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Laser-Induced Arcing in Cathode Ray Tubes

Laser-induced arcing in cathode ray tubes has been used to study the effect of spontaneous internal high-voltage arcs under normal operating conditions. Ruby and Nd:YAG laser systems were compared as laser sources for the breakdown. Various arc-suppression schemes for CRT systems were evaluated for future use.

Introduction

High-voltage arcs in cathode ray tubes (CRTs) have been a problem since their inception. As anode voltages have risen and as the electronic circuits used to drive the CRT have become more vulnerable to high-voltage transients, this problem has become increasingly serious.

Extensive efforts have been made in the past decade by various CRT manufacturers to reduce the frequency and severity of arcs occurring in picture tubes used in commercial television and data display products. Other companies (including IBM), who use these CRTs, are working to harden the drive circuits to withstand the high electric field, voltage, and current transients produced during a CRT arc.

One of the major stumbling blocks in this work has been the inability to create an arc within the CRT on demand under normal operating conditions. Although several methods to stimulate an internal arc have been attempted, unpredictable arc occurrence and difficulty in controlling the system under test make these tests unreliable. Recently, after reports of laser-induced breakdown of gas-filled spark gaps [1, 2], several authors [3, 4] used lasers to induce arcs between electrodes in CRT electron guns. This technique has proved to be a valuable method in studying the performance of various arc-suppression techniques.

Arcing (flashover) in cathode ray tubes

• *Arcing mechanism in a CRT*

Arcing in a CRT may be defined as a low-impedance gas discharge from regions of the tube at the anode potential to another electrode at lower potential. This discharge momentarily raises the potential of the electrode elements to values of the anode bias. In general, there are two types of arcing in a picture tube: "interelectrode" arcing and "trigger" arcing (or "creeping discharge"), which results from a complex insulator-charging phenomenon.

The interelectrode arc occurs between two adjacent gun electrodes which have a high voltage applied between them. This arc occurs in a vacuum, either because of field emission from microprotrusions or passage of particulate matter from low- to high-voltage electrodes. The trigger arc is initiated by a relatively uncontrolled buildup of potential on the insulating glass surfaces at the neck of the CRT tube and at the multi-form glass bead in the low-voltage region of the electron gun. This type of arc is usually preceded by a visual blue glow of the neck glass in the vicinity of the cathode.

Various approaches have been used to minimize the occurrence or severity of interelectrode arcs. In addition, some manufacturers have treated their CRTs to minimize

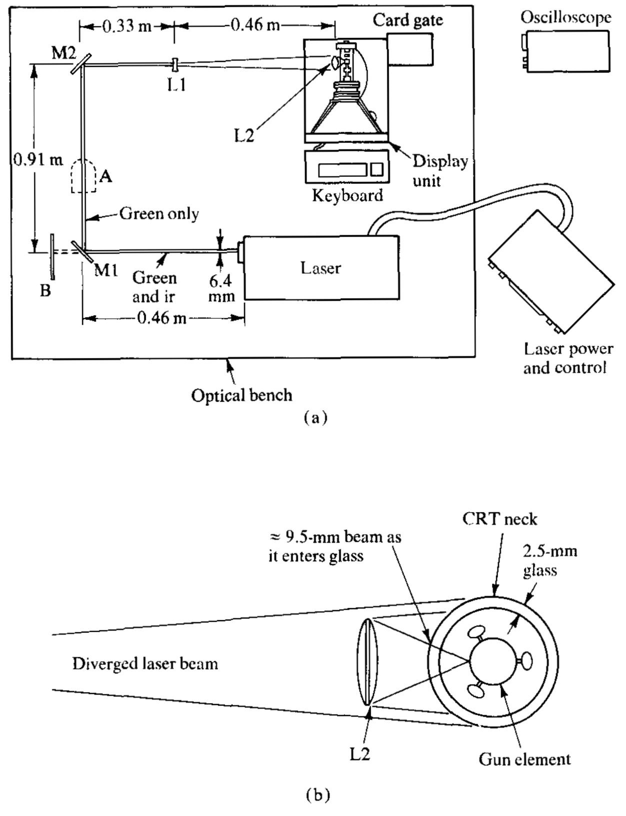

Figure 1 (a) Physical layout of Nd:YAG laser used to trigger arcs in CRT tubes; see text. (b) Magnified view of a laser beam focused on electrode.

