# HIGH DYNAMIC RANGE BEAM IMAGING WITH TWO SIMULTANEOUSLY SAMPLING CCDS

P. Evtushenko#, D. Douglas, JLab, Newport News, USA


*Abstract*

Transverse beam profile measurement with sufficiently high dynamic range (HDR) is a key diagnostic to measure the beam halo, understand its sources and evolution. In this contribution we describe our initial experience with the HDR imaging of the electron beam at the JLab FEL. Contrary to HDR measurements made with wire scanners in counting mode, which provide only two or three 1D projections of transverse beam distribution, imaging allows to measure the distribution itself. That is especially important for non-equilibrium beams in the LINACs. The measurements were made by means of simultaneous imaging with two CCD sensors with different exposure time. Two images are combined then numerically in to one HDR image. The system works as an online tool providing HDR images at 4 Hz. An optically polished YAG:Ce crystal with thickness of 100 μm was used for the measurements. When tested with a laser beam, images with a dynamic range (DR) of about $10^5$ were obtained. With the electron beam the DR was somewhat smaller due to the limitations in the time structure of the tune-up beam macro pulse.


## MOTIVATION

High current CW SRF LINACs with average current of several mA have been used to provide electron beam for high average brightness, high power IR FELs [1]. It is proposed that LINACs with similar average current and beam energy in the range 0.6 – 1.2 GeV can be used as the drivers for next generation of high average brightness light sources operated in X-ray wavelength range in seeded FEL configuration [2-5]. The existing pulsed FELs, operating now in the soft and hard X-ray wavelength ranges, utilize average currents many orders of magnitude less than the above-mentioned mA. At the same time, operation of the IR/UV-Upgrade at Jefferson Lab with average current of up to 9 mA has provided an experience base with high-current LINAC operation [1]. The primary operational difference between such high current LINACs and storage rings, even with a few hundred mA of average current, is that LINAC beams have neither the time nor the mechanism to come to equilibrium, in contrast to storage ring beams, which are essentially Gaussian. This has significant operational impact. When a LINAC is setup, by establishing the longitudinal and transverse match, a tune-up beam with small average current is used. Such an accelerator setup is based most frequently on measured mean and RMS parameters such as beam size, bunch length, and energy spread. When going from tune-up mode to higher duty cycle and CW operation, it is frequently found that the "best" RMS-data-based setup must be changed to allow for high current operation to eliminate beam losses. Even when this modification is successful, it is time-consuming process involving some trial and error. It is frequently unclear what the sources of the problem are, and which adjustments to the low-density parts of the phase space distribution were effective in improving performance. This is highly undesirable for any user facility where high availability is required. Also of significance is that the resulting setup does not necessarily provide the best beam brightness and is a compromise between acceptable brightness and acceptably low beam losses.

Contributing to this problem is the fact that the measurements used for machine setup are typically based on methods with a DR of $10^3$ or even less. It is not surprising that the relevant (from the high current operation and beam loss point of view) low-intensity and large-amplitude parts of the phase space are simply not visible during machine tuning.

Therefore, we think that the proper solution to the aforementioned tune-up problem is to base the tuning on the measurements with much larger, than routinely used now, DR, such that the very low intensity and large amplitude parts of phase space distribution are taken in to account from the very beginning. We are presently developing such diagnostics at the JLab FEL. The ultimate goal is to be able to measure both the transverse and longitudinal phase space with a DR of about $10^6$. Measurements of both phase spaces can be based on the HDR transverse beam profile measurements, which is the first step in our program. One of the techniques we are developing is the HDR beam imaging. Here we present our technique and first results of transverse beam profile measurements with extended DR and its application to emittance and Twiss parameters measurements.

