OPTICAL SYNCHROTRON RADIATION BEAM IMAGING WITH A DIGITAL MASK

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Abstract

We have applied a new imaging/optical masking technique, which employs a digital micro-mirror device (DMD) and optical synchrotron radiation (OSR), to perform high dynamic range (DR) beam imaging at the JLAB Energy Recovery Linac (ERL) and the SLAC/SPEAR3 Synchrotron Light Source. The OSR from the beam is first focused onto the DMD to produce a primary image; selected areas of this image are spatially filtered by controlling the state of the micro-mirrors; and finally, the filtered image is refocused onto a CCD camera. At JLAB this technique has been successfully used to view the beam halo with a DR~10^5 and at SLAC, to measure the point spread function (PSF) of the SPEAR3 visible beam line with a DR~10^6; and to filter out the bright core of the stored beam in order to study the turn-by-turn dynamics of the ~10^{-3} weaker injected beam.

INTRODUCTION

Previously, we have demonstrated a novel, high DR beam imaging method at the University of Maryland Electron Ring (UMER) [1]. The optical system consisted of two optical channels. In the first channel light generated by a phosphor screen is imaged onto the DMD where the mask was generated. The second channel reimages the DMD onto a CCD camera. In order to easily use the DMD in an imaging system, two compensations: a 45^0 rotation of the DMD about the normal to its surface and a horizontal rotation of the CCD by the Scheimplug angle are required.

The DR of the system with beam was measured to be ~10^5. However, the DR achieved on the beam itself was less. This was due to the maximum strength of our focusing solenoid, the size of the imaging screen and the collection efficiency of our optics. Measurements of the point spread function of the optical system showed that the wings of the PSF did not limit the DR achieved with the beam. In addition diffraction by the DMD was shown to have a negligible effect on the imaging resolution [2].

To develop the DMD masking technique further and to demonstrate its applicability and effectiveness for more intense beams, we have imaged the beam of two other accelerators: the JLAB ERL and the SLAC/SPEAR3 light source with intense OSR that is parasitically produced in both of these machines. Extensions of the basic optical design used at UMER were employed at both of these facilities.

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JLAB MEASUREMENTS

Beam halo measurements at JLAB employed an optical synchrotron radiation port at the end of the first dipole magnet after the super conducting accelerating section as shown in Fig. 1. The beam energy for our experiments was 135 MeV. The primary optical system transported the OSR from the accelerator vault to an optical table containing the DMD and a 16 bit, cooled CCD camera (Apogee Instruments E47) located in a shielded gallery. A sketch of the system and a ray tracing diagram are also shown in Fig. 1. Lens L1 is a singlet (f = 1.5m) and L2-5 are achromats with focal lengths: 860, 300, 200 and 200mm, respectively. Mirrors (M) are front surface aluminized for high reflectivity in the visible.

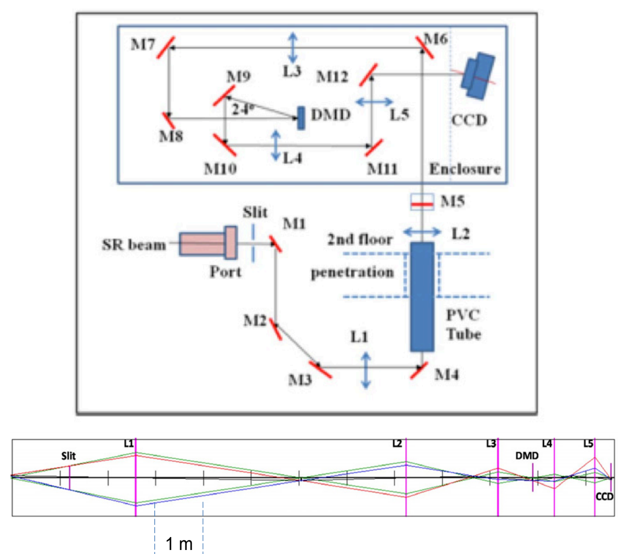

Figure 1: (top) layout of the optical transport showing mirrors (M) and lenses (L); (bottom) ray tracing diagram.

Fig. 2 shows OSR images of the beam in CW mode, i.e. I = 0.63mA, a micro-pulse repetition rate of 4.68 MHz, and a charge of 135pC/micropulse. A 654x90nm band pass filter and a ND=0.4 filter were used in the optical train. The images are taken with progressively lower intensity threshold masks on the DMD to reveal more and more of the halo. The integration times required to bring the peak intensity up to a comparable level for each image are shown in the lower left corner and the yellow outlined image is the unmasked beam.

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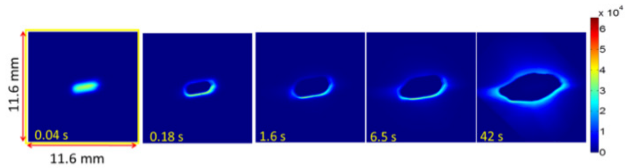

Figure 2: Images of unmasked and masked beam images; color bar shows the intensity scale in units of 10^4.

