Performance of the Electron Beam Diagnostics at Jefferson Lab's High Power Free Electron Laser*

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Abstract

We describe the performance and current status of the electron beam diagnostic complement for Jefferson Lab's IR-FEL oscillator. In addition measurements for the driver-accelerator are presented. Beam diagnostics devices include optical transition radiation profile monitors, multi-slit beam emittance measurement, coherent transition and synchrotron radiation based bunch length monitors, both strip-line and button antenna BPM's and pick-up cavities for longitudinal transfer function measurement. All device are controlled via the EPICS control system.

1 OVERVIEW

Diagnostics in a high power FEL such as the JLab IR-FEL [1] were crucial to smoothly commission the driver-accelerator, measure and control the beam parameters. Among the parameters that must be thoroughly measured and controlled over the beam generation and transport, transverse emittance and longitudinal bunch length are probably the most important since their degradation can significantly affect the beam brightness and consequently degrade the laser gain. A generic diagnostic consists of a detector mounted on the beam line that is required to operate in the so-called "tune-up mode", a low duty cycle beam mode that can be used during machine setup without damaging any beamline components. The choice to perform most of the measurements at low duty signal is legitimate: in the Jefferson Lab's IRFEL the beam physics is dominated by single bunch effects (the inter-bunch distance cannot be smaller than $\simeq 4.02$ m). The signal from the detector is treated with a appropriate system (digitizer, ADC, etc...) and pre-processed on an input-ouput controller (IOC) operating under the VxWorks environment. The generated data are sent on the local network and can be accessed from any application running on one of our HP-9000 workstations connected to the local network. In parallel to the EPICS system it is possible to access some of the data using the Cdev protocol. For many purposes, especially during commissioning activities, we have developed high level applications based on the Tcl/Tk scripting language or the MATLAB package.

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2 BEAM POSITION

The beam position monitoring system consists of two types of detector: stripline detectors that provide a low RF-impedance so that no beam degradation due to wakefield occurs and the button antenna detector which are used in large aperture vacuum chambers required in the resonator bypass chicanes and the recirculation arcs. Two different electronics are used for processing the signal: the 4-channel electronic is used since it offers a high reproducibility. This electronic consists of 4 detectors for each of the 4 antenna. In the wiggler region, the switched electrode electronic [2] is used: it switches the signal between each pair of the four antenna and offers a higher dynamics range compared to the 4 channels electronics. The most stringent requirement on the BPMs concern the six BPMs located in the wiggler insertion region: the demand on position measurement accuracy is 45 μm. During the commissioning of the driver accelerator we have been able using saved value of the reading from the BPM's to routinely achieve a very reproducible orbit which significantly expedites the startup of the laser. It has also been used to test the lattice first order transfer matrix using the difference orbit method. The SEE electronics also provides a "B-scope" feature which consists of acquiring and recording for off-line analysis the beam position at higher frequency (e.g. 30 Hz). This feature enables the operator to quantify beam jitter and identify potential frequency dependent beam motion.

3 MOMENTUM COMPACTION & COMPRESSION EFFICENCY

One must carefully set up the bunching elements to achieve ultrashort bunch length at the wiggler insertion. We characterize the compression efficiency of the lattice by measuring the transfer function $<\phi_{laser}|\phi_{out}>$. The phase of the photocathode drive laser ϕ_{laser} is modulated and the output phase ϕ_{out} after a section of the transport is measured using a stainless pill-box cavity by detecting the fundamental mode TM_{010}. The signal is processed with a precise phase detector: the signal is phase shifted and mixed with the reference master oscillator signal. Before the measurement the phase shifter is set to insure the cavity is at zero-crossing. An example of measurement of $<\phi_{laser}|\phi_{out}>$ transfer map is presented in figure 1. There are four pickup cavities in the driver-accelerator: located downstream of the 10 MeV cryomodule in the injector, at the linac front end, at the exit of the first and second recirculation Bates-type arcs. The three latter cavities are also used to measure 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. Nonlinear 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].

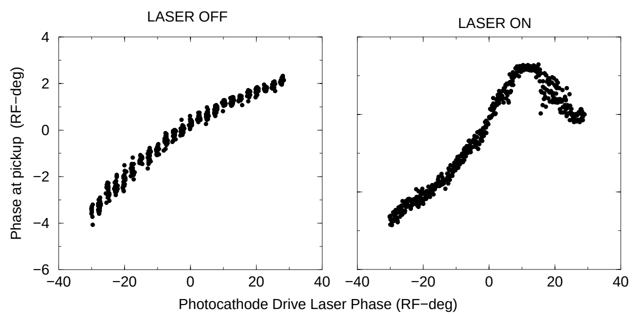

Figure 1: Effect of the laser on the $< \phi_{laser} | \phi_{out} >$ transfer function.

