BEAM HALO MEASUREMENTS AT UMER AND THE JLAB FEL USING AN ADAPTIVE MASKING METHOD*

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Abstract

Beam halo is a challenging issue for intense beams since it can cause beam loss, emittance growth, nuclear activation and secondary electron emission. Because of the potentially low number of particles in the halo compared with beam core, traditional imaging methods may not have the sufficient contrast to detect faint halos. We have developed a high dynamic range, adaptive masking method to measure halo using a digital micro-mirror array device (DMD) and previously demonstrated its effectiveness experimentally on the University of Maryland Electron Ring (UMER). In this paper we present recent data from UMER as well as preliminary results from the Jefferson Lab Free Electron Laser (FEL).

INTRODUCTION

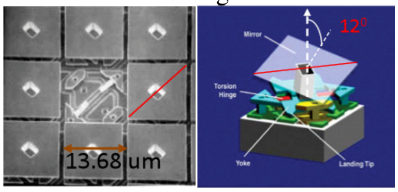
With the development of accelerators with intense beams such as the SNS, and FEL's [1], beam halo has become an important issue. In cases where beam halo occurs in high intensity beams, it can cause damage to the accelerator system. Beam halo can be caused by parametric resonances or nonlinear forces due to space charge [2], as well as field emission, light scattered on photo-cathodes, or by numerous other phenomena. The mechanisms responsible for halo are not yet well understood and experimental data is sparse.

The challenge in measuring halo is its low intensity compared to the beam core [3]; the ratio can be 10^{-5} or less. In order to have a meaningful measurement of the spatial distribution of halo particles, a method with high dynamic range is required.

Previously [4], a new method to image halos with an adaptive optical mask technique based on a digital micro-mirror array device (DMD) was proposed and initial tests of this device with a laser beam were presented. In [5] a complete optical system to realize this idea was developed and used to image the halo of a real electron beam at the UMER facility.

The DMD that was used is an array of 728 x 1024 individually addressable micro-mirrors. A segment of the array and a mechanical drawing of one element [6] are shown in Fig. 1(a) and 1(b). Each micro-mirror is 13.68 x 13.68 microns in size and can be rotated along the diagonal either $+12^0$ or -12^0. Light from an external source can be reflected from mirrors in one state, e.g. $+12^0$, along a desired optical path, while the light reflected by mirrors in the opposite (-12^0) state will be directed 48^0 away from this optical path. Thus, when incorporated into an imaging system, this device can be used as a 2D spatial filter.

We first optically transport an image of the beam, e.g. that produced on a phosphor screen, onto the DMD. Then after masking out the higher intensity beam core, the filtered image is reimaged onto a CCD camera and integrated over an increased number of frames to achieve an image of the halo with an enhanced dynamic range. This process is illustrated in Fig. 2.



(a) (b)

Figure 1: (a) Segment of the DMA; (b) mechanical drawing of individual micro-mirror and substructure [6].

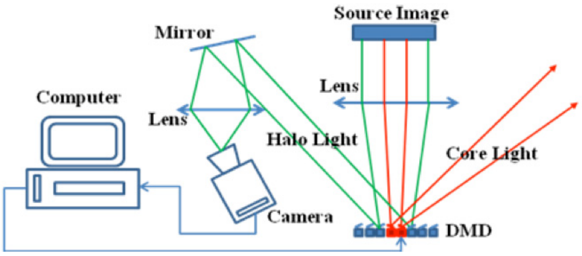


Figure 2: Process of halo measurement using the DMD.

The advantages of applying the technique we have developed are: 1) it uses a flexible imaging system, which can view any beam induced radiation, produced e.g. from an intercepting phosphor, YAG, or OTR screen, as well as a non interceptive source such as optical synchrotron, edge or undulator radiation; 2) the DMD can be combined with an inexpensive 8 bit (or higher) camera for time integrated beam studies; 3) if the beam core shape varies, the DMD mask can be generated quickly and adaptively to changing conditions.

Previous experiments [5], which were done in the injection part of University of Maryland Electron Ring (UMER) demonstrated a dynamic range of ~10^5, which match the results obtained with a laser and a standard 8 bit CCD camera [4], with no discernable effect on the image quality due to diffraction and scattering produced by the DMD. In this paper, we will discuss additional halo studies performed in the UMER ring itself, as well as preliminary halo measurements recently obtained at the

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Jefferson Lab FEL facility using optical synchrotron radiation.

EXPERIMENTS AT UMER

Experiment Setup

UMER [7] is low energy storage ring which was built to study space charge effects which can be scaled to higher energy machines. It transports a pulsed electron beam which can vary in length from 10 to 100 ns in duration. The beam energy is 10 keV, and the current can be varied from 0.6 mA to 80 mA. The imaging optics described in [5] was adapted to the UMER ring chamber 7 which also has a phosphor screen to image the beam.

