Image Sensor Technology for Beam Instrumentation

R. Jung

Abstract

Beam monitors using cameras have evolved from qualitative beam observation to precision measurements. After a description of the two main TV standards, the various sensors: TV tubes (Vidicon), solid state sensors (Interline and Frame Transfer CCDs, CMOS and CID X-Y matrices), and Fast Shutter/Intensifiers of the MCP type are reviewed. Comparative resolution measurements for the various sensors described are given. The two types of sensor acquisition hardware: “frame grabbers” and “digital cameras”, are described. Finally the special requirements and the image processing for beam instrumentation are reviewed, including radiation hardness, spectral sensitivity, fast acquisitions and enlarged dynamic range.
Abstract: Beam monitors using cameras have evolved from qualitative beam observation to precision measurements. After a description of the two main TV standards, the various sensors: TV tubes (Vidicon), solid state sensors (Interline and Frame Transfer CCDs, CMOS and CID X-Y matrices), and Fast Shutter/Intensifiers of the MCP type are reviewed. Comparative resolution measurements for the various sensors described are given. The two types of sensor acquisition hardware: “frame grabbers” and “digital cameras”, are described. Finally the special requirements and the image processing for beam instrumentation are reviewed, including radiation hardness, spectral sensitivity, fast acquisitions and enlarged dynamic range.

INTRODUCTION

Television cameras have been used since the early days of accelerators for beam observation. The main application was for a long time the observation of screens for beam steering purposes through transfer lines and for the first turn around circular machines. With the construction of lepton machines, producing enough synchrotron radiation, and high intensity proton storage rings, the use of TV based monitors was extended to the measurement of beam dimensions for machine optimisation and Luminosity estimation. Instruments of this type were developed in several laboratories in the 1970’s with tube TV cameras and included some form of digitisation and numerical processing for beam size extraction. Despite the usefulness of these instruments, it took a certain number of years to have them accepted as precision instruments. The CCD sensor, with its more than 100 000 cells with silicon engraved precision of a few microns, came to maturity in the early eighties, just in time for LEP. The recent improvements of the CMOS sensors and the interest of industry and universities in machine vision, have induced enormous progress in the field and there is now a wide variety of hardware and software available, some of which are directly useful for Beam Instrumentation.

Camera based beam monitors have now acquired a competitive position in beam instrumentation and are recognised as indispensable instruments in accelerators, and the users now have maximum expectations from them.
TV STANDARDS

The original cameras were for TV broadcasting use. This application has imposed a certain number of features which are still applied in the field:
- the aspect ratio of 4/3 between Horizontal and Vertical image dimensions
- the interlace technique by which the full image is scanned and reconstructed with two frames so as to limit the TV transmitter bandwidth
- the number of TV lines, which have to be an odd number, generated by a simple to build divider. The choices for the number of lines were:
  \[ 525 = 3 \times 5^2 \times 7 \quad \text{[USA]} \quad \text{and} \quad 625 = 5^4 \quad \text{[Europe]} \]
- the frame frequency which is the mains frequency in order to maximise the noise rejection and satisfy flicker requirements acceptable to the human eye: 60Hz in the USA and 50 Hz in Europe, and image frequencies which are half these values: 30 and 25 Hz
- the gamma correction for best visual contrast in monochrome reproduction, which states that the Object-to-TV monochrome image intensity relation is not linear but should follow a law of the type:
  \[ I_{\text{image}} = k \left( I_{\text{object}} \right)^\gamma \]
  with \( \gamma = 1.2 \) for the whole chain. This value was determined by the movie film industry for black/white films to compensate the loss of colour contrast. But for colour TV, \( \gamma = 1 \) of course. This should also be the case for Instrumentation.

The cameras, including the focusing lens, tend to reproduce the spectral sensitivity of the eye, peaked around 550nm, and spanning from 400 to 700nm.
- the synchronisation patterns for driving TV receivers, see Figure 1.

**FIGURE 1.** Timing diagrams and amplitude standards for an RS170 [USA] odd TV frame and a CCIR [Europe] even TV frame.
The previous features were translated into TV standards, RS170 (or EIA170) for the USA and CCIR for Europe to which all analog TV cameras comply. As can be seen in Figure 1, these standards are close to each other. The signal delivered by a TV camera is called the “composite video” signal. Only the so-called digital cameras don’t comply to these TV standards.

A typical block diagram for a complete system is given in Figure 2.

