HIGH DYNAMIC RANGE BEAM PROFILE MEASUREMENTS

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Abstract

In future high intensity, high energy accelerators, beam loss has to be minimized to maximize performance and reduce activation of accelerator components. It is imperative to have a clear understanding of the mechanisms that can lead to halo formation and to have the possibility to test available theoretical models with an adequate experimental setup. Measurements based on optical transition radiation (OTR) provide an interesting opportunity for high resolution measurements of the transverse beam profile. In order to be applicable for measurements within the beam halo region, it is of utmost importance that a high dynamic range is covered by the image acquisition system.

The existing camera system as it is installed in the CLIC Test Facility (CTF3) is compared to a step-by-step measurement with a photo multiplier tube (PMT) and measurements with a cooled charge injection device (CID) camera. The latter acquisition technique provides an innovative and highly flexible approach to high dynamic range measurements and is presented in some detail.

INTRODUCTION

For a future linear collider, it will be of central importance to have a detailed understanding of beam halo formation, since beam losses in high intensity machines will cause severe activation of the surrounding vacuum chambers and thus complicate maintenance and increase costs.

Until now, only limited experience on halo formation in dedicated experimental approaches is available on the international scene, see e.g. [1,2]. Besides the need for an improvement of existing theoretical models, beam diagnostic techniques need to be developed that allow experimental verification.

One possible approach towards high dynamic range measurements is the exploitation of OTR created by the electron beam when passing through a thin screen introduced into the beam line. This kind of radiation has been successfully used for diagnostic purposes for more than 30 years now and guarantees a fast time response and very good linearity with the beam signal over a wide intensity range [3].

The typical setup for beam profile measurements in CTF3 is composed of a set of achromatic lenses, mirrors, optical density filters, and a standard CCD camera with 8-bit digitization. It is obvious that the latter clearly limits the overall performance, and does not give access to halo measurements with the necessary dynamic range. A possible halo monitor needs to cover a dynamic range of at least 10^5 to allow the verification of any theoretical model. This paper focuses on test of two devices investigated as possible beam halo monitors and the comparison of their performance with respect to the standard CCD camera system at CTF3.

EXPERIMENTAL SETUP

Beam halo studies were started at CTF3 some years ago [4], where the principal feasibility of a core masking technique was demonstrated. In the present context, different acquisition techniques were studied that might be eventually combined with this technique in future measurements. With the aim to simulate a light distribution that comes close to what is expected in CTF3, an Opto-Electronics PLS20 pulsed diode laser was used in our lab. For image acquisition, three different techniques were used. First, beam profile data was taken with a standard 8-bit CCD camera as it is used in all present installations at CTF3. To adapt the measurement to the available light level, optical density filters were used for optimization of the image.

Second, a small Hamamatsu photomultiplier tube (PMT) type R7400U was installed in a metallic box with a circular aperture variable in diameter between 0.3 mm and 2 mm. The step size for translation of the PMT in horizontal and vertical direction was 100 μm for the measurements. A de-convolution of the initial data was performed to ensure comparability to the measurements from the CCD and CID cameras.

Finally, a SpectraCAM® system, based on CID technology, was used. Although it was invented more than three decades ago by G. Michon at General Electric [5], and although it offers a number of interesting advantages in direct comparison to CCD cameras, CID technology is still not widely used in the field of particle accelerators. The "charge injection device (CID)" derives its name from its unique ability to clear individual pixel sites of photon-generated charge by injecting the charge directly into the substrate.

Similar to most micro-electronic devices built today, the CID is manufactured with silicon technology. A single crystal silicon wafer forms the substrate of the device. The insulating Si substrate is doped with boron to make it electrically conductive (p-type). Upon the substrate, an n-doped epitaxial layer is grown. As the thickness of the epitaxial layer is increased, the full well capacity and NIR response also increase. The epitaxial layer is slightly doped in such a manner as to cause minority signal carrier diffusion into the bulk silicon. Next, a thick field oxide is grown in a checker board pattern across the surface of the wafer. The field oxide is an isolating layer, a dielectric film, composed of silicon dioxide. A thin gate oxide of about 400 nm of SiO_2, is grown over the remaining exposed epitaxial layer. Conductive poly-silicon is then applied in thin strips that regularly crisscross the entire surface of the imager forming the row and column electrodes.

