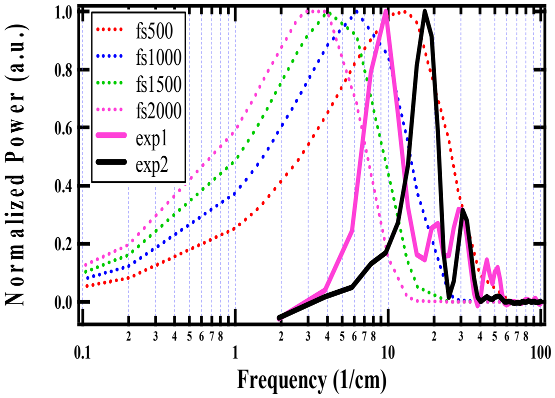


Fig.4. Comparison between the measured THz spectra and calculations with different bunch lengths. Exp1 and Exp2 correspond to the spectra shown in the left and the right column in Fig.3, respectively. The estimated bunch lengths agree with the KKT results.

Since we are dealing with THz pulses with time duration on the order of a few picoseconds or shorter, the electric field of each individual pulse only has a few cycles or less. This has been referred to as single-cycle electric field that has drawn much research interests for basic research. Compared with other ultrashort optical pulses in the visible and near IR, this type of pulse imposes certain difficulties in the determination of its temporal pulse width because of the limited number of fringes in the time window. The clear temporal intensity profile does not exist anymore and the electric field may give a better idea of the temporal characteristics. This is especially true for the measurement using polarization autocorrelation method.

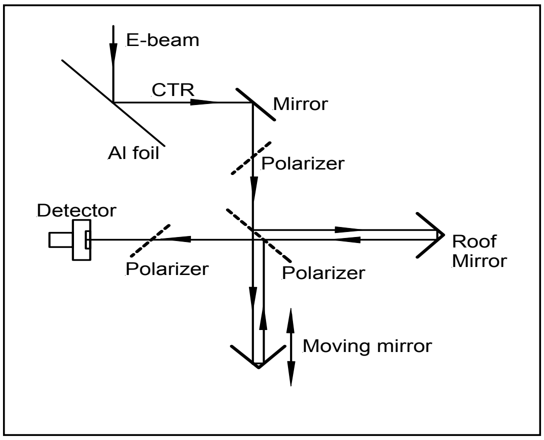


Fig.5. Simplified optical layout of a polarization autocorrelator (Martin-Pupllet interferometer). The optical pulses come from the optical transitional radiation generated by the short electron bunches interacting with a thin aluminum foil.

To have a further look at the issue, we took data from an autocorrelator, or the so-called Martin-Puplett interferometer (MPI)[7]. Fig.5 is an optical schematic of the MPI. It was set to measure the coherent optical transitional radiation (CTR) when a thin aluminum foil was inserted into the electron beam path. The MPI is a modified Michelson interferometer with thin wire grid polarizors and beam splitters. A Golay cell was used as a detector. The MPI is actually a polarization autocorrelator and the detected signal is the electric field correlation of two input replica pulses. The width of the autocorrelation traces is an indication of the input pulse width, but is not exactly the same as the width of the temporal intensity profile which is normally used for the determination of an ultrashort pulse length. In fact for a Gaussian distribution, a factor of 0.7 applies. The measured autocorrelation trace from our experiment is given in Fig.6 along with a Gaussian fitted center peak and the envelope. The FWHM values obtained from KKT method and MPI are in general agreement with each other, as can be seen from (c1) in Fig.3 and the fitted curve in Fig.6 (where data comes from beams under same condition) . However, there are some errors which come from many factors and can be above 10%. The precision of the fitting data is primarily limited by the number of available fringes in the pulse. In the present case, there are only a few fringes and fitting is impractical. However, to obtain the fitting (blue curve) we generated the dotted curve by inverting value of the solid curve which lay below a baseline from the asymptotic limits. We note in passing, however, that in practice the central peak is frequently used as an indication of the bunch length because this peak has a clear envelope of its own which is easy to fit.

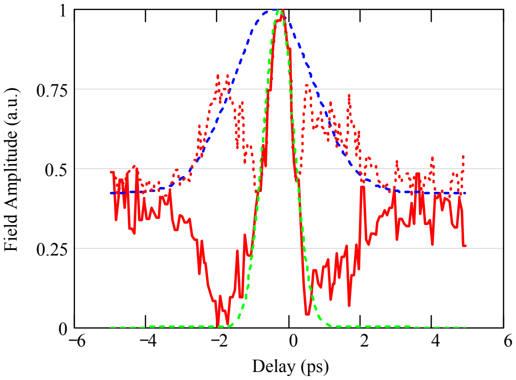


Fig.6. The red solid line is an CTR autocorrelation trace from MPI. Blue dotted curve is the fitted envelope with 1.34ps FWHM. Fitted central peak 0.71ps FWHM(green dashed line).

SUMMARY

The temporal characterization of sub-picosecond relativistic electron bunches has been performed through the measurements of THz radiation and subsequent KKT analysis. Comparisons between the CSR calculation and the result from an MPI that measures the CTR were presented. The issues with the determination of short THz pulse length are also discussed. The KKT analysis of the CSR may become a useful tool for bunch shape measurement but the precision primarily depends on the spectral measurement, especially at the lower frequency end in our case. Further studies along with a comparison with other methods such as electro-optical sampling will be helpful to clarify the above mentioned issues.

Acknowledgement

The authors would like to thank the FEL team for their assistance during the experiment and for beam operations. This work is supported by the Office of Naval Research, Research, the Joint Technology Office, NAVSEA PMS-405, the Air Force Research Laboratory, the US Army Night Vision Lab, the Commonwealth of Virginia and DOE Contract DE-AC05-84ER40150.

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