flashover or creeping discharge [5]. It should be noted, however, that arcs induced by lasers or by other mechanisms are of the interelectrode type arc; thus, they have no direct relationship with creeping discharge in CRTs.

An interelectrode arc is thought to have three significant phases [6]. In the first, incipient phase conditions are established that allow a regenerative buildup of current. Usually, some source of low-level current exists around the electrodes. This electron source may be due to leakage from the thermionic cathode system, field emission from a contaminated surface, or secondary emission caused by microscopic particles bombarding an electrode. If the electrons transfer sufficient energy to the more-positive electrode, they may liberate adsorbed gases. Some of these gas atoms can be ionized and may drift back to the site of the electron source, in which case more electrons will be released. The second phase of the arc occurs when a dense plasma is created in the gap between the electrodes. Currents of hundreds of amps may flow through this short circuit. In the third phase, the arc is quenched when the energy stored in the tube capacitor is dissipated.

- *Simulation of an arc in a CRT*

It is generally acknowledged that most interelectrode arcing is caused by loose particles in the electron gun and in the tube neck. These particles can originate inside the tube as residue from the screen or the internal coating (*e.g.*, ®Aquadag), or outside the CRT from contamination during the production cycle or from gun weld splashes.

While the factors contributing to internal arcs in CRTs are well defined, one of the problems hindering the study of arcs is the inability to create an arc in the CRT on demand under normal operating conditions. Several methods have been tried in the past to simulate an interelectrode arc. These include 1) using "dirty" or gaseous CRTs that have not been properly "spot-knocked," or arced at high voltage in the final CRT manufacturing step; 2) applying either a mechanical shock or an external high-voltage electrostatic field to the neck of the CRT; 3) using an external spark gap; 4) inserting a magnetically controlled ball bearing [7]; or, recently, 5) using a laser to trigger the arc [3].

The first two techniques are neither predictable nor reliable. In the second, care must be exercised when using a mechanical shock to avoid imploding the tube. In addition, the effects of an applied field may disrupt or mask the effects of an actual arc. In the third method, although an arc can be produced predictably, many argue that its characteristics are different from those of a true CRT arc because it is produced in air rather than in a vacuum. This argument has merit, since once the air is ionized it supports conduction much longer than in a vacuum, because a source of ions is continuously available. The effects of an external arc thus tend to be more severe than in a true CRT arc and may represent a worst-case condition. However, the laser technique utilizes the intense energy density that can be delivered by the laser through the glass envelope of the CRT to ionize a small amount of material from the surface of the gun electrodes in a high-voltage gap; therefore, one can initiate and sustain arcs predictably. For these reasons, we concentrated on the laser-induced arc method for our study of arcs and arc-suppression techniques.

Performance evaluation of an arc-suppressed CRT

The laser beam power must be sufficient to generate a partially ionized metallic vapor and low enough not to cause major mechanical destruction. Free electrons are accelerated in the intense field to ionize the vapor to provide a momentary short-circuit path across the electrode gap. Two types of lasers (which can supply sufficient energy) are easily available. In our experiment, Q-switched ruby lasers (694.3 nm) and either Nd-doped:YAG lasers (1.06 μm) or frequency-doubled Nd:YAG lasers (533 nm) were evaluated.

