A NEW HIGH-SPEED CRT

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Abstract — A novel high-speed CRT for oscillographic applications is described. Outstanding features in this device are a large-area microchannel-plate electron multiplier, a high-bandwidth deflector and peculiar electron optics with a box-shaped scan expansion lens. In this text, a cursory look at the state of the art of fast oscillography is followed by the description of the CRT design, construction, and performance.

I. INTRODUCTION

High-speed oscillography is an exciting art, one of these disciplines in which performance barriers are a primary challenge and where questions of economic nature are less frequently asked. Fast oscillographic techniques employ cathode ray tubes (CRTs), which are devices of formidable signal conversion capacity and adaptability. As an illustration of this adaptability, it is worth noting that commercial television displays started out as mere adaptations of oscillographic CRTs, but a viable substitute has not emerged yet in spite of prevalent belief that an inherently more suitable TV display can and should be found.

An oscillographic display can be viewed as an operation of the type:

$$F(V, t) \rightarrow f(V, V'(t)) \rightarrow \phi(x, y), \qquad (1)$$

where V' is a linear function of time during the period of observation, representing a time base of the horizontal sweep. The right-hand side in the above expression does not contain time, indicating that our time-dependent signal $F(V, t)$ has been converted into something permanent. The display $\phi(x, y)$ will then last, either frozen on a photographic medium or in the memory of an observer. Today there is a growing tendency to use digital storage media to preserve results of $F(V, t) \rightarrow \phi(x, y)$ conversion, to facilitate transport and processing of results. Here, a variety of devices are used to capture and digitize time-dependent electrical signals: scan converters,[1] electron-beam digitizers,[2] and solid-state and analog-to-digital converters. Though we are witnessing rapid growth in performance of purely solid-state conversion devices, electron-beam-based devices lead the way in high-speed conversion performance. And the fastest signal converters available today are classical real-time oscilloscopes. What is classical about these instruments is their basic architecture, like the trigger and time-base concept, short-term storage of the signal in a delay line, then a basic CRT display, etc. There is nothing classical about components for this system, however. The circuitry, the implementation of architecture, and the displays have reached high levels of sophistication. Design and performance considerations for one such display CRT is the topic for this article.

II. FACTORS GOVERNING CRT SPEED

There are two major factors describing a fast CRT performance: its vertical bandwidth and its writing speed. In a CRT, these two performance parameters are to a large extent mutually independent, although they become very much interrelated when the system design is considered.

A. Vertical Bandwidth

When we speak about a bandwidth of a CRT, we, by convention, imply an upper cutoff frequency used in a low-pass filter mode. Moreover, it is customary to use this single parameter, the "bandwidth," which belongs to frequency domain family of phenomena, to describe performance of a CRT device typically used to display phenomena in time domain. What all this amounts to is that one would like to have a CRT deflection structure where the deflection of an electron beam at the screen follows a sinusoidal electrical signal imposed on the deflector both in amplitude and in phase as closely and as monotonically as possible. When the amplitude of the sinewave on the screen drops to 0.707 of the amplitude corresponding to dc deflection, the frequency where it happens is pronounced to be a "3-dB bandwidth" of this tube. An approximate formula, much in use, to relate the risetime of a CRT to its bandwidth is:

$$t(ns) = \frac{0.35}{f_{3dB}\,(\mathrm{GHz})} \qquad (2)$$

Electrostatic parallel deflection plates cannot be used to uniformly deflect electron beams at frequencies much beyond 100 MHz, unless they are made extremely short. As the frequency increases, the finite time of electron transit through deflection plates causes the deflection sensitivity to drop to zero and then to oscillate around zero in a fashion $\sin(kf)/kf$, where k is a constant characteristic of a tube design.[3] What is less well known is that in electrostatic deflection plates which are not parallel but flared to optimize the deflection sensitivity,[4] the frequency response never becomes zero although it steadily decreases toward higher frequencies. One could, then, at least in principle, produce a compensation network and utilize such flared deflectors to attain very high bandwidths, at a great loss in deflection sensitivity, of course. The problem is that it is not practical to drive capacitive loads which such deflectors represent, so what is in widespread use for fast deflectors are structures which employ both inductive and capacitive elements. The deflector thus comprises an electrical delay line, with constant impedance and with electrical signal propagation velocity which matches the electron beam velocity, to reduce transit time attenuation phenomena. Analytical techniques have been developed for the design of distributed deflection structures.[5] Still, such techniques apply to deflectors with certain uniform properties and in the design of actual deflection structures final touches are done empirically, causing some to view the design of fast deflectors as an art. The state of this art is that CRTs with bandpass from dc to several GHz can be built today.

