BEAM HALO MONITOR BASED ON AN HD DIGITAL MICRO MIRROR ARRAY*

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Abstract

A beam halo monitor is an essential device to pursue studies of halo particles produced in any particle accelerator as to investigate the effects of disturbances, such as field kicks, gradient errors, *etc*. A fast, least intrusive, high dynamic range monitor will allow the detection and potentially control of particles at the tail of a transverse beam distribution. Light generated by a beam of charged particles is routinely used for beam diagnostic purposes. A halo monitor based on a digital micro-mirror device (DMD) used to generate an adaptive optical mask to block light in the core of the emitted light profile and hence limit observation to halo particles has been developed in close collaboration with CERN and University of Maryland. In this contribution an evolution of this monitor is presented. A high definition micro mirror array with 1920x1080 pixels has been embedded into a MATLAB-based control system, giving access to even higher monitor resolution. A masking algorithm has also been developed that automates mask generation based on user-definable thresholds, converts between CCD and DMD geometries, processes and analyses the beam halo signal and is presented in detail.

INTRODUCTION

For any high intensity accelerator, it is of central importance to have a detailed understanding of the beam halo formation to possibly control and detect beam losses. The latter are associated with potentially negative effects, such as activation of the surrounding vacuum chambers, emittance growth, increased signal background and therefore complicate machines maintenance and increase costs. Beam halo is present in beam phase-space and can be described as the low intense particles at large radii away from the more intense 'core' part of the beam, where the majority of the particles are normally concentrated. Experimental studies into the mechanisms controlling the formation of halo and their interactions, such as space-charge or parametric resonances, etc. need to be performed to verify measurements with theory or simulation [1]. A major challenge in beam halo monitoring is detection of the small number of particles in the transverse tail region of the beam distribution. This needs a high dynamic range measurement able to distinguish between the intense 'core' and the faint 'halo' part of the beam. Here, a beam halo monitor is devised exploiting light generated by charged particle beams, either through optical synchrotron radiation (OSR), optical transition radiation (OTR) or luminescent screens [2]. This monitor measures halo particles by performing a special observational technique with an adaptive masking method that can image a beam halo with a high dynamic range (HDR) [3]. The monitor uses state-of-the-art high-definition digital micro-mirror-array device (HD-DMD) technology equipped with the unique ability to program mirrors to adapt to any desired shape of a particle beam. This monitor is investigated in the laboratory with a proof-of-principle experiment by using HeNe laser and a 14-Bit (A/D) CCD sensor. This is incorporated into a simple optical imaging system that employs a flexible core masking routine to suppress the core part of the beam by deflection using a number of micro-mirror arrays on the HD-DMD, to allow the observation of halo. In addition, this imaging technique is hampered by dynamic range (DR), since the CCD sensor has only an intrinsic DR of 10,000. Neutral density (ND) filters are utilized to reduce the core intensity and avoid the CCD sensor from being saturated at short exposure times. An HDR$\geq 10^5$ is imperative to clearly observe a halo profile within the low intense 'tail' distribution of the beam. The monitor can then be used to properly benchmark beam models in accelerators. Here, a layout of an improved higher resolution monitor is presented together with initial measurements of transverse beam profiles with various mask sizes to identify halos and illustrate the performance of the halo monitor.

HD-DMD TECHNOLOGY

The halo monitor is based on micro-opto-electromechanical system (MOEMS) technology known as Digital Micro-mirror Device (DMD). The DMD uses the DLP Discovery 4100 platform with a 0.95 1080p chipset created by Texas Instruments for enabling high-definition and high performance spatial light filtering [4]. This DMD consists of a DLP9500 2-D array of 1-bit CMOS memory cells arranged in a grid of 1920×1080 micro alumina mirrors of size 10.8μm × 10.8μm. The DMD has an optical fill factor of 85%, with a fast crossing over time of 22 μs for the micro mirrors. The device is used as an adaptive optical device where each mirror in the DMD can be controlled individually to direct light in different directions depending on the micro mirror state. Individually each mirror can be set to two stable binary 'states' that is either 0 or 1, corresponding to an angle of -12^{o} or $+12^{o}$, respectively. The mirrors are switched digitally to their angular positions, corresponding to the contents of the CMOS memory cell state (0 or 1), after a mirror 'clocking pulse' is applied. This pulse corresponds to a waveform voltage of ±28 *V* in

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the DLP9500 when writing a logic 0 or 1 into the CMOS memory cell. In the 1-state (on) the DMD mirrors are tilted by +12° and the light is reflected in a direction 24° with respect to the incident rays, while in the 0-state (off), light is directed 48° away from this path, see Figs 1 and 2. Therefore, DMD technology allows an adaptable reflective mask to be generated by specific instruction of a user-defined programmable spatial filter code to 'flip' micro-mirrors by either +12° or -12°.

