SINGLE PASS COLLIDER MEMO

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Introduction

Since the luminosity in a linear collider depends on the horizontal and vertical emittance (ϵ_x, ϵ_y) as $1/\sqrt{(\epsilon_x \epsilon_y)}$ a possible method for improving the performance would be to decrease one or both of these numbers. Once this has been done in a damping ring for example, great care must be taken to avoid effective emittance growth in the remainder of the collider. Therefore an effort should be made to measure ϵ , (x and y), as accurately as possible, both during machine development and operationally.

One technique used for measuring ϵ is to insert a luminescent screen in the path of the beam and measure the size of the spot of light made as the beam passes with a television camera and some associated electronics. This has advantages over sampling type techniques (such as wire scanners) because it provides full pulse to pulse two dimensional information. As the focussing of an upstream quadrupole is adjusted the square of the beam size will trace out a parabola (Ref 1) given by:

$$\sigma_{11}^2 = \sigma_{11}(R_{11} + KR_{12})^2 + 2R_{12}(R_{11} + KR_{12})\sigma_{12} + R_{12}^2\sigma_{22} \quad (1)$$

where σ_{11}^2 is the square of the horizontal beam size on the luminescent screen, K is the quad strength, σ_{ii} are the beam parameters at the quad and R_{ii} are the transfer matrix elements between the quad and the luminescent screen. Figure 1 shows a typical layout used in this experiment. The accuracy of this technique depends on the nature of the screen, imaging system, television camera, and signal processing electronics. In this note we discuss each of these topics excluding the screen. The hope is to outline how the resolution of such a system can be specified.

In as much as a spot of light is a pulse of light, $I(x)$, the response of the light gathering and signal processing instruments to this pulse can be evaluated using a method analogous to that used in evaluating the pulse response of an electronic circuit. The performance is best characterized by an amplitude response versus

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spatial frequency function, often referred to as the modulation transfer function (*MTF*). The measured size of the spot, $I_m(x)$, is almost always larger than the real spot, $I_r(x)$ and is given by :

$$I_m(x) = F^{-1}(MTF_{sys}I_r(k)) \quad (2)$$

where F^{-1} is the inverse fourier transform and MTF_{sys} is the *MTF* of the whole system; in this case

$$MTF_{sys} = MTF_{screen}MTF_{optics}MTF_{camera}MTF_{electronics}, \quad (3)$$

and $I_r(k)$ is the fourier transform of the spot. The full system specification includes the variation of the *MTF* over the whole image. Industrial standards exist for evaluating each of these *MTF*'s.

Optics

The *MTF* of a perfect, diffraction limited lens is given by:

$$\frac{2}{\pi} [\cos^{-1}(y) - y\sqrt{1-y^2}]$$

where y is the wave number, k , normalized to the cutoff frequency:

$$y = k/k_0$$

$$k_0 = \frac{D}{\lambda s''}.$$

D is the lens aperture, λ is the wavelength of the light and s'' is the lens to image distance. In a real lens the *MTF* is degraded by aberrations. Figure 2 shows both the maximum and actual *MTF* for a typical good quality lens. The best *MTF* is usually achieved midrange in the aperture settings of a particular lens. Figure 3 shows the variation of *MTF* with iris setting at a set spatial frequency for a typical 135 mm lens. Off-axis *MTF* can be considerably lower. Figure 4 shows some factory data for a good quality lens.

The *MTF* can be considerably degraded due to glare from any external light source or reflections of the phosphor emission. This is minimized with a proper coating of the interior of the screen housing.

Camera

Most commercially available cameras have been optimized for broadcast or surveillance use. Typically this involves extending the dynamic range of the camera at the expense of resolution. The requirements that the beam spot measurement technique makes on the camera are the following:

1. High resolution - good *MTF*
2. Good linearity
3. Low 'blooming' (outward diffusion of specular highlights in the picture)
4. Low noise over the dynamic range of interest
5. Low lag (image retention for several fields).

