THE QUADRUPOLE LENS JOINS LONG LINE OF CRT IMPROVEMENTS

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CRTs In Oscilloscopes

Although relatively ancient in concept, the modern CRT is the primary signal-detection and output port for the modern oscilloscope. Flat panels, electroluminescence, and LEDs have challenged but are unable to replace the CRT. The CRT, itself, is a remarkable device. As circuit technology has advanced, the CRT has not stood still.

Inexpensive logic has allowed us to incorporate in portables features that were previously practical only in the more expensive lab scopes. Three of these features are alphanumeric readout, display cursors, and autofocus. In addition, circuit designers have been able to reduce costs by driving the CRT directly from integrated circuits. System designers have been able to reduce size and weight without compromising the display size or heat-dissipation.

Let's consider for a moment what these achievements mean for the CRT designer.

Roughly speaking, the instrument's bandwidth dictates how fast the fastest sweep rate must be. Sweep rate, in turn, determines the trace-brightness or writing-speed requirement. Secondly, alphanumeric CRT readout requires fine spot size and no visible jitter. The compactness of the instrument package is limited directly by the CRT length, as well as indirectly by the power needed to drive the deflection system. More power requires larger transformers, less dense circuitry, and more volume to dissipate heat.

Consequently, for a given bandwidth and a specified display size CRT designers focus on four parameters:

1. Trace brightness or writing speed
2. Trace quality (spot size)
3. Tube length
4. Power consumption

These four parameters interrelate complexly. Trace quality is influenced by such CRT factors as lens aberrations, space-charge repulsion within the beam, deflection defocusing, and the magnifications of the optical system. These CRT factors, in turn, interact with brightness, tube length, and power – parameters 1, 2, and 3. Therefore, the CRT designer always finds optimization difficult. These problems have driven the CRT to take another step upward. This step is the new quadrupole scan expansion CRT[1].

The Evolution of the CRT

Figure 1 shows a CRT as the output port of a system, interfacing to X and Y deflection amplifiers and to a Z-axis beam-intensity modulating circuit. The focus system and low- and high-voltage power supplies are not shown. This simple *monoaccelerator* CRT closely resembles the earliest oscilloscope CRTs, which used only a beam source that also accelerated the beam toward the phosphor target, an axi-symmetric (round) focus lens, and two sets of simple deflection plates.

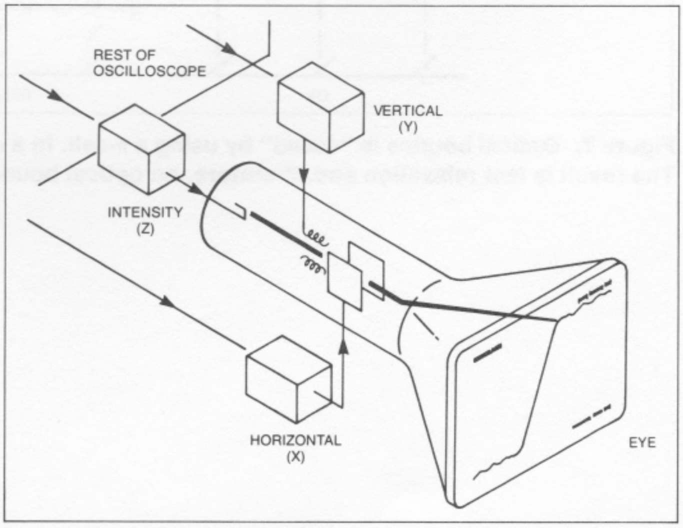

Figure 1. The CRT as part of a system.

Although monoaccelerators can produce excellent traces, writing rate can be a problem. To display fast signals, the beam energy must be increased to the point where the deflection sensitivity becomes very poor. Consequently, deflection requires too much power. These problems led to the introduction of the post-deflection acceleration (PDA) designs. In these designs, the beam is accelerated only modestly before deflection. This low-energy beam is again accelerated following deflection. In this way, higher writing speed is attained.

One post-deflection scheme, the helix PDA, was used by Tek in the late 50s and 60s. Helix PDA use was common when Tek started using it in oscilloscopes.

In this type of PDA CRT, a resistive helix distributes the accelerating voltage so that while the writing speed is substantially increased, the deflection sensitivity is more or less preserved; in some cases, it drops, but not severely.

In the 60s, deflection sensitivity in the helix scheme was improved by shaping the accelerating field with an electron-transparent electrode. This electrode was often a grid of fine metal wire, hence the name "framegrid PDA" was applied to these improved tubes. In 1965, Chris Curtin developed the first truly high performance CRT for a Tektronix portable, the 453.

In the late 60s, CRTs using a fine metal mesh as a lens to shape the accelerating field were introduced; these came to be known industrywide as "mesh scan expansion CRTs."

Scan expansion designs use a post-deflection lens to magnify in both axes as much as three times. Because deflection system power is proportional to the square of the electron energy in the deflection region and inversely proportional to the square of the scan magnification, designs using both scan expansion and post-deflection acceleration enjoy both improved deflection sensitivity and higher writing speed.