**FIGURE 2.** Block diagram of a complete camera system.

**TUBE CAMERAS**

The tube cameras were the first available image sensors. The only interest nowadays is for their radiation resistance, and hence the whole camera has to be made with tubes, i.e. image sensor but also amplifiers and other active elements. Only the Vidicon, Figure 3, the most popular of them, and the SIT image sensors will be mentioned.

**FIGURE 3.** Schematic view of a Vidicon TV tube with deflection coils and lens.

The Vidicon sensor is an evacuated tube, with a photoconductive target on which the scene of interest is imaged. The conductivity of the target is a replica of the scene
illumination. The face of the target towards the input window is coated with a transparent metallic layer connected to the signal output of the tube. A low energy electron beam scans orthogonally the inner surface of the target and the video output signal follows the illumination of the scene. The electron beam is focused with a solenoid coil and its deflection is controlled by magnetic fields generated by the deflection coils. The image is scanned in the usual raster scan every second line. The Vidicon has a sensitivity better than the eye in approximately the same spectral range, a gamma of around 0.7 and a rather long remanence of several frames. It has a very high radiation resistance.

The SIT (Silicon Intensified Target) is a two-stage tube. The first stage is an intensifier using a photocathode onto which the scene is imaged. The electrons emitted by it are accelerated to a silicon target made of tightly spaced p-n diodes where the accelerated electrons create electron-hole pairs. A scanning electron beam neutralises the holes which are collected on the scanning side of the target and again generates the video signal, which is the replica of the scene. Due to the two stages, a gain of 1000 or more can be achieved with respect to the Vidicon. These tubes have a high sensitivity, a spectral range depending on the photocathode type, in general extended towards the Infra Red up to 800 nm, a low remanence and a gamma of 1. Due to the silicon target, these tubes are less radiation resistant than the Vidicon.

Tube cameras are used in high radiation areas where the integrated doses exceed $10^4$ Gy ($10^6$ rad). They suffer from external magnetic fields, which necessitate magnetic shielding and are most perturbing in pulsed machines. As for any standard TV camera, they can be connected to TV monitors for direct observation and the composite video signal can be digitised for further processing by the standard “frame grabbers”. Due to the scanning mechanism, there is a time difference of one mains period between top and bottom of the same frame, and between two adjacent TV lines. This is in general not a severe limitation in usual instrumentation applications where time resolution is not a requirement. Their spatial resolution is quite good, see Figure 16.

**SOLID STATE CAMERAS**

Solid state sensors of the CMOS type appeared in the late sixties and CCDs in the early seventies. Despite its later appearance, the CCD sensor developed faster to a mature technology and is presently the dominating technology. It is mainly the field of the large solid-state electronics companies and has for the moment the exclusivity for scientific type applications. CMOS is catching up rapidly. Because of its simpler technology, similar to that used for producing RAM, it is a field open to many companies, of all sizes, including university laboratory spin-offs. With this technology, it is possible to integrate on the same chip the image sensor and signal processing functions, including ADCs and digital processing.

Only sensors of the area type will be considered here. The linear sensors exist mainly in CCD technology. They are a simplified version of the area sensor. They have many commercial applications and can be interesting in beam instrumentation applications where a one dimensional information is of interest and where the readout speed is the main concern.
Both CCD and CMOS sensors are based on the photoelectric effect in silicon. When a photon of appropriate wavelength, in general between 200 and 1000nm, hits silicon, it generates an electron-hole pair. If an electric field is present, the electron and the hole are separated and charge can accumulate, proportional to the number of incident photons and hence reproduce the scene imaged onto the detector if a proper X-Y structure is present. Each basic element, defining the granularity of the sensor, is called a pixel (picture element). An image is composed of typically 400 x 300 pixels, with dimensions of the order of 10 to 25 µm. Two types of techniques can generate the pixel structure: a MOS capacitor or a p-n junction: see Figure 4.

**FIGURE 4.** MOS capacitor and p-n diode structures for image sensors.

A positive bias applied onto the MOS gate creates a depletion region where the electrons are accumulated, whereas the holes disappear in the substrate. Electrons created in the substrate are either attracted to the depletion region or are lost if created too far from it. This process is characterised by the Quantum Efficiency, having a maximum varying between 40% and 80%, depending on the technology. The electrons are accumulated for a certain length of time in order to generate enough signal at read-out. In TV type applications, this integration length is limited by the mains frequency. Maximum accumulated charges are typically of the order of 300 000 electrons. As in any semiconductor device, there are also thermally generated electron-hole pairs which add to the useful signal and generate so-called dark current. In order to improve the sensitivity and reduce the noise, the sensors can be cooled, as the thermal current in silicon is divided by two every 8°K. The cooling ranges from tens of degrees, achieved with Peltier cells, down to cryogenic cooling in extreme cases.

