Towards the Limits of Frame Transfer CCDs in Beam Instrumentation

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Abstract. CCDs are used for beam position and beam size measurements with screens and synchrotron radiation monitors. They have a large spatial resolution and a high dynamic range which make them interesting for high resolution two-dimensional measurements. In most applications, the video signal is digitised with a frame grabber and the beam parameters then computed. The results are limited in resolution, usually to 8 bits, and in rate. These restraints were seen as major limitations for fast and precise beam observations with synchrotron light monitors in LEP, where the revolution frequency is 11 kHz. They have been overcome by using the characteristics of Frame Transfer CCDs. Advantage is taken of the separate Image and Memory areas on the CCD chip to control independently the integration and digitising periods to achieve a 12 bit amplitude resolution at the individual pixel level. Using the CCD as a buffer memory, together with a pulsed intensifier, it is possible to make 9 to 18 two-dimensional beam spot acquisitions up to a rate of 11 kHz. The most recent development uses the CCD as a summing device to perform on-chip horizontal or vertical beam projections and several hundred successive profiles can be acquired in this mode.

INTRODUCTION

Synchrotron light telescopes are the basic operational instrument for transverse emittance measurement in LEP. The instruments, called BEUV (for Beam Emittance in the UV) are foreseen not only for TV observation by the Control Room operators, but also for precision emittance measurements. When looking more precisely into the CCD architecture, it was realised that a CCD is not only good for TV observation, but can also be considered for powerful and economic transient beam behaviour observations down to the LEP turn-by-turn rate of 11 kHz, by combining a Frame Transfer CCD with a fast intensifier (1). Various CCDs were investigated and a modular system was built over the years as development time became available and needs were expressed. For the LEP start-up in July 1989, four BEUV telescopes and fifteen Luminescent Screens (LS) were opera-

tional for TV observation (2, 3). Soon after, the BEUV images were digitised and profiles calculated. In 1990, the fast shutters and the 11 kHz “burst” acquisition for up to 9 turns were put into operation. The following years were mainly devoted to increasing the telescope’s precision from the original aim of 1 nm to the 0.1 nm range (4). Finally, in 1996, the fast turn-by-turn profile acquisition is being put into operation. No major change of the system was necessary over this period, and only the original proximity focused diode intensifier was replaced by a more modern MCP (Multi Channel Plate) intensifier.

UNCONVENTIONAL USES OF FRAME TRANSFER CCDs

Several types of solid state detectors have been developed for the TV market. The main types are the Frame Transfer (FT) and the Interline (IL) CCDs. Another type, the CID (Charge Injection Device) X-Y matrix is used for high radiation applications. The Frame Transfer CCD was chosen because of its versatile signal processing and operational possibilities. These detectors are used essentially in scientific applications as they are more expensive, they use larger silicon areas, than the Inter Line detectors which are the main technology used in the consumer market and are produced in large quantities. Cameras with X-Y CID matrices are the most expensive of the three types. Different types of detectors are used in SPS and LEP and have been compared for resolution: Figure 1.

FIGURE 1: Resolution test: the video signal modulation is plotted as a function of the spatial frequency of a reference plate used in a standard test set-up. Left: direct measurement result, Right: result normalised by the pixel size.

Most cameras, except the low cost MOS X-Y matrix surveillance camera, have comparable resolutions, which justifies the choice of the more economical IL CCD cameras for LS observation and standard video acquisitions (5, 6). In these applications, the CCIR standard signals are digitised by Frame Grabber type converters

with an 8 bit resolution, i.e. 254 grey levels. For the more demanding application of the LEP Synchrotron Light Telescopes BEUV (3), a FT CCD chip, Thomson type TH7863, was selected. This chip was well documented, had peripheral chips available and has also a better figure of merit in normalised resolution, see Figure 1, which is important for fast profile measurements with a minimum number of pixels. The amplitude resolution of this chip is close to 12 bits, i.e. 4095 grey levels, and has improved over the years, well beyond the 8 bits available with the usual video frame grabbers. Frame grabbers normally operate on the composite video signal which results in a loss of horizontal resolution. It was therefore decided to digitise the pixels individually over at least 12 bits. A compromise had to be found between digitising speed and resolution, taking into account the long distances, up to 500 m, between camera and ADC, the loss of charges as a function of shift rate and the thermal noise integration (7). A 12 bit ADC was chosen for precision digitisation and is operated at 450 kHz, except when speed is the major requirement as for the fast projection scheme, where a 1 Mhz rate is used. The thermal noise is minimised by cooling the CCD chip with Peltier cells, the whole telescope has cooled air circulation. The 12 bits also relax the constraints on the light level control for precision profile calculations and ease operation. In certain applications, like beam tail measurements, the 12 bit resolution is not sufficient. The range is extended by attenuating the dense part of the beam core by a factor twenty with a so-called “corona filter”, while acquiring directly the low density beam tails (4). The dynamic range is then equivalent to 10^5 , with the normal Signal-to-Noise ratio. Tails up to 12 sigmas from the central core could be measured in this way (8).