The Mesh Scan Expansion CRT

The mesh PDA CRT (figure 2(A)) has a final divergent lens formed of a very fine wire electroformed mesh. The beam passes through this mesh. After passage, the beam is deflected away from the long axis by fields formed between the mesh and the high-voltage conductor on the wall of the CRT. These fields magnify the scan up to three times. This form of scan expansion has enjoyed great success over the past decade, and has become almost universal in high-performance scopes.

In spite of this success, CRTs employing mesh technology have serious drawbacks:

1. The mesh intercepts and scatters the beam.
2. The mesh emits secondary electrons and produces the phenomenon of mesh halo around the spot. (Unless it is coated with MgO, which partially relieves the problem.)
3. The mesh is easily contaminated by small particles during manufacturing, causing defects visible in the display.
4. Horizontal sensitivity is difficult to increase.

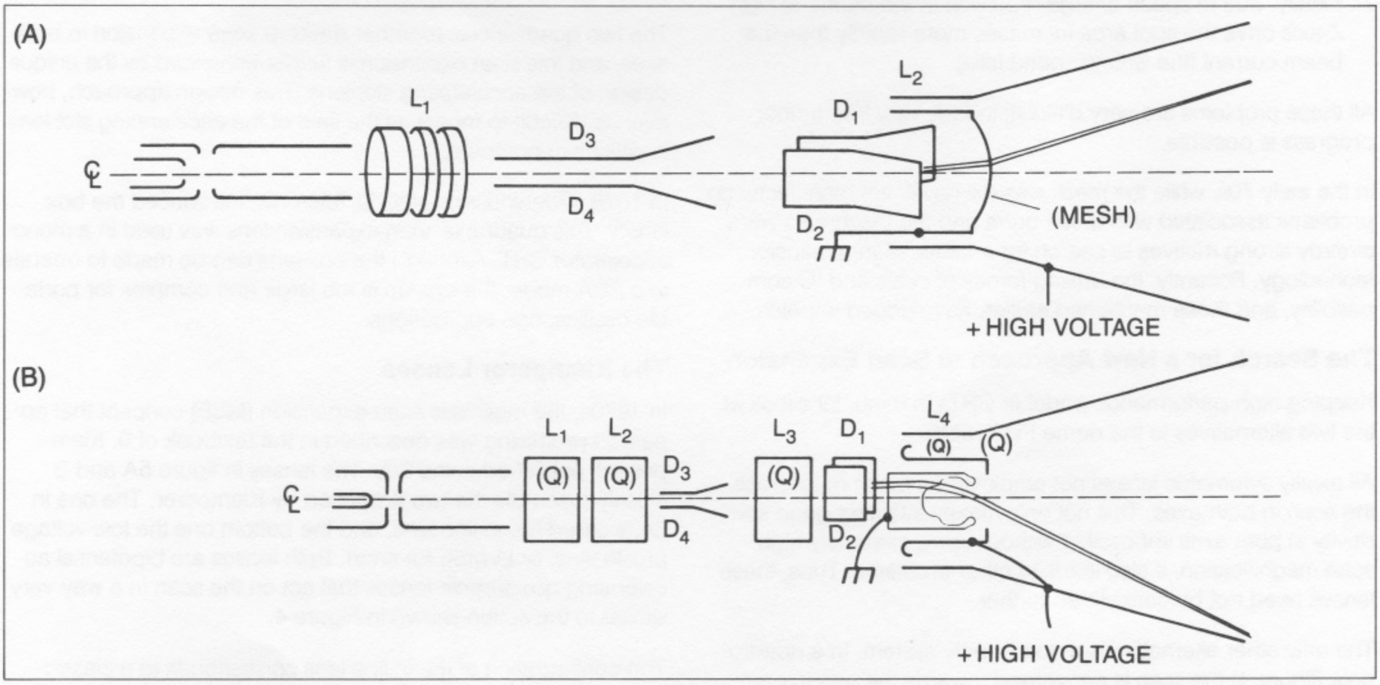

Figure 2. Schematic diagrams of (top) the conventional mesh CRT, and (bottom) the new quadrupole meshless scan expansion (MSE) CRT.