## EXPERIMENTAL SETUP

Operation of the JLab FEL relies very heavily on the transverse beam profile measurements made in many places around the machine. Even with a relatively compact footprint the IR and UV recirculators beamlines have 62 viewers and synchrotron light monitors in total. This has allowed us to accumulate a lot of experimental experience with transverse beam profile measurements. From this experience we know the intensity of the beam image on the CCD matrix from OTR or YAG:Ce viewer with the typical beam size and with the amount of beam charge in the tune-up macro pulse. It also agrees well with calculations. Thus one can tell that, for the measurements with the OTR and DR of $10^6$ an additional gain in the range between 10 and 100 would be needed, and the measurements with YAG:Ce may not need additional

*Work supported by US DOE office of Basic Energy Sciences under the early career program; DOE award number FWP#JLAB-BES11-05
# Pavel.Evtushenko@jlab.org

ISBN 978-3-95450-119-9

gain. One of our goals is to develop a diagnostic that would be affordable, hence could be used in many locations at an accelerator, and would not be expensive to repair. For this reason we decided to use non-scientific CCD cameras that are produced in large volumes. Among such cameras we select ones with best signal to noise ratio (SNR), which is typically 57 dB. To make the measurements with the DR of about 120 dB (~$10^6$), at least two sensors are required. The original idea was to have two cameras and an optical setup with the beam splitter where the cameras would be aligned with an accuracy better than one pixel and would have the same magnification. The optical path of one of the sensors would have an image intensifier to provide the additional gain. The two cameras would be operated with different gain or/and different exposure time. One of the sensors with smaller gain would measure the brightest fraction of the distribution, while the camera with higher gain or/and exposure time would beam measuring less intense fraction of the distribution. Some fraction of the second CCD sensor will be saturated. One concern here is that the saturation might lead to the charge bleeding to the neighboring pixels and therefore affect linearity. We check for this in the algorithm that combines images from two sensors in to one HDR image. In practice, we did not find any evidence that this an effect that, we had to correct for. As we were preparing for the experiment a camera with beam splitter and two CCD sensors had become commercially available [6]. We decided to use the camera for the first measurements. On one hand this simplifies the optical setup, since the alignment of the CCD sensors relative to each other is made, on the other hand it has the disadvantage that one does not have the additional gain from image intensifiers. However, since it was planned to use a YAG:Ce viewer, it was not expected that the absence of the additional gain would be a problem.

The camera has independent electronic gain control for both sensors. However, its use does not improve the sensitivity of a CCD sensor, i.e., it does not make low intensity light undetectable with zero gain detectable with higher gain. A note should be made that, usually, higher electronic gain in the camera worsens the SNR. This is very undesirable especially for the HDR measurements. The electronic gain of the camera is used to cross calibrate the two sensors - to balance them. For this purpose the integration time of the sensors is set equal and the gain of one of the sensors is adjusted to minimize the difference of intensities of the two sensors. The gain can be negative as well as positive. We choose to adjust the gain of the sensors that needs to be adjusted negative to prevent SNR degradation.

For the measurements, results of which are presented here, we used 100 μm thin YAG:Ce crystal scintillator optically polished on both sides. The crystal was inserted in to the electron beam at normal incidence. Behind the YAG:Ce crystal a stainless mirror was mounted at 45 degrees relative to the beam direction. Such, the scintillation photons were directed out of the beamline

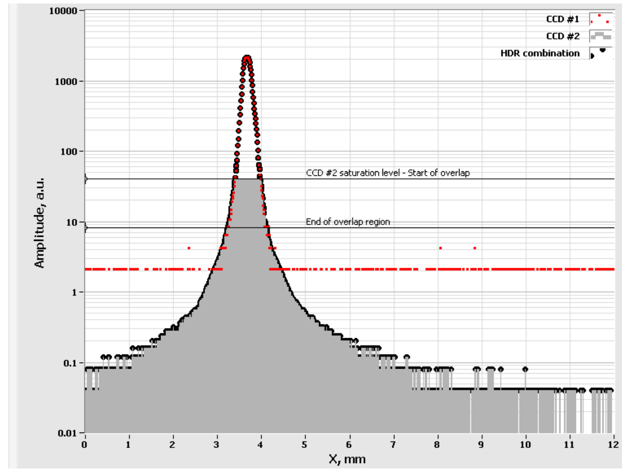


Figure 1: HDR algorithm example.

through a viewport at 90 degrees. Orienting the scintillator normal to the beam direction (not 45 degree as sometimes done) serves two purposes. First, it places all the crystal in to the focal plane of the lens preventing any problems due to the finite depth of field of the imaging optics. Second, it mitigates the effect of the finite crystal thickness on the transverse resolution. Since a scintillator is transparent at the wavelength it emits, an infinitely small beam passing though a 100 μm thin scintillator set at 45 degrees to its direction, will appear to the observer as infinitely thin in one direction and as a $100\sqrt{2}$ μm long line in the orthogonal direction. That was an important aspect for the viewer we used, as it was built for measurements of beams with the transverse size down to, at least, 50 μm or smaller.

