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MEASURING AND CHARACTERIZING ULTRASHORT BUNCHES IN THE JEFFERSON LAB FREE ELECTRON LASER

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Abstract

The characterization of ultrashort bunches is essential when dealing with free-electron laser driver accelerators. In such high-brightness accelerators, short bunch lengths are required to achieve the high peak current needed for high laser gain. Also, because of the high charge per bunch involved, the bunching process can potentially be altered via space-charge forces. In the high-power free-electron laser at Jefferson Lab, several methods are used simultaneously to monitor the longitudinal distribution. These methods include frequency-based devices that measure the bunch frequency spectrum by detecting coherent transition radiation, and time-based methods such as zero-phasing or M_{55} transfer map measurements using the "time-of-flight technique". In this paper we discuss measurements performed with the different devices and compare them with numerical simulations. We also present results of parametric studies of these various devices versus the RF phase of different critical elements in the machine.

1 GENERAL LAYOUT

Accurate beam instrumentation is essential for smooth commissioning of any accelerator. The diagnostics for Jefferson Lab's FEL accelerator have two main purposes: to allow set up of the accelerator and to monitor changes in beam conditions during production runs [1]. A diagram of the overall facility appears in Ref. [2]. Beam, originating in a 350 kV high average current injector, is accelerated to 10 MeV, merged onto the main linac beam line, and accelerated to 38 MeV. After passing through a wiggler, the used beam is recirculated to the beginning of the accelerator and its energy recovered, thereby reducing the overall demand on the linac RF systems. The main beam parameters are summarized in Ref. [2].

2 IR INTERFEROMETRY

The bunch length will be determined at several locations in the accelerator. The main measurement was completed at 38 MeV just downstream of the wiggler, i. e., at the location where one would like the bunch length to be minimized. Also, for beam verification purposes, a device at 10 MeV is installed. In the measurements, a polarizing Michelson interferometer and detector (Golay cell) are used to measure the power spectrum of transition radiation from a thin aluminum foil by autocorrelation [3]. An estimate of the bunch profile can be derived from the measured interferogram. The University of Georgia has build the interferometer and and the EPICs software to automatically perform the autocorrelation measurement. The range of the device is approximately 0.2-5 psec, and it is desired to have a result good to 0.1 psec.

An example from our first autocorrelation measurements is given in Figure 1. This interferogram clearly indicates that the rms bunch length is shorter than 250 μm. At this moment, the precision is limited because final alignment of the interferometer mirrors has not occurred; even a delta function bunch would have a finite indicated width of about 150 μm.

Figure 1: Interferogram measured at IRFEL wiggler

3 ZERO PHASING

The primary standard method used for precise determination of the longitudinal distribution is based on the zero-phasing method [4]. In the zero-phasing measurement, a longitudinal (accelerating) mode is phased to the zero-crossing of the accelerating wave. A linear energy ramp is induced front-to-back in the bunch. A distribution function is obtained by transversely diagnosing the beam at a dispersed location. Data from both zero-crossings, the positive and negative going crossings, are used to obtain an estimate of the slope of the longitudinal phase space. The measured slope is substantial when the rms beam sizes of the two crossings are different.

Examples of measurements taken at the Jefferson Lab IRFEL appear in Figures 2-4. Figure 2 is the profile on the $< \delta_{linac}, \phi_{out} >$ where δ_{linac} is the energy variation at the linac exit. For such a measurement we modulate the gradient of the last cavity of the linac while measuring the time of arrival at the aforementioned cavities. Non-linear fit of these longitudinal transfer map, or alternative Tchebychev analysis [8], can be used to extract M_{55}, T_{555}, or M_{56}, and T_{556} first and second order transfer matrix coefficients and compare them with optics code. On the other hand, the transfer function pattern can also be used to set the machine in a reproducible way, i.e. by checking time to time whether these patterns are unchanged. They can also be compared to simulated transfer functions generated with particle pushing code such as PARMELA [3].

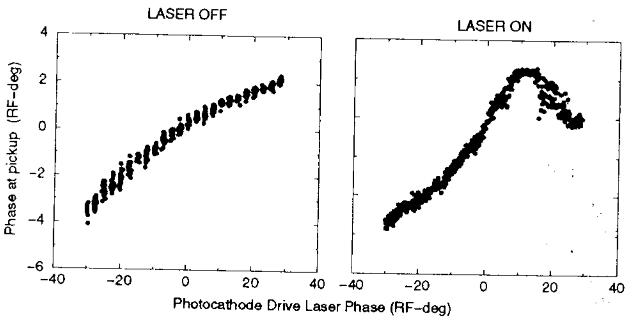

Figure 1: Effect of the laser on the $< \phi_{laser} | \phi_{out} >$ transfer function.