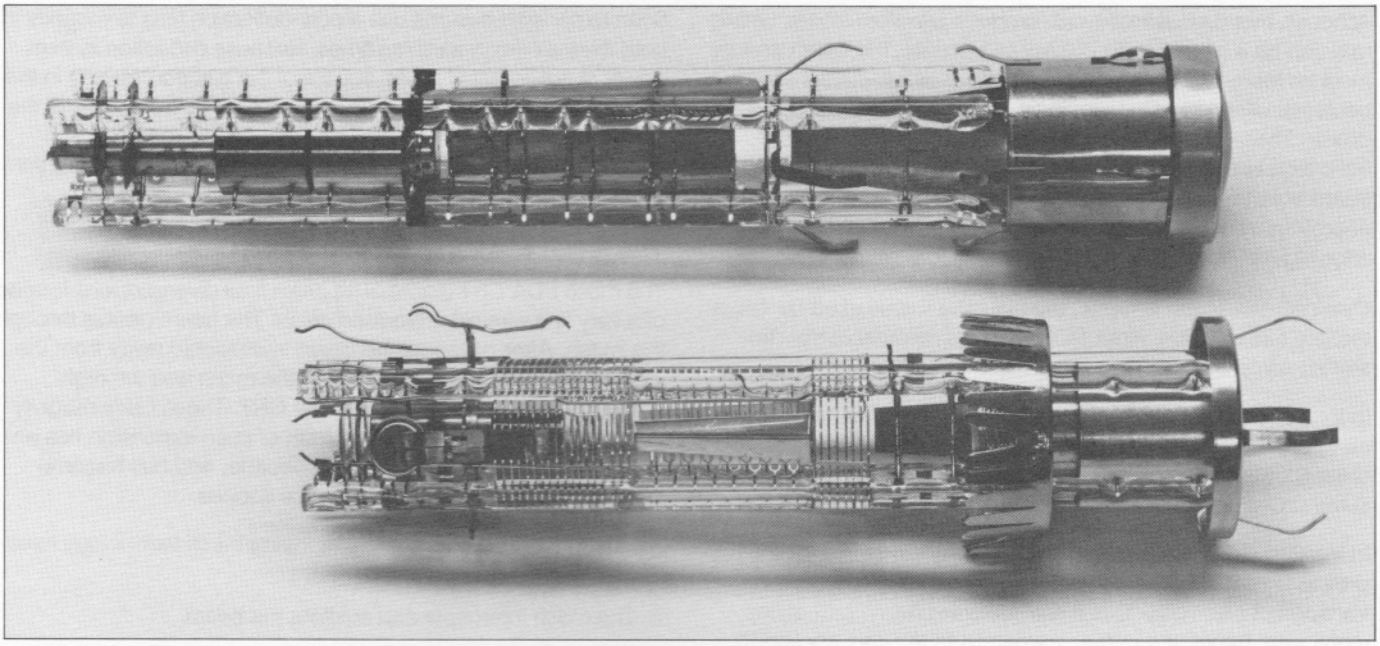

Figure 3. The MSE system (bottom) offers more scan expansion than a conventional mesh system, allowing shorter deflection plates and a shorter overall gun for the same performance level.

5. The horizontal deflectors have fairly high capacitance.
6. Most important, the deflection system is not sensitive enough to be compatible with high-speed IC drivers.
7. Finally, due to space-charge repulsion in the beam, at high Z-axis drive the spot area increases more rapidly than the beam current (the writing speed falls).

All these problems are very difficult; in fact, very little further progress is possible.

In the early 70s, while the mesh was still novel, the manufacturing problems associated with mesh burrs and the mesh halo were already strong motives to search for a better scan-expansion technology. Recently, the driving forces of costs and IC compatibility, and those mentioned earlier, have added impetus.

The Search for a New Approach to Scan Expansion

Keeping high-performance portable CRTs in mind, let's look at the two alternatives to the dome PDA mesh.

All axially symmetric lenses not employing a mesh must cross the scan in both axes. This not only makes attaining good sensitivity in both axes impossible without using extremely high scan magnification, it also leads to other problems. Thus, these lenses need not be considered further.

The only other alternative is a quadrupole system. In a quadrupole (figure 4) the scan is converged towards the axis in one plane (A) and diverged away from the axis in the other (B). The crossection normal to the center axis of the lens (C) shows the classic hyperbolic-shaped equipotential lines.

In 1971, Martin and Deschamps[3], at Thomson-CSF, introduced a short 11.5-inch scan-expansion CRT. This CRT employed two quadrupoles. One quadrupole was placed between the two sets of deflectors, and the second was located just ahead of an accelerating slot-aperture lens. The aperture lens exits into high-voltage post-acceleration space.

The two quadrupoles together develop scan expansion in both axes, and this scan expansion is further enhanced by the unique design of the accelerating slot-lens. This design approach, however, is difficult to model as the field of the accelerating slot lens is difficult to compute.

In 1978, Odenthal and Hall, at Tektronix, introduced the box lens[4]. This quadruple scan-expansion lens was used in a mono-accelerator CRT. Although the box-lens can be made to operate in a PDA mode, the system is too large and complex for portable oscilloscope applications.

The Klemperer Lenses

In 1970s, the meshless scan expansion (MSE) concept that appeared promising was described in the textbook of 0. Klemperer[5] published in the 30s. The lenses in figure 5A and B closely resemble the two proposed by Klemperer. The one in 5A is called the in-line lens, and the bottom one the low-voltage profile lens, or LVMSE for short. Both lenses are bipotential accelerating quadrupole lenses that act on the scan in a way very similar to the action shown in Figure 4.

The configuration of the in-line lens corresponds to a classic electrostatic field problem. In this case, the field can be obtained by solving LaPlace's equation in cylindrical coordinates by the separation of variables method. This solution leads to a sum of terms of the form $I_m(kr)\cos(m\theta)\cos(kz)$, where $I_m(x)$ is the modified Bessel function. Because these lenses have two planes of symmetry, only terms in even values of m appear. The resulting series is the well known Fourier-Bessel expansion[6].