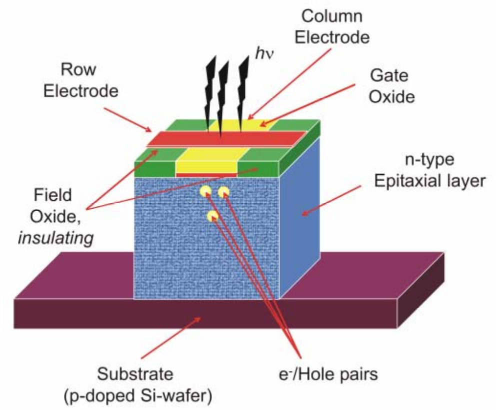

Figure 1: Schematic view of a single pixel on the CID imager.

The two orthogonal poly-silicon electrodes are electrically isolated and connect pixels to the processing electronics at the periphery of the device. One electrode is designated the column or "sense" electrode and the other is the row or "drive" electrode. The region at the intersection of the two electrodes under the thin gate oxide delineates the active charge-storage area for each pixel. A schematic view of a single pixel is shown in Figure 1.

Each pixel on the CID imager is individually addressable and allows for random access non-destructive pixel readout.

During image acquisition, the photon-generated charge is typically stored under the row (or drive) electrode (see stage 1), Fig. 2. In order to determine the level of accumulated charge, the column (or sense) electrode is allowed to float, and the 1st voltage sample is taken on the electrode (see stage 2). Next, the row (or drive) electrode voltage is collapsed thereby causing the photon-generated charge to transfer to the column (or sense) electrode. At this point, the 2nd voltage sample is acquired (see stage 3). The voltage difference between the 2nd voltage sample and the 1st voltage sample is proportional to the amount of photon-generated charge at the pixel site. At this point, the column and row electrodes may be returned to their original bias conditions allowing for the continued integration of photon-generated charge (see stage 1), or alternatively, the voltages on both electrodes can be collapsed thereby causing the pixel to be cleared of charge (see stage 4).

In our measurements, we first did a fixed time exposure of the entire CID chip. Then the acquisition was limited to the region of interest, i.e. the area around the laser spot. This sub-array could then be cycled tens or even hundreds of thousands of times during the acquisition process and thereby allowed to extend the dynamic range by 3 to 4 orders of magnitude. The cycle time from 0 to the threshold signal is automatically adjusted by the camera system based upon the real-time observation of the signal accumulation rate on the user-defined 'Control Region' where illumination should be at its maximum.

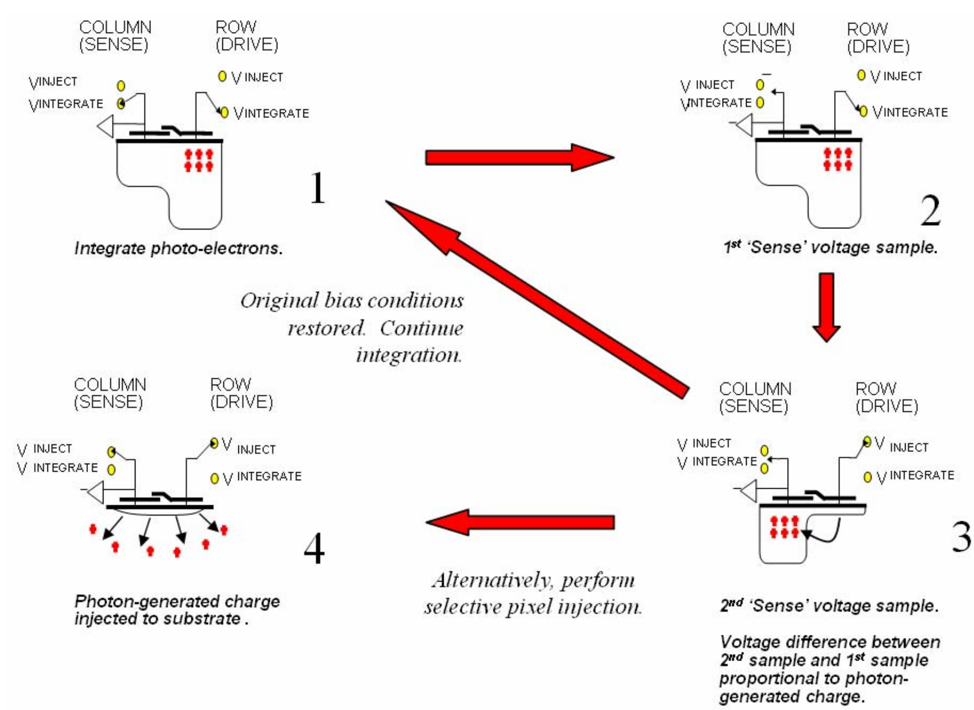

Figure 1: CID readout process and charge return.