B. Writing Speed

In viewing periodic waveforms, one is seldom concerned with a question of writing speed since any brightness level in a display can be built up by successive impact of electrons over the trace. In viewing single transient phenomena, especially if transients are rare or expensive to produce, the question of writing speed becomes paramount, and this is where the greatest progress was made in recent years. In conventional oscillography, a camera is attached to an oscilloscope, the sweep trigger is set and when the event occurs, the image of the spot moving over the screen is recorded on film. Oscillography with conventional CRTs will record spots moving in excess of 10^9 cm s^{-1}. Using new approaches, such as amplifying the effect of electrons at the screen, spots moving faster than 3×10^{10} cm s^{-1} can be recorded. Various techniques have been used in the past to enhance the trace recording capability. The oldest was to put photographic film inside the evacuated envelope and to write directly on film. In 1930 a technique was developed to write with electrons directly on film in atmosphere through a Lenard window.[6] Using a 1-mA beam at 75 keV emerging through a 16-μm thin foil, photographic writing speeds of 10^6 cm s^{-1} were attained. Today, a favorite technique is to use a microchannel-plate amplifier to multiply the number of electrons impinging on the fluorescent CRT screen. This approach is employed in the CRT described in this paper.

The writing speed of an oscillographic system depends on such factors as camera quality, film sensitivity, and the brightness of the trace on the CRT screen. This trace brightness, under conditions where phosphor is not saturation limited, is proportional to the energy density deposited by the electron beam, namely:

$$B_T \sim (I_B \times V)/TW, \tag{3}$$

where B_T is trace brightness, I_B is the current in the electron beam, and TW is the tracewidth. The trace brightness thus determines the linear writing speed of a system, expressed in cm s^{-1} for spot travel velocity. Since CRT spots and screens vary in relative size, a more meaningful indicator of capability to acquire information is the information writing speed (IWS), which is expressed in a number of resolvable dots that can be recorded per unit time:

$$\mathrm{IWS} \sim (I_B \times V)/TW^2. \tag{4}$$

The information writing speed measured in tracewidths per second, the total number of tracewidths which the system can resolve, and the fidelity of frequency response (bandwidth) are then parameters which describe how fast an oscillograph is.

In the proportionality (4), the expression on the right-hand side can be recognized as power density in a CRT beam where it impacts the screen. Attainable power density in an electron beam has an upper limit given by the modified Langmuir expression:[7]

$$D \sim \rho_c V^2 \Theta^2, \tag{5}$$

where D is maximum power density available in the focused spot, ρ_c is current density at the cathode, V is the screen potential, and Θ is the angle of convergence of the electron beam cone as it comes into focus at the screen. Performance of conventional CRTs can always be traced back to the above expression. The product $V^2\Theta^2$ leads to the beam deflection region and indicates that CRT performance will fall proportionally to the square of deflection sensitivity in electrostatically deflected CRTs. This is unfortunate, since the properties of silicon used in high-bandwidth solid-state amplifiers limit the amplitude of signals available to drive deflectors. While voltage swings of more thant 10 V cm^{-1} are available in low bandwidth applications, amplifiers in the gigahertz region rather provide something like 1 V cm^{-1}. CRT performance can be regained to a degree by increasing the cathode loading ρ_c and, indeed, this has been the trend which started early in this decade. Improvements in design techniques have brought a classical CRT to its theoretical limits and the art advanced further when viable methods were found to boost the effect of electron-beam impact available at the screen. Today there are two such methods in general use. One approach is to let the electron beam impact an array of diodes on a wafer of silicon.[1] Each electron impacting with energy of 10 keV will produce around 2000 electron-hole pairs; the charge is collected and electronically read out. The other, more recent technique, employs microchannel-plate multipliers, a technique which is a fallout from advances in night-vision developments. A microchannel plate[8] is an area electron multiplier, which for each incoming electron produces from 1000 to 10,000 electrons. These output electrons are then attracted to an adjacent phosphor screen to produce an image of the oscilloscope trace. The microchannel plate (MCP) multiplier technology is relatively young, it emerged in late 1960's. Early experiments, performed in 1972, with CRTs which had MCP multipliers built in to enhance the writing speed, established the basic traits of such devices[14] and fulfilled high expectations. Large-area rectangular (8×10 cm) MCP multipliers have only recently become available and one such MCP is used in our high-speed CRT.