From these earlier works, we developed an extensive software package to model Klemperer lenses of both types. Because Fourier methods alone will not solve the second class of Klemperer lenses, relaxation methods in cylindrical coordinates were used to calculate the field. The Fourier-Bessel expansion was then used to analyze the field near the center axis of the lens. Something in excess of 20,000 lines of FORTRAN code were written to investigate these interesting structures. This effort lead to the new quadrupole MSE CRT design[7,8], which is discussed next.

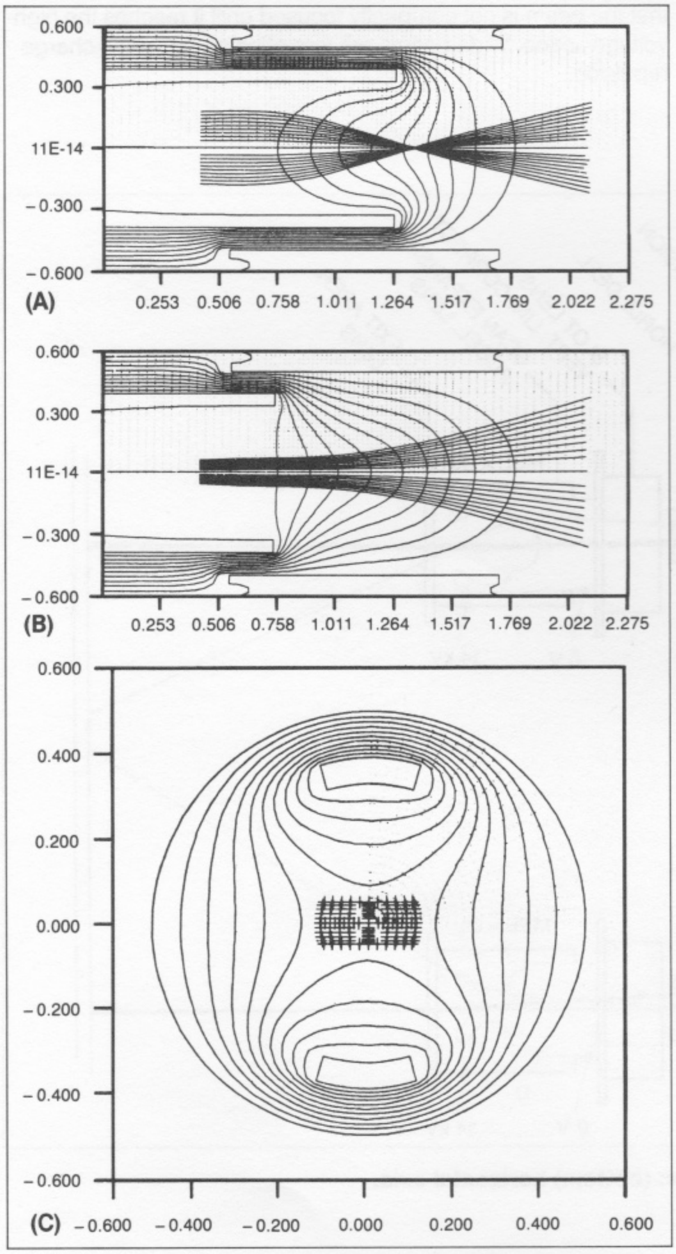

Figure 4. These computer-plotted diagrams show the action of quadrupole lenses in (A) vertical plane, (B) horizontal plane, and (C) cross-section of lens. In a quadrupole, the scan is converged towards the axis in one plane (A) and diverged away from the axis in the other (B). The cross-section normal to the center axis of the lens (C) shows the classic hyperbolic shaped equipotential lines.

