ELECTRON BEAM DIAGNOSTICS OF THE JLAB UV FEL

P. Evtushenko#, S. Benson, G. Biallas, J. Coleman, C. Dickover, D. Douglas, M. Marchlik,
D. Sexton, C. Tennant, Jefferson Lab, 12000 Jefferson Ave, Newport News, VA, 23606 U.S.A.

Abstract

In this contribution we describe various systems and aspects of the electron beam diagnostics of the JLab UV FEL. The FEL is installed on a new bypass beam line at the existing 10kW IR Upgrade FEL. Here, we describe a set of the following systems. A combination of OTR and phosphor viewers is used for measurements of the transverse beam profile, transverse emittance, and Twiss parameters. This system is also used for alignment of the optical cavity of the UV oscillator and to ensure the overlap between the electron beam and optical mode in the FEL wiggler. A system of beam position monitors equipped with log-amp based BPM electronics. Bunch length on the order of 120 fs RMS is measured with the help of a modified Martin-Puplett interferometer. The longitudinal transfer function measurement system is used to setup bunch compression in an optimal way, such that the LINAC RF curvature is compensated using only higher order magnetic elements of the beam transport. This set of diagnostic systems made a significant contribution in achieving first lasing of the FEL after only about 60 hours of beam operation.

JLAB UV DEMO

The JLab UV Demo uses the same injector and SRF LINAC as the IR Upgrade [1]. It has been designed to operate in the wavelength range from 250 nm through 1 um with a pulse energy of 25 uJ. The FEL is operated at 60 pC bunch charge and 135 MeV beam energy. It has been designed assuming the following electron beam parameters transverse emittance of 5 mm-mrad, peak current of 200 Amp and relative energy spread of 4e-3. The expected average power is about 100 W when operating at 400 nm with water cooled mirrors and bunch repetition rate of 4.678 MHz. When cryogenically cooled mirrors are used the average power is expected to be of the order of 1 kW at a higher beam repetition rate.

TRANSVERSE BEAM PROFILE MEASUREMENTS

Operation of the JLab IR/UV Upgrade relies heavily on transverse beam profile measurements. There are 33 viewers in the UV FEL beam line. Four different types of viewers are used. In the injector for 9 MeV beam YAG:Ce viewers are used. The viewers are 100 um thin optically YAG:Ce crystal oriented normal to the beam.

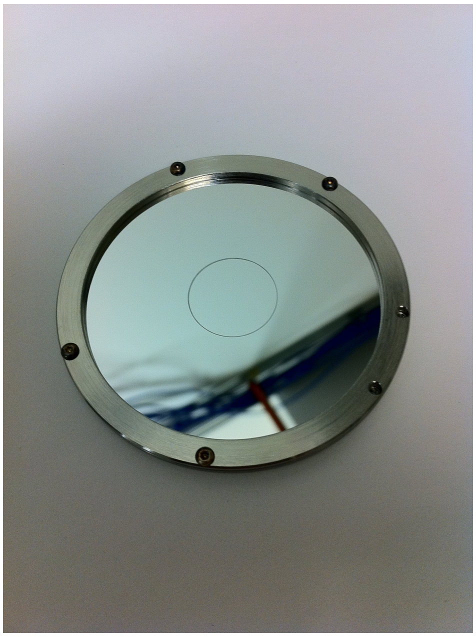

Figure 1: OTR viewer – aluminized Si wafer.

Behind the crystal there is a metal mirror set at 45 deg to the beam for imaging of the crystal. The viewers are essential for the injector setup and for quick recovery of the relative phases of the RF elements in the injector. One of the viewers is used for transverse emittance and Twiss parameters measurements with the help of two multislit masks. The resolution of the viewers is ~ 15 um.

