BUNCH LENGTH MEASUREMENTS AT JLAB FEL

P. Evtushenko, J. Coleman, K. Jordan, J. Michael Klopf, G. Neil, G. P. Williams
Thomas Jefferson National Accelerator Facility 12000 Jefferson Avenue, Newport News, VA 23606, U.S.A.

Abstract

The JLab FEL is routinely operated with sub-picosecond bunches. The short bunch length is important for high gain of the FEL. Coherent transition radiation has been used for the bunch length measurements for many years [1]. This diagnostic can be used only in the pulsed beam mode. It is our goal to run the FEL with CW beam and a 74.85 MHz micropulse repetition rate, which, with the 135 pC nominal bunch charge corresponds to the beam average current of 10 mA. Hence it is very desirable to have the possibility of making bunch length measurements when running CW beam with any micropulse frequency. We use a Fourier transform infrared (FTIR) interferometer, which is essentially a Michelson interferometer, to measure the spectrum of the coherent synchrotron radiation generated in the last dipole of the magnetic bunch compressor upstream of the FEL wiggler. This noninvasive diagnostic provides bunch length measurements for CW beam operation at any micropulse frequency. We also compare the measurements made with the help of the FTIR interferometer with data obtained using the Martin-Puplett interferometer [1]. Results of the two diagnostics agree within 15 %. Here we present a description of the experimental setup, data evaluation procedure and results of the beam measurements.

INTRODUCTION AND MOTIVATION

The Jefferson Lab Free Electron Laser (FEL) facility is a superconducting rf (SRF) energy recovery linac based light source [2]. It is capable of running CW electron beam with an average current of up to 10 mA. The nominal bunch charge is 135 pC. The maximum possible micro-pulse frequency is 74.85 MHz, which is the 20th subharmonic of the fundamental (1497MHz) frequency of the linac. The micro-pulse frequency can be reduced by a factor of 2n, where n is an integer ranging from 1 to 8. Thus the accelerator can be operated at the nominal bunch charge but at the lower average beam current that is essential for the machine setup and tuning. Another set-up used for tuning up the machine is pulsed beam mode, where the beam consists of 250 μs long macro pulses coming with a repetition rate of 2, 10 or 60 Hz. The micro-pulse frequency within such a macro pulse is not more than ~4.68 MHz. Thus the average beam current in the pulse beam mode is kept very low and this beam mode can be used for invasive measurements of the beam properties.

A modified Martin-Puplett interferometer built by U. Happek [1] has been used for several years for the bunch length measurements at JLab FEL. The interferometer is used with the coherent transition radiation (CTR). To generate the CTR, a view screen made of 100 μm thin gold plated silicon wafer is inserted in to the beam. This diagnostic is invasive and can be used only in pulsed beam mode. The challenge of the bunch length diagnostic was to be able to measure the bunch length when running CW beam with average beam currents from 0.5 mA to 10 mA.

The coherent synchrotron radiation (CSR) can be used for the bunch length measurements the same way as the CTR. The longitudinal bunch compression is finalized by the magnetic bunch compression placed upstream of the wiggler. The bunch length at the wiggler is almost the same as at the exit of the bunch compressor. In fact the amount of the CSR generated in the last dipole of the bunch compressor is very high. A beam line was built to transport the CSR to one of the FEL user labs where it will be used for user experiments [3]. We use a rapid-scan Michelson interferometer with the CSR for the noninvasive bunch length measurements when running CW beam.

USING COHERENT RADIATION FOR BUNCH LENGTH MEASUREMENTS

The underlining principals of using coherent radiation produced by an electron bunch for the bunch length measurements have been described in detail many times in the literature [4]. Here is a short summary of the principals upon which the measurements with coherent transition radiation, as well as for the ones with coherent synchrotron radiation, are based. Consider an electron bunch consisting of N_e electrons generating transition radiation (TR) or synchrotron radiation (SR). For a wavelength shorter than the bunch length, the radiation power is proportional to N_e, since for every electron there is on average another electron radiating in an opposite phase, and so the coherence term is zero. Both TR and SR are very broadband. For a wavelength much longer than the bunch length, all electrons radiate almost in one phase and, since the phase difference is constant, the radiation is coherent and therefore the power of the radiation is proportional to N_e^2. There is a transition region where the spectral power density changes from N_e to N_e^2. The position of this transition depends on the bunch length. Hence measurements of the radiation spectrum, which would cover the transition region, contain information about the bunch length. Rigorously it is expressed as follows, spectral power density associated with the radiation of the entire bunch is

$$P_b(\omega) = P_S(\omega)\left[N_e + N_e(N_e - 1)\left|\tilde{f}_b(\omega)\right|^2\right]$$

where $P_S(\omega)$ is the spectral density of a single electron radiation and $\left|\tilde{f}_b(\omega)\right|^2$ is the so-called longitudinal bunch form factor.

