MEASUREMENTS OF MARTIN-PUPLETT INTERFEROMETER LIMITATIONS USING BLACKBODY SOURCE

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Abstract

Frequency domain measurements with Martin-Puplett interferometer is one of a few techniques capable of bunch length measurements at the level of ~ 100 fs. As the bunch length becomes shorter, it is important to know and be able to measure the limitations of the instrument in terms of shortest measurable bunch length. In this paper we describe an experiment using a blackbody source with the modified Martin-Puplett interferometer that is routinely used for bunch length measurements at the JLab FEL, as a way to estimate the shortest, measurable bunch length. The limitation comes from high frequency cut-off of the wire-grid polarizer currently used and is estimated to be 50 fs RMS. The measurements are made with the same Golay cell detector that is used for beam measurements. We demonstrate that, even though the blackbody source is many orders of magnitude less bright than the coherent transition or synchrotron radiation, it can be used for the measurements and gives a very good signal to noise ratio in combination with lock-in detection. We also compare the measurements made in air and in vacuum to characterize the very strong effect of the atmospheric absorption.

MOTIVATION

At the JLab IR/UV Upgrade FEL facility the bunch length measurements are made with a modified Martin-Puplett interferometer (MPI) [1]. The measurements are made at full bunch compression at the beam energy of up to 135 MeV. When the IR FEL is operated with the bunch charge of 135 pC the bunch is routinely compressed down to 130 fs RMS. This value assumes that our data evaluation procedure is reasonable accurate. A procedure that operates in the frequency domain is described elsewhere [2]. A good quantitative agreement between the IR FEL performance and its 1D model was found when such bunch length measurements were used as the input to the model [3]. The other measured beam parameters used as an input for the model are energy spread, emittance and Twiss parameters at the wiggler. Since the beam parameters other that bunch length are relatively straight-forward to measure, the agreement gave us some confidence that the bunch length evaluation procedure is working reasonably well. However, when UV FEL was commissioned a much higher small signal gain was measured than the 1D model predicted [4]. When trying to explain the disagreement by hypothesizing, that some electron beam parameters were measured incorrectly, one comes to the conclusion that the error in the measurements would have to be very large, and only a combination of different parameters measured incorrectly could explain the disagreement between the measurements and the model. Since the bunch length is the least straightforwardly measured beam parameter it drew the most suspicion. The UV FEL is operated with the bunch charge of 60 pC and bunch length of 100 fs was measured at full compression.

In addition, the Coherent Transition Radiation (CTR) source used for the bunch length measurements in the UV FEL appears to be much brighter that the one used in the IR FEL. The same Golay cell detector was used with both beamlines. Besides the interferometric measurements we minimize the bunch length by maximizing the amplitude of the Golay cell. The measurements are averaged over the tune-up beam macro pulse due to the detector's time constant. With comparable bunch length, according to the MPI measurements, we had to reduce the integrated macro pulse charge by a factor of ~ 30, to have the same Golay cell signal amplitude. The macro pulse was shortened from 250 to 20 μs and the bunch charge was reduced from 135 to 60 pC. Since the power of the coherent radiation is proportional to the charge squared, the reduction of the charge actually reduces the CTR power by the factor of ~5. One possibility to explain the difference in efficiency of two setups is the better alignment of the one at the UV FEL beam line, which we indeed have. Yet, factor of 60 in brightness seemed to be too large to explain only by the alignment. These observation has contributed to the need to evaluate our MPI in terms of its applicability the bunch length of 100 fs and shorter.

A shorter bunch length corresponds to a broader spectrum and one might expect that the measurements become easier as the spectrum is affected less by the low frequency cutoff. The bandwidth of the MPI measurements with CTR is limited on the low frequency side by the size of the CTR radiator [5], and on the high frequency side by performance of the freestanding wire-grid polarizer beam splitter and analyzer. As the frequency becomes higher the wavelength of the radiation becomes smaller than the gap between the wires such that the wire-grids performance degrades. Hence, the MPI, whose operation relies of on the polarization, does not function properly. Therefore, our goal of the interferometer evaluation was to measure the high frequency limit of the overall setup.