Fig. 3 shows line scans taken across the diagonal of each of the images shown in Fig. 2 normalized by the integration times used to obtain each image. The insert in Fig. 3 shows a contrast enhanced image taken for the largest mask. The dim image of the beam seen in the center of the insert image is produced by OSR light scattered from the edges of the micro-mirrors produced at an intensity level ~10^{-5} below the peak value. The Figure shows that DR of the optical system is close to 10^7. This suggests that, with a smaller, more intense beam and/or improved optics, two more orders of magnitude may be possible in imaging the beam halo.

Calculations of the PSF of the JLAB optics due to diffraction by the limiting aperture in the optics, i.e. the slit, indicates that the wings of the PSF do not interfere with the measurement of the halo of the beam.

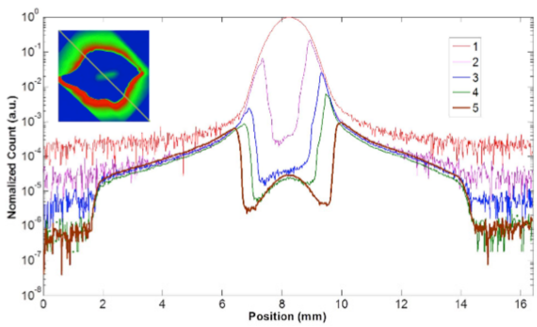

Figure 3: Diagonal line scans of the images shown in Fig. 2 with inserted high contrast image of the last mask.

Using the data shown in Fig. 2, a high DR 2D image of the beam can be reconstructed [2]. Further, by assuming that the intensity is proportional to the charge density the beam, one can determine the percentage of beam particles in any intensity range. An example of the reconstruction of the beam profile will be shown below in the discussion of the SLAC/SPEAR3 stored beam data that was taken using the same intensity masking technique.

SLAC/SPEAR3 MEASUREMENTS

To test the DMD masking technology on a very intense beam producing highly collimated OSR, a series of experiments were made at SPEAR3 operating at 3 GeV. In this case the visible light has a 150 x 20μm^2 rms source size with vertical opening angle of approximately 5mrad and a diffraction limited vertical spot size of about 60μm rms. During normal SPEAR3 operations the total circulating beam current is 350mA with charge distributed in approximately 280 bunches. Single-bunch top-up injection occurs at 5 min intervals with ~80pC/shot distributed into individual bunches at a 10Hz rate. The ratio between stored current in a single bunch and the injected pulse is typically 1nC/80pC.

It is of interest to image and measure the halo distribution of the stored beam itself, as well as to image the injected beam profile on a turn by turn basis, in order to diagnose the charge capture process. Optical beta function mismatch, charge filamentation and decoherence all contribute to the complex evolution of non-linear beam dynamics in 6-D phase-space. Since SPEAR3 operates around the clock for 9-10 mon/yr, it is desirable to collect injected-beam data during the short bursts of top-up activity every 5 minutes. Therefore one of the main goals of our experiments is to mask the bright core of the stored-beam with the DMD in order to image the 10^{-4} less-bright injected beam.

The optical diagnostic beam line at SPEAR3 accepts a 3.5 x 6mrad rectangular aperture of visible synchrotron light produced in the stored ring. A rectangular cold finger is present in the central region of the primary aperture of the beam line to absorb x-rays. This complex aperture which is located ~7 m from the OSR source point produces an window like shadow at the site of the first optical element which is a 150mm diameter, 2m focal length objective lens located ~17 from the source point. The latter images the photon beam onto an optical bench with magnification of 0.14 at the first image point to produce a diffraction limited spot size ~ 150 x 60μm^2 [3].

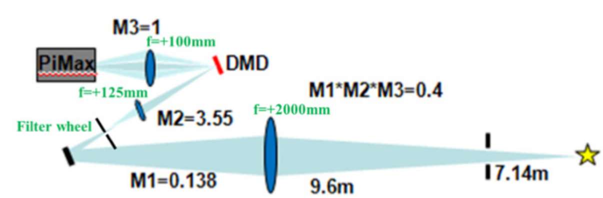

Figure 4: Optical imaging system at SPEAR3.

The SPEAR3 optical imaging system (see Fig. 4) is designed to have a field of view ~ 25mm in horizontal direction, in order to observe the injected beam, which undergoes betatron oscillations ±10mm in amplitude at the source point before damping into the stored beam. The secondary optics reimages the primary image formed by the objective lens onto the DMD surface. This is accomplished by a f =125mm, 50mm diameter lens which yields a magnification of M=0.4 at the plane of the DMD; this allows us to observe ±4mm excursions of the injected beam within the 10x14 mm array. A f=100mm, 50mm diameter lens reimages the DMD surface with a magnification of ~1 onto a fast-gated, MCP intensified PIMAX camera that is horizontally rotated to compensate for differences in optical path length from the surface of the DMD to the camera photocathode and to minimize distortion in the reimaging portion of our system [2].