III. THE MICROCHANNEL PLATE CRT

The evolution of electron optics from a conventional CRT to a sophisticated device like this tube is schematically depicted in Fig. 1. A conventional CRT with only vertical

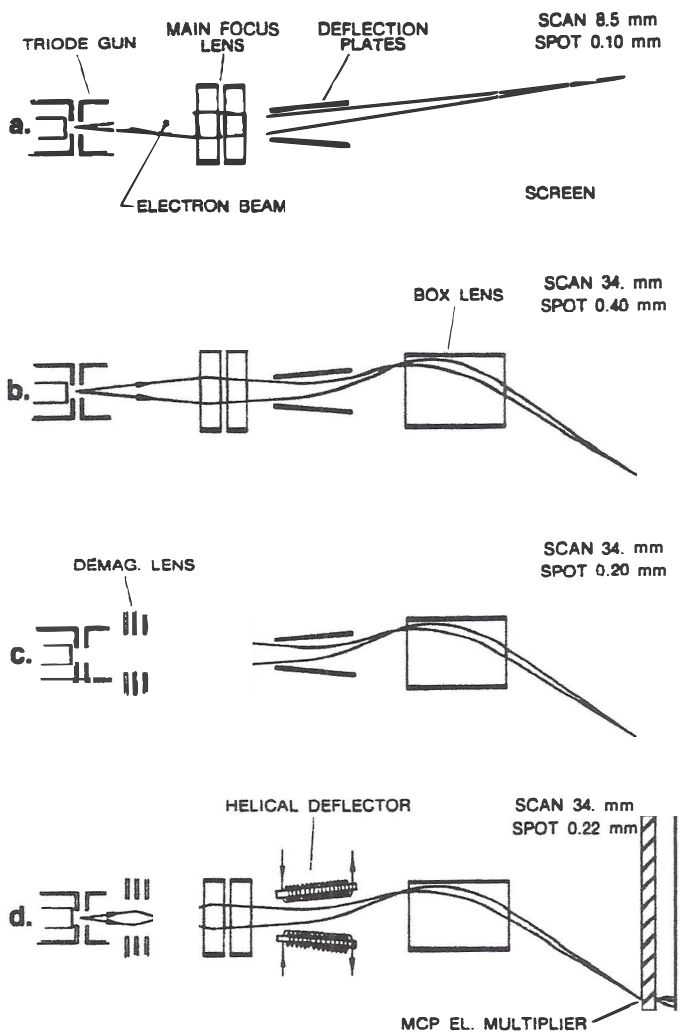

FIG. 1. Evolution of electron optics of the MCP CRT. Taking a conventional CRT representation (a), a scan-expansion box lens is added (b), then the spot demagnification lens (c), and finally the MCP election multiplier and helical deflector (d) to bring up the high-speed performance. Effects of various changes on total beam deflection and on the tracewidth are indicated along the side for comparison.

deflection plates is indicated for reference in Fig. 1a. A way to see how various changes influence the performance of this CRT is to follow two performance parameters: the amount of maximum deflection and the size of the spot at the screen; assume, then, that we have 8.5-mm deflection and 0.1-mm spot size in the beginning. In Fig. 1b, a novel scan expansion "box lens" is added.[9] This (in the vertical plane) is a strongly convergent lens, the effect of which is to magnify both the deflection and the spot size approximately four times. The deflection on the screen at this point attained its full value of 34.0 mm, but the spot size increased to 0.4 mm, which is too large to be desirable. To reduce the spot to a desirable value, a demagnification lens is added in Fig. 1c, its net effect is to reduce the spot magnification by a factor of two. At this point, the basic electron optical layout of the gun is finished and both the deflection and spot size approached their ultimate values of 34.0 and 0.2 mm, respectively. Finally, in Fig. 1d, elements which bring the high-speed performance up are added: the helical deflector which produces vertical deflection bandpass in excess of 2 GHz and the MCP electron multiplier, which allows spots moving across the screen in excess of 3×10^{10} cm s^{-1} to be recorded with a camera.