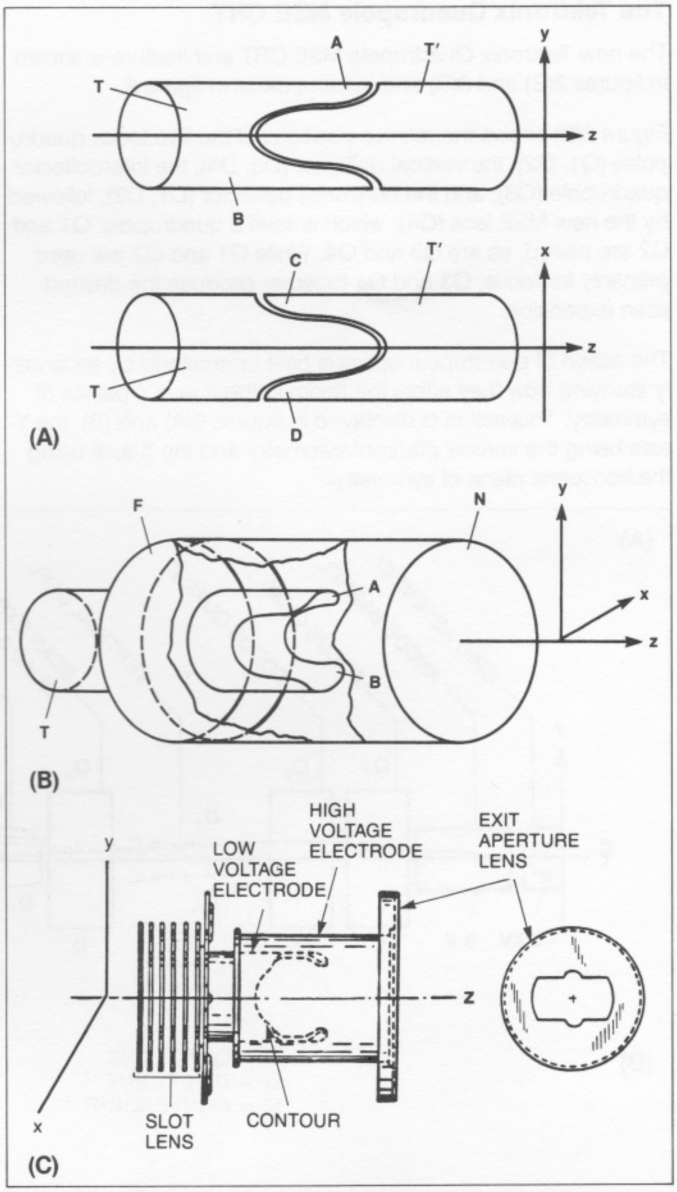

Figure 5. (A) The in-line Klemperer lens and (B) the type II Klemperer (low-voltage profile) lens. Klemperer described these lenses more than 40 years ago.[5] (C) The new low-voltage MSE configuration.

The Tektronix Quadrupole MSE CRT

The new Tektronix Quadrupole MSE CRT architecture is shown in figures 2(B) and 3(B) and in more detail in figure 6.

Figure 2(B) shows the relative positions of the two focus quadrupoles (Q1, Q2), the vertical deflector (D3, D4), the interdeflector quadrupole (Q3), and the horizontal deflector (D1, D2), followed by the new MSE lens (Q4), which is itself a quadrupole. Q1 and Q2 are paired, as are Q3 and Q4. While Q1 and Q2 are used primarily for focus, Q3 and Q4 together produce the desired scan expansion.

The action of quadrupole optics is best understood by separately studying how they effect the beam in the X and Y planes of symmetry. This action is displayed in figures 6(A) and (B), the Y-axis being the vertical plane of symmetry and the X-axis being the horizontal plane of symmetry.

Beginning with Q1, the behavior alternates between convergence and divergence in each plane of symmetry. In normal operation, the voltages of Q3 and Q4 are static, while those of Q1 and Q2 may be varied to maintain focus as the beam intensity changes. The field of the Q4 lens is roughly twice as strong in the horizontal plane as it is in the vertical. To gain sufficient vertical scan expansion, the Q3 lens is oriented to assist the vertical deflector and Q4 in crossing the scan through the axis at a sufficient angle.

A second important feature of this quadrupole configuration is that the beam is not compactly focused until it reaches the high-voltage space. Wide beams are less affected by space-charge repulsion.