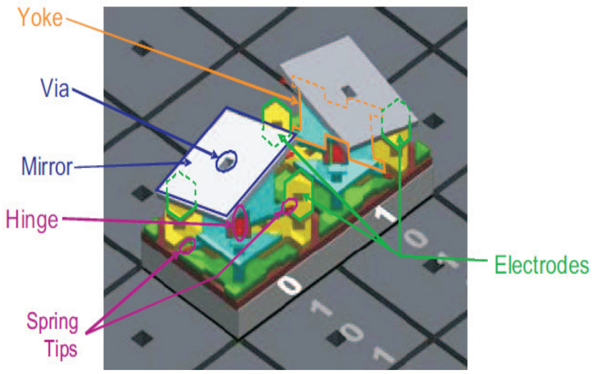

Figure 1: Schematic of DMD two pixels superstructure, from [4].

The basic structure of each DMD pixel (mirror) is a combination of opto-mechanical and electro-mechanical elements, see Fig. 3. The operation of the (DMD) array is determined by electrostatics with each mirror positioned over the corresponding CMOS memory cell, which plays a part in determining the state of the mirror. Mechanically the DMD array is separated by sub- and super-structures, where the substructure of the mirror pixels consists of a silicon substrate that is rigidly attached to an underlying yoke and a torsional hinge [5]. The yoke makes contact with the surface below on the spring tips, as shown in Fig. 2. An insulting layer on the top of the substrate isolates the super-structure from the substructure. Above the insulating layer is a thin metallic layer which forms the electrodes which holds the mirrors in position and supports the hinge. When an electrostatic potential is applied to the lower and upper electrodes an electrostatic torque is created. This torque developed between the underlying memory cell and the yoke and mirror against the restoring torque of the hinges causes mirror rotation in the positive or negative direction.

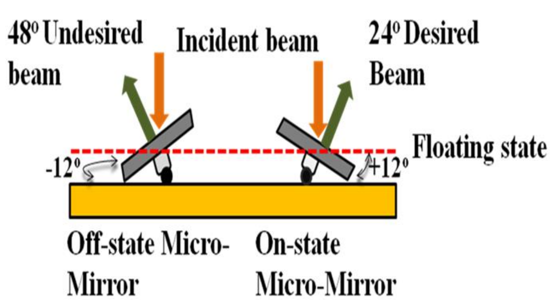

Figure 2: The Micro-mirror landing positions and light paths.

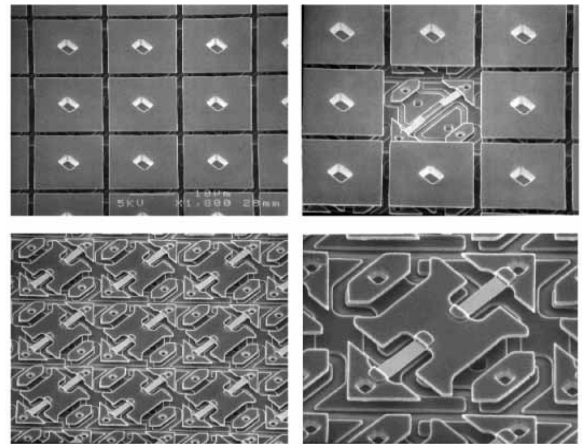

Figure 3: SEM pictures of DMD mirrors, from [6].

EXPERIMENTAL SETUP

To test the beam halo monitor and the HD-DMD technology, we present the filtering ability, the flexible core masking technique and the automation process with measurements using a simple light source in a laboratory environment. A continuous HeNe laser with an output power of 0.5mW and a single wavelength of 633nm is ideal for a proof-of-principle experiment, as the opening angle of the laser of 0.1° (1.41 mrad) is comparable to the OSR/OTR emitted by an electron beam at some 100 MeV [7]. Therefore, the radiation generated by a real-particle beam can be simulated by using a laser beam. The laser beam is Gaussian with sufficient light intensity and can be attenuated by optical neutral density filters to observe its beam halo.

Fig. 4 illustrates how beam halo monitoring with optical methods is performed. It shows how the laser beam is reflected by an HD-DMD into a 14-Bit CCD sensor that measures the 2D beam profile. Thereafter, an image is provided from the CCD, read into a mask generation code in MATLAB, where an adaptive mask is then created and applied to the beam core (red). The mask information is then sent from the control PC to the DMD to initialise the flipping of the mirrors. Now the central beam core (red) will be deflected, while the halo (blue) is still reflected into the CCD sensor. The challenge of measuring with a high dynamic range is increased, when measuring profiles at low intensities. One way to overcome this challenge is to increase the exposure time by scaling it with a factor of the mask size or threshold level.