The experimental setup is shown in Fig. 3. The image generated by the beam intercepting the phosphor screen is first focused onto the DMD. In order to obtain the best spatial filtering resolution, two lenses are used to control the magnification and focusing to allow the image of the of the phosphor screen to fully fill the DMD. Then, we adjust two additional lenses to reimage the image on the DMD onto a CCD camera to obtain the best spatial resolution of the final image of the beam or halo.

Each micro-mirror on the DMD reflects the incident light either $+24^0$ or -24^0, depending on its state. To acquire an image of the beam core, all the micro-mirrors are set to allow the entire beam image to go through the optical system as indicated by the red rays in Fig. 2. Then a mask based on intensity threshold is applied to the DMD, to filtered out the core, as indicated by green rays shown in Fig. 2. Thus only the halo image is transported through the second optical path.

The camera we used at UMER was an intensified, cooled, gated, 16-bit CCD camera made by Princeton Instruments Inc. (PIMAX2). As mentioned previously [5], the camera body (no lens attached) is tilted at 24^0 in order to compensate for the Scheimpflug effect [8].

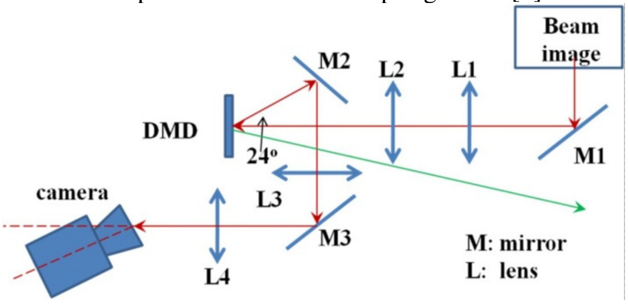

Figure 3: Optics system for halo measurement at UMER.

The data acquisition procedure was as follow: 1) take a beam picture without any mask; 2) define the core by setting an intensity threshold or predetermined shape; 3) generate a core mask and apply to the DMD; 4) take another beam picture with more integration frames.

Results from UMER

In order to investigate how the halo changes, corresponding to the variations of matching conditions of the injected beam into the ring lattice, we varied the current of a quadrupole magnet, which was located several lattice periods upstream of the injector, to induce and change the halo. We changed the current of the quadrupole from its default value to 49.7% of this number. In [9], we presented the results of experiments done with a 21 mA beam. We saw that the entire phosphor screen was illuminated by the large extent of halo, because the beam core was too large (almost 2/3 of the 32 mm diameter screen). We redid this experiment with a smaller size beam, whose current is 6 mA, in order to better view the halo and our results are presented here.

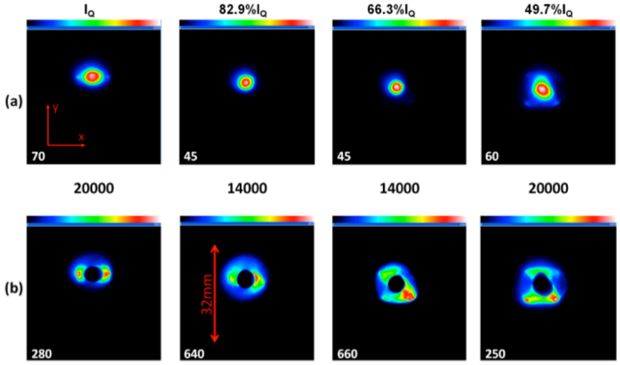

Figure 4: Beam (a) and halo (b) images with quadrupole current variation.

Unmasked beam images are shown in Fig. 4 (a) for various settings of the quadrupole focusing strength. The number in the lower left corner of each picture indicates the number of frames integrated by the camera before readout. After that, a threshold mask is generated based on the peak intensity level of the core (count number shown below Figs. 2 (a)) and applied to the DMD. The halo images are presented in Fig. 2 (b).

Comparing the pictures in Fig.4 (a), we see that the beam centroid gradually moves downward; this effect is most likely due to misalignment of the quadrupole with respect to the beam trajectory. By decreasing the quadrupole current, the beam shrinks in the horizontal (x) direction and expands in the vertical (y) direction. As shown in Fig. 4 (b), as the quadrupole current decreases, particles escape from the beam core and appear to rotate in the halo region. The typical halo size is 2-3 times greater than that of the beam core.