The readout mode of the accumulated charges will define the type of sensor: CCD or XY matrix read-out. The solid state sensors which have been used as examples in this tutorial are presented in Figure 5.

**FIGURE 5.** Solid state sensor cameras: From left to right: Frame Transfer and Inter-Line CCDs, CID and CMOS XY sensors. The last one is a complete TV system.
CCD sensors

There are two types available: the InterLine (IL) and the Frame Transfer (FT) sensors. Both work on the same readout principle, charge transfer, but the IL uses roughly half the silicon surface of that needed for a FT sensor and is hence more economical.

Inter Line sensors

The structure is given in Figure 6. The image charges are collected in the individual pixels. After the integration period, these charges are transferred to vertical storage areas. The whole image is frozen at that given moment and all pixels have been exposed during exactly the same period. The integration period can easily be lowered to microseconds, if enough light is available, which is often called the “electronic shutter” function. The image charge to vertical memory transfer occurs in one clock period and takes in general less than 1μs. From there onwards, the charges are shifted line-by-line towards the Horizontal output register. Each line is then shifted out towards the unique Output amplifier where the charges of each pixel are converted into voltage by the “floating diffusion” capacitance. All these operations occur during one frame period. There are little individual elements in the readout chain, so the “fixed pattern” noise generated by these differences is kept small.

The light collection area is smaller than the chip because of the Vertical Memory columns. This is in general characterised by a filling factor. Because of this, the Horizontal and Vertical resolutions can be different. Some cameras have double the described structure for best interlace resolution. They can work in “progressive scan” where the whole image, i.e. the two frames, are read together.

FIGURE 6. Inter Line CCD structure: after the integration period, the collected charges are all transferred to the column storage area, from there they are clocked down to the line storage register and finally clocked out to the Output amplifier, all during the next integration period. The storage registers are metallised (shaded area) to protect them from incident light.
**Frame Transfer sensors**

The structure of a Frame Transfer (FT) CCD is given in Figure 7. The scene is imaged onto the Image Area which can be 100% available for integrating the incident light. After the integration period, the full Image Area is transferred to the Memory Area. The “image” is then shifted line by line to the output register, from where it is clocked out to the output amplifier at the chosen rate, which can be the standard TV rate.

![Frame Transfer CCD structure](image)

**FIGURE 7.** Frame Transfer CCD structure: after the integration period, the charges of the Image area are shifted into the Memory area, and from there read out line by line into the OUT register from where they are clocked out into the output amplifier.

The Memory and Output registers are protected by a metallic layer from the ambient light. The columns are defined by the silicon structure, with so-called stop-bands, whereas the lines are defined by electrodes deposited onto silicon oxide. These same electrodes will control the various shifts of the charges by well defined timing sequences. This is shown in Fig. 8 for a four-phase system, corresponding to a column during integration and at four different moments of a charge shift sequence. The lower rectangle in each line corresponds to the silicon substrate. Above it, is a SiO$_2$ layer, and above, the polisilicon electrode structure, with a four-fold periodicity. The electrodes which are positively biased are represented in black. The first line corresponds to the integration period. The charges are collected under the first three electrodes. This defines the active pixel. The centre of charge is below the central biased electrode.

Once the integration period is over, the bias voltage of the first two electrode sets is turned off, while the voltage of the third set is turned on. At the end of this transition, the charges have moved to the right, and so on, until the fifth line, when the charges have moved by one full period to the right. One full pixel shift takes place in approximately 1 $\mu$s. A full shift from Image to Memory area takes typically 300 $\mu$s. This is short compared to the 16.7 or 20 ms of one TV frame, but can induce a vertical “smearing” of the image in some cases.

For the next TV frame, the sensor has to produce an image, shifted by one line. This does not reproduce exactly the TV tube raster scan as all charges are always collected. What is done instead, is to shift the previous electrical pattern of the bias electrodes by two electrodes, the accumulation of charges being now centred under the white electrode of the first line in Figure 8. The centre of charge is hence shifted by two
electrodes or half a pixel, which is satisfactory for a TV monitor, and can be of some use for precision measurements.