A 300 mm telephoto lens was used to image the crystal on to the CCD matrix. The magnification is such that one pixel of the matrix corresponds to about 11.7 μm on the viewer. The vertical field of view is about 8 mm and the aspect ration of the field of view is 4:3.

Tune-up beam mode is used at the JLab FEL for measurements with intercepting beam diagnostics. The time structure of the beam is the following. The photo cathode drive laser maximum repetition rate of 74.85 MHz is reduced by the factor of $2^n$ with the help of fast electro-optical cell. For the tune-up beam n is 4 or higher. From the "infinite" pulse train of ~ 4.67 MHz 250 μs long macro pulses are allowed through a Pockels cell. The macro pulses follow at 2 Hz repetition rate. To improve average extinction ratio two mechanical shutters are used to open a time window slightly longer than 250 μs. The repetition rate of the micro pulses can be reduced further from 4.67 MHz to ½, ¼ or ⅛ of this and the macro pulse can be made correspondingly longer. When an image intensifier is not used, the increase in the DR comes mainly from the integration time difference of two sensors. The largest increase is possible with the largest ratio of the integration times. This is limited by the minimum integration time of the camera (~20 μs) and by longest allowable macro pulse length. At the time of the measurements the macro pulse length was always limited to 400 μs. This limited the DR increase to about 20. To



ISBN 978-3-95450-119-9

further improve the DR we average the data over 16 images. It takes 8 seconds to get a new image, which seems to be acceptable for the improved DR.

## COMBINING HDR ALGORITHM

An imperative element in such measurements is the algorithm used to combine two images in to one with larger DR. The algorithm that we use is illustrated in the Fig. 1 and works in the following way. It operates on the rows of an image and therefore is essentially 1D. As the first step, the intensity of each image is normalized to the integration time, such that the images can be compared. Then the algorithm looks for the regions of saturation in the data of the sensor with longer integration time. If no saturation is found, only the normalized data from the longer integrating sensor are used. When saturation regions are present the corresponding row of the combined HDR image contains three kinds of regions. First is the region where longer integrating sensor is saturated, for this part only the data from the shorter integrating sensor are used. Second, the most important kind, are regions where the data from both detectors overlap. It is a requirement to setup the combination of the integration times so that there are such regions and the data overlap over substantial span of the amplitude. In our case we have overlapped the data by 0.5 – 1 orders of magnitude. The importance of this data is that it checks the cross calibration of the two sensors and ensures continuity and linearity of the HDR image intensity. For this region of the HDR image we use average of the data from two sensors. The third kind of data are from the longer integrating sensor that are less intense than the ones in the overlapping region. Here the data from the shorter integrating sensor have SNR of about 1 and are not used.

## BEAM SIZE AND LEVEL OF INTEREST

As mentioned earlier the LINAC beams in general do not have Gaussian distribution. It is observed with the JLab FEL beam regularly, and complicates the task of transverse beam size measurements. Even more, it suggests that the question of "what is the proper and relevant measure of the size?" might need to be revised. Here we use RMS width of the beam distribution projections to the X and Y axis. To calculate the RMS width one needs to decide on the fraction of the image to be used for the projection, usually referred to as region of interest (ROI) and on the fraction of the 1D projection used for the RMS width calculations, i.e., 1D-ROI. This is where the availability of HDR data makes a significant difference, as shown below. We use another numerical algorithm to remove the ambiguity from setting both the 2D and 1D-ROI. In the first step, the entire image is projected to either axis and the two projections are sent through a low pass filter to remove high frequency noise. Then the maximum of a projection is found. It is assumed, that the beam distribution is far enough from the edges of the field of view, so that the edges can be used to

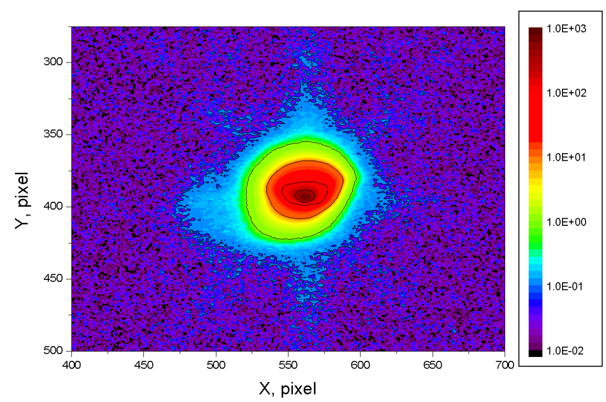


Figure 2: HDR beam profile.

