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Sub-Picosecond Electron Bunch Length Measurement*

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Abstract

A subpicosecond electron bunch length measuring system has been developed at the SUNSHINE facility. The method is based on an autocorrelation technique in the frequency domain utilizing the coherent radiation emitted from the electron bunch at wavelengths equal and longer than the bunch length. The radiation spectrum is the Fourier transform of the electron bunch distribution and measuring this spectrum in a far-infrared Michelson interferometer allows the determination of the bunch length down to the femto-second regime. The experimental setup and measurement of subpicosecond electron pulses including possible improvements to maximize the bunch information available from an interferogram will be described.

1 INTRODUCTION

The ability to measure sub-picosecond electron bunches greatly determines the progress to produce ultra short electron and radiation pulses as desired for future linear colliders, x-ray FEL's or the development of far infrared(FIR) coherent radiation of very high intensity. At the SUNSHINE facility sub picosecond electron bunches can be generated down to 100 f-sec rms[1]. To aid this development a FIR Michelson interferometer has been developed for bunch length measurement[2] which is based on a frequency-resolved autocorrelation technique [3] utilizing coherent transition radiation emitted at wave lengths equal to or longer than the bunch length while the electron beam passes through a thin Al-foil. This FIR Michelson interferometer works in such a way that the primary signal is the Fourier transform of the radiation spectrum which is exactly what is desired to obtain information about the bunch length[2,4]. Unlike time-resolved technigues which suffer from technical limitations and high cost, this method allows to determine the electron bunch length in the subpicosecond range without complicated hardwares.

2 PRINCIPLE OF THE TECHNIQUE

Transition radiation (TR) can be generated when the electron beam passes throught a thin metalic foil. At wave lengths longer than the bunch length the radiation is coherent and the intensity of the radiation is proprotional to the square of the number of electrons per bunch. The intensity is therefore very high such that room temperature radiation detectors can be used and its spectrum includes information about the particle distribution in the bunch. The coherent power spectrum of TR from an electron bunch can be written like

$$P_{tot}(\lambda) = P_e(\lambda)\,[N + N(N - 1)\,f(\lambda)],$$

where $P_e(\lambda)$ is the spectral radiation power from a single electron and N is the number of electrons per bunch. The form factor $f(\lambda)$ is defined by

$$f(\lambda) = \left|\int dz\, e^{i2\pi z/\lambda}\, S(z)\right|^2,$$

and is the Fourier transform of the longitudinal particle distribution S(z) normalized to unity.

The frequency information can be extracted from a FIR Michelson interferometer in the from of a power spectrum. Radiation entering the Michelson interferometer is split into two parts by a polyethylene beam splitter and directed into two different directions to be reflected back by mirrors. One mirror is fixed in position while the other mirror can be moved to change the path length. After reflection the beams are combined again and sent to a bolometer to measure the intensity. In this arrangement one can use one part of the coherent radiation pulse as a scale to scan the other part. While the two path lengths are different by more than the bunch length both pulses arrive at the bolometer at different times and generate a signal independent of the path length difference. As, however, the path length difference becomes comparable to the bunch length both radiation pulses overlap and the coherent fields add up thus generating an increase in intensity and signal at the bolometer. Energy conservation is met if all radiation in the Michelson interferometer is considered [2]. The bolometer signal recorded as a function of the path length difference is called the interferogram and is the Fourier transform of the radiation spectrum. By observing the autocorrelation interferogram of coherent TR one can derive the bunch length. Since this method is based on optical principles it works for any short bunchlength provided that optical elements are avaialble and used for the frequency range corresponding to the Fourier transform of the particle distribution.

To generate TR we use an Al foil which is tilted by 45^o with respect to the electron path and the backward TR is then emitted at 90^o with respect to the beam axis. The radiation exits through a polyethylene window from the beam pipe and enters the FIR Michelson interferometer.

In the analysis of the interferogram one must eliminate all effects which alter the radiation spectrum and may therefore lead to erroneous bunch length measurements. Specifically, the beam splitter has a particular spectral response which comes from the interference of reflections from the front and back of the beam splitter. These effects can be calculated from material constants and thus, in principle, be eliminated. The detailed analysis and formalism for this has been reported in [2]. A similar concern relates to water absorption for a Michelson interferometer set up in air. The water absorption lines are very narrow and therefore do not affect the overall radiation spectrum as the beam splitter does. In first approximation, we can therefore neglect water absorption effects. However, more than just a measure for the bunch length can be obtained from the exact form of the interferogram if we eliminate water absorption as well.