**FIGURE 8.** CCD structure and timing sequence for a four phase sensor for the integration period and a complete shift of one pixel. The biased electrodes are in black, and the charge collection areas are the shaded areas below the biased electrodes. During the integration, one electrode (grey shaded) is biased at a smaller voltage.

Frame transfer CCDs have in principle the best sensitivity as the full silicon area is available for photon-to-charge conversion. They have for the same reason a good resolution for a given pixel size, a high output signal and a good uniformity. Their disadvantage comes from the many charge shifts, typically from 300 to 1000 from the closest to the furthest away pixel. In Figure 9 is a measurement of charge transfer efficiencies (CTE) made at different pixel readout frequencies. It should be pointed out that the individual shifts are very efficient: in this example from 99.97% to 99.99%.

**FIGURE 9.** Measured Charge Transfer Efficiencies [CTE] as a function of readout frequency. The normal TV readout frequency is close to 7 MHz.
The lower spectral sensitivity of the CCD is limited by the electrode and protection window transmittances to wavelengths longer than 400nm. To go below these wavelengths, either UV scintillator coatings or back illuminated CCDs are used. The coated CCDs are a much cheaper solution, but their resolution is limited by the emission angle of the coating. The back-illuminated CCD has a normal CCD structure illuminated from the back. The silicon has to be thinned so as to avoid the recombination of the photon generated electrons with holes before reaching the collecting potential well. The efficiency can be the double of an ordinary CCD, see Figure 18. This process results of course in a higher cost.

**X-Y CMOS sensors**

In a CMOS sensor, each pixel comprises of a photodiode with a MOS switch and is individually addressable in the following way. All gates on one line are connected to a Vertical register and all drains of the MOS transistors in one column are connected to a sense line connected through a transistor, controlled by the Horizontal register, to the video output amplifier: see Figure 10. Each pixel is read sequentially once per frame.

Some more elaborate detectors of this type use several MOS transistors. Others, rather then reading sequentially the integrated charge, integrate sequentially the current generated by each photodiode for a given time, the most elaborate with a log amplifier in order to achieve the highest dynamic range.

![FIGURE 10. X-Y matrix CMOS image sensor: the Y selection register selects a pixel row, of which the X selection register selects a pixel at the intersection of both lines, which is connected to the output amplifier.](image-url)
The major disadvantages of this architecture are a potential lower sensitivity due to the smaller photo-active surface available and a Fixed Pattern Noise due to the differences in the individual transistors. These disadvantages are disappearing rapidly as the technology progresses and as more signal processing functions are incorporated on the sensor chip, which is easy in this technology. Recent sensors have a performance comparable to or even better than the best Frame Transfer CCDs, see Figure 16. The possibility to integrate signal processing circuits on the silicon of the sensors is a big advantage. The suppression of the Fixed Pattern Noise by double correlated sampling is one of the important functions which are available. There can also be an automatic integration time adjustment for best dynamic range with fixed diaphragm optics. This can be a disadvantage in pulsed light operation, frequent in accelerator environments, unless precautions are taken. Some of the chips also incorporate an ADC, resulting in a true digital image sensor of small dimension. These components will probably be the dominating next generation image sensors.

**X-Y CID sensors**

The CID (Charge Injection Device) is an X-Y sensor of the MOS family, with a specific pixel structure, see Figure 11. Each pixel comprises of two overlapping MOS photogates and the charges are read non-destructively when they are shifted from one photogate to the other. The integration can be resumed after readout, in principle for each pixel individually, if the signal level is too low. The charges are discarded before a new integration period by “injection” into the substrate. The well capacity can be of $10^6$ charges. As the charges are not shifted around the sensor, there is no image smearing.

**FIGURE 11.** Schematic representation of an X-Y matrix CID image sensor: the X and Y selection initiates the charge transfer between the two sites of the corresponding pixels, which induces a signal on the sense line connected to the output amplifier.
As for the other CMOS sensors, processing functions can be incorporated on the sensor chip to reduce Fixed Pattern Noise and perform elaborate image and signal processing. These sensors are the most radiation resistant solid state sensors. Unfortunately, this technology is single-sourced.