A television camera can be broken down into two subsystems, the image receiver (camera tube or solid state sensor) and the amplifier chain. Typical camera tubes consist of a photoconductor faceplate placed behind a transparent conductive layer. An electron beam scans the active photoconductor area and, if a local area has been illuminated, a signal from the scanning or reading beam will pass through the photoconductor and continue through the conductive layer to the preamplifier. This type of tube is in wide use with a variety of photoconductors and is known generically as a vidicon. Except for a few large return beam tubes, vidicon tubes have the best resolution available, often much better than solid state sensors. The resolution of a vidicon depends on the photoconductor, its sensitivity and granularity, the impedance of the conductive layer and the size and shape of the scanning beam. In the best vidicons, the resolution is limited by the electron optics of the scanning beam. Typical tubes are 0.7" (or 1.0") in diameter and have a 3 X 4 active area aspect ratio with a diagonal of 11 (16) mm. Some larger, relatively expensive, 2 in. tubes are available.

The *MTF* of most camera tubes can be approximated by a gaussian and

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is usually quoted in units of 'TV lines per picture height for 50% (or lower) amplitude response'. This can be converted to usable units (% *MTF* as a function of mm^{-1}) on the tube face with the following

$$1 \text{ TVL/PH} = 0.65/w_a \text{ cycles/mm.}$$

w_a is the width of the active area. This refers only to the horizontal *MTF*, along the high sweep speed direction of the camera tube. The vertical *MTF* is more complex because of the well defined vertical line structure (525 interlaced lines/frame). Because of this the observed spot may actually appear smaller than the real spot due to aliasing. Television horizontal resolution standards have been set such that vertical and horizontal resolutions are equal. For the standard 30 frame/second composite video this implies a 4.5 MHz. electronic bandwidth.

Figure 5 shows performance specifications of some typical vidicons. The highest resolution commonly available vidicon tube, with an Sb_2S_3 photoconductor exhibits non-linearity, high lag and blooming so it is not usable. An additional problem with these vidicons is their susceptibility to burn, i.e. a bright image becomes permanently marked on the photoconductor. The other high resolution tube ('SATICON'- Se-As-Te photoconductor) is replacing the Sb_2S_3 tube in industry but the sensitivity is much lower. The 'ULTRICON' tube is commonly in use for these measurements because it has high sensitivity and very low blooming. It has a segmented Si photoconductor with about 72 diodes/mm. This tube exhibits very good lag and blooming properties but has comparatively poor resolution.

In a machine which is locked to the line frequency (60 Hz.), a well defined phase relationship exists between the flash of light from the phosphor and the camera tube scanning beam. To avoid reading that part of the image just as the beam passes through the screen, it is sometimes necessary to provide phase adjustment on the camera. In addition, cameras with non-negligible blooming will indicate a larger beam spot as the delay between the flash of light and the reading beam becomes longer. This effect is small in tubes with discrete photoconductors such as the ultricon.

Electronics and data acquisition

In a typical system the amplified composite video signal (RS-170) is carried out of the accelerator housing on a 75Ω cable to a local transient waveform digitizer system or to a modem for broadcast to a remote digitizing system. These digitizing systems can themselves be quite complex. The video amplifier in all but the cheapest cameras have bandwidths in excess of 10 MHz. (The width of the active area is swept in $52 \mu s$ so this is equivalent to $1/500$). Transient digitizers are available with a variety of speeds ranging from 100 MHz to 50 KHz. A 20 MHz, 8 bit digitizer has 7.5 effective bits at 10 MHz. Care must be taken if the signal is modulated and transmitted over a cable TV system since the channel widths typically limit the signal to a 4.5 MHz bandwidth.

