

BUNCH COMPRESSION, RF CURVATURE CORRECTION AND R_{55} , T_{555} AND U_{5555} MEASUREMENTS AT JLAB FEL*

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Abstract

The JLab IR/UV FEL Upgrade operates with the bunch length compressed down to 100-150 fs RMS. An indispensable part of the bunch compression scheme is the correction of the so-called LINAC RF curvature. Unlike other systems – where the RF curvature gets corrected using higher a harmonic LINAC – our system utilizes magnetic elements of the beam transport system to correct and adjust the second and third order correlation terms. These are expressed in terms of the transport matrix elements T_{566} and U_{5666} . The linear correlation term described by R_{56} is adjusted using the magnetic system as well. The large energy spread induced on the beam by the FEL operation is compressed as a part of the energy recovery process. As in the case of bunch length compression, this energy compression is optimized by properly adjusting high order transport matrix elements. In this contribution we describe the system used for direct measurements of the transport matrix elements R_{55} , T_{555} and U_{5555} and its impact on the operation and bunch compression. Results of the measurements are presented together with the bunch length measurements including the data showing resolution and accuracy of the system.

JLAB IR/UV UPGRADE

The JLab IR/UV Upgrade is an energy recovery LINAC that is used to drive two FELs oscillators. The IR FEL operates in the wavelength range from 1 μm through 10 μm with the energy per pulse of 120 μJ [1]. The UV FEL has been designed to operate in the wavelength range from 250 nm through 1 μm with pulse energy of 25 μJ . The same injector and SRF LINAC are used to operate both FELs. The IR and UV FELs are operated at 135 pC and 60 pC bunch charge respectively and 135 MeV beam energy. High peak current is critical for high performance operation of both FELs. This makes the optimal longitudinal match, i.e., bunch compression extremely important.

LONGITUDINAL COMPRESSION

The following is another reason to make sure that, as much of the charge in the bunch is a part of a distribution with well-defined time-energy correlation, that is there is no significant charge in tails that have the correlation different from the core of the beam. The IR/UV Upgrade is a high current CW system that has demonstrated operation with average current of up to 9 mA. Operation

of such system requires careful management of the beam phase space everywhere in the machine since even relatively small fraction of the beam when lost on a CW basis could damage the machine. The FEL interaction increases the beam energy spread significantly and changes the longitudinal phase space distribution in this way. After the beam is been used it is decelerated in the LINAC down to the energy close the one of the injection. During the energy recovery process the large energy spread beam gets stretched longitudinally before reentering the LINAC and then gets energy compressed during the deceleration. Such the longitudinal phase space is manipulated very actively before as well as after the FEL interaction. The manipulation relies on certain correlations in energy-time phase space. Thus, if the low intensity tails have correlation different from the core of the beam they will not be manipulated properly in terms of longitudinal match as the core of the beam.

The evolution of the bunch length and the longitudinal phase space in the JLab FEL is following. The beam is generated from GaAs photocathode by the drive laser pulse that has approximately Gaussian distribution. The RMS length of the drive laser pulse is 13.5 ps, which was measured with the help of streak camera. Before entering the injector booster accelerator unit the bunch gets compressed by normal conducting buncher cavity down to about 5 ps RMS. When accelerated in the booster that consists from two 5-cell SRF cavities, the beam gets compressed down to about 2.5 ps RMS. The compression happens in the first SRF cavity where beam becomes relativistic. The second cavity of the booster has no effect on the bunch length due to the beam been relativistic. However, it is used to minimize the correlated energy spread. At this stage we are trying to keep the beam as long as reasonable to minimize the longitudinal space charge effects in the LINAC [2]. Here it is also important to keep the uncorrelated energy spread small, since ultimately it can determine the minimal achievable bunch length. This is easy to see if one remembers that the longitudinal compression is a rotation of the longitudinal phase space by 90 degree. Next the beam gets accelerated 10 degree off-crest in the SRF LINAC to the full energy. Thus non-linear time-energy correlation is imprinted on the longitudinal phase space. Downstream of the LINAC the bunch is compressed magnetically. In the case of the IR FEL the compression is made with the combined R_{56} of the first 180 degree arc and the chicane. In the UV FEL beam line the compression is accomplished with the R_{56} of the arc only, such that compression is finalized at its last dipole. The bunch length measured at full compression is ~ 100 fs RMS for the UV FEL beam line and ~ 130 fs RMS for the IR FEL. To achieve this the