4 BEAM TRANSVERSE ENVELOPES

Except in the 350 keV beam generation region, the beam transverse densities are measured exclusively by detecting the backward optical transition radiation produced at the surface of a 2 μm aluminum foil. The foil is imaged with an aberration-optimized optical system on a CCD array whose video ouput is digitized by the means of DATACUBE image processing board running on its own IOC. Beam 2D density, projection, centroid position and rms size are computed on the CPU of the dedicated IOC before being broadcasted on the local network. Because of the difficulty to observe OTR in the 350 keV region, we have instrumented this beam line with a highly sensitive wire scanner that can profile beam at the gun exit, after the first solenoidal lens, and with a fluorescent screen at the entrance of the 10 MeV accelerating structure to check beam transverse envelope. Along with (pure betatron) beam size measurement, some of the OTR monitors are located in high dispersion region, e.g. compressor and decompressor chicanes and recirculation arcs, to measure the beam energy spread. An example of energy spread distribution measured in the decompressor chicane located downstream the undulator is shown in figure 2. It is also planned to use synchrotron radiation to monitor the beam spot during cw operation. Unfortunately because of our bend curvature $\rho \simeq 0.6$ m the critical wavelength is of the order of $\lambda_c = 4\pi\rho/(3\gamma^3) \simeq 7$ μm which implies the use of very sensitive (and expensive) camera that will be installed once beam physics experiments are

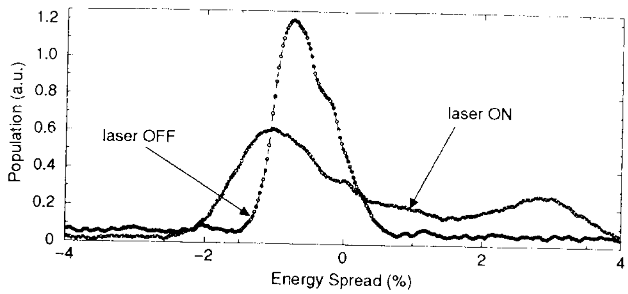

Figure 2: Example of energy spread distribution variation when the FEL is off or turned on.

completed (to avoid damaging them).

Two types of emittance measurement have been implemented: In the 10 MeV injection line, where the beam is space-charge-dominated, the transverse emittance is measured with a multislit [5] mask that can provide emittance, Twiss parameters at 1 Hz level and transverse trace-space isocontours at 0.5 Hz; an example of generated beamlets is shown in figure 3. In the 38+ MeV region, the emittance is measured using the standard beam envelope fitting technique, i.e., either quadrupole scan or multi-monitor methods. A Tcl/Tk application has been written to automate the measurement as much as possible and render it flexible by letting the user choose any quadrupole/profile monitor he/she desired to use for the measurement. Such automation is possible thanks to the use of the Artemis [10] modelserver, an online updated model of the beamline lattice capable of providing to any applications "real world" machine transfer matrices in real time. Based on quadrupole scan technique we have also implemented a transverse phase space tomographic reconstruction [9].

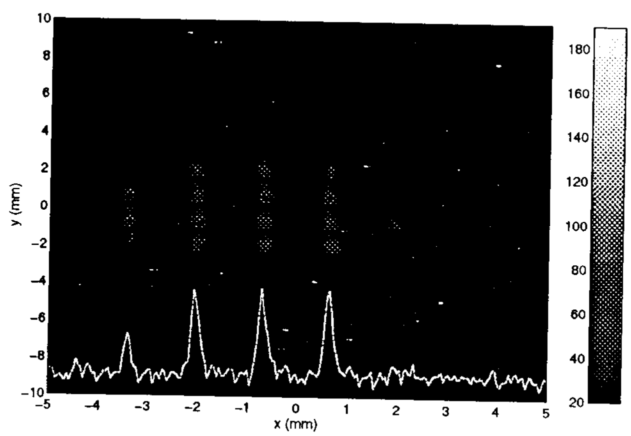

Figure 3: Example of beamlets pattern generated by the multislits mask from which the Twiss parameters and emittance are inferred.