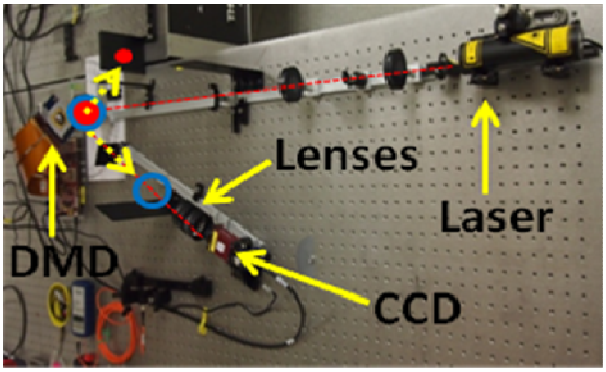

Figure 4: Photograph of proof-of-principle experiment at the Cockcroft Institute, UK.

In addition to the setup in Fig. 4, there are also two rotational compensations required to correctly take the geometry of the experiment into account. The first is to rotate the DMD 45^o about the optical axis as in Figure 5, to make the rotation axis of each micro-mirror coincide with the vertical, since the mirrors in the DMD are skewed and the setup requires flipping by ±12 ^{o} about the *x*-axis. The second compensation is to rotate the CCD camera in the horizontal plane by 24.7 ^{o}, due to distortion in the image plane of the beam [8].

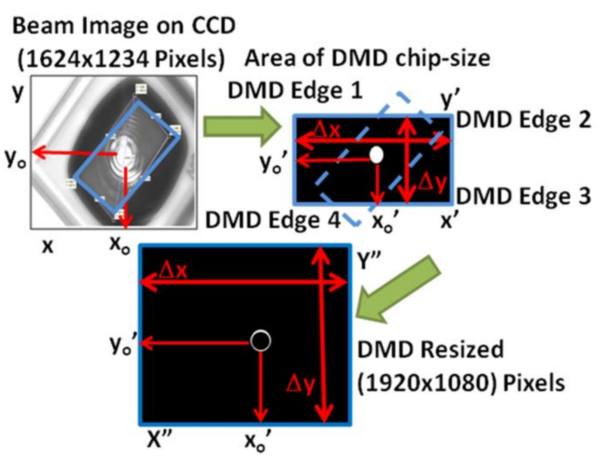

Figure 5: Illustration of DMD rotation and mask transformation procedure.

Mask generation requires re-scaling of the mask to the desired size. In Fig. 5 a calibration is done for the size of the DMD chip as the DMD pixel information needs to be transformed, due to the different matrix size of CCD and DMD. The different size and orientation of the DMD and the camera chips requires transformation to generate any arbitrary mask. The calibration performed in Figure 5 uses image processing in MATLAB to define the DMD chip edges inside the CCD image. There-from, it determines the DMD chip-size (Δx, Δy) in terms of CCD units (x', y'). A translation of the chip is then created with size $\Delta x*\Delta y$ and the pixels now set to 1 for inside the point of interest (x_o, y_o) and 0 for values outside the point of interest.

MASK GENERATION

The HD-DMD is fundamental in the mask generation process as it operates as the programmable spatial filter for a desired beam shape. The mask generation process is illustrated in Figure. 6. Initially the profile of the beam is measured with all mirrors in 1-state, so that all light is detected by the CCD sensor using image processing within MATLAB Imaqtools. The CCD image is a 14-bit image with 16,383 different shades of black that is saved in *.tiff file format. The HD-DMD has only two states of operation and thus reads only a grey-scale image with a 1920×1080 matrix of elements with 0 or 1. Therefore, the stored CCD image needs conversion to greyscale in order to define a mask for the beam core. The mask threshold value is link to the image matrix intensity value. A user-defined threshold value can then be set in the MATLAB masking code which thereby can define various mask sizes for the core region. The generated mask file is then sent to the HD-DMD and causes the mirrors to tilt to +12^o and -12^o. The final part of the process is where the image is re-measured with the mask. In order to increase the dynamic range this will usually be done with longer exposure time. Finally, another image is acquired by the CCD camera and stored as *.tiff file.

Figure 6: Illustration of adaptive masking technique for an arbitrary beam profile.

A MATLAB program was written to control the CCD and to generate a mask to be sent to the DMD using a script *.m file. The algorithm is illustrated in Figure 7. Key procedures including CCD image acquisition, image processing and mask generation are highlighted.