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second order time-energy correlation is compensated for by introducing second order dependence of the path length on the energy, i.e., by introducing non zero second order transport matrix element T_{566} . This is accomplished by a set of sextupole magnets installed in the dispersive locations in the first 180 degree arc. A set of quadrupoles installed in the dispersive locations in the arc is used to adjust the R_{56} . Optimization of the sextupole and the quadrupoles settings can be made by systematically measuring the bunch length as a function the magnets settings. However, the second order LINAC RF curvature is compensated when the second order matrix elements T_{555} describing the transport from the LINAC entrance to the wiggler is set to be zero. In analogy the linear part of the compression is optimized when the R_{55} of the same part of the accelerator is made zero. Such, another diagnostic tool used to validate that the optimal settings of the sextupoles and the quadrupoles is the direct measurements of these matrix elements.

BUNCH LENGTH MEASUREMENTS AT FULL COMPRESSION

The bunch length is measured at full compression at the wiggler or either FEL 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. The modification of the MPI uses only one broad band IR detector, which is somewhat disadvantageous since no normalization to the source intensity variations can be made based on the interferometer measurements only. We employ Golay cell detector for the bunch length measurements. Besides measurements of the bunch length via the autocorrelation function of the CTR, measurements of the Golay cell amplitude itself is extremely useful for the bunch length minimization, since the amplitude of the Golay cell

detector is, roughly, inversely proportional to the bunch length. When the amount of the charge used for the measurements is kept the same the amplitude of the Golay cell can be calibrated using the autocorrelation measurements, such that it provides quantitative information of the bunch length. However, such calibration would be meaningful only when the longitudinal profile and the longitudinal bunch form factor do not change significantly. Practically during optimization of the longitudinal match we have been measured the RMS bunch length in the range from 100 fs through 500 fs. The TR radiator used for the bunch length measurements is a 60 μm thin Si wafer aluminized with the thickness of the Al layer of about 20 nm. A single crystal z-cut quartz window is used as a vacuum to air interface to maximize the transmission in the FIR region. A care must be taken to keep the Golay cell detector working in a linear regime. The measurements of the Golay cell amplitude as a function of the tune up beam macro pulse length are made to determine the linear range of the Golay cell. For the bunch length measurements setup at the UV FEL we found that to keep the Golay cell in the linear range we could use no more than 12 bunches of 60 pC. This required the operation with relatively short macro pulses, much shorter than what is used at the IR FEL. Overall the integral intensity of the CTR signal in the UV FEL beam line was measured to be 50 times higher than in the IR bema line. We attribute this partially to the shorter bunch length and partially to a better alignment of the system.

LONGITUDINAL TRANSFER FUNCTION MEASUREMENTS

Direct measurements of the R_{55} and T_{555} 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, which includes photo cathode drive laser, buncher cavity and two SRF cavities of the booster, is shifted simultaneously by the same amount thereby effectively changing the phase of the beam centroid at the entrance to the LINAC. The phase of the injector elements is modulated by modulating the phase of the common MO reference signal. The modulation is made at the frequencies low enough that the low level RF control modules of all RF injector elements can track the phase shift. Practically the modulation frequency of a few Hz is used. For the measurements beam of 250 μs long macro pulses at the repetition rate of 60 Hz is used. The modulation frequency is chosen to be not a sub-harmonic of the 60 Hz. Such, the 60 Hz beam samples in a random way the waveform of the phase modulation. To distribute the measurements points uniformly along the launch phase axis the triangular waveform of the modulation is used. The launch phase of the beam at the LINAC entrance is obtained from the measurements of the modulation drive signal made simultaneously with the beam phase arrival measurements

at the wiggler, and prior calibration made by DC shifting the phase of the beam via the longitudinal transfer

longitudinal transfer function measurements. Figure 1 shows three measurements with different settings of the

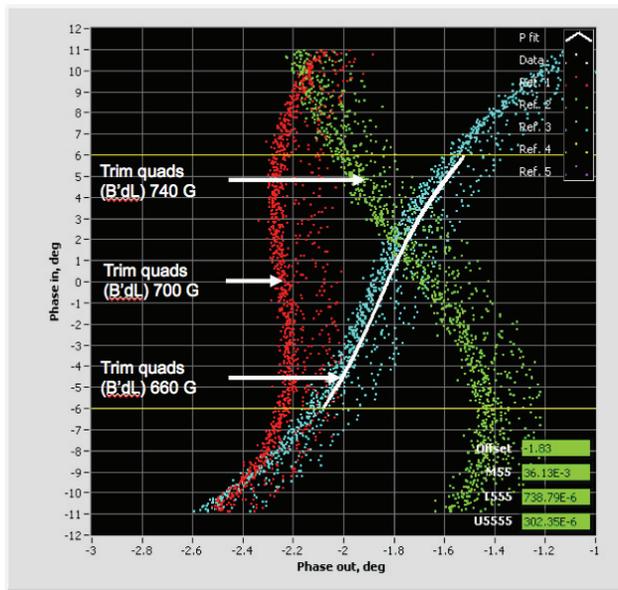


Figure 1: Variation of the R_{55} with the trim quadrupoles.