System evaluation

The system *MTF* can be obtained by multiplying the *MTF*'s for each component. Since the beam is expected to be gaussian, its fourier transform will also be gaussian and if the component *MTF*'s are also approximated as gaussian, the expected resolution is easily obtained. Thus (from (3))

$$1/\sigma_{sys} = \sqrt{1/\sigma_{lens}^2 + 1/\sigma_{camera-tube}^2 + 1/\sigma_{amp}^2 + 1/\sigma_{digitizer}^2}$$

where σ_{sys} refers to the rms of the *MTF*_{sys}. The *MTF* of a lens as given above can be approximated by a gaussian with $\sigma_{eff} = Ak_0 \approx .4k_0$. It is usual in these systems to have a limited s' , lens to object distance, because of the vacuum chamber. In addition, the system magnification, M , may be chosen by other considerations, typically to enhance the diagnostic functions of the screen. We can thus parameterize the various *MTF*'s with M and s' . Fixing M also fixes f , the lens focal length. The camera tube *MTF* may be obtained from the factory. Taking as example the 1 in. ulticon, a gaussian fit (figure 6) is reasonable and gives $\sigma_{ct} = 16 \text{ mm}^{-1}$. Additional components such as the video preamp have $\sigma_{amp} > 25 \text{ mm}^{-1}$ (for a 1 in. tube). The transient digitizer performance can be neglected since it is 2 times faster than the camera electronics. The system performance can be expressed as

$$1/\sigma_{sys} = \sqrt{(Ms'\lambda/AD)^2 + (1/M\sigma_{ct})^2 + (1/M\sigma_{amp})^2}$$

For example take the desired screen size to be 6×4.5 mm (1/2 the active area of a 1 in. ulttricon; so M in this case would be 2) and take s' to be 200 mm. D is then 10 mm ($f/13$) for a 135 mm lens. Also take $\lambda = 550nm$, typical for common phosphors. Thus, the expected σ_{sys} is approximately:

$$\begin{aligned} 1/\sigma_{sys} &= \sqrt{(55\mu m)^2 + (31\mu m)^2 + (12\mu m)^2} \\ &= 64\mu m = 16mm^{-1}. \end{aligned}$$

The estimation above uses only the diffraction limited lens MTF . Actual performance will be degraded by lens aberrations.

It is useful to compare this with optical bench tests. Typical MTF measurements on television camera systems use an analysis of the camera response to a resolution target with an oscilloscope (Ref 2). Accurate measurements with this technique are difficult and for this reason special MTF measuring instruments are used in industry. Laboratory measurements using a resolution target have given $1/\sigma_{sys} = 75\mu m$ for the square wave response function (sometimes called Contrast Transfer Function) corresponding to the above parameters. The CTF usually overestimates the MTF by up to 20% . Figure 7 shows a comparison between the two (from Ref 2).

Emittance Measurement

The measured beam size is given by (2) which becomes:

$$\sigma_m = \sqrt{(1/\sigma_{sys})^2 + \sigma_r^2}$$

in the gaussian approximation since the fourier transform of a gaussian has $\sigma_k = 1/\sigma_x$ and vice-versa for the inverse transform. In the above equation σ_{sys} is just as given in the previous paragraph and σ_r is the actual beam size. This can be rewritten in the conventional notation:

$$\sigma_{11}^2 = \sigma_{11}(real) + \sigma_{11}(sys).$$

Since the parabola (1) describes the square of the beam size, this systematic error simply produces an upward shift of the parabola, independent of K and σ_r . Equation (1) can be rewritten:

$$\sigma_{11}^2 = \sigma_{11} \left(K R_{12} + \frac{\sigma_{11} R_{11} + \sigma_{12} R_{12}}{\sigma_{11}} \right)^2 + \frac{R_{12}^2 \epsilon^2}{\sigma_{11}} \quad (4).$$

The derivative of (4) with respect to K will not depend on this systematic hence σ_{11} does not depend on σ_{sys} . Thus

$$\epsilon_m^2 = \frac{\sigma_{11}^2 \sigma_{11}^0}{R_{12}^2} + C$$

and the real emittance

$$\epsilon_r^2 = \frac{\sigma_r^2 \sigma_{11}^0}{R_{12}^2} + C.$$

C contains terms which are independent of σ_{sys} . The measured normalized emittance can be given as a function of the lattice and the incoming beam parameters (ϵ_r^n - real normalized emittance, β^0 - incoming β , and γ - beam energy):

$$\epsilon_m^n = \sqrt{\frac{\gamma \epsilon_r^n \beta^0 \sigma_{sys}^2}{R_{12}^2} + \epsilon_r^{n2}}.$$