FREE-STANDING WIRE-GRIDS

The wire-grids, used in our modified MPI, are made of Tungsten wires with diameter of 20 μm with period of 50 μm. There are a large number of publications dedicated to the subject, both theoretical [6,7] and experimental [8-10], to name just a few. Two dimensionless parameters are usually introduced. The first one is the ratio of the wire diameter to the grid period $S = d/p$. The second one is the ratio of the grid period to the radiation wavelength $\varkappa = p/\lambda$. There are several quite different mathematical

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approaches to describe electro-magnetic properties of the wire-grids. Some of the approaches (see references in [8]) result in relatively compact and simple formulas describing transmission and reflectivity of the wire-grids. These approaches, however, have limited applicability in terms of S and $\varkappa$ range. Other approaches that are much more elaborate mathematically supposedly are applicable for a grid with any S and $\varkappa$, however, require very involved calculations. Even more importantly, to our knowledge, all but one [7] of the models calculates performances of the ideal wire-grids. That is, the distance between wires is always exactly the same. It was also demonstrated experimentally that irregularities of the wire spacing affect the wire-grid characteristics rather significantly [10]. It is easy to see that the wire spacing of the grids used in our MPI is not uniform. This is one reason why, for now, we did not want to depend in our conclusions about practical characteristics of the wire-grids on calculations. Also, the goal of the measurements presented here was not a complete characterization of the wire-grid polarizers but, primarily, measurement of the high frequency cutoff of the whole experimental setup. It was suggested that, after first order measurements are made and the performance of the wire-grids is compared to the CTR spectra, one can judge if more accurate measurements and more elaborate data evaluation are needed.

THERMAL RADIATION SOURCE

The source of radiation used in the measurements presented here was a commercially available thermal source developed for a Fourier Transform Infrared Spectroscopy (FTIR) system [11]. There are several reasons why such a source was used. The first is that such a source is most affordable and is easily accessible. Our measurements were meant to be such. Technical reasons are that for an ideal blackbody source with sufficiently high temperature the spectral power density grows monotonically up to a frequency much higher that the frequency range of interest for the bunch length measurements. According to the well known Plank's spectral energy density

$$dU/d\nu = 8\pi\, \nu^2 c^{-3} \hbar\nu \left(e^{\frac{\hbar\nu}{k_B T}} - 1\right)^{-1},$$

a source with temperature of 10^3 K will reach its maximum power density at about 60 THz. This fits the idea of our experiment well. Thus we expect a spectrum with the spectral power density growing up to some point. Then, in the frequency range where the wire-grids polarizers do not function properly, no interference will occur. At yet higher frequencies the spectrum cannot be measured. As a result the measured spectral power density will decline with frequency. Our objective is to compare the highest frequency observed in the bunch length measurements to the frequency in the measured spectrum of the thermal source where the spectral power density starts to decline. Another important aspect of the blackbody radiation is its partial temporal coherence of the first order. The coherence time and effective bandwidth of a blackbody with Plank's spectral energy density were rigorously calculated [12]. The calculations were made for two different definitions of these quantities introduced by Wolf and Mandel. It was shown that the two definitions result in comparable values of the quantities. It is shown for Wolf's definitions that the coherence time and the effective bandwidth of the blackbody can be expressed as $\Delta\tau_c = 0.07\,\alpha$ and $\Delta\nu_{eff} \cong 1.37/\alpha$, where $\alpha = \hbar/k_B T$, h and k_B are the Plank's and Boltzmann's constants and T is the absolute temperature. Thus one calculates for a blackbody with temperature of 10^3 K the effective bandwidth of 28.5 THz and coherence length $l_c = c\,\Delta\tau_c$ of 1.01 μm. The important aspect for our measurements is to have a source with a bandwidth wider than the bandwidth of the wire-grid, or else one is just measuring the bandwidth of the source. The temperature of the thermal source can be optimized with the following rational. On the one hand it needs to be high enough to deliver enough power in the frequency range of interest. On the other hand increasing the temperature further increases the intensity of the radiation at shorter wavelength much more quickly than in the THz, i.e., FIR where intensity of the source increases much more slowly. The reason to consider temperature optimization due to such behavior of the thermal source is that the very broadband detectors of FIR used for the bunch length measurements are also sensitive to the mid-IR and visible radiation. When a significant amount of the radiation generated by the source and delivered to the detector is not polarized by the wire-grids, it is seen in the measurements as a large background and the interferogram appears to be just a small perturbation in the measurements. To mitigate this effect the input window of the detectors was covered with black polyethylene, which very effectively cuts off the visible and mid-IR radiation.

EXPERIMENTAL SETUP

At the JLab FEL facility one of the user labs is setup for experiments with the broadband coherent synchrotron radiation. The radiation is transported [13] to the lab from the exit of the last bunch compressor dipole, where the bunch length reaches its minimum. The optical table in the lab, where radiation is delivered, is equipped with two interconnected vacuum chambers and in vacuum FTIR. The vacuum chamber where different user experiments can be setup is large enough to accommodate the modified MPI as well as the thermal source. The pressure in the chamber during measurements was 100 mTorr or less.