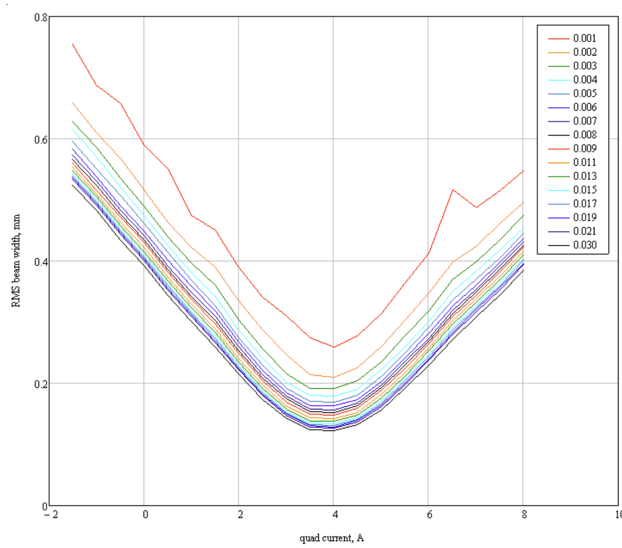


Figure 3: RMS beam size vs. quad current and LOI.

determine level of the background. That is made on both sides of the projection maximum. The range between the maximum and the background level is defined as 1. Then the main adjustable parameter of the algorithm is introduced; let's call it the level of interest (LOI), which can assume values between 0 and 1. Typically, as we try to include as much of the beam as possible in the projection, the level will be set to a few times 0.01, where 0.01 means 1 % from the projection maximum. The LOI and the filtered and normalized projection are used to determine two transverse coordinates at which the projection intensity equals the LOI. A numerical interpolation is used for this step. Important here is that the DR of the data, or its overall SNR, limits how low the LOI can be requested. For instance, in our standard measurements with the DR of about 500, the smallest LOI that typically can be used is 0.01 or higher. This depends critically on the noise performance of the camera. With the DR extended as described above, we found that we can robustly set the LOI as low as $5\times10^{-4}$. Consequences of this for the beam measurements are presented in the next section. An example of the image built by the algorithm is shown in Fig. 2. Note the intensity scale in Fig.2 is logarithmic.

