THE SCAN MAGNIFICATION LENS USED IN THE MICROCHANNEL PLATE CRT

Conrad Odenthal
Tektronix, Inc.
Beaverton, OR 97077

As space age technology advances, oscilloscope users have been asking for CRTs with increased bandwidth and writing speed, and with larger displays. Tektronix' latest answer to this problem is the T7100 CRT. This CRT employs a microchannel plate to increase writing speed, and uses distributed delay line deflectors in both the horizontal and vertical axes to provide bandwidths well in excess of the specified 1 GHz scope bandwidth **(Fig. 1)**. The microchannel plate acts as an electron beam amplifier. With a gain of over 10,000, the microchannel plate can make a low intensity electron beam appear very bright at extremely high writing speeds. With the microchannel plate (MCP) placed close to an aluminized screen, an additional high voltage of 10 kV applied to the screen further enhances the trace brightness without causing excess beam spreading.

Excess bandwidth is needed in the CRT because it is the last in a series of components, all of which individually have bandwidths well in excess of 1 GHz. When connected in series, however, succeeding components slightly degrade the input signal, so that a 1 GHz system results. Thus, the amplifier driving the CRT deflection plates also has a very high bandwidth, but because of power limitations, it can provide only eight volts to the CRT for a full screen display. Eight divisions of vertical scan thus require a CRT sensitivity of 1 div/volt. The sensitivity required for the CRT used in the 500 MHz 7904 scope was only 0.33 div/volt. Thus, a 3X increase in CRT sensitivity is required for a 1 GHz system. This increase should be accompanied not by a loss, but (hopefully) by a gain in display resolution.

In addition, for user convenience, the display must be large and have extremely good characteristics such as linearity and geometry. A display with good linearity will have a linear relationship between the spot deflected on the screen and the voltage applied across the deflector pairs. A display with good geometry will present raster lines as straight lines without any wiggles or bowing. Thus, when testing the CRT, an electronically generated raster can be superimposed in coincidence with the CRT graticule in both the horizontal and vertical directions.

Scan Expansion Methods

Scan expansion schemes such as the domed mesh and quadrupole lenses are known techniques, but are not necessarily the best designs to obtain optimum CRT compromises. For instance, the domed mesh provides scan expansion through the application of a high voltage field, but optimum microchannel plate gains are achieved when the electrons enter the channels at a relatively low voltage. In addition, the electron beam intercepts the mesh, generating secondary electrons which, when multiplied by the channels, could cause a ghost spot to appear as bright as the main beam.

A quadrupole scheme, while easily analyzed mathematically, would require the addition of other quadrupoles to produce a round spot. Placement of the extra quadrupoles sets limitations on deflection plate length needed to generate a large scan envelope in order to minimize spot magnification. In addition, it is highly desirable that the expansion lens (with its high magnification factors that are critical for alignment) contribute as little as possible to CRT misalignment rejects. The electron gun, with distributed delay line vertical and horizontal deflectors, and the CRT bulb, with the microchannel plate (MCP), are somewhat expensive, and additional costs because of CRT misalignment could raise production costs prohibitively. Therefore, it is desirable that the lens incorporate some features to correct for problems of slight misalignments in the CRT gun or expansion lens.