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

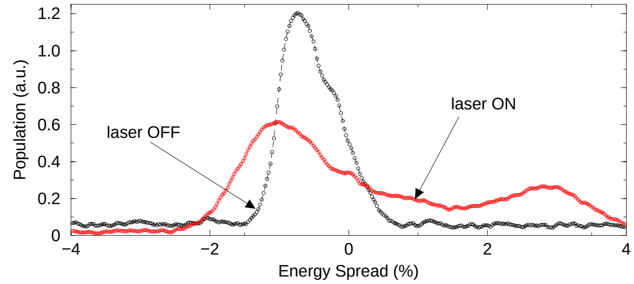

Figure 2: Example of energy spread distribution variation when the FEL is off or turned on.

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].

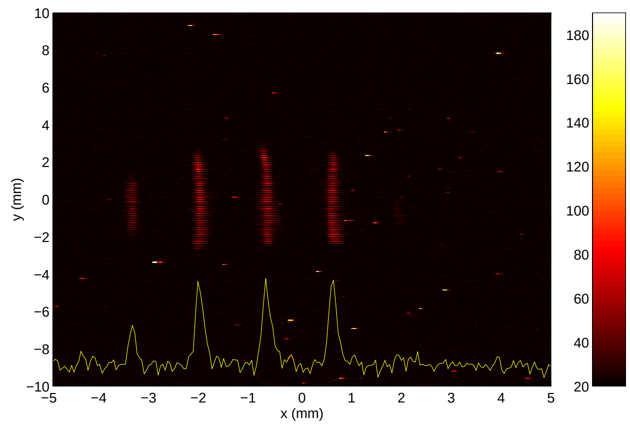

Figure 3: Example of beamlets pattern generated by the multislits mask from which the Twiss parameters and emittance are inferred.

5 BUNCH LENGTH

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

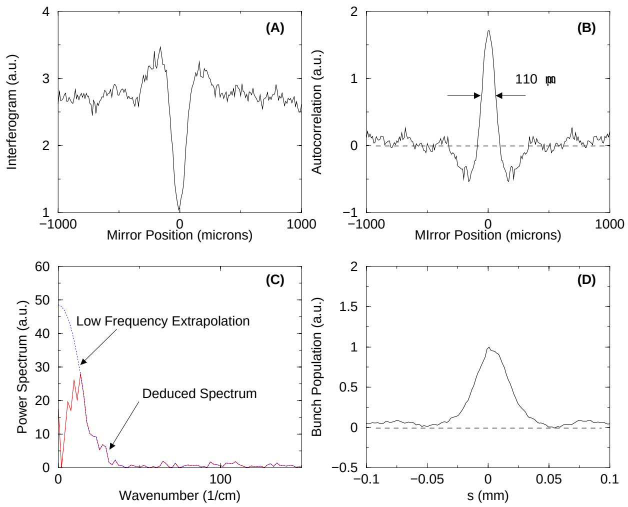

Figure 4: **(A)** raw data from the detector i.e. interferogram, **(B)** autocorrelation obtained from the interferogram, **(C)** energy spectrum obtained by fourier-transforming the autocorrelation, **(D)** bunch distribution obtained by hilbert-transforming the energy spectrum after low frequency extrapolation.

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.

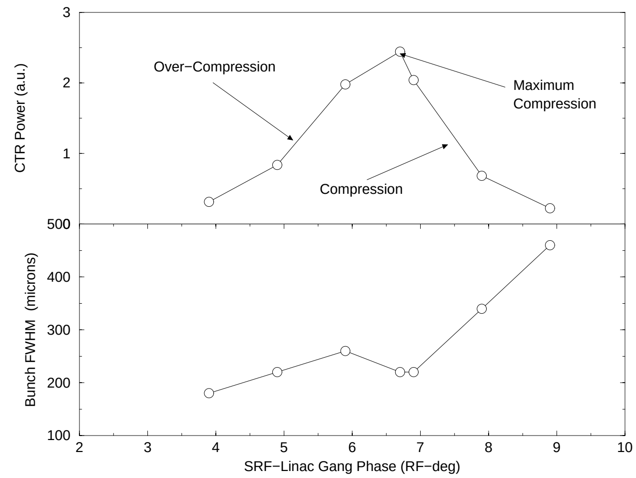

Figure 5: Limitation of CTR based bunch length measurement.

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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