• *CRT with high-impedance coating*

Experimental procedure The laser, an International Laser Systems Model LL-102 Nd:YAG, which had a 30-ns pulse width and a variable energy up to 250 mJ and which could be frequency-doubled to 533 nm, was arranged on an optical bench as shown in Fig. 1. Absolute stability of the bench and optical setup was not attempted, but the device was anchored to prevent inadvertent movement. The ir energy of the 6.4-mm-diameter laser beam passes through the first mirror M1, which reflects only the visible spectrum, and is absorbed by a cardboard baffle B.

The first mirror, which has two degrees of freedom, turns the visible beam 90° to the left and up slightly from parallel to the table. The second mirror M2, similar to the first and centered at the height of the CRT neck, intercepts the beam, turns it another 90° to the left, and returns it parallel to the table surface. The beam then encounters the first lens L1, a 25-mm-diameter, 54-mm-focal-length (f.l.) diverging lens, which spreads the beam diameter to ≈25 mm by the time it encounters the second lens L2. This 25-mm-diameter, 25-mm-f.l. converging lens is used to focus the beam to a fine spot on the electrode of the CRT electron gun.

This lens arrangement was used to prevent damage to the CRT glass envelope. The lens system spreads the beam over a relatively wide area as it passes through the glass envelope of the CRT, while still sharply focusing it on the electron gun element [see Fig. 1(b)]. We were very successful; no detectable damage occurred to the glass envelope, as had been reported by others [7], even though the CRT was subjected to many shots (in some cases over 500 at 20/s) at relatively high power (26 mJ). The laser beam power was measured at Point A, and although no attempts were made to calculate the losses due to the mirrors and lenses, they were <50%.

An IBM display with light pen and keyboard test vehicle was prepared by removing all external covers, opening the gate, and removing the CRT neck cone shield and the yoke shield in order to gain clear access to the electron gun. Also, the back cover of the spark gap socket was removed in order to observe the spark gaps. All other wiring, etc., was left untouched. At times, a small piece of solid wire was used under the rubber anode button to measure the CRT anode voltage. The unit was operated in TEST MODE during the test and the logic was periodically exercised via the keyboard to detect possible damage.

Observations The laser beam was focused on the corona curl of the G3 element (Point A of Fig. 2) and the laser energy was increased (at a repetition rate of 1 pulse/s) until small arcs were generated between G3 and G2. Although the display picture jumped due to high-voltage loading, the

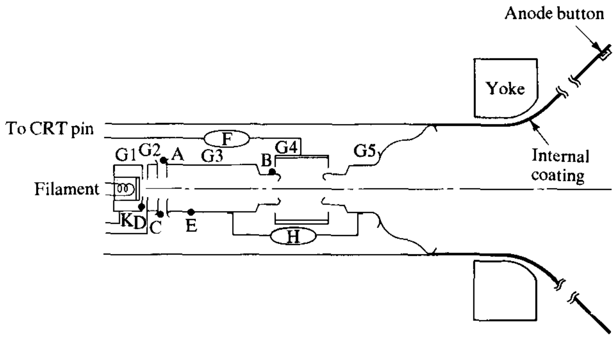

Figure 2 Conventional monochrome gun structure and impingement points of laser beam to induce an arc. See text for details; K denotes the cathode. In the internal surge-limited monochrome CRT gun structure, 15-kΩ specially treated ceramic resistors are located at points F and H; otherwise, the structure is the same as that of the conventional tube shown.

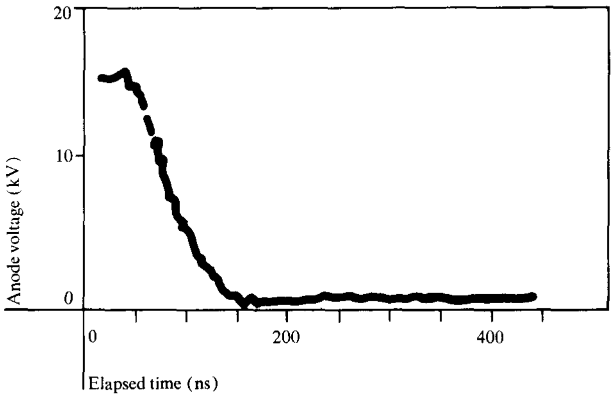

Figure 3 Voltage waveform at anode button during arc induction at G4 (conventional CRT).

high-voltage power supply did not trip out. (Ordinarily, when the high-voltage power supply detects a load >500 μA for a length of time, it shuts itself off and restarts after a delay of ≈10 s.)