Box Lens Description

The box lens, shown in **Fig. 2**, is a

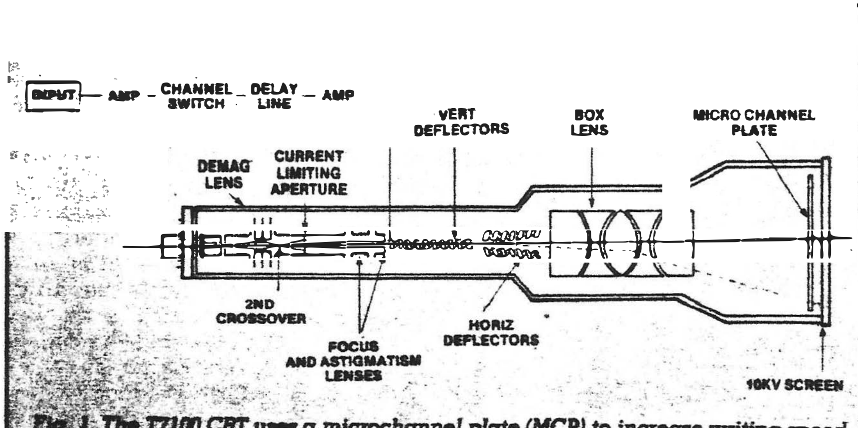

Fig. 1. The T7100 CRT uses a microchannel plate (MCP) to increase writing speed, and uses distributed delay line deflectors to provide bandwidths greater than 1 GHz. The box lens provides scan expansion.

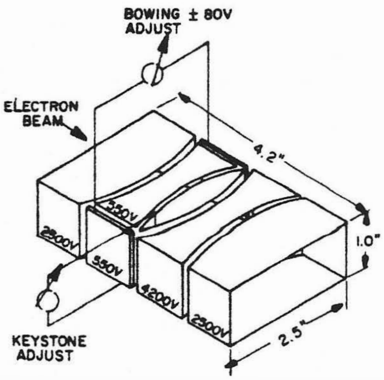

Fig. 2. The box lens can pass and magnify a large scan envelope, and enables convenient correction of bowing and keystone problems.

good answer to the requirements. The box dimensions are made as large as practical in order to pass a large scan envelope and yet to generate a short focal length without distortion for a large 6.8 x 8.5 cm display. Functionally, the box lens is the same as a quadrupole, with a positive focal length in the vertical axis and a negative focal length in the horizontal axis. In addition, it can generate, without distortion, a wide range of focal lengths in the horizontal and vertical axes by applying different voltages to the lens electrodes or by changing the positions or radii of the semicircular arcs.

For any given focal length, the box lens can pass and magnify a larger scan envelope than a quadrupole. This allows the centers of horizontal and vertical deflection to be greater distances from the lens, and long deflection plates can be used to achieve high deflection sensitivity. If necessary, a quadrupole could be placed between the horizontal and vertical deflectors to further enhance the vertical scan. The voltages and the "adjust" features in Fig. 2 will be discussed later.

One might ask how to obtain a round spot by passing an electron beam through the box lens with the scan diverging in one axis and converging in the other (Fig. 3). The astigmatism lens (Fig. 1) and electron beam interact to produce a real line image in the vertical axis, while at the same time producing a virtual line image in the horizontal axis. The box lens then reimages these lines to appear as a round spot on the MCP screen. Approximately 40 volts of negative bias are required on the astigmatism control to produce the line image separation. Apart from this small bias voltage, the focus and astigmatism controls required to obtain a best-focused spot are the same as most classical electrostatically deflected CRTs.

Optical Analogies

Using simple light optics formulas for thin lenses (Fig. 4), one can see how crossover magnification or total spot magnification (Mts) is related to scan magnification (Mscan).

$$Mbox = \frac{D}{B\tan\alpha},$$

where Mbox is the box lens magnification.

$$Mscan = \frac{D}{Z\tan\alpha}.$$

Therefore, we get

$$BMbox = \frac{D}{\tan\alpha} = ZMscan.$$

Total crossover or spot magnification is the product of the focus lens magnification and the box lens magnification.

$$Mts = Mfocus\ Mbox.$$

$$Mts = \left(\frac{B+E}{A}\right)Mbox.$$

Finally, if A is given a value of unity, total magnification is

$$Mt = ZMscan + EMbox.$$

$$Mt = \frac{D}{\tan\alpha} + EMbox,$$

where Mt represents a normalized Mts.