COMPARISON BETWEEN DIFFERENT TECHNIQUES

The result of the measurements with all three acquisition techniques is shown in Figure 4. While the data for the two camera systems are in substantial agreement in the central beam region, the maximum achievable dynamic range of the CCD camera used here is limited to about two orders of magnitude. The PMT setup clearly improves on that situation, covering five orders of magnitude. The averaging effect caused by the size of the scanning hole can clearly be seen in the plot. By choosing a different photomultiplier tube with a higher amplification of the signal and optimizing on the size and shape of the central aperture in the mask, one could possibly extend the dynamic range further with the PMT apparatus.

For the envisaged measurements in CTF3, the demonstrated dynamic range covers the required signal levels. The highest dynamic range and best results were achieved with the CID camera, where the maximum exposure time was set to ten minutes, which is still a reasonable time from a practical point of view – e.g. the energy resolved measurements in the spectrometer lines by step-by-step measurements with e.g. the slit dump take about the same time. Due to the limited dynamic range of the CCD on one hand, and the signal averaging aberration of the PMT setup on the other, the measurement with the CID camera showed a number of details that were not observable with the other two methods. Even though CCD cameras with even higher dynamic ranges of up to 14 bit exist, they are less favourable from an economic point of view.

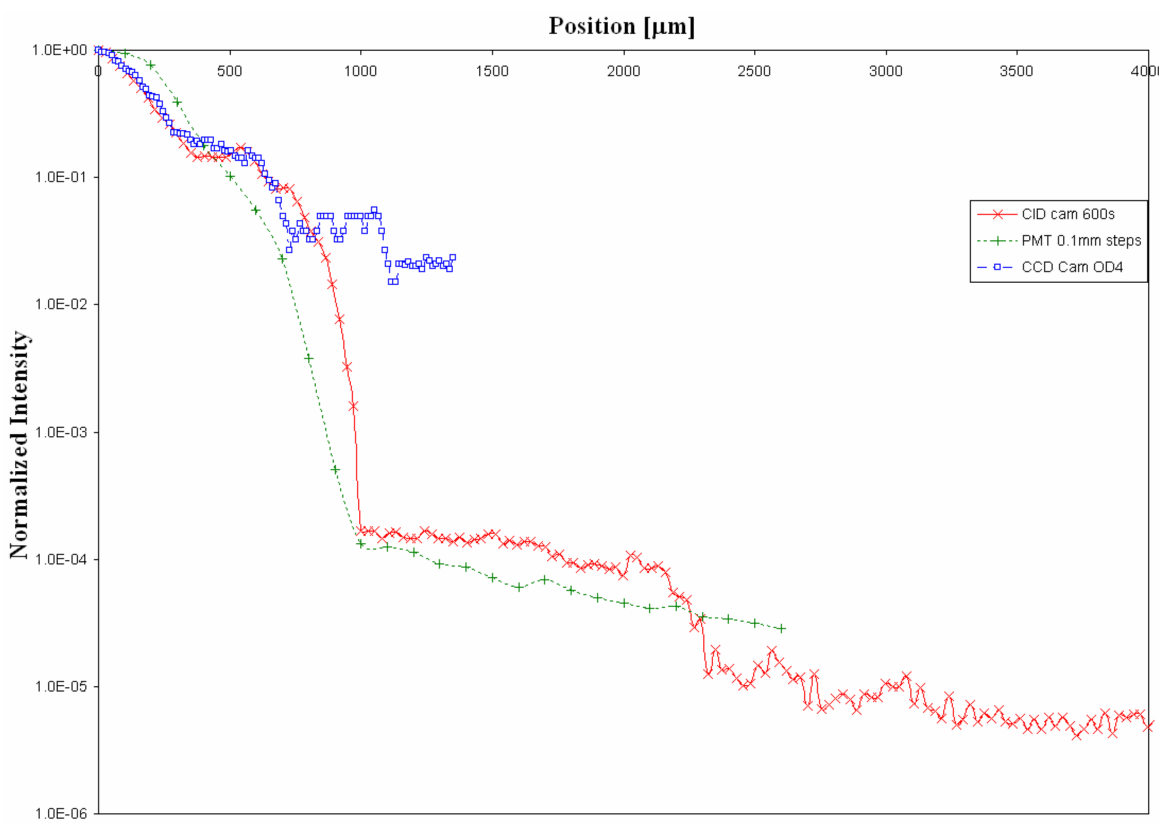

Figure 4: Comparison of the measured intensity distributions with the CCD camera, the SpectraCAM84 and the step-by-step acquisition with a small photomultiplier tube.

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