5 BUNCH LENGTH

During the early stage of the commissioning of the driver accelerator we have experimented with bunch length mea-

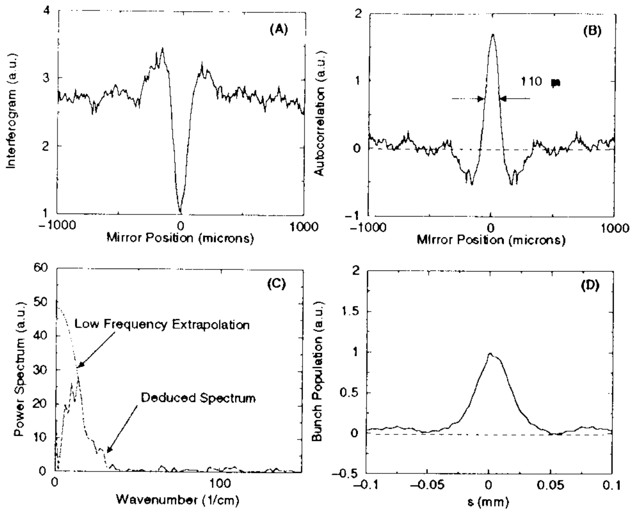

Figure 4: **(A)** raw data from the detector i.e. interferogram, **(B)** autocorrelation obtained from the interferogram, **(C)** energy spectrum obtained by fourier-transforming the autocorrelation, **(D)** bunch distribution obtained by hilbert-transforming the energy spectrum after low frequency extrapolation.

surement using zerophasing technique. This consists of inducing an energy ramp along the bunch by operating one or several cavities at the zero-crossing point and mapping the energy distribution into the horizontal plane with a spectrometer [4, 6]. Also this method enables the measurement of both bunch length and longitudinal phase slope; it is not practical for operation purposes compared to bunch monitor based on coherent radiation detection. The IRFEL has been instrumented with two of these latter monitors: one is located in the injector front end while the other in the wiggler region. From an interferogram measurement one can compute the bunch length, its frequency spectrum and reconstruct the longitudinal distribution as shown in figure 4. Currently only the interferometer located in the wiggler vicinity is fully commissioned: it has confirmed the ultra-short bunch length we were achieving of the order of 100 μm (RMS) [6]. In fact under routine operation to start up the laser, the interferogram is not measured, but the total CTR signal is maximized to ensure the bunch length is minimum at the undulator location, then fine adjustment of the linac phase is performed to compensate for the slippage effect, by measuring the output power of the laser and maximizing the FEL gain. The bunch length inferred from autocorrelation must be interpreted with care: during operation of the linac in overcompression mode, it could provide erroneous results as is shown in figure 5 where the simultaneous measurement of CTR power and bunch length (inferred from the interferogram) are presented versus the linac phase. One can see the discrepancy in the overcompression regime as the total CTR power decreases, yet the bunch length still decreases. This effect was traced back via numerical modeling and found to be due to tail formation in the bunch due to the space charge collective force. These tails are present in the interferogram function but are so weak that they are part of the baseline. Therefore the bunch length computed is not characteristic of the whole bunch, but only of its core.

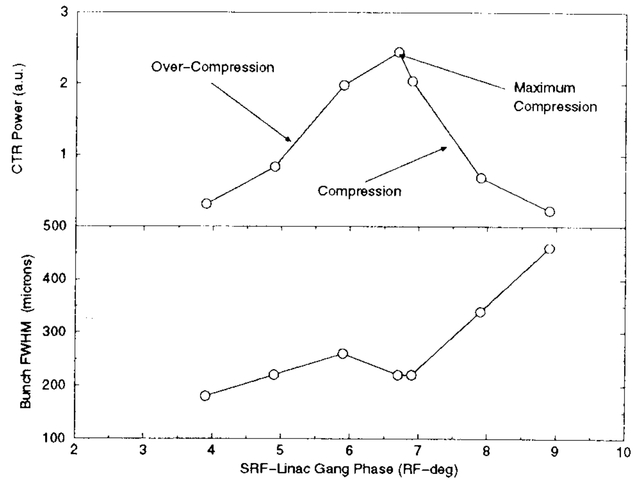

Figure 5: Limitation of CTR based bunch length measurement.

6 BEAM CURRENT AND CHARGE

There are two methods that can be used to measure the beam current. An averaging method consists in using the IRFEL dumps as Faraday cups which provide an absolute beam current measurement. A faster but relative method, capable of providing data at 10 kHz, consists in measuring the amplitude signal out of a pillbox cavity similar to the one used for the measurement of the longitudinal transfer functions described above. Such a method, after calibration, is used continuously to monitor the instantaneous beam current delivered at injector front end. Recently an integrator has been added so that we can measure the total charge delivered for a given period, typically between photocathode recesiation or wafer changes and monitor the photocathode performance.

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