If E could be made zero by superimposing the center of focus over the center of deflection, then spot magnification would be made directly proportional to scan magnification and independent of CRT length for any desired scan size, deflection sensitivity and gun voltage. Spot size would then be directly proportional to half-scan size (D), and inversely proportional to the half-scan angle (α) generated by the deflector pairs, where the angle α is small enough to be considered equal to its tangent. If twice the de-

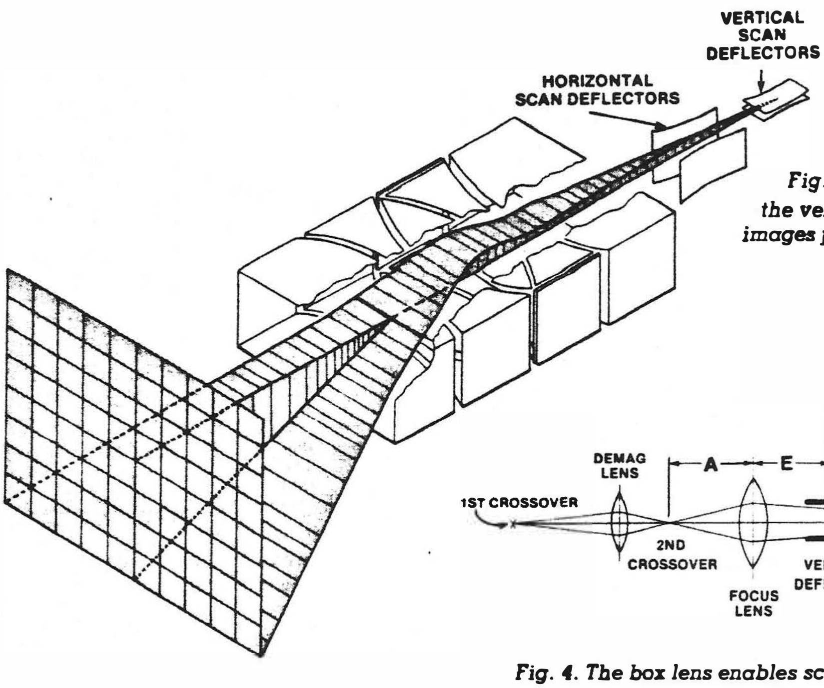

Fig. 3. The box lens reimages to a round spot the vertical and horizontal line images produced by the astigmatism lens.

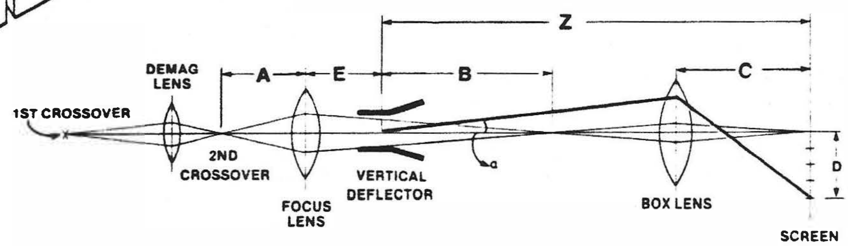

Fig. 4. The box lens enables scan expansion on the screen, while keeping the length of the CRT reasonable (21 inches).

flection voltage were available for scan, then tan α would nearly double and spot size could be half. Likewise, if scan size were doubled, then spot size would also double. Since the vertical deflectors are usually the critical deflector pair for sensitivity and bandwidth, E is usually chosen small, but not zero. Thus, the box magnification, Mbox, always adds to the spot magnification.

For example, in the T7100 CRT, Z = 13.4″ and Mscan = 4.5, so that ZMscan = 60.3. From Fig. 4 we get

$$Mbox = \left|\left(1 - \frac{C}{F}\right)\right|,$$

where F is the focal length of the box lens in the vertical direction. With C = 6″, F = 0.6″, and E = 2″, we get EMbox = 18, and Mts = 78.3.