Next, the laser beam was moved to the opposite end of G3 under G4 (Point B of Fig. 2) and pulsed again once per second. This scheme produced much more energetic arcs. The display screen became quite agitated, but the high-voltage power supply still did not trip out. The logic reset with each arc and keyboard clicking could be heard.

The voltage across the G4 spark gap was measured using an oscilloscope with a high-voltage probe. The spark gap did not break down until the potential drop across the gap approached 6000 V, even though the spark gap is rated at 1500 ± 500 V. A visible flash could be seen inside the CRT neck on G4 and the gap inside the socket had a visible breakdown. Next, the anode voltage was measured (Fig. 3).

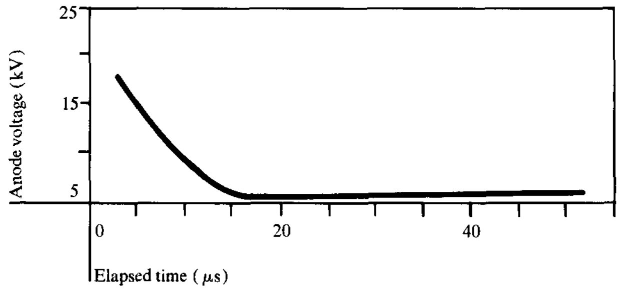

Figure 4 Anode voltage measured at anode bias point when G4 is arced with an internal surge-limited CRT.

Given an anode capacitance $C \approx 1.5$ nF and the rate of voltage change in time dV/dt, the current I drawn by the arc can be approximated from

$$I = CdV/dt. \qquad (1)$$

If the values $dV = 18$ kV and $dt = 125$ ns, measured from Fig. 3, are inserted in Eq. (1), $I = 216$ A, which is typical of arc currents quoted by others [7].

A good relative measure of the arc currents could be made in the following manner. The probe was attached to the spark gap return strap as close to the CRT socket as possible. The probe ground was attached to the opposite end of the strap where it connects to the CRT external grounding harness. The resulting voltage spike reached 3000 V. Since the inductance of this strap is ≈ 0.2 μH, the current transient is $\approx 1.5 \times 10^{10}$ A/s.

The laser was then focused on the G2 corona curl (Point C of Fig. 2). Strong arcs between G2 and G3 were plainly visible inside the tube. The G2 spark gap was visibly breaking down, the display screen was agitated, the logic reset, and the keyboard clicked as before. These results proved that arcs could be initiated between elements with a high potential difference between them; *i.e.,* 17 600 and 18 000 V between G2–G3 and G3–G4, respectively. Our next attempt was to initiate arcs between elements with much lower potential differences.

When the laser was focused on G1 (D in Fig. 2), strong visible arcs were generated between G1 and G2. The effect on the display screen was different from before; a bright streak or flash appeared on the screen with each pulse of the laser. The logic reset and the keyboard clicked intermittently. No spark gaps in the socket fired and no significant voltage transients could be detected on the spark gap return lead (the oscilloscope was triggered externally with a pulse from the laser control circuits because it could not be triggered internally as previously).

These results are consistent with expectations. Since there is only a 400-V difference between G1 and G2, the spark gap (rated at 1500 V) does not fire, and thus no current transients are induced in the spark gap return lead. The bright flashes occur because the arc causes the potential at G1 to be raised quite positive with respect to the cathode, resulting in a "zero-bias" condition. This forces the electron beam "on" to a high level, exciting the phosphor as it is swept across by the deflection circuits. Needless to say, the video drive circuit has no control under these conditions.