The thermal source radiation was collected and collimated by a 90 degree off-axis parabolic gold-coated mirror with a diameter of 2 inches. The mirror was set up to have its focus on the source filament. The visible radiation emitted by the source was used for the initial alignment of the setup. Between the source and the parabolic mirror, a mechanical chopper was installed. The reasons for using the chopper are a. the interferometer itself is a step scan device and works with amplitude modulated radiation only, b. the Golay cell detector is also a pulsed device that needs amplitude-modulated signals, and c. due to the low power level of the source and the use of

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room temperature detector, a lock-in detection technique had to be used, thus requiring modulation of the signal. A modulation frequency of 10 Hz was used. A Stanford Research System lock-in amplifier SR850 was used for the measurements. The amplifier was typically setup with 80 dB gain, time constant of 300 ms, and 12 dB/octave filter. The level of the Golay cell signal at the modulation frequency was on the order of 100 μV. The amplitude of the signal measured with the lock-in amplifier was sent to one of the outputs of the amplifier and was measured with a digital oscilloscope. A LabVIEW application controls the oscilloscope, downloads its waveforms and measurements at the rate of a few Hz and broadcasts the results over the Ethernet. Another LabVIEW application originally made for the bunch length measurements with the MPI was modified to use the data of the lock-in amplifier. To improve the signal to noise ratio we usually average over 4 to 16 measurements at each position of the scanning mirror. This in a conjunction with the 300 ms time constant and large number of points measured for each interferogram resulted in a relatively long one hour order of magnitude measurement time. This did not present any problems due to the high degree of overall automation.

MEASUREMENTS RESULTS

As mentioned earlier at the JLab FEL the bunch gets compressed down to about 100 fs RMS. Fig. 1 shows one of the CTR power spectra that according to our data evaluation corresponds to the RMS bunch length of about 110 fs. The analytical fit function used for the data evaluation with the parameters obtained by non-linear least square fit is shown as well. Spectrum of the thermal source measured with the same instrument is also shown in Fig. 1. The shape of the thermal source spectrum qualitatively agrees with our expectations presented above. The measured spectral density of the source starts to decrease at about 2.7 THz. At that frequency the CTR spectral density is reduced to the level of 5 % from it maximum. Our interpretation of the data shown the Fig. 1 is that when the instrument is used for an bunch length measurements at the level of 100 fs RMS, the measurements are not limited by the bandwidth of the interferometer. However, it is still possible that the beam measurements and their data evaluation are affected by the transfer function of the instrument. We do not consider these measurements as a comprehensive and final study of the transfer function, but rather as a demonstration that it can be made with a simple thermal source and, very importantly, room temperature detector – the same detector as used for the beam measurements. One way to estimate the bunch length, which would correspond to the bandwidth of the MPI is to use the bunch length evaluation procedure, normally applied, to the CTR spectra, to the spectrum of the thermal source. The result of this is ~ 47 fs RMS bunch length. This means that, for an electron bunch length near 50 fs, the bunch length measurements will be strongly affected by the bandwidth of the instrument unless the data evaluation takes the real transfer function of the MPI in to

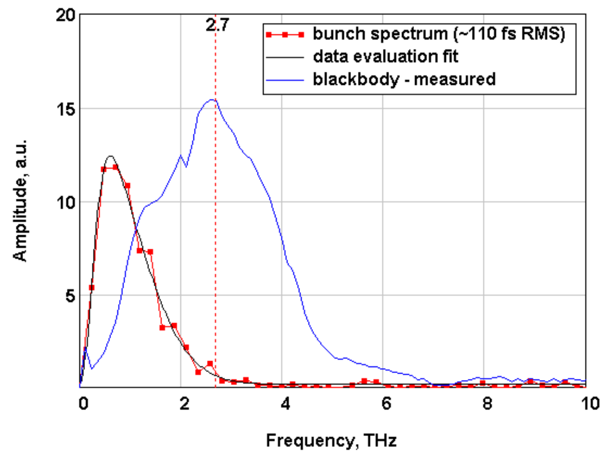

Figure 1: CTR and thermal source spectra.

account. Note that wire-grids with wire diameter and period up to four times smaller than ones we used are commercially available. Therefore, it might be possible to extend the applicability of the MPI for the bunch length measurements down to at least 25 fs RMS or smaller, dependent on the detectors bandwidth.