The FT CCD technology has many possibilities which are of special interest for the BEUV project. It uses two identical areas: an Image area on which the scene is imaged during the integration time, typically 20 ms, and a Memory area to which the Image area is shifted in 200 μ s after integration and from where the image information is transferred into the Output register line by line and read-out at the CCIR line frequency for a frame rate of 50 Hz. In normal video applications, these operations are controlled by custom chips locked to a well defined crystal controlled frequency and a whole cycle takes two mains periods. But one of the aims of BEUV is to measure turn-by-turn profiles in LEP for beam instability studies. A fast intensifier/shutter can select one particular bunch and turn, but the acquisition rate will still be 50 Hz and the correlation of successive pictures is not guaranteed at the LEP turn resolution. As the two areas of the TH7863 chip are made of 288 (V) times 384 (H) square pixels of 23 μ m in size and as far less pixels are needed for extracting the beam size information in good conditions, the Image to Memory transfer is subdivided into blocks of 30 lines shifted successively in 18 μ s, each shift locked to the LEP turn clock. In this way, it is possible to accumulate 9 profiles, taken at well defined turn intervals, in the CCD Memory if the beam is imaged just above the Image/Memory separation: Figure 2. This mode is called for obvious reasons the “Burst Mode”.

FIGURE 2: Principle of the Burst Mode.

As several bunches, up to 16 of the same type, can circulate in LEP, it is necessary to gate out the unwanted ones. This is done with an electro-optical fast shutter. The number of memorised images can be doubled by imaging the beam at the top of the CCD Image area. As still only a fraction of the CCD is used in the horizontal direction, several beam images could be memorised on one chip (9).

It was felt since the start, that 9, and even 18, images were somewhat restricting, and that in certain cases it was more interesting to acquire many more profiles, i.e. projections, over many turns. It is possible to do so by using the FT CCD to perform on-chip projections. The 'Fast Projection' mode is the logical extension of the 'Burst' mode. As in the latter mode, the beam is imaged onto the Image area of the CCD, and the beam image is shifted down towards the Memory area between two successive beam passages, in blocks of 30 lines, corresponding to a beam height of 3.3 mm in the BEUV case. The difference with the Burst Mode is at the Memory to Output Register shift. Instead of shifting the Memory into the Output Register line-by-line and reading out each line separately, the block of 30 lines is shifted all at once into the Output Register, which contains then the sum over 30 lines, i.e. the beam projection onto this axis. A block of 40 columns containing the whole beam projection is then read out in 40 μ s, and so on: Figure 3.

FIGURE 3: Principle of the Fast Projection Mode.

In this way, fast projections at the LEP revolution frequency of 11 kHz can be taken continuously with the 1 Mhz conversion rate of the 12 bit ADC. The projection on the other axis is obtained by rotating the beam image by 90°. If simultaneous H and V projections are required, they could be obtained at once by splitting the light beam in two, rotating one beam by 90° and projecting it at the side of the direct beam, and reading out 80 columns instead of 40 per projection. This doubles the read-out time and limits the fastest acquisition rate to one out of two LEP turns. The fast projection mode has of course a limitation next to its speed advantage. As the projection is done on the CCD itself, the dynamic range is limited to the full well capacity of the output register, whereas this limit applied before only to the pixel with maximum amplitude. For the vertical profile in LEP, which is the most demanding one, this ratio is of the order of 20. But on the other hand, the thermal noise integrated is approximately 30 times smaller than in the other modes, and hence the Signal-to-Noise ratio is not degraded. The profile resolution is now comparable to the one obtained by calculating projections with an 8 bit frame grabber, but with a rate of 11 kHz instead of 50 Hz!

FIGURE 4: Fast projection display. Seventy profiles (out of 3 000) of the horizontal projection of the image of a moving light source (pulsed LED) are displayed.

THE CCD CAMERA SYSTEM

The fast shutter gates out unwanted bunches, selects the time interval between measurements and provides some gain for single shot measurements. It is also used as a wavelength shifter to convert low wavelength UV light into the CCD band-

width which starts at 450 nm for a 20% quantum efficiency. This is interesting to decrease the image broadening by diffraction for the small LEP emittances (4). But the finite resolution of the MCP becomes a limiting factor for the whole system. A single stage MCP with an S20 photocathode on quartz is presently used. The use of short wavelengths down to 313 nm compensates the resolution degradation introduced. Going to a shorter wavelength of 254 nm was not beneficial, which may be due to the higher energy of the incoming photons. The major limitation with standard MCPs is a saturation effect in the electron multiplication at the 11 kHz rate. The consequence is an increasing amplitude limitation of the dense central part of the beam which deteriorates the precision of the profile measurement. It can nevertheless provide useful contour information for instability studies with the Burst Mode. The saturation disappears when decreasing the observation rate to 2 kHz, or every fifth LEP turn. A more interesting solution is to use a high current MCP. This has been tried out and gave better results in laboratory tests. Beam tests will be carried out as soon as LEP starts up in 1996.