At this point, we experienced our first hardware failure. The display logic gate began to smoke and the analog card video circuit failed. This is typical of the video circuit failures in the field. In the past, the only way of duplicating this failure in the laboratory was by enlarging the G1 or cathode spark gap to ≈ 3000 V (an out-of-specification condition) and arcing externally. The average laser power was measured at this point and the energy of each pulse was found to be ≈ 26.4 mJ. For a 30-ns pulse, the maximum power reached was ≈ 800 kW. The card was replaced, but before we could resume testing it again failed in the same way. We assumed that the CRT arced spontaneously in the same area due to the damage caused by the laser to the G1 element. This damage was minor, but visible to the eye as a slight scarring of the metal at the focus point of the laser beam very near the edges of the gap between G1 and G2.

Some degree of CRT arc-suppression has been achieved by applying a high-impedance internal coating around the neck and cone area of the bulb to reduce the surge current amplitude during an arc. This had been tried by several companies with limited success [3, 6, 8]. Recent improvements in the coating processes encouraged us to investigate further, and we replaced the previous CRT with a high-impedance coating. Otherwise, the tube was identical to a regular CRT. The laser was focused onto G3 near G4 as in Point B of Fig. 2 and the laser was pulsed once per second. The display screen was much less agitated, although the logic still reset. The keyboard did not click as often as with the standard CRT. Figure 4 shows the anode voltage as measured with the 1000:1 ac-coupled probe. Notice the change in scales from Fig. 3. Using Eq. (1) to calculate the arc current with $dV = 1000$ V, $dt = 2$ μs, and $C = 1500$ pF, the peak current is only 0.75 A, considerably less than the 216 A calculated with the standard CRT. No significant transients could be measured on the gap return strap due to the very low current.

The laser was re-aimed at the G3–G2 gap (C in Fig. 2) with similar results. The laser was then aimed at the G1–G2 gap (D). Bright flashes were produced on the screen, as with the standard CRT. The laser pulse rate was increased to 20 pulses/s while aimed at the G1–G2 gap and allowed to run for ≈30 s in an attempt to duplicate the previous card failure with the experimental CRT. The card did not fail.

• *Performance test with ruby laser*

The CRT vendor had experimented with a ruby laser, so we repeated the evaluation of the arc-suppressed CRT to establish a correlation with their results. The ruby laser (HADRON/TFG Model 104A) was in Q-switched mode (694.3 nm) and produced single 1-J 10–50-ns pulses. Each pulse was triggered manually. The remaining equipment setup and test procedure was identical with that used during the Nd:YAG laser test.

The results at low energy were quite similar to those obtained with the Nd:YAG laser. However, when the pulse energy was raised to 400 mJ, visible scarring of the gun electrodes could be seen after only a few pulses, but no detectable glass or circuit damage occurred.

Further investigation yielded an unexpected result: multiple arcing. Figure 5 shows the G2 spark gap voltage at a reduced time scale. In addition to the multiple arcing, all of the spark gaps in this socket were firing when a high-energy laser pulse was delivered. We assume this is due to the fact that the higher laser energy releases significantly more material, which creates a momentary "gassy" condition that pervades the entire gun structure. Multiple, simultaneous arcs then occur until this ionized "gas" is recollected. This multiple-arc condition may have resulted from the relaxation oscillator formed with the resistance of the high-impedance coating, the CRT capacitance, and the negative resistance of the gassy electron gun and the spark gap of the socket. The laser was refocused onto G1 in an attempt to duplicate the analog card failure observed with the Nd:YAG laser. No card failure was observed.