At the full beam energy of 135 MeV, mostly optical transition radiation (OTR) viewers are used. The OTR radiators are made of optically polished aluminized Si wafers. The aluminum coating is 250 nm thin and increases the yield of the TR by a factor of two. Most of the wafers are 250 um thin. We have also found that 60 um wafers with diameter of 50 mm can be easily used. The spatial resolution of the OTR measurements is diffraction limited. The resolution for our standard setup is 15 um. The transverse beam size varies between 200 um and 1 mm RMS.

Three OTR viewers are installed in the wiggler. These viewers are used for electron beam measurements and the FEL optical cavity alignment. As such, they are used to ensure the transverse overlap of the electron beam and the optical mode. The viewers are made of beryllium, which is chosen for its very low Z - to reduce the radiation dose to the wiggler, its relatively high melting temperature, and its ability to be polished to an optical quality surface. The beryllium viewers have a 0.5 mm diameter hole in the middle to further reduce the dose and to serve as an

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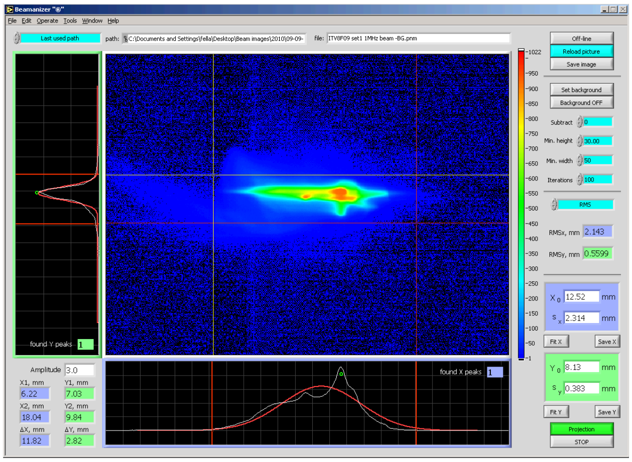
pavel.evtushenko@jlab.org

aperture for two HeNe alignment lasers. The angle of the optical cavity mirrors must be aligned better than 10 urad to ensure FEL startup. The difference in position of the optical mode and the electron beam needs to be maintained smaller than 150 um to prevent significant FEL gain reduction, while the relative angle between the optical mode and the beam must be less than 0.3 mrad when operating at 372 nm.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Subtract 0
Min. height 30.00
Min. width 50
Iterations 100
RMS
RMSx, mm 2.143
RMSy, mm 0.5599
X_0 12.52 mm
s_x 2.314 mm
Y_0 8.13 mm
s_y 0.383 mm
found Y peaks 1
found X peaks 1
Amplitude 3.0
X1, mm 6.22
Y1, mm 7.03
X2, mm 18.04
Y2, mm 9.84
ΔX, mm 11.82
ΔY, mm 2.82

Figure 2: Typical non Gaussian beam profile measured at JLab FEL.

The length of the optical cavity is about 32 m. To make the initial alignment of the optics easier, there are two additional viewers on the axis on the optical resonator. The viewers are placed approximately in the middle between the wiggler and either mirror, and have 5 mm diameter hole in center. These viewers are also used for electron beam measurements. During normal operation, the beam would pass through the hole and only outer low intensity parts of the beam interact with the viewer. To know both the beam position and approximate size, phosphor-coated viewers in place of OTR are used, due to their much higher light yield. The P46 phosphor was used to manufacture the viewers on 250 um thin aluminum substrate. In practice, these phosphor viewers can be used for complete transverse beam profile measurements by simply steering the beam completely off the hole.

The transverse beam size is also measured using visible synchrotron radiation (SR). Two essential and routinely used observation locations are in the middle of the 180 deg dipoles in the first and second recirculation arcs. Here, the horizontal beta function is very small, and therefore the transverse emittance contribution to the horizontal beam size is negligible compared to the size due to the horizontal dispersion and energy spread. These locations thus provide energy spread measurements downstream of the LINAC - before the FEL interaction and after the FEL interaction. The typical RMS energy spread measured upstream of the FEL is 0.35 %. This is one of the measurements made to ensure proper injector setup and phasing of the LINAC. Together with bunch length measurements it is used to estimate the longitudinal emittance. Assuming that the second order time-energy correlation is removed, as described below, and that the longitudinal phase space is upright where the bunch length is measured, we estimate the longitudinal emittance to be 47 keV-ps. The energy spread measurement is also needed for comparison between measured FEL performance and design codes. Energy spread measurements downstream of the FEL provide a good measure of the FEL efficiency and are used routinely for FEL optimization.