INTENSIFIERS

An intensifier is a vacuum tube type optoelectronic device. It comprises of a photocathode emitting electrons, a gain mechanism and a screen transforming back the electron flux to photons. In the first generation intensifiers, the gain was given by the electrostatic acceleration of the photoelectrons. It was moderate and the image distortions were not negligible. In the second generation, the gain is given by the multiplication of the electrons by secondary emission in a Multi Channel Plate (MCP) made of many little conductive glass tubes, typically 10 μm in diameter. One electron generates many electrons, which gives the amplification but also degrades the resolution of the device. There can be more than one plate. The principle is given in Figure 12.

![FIGURE 12. Operating principle of a MCP intensifier.](image)

Third generation intensifiers have a Gallium Arsenide photocathode in place of the usual multi-alkali photocathode of second generation intensifiers in order to increase the Infra Red response, which is not of concern in general in Beam Instrumentation. They will not be considered further here.

The intensifier can be used in DC or pulsed mode. Intensifiers are used to solve three different problems:
- not enough light available for a good Signal to Noise ratio
- wavelength shifting by proper choice of the photocathode and screen materials: the screen material is chosen for the best match with the sensor spectral sensitivity, and for a decay time compatible with the expected time resolution
- time resolution by gating the intensifier.

The intensifier is coupled to a CCD or another sensor either by lenses or by direct fibre optic coupling. The latter is the most compact and efficient method.

Intensifiers can produce very short gate times, down to a few nanoseconds and work up to a certain repetition frequency, 10kHz is often quoted by the manufacturers.
The reality is in general less good. In the LEP Synchrotron Light telescopes, it was soon realised that the MCP gave two problems. First, it induced a broadening of the beam spot, offsetting completely the gain on diffraction by working in the UV [1], and second it was not able to work for measurement purposes at the LEP revolution frequency of 11kHz. The last limitation is the most serious one and is thought to come from the lack of electron replacement in the MCP tubes. Systematic measurements were made on two types of MCPs: a standard one and a so-called “high strip current” type. In Figure 13 are given the normalised evolutions in amplitude and beam width for a 10 kHz repetition rate for different number of pulses per TV frame.

**FIGURE 13.** Comparison of Normal (open circles) and “High strip current” (full diamonds) MCP intensifiers for an increasing number of pulses per TV frame.
Left: normalised evolution of the signal level per pulse.
Right: normalised evolution of the spot size under the same conditions.
The measurements have been made at 10kHz with a Gain of 400.

The “High strip current” MCP has a better performance both in amplitude and for beam size conservation. The input signal level, gain and repetition frequency also influence the performance.

**DIGITAL IMAGE ACQUISITION**

The direct observation of a beam spot on a TV screen has long been the principal use of camera monitors in beam instrumentation. With the possibility to digitise the images, a new field was opened for these monitors: the evaluation and monitoring of beam emittances, replacing the SEM-Grids in transfer lines [2] and the wire scanners in circular machines where light emission was available in sufficient quantity. There are two main ways to digitise an image: either by using the standard composite TV signal, which are the so-called “frame grabbers” or by digitising the pixels individually, which is done by the “digital” or “slow scan” cameras.
Frame Grabbers

A frame grabber takes the TV standard signal, RS170 or CCIR, uses the synchronisation signals to start a frame recording and restart a new line, generates in general an internal clock, digitises the video signal with a fast ADC and stores the result in memory: Figure 14. There is sometimes a synchronisation on the actual pixel clock. The frame grabbers of this type are truly image source, i.e. camera or video recorder, independent.

![Block diagram of a Frame Grabber.](image)

**FIGURE 14.** Block diagram of a Frame Grabber.

Most of the frame grabbers use an 8 bit flash ADC, which is adequate for the majority of applications. There are often two samples digitised per pixel. The image digitising rate is in general half the frame rate, i.e. 30 or 25 Hz. The interface with the digital world is either through a standard bus system or a serial link. The most popular ones are the PCI bus and the RS 232 or better RS 422 interfaces. A few systems are compatible with the VME standard. The number of available PCI cards is growing fast as are the functionalities incorporated. The most simple frame grabbers come with no data processing. The more elaborate ones can have point-to-point transforms using Look-Up-Tables (LUTs) before and after the Frame Memory block for false colour generation or contrast enhancements. The most advanced ones incorporate processors with software to perform complex operations like zooming, non linear scaling, perspective correction, FFT and digital filtering. All these functions can be done on the whole image or on user-defined Regions Of Interest (ROI).