• *Discrete resistor arc-suppressed CRT*

Performance test with Nd:YAG laser The latest technique to limit the arc current, reported by the Sony Corporation, replaces the stainless steel rod connecting G3 and G5 and another rod that biases G4 (see Fig. 2) with specially treated ceramic resistors. This new method replaces the difficult coating step in the CRT manufacturing process.

A CRT sample with the arc-limiting resistors was tested again with the Nd:YAG laser, and the performance was compared with that of a high-impedance coated CRT. The test environment of this sample was identical to those with the frequency-doubled Nd:YAG laser, except that the laser beam was not diverged prior to focusing. (Glass damage had not been a significant problem in these tests.)

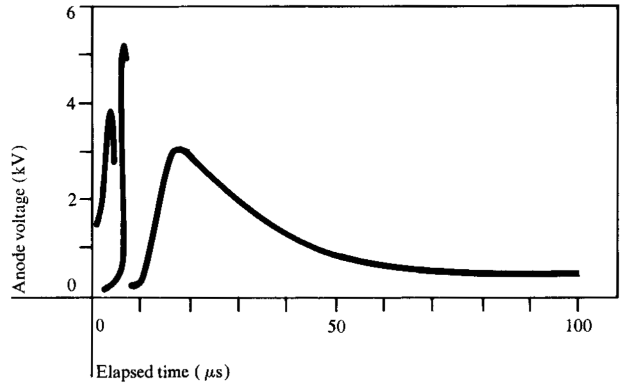

Figure 5 G2 spark-gap voltage at a reduced time scale when G2 is arced (internal surge-limited CRT).

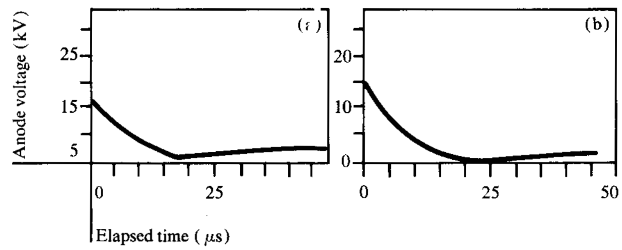

Figure 6 Anode voltage transients at anode bias point when an arc is induced in the internal surge-limited CRT (a) between G3 and G4, and (b) between G2 and G3.

Observations With the arc-suppressed internal surge-limited CRT installed, several shots were made at the G3–G4 electrode gap and the G2–G3 gap to test the effectiveness of the internal ceramic resistor. Typical CRT anode voltage waveforms are shown in Figs. 6(a) and (b). Currents of 1.8 and 1.5 A, respectively, were calculated using Eq. (1). The amplitude and duration of the arcs varied, but the slope of the voltage change remained fairly constant. The laser power used was measured at ≈3.5 mJ. As time went on, the slopes increased slightly as the laser warmed up and the laser energy increased. A maximum slope of 14 000 V/5 μs was measured; this is equivalent to a 4.2-A surge current, with a laser power of ≈7.9 mJ. One shot, however, yielded a disturbing result that could not be repeated (see Fig. 7). The distinct break points and the rapid slope suggest that the G3–G5 current-limiting resistors may have flashed over.

Next, the standard CRT was installed. The G3–G4 gap was arced, and the anode voltage traces showed slopes of 15 000 V/50 ns for $I = 450$ A, independent of laser power between 5 and 10 mJ. On several occasions the high-voltage power supply tripped off because of the arcing overload.

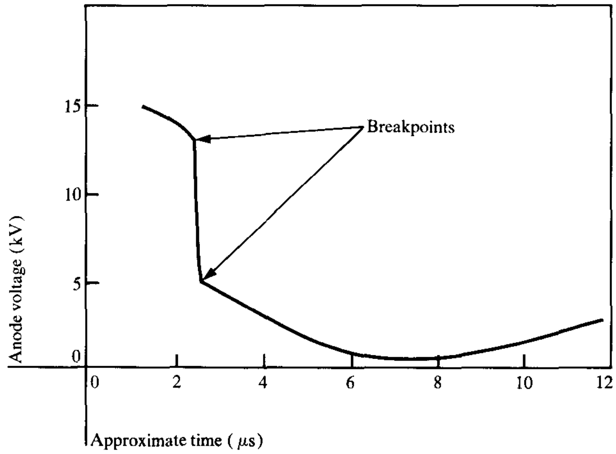

Figure 7 Voltage transient at anode bias point when an arc was induced at G3 and G2 in the internal surge-limited CRT (single unrepeatable shot).