Figure 8 shows the error made in the normalized emittance versus the resolution for various values of the parameter $E(\text{GeV})\beta^0/R_{12}^2$. It is clear that for a given system resolution, β^0/R_{12}^2 should be minimized. However, for a fixed β^0 , there is an optimum where $\beta^0 R_{12}^2$, the parabola curvature, is not too large. In the limit of large R_{12}^2 , small quadrupole current fluctuations can cause large spot size fluctuations leading to further systematic errors. Since these current fluctuations usually occur at the line frequency (or some harmonic) this is not easy to evaluate. For measurements which are always made at the same phase with respect to the 60 Hz, the limiting factor is not the quad current fluctuations, but the ability to measure the current with the shunt system. This is usually very good ($1/10^4$).

Conclusion

A luminescent screen provides a valuable diagnostic function and may also be a reliable tool. In order to have an operational emittance measuring system which does not necessitate large lattice changes, a careful examination of the screen system is required. In cases where β^0 is not known, a boot-strapping or two-screen method may be necessary. At very high energies improved cameras and optics are needed. Finally, no mention has been made of the screen properties and this is clearly a further source of problem at the level of tens of microns.

Figure 1. Typical experimental setup for emittance measurements using a television camera and a luminescent screen.

Figure 2. *MTF* of a diffraction limited lens compared with that of a real lens.

Figure 3. Variation of the *MTF* of a 135 mm lens at a particular spatial frequency for various aperture settings.

Figure 4. Calculated *MTF* for white light vs. distance from center of the object for a good quality enlarging lens. (Jos. Schneider and Co.) The plots show various magnifications (β) and apertures (k). Each of the 6 plots has 3 pairs of curves, a pair of curves corresponds to a given spatial frequency (10, 20, or 40 mm⁻¹). The pair of curves give the *MTF* for both the radial (sagittal) and tangential directions.

Figure 5. a) Response characteristics of various camera tubes. The four lines in the lower right corner of the plot refer to vidicon type tubes; Ultricon, Saticon, Vistacon (PbO) and Sb_2S_3 vidicon. The other tubes are either return-beam devices or have image intensifiers.

Figure 5. b) Typical resolution (*MTF*) data for selected camera tubes. Data for Ultricon ('Vidicon Si') are shown with data for a sulfide vidicon, an isocon (return beam device with a 2 in. face plate, a return-beam vidicon (not a production device), a CCD and a development version of a Saticon (Ref 3). This Saticon has lower sensitivity than the Saticon shown in figure 5a. The CCD *MTF* cuts off at 1/2 the sensor frequency.

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Figure 5. c) Typical lag characteristics for amorphous photoconductor tubes (Newvicon, Chalnicon and vidicon) with a Ultricon. Lag can change as the background lighting changes.

Figure 5. d) Spot size growth vs. light intensity for several tubes.

Figure 6. Factory data for the *MTF* of a 1 in. ultricon television camera tube.

Figure 7. Comparison of the square wave response function *CTF* and the true *MTF* (sine wave response).

Figure 8. Error made in the measurement of a $\epsilon_p^n = 3 \times 10^{-5} \pi$ rad - m beam. vs. $E\beta^0/R_{12}^2$. The horizontal line indicates an error equal to the real emittance.

Ref (1) Rees, J. and Rivkin, L.. SLAC-PUB-3305, March 1984.

Ref (2) Biberman, L. and Nudelman, S., **Photoelectronic Imaging Devices**, 1971.

Ref (3) Isozaki *et.al.* IEEE Trans. Electron Devices ED-28, 12, 1980.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5a

Fig. 5b

Fig. 5c

Fig. 5d

Fig. 6

Fig. 7

Fig. 8

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