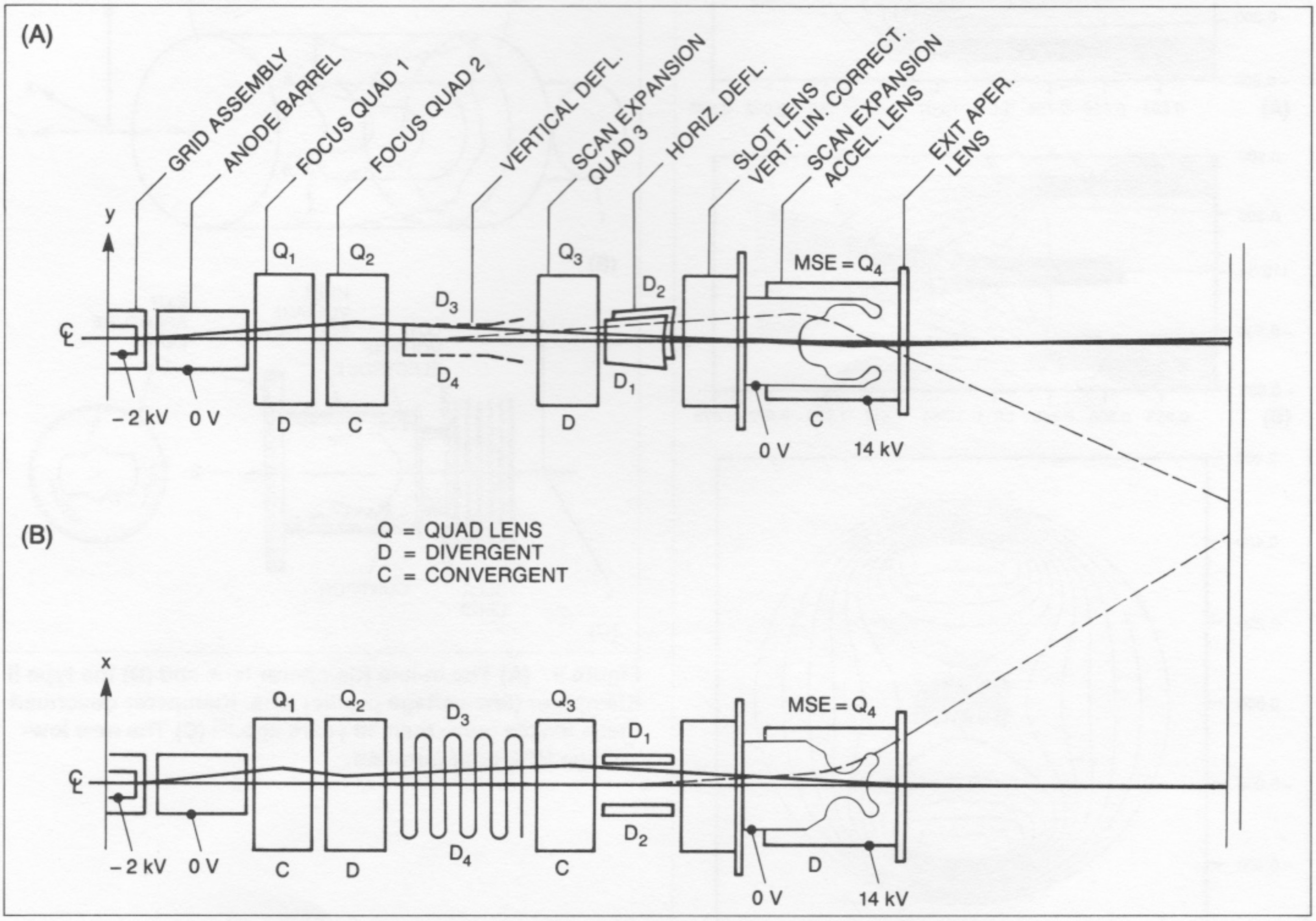

Figure 6. Schematic diagrams of MSE CRT: (top) vertical axis; (bottom) horizontal axis.

Technological Features of the Tektronix Quadruple Lens CRT

LVMSE lens

The contoured inner electrode shown in figure 5(C) is shaped to tailor the geometry and linearity of the display. Although this lens is predominantly a quadrupole, it also contains higher-order multipole elements, such as octopole ($m = 4$) and dodecapole ($m = 6$). Without these corrective elements, the display would be badly pincushioned. The Fourier-Bessel expansion, therefore, must include terms in $\cos(m\theta)$ for $m = 0,2,4,6$.

Figure 4 shows the distribution of equipotentials and the action on the scan in each axis. The lens has a horizontal focal length of about 0.4 inch and a vertical focal length of about 0.8 inch. The scan is expanded in quadrupole fashion, magnified 3.5X vertically and horizontally. At the same time, the electron beam is accelerated from 2000 volts to 16,000 volts.

Other important features of the MSE lens are that it is lightweight, very rugged, and simple to manufacture from a piece of stainless-steel tubing. After forming, the part is conditioned to withstand high-gradient fields. The result is an inexpensive high-quality lens that can survive high mechanical shock. Because the lens is small (approximately 2 inches in length and 1.5 inches in diameter) and is a simple bipotential system, it is excellent for portable applications.

Meanderline deflector

Figure 7(A) shows the unique Tektronix patented meandering-line deflector[9]. This deflector has a bandpass adequate for at least a 400-MHz applications. It also possesses the unusually high impedance (for a meanderline) of 335 ohms (side-to-side). It is etched in the flat from a single piece of stainless steel (figure 7(B)), formed at rodding, and held firmly in the glass rods to provide a lightweight, very rigid, and shock-resistant deflector. Compared to the helical deflector subassembly shown in figure 7(C), it is very inexpensive.

Snubber system

Another unusual feature of this CRT is the unique front snubber system that cradles the gun within the glass funnel. This snubber permits very little gun motion; shocks in excess of 150 g will not fracture the rods, funnel, or feedthroughs.