A typical autocorrelation interferogram from the SUNSHINE facility is is shown in Fig.1(a) and the corresponding radiation spectrum in Fig.1(b). Many water absorption lines are clearly visible.

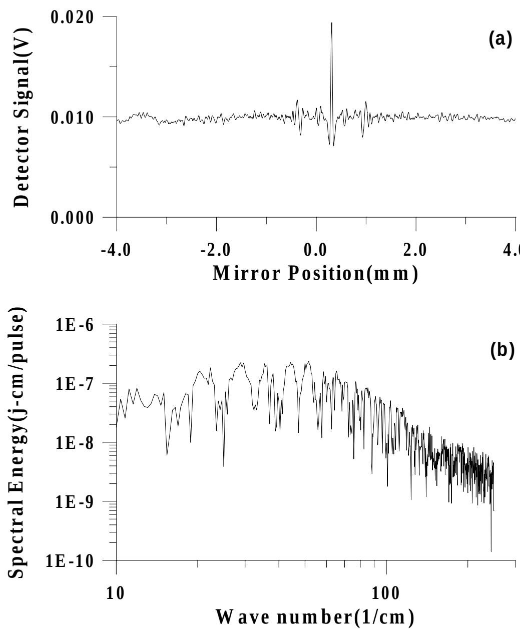

Figure:1 A typical interferogram for f-sec electron bunches at SUNSHINE.with 12.7μm thick beam splitter(a) and the Fourier transform of the interferogram(b)

Numerical elimination of beam splitter effects requires the knowledge or assumption of the actual electron distribution because the spectral modification is different for a gaussian or uniform particle distribution. The required correction is minimized if one uses a beam splitter which is thicker than about half the equivalent bunch length[2]. We define an equivalent bunch length as the length of a uniform bunch or equal to $\sqrt{2\pi}\sigma$ for a Gaussian bunch. With a thick beamsplitter the equivalent bunch length is then equal to or 75% of the FWHM of the interferogram for a uniform or Gaussian distribution, respectively.

Generally the equivalent bunch length can be derived from the interferogram for an arbitrary beam splitter thickness utilizing the graph in Fig.2.

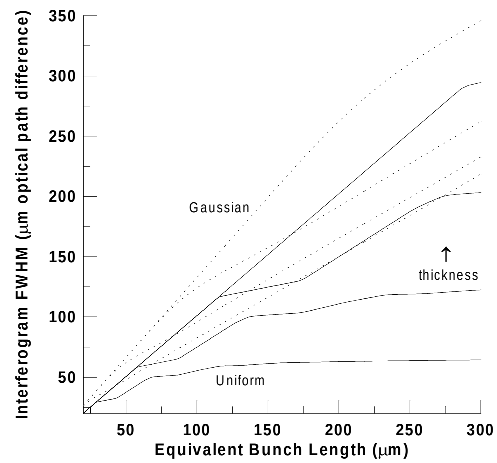

Figure:2 Equivalent bunch length as a function of the interferogram FWHM assuming a Gaussian (dotted line) or a uniform (solid line) bunch distribution for a 12.7, 25.4, 50.8, 127 μm thick Mylar beamsplitter[2].

From Fig.2 it is clear that a significant uncertainty about the bunch length exists if the general form of the particle distribution is unknown. For too thin a beam splitter and a uniform distribution no bunch length can be derived. Some knowledge of the bunch distribution is highly desirable to obtain the actual bunch length. In principle this information is lost in frequency domain measurements. However, from the form of the interferogram and spectrum some of this information can be recovered.

3 THE POWER SPECTRUM

Most realistic particle distributions can be assumed to be somewhere between a gaussian and uniform distribution. For each of these extremes we calculate the interferogram and radiation spectrum assuming the same equivalent bunch length. Both interferograms are shown in Fig 3(a). The difference is noticable in case of negligible extraneous spectral modifications. In case of real measured interferograms, however, the difference can be obscured by beam splitter effects and water absorption lines. At SUNSHINE an in-vacuum Michelson interferometer has been assembled which is expected to produce interferograms which can be interpreted in more detail as to the character of distribution.