Although this did not happen with the internal surge-limited CRT or in our other laser tests, it should be typical of a high-current arc.

Our next objective was to create analog card failures, especially in the video circuit. With the standard CRT still installed, the laser was focused on the G1–G2 gap. The video output transistor could be made to short fairly reliably after ≈3–50 arcs with a laser energy of 3.3 mJ at 1–10 pulses/s. Positioning and focusing of the laser spot were quite critical in obtaining good hard arcs. About five video cards failed in this test. The internal surge-limited CRT was then reinstalled. The first analog card failed after only ≈15 arcs at 5 mJ. However, the next card could not be made to fail even after ≈300 arcs at energies up to 25 mJ at 10 pulses/s. The third card would not fail after more than 500 arcs, even at high energy levels and with very careful lens focusing and placement. Finally, the standard CRT was installed and those cards that did not fail in the internal surge-limited CRT test were tested again. They all failed within 50 arcs on the standard CRT at ≈8 mJ.

Conclusions

We have shown that with high resistance in the current path, the maximum arc current is directly related to the series resistance by Ohm's Law, and that increasing the resistance decreases peak currents. However, simply increasing static resistance may not be an ideal solution. It is known that larger resistance values tend to decrease the effectiveness of the tube spot-knocking cycle. Even if arcing is no longer of concern, spot-knocking is still used to clean up stray emission or other foreign particles in the gun in the standard CRT manufacturing process.

The choice of how to implement the high-impedance path in CRTs varies among CRT manufacturers. The structure of the electron guns used is such that the discrete ceramic resistors in the connecting rods of the electrodes are best suited for data display CRTs where an Einzel lens type electron gun is used. In bi-potential color picture tubes, however, the resistor will not work, and a high-resistance coating around the neck area may be the best option [7].

Both methods of arc suppression proved to be quite effective in reducing the peak surge current. However, the arc-suppression system with two ceramic resistors has additional advantages over the high-impedance coating arc-suppression system. First, the CRT manufacturing process need only be modified to the extent necessary to replace the two connecting rods with two ceramic resistors on the electron gun. Second, since only the electron gun is modified, cathode ray tube reclaiming presents no difficulties. We have shown that increasing the series resistance inside the CRT can reduce the peak current ≈200 times. This improvement, accompanied by the reduction in the rate of current buildup and decay, did not interfere in any way with electrical and mechanical characteristics of the CRT.

For evaluation of the performance of the arc-suppression system, the use of a laser to induce arcing within the gun electrodes of a video display CRT under normal operating conditions proved to be very practical and reliable. The arc thus triggered appeared to be representative of spontaneous CRT arcs. This method of testing has many advantages over traditional methods, including repeatability, control of arc placement, and timing.

Both ruby and Nd:YAG lasers were effective in inducing an arc, but the Q-switched frequency-doubled Nd:YAG laser appears superior because of the capability for varying the output power level and a higher duty cycle. Very little energy is needed to trigger an arc (<1 mJ) and higher energy simply yields higher arc currents and more energetic results up to a point. At high beam energy, the technique of diverging and then reconverging the laser beam through a short-focal-length lens may be advisable to avoid glass damage. In addition to the need for controlling the energy level of the laser, focusing and beam-impact placement can be quite critical to achieving repeatable experiments. Arc effects could be significantly changed by moving the final lens slightly in any direction. The placement of the beam was especially critical in the G1–G2 gap.

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