INTERFEROMETERS

The first device we use is a modified Martin-Puplett interferometer [1]. That is a step-scan device installed in the accelerator vault right next to the beam line. A lens made of polished Picarin is set in front of the interferometer and is used to transform the divergent TR into a nearly parallel beam going in to the interferometer. Wire grids made of 20 µm tungsten wire are used as the polarizing beam splitter and as the polarizer-analyzer. The period of the grid is 50 µm. A linear stage with a step motor is used to change the position of the movable mirror in the adjustable arm of the interferometer. An off-axis parabolic mirror is then used then to focus the radiation onto the input window of the Golay cell detector. Figure 1 shows an example of an interferogram measured with the interferometer and the corresponding spectrum, which, as will be explained later, is a Fourier transform of the interferogram.

Another interferometer, which we use for the measurements with the synchrotron light, is a rapid-scan device. This interferometer is commercially available from Thermo-Nicolet, and called a Nexus 670. The optical beam line used to transport the synchrotron radiation to the user lab is all reflective and is made of off-axis ellipsoidal and plane mirrors [3].

A synchrotron radiation opening angle of 150 milliradians is collected from the accelerator. The final beam is collimated into the Michelson using a 6” focal length off-axis paraboloid. For the measurements presented here we used a beam splitter made of silicon. For the measurements with the synchrotron radiation we used a PY55 detector in conjunction with a PAPY 1153 amplifier, both made by Goodrich [5]. One fundamental difference between the two interferometers is the determination of the path length difference. In the rapid-scan interferometer the path length is changed by a free running mirror, which moves with constant velocity during a scan. To measure the path difference in the interferometer there is one more interferometer built into it. The additional interferometer utilizes a HeNe laser, the fixed and the movable mirrors of the main interferometer and a beam splitter which is nested inside the main interferometer beam splitter. The detector for the HeNe laser light is placed at the output port of the interferometer. During the interferometer scan, the signal of the HeNe detector is a sine function with one period of the signal corresponding to a path length change of one wavelength of the HeNe laser, which is 632.8 nm. Thus the effective sampling frequency of the rapid-scan interferometer is much higher than the one of our step-scan interferometer. The frequency resolution of the measurements with a Michelson interferometer depends on the scan range and in our measurements is typically about 50 GHz.

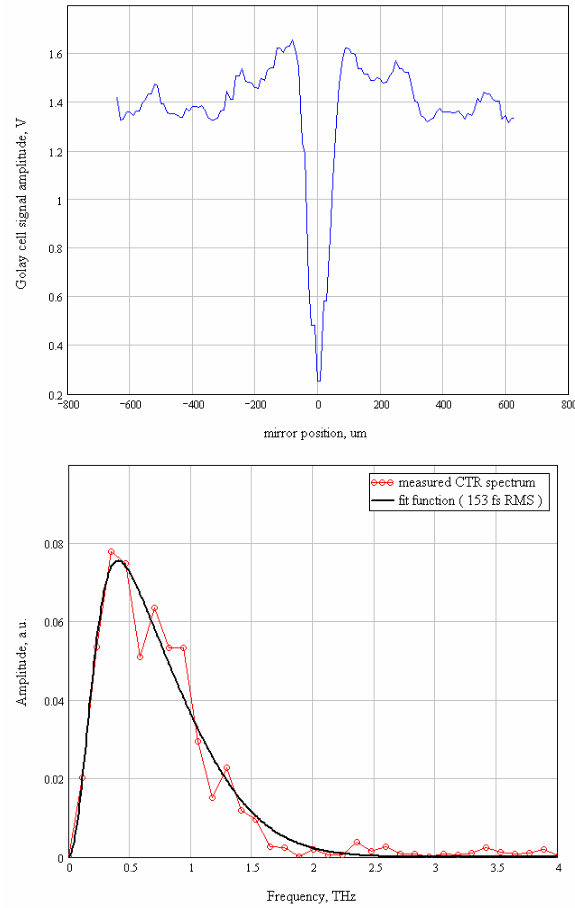


Figure 1: Interferogram measured with the modified Martin-Puplett interferometer and the corresponding spectrum.