The complete MCP CRT is shown in Fig. 2, which reveals almost the entire structure except for the MCP multiplier which is mounted inside the funnel adjacent to the screen. The design has a number of interesting details, such as the spot demagnifying lens (introduced in Fig. 1c). The role of this lens is to shorten the overall CRT length, since the same performance could have been obtained by lengthening the axial distance between the triode gun and the main focus lens (Fig. 1a). An undesirable side effect from additional lensing thus introduced is that electron beam trajectories arrive at the main focus lens with relatively steep angles (compare Figs. 1b and 1c). Since lens aberrations increase with the cube of the beam envelope angle, it was necessary to design an exceptionally good main focus lens. Conversely the same large beam envelope angle appears at the demagnification lens exit. There, however, lens aberrations are less bothersome since physical beam excursion from the axis is small in that region.[10] Another unusual detail in the design of this CRT is that the horizontal deflector is also in the form of a helical delay line, as compared to customary solid deflection plates. The reason for this lies not so much in CRT optics, but rather in a fact that a constant impedance helical deflector presents to the fast horizontal sweep generator was preferred to a capacitive load which ordinary plates produce. The functioning of the box lens, Fig. 3, has been described elsewhere.[9] Two details related to high-speed performance, the helical deflector, and the MCP multiplier, deserve a few more words.

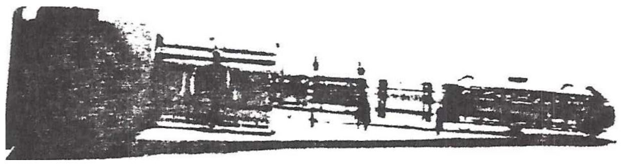

FIG. 2. The MCP CRT. The scan-expansion lens is plainly visible through the glass portion of the envelope, while the MCP multiplier is hidden in the ceramic portion of the funnel. Note the metal flanges joining the two portions of ceramic funnel. They are welded together to make the final seal.

A. Helical Deflector

The helical deflector with its side shields removed is shown in Fig. 4. It is in essence a pair of structures, each of which is a ribbon wrapped in a helical fashion, with a conductive solid core in the center. Each ribbon serves both as an electrical delay line and as one side of the deflector, since the voltage of electrical signals between two ribbons produces electrical fields which deflect the beam. A variety of

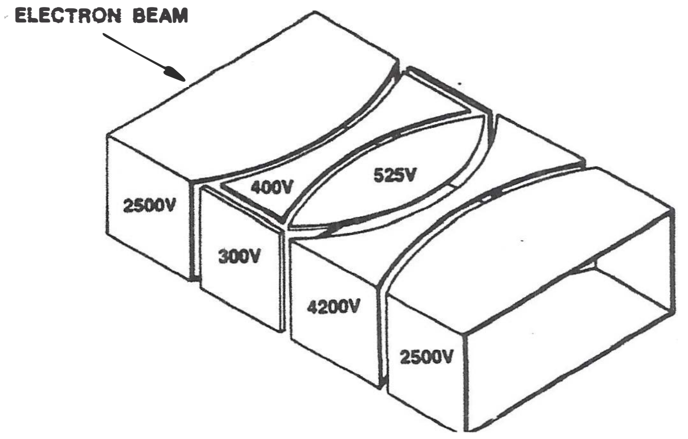

FIG. 3. Schematic of the box-like scan expansion lens. The lens is divergent in the horizontal plane, convergent in vertical.