There is also an intermediate type of interface, the “Digital Frame Grabber”, which starts at the Memory block of Figure 14 and accepts digital data, in general with the RS 422 standard. These frame grabbers are less general and more camera dependent.
Digital cameras

A so-called digital camera comprises of an image sensor and digitising circuits, delivering to the outside world digital information which is or can be processed further. Being independent of the video standards, the system can be optimised for best performance. As the sensor quality is closer to 12 rather than to 8 bits, these systems start in general at 12 bits and go frequently up to 16 bits, i.e. 65 000 grey levels instead of 256! The price to pay is a slower digitising frequency or a smaller digitised area, which is particularly well suited to Beam Instrumentation applications, where the beams are approximately ellipses located in a well known region. For CCD sensors, the digitiser is in general on a different card and takes full control of the sensor, i.e. integration start and stop, Image to Memory transfer and individual pixel read-out and conversion for best spatial precision. The digitiser can also take a reference dark level image to subtract from the real image, in order to get rid of thermal and fixed pattern noise, and hence increase the dynamic range. For CMOS sensors, the analog pre-processing, the ADC and some digital image processing can be incorporated on the sensor chip. This can correct the inherent lower Signal-to-Noise Ratio of these sensors and hence increase their dynamic range. Some available functions are: Automatic Gain Control (AGC), Fixed Pattern Noise suppression with double sampling, restricted data acquisition over user defined areas to increase the acquisition rate, to name a few. The image memory and bus interface board can perform more complex processing functions, as mentioned previously for the Frame Grabbers. A typical structure of a complete digital camera is given in Figure 15.

FIGURE 15. Block diagram of a digital camera.

To summarise, the advantage of these cameras is their better digital data quality, their disadvantage being the lack of a direct video image to follow in real time the beam behaviour. Some digital systems include image generators for that reason.

As mentioned previously, some less complete digital cameras end at the ADC and connect to a computer system through a “Digital Frame Grabber”.

![Digital camera diagram](image-url)
SPATIAL RESOLUTION MEASUREMENTS FOR THE VARIOUS SENSOR TYPES

These measurements were made with a standard test target [USAF 1951], see Figure 16, and a target-to-sensor magnification adjusted to have always a horizontal field of view of 10 cm, typical for screen observations. The images were acquired with a PCI frame grabber. The contrast C between the black and white bars of the test pattern and the Contrast Transfer Function (CTF) are defined as:

$$C = \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{max}} + V_{\text{min}}}$$

$$CTF = \frac{C_{\text{image}}}{C_{\text{testplate}}}$$

The results are summarised in Table 1 and Figure 16. The data for each camera are plotted as a function of the spatial frequency of the test plate, expressed in “Line pairs per mm”, together with the data of the Frame Transfer [FT] CCD camera for easy comparison. The measurements have been performed with the sensors used around SPS and LEP. They are representative of the different technologies.

The best resolution is achieved by the modern XY CMOS matrix. The performance improvement is enormous compared to a previous sensor tested two years ago [3]. The Frame Transfer CCD, now ten years old, comes second. The Inter Line camera comes next. The performance of the vidicon camera is good, probably better than expected by most users, slightly better than the CID camera, and makes this type of camera a good solution for radiation areas.

The performance degradation of the FT CCD camera with MCP intensifiers has to be noticed, see Table 1. This degradation will increase with repetition rate. Nevertheless, the high strip current MCP has an honourable performance and can be used when fast gating is a necessity.

**TABLE 1.** Spatial resolution measurements normalised to the full sensor size.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Line pairs for 50% CTF</th>
<th>Line pairs for 10% CTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY CMOS</td>
<td>200</td>
<td>310</td>
</tr>
<tr>
<td>CCD Frame Transfer</td>
<td>180</td>
<td>240</td>
</tr>
<tr>
<td>CCD Inter Line</td>
<td>140</td>
<td>230</td>
</tr>
<tr>
<td>XY CID</td>
<td>140</td>
<td>200</td>
</tr>
<tr>
<td>Vidicon</td>
<td>140</td>
<td>220</td>
</tr>
<tr>
<td>High strip current MCP [1kHz]</td>
<td>110</td>
<td>210</td>
</tr>
<tr>
<td>Normal MCP [1kHz]</td>
<td>40</td>
<td>130</td>
</tr>
</tbody>
</table>
FIGURE 16. Comparative resolution measurements for various cameras. The measurements were performed with a USAF 1951 standard test target and a PCI frame grabber. The results are plotted as a function of the spatial frequency of the target, expressed in “Line pairs per mm” for a 100 mm horizontal field of view.
SPECIAL FEATURES FOR BEAM INSTRUMENTATION

Beam Instrumentation is a small field compared to the consumer and machine vision markets. Hence commercially available devices are not specifically tuned towards this field and the specific demands for beam instrumentation have to be considered when choosing a system.