In our measurements one scan of the rapid-scan interferometer takes about 2 seconds. Since both interferometers we use are essentially Michelson interferometers, the same data evaluation procedure for the bunch length reconstruction can be applied to the data obtained from either interferometer.

BUNCH LENGTH RECONSTRUCTION

We use the following data evaluation procedure for the bunch length estimation. The procedure is similar to the one described in [6]. According to the Wiener-Khintchine theorem [7], the autocorrelation function is the Fourier transform of the power spectrum. We use a Fast Fourier Transform (FFT) algorithm to calculate the powers spectrum from the interferogram since the data are discrete. The power spectrum defines uniquely the amplitude of the components of the frequency domain representation of the pulse. However, information about the relative phases of the different Fourier components is lost in the interferometric measurement. This is why a direct pulse shape reconstruction from the power spectrum is not possible.

We assume a Gaussian shape of the bunch, with the RMS bunch length σ_t. The Fourier transform of the distribution function is also a Gaussian function. Thus we can write the Gaussian bunch power spectrum as $\tilde{P}(\omega) = C \cdot e^{-(\omega\sigma_t)^2}$, where C is a constant. In the measured power spectrum, the intensity is strongly reduced below a certain threshold frequency as shown in Fig. 1. The reduction of the spectral density is due to diffraction losses. The general Huygens' integral can be used to describe the diffraction losses [8]. Result of the integration of the general Huygens' integral is not an analytical function and is not very convenient to use for further data evaluation. We approximate the low frequency cut-off function with the following analytical function $F_{filter} = 1 - e^{-(\omega/\omega_0)^4}$, where ω_0 is the characteristic cut-off frequency. The product of the Gaussian power spectrum and the filter function is the modified power spectrum

$$f_{fit}(\omega) = \left(1 - e^{-(\omega/\omega_0)^4}\right) \cdot C \cdot e^{-(\omega\sigma_t)^2}.$$

Once the modified power spectrum is expressed as an analytical function it can be used as a fit function with the nonlinear least square fit (NLSF) to approximate a measured power spectrum. From such a fit we can obtain σ_t, which we define as the RMS bunch length. There are several options regarding the characteristic cut-off frequency ω_0. The best would be to have it measured, but such a measurement in the frequency range of the interests is very difficult. Another option, which we have used so far, is to add in the effects of ω_0 to the fit parameter and to make sure it stays consistent during the measurements.

EXPERIMENTAL RESULTS

The accelerator setup is always done in diagnostic mode with pulsed beam. In this mode the modified Martin-Puplett interferometer is used for the bunch length measurements. We routinely operate the machine with an RMS bunch length of about 150 fs. However, dependent on the machine setup we have been measuring RMS bunch lengths in the range from about 100 fs up to 200 fs RMS. That implies that we do indeed successfully reconstruct the bunch lengths from the interferometer measurements as was described in the previous section. Figure 1 shows an example of an interferogram measured with the step-scan interferometer, while the corresponding spectrum also shows the fit function, which is the result of the data evaluation. For this particular measurement the fit gives the RMS bunch length of 153 fs.

When the accelerator is set up we can run CW beam and use the rapid-scan interferometer. Our experience is that the results of the measurements with two interferometers agree to within about 15 %. It is very important that with the Michelson interferometer and synchrotron radiation we can do bunch length measurements as a function of the average beam current. Figure 2 shows spectra of the CSR measured at 0.31 mA, 0.62 mA, 1.25 mA and 2.5 mA of beam average current and the measured CTR spectrum measured with pulsed beam, all the measurements were done with the same machine setup. The figure also shows the corresponding fit functions and the resulting RMS bunch length. The measurements show that the bunch length is not changing when the average beam current is increased. This is what one would expect, since the average current is increased by increasing the pulse repetition rate, keeping the bunch charge constant. However, at present the FEL efficiency has been decreasing with beam current and one explanation would be that it is due to an increase in bunch length. These measurements are therefore critical in ruling this out.