High dynamic ranges images were taken using the stored beam alone in order to estimate the PSF of the

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SPEAR3 visible beam line. The stored beam was first imaged with an ND=2 filter and low MCP gain. Then successive threshold level masks were applied to the DMD to allow the 'halo' or tails of the PSF to be observed with increasing detail. For each intensity mask we increased the integration time to bring the peak intensity up to near the saturation level of the CCD sensor. Then by obtaining a number of images each of which examined a segment of the total intensity profile we are able to reconstruct a high dynamic range (~ 10^6) picture of the PSF as shown in Fig 5.

Fig. 5 (a, b) show the first 3 and last 4 decades of the PSF, respectively. The inserted image on the top right corner of (b) is the light distribution incident on the objective lens, i.e. the *aperture function* (AF) of the optical system that is produced as the OSR passes through the rectangular beam line aperture and rectangular cold finger. The cross like structure observed in (b) is the Fourier transform of the AF that is visible in the image plane. It is due to the horizontal and vertical structures of the AF. Note the additional slanted ray seen on the upper right quadrant of (b), which is caused by the tilted edge seen in the upper left side of the AF.

(a) (b)

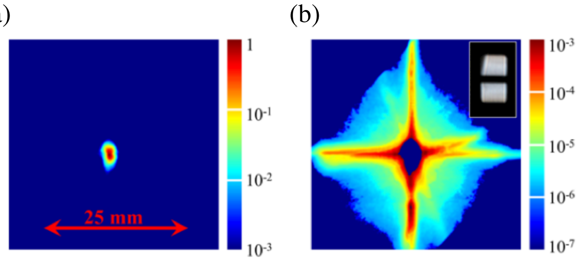

Figure 5: Log normalized intensity profile of the SPEAR3 stored beam; (a) first 3 decades; (b) last 4 decades and insert showing aperture function of the visible beam line.

As mentioned above, each injected pulse contains ~80pC and has a significantly larger spot size compared to the 280nC stored beam. Hence the stored/injected beam image contrast ratio is ~ 10^4. To acquire a single image for a given turn of the injected-beam, we typically gate the PIMAX camera for 15 exposures with no ND filters and maximum MCP gain. Charge accumulation is prevented either by kicking the injected beam out of the accelerator after the ~5ms damping time [4] or reducing the RF voltage below the capture threshold [5].

In order to image the injected beam in the presence of stored beam, we apply either a fixed rectangular mask or an intensity mask on the DMD to block out the core of the stored beam at a level of at least two orders of magnitude below the peak intensity. We also apply a narrow (~3ns) gate to the camera at the arrival time of the injected beam to block out unwanted light from subsequent buckets. A 5ms mechanical shutter (Uniblitz Inc.) is used to eliminate unwanted background light between camera exposure gates and camera readout, which can bleed through the photocathode/MCP of the PIMAX between injected beam pulses. With this shutter, in addition to gating, we achieve an extinction ratio of ~10^8. Images of the injected beam on each turn around the ring using a fixed size rectangular mask are shown in Fig. 6.

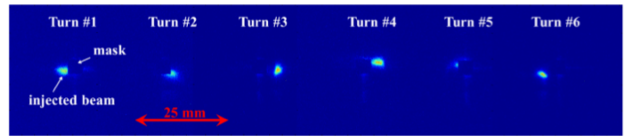

Figure 6: First 6 turns of the SPEAR3 injected beam with stored beam blocked by a fixed size rectangular mask.

Fig. 7 shows the injected beam at the same turn for different stored beam currents, using an intensity threshold mask. The radial rays seen outside the mask are due to the PSF at an intensity level of ~10^{-3} of the peak value.

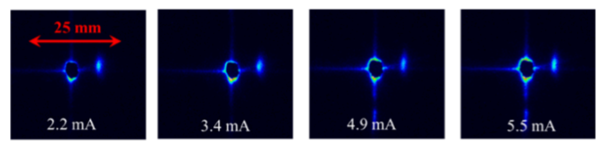

Figure 7: Fixed turn images of injected beam with stored beam blocked by intensity threshold masks for different stored beam currents.

SUMMARY

We have employed a novel masking technique to image the JLAB and SLAC/SPEAR3 electron beams with high dynamic range using a DMD. Furthermore, at SPEAR3, the DMD has been used to block out the stored beam to observe nonlinear beam dynamics of the weaker injected beam. Future studies at both accelerators are planned to extend the DR of the measurements using Lyot and/or apodizing stops and, at SPEAR3, to optimize the beta function match of the injected beam into the ring and to observe nonlinear filamentation and decoherence during the injected beam capture process.

ACKNOWLEDGEMENTS

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