Analog video cameras with fixed gain and a signal-to-noise ratio of 57 dB are used. The analog video signal is digitized by 10-bit frame grabber. Several beam size measures such as RMS, FWHM, peak-to-peak and Gaussian fit sigma are available online and are shared with the main EPICS based control system. The dynamic range of the beam transverse profile measurements is about 500.

BPM SYSTEM

The BPM system consists mainly of stripline BPMs, which are chosen for a compromise between the signal strength and the relatively small impedance perturbation they present to the beam line. Due to the space constraints and mechanical considerations, the two BPMs that are incorporated in the FEL wiggler chamber are button BPMs. These BPMs are placed right next to each end of the wiggler on both sides. The BPM system is equipped with electronics based on logarithmic amplifiers. The analog frontend is described elsewhere [2] and has a dynamic range of 55 dB. The electronics are located in the accelerator tunnel with the 1 m long RF cables between the BPMs and the frontend. The baseband output of the frontend is delivered to the outside of the tunnel, where it is digitized by a 14-bit ADC at a sampling rate of up to 2.5 MS/s. Thus, the BPM system allows observation of beam motion up to the frequency of 1.25 MHz. The resolution of the BPM measurements is ~ 10 um.

BUNCH LENGTH COMPRESSION AND MEASUREMENTS

The beam is generated in the DC photo gun by a laser pulse with an approximately Gaussian distribution and RMS duration of about 13.5 ps. The laser pulse length is measured with streak camera. Before accelerating in the booster to the injection energy of 9 MeV, the bunch is compressed to 5 ps RMS by a 1497 MHz buncher cavity. It is further compressed to 2.5 psec RMS during acceleration in the booster. The bunch length stays largely unchanged through both the merger section and the LINAC. The beam is accelerated in the LINAC 10 deg off-crest, imposing both linear and second-order time-energy correlations on the longitudinal phase space. Downstream of the LINAC, the beam is compressed magnetically by the combined R_{56} of the first Bates bend and the transport beam line between the bend and the FEL wiggler. The second-order time-energy correlation is minimized during the compression via the T_{566} by the sextupoles installed at dispersive locations in the Bates bend and in the bypass transport line. The correction of the second order time-energy correlation is an indispensable part of the compression process and allows bunch compression to ~ 100 fs RMS. The overall compression ratio of the bunch from the photocathode to the FEL wiggler is ~ 135.

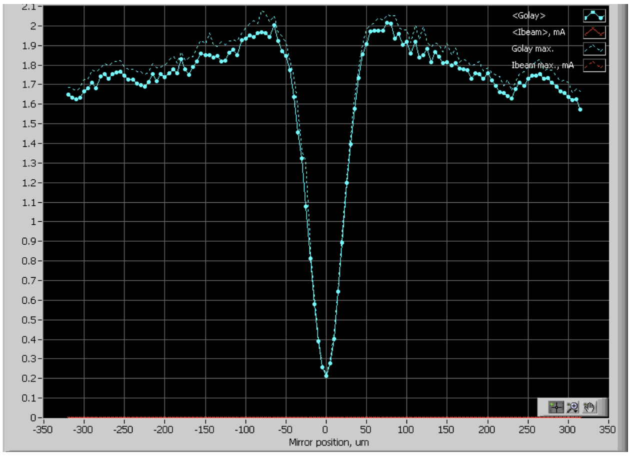

Figure 3: Autocorrelation function of CTR pulses measured with modified Martin-Puplett interferometer