EXPERIMENT AT JLAB FEL

Experiment Setup

The energy of the electron beam at the JLAB FEL accelerator [10] is 135 MeV. Various experiments such as the recently proposed Dark Light Project [11] require high current (10 mA), high beam quality and minimal halo. Thus, it is important to measure the spatial distribution of the beam with a high dynamic range. To fulfil the experimental requirement to measure the high current beam non-interceptively, we have developed a optical system similar to that described above, to image the beam/halo in optical synchrotron radiation (OSR) which is generated as the beam passes through a bending magnet.

The differences in the optics used for JLAB are: 1) a 10 mm wide vertical slit is used to restrict the horizontal extent of the OSR; 2) to transport the OSR from downstairs accelerator vault to the shielded upstairs gallery, which houses the DMD and secondary optics, an extra lens with a long focal length (1.5 m) is used to form an intermediate image in the transport line; 3) a separate target set at the same distance as the source is used to measure the optical magnification (0.71); 4) a 16 bit, 1024x1024 pixel, cooled CCD camera (Apogee Instruments Alta E47) is used to do the imaging.

Preliminary Results from JLAB

In our initial runs we used an electron beam with 1 ms macro pulse width, 60 Hz repetition rate and 4.68 MHz micro-pulse (60 pC/micro-bunch) repetition rate. We generated several masks based on threshold level. For each mask, we selected the appropriate integration time to bring the peak intensity of the image close to the saturation level of the camera (65K). To obtain a background image for each mask setting, we covered the optical transport tube which separated the vault and the gallery, and integrated for the same time period used to obtain the corresponding masked beam image.

Background-subtracted images are shown in Fig. 5, where the number in the lower left indicates the integration time used to obtain the particular image and the number in the lower right gives the threshold level for the generated mask. Fig. 5 shows the irregular spatial distribution of the beam halo.

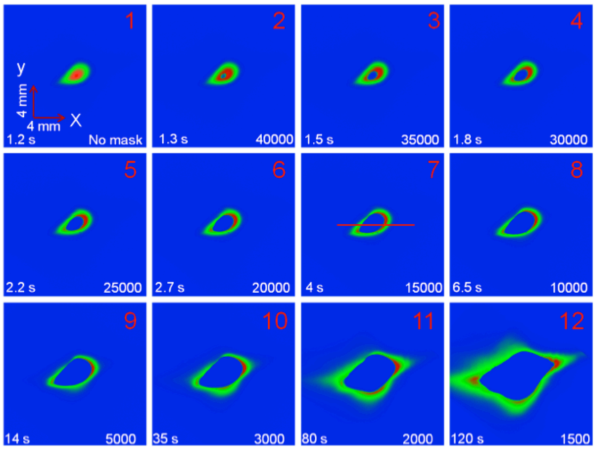

Figure 5: Unmasked and masked OSR images of the JLAB FEL beam.

When analyzing line scans across images 1, 3, 5, 7, 9, and 11 (note for reference the horizontal red line in Fig. 5), we normalized each one by the corresponding integration time used to obtain for each image. The normalized scans are shown in Fig. 6. As is observed in the tails of the line scans, the longer the integration time, the smaller the intensity fluctuations. The measured dynamic range of the system is great than 10^4. This value is expected to increase as we improve the optical system by reducing scattered light, filtering out diffraction effects and focusing the beam to a smaller spot size.

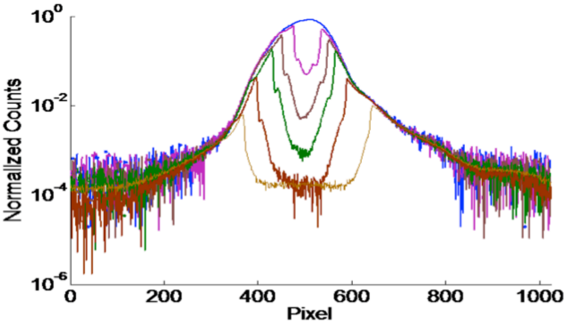

Figure 6: Normalized horizontal scans of beam profiles.

CONCLUSIONS

We present our latest experimental results of halo imaging studies at UMER using an adaptive masking method which incorporates a digital micro-mirror array. We demonstrate the generation and apparent rotation of halo in real space due to the mismatches produced by varying the focusing strength of a quadrupole magnet external to the ring. We also report preliminary halo images obtained with a similar optical setup using optical synchrotron radiation at the JLAB FEL and show that the dynamic range of the optical system exceeds 10^4. In the future, we will continue to study halo behaviour in UMER using this method. Future studies will include time-resolved beam halo profiling and multi-turn studies of the evolution of the halo. We will also image the halo from a CW (74.8 MHz) beam at the JLAB FEL using OSR and continue to improve dynamic range of the optical imaging system.

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