Most of the instruments are in a radiation environment where they have to survive. The radiation dose and the lifetime to be achieved will in general determine the choice of sensor to be used: TV tube, CCD, CMOS, or their radiation hardened counterparts. Tubes make of course the most resistant cameras. At the CERN SPS such cameras are used in areas with annual doses greater than $10^6$ Gy. Normal CCDs have shown a performance degradation at levels of 10 Gy. Radiation hard CCDs and CID s are claimed to resist from $10^3$ to $10^4$ Gy. The radiation causes a decrease in Charge Transfer Efficiency and an increase in dark current, resulting in an overall decrease in well capacity, i.e. in contrast, which is clearly visible on the CTF: see Figure 17. The local radiation environment will also influence the location of the processing electronics. In some accelerators this may mean that the processing takes place hundreds of meters from the sensor [4]. As a consequence, frame grabber acquisitions can be degraded with respect to pure digital acquisitions. This is visible in Figure 17 with the CTF measured for the same image sensor in video mode and in digital mode. One way to overcome this degradation can be to use fibre optic links as was done at RHIC [5].

The spectral sensitivity of the sensor has to match the available spectrum or select the best slice for the precision of the instrument. Representative spectral sensitivities are given in Figure 18. A certain number of cameras for visual applications include infrared filters, simulating the eye sensitivity for the best use of the commercial achromats which have been optimised between 450 and 650 nm. But a popular screen material, $\text{Al}_2\text{O}_3$ (Cr) has a peak emission around 700 nm, at the limit of the commercial IR filters, which has

---

**FIGURE 17.** Contrast Transfer Functions: Left: for new (full diamonds) and irradiated (open figures) CCDs. Right: Digital (full diamonds) and Frame Grabber (open circles) acquisitions with 1000 m of cable between sensor and digitiser.
given surprises in some accelerators! Some Vidicons had a similar spectral limitation. The more recent tubes have a spectral response extended towards the Infra Red which makes them well adapted to the Al₂O₃ (Cr) screens.

In general, colour cameras are of little or no interest in Beam Instrumentation.

**FIGURE 18.** Relative spectral sensitivities of common image sensors and spectral emission of some widely used screens.

Many commercial cameras come with Automatic Gain Control [AGC] to maximise the overall dynamic range of the camera. The AGC works in general by estimating the average light level over the sensor area and by changing the sensor gain until this average level reaches a pre-determined value. This can be a serious drawback in applications where the beam to be measured is a small bright spot on a dark background. The AGC can push the beam spot pixels into saturation, which will increase the measured beam size as demonstrated in the example in Figure 19.

**FIGURE 19.** Beam projections, together with their gaussian fits, obtained with and without Automatic Gain Control [AGC]: the sigma obtained with AGC is 45% larger than the one obtained without AGC.
Fast turn-by-turn beam cross-section acquisitions [3], beyond the mains frequency, are useful for beam instability or beam matching observations. The latter can be performed by measuring the profile variations over several turns after injection, but before filamentation. They can be made by using the CCD chip as an analog buffer memory. The principle is explained in Figure 20. It makes use of an intensifier used as a fast shutter and a Frame Transfer CCD used as memory. It is called the “Burst Mode”. The number of pulses stored on the chip can be doubled by using the full chip. The main limitation comes from the recovery time of the intensifier, limiting the acquisition frequency to around 10 kHz.

1st pulse arrives
advance 30 lines
2nd pulse
9th pulse
advance 30 lines
readout the complete memory area

FIGURE 20. Principle of the “Burst Mode”.

Given in Figure 21 is an example of four beam density profiles measured at different turns. The acquisition was limited to four turns to have a better spatial resolution in the vertical direction.

FIGURE 21. Two-dimensional beam density profiles measured on four different revolutions with the “Burst Mode”.
Projections are needed for emittance calculations and can be obtained in several ways. Most frame grabbers come with software, which in one way or another can perform projections of the data contained in a Region Of Interest (ROI). Another possibility is to perform the projection by hardware summing of the ROI in the frame grabber memory, which makes a 25 or 30 Hz rate possible. Finally the projection can be achieved by summing the charges of a beam cross-section directly on a CCD, in a mode which is an extension of the “burst mode” described previously: see Figure 22. This time, the charges are not only stored on the CCD, but the CCD is used as a processing circuit, performing on-chip the summing operation. Once again, the limitation comes from the intensifier. With a perfect intensifier, the operation could be performed at a 30kHz rate with a 12 bit ADC, 1000 times faster than the normal video image rate.