beam deflection structures are in use, i.e., in Figs. 5a through 5c we see schematic representations of deflectors with increasing bandwidth capability. In Fig. 5d we have our deflector. In progression from low to high bandwidth, deflectors follow definite trends in several aspects. The consistent trend is for inductive and capacitive elements to become smaller and smaller incrementally, until they begin resembling an electrical stripline laid over a ground plane. Indeed, each side of our deflector can be viewed as having a ground plane folded into a rectangular prism, around which runs a stripline. Concurrent with this trend is the trend towards lower electrical line impedances, from around 350 Ω per one side in case 5b to 100 Ω per side in Fig. 5d, and the trend for the future is projected still lower, towards 50-Ω impedances. At these impedance levels, another type of adaptation of the stripline becomes viable; namely, a "meander-line" deflector, which in essence is nothing but a stripline meandering around so as to coincide the net electrical signal velocity with the velocity of the electron beam it is supposed to deflect. In all cases except for a solid plate deflector as in Fig. 5a, the average group velocity of electrical signals is synchronized with electron beam velocity. And in high-quality CRTs, symmetrical deflects driven by push-pull amplifiers are used. Close inspection of the photograph of our deflector will reveal that the helix is supported by the internal ground electrode using brazed ceramic supports, a technique which permits precise mechanical alignment and good high frequency characterisitcs.[11]

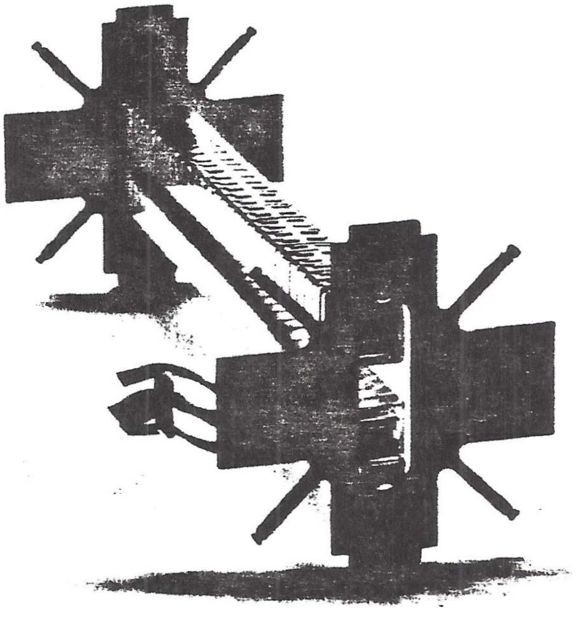

FIG. 4. The helical deflector. Electrical signals travel in helices in synchronism with electron beam, deflecting it. Note how helices are suspended off the internal ground structure, using ceramic pegs.