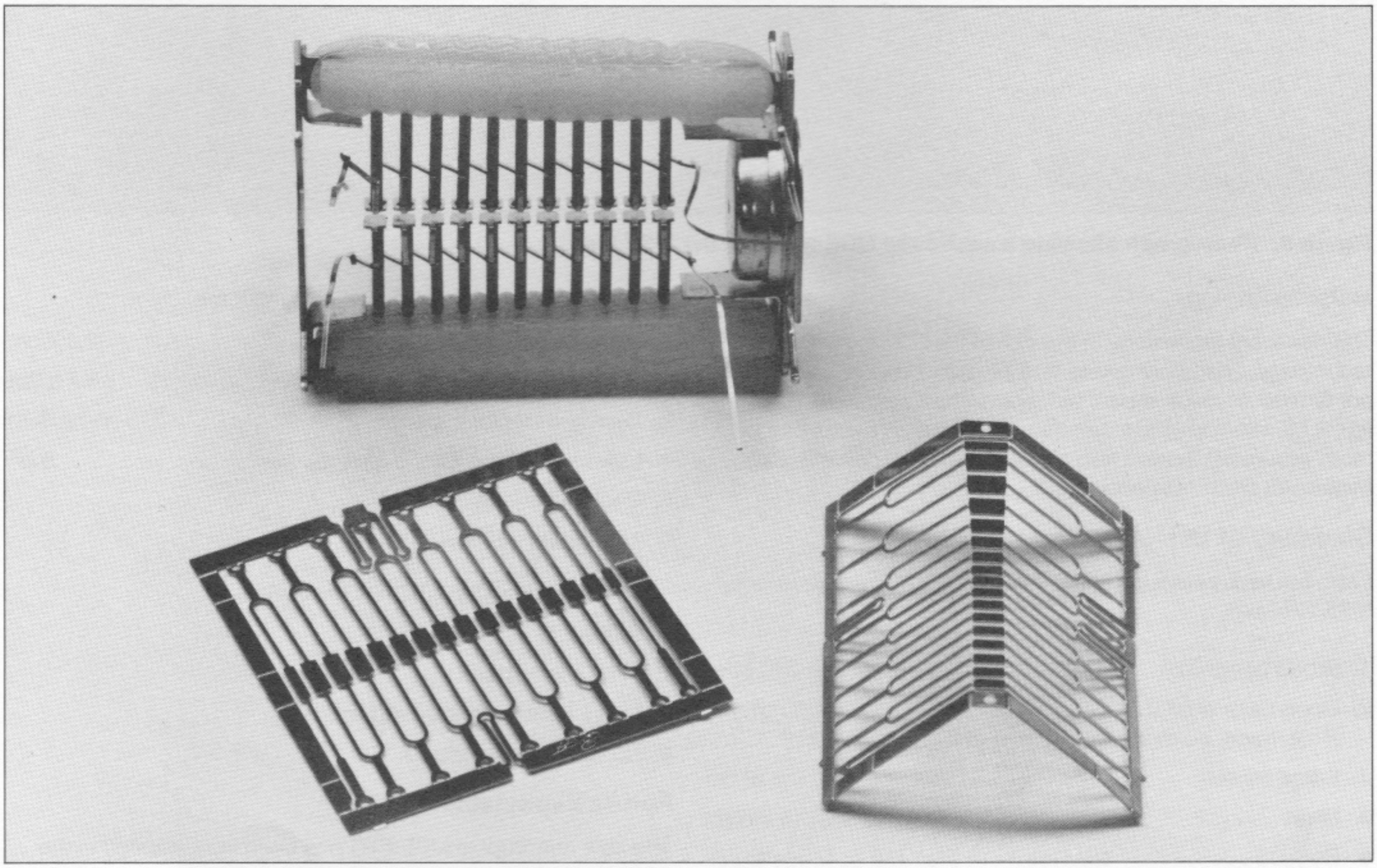

Figure 7. A meanderline in the flat (bottom left), the formed meanderline (bottom right), and a helical deflector (top).