If no scan expansion lens is used, Mscan = 1, and the required value of Z is 60.3″. With E = 2.0″, we then have Mts = 62.3. Thus, for any given value of anode length A, the spot size, neglecting the effect of spherical aberration and space charge, would be 0.8 times as large if no scan expansion were used. To obtain the same scan, however, the CRT would have to be over five feet long. Thus, to keep the value of Mbox and resulting spot magnification small, the CRT is made as long as practicable (21 inches).

Low-bandwidth, electrostatically-deflected CRTs, which do not have high deflection sensitivity or scan expansion lenses, are usually about 16″ long with Mts equal to 12. Thus, the microchannel plate CRT would have over 6.5 times the spot size of a conventional CRT with equivalent anode length if it were not for the crossover demagnification lens employed in the first anode section. This lens forms a second crossover which, after being demagnified about four times, is reimaged by the focus and astigmatism lenses (Fig. 1). The demagnifying lens, however, creates a highly divergent beam, the current of which is mostly blocked out by the current-limiting aperture in the anode section. Since only a small beam current is required to excite the microchannel plate, a bright display with a high writing speed is still the result.

Electron Optics

Plots of the equipotentials and trajectories as they lie along the center horizontal plane of the box lens would show how the scan envelope is magnitifed and spread by the lens, and would show how nicely the equipotentials along this plane follow generally the circular arcs described by the electrode gaps. This makes lens design simple when trying to determine the effect of the circular arcs on the horizontal scan. A wide range of horizontal focal lengths can be designed in this manner without disturbing the vertical scan, since it stays close to the axial plane and crosses this plane along the line shown (Fig. 3).

The vertical scan envelope behaves as if it were positioned inside a cylindrical lens. The trajectories are slowed and spread as they enter the low voltage portion of the lens (550 volts). See Fig. 2 and Fig. 3.

Then, under the influence of the high voltage (4200 V) electrode, they accelerate and cross over the center horizontal plane to be projected onto the screen.

Feasibility of the box lens was demonstrated in a working CRT before the lens was modeled on the computer. Because the lens was chosen to have a box shape, it was a simple matter to cut semicircular arcs into a metallic box and mount it onto a CRT gun.

Computer Modeling

Designing the lens, using actual working models, proved to be easier than computer modeling. In less than six months and at a cost of less than $3000, the lens described in this article was shown to be feasible. In retrospect, it was the proper choice of box dimensions that made the project a quick success. Had any other dimensions been chosen, curves other than semicircular arcs would have been necessary to obtain an acceptable display. A box as large as possible which would still fit comfortably in the round portion of the CRT bulb behind a 5" faceplate was needed. Various circular cuts were tried and a wide range of voltages applied in an effort to determine a working pattern for semicircular electrode shapes.

The lens was eventually modeled on the computer, resulting in a reduction of the number of electrodes from nine to four, although nine electrodes are used in the T7100 CRT for correction of misalignment problems encountered in the manufacture of the CRT.

Because of two-fold symmetry (X and Y), only one fourth of the volume of the lens needed to be considered for the solution of the LaPlace equation to determine the potential inside the lens. A total of 27,742 (97 x 26 x 11) computer memory locations were required to model the lens. Trajectories were then run through the model which gave 1% accuracy. A Liebman procedure with an overrelaxation factor was used to iterate the array to reduce the greatest voltage difference from the preceding iteration to less than 0.01%. Using a CYBER 73 computer, less than 90 CPU seconds were required to obtain the proper electric field for each design. The trajectory calculation took 15 CPU seconds each.

Display Distortions

Fig. 2 shows how differential voltages are applied across the elements to correct for vertical line bowing and vertical line keystoning. The keystone problem occurs because of either misalignment of the horizontal deflector pairs or misalignment of the electron gun and box lens. Normally, in CRTs with solid deflection plates, it is possible to adjust the side-to-side plate spacing to be parallel after gun fabrication. But, in the case of the T7100 CRT, distributed delay line horizontal deflector pairs are comprised of 30 individual segments, and such adjustment is impractical.