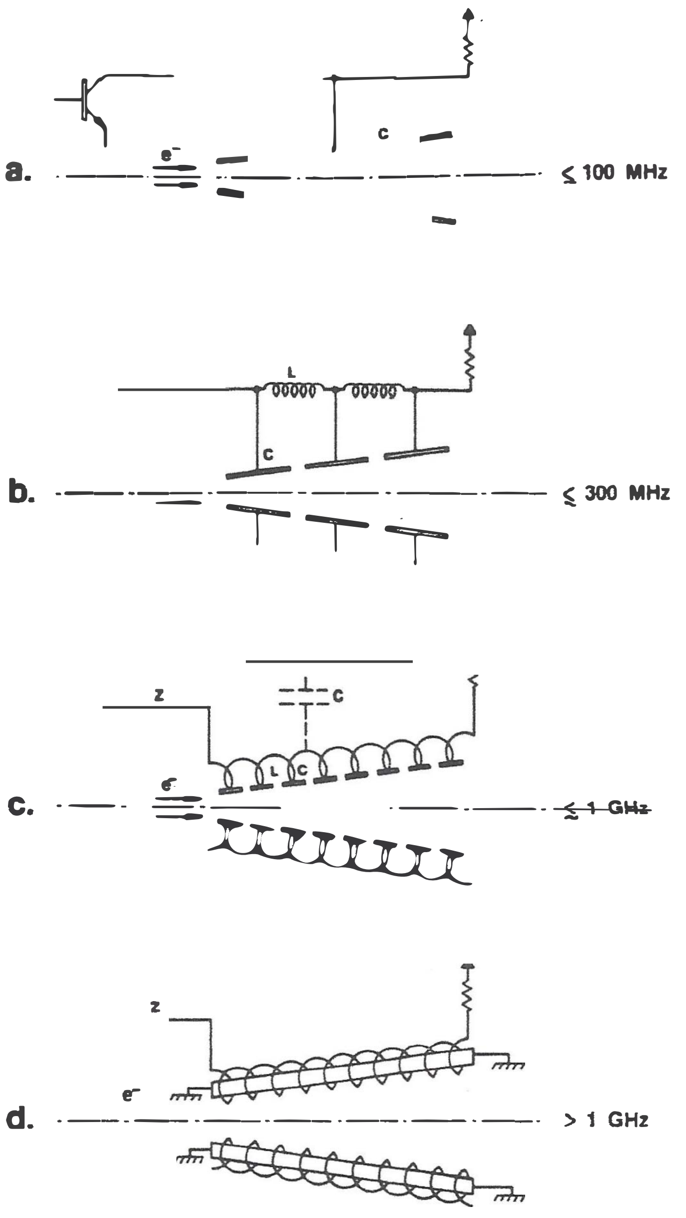

FIG. 5. Electron beam deflection strucures look more and more like signal transmission lines as requirements for bandpass increase.

B. The MCP Electron Multiplier

Electron multiplication using microchannel plates is today a well known technique. The MCP used in our CRT is a rectangular plate with sides of approximately 80 × 100 mm. It is 1 mm thick. The plate consists of an array of capillaries (channels) made out of lead glass and formed very precisely to match each other, so as to maintain uniform gain across the whole useful plate area. Figure 6 shows the top view and a section of typical plate, taken with a scanning electron microscope. The channels are 25 μm diameter, which with 1 mm thickness gives the customary optimal 40:1 diameter-to-length ratio for MCP operation.

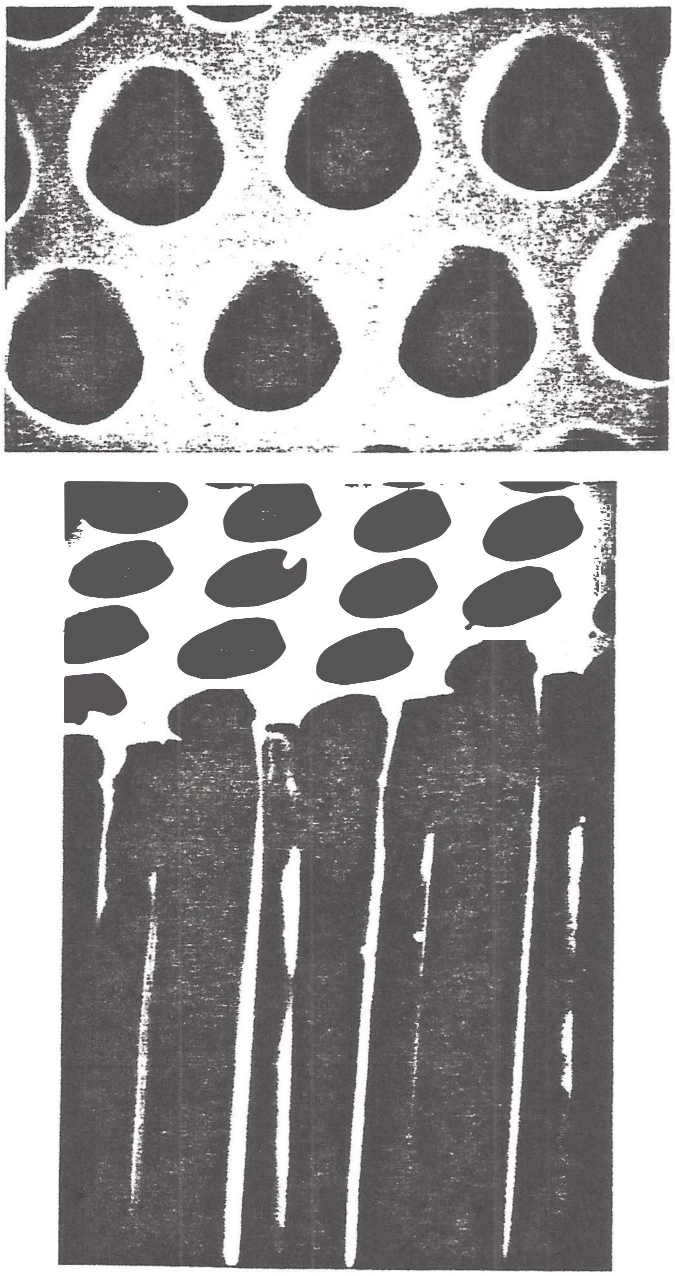

FIG. 6. Scanning electron micrographs of the MCP. Channels are 25 μm in diameter. Note some contamination on the sample.