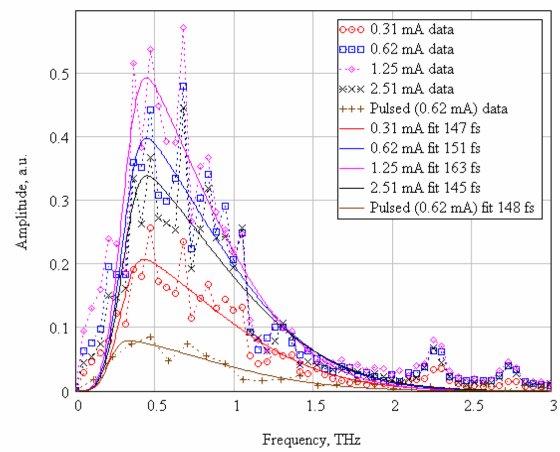
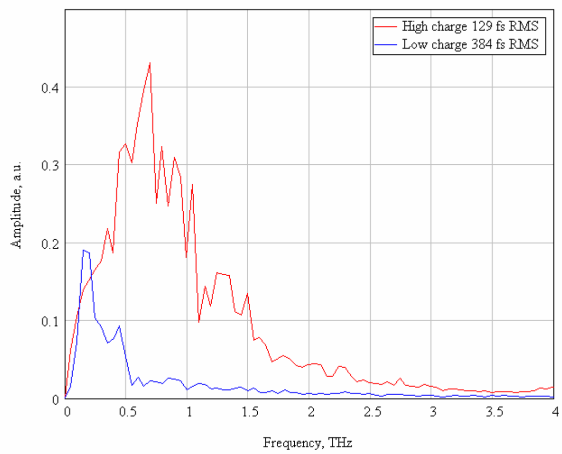


Figure 2: Spectra of the CSR measured at different average beam current with the CTR spectrum and the corresponding fit functions for bunch length reconstruction.

Another significant finding we have made is that the bunch length at the wiggler depends very strongly on the bunch charge. The bunch compression is normally optimized for the nominal bunch charge of 135 pC. When operating with much smaller bunch charge and without any changes in the machine setup, we have a much shorter bunch at the entrance to the linac. This results in a very small energy spread of the bunch at the exit of the linac. As a result, the M_{56} of the 180° bend and the chicane do not provide the same compression as for a bunch with nominal charge. As a result a bunch with a very small charge will be much longer at the wiggler than a nominal bunch. Figure 3.a shows measurements of the CSR spectrum of the nominal bunch, with an RMS bunch length of 129 fs, and that of a bunch with a very small charge where the RMS bunch length was measured to be 384 fs.

The rapid-scan interferometer provides more information than just a spectrum of CSR. Consider the interferometer scanning with the mirror velocity of 5mm/sec. Then the optical path length difference changes at a rate of 10 mm/sec. If the incoming radiation has, for example, a wavelength of 1 mm it will result in a modulation of the signal at the detector at a frequency of 10 Hz.



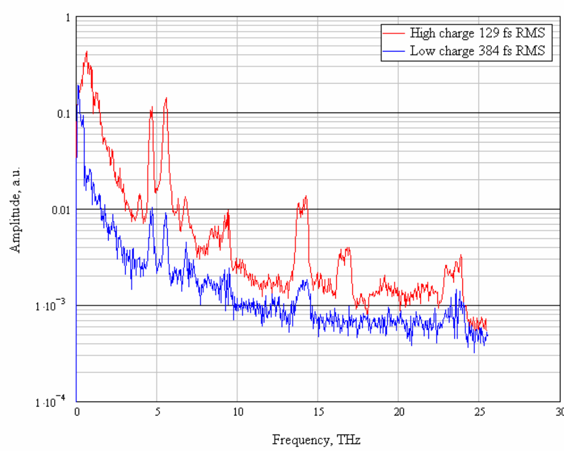


Figure 3: (a. top) spectra of the CSR measured at nominal bunch charge and much smaller bunch charge.;(b. bottom) the same data are shown on a logarithmic scale.

Thus different wavelengths measured by the interferometer be modulated at the detector at different frequencies. The frequency of the detector signal modulation is $f_M = 2v/\lambda$, where v is the velocity of the mirror during the scan and λ is the wavelength of the measured radiation. If the intensity of the incoming radiation is modulated, for instance due to a beam instability at some frequency, that will also result in modulation of the detector signal at that specific frequency. Hence the interferometer measurements also contain information about the beam stability. This technique has been used at numerous synchrotrons to diagnose and improve the beam stability [9]. Figure 3.b shows the data shown in Fig. 3.a on a logarithmic scale and over a bigger frequency span. The spectral power density peak at 4.69 THz corresponds to the radiation intensity modulation at 60 Hz; the next peak at 5.69 THz corresponds to the intensity modulation at 72.8 Hz and so on. We have yet to study in detail, the origin of all the observed beam modulations.

All the measured CSR spectra shown in Fig. 2 show local minima in the spectral power density, these are due to the water vapor absorption. This data corruption certainly reduces the accuracy of our bunch length reconstruction. To improve the setup we will switch to a newer Michelson interferometer operating in vacuum. It has been already demonstrated that such an interferometer can be operated in vacuum [10].

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