A system has been built progressively around the TH7863 chip with the aim to make optimum use of its capabilities for beam instrumentation. The first and still major application of the system is in the LEP synchrotron light telescopes, for precision emittance measurements, but the system is now finding other applications, such as the individual profile and position measurement of the four lepton bunches injected from SPS into LEP at 156 μ s intervals and observed with OTR screens, or the monitoring of the matching of the proton beams injected into SPS and in future into LHC, based on the measurement of the beam size oscillations during the first turns after injection and observed with fast screens (10).

The system has been split into three parts for best reliability and performance. The camera head comprises of a small card for the CCD and the phase drivers, with Peltier cell cooling of the CCD so as to reduce the thermal dark current to a minimum. This head is the only part mounted inside the BEUV telescopes. It is linked via a cable up to 2 m in length to a small crate which contains the specific CCD phase generators, a Sample&Hold for the pixel signal, line drivers to the control and read-out electronics, and a regulator set to generate locally the necessary voltages. These two elements, head and mini-crate, are located inside the normally inaccessible radiation area. The rest of the electronics is located in an accessible underground area, up to 500 m away from the camera head. These electronics (3) are in the VME standard and comprise essentially of two CPUs, an 8 bit video frame grabber for permanent beam size monitoring (4, 5), the slower 1 Mhz/12 bit ADC with full frame memory, a control card for choosing the various camera modes, timing units for controlling the MCP triggering in relation with the beam, video generators for mixing digital information and beam TV images for fast and direct Control Room information. The various modes are set by the VME control card which controls the phase generator card in the mini-crate. This card includes a sequencer chip which was, at the start, the standard Thomson chip for controlling the TH7863. With this chip it was possible to implement the following

modes: TV, Full Frame 1 Mhz or 450 kHz digital acquisitions and Burst. It is not possible to implement the Fast Projection with this chip. A Field Programmable Gate Array (FPGA) is used to replace now the original sequencer chip, all the rest of the system remaining unchanged. The acquisition rate is under the control of the ADC. Its buffer memory can contain the image of a full frame of 110×10^3 pixels, with one or nine 2D beam images, or a string of 3 000 fast projections, all of 12 bits. The software resident in the CPU calculates the projections and extracts the beam sizes with a gaussian fit, the results of which are superimposed on the beam image on the TV screens or transmitted to workstations for display and logging. Another CPU works with the VME Frame Grabber and projection calculator for generating a permanent real-time beam size video display.

RESULTS WITH BEAM

The real time beam observation in TV mode and the video display of the beam dimensions in the Control Room provide the operators with valuable qualitative information on the LEP beam behaviour. The precision beam emittance measurement is used for machine optimisation and studies. The major difficulty in this application comes from the poor knowledge of the real Twiss parameters of LEP during the various phases of operation. These parameters were not available up to now with sufficient precision and were the major source of error of the “measured” LEP emittances and calculated Luminosities. Once it was possible to measure the Twiss parameters with sufficient precision (11) and to take into account various perturbations like beam-beam beta-beating, it was possible to measure vertical emittances down to 0.2 nm with a precision of ± 0.1 nm when compared to the wire scanner measurements or the experimental luminosities (12). Beam tails have been measured with the “Corona filters” up to 12 sigmas away from the core, demonstrating exponential tails beyond 3 sigmas (8). Beam instabilities could easily be observed and quantified with the Burst Mode. Non gaussian beam cores have been observed in single shot mode, averaging out to gaussian shapes when integrated over the standard 20 ms. Different behaviours of the various bunches in the Bunch Train operation mode were easily observed with the MCP shutters, both in TV and digital mode.

The fast projection will be put in operation in 1996 and should provide useful coherent turn-by-turn information over hundreds of turns.

CONCLUSION

A flexible system has been built around a Frame Transfer CCD chip. This system is modular and has been completed over the years to fulfil evolving needs. It goes

far beyond the possibilities of a standard TV system and Frame Grabber digitiser. We consider it at the limit of what can be achieved with available CCDs in Beam Instrumentation applications. The system has a spatial resolution at the pixel level, i.e. 23 μm , and an amplitude resolution of 12 bits matching the chip's capability. It can acquire time coherent nine to eighteen two-dimensional LEP beam images and up to three thousand beam projections at a rate up to 11 kHz. It uses the CCD in these last two modes as a buffer memory and an image processor. High precision results have been obtained in profile measurements and only the LEP wire scanners have achieved comparable or better results (12).

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