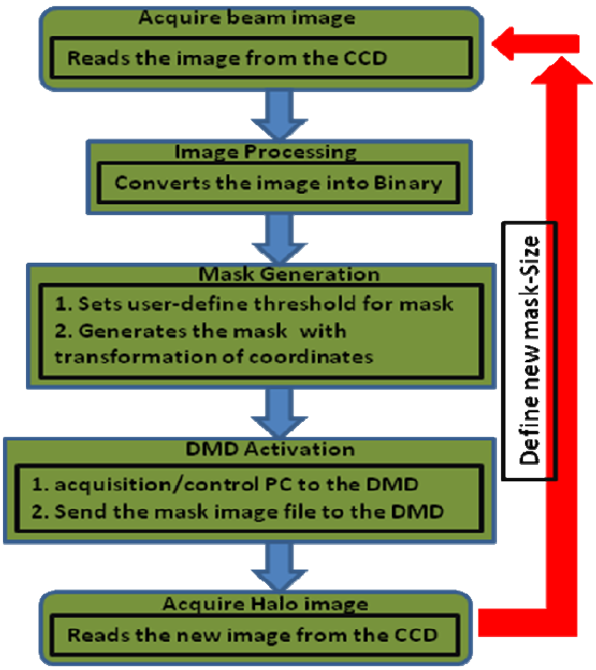

Figure 7: Illustration of masking code and control automation procedure for halo measurement.

MEASUREMENTS

A MATLAB program was written to control, the CCD and generate the mask, see Fig. 7. It creates the mask and allows for precise positioning of it on the DMD. In Fig. 8, when the HD-DMD is illuminated with the coherent laser beam, the DMD acts as a 2-D optical grating that creates diffraction pattern similar to a rectangular mesh in (a). With the correct compensation angles implemented in the geometry an undistorted image is observed in (c) as compared to (b).

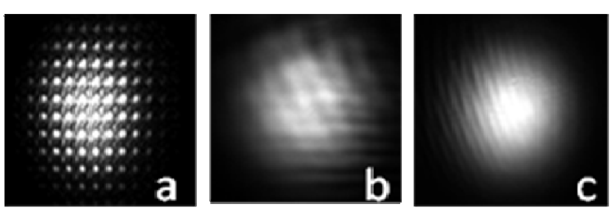

Figure 8: (a) Wavelength diffraction pattern with mirrors in floating state; (b) Distorted beam image; (c) Undistorted image with all pixels set at +12°.

The exposure time is varied inversely proportional to the mask threshold level for each measurement to achieve an optimum result as shown in Fig. 9. Increased exposure times will increase light intensity after each mask is applied and needs to be taken into account when combining information obtained in different measurements.

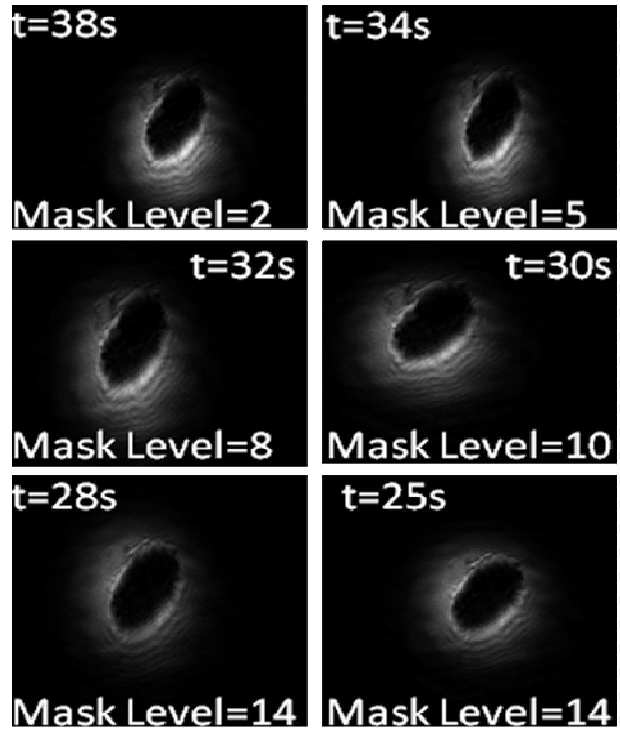

Figure 9: Different masks applied at various mask levels and exposure times.

CONCLUSION

This paper presented the mask generation process and the proof-of-principle setup of a halo monitor using state-of-the-art HD-DMD technology. The beam halo monitor and first results obtained in a laboratory setup at the Cockcroft Institute, UK were discussed. Initial results indicate access to a dynamic range of better than 10^6, opening up interesting opportunities with the high-resolution micro-mirror array. Future experiments are planned at the University of Maryland Electron Ring (UMER), where the HD-DMD shall be used in combination to existing halo monitors to study beam halo dynamics in special beam regimes.

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