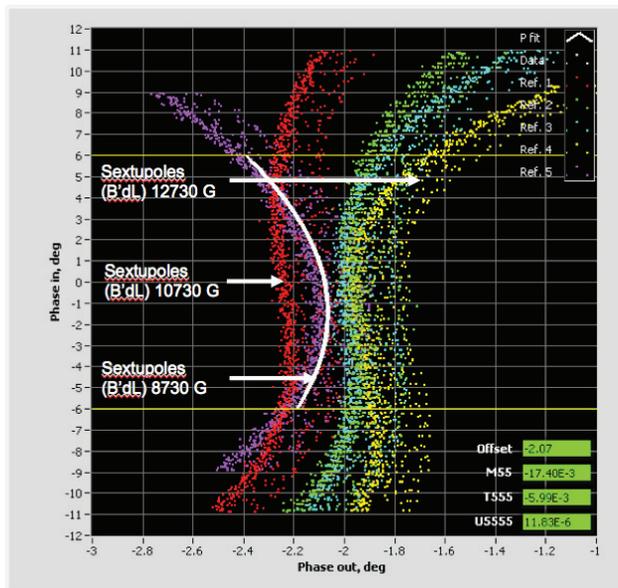


Figure 2: Variation of the T_{555} with the first arc sextupoles.

function system that is compared with DC phase shift of the LINAC via LLRF system.

In the vicinity of either FEL 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 degree is essential. Figure 1 and 2 shows examples of the

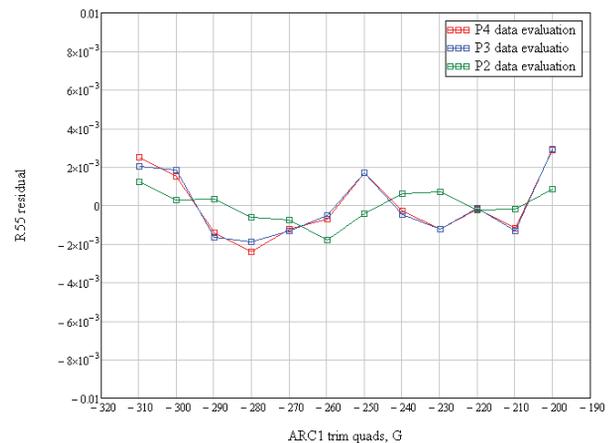


Figure 3: Residual between R_{55} measurements and linear model.

trim quads that mainly adjust the R_{56} of the first 180 degree arc and therefore the R_{55} of the whole system. The changes in the quadrupoles used in this example are about 6 % from the nominal one. Fig. 2 shows the changes in the longitudinal transfer function due to the changes in the sextupoles in the arc that mainly adjust the T_{566} of the arc and the T_{555} of the entire system. Polynomial of the third order is fitted to the measurements data to extract the R_{55} , T_{555} as well as U_{5555} . The examples of such data evaluation are shown in the Fig. 1 and Fig. 2 as well. We have attempted to make beam based measurements of the absolute accuracy of the matrix elements measurements. For instance the T_{55} was measured as a function of the trim quads settings changing the quads settings in the range of $\pm 25\%$ around its nominal settings as shown in Fig. 3. The dependence should be linear according to the beam transport model. Fitting the linear model to the set of T_{55} measurements and calculating the residual between the data and the model we can make an estimate of the absolute accuracy. The RMS deviation between the two can be considered as the absolute RMS error. Such procedure result in the absolute error of $\sim 1.6 \times 10^{-3}$ for the matrix elements measurements. Combined with the slope of the R_{55} dependency on the quads settings this error corresponds to the error in the magnets settings of about 1.2 G, which is $\sim 0.5\%$ of the magnets field integral. The reproducibility and accuracy of the magnets settings is few 10^{-3} as well. Therefore the estimate of the matrix elements measurements accuracy should be considered as an upper limit of the accuracy only.

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