**FIGURE 22.** Principle of the “Fast Projection” mode.

Given in Figure 23, is a multiturn projection obtained in this mode.

**FIGURE 23.** Multiple projections measured in the “Fast Projection” mode.

Another field of interest is a large dynamic range to study non-gaussian beam tails. Whatever the light source used, be it synchrotron light or screens, there is in general little energy available in the region of interest. Another limitation comes from the radiation environment which makes it safer to keep most of the electronics away from the beam tunnel, increasing the distance between sensor and digitiser. Digitising over 16 or more bits is in general not a solution, because of the Signal-to-Noise ratio. A possibility,
which has been used at Argonne [6] and in the LEP Synchrotron Light monitors to extend the dynamic range to 16 bits equivalent, is to attenuate the dense part of the beam by a known amount and reconstruct from a 12 bit image a 16 bit equivalent beam profile [7,8]: see Figure 24.

![Density filter with patterns for Horizontal and Vertical measurements.](image)

**FIGURE 24.** Left: density filter with patterns for Horizontal and Vertical measurements. Right: Vertical projection obtained with the filter position depicted left: the central part of the beam image is attenuated 10 times, still giving the centre of charge and sigma of the dense core distribution, while the non attenuated part shows clearly the tails, which are non-gaussian and extend to ±10 sigmas.

Other possibilities to extend the dynamic range of the acquired images are to use the selective integration possibility of the CID sensors or the logarithmic amplification available with some CMOS sensors, if enough light is available.

**CONCLUSION**

Beam monitors using image sensors are recognised now as precision instruments. Tube cameras are the most radiation hard sensors. The Vidicon is the most widely used. It has good resolution and sensitivity. Silicon Target tubes can be considered for higher sensitivity. The main drawbacks are the component lifetime, the availability in future of components and skilled maintenance personnel, the volume of the cameras and the influence of external magnetic fields.

Solid state cameras are taking over where the radiation levels are lower.

The CCD is the mature technology, with the Frame Transfer type the most interesting for scientific uses. They have special features which make them interesting for accelerator diagnostics, such as the burst and fast projection modes. Interline CCDs are only interesting for microseconds shutter speed and their lower cost.

CMOS sensors are developing fast. Their technology, similar to RAM, makes them cheaper to produce than CCDs, while now of better performance than most CCDs.
The machine vision and consumer markets will push them to the front of the scene while pushing their prices down. Due to the on-chip processing capabilities, and considering the progress made over the past few years, it seems that they will be the image sensors of the future.

Interface to the digital world is spreading rapidly. Driven by the machine vision market, the PCI bus cards offer is increasing rapidly and seems to dominate the field. The variety of the available cards and the power of their processing capabilities is very large.

Software was not touched upon in this tutorial. The demands for Beam Instrumentation are in general quite simple to satisfy. In the majority of applications, all that is needed is the centre of charge and the gaussian fits of the horizontal and vertical projections. Most of the Frame Grabbers come with sophisticated software, a fraction of which is of direct interest in the field of Beam Instrumentation. Added to it, there is a lot of software available commercially, for executing most of the necessary processing: perspective correction for screens, moments of distributions, digital filtering, to name a few. Once more, it is the machine vision market which has stimulated development. It is worthwhile to remember that it is estimated that half of the Vision Market, which amounts world-wide to more than a billion dollars, is represented by software!

To summarise, it can be said that it is presently possible to buy complete instruments comprising of sensor, digitiser and software, and most of the features described previously, are now available commercially. But, because of the small market of Accelerator Beam Instrumentation, many items available are not always satisfactory for these applications. Even worse, their specifications or descriptions are sometimes misleading and have to be analysed carefully.

The main aim of this tutorial was to present the potential user with the various technologies available, their performance and limitations, so he will be able to profit from this field, outside Accelerator Beam Instrumentation, which has a great potential and is changing very rapidly.

ACKNOWLEDGEMENTS

This tutorial condenses the experience accumulated together with my colleagues over the years on the optical monitors in the ISR, SPS and LEP. It is a pleasure to acknowledge their contributions, with a special mention for L. Robillard for his many sensor qualification measurements.

REFERENCES