Facing the CRT screen (Fig. 5), one can see how random misalignment of the horizontal deflectors can cause the keystone problem. For example, when the beam is

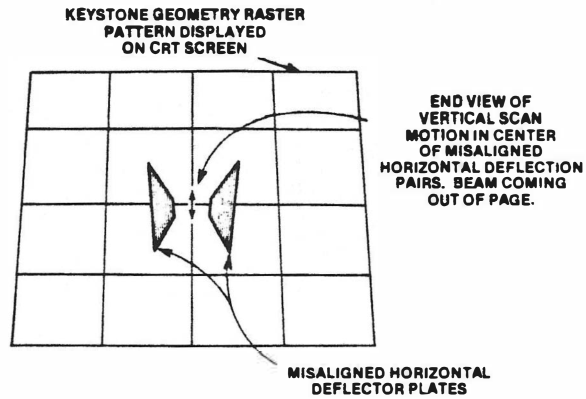

Fig. 5. The keystone effect is corrected by differential voltages applied across elements of the box lens (Fig. 2).

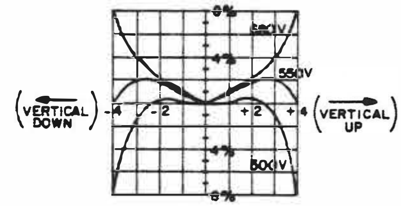

Fig. 6. Vertical nonlinearity of the display, in percent, is depicted as a function of position of the beam spot on the screen, in scale divisions. Optimum condition is achieved with 550 volts on the egg-shaped electrodes of the box lens (middle curve).

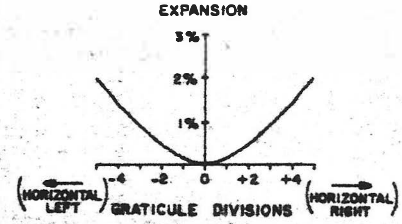

Fig. 7. Horizontal nonlinearity of the display is depicted as a function of position of the beam spot on the screen in scale divisions. The box lens is tailored to have a 2% expansion value at the edge of scan in order to compensate for a 2% compression in the output amplifier.

scanned to the lower half of the screen, it passes through the closer spaced portions of the deflector pairs where deflection sensitivity is greater. Conversely, when the beam is scanned to the top half of the screen, a smaller deflection sensitivity is the result because of the wider deflector pair separation. The misalignment shown in Fig. 5 is exaggerated for pictorial purposes, but in an actual CRT the side-to-side misalignment need only be 0.0005" to produce an objectionable amount of keystone distortion.

The vertical line bowing problem is a result of the imperfect alignment of the lens with the electron gun. With high magnification values, small misalignment problems are magnified and show up on the MCP screen as slightly bowed lines. Normally this slight bowing is acceptable if it occurs at the edge of the screen; at screen center, however, where greatest accuracy is expected, no perceptible bowing is tolerable.

Vertical linearity is depicted in Fig. 6 as a function of voltage on the egg-shaped 550 volt electrodes (middle curve). Ideally, the CRT should produce a display so that one volt applied across vertical deflectors will deflect the scan exactly one division. In the case of the T7100 CRT, when the beam is scanned up or down 2.5 divisions, a 2% nonlinear expansion occurs, so that an additional volt will actually change the scan 1.02 divisions. Nonetheless, this is still a very acceptable nonlinear characteristic, since the scan would have to change 1.05 divisions to be noticeably objectionable.

At the edge of the scan (+ or −4 divisions), a one-volt differential across the deflectors will change the scan exactly one division (0% nonlinearity). If the voltage on the egg-shaped electrode is changed from 550 volts to 680 volts, a one-volt change on the deflection plates will change the scan 1.08 division (8% nonlinear expansion) at the edge of scan (+ or −4 divisions). If the voltage is changed from 550 volts to 500 volts, the deflection will change 0.92 division (8% nonlinear compression) at the edge of scan.