The CTR spectrum shown in Fig. 1 was measured in air at atmosphere pressure, while the thermal source spectrum was measured in vacuum. We have repeated the measurements with the thermal source in air to demonstrate the magnitude of the atmosphere absorption. Two spectra of the thermal source measured in vacuum and in air are shown in Fig. 2, where vast amount of absorption lines in the frequency range of interest can be seen. The absorption lines do not appear in the CTR spectrum explicitly because such measurements are usually made with very poor frequency resolution to save time. This does not mean, of course, that the CTR measurements are not affected by the atmosphere absorption. Ideally, such setups should be used in vacuum. It is also interesting to see the effect of the atmosphere absorption in the time domain, i.e., on the interferogram itself. Figures 3a and 3b show two interferograms measured in vacuum and in air.

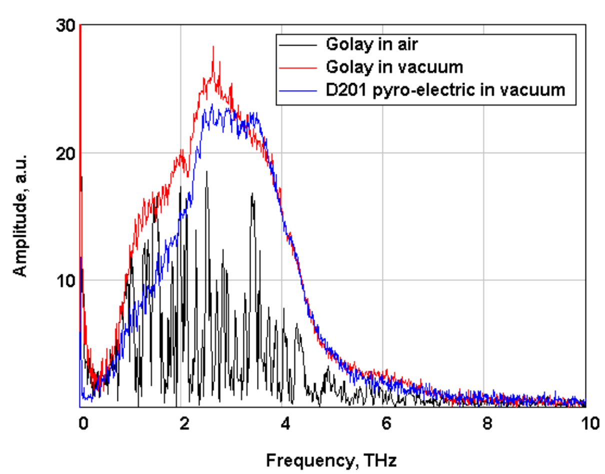

Figure 2: Thermal source spectra measured in air and vacuum by Golay cell and D201 pyro-electric detector.

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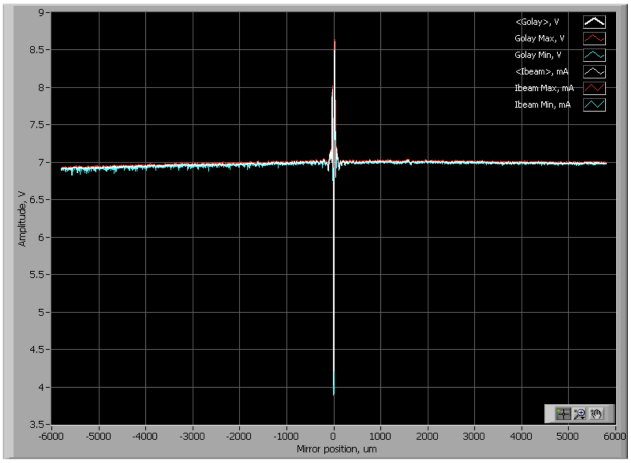

Figure 3a: Interferogram – thermal source in vacuum.

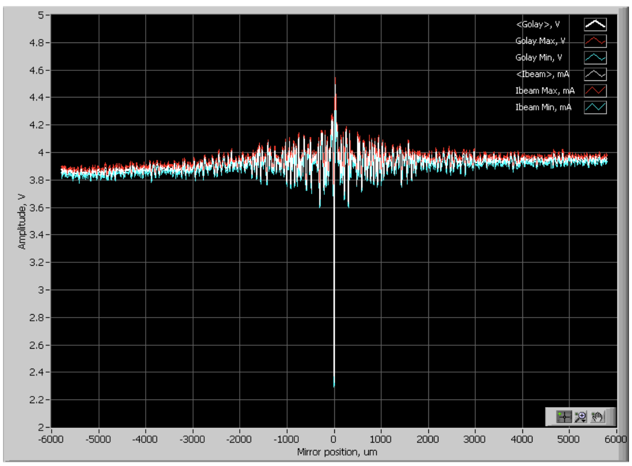

Figure 3b: Interferogram – thermal source in air.

While the in-vacuum interferogram has essentially only central burst, the interferogram measured in air has a very large number of oscillations extending to a very large path length difference.

Golay cell detectors are frequently used for measurements with MPI and are considered to have relatively flat wavelength response due their operational principles. Pyro-electric detectors are an alternative to the Golay cell with the price considerably lower but with possibility of strong dependence of the sensitivity on the wavelength. With the experimental setup described above it is straightforward to compare performance of the Golay cell and other detectors. Making measurements in vacuum we have compared the Golay cell and the FIR pyro-electric detector D201 made by Bruker. Results of the measurements are shown in Fig. 2. The two detectors perform quite similarly. While the D201 might be somewhat less sensitive in the frequency range up to about 3 THz it is not showing any very strong oscillations in its response. From this we can conclude that such detectors can be an attractive replacement for the Golay cell detectors when applied to the bunch length measurements.

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