ISBN 978-3-95450-119-9

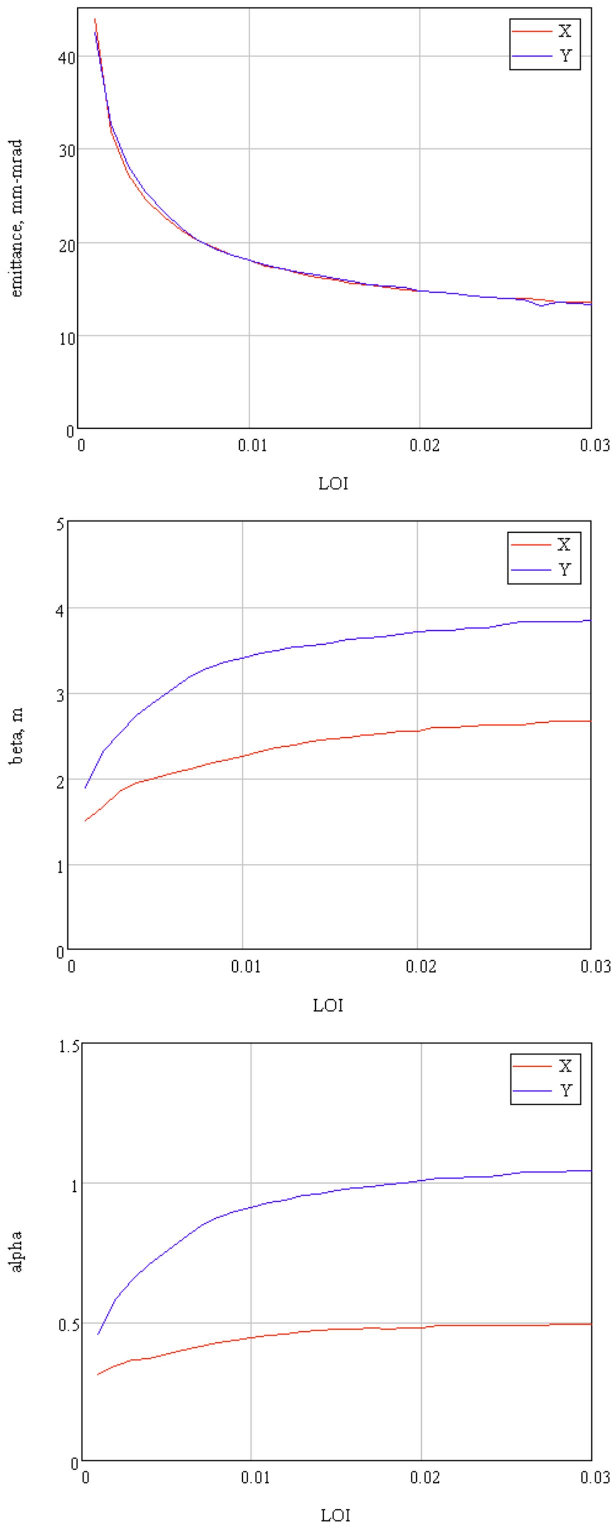


Figure 4: Emittance and Twiss parameters vs. LOI.

## EMITTANCE AND TWISS PARAMETERS

A single HDR measurement of the transverse beam profile can be revealing and interesting by itself, since at the corresponding level the beam halo can be seen directly. The next level of details and complexity would be the application of such measurements to the emittance and Twiss parameters measurements. To demonstrate how much the LOI affects the RMS beam size measurements and what impact this has on the emittance and Twiss parameters values, we consider a quadrupole scan that consists of 20 HDR images. Note that the HDR and LOI are directly related. The DR enables lower values of the LOI. Selecting different LOI we extract from every image not one value of the RMS beam size but an array, where beam size is a function of the LOI. In the example here we scan the LOI in the range from 0.001 through 0.03 in steps of 0.001. The results of such data evaluation are given in Fig. 3. Using the standard approach, assuming linear beam optics approximation, with the help of nonlinear least square fit, we obtain transverse emittance and Twiss parameters value. Results of such data evaluation are shown in Fig. 4.

## DISCUSSION AND OUTLOOK

As can be seen from Figs. 3 and 4, including the low intensity, large amplitude fraction of the beam in to the measurements of beam size, emittance and Twiss parameters makes a dramatic difference. This brings us back to the note made in the first section of this paper. As the emittance and Twiss parameters of the beam including halo are different from these on the beam without halo, it requires a somewhat different match, compared to the best peak brightness, to allow for high current operation. It is critical that the difference in the match is not too big. Then, when the match is adjusted for high current operation, the peak brightness and best match to the FEL undulator and the FEL performance are not altered significantly. On the other hand, it is possible that the application of the HDR measurements to establishing the match will help to fulfill these requirements.

We are planning to improve the DR further by adding image intensifiers to the setup and by allowing more flexibility in the tune-up beam time structure. We are currently building a set of diagnostics stations to be installed around the machine to enable such measurements in several places in the lattice.

## REFERENCES

[1] S. V. Benson et al., “Operational aspects of high power energy recovery LINACs”, Proceedings LINAC06, Knoxville, TN, USA, August 21-25, 2006

[2] D. Kraemer et al., “The BESSY Soft X-ray Free Electron Laser”, TDR, ISBN 3-9809534-0-8, BESSY, Berlin

[3] R. A. Bosch et al., “WiFEL: The Wisconsin Free Electron Laser”, Proceedings FEL2009, Liverpool, UK, August 23-28, 2009

[4] S. V. Benson et al., “A proposed VUV oscillator-based FEL upgrade at Jefferson Lab”, Journal of Modern Optics **58** 1438 (2011).

[5] J. N. Corlett et al., “Next generation light source R&D and design studies at LBNL”, Proceedings of IPAC12, New Orleans, LA, USA, May 20-25, 2012

[6] http://www.jai.com/en/products/ad-081ge



ISBN 978-3-95450-119-9