The spectrum, on the other hand, shows significant diference between both distributions as evident form Fig.3(b). The uniform distribution spectrum extends to greater frequencies compared to that for a Gaussian bunch. The measurements should be sufficiently accurate to allow the distinction between both distribution or at least to conclude which distribution the real bunch is closer to. With this information a more precise determination of the bunch length becomes possible.

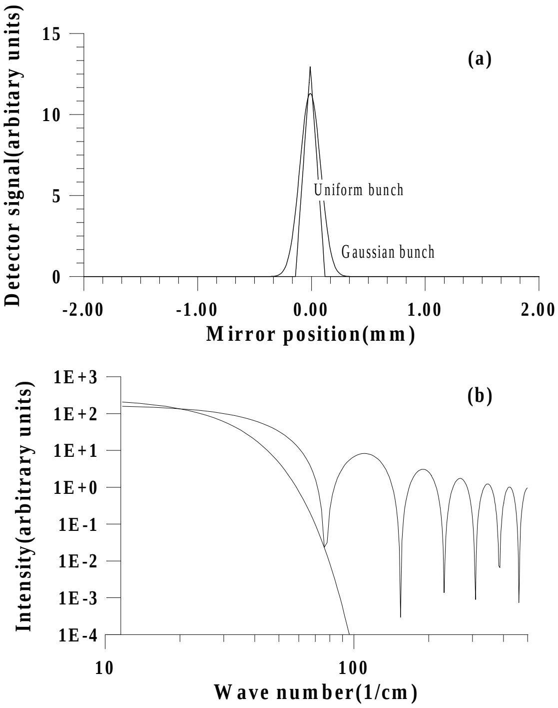

Figure:3 Calculated interferograms(a) and power spectrum(b) for a gaussian and uniform particle distribution of the same equivalent bunch length *l* = 160μm.

To obtain more information on the bunch distribution, we compare the measured power spectrum of Fig.1(b) with calculated spectrum of uniform and Gaussian distributions including beam splitter effects. This comparison is shown in Fig 4. To generate the appropriate spectra the actual equivalent bunch length must be known. Obviously, we must apply an iteration process. First we assume a bunch length, then we determine the closest particle distribution and determine from that the bunch length, etc.

The roll-off of the measured power spectrum at high frequencies looks more like that of a uniform than that of a Gaussian distribution which has a much faster drop-off of the spectrum.

The comparison would be greatly improved with the elimination of the multitude of water absorption lines in the measured spectrum. For the new in-vacuum Michelson interferometer at SUNSHINE, it is expected

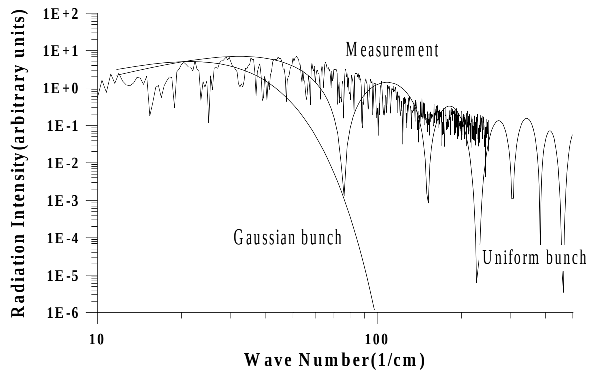

Figure:4 The power spectrum for a uniform and Gaussian distribution including 12.7 μm thick beam splitter effect in comparison with measurement.

that all water absorption lines in the power spectrum will disappear and the cleaner power spectrum is expected to reveal more detail of the bunch distribution.

4 CONCLUSION

A bunch length measurement method using an autocorrelation of the coherent transition radiation is capable to measure electron bunch lengths in the femtosecond range. The approximated bunch length is obtained directly from the autocorrelation scan. To obtain more detail of the bunch length, the power spectrum need to be considered including the frequency effect from beam splitter and water absorption lines. An in-vacuum system is expected to improve the frequncy information from the measurement.

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