Thus, vertical linearity at the edge of scan can be accurately controlled, and can be made to compensate for any nonlinearities in the output amplifier simply by adjusting the voltage on the egg-shaped electrode. Further changes on this electrode will significantly alter the total scan magnification.

In the horizontal axis, where timing accuracy is extremely important, the lens is tailored to have a 2% expansion value at the edge of scan to compensate for a 2% compression in the output amplifier (Fig. 7). Thus, the horizontal timing accuracy provided by the combination of CRT and output amplifier is extremely good.

Box Lens Versus Mesh Lens Operation at High Voltage

Another feature of the box lens is that the final lens voltage can be raised to as high as 24 kV without significantly altering the scan expansion or display characteristics. This permits the lens to be used in place of a domed mesh expansion

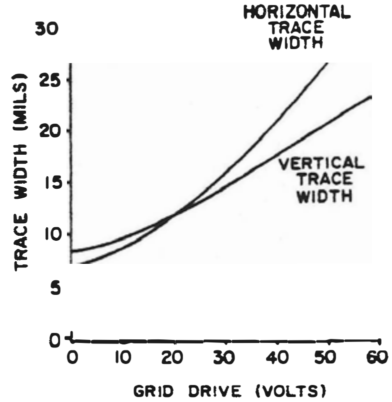

Fig. 8. Horizontal and vertical trace widths are shown as functions of grid drive voltage. A round spot is achieved at 20 volts, an optimum setting for normal viewing.

lens without a microchannel plate.

The only disadvantages of the box lens are that it is more bulky than the domed mesh and, when used without an MCP, the voltage applied to the forward bowtie-shaped electrode must be higher than the screen voltage. In addition, it is difficult to maintain a high voltage across the electrode gaps unless special precautions are taken to minimize field emission.

When operated at high voltage, however, the box lens offers a performance advantage over the domed mesh because it eliminates beam intercept and diffraction caused by the mesh. In addition, the scan magnification factor is about two times what can be achieved with a mesh. Thus, the deflection plates can be more widely separated with less flaring, or the gun can be operated at a higher voltage without losing deflection sensitivity. This permits the passing of a larger beam envelope, with reduced space charge effects, a feature used to improve trace brightness and/or reduce spot size. The results show that, for equal deflection sensitivity and screen high voltage, the spot size produced by the box lens is consistently two-thirds the size of that produced by the mesh lens for all beam currents.

Fig. 8 shows the variation of horizontal and vertical trace width as the grid drive is increased. Space charge, coupled with the difference in positions of the horizontal and vertical line images generated by the focus and astigmatism controls (Fig. 1), results in the horizontal spot size growing faster than the vertical. In this case, the spot will be round at 20 volts drive, which is probably the most used drive setting for normal viewing. Further increases in drive voltage (trace brightness) will cause the spot to become eliptical with the long axis in the horizontal direction.

A quadrupole, if it were to be inserted between the horizontal and vertical deflection pairs to enhance vertical scan, would reduce the beam convergence in the vertical direction, and would offset the tendency for the spot to be elliptical as grid drive and space charge are increased. In the T7100 CRT no quadrupole is necessary, because only a small amount of beam current is required to operate the microchannel plate and because the gun is not operated in a space-charge limited mode.

Conclusion

If bulkiness is not a problem, the excellent display characteristics, the simplicity of design, the ability to generate a variety of different focal lengths in both the horizontal and vertical axes, and the ability to correct for gun-lens misalignment problems should make the box lens highly desirable for oscilloscope displays that need high magnification factors. Thus, the box lens, although tailored for use in a high bandwidth microchannel plate CRT, should find, because of its versatility, some acceptance as a scan expansion lens for other CRT designs, both with and without post-deflection acceleration.