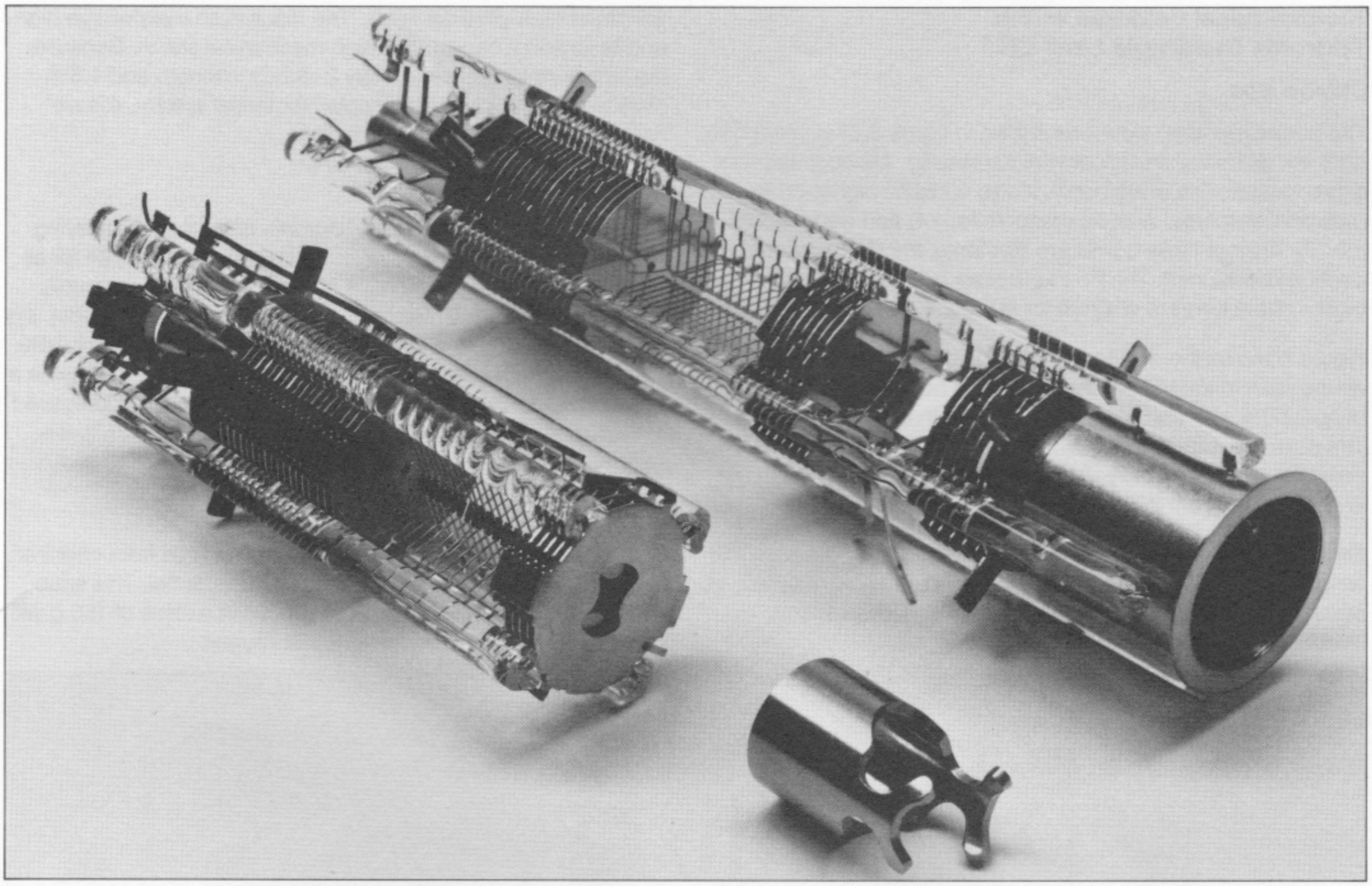

Figure 8. Photograph showing a sectioned MSE gun and the MSE lens.

Wafer technology

The dominant technology in the rest of the CRT is wafer-lens technology. The quadrupoles and several other components are formed as metal wafers with appropriate apertures (see figure 8). Although there are many wafer parts, wafers can be more accurately formed and aligned. Automated forming also makes the parts inexpensive.

Summary of Design Goals

From the user perspective, the key features of the Quadrupole MSE CRT are:

1. Broad bandwidth . . . . at least 300 MHz
2. Good trace quality . . . . 8-9 mil spot (crisp trace, no more than 30 mils at high Z-axis drive)
3. Large screen . . . . 8 × 10 cm
4. Short . . . . no more than 14 inches
5. Rugged . . . . survives more than 150 g, 11-ms shock
6. High writing speed . . . . WSI at least 3.0
7. CRT readout capability
8. Autofocus w/intensity

Features of interest to the circuit designers are:

1. Vertical deflection sensitivity . . . . 2.3 V/cm
2. Horizontal deflection sensitivity . . . . 3.7 V/cm
3. Vertical deflector impedance . . . . 335 ohms (S-S)
4. Low capacitance D1D2 . . . . 5 pF
5. Compatible with IC drivers
6. Low power consumption

Features of interest to CRT manufacturers:

1. Amenable to automation
2. Inexpensive parts
3. Good scheme for part alignment
4. No complex processes.

Future Expectations

The new quadrupole MSE CRT has been implemented in the 2400 family of oscilloscopes. (See "High-Speed Monolithic Horizontal Amplifier . . .," *Technology Report,* June 1983). Most of the design goals have been met in this application. It is expected that even better results will be achieved with this new technology. The quadrupole lens should replace mesh scan expansion in most real-time waveform CRTs. ☐

Elementary Design Rules

B = power density in beam (writing speed or trace brightness)

= energy/unit area/unit time

$\sim$ (beam current) × (accelerating voltage)/(trace width)

$= I_b \times V_p / T_w$

V_d = deflection voltage required

$\sim$ (gun voltage)/(scan magnification)

$= V_g/M$

P = power required by the deflector

= (deflection voltage)^2/(impedance)

$= V_d^2/Z$

$\sim (V_g/M)^2$

Fourier-Bessel Expansion

$$V(r,\theta,z) = \sum_{k=0}^{\infty} \sum_{m=0}^{\infty} Cmk \, I_{2m} (\hat{k}r) \cos(2m\theta) \cos(\hat{k}z)$$

where:

R = radius at which boundary values $V(\theta,z)$ hold

L = length of field region where symmetry conditions $V(\theta, L-z) = V(\theta,z) = V(\pi-\theta,z)$ are assumed

$I_m(r)$ = modified Bessel function of order m

$\hat{k} = (2\pi/L)k$

$C_{mk} = (1/N_{mk}) \int\int V(\theta,z) \cos(2m\theta) \cos(\hat{k}z) \, d\theta \, dz$

$N_{mk} = 4\pi^2 I_{2m} (\hat{k}R)$

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