A few important design parameters governing the application of an MCP multiplier are the "strip current," the "bias angle" and the "end-spoiling," this last one related to electron optics of producing the output image. The term "strip current" is used to describe the current flowing through the MCP under operating conditions. Namely, the process of electron multiplication in each channel will upset uniform potential distribution along channel walls, and the amplification will stop because of this saturation. Maximum current an MCP can deliver on output (and thus maximum brightness on the screen) has a value which roughly equals the strip current. Typical plates will have resistivities of 1000 MΩ/cm^2 of plate area and the goal is to reduce these resistivities. The strip resistivity is very dependent on conditions under which the MCP is processed, such as temperature and contaminants normally produced in glass CRT sealing.

In the MCP CRT, the final seal, except for the vacuum tipoff, is made by inert welding of two metal flanges in the funnel, which results in minimal contamination. The CRT is subsequently baked for extended periods, to purge the H_2O adhered to active surfaces. In spite of all the precautions in MCP processing, its gain still exhibits some instability,[12,13] namely, the gain deteriorates with electron bombardment, following a curve which looks similar to a decaying exponential. So all CRTs are pre-aged to approximately 50% of their initial gain, which significantly slows down subsequent gain deterioration. MCP gains typically used will be around 5000X. As plate gain approaches its maximum, spontaneous electron emission starts at random points. So the voltage bias applied to an MCP is typically lowered when high gain is not needed, within an operating range of 600-1200 V.

Channel axes in the MCP are not perpendicular to end surfaces, but are rather inclined by a so-called "bias angle," which is typically 15° to 20°. The purpose for this channel inclination is to arrange such geometry where the beam from the electron gun always strikes the portion of a channel wall close to the input end of the channel. Otherwise lack of electron gain would occur with normal impact; an MCP with no bias angle would exhibit a low-gain area in the center of the screen. On the other side, with "end-spoiling" one extends the metalization on the output end of the MCP to reach somewhat inside the channel. This kills the channel gain at the very end of the channel and thus provides a degree of mechanical collimation for output electrons. This, together with high electric field used to accelerate these electrons to the screen (12 kV over 3 mm) results in very small deterioration of resolution from using the MCP multiplier.

IV. SUMMARY

A CRT suitable for viewing and recording fast transient signals has been developed. The active screen area is 6.8 × 8.5 cm, and the overall tube length is 53 cm. The trace-width of around 0.25 mm is esthetically very pleasing and allows one an experience, in using the oscilloscope, to switch through decades of sweep speeds with the trace on the screen remaining seemingly unchanged in appearance. The high-speed deflector and the novel large-size MCP electron multiplier allow vertical bandpass in excess of 2 GHz and trace velocities in excess of 3×10^{10} cm s^{-1} to be recorded.

The electron optics in this tube is unique and is directed towards increasing the beam current density at the screen within a set of limitations, such as CRT length, screen size, deflection sensitivity, and trace quality. Beam optics optimization towards increasing current, while seemingly paradoxical at first thought, since such high electron gain is available in the microchannel plate, is necessary for a different reason than in classical CRTs. There, one needed sufficient beam current density to produce sufficient light output from a phosphor screen. With MCP multipliers, obtaining adequate light output from the screen is not a problem, since even a single electron entering a channel can be recorded on film. The limitation becomes statistical, for a beam sweeping swiftly across the MCP input side will be able to deposit only a limited number of electrons along its path. As an example, if the beam was moving at 3×10^{10} cm s^{-1} (approximate velocity at recording a 1-GHz sinewave over the whole screen) and the beam current was 1 μA all we would deposit within one 0.25-mm trace length would be five electrons.

V. ACKNOWLEDGEMENT

The development of the MCP CRT was done by a team of very dedicated and capable people under the leadership of Dennis Hall. The author was related to the project organizationally and had a privilege to be able to participate in many technical discussions. A great deal of information contained in this paper was provided by George Hashizume, Roger Bateman, Conrad Odenthal, and Al Christie, which is here gratefully acknowledged. Another source of information to the author were discussions with Benjamin Kazan, who provided some insight into early work in this field.

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