The bunch length is measured at the wiggler with a modified Martin-Puplett interferometer (MPI). The MPI measures the autocorrelation function of the coherent transition radiation (CTR) pulses. Due to the prompt response of the transition radiation (TR), the longitudinal profile of the TR pulse is the same as a longitudinal distribution of the charge in the bunch. The data evaluation extracting the RMS bunch length is performed in the frequency domain. According to the Wiener-Khintchine theorem, the Fourier transform of the autocorrelation function is the power spectrum. We assume a Gaussian distribution of the charge and therefore a Gaussian power spectrum. The low frequency cut-off in the experimental setup due to the finite size of the TR radiator and due to diffraction losses is approximated with a simple analytical function. The product of the Gaussian power spectrum and the filter function is an analytical function where the RMS bunch length is a parameter. A nonlinear least squares fit is used to fit the analytical model to the experimentally measured spectrum. The measurements are made with low duty cycle tune-up beam, since the TR viewer needs to be inserted into the beam. The CTR spectrum measurements are thus an average over the number of bunches in a diagnostic macro-pulse. Here an assumption is made that there is no significant variation in the bunch length over the measurement time.

LONGITUDINAL TRANSFER FUNCTION MEASUREMENTS

A set of sextupole magnets installed at dispersive locations introduces a controllable second second-order dependence of the path length on energy. This is used to compensate for the second order correlation imposed on the longitudinal phase space by the LINAC. Thus, the T_{566}^{comp} transport matrix element of the compressor is adjusted. In a similar way, trim quadrupoles installed at the dispersive locations in the first arc are used to adjust the linear correlation between the energy and the path length i.e. the transport line R_{56}^{comp}. Direct measurements of the R_{55}^{total} and T_{555}^{total} matrix elements from the entrance to the LINAC to the FEL wiggler are made to ensure the correct settings of these sextupoles and the trim quads. For these measurements the phase of all injector elements is shifted simultaneously by the same amount thereby effectively changing the phase of the beam centroid at the entrance to the LINAC. In the vicinity of the wiggler, a 1497 MHz pillbox cavity is used to measure beam arrival phase. The measurements are made with the help of a heterodyne receiver in which the signal of the cavity is mixed down to baseband with the 1497 MHz master oscillator. The RMS resolution of the receiver is 130 fs. Note that for the operation of this system, the large energy and phase acceptance of the accelerator respectively of 15 % and 30 deg is essential.

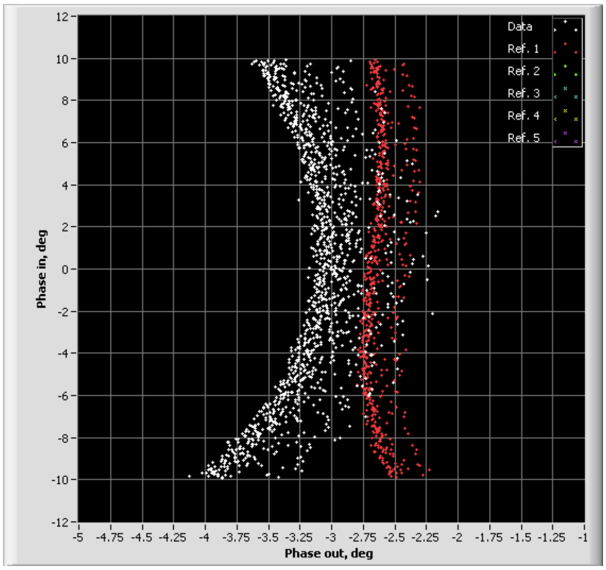

Figure 4: Longitudinal transfer function measurements with optimally adjusted (red) and not adjusted (white) sextupoles.

REFERENCES

[1] S. Benson et. al., “High power operation of the JLab IR FEL driver accelerator”, PAC07 Albuquerque, NM, USA, p. 79 (2007).
[2] D. Sexton et. al, BIW06 proceedings, Batavia, IL, USA, (2006) .